SUPERCONDUCTING ACCELERATING STRUCTURES FOR HIGH-CURRENT ION BEAMS

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ABSTRACT

A series of superconducting structures for the acceleration of high-current ion beams is being developed, and two prototype Nb cavities are under construction. These cavities operate in a frequency-velocity range which, for superconducting structures, has been little explored: frequencies of 0.4 GHz to more than 1 GHz, and velocities of 0.1 to 0.5 c. Issues discussed include: need for strong beam loading ($\sim 10^4$), need for strong focusing elements located close to the cavities, minimization of beam impingement and beam instabilities.

INTRODUCTION

Superconducting cavities have been designed and used to accelerate a wide range of particles traveling at velocities from less than .01 c to nearly c; the frequencies range from less than 50 MHz to several GHz. A review of the state of the art in the application of rf superconductivity (RFSC) to particle accelerators can be found in reference 1 and in other contributions to this conference.

Most of the development work on superconducting accelerating structures has, so far, been directed toward high-energy electron accelerators and heavy-ion boosters for electrostatic accelerators. While the former have been used to accelerate beams of several mA, the latter have been restricted to currents of μA. Figure 1 shows the various superconducting accelerating structures which are either in use or at the advanced development stage; as can be seen, they are situated in two distinct regions in the frequency-velocity plane. The application of RFSC to high-current ion accelerators will require the development of structures in a region which, with a few exceptions, has been unexplored.

It may seem, at first, that superconducting cavities have little to offer in applications where the amount of power absorbed by the beam is large compared to the rf power dissipated in the cavity even if it were normal conducting; but, nevertheless, they have distinct other advantages which make them attractive for high-current ion accelerators.

Because of their low power dissipation, superconducting structures do not need to be designed to maximize the shunt impedance, and new designs which would be inefficient for a normal conducting cavity can be explored. For example, superconducting resonators can be designed with much larger apertures that would be practical for normal conducting resonators. Superconducting accelerators can also be built from very short structures, resulting in an increase in flexibility and reliability. An attractive feature of existing superconducting, low velocity linacs is that they consist of an array of relatively short, independently phased accelerating cavities. Consequently, operation with a fraction of the cavities off line is possible: full performance can be restored by increasing the fields in the remaining cavities by roughly the same fraction and rephasing the resonators. Finally, superconducting resonators have the demonstrated capability of operating continuously at high accelerating fields.

MAJOR DEVELOPMENT WORK AREAS

Resonator Geometry

It has often been the experience in superconducting accelerators that new applications require new cavity designs and that normal conducting designs make poor superconducting designs. Early development of superconducting structures in the frequency-velocity range discussed here dealt with cavity geometries which either showed little promise,[2] or were not entirely appropriate for the applications presently considered.[3] The most successful existing slow-wave superconducting structures are based on some form of resonant line with the beam traversing the high voltage region. An extension of this resonator class to higher frequencies and velocities is the coaxial half-wave or spoke resonator shown in figure 2.

Beam Impingement

There is little experimental data on the amount of beam impingement a superconducting cavity can tolerate, but it should not exceed a few watts per cavity. Depending on the application, this can translate to as little as a few parts per million of the beam hitting each resonator. While this is of concern, superconducting resonators can be designed with much larger beam apertures than normal conducting cavities, and beam scrapers can be located along the beam line to prevent particles traveling far off axis from hitting a superconducting surface.

Focusing

Space charge effects associated with large beam currents will cause the beam to blow up rapidly, at least at the low energy end of the accelerator, and strong and frequent focusing will be required. Because a superconducting resonator must go through its transition temperature in an environment free of magnetic field, permanent quadrupoles cannot be located inside the drift tubes as is done for normal conducting structures. Present designs call for focusing elements located between the accelerating structures; superconducting focusing elements, such as solenoids, could be turned on after the cavities have become superconducting. Experiments at lower frequency indicate that superconducting resonators can maintain their rf properties in the presence of high dc magnetic fields;[4] these results which were obtained at low rf field have recently been confirmed at high rf fields. Superconducting solenoids could be located very close to superconducting structures with only a moderate amount of shielding.

Beam Instabilities[5]

Because of the high Q of the modes of superconducting cavities, beam instabilities due to the excitation of higher order modes can be a problem. This is mostly the case, however, in recirculating linacs and storage rings where there is a closed feedback loop between beam and rf modes. Since the high current ion accelerators which are contemplated are single-pass linacs, multipass beam breakup will not be an issue.

There remain several possible causes of beam breakup in single-pass linacs, however the character istics of the low velocity linacs minimize the possibilities. One possible source of beam instability is the single-pass regenerative beam breakup which is caused by the propagation of the higher mode power from the output end of the structure towards the front. The current threshold for that instability varies as the reciprocal of the square of the resonator length, and all the designs for the superconducting accelerators which are under consideration are composed of short, completely decoupled cells.

Another source of instability is the single-pass cumulative beam breakup which is not an instability in time but is an amplification of the misalignment along the length of the accelerator. Since we are concerned with low velocity particles, their velocity will change along the accelerator and there will be only a small number of identical successive structures.

Another favorable characteristic of single-cell, low-velocity superconducting structures is that the accelerating mode has the lowest frequency and the higher-order modes are far removed. Finally, because of the beam loading, the loaded Q of the resonator will be low ($\sim 10^5$), and it should be easy to reduce the loaded Q of the harmful higher-order modes which are not already loaded by the coupling mechanism.

Beam loading, Control

Since existing superconducting ion accelerators are used as boosters for electrostatic accelerators, the beam currents have always been very small; the power supplied by the cavity to the beam is substantially less than the power dissipated in the cavity walls to generate the accelerating fields and beam loading has not been an issue.

When accelerating beams of several tens of mA, on the other hand, the power supplied to the beam will be several orders of magnitude higher than that dissipated in the cavity, and the cavity will be heavily beam loaded. This fact should simplify some of the problems associated with the stabilization of low-velocity superconducting structures. Typically, the variations in resonant frequency caused by ambient vibrations can be orders of magnitude larger than the intrinsic bandwidth of the resonator. Phase stabilization of a low-velocity superconducting structure is accomplished in one of several ways: one way is by broadening the loaded bandwidth by intentional overcoupling and using negative phase feedback;[6] another way is by using an external voltage-controlled variable reactance.[7] In the case of very heavily beam loaded structures, on the other hand, the external Q--and thus the loaded Q--of the resonator will be very low in order to transfer efficiently power between the rf source and the beam. The transient behavior of the fields in a heavily beam-loaded superconducting cavity will be very similar to that of a normal conducting cavity, and the vibration problem will be eliminated. Since the loading due to the external Q is fixed, the loaded Q of the resonator will be low even when no beam is present.

One consequence of the heavy beam loading is that, in the event of a resonator becoming normal, the beam itself will generate large rf fields in the structure which could cause a large consumption of cryogen. To guard against that eventuality, fast frequency tuners will be needed to change the resonator frequency by many bandwidths and reduce the coupling between cavity and beam. An unknown, at present, is whether a cavity which has become normal can recover and be brought back on line without turning off the beam.

Materials

While the discovery of the high-T_c superconductors has raised the possibility of superconducting accelerators operating, someday, at liquid nitrogen temperature, the amount of technological development required when compared to the one which brought the niobium technology to the present state of the art, makes it unlikely that it will happen in the near future. The niobium technology, on the other hand, is still far from achieving its full potential, and the Nb_3Sn technology is still in its infancy;[8] both of them should be pursued aggressively, but Nb remains the likely choice for near term applications.

For longer term applications, Nb_3Sn offers some attractive features. While reduction of rf losses is of secondary importance for high-current machines, the possibility of operating at higher surface magnetic fields may be of interest. Also, the higher transition temperature of Nb_3Sn may improve thermal stability and reduce sensitivity to beam impingement.

PROTOTYPE CAVITIES

As a first step in the frequency-velocity region of interest, the two superconducting cavities shown in figures 3 and 4 are under development and construction. Both of them operate around 400 MHz and are optimized for particle velocities of about .16 c. Because they are two-gap structures with wide velocity acceptance, they can efficiently accelerate ions of energy between 5 and 50 MeV/amu. Both structures have a center conductor fabricated of high thermal conductivity Nb sheet, filled with liquid helium. The outer conductors are fabricated of explosively bonded Nb on Cu, a technique which has been developed for, and used extensively in, the Argonne ATLAS accelerator.[9]

ACKNOWLEDGMENTS

I would like to thank R. Benaroya, C.L. Bohn, and K.W. Shepard for many useful discussions and their collaboration in the experimental program. This work was supported by the U.S. Department of Energy under contract W-31-109-ENG-38 and by the U.S. Army Strategic Defense Command.

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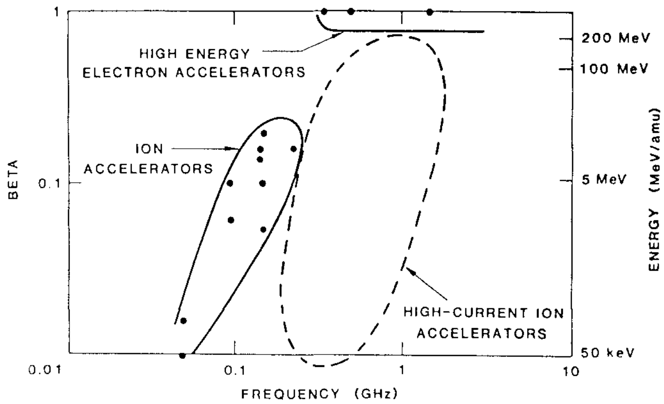

Figure 1: Phase velocity vs frequency of the superconducting cavities which are in use or at the advanced development stage

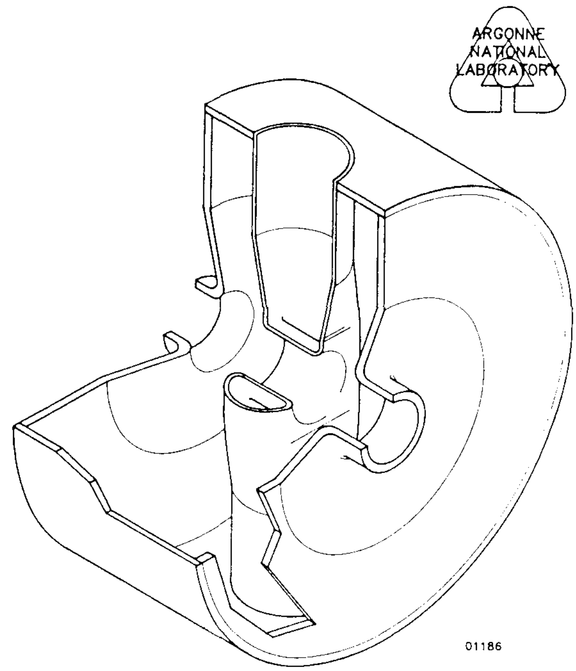

Figure 2: Conceptual design of a spoke resonator operating at 850 MHz and optimized for a particle velocity of 0.28 c

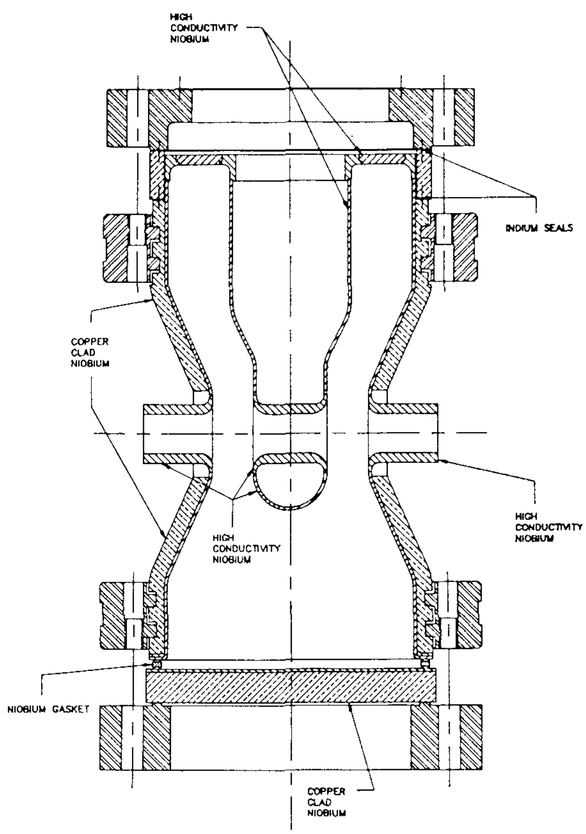

Figure 3: Coaxial quarter-wave resonator; 425 MHz, 0.155 c

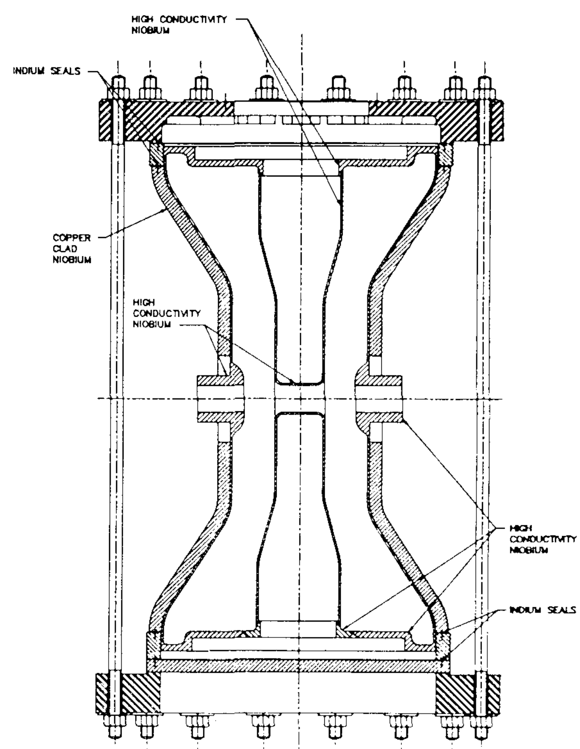

Figure 4: Coaxial half-wave resonator; 425 MHz, 0.18 c