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THE DESIGN OF THE RF CAVITY FOR THE HEAVY ION STORAGE RING FOR ATOMIC PHYSICS*

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An rf cavity and drive system have been designed for the proposed "Heavy Ion Storage Ring for Atomic Physics," HISTRAP, at Oak Ridge. A peak accelerating voltage of 2.5 kV per turn is required with a continuous tuning range from 200 kHz through 2.7 MHz. A single-gap, half-wave resonant configuration is used with biased ferrite tuning. The cavity structure is completely outside of the beam line/vacuum enclosure except for a single rf window that serves as an accelerating gap. Physical separation of the cavity and beam line permits in situ vacuum baking of the beam line components at 300°C. A prototype cavity was designed, built, and tested. [1] Development of frequency synthesizer and tuner control circuitry is under way.

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1. Introduction

HISTRAP [2] is a proposed 46.8-m circumference synchrotron-cooler-storage ring optimized for advanced atomic physics research. It is injected with heavy ions from either the Holifield Heavy Ion Research Facility (HHIRF) 25-MV tandem accelerator or a dedicated 14.5-GHz ECR source via an 0.25-MeV/nucleon RFQ linac. Prototypes of major components of HISTRAP have been designed, fabricated, assembled, and tested. Included are an rf cavity with drive system, a dipole magnet and field mapping facility, [3] and a beam line section which has been pumped to a vacuum of 4 x 10^{-12} Torr. [4] A plan view of HISTRAP is shown in Fig. 1 and some general machine parameters are listed in Table 1.

In the standard high-current operating mode, heavy ions from the tandem accelerator are injected into HISTRAP with a magnetic rigidity of about 1.0 Tm and with circulation frequencies between 1.0 MHz for $^{12}C^{6+}$ and 0.38 MHz for $^{238}U^{43+}$. These ions are either accelerated to a maximum magnetic rigidity of 2.67 Tm with circulation frequencies between 2.7 MHz and 1.0 MHz, or decelerated to a minimum magnetic rigidity of 0.10 Tm with circulation frequencies between 0.10 MHz and 0.038 MHz. Other beam species may be injected with a variety of charge-to-mass ratios and kinetic energies. The longitudinal phase-space area of the injected beam depends upon its mass and kinetic energy per nucleon. This is particularly true for post-stripped beams from the tandem accelerator where the stripper foil thickness and resultant induced energy spread depend on ion species. In fact, most of the rf cavity voltage is needed to provide phase space area for injected beams.

2. RF Requirements

For all ion species of interest, the maximum required peak accelerating voltage is 2.5 kV per revolution. A frequency range between 0.2 MHz and 2.7 MHz is adequate using harmonic numbers between one and six. For operation with typical ions in the accelerating mode, the rf must tune over most of the available range within a period of about 0.5 s. The frequency must track with the dipole magnetic field of the synchrotron in order to maintain constant beam radius during acceleration.

Given the required accelerating potential, the rf system requirements appear to be quite modest. However, the required frequency swing is very large; continuous tuning without band switching is preferred; and the relatively compact accelerator configuration and large aperture (15 cm) provide little space along the circumference (1.3 m) for an accelerating system. Vacuum requirements for HISTRAP are such that all beam line vacuum components must withstand baking at 300°C. Consequently, rf system components which are not compatible with the baking process must be thermally isolated from the beam lines.

3. Prototype cavity

The selected rf cavity configuration has a ferrite-loaded, half-wave coaxial resonator with a single accelerating gap as shown in Fig. 2. The center conductor is concentric with, but completely separate from, the beam line and accelerating gap, except for retractable contact rings that establish electrical contact between the cavity and the accelerating gap as shown in Fig. 3. When vacuum bake-out of the beam line is required, the contact rings are retracted so that the cavity components are thermally isolated from the beam line. Water cooling on the center conductor is provided for removal of both normal rf heating and heat radiated from the beam line during bake-out. A second set of contacts on the ends of the cavity is used to suppress rf resonant modes on the beam line.

Characteristics of the cavity are listed in Table 2. The unusually wide tuning range for a single-cavity accelerating system, cavity size limitations, and relatively low frequency result in rather stringent requirements for the ferrite load. Very high permeability is required in order to obtain the large rf tuning range and to minimize the use of extra shunt capacitance for reaching the low end of the tuning range. TDK-type SY7 ferrite, which has been used elsewhere in similar accelerator applications, was selected. SY7 ferrite has a low Curie temperature, 90°C, and a tendency to become unstable at moderate rf excitation levels, but it should be satisfactory at the power levels required by HISTRAP. The cavity was designed to hold as much ferrite as possible, thus minimizing the rf power dissipation per unit of ferrite volume. The ferrite rings are separated by 6.4-mm thick copper rings which are water cooled by peripherally attached copper water lines. The expected ferrite temperature rise under full rf excitation is about 5°C.

An array of three individual "figure-eight" bias windings produces up to 3000 ampere turns of bias field in the ferrite in order to swing the permeability from 1400 to 8. Leads from each half winding are extended out of the cavity through the several ports in the cavity's outer conductor. External connections are used for closing each figure eight and for placing the turns in series or parallel configurations. Space and connection ports are available for up to a total of five turns if more bias excitation is required.

4. Prototype test results

A prototype cavity was designed, fabricated, assembled, and tested. The prototype has only 16 ferrite rings at this time; a number sufficient to check most required characteristics. Figure 4 shows a photograph of the cavity partially assembled with the 16 rings in place. Ferrite specifications for the rings are listed in Table 3. When the cavity is operated with only 16 rings, extra shunt capacitance is required to obtain the required tuning range. Consequently, the designed rf field intensity level in the ferrite is reached with about half of the normal cavity rf voltage.

The ferrite rings were tested individually to determine respective permeability, magnetization, and rf loss characteristics. Typical values of initial permeability are between 2000 and 3000 and rf loss characteristics are safely within specification. Measurement of magnetization characteristics was not successful on individual rings due to intrinsic inductances in the test circuit. However, values of permeability calculated from cavity tuning data, shown in Fig. 5, indicate that 3000 ampere turns of bias are sufficient to drive the permeability down to a value of less than eight.

The cavity has operated with rf excitation levels up to about 400 W. Excitation to full input power requires a driver system which is not available at this time. Data obtained at the 400-W level is shown in Fig. 6. The shunt resistance of the cavity as seen across the accelerating electrodes is nearly constant throughout the required tuning range at about 80 ohms. Values of Q are directly proportional to frequency and go from less than one at the minimum frequency to about 10 at the maximum frequency. The low Q characteristic is especially desirable for loading the planned broadband driver amplifier system. At the low end of the tuning range, it is difficult to determine the actual resonant frequency, but it is possible to drive the cavity at frequencies substantially below resonance. The Q dependence on frequency provides a good compliment for the ferrite magnetization dependence in that Q is lowest in the frequency region where the permeability is the steepest function of bias.

It has been suggested [5] that ferrite instabilities such as the "Q loss" effect can be avoided by keeping the rf field-frequency product below 15 mT-MHz. For worst case conditions in the HISTRAP cavity, the maximum field-frequency product is about 10 mT-MHz.

5. RF power drive system

A 20-kW broadband rf power amplifier is planned for driving the HISTRAP cavity. The amplifier is mounted close to the cavity to simplify coupling. Impedance matching is accomplished through the use of an impedance transformer. The rf drive signal is derived from a programmable frequency synthesizer. Bias current for the cavity's ferrite will be obtained from a programmable dc power supply. Analog programming signals for both the synthesizer and the bias power supply are derived from a Hall field probe in one of the eight dipole magnets. A diagram of the controls for the rf system is shown in Fig. 7.

The rf controls are based upon the use of a frequency synthesizer which is capable of switching frequency in about a microsecond in response to variations in digital frequency information (at least one such synthesizer is commercially available). An analog-to-digital converter derives a reference frequency from the Hall probe signal produced in one of the dipole magnets. Feedback loops with signals derived from beam position and phase provide reference frequency updating between ADC sampling cycles.

6. Summary

The feasibility of operating an rf cavity with the tuning range required by HISTRAP was demonstrated. Characteristics of the cavity were measured. Development of appropriate tuning and drive circuitry is under way. Demonstration of cavity operation at full rf power will be attempted when a larger power amplifier becomes available.

References

[1] S. W. Mosko et al., Proc. of the 1989 IEEE Part. Accel. Conf., pp. 193.

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[3] B. A. Tatum et al., Proc. of the 1989 IEEE Part. Accel. Conf., pp. 393.

[4] J. W. Johnson et al., J. Vac. Sci. Technol. A 7 (3) (May/June 1989) 2430.

[5] M. L. Plotkin, private communication.

Figure captions

Fig. 1. A plan view of HISTRAP showing its injection beam line with an ECR source on the left, a transfer line from the tandem, and an extracted ion beam line on the right.
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Fig. 2. A cutaway longitudinal view and an end view of the HISTRAP rf cavity.
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Fig. 3. A sectional view of the accelerating gap showing the gap insulator and the contact rings between the cavity and the beam line.
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Fig. 4. A photograph of the rf cavity with the top half of the outer conductor raised. The 16 ferrite rings are in place with their cooling plates interspaced. Vacuum capacitors are connected across the accelerating gap.
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Fig. 5. Relative permeability of the SY7 ferrite rings as a function of toroidal dc excitation.
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Fig. 6. Cavity "Q" and shunt resistance as a function of frequency.
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Fig. 7. A block diagram of the rf system controls showing the primary reference frequency source and feedback loops for fine tuning. Additional feedback loops are required for cavity tuning and amplitude control.

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Table 1

Accelerator Parameters

Circumference	46.8 meters
Maximum Rigidity	2.67 Tesla meters
Dipole Magnets	8
Quadrupole Magnets	12
Accelerating Sectors	1
Vacuum System - Base Pressure	10^{-11} Torr

Table 2

RF cavity characteristics

Peak rf voltage	2500 volts
Tuning range	0.2 to 2.7 MHz
Overall length	1.2 meters
Beam tube diameter	0.15 meters
Center conductor OD	0.254 meters
Outer conductor ID	0.648 meters
Ferrite rings	
Material	TDK SY7 (NiZn)
ID	0.3 meters
OD	0.5 meters
Thickness	0.025 meters
Rings per cavity	28
Ferrite cooling	water-cooled Cu separators
Peak power density in ferrite	2000 mW/cc
Ferrite permeability range	8 to 1400
Peak ferrite bias current	3000 ampere turns
Shunt capacitance required	6000 pF
Total peak cavity rf drive power	20 kW

Table 3

Ferrite specifications

Initial permeability	2500
RF excitation loss at 0.2 MHz and 275 gauss rf field	<0.06 W/cc
RF excitation loss at 2.5 MHz and 22 gauss rf field	<0.06 W/cc

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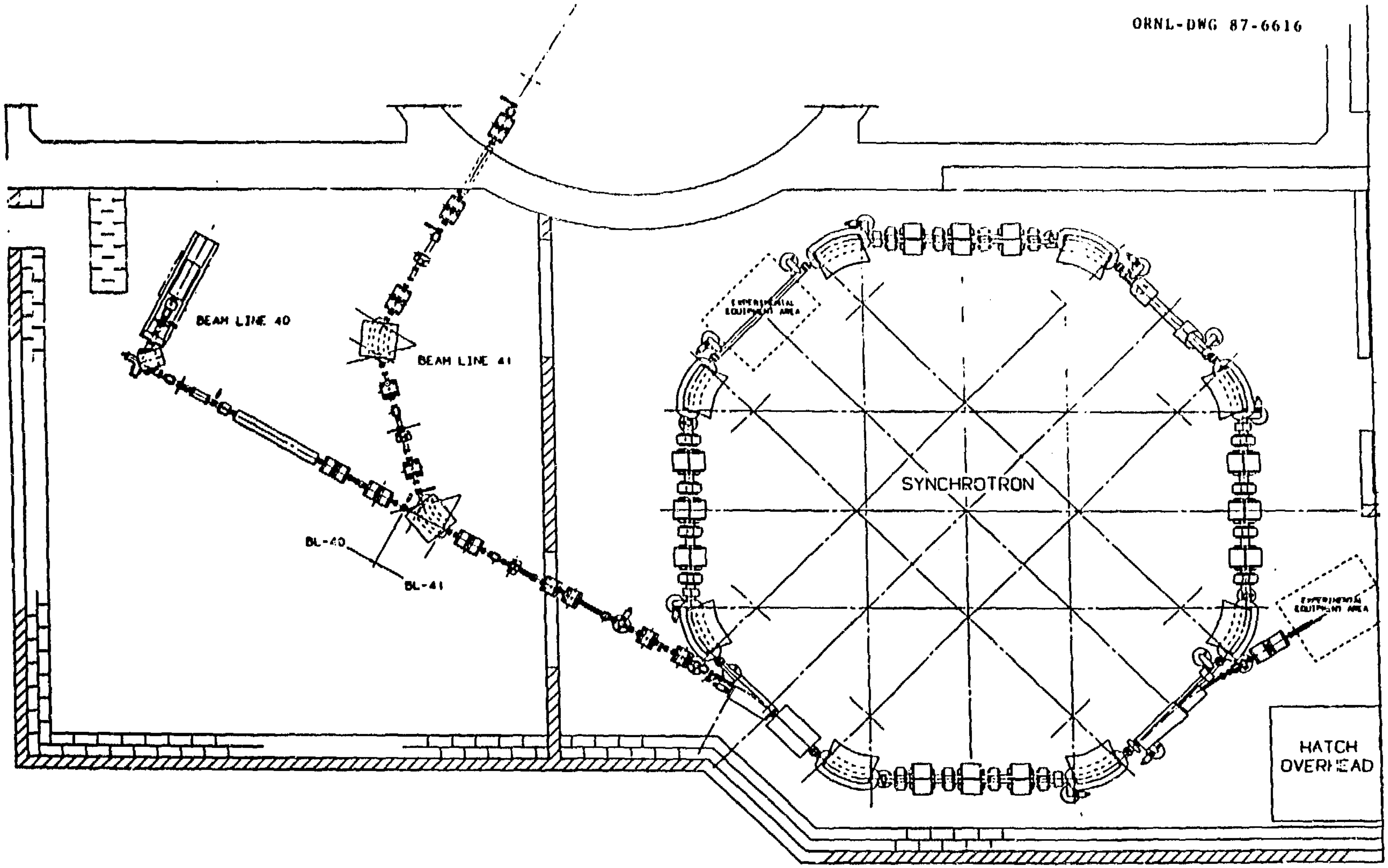
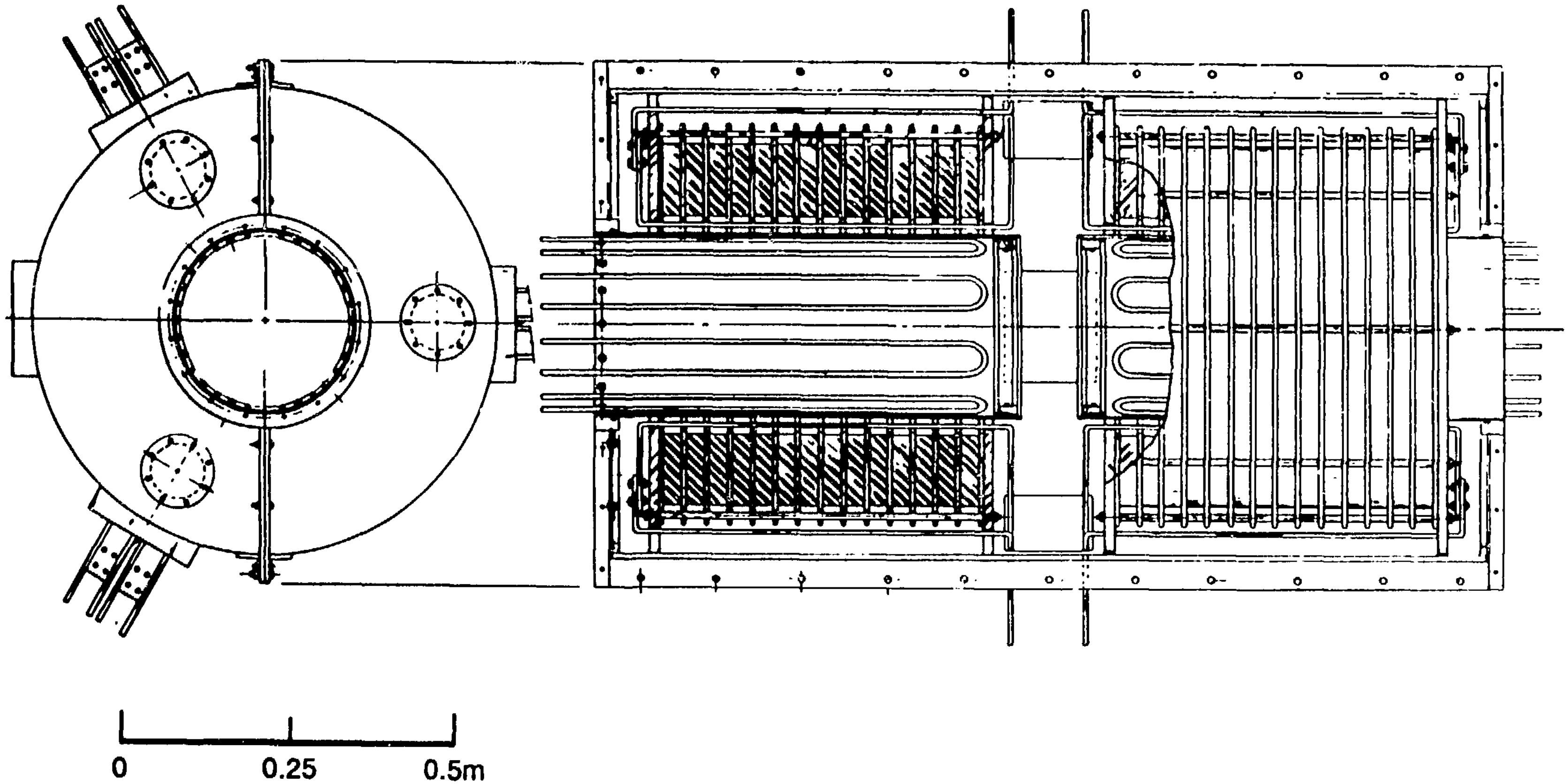


ORNL-DWG 87-17429R



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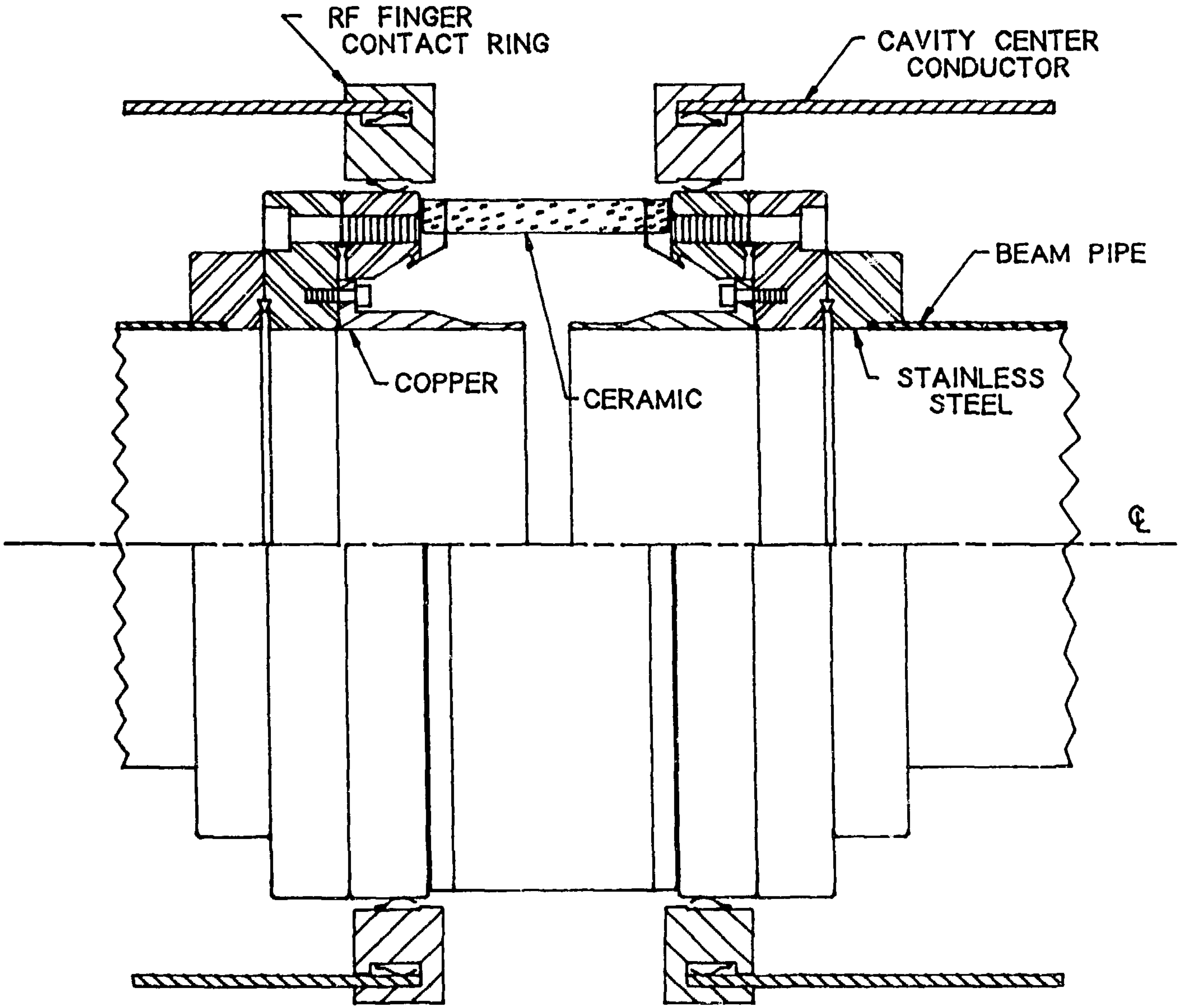

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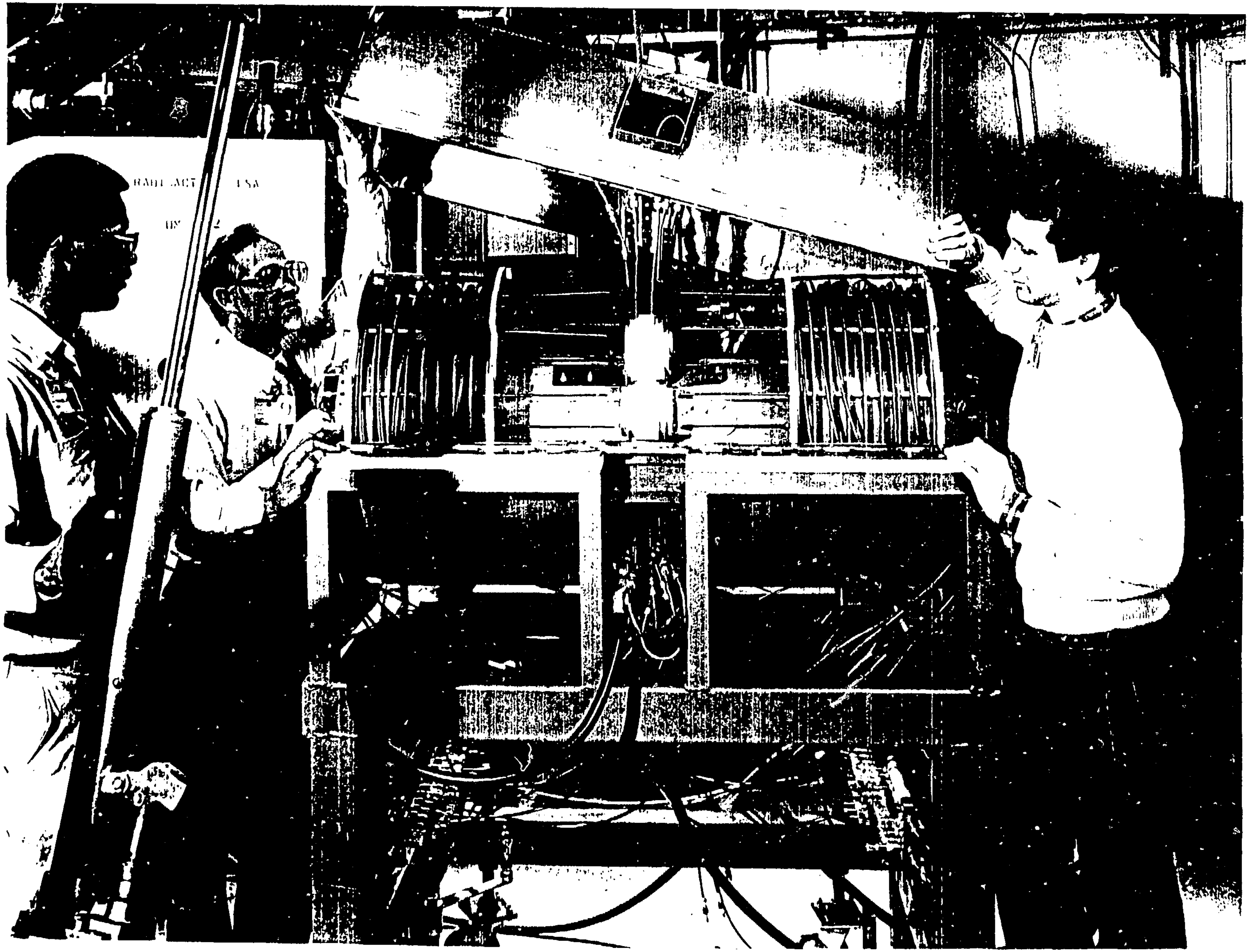

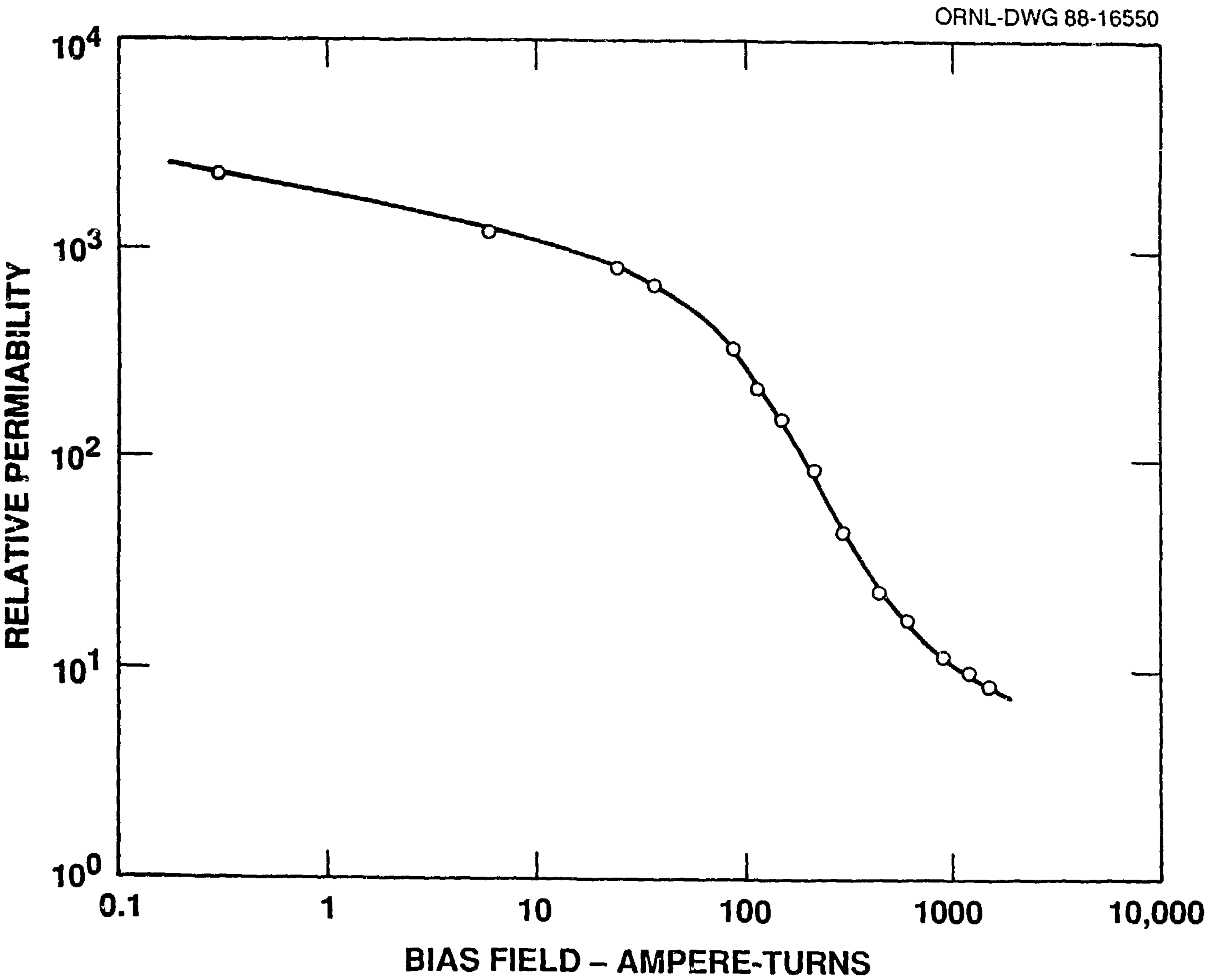
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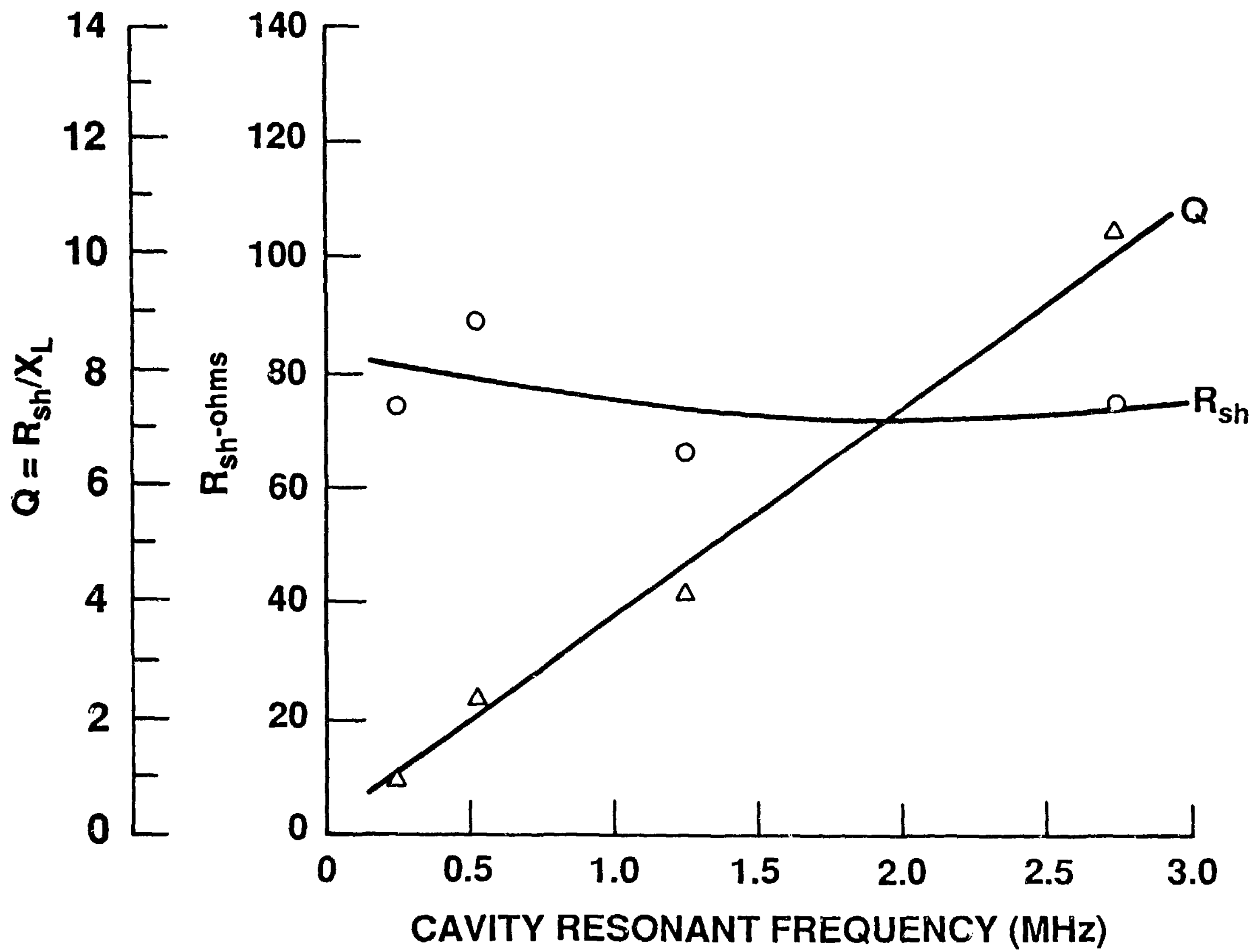
RELATIVE PERMIABILITY
10^4
10^3
10^2
10^1
10^0
0.1
1
10
100
1000
10,000
BIAS FIELD – AMPERE-TURNS

ORNL-DWG 88-16551



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