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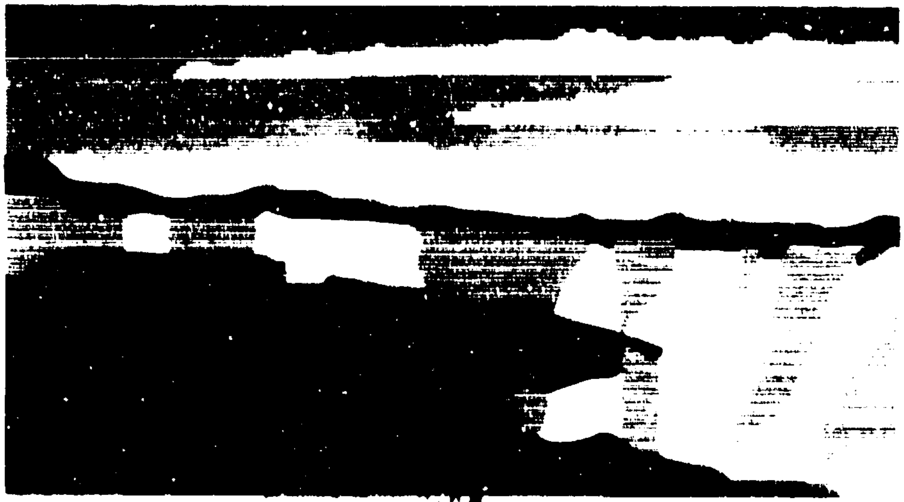

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SUPERCONDUCTING RFQ DEVELOPMENT AT LOS ALAMOS*

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Abstract

We are investigating the performance capabilities of a niobium, superconducting, radiofrequency-quadrupole (RFQ) accelerator for high-field continuous-wave operation, to provide greater acceleration and stronger focusing of low-velocity ion beams. We present the results of our RFQ beam-dynamics studies, which test new design methods for increasing the beam transmission, our cavity-design calculations, and some mechanical-design aspects of a short, superconducting RFQ 4-vane prototype structure that will be tested at high fields during the coming year.

Introduction

The Radiofrequency Quadrupole (RFQ)[1] is used for the acceleration of low-velocity ions. Its capacity for acceleration of high beam currents depends on the strength of the rf electric fields that are used for focusing. High electric fields also increase the energy gain within a given length, producing more compact RFQs. In a recent experiment[2], CW peak surface electric fields of 128 MV/m, limited by field emission, were measured in a niobium superconducting split-ring cavity, whose drift tubes were modified by welding four 7-cm niobium fingers to obtain an rf quadrupole geometry in the gap. This field is greater by at least a factor of 3 than is used for the design of copper RFQ cavities. It is of great interest to determine what electric field can be achieved in superconducting versions of the conventional 4-vane or 4-rod RFQ structures, especially with longer vanes, and to evaluate these structures for superconducting applications[3][4]. Superconducting RFQ development would benefit those stand-alone RFQ applications, where the RFQ is the main accelerator. Successful development of a high-field superconducting RFQ would result in a significant advance in RFQ technology, towards higher beam intensities in more power efficient and compact structures.

Recently, work has been carried out to evaluate the 4-rod RFQ cavity for acceleration of heavy ions[5][6]. The concept of an RFQ accelerator system composed of an array of short RFQlets was proposed, and a 0.5m long lead (plated on copper) superconducting prototype cavity operating at 50 MHz, was built and successfully tested. If the superconducting RFQ is to be useful for high-current applications, we believe it is desirable to develop it as a single structure, whose length might be in the range of about one to three meters. With a single structure, one avoids the problem of matching of the high-current beam between RFQ cavities. Whether such a long RFQ is compatible with the practical constraints imposed by the rf superconducting technology must be determined. Furthermore, high-current applications require that the betatron phase advance per focusing period for zero current must be less than 90° to avoid the beam-envelope instability. At low frequencies this beam-dynamics constraint generally limits the electric fields that can be used. This is because the focusing period, which is proportional to the wavelength, is larger at lower frequency. Then, for a given betatron phase advance per unit length, the larger focusing period corresponds to a larger phase advance per focusing period. For proton applications, frequencies larger than about 200 MHz, depending on injection energy, are required for high-field operation. At these frequencies the 4-vane RFQ structure has been most attractive, and therefore our initial work has been directed towards the 4-vane structure. Our work consists of two parts: 1) beam-dynamics design studies to evaluate the performance that might be expected for a high-field proton RFQ, and 2) cavity calculations and mechanical-design studies for a high-field 4-vane RFQ cavity.

Beam Dynamics Design Studies

We have carried out an RFQ beam-dynamics design study for high-field, high-current proton RFQ linacs. The objectives of the study were to 1) develop design procedures to a) reduce particle losses in the RFQ, and b) produce more compact RFQs, 2) determine the length and power requirements, 3) determine beam quality, and 4) evaluate performance characteristics as a function of frequency.

The study was conducted using the RFQ beam dynamics code PARMTEQ[7], which generates the cell geometry and does numerical simulation of the beam through the RFQ, including the space-charge forces. The d.c. input beams were assumed to be perfectly matched and aligned. Except for two new features, standard Los Alamos RFQ design procedures[8] were used to synthesize an RFQ that consisted of four sections, 1) radial matcher, 2) shaper for initial bunching, 3) gentle buncher for adiabatic bunching and 4) accelerator. The first new feature is to modify the shaper section to include an initial subsection, where the synchronous phase is held constant at $\Phi = -90°$ to provide better longitudinal bunching. This subsection is called the porch, and its purpose is to reduce the particle losses, which typically range from a few to 10% in conventional RFQ designs. The second new feature is to ramp the intervane voltage in the accelerator section to shorten the RFQ or to provide higher final energy in the same length.

The fixed parameters of the study are listed in Table 1. The variable parameters include the rf frequency f, the vane modulation parameter at the end of the gentle-buncher section, m_g, the aperture parameter $\alpha = 2\pi a_g / \beta\lambda$, where a_g is the radial aperture at the end of the gentle buncher section, and βc is the injection velocity, and the porch parameter $\Lambda = Z_p/Z_s$, where Z_p defines the length of the porch subsection, and Z_s the length of the shaper section. The number of particles chosen for the runs varied from several thousand to 10000, and was chosen to produce statistically reliable results for emittances and particle losses. General

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*Work supported by Los Alamos National Laboratory Institutional supporting research under the auspices of the United States Department of Energy the longitudinal emittance, and the power dissipation from lost particles had the largest statistical uncertainty. Values of m_g were varied over a range defined by the beam-current limit $I_{lim} \geq 125$mA, corresponding to a 50 mA operating current. The aperture parameter should be large to maximize transmission, but it's value is limited by the effects of higher multipoles. We have used $\alpha = 1.5$ and 2.0. Table 2 shows some results at 350 MHz for $E_S = 40$ and 80 MV/m, without a voltage ramp in the accelerator section. Without the porch, the beam transmissions range from 97 to 99%. These are already high because of the large aperture. One can see that the porch subsection provides transmissions exceeding 99%. The higher peak field of 80 MV/m produces a significant reduction in vane length by about a factor of 3. The power values listed in Table 2 are P_l, beam-power loss on the vanes, P_O, ohmic rf power loss, and P_{Nb}, total power loss in Niobium which determines the total helium-cooling requirement. At $\alpha = 1.5$, the power losses are mostly from radial beam losses, whereas for $\alpha = 2.0$, the beam losses are comparable to the rf ohmic losses.

TABLE 1
Fixed Parameters of Beam Dynamics Study

Symbol	Description	Value
mc^2	Mass	938.2796 MeV
W_i	Initial Kinetic Energy	0.050 MeV
W_f	Final Kinetic Energy	2.5 MeV
I	Beam Current	50mA
I_{lim}	Minimum Beam Current Limit	125mA
ε_i	Initial normalized rms emittance	0.0075 πcm.mrad
φ_g	Synchronous phase at end of gentle buncher section	-35°
φ_f	Synchronous phase at end of RFQ	-35°
Θ	Nominal temperature of rf cavity	4.2°K
$R_{RES.}$	Residual rf surface resistance	$100 \times 10^{-9} \Omega$

TABLE 2
Some Results at 350MHz

E_S(MV/m)	40		80	
α	1.5	2.0	1.5	2.0
V(kv)	83	97	185	210
a_g(cm)	0.21	0.28	0.21	0.28
m_g	1.878	1.625	2.325	1.939
Λ	0.6	0.6	0.6	0.6
L(m)	2.73	3.74	1.01	1.10
T(%)	99.5	99.6	99.0	99.8
ε_t(cm.mrad)	0.010	0.011	0.014	0.016
ε_l(deg.MeV)	0.523	0.475	0.46	0.18
P_l(W)	52	15	263	10
P_O(W)	9	12	16	21
P_{Nb}(W)	61	27	279	31

Next we modify the standard RFQ design procedure in the accelerator section by increasing the intervane voltage and the radial aperture a proportional to ß, and keeping m constant. This would be accomplished by designing the cavity cross section or by adjustment of tuners so the local resonant frequency decreases along the structure. It results in an approximately constant axial acceleration field E_O, rather than an E_O dependence proportional to $ß^{-1}$ as is obtained with constant vane voltage. The penalty for this modification will be a decreasing quadrupole gradient and an increased rf power dissipation, which for superconducting applications may be acceptable. We have tested this procedure for the 350 MHz RFQ designs with $\Lambda = 0.6$ and for a final energy of 3.7 MeV rather than 2.5 MeV. In Table 3, we show two lengths L_f and L_r, and ohmic power losses P_f and P_r, where the subscripts f and r refer to flat and ramped voltage distributions. The results show that a large reduction in length can be obtained with corresponding, but acceptable, increases in rf power.

At 200 MHz acceptable solutions were obtained at 40 MV/m but at 60 MV/m and above, the transverse focusing was too strong and the envelope instability led to poor transmission. Therefore, one cannot take advantage of very high fields for high-current applications at frequencies less than or equal to about 200 MHz for protons, unless larger apertures can be used to reduce the quadrupole gradient or the injection energy is increased. At 500 MHz fields of about 60 MHz and above are needed to obtain the required current limit.

TABLE 3
3.7 MeV Results at 350 MHz with Ramped Voltage

E_S(MV/m)	L_f(m)	L_r(m)	P_f(w)	P_r(w)
40	4.48	3.05	18	40
50	3.23	2.21	22	50
60	2.46	1.67	25	56

Superconducting 4-vane Cavity Work

To evaluate the high-field performance characteristics of a superconducting RFQ, we are designing and building a niobium 4-vane cavity (Fig. 1). This cavity will be tested in a liquid-helium cooled cryostat in the rf superconducting laboratory at Los Alamos. The objectives of this work are to 1) learn how to fabricate the niobium 4-vane cavity, especially with regard to the electron-beam welding techniques, 2) determine the surface electric field that can be achieved, and 3) evaluate possible operational problems such as multipacting that could limit the performance.The operating temperature will be 1.7° K, chosen for superfluid liquid-helium cooling. The nominal frequency is 425 MHz, but the only real constraint on frequency is that the cavity frequency must remain within the rated bandwidth of our power amplifier, which extends from 395 to 440 MHz.

The performance of the cavity as predicted by SUPERFISH and MAFIA is given in Table 4, together with some of the geometry parameters. The field and voltage values in Table 4 are scaled to give $E_S = 1$MV/m, where E_S is the maximum peak surface electric field between vanes at the RFQ midplane. The ratio B_S (vane end)/E_S is a factor

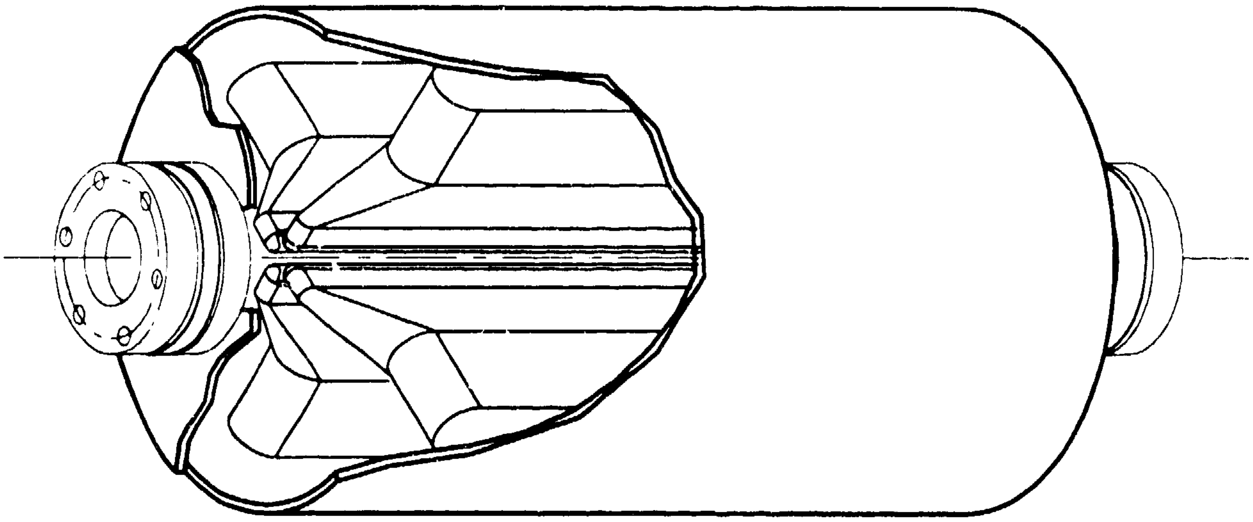

Fig. 1 The superconducting niobium 4-vane cavity.

of 1.5 to 2 smaller than that of typical elliptical cavities used for acceleration of high-β particles.

TABLE 4
Calculated Performance Parameters of Prototype RFQ Cavity at 1.7°K

a	0.437 cm
l_{vane}	30 cm
l_{cavity}	31.5 cm
QR_s	48Ω
B_s (midplane)	3.8 Gauss
B_s (vane end)	11 Gauss
W	0.27×10^{-3} J

At the operating temperature of T=1.7°K, we anticipate that the rf surface resistance will be dominated by the residual resistance, which is expected to lie within a range of about $R_s = 10 \times 10^{-9}$ to 100×100^{-9} Ω. This will correspond to an unloaded Q in the range of $Q = 4.8 \times 10^{8}$ to 4.8×10^{9}.

Summary

Superconducting RFQ applications can benefit from two modifications to the standard RFQ design procedure. First, in addition to choosing as large an aperture as possible, the use of a perch for the initial synchronous-phase profile can improve the transmission efficiency to over 99%, reducing heating caused by beam losses to low values. Second, the use of a ramped vane-voltage profile in the accelerator section increases the axial accelerating field and shortens the RFQ or allows the final energy of an RFQ of a given length to be extended to higher values. For applications with low beam currents, the long adiabatic bunching section could be replaced by a separate conventional buncher cavity. Then the RFQ could consist of an accelerator section alone with a ramped voltage profile. In a few meters a proton RFQ with a peak surface electric field E_s = 40MV/m could provide acceleration to final energies of more than 10 MeV.

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