ระบบคลื่นความถี่วิทยุของ เครื่องกำเนิดแสงสยาม ณ ศูนย์ปฏิบัติการวิจัยเครื่องกำเนิดแสงซินโครตรอนแห่งชาติในประเทศไทย

Mr. Klaus Haß

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IN THAILAND

Mr. Klaus Haß

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อิเล็กตรอนที่หมุนเวียนภายในวงแหวนสะสม (storage ring) ของแหล่งรังสีซินโครตรอน จะสูญเสียพลังงาน โดยการปล่อยรังสีออกมาแล้วจะเคลื่อนที่ช้าลง. โพรงความถี่วิทยุ (RF) ภายในวงแหวนสะสมจะคืนพลังงานนี้กลับไปให้อิเล็กตรอนเหล่านั้น. สมบัติของโพรงความถี่วิทยุ ที่ใช้ในวงแหวนสะสม มีความสำคัญเป็นอย่างมากต่อการดำเนินการของวงแหวน. ประเด็นหลักของวิทยานิพนธ์นี้ คือโพรงความถี่วิทยุ ที่จะนำไปใช้ในวงแหวนสะสมของสยามโฟตอนในอนาคต โหมดของโพรงสามารถที่จะบอกถึงลักษณะเฉพาะของโพรงนั้นๆได้ ซึ่งแต่ละโหมด จะมีลักษณะคล้อยตามความถี่ของการสั่นพ้อง, ความต้านทานเชิงซ้อนชันต์ และ ค่า Q. โหมดที่มีความถี่ต่ำสุดจะถูกใช้เร่งลำแสงอิเล็กตรอน และโหมดอันดับสูงขึ้น อาจจะนำไปสู่ความไร้เสถียรภาพของการเคลื่อนไหวของอิเล็กตรอน ที่เรียกกันว่า coupled-bunch instabilities.

การจำลองแบบของโพรงของ วงแหวนสะสม สยามโฟตอน ใช้โปรแกรมคอมพิวเตอร์ MAFIA และได้คำนวณ ความถี่การสั่นพ้อง, ค่า Q, และความต้านทานเชิงซ้อนชันต์ ของ โหมดที่สำคัญทุกโหมด. โปรแกรมคอมพิวเตอร์ ZAP ใช้ในการศึกษา coupled-bunch instabilities. นอกจากนี้ ยังได้เสนอการปรับโพรงโดยการสอดใส่ SiC ที่มีความต้านทานสูง เข้าไปในลำแสง เพื่อดูดกลืนสนามที่มีโหมดอันดับสูงต่อไป.

การวัดความถี่การสั่นพ้อง และค่า Q ทำได้ด้วยเครื่องวิเคราะห์สเปคตรัม ผลที่ได้แสดงให้เห็นว่า ค่าของความถี่การสั่นพ้อง ที่วัดได้ และที่คำนวณได้ ใกล้เคียงกันอย่างน่าพอใจ. อย่างไรก็ตาม ค่า Q ที่วัดได้นั้น มีค่าประมาณ ร้อยละห้าสิบ เมื่อเทียบกับค่าที่คำนวณได้. การที่ค่า Q ลดลงอาจจะมีสาเหตุจากการใช้โพรงในวงแหวนสะสม SORTEC ซึ่งโพรงนี้ได้ใช้งานเป็นเวลาเพียงไม่กี่ปี ก่อนที่จะเคลื่อนย้ายมาประเทศไทย

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KLAUS HAß: THE RF SYSTEM OF SIAM PHOTON SOURCE AT NSRC IN THAILAND,
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SYNCHROTRON RADIATION SOURCE / STORAGE RING / RF-CAVITY/ MODE / RESONANCE FREQUENCY / Q-VALUE / SHUNT IMPEDANCE / WAVE GUIDE / COUPLED-BUNCH INSTABILITY

Electrons that circulate inside a storage ring of a synchrotron radiation source loose energy by emission of radiation and slow down. A Radio Frequency (RF) cavity inside a storage ring is used to give back this energy to the electrons. The properties of the RF cavity, used in the storage ring, are very important for the operation of the ring. The RF cavity, used in the Siam Photon storage ring in the future, is the main subject of this thesis. A cavity can be characterized by its modes. Each mode is characterized by its resonance frequency, shunt impedance and Q-value. The mode with the lowest resonance frequency is used to accelerate the electron beam, and higher order modes may lead to instabilities of the electron motion, the so-called coupled-bunch instabilities.

Modeling of the cavity of the Siam Photon storage ring is carried out with the computer code MAFIA, calculating resonance frequencies, Q-values, and shunt impedances of all important modes. Coupled-bunch instabilities are investigated with the computer code ZAP. Furthermore, a modification of the cavity by the insertion of highly resistive SiC into the beam duct to absorb the fields of higher order modes is proposed.

The resonance frequencies and Q-values are measured with a Spectrum Analyzer. The results show good agreement between the measured and calculated resonance frequencies. However the measured Q-values are in the order of about 50% compared to calculated values. The reduction of the Q-values could be caused by the operation of the cavity in the SORTEC storage ring where it was used during the few years before it was transferred to Thailand.

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Klaus Haß

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Chapter I

Introduction

1.1 Physical Background

A synchrotron light source like Siam Photon Source at NSRC in Thailand generates synchrotron radiation by electrons, circulating inside a storage ring with almost the speed of light. The electrons are captured in bunches, which are usually separated by equal distances around the ring.

By the emission of radiation, the electrons loose energy and slow down. To keep them on a stable orbit, this energy must be given back to the electrons. Furthermore electrons within a bunch repel each other, and the bunched structure is not stable. Because of this, a synchrotron light source cannot operate without a radio frequency (RF) accelerating system. It consists of an RF cavity, which is installed in one of the straight sections of the storage ring. During operation of the storage ring, alternating electromagnetic waves resonate inside the cavity and supply the electron beam with an appropriate amount of energy. Furthermore the bunches of the electron beam are focussed by oscillation of the electromagnetic fields in time. Details of theory and operation of RF cavities were published by S. Turner (Turner, 1991).

Because the cavity is made of highly conducting material, there are boundary conditions on the inner cavity surface, and only waves with specific frequencies can resonate inside a cavity. A wave with this specific resonance frequency is called a cavity mode. An RF cavity has an infinite set of discrete modes. Each mode can be characterized by a resonance frequency, a Q-value, which is a measure for the quality of the mode, and a shunt impedance, which is a measure for the strength of interaction between the cavity and the electron beam. A distinction is made between monopole modes, that accelerate the electrons longitudinally, and dipole modes that deflect the electrons. The mode with the lowest resonance frequency is the so–called fundamental mode.

The electrons are accelerated by the oscillating electric field of the fundamental mode that resonates in a gap inside the cavity. Electrons gain the maximum amount of energy, if they pass the gap at the time when the field is in the right direction and at its maximum value. Electrons that arrive a short instant earlier or later perform oscillations around the optimal phase. This leads to a stabilization of the phase of the electron motion and the bunch shape. This effect is called longitudinal focusing.

To make phase stability of the electron motions possible, the frequency of the fundamental mode must be equal to a multiple integer of the revolution frequency of the electrons. This multiple integer is usually equal to the number of bunches inside the ring. The resonance frequencies of the modes depend on the inner shape of the cavity, and thus the dynamics of the electrons are very sensitive to this shape. The resonance frequencies can be adjusted by tuners, which are attached at different ports of the cavity. The tuners can be moved into and out of the cavity and allow small changes of the shape of the surface inside the cavity and thus a change of the resonance frequencies.

Modes with higher resonance frequencies, so–called higher order modes, can be excited by the circulating electron beam. If the frequency of the mode is close to a multiple integer of the revolution frequency of the electrons, the beam resonates with the excited mode of the cavity. This may lead to undesired longitudinal or transverse oscillations of the electron bunches around the ring. These oscillations are called synchrotron and betatron oscillations respectively. If the amplitudes of these oscillations grow with time, the beam motion may become unstable. These phenomena are called coupled–bunch instabilitiese (Cole, 1985; Zichichi et al., 1977).

The cavity is fed with an RF signal, with frequency equal to the resonance frequency of the fundamental mode. The signal is usually generated by a klystron and transmitted to the cavity by a wave guide system. The wave guide is connected to the cavity at a cavity port by an input coupler. It is important to match the impedance of the cavity with the impedance of the wave guide system and the klystron to ensure optimal coupling. Otherwise a large amount of the signal would be reflected by the cavity, which would result in high power losses. The coupling between the input coupler and the cavity is characterized by a so–called coupling factor, which is different for every mode.

1.2 The Siam Photon Source

The Siam Photon light source of National Synchrotron Research Center (NSRC) in Thailand maintains the synchrotron facility that was used for industrial applications by the former SORTEC Corporation in Tsukuba, Japan. After SORTEC was closed down, the machine was donated to Thailand, where it is scheduled to be used for advanced spectroscopic research. Because of this usage, an upgrading of the storage ring is necessary. The beam properties will be improved and four straight sections will be added into the ring for the insertion of so–called insertion devices, which generate radiation of high quality.

The Siam Photon light source consists of a short linac, a booster synchrotron and a storage ring. A drawing of the Siam Photon source is shown in figure 1.1

In the linac, the electron bunches are generated and accelerated up to 40 MeV. At this energy they are transported by low energy transport line and injected into the booster synchrotron, where they are accelerated up to 1 GeV. At this energy, the electrons are transported by high energy transport line and

Figure 1.1: Drawing of the Siam Photon source

injected into the storage ring. Both rings, the booster synchrotron and the storage ring, have one RF cavity (Kodaira et al., 1992; Awaji et al., 1992).

Each storage ring is characterized by so–called ring parameters, which characterize the design and operation condition of the ring. Because of the upgrading of the storage ring, the ring parameters of the former SORTEC ring and the Siam Photon Source are different. Although the Siam Photon Source ring is not set up yet, when this thesis is written, the ring parameters have been calculated already (Kengkan et al., 1998; Pairsuwan and Ishii, 1998).

Because of the future upgrading plan, the author of this thesis joined a ten month training during an upgrading program of the Photon Factory storage ring at IMSS, KEK in Tsukuba, Japan. The Photon Factory storage ring was upgraded to low emission operation, and four new cavities were installed into the ring. These cavities and a beam duct, which is connected to the cavities, were newly designed by the RF group of Photon Factory. The inner surface of the newly designed beam duct contained high resistive SiC, which can be used to absorb the fields of the undesired higher order modes, which leads to an improvement of the electron beam quality (Izawa et al., 1998b; Izawa et al., 1998a). This kind of design could be very useful for a future upgrading program of the Siam Photon storage ring.

The experience gained during this training is essential for a successful operation and possible upgrading of the Siam Photon storage ring. Because of this, a report of the installation and operation of the new cavities in the Photon Factory storage ring is presented in this thesis.

1.3 Research Objectives and Purposes of the Study

Investigation of the properties of the RF cavity of the Siam Photon storage ring and its effects to the electron bean inside the ring is the main subject of this thesis. Evaluation of the resonance frequencies, Q–values and shunt impedances of the storage ring cavity, and the effect to the electron beam, is done partly by measurements and partly by computer simulation. The dependence of the frequencies of the most important modes on the tuner positions is also measured.

Furthermore a modification of the storage ring cavity due to a reduction of the Q–values and shunt impedances of higher order modes by insertion of the high resistive SiC inside the beam duct is proposed.

1.4 Scope and Limitations of the Study

The research work contains a computational part and an experimental part. The computational part contains a modeling of the cavities of Siam Photon, where properties of all important cavity modes are investigated. Furthermore a proposal for a redesign of the cavity is given. This can be done by a modification of the beam duct shape inside the cavity and insertion of highly absorbing SiC inside the duct (Izawa et al., 1994). The SiC material is used to absorb the fields of the undesired higher order modes in a region, where the fields of the fundamental mode are small. This reduces the Q–values and shunt impedances of the higher order modes. The dependence of the cavity parameters on the change of the cavity geometry is investigated and presented in detail.

The redesigned cavity is then investigated in the same way as the original one. The results are compared and discussed. Investigations of the properties of the cavity of the booster synchrotron, where the electrons are accelerated before they are injected into the storage ring, are also carried out.

With the data of the original and redesigned cavity, the possibility of longitudinal and transverse coupled–bunch instabilities in the storage ring are investigated. The parameters of both, the old SORTEC ring and the Siam Photon source ring, are used for the investigations of possible coupled–bunch instabilities. The results are compared and discussed. A report of the computational work is published (Haß et al., 1998).

In the experimental part of the research, the properties of the storage ring cavity have been measured in detail. Resonance frequencies, Q–values and coupling factors of all important modes have been measured. The results are compared with those of the modeling. Two tuners are attached to the cavity, which can be moved by hand within a range of 15 cm during the measurement. The dependence of the frequencies of the fundamental mode and most important higher order modes on the tuner positions have also been measured.

1.5 Significance of the Study

The properties of the cavity have not been measured in detail, when it was operating at the SORTEC facility. A study of the cavity characteristics is very important to enable optimal operation of the cavity. If the interaction between the cavity and the electron beam is known, the operation of the cavity may be optimized, and problems due to the cavity operation can be solved efficiently.

When the Siam Photon storage ring will be upgraded in the next future, the operation condition will change, and the operation of the cavity has to be adjusted in an appropriate way. Because of this, a detailed knowledge of the cavity properties is essential. Furthermore, the experience gained during the upgrading program of the Photon Factory storage ring will be very useful for the set up and upgrading of the Siam Photon source.

1.6 Outline of the Thesis

In the second chapter of this thesis, the theory of RF cavities is given in detail. The beam dynamics due to effects of the fundamental mode and higher order modes are explained. Definitions and explanations of all significant ring parameters are included.

In the third chapter, a report of the installation and operation of new damped cavities at the Photon Factory storage ring is presented.

The fourth chapter describes the computational research work. The modeling of the cavities of the storage ring and the booster synchrotron are presented. The change of the properties of the storage ring cavity due to a change of the inner cavity surface and insertion of SiC into the beam duct is presented in detail. Finally one specific design is chosen as a proposal for a modification of the storage ring cavity. With the data of the modes of the original and modified cavity, the possibility of coupled–bunch instabilities is presented, while the ring parameters of both, the old SORTEC ring and the upgraded Siam Photon source storage ring are taken into account.

The fifth chapter contains the experimental part of the research. The measurement of the resonance frequencies, Q–values and coupling factors of the storage ring cavity are presented. The results are compared with the data that were found by computation. The measurement of the change of the resonance frequencies of the most important modes due to a movement of the tuners is also presented.

The last chapter contains a conclusion of the research work, and the results found by the investigations are summarized.

Chapter II

Theoretical Part

2.1 Basic Properties of an RF Cavity

2.1.1 The Maxwell Equations and its Solutions inside a Cavity

This section covers the maim properties of a cavity as a resonator. The most important physical values for the description of the properties of a cavity are derived. Details about RF theory were published by S. Turner (Turner, 1991).

An ideal cavity in general is defined as a dielectric, limited by perfectly conducting walls. The dielectric is supposed to be linear, isotropic and time invariant. The induced currents and charge densities inside the cavity are supposed to be zero. In this case, the Maxwell equations may be written as:

$$\nabla E = 0 \qquad \nabla H = 0$$
$$\nabla \times E = -\mu \frac{\partial H}{\partial t} \qquad \nabla \times H = \sigma E + \varepsilon \frac{\partial E}{\partial t} \tag{2.1}$$

where ε and μ are the electric and magnetic permeabilities and σ is the conductivity of the dielectric. With this the wave equation for the electric field inside a dielectric with the above mentioned properties may be derived:

$$\nabla^2 E = \mu\sigma \frac{\partial E}{\partial t} + \frac{\partial^2 E}{\partial t^2} \tag{2.2}$$

Furthermore on the perfectly conducting walls limiting the cavity, the following boundary condition must be fulfilled:

$$n \times E = 0 \tag{2.3}$$

where n is a vector perpendicular to the surface of the cavity walls. With this, the solution of the wave equation (2.2) is determined uniquely and may be written in the form:

$$E(x, y, z, t) = \sum_n a_n(t) E_n(x, y, z) \tag{2.4}$$

where $a_n(t)$ is a discrete set of time dependent and orthogonal functions. If this solution is inserted in the wave equation (2.2), the following differential equation for the time dependent functions $a_n(t)$ may be derived:

$$\frac{\partial^2 a_n(t)}{\partial t^2} + \frac{\sigma}{\varepsilon}\frac{\partial a_n(t)}{\partial t} + \frac{k_n^2}{\varepsilon\mu} a_n(t) = 0 \tag{2.5}$$

The parameter k_n together with the electric field E_n of (2.4) satisfy the homogenous Helmholtz equation

$$\nabla^2 E_n + k_n^2 E_n = 0 \tag{2.6}$$

The solution of (2.5) is:

$$a_n(t) = e^{-\frac{t}{\tau}}(C_1 \cos \Omega_n t + C_2 \sin \Omega_n t) \tag{2.7}$$

where C_1 and C_2 are integration constants which depend on the initial field distribution and

$$\tau = \frac{2\varepsilon}{\sigma} \tag{2.8}$$

$$\Omega_n = \frac{k_n}{\sqrt{\varepsilon\mu}}\sqrt{1 - \frac{1}{4}\left(\frac{\sigma\sqrt{\varepsilon\mu}}{\varepsilon k_n}\right)^2} = \omega_n\sqrt{1 - \frac{1}{4Q_n^2}} \tag{2.9}$$

These expressions show, that the electric field inside an undriven cavity is made up of the sum of standing fields each of which has form and frequency defined by the eigenfunctions and eigenvalues of the set. Each function $E_n(x, y, z)$ defines a resonance mode whose resonance angular frequency is ω_n. The quality factor Q_n is a dimensionless quantity that depends on the resonance frequency ω_n and the time constant τ of the mode.

2.1.2 The Q-Value of a Cavity Mode

An electromagnetic mode of a cavity is defined as a solution of the form (2.4) for one discrete value of n. For the derivation of the Q-value of a cavity mode, we assume that the electric and magnetic field may be written as:

$$A(x, y, z, t) = A(x, y, z)e^{(-\alpha + i\omega)t} \tag{2.10}$$

Substituting this expression into the Maxwell equations (2.1), the following identity may be derived:

$$-\frac{1}{2}\int_S P ds = \frac{1}{2}\int_V EJ^* dV - 2\alpha(U_H + U_E) + 2i\omega(U_H - U_E) \tag{2.11}$$

where $P = E \times H^*$ is the complex pointing vector and J is the current density. U_E and U_H are the average electric and magnetic energies, evaluated as the volume integral over the square of the fields. The intagration on the right hand side is taken over the cavity volume V and the surface of this volume s on the left hand side. The first expression on the right hand side is the power wasted in the dielectric and in the walls of the cavity.

$$\frac{1}{2}\int_V EJ^* dV = \frac{1}{2}\int_V \sigma \mid E \mid^2 dV = W \tag{2.12}$$

If we assume that the cavity is not fed from outside, both sides of (2.11) must be zero. Equating the real and imaginary parts, we obtain:

$$\alpha = \frac{W}{2(U_E + U_H)}; \qquad U_E = U_H \tag{2.13}$$

Thus we see that $1/\alpha$ has the same meaning as the time constant (2.8). The quality factor Q_n may be generalized by the definition:

$$Q_n = \frac{\omega_n}{2\alpha} = 2\pi \frac{U_E + U_H}{W T_n} = \frac{\omega_n U}{W} \tag{2.14}$$

where T_n is the period of the resonance frequency and $U = U_E + U_H$. The physical meaning of the Q-value is thus the ratio of the stored energy and the energy dissipated per cycle, multiplied with a factor of 2π.

The current density J only flows on the surface of the cavity within the skin depth δ, which is given by:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \tag{2.15}$$

Thus equation (2.12) may be written as:

$$W = \frac{1}{2}\int \frac{1}{\sigma\delta} I_{surf}^2 ds = \frac{1}{2}\int \sqrt{\frac{\mu\omega}{2\sigma}} I_{surf}^2 ds \tag{2.16}$$

Because U is independent of σ, we get the relation:

$$Q \propto \sqrt{\sigma} \tag{2.17}$$

2.1.3 The Coupling Coefficient

So far no external losses have been considered. The Q–value of a cavity mode is given by (2.14) where W represents the losses in the cavity. If the cavity is coupled to a transmitter and a transmission line, energy dissipates in the external system and the Q–value changes. The Q–value of the external system Q_{ext} is defined by:

$$Q_{ext} = \frac{\omega_n U}{W_{ext}} \tag{2.18}$$

where W_{ext} is power wasted in the external system. The loaded Q–value of the cavity Q_L is defined by:

$$Q_L = \frac{\omega_n U}{W + W_{ext}} \tag{2.19}$$

which leads to

$$\frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_{ext}} \tag{2.20}$$

with Q_o given by (2.14). The so–called coupling coefficient β is defined by:

$$\beta = \frac{Q_o}{Q_{ext}} = \frac{W_{ext}}{W} \tag{2.21}$$

which leads to:

$$Q_o = Q_L(1+\beta) \tag{2.22}$$

Three cases of coupling can be distinguished:

1. Critical coupling: $\beta = 1$, $Q_L = Q_o/2$
2. Under–critical coupling: $\beta < 1$
3. Over–critical coupling: $\beta > 1$

2.1.4 A Cavity with External Excitation

With an external excitation force $Ce^{i\omega t}$, the differential equation for the electric field of mode n inside a cavity (2.5) becomes:

$$\frac{d^2E}{dt^2} + \frac{\omega_n}{Q_n}\frac{dE}{dt} + \omega_n^2 E = Ce^{i\omega t} \tag{2.23}$$

If the trial solution $E = A(\omega)e^{i\omega t}$ is inserted into this equation, we get:

$$A(\omega) = \frac{C}{\omega_n^2 - \omega^2 + \frac{i\omega\omega_n}{Q_n}} \tag{2.24}$$

thus for $\omega \to \infty$, $A(\omega) \to 0$ and $A(\omega) = C/\omega_n^2$ for $\omega = 0$. If the external frequency ω is close to the resonance frequency ω_n, then

$$\omega_n^2 - \omega^2 = (\omega_n - \omega)(\omega_n + \omega) \approx 2\omega_n \Delta\omega \tag{2.25}$$

with $\Delta\omega = \omega_n - \omega$ and

$$A(\omega) \approx \frac{C}{2\omega_n\Delta\omega + \frac{i\omega_n^2}{Q_n}} \tag{2.26}$$

Thus $A(\omega)$ is maximum for $\Delta\omega = 0$. In this case the cavity is tuned to the resonance frequency and

$$\mid A(\omega_n) \mid = \frac{CQ_n}{\omega_n^2} \tag{2.27}$$

Because $Q_n >> 1, \mid A(\omega_n) \mid >> A(0)$ and $A(0) \approx 0$ may be assumed.

The stored energy in the cavity U is proportional to the square of the amplitude of the field.

$$U \propto \mid A(\omega) \mid^2 = \frac{\frac{C^2}{4\omega_n^2}}{\Delta\omega^2 + \frac{\omega_n^2}{4Q_n^2}} \propto \frac{1}{\Delta\omega^2 + \left(\frac{\omega_n}{2Q_n}\right)^2} \tag{2.28}$$

The quality of a resonator may be characterized by the width of the resonance (see figure 2.1). If $\Delta\omega_H$ is defined as the full width at half height of the $U(\omega)$ curve:

$$\mid A(\omega_n \pm \Delta\omega) \mid^2 = \frac{\mid A(\omega_n) \mid^2}{2} \tag{2.29}$$

Figure 2.1: Amplitude of the excited mode $| A(\omega) |^2$ around the resonance frequency

we get with (2.28):

$$Q_n = \frac{\omega_n}{\Delta\omega_H} \qquad \text{with} \qquad \Delta\omega = \pm\frac{\Delta\omega_H}{2} \tag{2.30}$$

Thus for $\omega = \omega_n \pm \Delta\omega$ the amplitude $A(\omega)$ has decreased to $A(\omega)_{max}/\sqrt{2}$ and the stored energy is reduced by a factor 1/2. From (2.30) it is clear that Q_n is a measure of the "narrowness" of the resonance and is therefor a measure for the quality of the cavity.

2.1.5 Reflection of a Wave by a Cavity

If an electromagnetic wave is sent to a cavity by a wave guide system, the cavity acts as a load, and a part of the wave is reflected by the cavity. The reflection coefficient $r(\omega)$ is defined as the ratio between the reflected electric field of the wave $E^-(\omega)$ and the input field of the wave $E^+(\omega)$.

$$r(\omega) = \mid r(\omega) \mid e^{i\phi} = \frac{E^-(\omega)}{E^+(\omega)} \tag{2.31}$$

where ϕ is the phase of the reflection coefficient. The forward traveling wave and the reflected wave interfere and form a standing wave pattern inside the wave guide. The field along the wave guide is given by:

$$E(\omega, z) = E^+(\omega)(1 + \mid r(\omega) \mid e^{i(\phi+2kz)}) \tag{2.32}$$

where z is the distance from the cavity and k is the propagation constant of the wave. If attenuation along the wave guide is negligible, k is real. Thus the amplitude of the wave is maximum for $\phi + 2kz = 2n\pi$ and minimum, for $\phi + 2kz = (2n+1)\pi$ where n is an integer. The ratio S of the maximum and minimum of the field amplitude is called the voltage standing wave ratio (VSWR) and is defined by:

$$S(\omega) = \frac{1 + \mid r(\omega) \mid}{1 - \mid r(\omega) \mid} \tag{2.33}$$

A corresponding transmission coefficient $t(\omega)$ is defined as the ratio of the electric field that resonates inside the cavity and the input field. The relation between the reflection coefficient and the transmission coefficient is:

$$\mid r(\omega) \mid^2 + \mid t(\omega) \mid^2 = 1 \tag{2.34}$$

If the cavity is excited externally, the transmission coefficient is proportional to the amplitude $A(\omega)$ of the field that resonates inside the cavity (2.24). Thus the reflection coefficient is minimum at the resonance frequency, and at frequencies close to resonance, the amplitude of the signal that is reflected by the cavity gives a resonance curve, and the width of the curve is a measure for the Q–value of the resonance mode (see figure 2.2). At frequencies far away from the resonance frequency, $r(\omega) \approx 1$. If $\mid r(\omega) \mid^2$ at $\omega_n \pm \Delta\omega$ is given by

$$\mid r(\omega_n \pm \Delta\omega) \mid^2 = \frac{\mid r(\omega_n) \mid^2 + 1}{2} \tag{2.35}$$

Figure 2.2: Amplitude of the reflection coefficient $\mid r(\omega) \mid^2$ around the resonance frequency

then with (2.34) and in analogy to (2.30):

$$Q_n = \frac{\omega_n}{\Delta\omega_H} \quad \text{with} \quad \Delta\omega = \pm\frac{\Delta\omega_H}{2} \tag{2.36}$$

By measuring the reflection coefficient at resonance, the coupling factor β can be calculated. It is given by the relation

$$\beta = \frac{1+ \mid r(\omega_n) \mid}{1- \mid r(\omega_n) \mid} \qquad \text{over–critical coupling} \tag{2.37}$$

$$\beta = \frac{1- \mid r(\omega_n) \mid}{1+ \mid r(\omega_n) \mid} \qquad \text{under–critical coupling} \tag{2.38}$$

Expression (2.37) is identical with the voltage standing wave ratio (2.33) at resonance. Figure 2.2 is thus an example for the resonance curve of critical coupling, because in this figure $r(\omega_n) = 0$ is assumed, correspnding to $\beta = 1$.

For a distinction between over–critical and under–critical coupling, the sweep of the phase $\phi(\omega)$ of the reflection coefficient must be considered. If ω sweeps out a sufficiently wide range over the resonance curve, the phase sweeps out a range between 0 and 2π. The relation of this sweep due to the kind of coupling is given as follows.

1. Under–critical coupling: Phase sweep $< \pi$
2. Critical coupling: Phase sweep $= \pi$
3. Over–critical coupling: Phase sweep $= 2\pi$

2.2 Cylinder Symmetric Wave Guides and Cavities

Wave guides which are used to transmit electromagnetic waves between two different points in space usually have rectangular or circular cross section. The RF cavities considered in this work are basically of cylinder symmetric shape. Thus the fields of a system with cylinder symmetric symmetry are considered in more detail. For the case of a propagating wave inside a cylinder symmetric wave guide, the electric and magnetic fields may be written as:

$$A(r,\phi,z,t) = A(r,\phi)e^{i(\omega t-\kappa z)} \tag{2.39}$$

where κz is the phase advance of the wave as it travels along the distance z, and the wavelength λ_g is defined as minimum distance between two points with equal phase at the same time. With v_p defined as the phase velocity, these values are related by the following expression:

$$\lambda_g = v_p T = \frac{v_p}{\nu} = \frac{2\pi}{\kappa} \tag{2.40}$$

The source free Maxwell equations in cylinder coordinates become:

$$E_r = -\frac{i}{k_c^2}\left(\kappa\frac{\partial E_z}{\partial r} + \frac{\omega\mu}{r}\frac{\partial H_z}{\partial \phi}\right) \quad E_\phi = \frac{i}{k_c^2}\left(-\frac{\kappa}{r}\frac{\partial E_z}{\partial \phi} + \omega\mu\frac{\partial H_z}{\partial r}\right)$$

$$H_r = \frac{i}{k_c^2}\left(\frac{\omega\epsilon}{r}\frac{\partial E_z}{\partial \phi} - \kappa\frac{\partial H_z}{\partial r}\right) \quad H_\phi = -\frac{i}{k_c^2}\left(\omega\epsilon\frac{\partial E_z}{\partial r} + \frac{\kappa}{r}\frac{\partial H_z}{\partial \phi}\right) \tag{2.41}$$

where the so–called cut–off wave vector k_c is given by the relation:

$$k_c^2 = \omega^2\mu\varepsilon - \kappa^2 \tag{2.42}$$

From this expression it is evident that the fields are uniquely determined by the longitudinal components E_z and H_z. In the case $H_z = 0$, the wave is called transverse magnetic (TM) and if $E_z = 0$, the wave is called transverse electric (TE). The longitudinal fields are determined by the wave equation:

$$\nabla_t^2 A_z + k_c^2 A_z = 0 \tag{2.43}$$

where A_z is the longitudinal field H_z or E_z, and ∇_t is the Nabla operator acting only on the transverse coordinates. If the boundary condition (2.3) is given on the walls of the wave guide, equation (2.43) may be solved for an infinite number of discrete real values of the eigenvalues k_c^2, and the solutions are the corresponding eigenfunctions. For a wave guide with radius a, the solutions are given by:

$$E_z = E_{mn}J_m(k_c r)\cos m\phi \quad H_z = H_{mn}J_m(k_c r)\cos m\phi \tag{2.44}$$

where J_m is the Bessel function of first kind and order m.

2.2.1 Classification of Modes

TE modes

In the case of TE modes, the cut–off wave vector k_c is given by the relation:

$$k_c a = P'_{mn} \approx \sqrt{\left(n + \frac{2m+1}{4}\right)^2 \pi^2 - \frac{4m^2+3}{4}} \tag{2.45}$$

with $m = 0, 1, 2 \ldots$, $n = 0, 1, 2 \ldots$ and P'_{mn} is a root of the derivative of the Bessel function $J'_m(x)$. The integer n counts the zeros of $J'_m(x)$. The case $m = n = 0$ corresponds to $k_c a = 0$. The wave with the lowest cut–off wave vector different from zero , corresponding to $n = 0$ and $m = 1$ is the TE_{11} mode. The solution of (2.41) is:

$$\begin{aligned} E_r &= H_{mn}\frac{i\omega\mu m}{k_c^2 r} J_m(k_c r)\sin m\phi \quad & H_r &= -H_{mn}\frac{\kappa}{k_c} J'_m(k_c r)\cos m\phi \\ E_\phi &= H_{mn}\frac{i\omega\mu}{k_c} J'_m(k_c r)\cos m\phi \quad & H_\phi &= H_{mn}\frac{\kappa m}{k_c^2 r} J_m(k_c r)\sin m\phi \end{aligned} \tag{2.46}$$

TM Modes

In the case of TM modes, the cut-off wave vector k_c is given by the relation:

$$k_c a = P_{mn} \approx \sqrt{\left(n + \frac{2m-1}{4}\right)^2 \pi^2 - \frac{4m^2-1}{4}} \tag{2.47}$$

with $m = 0, 1, 2 \ldots$, $n = 1, 2, 3 \ldots$ and P_{mn} is the n^{th} root of the Bessel function $J_m(x)$. The wave with the lowest cut–off wave vector, corresponding to $n = 1$ and $m = 0$ is the TM_{01} mode. The solution of (2.41) is:

$$E_r = -E_{mn}\frac{\kappa}{k_c} J'_m(k_c r)\cos m\phi \quad H_r = -E_{mn}\frac{m(\sigma + i\omega\varepsilon)}{k_c^2 r} J_m(k_c r)\sin m\phi$$

$$E_\phi = E_{mn}\frac{\kappa m}{k_c^2 r} J_m(k_c r)\sin m\phi \quad H_\phi = -E_{mn}\frac{\sigma + i\omega\varepsilon}{k_c} J'_m(k_c r)\cos m\phi \tag{2.48}$$

The waves may further be classified by the parameter m. Modes with $m = 0$ have no ϕ–dependence and its fields are cylinder symmetric. Modes with $m = 1$ are called dipole modes, modes with $m = 2$ quadrupole modes and so on. Modes with $m > 0$ have two possible polarizations. Equation (2.44) with $\cos m\phi$ replaced by $\sin m\phi$ is obviosly also a solution of (2.43) and corresponds to the other polarization. In a perfectly symmetric cavity, both polarizations have the same cut–off frequency, and the mode is double degenerated. However in a real cavity, there is no degeneration due to these polarizations because the symmetry is never perfect.

A stub of a wave guide may have properties of a resonance cavity. If the cross section of the guide, the frequency of the guide mode in operation and the number p of half wavelength included are given, the axial length d of a resonance cavity should be:

$$d = \frac{p\pi}{\sqrt{\omega^2\varepsilon\mu - k_c^2}} \tag{2.49}$$

In the case of $\kappa = 0$, the corresponding cut–off frequency ω_c is given by:

$$\omega_c = \frac{k_c}{\sqrt{\varepsilon\mu}} \tag{2.50}$$

2.2.2 Beam Coupling Impedances

A cavity can be excited by an electric convection current inside the cavity, a current carried by a probe or a loop or a tangential electric field on the surface of the cavity. The n^{th} resonance term of the electric field with ω close to the resonance frequency ω_n of the operating mode may be written as:

$$E(\omega) = \frac{1}{1 + i\tan\phi}\frac{E_n \int JE_n^* dV}{2P_n} \tag{2.51}$$

where P_n is the power dissipated in the walls for the corresponding mode, J the exciting current, E_n is the field of the corresponding mode (2.44), (2.46), (2.48) and

$$\tan\phi = Q_n\left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right) \tag{2.52}$$

where Q_n is the Q–value of the mode.

Now we consider the excitation of a cavity by a convection current of a charged particle beam with velocity v that transverses the cavity on the z–axis and is modulated by the frequency ω. The physical current is:

$$\mathrm{Re}\left[I_b(0)e^{i\omega(t-\frac{z}{v})}\right] = \mathrm{Re}\left[e^{i\omega t}I_b(0)e^{-i\frac{\omega z}{v}}\right] \tag{2.53}$$

The corresponding complex amplitude is:

$$I_b = I_b(0)e^{-ihz} \tag{2.54}$$

with $h = \frac{\omega}{v}$.

The Panofsky–Wenzel Theorem

The Panofsky–Wenzel Theorem describes the relation between the transverse force $F_\perp$ acting on a beam of charged particles with velocity v and the electric field. If the gap of the cavity, where the electrons are accelerated extents between 0 and l, the Panowsky–Wenzel theorem can be written as:

$$i\omega\int_0^l F_\perp e^{ikz}\frac{dz}{\nu} = \left[E_\perp e^{ikz}\right]_0^l - \int_0^l \nabla_\perp E_z e^{ikz}dz \tag{2.55}$$

where $\nabla_\perp = \nabla - \frac{\partial}{\partial z}$ is the Nabla operator acting only on the transverse coordinates. The left hand side of (2.55) describes the transverse momentum gained by a unit charge. The first term on the right hand side usually vanishes due to symmetry reasons. This relation shows that TE waves, where $E_z = 0$, have no effect to the transverse motion of the particle. Furthermore there is also no longitudinal force due to the motion of the particle, because in this case the energy is supplied or extracted to the particle, which can be caused only by the longitudinal electric field E_z. Since this field is zero, consequently TE modes have no effect to the beam at all.

The effect of TM modes is different for monopole and dipole modes. Monopole modes change the longitudinal momentum of a particle. Usually the mode with the lowest resonance frequency is the so–called fundamental mode that is used to accelerate the beam. Higher order monopole modes give rise to longitudinal oscillations of the particle beam as will be explained in the next section in more detail. Dipole modes of TM type change the transverse momentum of the particles and give rise to transverse oscillations of the beam.

Longitudinal Coupling Impedance

If we assume that a particle passes the cavity with constant velocity and arrives at the plane $z = 0$ at $t = t_o$, the real voltage gain V experienced by the particle is:

$$V = \mathrm{Re}[\int E_z e^{i\omega(t_o + \frac{z}{v})} dz] = \mathrm{Re}[e^{i\omega t_o} \int E_z e^{ihz} dz] \tag{2.56}$$

Therefore the complex amplitude of the effective accelerating voltage is:

$$V_{||} = \int_{-\infty}^{\infty} E_z e^{ihz} dz \tag{2.57}$$

The wave vector k is given by the relation:

$$k_c^2 = k^2 - h^2 = -\frac{\omega^2}{v^2}\left(1 - \frac{v^2}{c^2}\right) = -\frac{k^2}{\beta^2\gamma^2} \tag{2.58}$$

where β and γ represent the relativistic factors for a particle with velocity v.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad \beta = \frac{v}{c} \tag{2.59}$$

Equation (2.57) represents the Fourier transform of E_z with respect to z for a propagation constant ih. From the Helmholtz equation (2.43) and its solution (2.44), the Fourier Transform of E_z for a cavity with cylinder symmetric shape is given by:

$$V_{||}(r\phi) = V_{||}(r = 0) I_o \left(\frac{kr}{\beta\gamma}\right) \tag{2.60}$$

where $I_o(z)$ is the modified Bessel function of first kind and zero order. Equation (2.60) is only valid if r does not exceed the minimum radius of the cavity aperture along the z axis. Combining (2.54) and (2.57), we find:

$$V_{||} = \frac{\int E_z I_b^* dz}{I_b^*(0)} \tag{2.61}$$

The driving term in (2.51) thus can be written with (2.54) and (2.57) as:

$$\int J E_n^* dV = I_b(0) \int E_{nz}^* e^{-ihz} dz = I_b(0) V_{||n}^* \tag{2.62}$$

By definition, the longitudinal impedance seen by the beam is:

$$Z_{||}(\omega) = -\frac{V_{||b}}{I_b(0)} \tag{2.63}$$

where $V_{||b}$ is the effective accelerating voltage induced by the beam itself. Using (2.51), (2.57) and (2.62) it becomes:

$$Z_{||}(\omega) = \frac{1}{1 + i\tan\phi} \frac{| \int E_{nz} e^{ihz} dz |^2}{2P_n} \tag{2.64}$$

With (2.52), it can be written as:

$$Z_{||}(\omega) = \frac{R_{||n}}{1 + iQ_n \left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right)} \tag{2.65}$$

where $R_{||n}$ is the longitudinal shunt resistance of the cavity at its n^{th} resonance frequency on the cavity axis.

$$R_{||n} = \frac{| \int E_{nz} e^{ihz} dz |^2}{2P_n} = \frac{| V_{||n} |^2}{2P_n} \tag{2.66}$$

For the beam, in the vicinity of a resonance, the cavity behaves as a parallel resonance circuit. This definition holds regardless if the RF source is the beam itself or an external generator.

Transverse Coupling Impedance

If in (2.55) the velocity v is replaced by $\beta = v/c$ and divided by ω, it has the dimension of a voltage.

$$V_{\perp} = \int F_{\perp} e^{ihz} \frac{dz}{\beta} \tag{2.67}$$

It is called the effective deflecting voltage produced by the cavity. The integral is taken along the cavity axis between points, where the electromagnetic field of the cavity is negligible. From the Panofsky–Wenzel theorem (2.55) we get:

$$V_{\perp} = -\frac{1}{ik} \int \nabla_{\perp} E_z e^{ihz} dz \tag{2.68}$$

where $k = \omega/c$. If the dependence of E_z on the transverse coordinates is neglected, and the integral is taken at fixed transverse coordinates, we get with (2.57):

$$V_\perp = -\frac{1}{ik}\nabla_\perp V_\parallel \tag{2.69}$$

For a mode deflecting in x–direction, E_z is zero on the z–axis. If it is moreover assumed to be independent of y, its Taylor expansion is given by:

$$E_z = x\frac{\partial E_z}{\partial x}\mid_o + \cdots \tag{2.70}$$

For a beam close to the z–axis (2.68) may be written as:

$$V_x = -\frac{1}{ik}\int\frac{\partial E_z}{\partial x}\mid_o e^{ihz}dz \tag{2.71}$$

If the beam traverses the cavity at a fixed distance x_o off axis, with (2.54) and (2.70) the driving term becomes:

$$\int JE_n^* dV = I_b(0)x_o\int\frac{\partial E_{nz}^*}{\partial x}\mid_o e^{-ihz}dz \tag{2.72}$$

The transverse coupling impedance is defined as:

$$Z(\omega) = i\frac{V_x}{I_b(0)x_o} \tag{2.73}$$

where $I_b(0)x_o$ is the dipole moment of the beam current. The factor i ensures that in the case of resonance, the impedance is real and positive. Using (2.51), (2.71) and (2.72) it becomes:

$$Z_x = \frac{1}{k}\frac{1}{1+i\tan\phi}\frac{\mid\int\frac{\partial E_{nz}}{\partial x}\mid_o e^{ihz}dz\mid^2}{2P_n} = \frac{k_n^2}{k}\frac{1}{1+i\tan\phi}\frac{\mid V_{xn}\mid^2}{2P_n} \tag{2.74}$$

where $k_n = \omega_n/c$. Taking into account (2.52) it may be written as:

$$Z_\perp(\omega) = \frac{k_n^2}{k}\frac{R_{\perp n}}{1+iQ_n\left(\frac{\omega}{\omega_n}-\frac{\omega_n}{\omega}\right)} \tag{2.75}$$

$R_{\perp n}$ is the transverse shunt resistance of the cavity at its n^{th} resonance frequency, given on the cavity axis.

$$R_{\perp n} = \frac{\mid\frac{1}{k_n}\int\nabla_\perp E_{nz}\mid_o e^{ihz}dz\mid^2}{2P_n} = \frac{\mid V_{\perp n}\mid^2}{2P_n} \tag{2.76}$$

In the case of resonance, the expression simplifies to:

$$Z_\perp(\omega) = k_n R_{\perp n}(\omega) \tag{2.77}$$

In (2.76) the shunt resistance $R_\perp$ is defined in terms of the power loss P in the cavity walls for a given level $\mid V_\perp\mid$ of the deflecting voltage on the cavity axis.

Again this definition holds regardless if the RF source is the beam itself or an external generator.

Another important value is the ratio of the shunt impedance (2.66) or (2.76) and the corresponding Q–value of the mode.

$$\frac{R_s}{Q} = \frac{V_o^2}{2\omega U} \tag{2.78}$$

with V_o equal to $V_{n\|}$ or $V_{n\perp}$. Since $U \sim V_o^2$, this expression only depends on the cavity geometry. Thus this value can be evaluated by computer calculations very exactly. It allows, for example, the comparison of the effectiveness of different structures.

2.3 The Effect of an RF Cavity to a Charged Particle Beam

2.3.1 Storage Ring Parameters

The storage ring parameters, which are necessary for an understanding of the interaction of the cavity with the electron beam, are given in this section.

The Synchronous Particle

The particle that travels on the designed orbit with the designed energy is called the synchronous particle. Its energy gain during the passage of the RF cavity is exactly equal to the energy lost by synchrotron radiation during one revolution.

The Momentum Compaction Factor

The momentum compaction factor α is defined by

$$\alpha = \frac{p}{L}\frac{dL}{dp} \tag{2.79}$$

where p is the relativistic particle momentum and L is the circumference of the beam orbit. Thus the momentum compaction factor is the ratio of the relative change of the circumference of the particle orbit and the relative momentum change. It is a characteristic constant for every storage ring.

Emittance and β–Function

The equation of motion for a horizontal or vertical transverse coordinate y is given by:

$$y(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos(\phi(s) + \lambda) \tag{2.80}$$

where s is a coordinate tangential to direction of the ideal path and λ the starting phase. The amplitude of this motion consists of two factors. The factor $\sqrt{\varepsilon}$ is the beam contribution to the amplitude and called emittance, and $\sqrt{\beta(s)}$ is a periodic function, which describes the modulation of the amplitude due to the structure of the ring. This function is called β–function. The phase $\phi(s)$ must satisfy the condition:

$$\phi(s) = \int \frac{ds}{\beta(s)} \tag{2.81}$$

The horizontal and vertical emittances are constants, the horizontal and vertical β–functions are characteristic functions for each storage ring.

Betatron Tune

Excited dipole modes inside the cavity cause deflections to the particle beam. Particles which are deflected experience a restoring force by the focussing elements of the ring. This leads to transverse oscillations around the ring, which are called betatron oscillations. For each ring, a characteristic horizontal and vertical betatron frequency ν_x, ν_y is given. The ratio of the betatron frequency and the revolution frequency ν_o is called betatron tune.

$$\nu_\beta = \frac{\nu_{x,y}}{\nu_o} \tag{2.82}$$

Chromaticity

The betatron tune is defined for the synchronous particle. However it is a function of the particle momentum $\nu_\beta = \nu_\beta(p)$. The ratio of the relative momentum change and the relative change of the betatron tune is called the chromaticity.

$$\xi = \frac{\nu_\beta}{p}\frac{dp}{d\nu_\beta} \tag{2.83}$$

where p is the particle momentum and ν_β is the horizontal or vertical betatron tune. Also in this case, the values for horizontal and vertical chromaticities are usually different. Furthermore, chromaticities can be adjusted by sextupole magnets. Because of this, natural chromaticities, which are chromaticities due to the ring structure, if no sextupole magnets are used, must be distinguished from chromaticities during operation.

2.3.2 The Effect of the Fundamental Mode

The fundamental mode of a cavity is the monopole mode with the lowest resonance frequency. It is by far the most important mode and gives the desired effects to the electron beam. All other modes are affecting the beam by introducing beam instabilities and are called higher order modes.

The fundamental mode has two main effects. First it supplies energy to the particles which is lost by emission of synchrotron radiation. Second it

Figure 2.3: Energy gain eV of the electrons in the cavity versus time, U_o: enregy loss by synchrotron radiation per revolution

captures the bunches of the beam by its oscillating electric field. Because the electrons are accelerated by alternating electromagnetic fields, the energy gain is a periodic function of time. It is shown in figure 2.3, where U_o is the energy lost by synchrotron radiation during one revolution and eV is the energy gain. Only particles that pass the cavity at times at which $eV > U_o$ get a sufficient amount of energy and can be stored in the storage ring. This effect leads to a focussing of the electron bunches and is called weak focusing or longitudinal focusing.

By these effects, the particles stay on an equilibrium orbit around the ideal path around the storage ring, and the bunched structure is stabilized. The physics of these processes are described in this section (Wilson et al., 1985).

Longitudinal Focusing

The shape of a cavity contains a gap, where the accelerating voltage is supplied to the beam. Particles can only be accelerated if the field is in the right direction during the passage of the particle. The frequency of the accelerating mode must thus be a multiple integer of the revolution frequency. Particles within a bunch have slightly different energies. Particles with different energies have different revolution frequencies, because they have different paths and speeds as they move around the ring.

To explain the effect of weak focusing, let us assume, that the revolution frequency of the particles decrease with increasing energy. The synchronous particle passes the cavity at the time, when $eV = U_o$ in figure 2.3 on the falling part of the curve.

Consider a particle within the same bunch that has a higher energy and passes the cavity at the same time as the synchronous particle. At the next passage of the cavity gap, the synchronous particle gets the same amount of energy again, and the particle with higher energy arrives later at the gap. It then receives a lower amount of energy as the synchronous particle, and its energy is reduced. After one more revolution, the particle arrives earlier because its revolution frequency has increased due to the reduction in energy.

If the revolution frequencies of the particles increase with increasing energy, the particles are focussed on the rising part of the curve where $eV = U_o$ of figure 2.3. In electron storage rings, particles with higher energy usually have lower revolution frequencies, because their speed is very close to the speed of light, and the effect of increase in speed is less important than the increase in path length, which is caused by an increase of the bending radius of the bending magnets with higher energies.

By these effects, the particles oscillate longitudinally around the optimal phase of the RF voltage with a characteristic frequency ν_l and are focused in energy and phase. The characteristic frequency is a constant for each storage ring and is called synchrotron frequency. Furthermore the synchrotron tune ν_s is defined as the ratio of the synchrotron frequency and the revolution frequency:

$$\nu_s = \frac{\nu_l}{\nu_o} \tag{2.84}$$

The Equations of Motion due to the Fundamental Mode

In his section, transverse motions of the particles are ignored and the motion is supposed to take place in the longitudinal direction s only. If the momentum of the particle is p the equations of motion are:

$$\frac{\partial s}{\partial t} = \frac{p}{m\gamma} \qquad \frac{\partial p}{\partial t} = eE_l \tag{2.85}$$

where γ is the relativistic factor (2.59) and $E_l(s,t)$ is the longitudinal accelerating electric field. If the circumference of the ideal orbit is L, we can define an average radius by $r = L/2\pi$, a scaled angle $\Theta = s/r$ and an angular momentum $p_\Theta = rp$. With this the equations of motion (2.85) become

$$\frac{\partial \Theta}{\partial t} = \frac{p_\Theta}{m\gamma r^2} \equiv \omega_o \qquad \frac{\partial p_\Theta}{\partial t} = erE_l \tag{2.86}$$

where ω_o is the revolution frequency which may vary in time due to energy changes. If time dependence of the accelerating frequency ω_{rf} due to frequency modulation is taken into account, the phase of the RF field ψ is given by

$$\psi(t) = \int \omega_{rf}(t)dt \tag{2.87}$$

Because the accelerating field E_l is periodic in Θ and t it can be expanded in a Fourier series of traveling waves which has the form:

$$E_l = \sum_{n=0}^{\infty} E_n \cos(n\Theta + \delta_n) \sin\psi(t) =$$

$$\frac{1}{2}\sum_{n=0}^{\infty} E_n[\sin(\psi + n\Theta + \delta_n) + \sin(\psi - n\Theta - \delta_n)] \tag{2.88}$$

Inserting (2.88) in (2.86) leads to

$$p_\Theta = \frac{1}{2} er \sum_{n=0}^{\infty} E_n \int_0^t [\sin(\psi + n\Theta + \delta_n) + \sin(\psi - n\Theta - \delta_n)] dt \tag{2.89}$$

The main contribution to this integral comes from one integer h for which $\frac{d}{dt}(\psi - h\Theta)$ is approximately zero. All other terms have much higher oscillations and their contribution to the integral may be neglected. The number h is the harmonic number and is usually equal to the number of bunches inside the ring. It is related to the RF frequency by $h\omega_o = \omega_{rf}$. It is convenient to consider the motion of particles relative to the RF phase. Therefore we introduce a new phase variable ϕ which is the phase of the accelerating voltage relative to that of the particle:

$$\phi = \psi(t) - h\Theta + \delta \tag{2.90}$$

If the phase constant δ is set to $-\delta_h$, the accelerating field is simply $E_l = \frac{1}{2} E_h \sin\phi$. The equations of motion become with these definitions:

$$\frac{\partial \phi}{\partial t} = \omega_{rf} - h\omega_o \qquad \frac{\partial p_\phi}{\partial t} = -\frac{1}{h}\frac{\partial p_\Theta}{\partial t} = \frac{eV}{2\pi h}\sin\phi \tag{2.91}$$

where V is the accelerating voltage, given as the line integral of the electric field along the cavity axis. The Hamiltonian of the particle in these coordinates is given by:

$$H(p_\phi, \phi) = \sqrt{\frac{c^2 h^2}{r^2} p_\phi^2 + m^2 c^4} + p_\phi \omega_{rf} + \frac{eV}{2\pi h}\cos\phi \tag{2.92}$$

The Transit Time Factor

The accelerating gap of the cavity has a finite length and the accelerating fields change during the passage of the particle. This changes the value of the effective accelerating voltage. We suppose the origin to be the center of the cavity and the gap width to be g. If the integration variable is changed from t to Θ, the integration of (2.91) must be taken between $-g/2r$ and $g/2r$ The change in momentum is then:

$$\Delta p_\phi = er \int E_l dt = \frac{ehrE_h}{\omega_{rf}} \int_{-\frac{g}{2r}}^{\frac{g}{2r}} \sin(h\Theta + \phi) d\Theta$$

$$= \frac{ehrE_h}{\omega_{rf}} \left(\sin\phi \int_{-\frac{g}{2r}}^{\frac{g}{2r}} \cos h\Theta d\Theta + \cos\phi \int_{-\frac{g}{2r}}^{\frac{g}{2r}} \sin h\Theta d\Theta \right) =$$

$$F \frac{ehV}{\omega_{rf}} \sin\phi; \qquad F = \frac{\sin\frac{hg}{2r}}{\frac{hg}{2r}} \tag{2.93}$$

The factor F is called the transit time factor. It has a maximum value of 1 at $g = 0$ as expected and decreases slowly as g increases. The effect of the transit time factor is, that the accelerating voltage experienced by the particle decreases by the transit time factor due to the finite gap width.

Energy Loss by Synchrotron Radiation

If charged particles are accelerated, radiation is emitted. The radiated power is taken away from the kinetic energy of the particles. Thus energy must be supplied to the particles if they are stored in the storage ring at fixed energies. Particles performing circular motion as they pass a bending magnet with radius of curvature ρ emit radiated power P_γ, given by:

$$P_\gamma = \frac{dU}{dt} = \frac{C_\gamma c U^4}{2\pi\rho^2} \tag{2.94}$$

where e and m are charge and mass of the particle, U its total energy and

$$C_\gamma = \frac{4\pi}{3}\frac{r_e}{(mc^2)^3}; \qquad r_e = \frac{e^2}{mc^2} \tag{2.95}$$

r_e is the classical particle radius. For electrons the numerical value for C_γ is $8.85\ 10^{-5}\ m/GeV^3$. The energy loss per revolution U_o is:

$$U_o = \frac{RC_\gamma U^4}{\rho^2} \tag{2.96}$$

Obviously particle with higher energy emit more energy by synchrotron radiation than particle with lower energies. This means that energy spread of particles within an electron beam is reduced by this effect. Emission of synchrotron radiation only has a significant effect to the beam motion if its energy is large, that is if $U >> mc^2$. In this case, $p_\phi = Ur/c$ and

$$\frac{dp_\phi}{dt} = \frac{r}{c}\frac{dU}{dt} = \frac{Kp_\phi^4}{\rho^2} \qquad K = \frac{c^4 C_\gamma}{2\pi r^3} \tag{2.97}$$

and the equations of motion (2.91) become:

$$\frac{\partial\phi}{\partial t} = \omega_{rf} - h\omega_o \qquad \frac{\partial p_\phi}{\partial t} = \frac{eV}{2\pi h}\sin\phi - \frac{Kp_\phi^4}{\rho^2} \tag{2.98}$$

2.3.3 The Effect of Higher Order Modes

While the fundamental mode is excited in the cavity by an external generator, usually a klystron, higher order modes can be excited by the particle beam. If an electron bunch passes the cavity, it induces a voltage in each cavity mode by the electric field that the bunch carries with it. This induced voltage interacts with the following bunches. If the bunched electron beam is in phase with an excited higher order mode, the beam resonates with the higher order mode and the beam may become unstable. These phenomena are called coupled–bunch instabilities (Zichichi et al., 1977).

If the beam resonates with a higher order monopole mode, the amplitude of synchrotron oscillations may grow, which leads to bunch lengthening. If the

Figure 2.4: Motion of the bunches in synchrotron phase space due to the parameter a

beam resonates with a dipole mode, amplitudes of betatron oscillations may grow, which leads to an increase of the bunch cross section. In the worst case, particles may hit the walls of the vacuum chamber and get lost. The effect of the bunch lengthening and increase of the cross section both reduces the quality of the emitted synchrotron radiation, and these effects should be avoided.

Higher Order Monopole Modes

The phase condition for coupled–bunch instabilities can be derived as follows. Electron bunches circulating in a storage ring establish properties of coupled harmonic oscillators, which have different orthogonal modes. Each mode is characterized by the integer parameters μ and a. The parameter μ is the mode number that indicates the phase advance between adjacent bunches and may take values between 0 and $M-1$, where M is the number of bunches inside the ring (usually equal to the harmonic number h). The phase advance between adjacent bunches is $2\pi\mu/M$.

The parameter a is an integer that describes the characteristic of motion in the synchrotron phase space. The synchrotron phase space is defied as the space spanned by the time carried along the particle trajectory τ, and the relative angular velocity with respect to the synchronous particle $\dot{\tau}$. It is shown in figure 2.4. The mode $a = 1$ is called the dipole mode, where the bunches move rigidly as they execute longitudinal synchrotron oscillations. In the case of the quadrupole mode, corresponding to $a = 2$, the head and tail of the bunch oscillate longitudinally out of phase. To each mode, there corresponds an infinite number of eigenfrequencies, which are given by:

$$\omega(\mu, a, n) = \omega_o(nM - \mu - a\nu_s) \tag{2.99}$$

where n is an integer and ν_s is the synchrotron tune (2.84).

Instabilities of the bunch motions may occur, if a frequency of a bunch mode lies close to a resonance frequency of a higher order monopole mode of a cavity, so that the RF frequency can couple to the bunch mode frequency. The effect lies within a complex frequency shift $\Delta\omega$ of the bunch mode, while the motion is described by $e^{i(\omega+\Delta\omega)t}$. The growth rate $1/\tau_g$ is defined by

$$\frac{1}{\tau_g} = -\mathrm{Im}(\Delta\omega) \tag{2.100}$$

The value τ_g is called the growth time. Obviously a positive growth rate can cause an increase in amplitude of the motion and thus a possible instability. In the case $a = 1$, an analytical approximation for the growth rate is given by:

$$\frac{1}{\tau_g} = \frac{\alpha I}{4\pi U \nu_s}\Big(\sum_{n=-\infty}^{\infty} e^{-(\omega(\mu,a,n)\sigma_t)^2}\omega(\mu,a,n)\mathrm{Re}[Z_{||}(\omega(\mu,a,n)]\Big) \tag{2.101}$$

here α is the momentum compaction factor (2.79), I the total beam current, σ_t the rms bunch length in the time domain, U the beam energy and $Z_{||}(\omega)$ given by (2.65).

Longitudinal Damping

On the other hand synchrotron radiation, which is emitted by the beam, causes a damping of synchrotron oscillations. The energy of electrons performing synchrotron oscillations change periodically. If the energy of the particle is higher than the energy of the synchronous particle, it radiates more energy, and its energy decreases. If the energy is lower than the energy of the synchronous particle, it radiates less energy than the synchronous particle, and its energy increases. These effects lead to a reduction of the amplitudes of synchrotron oscillations. If the motion of the particle is displayed in phase space, spanned by the particle energy U and the time τ relative to the synchronous particle, it spirals into the center of the phase space as shown in figure 2.5. The damping rate for synchrotron oscillations $1/\tau_{rad}$ is approximately given by:

$$\frac{1}{\tau_{rad}} = \frac{r_e}{3}\left(\frac{U}{mc^2}\right)^3 \frac{4\pi c}{L\rho} \tag{2.102}$$

where r_e is the classical electron radius (2.95) and L the circumference of the beam orbit.

In addition to the radiation damping, there occurs so–called "Landau damping" of the bunch modes, which is caused by the spread of synchrotron frequencies within a bunch and nonlinear effects. It is given by (Kobayakawa et al., 1986):

$$\frac{1}{\tau_{lan}} = \frac{a}{2(a+1)}\frac{\omega_s \phi^2}{16} \tag{2.103}$$

where $\phi = 2.23\omega_{rf}\sigma_t$ and $\omega_s = \omega_o \nu_s$ is the synchrotron angular frequency. The total damping rate is the sum of the radiation damping rate and the Landau

Figure 2.5: Damping of synchrotron oscillations in phase space spanned by the time τ and energy E

damping rate.

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{lan}} \tag{2.104}$$

In conclusion, a coupled–bunch mode is considered as unstable, if its growth rate is higher than its total damping rate.

Treshold Current

The bunch motion can be described by:

$$\exp((\frac{1}{\tau_g} - \frac{1}{\tau_{tot}} + i\omega(\mu, a, n))t) \tag{2.105}$$

Equation (2.101) shows, that the growth rate rises linear with average beam current. This is also true for regions where this equation is not a good approximation. Thus a threshold current I_{tr} for a particular coupled–bunch mode, for which the growth rate of the mode is equal to the total damping rate, can be defined:

$$I_{tr} = I_{op}\frac{\tau_g}{\tau_{tot}} \tag{2.106}$$

where I_{op} is operation current for which the growth rate was calculated. With the threshold current stored in a bunch mode, transitions between stable and unstable oscillations may occur. The threshold current is thus the maximum current that may be stored in the corresponding coupled–bunch mode.

Higher Order Dipole Modes

As seen in section 2.2.1, dipole modes in a cylinder symmetric cavity are double degenerated. Two degenerated dipole modes, which have the same resonance frequencies, may be distinguished in terms of their effect to the beam. A mode is called h–type dipole mode, if it deflects the beam horizontally, and v–type dipole mode, if it deflects the beam vertically. Because of imperfections of the cylinder symmetry of the cavity due to tuner ports or construction imperfections, the resonance frequencies, corresponding Q–values and shunt impedances of h–type and v–type dipole modes are slightly different.

The formalism of transverse coupled–bunch instabilities is very similar compared to the longitudinal case. A coupled–bunch mode is characterized by the parameters μ and a, which are defined in the same way as in the longitudinal case. The bunch mode frequencies for transverse coupled–bunch-modes are given by:

$$\omega(\mu, a, n) = \omega_o(nM - \mu - \delta\nu_\beta - a\nu_s) \tag{2.107}$$

where $\delta\nu_\beta$ is the fractional part of the betatron tune. In the transverse case, the value $a = 0$ is also possible. The analytical approximation for the growth rate in this case is given by:

$$\frac{1}{\tau_g} = \frac{I\omega_o\beta}{4\pi U}\Big(\sum_{n=-\infty}^{\infty} e^{-(\omega(\mu,a,n)\sigma_t)^2}\mathrm{Re}[Z_\perp(\omega(\mu, a, n))]\Big) \tag{2.108}$$

where β is the average β–function of the ring and $Z_\perp(\omega)$ is given by (2.75).

Transverse Damping

Betatron oscillation of particles are damped by the acceleration of the particles by the fundamental mode, when they pass the cavity. Because the acceleration is in direction to the beam axis, the longitudinal component of the particle momentum p increases by δp and the slope of the momentum vector decreases as indicated in figure 2.6. If there was no acceleration, the particle would travel on the dashed path, due to the damping effect it travels on the solid path, corresponding to a lower amplitude of betatron oscillations. The radiation damping rate in the transverse case is approximately half of the value for the longitudinal case (2.102).

Landau damping in the transverse case is caused by a spread in synchrotron and betatron frequencies within a bunch. The effect due to a spread in betatron frequencies is much smaller and may be neglected. In this case, the Landau damping rate is the same as in the longitudinal case (2.103). Note that in the case of $a = 0$ no Landau damping occurs in this approximation.

Figure 2.6: Damping of betatron oscillations s: longitudinal, z: transverse coordinate $\vec{p}$: particle momentum, $\delta\vec{p}$: increase of the longitudinal particle momentum due to RF acceleration

Chapter III

The Cavities of Photon Factory

The Photon Factory storage ring in Tsukuba, Japan was closed down from early 1996 to September 1997 for an upgrading to low emission program. From October to December 1996 it was temporary in operation for a scheduled user run. During this period the commissioning of the ring was carried out (Izawa et al., 1998b). The storage ring has four RF cavities which were replaced by new ones during the closing period. During the scheduled user run at the end of 1996, the ring operated with two old and two new cavities. The author of this thesis joined the upgrading program from May 1997 to April 1998, when the last two cavities were installed. The properties of the new damped cavities and their operation in the storage ring are described in this chapter.

3.1 The Damped Cavities

The structure of new damped cavities for installation in the Photon Factory storage ring and a third generation VUV–SX synchrotron radiation source at a future project of the University of Tokyo have been developed (Kamiya et al., 1994; Takaki et al., 1996). For these rings, coupled–bunch instabilities due to higher order modes in an RF cavity is a serious problem, when a stable beam with high current is required. The damped cavities have large beam ducts, which are partly made of a SiC microwave absorber. Higher order modes which have frequencies higher than the cut–off frequency of the beam duct are expected to propagate out of the cavity and to be damped by the SiC parts. Low power measurements using a cold model of the cavity showed that the SiC beam duct strongly reduces the Q–values of higher order modes in the cavity (Koseki et al., 1994; Koseki et al., 1995a; Koseki et al., 1995b).

The parameters of the fundamental mode were calculated with the computer code SUPERFISH (Billen and Young, 1992). The result was a resonance frequency of 500.1 MHz, a shunt impedance of 7.68 MΩ and an unloaded Q–value of 44000. The normal operating voltage of the cavity system is 1.5 to 1.7 MV for both rings. In the Photon Factory storage ring, where four cavities are used, the nominal gap voltage per cavity is 0.4 to 0.45 MV. Taking into account the reduction of the Q–value by 10% for the actual cavity, the gap voltage requires an input power of about 30 kW that dissipates in the cavity. The value for the wall losses is 150 kW and has large safety margin and operational flexibility.

Figure 3.1: Schematic view of a damped cavity of the Photon Factory storage ring, dimensions in mm

Figure 3.2: New designed input coupler of the Photon Factory storage ring

ν (MHZ)	Q–value	$R_s/Q(\Omega)$	Mode
794	35900	52	TM_{011}
1312	8500	9.2	TM_{020}
1373	26800	9.0	—

Table 3.1: Higher order monopole modes of the Photon Factory storage ring

ν (MHZ)	Q–value	$R_t/Q(\Omega/\mathrm{m})$	Mode
703	40000	6.5	TE_{111}
793	43600	255	TM_{110}
989	22000	415	TM_{111}

Table 3.2: H–type dipole modes of the Photon Factory storage ring

ν (MHZ)	Q–value	$R_t/Q(\Omega/\mathrm{m})$	Mode
706	10300	6.5	TE_{111}
789	9000	255	TM_{110}
991	23200	415	TM_{111}

Table 3.3: V–type dipole modes of the Photon Factory storage ring

The high power model cavity was manufactured by Keihin Product Operation of Toshiba Corporation (Miura et al., 1995). Figure 3.1 shows the cross–sectional view of the high power model. The main part of the cavity is made of class 1 OFHC copper which had been treated with a Hot Isostatic Press before. A cooling water flow of 200 l/min is available with a pressure drop of 4 kgf/cm^3. The cavity has two beam ports and four side ports for an input coupler, a movable tuner and two fixed tuners. U–tight seal gaskets are adopted at the interface between the ports and the attached equipment. Figure 3.2 shows the input coupler of the cavity. The coupler was newly designed, based on the requirements of a 508 MHz APS cavity at the TRISTAN ring at KEK. The shape of the top of the coaxial line, where the coupling loop is placed, has been changed, and the positions of the short plates of the rectangular wave guide and the coaxial line was optimized in order to obtain minimal reflection at the operation frequency of 500 MHz (Nagatsuka et al., 1995). The fixed tuner is a cylindrical copper block with an ICE flange and was used in both, the new and the old cavities. Two of these tuners are attached to the bottom and the side port of each cavity. Higher order modes with high Q–values and frequencies below the cut–off frequency of the beam duct remain inside the cavity. These dangerous modes, which can cause coupled–bunch instabilities, are listed in tables 3.1, 3.2 and 3.3. The Q–value is defined by (2.14) and the values R_s/Q or R_t/Q are equal to (2.78).

These modes can be detuned to avoid these instabilities. For this purpose, the lengths of the fixed tuners were adjusted in order to shift the frequencies of the higher order modes away from the coupled–bunch–mode frequencies. This frequency shift method using two fixed tuners to detune higher order modes was first developed at Photon Factory (Izawa et al., 1988; Kobayakawa et al., 1989). Figure 3.3 shows an example of a frequency mapping of detuned higher order modes. Because the synchrotron tune $\nu_s << 1$, the bunch mode frequency in the longitudinal case (2.99) is equal to a multiple integer of the revolution frequency as indicated in the last column of the figure. In the transverse case the bunch mode frequencies differ from the longitudinal case by the fractional part of the betatron tune, indicated by f_{bx} and f_{by} according to equation (2.107).

The measurement of the unloaded Q–value of the accelerating mode with all equipment described above attached gave a value of 39500. With this and the result of the SUPERFISH calculation, the impedance of the accelerating mode was estimated to be 6.9 MΩ.

The SiC part of the beam duct was manufactured by Toshiba Ceramics Co. Ltd, and the trade name is CERASIC–B. It is fabricated by sintering in an argon atmosphere under normal pressure. It has an inner diameter of 140 mm, an outer diameter of 160 mm and a length of 150 mm. The resisitivity of the SiC material is about 50 Ωcm in a frequency range of 1 to 5 GHz. It was fixed inside the beam duct by a shrink–fit process (Izawa et al., 1995; Izawa et al., 1996). The beam duct itself consists of copper and has a water cooling channel on the outer surface. Since SiC has a high thermal conductivity of 100 W/mK, the temperature rise of the beam duct due to the power dissipation in the SiC is negligible under normal operation condition of the storage ring.

3.2 Installation of the first two Cavities and Beam Test

The operation of the storage ring with two new and two old cavities was successful during the scheduled user run from October to December 1996. A high current storage was attempted on December 12. An evacuation chamber is placed between the two cavities. It contains two 400 l/s ion sputter pumps, two Titanium sublimation pumps, three vacuum gauges, and a quadruple residual gas analyzer. The base pressure was 10^{-10} Torr after baking. Conditioning of the cavities was carried out in CW and pulse mode. An RF power of up to 90 kW for CW mode and 120 kW for pulse mode was put into the cavities during conditioning. Figure 3.4 shows the vacuum pressure and the output power of the klystron during the first beam storage after the installation of the first two cavities. Since each cavity is driven by one klystron, the klystron power equals the input power for each cavity. The stored current is also indicated in the figure. The vacuum pressure ranged around 10^{-8} Torr before an elapsed time of about five hours and 10^{-7} Torr thereafter. The vacuum pressure became higher with increasing stored current at first and then gradually decreased. Apart from this slow change in pressure, burst outgasing occurred. The worst one happened after an elapsed time of 3.5 hours. However the peak pressure did not exceed the range of 10^{-7} Torr. About ten hours after the first beam injection, a stored current of more than 400 mA was attained without any serious RF or vacuum problems.

Figure 3.3: HOM mapping of the cavity l: monopole mode, h: h–type dipole mode v: v–type dipole mode, f_r: revolution frequency, n: integer, f_{bx}, f_{by}: fractional parts of betatron tunes

Figure 3.4: Change of the vacuum pressure during the first storage

The conditioning continued for four days with a maximum stored current of 500 mA. After the conditioning, the base pressure decreased to the range of 10^{-9} to 10^{-10} Torr at a stored current of 350 mA, the nominal stored current in the user run. No burst outgasing was observed during the operation after conditioning.

The detuning of the higher order modes was quite successful. No transverse coupled–bunch instabilities could be detected. Longitudinal instabilities still occurred, but they were supposed to be caused by the two old cavities, because the frequency of the beam spectrum was different from the resonance frequency of the higher order modes in the new cavities.

At the end of the scheduled user run an increase of the stored current to its maximum was attempted. The maximum stored current was 500 mA until that time. As mentioned above, the conditioning in CW mode was performed below an input power of 90 kW. During the operation, the vacuum pressure began to rise when the input power exceeded 90 kW, which was caused by wall dissipation and beam loading. Since the cavity gap voltage was lower during operation than under conditioning, it was suggested, that the outgasing was caused by the input coupler. The maximum stored current of 773 mA was achieved during this operation, which is the record of the Photon Factory storage ring. No transverse coupled–bunch instability was observed up to the maximum current. A longitudinal instability was clearly observed on the spectrum analyzer, but it was not very harmful. The injection rate did not decrease drastically, and the quality of the beam seen in the synchrotron radiation light monitor was not much different from the quality of a low stored current. The only problem that occurred during the operation of the ring at the high current was a decrease in the lifetime of the beam. This problem could be solved by conditioning under high current operation. In the scheduled operation, which started in October 1997, the longitudinal instabilities, which were caused by the old cavities, were expected to disappear.

3.3 Operation with four new Cavities

The last two cavities were installed in the ring during the summer shot down in 1997. Conditioning of the cavities was carried out in the same way as for the first two cavities. The operation of the ring started after the reconstruction of the ring for new low emittance optics on 3. October 97. The scheduled user run started on 4. November (Izawa et al., 1998a). Figure 3.6 shows the change of the vacuum pressure at the cavity section, where the last two cavities were installed. The vacuum pressure ranged around 10^{-8} Torr at first, however decreased to the range of 10^{-11} Torr after about one month. At the end of March 1998 the vacuum pressure was below 10^{-10} Torr at a stored current of 400 mA. Figure 3.7 shows the number of beam dumps which took place during the operation from 3. October 97 to 20. March 98. Roughly speaking RF tips occur only once or twice a month.

The detuning of higher order modes was quite successful. No coupled–bunch instability could be detected due to the higher order modes of the cavities

Figure 3.5: Change of the vacuum pressure at high stored current

Figure 3.6: Change of the vacuum pressure at the cavity section

Figure 3.7: Number of beam dumps during the beam storage

at the operation point. However, weak longitudinal coupled–bunch instabilities were still observed. They might be caused by other components around the ring, since the frequencies of the beam spectrum are different from the resonance frequencies of the higher order modes of the cavities. These longitudinal instabilities are not so harmful for the operation of the ring.

3.4 Summary

The Photon Factory light source is upgraded to a low emission VUV-SX storage ring, and four new RF cavities are installed into the storage ring. For this purpose, new damped cavities, an input coupler and a beam duct, which is connected to the cavities, are newly designed.

The resonance frequency of the fundamental mode is 500 MHz. Higher order monopole and dipole modes are calculated with the computer code SUPERFISH. The cavity has large beam ducts, corresponding to low cut–off frequencies. Higher order modes with frequencies above the cut–off frequency propagate into the beam duct and are absorbed by SiC material, that is introduced inside it. Higher order modes with frequencies below the cut–off frequencies are shifted away from the coupled–bunch mode frequencies. For this purpose, the cavity has one movable tuner and two fixed tuners. The lengths of the fixed tuners are chosen in order to adjust the frequencies of the higher order modes in this way.

From October to December 1996, the storage ring is temporary in operation with two new and two old cavities installed. Conditioning of the ring and the cavity is carried out during four days, when a maximum stored current of 500 mA is achieved. After this time, the pressure inside the ring decreases to the range of 10^{-9} to 10^{-10} Torr, and the stored current is equal to the nominal operation current of 350 mA. After the conditioning, a maximum stored current of 773 mA is achieved, which is the Photon Factory record.

The detuning of the higher order modes of the cavities is quite successful. Only longitudinal coupled–bunch instabilities, which are caused by the old cavities, can be observed.

After the complete reconstruction of the ring, when the last two cavities are installed, the operation starts in October 1997. At the end of March 1998, the pressure is below 10^{-10} Torr. and the stored current is 400 mA. No coupled–bunch instabilities are observed during operation.

Chapter IV

Computational Part

4.1 Research Procedure

4.1.1 The Beam Duct of the Storage Ring Cavity

The modeling of the cavity has been carried out with the computer code MAFIA (Weiland, 1993). This is a three dimensional electromagnetic field calculation program, which uses the final integration technique (FIT). This method can be applied to static harmonic and time dependent fields. It is based on a computer compatible reformulation of the Maxwell equations in integral form. It generates practical solutions on computers and also retains all analytic properties of the electromagnetic field.

The analytical equations are discretized onto two grids, which are orthogonal to each other. This yields a set of matrix equations, each of which is the discrete analogue to one of the original Maxwell equations.

A drawing of the cavity, which was manufactured by Mitsubishi Electric Corp., is shown in figure 4.1. The parts of the cavity and attached equipment are explained in table 4.1. From this drawing it can be seen, that the part of the storage ring beam duct, which is connected to the cavity, has a rectangular shape with its short planes replaced by semicylinders. It has two symmetry planes. Its cut–off frequencies have been calculated and compared with those of a rectangular shaped wave guide with the same cross section of $A = 3870$ mm^2 and the same length of its short side $b = 38$ mm. The cut–off wave vector k_c of a rectangular wave guide is given by (Jackson, 1975):

$$k_c^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 \tag{4.1}$$

In this case, $b = 38$ mm and $a = A/b = 102$ mm, m and n are integers, and the cut–off frequency is given by $\nu_c = k_c c/2\pi$.

The six lowest values of (4.1) are compared with the values obtained by the modeling. The modes are classified by their boundary condition on the symmetry plane. The condition

$$n \times E = 0; \quad n \cdot H = 0 \tag{4.2}$$

is called electric boundary condition and

$$n \times H = 0; \quad n \cdot E = 0 \tag{4.3}$$

3	Sputter ion pump	4	Titanium getter ion pump
7	Turbomolecular pump	10	Manual tuner
11	RF input	12	Monitor port
13	Window	14	Gauge port
15	Support	16	Spacer flange

Table 4.1: Definitions of the cavity parts and attached equipment

is called magnetic boundary condition. For the numerical investigations, the frequency ν of the propagating mode has been set to 10 GHz, and the propagation constant κ has been calculated. The cut–off wave vector is given by the relation:

$$k_c^2 = k^2 - \kappa^2 \tag{4.4}$$

in accordance with (2.42).

4.1.2 The Cavity of the Storage Ring

The cavity has large nose cones, which are separated only by a small gap of 23 mm. For the modeling of the cavities, the ports of the tuners and input coupler have been ignored.

Because of the non cylindrical shape of the beam duct, the modeling of the cavity had to be carried out for monopole modes, v–type and h–type dipole modes separately, while the beam duct was replaced by a cylinder symmetric duct with radius in accordance with the cut–off frequencies, found by the investigations of the beam duct. By this way, the real cavity was approximated by a perfectly cylinder symmetric one, which is expected to have the same properties. This provides a significant simplification of the modeling.

Monopole Modes of the Storage Ring Cavity

The cut–off frequencies for a monopole mode of a cylindrical shaped wave guide is given by (2.47) with $m = 0$. A numerical evaluation of this equation gives the following relation between the beam pipe radius a and the wave vector of the lowest cut–off frequency k_c, corresponding to $n = 1$:

$$a = \frac{2.405}{k_c} = \frac{c}{2.6126\nu_c} \tag{4.5}$$

With this relation, the radius of the beam pipe with a cut–off frequency equal to the cut–off frequency found by the investigation of the beam duct was calculated, and in the modeling, the beam duct was simulated with a cylindrical duct with this radius.

TM modes with electric and magnetic boundary conditions on the symmetry plane of the cavity have been investigated separately. The mode with the lowest frequency is the fundamental mode that accelerates the electron beam.

Figure 4.1: Drawing of the storage ring cavity, dimensions in mm

Because this mode is essential for the operation of the cavity, its values have also been calculated with the computer code SUPERFISH (Billen and Young, 1992). This computer code is similar to MAFIA, but restricted to two dimensional calculations.

Dipole Modes in the Storage Ring Cavity

The cut–off frequency of dipole modes inside a cylinder symmetric wave guide is given by (2.45) with $m = 1$. A numerical evaluation of this equation gives the following relation between the beam pipe radius a and the wave vector of the lowest cut–off frequency k_c, corresponding to $n = 0$:

$$a = \frac{1.84118}{k_c} = \frac{c}{3.4126\nu_c} \tag{4.6}$$

With this relation, the radius of a cylindrical wave guide with cut–off frequency equal to the cut–off frequency of the beam duct mode was calculated, and again the beam duct of the cavity was simulated by a cylindrical wave guide with this radius. Because of this, h–type and v–type dipole modes have to be investigated separately.

4.1.3 The Cavity of the Booster Synchrotron

The cavity of the booster synchrotron, which was manufactured by Toshiba, is used to accelerate the electron bunches up to 1 GeV for their injection into the storage ring. Because the bunches remain only a relatively short time in the booster synchrotron, effects on beam instability, caused by higher order modes, are less important compared to the storage ring system. The shape of the cavity, which is shown by figure 4.2, is cylinder symmetric and quite simple. It also has large nose cones, which are separated by a gap of 18.2 mm width.

The cavity of the booster synchrotron has been investigated in the same way as the storage ring cavity with the computer code MAFIA. For comparison, the properties of the fundamental mode were also investigated with the computer code SUPERFISH.

4.1.4 Coupled–Bunch Instabilities

For an investigation of the coupled–bunch instabilities the data of the old SORTEC ring (Kodaira et al., 1992), given in table 4.2, as well as the data of the upgraded Siam Photon storage ring were used. The parameters of the upgraded Siam Photon storage ring were calculated before the reconstruction (Kengkan et al., 1998; Pairsuwan and Ishii, 1998). However these papers were published in 1997, and at the time when this thesis was written, some parameters had changed again. The updated parameters are shown in table 4.3. Only parameters that are different from the SORTEC ring are given.

The change in the ring parameters lead to a change in the numerical values for the damping and growth rates of the coupled–bunch instabilities. Equation

Figure 4.2: Drawing of the booster synchrotron cavity, dimensions in mm

Ring circumference	43.73 m
RF frequency	118 MHz
Harmonic number	18
Beam energy	1 GeV
RMS Momentum spread	4.62 10^{-4}
Momentum compaction α	0.185
x–emittance, y–emittance	0.622 μm rad, 0.062 μm rad
Average β_x, β_y	4.360 m, 6.550 m
Average current	200 mA
Synchrotron tune ν_s	0.007069
Bunch length	8.8 cm
Betatron tune ν_x, ν_y	2.20, 2.23
Chromaticities ξ_x, ξ_y	2.26, -1.63
Natural Chromaticities ξ_{x0}, ξ_{y0}	-2.99, -0.20
Field strength of bending magnets	1.2 T
Cavity gap voltage	100 kV
Cavity wall material	Copper

Table 4.2: Parameters of the SORTEC storage ring

Ring circumference	81.3 m
Harmonic number	32
Momentum compaction α	0.0214
Natural emittance	72π nm rad
Average β_x, β_y	7.072 m, 6.598 m
Average current	300 mA
Synchrotron tune ν_s	0.003319
RMS bunch length	4.463 cm
Betatron tune ν_x, ν_y	4.76, 2.82
Natural chromaticities ξ_{x0}, ξ_{y0}	7.59, -6.73

Table 4.3: Parameters of the Siam Photon storage ring

(2.102) shows that the radiation damping rate is inversely proportional to the ring circumference, and thus the enlargement of the ring leads to a reduction of the radiation damping rate. Furthermore, the revolution frequency decreases by the enlargement, and together with the reduction of the synchrotron tune ν_s and the rms bunch length, the Landau damping rate (2.103) also decreases.

For the calculation of the radiation damping rate (2.102), the bending radius of the bending magnets ρ had to be taken into account. It was found by the relation $p = eB\rho$, where p is the particle momentum, e its charge and B the magnetic field strength (Murphy, 1989). With this, a bending radius of 2.78 m was evaluated.

Longitudinal and transverse coupled–bunch instabilities were calculated with the computer code ZAP (Zisman et al., 1986). This is an accelerator physics code, which can calculate the performance of storage rings in terms of the effects of beam intensity dependent phenomena and the limitations they impose. It provides two formalism for the calculations of the growth rates, the "Zotter formalism" (Laclare, 1980) and the "Wang formalism (Wang, 1980). In the longitudinal case and $a = 1$, the Wang formalism coincides with the analytical expression (2.101).

The calculations of transverse coupled–bunch instabilities were carried out for h–type and v–type dipole modes separately, while different values for the chromaticity and beam pipe radius, according to the results of the modeling of the beam duct, were taken into account.

The Wang formalism is valid in the region of short bunch lengths. Because the rms bunch lengths of 8.8 cm in the SORTEC ring and 4.5 cm in the Siam Photon ring are relatively large, the Zotter formalism is expected to give more reasonable values, and these results are presented. The obtained values are the maximum growth rates, which were found by shifting the RF frequency to the closest bunch–mode frequency.

4.1.5 Modification of the Storage Ring Cavity

A proposal for a modification of the inner cavity surface and insertion of SiC material in appropriate regions to improve the cavity properties is carried out. The definitions of various dimensions are displayed in figure 4.3.

Modification of the inner Beam Duct Shape

As a first modification the position z_3 of the cavity was changed from 152.6 mm to 200.0 mm to increase the "smoothness" of the beam duct. As a next step, the material of the tapered section of the inner beam duct was replaced by SiC, so the material changes from Copper to SiC at the distance z_2, seen from the symmetry plane of the cavity. The value for z_2 was then varied to see the effect of the SiC to the cavity modes.

For a more effective use of the high resistive SiC, corresponding to a higher absorption of the fields of higher order monopole modes, the inner radius of the

Figure 4.3: Definitions of the cavity dimensions due to the modification

beam duct r_2 has to be enlarged. This generates a region, where the fields of the higher order monopole modes and dipole modes are present, while the field intensity of the fundamental mode is small. An enlargement of the inner beam duct radius of course changes the frequency of the fundamental mode, which must be readjusted to the original value of 118 MHz either by a reduction of the gap width $2z_1$, or by an increase of the outer beam duct radius r_3.

A reduction of the gap width increases the field intensity inside the gap, which may lead to cooling problems if the width becomes to small. In addition to this, the thickness of the beam duct $r_3 - r_2$ decreases if r_3 is kept constant and r_2 is increased. This may lead to similar problems. The beam duct thickness was given a minimum of 20 mm.

Because an increase of the beam duct reduces the shunt impedance of the fundamental mode, the limits of the RF power should be taken into account. The real shunt impedance of the cavity is 2.7 MΩ. and the gap voltage is 100 kV (Awaji et al., 1992), which leads to a power loss of 3.7 kW in the cavity. The total input power is 12 kW and the maximum power 14 kW. This means that the cavity power loss may be increased by 2 kW to a maximum power of 5.7 kW, which corresponds to a minimum shunt impedance for the fundamental mode of 65% compared to the original value. Thus the shunt impedance was given a maximum reduction of 30%, to give room for possible unexpected power losses and tolerances. This corresponds to a 43% higher input power.

The modeling of the modified cavity was again carried out with the computer code MAFIA (Weiland, 1993), and the results were compared with the values of the original cavity

The use of SiC inside the beam duct gives rise to Joule heat, because of the low conductivity of the SiC of $\kappa = 5\ \Omega^{-1}m^{-1}$. The magnitude of the power loss due to this effect can be estimated by calculating the shunt impedance of the fundamental mode for the cavity with SiC replaced by Copper. Because the Joule heat inside the beam duct in the cavity made by Copper is negligible, compared to the Joule heat in the cavity containing SiC, the heat P_{SiC} dissipated in the SiC part due to the fields of the fundamental mode may be calculated by the relation:

$$P_{SiC} = \frac{V_o^2}{R_{SiC}} - \frac{V_o^2}{R_{Cu}} \tag{4.7}$$

where V_o is the cavity gap voltage. Because the SiC absorber is placed in a region, where the fields are dominated by the higher order modes, the power loss due to the fundamental mode just gives an indication if the power loss in the SiC part is too high or not. For calculations of the total power loss, all important higher order modes and heating effects due to the electron beam must be taken into account.

Figure 4.4: E–field (left), B–field (right) of mode No. 1 of table 4.4

4.2 Results

4.2.1 Propagation Modes of the Beam Duct

The results for the propagation modes of the beam duct are given in table 4.4. The values for m and n concerning eq. (4.1) are given as subscripts to TE and TM. Note that the frequencies obtained in the case of the rectangular shaped approximation are the same for mode No. 4 and 6, because eq. (4.1) is valid for both TE and TM type modes. The results show good agreement between the numerical results and the analytical ones for the first four modes, which are most important for the modeling of the cavity. Field plots of the first four modes of table 4.4 are shown in figures 4.4–4.7. In this and the following field plots, field vectors that lie within the plane of the paper are indicated as arrows, and field vectors that lie perpendicular to the plane of the paper are indicated as small circles.

Dipole modes inside the cavity which are polarized in the way that they deflect the electron beam vertically (v–type dipole modes) couple with mode No. 1. This can be seen clearly from figure 4.4, where the magnetic fields of this mode are shown. Because the field lines are horizontal, they deflect the

Figure 4.5: E–field (left), B–field (right) of mode No. 2 of table 4.4

Figure 4.6: E–field (left), B–field (right) of mode No. 3 of table 4.4

Figure 4.7: E–field (left), B–field (right) of mode No. 4 of table 4.4

Mode No.	$\beta(\mathrm{m}^{-1})$ (MAFIA)	ν_c (GHz) eq. 4.4	ν_c (GHz) eq. 4.1	Type	Boundary condition at x = 0, y = 0
1	207.32	1.522	1.471	TE_{10}	mag, el
2	200.50	2.969	2.945	TE_{20}	el, el
3	191.45	4.103	3.947	TE_{01}	el, mag
4	190.21	4.207	4.212	TM_{11}	mag, mag
5	189.08	4.309	4.412	TE_{30}	mag, el
6	187.02	4.503	4.212	TE_{11}	mag, mag

Table 4.4: Propagation modes of the beam duct

beam in vertical direction. Conversely h–type dipole modes, which deflect the beam horizontally, couple with mode No. 3 (figure 4.6). Monopole modes of TM type couple with mode No. 4. TE–type monopole modes of the cavity, which couple with mode No. 2, have no effect to the electron beam and are therefor not investigated (see section 2.2.2, the Panowsky Wenzel theorem). The cut–off frequency of a cavity mode is equal to the cut–off frequency of the beam duct mode to which it is coupled. Hence if the frequency of the cavity mode is higher than the cut-off frequency, it propagates into the beam duct, and it remains inside the cavity, if its frequency is lower.

4.2.2 Monopole Modes of the Storage Ring Cavity

According to the results of the modeling of the beam duct, the cut–off frequency for TM–type monopole modes is 4.207 MHz. This corresponds to a beam duct radius of 27.293 mm for a cylindrical shaped wave guide, according to equation (4.5), and the modeling was carried out with this kind of wave guide as beam duct.

The calculations of modes with electric boundary condition established a number of 49 modes below cut–off. The first six modes, are displayed in table 4.5 The complete results of all modes are given in the appendix in tables A.1–A.2. The shunt impedances R_s, which are given in the tables are related to $R_{\|n}$ of equation (2.66) by $R_s = 2R_{\|n}$.

Mode No. 1 is the fundamental mode that accelerates the electron beam. Calculations of this mode with the computer code SUPERFISH led to a resonance frequency of 122.67 MHz, a Q–value of 25024 and a shunt impedance of 4.425 MΩ. The resonance frequency given by the manufacturer Mitsubishi is 118 MHz. Thus the obtained values are in agreement with a difference of 3%, which may be caused by neglecting of the tuner and input–coupler ports. Plots of the electric and magnetic fields of the accelerating mode are given in figure 4.8.

Investigations of TM type monopole modes with magnetic boundary condition on the symmetry plane established a number of 44 modes below cut–off. All modes except those presented in table 4.6 were found to have a shunt impedance of zero, which means that these kinds of modes do not effect the electron beam.

Figure 4.8: E–field (left) and B–field (right) of the fundamental mode of the storage ring cavity

Mode	ν (MHz)	Q–value	$R_s(K\Omega)$	$R_s/Q(\Omega)$
1	121.40	24929	4313.65	173.06
2	499.27	34917	110.47	3.16
3	766.32	49257	99.02	2.01
4	907.02	39179	70.13	1.79
5	991.39	50581	52.10	1.03
6	1243.23	45733	50.76	1.11

Table 4.5: TM–type monopole modes with electric boundary condition of the storage ring cavity

Mode	ν (MHz)	Q–value	$R_s(K\Omega)$	$R_s/Q(\Omega)$
14	2391.88	63054	0.67	0.107
15	2392.18	35617	25.51	0.716
25	3134.11	37909	12.26	0.323
36	3782.88	36437	122.49	3.362

Table 4.6: TM–type monopole modes with magnetic boundary condition of the storage ring cavity

Also modes presented in the table have a quite low shunt impedance and their effect to the beam should be negligible. The field distribution of these kinds of modes show characteristics of fields that resonate inside a stub of a coaxial line, that is shortened at both ends. An example is given in figure 4.9, where field plots of the first mode, which has a frequency of 375.79 MHz, are presented.

This characteristic is due to the large nose cones of the cavity. With magnetic boundary condition on the symmetry plane, which lies inside the gap, the current on this plane is small, and the effect of the gap may be neglected. Consequently, the fields do not propagate into the beam duct, and the shunt impedance is almost zero.

4.2.3 H–Type Dipole Modes of the Storage Ring Cavity

According to the results of section 4.2.1, h–type dipole modes have a cut–of frequency of 4.103 GHz. By equation (4.6) the radius a of a cylindrical beam duct with this cut–off frequency is 21.43 mm, and the modeling was carried out with this kind of wave guide as beam duct. The results for the first three modes with electric boundary condition on the symmetry plane are shown in table 4.7. The complete results of all 79 modes below cut–off are given in the appendix in tables A.3–A.4. The transverse shunt impedance R_t is equal to the coupling impedance at resonance $Z_\perp(\omega_n)$ of equation (2.77). Field plots of mode

Figure 4.9: E–field (left) and B–field (right) of the first monopole mode with magnetic boundary condition of the storage ring cavity

Figure 4.10: E–field (left) and B–field (right) of the first h–type dipole mode of the storage ring cavity

No. 1 are given in figure 4.10.

Note the small difference in the beam duct radius in these figures compared with figures 4.8 and 4.9. The results for modes with magnetic boundary conditions are given in table 4.8. There is a total of 74 modes below cut–off, but all modes except those presented have a value for R_t/Q of less than 0.02 Ω/m and give no significant effect to the beam.

4.2.4 V–Type Dipole Modes of the Storage Ring Cavity

The calculations for v–type dipole modes was carried out in the same way as for h–type modes. The cut–off frequency for these kinds of modes is 1.522 GHz, which is equivalent to a radius of a cylinder symmetric beam duct of 57.759 mm, according to equation (4.6). The result is given in table 4.9. Because the cut–off frequency is much lower than for h–type modes, there are only ten modes below cut–off, and all these modes are presented.

Mode	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
1	504.17	30591	3566.60	116.59
2	642.01	17149	7559.79	440.83
3	800.54	45632	3331.59	73.01

Table 4.7: H–type dipole modes with electric boundary condition of the storage ring cavity

Mode	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
27	2418.07	38981	1699.86	43.61
45	3166.73	39837	1663.19	41.75
59	3584.85	44400	173.60	3.91
66	3874.79	32561	2379.56	73.08

Table 4.8: H–type dipole modes with magnetic boundary condition of the storage ring cavity

Mode	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
1	504.15	30557	3503.67	114.66
2	641.87	17125	7471.47	436.29
3	800.50	45620	3331.63	73.03
4	930.60	55587	1131.20	20.35
5	965.90	58290	1348.25	23.13
6	1024.09	48285	1895.67	39.26
7	1265.23	52253	664.14	12.71
8	1281.09	78884	321.06	4.07
9	1494.65	65412	126.90	1.94
10	1510.47	72970	561.14	7.69

Table 4.9: V–type dipole modes with electric boundary condition of the storage ring cavity

Mode	ν (MHz)	Q–value	$R_s(K\Omega)$	$R_s/Q(\Omega)$
1	117.29	18662	1550.00	83.21
2	713.94	30109	30.88	1.02
3	998.14	35676	51.47	1.43
4	1205.48	26965	67.90	2.50
5	1397.12	32534	92.49	2.88
6	1542.11	18771	156.63	8.93
7	1769.29	35852	34.61	1.95

Table 4.10: TM–type monopole modes with electric boundary condition of the booster synchrotron cavity

Mode	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
1	493.37	8300	2562.74	308.76
2	752.58	29687	622.43	20.97
3	1026.95	40328	442.06	10.96
4	1238.25	31042	428.96	13.81
5	1262.00	66647	87.11	1.37
6	1429.04	39954	406.43	10.04

Table 4.11: Dipole modes with electric boundary condition of the booster synchrotron cavity

A comparison with table 4.7 establishes that frequencies, Q–values and shunt impedances are the same for both kinds of modes with an error of a few percentages. This shows that the radius of the outer part of the beam duct does not influence the properties of the cavity. Much more important is the fact that the number of v–type dipole modes is much less, because of its lower cut–off frequency. Thus the deflection of the electron beam due to all modes is expected to be larger in the horizontal direction. The results for v–type modes with magnetic boundary condition on the symmetry plane was a shunt impedance of zero for all modes below cut–off.

4.2.5 The Cavity of the Booster Synchrotron

The results of the computation for TM monopole modes of the booster synchrotron with electric boundary condition on the symmetry plane is displayed in table 4.10. The cut–off frequency of the beam duct for monopole modes is 1.913 GHz, and all modes with frequencies below cut–off are given.

Here again mode No. 1 is the fundamental mode that accelerates the electron beam. The results of the calculations with SUPERFISH was a resonance frequency of 117.97 MHz, a Q–value of 18756 and a shunt impedance of 1586.8 KΩ. Thus both results are in very good agreement. The resonance frequency given by

Figure 4.11: E–field (left) and B–field (right) of the fundamental mode of the booster synchrotron cavity

the manufacturer is 118 MHz. Thus the obtained results may be considered to be reasonable and to have a good accuracy. Field plots of the fundamental mode are given in figure 4.11

Investigation of monopole modes with magnetic boundary condition on the symmetry plane showed that all modes below the cut–off frequency have shunt impedances of zero.

Investigations of dipole modes with electric boundary condition on the symmetry plane lead to the results shown in table 4.11. Here again all modes with frequencies below the cut–off frequency of the beam duct, which is 1.456 GHz for dipole modes, are given. Because the beam duct of this cavity has a real cylinder symmetric shape, h–type and v–type dipole modes are degenerated and have the same cut–off frequency. Thus a total of 12 dipole modes below cut–off are present in the cavity. Field plots of the first mode are shown by figure 4.12.

Calculations for dipole modes with magnetic boundary condition on the symmetry plane established four modes below cut–off and only the highest mode has a shunt impedance different from zero. Its Q–value is 24680 and its shunt

Figure 4.12: E–field (left) and B–field (right) of the first dipole mode of the booster synchrotron cavity

Figure 4.13: E–field (left) and B–field (right) of a dipole mode with magnetic boundary condition of the booster synchrotron cavity

impedance 7.16 Ω/m. Its frequency is with 1456.52 MHz slightly below cut–off, but the field plots of this mode in figure 4.13 show that the fields resonate inside the beam duct. The reason may lie within a computational error, and the computer code may have found a cut–off frequency slightly below 1456 MHz for the beam duct. Because the shunt impedance is quite low, no serious effects to the electron beam are expected by this mode anyway.

4.2.6 Longitudinal Coupled–Bunch Instabilities in the SORTEC Storage Ring

The radiation damping rate of the SORTEC storage ring (2.102) is 208.7 s^{-1}. The results for the Landau damping rates (2.103) and the total damping rates (2.104) are given in table 4.12.

The growth rates and threshold currents for each higher order monopole mode given in table 4.5 were calculated. The results are shown in table 4.13. Only unstable modes with threshold currents lower than the operation current of

a	$1/\tau_{lan}(s^{-1})$	$1/\tau_{tot}(\mathrm{s}^{-1})$
1	1069.2	1277.9
2	1425.5	1634.3
3	1603.7	1812.5
4	1710.6	1919.4

Table 4.12: Longitudinal damping rates of the SORTEC storage ring

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
2	498.2	4, 1	64839	3.94
		2	46682	6.71
3	760.0	9, 1	27937	9.15
		2	49962	6.54
4	904.7	12, 1	10753	23.77
		2	26611	12.28
		3	1949	185.99
5	989.9	7, 1	5032	50.79
		2	14909	21.92
6	1245.6	10, 2	4139	78.97

Table 4.13: Growth rates and threshold currents for longitudinal coupled–bunch instabilities of the SORTEC storage ring

200 mA are given. The threshold currents are quite low in some cases, which establishes the necessity to detune the corresponding higher order modes and move its resonance frequencies away from the coupled–bunch–mode frequencies. This can be done by adjustment of the tuners of the cavity to appropriate positions.

The obtained results establish an upper limit of the growth rates, so in reality the threshold currents are higher. For a comparison, calculations have been performed, where the first 20 higher order modes have been taken into account together, without shifting the RF frequencies to the bunch mode frequencies, so the distribution of the cavity mode frequencies in relation to the bunch mode frequencies was random. The results were growth rates in the order of 1 –10 s^{-1}, which is much lower than the damping rates. So stable operation of the cavity can be expected, if the frequencies of the higher order modes are not too close to the bunch mode frequencies. In addition to this, the bunch mode instabilities are due to longitudinal oscillations of the bunches. This means, that oscillation take place on the beam axis, and the beam does not get lost by hitting the chamber walls. Instead of this, the effect of longitudinal oscillations is mainly a broadening of the bunches.

a	$1/\tau_{lan}(s^{-1})$	$1/\tau_{tot}(\mathrm{s}^{-1})$
0	0	104.38
1	1069.15	1173.53
2	1425.53	1529.91
3	1603.72	1708.10

Table 4.14: Transverse damping rates of the SORTEC storage ring

4.2.7 Transverse Coupled–Bunch Instabilities in the SORTEC Storage Ring

The radiation damping rate in the transverse case is approximately half of the value for the longitudinal case (Murphy, 1989), so its value is 104.4 s^{-1}. Landau damping in the transverse case is caused by a spread in synchrotron and betatron frequencies within a bunch. In this calculation, the spread in the betatron frequencies is ignored, and the Landau damping rate is the same as in the longitudinal case (2.103). Note that in the case $a = 0$, no Landau damping occurs. The values for the Landau damping rates and total damping rates are given in table 4.14

The results of the growth rates and threshold currents for h–type and v–type transverse coupled–bunch instabilities are shown in table 4.15 and 4.16. Again only unstable modes, which have threshold currents below 200 mA, are given.

The bunch–mode frequencies of both types of modes are the same. The differences between the h–type and v–type growth rates are due to differences in the chromaticity. The first three h–type and v–type modes establish possible instabilities, because the corresponding growth rates are quite large. Thus a total of six modes seem to be dangerous. It is very important to tune the frequencies of these modes away from the coupled–bunch–mode frequencies to avoid any instabilities. Especially modes with $a = 0$ seem to be very dangerous, because of the absence of Landau damping. In reality however, also a spread in synchrotron tune occurs, and the total damping rate can expected to be higher than in this approximation. Because of this, modes 4–6 in the v–type case seem to be harmless. Since transverse oscillations occur perpendicular to the beam axis, a growth in amplitude of these motions may cause particles to hit the chamber walls and thus might get lost.

4.2.8 Longitudinal Coupled–Bunch Instabilities in the Siam Photon Storage Ring

The longitudinal radiation damping rate (2.102) was found to be 116.7 s^{-1}, and the values of the Landau damping rates (2.103) and the total damping rates (2.104) are given in table 4.17. It can be seen that the damping rates are much lower compared to the SORTEC ring, which gives rise to lower

Cavity Mode	ν (MHz)	μ, a (eq. 2.107)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
1	477.3	15 ,0	2703	7.72
		1	2843	82.56
2	615.0	12, 0	3174	6.58
		1	5211	45.04
		2	3805	80.42
3	772.2	6, 0	607	34.39
		1	1510	155.43
		2	1657	184.66

Table 4.15: Growth rates and threshold currents for h–type transverse coupled–bunch instabilities of the SORTEC storage ring

Cavity Mode	ν (MHz)	μ, a (eq. 2.107)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
1	477.3	15, 0	4173	5.00
		1	2500	93.88
2	615.0	12, 0	5638	3.70
		1	5953	39.43
		2	2793	109.55
3	772.2	6 ,0	1273	16.40
		1	2211	106.15
		2	1706	179.63
4	903.4	6, 0	215	97.10
5	936.1	1, 0	211	98.94
6	995.2	10, 0	207	100.85

Table 4.16: Growth rates and threshold currents for v–type transverse coupled–bunch instabilities of the SORTEC storage ring

a	$1/\tau_{lan}(s^{-1})$	$1/\tau_{tot}(\mathrm{s}^{-1})$
1	72.7	189.4
2	96.9	213.6
3	109.1	225.8
4	116.3	233.0

Table 4.17: Longitudinal damping rates of the Siam Photon storage ring

threshld currents. The calculations of growth rates and threshold currents have been carried out in the same way as in the case of the SORTEC ring. The results are presented in tables 4.18–4.20.

The results show that altogether 30 modes may lead to coupled–bunch instabilities. The reason for this large number of modes compared to the SORTEC ring is caused by a reduction of the damping rates and by a change of the ring parameters. Especially the reduction of the synchrotron tune, the revolution frequency and the rms bunch length by about a factor of two, the increase of the beam current from 200 to 300 mA as well as the enlargement of the ring circumference leads to a reduction of the threshold currents. A relatively short bunch length leads to higher growth rates especially for the cases of $a > 1$. In this case, oscillations occur within one bunch. If the bunch length is reduced, the repulsions between the electrons within a bunch become stronger, and the growth rates for these kinds of oscillations increase.

4.2.9 Transverse Coupled–Bunch Instabilities in the Siam Photon Storage Ring

The radiation damping rate in the transverse case was found to be 58.34 s^{-1} as half the value of the longitudinal damping rate. The results for the Landau and total damping rates are presented in table 4.21.

For the Siam Photon storage ring, only natural cromaticities are given. The real cromaticities cannot be known before the operation of the ring starts, because they can be adjusted by sextupole magnets. Because of this, the chromaticities were set to zero for the calculations of the transverse coupled–bunch instabilities. In this case, the results for h–type and v–type instabilities are found to be the same within an error of about 1%. The results are presented in table 4.22. It can be seen that in principle 18 h–type and v–type dipole modes may cause coupled–bunch instabilities, in comparison to nine dangerous modes in case of the SORTEC ring. The reasons for the reduction of the threshold currents are the same as in the longitudinal case.

Especially for the case $a = 0$, the threshold currents are quite low. However in this approximation, where spread of synchrotron frequencies are ignored, no Landau damping occurs in this case, and the total damping rate reduces to 58.34 s^{-1}. Probably this value is not realistic, because Landau damping due to a spread in betatron frequencies may be in the same order of magnitude, and

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
2	497.8	7, 1	51894	1.09
		2	10002	6.41
		3	305	222.05
3	767.0	16, 1	46869	1.21
		2	23555	2.72
		3	1932	35.22
4	907.1	22, 1	36252	1.57
		2	23201	2.76
		3	4101	16.51
		4	381	183.48
5	991.9	13, 1	25627	2.22
		2	19611	3.27
		3	3515	19.27
		4	353	198.03
6	1242.7	17, 1	19157	2.97
		2	23008	2.79
		3	8717	7.77
		4	1684	41.51
7	1482.3	18, 1	9051	6.28
		2	15467	4.14
		3	7412	9.14
		4	1857	37.64
8	1497.1	22, 1	15516	3.66
		2	27047	2.37
		3	13906	4.87
		4	2690	25.99
9	1570.9	10, 1	11060	5.14
		2	21225	3.02
		3	14322	4.73
		4	4916	14.22
10	1655.7	1, 1	9034	6.29
		2	19259	3.33
		3	14576	4.65
		4	5617	12.45

Table 4.18: Growth rates and threshold currents for longitudinal coupled–bunch instabilities of the Siam Photon storage ring 1

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
11	1781.1	3, 1	7225	7.86
		2	17825	3.60
		3	16160	4.19
		4	7499	9.32
12	1943.3	15, 1	7535	7.54
		2	22129	2.90
		3	25103	2.70
		4	14769	4.73
13	2009.6	1, 2	508	126.16
		3	635	106.65
		4	417	176.64
15	2146.0	6, 3	240	282.19
16	2253.0	3, 1	1668	34.06
		2	6587	9.73
		3	8597	7.88
		4	5700	12.26
17	2301.1	16, 1	1017	55.87
		2	6408	10.00
		3	11512	5.88
		4	9833	7.11
18	2422.7	17, 1	5017	11.33
		2	22899	2.80
		3	43441	1.56
		4	44217	1.58
19	2463.2	28, 1	457	124.33
		2	2159	29.68
		3	3808	17.78
		4	3451	20.26
20	2478.0	0, 2	331	193.62
		3	632	107.16
		4	573	122.00
21	2544.4	18, 1	1656	34.31
		2	8337	7.69
		3	17861	3.79
		4	20850	3.35

Table 4.19: Growth rates and threshold currents for longitudinal coupled–bunch instabilities of the Siam Photon storage ring 2

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
22	2618.1	6, 1	824	68.96
		2	4394	14.59
		3	9838	6.88
		4	11895	5.88
23	2702.9	29, 2	386	166.03
		3	892	75.92
		4	1093	63.96
24	2880.0	13, 2	547	117.16
		3	1547	43.78
		4	2073	33.72
25	2942.6	30, 2	1072	59.78
		3	2971	22.80
		4	4390	15.92
26	2980.5	8, 3	500	135.45
		4	711	98.32
28	3023.8	20, 2	232	276.25
		3	656	103.24
		4	973	71.86
29	3053.2	28, 2	326	196.59
		3	963	70.33
		4	1508	46.36
30	3130.7	17, 2	555	115.48
		3	1739	38.94
		4	2910	24.02
31	3204.4	5, 2	813	78.83
		3	2802	24.17
		4	5321	13.14
34	3370.4	18, 2	556	115.27
		3	2158	31.38
		4	4674	14.96
38	3628.4	24, 4	241	290.07

Table 4.20: Growth rates and threshold currents for longitudinal coupled–bunch instabilities of the Siam Photon storage ring 3

a	$1/\tau_{lan}(s^{-1})$	$1/\tau_{tot}(\mathrm{s}^{-1})$
0	0	58.4
1	72.7	131.1
2	96.9	155.3
3	109.1	167.4

Table 4.21: Transverse damping rates of the Siam Photon storage ring

Cavity Mode	ν (MHz)	μ, a (eq. 2.107)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
1	469.2	0, 0	4345	4.03
		1	837	46.97
2	605.6	27, 0	8151	2.15
		1	2616	18.19
		2	373	124.89
3	764.3	16, 0	3006	5.82
		1	1536	25.60
		2	349	133.48
4	897.0	12, 0	841	20.81
		1	592	66.41
		2	185	251.80
5	930.1	3, 0	950	18.43
		1	720	54.60
		2	242	192.50
6	989.1	19, 0	1211	14.45
		1	1037	37.91
		2	394	118.23
7	1228.8	18, 0	267	65.56
		1	352	111.69
		2	207	225.04
8	1247.3	13, 0	124	141.17
		1	168	234.02
10	1475.8	15, 0	125	140.04
		1	239	164.50
		2	202	230.61

Table 4.22: Growth rates and threshold currents for transverse coupled–bunch instabilities of the Siam Photon storage ring

Figure 4.14: Reduction of Q–values and shunt impedances of the fundamental mode (circles), the second higher order monopole mode (squares) and the first dipole mode (triangles) due to a variation of z_2 of the original cavity

thus the real total damping rate may be much higher. This means that in reality only the first three modes, which have rather low threshold currents may be dangerous.

4.2.10 Modification of the Storage Ring Cavity

The dimensions of the inner cavity surface are defined in figure 4.3. The change of the position z_3 from 152.6 mm to 200.0 mm to increase the "smoothness" of the beam duct gives no significant effect to the cavity modes.

The material of the tapered section of the inner beam duct was replaced by SiC, so the material changes from copper to SiC at the distance z_2, seen from the symmetry plane of the cavity. Then the distance z_2 was varied. The result is shown in fig. 4.14, where the Q–values and shunt impedances as a function of z_2 are shown for the fundamental mode (circles), the second higher order monopole mode (squares) and the first dipole mode (triangles). It can be seen that a use of SiC inside the beam duct mainly affects the dipole modes, while Q–values and shunt impedances of the monopole modes remain high.

Investigation of this kind of cavity with z_2 = 15 mm showed that four higher order monopole modes could still lead to coupled–bunch instabilities. These modes could be handled by appropriate adjustments of the cavity tuners. Thus this modification, would give a significant improvement of the cavity. The technical procedure of the reconstruction would be relatively simple, because only the beam duct inside the cavity, which can be removed, has to be reconstructed, while the cavity itself need not to be modified.

Enlargement of the Beam Duct Shape

As a next step the inner radius of the beam duct r_2 was enlarged. The frequency of the fundamental mode must be readjusted to the original value of 118 MHz either by a reduction of the gap width $2z_1$, or by an increase of the outer beam duct radius r_3.

The results of the reduction of the gap width $2z_1$ established no significant reduction of the Q–values and shunt impedances of all modes. This is probably due to the small gap width, that restricts the fields inside the duct to a narrow area around the symmetry plane. In conclusion, this procedure cannot lead to an improvement of the cavity properties. An increase of the gap width would lead to a reduction of the shunt impedance of the fundamental mode. As a consequence, the gap width of 23 mm was left unchanged.

The results show that it is more useful to enlarge the inner beam duct radius r_2 and to adjust the outer radius r_3 to keep the frequency of the fundamental mode constant. The relation between r_3 and r_2 for this case is shown in fig. 4.15. This procedure reduces the shunt impedance and Q–value of the fundamental mode. The relation between r_2 and the shunt impedance of the modes is shown in fig. 4.16. While the impedance of the fundamental mode decreases approximately linear (circles), the shunt impedance of the second higher order monopole mode has a minimum at $r_2 = 90$ mm (squares), and the transverse impedance of the first dipole mode has a maximum at $r_2 = 80$ mm (triangles).

The reduction of the Q–values is the same for the fundamental mode and the second higher order mode and presented by circles in fig. 4.17. It can be seen that an enlargement of the beam duct leads to a high reduction of the Q–values for the dipole modes (triangles in figure 4.17).

Cavities with $r_2 = 120.0$ mm and $r_2 = 86.5$ mm were investigated further, while z_2 was varied and the effect on the change of the Q-values and shunt impedances of the modes was investigated. The results are shown in fig. 4.18 for $r_2 = 86.5$ mm and in fig 4.19 for $r_2 = 120.0$ mm. The symbols are defined in analogy to fig. 4.14

It can be seen that for larger r_2, the absorbing effect of the SiC is higher and more different for the fundamental mode and the second higher order mode. Because of this it is possible to absorb a significant part of the fields of the higher order monopole and dipole modes, while leaving the fields of the fundamental mode undisturbed.

As explained in section 4.1.5, the shunt impedance of the fundamental mode is given a maximum reduction of 30%. Because of this the cavity with

Figure 4.15: Relation between r_2 and r_3 for constant frequency of the fundamental mode

Figure 4.16: Relation between r_2 and the shunt impedance of the fundamental mode (circles), the second higher order monopole mode (squares) and the first dipole mode (triangles)

Figure 4.17: Relation between r_2 and the Q–values of the fundamental mode and the second higher order monopole mode (circles) and the first dipole mode (triangles)

Figure 4.18: Reduction of Q–values and shunt impedances of the fundamental mode (circles), the second higher order monopole mode (squares) and the first dipole modes (triangles) due to a variation of z_2 for $r_2 = 86.5$ mm

Figure 4.19: Reduction of Q–values and shunt impedances of the fundamental mode (circles), the second higher order monopole mode (squares) and the first dipole modes (triangles) due to a variation of z_2 for $r_2 = 120$ mm

$r_2 = 86.5$ mm was chosen as a suitable modification of the original cavity. The value of z_2 was given a minimum of 60 mm to keep the shunt impedance above its minimum value. From fig, 4.18 it can be seen that the SiC reduces the Q–value and shunt impedance of the fundamental mode by 11%, while the reduction is 44% for the second higher order mode and 97% for the first dipole mode. The reduction of the shunt impedances due to the change in the cavity shape is 21% for both monopole modes, leading to a total reduction of 30% for the fundamental mode. The rise of the transverse impedance of the first dipole mode by 26% has no significant effect, because of the high absorption by SiC. A detailed drawing of the original cavity and the modified cavity is shown in figure 4.20.

Modes of the Modified Cavity

The results for the first six monopole modes are given in table 4.23. The effect of the SiC on the different modes can be seen from fig. 4.21 and 4.22. Fig. 4.21, which displays the fields of the fundamental mode, shows that the field intensity vanishes in the region, where the beam duct consists of SiC. On the other hand, fig. 4.22 shows fields of mode No. 6. This mode propagates far into the tapered region and thus the SiC absorbs these fields, resulting in a very low Q–value and shunt impedance of this mode. The results for dipole modes are shown in table 4.24 for h–type and in table 4.25 for v–type modes. It can be seen clearly that the damping effect of the SiC material is much higher for dipole modes than for monopole modes, which is due to their lower cut–off frequencies. Note further that the difference between the Q–values and shunt impedances of h–type and v–type dipole modes is larger with the modified cavity. This is caused by the increase of the inner beam duct radius, which causes the fields to propagate deeper into the beam duct, and the difference of the beam duct radius becomes more effective to the modes.

For estimation of the power loss inside the cavity due to the fields of the fundamental mode by equation (4.7), the shunt impedance of the fundamental mode of the modified cavity with the SiC part replaced by Copper had to be calculated. The result was $R_{Cu} = 3.3857$ MΩ. With a cavity gap voltage V_o of 100 kV and a shunt impedance R_{SiC} of 3.0247 MΩ (table 4.23), the power loss P_{SiC} is 352.51 W. The heat must be absorbed by cooling channels inside the beam duct walls. Because the thermal conductivity of SiC is quite high, the dissipated power may be absorbed by cooling channels inside the cavity walls without serious problems (Izawa et al., 1994). However caution must be taken due to this problem, when the cavity is rebuild, and, possibly, the cooling system inside the beam duct walls must be improved.

Coupled–Bunch Instabilities by Use of the Modified Cavity in the SORTEC Storage Ring

The maximum growth rates, corresponding to minimum threshold currents of the modified cavity were again calculated with the computer code ZAP (Zisman et al., 1986). The results for unstable modes with

Figure 4.20: Drawing of the original cavity and the modified cavity, dimensions in mm

Figure 4.21: E–field (left) and B–field (right) of the fundamental mode of the modified cavity

Figure 4.22: E–field (left) and B–field (right) of a higher order monopole mode of the modified cavity

Mode	ν (MHz)	Q–value	$R_s(K\Omega)$	$R_s/Q(\Omega)$
1	117.78	21644	3024.70	139.75
2	547.26	29708	57.82	1.95
3	765.16	27009	45.32	1.68
4	933.53	14040	22.13	1.58
5	1084.35	12456	8.51	0.68
6	1309.00	629	0.84	1.33

Table 4.23: TM–type monopole modes of the modified cavity with electric boundary condition

Node	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
1	457.83	406	156.63	385.79
2	595.14	1910	140.98	73.81
3	789.68	5808	100.65	17.33

Table 4.24: H–type dipole modes of the modified cavity with electric boundary condition

Mode	ν (MHz)	Q–value	$R_t(K\Omega/m)$	$R_t/Q(\Omega/m)$
1	457.05	577	214.11	371.08
2	594.90	2553	179.73	70.40
3	789.56	6592	110.94	16.83

Table 4.25: V–type dipole modes of the modified cavity with electric boundary condition

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
2	544.1	11, 1	31497	8.11
		2	28203	11.59
3	767.0	9, 1	12581	20.31
		2	22774	14.35
4	930.9	16, 1	2961	86.32
		2	7759	42.13
		3	3485	110.15
5	1081.7	3, 2	1667	196.08

Table 4.26: Growth rates and threshold currents for longitudinal coupled–bunch instabilities in the SORTEC storage ring by use of the modified cavity

a threshold current of less than 200 mA are shown in table 4.26. The result shows that only three modes have a significant effect to the beam and may cause coupled–bunch instabilities. The threshold current for mode No. 5 is very close to the operation current of 200 mA, and remembering that the values are minimum values, the threshold current for this mode is expected to take a value of higher than 200 mA.

The results for the transverse case and $a = 0$ establishes a threshold current of 155.79 mA for the first h–type dipole mode, 72.24 mA for the first v–type dipole mode and 130.48 mA for the second v–type dipole mode. All other dipole modes do not establish any possible instabilities. This means, remembering again, that the threshold currents are lower limits and in addition to this, Landau damping due to the betatron spread for the case $a = 0$ has also been ignored, that in fact transverse coupled–bunch instabilities are not at all expected to be present in the modified cavity.

In summary only the first three higher order monopole modes can cause coupled–bunch instabilities, compared to a total of 14 modes in the case of the original cavity. These three remaining modes can be detuned easily by a proper adjustment of the cavity tuners. The expense for this is a 43% higher input power which has to be supplied to the cavity due to reduction of the shunt impedance of the fundamental mode by 30%.

Coupled–Bunch Instabilities by Use of the Redesigned Cavity in the Siam Photon Storage Ring

The same calculations as in the last section have been carried out with the cavity parameters of the redesigned cavity. The results of the longitudinal growth rates and threshold currents are given in table 4.27. It can be seen that five modes may cause coupled–bunch instabilities, while the threshold currents of the first four modes are quite low, which shows that these modes

Cavity Mode	ν (MHz)	μ, a (eq. 2.99)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
2	545.7	20, 1	28520	1.99
		2	6607	9.70
		3	333	203.38
3	767.0	16, 1	16790	3.38
		2	10019	6.405
		3	1570	43.14
4	933.0	29, 1	11343	5.01
		2	7678	8.35
		3	2390	28.34
		4	435	160.70
5	1084.2	6, 1	3910	14.53
		2	3574	17.93
		3	1562	43.36
		4	420	166.44
6	1309.0	3, 1	287	197.98
		2	383	167.33
		3	258	262.50

Table 4.27: Growth rates and threshold currents for longitudinal coupled–bunch instabilities in the Siam Photon storage ring by use of the modified cavity

could be dangerous.

The results for v–type and h–type transverse coupled–bunch instabilities are shown in table 4.28 and 4.29. The main difference between h–type and v–type coupled–bunch instabilities is due to the difference in the beam duct cross–section. Because in the modified cavity, the whole beam duct is enlarged, the beam duct has a greater influence to the growth rates, and the differences between h–type and v–type instabilities are larger as in the case of the original cavity. Because of this, the results are given separately.

These modes are not expected to cause any serious instabilities, remembering, that these values are minimum values, and the damping rate for the case $a = 0$ should be higher in reality. Taking both aspects into account, the real threshold current should be above 300 mA.

In summary, four higher order monopole modes alone could cause coupled–bunch instabilities, if the redesigned cavity was used in the Siam Photon Source storage ring. If the tuner positions are adjusted carefully, the frequencies of these modes could be shifted away from the bunch mode frequencies and stable operation could be expected.

Cavity Mode	ν (MHz)	μ, a (eq. 2.107)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
1	421.3	13, 0	200	87.53
2	561.3	7, 0	155	112.94
3	753.1	19, 0	95	184.26

Table 4.28: Growth rates and threshold currents for h–type transverse coupled–bunch instabilities in the Siam Photon storage ring by use of the modified cavity

Cavity Mode	ν (MHz)	μ, a (eq. 2.107)	$1/\tau_g$ (s^{-1})	I_{tr} (mA)
1	421.3	13, 0	275	63.65
2	561.3	7, 0	205	85.39
3	753.1	19, 0	102	171.62

Table 4.29: Growth rates and threshold currents for v–type transverse coupled–bunch instabilities in the Siam Photon storage ring by use of the modified cavity

4.3 Summary

The properties of all important modes of the storage ring cavity and the booster synchrotron cavity of the Siam Photon source are evaluated with the computer code MAFIA. For each cavity mode, resonance frequencies, Q–values and shunt impedances are calculated.

The resonance frequency of the fundamental mode of 118 MHz for both cavities can be confirmed within an error of a few percent. Higher order monopole and dipole modes with resonance frequencies up to their cut–off frequencies are investigated. The results show, that only modes with electric boundary condition on the symmetry plane of the cavity have a significant effect to the electron beam in the storage ring.

In the case of the booster synchrotron cavity, six higher order monopole modes and six dipole modes are found. Because each dipole mode is double degenerated, the total number of dipole modes is twelve

In the case of the storage ring cavity, the beam duct is not cylinder symmetric. Because of this, a modeling of the beam duct is carried out to evaluate the cut–off frequencies for monopole modes, h–type and v–type dipole modes. During the modeling of the cavity, the beam duct is simulated with a cylinder symmetric wave guide with the same cut–off frequency of the kind of mode under investigation.

By this procedure, 49 monopole modes, 10 v–type and 79 h–type dipole modes are found. The large difference between the number of modes for h–type and v–type dipole modes is due to the differences between their cut–off frequencies.

With the obtained data of the cavity modes, the possibilities of coupled–bunch instabilities are calculated with the computer code ZAP. The ring parameters of the SORTEC storage ring and the Siam Photon storage ring are taken into account. Radiation, Landau and total damping rates are calculated analytically By comparison of the obtained growth rates with the damping rates, threshold currents are calculated.

The calculations with the use of the SORTEC storage ring parameters show, that five higher order monopole modes, three h–type and six v–type dipole modes can lead to coupled–bunch instabilities. The difference between the number of dangerous h–type and v–type dipole modes is due to the difference between the horizontal and the vertical chromaticity.

In the case of the Siam Photon storage ring, the number of dangerous modes increases drastically. The reason for this is mainly a high reduction of the damping rates due to the different ring parameters. The results show that a total of 30 higher order monopole modes and 18 dipole modes can lead to coupled–bunch instabilities. Because the chromaticities are set to zero during this calculations, the results for h–type and v–type dipole modes are found to be the same.

In the last part of this chapter, a modification of the storage ring cavity is suggested, and the change of the cavity properties due to a change of the cavity geometry is investigated in detail. Finally a specific cavity shape is chosen as a proposal for a modification. This cavity contains high resistive SiC inside the beam duct, for absorption of the fields of higher order modes. Limitations due to the RF power supply are taken into account, and the amount of power that dissipates in the SiC material is estimated.

The modes of the modified cavity are calculated. Shunt impedances and Q–values of higher order monopole modes and dipole modes are drastically reduced by the use of SiC inside the beam duct. This makes these modes less dangerous.

The possibilities of coupled–bunch instabilities are calculated again. Investigations with the SORTEC storage ring parameters gives a number of four dangerous higher order monopole modes, and no dipole modes are expected to cause any instabilities. Calculations with the Siam Photon source parameters establishes five dangerous higher order monopole modes and six dangerous dipole modes.

Chapter V

Experimental Part

The properties of the cavity of the storage ring are measured in detail. Resonance curves of reflection and transmission coefficients of different modes can be observed. For the explanation of resonantce curves see subsections 2.1.4 and 2.1.5. For each mode the resonance frequency, the Q–value and the coupling coefficient β can be measured. Because the input coupler and all the equipment which is used during operation of the cavity is attached during the measurement, the measured Q–values are loaded Q–values. By measuring the loaded Q–values and coupling coefficients, the unloaded Q–values can be calculated by equation (2.22). By comparison with the results of the computer simulation, some of the modes can be identified as TM–type monopole modes, dipole modes, etc., and the shunt impedance or coupling impedance can be calculated by multiplying the measured unloaded Q–value with the calculated value of R_s/Q_o or R_t/Q_o, which are presented in section 4.2.

Two tuners are attached to the cavity. During operation in the storage ring, one tuner is used as a manual tuner and can be adjusted by hand, and the other tuner is adjusted by a driving device automatically. The dependence of the resonance frequencies on the tuner positions are also measured. During the measurement both tuners can be moved by hand, and the scale reading ranges between 0 and 150 mm, while at a reading of 0 mm, the tuners are placed most far inside the cavity. The scale reading at which the tuner surface matches with the inner cavity surface is unknown.

Two vacuum pumps and the input coupler are attached to the cavity. The input coupler consists of a coupling loop, which is placed parallel to the beam axis. This position corresponds to the maximum coupling coefficient for the fundamental mode. The relation between the coupling coefficient β and the angle θ between the coupling loop and the beam axis is given by:

$$\beta = \beta_o \cos^2(\theta) \tag{5.1}$$

where β_o is the maximum coupling coefficient. The input coupler is connected to a wave guide stub that has a T–junction. The length of the stub is equal to a quarter of the wavelength of the fundamental mode, which corresponds to an infinitely high impedance. Because of this, no measurement errors due to effects of the stub are expected. A ceramic window is placed inside the wave guide stub, which is used as the interface between the vacuum environment inside the cavity and the environment of atmospheric pressure inside the wave guide system.

The values of the transmission and reflection coefficients are given in dB or dBm. These values are defined relative to a reference voltage V_o or reference power P_o. If V_1 or P_1 is the absolute voltage or power, its dB value is defined by:

$$V_1[\mathrm{dB}] = 20\log_{10}(\frac{V_1}{V_o}) \tag{5.2}$$

$$P_1[\mathrm{dB}] = 10\log_{10}(\frac{P_1}{P_o}) \tag{5.3}$$

Because $P \sim V^2$, the dB values for power and voltages are the same, and no distinction between power and voltage is necessary. The power is sometimes measured in dBm. This is an absolute power value, and the definition is the same as in (5.3) with the reference power P_o set to 1 mW. Furthermore $P \sim E^2$, and the resonance curves of the electric field of the wave as explained in subsections 2.1.4 and 2.1.5 also have the same shape.

5.1 Measurement Procedure

For the measurement procedure, the following equipment is used:

1. Advantest Spectrum Analyzer TR 4173
2. Hewlett Packard Transmission/Reflection measurement test kit HP85044A
3. Hewlett Packard Calibration kit HP85032B
4. Nihon Koshyuha Coaxial tapered tube TM–120D–SJ
5. Nihon Koshyuha Flange BFX–120–D
6. Coaxial cables with N–type or BNC connectors to connect the equipment to each other.

The measurement is carried out at room temperature, and the cavity is evacuated to the range of 2–5 10^{-2} Torr, while one of the two vacuum pumps are in operation. The tapered tube (item 4) is connected at the T– junction of the wave guide stub with the flange (item 5). It terminates with an N–type connector where coaxial cables can be attached. The tapered tube is specially designed to match the impedances of the cavity and the attached cables over a sufficiently wide frequency range properly. A signal that is send to the input port of the tapered tube transmits it completely. No reflection is caused by the tapered tube, and thus, no measurement errors are expected to be caused by it. A drawing of the tapered tube is shown in figure 5.1.

The measurement of the reflection and transmission coefficients have been carried out with the Spectrum Analyzer (item 1). This device has a so–called “Tracking generator output option”, which may be used as a signal source. The

Figure 5.1: Drawing of the tapered tube, dimension in mm

Resolution bandwidth	300 Hz
Video bandwidth:	300 Hz
Input attenuator	0 dB (minimum)
Tracking generator level:	0 dBm (maximum)
Sweep time:	2 s or larger

Table 5.1: Standard settings during the measurement

input channel is tuned to the same frequency as the signal of the tracking generator, and the magnitude of the detected signal is displayed on a screen. The phase of the detected signal can also be measured

When measuring the resonance curves of the transmission or reflection coefficient, the tracking generator sweeps out an appropriate frequency range. The sweep is carried out during a period equal to the sweep time in steps equal to the resolution band width. The standard settings are shown in table 5.1. The Spectrum Analyzer has some help functions like peak search or differential measurement, which makes the measurements more exact and convenient.

5.1.1 Reflection Measurement

For the measurement of the reflection coefficient, the Transmission/Reflection measurement test kit (item 2) has to be used. This device contains a directional bridge that splits the reflected signal from the input signal. The tracking generator output of the Spectrum Analyzer is connected to the RF input port of the test kit. The kit splits the input signal by a power splitter to generate a reference signal. Because there is no input channel for a reference signal at the Spectrum Analyzer, the reference signal output of the test kit must be terminated by a 50 Ω load to avoid reflections. The input signal then passes the directional bridge, and terminates at a test port, which is connected to the tapered tube by a coaxial line. The reflected signal of the cavity is detected by the directional bridge and connected to the input channel of the Spectrum Analyzer. The set up of the experiment is shown in figure 5.2.

To calibrate the errors of the attached instruments and cables, the set up must be disconnected from the tapered tube and the cable must be terminated with a short to simulate total reflection. The short is contained in the calibration kit (item 3). With this set up, the frequency response can be eliminated by a normalize function of the Spectrum Analyzer. After this the cable must be connected to the cavity again. If the frequency range of the sweep is changed, the calibration must be carried out again. Because the band width of the resonance curve is very small, the frequency response of the cables and instruments is almost constant over this range, and the calibration procedure can be avoided in most cases.

The Spectrum Analyzer has a calibration output port, that can be used for calibration of the error of the Spectrum Analyzer itself. Unfortunately this

Figure 5.2: Experimental set up of the measurement of the reflection coefficient

port is probably broken and can not be used. Because of this, the absolute value of 0 dB, corresponding to total reflection can not be fixed on the screen. This gives some arbitrariness for the measurement of the coupling coefficient β and the loaded Q–value of a cavity mode, because for this the absolute value of the reflection coefficient at resonance is necessary (see subsections 2.1.3 and 2.1.5). After the instruments have been adjusted properly, the resonance curve of the reflection coefficient can be seen on the screen of the Spectrum Analyzer.

For measurement of the phase of the reflection coefficient, which is necessary for distinction between over–critical and under–critical coupling, the calibration has to be carried out again in the same way. In this case, the phase response of the attached cables and instruments are very sensitive to the frequency and the calibration cannot be avoided.

For a distinction between under–critical and over–critical coupling, a polar display on the so–called "Smith Chart" is useful. This chart shows the magnitude and phase of the reflection coefficient simultaneously. The trace of the curve in this display is a circle. In the case of over–critical coupling, the origin of the Smith chart is located within this circle, and the phase of the reflection coefficient sweeps out 360^o. If the origin is outside the circle, the phase sweep is smaller than 180^o, and this is the case of under–critical coupling. In the case of critical coupling, the circle touches the origin of the Smith chart, which corresponds to a phase sweep of exactly 180^o (see subsection 2.1.5).

5.1.2 Transmission Measurement

For the measurement of the resonance curve of the transmission coefficient, the tracking generator output channel is connected directly to the tapered tube. As explained in subsections 2.1.4 and 2.1.5 the transmission coefficient is proportional to the amplitude of the excited mode inside the cavity. It is detected with a small pick–up antenna inside the cavity, which has a BNC–type connector on the outer cavity surface. This port is connected with the input port of the Spectrum Analyzer. The set up of the experiment is shown in figure 5.3.

For the calibration procedure, the cables that are connected to the cavity must be removed from it and connected together directly to simulate total transmission. Then the normalization procedure has to be carried out and the cables must be connected to the cavity again. Also in the case of transmission, the calibration is not necessary in most cases.

After the instruments are adjusted properly, the resonance curve of the transmission coefficient can be seen on the screen. Because the coupling of the pick up inside the cavity is very low, the detected signal is much weaker compared to the signal of the reflection measurement. However the resonance curves can be seen quite clearly for most of the modes. The advantage of the transmission measurement is, that it is not necessary to measure absolute values of the transmission coefficient for the determination of the loaded Q–values. Only the width of the curve at half maximum has to be measured, which corresponds to an attenuation of -3 dB. Because of this, the results for the loaded Q–values

Figure 5.3: Experimental set up of the measurement of the transmission coefficient

are expected to be more exact and more reliable compared to the results of the reflection measurement. Because of this the transmission measurement procedure is used to measure the resonance frequencies and loaded Q–values of the modes, and the reflection measurement procedure is used to measure the coupling coefficient β, which is necessary to calculate the unloaded Q–value. The properties of the fundamental mode and higher order modes were measured by this method.

During the measurement of the resonance curves of the modes, the scale reading of the manual tuner is 135 mm and that of the automatic tuner 150 mm, corresponding to its longest way out of the cavity.

5.1.3 Measurement of the Effect of the Tuner Positions

The dependence of the resonance frequencies on the tuner positions are also measured. The fundamental mode, the first higher order monopole mode and the first h–type and v–type dipole mode are investigated. The manual tuner is kept fixed, at scale readings of 120, 135 and 150 mm and the automatic tuner is moved over the full range of the scale reading between 0 and 150 mm. If the position of the manual tuner is moved below a scale reading of 110 mm, the frequency of the fundamental mode is higher than 118 MHz over the full range of the automatic tuner position. Thus the adjustments of the manual tuner to these positions seem to be most suitable.

In the second measurement series, the positions of the manual tuner is adjusted to scale readings between 150 and 110 mm with 5 mm steps. The position of the automatic tuner is then adjusted to a position, where the resonance frequency of the fundamental mode is 118 MHz $\pm$ 2 KHz. At these tuner positions, the frequencies of the first higher order monopole mode and the first h–type and v–type dipole modes are measured. The results are compared with the frequencies of the coupled–bunch modes (2.99) and (2.107).

Resonance frequency ν_r:	117.9045 MHz $\pm$ 500 Hz
Loaded Q–value Q_L:	2869
Coupling coefficient β:	3.65
Unloaded Q–value Q_o:	13340
Shunt impedance R_s:	2.3086 MΩ
Q_m/Q_c:	0.54

Table 5.2: Measured properties of the fundamental mode

5.2 Results

5.2.1 The Fundamental Mode

The resonance curve of the reflection and transmission coefficient of the fundamental mode is shown in figure 5.4.

In the case of the reflection measurement, the resonance frequency of the mode is found to be 117.9048 MHz, and the frequency span is 300 KHz. The average value of the reflection coefficient at the edges of the curve, corresponding to $\nu_r \pm 150$ Hz, is set to 0 dB. With these settings, the reading at resonance is -4.88 dB. This corresponds to a reflection coefficient of 0.570 and a voltage standing wave ratio (2.33) of 3.65. The phase measurement established a phase sweep of 360^o over the range of the resonance curve, corresponding to over–critical coupling. Thus by (2.37), the coupling coefficient is equal to the voltage standing wave ratio at resonance. Calculation of $r(\nu_r \pm \Delta\nu)$ of equation (2.35) leads to -1.788 dB. The frequencies at which the reflection coefficient takes this value are found to be 117.8794 MHz and 117.937 MHz, which gives $\Delta\nu_H = 57.9$ KHz by equation (2.36). Finally the loaded Q–value is found to be 2036 and with (2.22), the unloaded Q–value is 9473

In the case of the transmission measurement, the resonance frequency is found to be 117.9043 MHz, which differs from the value of the reflection measurement by only 500 Hz. The full width at half maximum of the resonance curve is found by differential measurement relative to the peak of the curve. The amplitude of half maximum corresponds to an attenuation of -3 dB relative to the maximum. The corresponding frequencies are found to be 117.8824 MHz and 117.923.5 MHz, which gives a frequency difference of 41.1 KHz. The loaded Q–value is found to be 2869 by (2.30) and with (2.22) and a coupling factor of 3.65, found by the reflection measurement, the unloaded Q–value is 13340. If this value is multiplied with the value for R_s/Q, of 173.06 Ω, as given in table 4.5, the shunt impedance is found to be 2.3086 MΩ. Because of reasons described above, these value are more reasonable and more accurate compared to the Q–value and shunt impedance found by the reflection measurement. The properties of the fundamental mode are summarized in table 5.2. The measured unloaded Q–value Q_m is compared with the calculated Q–value Q_c of table 4.5.

Figure 5.4: Reflection coefficient $\mid r(\nu) \mid^2$ (upper graph) and transmission coefficient $\mid t(\nu) \mid^2$ (lower graph) as a function of ν of the fundamental mode

5.2.2 Higher Order Modes

All higher order modes below a frequency of 1 GHz are measured, and a total of 36 modes are found. The results are shown in table 5.3. As explained above, the measured coupling coefficient is connected with a relatively high error. Because of this, the loaded Q–values should be taken as much more accurate than the unloaded Q–values. Furthermore 28 higher order modes above 1 GHz are measured, and the results are given in table 5.4. The modes are chosen in correspondence with the calculated ones, so most of the modes can be identified. The results show that most of the calculated monopole and dipole modes, that have electric boundary condition on the symmetry plane, can be observed by measurement. Modes that cannot be measured have coupling coefficients which are too small.

The results of table 5.3 show that there exist much more higher order modes compared to the number of modes that have been calculated. The additional measured modes are modes which have negligible effects to the electron beam. These modes are any kinds of modes which have magnetic boundary condition on the symmetry plane of the cavity, TE–type modes and modes with $m > 1$ in equation (2.48), which are called quadrupole modes, octupole modes etc.. The Q–values of these modes are of the same magnitude, but the shunt impedances or transverse impedance are very small, and thus these modes have no significant effect to the electron beam.

The correspondence between the measured and calculated modes is shown in table 5.5. The ratio of the measured and calculated unloaded Q–values Q_m/Q_c and the shunt impedances R_s of monopole mode or R_t of dipole modes are calculated by using the reslts of the computational part. In some cases, the identification of the modes is a bit uncertain. The density of the modes increases with higher frequencies, and in some cases, several modes have frequencies close to one calculated mode. The distinction between h–type and v–type dipole modes is also a bit arbitrary. With the calculated modes, the resonance frequencies of the v–type modes are a little bit lower than in the case of h–type modes, and because of this, for two measured modes, which frequencies are very close to the frequencies of a dipole mode, the measured mode with the lower frequency is assigned as the v–type mode.

The measured modes No. 10 and 37 correspond to dipole mode No. 2 and 6. However with these frequencies, only one dipole mode can be observed and the mode is arbitrary assigned as the v–type mode. The absence of the second dipole mode may be caused either by an overlap of the resonance curves, or by a coupling coefficient of approximately zero for one of the modes.

The measured Q–values and shunt impedances of the fundamental mode as well as the higher order modes have only a magnitude of about 50% compared to the calculated values A possible explanation for this is the fact, that the cavity operated in the SORTEC storage ring for several years before it was transferred to Thailand. During operation of the ring, the conductivity σ of the inner cavity surface could have been decreased, which leads to higher energy dissipation on

No.	ν_r (MHz)	Q_L	β	Q_o
1	374.0	603	35.1	21770
2	424.1	2120	6.4	15770
3	498.1	3029	4.42	16415
4	506.3	16411	0.024	16805
5	507.5	15269	0.14	17451
6	516.6	14718	0.475	21714
7	613.0	2691	0.024	2755
8	623.7	8723	1.37	20652
9	630.2	1942	1.13	4139
10	640.4	5098	1.15	11183
11	644.5	16161	1.09	33815
12	646.7	11228	0.30	14551
13	648.5	1374	1.39	3287
14	701.0	8998	0.01	9896
15	702.6	15861	0.28	20321
16	729.4	13762	0.19	16322
17	736.1	17000	0.09	18474
18	764.6	18650	3.86	90720
19	766.1	1944	4.34	10373
20	828.2	30845	0.42	43906
21	847.4	11952	0.44	17170
22	848.3	10221	1.00	20442
23	852.3	12702	1.64	33593
24	852.8	21699	0.026	22261
25	899.8	28429	0.013	28789
26	900.9	25703	0.18	30413
27	906.1	21548	0.01	21767
28	919.0	2327	2.12	7260
29	935.0	13997	0.75	24494
30	955.0	8794	0.058	9300
31	966.6	12889	0.82	23453
32	967.8	23124	0.26	29207
33	968.4	9188	2.54	32533
34	980.1	35066	0.077	37778
35	982.2	4473	3.25	18996
36	988.8	2252	4.62	12658

Table 5.3: Measured higher order modes below 1 GHz

No.	ν_r (MHz)	Q_L	β	Q_o
37	1025.8	8361	1.83	23700
38	1241.4	4293	1.74	11748
39	1242.2	4826	0.35	6533
40	1264.0	1448	23.18	35008
41	1266.1	10962	1.23	24391
42	1267.4	6706	1.90	19471
43	1286.1	38622	0.017	39260
44	1286.4	26307	0.45	38145
45	1494.8	5526	0.17	6493
46	1496.8	14296	0.02	14590
47	1500.2	13515	0.27	17186
48	1500.8	9529	1.56	24348
49	1510.7	9740	0.01	9838
50	1512.7	25510	0.09	27744
51	1569.2	5170	0.033	5340
52	1571.4	9977	0.64	16338
53	1572.6	11869	0.12	13334
54	1654.0	15357	0.01	15488
55	1779.7	9615	0.127	10832
56	1940.4	8153	0.187	9679
57	2140.8	3414	0.012	3455
58	2250.7	3907	5.17	24094
59	2299.7	4545	0.018	4627
60	2300.4	1330	0.026	1365
61	2618.6	7793	0.047	8161
62	3054.0	3881	0.047	4065
63	3132.0	7439	0.39	10342
64	3370.9	4836	0.178	5695

Table 5.4: Measured higher order modes above 1 GHz

No. tab. 5.3, 5.4	Calc. mode table, number	kind	Q_m/Q_c	R_s (KΩ) or R_t (KΩ/m)
1	figure 4.9	monopole	—	—
3	4.5, No. 2	monopole	0.47	51.87
4	4.9, No. 1	v–type dipole	0.55	1926.86
5	4.7, No. 1	h–type dipole	0.57	2034.61
10	4.9, No. 2	v–type dipole	0.65	4879.03
19	4.5, No. 3	monopole	0.21	20.85
27	4.5, No. 4	monopole	0.56	38.96
31	4.9, No. 5	v–type dipole	0.40	542.47
32	app. 2, No. 5	h–type dipole	0.50	663.38
36	4.5, No. 5	monopole	0.25	13.04
37	4.9, No. 6	v–type dipole	0.49	930.46
38	4.5, No. 6	monopole	0.26	13.04
41	4.9, No. 7	v–type dipole	0.47	310.01
42	app. 2, No. 7	h–type dipole	0.37	230.56
43	4.9, No. 8	v–type dipole	0.50	159.79
44	app. 2, No. 8	h–type dipole	0.48	145.19
45	4.9, No. 9	v–type dipole	0.10	12.60
46	app. 2, No. 9	h–type dipole	0.22	23.55
48	app. 1. No. 8	monopole	0.41	25.51
49	4.9, No. 10	v–type dipole	0.13	75.65
50	app. 2, No. 10	h–type dipole	0.38	180.09
52	app. 1, No. 9	monopole	0.33	17.46
54	app. 1, No. 10	monopole	0.30	15.50
55	app. 1, No. 11	monopole	0.21	10.84
56	app. 1, No. 12	monopole	0.19	16.92
57	app. 1, No. 15	monopole	0.06	0.67
58	app. 1, No. 16	monopole	0.31	16.67
59	app. 1, No. 17	monopole	0.08	5.67
61	app. 1, No. 22	monopole	0.15	15.73
62	app. 1, No. 29	monopole	0.06	0.83
63	app. 1, No. 30	monopole	0.15	15.32
64	app. 1, No. 34	monopole	0.09	10.03

Table 5.5: Correspondence between measured and calculated higher order modes

the cavity surface and thus to a reduction of the Q–values. Because $Q \propto \sqrt{\sigma}$ by equation (2.17), a reduction of the conductivity by a factor of 1/4, would lead to a reduction of the Q–values by 50%. The reduction of the conductivity may be caused by sputtering of ions into the cavity by the vacuum pumps during operation. Another reason could be insufficient contacts among the different parts of the cavity body, This property depends on the fabrication procedure of the cavity.

During operation of the cavity in the SORTEC storage ring, the shunt impedance is reported as 2.70 MΩ (Awaji et al., 1992), which is much lower than the calculated value. If the shunt impedance decreases, the Q–value must decrease by the same factor, because the ratio R_s/Q only depends on the cavity geometry and remains constant. When this report was given in 1992, the ring has been operating for a few years already, and the Q–values and shunt impedance could have been decreased during operation time. During further operation of the ring, the values could have decreased further down to the value that is measured at present.

Another indication for this explanation is the fact, that for all Q–values, at least for modes with resonance frequencies of up to 1 GHz, the ratio of measured and calculated Q–values is approximately the same, namely around 50%. A change in the conductivity of the cavity surface would lead to a reduction of the Q–values of all modes by about the same factor.

In addition to this, the cavity has many ports on its inner surface. Two vacuum pumps are connected directly to the cavity, two monitor ports and one window are attached to it. The power, that dissipates in this equipment may be in the same order as the power that dissipates on the cavity surface, because the resistivity of the material of the attached equipment is much higher than the resistivity of the cavity walls. Furthermore, the holes in the surface lead to a distortion of the current that flows on the surface. All these effects lead to a rise in the power consumed by the cavity and a reduction of the Q–values. These effects are not considered in the computational part. In the case of the 500 MHz cavities of Photon Factory, the measured Q–values are in the order of 90% of the calculated values, but in the case of the 118 MHz cavity of Siam Photon source, the structure and fabrication procedure is different, and the measured values should be reasonable.

5.2.3 The Effect of the Tuner Positions

The response of the resonance frequency of a mode due to a movement of the tuners is different for every mode. If the region where the tuner is located is dominated by the electric field, the resonance frequency rises as the tuner is moved into the cavity. If this region is dominated by the magnetic field, the frequency decreases as the tuner is moved in (Collin, 1992).

The change of the resonance frequency of the fundamental mode and the first higher order monopole mode due to the tuner movement is shown in figure 5.5. Note that in this and the following figures, the tuner is moved out of the

Figure 5.5: Dependence of the resonance frequencies of the fundamental mode (upper graph) and the first higher order monopole mode (lower graph) on the automatic tuner positions

cavity as the scale reading increases. The result for the fundamental mode shows that the resonance frequency rises, when the tuners are moved into the cavity. The curves are qualitatively in agreement with the theory. The result is quite different in the case of the first higher order monopole mode. It can be seen that as the automatic tuner is moved into the cavity, starting from a scale reading of 150 mm, the frequency rises in the same way as the frequency of the fundamental mode up to a scale reading of about 100 mm. Then the slope decreases until the resonance frequency reaches a maximum at around 70 mm. Below this scale reading, the frequency decreases rapidly. Observations on the Spectrum Analyzer show, that this strange behavior is caused by interference with another mode. A mode which has a lower resonance frequency as the mode under consideration can be seen on the Spectrum Analyzer. The frequency of this mode has a stronger dependence on the tuner position than the first higher order monopole mode. As the tuner is moved in, the frequencies of the two modes become closer, and at a scale reading of around 100 mm, the modes start to interfere. As the tuner is moved in further, the resonance frequency is more and more dominated by the disturbing mode, and because of this, the frequency decreases.

The curves for the first dipole modes are shown in figure 5.6. The result is similar to the case of the first higher order monopole mode. The reason for this behavior is not completely clear. However it can be observed, that as the tuner is moved, the frequencies of both modes may become close to each other and start to interfere. In some cases, the resonance curve of one mode is located on the slope of the other mode. In addition to this, the coupling of the modes depend very strongly on the tuner positions, and at some positions, only one mode can be observed. All these effects of course have significant influences to the resonance frequencies.

It may also be possible that the dominance of the field of the mode around the surface of the tuner changes from electric to magnetic as the tuner is moved into the cavity. In this case, the resonance frequency may have a maximum around the tuner position, where the dominance changes.

Adjustment of the Tuner Positions to Proper Fundamental Mode Frequencies

The two different tuner position at which the frequency of the fundamental mode is 118 MHz $\pm$ 2 KHz are shown in figure 5.7 (upper graph). The scale reading of the manual tuner is indicated on the x–axis and the position of the automatic tuner is shown on the y–axis.

The resonance frequency of the first higher order monopole mode at these tuner positions are shown in figure 5.7 (lower graph) and for the dipole modes in figure 5.8. The frequencies of the coupled–bunch modes are indicated as straight lines in these figures with n corresponding to $nM \pm \mu$ in equations (2.99) and (2.107).

The results show that at the scale reading of 125 mm of the manual tuner, the resonance frequencies of the first higher order monopole and the first v–

Figure 5.6: Dependence of the resonance frequencies of the first v–type (upper graph) and h–type (lower graph) dipole mode on the automatic tuner positions

Figure 5.7: Dependence of the automatic tuner position on the manual tuner position (upper graph) and dependence of the resonance frequency of the first higher order monopole mode on the manual tuner position (lower graph) with v_r of the fundamental mode fixed to 118 MHz

Figure 5.8: Dependence of the resonance frequency of the first v–type (upper graph) and h–type (lower graph) dipole mode on the manual tuner positions with v_r of the fundamental mode fixed to 118 MHz

type dipole mode have a maximum, and the resonance frequency of the first h–type dipole mode has a minimum. In all three cases, the resonance frequencies are most far away from the coupled–bunch mode frequencies at these extremal points. Thus during operation of the cavity, the manual tuner should be adjusted to the scale reading of 125 mm.

5.3 Summary

The properties of the storage ring cavity are measured with a Spectrum Analyzer, that has a Tracking generator output option, which can be used as a signal source. The cavity properties can be measured by observing resonance curves of the transmission and reflection coefficient of the cavity modes. The resonance curves can be observed on the screen of the Spectrum Analyzer, and resonance frequencies, Q–values and coupling coefficients of each mode can be evaluated.

In the case of the transmission measurement, the cavity is fed with the signal of the tracking generator output. The signal of the excited mode inside the cavity is detected with a small antenna inside the cavity. For the measurement of the reflection coefficient a transmission/reflection test kit must be used. This device can split the reflected signal from the input signal with a directional bridge.

The resonance curve of the reflection coefficient has a minimum and the curve of the transmission measurement has a maximum at the resonance frequency. The loaded Q–value can be evaluated by the full with at half maximum of the resonance curve of the transmission measurement. If the resonance curve of the reflection coefficient is used to measure the loaded Q–value, the absolute value of the reflection coefficient must be measured. Because the instrument itself cannot be calibrated, this absolute value contains some arbitrariness. Because of this, the transmission measurement is expected to give more exact results for the loaded Q–values.

The coupling coefficient can only be measured by reflection measurement. It is given as the VSWR at the resonance frequency in the case of over–critical coupling, and its inverse in the case of under–critical coupling. The determination of the kind of coupling can be made by measurement of the phase of the reflection coefficient around the resonance.

The unloaded Q value is calculated with the measured loaded Q–value and the coupling coefficient. The shunt impedance or transverse impedance is calculated by multiplication of the unloaded Q–value with the ratio of the impedance and the Q–value, which is found in the computational part.

The resonance frequency of the fundamental mode is found as 117.9 MHz, which is in good agreement with the computational result. The measured unloaded Q–value is only 54% of the calculated value. The coupling coefficient is found to be 3.65, which is higher than expected.

Measurement of higher order modes lead to a total number of 36 modes below a frequency of 1 GHz. These are much more modes as found by the computational research. Modes that are not found by computation are modes which have no effect to the electron beam, for example TE–type modes, quadrupole modes, octupole modes or modes with magnetic boundary condition on the cavity symmetry plane. The mode kind cannot be determined by this kind of measurement.

Most of the modes with frequencies above 1 GHz, which are found by the computational research, can also be measured. All modes which are found to be important for coupled–bunch instabilities are investigated. A total of 28 modes with resonance frequencies above 1 GHz are measured.

Comparison of the measured modes with the calculated modes, shows that the resonance frequencies are in good agreement, and the measured unloaded Q values of most of the modes are approximately half of the values found by the computational research. The reason for this is the fact, that a lot of equipment is attached to the cavity, that could lead to power dissipation which could be in the order of the power that dissipates in the cavity walls. The inner surface could have been deteriorated during the operation of the cavity in the SORTEC storage ring.

The change of the resonance frequencies of the fundamental mode and three higher order modes due to a movement of the tuners is also investigated. The manual tuner is fixed at three different positions and the automatic tuner is moved over its full scale range of 15 cm. The result of the fundamental mode is qualitatively in agreement with the theory. The frequency raises when the tuner is moved in. In the case of the first higher order monopole mode and the first v–type and h–type dipole mode, all frequencies have a maximum at a certain position of the automatic tuner. This unusual behavior is caused by interference of the measured mode with other modes, a change of the coupling of the mode due to the tuner movement or a change of the dominance of the field kind at certain position of the tuner.

In another measurement series, the manual tuner is fixed to nine different positions, and the position of the automatic tuner is adjusted to a positions, where the resonance frequency of the fundamental mode is exactly 118 MHz. At these tuner positions, the resonance frequencies of the first higher order monopole mode and the first h–type and v–type dipole mode are measured. These frequencies are compared with the frequencies of the coupled–bunch modes. The results show, that all frequencies have minima or maxima at the scale reading of 125 of the manual tuner. For all three modes, the resonance frequencies are most far away from the coupled–bunch mode frequencies at this position. Thus the position of the manual tuner should be adjusted to this scale reading during operation of the storage ring.

Chapter VI

Conclusion

6.1 The Cavities of Photon Factory

The cavities and the beam duct that are installed in the Photon Factory storage ring are mainly designed for suppression of coupled–bunch instabilities which are caused by higher order cavity modes. Modes with frequencies higher than the cut–off frequency of the beam duct propagate out of the cavity and are absorbed by the SiC material of the beam duct. In the case of modes with lower resonance frequencies, the frequencies are shifted away from the coupled–bunch mode frequencies by an appropriate design of the two fixed tuners.

Since no coupled–bunch instabilities due to higher order cavity modes are observed in the upgraded Photon Factory storage ring, these methods seem to be very useful and should be recommended for future applications at the Siam Photon source.

6.2 The Computational Research

The properties of the storage ring cavity and the booster synchrotron cavity have been investigated by computer simulation. Resonance frequencies, shunt impedances and Q–values of all important modes with resonance frequencies up to the cut–off frequency of the beam duct were calculated.

Longitudinal and transverse coupled–bunch instabilities were investigated first by using the parameters of the SORTEC ring. A total of 14 modes were found to be dangerous and could give rise to coupled–bunch instabilities. However the storage ring was operating successfully, when it was used at the SORTEC facility. This emphasizes the fact, that the obtained growth rates are upper limits due to a tuning of the resonance frequencies to one of the coupled–bunch mode frequencies, and in general the effects of the higher order modes to the beam should be much smaller.

When the ring will be reconstructed at NSRC, most of the ring parameters change and the operation conditions will be quite different compared to the SORTEC ring. The main effect is a drastic reduction in the damping rates, which causes a high decrease of the threshold currents. Because of this, a total of 48 modes may cause coupled–bunch instabilities.

This shows that the operation of the Siam Photon source ring could be less stable compared to the SORTEC storage ring. Because of this, a reconstruction of the cavity as proposed in chapter 4.2.10 could be necessary. The redesigned cavity contains SiC material inside the beam duct, which was used in the Photon Factory storage ring for absorption of the fields of the higher order cavity modes successfully.

For a reduction of the Q–values of undesired modes, the inner and outer radius of the beam duct must be enlarged in a way that the frequency of the fundamental mode remains unchanged, and the gap width of 23 mm should be kept constant. The effect of the enlargement is a higher separation between the fields of the fundamental mode and higher order modes, which makes a use of SiC inside the beam duct more effective. On the other hand, this procedure leads to a reduction of the shunt impedance of the fundamental mode that makes a higher power input necessary.

Because of this, technical limitations should be taken into account. The enlargement of the beam duct ports of the cavity would result in a complicated technical procedure, that would require a reasonable amount of time and money. Possibly, this work has to be done in Japan by the manufacturer. Thus the question, if the modification of the cavity will be carried out or not, is probably a question of the budget and time schedule of NSRC.

If the redesigned cavity would be operating in the Siam Photon source ring, a total of 11 modes could cause coupled–bunch instabilities. This number is a little bit lower as the number that was found in the SORTEC storage ring, when the original cavity was used. Thus, if the redesigned cavity would be used in the Siam Photon source storage ring, stable operation of the ring could be expected, and improvement of the beam properties could be possible.

6.3 The Experimental Research

The situation changes drastically, if the measured data instead of the calculated data are taken into account. The measurement shows that the real shunt impedance and Q–value of the fundamental mode are only in the range of 50–60% of the calculated values. The difference may be caused by a decrease of the conductivity of the inner cavity surface, insufficient contact among the parts of the cavity body, and the ignorance of the attached equipment and ports inside the cavity by the computational research.

Because of the low Q–value of the fundamental mode, a higher input power is necessary. Thus, a redesign of the cavity in a way, that would lead to a further reduction of the shunt impedance of the fundamental mode should not be recommended. If this would be done, the shunt impedance of the fundamental mode would become so low, that the cavity could become useless. Instead of this, a construction of a new cavity would be more useful.

On the other hand, the Q–values and impedances of the higher order modes decrease by the same factor compared to the results of the computational part. This would reduce the possibility of coupled–bunch instabilities, and the operation of the ring could be more stable.

Investigations of the dependence of the resonance frequencies on the tuner positions show, that the first higher order monopole mode and the first h–type and v–type dipole mode can be detuned easily by an adjustment of the manual tuner to a suitable position. This frequency shift method was carried out with the cavities of the Photon Factory storage ring successfully. In the case of the Siam Photon storage ring cavity, this method can be applied easier and more efficiently, because it has two movable tuners.

6.4 Future Perspective

At the time when this thesis was written, the modification of the storage ring cavity is not planed, and the Siam Photon source is scheduled to operate with the original cavity. The results of this thesis show that higher order modes of the cavity could lead to dangerous beam instabilities. On the other hand insertion devices are planned to be installed in the straight sections of the ring. This would lead to higher radiation power, higher radiation damping rates and a reduction of coupled–bunch instabilities.

Further investigations of the cavity are planned. NSRC is planning to purchase a Network Analyzer in the near future. With this device, the cavity properties can be measured more accurately. The instrument can be calibrated properly, which leads to a very much higher accuracy with the measurements of the coupling coefficients. In addition to this, the measured amplitudes can be compared with a reference signal. This improves the accuracy further.

In addition to this further measurements will possibly be carried out. The wave guide stub, which is connected to the cavity, and the input coupler should be investigated. Different kinds of antenna, which couple with different kinds of modes have been designed and can be constructed. With these antennas, higher order modes can be investigated more accurately. Also the RF system of the booster synchrotron should be investigated.

When the cavity is installed in the ring, high power operation has to start. The work that has to be done is similar to the procedures that were carried out during the upgrading of the Photon Factory storage ring and are reported in chapter 3. Because of this, the experiences gained during the ten months stay at Photon Factory play an important role and can surely be applied at the set up of the RF system of the Siam Photon source.

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Appendix

Appendix I

Modes of the Storage Ring Cavity

The complete results for all monopole modes and h–type dipole modes of the storage ring cavity are listed in this appendix.

Mode	ν (MHz)	Q–value	$R_s/Q(\Omega)$
1	121	24926	173.0581
2	499	34917	3.1639
3	766	49257	2.0102
4	907	39179	1.7918
5	991	50581	1.0284
6	1243	45733	1.1085
7	1482	62956	0.5639
8	1499	59966	1.0479
9	1572	49301	1.0689
10	1655	51143	1.0006

Table A.1: Monopole modes of the storage ring cavity 1

Mode	ν (MHz)	Q–value	$R_s/Q(\Omega)$
11	1781	51798	1.0718
12	1942	51266	1.7477
13	2009	49575	0.4750
14	2111	59906	0.0003
15	2146	55161	0.1947
16	2253	77727	0.6897
17	2300	58701	1.2261
18	2424	53555	5.6440
19	2465	69388	0.4627
20	2478	71756	0.0807
21	2546	52456	3.0720
22	2620	56165	1.9275
23	2704	63302	0.2016
24	2881	64867	0.5484
25	2945	66869	1.3471
26	2978	75293	0.2450
27	2996	79356	0.0057
28	3024	74764	0.3675
29	3052	71298	0.2050
30	3130	71115	1.4816
31	3205	63019	3.4333
32	3332	75192	0.0994
33	3344	76116	0.0010
34	3372	62400	1.7608
35	3463	84955	0.1396
36	3518	57914	0.0038
37	3573	72636	0.1231
38	3628	64066	0.7436
39	3732	77821	0.1005
40	3754	107995	0.1106
41	3778	79912	0.0054
42	3807	83708	1.0697
43	3878	80961	0.0828
44	3901	79653	0.9478
45	3964	96120	0.4687
46	4030	83125	0.0015
47	4033	71951	1.7524
48	4114	61721	1.8125
49	4161	62120	0.8754

Table A.2: Monopole modes of the storage ring cavity 2

Mode	ν (MHz)	Q–value	$R_t/Q(\Omega/m)$
1	504	30591	116.5909
2	642	17149	440.8283
3	801	45632	73.0094
4	931	55625	20.0451
5	966	58295	22.7131
6	1024	48300	38.2980
7	1265	52311	11.8410
8	1281	78826	3.8062
9	1495	65488	1.6144
10	1511	73713	6.4910
11	1586	63598	4.7489
12	1609	82845	4.5681
13	1673	54801	7.9459
14	1687	99099	0.2833
15	1800	56925	6.0066
16	1878	108380	0.9933
17	1974	65664	3.6319
18	2028	35903	0.2679
19	2112	60600	2.9124
20	2119	57791	8.1530
21	2125	116076	0.5062
22	2131	110262	0.0571
23	2241	75199	5.5371
24	2290	60386	6.1463
25	2311	126112	1.2581
26	2413	60609	14.0454
27	2461	94200	0.4510
28	2468	100876	0.0929
29	2476	72078	0.1803
30	2492	126578	0.0119
31	2554	59709	3.3473
32	2593	120721	0.0014
33	2644	58780	1.8053
34	2700	140679	0.0012
35	2733	55318	0.4653
36	2845	46349	51.0111
37	2896	132418	0.0668
38	2908	67405	7.3136
39	2968	84850	0.5427
40	2990	90902	0.0006

Table A.3: H–type dipole modes of the storage ring cavity 1

Mode	ν (MHz)	Q–value	$R_t/Q(\Omega/m)$
41	2998	144100	0.0384
42	3007	78446	1.2646
43	3034	118321	0.1929
44	3046	87917	0.2044
45	3064	130380	0.0007
46	3094	81715	3.0035
47	3154	137362	0.1038
48	3169	81869	0.9947
49	3321	77884	0.0287
50	3325	138333	0.0005
51	3337	79561	0.0007
52	3341	141571	0.0133
53	3343	140680	0.0154
54	3348	83417	0.1736
55	3450	97145	0.3678
56	3501	45305	25.5121
57	3533	56511	26.3874
58	3540	139583	0.0150
59	3571	71781	7.6530
60	3588	165442	0.0683
61	3636	61506	8.5683
62	3718	115989	0.0367
63	3720	96719	0.0621
64	3737	113722	0.0492
65	3765	95774	0.0000
66	3768	147780	0.0001
67	3770	119257	0.0011
68	3784	85960	0.0128
69	3860	83018	0.5919
70	3867	146445	0.3222
71	3872	81406	0.5768
72	3880	166793	0.0136
73	3933	91690	1.4545
74	3971	52646	0.8596
75	4015	84315	0.0585
76	4019	103076	0.6715
77	4020	59318	2.3247
78	4022	47288	3.7981
79	4080	53267	11.6557

Table A.4: H–type dipole modes of the storage ring cavity 2

Personal History of the Author

Mr. Klaus Haß was born on 27. June 1964 in Geldern, Germany. After he finished his high school education in 1986 he started a course in Physics at the University of Duisburg in Germany. After two years he passed the so–called “Vordiplom examination” with the mark “gut” (good).

After that, in the year 1988, he resigned from the University of Duisburg and continued his course work in Physics at the University of Kőln, Germany. In 1993 he could finish his course and received his Diploma Degree, which is equivalent to a Masters Degree, with the mark “gut” (good). The topic of the Diploma thesis was: “About the problem of electromagnetic wave propagation through wave guides with ’cut-off’ ”. During the final year of his course he possessed a position as a research student and had to look after students during their practical laboratory training.

In December 1994 Mr. Klaus Haß settled over from Germany to Thailand, and in May 1995 he started to work as assistant teacher at Ubon Ratchathani University. He resigned from this position in September 1996 and temporary joined a research project at Forum for Theoretical Science of Chulalongkorn University in Bangkok. Since the beginning of 1997 he works as research assistant at National Synchrotron Research Center (NSRC) in Nakhon Ratchasima. In May 1997 he entered a Ph. D. course in accelerator Physics at Suranaree Univerity. From May 1997 to April 1998 he stayed at Photon Factory at KEK in Tsukuba, Japan, where he joined a training program about the RF accelerating system of the Photon Factory storage ring.