DESIGN AND APPLICATION POSSIBILITIES OF SUPERCONDUCTING RADIO-FREQUENCY QUADRUPOLES

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Abstract

In recent experiments,[1] cw surface electric fields in excess of 100 MV/m have been obtained in a superconducting rf quadrupole (SCRFQ) device. In this paper we explore some design and application possibilities of SCRFQs which have been opened by these results. For example, SCRFQs may be able to accelerate higher cw currents than is now possible. Also, highly-modulated SCRFQs could be designed to provide compact, high-longitudinal-gradient devices. Some conceptual designs and applications will be discussed.

Introduction

The radio-frequency quadrupole (RFQ) accelerator structure which is based on the concept of spatially homogeneous focusing[2,3] is applied in many low energy ion accelerators. It provides strong focusing and acceleration of ion beams which makes it especially attractive for the production of high-current high-brightness beams.

RFQ injectors have facilitated the introduction of new high-current ion sources, as well as electron cyclotron resonance (ECR) sources and electron beam ion sources (EBIS), for highly charged heavy ions.

Operational simplicity makes RFQ structures attractive for applications previously using electrostatic machines, e.g., neutron production and ion implanters. The main field of application, however, is high current ion accelerators in which a significant improvement in brightness has been achieved with specially designed RFQs.[3,4]

The maximum ion current that can be transported through an RFQ structure is roughly proportional to the voltage U between the RFQ electrodes. In normally-conducting RFQ structures, rf power requirements lead to pulsed operation with moderate voltages and small aperture. This approach is well suited for high current synchrotron injectors and combinations with an ECR or EBIS ion source.

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Since the first proposal of the RFQ principle, attempts have been made to build a cw RFQ with high beam power. Cw RFQ accelerators have been constructed and operated at Los Alamos and Chalk River.[5] Proposals for SCRFQs have also been made in the past.[6,7]

Very high field strengths in an SCRFQ resonator have been recently obtained by two of the authors[1]. These results indicate that superconducting rf technology may appreciably extend the range of options for RFQ designs.

In the following sections some examples for conceptual SCRFQ designs will be discussed which indicate some of the new possibilities.

Design Considerations

The choice of the focusing and accelerating fields along the RFQ determines the properties of the ion beam. Generally, RFQ design has been studied in great detail to tailor the RFQ for the requirement of the specific application.[3,4]

The basic input parameters: injection energy T_i, structure frequency f, electrode voltage U, and average aperture a_m have to be chosen to match for the source emittance,the required beam emittance and ion current at the RFQ output. Other possible limits such as sparking, power density problems, rf efficiency, and mechanical stability have to be taken into account as well.

In RFQ structures the longitudinal accelerating field is roughly proportional to the frequency and, for a compact RFQs the frequency should be as high as possible. On the other hand, preserving the beam emittance requires "slow" acceleration and a comparatively long structure. This is one of the typical tradeoffs in RFQ design for which beam dynamics, rf, and mechanical design have to be balanced.[4]

A typical result of these design studies is a voltage around 100 kV, a minimum aperture radius of 1.5 to 3 mm for frequencies between 100 and 400 MHz.[8] For the 4-rod RFQ higher voltages and bigger apertures are usually chosen, which leads to shorter structures and eases rf and mechanical tolerances. At the low frequency of 27 MHz, voltages of up to

200 kV for acceleration of low charge state uranium have been proposed.[9]

Irrespective of the application, normally conducting RFQs have been designed to operate at surface fields between 1.5 and 2.5 the Kilpatrick field (E_k).[10] For high duty cycles more conservative values of 1.5 to 1.7 E_k are usually chosen.

In most RFQ designs, a majority of cells (half periods of the electrode modulation which correspond to a drift tube of a $\beta\lambda/2$-type accelerator) is used not for accelerating, but for transporting and bunching the ion beam: for example 200 out of 286 cells for the GSI HLI-RFQ.[11] This will not change much with higher electrode voltages. For the bunching section, higher fields can improve the design only in cases where focusing strength is the limiting factor.

High fields make significant improvements for three different cases of cw accelerators: (1) high currents and light ions (P,D), (2) highly charged heavy ions accelerators (ECR-RFQ combinations) (3) low charge state beams (e.g. radioactive beams, molecular ions, clusters).

Superconductivity brings a different set of constraints into the design process of RFQs. Sparking of the type observed in normal-conducting structures and expressed in terms of the Kilpatrick limit is usually not seen in superconducting structures. What is usually observed is a soft barrier caused by non-resonant electron emission (field emission). The dependence of the field emission limit on various parameters is not well understood, however it seems to be virtually independent of frequency.

Another limit is set by the rf critical field of the superconducting material which, for niobium, is slightly higher than 2000 gauss. Magnetic fields in excess of 1500 gauss have been achieved in actual superconducting structures. RFQs have surface magnetic field to surface electric field ratio which are smaller than usually seen in superconducting structures and, with some attention to the design to avoid current concentration, the surface magnetic field should not be a limiting factor.

For low-frequency, low-current applications, SCRFQ structures will suffer microphonic-induced phase noise similar to that previously experienced in helically-loaded SC structures.[12,13] While this is not expected to be an insuperable problem, structure design must fully consider the mechanical stability required for rf phase control.

Examples

Superconductivity is a natural solution to the problem of cw operation of accelerators. Prospects for this application are enhanced by results of the first test of a short SCRFQ structure, in which high surface electric fields (130 MV/m) and high inter-electrode voltages (300 kV) were obtained. Although these experimental results need to be confirmed in longer structures, they are most encouraging and we have developed a set of design examples based on an inter-electrode voltage of 300 kV:

1. Assuming a voltage of 300 kV between the electrodes, a 10 MeV D^+ RFQ operating at 400 MHz with a 100 mA output beam with a normalized emittance of 1 π mm-mrad could be as short as 1.8 m; its length at a frequency of 200 MHz, with even higher current, would still be very attractive (3.5 m). For a

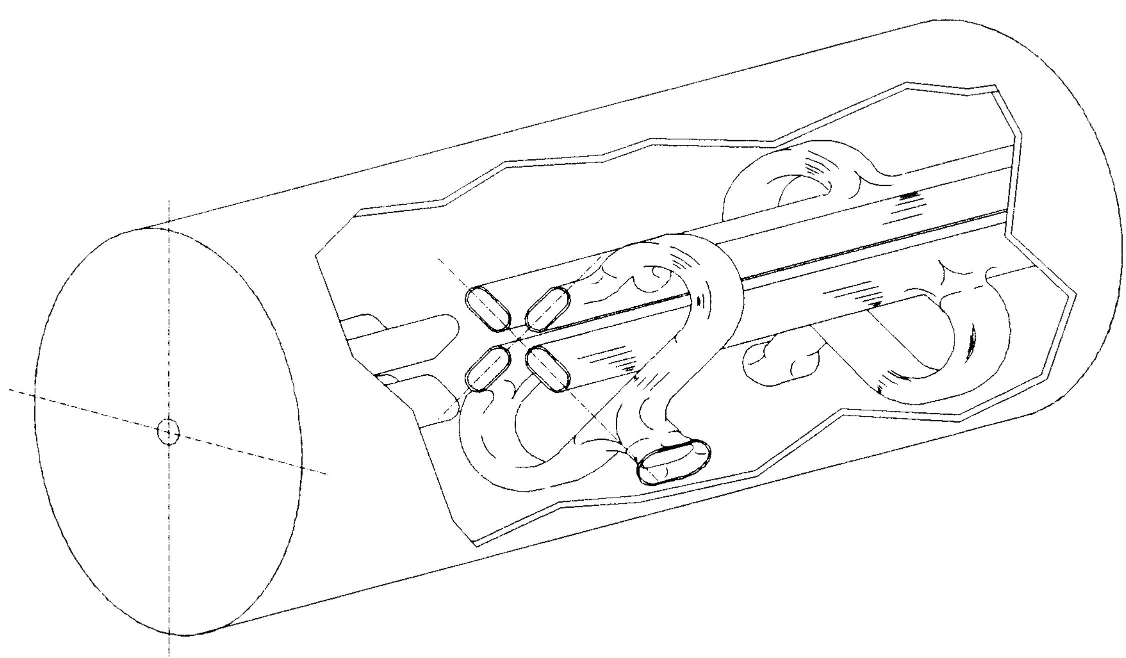

Fig. 1 Conceptual design of a low-frequency SCRFQ accelerator structure.

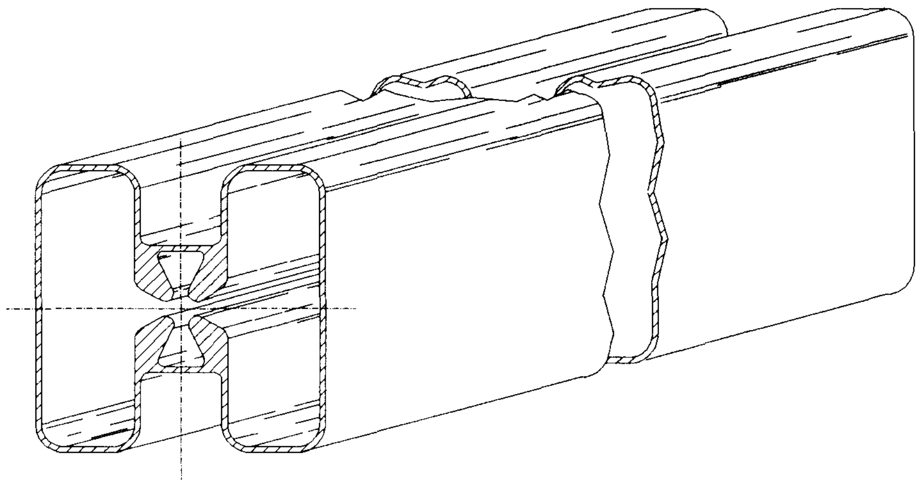

Fig. 2 Conceptual design of a high-frequency SCRFQ accelerator structure.

similar proton accelerator, the length would be 2.5 m at 400 MHz. In these examples, the RFQ has a high average accelerating field even when compared with conventional accelerating cavities. Taking into account that no lenses and cryostats have to interrupt the structure, the accelerating field of 5-8 MV/m in the structure roughly correspond to the actual "real estate gradient". By allowing a slight increase in the transverse emittance and the structure length, the current capability of such an accelerator could be as high as 500 mA.

2. Highly charged heavy ions can efficiently be produced in ECR sources.[14] Extrapolating the source development to a beam of U^{30+} and assuming ATLAS-like harmonic bunching off a 300 kV platform one avoids the need for a relatively long RFQ bunching section. With a 300 kV electrode voltage, a 100 MHz, 1 MeV/u RFQ can be relatively short: L = 2.1 m. The structure length would scale inversely with the charge to mass ratio.

3. An SCRFQ could also be very attractive for radioactive beam acceleration. One of the authors recently designed an RFQ accelerator for $^{27}Al^{1+}$ at ISOLDE.[15] This accelerator will produce 1 MeV/u, and is a machine of size similar to the pre-stripper portion of the UNILAC at GSI. Optimizing an SCRFQ for this application, again assuming 300 kV inter-electrode voltage, results in a surprisingly compact accelerator. For a frequency of 100 MHz the total RFQ length is 6.9 m. Injecting at 100 MHz and doubling the frequency at 0.4 MeV/u would reduce the total length to 5.1 m.

Conceptual designs for SCRFQs operating at low and high frequencies are shown in figures 1 and 2 respectively.

Conclusions

Compact, cw SCRFQ accelerators with high gradients and high currents can be designed for a variety of applications. Further experimental work is needed to determine with better confidence the parameter values which can be used in the design of SCRFQs. In the case of low current applications the beam dynamics design does not require any major change from present designs. For high current applications, development would probably be required to handle the high beam power, e.g. 1 MW in example 1. Beam impingement in an important outstanding issue: solutions for radial matching must be improved, and fuller understanding of halo formation and emittance growth mechanisms is necessary.

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