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

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

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.

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 cm^2 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. The results of these experiments 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]

The first of these cavities to be fabricated was a 400 MHz coaxial quarter-wave structure optimized for particle velocity 0.15c.[3] It yielded an average cw accelerating gradient of 12.9 MV/m with 21 W of rf power input to the cavity. This corresponded to an energy gain of 0.820 MV per unit charge.

Subsequently a 355 MHz coaxial half-wave structure optimized for particle velocity 0.12c was fabricated.[3] It yielded an average cw accelerating gradient of 18 MV/m with 40 W power input to the cavity. This corresponded to an energy gain of 1.26 MV per unit charge. 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 includes the fabrication of a 2-gap, 850 MHz spoke resonator.[1] In addition, the 3-gap, 850 MHz spoke resonator shown in Figure 1 is planned for construction. This resonator should provide a larger real-estate gradient than is available with 2-gap structures.

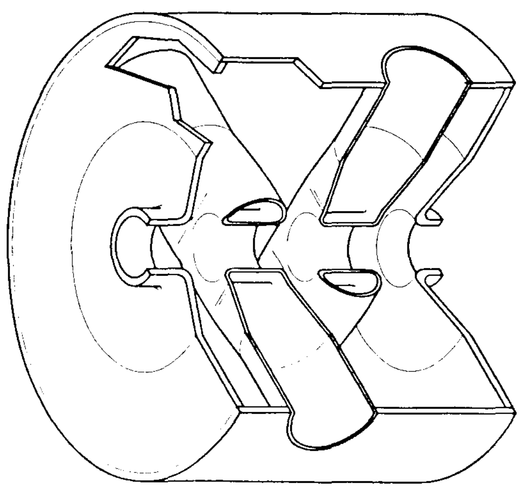

Fig. 1. Conceptual design of a 3-gap spoke resonator.

During its cryogenic tests, the first superconducting RFQ device was operated at fields a factor of three higher than have been reported for cw operation of normally-conducting RFQ structures.[4] 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.[5]

III. Superconducting Materials

High-T_c Superconductors. We have constructed and used several apparatuses for measurements of rf surface resistance (R_s) at frequencies from 0.15 to 40 GHz and rf surface magnetic fields (B_{rf}) as high as 640 gauss.[6] The most recent to be constructed is a coaxial quarter-wave cavity designed

*Work supported by the U.S. Department of Energy under contract W-31-109-ENG-38 and the U.S. Army Strategic Defense Command.

specifically for measurements of disk-shaped samples at 820 MHz and 4.2 K, and at B_{rf} ranging to hundreds of gauss.[7] The frequency was chosen to be representative of an accelerator.

A wide variety of films on silver and dielectric substrates spanning an enormous range of materials and fabrication techniques were measured with the quarter-wave cavity.[6] Most were approximately 24 mm in diameter by 0.5 mm thick. Most of the films on silver substrates covered all surfaces of the substrate. The qualitative behavior of the surface resistance of films on silver substrates is identical for each material: R_s increases monotonically with field amplitude through a transition region characterized by a strong field dependence, and then saturates at high field at a value of a few percent of the normal-state R_s just above T_c. This is a signature of the polycrystalline nature of the films and does not reflect their intrinsic properties. For example, R_s of epitaxial films on dielectric substrates degraded at high fields, but were substantially better than R_s of the polycrystalline films at high fields. Nevertheless, the degradation in R_s needs to be mitigated by a suitable process of materials engineering before high-T_c superconductors can be of use in accelerating cavities.

In light of these results, niobium and its alloys will likely remain the materials of choice in the near future for accelerator 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.[4] With this vane geometry, cw fields of 128 MV/m could be sustained over a surface area of order 10 cm^2 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[8], and we are now building a facility for this. We are also beginning to investigate films of niobium alloys for applications in accelerating cavities.

III. Theoretical Considerations (U)

Beam Impingement. We study 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. 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.[9] Assuming the accelerating structure is fabricated from RRR=250 niobium, which has thermal conductivity ~1 W/cm-K at 5.2 K,[10] the temperature rise at the niobium-vacuum interface will be of order 0.2 K. Since niobium has T_c=9.2K, this temperature increase would not present a serious problem for a cavity operating at 4.2 K.

The rate of heat removal restricts the amount of beam which can be permitted to impinge on a resonator. A 2D-Gaussian beam (σ_{rms}=0.6 mm) of H^- ions with 200 MeV energy and 100 mA current is assumed. Given a perfectly centered beam and a 1 W/cm^2 heat flux, the drift tube aperture would need a minimum diameter of 6.7 mm to prevent thermal runaway. By comparison, a typical superconducting resonator such as the structures described above has an aperture of order 25 mm. Thus, we conclude that, given large apertures in the constituent resonators, beam impingement in a superconducting linac will not result in a thermal management problem. Moreover, both beam scrapers and focusing elements can be placed between the resonators to reduce beam impingement further.

If beam impingement were to occur despite these preventive measures, then cryogen would be consumed. The amount would depend on the beam flux impinging on the accelerator. As an illustration, we consider an accelerator consisting of 200 superconducting resonators each of which is being impacted by beam over a 5cm^2 area resulting in a heat flux of 1 W/cm^2. Liquid helium evaporates at a nominal rate of 1.4 l/W-hr. Therefore, in this example, the rate of liquid helium consumption would be less than 0.4 l (nominally 50 g) per second of operation.

Cumulative Beam Breakup. A section of 352 MHz niobium coaxial half-wave cavities is currently being designed for experiments with a D^- beam of energy 7.5 MeV and current 80 mA. The section is a step along ther development path toward a full superconducting high-current ion linac. We assume both the section and the full linac will provide a real-estate gradient of 4.5 MV/m. We consider cumulative beam breakup (BBU) in both cases by applying a BBU formalism developed elsewhere.[11] The notation and equations cited here correspond to the notation and equations of Ref. 11. We assume pessimistically a misaligned beam with the worst possible beam-cavity resonance, for which $\omega\tau=4\pi(1+1/2Q)$ and $p(\omega\tau)=Q/\pi$ [cf. eq. (18)], to calculate the Q of the corresponding deflecting mode needed to keep the transverse displacement below approximately twice the initial displacement at the exit aperture of the linac.

To calculate the geometry factor Γ of the deflecting modes, we model the coaxial half-wave geometry as a TEM cavity in which the inner and outer conductors have radii a and b, respectively, and the cavity has height $h=\lambda_o/2$, where λ_o is the wavelength of the fundamental (accelerating) mode. From eq. (4), the corresponding geometry factor is

$$\Gamma = \frac{8\omega\left[si\left(\frac{\omega b}{\beta c}\right) - si\left(\frac{\omega a}{\beta c}\right)\right]^2}{\pi \epsilon_o c^2 h \ln(b/a)} .$$

To evaluate Γ numerically, we choose b=2a and $a+b=\beta\lambda_o/2.2$, consistent with the design of slow-wave structures.[12]

We assume the section consists of five 352 MHz cavities with no focusing. The geometry factor is $\Gamma=5.97\times10^{-7}\omega\ \Omega/m^2$. The initial and final beam energies are 7.5 MeV and 10.9 MeV, respectively, for which $\beta(0)=.089$, $\gamma(0)=1.004$, and $\beta(\mathcal{L})=.107$, $\gamma(\mathcal{L})=1.006$. The section therefore provides approximately a coasting beam with $\beta=.089$, $\gamma=1$, $\langle I\rangle=.08$ A, and no net focusing. The spacing between cavities is taken to be $L\approx2\beta(0)\lambda_o=.152$m, and the total accelerating length is $\mathcal{L}\approx4L=.608$m. Given the worst-case resonance, the steady-state displacement dominates. From eqs. (2) and (17), the Q which allows transverse displacement ξ_∞ at $\mathcal{L}$ is

$$Q = \frac{2p}{\langle I\rangle Ze}\,\frac{\omega}{\Gamma}\,\frac{L}{\mathcal{L}^2}\,\ln^2\!\left(\frac{2\xi_\infty}{\xi_o}\right).$$

We find $Q\leq1.9\times10^7$ assures $\xi_\infty/\xi_o\leq2$. By comparison, the external Q of the accelerating mode required to couple to the high current should be $\sim10^5$. The rf coupling would probably also provide an external $Q<10^7$ for the deflecting mode and thereby control BBU.

We now consider a full linac, the basic conceptual idea of which is to extend the section to accelerate a $\langle I\rangle=100$ mA D^- beam from 5 MeV to 200 MeV, for which $\beta(0)=.0728$, $\gamma(0)=1.003$, and $\beta(\mathcal{L})=.428$, $\gamma(\mathcal{L})=1.106$. We treat this beam as nonrelativistic ($\gamma=1$) and assume a linear accelerating gradient ($d\gamma/ds=G=2.37\times10^{-3}m^{-1}$). With a 4.5 MV/m real-estate gradient, the linac length is $\mathcal{L}=43$m. We assume the cavities all have $\Gamma=5.97\times10^{-7}\omega\ \Omega/m^2$ and are spaced in the manner $L=L_o[\beta/\beta(0)]$ with $L_o=.124$m, so that the total number of cavities is $N(\mathcal{L})=\int ds/L(s)=88$. We also assume that 10T solenoids occupy 25% of the linac and are equivalent to a uniform focusing field B=5T along the whole linac. Then, from eq. (20) with $\phi=-30^o$, the net transverse focusing wavenumber is $k_T\approx k_B$. As specified, this linac provides a nonrelativistic, slowly accelerated beam with strong solenoidal focusing, and thereby fulfills the assumptions leading to eqs. (21) and (22). The strong focusing provides an oscillatory steady-state displacement, and the transient term dominates. Evaluating the maximum amplitude ξ_{max} from eq. (22) and using equations (2) and (20) for $\epsilon(0)$ and $k_B(0)$, respectively, we find that the Q which allows transverse displacement ξ_{max} at $\mathcal{L}$ is

$$Q = 2\frac{B}{\langle I\rangle N}\,\frac{\omega}{\Gamma}\,\ln\!\left[\frac{2\,\xi_{max}}{\xi_o}\sqrt{\pi\,\frac{\langle I\rangle N}{B}\,\frac{\Gamma}{\omega}\,Q}\right].$$

As indicated in Fig. 2, the maximum transverse displacement is a sensitive function of the Q of the deflecting mode. We find approximately $Q\leq5.5\times10^6$ assures $\xi_{max}/\xi_o\leq2$. Just as for the section, the rf coupling would probably provide an external Q lower than this and thereby control BBU.

The limits on Q would be larger than those calculated here if a more realistic set of assumptions were used. For example, the frequencies of the higher-order modes in coaxial half-wave structures would be substantially removed from a harmonic of the fundamental (accelerating) mode due to capacitive laoding. This means the magnitude of the resonance function $p(\omega\tau)$ would be much less than we assumed, and BBU growth would be correspondingly lower. Other mitigating factors are listed in Ref. 11.

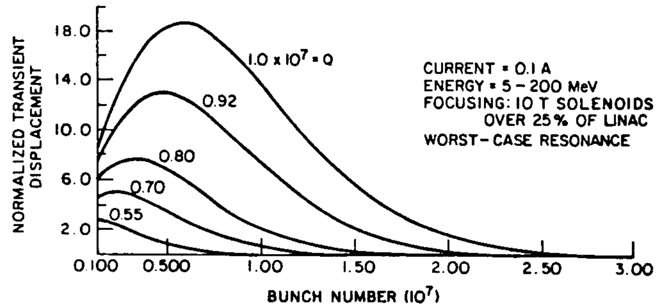

Figure 2. Normalized transient displacement ξ_M/ξ_o vs. bunch number M at the last cavity of the full D^- linac (see text). Curves correspond to different values of Q of the deflecting mode.

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.

References

1. J.R. Delayen, Nucl. Instrum. and Meth., **B40/41**, 892 (1989), and Proc. 1988 Linear Accelerator Conference.
2. J.R. Delayen, Proc. 4th Workshop on rf Superconductivity, KEK, ed. by Y. Kojima, 249 (1989).
3. J.R. Delayen, C.L. Bohn, and C.T. Roche, these Proceedings.
4. J.R. Delayen and K.W. Shepard, these Proceedings.
5. A. Schempp, H. Deitinghoff, J.R. Delayen, and K.W. Shepard, these Proceedings.
6. J.R. Delayen, C.L. Bohn, and C.T. Roche, J. Supercon., **3**, 243 (1990) and Proc. 1990 Applied Superconductivity Conference, Aspen, CO 24-28 Sep 90.
7. J.R. Delayen, C.L. Bohn, and C.T. Roche, Rev. Sci. Instrum., **61**, 2207 (1990).
8. Q.S. Shu, J. Graber, W. Hartung, J. Kirchgessner, D. Moffat, R. Noer, H. Padamsee, D. Rubin, and J. Sears, Cornell University Report CLNS-90/1005 (1990).
9. D. Lyon, Adv. Cryo. Eng., **10**, 371 (1965).
10. H. Elias and W. Weingarten, CERN/EF/RF 82-8 (1982).
11. C.L. Bohn and J.R. Delayen, these Proceedings.
12. J.R. Delayen, Nucl. Instrum. and Meth., **A259**, 341 (1987).