Superconducting Magnet for Non-Neutral Plasma Research

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***Abstract* — A superconducting magnet intended for non-neutral electron plasma research has been developed and manufactured. The 260 mm room-temperature horizontal bore magnet consists of a main 3 T coil and of two orthogonal pairs of saddle-shaped steering coils, each capable of producing transverse fields of up to 0.03 T. The axial field is homogeneous in a 100 mm diameter and 600 mm long cylindrical volume within 0.25%, the azimuthal inhomogeneity within the same volume is less than 0.01%. All windings operate in a persistent current mode. The liquid helium evaporation rate is less than 6 l/day. The magnet has operated successfully at the University of California, Berkeley, since the first half of 1995.**

I. Introduction

Over the last decade, non-neutral plasma studies have proven to be one of the most fruitful areas of research in basic plasma physics [1],[2]. Pure electron, ion, positron, and anti-proton plasmas have been created. Non-neutral plasma research is applicable to several other physics disciplines, such as two-dimensional fluid dynamics, atomic clock research, ion cyclotron mass spectroscopy, and fundamental studies of anti-matter.

Non-neutral (or charged) plasma is typically confined in Penning-Malmberg traps, which employ an electrostatic well for axial confinement, and an axial magnetic field for radial confinement.

Experiments have shown that the lifetime of the confined plasmas is proportional to B^2/L^2, where B is the magnetic field strength and L is the plasma length. Confinement times of many hours (even days) require field strengths of several tesla for long plasmas. In addition,

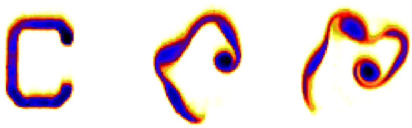

Fig. 1. Evolution of a pure-electron plasma/two-dimensional vortex structure in a Penning-Malmberg trap.

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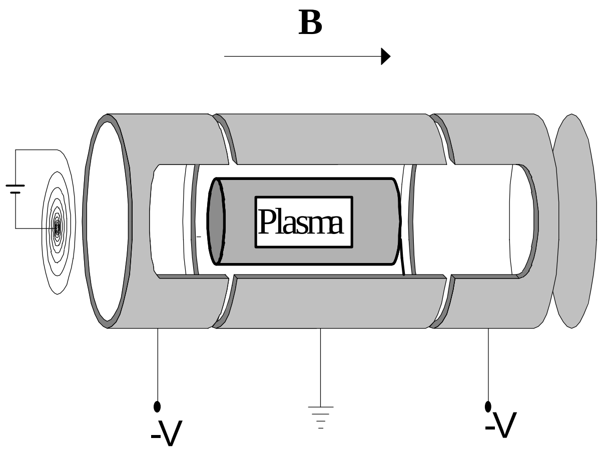

Fig. 2. Penning-Malmberg trap.

strong magnetic fields will induce cyclotron cooling of the plasma. As the cooling time is proportional to B^{-2}, high fields are required to obtain significant cooling rates.

The plasma lifetime is degraded by magnetic field errors and misalignments. The most important class of errors are azimuthal asymmetries, which can couple angular momentum into the plasmas. Azimuthal asymmetries must be reduced to approximately 0.01% to minimize this problem. In addition, the magnetic field must be accurately aligned with the electrode structure that generates the trap's axial well. Consequently the magnetic field must be sufficiently steerable to compensate for any mechanical misalignments between the magnet and the electrodes. Note that extreme axial homogeneity is not required for good confinement; axial homogeneity to a few percents is sufficient.

The uniform magnetic field region must encompass the entire plasma. As the plasmas may be as large as 0.5 m in length and 50 mm in radius, and as extra room is necessary for the electrode structure and vacuum pumping, the magnet bore must be relatively large. Easy access from both ends requires a room-temperature, horizontal bore magnet.

II. Main Magnet

To meet the specifications, the main magnet consists of 5 subcoils. The magnet geometry was optimized using a specially developed computer code which minimizes the

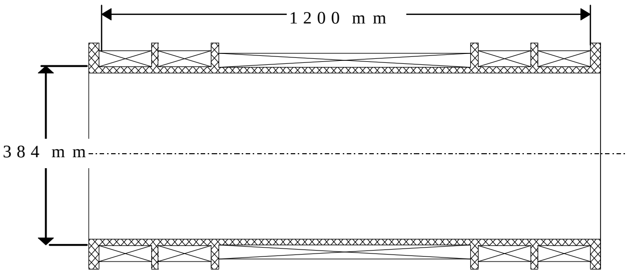

Fig. 3. The geometry of the main magnet

functional $F = \int \left(\vec{B}_0^{\,2} - \vec{B}(\vec{r})^2 \right) / \vec{B}_0^{\,2} \cdot d\vec{r}$ over the required volume. Here $\vec{B}(\vec{r})$ is the computed field induction at the point with radius-vector $\vec{r}$, and $\vec{B}_0$ is the nominal value of uniform field induction. The geometry of the main magnet is shown in Fig. 3 and the axial field distribution and homogeneity are shown in Fig. 4.

All subcoils are wound onto a common fiberglass bobbin, which is carefully machined to obtain the required azimuthal field homogeneity. For the same reason, special attention was paid to the geometry of interconnections between the subcoils as well to the bus-bars between the ends of the magnet and the current leads.

The coils are wound of enamel-insulated NbTi multifilamentary wire. For most layers 1.2 mm diameter wire is used, the number of filaments is 210, and the Cu/Sc ratio is about 1.4:1. Several upper layers of one coil are wound with similar, but smaller (1.0 mm diameter) wire. These upper layers are used to tune the exact number of turns necessary for field homogeneity. The total wire length is approximately 30 km, the total inductance of the main magnet is 76 H, the operational current at 3 T is 130 A, the average current density 1.2×10^8 A/m^2, and the stored energy 650 kJ.

In order to obtain high time stability of the main magnet field as well as to decrease liquid helium evaporation, the main magnet is supplied with a thermally-activated persistent current switch, non-inductively wound of multifilamentary 0.7 mm diameter NbTi wire in a resistive (CuMn alloy) matrix. Its full normal resistance at liquid helium temperature is 23 Ohm, and its inductance is approximately 0.07 mH. Prior to charging the main magnet, the persistent switch is activated by an electrical heater. After charging is started, the heater can be switched off while the switch stays partially normal due to charging voltage if the Joule heating exceeds 0.7 W. Switching off the heater becomes possible due to properly chosen thermal insulation of the switch and is helpful to decrease evaporation of liquid helium during magnet charging**.** The switch is electrically shunted to prevent its overheating in the event that it quenches while the magnet remains superconducting. The magnet itself is passively quench protected by three electrical shunts.

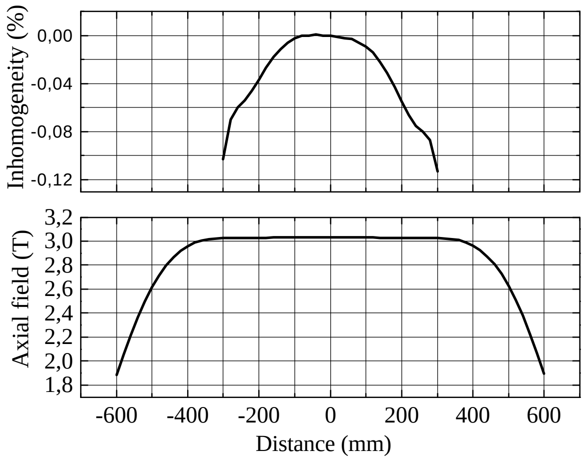

Fig. 4. The field distribution and the homogeneity of the main field along the axis of the magnet.

III. Steering Windings.

Two orthogonal pairs of saddle-shaped steering windings (Fig. 5) are wound onto a common fiberglass cylinder. The cylinder's inner diameter fits the outer diameter of flanges of the main coil bobbin. The role of the steering coils is to correct the field of the main magnet, as well as to vary the transverse field over a wide range.

Both pairs of steering windings are wound of 0.85 mm diameter NbTi multifilamentary wires, whose Cu/Sc ratio is approximately 1.4:1. Four sets of special saddle-shaped grooves are cut onto the outer surface of the cylinder and each single-layered steering winding is placed into a groove and fixed there with a cryogenic glue «Cryoseal» [3]. The length of the straight portions of the grooves is 1200 mm. Each half of each dipole winding consists of 79 turns (the wire length is 235 m). The parameters of each dipole are as follows:

- central field induction is 30 mT at 150 A;
- field inhomogeneity in the 600 mm interval along the axis is about 1%;

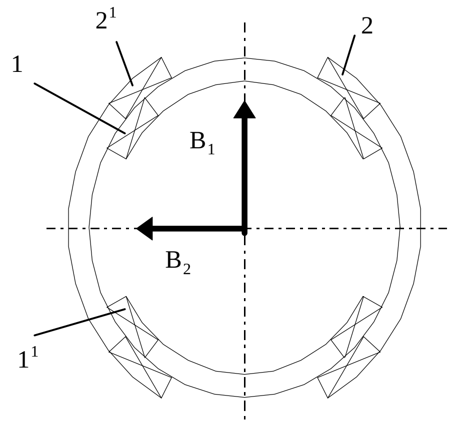

Fig. 5. Schematic of steering coils

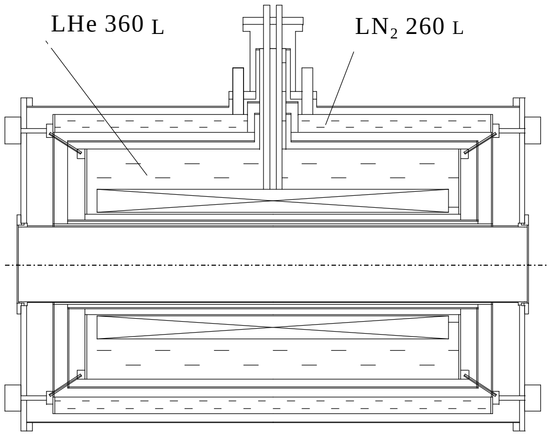

Fig. 6. General layout of the cryostat

– inductance of each windings is approximately 10 mH;
– stored energy at 150 A is 110 J.

The steering windings are charged independently, and each of them is supplied with a persistent switch made of the same wire as the winding. The wire length in each switch is 6.2 m, the full normal resistance at 4.2 K is 0.3 Ohm, and the inductance is approximately 10 μH.

IV. CRYOSTAT

The main layout of the cryostat is shown in Fig. 6. The magnet assembly is placed onto an inside tube of the cylindrical helium vessel. The helium vessel is surrounded by liquid nitrogen vessel, and there is an additional vapor-cooled radiation shield between the nitrogen and helium vessels. The shield is thermally attached to the vertical neck tube. In addition to cryogen replacement and evaporation, the neck is used for three pairs of demountable current leads and for the heater wires. Twelve tensioned fiberglass supports (six from each side) are used to hold the helium vessel and the magnet, and to adjust the clearance between the cold and warm central tubes. The helium and nitrogen vessels, and the cylindrical part of the outer casing, are made of stainless steel. The side flanges of the casing, central warm-bore tube and most of radiation shields are made of aluminium. Almost all the surfaces of the helium and nitrogen vessels and of the radiation shields are covered with several layers of superinsulation. If necessary, the cryostat can be disassembled relatively easily.

V. TEST RESULTS

Both main magnet and steering coils were tested in an open cryostat prior to final assembly. During the test, nominal field inductions (3 T in the main magnet and 30 mT in both steering windings) were obtained without quenching.Magnetic field measurements showed a very good (within the measurement accuracy) coincidence with calculated values. In the persistent modes, the time stability was better than $4\cdot10^{-7}$ per hour for the main magnet and better than 10^{-5} per hour for both steering coils.

All windings proved able to operate at full fields in gaseous helium until liquid helium has almost totally evaporated. In a steady-state mode of operation (with all 6 current leads disconnected) liquid helium evaporation rate was about 6 l/day.

Nowadays the magnet is in successful operation in the Physics Department at the University CA, Berkeley (Fig. 7).

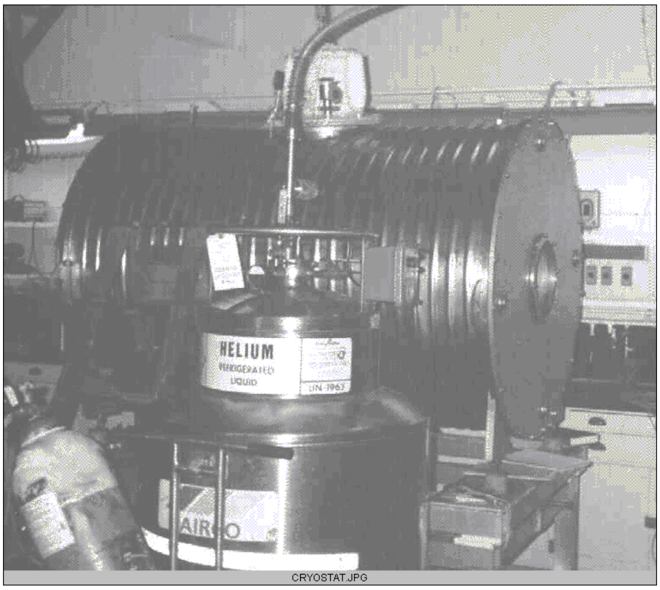

Fig. 7. Testing of the magnet at the University CA.

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