MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

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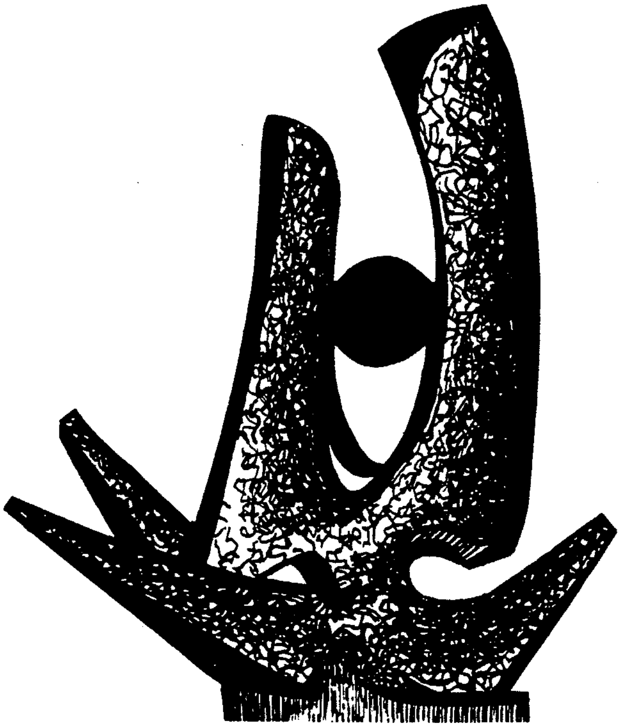

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MAGNETIC STRUCTURE FOR A SUPERCONDUCTING VARIABLE FREQUENCY ELECTRON CYCLOTRON RESONANCE ION SOURCE*

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Introduction

Electron cyclotron resonance (ECR) ion sources are, at present, the leading source of highly charged dc beams of positive ions. Fully stripped light ions through argon have been obtained, and ionization levels of 25-35 electrons removed have been obtained for heavy mass species. Major applications of ECR ion sources for highly charged ions now include approximately 30 nuclear, atomic and high energy physics laboratories world-wide.[1]

ECR ion sources have their origins in fusion confinement experiments of the early 1970's.[2,3] The basis for this ion source technology is the ionization of gas molecules by hot electrons in a Minimum B magnetic bottle. An ECR ionization cell is shown schematically in Fig. 1. The magnetic field increases in all directions when moving away from the center. Confined electrons bounce between magnetic mirrors at the chamber walls, crossing a set of nested surfaces of constant magnetic field. On one surface the electron gyrofrequency is resonant with microwaves injected into the chamber. On this surface electrons are stochastically accelerated to keV energies before becoming de-confined. These hot electrons then ionize gas atoms. The ion produced in this process are also confined by in the magnetic field, and will be further ionized until they also become de-confined. ECR sources for highly charged ions generally have two ECR cells in series. Plasma generated at high pressure in the first cell diffuses across a pressure gradient into the second cell, where further ionization occurs at lower pressure. In these devices, the ionization rate tends to scale with the plasma density, but the plasma density is limited by a cut-off condition for microwave propagation into the plasma.

For electrons, the rotation frequency is 2.8 GHz per kilogauss of magnetic field. Most ECR ion sources have used klystrons in the frequency range of 6-14 GHz as the microwave sources, with corresponding resonance fields of 2-5 kG, and peak mirror fields at the ends and side walls that are at most 8 kG. These sources have used hollow copper coils for the axial mirrors in combination with a rare earth permanent magnet hexapole for the radial magnetic field. At higher resonance frequencies, superconducting magnet designs are competitive both in terms of construction and operating cost.

SC-ECR MAGNETIC FIELD DESIGN

The SC-ECR ion source, now under construction, is shown in Figs. 2-3, with a summary of the main source parameters in Table 1, and the design axial and radial magnetic field profiles in Fig.s 4-5. The six circular coils, arranged in three groups of two, to produce three axial mirrors, are mounted on the outside of a stainless steel cylinder at the center of the helium vessel. The six coil hexapole coil is mounted on the inside of this cylinder. The circular coils will be wet-wound in place with Stycast 2850 FT epoxy. The hexapole coils will be wound separately and potted before installation. Since the hexapole coil field scales with r^2, and a field of 1.5T is required at the plasma chamber wall, the hexapole is positioned at close to the plasma chamber as possible to minimize the field at the conductor. It is for this reason that the radiation shield has been eliminated from the inner bore of the cryostat. Radial access ports for the second cell pass midway between the circular coils of the second and third axial mirrors and the centers of three of the hexapole coils. These ports set a mechanical constraint on the azimuthal width of the hexapole coils. A 5 cm. iron return yoke serves as the outer wall of the cryostat. The helium vessel is mounted off the yoke top with a set of nested stainless steel tubes. E-glass links located opposite the access ports at the second cell mid-plane provide the radial supports. The heat load is dominated by seven sets of vapor cooled leads.

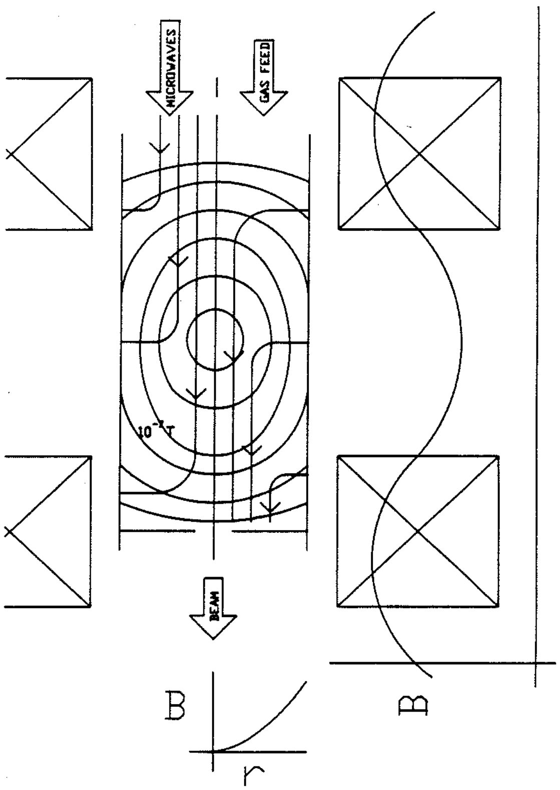

Figure 1. A conceptual view of the ionization cell in an ECR ion source. The ionization process centers around a magnetic bottle created by the superposition of axial mirror and a hexapole magnet.

TABLE 1
SC-ECR ION SOURCE MAIN DESIGN PARAMETERS

No. of Plasma Stages	2
Resonance Frequency Range	6-35 GHz
Resonance Field Range	0.2 - 1.2 T
Full Axial Length	100 cm.
Number of Magnetic Mirrors (3 groups of 2 coils)	3
Mirror Coil Bore	29 cm
Mirror Coil Cross-sectional Area	10 cm^2
Peak Field on Axis	1.5 T
Plasma Ch. Bore	14 cm
Hexapole Coil Bore	20 cm
Hexapole Coil Cross-sectional Area	10.4 cm^2
Peak Field Plasma Ch. Wall	1.5 T

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In the design of this magnet the following considerations are most important. In the case of the hexapole magnet, the radial field increases with the square of the radius, so the ratio of the plasma chamber radius to the hexapole magnet radius is critical. In addition, with six coils in series, each coil must be protected from the stored energy of the other five coils during a quench. The six solenoid coils are independently excited, so coil protection issues are less critical, but the boundary stresses resulting from the axial and radial loads are more important than for the hexapole coils. The peak fields occur near the ends of the magnet where the hexapole coil ends, yoke end plates and outer circular coils interact. A quasi-3D model for the end effects was developed. In this model, the total field is constructed from a superposition of a 3D, iron free hexapole field with an azimuthally symmetric poisson calculation for the circular coils and iron. This model neglects a small enhancement of the field at the ends arising from hexapole-yoke interaction but is not sensitive to finite mesh effects in full 3D codes.

During the design process, an alternate 2-mirror profile with higher mirror strength has also been under consideration. This profile is also shown in Fig. 4. The axial forces on the outer coils of the 3-group are higher than in the standard axial profile, and the highest radial stresses occur on the middle coil of that group. The circular coil design studies are based on the extreme features of this axial profile.

Coil Design

The source geometry requires that the coils be axially compact to allow access for the RF components and for pumpimg ports, and radially compact for maximum efficiency. The additional requirement of low liquid helium usage dictates the use of potted, high current density coils with a large number of turns instead of the intrinsically more reliably cryostable coils. The use of low current coils complicates the problem of protecting the coils in case of a quench. We have previously built[4,5] superconducting quadrupoles and dipoles with current densities of up to 18 kA/cm^2 , comparable to those required here, but at lower peak fields and current densities. The wire and coil parameters for the SC-ECR source are listed in Table 2. The peak fields on the conductor are not easy to calculate, a true three dimensional problem with an iron return yoke and flux coupling only in the ends. Therefore a conservative approach is required in choosing the operating points <u>vis-a-vis</u> short sample limits.

The relatively small stored energy in the solenoid coils, together with the fact that the mutual inductance is only 30% of the stored energy, means that protection is straight forward. Quench calculations, involving a number of different scenarios about quench delay sequences, predict a maximum of 600 volts in any one coil. Because of the inherent layering of the coils the maximum voltage between any two adjacent wires is only 80 volts. The hexapole coils are a more serious problem, because of the larger stored energy and the likelihood that the entire stored energy will end up in a single coil. We were forced to use larger wire and higher operating currents in order to reduce the high voltages induced during a quench. This still results in unacceptably high voltages for a randomly wound coil, such as we used for the quadrupoles and dipoles. We have therefore gone to an ordered winding. This reduces the maximum voltage between adjacent wires to 70 volts. Although time consuming, test coils of over 790 turns have been wound in 6 hours, approximately twice the time required to wind a 3600 turn quadrupole coil. A cross section of one of the test hexapole coils is shown in Fig. 6. The coils are wet wound with Stycast 2850 FT epoxy.

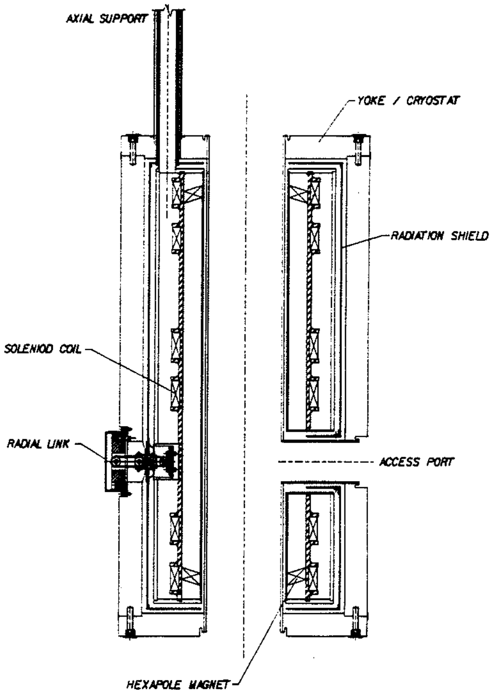


Figure 2. An axial sectional through the SC-ECR ion source cryostat.

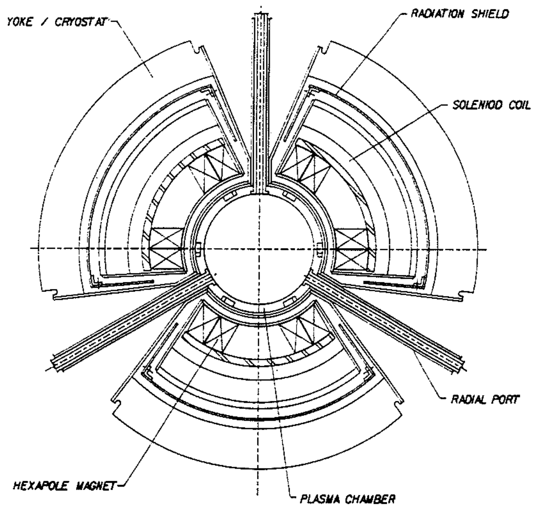


Figure 3. A transverse section of the SC-ECR cryostat through the mid-plane of the middle and lower circular coils groups.

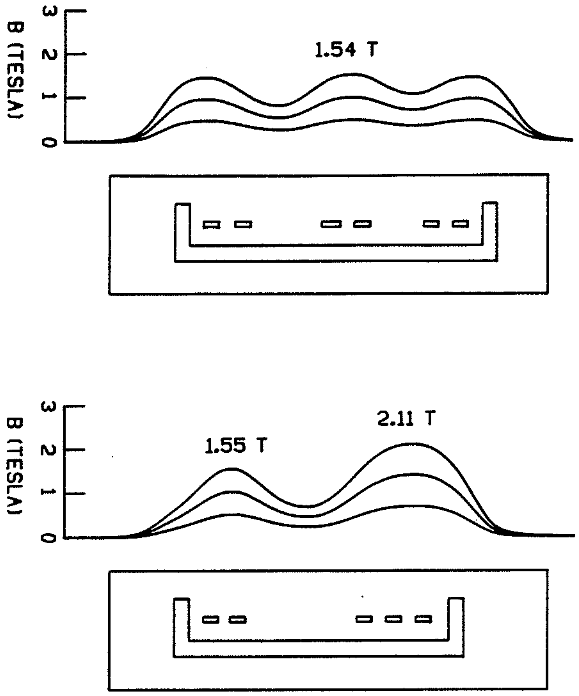


Figure 4. Two axial field profiles are under consideration for the SC-ECR. The upper profile corresponds to the 6 coil geometry shown in Fig. 2. The grouping of the 6 coils into 3 groups produces 3 axial mirrors. The lower, two mirror profile, represents an alternate source design concept that may be adopted. Since the lower profile requires higher performance from the circular coils, it has been used to study the maximum coil stresses. In both cases, curves are shown for 1/3, 2/3 and full excitation of the coils. Peak axial fields are as indicated.

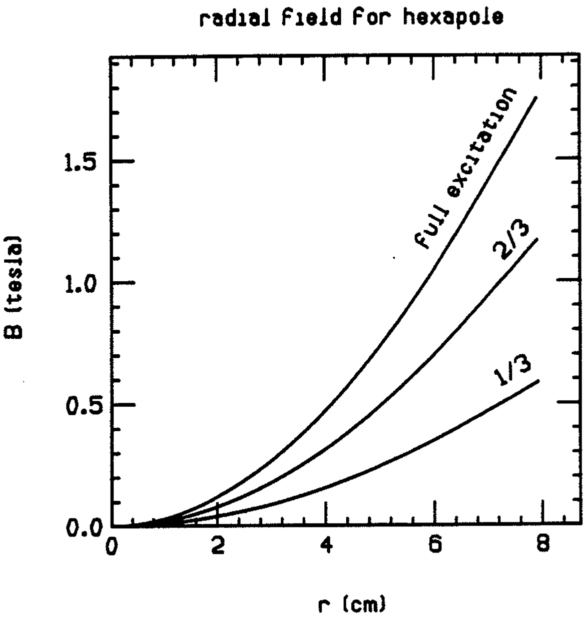


Figure 5. The radial field profile of the hexapole coil is shown. This hexapole would be used for either of the circular coil profiles shown in Fig. 4.

TABLE 2
COIL AND WIRE PARAMETERS

	Hexapole	solenoids
Current density	20	18 kA/cm^2
Stored energy	120	65 kJ (Total)
Max operating current	250	56 Amps
B max	4.5	4.5 T
Turns	790	3100-3900
Conductor diameter	0.995	0.5 mm
Cu:sc ratio	3.4	4.5
Ic(4.2K,5T)meas.	418-445	94 Amps

COIL COMPOSITE STRENGTH TESTING

Strengths of the coil composite and it's individual component materials must be known to provide design values for stress analysis. This data was obtained through reports in literature[6-9] and the results of our own testing as discussed below. This testing included cold shocking in liquid nitrogen prior to loading.

Bobbin to Coil Bond Tension

This testing consisted of a layer of superconducting wire epoxied between 1" diameter 304 stainless steel cylinders. Best and most consistent results were obtained by acid etching the cylinders for good epoxy adhesion. Other stainless steel preparation methods gave inconsistent results. The cylinders were then pulled apart with the strength being monitored by a calibrated strain stud. Average fracture strengths were 4600 psi, consistent within +/- 15%. This information was also used for the coil composite tensile strengths, as the samples failed by debonding from the wire and not by debonding from the stainless steel cylinders.

Coil Composite Shear Strength and Coil to Bobbin Bond Shear Strength

Strength testing was done on sections cut from an actual coil previously tested in LHe. The section was clamped halfway across its inner and outer surfaces with a load applied perpendicular on the other half of one of the surfaces. Two samples were tested with

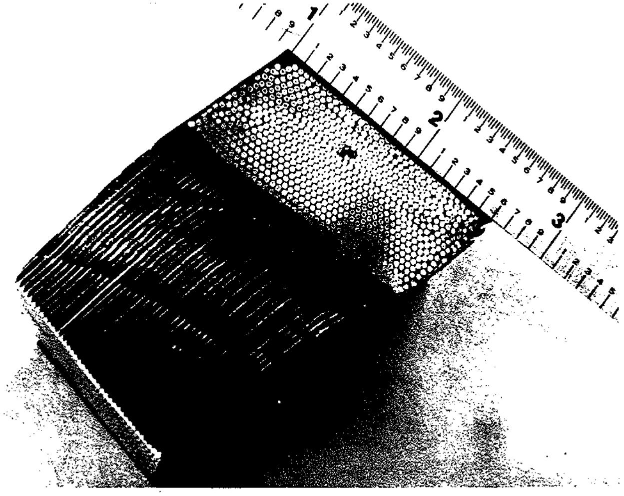


Figure 6. A section through the end of a test hexapole coil shows the relatively well ordered random wind, achieved by using a constant length end geometry.

both shearing at approximately 2500 psi. Testing of the coil to bobbin bond shear strength is incomplete at this time. One test of stainless steel bonded to stainless steel with epoxy has been done, and a strength of 1300 psi obtained.

Coil Composite Compressive Yield Strength and Hoop Tensile Yield Strength

Composite compressive yield strength was taken as that of the weakest material in the composite, the copper in the wire which has a value of 10 ksi. Hoop tensile yield strength was taken as being that of the superconducting wire, about 25000 psi. Even though stress on the wire may be this high, stress on the epoxy is much less at the same level of strain. Also for a wet wound coil, the epoxy sees only the stress due to magnetic loading. For a free coil the epoxy sees a stress level equal to that from the magnetic loading less that due to coil relaxation after bobbin form removal.

ECR COIL STRESS ANALYSIS

Finite element stress analysis was done for the ECR hexapole and solenoid coils using the displacement method of analysis--utilizing eight node parabolic isoparametric elements, three point Gauss-Legendre integration, and a banded matrix solver. Plane strain analysis was used for the hexapole coils ignoring the ends, and axisymmetric analysis was used on the solenoid coils. Magnetic loadings were in the form of force densities calculated from the results of field calculations. For the solenoid coils, loads due to winding tension were also included being added as an initial strain from the results of a separate calculation. The coils were analysed as an orthotropic composite of homogenous cross-section. Both types of coils were analyzed for various boundary conditions keeping in mind the ability to obtain these conditions in actual practice.

Solenoid Coil Analysis

Stress Analyses of the solenoid coils were done with loads from the self field, from the hexapole coil end field contributions, and from a constant winding tension. Three boundary cnditions were examined:

1. Fixed Case - Coils potted to the bobbin (coil wet wound on bobbin and cured) with the outside diameter free.
2. Free Case - Coil wound on the bobbin form and removed after which the coil is installed on the actual bobbin, restrained only on surfaces under compression.
3. Sleeved Case - Like condition 2 with a sleeve compressing the outside diameter.

Such current in the hexapole coils ends can be parallel or anti-parallel to the solenoid current, load from both situations were analyzed. Significant results of each case are discussed below.

Free Coil Case

Load contributions due to anti-parallel hexapole end used solenoid coil currents presented the highest hoop stresses of any case considered, about 15000 psi maximum at the outside diameter. For the case of parallel currents, the internal shear stresses reached 1900 psi.

Sleeved Case

The initial reason for investigating the sleeved case was to reduce shear stresses in the free case (parallel currents). A 15000 psi compressive load on the outside of the coil was used. This contributed to a reduction of only 10% in shear stress, reducing it to a maximum of 1700 psi.

Fixed Case

With antiparallel currents in the hexapole coil ends, all stresses were low enough to not be considered a problem. With parallel end currents, tension stresses of over 1400 psi were found in the coil and along the bobbin boundary with the coil. Shear stresses inside the coil were reasonable, but shear stresses on the boundary reached a maximum of 850 psi, again which forces a dependence on good adhesion of the epoxy to the stainless steel bobbin. These boundary stresses occurred at different locations with areas of high boundary tension having low boundary shear stress and areas of high boundary shear having little tension stress.

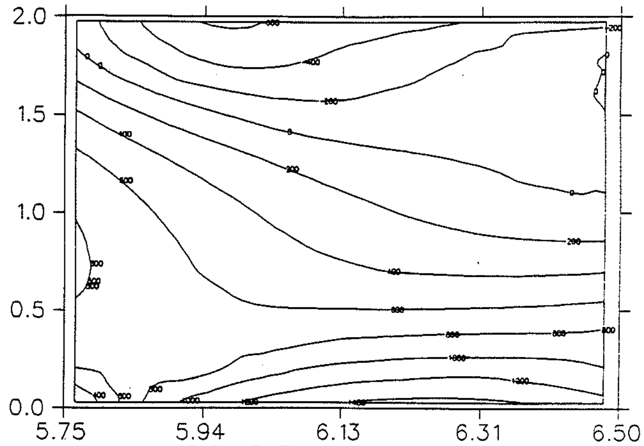
The fixed case design has been chosen for our first test coil, as most all stress levels within the coil were at least a factor of two lower than their assumed limiting values. Stress contour maps of the minimum and maximum principal stresses for this case are shown in Fig. 7. The fixed coil case is also the easiest scheme for coil winding, with the boundary conditions in practice being close to those used for analysis. Boundary shear values at the bobbin interface on the inside diameter are somewhat high, but since this region is also under radial compression, an additional advantage is obtained through frictional resistance. The disadvantage of the free coil cases were the high internal shear stress, more complicated coil-bobbin assembly, and the difficulty of providing a free sliding surface on the compression end of the coil, while restraining it from axial movement.

Hexapole Coil Analysis

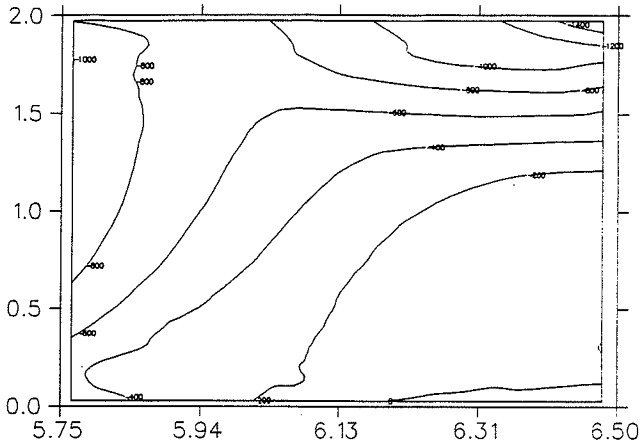
Analyses of the hexapole coils were done in the same fashion as for the solenoid coils, and several boundary conditions investigated. Although stresses were lower than those in the solenoid coils, effort was made to minimize tensile stresses. Analysis of most boundary conditions presented no areas of concern. The exceptions were the fully potted in place design which gave tensile stress concentrations in the inside edges, and a banded coil assembly which gave high compressive stress concentrations in these same edges. The design chosen for our initial test coil was a coil wound on a form, removed, and then placed around it's back on the winding form. In practice, each hexapole coil is restrained azimuthally by shimming with contact with an adjacent coil. This leaves the inside edges free of tension while simulating freedom to slide along the adjacent coil boundary through the fact that the adjacent coil should move in the same way. This initial coil concept and restraints was successfully tested. The results of this test are summarized in Fig. 8.

Temperature Effects

The measured contraction per unit length for the epoxy at 77°K is 0.00375. For the coil composite it was measured at 0.0031. For the wire it was taken as that of copper. The coil will then experience a circumferential shear between the wire and the epoxy of about 700 psi upon cooldown. Temperature induced boundary shear or boundary tension increases should be



MAX. P.S., PARALLEL+WINDING, FIXED



MIN. P.S., PARALLEL+WINDING, FIXED

Figure 7. Maximum and minimum principal stresses in the circular coil that is adjacent to the hexapole coil end, for the case where these currents are parallel and the circular coil geometry is that of the lower trace in Fig. 4. Compressive stresses are indicated with negative values.

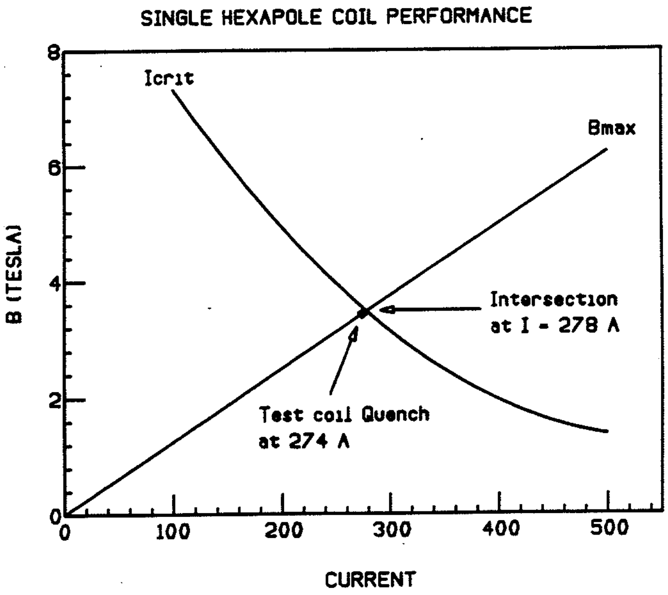


Figure 8. Individual hexapole test coils quenched without training near the predicted critical current in tests at Fermilab.

only about 200 psi since the unit thermal contraction for 304 stainless steel is close to that of the composite.

Acknowledgements

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