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Design, fabrication, and characterization of a solenoid system to generate magnetic field for an ECR proton source

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Abstract. Solenoid coils with iron jacket (electromagnets) have been designed and developed for generation and confinement of the plasma produced by an electron cyclotron resonance source operating at 2450 MHz frequency. The magnetic field configurations designed using the solenoid coils are off-resonance, mirror, and flat, satisfying electron cyclotron resonance condition along the axis of the plasma chamber. 2D Poisson software was used for designing. Details of design, fabrication, and magnetic field mapping of the solenoid coils are presented in this paper.

Keywords. ECR plasma source; electromagnet; poisson software.

1. Introduction

An electron cyclotron resonance (ECR) plasma source operating at 2450 MHz frequency is under development for extracting 30 mA proton beam current at 50 keV beam energy. This source will be used as an injector for the 100 MeV proton linac, proposed to be constructed as initial part of a 1 GeV proton synchrotron (Bhawalkar *et al* 2003). An ECR plasma source finds potential applications in accelerators for producing singly as well as multiply charged ion beams (Bilman *et al* 1972; Taylor & Wills 1991; Baskaran *et al* 1992, 1993). Different magnetic field configurations like off-resonance, resonance, mirror with and without permanent magnets, have been widely used to produce heavy and multiply charged ion beams to confine the plasma axially as well as radially (Alton & Smith 1994; Drentje 2003; Mishra *et al* 2004; Koivisto *et al* 2004; Saitoh *et al* 2004). In the presence of the magnetic field, as the charged particles are forced to gyrate along the magnetic field lines, their diffusion perpendicular to the magnetic field lines is restricted, thereby confining the plasma radially to produce homogeneous, high-density plasma. ECR proton and deuteron sources (Celona *et al* 2000, 2004; Gobin *et al* 2004; Ciavola *et al* 2004; Delferriere *et al* 2008) have been widely used for development of high-energy accelerators for transmutations (Carminati *et al* 1993; Lagniel 1998a, 1998b), neutron spallation (France *et al* 1996; Lagniel *et al* 1997), and material science research (Schriber 1994; Tojyo *et al* 2002; Biri *et al* 2008). Standard software packages like Poisson and Pandira (http://laacg1.lanl.gov), Opera (www.vectorfields.com),

*For correspondence; Present address: sunil.kumar.jain@cern.ch and Intmag (Becker 1989, 1990) are commonly used for simulation of magnetic field patterns using solenoid coils, or permanent magnets. In the present case, the requirement is to get the singly charged ion beam (proton). Accordingly, conventional solenoid coils have been used to produce the ECR plasma, as the solenoid produced magnetic field configurations have been widely used by the ECR community for the extraction of singly charged ion beams.

The '2D Poisson' software package has been used in the present work for simulation of the magnetic field pattern using solenoid coils with iron jacket (electromagnet) for shielding the fringing magnetic field and to reduce the power consumption. The use of jacket is to provide a return path for the magnetic field lines and thereby shield the adjacent components. The use of electromagnet has wide flexibility of tuning the plasma to get the best operating conditions. The use of electromagnet (instead of permanent magnets) helps one to investigate the plasma parameters to optimize the beam current. A conventional ECR ion source uses the principle of adiabatic invariance for mirror reflection, and high magnetic field mode of operation to successfully generate and confine plasma.

2. Design of the electromagnet

The magnetic field required to satisfy the ECR resonance condition (Geller 1966; Brown 1989; Zhang 1999) is given by $f = 2{\cdot}8B$ (from the electron cyclotron frequency expression $\omega_{ce} = eB/m$, where f is the microwave frequency (in MHz), B is the critical magnetic field (gauss), m is the mass of an electron, and e is the electronic charge. The magnetic field corresponding to a microwave frequency of 2450 MHz is 875 gauss. The magnetic field in the plasma chamber was analysed by using the 2D Poisson software.

To start the simulations, the initial parameters of the solenoid coils with iron jacket were fixed as: inner radius 75 mm, outer radius 150 mm, the gap between solenoid coils 20 mm, width to be 70 mm and 80 mm for middle and side solenoid coils respectively. Three solenoid coils were used to get; (i) mirror field, (ii) flat field, and (iii) off-resonance field configuration. Two side solenoid coils, which were identical, generated the mirror field, and the middle solenoid coil was used to compensate the dip in the magnetic field, to have a flat magnetic field. The use of flat field configuration with high field in the centre has been reported to provide better extraction of proton current in the high intensity light ion sources (Celona *et al* 2000, 2004; Gobin *et al* 2004; Ciavola *et al* 2004; Delferriere *et al* 2008). The combinations of these three solenoid coils can also produce the off-resonance magnetic field. The permeability table for soft iron, low carbon, TATA 'A' grade steel has been incorporated in the Poisson code itself. A number of iterations were carried out to get the desired magnetic field configurations. This was accomplished by varying the size of the solenoid coils, thickness of iron jacket, and amp-turns (NI). The optimum values of NI for the side and middle solenoid coils were obtained to be 12950 and 8250 respectively. Based on these parameters, the total length of the conductor was calculated. A copper conductor having a square cross-section of 5 mm $\times$ 5 mm with hole diameter 3 mm for water cooling was used. The optimized design parameters for solenoid coil with iron jacket are presented in table 1. The optimized axial flux along the axis of the source is shown in figure 1. The optimized magnetic field profiles using Poisson software for (a) mirror magnetic field, and (b) flat magnetic field are shown in figure 2. The calculation was also performed analytically (Montgomery 1966) using standard relations for calculating magnetic field.

Table 1. The optimized design parameters for solenoid coil with iron jacket.

Description	Solenoid coil 1	Solenoid coil 2	Solenoid coil 3
Coil type		Water cooled solenoid coils	
Coil size	ϕ300 mm × 80 mm	ϕ300 mm × 70 mm	ϕ300 mm × 80 mm
Bore diameter		ϕ150	
amp-turns (NI)	12950	8250	12950
Conductor size	Rectangular with cross-section 5 mm × 5 mm × hole diameter 3 mm		
N,N/L,L	144, 12, 12	110, 10, 11	144, 12, 122
Total conductors length	95 m	80 m	95 m
Power supply		0–32 V, 100 A dc (Three)	
Coil resistance (measured)	0·146 ohms	0·127 ohms	0·156 ohms

3. Fabrication of the electromagnet

The solenoid coils were fabricated using super enameled hollow copper conductor (refrigeration type) of square cross-section (5 mm × 5 mm) with hole diameter 3 mm (for water circulation). The insulation to the conductor layer was provided using 'H' class fibreglass insulation tape. The diameter of the bore was 150 mm so that plasma chamber including water-cooling jacket and high voltage insulator could be fitted in this. One side flange of the plasma chamber was split type, so that the solenoid coils could be fitted to the plasma chamber. The bore of the solenoid coils was fabricated using high voltage glass epoxy. Each side solenoid coil had 12 turns/layer (N/L), and 12 layers (L) {i.e. 144 turns (N)}, and the central solenoid coil had 10 turns/layer (N/L) and 11 layers (L) {i.e. 110 turns (N)}. The total length of the conductor used for the side solenoid coils and the central solenoid coil was 95 meters and 80 meters respectively. The coils were impregnated into high voltage, high temperature epoxy for the outer layer insulation. The iron jacket of the solenoid coils was fabricated from 10 mm thick low carbon TATA 'A' grade steel. The jacket was fabricated in five parts consisting of two side plates and three cylindrical shapes, of diameter equal to the

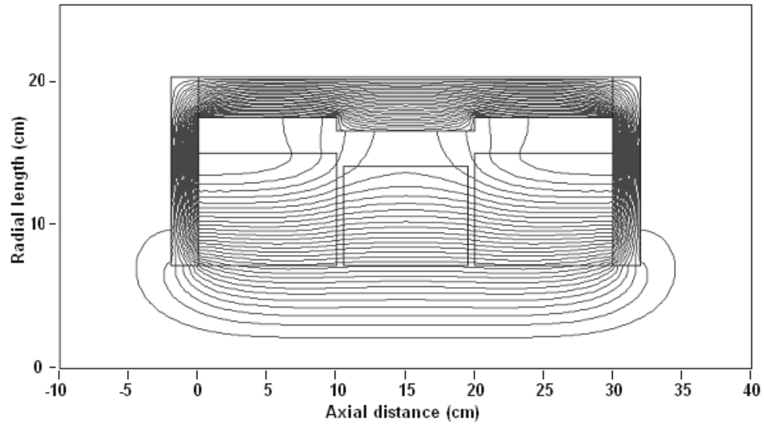

Figure 1. The optimized axial flux along the axis of the source.

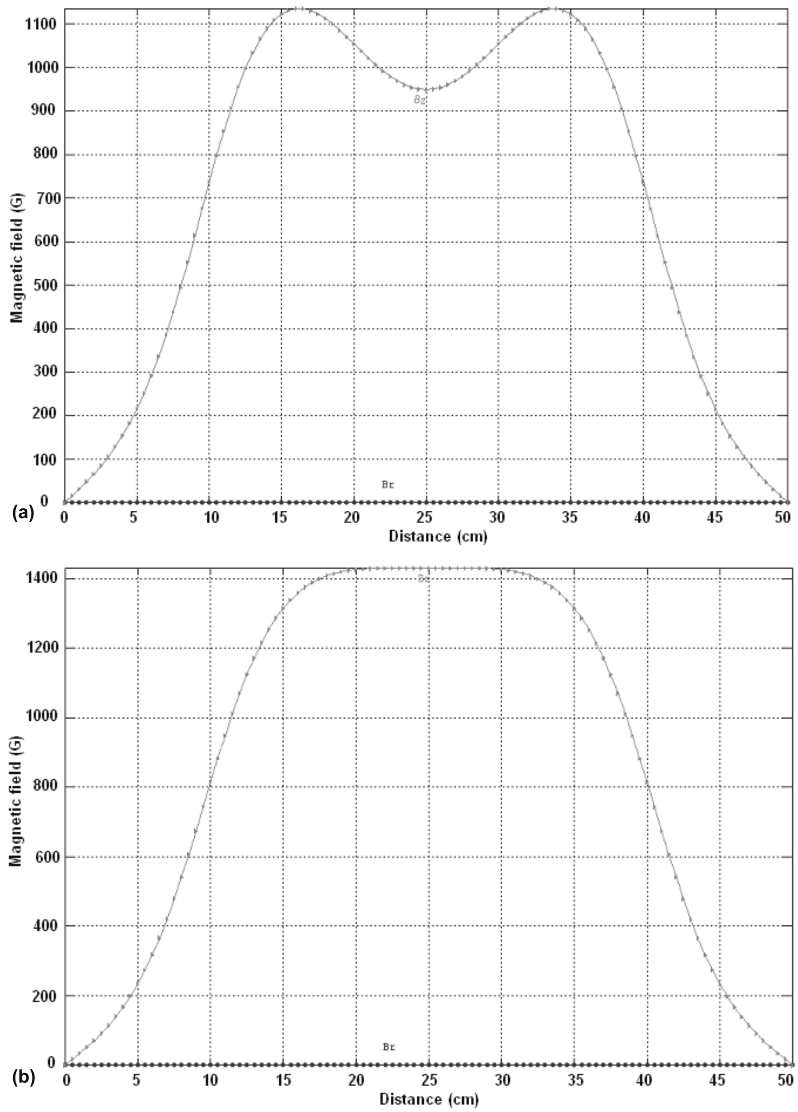

Figure 2. The optimized magnetic field profiles using Poisson software for **(a)** mirror magnetic field, and **(b)** flat magnetic field.

bore diameter of the solenoid coils. These electromagnets were placed around the plasma chamber to produce the necessary magnetic field. The cross-sectional view of the integrated assembly of the three-solenoid coils with iron jacket (electromagnet) is shown in figure 3.

The solenoid coils were cooled using low conductivity water (conductivity less than 1 μS/cm) having inlet temperature of 27°C. Based on the length of the conductor, water pressure drop and flow, the inlet and outlet connections were provided. Total five inlet and five outlet connections were provided. The water flow rate 3 liter/min. and pressure 3·5 kg/cm^2 was maintained. The rise in temperature was restricted to less than 20°C. The inductance and resistance of the solenoid coils were measured using precision LCR meter (Model:PM6306,

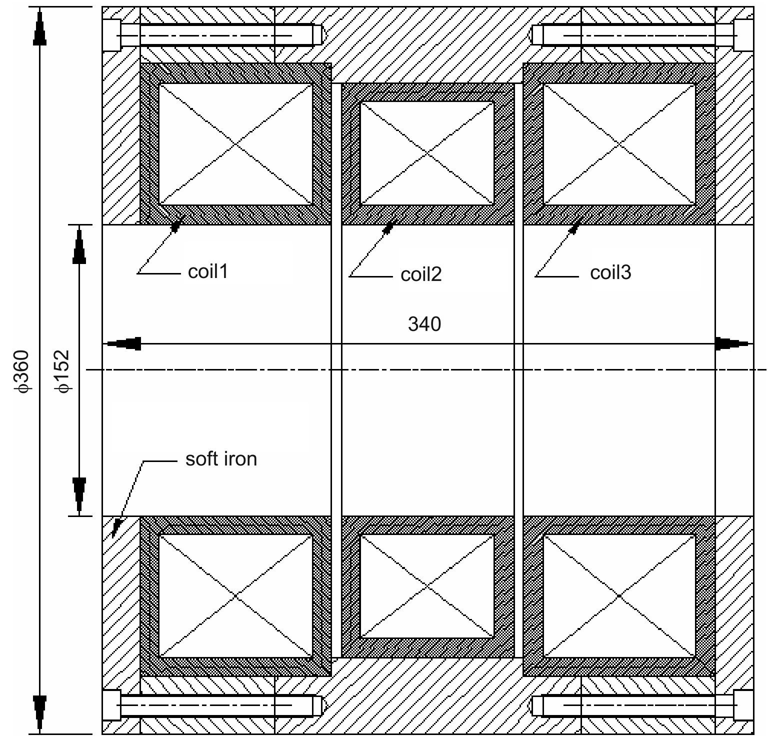

Figure 3. The cross-sectional view of the integrated assembly of the three-solenoid coils with iron jacket (electromagnet).

Make:Fluke). The high voltage insulation to the solenoid coils up to 5 kV dc was tested using high voltage Megger (Model:220123-47, Make:Megger, Biddle, England).

4. Magnetic field mapping

The performance of an electromagnet gets influenced by the design and material limitations, errors in construction, and the stability of the power supply used to energize it. Therefore, after the electromagnets are built, they have to be tested for their performance. The magnetic field measurements were done using computer controlled three-axis coordinate measuring machine (Jain *et al* 2010). A Hall probe (MPT-141) was attached at the Y-arm with a probe holder. The Hall probe had field ranges of 0·3, 0·6, 1·2, 3·0 tesla and corresponding serial/general purpose interface bus (GPIB) resolutions 0·001, 0·01, 0·01, 0·01 G, respectively. The probe size was 15 mm × 5 mm × 2 mm, with sensitive area 1 mm × 0·5 mm. Measurement rate was 10 measurements per second. The error associated in the magnetic field measurements was less than 0·5%. The electromagnets were energized using three independent dc power supplies of rating 0–32 V and 100 A. The stability of the power supplies was 0·1%.

The quality of the electromagnets was fully characterized before installation in the dynamical environment. The successful operation of an ECR source greatly depends on the quality of the magnetic elements and uniformity in the magnetic field (better than 5 G). Imperfections in

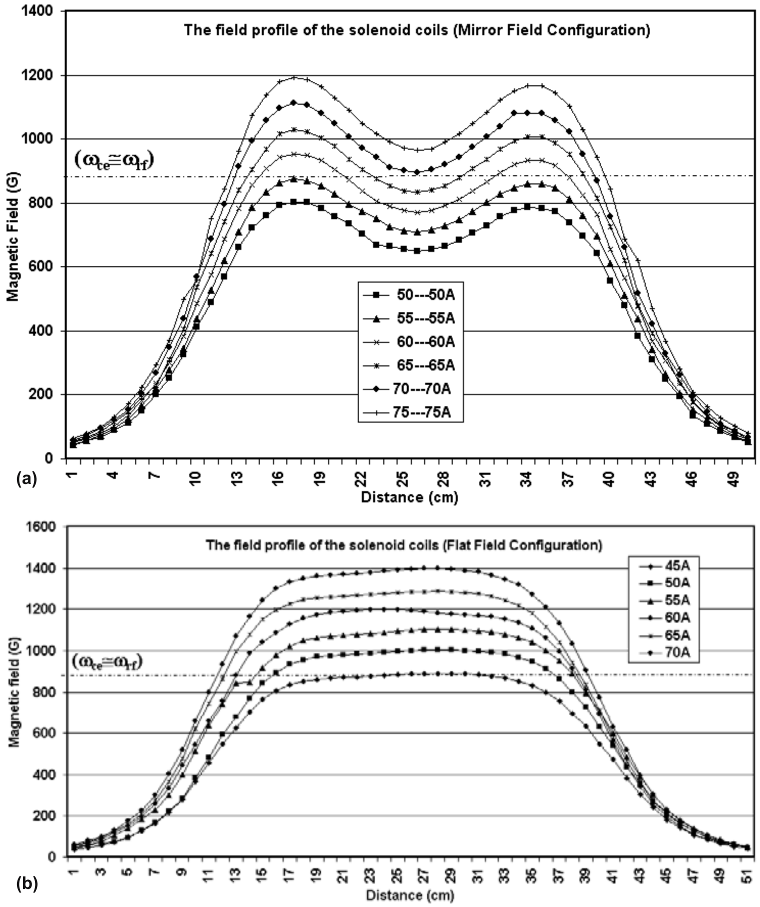

Figure 4. The measured magnetic field profiles along the axial distance for **(a)** mirror magnetic field, and **(b)** flat magnetic field.

the magnetic field can cause diffusion of the plasma particles to the wall of the plasma chamber. The measured magnetic field profiles along the axial distance for (a) mirror magnetic field, and (b) flat magnetic field are shown in figure 4. The measured values (i.e. experimental data shown in figure 4) and the design values (i.e. simulation results shown in figure 2) agree within 3%. The electromagnets were characterized for 45 A to 75 A at steps of 5 A. The variation of magnetic field with solenoid current is shown in figure 5. It is observed to be linear with a slope of 21·5 G/A. The ampere-turns were determined to produce the maximum possible magnetic field on the axis. The size and the power consumption of the solenoid coils were the limiting factors. In order to increase the axial magnetic field and to obtain the required distribution, soft iron jacket were used. The mirror ratio (maximum to minimum) field of the electromagnet was 1·1. A maximum flat field of 1400 G was obtained when all the three coils were independently energized. Using these magnets, ECR plasma was successfully produced (Jain *et al* 2007) using nitrogen, argon, and hydrogen gases. The plasma was characterized using a Langmuir probe (Jain *et al* 2006). A total ion beam current of 2·5 mA was extracted, with two-electrode extraction geometry, at 15 keV beam energy.

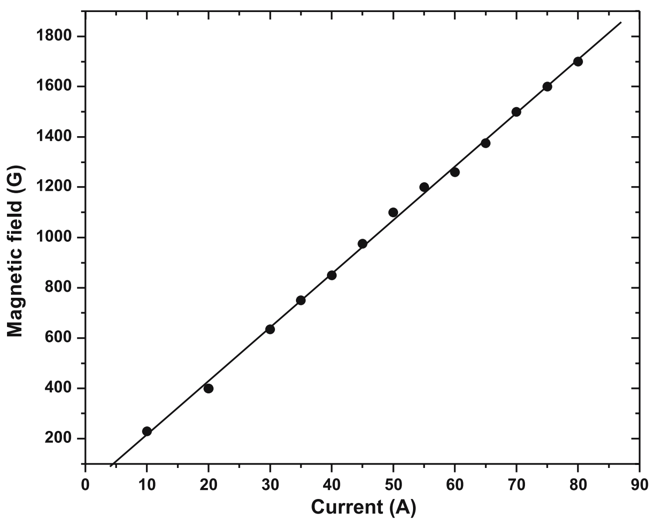

Figure 5. The variation of the magnetic field with solenoid current.

5. Conclusions

The solenoid coil magnets described here offers a continuous control of the axial magnetic field, giving tuning capability. The fine tuning the magnetic field is very important for the stability of an ECR plasma source, as any small change in the distribution of the axial magnetic field can results large changes in the source parameters. The three solenoid coil system is capable of producing off-resonance, mirror, and flat magnetic field configurations. A mirror ratio of 1·1 and a maximum flat field of 1400 G has been obtained. The measured values and the design values are found to have a good agreement within 3%.

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