Performance of the MIT-Bates South Hall Ring 2856 MHz CW RF Cavity System*

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Abstract

A single-cell, 10 kW, cw 2856 MHz RF cavity and associated control system, designed and fabricated at Atomic Energy of Canada Limited's Chalk River Laboratories, has been installed in the Bates Linear Accelerator Center South Hall Ring (SHR). The SHR is a 1000 MeV electron beam storage ring designed to operate with all (1812) RF buckets filled and a circulating current of 80 mA. This paper describes the commissioning and performance of this RF system.

1. INTRODUCTION

The South Hall Ring (SHR) 2856 MHz RF system comprises a high-power, single-cell, cw RF cavity, a 50 kW cw klystron transmitter, and associated RF control systems. Table 1 summarizes the essential parameters of the RF system. Details of the rf and mechanical design of the 2856 MHz RF cavity, built at Chalk River Laboratories for the MIT Bates Linear Accelerator Center, have been presented in earlier publications [1,2], and other papers at this conference provide details of the RF control systems [3] and higher-order-mode damping [4].

Tests of the cavity with SHR beam were made during preliminary operation of the ring at low beam current and energy (~10 mA at 330 MeV). Beam storage without RF power to the cavity showed expected lifetimes (~10 ms), consistent with beam-circulation energy loss and ring energy aperture. With RF power to the cavity, decay of the monitored beam current to $1/e$ level was observed to be in excess of thirty seconds.

Since every RF bucket in the SHR is filled, no active longitudinal feedback system is feasible to reduce potential multi-bunch instabilities. This constraint dictated a design with the lowest possible longitudinal impedance for all higher-order modes that could excite such instabilities. The result is a system with a single cell (the lowest possible number), with no trapped higher-order modes (all significant higher-order modes are above cut-off for propagation in the beam pipe). The entire voltage required for bunch compression and the power required to compensate for synchrotron losses must be supplied by this single high-power cell. The maximum cw power dissipation rating of 10 kW represents an average surface power dissipation density over 60 W/cm^2. The requirements on the RF control system are equally demanding, as the required operating power range is from less than 100 W to 10 kW, to accommodate the full range of energies and operating modes of the SHR. This paper presents the performance results from commissioning tests performed at MIT-Bates, and preliminary operational experience with the RF cavity system.

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

Frequency	2856.000 MHz
Gap Voltage	> 129 kV
On-axis RF field	> 2.6 MV/m
Power dissipation	<100 W to 10 kW
Amplitude regulation	± 1.0%
Phase regulation	± 1.0°
Tuning range	±500 kHz

2. LOW-POWER MEASUREMENTS

Before final installation into the ring, a series of low-power measurements of the cavity properties were made. The normalized shunt impedance (R/Q) of the fundamental TM_{010} mode was 50.2 Ω, measured (see Figure 1) using a standard bead-pull technique with a 1.0 mm diameter by 3.5 mm long metal bead. These measurements were in good agreement with the R/Q of 49 Ω calculated with SUPERFISH and URMEL. The higher-order longitudinal modes were so strongly damped that similar bead-pulls could not be performed with sufficient accuracy to determine the higher-order-mode longitudinal impedance.

A coaxial-wire technique was employed to determine the cavity coupling impedance over the range 45 MHz to 10 GHz. The measurements were performed using tapered, coaxial input

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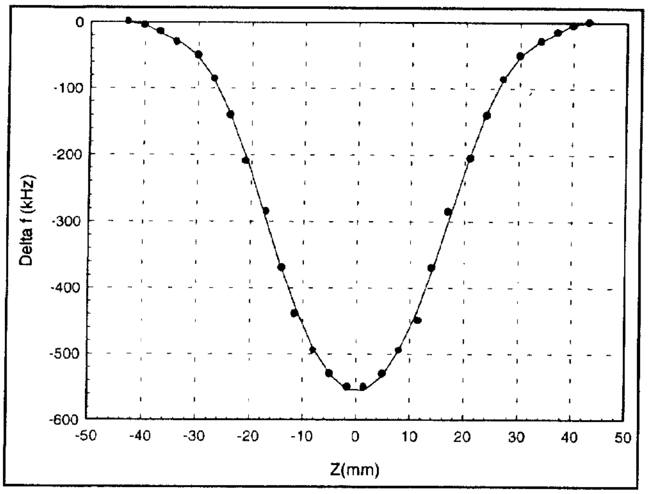

Figure 1 Bead-pull of TM_{010} mode along axis of RF cavity with 1.0 mm diameter, 3.5 mm long metal bead giving a cavity R/Q of 50.2 Ω

and output sections to transmit RF through the cavity to a HP 8510 network analyzer. The cavity transmission properties were determined by comparing the cavity-transmitted signal with that passing through the measurement structure when the cavity was replaced by a simple, cylindrical, coaxial-guide section as reference. The coaxial centre conductor was machined to have a series of smooth, transition-matching steps conforming to the inner dimensions of the cavity. Reflections from the ends of the structure were eliminated using short coaxial sections lined with high-frequency, RF-absorptive material and placed between the cavity or reference section and the tapered end sections. The only higher-order modes observed using this technique were the TM_{110} (4.3 GHz) and the TM_{111} (6.2 GHz) dipole modes with longitudinal impedances of 2 kΩ and 14 kΩ, respectively.

3. Installation and Commissioning

All cavity vacuum parts, with the exception of the ferrite-loaded HOM dampers [4], were disassembled, cleaned and baked-out at 200°C before reassembly and installation in the ring. A base pressure of $\sim 3\times10^{-9}$ torr was established within a few days. The dampers were excluded, as they were not ready when the rest of the cavity was installed. Instead, short spool pieces were inserted in place of the dampers. Unlike the situation with most RF cavities, these dampers are not essential for reducing the Q's of the higher-order modes. They are used only to attenuate the propagating higher-order modes in the beam-pipe, reducing the likelihood of any significant RF standing-wave being present in the beam-line.

The rf input coupling factor, β, is adjustable in a set of fixed steps as described in [2]. A coupling of $\beta = 4.5$ was selected for the cavity commissioning and initial experiments. The initial RF conditioning was uneventful. RF pulses, a few microseconds long with a peak power of 100 to 1000 W, were applied at the start. Within several hours, the cavity could be operated in cw mode at up to ~500 W. Some outgassing from electron multipactoring was observed in the range from 500 to 1000 W, but additional pulse conditioning at ~10 kW peak eliminated this barrier within a few hours. The peak RF power was gradually increased to 15 kW, and the duty factor increased to raise the average power to 10 kW and complete the pulse conditioning after approximately 16 hours. The pressure gradually increased with increasing RF power, but remained below $\sim 2\times10^{-8}$ torr. Within 24 hours of commencing RF conditioning, the cavity could operate continuously at over 10 kW RF dissipation. After several days of high-power operation, the cavity pressure at full power was typically less than 5×10^{-9} torr.

The cavity dissipated-power range is so large that the cavity's fundamental-mode frequency would vary greatly with a fixed cooling-water inlet temperature. Thus, a 12 kW water chiller is used to supply the cavity cooling water, with a temperature set-point chosen to provide a cavity body temperature of approximately 35°C. At 10 kW RF power dissipation in the cavity, the inlet water temperature is about 15°C.

4. Control System

The cavity RF voltage-feedback loop uses an In-phase/Quadrature (I/Q) controller, described in detail in reference [3]. The use of the I/Q controller produces clean RF spectra of the kind shown in Figure 2. The noise floor is 70 dB down, which is just 5 dB up from the floor on the input to the system. Suppression of power-supply-induced ripple can be seen by comparing Figure 3 with Figure 4. Ripple is reduced to the level of the noise floor, and mixer harmonics are suppressed by more than 20 dB (at a 1.0 kHz AM rate). The I/Q controller has been demonstrated to regulate at power levels from less than 50 W to over 10 kW without any additional adjustment to the feedback loops.

The cavity RF tuning circuit, described in more detail in reference [3], maintains the cavity resonance within 0.6° of the voltage circuit's RF phase set-point by adjusting a tuning plunger driven by a linear actuator in 1 μm steps. This tuner compensates continuously for the frequency shifts produced as the cavity temperature varies by a few degrees within the chiller temperature-regulation deadband. Note that the voltage-feedback loop adjusts the RF-drive phase and power to maintain the desired cavity voltage and phase, so the small variations in cavity frequency do not affect the voltage. The tuning circuit locks onto resonance consistently for cavity power as low as 50 W.

Closed-loop control of the klystron gain and phase [3] is always active. Stable operation of these loops with the voltage feedback loop permits operation over a wide range of klystron cathode voltage and power level (including 100% AM modulation).

Phase modulation from the 10 kHz to 1 MHz rate with up to a ±180° range was performed. As the rate and range were increased, the noise floor rose, and increased phase-modulation-to-amplitude-modulation (PM-to-AM) conversion was observed. This is consistent with the 1.5 dB PM-to-AM specification for the digital phase shifter and the eight-bit quantization used.

Amplitude modulation from 100 Hz to 100 kHz with a depth of 95% was demonstrated. Full 100% modulation was not possible, because the dynamic range of the voltage-control loop prevents complete attenuation. Harmonic content also increased with increased depth and rate. When the voltage loop is not used, harmonics inherent to the mixer are seen, as shown in Figure 3. Use of the voltage loop provides significant linearization, demonstrated in Figure 4; however, at high AM rates, harmonics can fall outside the voltage-loop bandwidth and will not be suppressed.

5. CONCLUSION

The Bates SHR 2856 MHz cavity demonstrates a significant expansion of the operating domain for cw room-temperature RF cavities. The average, wall-dissipated power density is more than three times higher than the high-power room-temperature cavities proposed for the new B-factories, giving a peak electric field greater than 2.6 MV/m, approaching that of super-conducting cavities.

The RF control system also represents a significant extension to traditional methods used on room-temperature cavities, demonstrating the effectiveness of a broad-band I/Q controller at eliminating narrow-band disturbances near the reference frequency, while maintaining as large a bandwidth as possible. The large dynamic control range has already been used extensively during initial operation of the SHR.

The full operating range of the RF cavity and control system will be tested more thoroughly over the next year, as the commissioning of the SHR is completed.

6. REFERENCES

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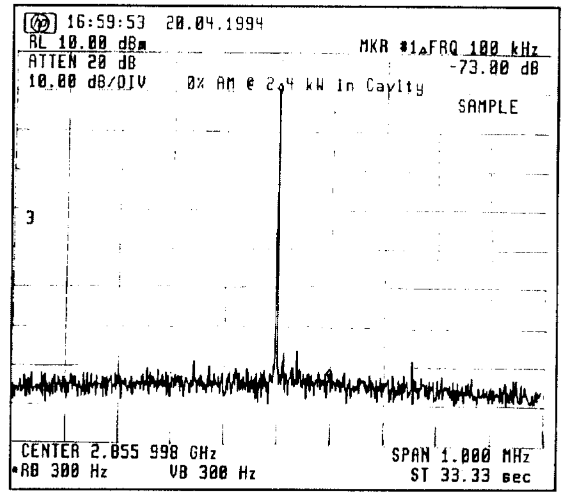

Figure 2 Wide-band RF spectrum of cavity with unmodulated reference and RF feedback loops closed

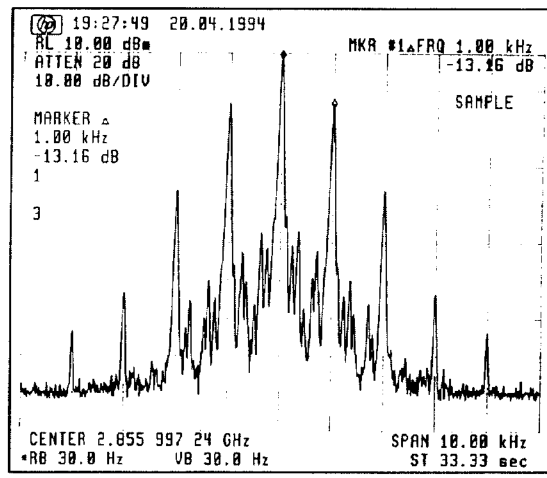

Figure 3 Narrow-band RF spectrum of cavity with 50% AM and I/Q RF feedback loop open.

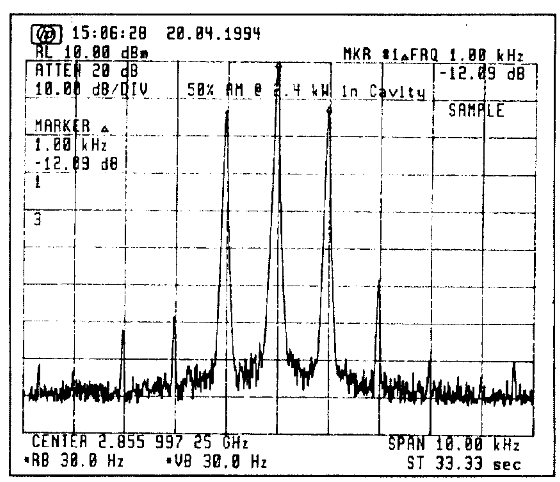

Figure 4 Narrow-band RF spectrum of cavity with 50% AM at 1 kHz and I/Q RF feedback loop closed.