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Toward a Compact Levitated Superconducting Dipole for Positron-Electron Plasma Confinement

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Abstract. This paper describes the design of a compact levitated superconducting coil for the production of a magnetic dipole field to eventually trap positron-electron plasma. The closed 300 turn coil is to be constructed from Bi-2223 high-T_c superconducting tape, directly cooled on a cryogenic cold head (with thermal contact enhanced using helium gas), and inductively energized with a second superconducting coil mounted on the same cold head. Levitation will be achieved from above using a water-cooled copper coil outside the vacuum chamber and its current will be feedback controlled using vertical position information from a laser ranger.

INTRODUCTION

The APEX (A Positron-Electron EXperiment) collaboration aims to produce a magnetically confined pair plasma consisting of nearly equal numbers of positrons and electrons [1,2,3]. This would enable study of the unique stability and wave propagation properties predicted for such systems. The magnetic dipole field [4] has good confinement properties for both quasi-neutral and non-neutral plasmas (as well as for single-charged particles) [5,6,7] and is therefore a promising configuration for this project. This paper describes plans to create a compact levitated superconducting dipole trap suitable for conducting such experiments.

LEVITATION PHYSICS

A circular current-carrying coil can be magnetically levitated using the field of a larger "lifting" coil. In addition to force balance requirements, one must address the stability of the equilibrium. The magnetostatic version of Earnshaw's theorem indicates that not all six degrees of freedom (three translational and three rotational) can be simultaneously stable without employing active feedback. We describe a configuration in which only one degree of freedom is unstable, namely vertical displacement, which makes feedback stabilization feasible [8,9].

A simplified picture of the levitation scenario is described by a small magnetic dipole (the levitated or "floating" coil) experiencing a net vertical force due to the gradient of the field produced by a second "lifting" coil. The force is given by $\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\vec{B}$, where $\vec{\mu}$ is the magnetic dipole moment of the floating coil and $\vec{B}$ is the magnetic field

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produced by the lifting coil. If the dipole is aligned with the field of the lifting coil so that stability to tilt displacements is assured, then the lifting coil should be placed above the floating coil; the aligned dipole is attracted to the region of stronger field. The conditions for equilibrium (balancing the magnetic force and the weight) can be expressed in a normalized fashion as

$$-K\frac{(z/R_L)}{\left((z/R_L)^2+1\right)^{5/2}}=1 \tag{1}$$

where z is the vertical position of the floating coil relative to the center of the lifting coil, R_L is the radius of the lifting coil, and K is a dimensionless parameter that is given by

$$K=\frac{3\pi\mu_0}{2m_F g}\left(\frac{R_F}{R_L}\right)^2 I_L I_F \tag{2}$$

This parameter depends on the weight of the floating coil $m_F g$, the ratio of the radii of the floating (R_F) and lifting (R_L) coils (squared) and the product of the number of amp-turns of current in the two coils ($I_L I_F$). The lifting parameter must exceed a threshold value of about 3.5 for equilibrium solutions to exist. Then, because the gradient of the on-axis field of the lifting coil has a maximum (at a position below the center of the lifting coil and at of distance of half its radius), there are two equilibrium positions. Figure 1 shows the vertical magnetic force on the floating coil normalized to its weight (left side of Eq. 1) versus the vertical position of the floating coil where the origin is at the center of the lifting coil. The lower equilibrium position is preferable as it is stable to the two degrees of horizontal or "sliding" displacements, and unstable to only one degree of freedom - vertical displacement. By employing active feedback on the vertical displacements, stable levitation of the floating coil can be achieved.

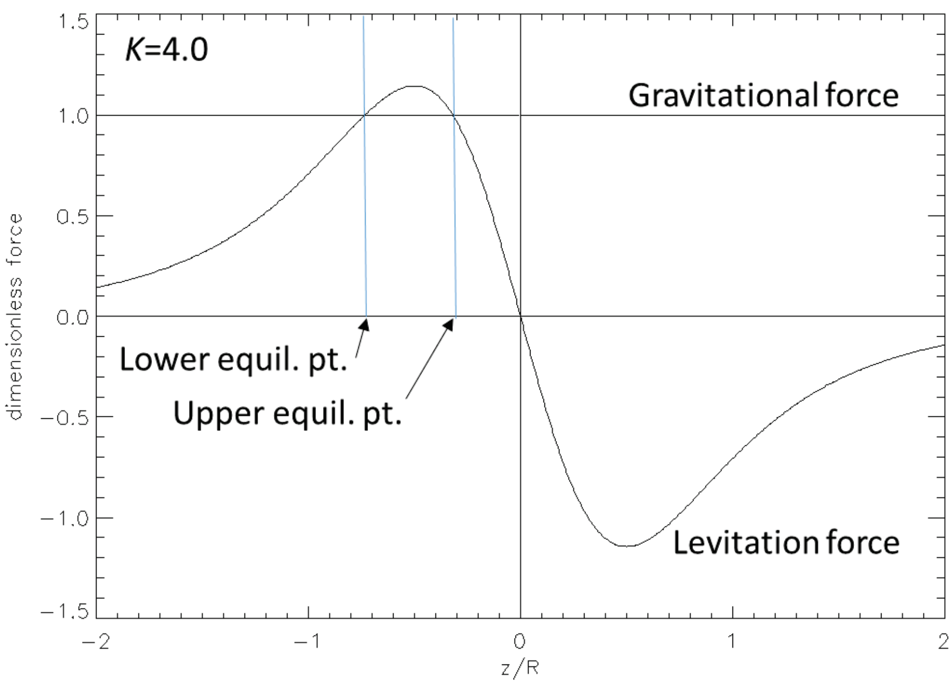

FIGURE 1. Magnetic levitation force on the floating coil normalized to its weight as a function of its vertical position relative to the center of the lifting coil.

The results of a more detailed stability analysis are shown in Fig. 2. The contours in Fig. 2 represent values of a stability parameter for different equilibrium vertical locations and radii of the lifting coil (in units of the radius of the floating coil). For each class of displacement, derivatives of the components of the magnetic field of the lifting determine whether the resulting force is restoring (stable) or not (unstable). Solid contours in Fig. 2 represent stability and dashed contours instability. Panel (a) shows (in)stability to both slide and tilt displacements superimposed and panel (b) show vertical stability. The regions of vertical stability (solid purple (online) and instability (dashed red (online)) are complementary to the regions of slide stability (solid purple (online)) and instability (dashed red (online). There is no region of parameter space that is stable to both vertical and slide displacements. Tilt stability (solid green (online)) is assured if the lifting coil is significantly larger than the floating coil. Also indicated on this figure are the configurations of past levitated dipole experiments, Mini-RT, RT-1, and LDX. All operated in the region of slide and tilt stability and vertical instability, as will the project described in this paper.

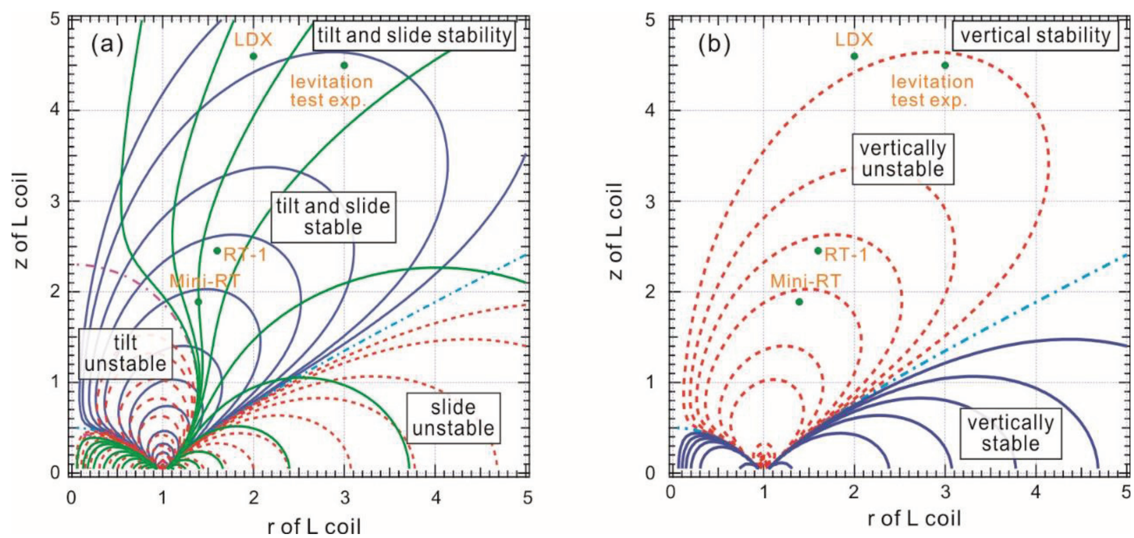

FIGURE 2. Results of stability analysis for levitation of a floating coil in the field of a lifting (L) coil for various equilibrium vertical positions and lifting coil radii (relative to the radius of the floating coil). (a) Solid contours indicate stable values of the stability parameter for slide and tilt and (b) for vertical displacements while dashed contours are unstable regions.

BASIC DESIGN CONCEPT AND DEVELOPMENT STATUS OF APEX-D

Based on the levitation and stability analysis described in the previous section, we are developing a compact levitated dipole experiment, APEX-D ("D" for dipole), for the magnetic confinement of electron-positron pair plasmas [1]. In order to realize simultaneous trapping of positrons and electrons as a plasma, we plan to use closed magnetic field lines generated by a superconducting (SC) levitated dipole field coil. In this section, we describe the machine characteristics suitable for the formation of matter-antimatter plasmas by comparing with previous levitated dipole experiments. Together with these considerations, we report on a basic design concept for APEX-D and its development status.

Overall Concept of APEX-D

Because the intensity of available positron sources is far weaker than that of electrons, we need to develop a small-volume confinement geometry in order to generate high density electron-positron plasmas. This consideration imposes strong constraints on the structure and operation of APEX-D as a levitated dipole experiment. In fusion-oriented levitated dipole experiments, for example Mini-RT and RT-1 at the University of Tokyo [6,10], the SC coils are cooled by circulation of 20 K He gas [11,12]. In these experiments, the SC coils are directly energized and demagnetized using external power supplies. The SC coil case for these experiments contains structures for He gas circulation with removable connectors, a persistent current switch (PCS), removable current feedthroughs, and thermal insulation structures, together with the SC tape winding itself. In a compact SC coil for APEX-D, it is not feasible to install and operate such complicated systems inside the coil case. One of the major differences in the operation environment for APEX-D compared to that of fusion-oriented experiments is the heat input characteristics into the SC coil winding. Because the SC coil of APEX-D is operated in the UHV environment with very low density ($< 10^{12}$ m^{-3}) plasma, it is not necessary to place the thermal insulating structures inside the coil case. A simpler coil system is therefore possible, as shown in Figure 3 (b), which permits direct cooling by the thermal contact with the cold head of a cryocooler. Figure 3 (a) shows basic design ideas for this compact dipole experiment with the following characteristics:

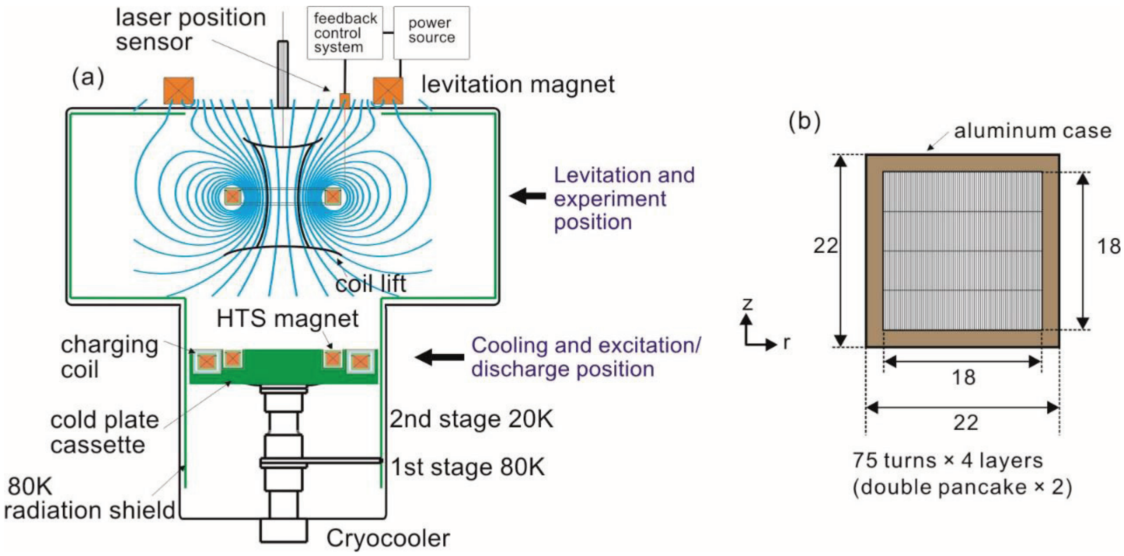

FIGURE 3. (a) Conceptual schematics for a compact levitated dipole experiment for the trapping of pair-plasmas and (b) cross section of its SC floating coil winding.

- **Direct cooling of the SC coils by thermal contact:**

We plan to cool the SC coils (both the floating coil and the charging coil) by direct thermal contact with the cold head of a cryocooler. In order to minimize heat input into the SC coils, while keeping good thermal contact with the cryocooler, a thermal insulating layer (or radiation shield) is placed near the vacuum chamber walls instead of inside the coil case. According to the previous experiments on RT-1, an increase of neutral gas pressure significantly enhances heat input into the SC coil. Thus it would be advantageous to maintain a UHV environment in the entire experiment period for pair-plasmas, in contrast to high-temperature fusion plasma experiments. With this method, we have realized SC transition for a test coil. The simplified and compact SC coil structure has another advantage in that it reduces the scrape-off region associated with field lines from the trapping volume which intersect the coil case.

- **Inductive charging:**

For magnetic excitation and demagnetization of the SC floating (F) coil, we will employ an inductive charging and discharging method in order to simplify the F coil design. For this purpose, an open lead charging (C) coil, connected to an external power supply will be located close to the F coil (see Fig.3). The operation scheme is as follows. First, the C coil is turned on while the F coil temperature is above the critical temperature, T_c. After the F coil is cooled below T_c, the C coil is turned off. A persistent current is thereby induced in the F coil in order to conserve the magnetic flux inside the F coil. On discharging, the C coil current is increased from zero to a certain value so that the persistent current in the F coil becomes zero. Then the F coil is heated above T_c, and the C coil is turned off. Because these operations are conducted solely by the C coil and its power supply, we do not need to install a complicated direct charging system and associated switches for the F coil.

- **Magnetic lifting of the SC coil:**

Many levitated dipole experiments use mechanical lift systems for the SC coil. Such a system is essential for an experiment with a large confinement volume and operated with high-temperature plasmas, where the SC F coil is charged and discharged at the bottom of the chamber far below the experimental position. We plan to magnetically lift the SC F coil from the cold head to the experimental position. Whereas this is not practical in fusion levitated dipole experiments, in the present compact experiment, it is possible that to magnetically lift the F coil using a normal water-cooled copper lifting (L) coil located outside the vacuum. Such a system is advantageous to carry out a levitated dipole experiment on a positron beamline, where space is limited.

Coil Parameters and Operation Temperature

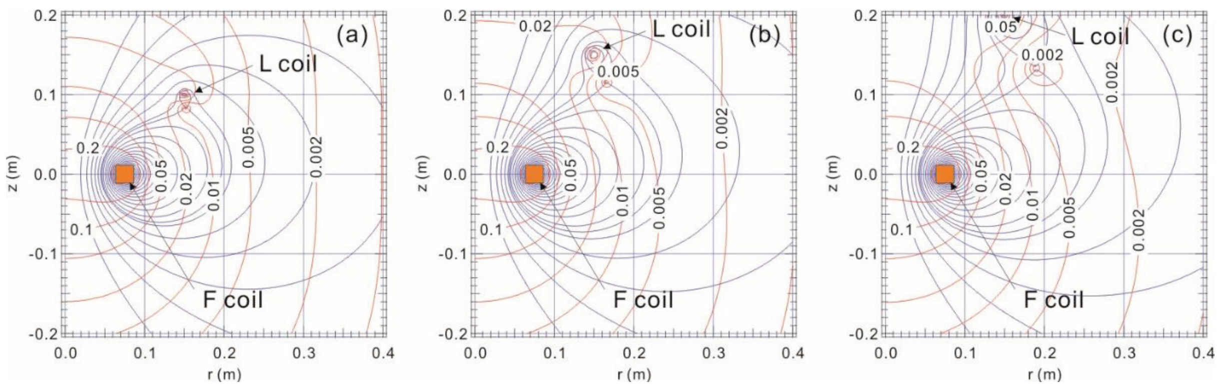

FIGURE 4. (a) Magnetic field lines and strengths (in T) generated by the combination of F and L coils. Major radii of the F and L coils are chosen to be $R_F = 7.5$ cm and $R_L = 15$ cm. Bold lines show the separatrix and the outermost scrape-off region.

We plan to use Bi-2223 high-T_c SC tape for both the F and C coils. In early 2017, we made a small test winding with Bi-2223 tape in collaboration with NIFS, Japan, which have since been used for cooling and excitation tests at IPP Garching. Figure 4 shows magnetic field configurations generated by the combination of the planned parameters of F and L coils. For the formation of high density plasmas in a small volume, small major radius R_F of the SC coil winding is preferable. On the other hand, a coil with small R_F has a larger scrape-off region, where magnetic field lines intersect the coil structure. Field calculations close to the coil structure have been performed and lead us to choose a coil of $R_F = 7.5$ cm with 300 turns. The total weight of such a coil winding including a simple aluminum case is 1.6 kg. Figure 4 shows field calculations for three locations (and equilibrium currents) for the lifting (L) coil. When the L coil is located at z = 20 cm in Figure 4 (c), the L coil current needed for the F coil levitation is 4.5 kA, which can be generated by a conventional water-cooled copper coil winding. As shown in Fig. 4, the scrape-off region generated by this coil is relatively small. The confinement volume of this coil is approximately 35 liters, though it depends sensitively on other parameters. The maximum field strength inside the coil winding, at the rated coil current of $I_F = 100$ A, is $B_z = 0.74$ T. By comparing with critical temperatures for Bi-2223 tapes, a coil operating temperature below approximately 50 K is required. When the coil winding is cooled to 20 K, the heat input needed for the temperature rise to 50 K is 3000 J. In order to operate the cooled coil for the order of an hour, heat input power must be limited to less than ~ 1 W, which can be realized by a thermal radiation shield cooled by the first stage of a cryocooler (Fig. 3 (a)).

Development of Feedback Levitation System

We developed a magnetic levitation system using a proportional-integral-derivative (PID) feedback control circuit. Figure 5 shows (a) the schematic of the levitation test experiment and (b) the results of a long time levitation test using a cylindrical neodymium magnet of diameter 20 mm, height 3 mm, and weight of 7 g. Including buffer material wrapped around the magnet, the total weight of the magnet was 8.4 g. The magnet position was monitored by a laser sensor, whose signal was sent to a feedback controlled circuit for the power supply of the levitation coil. The field strength at the magnet surface was 0.18 T, according to measurements with a Hall sensor. We approximate this magnet as a current loop of 2990 A and diameter of 20 mm. Stability analysis of the vertical motion of the magnet with this approximation showed good agreement with the experimental results. The equilibrium coil position, the L coil current I_{L1} and position signal V_{i1} from a laser sensor are uniquely determined.

The equilibrium is determined by the equation of motion and the flux conservation law for SC coils. Two conditions must be satisfied: 1) that the coil is not too heavy (or the L coil current is strong enough) so that the equilibrium has a real solution, and 2) that the system can be stabilized with the used P value in the feedback circuit. The F coil is levitated at a certain point according to the values of a reference voltage for the feedback circuit and P. Small deviations from the equilibrium state can be controlled by the D component of the feedback circuit and its process is adjusted by the I component. The circuit developed for the test experiment will be used to control the levitation of the F coil in APEX-D.

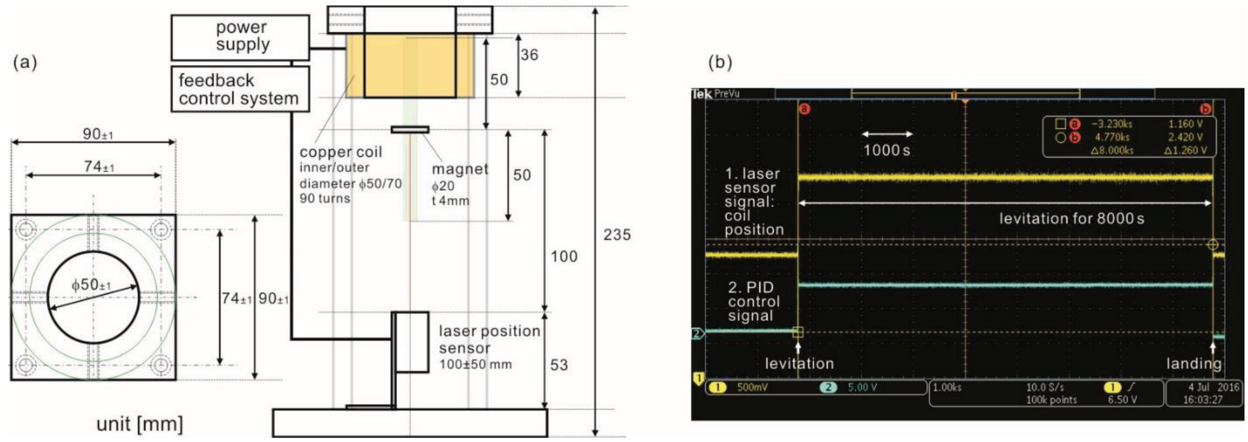

FIGURE 5. (a) Schematic of a permanent magnet levitation experiment and the levitation control system. (b) Long time (approximately 8000 s) behavior of (1, yellow) the analogue output signal of a laser position sensor and (2, cyan) PID control signal during the levitation of a permanent magnet.

SUMMARY

This paper describes basic physics of magnetic coil levitation and design plans for levitation of a compact high-T_c superconducting coil using a normal conducting lifting coil with active feedback on vertical displacement using laser ranging detectors. The coil is to be inductively charged using a second superconducting coil, both of which are cooled by a single cryo-cooler located below the confinement region. To date, the coil design has been determined, the cryo-cooling and lifting coil system are under development, and a proto-type feedback levitation system has been successfully demonstrated.

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