# RF SYSTEM FOR THE STA SR RING

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## Abstract

The RF system for the STA 8GeV storage ring has been determined to adopt four 1-MW klystrons and 508MHz cavities, which are located in four 6.5-m straight sections with low betatron functions. The accelerating voltage amounts to 12MV in order to compensate for the energy loss due to synchrotron radiation in bending magnets (8.3MeV) and in insertion devices (3.2MeV) and parasitic energy loss (0.5MeV). An overvoltage ratio of 1.33 gives a sufficient quantum lifetime. Since thirty-two single-cell cavities or fourteen 3-cell cavities are used in this RF system, a singe-cell cavity and a 3-cell cavity, in which each cell is coupled with off-axis slots, were studied. The RF characteristics were calculated with the computer codes developed in RIKEN and were measured by using model cavities. Methods to cure the coupled-bunch instabilities will be taken for a beam current of 100mA.

## Introduction

An 8GeV synchrotron radiation facility is now under design, supported by Science and Technology Agency of Japanese Government (STA) [1]. It consists of a storage ring, a booster synchrotron and a 1.5GeV linac. Both the RF systems of the storage ring and the synchrotron operate at a frequency of 508MHz. This choice of the frequency depends on the availability of high power sources and the technical development for almost all circuit devices in Japan. Since the goal beam current in the storage ring is more than 100mA in a multi-bunch operation, it is necessary to design the RF system in consideration of not only the conversion efficiency of RF power into beam power but beam stability.

## RF parameters and system design

The RF parameters are listed in Table 1. The energy loss per turn due to synchrotron radiation in bending magnets is 8.3MeV. The additional energy loss due to insertion devices depends on the final distribution of undulators and wigglers and their characteristics. This energy loss is estimated at 3.2MeV by the specifications of the typical insertion devices. Other energy losses due to cavities and vacuum chambers are evaluated to be 0.5MeV. The total energy loss amounts to 12MeV per turn. The peak RF voltage is 16MV to get a sufficiently long quantum lifetime.

The RF system is designed to satisfy the following conditions.

Table 1 RF parameters of the storage ring

| | |
|---|---|
| Beam energy | 8 GeV |
| Circumference | 1429 m |
| Revolution frequency | 210 kHz |
| Radio frequency | 508.6 MHz |
| Harmonic number | 2424 |
| Synchrotron radiation loss in bending magnets | 8.3 MeV |
| Energy loss in Insertion devices | 3.2 MeV |
| Parasitic energy loss per 100 mA | 0.5 MeV |
| Maximum RF voltage | 16 MV |
| Quantum lifetime | > 1 day |
| Number of 1-MW klystrons | 4 |

(1) The input power to a cavity is lower than the threshold power of an RF window;
(2) The accelerating voltage in a cell is limited by RF breakdown;
(3) The beam current is more than 100mA;
(4) RF cavities are installed in four 6.5-m straight sections; and
(5) A 1-MW klystron supplies RF power in a straight section.

Two types of RF systems have been studied. One uses thirty-two single-cell cavities and the other uses fourteen 3-cell cavities. Table 2 lists these system parameters. Here, it is assumed that the shunt impedance per unit length is 22.5MΩ/m and the threshold power of a window is 200kW in both systems. Since each cavity has an input coupler, the RF system using single-cell cavities has a capacity for accepting a higher beam current than the other system. On the other hand, the RF system using 3-cell cavities needs less RF power and includes simpler transmission lines from RF power sources to cavities.

Table 2 Comparison between two types of RF systems

| | RF system using single-cell cavities | RF system using 3-cell cavities |
|---|---|---|
| Number of cavities | 32 | 14 |
| Arrangement of cavities | 8 cavities x 4 | 4 cavities x 3<br>2 cavities x 1 |
| Power dissipated in cavities | 1.2 MW | 0.9 MW |
| Total RF power at 100mA | 2.7 MW | 2.3 MW |
| Maximum beam current | 0.2 A | 0.16 A |

## Design of model cavities

It is necessary to compare the RF characteristics of two types of cavities. A single-cell cavity with re-entrant nose cones and a 3-cell cavity with inductive coupling slots have been fabricated. The 3-cell cavity is shown in Fig. 1, while the single-cell cavity is assembled with the center cell of the three cells and two end plates. Program codes HAX [2] and URMEL [3] are used to calculate the RF characteristics of the single-cell cavity. The shunt impedance is optimized by taking the gap size between nose cones as a parameter.

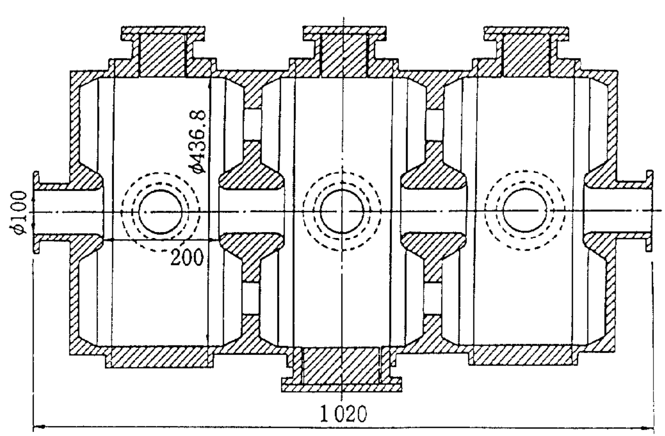


Fig. 1. Cross section of the 3-cell cavity.

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Since the coupling slots in the 3-cell cavity is not symmetric with respect to the beam axis, a three-dimensional code MAX3D [4] based on the finite element method is used to investigate the influence of the coupling structure. The region under analysis is a quarter of a coupling disk and two half-cells. Figure 2 shows the electric field distribution of the π mode. The shunt impedance and the coupling factor are calculated as a function of the slot angle. The result is shown in Fig. 3. The coupling factor is needed to be high because the field sensitivity for tuning errors is low [5]. Large slots, however, lower the shunt impedance. In the model cavity, two coupling slots whose azimuthal angle is 45 degrees are machined to achieve more than 1% coupling with suppressing the extreme drop of the shunt impedance.

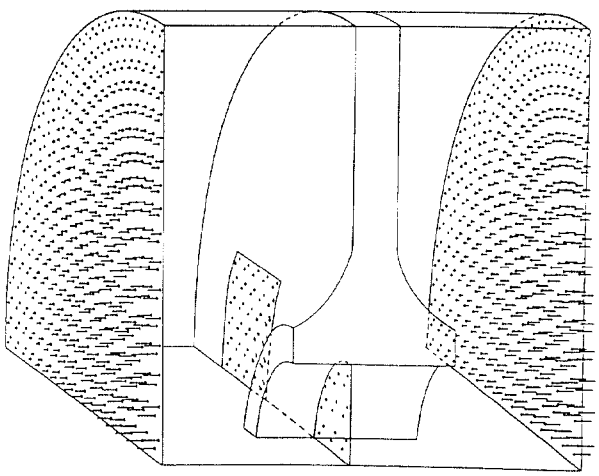

Fig. 2. Calculated electric field distribution of the π mode. Bars indicate the strength and the direction of the electric field at each element.

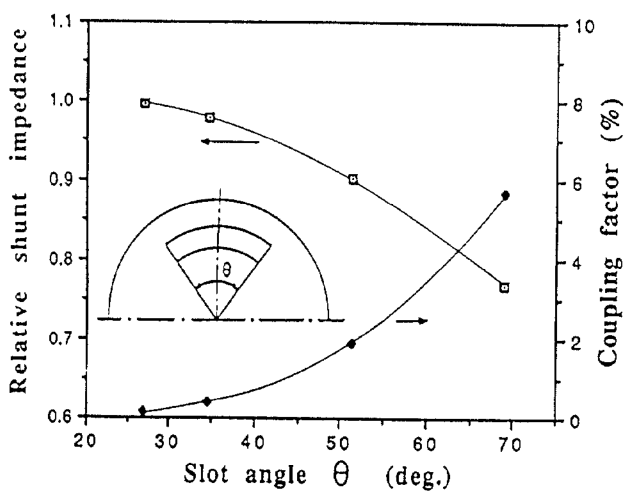


Fig. 3. Slot angle dependence of shunt impedance and coupling factor in a multi-cell cavity with inductive coupling slots.

## Fabrication and experimental results

The fabrication process of the model cavities was divided into four steps as follows. The RF characteristics were measured in each process.

In the first step, the model cavity was machined out of 6061 aluminum alloy. The overall machinery accuracy was within ±0.1mm. Each cell had the same cavity diameter and small holes for measuring probes. Resonant frequencies and Q-values were measured by the reflection method with a network analyzer. Eighteen resonant modes were observed below 1.5GHz in the single-cell cavity. Four modes were measured precisely because they were found to have high impedance values from calculations. Table 3 shows the results of measurement and calculation. The value of $R/Q$ were obtained from the electromagnetic field strength on the beam axis [6], where $R$ is the impedance of the cavity and $Q$ is the Q-value. In the 3-cell structure, triple modes were examined, whose phase shifts per cell were 0, π/2 and π. In the π mode of the fundamental mode, the field ratio of the center cell to the end cell was measured to be about -2.3.

Table 3 RF characteristics of the single-cell cavity

| type | Frequency (MHz) meas. | calc. | Unloaded Q meas. | calc. | R/Q (Ω or Ω/m) meas. | calc. |
|---|---|---|---|---|---|---|
| TM010 | 499.6 | 500.1 | 22000 | 26100 | 232 | 230 |
| TM011 | 747.2 | 749.2 | 18300 | 22400 | 54.1 | 53.6 |
| TM110 | 844.8 | 844.1 | 28900 | 36000 | 310 | 390 |
| TM111 | 1050 | 1053 | 21000 | 28500 | 620 | 580 |

In the second step, the end cell radius was enlarged to make a "flat" π-mode in the 3-cell cavity. The cutting allowance was calculated to be 3.2mm by substituting the measured resonant frequencies into an equivalent circuit [7]. Figure 4 shows the longitudinal electric field of the accelerating mode. The electric field $E$ in the cavity is normalized so that the integral of $|E|^2$ over the cavity is unity. The experimental results are listed in Table 4. The shunt impedance of the accelerating mode increased from 12MΩ to 15MΩ, which was nearly three times as high as the shunt impedance in the single-cell cavity. However, the impedances of the higher-order modes (HOMs) were lower than twice the impedances in the single-cell cavity. The coupling factor between adjacent cells was found to be 1.3% from resonant frequencies.

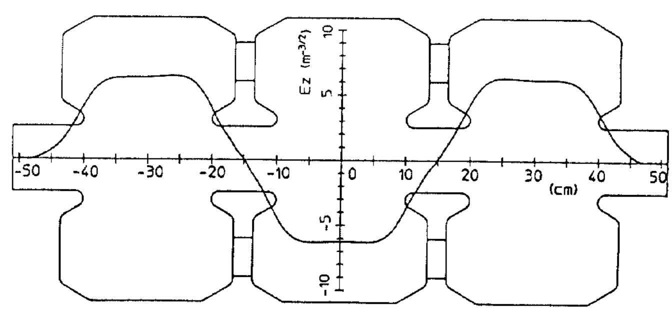


Fig. 4. Measured electric field distribution of the π mode in the 3-cell cavity.

Table 4 Experimental results of the 3-cell cavity

| type | Phase shift per cell | Frequency (MHz) | Unloaded Q | R/Q (Ω or Ω/m) |
|---|---|---|---|---|
| TM010 | π | 491.0 | 19900 | 754 |
| | π/2 | 492.6 | 22400 | 0.25 |
| | 0 | 495.7 | 22000 | 0.02 |
| TM011 | π/2 | 737.8 | 20000 | 95 |
| TM110 | 0 | 840.3 | 30000 | 433 |
| TM111 | 0 | 1004 | 17300 | 1100 |

In the third step, ports for an input coupler, frequency tuners and damping couplers were machined. Axially-asymmetric modes were split into two orthogonal modes because the degeneracy was broken by the ports whose diameters were different from each other. In this step, the Q-values in the HOMs were damped by the gap between a filler and a port. A damping factor of 4 was measured in a $TM_{111}$-like mode.

In the final step, the inner surface of the cavity was buffed to increase the Q-value. The roughness was improved from 3μm to better than 0.5μm. As a result, the Q-value of the accelerating mode was increased by 5%.

## Coupled-bunch instability and cures

The HOMs of accelerating cavities cause a coupled-bunch oscillation in a multi-bunch operation. The oscillation is executed at harmonics of the revolution frequency [8]. Because the spacing between harmonics is not wide enough compared with the bandwidth of a HOM impedance, it will be difficult to suppress coupled-bunch instabilities greatly by changing the accelerating frequency and the betatron tune in the operation. Therefore, it is necessary to evaluate the threshold beam current of the instabilities, which is calculated approximately by equalizing their growth-rate to the radiation damping rate. The results for longitudinal and transverse coupled-bunch instabilities obtained by using the ring parameters and the expected impedances of cavities made of copper are given in Fig. 5. The calculations are carried out for two cases: (1) Even if all cavities are designed to be identical, the HOM frequencies of all cavities are different because of mechanical errors in their fabrication. The peak impedance in a HOM frequency is assumed to be $0.1NR$, where $N$ is the number of cavities. (2) The HOM frequencies of all cavities are separated so that there is no superposition of the impedance. It is realizable by adjusting the size of each HOM tuner.

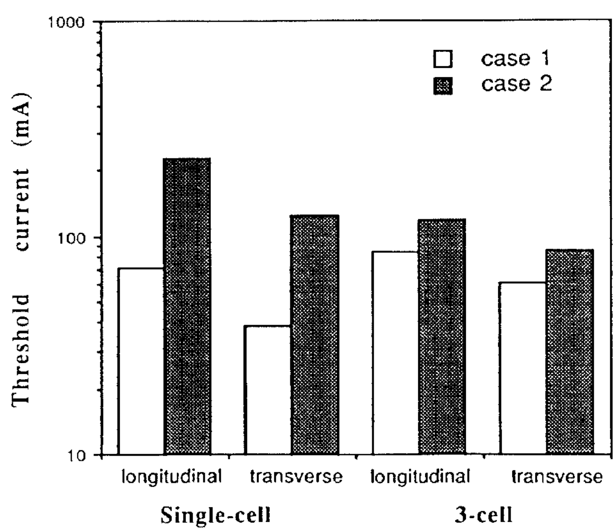


Fig. 5. Threshold current of longitudinal and transverse coupled-bunch instabilities in two types of RF systems. (1) HOM impedances of the cavities overlap each other; and (2) they are separated.

The threshold currents in both RF systems are lower than 100mA in the former case. In the RF system using single-cell cavities, however, the threshold is increased more effectively, provided the HOM frequencies of all cavities are discrete. Furthermore, some methods are being investigated to get a sufficient threshold; A damping coupler for a critical mode is mounted to the cavity in order to reduce the impedance. And other methods are a feedback control system for suppressing the coupled-bunch oscillation and a 3rd harmonic RF system, which is combined with the fundamental RF system to provide additional Landau damping.

## Conclusion

Two types of RF systems for the STA storage ring were studied. The RF system using 3-cell cavities has a higher efficiency for conversion of generator power into beam power than the one using single-cell cavities because that requires more accelerating cells owing to the power limitation of an RF window and the shunt impedance of the 3-cell cavity is nearly three times as high as that of the single-cell cavity. Although the 3-cell cavities are about half the number of the single-cell cavities, the maximum HOM impedance of the 3-cell cavity is about 1.5 times as high as that of the single-cell cavity. Therefore, the threshold current of the coupled-bunch instabilities is dependent on the distribution of the HOM frequencies. The RF system using single-cell cavities is capable of storing a higher beam current than the other system when the HOMs of all cavities are separated properly. High power tests using a 1-MW klystron and 508MHz cavities are planned to determine the specifications of the practical RF system.

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