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A NEW SUPERCONDUCTING HEAVY ION ACCELERATING STRUCTURE USING CHEMICALLY POLISHED LEAD SURFACES*

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Abstract

A new heavy ion accelerating structure has been developed which together with a parallel development in chemical polishing techniques makes possible very high accelerating fields for a wide range of particle velocities using inexpensive and easily handled materials. This "Split Ring" accelerating structure has a peak magnetic field approximately one third that of other inductively loaded accelerating structures (less than 100G at 1MV/m accelerating field) and a peak electric field less than 6 times the effective accelerating field. In addition, a chemical polishing technique appropriate for use on electroplated lead surfaces has been developed which greatly reduces the electric field emission of electrons from the surface. Surface fields greater than 25MV/m have been obtained in superconducting resonators with polished lead surfaces with no detectable loss due to field emission. Using these techniques, we have achieved an accelerating field greater than 4 MV/m in a superconducting structure and have begun long term tests. Preliminary results indicate no surface degradation at high fields (> 3MV/m) for relatively long times (14 hours).

I. Introduction

This paper outlines results of a development project intended to increase the accelerating potential for heavy ions available from superconducting resonant structures. The concept underlying this work has been to treat both the superconducting material characteristics and the configuration of the resonator as experimental parameters which could be varied in order to optimize the performance. By radically varying the resonator form and configuration, we have attempted to separately adjust the surface magnetic and electric fields while maximizing the potential gradient along the beam axis. In this way, a balance between electric and magnetic breakdown has been achieved in a structure that establishes the accelerating potential with a minimum of displacement current.

From this perspective, a new superconducting heavy ion accelerating structure, called the split ring, has been developed. At low particle velocities the split ring provides a larger accelerating field for given surface electric and magnetic fields than other proposed superconducting structures. When the above balance in surface fields is achieved, field emission potential and critical magnetic field are of equal importance as materials parameters; a decrease in field emission is equivalent to an increase in critical field. With this in mind, improved chemical polishing techniques have been developed for superconducting Pb which yield field emission potentials above 25 MV/m. A prototype superconducting split ring resonator, fabricated from chemically polished Pb electroplated onto copper, has been operated at accelerating gradients above 4.5 MV/m, and run continuously above 3 MV/m for extended periods with no degradation in performance.

In addition to low surface fields, the split ring structure has the following advantages: The mechanical stability of the split ring is much greater than the helix and approaches that of the re-entrant cavity; thus, the problems of phase stabilization[1] are simplified. Also, for a given resonator diameter, the split ring operates at a frequency about three times lower than the re-entrant cavities, which relaxes the requirements for bunching of a particle beam.

These results imply that superconducting split ring resonators can be useful components of a heavy ion accelerator and that simple materials (Pb plated Cu) can be used for this purpose. For example, with presently available superconducting materials 3 meters of split ring resonators injected by an EN tandem machine would increase the useful mass range of the tandem by a factor of three while the energy at low mass would be increased by a factor of two. In what follows, the split ring structure and the results of superconducting tests are discussed in detail.

II. The Split Ring Resonator

Figure 1 shows the prototype superconducting split ring element. The relevant rf eigenmode of the structure consists of equal and opposite charges on the drift tubes, oscillating through the inductive path formed by the circular loop (split ring). To form an isolated resonator, the ring is enclosed in a cylindrical housing, with holes in the end planes to provide beam access. Because of the balanced current flow in the split ring itself, rf properties of the accelerating structure are nearly independent of the cylindrical housing. Thus it has been possible to demountably join the split ring to the wall via a superconducting joint, thereby simplifying the construction and processing of accelerating sections.

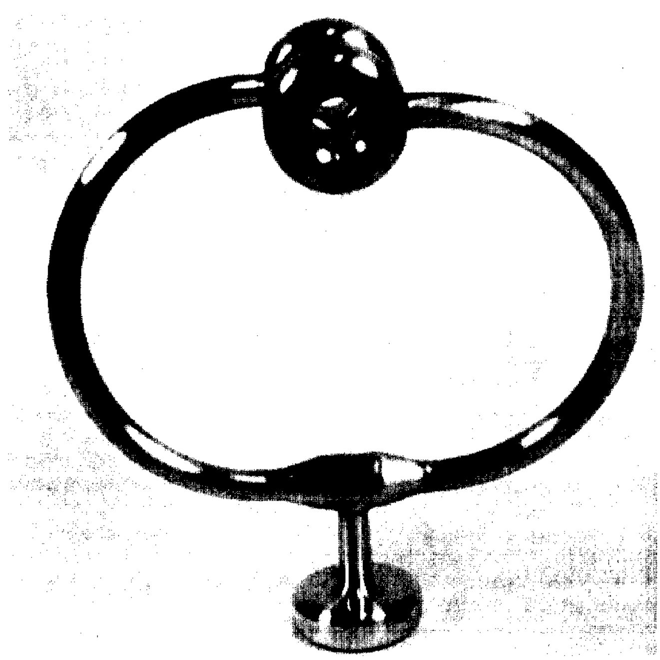

Fig. 1. Prototype 240 MHz superconducting split ring element. The drift tubes are connected by an inductive ring of five inch mean diameter. The ring element demountably joined to its housing through an Indium vacuum seal.

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In principle, any number of split ring elements can be stacked into a single housing. However, the ring to ring rf coupling then prevents the independent phasing of the ring elements and reduces the range of particle velocities over which the structure operates efficiently. Work to date has been to develop resonators containing a single ring element. The velocity acceptance of this configuration provides 90% of the peak energy gain for reduced particle velocities $\beta = v/c$) in the range $0.84\ \beta_o \leq \beta \leq 1.25\ \beta_o$, where β_o is the optimum velocity; a range of more than a factor of two in particle energy.

The rf properties of several different split ring resonators are shown in Table I. Common features are: low peak surface fields and low rf losses, neither feature varying strongly with the optimum particle velocity. The first two columns of Table I refer to resonators (HSR-1, HSR-2) using a prototype superconducting split ring designed before a quantitative model for the split ring structure had been developed. In resonator HSR-1, used for initial superconducting tests, the ring was mounted in a 10 inch I.D. cylinder 7 inches in length, so that the end plates were relatively far from the ring and the accelerating gradients quoted for this structure are for a long array of such rings. Resonator HSR-2, a prototype single ring resonator, 3.5 inches in length and suitable for use in a phased array for a particle accelerator, shows the effects of increased capacitive loading by the end planes as an increase in its peak magnetic field. Data for HSR-1 and HSR-2 are the results of bead tests and experimental runs on a superconducting resonator. These data have also provided an exacting test for model calculations. A successful analytic model for the split ring has been developed and was used to design the more nearly optimum single ring resonators (T7,T6) shown in the third and fourth columns of Table I.

Table I.

	HSR-1	HSR-2	T7	T6
f_o(MHz)	240	235	150	150
β_o	.07	.08	0.1	.05
E_m(MV/m)	5.0	5.6	5.5	6.4
B_m(G)	91	121	105	91
$(\frac{\Delta f}{f_o})$	1.4×10^{-5}	1×10^{-5}	1×10^{-6}	5×10^{-6}
D_r(cm)	12.6	12.6	23	23
D_t(cm)	0.95	0.95	3.81	1.91

Table I. Properties of several split ring resonators. The surface fields (E_m and B_m) and frequency shift ($\Delta f/f_o$) correspond to an rf level giving 10^6 V/m energy gain per unit charge for a synchronous particle. The radiation pressure induced frequency shift for the 150 MHz rings has not yet been measured; but are scaled from HSR-1. The variables in the left hand column are as defined for Table II with the addition of D_r, the diameter of the ring, and D_t the diameter of the ring tubing.

The analytic model will be described more completely elsewhere,[2] but consists basically of: firstly, a numerical solution of the essentially electrostatic problem of the surface and axial electric fields associated with a given drift tube and end plane geometry, and secondly, a representation of the inductive ring as a transmission line, (the characteristics of which are completely determined by the resonator geometry) terminated by the capacitance of the drift tube. It was found necessary to include to first order the electrostatic interaction between drift tube and ring to obtain an accurate description of the split ring resonators. Calculations based on this model, with no free parameters, agree with measured frequencies and surface and axial electric and magnetic fields to an accuracy of 5% and predict within 15% the energy content and shunt impedance for all resonators studied.

The T6 and T7 split ring resonators are designed to operate at 150 MHz and provide a 2.5cm diameter beam aperture with optimum particle velocities β=.05 and .10 respectively. The useful particle velocity range of these two structures spans nearly the entire range required for heavy ion acceleration. Table II compares the properties of the T6 and T7 resonators with the several other proposed low velocity superconducting resonators. The peak surface magnetic field for the split ring is nearly a factor of three lower than for the other inductively loaded structures. It should also be noted that the peak surface electric field in the split ring is determined by the drift tube geometry, and is about 30% lower than can be obtained in helically loaded structures and less than can be obtained in re-entrant cavities for phase velocities $\beta < 0.12$ ($\sim$ 6 MeV/nucleon particle energy).

Table II.

	T6 Ring	T7 Ring	Helix Ref(1)	Spiral Ref(2)	Re-entrant cavity (3)
f_o	150 MHz	150	92	129	437
β_o	.05	.10	.04	.04	.10
E_m	6.4MV/m	5.5	8.0	6.5	6.8
B_m	91 G	105	261	262	108
U_1	0.1 J	0.21	0.28	0.22	1.7
P_1	4.1×10^6w	5×10^6	3.4×10^7	1.9×10^7	5.2×10^7
$(\frac{\Delta f}{f})$	5×10^{-6}	1×10^{-6}	7×10^{-4}	7×10^{-6}	3.6×10^{-6}

Table II. Comparison of the properties of the proposed superconducting heavy ion accelerating structures. The left hand column variables are:

f_o = resonant frequency, β_o=optimum particle velocity,
E_m, B_m = peak surface fields, U_1=rf stored energy/meter,
P_1 = rf power loss/meter per unit surface resist. $(\frac{\Delta f}{f})$=radiation pressure induced pressure shift,
$E_m, B_m, U_1, P_1, (\frac{\Delta f}{f})$ are values for a field level producing 10^6V/m energy gain per unit charge.

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The split ring has excellent mechanical properties, the radiation pressure induced frequency shift being comparable to that observed in the spiral[3] and re-entrant cavities and about two orders of magnitude smaller than for the helix. Additionally, the split ring has fewer vibrational modes that interact significantly with the rf field than the helix. These properties indicate that the problem of controlling the rf phase of the resonator is considerably less severe than for helical resonators.[1]

III. Experimental Results

A. Chemical Processing of Lead (Pb) Surfaces

The electrical characteristics of the split ring accelerating structure have been designed in such a way as to ameliorate some of the problems of superconducting materials development. The most striking feature of the split ring is its very low magnetic field, which opens the possibility of using a material other than niobium to achieve high accelerating fields. Whereas niobium is the only material capable of achieving the peak field of 1200 G necessary to reach 4 MV/m in a helix or spiral, the split ring requires a peak field of about 400 G, a value easily achieved not only for Niobium, but also with superconducting Lead (Pb). However, a major problem with the use of Pb, and other superconducting materials, at high accelerating fields is losses induced at the surface by electric fields. For the Pb surfaces previously studied, emission of electrons from sharp points on the microscopically irregular surface limited maximum surface fields to approximately 12-15 Mv/m. A chemical polishing procedure for Pb surfaces has been developed[4] which results in a smoothing of microprotrusions on the surface and reduces electric field emission effects such that surface electric fields of 25-30 MV/m have been routinely achieved in our laboratory.

B. Test of Superconducting Resonators

The results of the above measurements were sufficiently encouraging that the first tests of the prototype split-ring accelerating structure were made with a polished surface. A prototype split ring resonator was fabricated from OFHC copper, electroplated with Pb, and chemically polished as indicated above. The resulting high field performance of the HSR-1 resonator is shown in Fig. 2. Multipactor phenomena initially limited fields to relatively low levels, but these limiting levels could be raised and rapidly eliminated by a process of "conditioning" where the resonator was operated at a high field in the presence of a small amount of helium gas. After this process, the multipactor levels did not reappear as long as the resonator was kept at helium temperature.

The HSR-1 resonator was operated at a maximum accelerating gradient of 4.7 MV/m, a value equal to the highest attained with niobium heavy ion structures. At the maximum field, no sudden onset of either electric or magnetic breakdown was observed. Instead, a gradual degradation of the cavity Q with rf amplitude induced a slow thermal breakdown, requiring a period of several seconds, at gradients above 3.5 MV/m. The rf power loss at 3.5 MV/m was 1.4 watt which correlates well with the expected maximum cooling capacity of superfluid helium through the tubing forming the ring (1.1 watt at 1.8°K).

The HSR-1 resonator has been cycled many times to room temperature and operated continuously for fourteen hours at accelerating gradients above 3.0 MV/m with no observable degradation in performance. During these tests, we have seen no evidence of the growth of "whiskers" on the Pb surfaces which, it had been feared, might limit the use of Pb surface in applications requiring high electric fields.

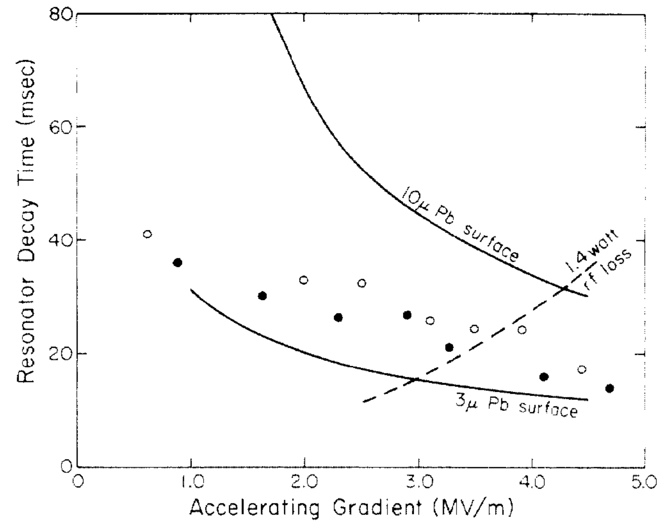

Fig. 2. Measured superconducting performance of the HSR-1 split ring resonator at 1.8°K. Open and closed circles refer to two different runs, between which the resonator was brought to room temperature. The solid lines are performance predicted from calculated electrodynamic properties of the split ring and small sample measurements of the superconducting rf surface resistance for polished Pb surfaces of 3μ and 10μ thickness. The Pb surface on the split ring is of 6μ average thickness and the thickness varies by roughly a factor of two.

In Fig. 2, the observed performance of the HSR-1 resonator is compared with performance predicted on the basis of the calculated surface magnetic field distribution and small sample measurements of surface resistance on similar superconducting polished Pb surfaces. The small sample tests were made in a $\lambda/2$ coaxial line resonator, operated at 200 MHz. In this resonator the center conductor was greatly constricted at the point of maximum current, accentuating the effect of rf magnetic field on surface induced losses. Polished Pb surfaces of 3μ and 10μ thickness were tested. The results indicate that the surface resistance R_s decreases with thickness; a 10μ surface yielded $R_s = 3 \times 10^{-7}\ \Omega$, at 2.2°K and 300 G magnetic field. The Pb surface of the HSR-1 resonator varied in thickness by roughly a factor of two from an average of 6μ due to difficulties in electroplating the irregular geometry. As indicated in Fig. 2, the observed performance of the full scale resonator is within the values predicted from the 3μ and 10μ thickness small sample tests and tends to confirm the reliability of the material and processing technique.

IV. Summary and Conclusions

Prototype superconducting split ring resonators have been tested with a chemically polished, superconducting Pb surface and have been operated at accelerating field gradients up to 4.7 MV/m (energy gain per unit charge). The rf losses in the prototype resonator correlate well with small sample measurements of the superconducting Pb surface resistance at high magnetic fields; an indication that the polished Pb superconductor behaves in a predictable manner. A mathematical model for the split ring resonator has been completed and preliminary design results indicate that it will be possible to obtain the same performance as achieved in the prototype tests in resonators designed for any particle velocity in a range of at least $\beta= .04$ to $\beta= 0.12$.

These results imply that superconducting split ring resonators can be useful components of a low β heavy ion accelerator. In particular, at equal accelerating potentials, it has been shown that full scale superconducting Pb plated split ring resonators can provide power dissipation equivalent to a Niobium helical resonator. Also, small sample chemically polished Pb surfaces indicate that this loss can be reduced by at least a factor of two. If the split ring structure were fabricated from Niobium (and previously reported surface critical fields for Nb were achieved)[5] the accelerating potential will be improved by about a factor of two over the Niobium helix. It should also be noted that the split ring geometry may have applications as a normally conducting accelerating component because of its high shunt impedance.

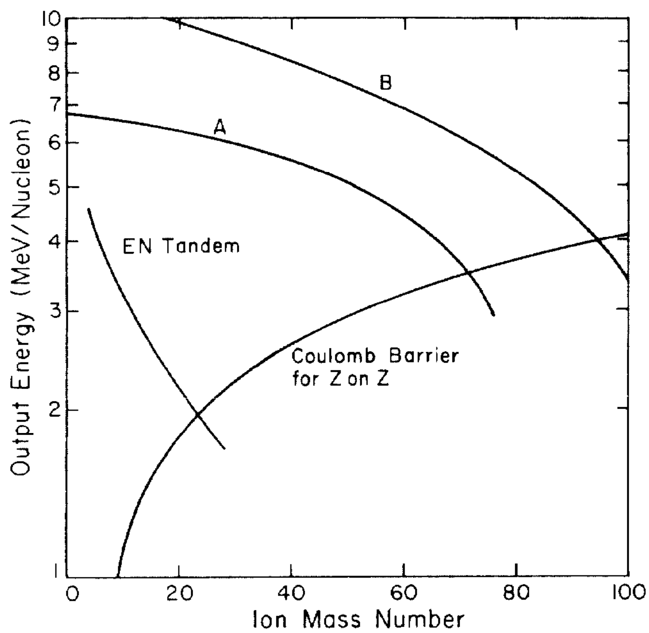

Fig. 3. Maximum output energies for a superconducting heavy ion accelerator consisting of three meters of split ring resonators, injected with a beam stripped at the output of an EN Tandem. Curve A is projected for superconducting Pb and curve B for Nb.

The electrodynamic properties of the split ring structure imply larger accelerating gradients for heavy ions at low β for any superconducting material, than for other proposed superconducting structures. Figure 3 provides an example of the capability that the split ring structure could provide, if superconducting material properties that have been demonstrated in single resonators can be achieved in a reproducible and controllable manner on a large scale. It should be noted that if the superconducting material yielding performance curve B in Fig. 3 were used with helical resonators in an accelerator of the same length, the performance would be reduced to a curve slightly above curve A.

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