RECENT DEVELOPMENTS IN HIGH-CURRENT SUPERCONDUCTING ION LINACS

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Abstract

Recent experimental and analytical results in the areas of resonator geometry and beam physics are very encouraging for superconducting high-current ion accelerators. Based on these results, a short accelerating section of niobium resonators and focusing elements is under development. It will be tested with high-current beam in order to study focusing and beam loading/control. In addition, new resonator geometries are under construction for use at frequencies and velocities which are higher than those spanned by currently available superconducting resonators for ions.

I. INTRODUCTION

The technology of radio-frequency superconductivity (RFSC) offers 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 resonators. Another key advantage is that superconducting low-velocity linacs are comprised of relatively short, independently phased accelerating cavities. If a resonator is off-line, the linac can still be operated with full performance by increasing and rephasing the fields in the remaining cavities. Recent efforts in the development of RFSC components at our laboratory have focused on extending the existing technology base for low-brightness, low-frequency ion accelerators into that required for high-brightness, high-frequency linacs.

II. NIOBIUM RESONATOR DEVELOPMENT

A. Accelerating Cavities

1. Coaxial quarter-wave geometry

The first superconducting accelerating cavity to be fabricated as part of our development effort was a 400 MHz coaxial quarter-wave structure. It consisted of an inner conductor fabricated from sheet niobium and an outer conductor fabricated from sheet niobium explosively bonded to copper.

The cavity achieved an average (wall-to-wall) accelerating gradient of 12.9 MV/m under continuous-wave fields.[2] This cavity can accelerate ions of energy in the range 4-40 MeV/amu. The properties of the resonator are summarized in Table 1.

As shown in Figure 1, Q varied from $4.1\text{x}10^8$ at low rf field amplitude to $1.4\text{x}10^8$ at the highest field achieved. The gradient of 12.9 MV/m was achieved with 21 W of rf power input to the cavity.

Table 1. Properties of the coaxial quarter-wave resonator.

Frequency	400 MHz
β_o	0.15
Energy gain[a)]	63.5 kV
Peak surface E field[a),b)]	3.2 MV/m
Peak surface B field[a),b)]	58 G
Energy content[a)]	9.6 mJ
Geometrical factor QR_s	38.3 Ω

[a)]at an accelerating field of 1 MV/m.
[b)]calculated from Ref. 3.

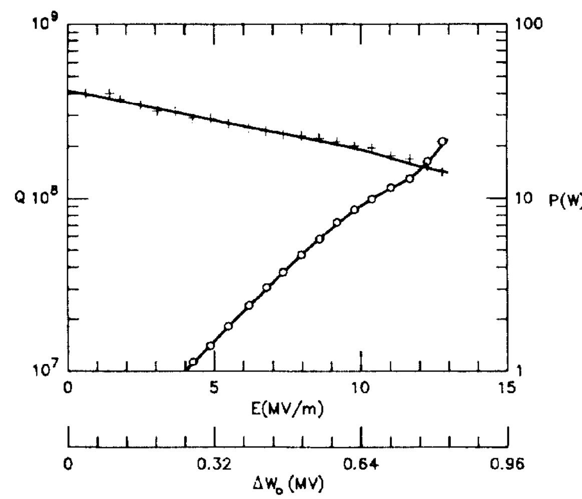

Figure 1. Q-curve (+) and power dissipation (o) for the 400 MHz quarter wave resonator.

2. Coaxial half-wave geometry

A 355 MHz coaxial half-wave structure was subsequently fabricated entirely from sheet niobium. It achieved an average (wall-to-wall) accelerating gradient of 18.0 MV/m under continouous-wave fields.[4] The properties of the resonator are summarized in Table 2. An average cw accelerating gradient of 18.0 MV/m was achieved with 40 W of rf power input to the cavity, while 10MV/m was achieved with 2.2W. As shown in Figure 2, Q varied from $7.7\text{x}10^8$ at low rf field amplitude to $1.2\text{x}10^8$ at the highest field achieved. This would provide an energy gain of 1.26 MV per unit charge.

Table 2. Properties of the coaxial half-wave resonator.

Frequency	355 MHz
β_o	0.12
Energy gain[a)]	70.0 kV
Peak surface E field[a),b)]	3.2 MV/m
Peak surface B field[a),b)]	52 G
Energy content[a)]	12 mJ
Geometrical factor QR_s	53.3 Ω

[a)]at an accelerating gradient of 1 MV/m.
[b)]calculated from Ref. 3.

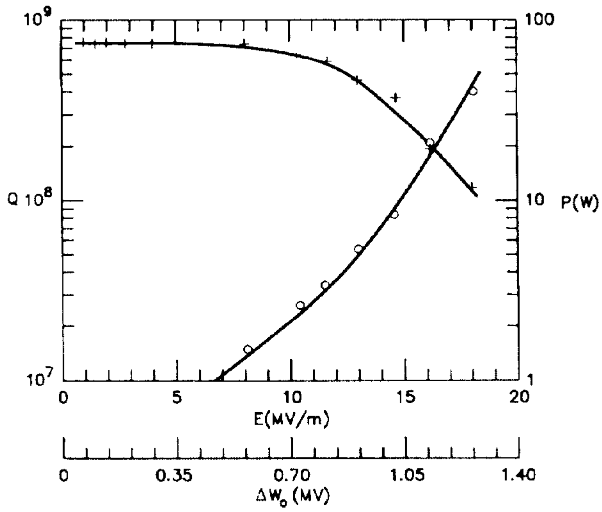

Figure 2. Q-curve (+) and power dissipation (o) for the 355 MHz coaxial-half-wave resonator.

3. Spoke resonator

The spoke-resonator geometry shown in Fig. 3 is being investigated for use at frequencies which are higher than can be achieved with practical resonator designs incorporating coaxial geometries. A 2-gap, 850 MHz, $\beta_0 = 0.28$ spoke resonator is in final assembly at this writing and will soon be tested. As part of the design process, the 3D cavity code MAFIA[5] was used to calculate the fields in this cavity and thereby establish its dimensions. The geometry can be straightforwardly extended to multigap designs which should provide larger real-estate gradients than would be achievable with 2-gap structures.[6]

B. Superconducting RF Quadrupoles

Recent experimental data[7] suggest that RFSC may appreciably extend the range of options for an RFQ design. In particular, one may be able to achieve cw beam currents in a superconducting RFQ (SCRFQ) unattainable with normal conducting structures due to sparking limits and power consumption considerations.[8]

We have initiated analytical and simulation studies to calculate current limits for SCRFQs which differ from the conventional RFQs in two main aspects: 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.

We take the overall current limit to be the value at which the

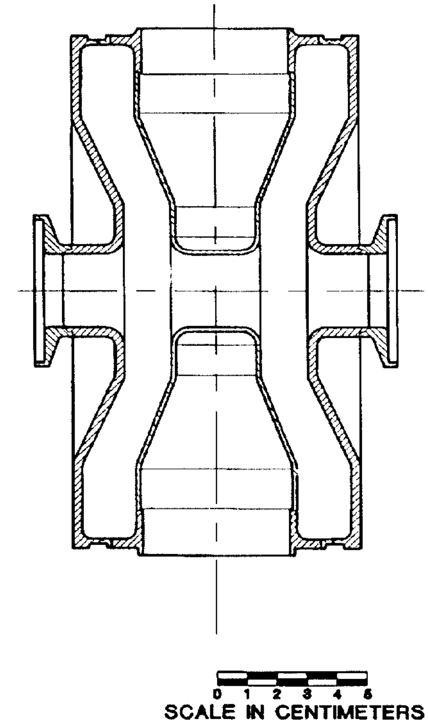

Figure 3. 850 Mhz, β=0.28, 2-gap spoke resonator.

transverse and longitudinal limits are equal. First, we calculate the upper bound I^0_{lim} 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. The real current limit I_{lim} corresponds to only a small fraction of the particles hitting the vanes; it is characterized by a halo impact parameter ρ : $I_{lim} = \rho\, I^0_{lim}$. Next, we estimate the lower bound on the current limit by computing ρ for a Gaussian distribution, generally regarded as the worst case scenario for a particle density inside linacs, under different assumptions for the beam spill tolerance.

Preliminary estimates suggest that I^0_{lim} of SCRFQs is at least a factor of five higher than that of normal conducting RFQs, while our pessimistic estimate gives $\rho \approx 1/3$. Further work, principally concentrated on approaches to compute beam halo by analytic modelling and N-body calculations, is in progress. The results will be published elsewhere.

III. Cumulative Beam Breakup

Beam instabilities must be considered in the design of accelerators for high-current beams. In superconducting linacs for ion beams, the constituent cavities are short and independently phased, and cumulative beam breakup is therefore expected to be the dominant transverse instability. Moreover, superconducting linacs run cw, and the steady-state properties of their beams are therefore of primary interest.

An analytic model of cumulative beam breakup has been developed which is applicable to both low-velocity ion and high-energy electron linacs.[9-11] We used this model to investigate cumulative beam breakup in two superconducting linacs comprised of 352 MHz coaxial half-wave resonators supplying a 4.5 MV/m real-estate gradient.[12] The first is the five-cavity section described below which is being designed for testing with a deuterium beam of energy 7.5 MeV and current 80 mA. It was modelled pessimistically using a tightly bunched, unfocused coasting beam which was misaligned at the entrance aperture of the accelerator. Under conditions of a worst-case beam-cavity resonance, a maximum Q of 2×10^7 for the deflecting mode assured steady-state growth no larger than approximately twice the initial beam offset. The second is a 100 mA linac for the acceleration of protons from 5 MeV to 200 MeV. It was modelled using a nonrelativistic, tightly bunched beam which was misaligned at the entrance aperture of the accelerator. 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 a maximum Q of 5.5×10^6 for the deflecting mode assured 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 considerably less than this. The rf coupling would therefore probably also provide an external $Q < 10^6$ for the deflecting mode and thereby control beam breakup.

IV. Superconducting Section Development

A section consisting of five niobium resonators interspersed with focusing elements is currently being designed for beam tests at the exit aperture of the Continuous Wave Deuterium Demonstrator (CWDD). CWDD, a 352 MHz cryogenically cooled copper accelerator, is currently under construction. It is projected to provide a deuteron beam of energy 7.5 MeV and current 80 mA, which would be the first beam available for high-current beam tests of our superconducting cavities.

Insofar as possible, the section is being designed to provide current-independent performance while preserving emittance. Focusing will be provided by superconducting magnetic elements located between the cavities.

Preliminary beamlines have been generated using the TRACE 3D code, modified to model independently-phased multigap cavities, assuming the cavities operate at 352 MHz and provide average accelerating gradients of 10 MV/m, which is a reasonable assumption in view of the data presented above. Both 2-gap coaxial half-wave resonators and 3-gap spoke resonators are being considered. The 3-gap structures would provide a real-estate gradient of order 25% larger than that of the 2-gap structures; however, 3-gap spoke resonators have not yet been fabricated. These preliminary results are currently being refined with N-body simulations using a modified version of PARMILA.

Once constructed, 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.[12]

V. Summary and Future Work

Recent developments in rf superconductivity have been very promising. Niobium resonators fabricated for high-brightness ion acceleration have yielded cw average accelerating gradients as high as 18 MV/m. In a superconducting RFQ geometry, high cw surface electric fields were sustained over surface areas of order 10 cm^2.[7] Analyses of cumulative beam breakup in superconducting linacs comprised of decoupled, independently phased cavities were likewise encouraging.

In addition to the construction and testing of a superconducting section, future work will include the development of superconducting cavities operating at higher frequencies and velocities. Fabrication of a 2-gap, 850 MHz, $\beta_0=0.28$ spoke resonator is nearly complete. We plan also to build multi-gap spoke resonators.

The design of superconducting RFQs has been initiated, and construction of superconducting RFQs for tests with beam is slated to begin shortly. Plans include beam tests of superconducting RFQs on Culham's Ion Source Test Stand.

VI. Acknowledgements

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