DESIGN FOR A SUPERCONDUCTING NIOBIUM RFQ STRUCTURE

ANL/CP--75930

DE92 041126

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Abstract

This paper reports a design for a niobium superconducting RFQ operating at 192 Mhz. The structure is of the rod and post type, novel in that each of four rods is supported by two posts oriented radially with respect to the beam axis. Although the geometry has four-fold rotation symmetry, the dipole-quadrupole mode splitting is large, giving good mechanical tolerances. The simplicity of the geometry enables designing for good mechanical stability while minimizing tooling costs for fabrication with niobium. Results of MAFIA numerical modeling, measurements on a copper model, and plans for a beam test are discussed.

Introduction

Although cw electric fields exceeding 100 MV/m have been achieved in a superconducting niobium RFQ structure, the structure tested had vanes only 6.5 cm long, and was not suitable for accelerating beam [1]. While several possible superconducting RFQ accelerating structures have been proposed [2, 3], neither high gradients nor adequate mechanical stability have been reported.

The RFQ design presented here is intended as a next development step for the niobium short-vane RFQ, and has the following goals:

1. See if high accelerating fields can be obtained in a superconducting RFQ structure of useful length (50 cm).

2. Be designed to permit testing with beam at the ATLAS heavy-ion facility.

3. Be sufficiently mechanically stable to permit cost-effective operation in low-beam-current applications. This is a most important requirement, since phase-stabilization of superconducting structures in low-current applications can be expensive and difficult [4, 5].

The potential for testing with an ATLAS heavy-ion beam provides great flexibility [6]. The velocity profile, and the vane modulation, can be specified without knowing precisely what electric field gradients can be achieved, since the charge-to-mass ratio Q/A of a test beam can be varied over a substantial range, from 1/10 to 1/2. A test area is available in which a bunched beam of velocity as low as .02 c can be made available. To permit such testing, the entrance velocity of the structure is chosen to be 0.02 c, and the operating frequency to be the 16th harmonic of the ATLAS bunching frequency, or 194 MHz.

The Resonator Geometry

Figure 1 shows the resonator geometry chosen. Although the structure has four-fold rotational symmetry, as is shown below, the dipole-quadrupole mode separation is large, yielding good mechanical tolerances. The mode separation results from the large electric-field coupling between the longitudinal rods or vanes, the inductive coupling between the radial posts being relatively weak in this geometry.

The four-fold symmetric rod and post geometry has several advantages for construction of a superconducting niobium RFQ:

1. The good mechanical tolerances are compatible with the need to heavily chemically polish the niobium surface, with resulting uncertainties of tens of microns in the final position of the interior cavity surfaces.

2. The cost of tooling and fabricating in niobium are minimized by the simplicity of the structure, which can be formed by joining eight simple "T" sections.

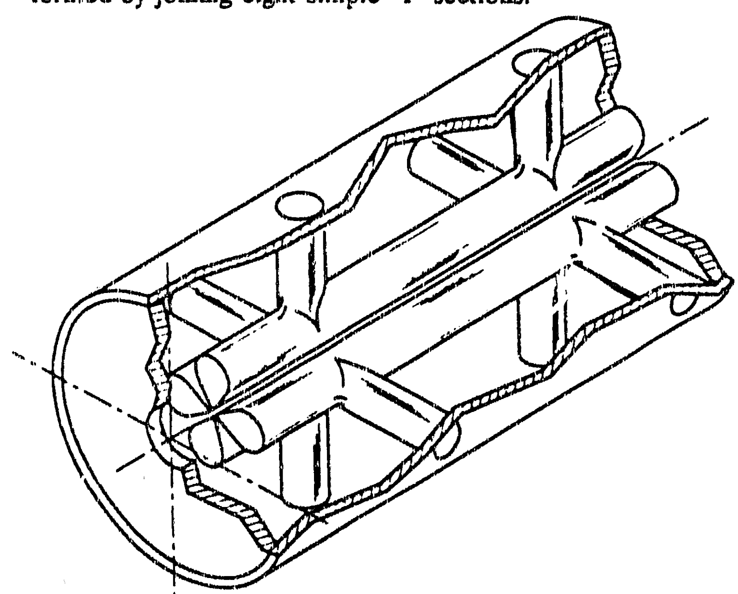

Fig. 1 194 MHz, four-fold symmetric rod and post structure. The vanes or rods are 50 cm long. The relatively large diameter of the rods is not only practical in a superconducting structure, but desirable for good mechanical stability.

3. Since peak surface field, rather than shunt impedance, is the primary design constraint for superconducting niobium structures, the rod and post structure can assume massive proportions, providing excellent mechanical stability.

Vane Design

The design goal is to match an ATLAS $^{238}U^{24+}$ beam on the optimistic assumption that surface fields as high as were obtained in the earlier short vane tests can be repeated in the larger RFQ structure. If the superconducting structure is limited to lower surface fields, it will be matched to (lighter ion) beams of higher Q/A, so that a beam test at ATLAS would be possible for a range of possible accelerating gradients.

With the above considerations giving the starting point for the design, we assume the following parameters:

Frequency	194 MHz
Vane Voltage	200 KV
Entrance velocity	$\beta_0 = 0.02$
Transverse Emittance	$\epsilon_x = 10\pi$ mm-mrad
Longitudinal Emittance	$\epsilon_z = 40\pi$ KeV-nsec
Minimum aperture (radius)	3mm

The vane modulation is chosen to yield as high an accelerating gradient as is consistent with good longitudinal and transverse focussing, and the requirement to maintain a low peak surface electric field. Some parameters of the resulting design are:

Modulation factor	2.34
Synchronous Phase	-30°
Number of cells	24
Overall Length	50 cm
Peak surface electric field	120 MV/m
Mean Accelerating Gradient	8 MV/m

It should be noted that the above accelerating gradients do not represent the expected performance for the superconducting structure, but are the upper limit of possible performance which could still be tested with beam at ATLAS. A gradient of half the above values would represent exceptional performance for a cw RFQ.

Resonator Modeling

Structure design has been based on numerical modeling using the MAFIA code. Key parameters have been checked by measuring the properties of a room-temperature model resonator (with unmodulated vanes). The model resonator is of slightly larger OD and lower frequency than the planned superconducting niobium structure shown in Fig 1. It is, however, sufficiently close to the final version to show qualitatively the electromagnetic and mechanical properties of the design and is the version discussed below.

Eigenfrequencies

The lowest electromagnetic modes of the structure were calculated and measured as:

Mode	MAFIA Result	Model Measurement
Quadrupole	160 MHz	158 MHz
Dipole	179	179
	179	179

Although within the bandwidth of the normally conducting model the two dipole modes are degenerate, they will surely be distinct in the superconducting resonator. The dipole-quadrupole mode separation is ample, and insures broad mechanical tolerances for the structure, simplifying construction in niobium.

Mechanical Stability

A high-degree of mechanical stability is particularly desirable for low-beam-current applications of the device because of the difficulty of stabilizing the rf phase of high-Q superconducting resonators in the presence of microphonic-induced-excitation of mechanical vibrational modes of the cavities.

This difficulty is best quantified as the reactive power capability required of the resonator rf tuning system, given by

$$P_{react} = 8\pi\ \delta f\ U_{rf}$$

where δf is the p-p eigenfrequency jitter, and U_{rf} is the total rf electromagnetic energy in the resonant cavity. The present fast-tuning system for ATLAS operates at a typical capacity of P_{react} = 10 KVA, with a maximum capacity of 30 KVA.

The electromagnetic field energy for the quadrupole mode of the copper model structure was calculated by MAFIA and checked by bead-pull frequency-perturbation measurements as: U_{rf} = 2.6 Joules for a vane voltage V_{vane} = 100 KV (the voltage between adjacent vanes is twice this value).

The mechanical stability exhibited by the copper model is excellent. Under conditions typical for operation of superconducting resonators for the ATLAS linac, ambient microphonic-induced rf eigenfrequency jitter was less than 50 Hz, peak-to-peak. In previous development, the microphonic behaviour of room temperature models has been a good indicator of on-line behaviour for superconducting resonant cavities in the ATLAS linac.

This observed level of vibration is within the capacity of the existing phase-stabilization system for V_{vane} < 300 KV, well beyond any performance expectation for the superconducting RFQ.

Field Flatness and Surface Fields

MAFIA results indicate that variation of the rf voltage along any vane or rod due to inductive voltage drop is less than 3%. The variation is small and can be accommodated by slight variations in the cell length along the modulated vanes.

The peak surface electric field, occurring at the vane tips, is estimated to be 60 MV/m for V_{vane} = 100 KV.

The peak surface magnetic field B_{max}, calculated by MAFIA, occurs at the junction between rods and posts, and B_{max} = 590 gauss for V_{vane} = 100 KV. This value is calculated for a junction of two simple cylinders at right angles. The final design will shape this junction to reduce the peak by 10-15%. Even so, the surface magnetic field may be the performance limitation for this structure. Superconducting heavy-ion structures currently in use in the ATLAS linac have frequently operated at B_{max} > 700 gauss do not routinely operate cw at $B_{max} \geq$ 1000 gauss [7].

Conclusions and Future Plans

A rod and post RFQ geometry with fourfold rotational symmetry has very good electromagnetic and mechanical properties for implementation as a superconducting RFQ structure.

Questions which can be resolved only by testing a superconducting device are:

1. Can the high electric surface fields (> 100 MV/m) obtained in a short niobium RFQ be repeated in a structure of useful length?

2. Do multipacting phenomena in such a structure present severe operational problems?

Work is currently in progress to construct and test the superconducting device described above as a collaboration between Argonne National Laboratory and AccSys Technology Inc.* (through the U. S. Department of Energy SBIR program).

Acknowledgements

The authors wish to acknowledge the contribution of AccSys Technology Inc.* in constructing the model of the RFQ resonator, and J. Delayen for helpful discussions.

The work at Argonne National Laboratory was performed under the auspices of the U. S. Department of Energy and funded by the U. S. Army Strategic Defence Command.

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11/18/92