DEVELOPMENT OF SUPERCONDUCTING RESONATORS FOR THE ARGONNE HEAVY-ION LINAC*

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Abstract

Recent developments include a method for conditioning resonators which has produced a significant increase in accelerating gradient and also a design for a split-ring resonator with an optimum particle velocity of 0.16 c. Results of using a 1500 watt rf source to condition superconducting split-ring resonators are described. By repetitively pulsing for a few msec to field levels as high as an 8 MV/m effective accelerating field E_a, electron loading at high field levels has been substantially reduced. After such conditioning, continuous operation at $E_a > 6$ MV/m, corresponding to a peak surface electric field of 30 MV/m, has been obtained. A split-ring resonator designed for an optimum particle velocity $\beta = v/c = 0.16$ is also described. The 145.5 MHz resonator is contained in the same 16 inch diameter, 14 inch length housing used for the $\beta = 0.1$ Argonne split-ring. In design of the split ring element, a 20% reduction in peak surface electric field has been achieved with no significant increase in surface magnetic field.

Introduction

This paper describes two separate developments of superconducting resonators for the Argonne heavy-ion linac.

The first section describes results obtained with a pulsed-rf conditioning technique which has been applied in off-line tests of two $\beta_o = .06$ split-ring resonators and produced accelerating gradients appreciably higher than have been previously obtained.

The second section describes the geometry and electromagnetic properties of a 145.5 MHz, $\beta_o = .16$ split ring resonator designed to extend the velocity range of the heavy-ion linac, and to be compatible with the existing linac cryogenic, vacuum, and electronic systems.

Off-Line Tests of Low-Beta Resonators

Seven low-beta ($\beta_o = .06$) niobium split ring resonators have been constructed and tested. The 97 MHz resonators are essentially identical in design to the previously described Argonne $\beta_o = 0.1$ split-ring, except that the resonator length is scaled from 14 to 8 inches, with a proportionate decrease in the drift-tube length.[1] The length change reduces the optimum particle velocity for the structure from $\beta = v/c = 0.1$ to $\beta = .06$.

Figure 1 curve A shows performance typical of the first five resonators tested. The accelerating field E_a is defined as the energy gain per unit charge for a synchronous particle, averaged over the interior resonator length of 20.3 cm. Thus for $E_a = 1$ MV/m, a synchronous particle will gain an energy of 0.203 MV per unit charge in traversing the resonator.

The performance shown in curve A is similar to that previously obtained with $\beta_o = 0.1$ split-ring resonators.[2]

For the tests reported here, the resonators were electropolished, assembled, and pumped to a vacuum of typically 5×10^{-7} torr prior to cooldown.

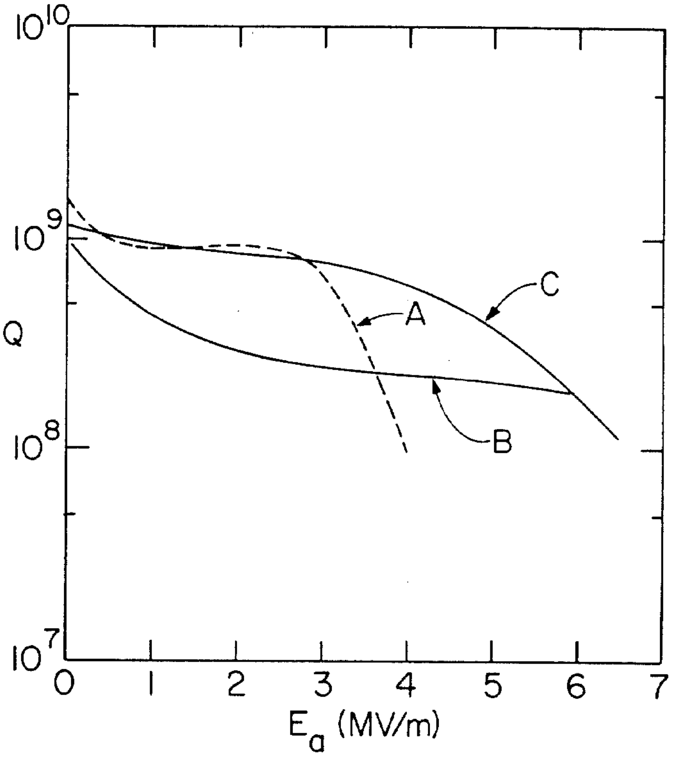

Figure 1. Resonator Q vs effective accelerating field level in initial tests of low-beta split-ring resonators. Curve A is typical of the first five resonators tested. Curves B and C are for the sixth and seventh resonators.

Upon being cooled to 4.2 K the resonators exhibit heavy electron loading due to multipacting which limits field level to $E_a < .01$ MV/m. Operation of the resonator with a few watts of input power, so-called rf conditioning, gradually eliminates multipacting, and over a period of ∿ 1 hr the attainable accelerating field increases to typically $E_a = 2$ MV/m, still limited by electron loading, accompanied now by x-ray emission. The electron loading at this point is characterized by a gradual onset with increasing field level, as opposed to the sudden onset characteristic of low-level multipacting barriers.

Further reduction of electron loading is obtained by conditioning the resonator in a manner distinct from the relatively gentle conditioning process effective for low-level multipacting. The method used is to operate the resonator at as high a field level as possible, in the presence of $\sim 10^{-5}$ torr of He^4 gas,[3] either in a pulsed mode or continuous (CW) mode. In the CW mode the attainable field level is limited by abrupt thermal instability at some rf power input which can vary during the conditioning process over a range of 2 - 20 watts. At the limit of thermal stability, resonator breakdown occurs by growth of a normal region on a resonator interior surface, driven by absorption of rf power. This process is characterized by a relaxation time of several milliseconds, and during this period of time, sufficient rf input power can briefly produce accelerating fields greater than the limit of thermal stability.

An effective method of conditioning a resonator is to operate in a pulsed mode, with a low duty factor (1-2%) at as high a field level as possible. The

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performance shown in Fig. 1, curve A was obtained after typically one hour of such conditioning, using a 400 watt rf source which would pulse the resonators to field levels E_a = 6-6.5 MV/m.

In tests of the two most recently completed low-beta resonators, a 1500 watt rf source was available for the conditioning process, and the resonators could be pulsed to levels E_a = 7-8 MV/m. Following such conditioning, the two resonators performed as shown in curves B and C of Fig. 1. The curves shown extend to the limit of thermal stability at 4.2 K. The accelerating gradients achieved (E_a = 5.74, 6.18 MV/m) are $\sim$ 20% greater than previously obtained at this laboratory.

Split Ring Resonators with β_o = .16

Design Objective and Constraints

The Argonne heavy ion linac is an array of two types of split-ring resonators which accelerate most efficiently for a particle velocity $\beta_o = v/c = .06$ for the low-beta design and $\beta_o = .1$ for the high-beta. Each type accelerates with greater than 80% of the optimum efficiency for a range of velocities $.76\ \beta_o < \beta < 1.42\ \beta_o$.

Because of the finite velocity range, to extend the linac by adding resonators of the $\beta_o = 0.1$ type would give less than optimum performance, particularly for the lighter ions. Thus a study was undertaken to determine the feasibility of constructing a superconducting resonator to be compatible with all existing linac systems and with an optimum particle velocity $\beta_o > .14$. A major design constraint is to maintain the resonator diameter at 16 inches to fit the existing cryostat design.

Analytic Method and Designs Considered

Resonators of the split-ring and spiral type were considered. Both types consist of an outer cylindrical housing, coaxial with the beam axis, which contains a loading structure. The loading structure is formed of drift tubes coupled through an inductive loading arm either to another drift tube or to the housing (Fig. 2). For a given resonator geometry, the electrodynamic properties can be calculated from a model which considers the drift tube as a capacitive element terminating a transmission line formed by the loading arm.[4] The drift tube capacitance and line parameters can be calculated numerically from the geometry in a near-field static approximation. This approximation is valid since the resonators considered are heavily-loaded low-beta structures, thus the free-space wavelength for the accelerating eigenmode is considerably longer than any resonator dimension. The numerical calculations are greatly simplified by the quasi-cylindrical symmetry of the resonator elements. Tests of a number of split-ring geometries have shown this analytic method to estimate surface fields and eigenfrequency to within 5-10% of measured values and the rf energy content to within 10-20%.[4]

Three different types of resonators were considered. For each type, the design method was to incrementally vary the size and shape of the drift tubes and loading arm, and, with the constraints of fixed housing and eigenfrequency, to use the above model to calculate the properties of each different geometry. Although this method does not precisely define an optimum geometry, in practice thirty or forty trials seemed to achieve a good balance of the critical parameters, primarily the peak surface electric and magnetic field. A novel design feature was to allow the loading arm to assume an elliptical cross-section rather than being restricted to a circular form.

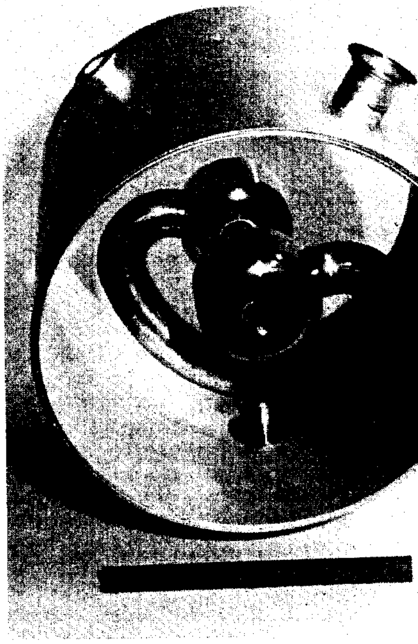

Figure 2. Copper model of the β_o = .16, 145.5 MHz split-ring resonator. The resonator diameter is 16 inches.

The three resonator types considered were a 97 MHz spirial resonator, and 97 MHz and 145.5 MHz split-ring resonators. The spiral and 145.5 MHz split-ring were constrained to the same housing, 16 inch diameters and 14 inch length, as the existing $\beta_o = .1$ split ring. To fit a 97 MHz split ring resonator within a 16 inch diameter housing was found impractical for $\beta_o > .14$. The resonator length increases with increasing β_o, and the aspect ratio of the drift tubes becomes unfavorable, so that the peak surface fields exceed acceptable limits.

While it proved possible to achieve acceptably low surface fields in the spiral loaded structure, the rf energy content was increased more than four-fold over the $\beta_o = .1$ split-ring. Stabilization of the rf phase of the class of superconducting resonators discussed here requires a fast tuning system to overcome the effects of ambient mechanical vibration on the eigenfrequency.[5] The reactive power input to the fast tuning system is directly proportional to the stored rf energy, and for the spiral resonator considered would exceed the capability of the existing tuning system.

145.5 MHz Split-Ring Resonator

The design of choice is the 145.5 MHz split-ring, for which a full-scale copper model has been constructed, shown in Fig. 2. The resonator end-plates are removed to show the split-ring loading structure. Table I compares the principal features of this resonator with the β_o = .06 and .1 designs. In the design, particular emphasis was placed on minimizing the peak value of the surface electric field, since present resonator performance is limited by electron loading, presumably caused by field-emission.

Table I. Comparison of the principal electrodynamic properties of the proposed $\beta_o = .16$ and the present split-ring resonators.

Optimum Velocity β_o	Resonant Frequency	Peak Surface Fields* Electric	Peak Surface Fields* Magnetic	RF Energy Content*
.066	97 MHz	4.8 MV/m	129 G	.069 J
.106	98	4.7	182	.159
.163	145.5	3.9	145	.168

*At an effective accelerating field E_a = 1 MV/m.

The resonator seems best described in terms of changes from the $\beta_o = .1$ split-ring. The drift-tube diameter has been increased from 10 to 12 cm, allowing an increase in the radius of curvature at the ends of the drift tubes, which decreases the peak surface electric field as shown in Table I. The resonant frequency of the accelerating mode has been increased from 97 to 145.5 MHz primarily by decreasing the length of the loading arm from 50 to 30 cm. The increase in frequency causes a proportionate increase in the rf current in the loading arm for a given accelerating field. To keep the peak surface magnetic field within acceptable limits, the loading arm diameter is increased from 3.2 cm to 5.1 cm.

The increased size of the drift tubes and loading arm within the fixed 16 inch resonator diameter reduces the radial clearance between the various elements and caused objectionably large surface electric fields along the loading arms. This problem is overcome by making the cross-section of the loading arm elliptical with the major axis parallel to the beam-axis. An additional advantage of the elliptical geometry is a 15% reduction in peak surface magnetic field. The ellipse chosen has a major diameter of 5.84 cm and a minor diameter of 4.26 cm.

As is shown in Table I, the electrodynamic properties of the resonator are satisfactory in all respects and performance of a superconducting version is expected to equal or exceed that of the existing niobium split-ring resonators.

Conclusions

Off-line tests of $\beta_o = .06$ split-ring resonators have yielded accelerating gradients substantially higher than had been anticipated for this structure. The extent to which this performance can be realized in long-term on-line operation remains to be seen.

It has been found possible to design a split-ring resonator with excellent electrodynamic properties which can efficiently accelerate particles with velocities as high as $\beta = .23$. Construction of a superconducting niobium resonator of this design is in progress.

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