Recent developments in rf superconductivity for high-brightness and high-gradient ion beam accelerators

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FEB 14 1992

ABSTRACT

Recent progress in an on-going development program leading to the design of superconducting continuous-wave (cw) linear accelerators for high-brightness ion beams is reviewed. A new spoke-resonator geometry incorporating a half-wavelength resonant line was fabricated and tested. This geometry serves as the basis for the constituent cavities of a superconducting section being designed for high-current testing with a deuterium beam. Considerable progress has been made in the design of this section. A multi-phased program leading to the development of a superconducting radio-frequency quadrupole (SCRFQ) has been initiated. Design considerations and test results from the various activities are presented.

1. INTRODUCTION

The technology of radio-frequency superconductivity (RFSC) offers significant advantages for the production of high-current, high-brightness ion beams.¹ A fundamental advantage is that thermal management of the accelerator is accomplished inherently due to the very low wall losses in the constituent superconducting resonators. This has been exploited in the construction of a number of superconducting linacs designed to produce either high-energy electron beams or low-current, high quality ion beams for scientific applications.^{2,3} These linacs are economical to operate, and they run cw (a duty factor of 100%), virtually unattended, for long periods. Another key advantage is that superconducting low-velocity linacs are comprised of relatively short, independently phased accelerating cavities. This adds reliability, because if a fraction of the cavities are off-line, the linac can still be operated with full performance by increasing and rephasing the fields in the remaining cavities.

Efforts by our group have focused on extending the existing technology base for low-brightness, low-frequency ion accelerators into that required for high-brightness, high-frequency linacs. In this paper, we discuss our most recent experimental results in niobium resonator development and recent theoretical results concerning current limits in superconducting RFQs. This is followed with a description of the design of a superconducting section for high-current ion-beam tests. We also include a synopsis of future work motivated by these results.

2. NIOBIUM RESONATOR DEVELOPMENT

Superconducting accelerators require resonator designs which are distinct from those employed in normal-conducting accelerators. Because of their low power dissipation, superconducting cavities do not need to be designed to maximize the shunt impedance, and new designs which would be inefficient for normal-conducting cavities can be explored. Successful superconducting cavities operate with a minimum amount of electron loading in the form of multipactoring (resonant electron emission) and/or field emission (nonresonant electron emission).

Our designs of niobium resonators for the acceleration of high-brightness ion beams incorporate coaxial resonant lines with the beam traversing the high-voltage region. This approach was found to be successful in the development of existing slow-wave structures at lower frequencies.^{3,4} These resonators are 2-gap structures and therefore can efficiently accelerate a broad range of particle mass and velocity.

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Development work on coaxial quarter-wave and half-wave accelerating resonators by our group was described in a paper at the 1991 SPIE Symposium⁵. Tests of these resonators yielded average accelerating gradients between 12 MV/m⁶ and 18 MV/m.⁷

The 2-gap spoke resonator geometry shown in Figure 1 is being investigated for use at frequencies which are higher than can be achieved with practical resonator designs incorporating coaxial geometries. In the fundamental accelerating mode, the inner conductor acts as a half-wavelength resonant line. This geometry is easier to fabricate reliably than is the coaxial half-wave geometry because there are fewer welds, and the critical welds located in the vicinity of high rf surface magnetic fields are accessible for visual inspection and polishing during the manufacturing process. The geometry can also be straightforwardly extended to multigap designs which should provide larger real-estate gradients than would be achievable with 2-gap structures.

Figure 1. Conceptual design of a 2-gap spoke resonator.

Figure 2. 850 MHz, $\beta=0.28$, 2-gap spoke resonator prior to the welding of the end plates.

A 2-gap, 850 MHz spoke resonator optimized for $\beta=0.28$ has been fabricated from high-purity niobium (RRR = 250) and is undergoing initial tests. As is pictured in Figure 1, it consists of an inner conductor fabricated from 0.16-cm-thick sheet niobium and an outer conductor fabricated from 0.32-cm-thick sheet niobium. During testing, the cavity was cooled by immersing it in liquid helium.

The inner surface of the resonator was processed by a combination of mechanical and chemical polishings. The chemical polishing procedure consisted of filling the niobium cavity with a 2:1:1 solution of phosphoric acid, nitric acid, and hydrofluoric acid, respectively. This was followed by rinsing the piece in a 5% solution of H_2O_2 to remove insoluble niobium salts and then rinsing with deionized water of semiconductor purity. After the final chemical polish the resonator was stored in a deionized water bath for approximately 48 hrs. prior to mounting the rf pickup and drive coupling loops. The final step prior to rf testing of the cavity was to clean ultrasonically the structure in a high-purity methanol bath. A high-temperature anneal of this cavity was not performed prior to the first RF-test. However improvements due to annealing will be investigated in future experiments. Additional details concerning fabrication and niobium surface preparation of niobium cavities are available elsewhere.⁶

To provide rf power, a hermetically sealed variable coupling probe was installed at a port on the outer cylinder connecting the inner and outer conductors of the resonator. This probe allowed us to critically couple rf power to the cavity while testing at different power levels. An rf pickup probe was installed at the opposing port

(see Figure 2). The cryostat was surrounded by mu-metal to shield the resonator from ambient magnetic fields. A phase-locked loop was used to counter the effects of eigenfrequency noise due to ambient vibrations and microphonics.

Several multipacting levels which appeared at low power levels processed out almost immediately. X-ray radiation was monitored with a NaI(Tl) detector located external to the cryostat. Electron loading in the form of field emission was present, and x-rays were therefore generated. By measuring the bremsstrahlung from the most energetic electrons, the average accelerating gradient was calculated.

During the first series of tests, cw accelerating fields of 11 MV/m were obtained with very little Q degradation due to field emission. The resonator will be further tested after additional chemical and heat processing of the surface. A photo of this resonator just prior to final welding of the end plates appears in Figure 2. As part of the design process, the 3D cavity code MAFIA⁸ was used to calculate the fields in this cavity and thereby specify its dimensions.

3. CURRENT LIMITS IN SUPERCONDUCTING RFQs

This initial superconducting RFQ device has operated at fields a factor of three higher than have been reported for cw operation of normally-conducting RFQ devices.^{9,10} The present results suggest that RFSC may appreciably extend the range of options for RFQ design.¹¹ For example, the use of RFQ vanes with deep modulations to provide simultaneous acceleration and strong focusing may enable very high real-estate gradients (tens of MV/m) to be achieved. If so, correspondingly compact linacs could be developed for the acceleration of high-current beams provided beam impingement can be held to a manageable level.

The experimental data taken with the RFQ geometry mentioned earlier suggest that RFSC may appreciably extend the range of options for an RFQ design. In particular, it may be possible to achieve cw beam currents in a SCRfQ which are unattainable with normal-conducting structures due to sparking limits and/or power dissipation in the walls of the structure.

We have initiated analytical and simulation studies to calculate current limits for SCRfQs which differ from the conventional RFQs in two main respects: very high cw electric fields can be sustained on the superconducting surface, and the tolerance to beam impingement is unknown but probably less than for normal-conducting RFQs (NCRFQ).

The overall current limit is taken to be the value at which the transverse and longitudinal limits are equal. The upper bound $I_{\max}$ is defined as the current of a uniformly charged ellipsoid at which the maximum extent of the beam envelope is equal to the minimum aperture inside the RFQ.¹² The actual current limit $I_{\lim}$ in an SCRfQ is reached when only a small fraction of the particles hit the vanes, thereby constituting a thermal load. It is characterized by a "halo impact parameter" ρ : $I_{\lim} = \rho I_{\max}$. We estimate a lower bound on the current limit by computing ρ for a Gaussian distribution, generally regarded as the worst-case scenario for a current density inside linacs, under different assumptions for the beam-spill tolerance.

Preliminary estimates suggest that $I_{\max}$ for SCRfQs is at least a factor of five larger than for NCRFQs. Our pessimistic estimate gives $\rho \approx 1/3$, indicating a current limit in SCRfQs which is about twice that in NCRFQs. Further work is in progress, and is focused on refining this estimate via the computation of beam halo by analytic modelling and N-body calculations.

4. SUPERCONDUCTING SECTION DEVELOPMENT

The preliminary design of a section consisting of five niobium spoke resonators interspersed with superconducting quadrupole focusing elements has been formulated. A conceptual drawing of the section appears in Figure 3. Once constructed, the section will be installed at the exit aperture of CWDD, a 352 MHz cryo-copper

Figure 3. Conceptual drawing of a high-current superconducting test section designed for a 7.5 MeV deuterium beam. It comprises 5 accelerating cavities operating at 352 MHz; focusing is provided by superconducting quadrupoles located between the cavities.

accelerator which is projected to provide a deuterium beam of energy 7.5 MeV and current up to 80 mA. The section will be used principally for experiments concerning beam dynamics in superconducting high-current ion linacs as well as for the development of diagnostic tools and beam-control systems for use with these linacs. Issues associated with focusing and beam loading/control will be explored. Experiments are projected to include measurements of: beam impingement and beam breakup, stability with respect to beam modulation in both amplitude and phase, the influence of gas condensation on long-term operation, effects of failure of individual linac elements on the beam dynamics, and assorted beam-physics experiments which take advantage of the independent operation of the linac components.

The cavities are designed to operate at 352 MHz and assumed to provide average accelerating gradients of 10 MV/m, an assumption which is based on the existing experimental data.^{6,7} Both 2-gap and 3-gap spoke resonators are currently being considered. The spoke-resonator geometry is favored over the coaxial half-wave geometry due to its relative ease of fabrication. The cavities will be cooled either by immersing them in liquid helium, or by surrounding them with jackets filled with liquid helium. The former approach has the advantage of simplicity but the disadvantage of requiring many hermetic seals. The latter approach (depicted in Figure 3) has the advantage of avoiding the need for hermetic seals but the disadvantage of a more complicated cavity design. Superconducting quadrupole magnets were chosen over solenoids as focusing elements because, at higher beam energy, they would provide a more compact design which, in turn, would result in higher real-estate gradients for the linac.

Insofar as possible, the section is being designed to provide current-independent performance while preserving emittance. Preliminary beamlines were generated using the TRACE3D code, modified to model independently phased multigap cavities. The TRACE3D results were then substantiated with N-body simulations using a modified version of PARMILA. The 3-gap structures would provide a real-estate gradient of order 25% larger than the 2-gap structures; however, 3-gap spoke resonators have not yet been fabricated.

5. SUMMARY AND FUTURE WORK

Figure 4. Conceptual design of a 3-gap spoke resonator.

Recent developments in rf superconductivity continue to be very promising. The high gradients achieved with coaxial resonators have been extended to a new geometry at higher frequency fabricated for high-brightness ion acceleration. Earlier work on RFQ geometries indicated that RFSC technology may provide an extended range of options for RFQ design, including the possibility of developing RFQs for the acceleration of high currents at high real-estate gradients. Analytical studies have shown that current limits for superconducting RFQs should be at least a factor of two higher than normal conducting devices. The design of superconducting RFQs has been initiated, and we plan to begin shortly the construction of superconducting RFQs for tests with beam.

In addition to the construction and testing of a superconducting section, future work will include the development of superconducting cavities for high-brightness ion linacs operating at higher frequencies. Work in progress includes the fabrication of a 3-gap, 850 MHz, $\beta_0=0.28$, spoke resonator like that shown in Figure 4.

The design of superconducting RFQs has been initiated, and construction of superconducting RFQs for tests both without and with beam is slated to begin shortly. Plans include tests of a superconducting cavity using the high-current beam from Chalk River Nuclear Laboratory's RFQ-1250, and tests of superconducting RFQs using the high-current beam from Culham Laboratory's Ion Source Test Stand.

6. ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy and supported by the U.S. Army Strategic Defense Command and the Office of Naval Research. We are grateful to C. Batson for his assistance in all phases of the experiments discussed herein.

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