PROTOTYPE NIOBIUM RESONATORS FOR HIGH-CURRENT ION BEAMS

J. R. Delayen and C. L. Bohn
Argonne National Laboratory
Engineering Physics Division
9700 South Cass Avenue
Argonne, Illinois 60439

ABSTRACT

We are developing and constructing a series of niobium resonators for the acceleration of high-current ion beams. These structures are designed to operate at frequencies of 350 MHz to over 1 GHz and velocities of 0.1 c to 0.5 c. Both coaxial quarter-wave and coaxial half-wave geometries are being explored. By comparing quarter-wave and half-wave structures of the same frequency and velocity, we plan to quantify the relative performance of these two distinct geometries.

1. INTRODUCTION

Superconducting cavities offer a number of advantages with respect to applications in the acceleration of high-brightness ion beams.[1] Because they carry an inherently low intrinsic surface resistance, these structures need not be optimized with respect to shunt impedance, so that new designs which would be inefficient for normal-conducting cavities can be explored. For example, compared to normal-conducting resonators, superconducting resonators can be relatively short with large beam apertures. Moreover, they can be independently phased within a linear accelerator (linac) so that they degrade gracefully, i.e., a loss of cavities and/or focussing elements can be compensated by adjusting the phases and amplitudes of the fields in the working cavities. These advantages motivated, at least partly, the construction of superconducting boosters for low-current ion beams. These boosters have operated reliably in the continuous-wave (cw) mode, accumulating over 50,000 hours of beam on target with minimal supervision. The history of superconducting linacs and of the associated technical issues is reviewed in Ref. 2; the state of the art of radio-frequency (rf) superconductivity (sc) as applied to particle accelerators is reviewed in Ref. 3; and the current status of superconducting heavy-ion accelerators is reviewed in Ref. 4.

We seek to expand the existing technology base for low-brightness, low-frequency ion accelerators into that required for high-brightness, high-frequency linacs. Current plans toward this end involve the design, fabrication, and construction of one or more fully automated superconducting sections for testing at the exit apertures of high-brightness ion accelerators projected to be available in the early-to-mid 1990s. These sections would be used to study accelerator issues such as beam impingement, focussing, beam instabilities, and beam loading/control (which are discussed relative to linacs for high-brightness beams in Ref. 1).

In this paper, we describe the ongoing effort to develop niobium resonators for these sections and comment on alternative materials for cavity fabrication.

2. RESONATOR DEVELOPMENT

The various superconducting resonators developed to date have been for applications in high-energy electron accelerators or heavy-ion boosters for electrostatic accelerators. Accordingly, as is indicated in Figure 1, superconducting structures which are either in use or in the advanced development stage occupy two distinct regions of the frequency-velocity plane which lie outside the region of interest. Early development of superconducting structures in the frequency-velocity range of interest here involved cavity geometries which either showed little promise,[5] or were not entirely appropriate for this application.[6] Since the most successful existing slow-wave superconducting structures are based on some form of resonant line with the beam traversing the high-voltage region, the development approach we are taking involves extending this resonator class to higher frequencies and velocities.

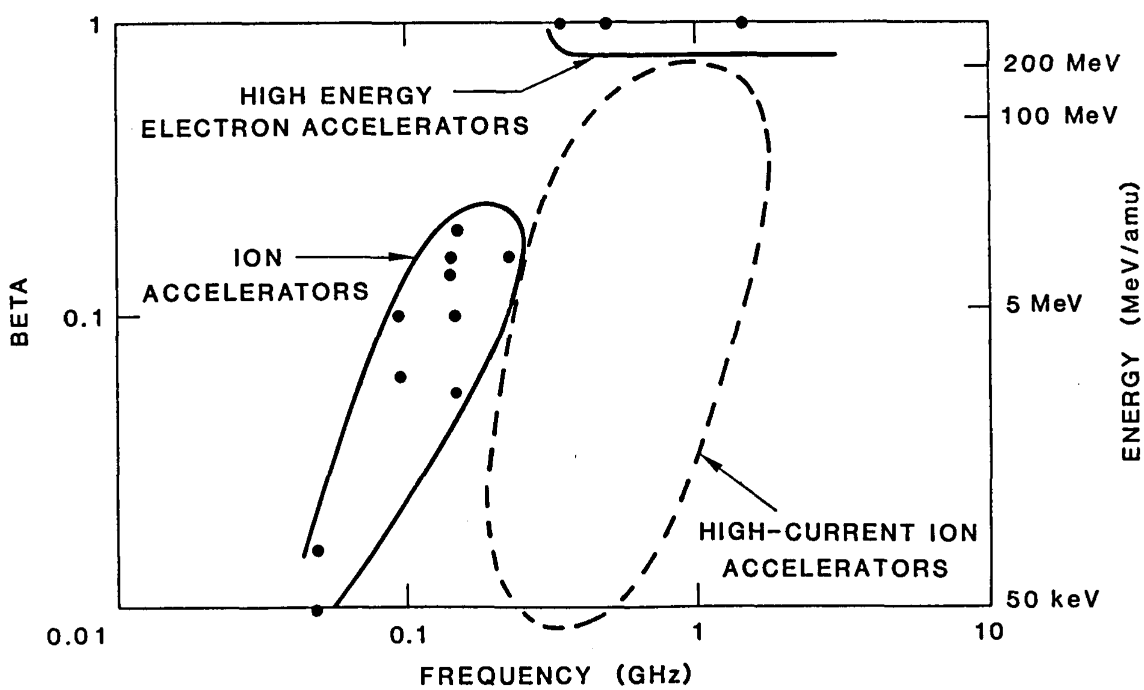


Figure 1. Phase velocity versus frequency of the superconducting cavities which are in use or at the advanced development stage.

The first superconducting accelerating cavity to be fabricated as part of the this program is the 425 MHz, 0.16 c quarter-wave resonator pictured in Figure 2. The inner conductor is formed from 0.16-cm-thick sheet niobium and is filled with liquid helium during testing. The outer conductor was fabricated from a process developed for the Argonne Tandem Linear Accelerator System,[9] in which a sheet of niobium of a few mm thickness had been explosively bonded to copper. The copper, a good thermal conductor, takes heat from the niobium, a relatively poor thermal conductor, and deposits it in an adjacent liquid helium reservoir. By design, this cavity can efficiently accelerate ions of energy in the range 5 to 50 MeV/amu.

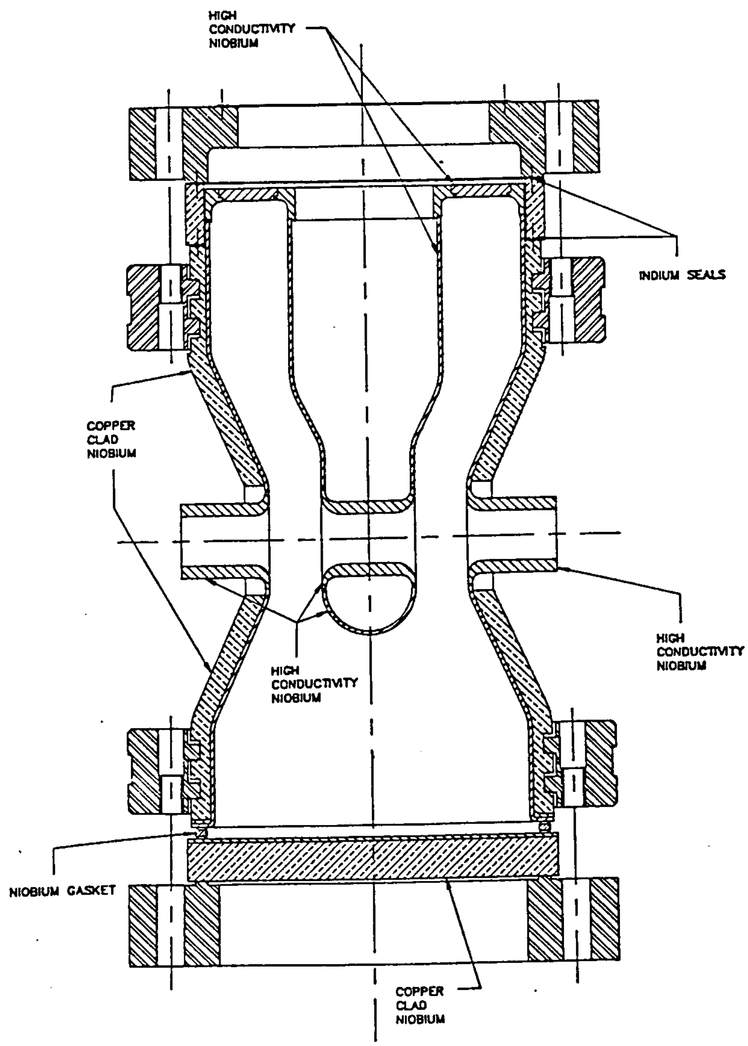
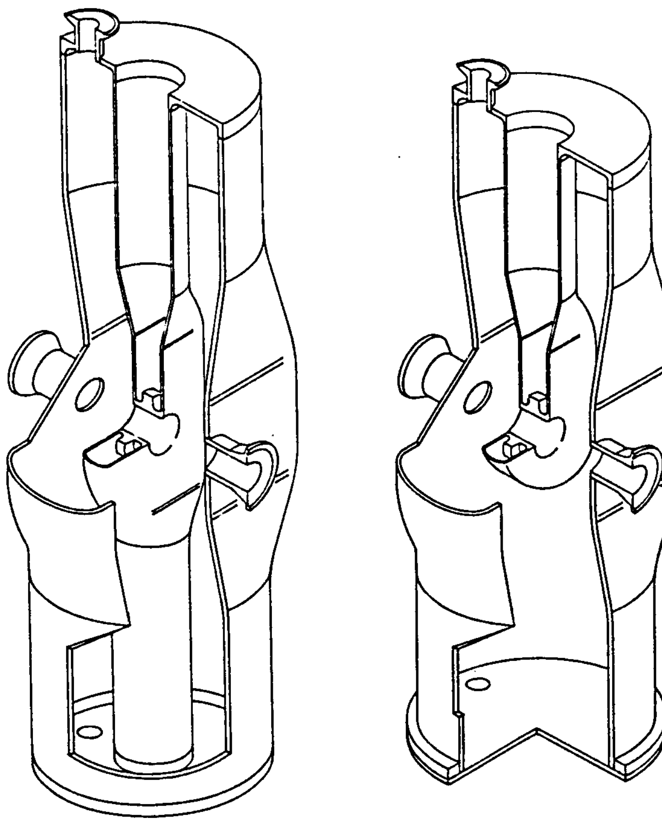


Figure 2. Coaxial quarter-wave resonator of frequency 425 MHz and particle velocity 0.155 c fabricated with a copper-clad niobium outer conductor.

Other cavities in fabrication include the 352 MHz, β = 0.12 coaxial quarter-wave and coaxial half-wave structures pictured in Figure 3. The inner conductors of these cavities are made from 0.16-cm-thick sheet niobium, and the outer conductors are made from 0.32-cm-thick sheet niobium. Relative to the half-wave, the quarter-wave structure should have less power dissipation but should sustain a lower accelerating gradient.[8] We plan to quantify these differences with the two cavities. Both are currently in fabrication.



(a) (b)

Figure 3. Conceptual design of (a) a coaxial half-wave resonator and (b) a coaxial quarter-wave resonator of frequency 352 MHz and particle velocity 0.12 c fabricated with high-conductivity sheet niobium.

Shown in Figure 4 is an additional cavity in fabrication, an 850 MHz, β = 0.28 spoke resonator. The inner and outer conductors are sheet niobium which have the same thicknesses and are cooled in the same manner as the cavities of Figure 3.

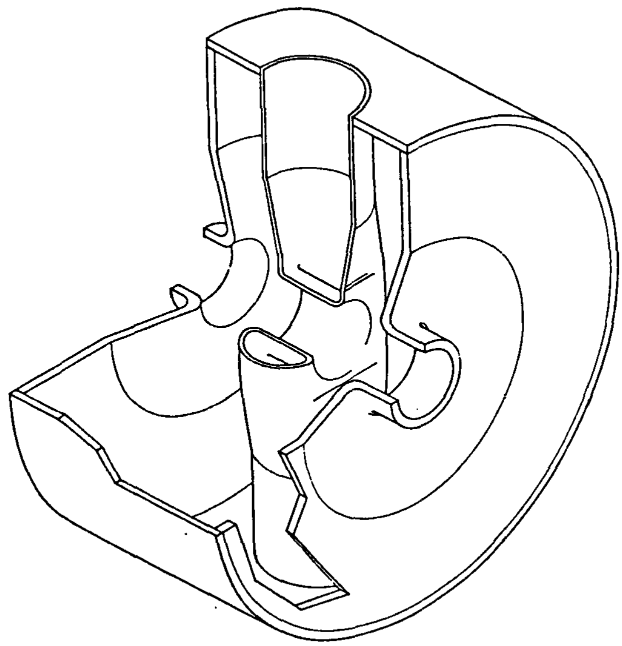


Figure 4. Conceptual design of a spoke resonator of frequency 850 MHz and particle velocity 0.28 c.

In a high-current ion linac, strong and frequent focussing will be required to counter the effects of space charge. Because the resonators must go through their transition temperature in an environment essentially free of magnetic fields, permanent magnets cannot be located inside the cavities as they are in an Alvarez structure. Instead, one possibility is to use superconducting electromagnets which are turned on after cooldown of the linac. Experiments at lower frequency indicate that the rf properties of superconducting niobium resonators remain intact in the presence of high dc magnetic fields;[9] these results, which were obtained at low rf fields, have been confirmed at high rf fields. Accordingly, one possible configuration for reducing beam impingement on the cavity walls involves the use of solenoids and beam scrapers, as illustrated in Figure 5.

Once fabricated and tested with high field, these prototype cavities will be used for experiments related to the remote operation of a linac. Methods for forced-flow cooling, slow and fast tuning, and automated rf control will be developed, and the long-term stability and associated reconditioning requirements will be identified.

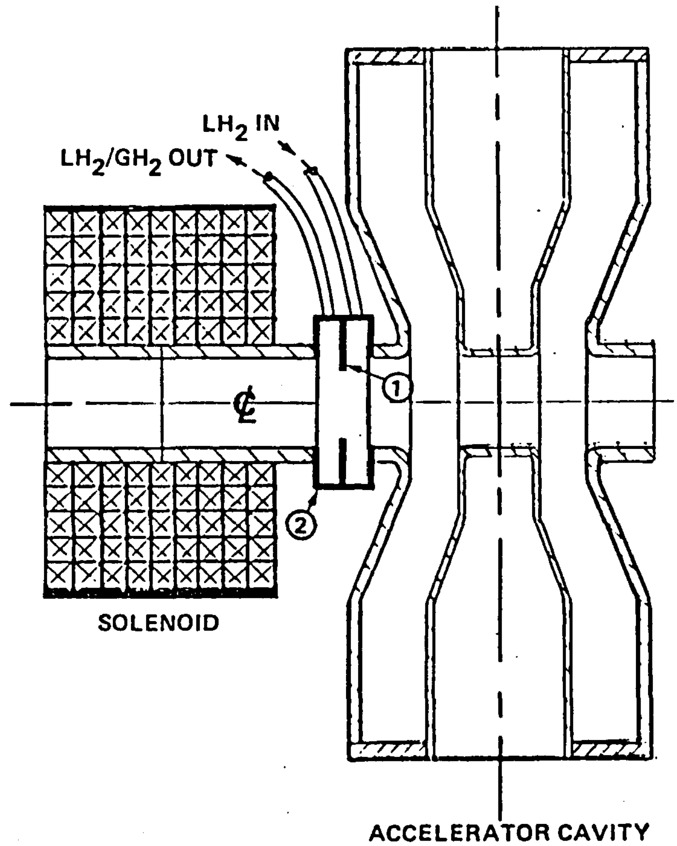


Figure 5. Conceptual focussing arrangement of a superconducting solenoid, beam block (1) to reduce beam impingement, and thermal isolator (2).

3. MATERIALS DEVELOPMENT

Niobium is the material of choice for near-term applications, forming the baseline material for cavity fabrication. Yet, niobium technology is still far from achieving its potential. The theoretical cw performance of low-velocity structures such as those described here is of order 25 MV/m, and of high-velocity structures, e.g., elliptical cavities, is of order 45 MV/m. To date, the best values achieved are about half of theoretical. Field emission loading and thermal instabilities are the major limiting factors in the achievement of high accelerating gradients, and surface processing to reduce these phenomena is the current focus of R&D in this technology.[10,11]

There are a number of alternative materials offering potential advantages over niobium: thin films of niobium and copper sequentially deposited on the interior of an aluminum infrastructure (Nb-Cu-Al), Nb_3Sn or NbN, and high-temperature superconductors (HTS). Their advantages are principally in the form of simpler manufacturing and increased reliability. These advantages are summarized in Table 1.

Table 1. Impacts of Alternative Superconducting Materials

Material	Benefits (relative to sheet niobium)
Nb-Cu-Al ("Near-term": 3-5 years)*	• Easier mass production of resonators. • Reduced sensitivity to beam impingement via thin-film Nb.
Nb_3Sn/NbN ("Mid-term": 5-7 years)*	• Higher operating temperature. • Reduced sensitivity to beam impingement • Higher accelerating gradient.
HTSC ("Long-term": >7 years)*	• Higher operating temperature (no LHe). • Potential for higher accelerating gradient. • Potential for reduced sensitivity to beam impingement.

*Timing is estimated based on current status of corresponding R&D.

Regarding the conventional superconductors, all of their advantages could be obtained by first preparing a Nb-Cu-Al cavity and then applying tin or nitrogen to obtain Nb_3Sn or NbN using a vapor diffusion process.[12] This would provide a higher transition temperature than niobium (14-17 K versus 9.2 K) and would allow for correspondingly higher operating temperatures. It also would accommodate higher peak surface magnetic fields (~5 kG versus ~2 kG for niobium). In turn, improvements in thermal stability and less sensitivity to beam impingement may result, and higher accelerating gradients could in principle be achieved. These technologies are in their infancy, yet in view of their potential benefits, they should both be aggressively pursued.

High-temperature superconductors have the potential to provide all of these advantages and also eliminate the need for liquid helium.[13] Before they can be used, however, their rf performance must first be improved to allow low surface resistances at high peak fields. For example, at its operating temperature, an accelerating cavity will require surface resistances no higher than a few tens of micro-ohms at surface fields as high as a few hundred gauss and at frequencies in the range 200-1800 MHz. The rf performance of bulk polycrystalline HTS indicate that at low fields, sufficiently low surface resistances are obtained, but at high fields the surface resistance is too large by a factor of ~100.[14,15] However, the data also indicate that this material remains superconducting at high rf fields, which is favorable. Moreover, there is no known fundamental physics which would preclude the eventual achievement of useful surface resistances at high rf fields.

The ceramic-oxide HTS materials are poor thermal conductors, a property which motivates the development of thin films on high-conductivity substrates. To be useful in accelerating cavities, the rf properties of these films will have to be compatible, and the film deposition process must be adaptable to substrates of complicated shape, like the resonators of Figures 3 and 4. Accordingly, considerable technological development is required.

4. CONCLUSIONS

Work is underway in the form of a development program leading to superconducting niobium sections for testing with high-brightness beams. Regarding alternative materials, only high-temperature superconductors are currently being pursued in earnest. Conventional superconductors in the form of thin-film niobium and Nb_3Sn/NbN also have the potential to provide substantially simpler manufacturing and improved reliability and could be available sooner than HTS.

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