APPLICATION OF RF SUPERCONDUCTIVITY
TO HIGH-BRIGHTNESS ION-BEAM ACCELERATORS

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Abstract

A development program is underway to apply rf superconductivity to the design of cw linear accelerators for high-brightness ion beams. The key issues associated with this endeavor have been delineated in an earlier paper. Considerable progress has been made both experimentally and theoretically to resolve a number of these issues. In this paper we summarize this progress. We also identify current and future work in the areas of accelerator technology and superconducting materials which will confront the remaining issues and/or provide added capability to the technology.

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I. INTRODUCTION

The motivation and issues associated with the application of rf superconductivity to linear accelerators for high-brightness ion beams have been discussed in an earlier paper.[1] The following major development work areas were identified: Resonator Geometry, Beam Impingement, Focusing, Beam Instabilities, Beam Loading/Control, and Materials. Since the publication of this paper, a number of promising experimental results have been obtained in the areas of Resonator Geometry and Materials. Niobium cavities with coaxial quarter-wave and half-wave geometries have yielded cw accelerating gradients as high as 18 MV/m. A resonator with an RFQ geometry sustained cw electric fields as high as 128 MV/m over a 10 cm² surface area. The rf surface resistance of a wide variety of high-T_c superconductors have been measured in the presence of high rf surface magnetic fields. These experiments are crucial for identifying suitable materials for accelerator applications. The results are summarized here. In addition, beam impingement and cumulative beam breakup have been calculated for high-brightness ion linacs, and the results are presented here.

II. NIOBIUM RESONATORS

Our approach to the development of niobium resonators for the acceleration of high-brightness ion beams is based on the use of some form of resonant line with the beam traversing the high-voltage region. This approach was found to be successful in the development of existing slow-wave superconducting structures at lower frequencies.[2] Our efforts have focused on extending this resonator class to higher frequencies and velocities.

The first of these cavities to be fabricated was a 400 MHz coaxial quarter-wave structure optimized for particle velocity 0.15c [3,4]. It yielded an average (wall-to-wall) cw

accelerating gradient of 12.9 MV/m. This corresponded to an energy gain of 0.820 MV per unit charge. At this gradient a cavity Q_0 of 1.4×10^8 was measured. The associated peak surface electric and magnetic fields were approximately 41 MV/m and 470 G, respectively. Average accelerating gradients as high as 14 MV/m were achieved in the pulsed mode.

Subsequently, a 355 MHz coaxial half-wave structure (shown in Fig.1) optimized for particle velocity $0.12c$ was fabricated.[4] It yielded an average cw accelerating gradient of 18 MV/m. This corresponded to an energy gain of 1.26 MV per unit charge. At this gradient a cavity Q_0 of 1.2×10^8 was measured (see Fig. 2). The associated peak surface electric and magnetic fields were approximately 58 MV/m and 936 G, respectively. At 10 MV/m, the power dissipation was 2 W. The accelerating gradient of this cavity is the highest achieved in a low-velocity structure. Because of its promising performance, this resonator is the prototype cavity for a superconducting section which is planned for fabrication and testing with a D⁺ beam of energy 7.5 MeV and current 80 mA.

Work in progress on accelerator cavity design includes the fabrication of a 2-gap, 850 MHz spoke resonator.[1] In addition, a 3-gap, 850 MHz spoke resonator [5] is planned for construction. This resonator should provide a larger real-estate gradient than is available with 2-gap structures.

A superconducting rf quadrupole structure (RFQ) has been designed to investigate the cw field gradients obtainable with a realistic vane geometry. During its cryogenic tests, the device was operated cw at fields a factor of three higher than have been reported for cw operation of normally-conducting RFQ structures.[6] The results suggest that rf superconductivity may appreciably extend the range of options for RFQ design. Possible applications and designs of superconducting RFQs are under study.[7]

III. SUPERCONDUCTING MATERIALS

High- T_c Superconductors. We have constructed and used several apparatuses based on resonant cavities for measurements of rf surface resistance of high- T_c superconductors. These experiments spanned frequencies from 0.15 to 40 GHz and rf surface magnetic fields as high as 640 gauss.[8,9] The general behavior of these materials is that the surface resistance increases monotonically with increasing rf field amplitude, saturating at high field at a value a few percent of the normal-state surface resistance just above T_c . Our data indicate that at low fields, sufficiently low surface resistances are achieved. However, at high fields (e.g., >100 G) the surface resistance is too large by a factor of about 100 to be useful in accelerators. While work on high- T_c superconductors is continuing, these results indicate that niobium and its alloys will likely remain the materials of choice in the near future for high-power applications.

Niobium. A "voltage platform" was constructed to determine, for a realistic (four-finger) vane geometry, the field gradients which could be expected in the cw operation of a superconducting RFQ.[6] With this vane geometry, cw fields of 128 MV/m could be sustained over a surface area of order 10 cm² and were limited by the inefficient cooling of the vanes. In pulsed operation, 210 MV/m could be maintained for times in excess of 1 msec. These results indicate that there is no fundamental reason preventing niobium resonators from operating at gradients substantially higher than those routinely achieved today.

An increase in achievable surface fields has been obtained by high-temperature treatment of niobium structures [10], and we are therefore building a facility to do this. We are also beginning to investigate films of niobium alloys for applications in accelerating cavities.

IV. THEORETICAL CONSIDERATIONS

Beam Impingement. We have studied beam impingement with a model which includes heat transport both in the resonator wall and at the interface between the resonator wall and the cryogen.[5] The model incorporates the worst-case assumption that the ions will deposit their total kinetic energy (taken to be 200 MeV) at the niobium-vacuum interface. The heat-transport problem is approximated as one-dimensional heat flow across a plane. The cryogen is assumed to be liquid helium at 4.2 K (He I).

The heat-transport problem is dominated by the interface between the resonator wall and the liquid helium. To maximize the heat flux while minimizing the temperature difference at the interface, it is necessary to operate in the nucleate-boiling regime and to avoid film boiling. This will limit the rate of heat removal to 1 W/cm^2 and the temperature difference between the wall and bath to 1 K.[11] Assuming the accelerating structure is fabricated from RRR=250 niobium, which has thermal conductivity $\sim 1 \text{ W/cm-K}$ at 5.2 K,[12] the temperature rise at the niobium-vacuum interface will be of order 0.2 K. Since niobium has $T_c=9.2 \text{ K}$, this temperature increase would not present a serious problem for a cavity operating at 4.2 K.

The study has shown that, given large apertures in the constituent resonators, beam impingement in a superconducting linac should be a manageable problem.[5] Moreover, both beam scrapers and focusing elements can be placed between the resonators to reduce beam impingement further.

Cumulative Beam Breakup. The cumulative beam breakup instability is caused by interaction between the beam and deflecting higher-order modes in the accelerating cavities. The most problematic deflecting modes have longitudinal electric-field components which are zero along the beam axis and change sign across the axis. The initial bunch of a misaligned beam excites the deflecting mode in the initial cavity which

deflects trailing bunches. The deflected bunches then couple more strongly to the deflecting mode in the next cavity causing further deflection of trailing bunches, etc.

An analytic model of cumulative beam breakup has been developed which is applicable to both low-velocity ion and high-energy electron linacs.[13] The model includes arbitrary velocity, acceleration, focusing, initial conditions, beam-cavity resonances, and variable cavity geometry and spacing along the accelerator. A "continuum approximation" is made in which the transverse kicks in momentum imparted by the cavities are smoothed over the length of the linac. The resulting equation of transverse motion is then solved via the WKBJ method.[13]

We investigated cumulative beam breakup in two superconducting linacs comprised of 352 MHz coaxial half-wave resonators supplying a 4.5 MV/m real-estate gradient.[5] The first is a five-cavity section to be tested with a beam of energy 7.5 MeV and current 80 mA. The section was modelled pessimistically using a tightly bunched, misaligned coasting beam with no focusing. Under conditions of a worst-case beam-cavity resonance, the steady-state solution dominates. A maximum Q of 2×10^7 for the deflecting mode assures steady-state growth no larger than approximately twice the initial beam offset. The second is a 100 mA linac from 5 MeV to 200 MeV, which was modelled using a nonrelativistic, tightly bunched, misaligned beam. The linac was assumed to provide a linear acceleration profile and strong solenoidal focusing (10 T solenoids over 25% of the linac). It was found that the transverse behavior of the beam is very sensitive to the Q of the deflecting mode. Under conditions of a worst-case beam-cavity resonance a maximum Q of 5.5×10^6 for the deflecting mode assures transient growth no larger than approximately twice the initial beam offset.

In summary, a maximum Q of order 5×10^6 for the deflecting modes in the constituent resonators of these superconducting linacs should suppress the cumulative beam breakup instability under worst-case conditions. In actual operation, the external Q of the

accelerating mode due to the rf coupling loops is expected to be about two orders of magnitude less than this. The rf coupling would probably also provide an external $Q < 10^6$ for the deflecting mode and thereby control beam breakup.

V. CONCLUSIONS

Recent results in the work areas of Resonator Geometry, Beam Impingement, Beam Instabilities, and Materials (i.e., niobium) make the prospects for superconducting high-brightness ion accelerators very encouraging. We are now developing a section of resonators and focusing elements to test with high current and thereby gather results in the work areas of Focusing and Beam Loading/Control. In addition, we are designing superconducting RFQs and plan eventually to explore the possibility of constructing compact linacs from RFQs for the acceleration of high-current ion beams.

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FIGURE CAPTIONS

Figure 1. 355 MHz coaxial half-wave resonator, $\beta_0=0.12$.

Figure 2. Q-curve for the 355 MHz coaxial half-wave resonator.

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