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RF system of the SPring-8 storage ring

Hiroyasu Ego, Masahiro Hara,*
Yoshitaka Kawashima, Yuji Ohashi,
Takashi Ohshima and Takeo Takashima

SPring-8, Kamigori, Ako-gun, Hyogo 678-12, Japan.
E-mail: hara@sp8sun.spring8.or.jp

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Construction of three RF stations in the storage ring of SPring-8 has been completed. The design concept concentrates on avoiding a coupled-bunch instability which limits the stored current or makes the synchrotron radiation beam unstable. The cavity is bell-shaped to reduce the coupling impedance of the higher-order modes. The cavity dimensions are trimmed systematically to distribute the higher-order mode frequencies. Each cavity has two movable tuners. The temperature of the cavity cooling water is controlled within 0.02 K and the water flow is kept constant. The construction and commissioning of the SPring-8 storage ring RF system is reported.

Keywords: RF systems; coupled-bunch instabilities; cavities.

1. Introduction

SPring-8 is the largest third-generation light source in the world. The facility consists of the linac (1 GeV), the booster synchrotron and the storage ring (8 GeV). The features of the SPring-8 storage ring are low emittance and optimization for insertion devices.

The RF system provides accelerating voltage and power to compensate the energy loss of the stored beam due to synchrotron radiation at dipole magnets and insertion devices and the excitation of parasitic modes. Sufficient overvoltage is needed to keep the longitudinal beam motion stable and maintain an adequate beam lifetime. Other important roles of the RF system are to determine the circumference and to control the bunch timing.

The RF system is composed of cavities, which accelerate electron beams, high-power waveguides, which transport high-power microwaves to the cavities, klystrons and their power supplies, which amplify the microwaves, a low-level control system, which feeds an RF signal controlling the phase and amplitude, a timing system, which delivers a reference RF signal to RF stations, and a computer control system.

2. Main RF parameters

The accelerating frequency is 508.58 MHz. The energy loss per turn in the bending magnets is 9.226 MeV. The total energy loss per turn amounts to about 13 MeV when all insertion devices are installed. The harmonic number is 2436. Any number of bunches up to 2436 can be stored in the storage ring. The bunch length depends on the accelerating voltage, current and the number of bunches. The typical value is $\sigma_l = 4.3$ mm in the multi-bunch operation without insertion device. There are four RF stations (*A*, *B*, *C*, *D*) symmetrically arranged around the ring. Each station has one klystron and eight single-cell cavities. At present, three stations (*B*, *C*, *D*) have been completed. In the commissioning phase, the stored current is less than the nominal current. Typical RF parameters in the commissioning phase are listed in Table 1.

Table 1
Typical RF parameters in commissioning.

Beam energy	8 GeV
Momentum compaction factor	1.46×10^{-4}
Frequency	508.579343 MHz
Harmonic number	2436
Revolution frequency	208.77 kHz
Number of RF stations	3
Number of RF cavities per station	8
Total acceleration voltage	12 MeV
Energy loss per turn	9.226 MeV
Synchrotron frequency	1.5 kHz

3. Cavity

The design is concentrated on avoiding a coupled-bunch instability which limits the stored current in multi-bunch operation (Hara *et al.*, 1994). In the SPring-8 storage ring it is difficult to avoid the coupled-bunch condition because the revolution frequency is very low (209 kHz). Furthermore, a large number of cavities (32) are needed because the radiation loss is large.

The cavity shape has been optimized. The designed inner structure is shown in Fig. 1. The cavity has a bell-shaped structure, which is optimized to reduce the impedances of several dangerous higher-order modes (HOMs), while the shunt impedance of the fundamental mode (TM010) is not reduced less than 5.5 MΩ. The *Q* values and shunt impedances of HOMs were measured for the prototype cavity made of aluminium, and the resonant modes were confirmed from the electric or magnetic fields measured by the bead perturbator method (Ego *et al.*, 1996).

A plural plunger system has been adopted. The cavity has three tuner ports: one is used for tuning the fundamental frequency, one is used to control dangerous HOM frequencies, and one is used as a fixed tuner. The frequency response for the HOM plunger position is shown in Fig. 2.

The temperature of the cavity cooling water is controlled within ±0.02 K and the water flow is controlled.

The systematic modification of the inner structure is applied to each of the individual cavities. By this method, HOM frequencies are systematically distributed.

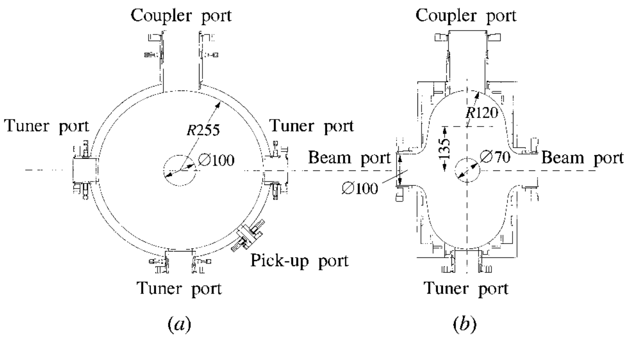

Figure 1
Cross-sectional view of the cavity (bell-shaped inner structure) (*a*) across the beam axis, and (*b*) along the beam axis. Dimensions in millimetres.

The coupler ports of the cavities are set alternately in vertical and horizontal directions in the cavity assembly. By this method, the number of systematic modifications could be reduced by half.

The cavity assembly in one of the stations is shown in Fig. 3.

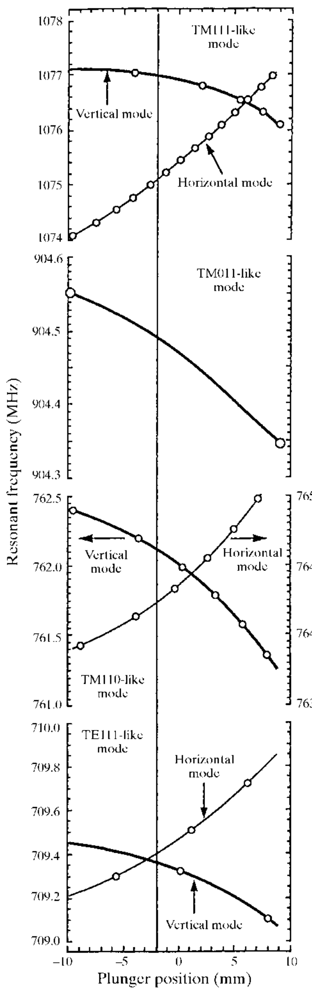

Figure 2
Resonant frequencies of HOMs are shown as a function of HOM plunger position. The fundamental mode frequency is kept constant using the other plunger.

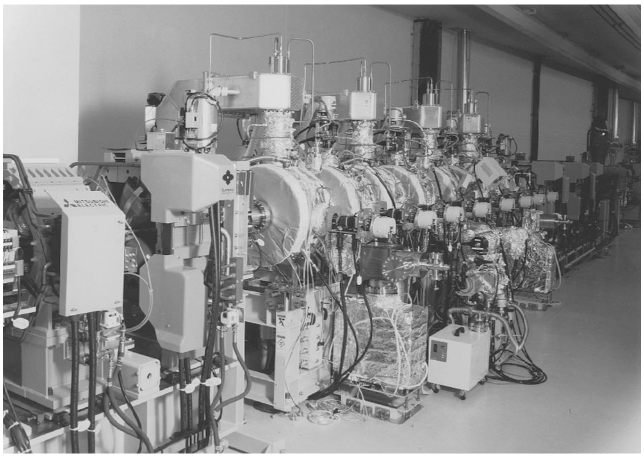

Figure 3
Photograph of a cavity assembly in one of the RF stations.

4. Klystron and its power equipment

A 1 MW klystron (Toshiba E3786) is used to drive eight single-cell cavities. The maximum voltage and the current of the power supply are 90 kV and 20 A, respectively. The power supply is thyristor-regulated and is basically a six-phase rectifier, and has no crowbar circuit and no large capacitor bank. The klystron power supplies in the three stations are phase-shifted by 20° to each other at their input transformer to reduce a rippling effect.

High-power microwaves are transported using waveguides from the klystron to the single-cell cavities. On the way to the cavities, a three-port circulator is used to protect the klystron from the reflected wave from the cavities. The RF power is divided into eight using seven magic-Ts and fed into single-cell cavities by couplers shown in Fig. 4.

5. Low-power system

The low-power RF control system of the SPring-8 storage ring was assembled using NIM modules at the end of 1996. The system consists of a 508.58 MHz reference signal line, an automatic level control (ALC) and phase-lock loop (PLL) of the RF power, cavity tuning system, anode modulation, interlock and monitoring, shown in Fig. 5. In the reference signal line, phase-stabilized optical fibres are used to transmit a synthesized 508.58 MHz signal with an accuracy of ±0.1° with PLL (Hara *et al.*, 1997). The

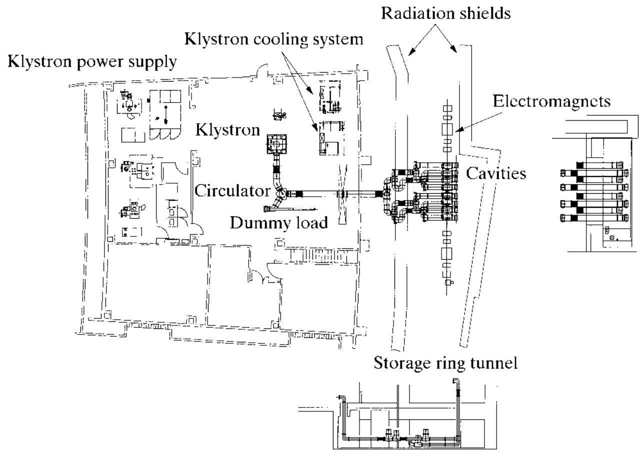

Figure 4
Arrangement of the RF instruments in one of the RF stations.

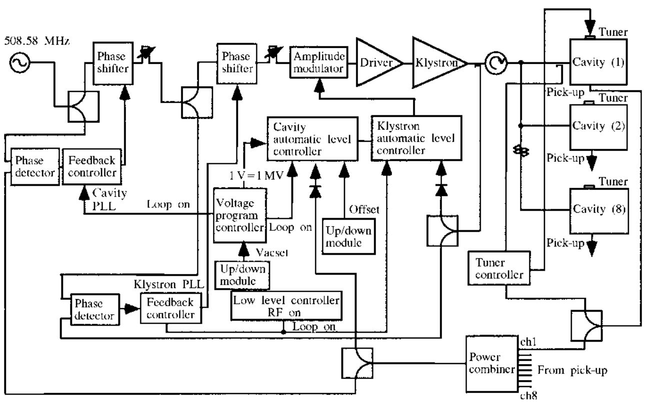

Figure 5
Block diagram of the low-power system.

phase difference between each cavity was measured and set to the corresponding value using the phase shifters. Attenuation in the cables from pick-up ports on the cavities and from the directional couplers was measured using a network analyser. The ALC and PLL are used to keep the cavity voltage and the phase constant. The cavity tuning is used to keep the resonant frequency at 508.58 MHz. All cavities are detuned by $-5°$ to avoid Robinson instabilities. The anode modulation is used for stable operation of the klystron. The monitoring is to check the status of operation.

6. Control system

The computer control program was at first developed for cavity conditioning. This program was improved and developed for operation of the RF system under the frame of the SPring-8 control system (Ohshima *et al.*, 1996).

The RF control system is composed of three panels: a main panel, a panel for klystron power supplies, and a low-level control panel for each RF station. By using the main panel, the total accelerating voltage and the phase of each RF station and the frequency of the master oscillator can be set; the present voltage, phase and the vacuum pressure of each RF station are displayed. The control panel for the klystron power supplies is used to start up the RF system, to shut down, and to monitor the status of the power supplies. The main control panel is shown in Fig. 6. These control panels work well.

7. Operation

Low-power and high-power tests for the RF components were carried out at a test stand before installation (Hara *et al.*, 1997). The installation of three RF stations was completed in November 1996. To check the total system before commissioning, each RF station was operated up to 800 kW for conditioning. RF power of up to 90 kW was successfully fed to each cavity with the help of computer control. About 89% of the power from the klystron was fed to the cavity because the coupling coefficient of the input coupler was tuned to 2.0.

Before the commissioning of the storage ring, calibration of the acceleration voltage and the station phase adjustment were performed without a beam. The acceleration voltage was calculated from the measured RF pick-up signal by using the power meter. This was compared with the calorimetric method of measuring the wall loss of the cavity. These values agreed within 10%.

From March to July 1997, the first phase commissioning of the storage ring was carried out. The first turn was observed on 14 March. Twenty turns were observed with the on-axis injection on 21 March and, after an energy correction and rough tune survey, 24 turns were observed with sextupole magnets excited. On 25 March, RF acceleration voltages in the *B*, *C* and *D* stations were set to 4.0, 3.0 and 4.0 MV, respectively, to make the beam RF-captured. At first, the phase of station *B* was adjusted with the *B* station RF power turned on; the beam circulated for 45 turns. Then, the RF power of station *C* was turned on and the phase was adjusted; the beam circulated 100 turns. Then, the RF power of station *D* was turned on and the phase was adjusted; the beam circulated 600 turns. After that, the acceleration frequency was adjusted to reduce the average closed-orbit distortion and at $f_{\rm RF}$ = 508.57936 MHz the first RF capture was realized. The frequency difference from the designed value, $\Delta f_{\rm RF} = -640$ Hz, corresponds to the orbit difference ΔL = 1.8 mm from the designed one.

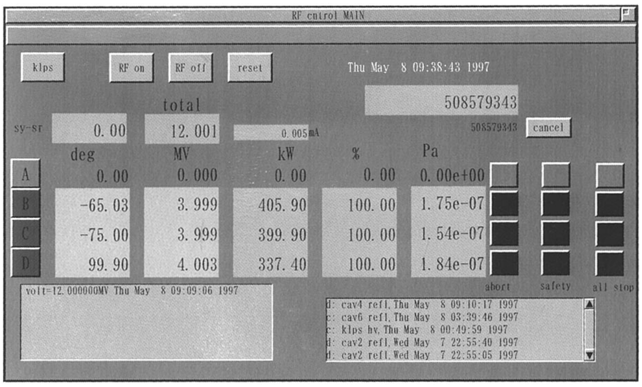

Figure 6
RF main control panel.

During the operation of the cavity cooling system, the temperature deviation of the cooling water was within $\pm 0.02°$ (measured by a platinum resistor with an accuracy of $0.01°$) when the RF power into eight cavities was less than 400 kW. This was ten times better than the specification value.

During operation of the RF system, a vacuum leakage was found in one tuner, which was temporarily replaced with a fixed tuner. No other severe faults were found during the commissioning.

During this commissioning, the value of the stored current was limited to 20 mA and no multi-bunch instability was observed.

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