A 2856 MHz RF Cavity for the MIT-Bates South Hall Ring*

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ABSTRACT

A single-cell 2856 MHz RF cavity for the MIT-Bates Linear Accelerator Laboratory South Hall Ring (SHR) has been designed and built at AECL's Chalk River Laboratories. The SHR is an electron beam storage ring designed to operate with all (1812) RF buckets filled and a circulating current of 80 mA. The RF cavity, designed for CW operation with 10 kW wall dissipation, has a 40 mm diameter beam aperture, on-axis higher-order mode damping and an iris-coupled RF input. This paper describes the cavity RF and mechanical design, the system fabrication and the results of measurements on the completed cavity.

INTRODUCTION

The MIT-Bates Linear Accelerator Center is building an electron storage ring, known as the South Hall Ring (SHR), for medium-energy nuclear physics experiments. The ring will have two modes of operation: a pulse stretcher mode that provides an external CW electron beam from a 1% duty factor injection linac, and an internal target mode that stores the electron beam in the ring, to provide high average current for targets internal to the ring. The SHR has a 190 m circumference, and is designed to store up to 80 mA of electrons at energies from 300 to 1000 MeV. At the ring RF frequency of 2856 MHz (the same as the linac frequency), the harmonic number is 1812 and every bucket is filled with electrons. The high average current with all buckets full constrains the ring RF system to have very low longitudinal impedance at all frequencies other than 2856 MHz, to avoid multi-bunch instabilities, while providing bucket voltages of up to 129 kV to maintain and control beam bunch shape and energy. A single-cell standing-wave RF cavity has been designed and built to meet these RF requirements with the specifications shown in Table 1.

A series of computations have been performed to analyze and optimize the designed cavity performance. These include an analysis of cavity modes using the RF computer codes, SUPERFISH, SEAFISH, and URMEL, and an analysis of cavity temperature and thermal-mechanical stress at a nominal 10 kW dissipated RF power using the MARC code.

A cross section of the cavity is shown in Figure 1. The main cavity body is fabricated from brazed oxygen-free electrical (OFE) copper segments with embedded water-cooling channels. The cavity uses iris coupling with adjustable β and a mechanical tuning plunger described in more detail elsewhere.[1]

Table 1: Specifications for the MIT-Bates SHR RF Cavity

Frequency	2856.000 MHz
Gap voltage	129 kV
On-axis rf electric field	> 2.6 MV/m
Power dissipation	> 10 kW
HOM Impedance	
Longitudinal	< 500 Ω
Transverse	< 100 kΩ
Beam aperture	40.0 mm

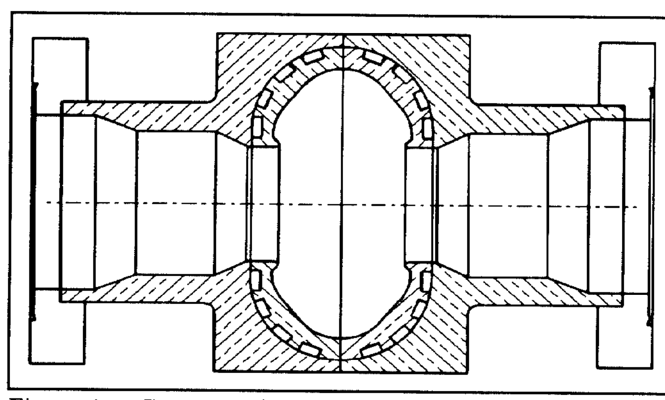

Figure 1 Cross section of MIT-Bates SHR RF cavity showing the copper body with embedded water-cooling channels.

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RF DESIGN

The RF design challenge is to find a cavity profile that maximizes the cavity shunt impedance at 2856 MHz, important for RF operating efficiency, while minimizing the longitudinal and transverse shunt impedance in higher-order modes (HOM), important for beam stability. The high average beam current of the SHR with beam in every RF bucket makes reduction of the effective HOM impedance critical.

The cavity profile design for the SHR has a large 40 mm beam aperture, through which HOM's are coupled out of the cavity and into the 60.3 mm diameter beam-pipe. The profile was adjusted to maximize the separation between the TM_{010} fundamental mode at 2856 MHz and the next lowest azimuthally symmetric (monopole) transverse magnetic (TM) modes. All these TM modes, other than the TM_{010}, and all cavity dipole modes are above the corresponding mode cut-off frequencies in the beam-pipe: 2914 MHz for dipole modes and 3806 MHz for monopole TM modes. This permits damping of HOMs by a thin layer of RF-absorbing ferrite distributed azimuthally inside the beam-pipe, in the region near the cavity. Conceptually, this approach is very similar to that used by Cornell in their design of HOM dampers for super-conducting cavities for a B-factory.[2]

The results of an analysis of the first few TM monopole modes are given in Table 2. The Q of each mode was determined from SEAFISH computations, and includes both surface RF losses from the finite conductivity of the copper cavity as well as volume RF losses in the HOM damper ferrite. Since only the TM_{010} mode is below the cut-off frequency of the beam-pipe, it is not significantly damped by the ferrite and is the only mode with a high Q. The modes that are anti-symmetric about the cavity mid-plane propagate out of the cavity so well, as indicated by their low Q's, that SEAFISH could not accurately find the resonant frequencies. Thus, the Q's for these modes should be regarded as upper limits.

Table 2: Computed SHR cavity azimuthally symmetric mode characteristics

Frequency (MHz)	Longitudinal Shunt Impedance (kΩ)	Q
2870	953.0	19 480
5204	0.07	50
6000	0.18	81
8100	0.11	43
8167	1.1	209

Table 3: Significant SHR Cavity Dipole Modes Below 10 GHz

Frequency (MHz)	R' (undamped) (kΩ)	R' (damped) (Ω)	Q (damped)
3972.0	237.2	279	23
6029.8	104.7	51	14

Table 3 gives the results of URMEL calculations for all dipole modes up to 10 GHz with the radially independent transverse shunt impedance parameter, R', greater than 100 kΩ. However, all these modes are above the TE dipole mode cut-off frequency of the beam-pipe, and are strongly damped by losses down the beam-pipe. The effective Q of these modes was computed by a technique described by Mosnier.[3] The Q, once these losses are considered, drops below 25. Consequently, no dipole modes below 10 GHz have significant longitudinal shunt impedance.

MECHANICAL DESIGN

Each half of the cavity is machined from two OFE copper segments that are machined with accurately matching surfaces. Four water-cooling channels are machined into this surface on the inner half cavity. The two segments are then brazed together to form the complete cooling channels in each half cavity. This braze is performed before the final machining of the inner cavity profile.

In each half cavity, the two outer channels are connected in series and the two inner channels are connected in series. For a ΔT of 10°C, the total flow required is 0.24 L/s through the cooling channels. With these four parallel cooling circuits, the flow velocities, v, are 3 m/s and 4 m/s in the outer and inner cooling channels, respectively. These flow velocities were chosen to give a fully turbulent flow with the highest possible heat transfer coefficient to the copper cavity body.

Heat fluxes, calculated by SUPERFISH, and the film heat-transfer coefficients for the water cooling, were used to calculate the copper temperature distribution using the MARC finite-element code. The temperature distribution is fairly uniform in the radial direction, with the highest value predicted to be 48°C, based on a water inlet temperature of 15°C. The water-cooling strategy is to regulate the output temperature to a fixed value, using an external water-cooling system. The set-point value for the outlet temperature is 25°C. Thus, with no input power, the cavity body is at 25°C. As the dissipated power increases, the inlet water temperature decreases to maintain the same outlet temperature. For the design temperature difference of 10°C at full power (10 kW), the inlet temperature will be 15°C. This scheme is easy to implement and reduces the average temperature change of the cavity body, from zero to 10 kW dissipated RF power, to less than 10°C.

The MARC code was used to perform a thermal-stress analysis, including the small additional effects of vacuum and water pressure. The highest von Mises equivalent stress is calculated to be 28 MPa at the cavity nose region near the beam aperture. However, this is well below the yield strength of annealed copper, which is approximately 60 MPa.

The predicted thermally induced cavity deformation produces an increase in the cavity wall radius of about 0.010 mm. This deformation results in an estimated 360 kHz frequency shift of the cavity from zero power at 25°C cavity body temperature to 10 kW dissipated power with 15°C inlet water. At the power levels considered in this analysis, the results scale linearly with power level, so operation at higher dissipated power up to about 15 kW should be possible while remaining well below the yield strength of copper.

LOW-POWER RF MEASUREMENTS

After completion of cavity fabrication and assembly of the cavity tuner and RF drive coupler, the relative distribution of the axial RF electric field was measured using the dielectric-bead frequency-perturbation method (the bead-pull technique). Several distributions were measured to determine the Q-normalized shunt impedance (R/Q) of the cavity at the TM_{010} mode and any TM azimuthally symmetric higher-order modes below 6 GHz. A typical TM_{010} measurement, shown in Figure 2, gives an R/Q of 49 Ω, in good agreement with calculated design value.

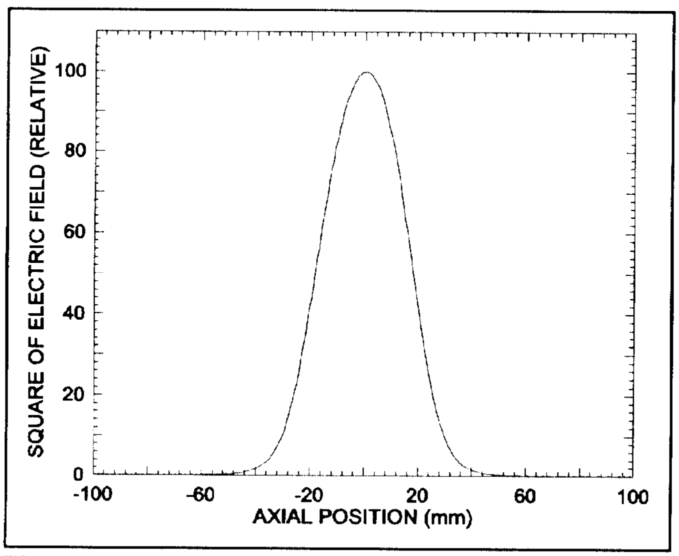

Figure 2: Squared RF electric field distribution from bead-pull on TM_{010} mode.

Measurement of the longitudinal electric field distributions of HOMs was more difficult, since the modes couple strongly to beam-pipe. Any discontinuities in the beam-pipe, such as occur at an open end flange during the measurement, produce standing wave patterns in the beam-pipe and splitting of the cavity mode. A typical measurement of a TM_{020}-like cavity mode, Figure 3, shows the presence of the standing wave in the beam-pipe sections on either side of the cavity, indicating the large coupling of the mode out of the cavity. The R/Q for this distribution is less than 1 Ω.

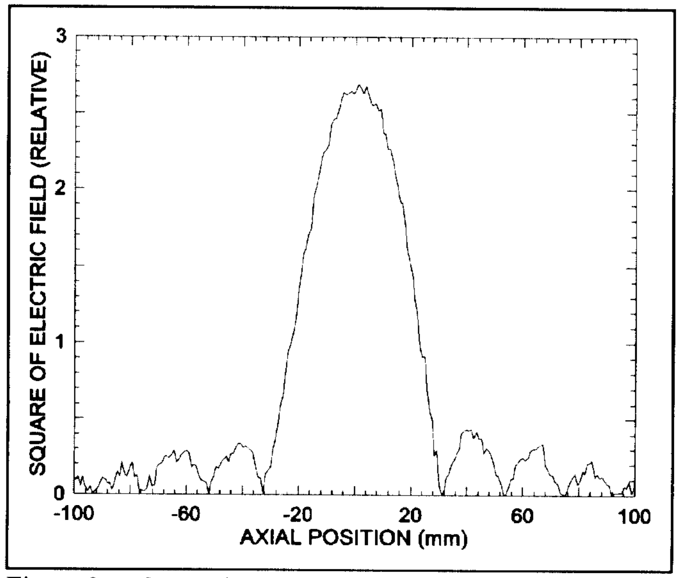

Figure 3: Squared RF electric field from bead-pull on TM_{020}-like mode at 5807 MHz.

Additional measurements of the broad-band shunt impedance to higher frequencies will be made before final cavity installation in the SHR.

CONCLUSION

A high-power CW 2856 MHz cavity has been designed and fabricated at AECL's Chalk River Laboratories for the MIT-Bates SHR. The cavity is characterized by a large 40 mm beam aperture and highly damped HOMs. The cavity is presently at MIT-Bates, awaiting final low-power testing and installation.

REFERENCES

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