125MHz CAVITY FOR NAR

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Abstract

This article describes the design of an rf cavity installed in NTT's Normal-conducting Accelerating Ring (NAR), considering both the beam loading effect just after high current injection and HOM's transverse impedances.

It was found using the 3D-program "MAFIA" that transverse HOM's impedances, except for the TM110 mode, were of a negligible order of less than 10^{-9} MΩ in the case of an acceleration gap width of 2 cm. In the NAR, multiturn single cycle injection was applied because of extremely long damping time of the 13 MeV injection beam. To estimate the induced rf voltage by the injected beam and the energy spread by bunch rotation, behavior of injected electrons on the energy rf-phase space was simulated.

The Re-entrant type 125 MHz cavity with a gap of 2 cm and the detuning frequency of -1 MHz was fabricated.

Introduction

In order to investigate the feasibility of economical and compact synchrotron radiation sources for lithography, NTT has developed a synchrotron radiation facility that includes Normal-conducting Accelerating Ring (NAR) with final energy 800 MeV[1]. In the NAR, the injected 13 MeV beam from the linac is accelerated to the final energy and directly stored.

In such an acceleration scheme[2], injection operation is carried out only one time because of the extremely long damping time. Therefore, high current beam, that is, more than 0.5 A, must be injected during several μs. After injection, the bunch rotation starts to exchange time spread to energy spread in the separatrix. In the range from injection energy to about 100 MeV, the beam size and energy spread are usually wide. Energy spread caused by bunch rotation in such an energy region must be suppressed as narrow as possible. Furthermore, to keep the phase stability condition, it is important to reduce the induced rf voltage by the injected beam itself.

There are many current limiting factors relating to a cavity. The dangerous instabilities leading to beam loss are classified into long time range and short time. The Transverse Coupled Bunch Instabilities (TCBI) belong to the former, the latter is the head tail one. It is known that the TCBI are caused by Higher Order Mode (HOM) of a cavity that has a transverse electric or magnetic field across the beam passing portion. It is practically impossible to design an accurate frequency of HOM. It is better idea to design a cavity structure to lower HOM's impedances.

This article describes the design of NAR's cavity, considering both, beam loading effect just after high current injection and HOM's transverse impedances.

Requirement of NAR's cavity

In the NAR's accelerating scheme, the required rf voltage ranges from 3 KV to 60 KV. The former is decided by the required bucket height just after injection, described later, the latter is related to Touschek life time at 800 MeV.

The radiation loss at 800 MeV is 20 KeV and the dissipated power in a cavity is not so high.

Therefore, the following two factors are the most important, the first is high rf capture efficiency and the second is reducing beam loss during acceleration.

Higher rf voltage certainly makes rf capture efficiency higher, but at the same time the energy spread becomes wider by bunch rotation[3]. In the NAR's CHASMAN-GREEN type lattice, the maximum dispersion function is about 2 m[1]. So, it is necessary to suppress the energy spread to less than 2 % which corresponds to the beam size of 80 mm wide. In order to obtain beam current of several hundred milli-amperes at the final energy, a beam current of about 1 A may be injected. High current beam injection induces high rf voltage in a cavity just after injection. In such a high current injection operation, while keeping the phase stable, it is necessary to reduce the induced voltage to avoid a wide energy spread.

Beam loss due to instabilities caused by an rf cavity must be avoided, especially during the acceleration period, because the radiation damping time in the low energy region is extremely long. It is difficult to predict all the cause of the instabilities. Longitudinal instabilities will not affect beam current loss, but the transverse limits the stored beam current[4]. The HOM inevitably exists in any cavity and its frequency can not be accurately designed. It may be practical to decrease the HOM transverse impedances to a negligible order.

Calculation of Higher Order Mode impedance

Representative types of cavities that have been used in many accelerators are a Re-entrant type VHF cavity or a Pillbox like UHF one. HOM impedances of both types were estimated using the 3D program "MAFIA"[5]. Using this program, monopole and dipole mode, et al, were estimated on a cylindrically symmetric structure on a beam passing Z-axis.

The structure of the cavity was decided in order that the frequency of the fundamental TM010 mode with an acceleration gap width of 2 cm coincided with about 125 MHz. The HOMs were estimated for four kinds of gaps, that is, 2, 10, 20 and 30 cm. Other sizes, except for the gap, are the same for all the calculation models. Figure 1 shows, as an example, a quater part of a calculation model of a cavity with a gap width of 10 cm. In the case of a gap width of 30 cm, it corresponds to the Pillbox type.

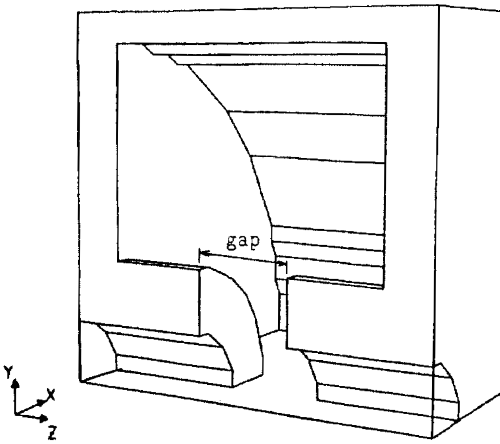

Figure 1 A quater part of a cavity with gap width 10 cm

The HOM, which has an electric or magnetic field across the beam passing Z-axis on the transverse plane, that is, TM110, TM111, TE111, et al, may cause TCBI. In a range of less than 1 GHz, the gap dependance of the impedance is shown in Fig. 2. The transverse: R_T and the longitudinal impedance : R_L are defined as,

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$$R_T = \int \{(E_T + c \cdot B_T) \cdot \exp(i\omega z)\}\, dz / P$$

$$R_L = \int E_L \cdot \exp(i\omega z)\, dz / P$$

where E_T and B_T are the transverse components of the electric and magnetic field respectively. E_L is the longitiudinal electric field component. c and ω are the light speed and resonant frequency, respectively. P is the power loss in the cavity that is assumed to be made from copper.

The R_L of the fundamental mode almost does not depend on the gap width within factor 3 as shown in Fig. 2. The R_T of the HOM, except for the TM110 mode, remarkablly decreases in order as the gap width becomes narrower. This feature is characterized by the relationship between the field pattern of the HOM and the gap width. A resonant phenomenon with a high quality facter is essentially formed by the cavity body, which is the surrounding part beyond the acceleration nose in the cavity. The HOM except for the TM110 mode has an electric field that is perpendicular to the Z-axis at the cavity center. Therefore, in a case of a narrow gap, the electric field in the cavity body will not spread to the beam passing portion through the gap. The difference in field patterns between the TM110 and TM111 mode with a gap width of 2 cm is indicated in Fig. 3. It is found that the electric and magnetic field of the TM111 are isolated from the cavity body by a narrow gap. As a result, the R_T of such a HOM becomes extremely low.

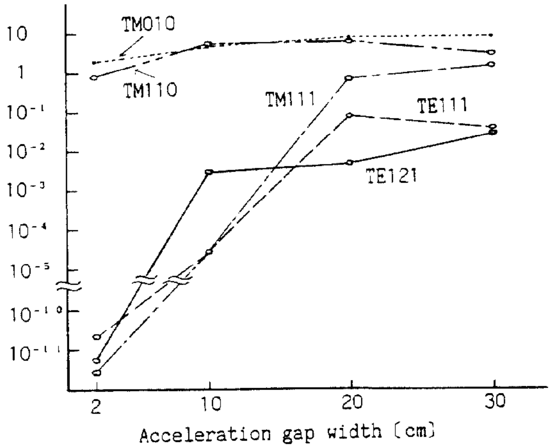

Figure 2 Gap dependance of the impedances

Even if a frequency of a HOM except for the TM110 unfortunately coincides with the one that interacts with the bunched beam, TCBI will not occur. The TM110 mode with an elctric field, which has the same direction as that of fundamental mode TM010, still has high impedance. Even if TCBI unfortunately occur by the TM110, it is easy to avoid by changing operating betatron tune a little because of its high quality factor Q of more than 10^4.

By making the gap width 2 cm, the dangerous HOM is only TM110 and the R_L of TM010 is still large enough for energy in the NAR. This gap width was therefore adopted in the 125 MHz cavity.

Beam loading effect just after injection

The injected and the rf captured beam current mainly decide the stored current at the final energy. The injection energy of the NAR is 13 MeV whose damping time is extremely long in the NAR, so multiturn single cycle injection was applied. An injected beam of more than several hundred milli-amperes during several μs makes total rf voltage very high in a tuned cavity, because the tuner and rf voltage feedback systems can not respond to rapid voltage change.

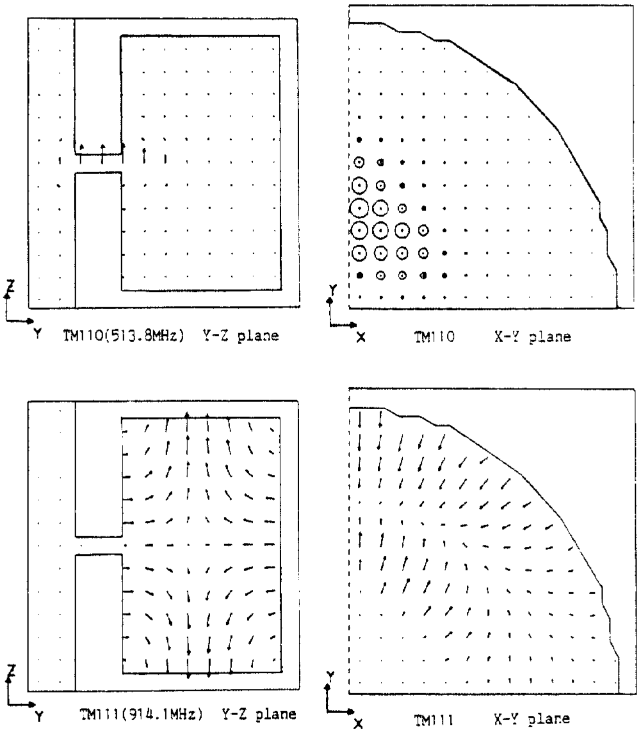

Figure 3 Difference of the electric field between TM110 and TM111 (Arrow and circle show the direction; the length and the radius indicate the strength)

Bunching process and induced voltage after injection on the detuned condition are simulated on CPU. A cavity is modelled by a parallel resonant circuit of LCR. Rf voltage induced by beam current is in proportion to cos ψ. ψ :detuning angle of the cavity. If the quality factor Q is much higher than 1, the induced voltage is in inverse proportion to the detune frequency. An injection beam from the linac[6] with a bunch interval of 0.3 ns is treated as a coasting beam because bunching frequency 3 GHz of the linac beam is higher than the cut off frequency of a beam duct.

The energy spread of the injected beam is assumed to be a gaussian distribution of 0.5 % dispersion. An electron is modeled as a δ function with elementary electric charge. The induced voltage by transit of an electron through the cavity continues with decay where the decay time of 6.5 μs, which is determined by the quality factor, et al. The induced rf voltage by each electron are all accumulated at every transit. The total rf voltage that acts on each electron is the vector sum of the externally driven rf voltage and the induced one. Movement of each electron on an energy phase space is continuosly investigated from injection time. Lattice parameters and circuit constants of the cavity used in the simulation are summarized in Table 1.

Table 1 Parameters used in the simulation

Bending radius : 1.85 m
Accelerating frequency : 125 MHz
Momentum comp. factor : 0.021
Harmonic number : 22

Shunt impedance : 1.4 MΩ
Quality factor Q : 15000
Coupling β : 4.85

Calculated behavior of an electron distribution and line density are shown in Fig. 4. Rf voltage vs time is plotted in Fig. 5 in the case of an injected beam current of 1 A.

The synchrotron frequency at 3 KV rf voltage is about 23 KHz. The first concentration of electrons occurs at a quater period of synchrotron oscillation from injection. At that time, the line density is the sharpest as shown in Fig. 4. Both the 125 MHz component of the beam current and the induced voltage have a peak value at about 15 μs. They oscillates at about twice the synchrotron frequency. After that, they become smoother because the speed of an electron in an energy phase space depends on the rf phase where the electron exists, so the electron distribution becomes Z-shape as shown in Fig. 4. It is important to suppress the induced voltage at a quater of synchrotron oscillation period.

In Fig. 5, it is found that the induced voltage is decreased by detuning the cavity. The maximum dispersion function in the NAR is about 2 m and it is necessary to lower the bucket height to less than 2 %, which corresponds to the rf voltage 3.8 KV. Consequently, a detuning frequency of at least -0.5 MHz is required for 1 A injection. Considering the simulation result, a detuning range of -1 MHz was designed with double plunger-type tuners for the NAR's cavity.

The tuner is usually controlled to minimize the reflection power for beam loading. But as described above, in the NAR, the tuners must be held in a several MHz detuned condition to suppress an increase of the bucket height during the low energy region. In the higher one, where a higher rf voltage is required and the damping time is comparablly short, the tuner control mode is changed to the usual feedback operation.

Characteristics of the fabricated cavity

On a basis of the design concept described above, a 125 MHz cavity has been fabricated from oxygen free copper. The shunt impedance of 1.39 M Ω and the Q of 15300 were obtained. Existance of the TM110 mode with a resonant frequency of 493 MHz was clearly verified by a method in which a metallic object such as a perturbator was moved along the Z-axis. The electromagnetic field of other transverse HOM in the frequency range of less than 1 GHz, was not observed in the beam passing portion. The cavity has already been installed in the NAR and works well without any problems.

Conclusion

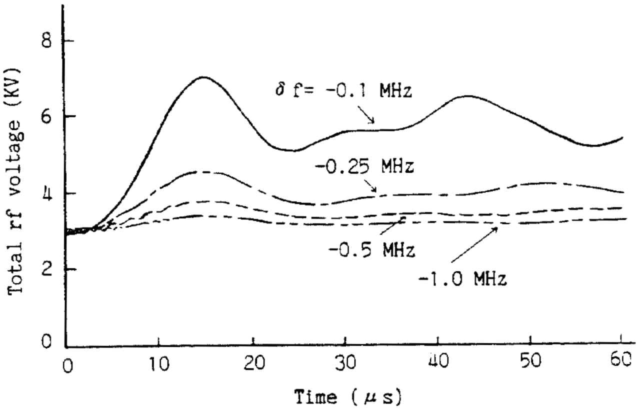

Figure 5 Simulatedd rf voltage after injection

The 125 MHz cavity for the NAR was designed considering both a high current injection operation and gap dependance of the HOM. It was found that the rf voltage in the cavity induced by an injected beam of 1 A, can be sufficiently suppressed by a 1 MHz detuning condition and the total rf voltage that corresponds to a bucket height of less than 2 %, can be achieved. The HOM's electromagnetic coupling between the cavity body and the beam passing portion was found to be affected by the acceleration gap. By making the gap width 2 cm, the transverse HOM impedances, except for the TM110, were reduced to negligible order.

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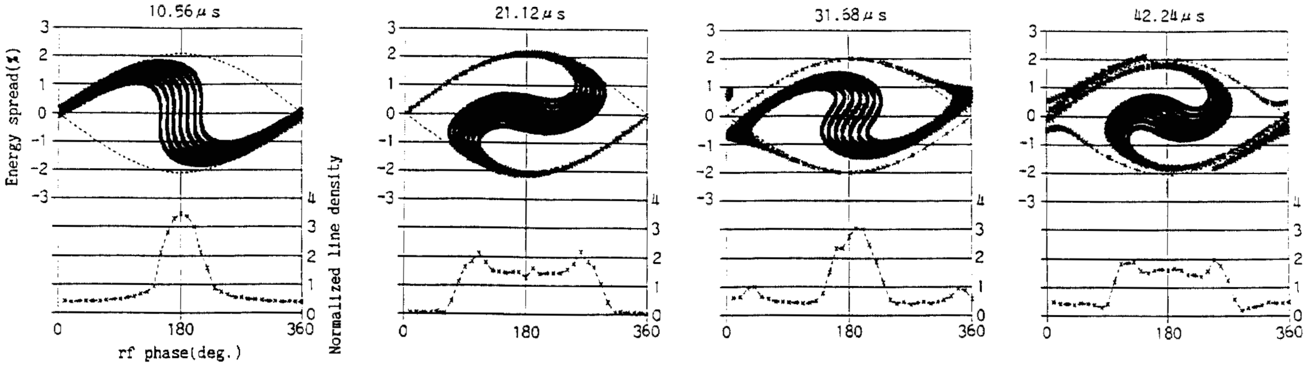

Figure 4 Behavior of electrons after injection on -0.25 MHz detuned condition. Accelerating frequency is 125 MHz, driving rf voltage is 3 KV. Dotted line shows the separatrix.