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Abstract

The conceptual design for a superconducting Electron Cyclotron Resonance Ion Source (ECRIS) is presented. It is designed to take advantage of frequency scaling in ECRIS and be driven at 28 GHz by a laboratory scale gyrotron. In Fig. 1 the basic superconducting coil configuration for the Gyrotron-driven ECR (GECR) using 4 solenoid coils and a set of sextupole coils is illustrated. These coils are surrounded by a warm bore iron yoke. Possible applications include cyclotrons, heavy-ion synchrotrons, ion implantation in semiconductors, and experiments in atomic physics.

Introduction

Developments in ECR ion sources, high frequency microwave sources, and superconducting wire technology make the prospect of building a high frequency ($f \geq 28$ GHz) ECRIS attractive and feasible. The evidence for higher performance at higher frequencies for ECRIS has been growing stronger, beginning with the early results from Grenoble on Minimafios-16GHz.[1] Development has continued at Grenoble[2] and the performance of ISIS at Jülich has added to the strength of the idea.[3] The figure of merit for an ECRIS plasma is $n_e\tau_i$ where n_e is the plasma density and τ_i is the ion confinement time. The Grenoble results indicated that n_e scales with f^2 The shift of the charge state distribution to higher average charge with increasing frequency indicates an increase in the $n_e\tau_i$ product, although at a rate slower than f^2.

More than 30 ECRIS have now been built and operated.[4] A large majority are conventional sources using room temperature copper solenoid coils and permanent multipole magnets. Most of these sources operate between 5 and 10 GHz. The present upper limit on frequency for conventional sources is about 20 GHz, which is set by the maximum sextupole field which can be produced using Nd-Fe rare earth magnets. Four superconducting ECRIS have been built and operated: HISKA[5], ECREVETTE, ECREVIS[6], AND ISIS.[3] ISIS operates at 14 GHz, the highest frequency used so far in superconducting sources. ECREVIS was the largest superconducting source built with a plasma volume of 85 liters. A new superconducting ECRIS is under construction at MSU and will be tested initially at 6.4 GHz. The coils are designed to produce magnetic field sufficient for 30 GHz operation.[7]

Gyrotrons appear to be the best microwave source in the frequency range 20 to 100 GHz with cw power levels greater than 10 kW. For example, 200 kW cw tubes were developed for plasma fusion work and have been used to heat plasmas in mirror devices and Tokamaks. Recently, Varian Associates has announced the development of a "laboratory scale" gyrotron at 28 GHz with adjustable power from 0 to 15 kW,[8] which matches the requirements for a high frequency ECRIS well

Design Issues

Perhaps the most important issue in the design of a high frequency superconducting ECRIS is how large to make it. The plasma chamber should be sufficiently over moded at the operating frequency. This requires $d \geq 2\lambda$ where d is the chamber diameter and λ is the free space wavelength. At 28 GHz this places a lower limit of 2 cm on the cavity diameter. An important question concerns how the optimum power density scales with frequency. This is difficult to predict theoretically since the detailed understanding of the electron loss mechanism in an ECR plasma is missing. If the loss mechanism is independent of RF frequency and plasma density, and the plasma density scales as f^2 then the optimum power density would likewise scale as f^2. In Fig. 2, the optimum average power density used to produce high charge state xenon for three sources is plotted as a function of their operating frequency. These data are reasonably well represented by

$$p=3.3\ f^{2.3} \qquad (1)$$

where p is the power density in W/cm^3, and f is in GHz. Evaluating this expression for 28 GHz gives an optimum power density of 8 W/cm^3 or 8 kW for a small (1 liter plasma) ECRIS As long as $d \geq 2\lambda$ there is little evidence that larger plasma volume yields better performance.[4]

Although reducing source size with increasing frequency appears attractive from the point of view of ECRIS physics, practical considerations of building a superconducting ECRIS place a lower limit on the size. The current density needed to produce a given field strength scales inversely with the characteristic dimensions of the coils. Additionally, if the coils are made too small the relative space required by the cryostat increases, which in turn increases the ratio of the radius of the sextupole coils to the radius of the chamber wall. Since the sextupole field strength increases as radius squared, moving the coils out requires higher currents and higher magnetic fields in the sextupole windings. The design discussed below is based on trying to minimize the plasma volume consistent with the constraints placed on it by cryostat and coil design issues. We chose to use a sextupole field for radial confinement, because all the successful high charge state ECRIS have used either sextupoles or octupoles. The higher the multipole number, the higher the local fields in the multipole coils become. If it can be demonstrated that a quadrupole field is as effective as a sextupole, then a quadrupole coil, as has been proposed,[10] would be advantageous.

A major part of the design effort focussed on developing an appropriate coil configuration which produced the desired magnetic fields and kept the current densities and peak field well below the short sample limit for commercially available Nb-Ti wire. The calculations of the 3 dimensional fields were approximated by superimposing separate 2 dimensional calculations for the sextupole coils and the solenoid coils. This technique avoids the computational complexities related to a full 3 dimensional calculation, and hence allows much more rapid iteration in the design. It does not allow the local field to be calculated in the superconductor at the ends of the sextupole. This can be allowed for by making the coil design sufficiently conservative. Calculations including the iron yoke were done with the POISSON code. The effect of the yoke on the sextupole field is small because the iron is relatively far from the sextupole coils.

In Fig. 3, an elevation view of the Gyrotron-driven ECR source (GECR) design is shown. The source has four solenoid coils which produce a peak axial field between first and second stage of 2T and 1.5 T peak at extraction. This basic field configuration is patterned after the axial field used in the LBL ECR, scaled up by the ratio of the frequencies (28 GHz vs 6.4 GHz). The iron yoke increase the axial field about 10% as indicated in Fig. 4. It also serves to define the magnetic field center and isolate the source from the effects of any ferromagnetic structures nearby. The design parameters are summarized in Table 1. The peak magnetic field and the highest current densities in the superconductor occurs in the sextupole coils. The wire is assumed to fill 66% of the coil cross section with the remaining area taken up by insulation and epoxy. The operating point for the maximum combined magnetic field for the solenoid and sextupole coil is shown in Fig. 5. along with the the short sample characteristics of commercially available 0.5 mm diameter Nb-Ti wire with a copper to superconducting ratio of 1.6 to 1. The operating point for the sextupole is about 80% of the short sample limit.

Because the RF power density will be quite high if Eq.1 is accurate, a carefully designed water cooled plasma chamber wall is required. A single gyrotron will supply power to both the first and second stage plasmas. This can be done by coupling a small part of the power flowing into the second stage into the first stage as indicated schematically in Fig. 3. Another possibility is to use an adjustable external power splitter.

Conclusion

It appears both feasible and highly desirable to build a compact superconducting ECRIS, which can operate at RF frequencies up to 28 GHz. The next stage of this project is to develop a detailed engineering design of the cryostat and superconducting coil structure.

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Table 1
Design Parameters for the GECR

Plasma Chamber	
Diameter (cm)	7.0
Length (cm)	30.0
RF	
Frequency (GHz)	28.0
Max. Power (kW)	15.0
Solenoid Coils	
Inner radius (cm)	8.0
Outer radius (cm)	9.0
Width (cm)	5.0
Coil cross section cm^2	5.0
Amp-turns (kA-t)	165,165,68,180
j_c in the superconductor (A/mm^2)	1440.0
Stored energy (kJ)	12.5
B_{max} on axis (T)	2.0
Sextupole coils	
Inner radius (cm)	4.9
Outer radius (cm)	6.4
Width (cm)	1.5
Length (cm)	35.0
Coil cross section (cm^2)	2.25
j_c in the superconductor (A/mm^2)	1867.0
Stored energy (kJ)	10.2
B_{max} in superconductor (T)	4.5
Sextupole field at chamber wall (T)	1.5
Superconducting NbTi wire	
Copper to superconductor	1.6:1
Wire diameter (mm)	0.5

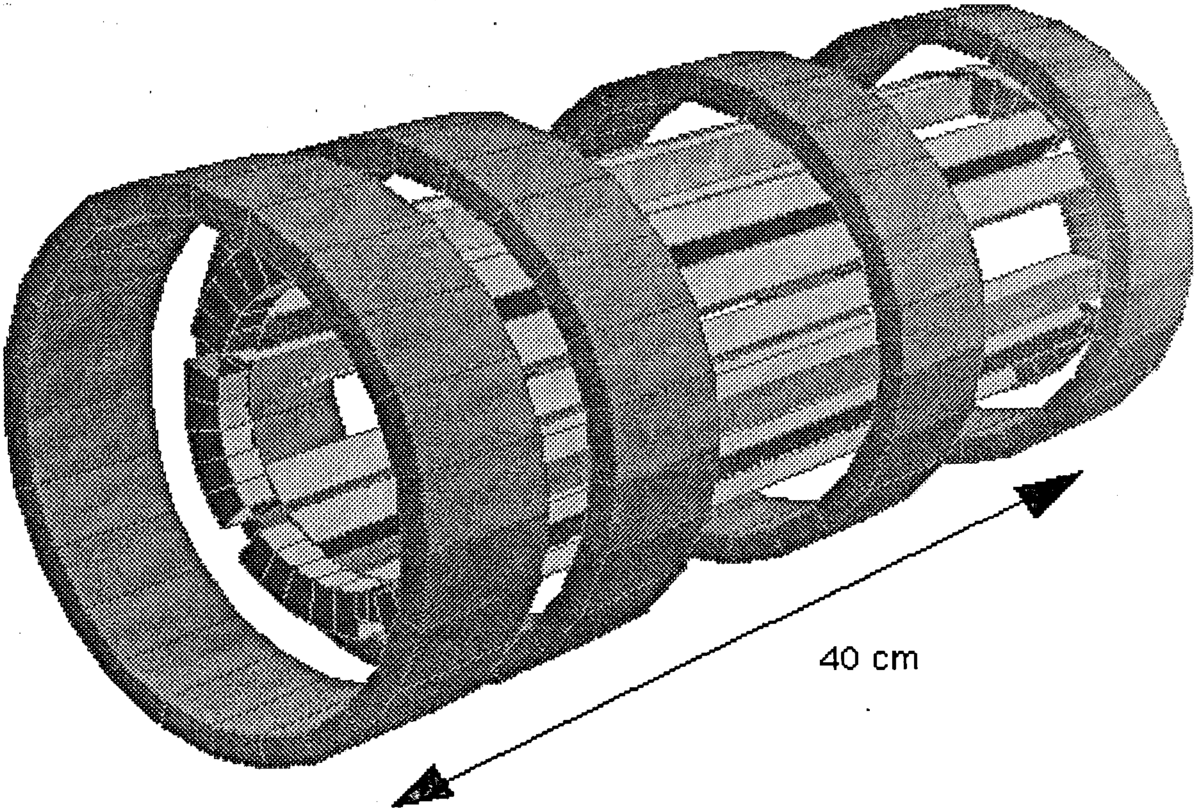

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Fig. 1. Isometric view of the superconducting solenoid and sextupole coils of the GECR without the iron yoke. The two solenoid coils in the foreground provide the 2 T mirror field between first and second stage. The ends of the sextupole coils are not accurately shown in this figure.

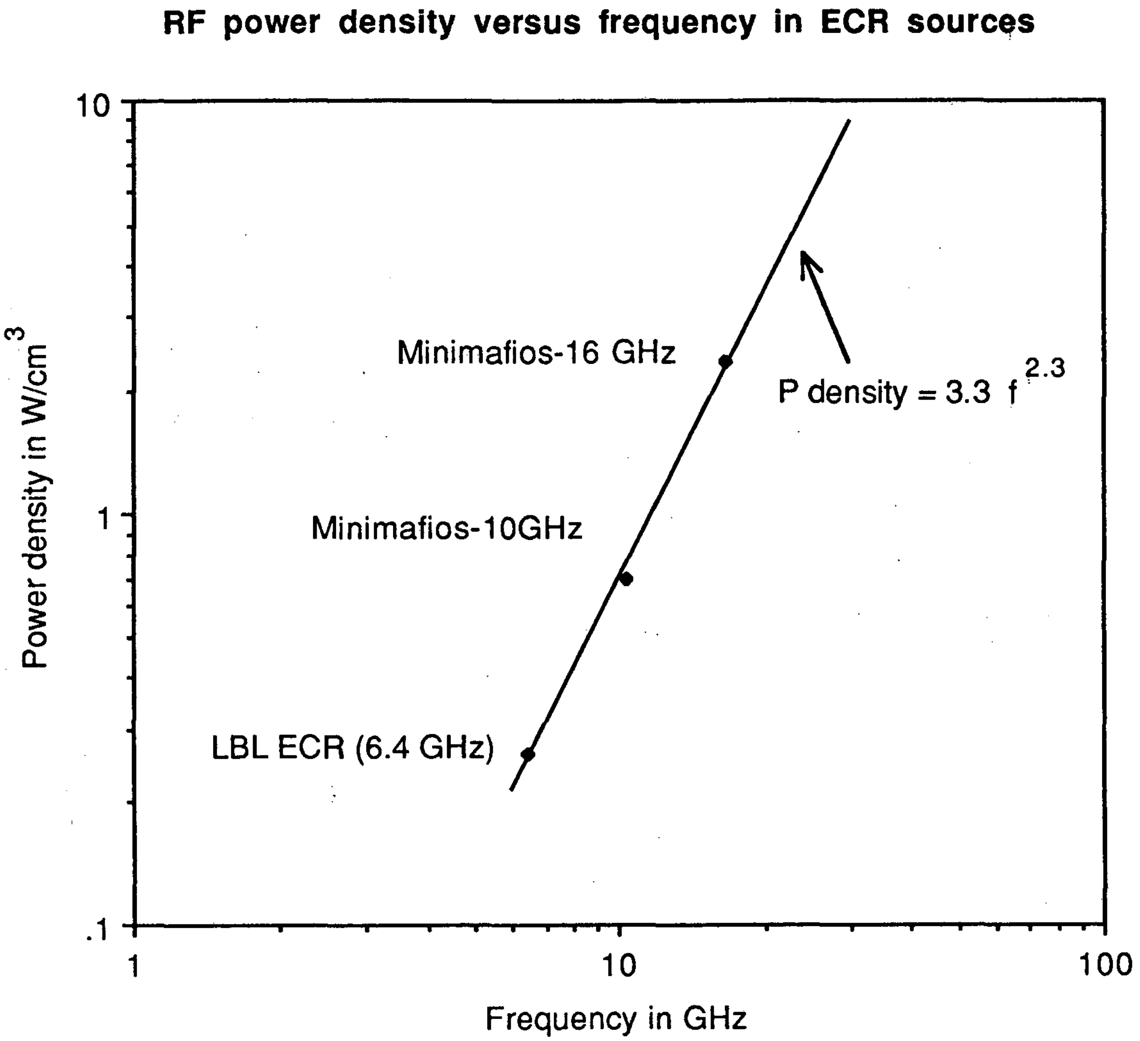

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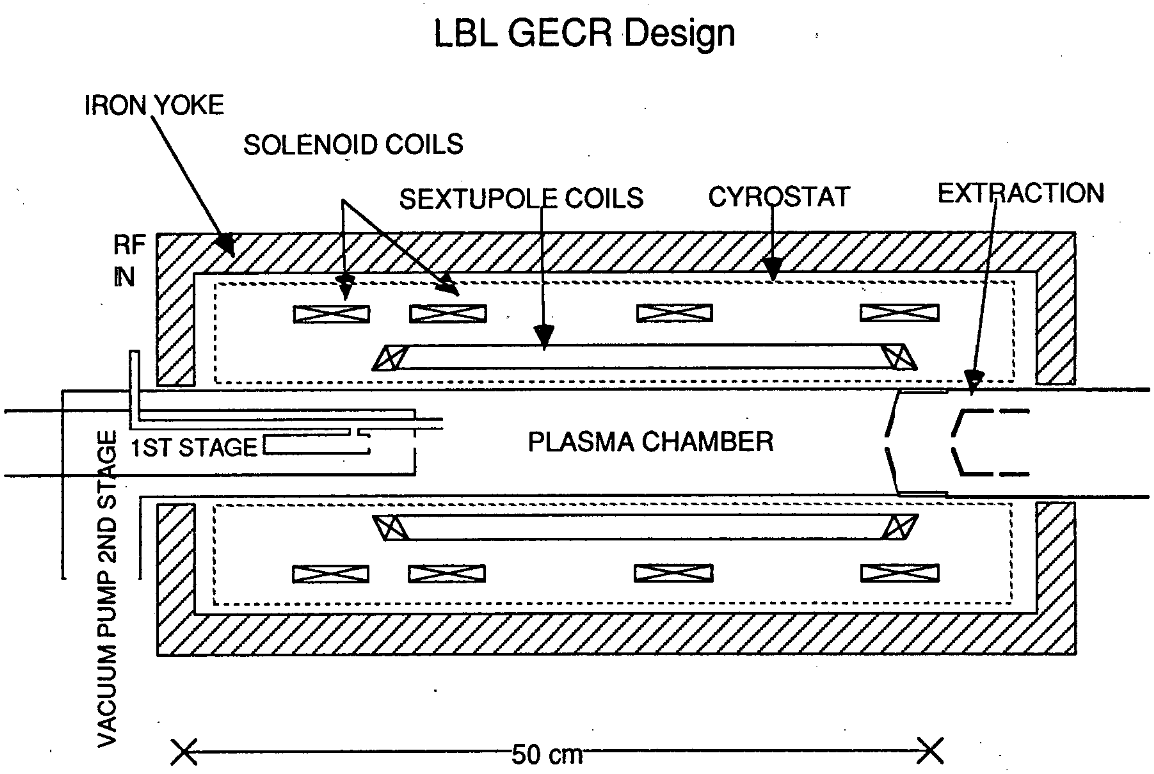
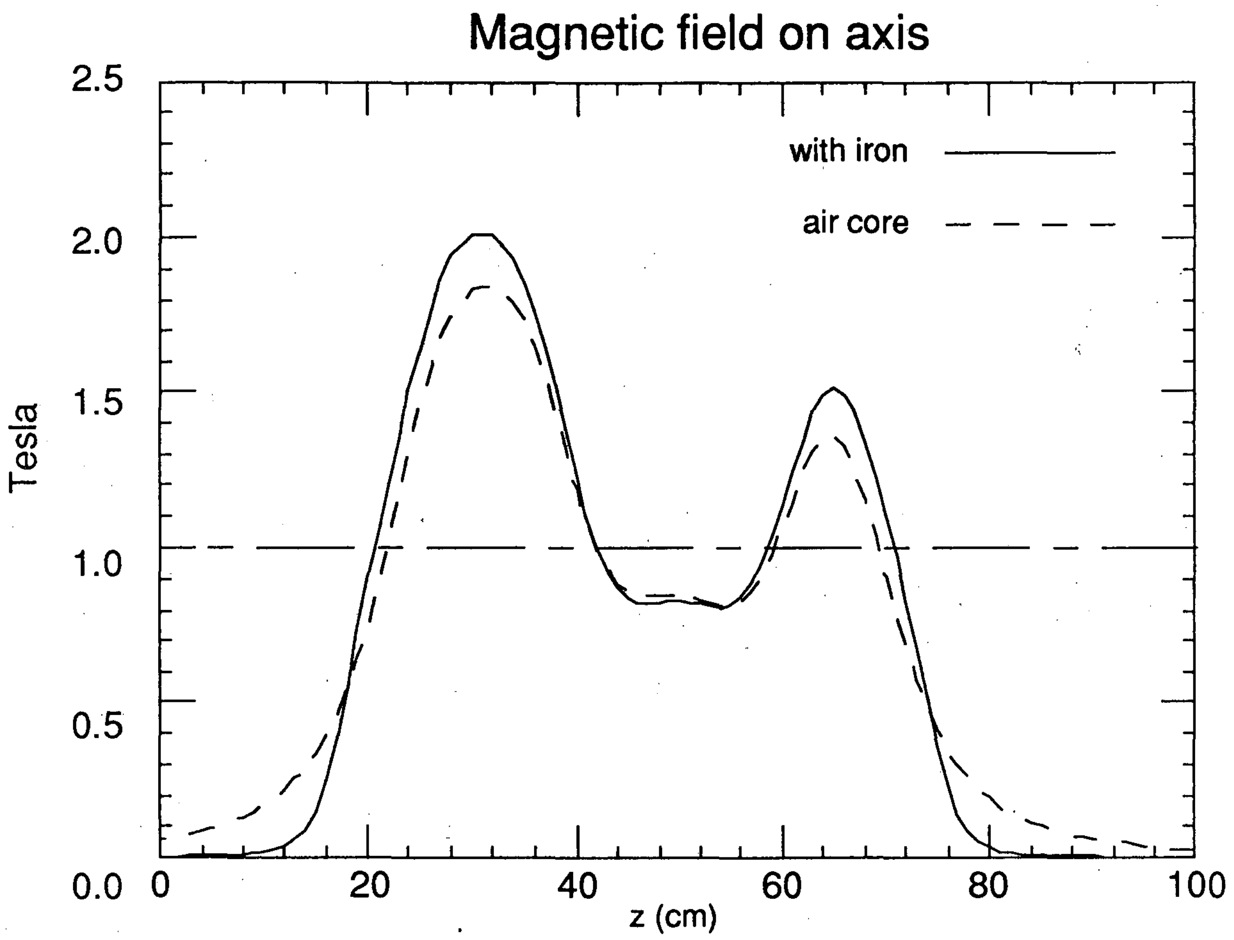
Fig. 2. The optimum RF power density for the production of high charge state xenon is plotted as a function of frequency for three sources: the LBL ECR at 6.4 GHz, Minimafios-10GHz,[1] and Minimafios-16GHz.[9] The solid line is a power law fit to the data.



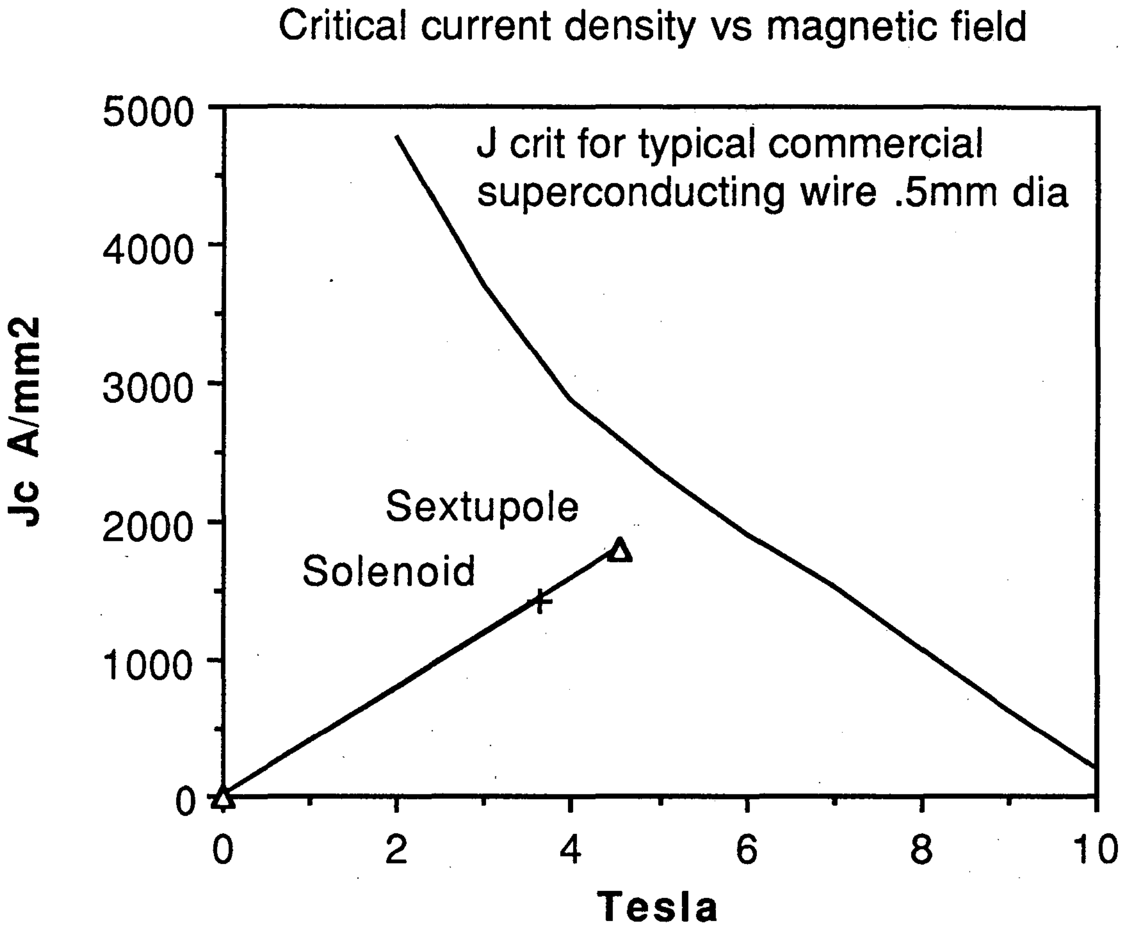
XBL 895-1916

Fig. 3. An elevation view of the GECR showing the main components. The cryostat is schematically indicated by the dotted lines.



XBL 895 1917

Fig. 4. A plot of the magnetic field on axis for the GECR at design field. Dotted line shows an air core calculation and the solid line shows a calculation including the effect of the iron yoke. The broken line at 1.0 Tesla indicates the resonant B-field at 28 GHz.



XBL 895-1918

Fig. 5. A plot of the critical current in the superconductor for 0.5 mm NbTi wire. The load lines show the operating points for the sextupole and solenoid in their combined fields.

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