Levitated Dipole Experiment

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**A Facilities and Resources**
The Plasma Physics Laboratory of Columbia University and the Plasma Science and Fusion Center (PSFC) of the Massachusetts Institute of Technology propose to conduct experiments using the Levitated Dipole Experiment (LDX). LDX is an entirely new research facility to test whether fusion can benefit from nature’s way to confine high-temperature plasma [1]. The dipole fusion concept is motivated by satellite observations of planetary magnetospheres that show centrally-peaked plasma pressure profiles forming naturally when the solar wind drives plasma circulation and heating. Unlike tokamaks, stellarators and RFPs, stable dipole confinement derives from plasma compressibility instead of the shear of magnetic field lines and average good curvature [2, 3, 4]. The dipole magnetic geometry can stabilize plasma at very high $\beta$, or plasma pressure [5], and the absence of magnetic shear is expected to decouple particle and energy confinement. For these and other reasons, the dipole fusion concept offers an alternate path to fusion power—one that avoids both the use of tritium fuels and the need for expensive materials and breeding technologies but requires the development of high field, high-temperature levitated superconducting magnets.

The LDX experiment is also an important partnership between plasma scientists and magnet technology experts. LDX incorporates innovative engineering and design in its three superconducting magnets [6]. The floating coil is made from advanced Nb$_3$Sn conductor having a critical current more than 1.5 times greater than the ITER conductor that will allow the coil to levitate safely for several hours [7, 8]. The charging coil, constructed in St. Petersburg, Russia (by the same group that built ITER’s TF model insert coil), is made from 35 km of NbTi conductor formed into a large, 8-ton, 4 MA coil [9]. The levitation coil is fusion’s first high-temperature superconducting magnet, and it will be operated continuously to counter-balance the gravitational force on the floating coil [10].

While the fabrication of the LDX facility has proven to be more challenging than originally anticipated, all three magnets have been wound and tested to a degree the gives confidence that all research objectives of the experiment can be achieved. Based on the likely delivery schedule of the superconducting coil from St. Petersburg, we expect to begin plasma experiments within our present grant period. This proposal provides for the systematic scientific investigation of dipole confinement and stability and for the first exploration of the dipole fusion concept.

The remainder of this proposal is organized into several parts and explicitly addresses each of the items requested in DOE Notice 03-19. These are:

1. Statement of the goal of the proposed research and a summary of both the scientific and educational objectives.
2. Short synopsis of the research plan.
3. Results and deliverables expected at the end of the project period.
4. Brief review of the dipole fusion concept (Section 4). This section explains why the dipole
fusion concept is an attractive pathway to practical fusion energy since it may make possible the burning of deuterium fuel.

5. Discussion of how the research plan elucidates the physics principles of the dipole fusion concept (Section 5).

6. Short description of the LDX experimental device, plasma parameters, and diagnostics (Section 6). This section also serves as a report of our prior grant activities that fabricated the LDX device and developed the physics of the dipole confinement and stability.

7. Detailed LDX research plan (Section 7) including our major research activities that will achieve our scientific objectives. LDX explores an entirely new confinement configuration. Because the LDX links fusion research to space plasma physics it has attracted a lot of public interest and the LDX research plan incorporates educational and outreach activities.

8. Finally, Section 8 describes the adequacy of the budget and the research facilities. Further details of the LDX research facility including the superconducting magnets, and support systems are included in the section entitled “Facilities and Resources.”

The LDX website, http://www.psfc.mit.edu/ldx/, describes the design and daily operation of LDX, lists 40 status reports describing the month-by-month fabrication of LDX, and presents several presentations, reprints, and preprints.

1 Goal of Proposed Research

This renewal proposal requests funds to carry out a three-year scientific study made possible by the construction of the entirely new and innovative LDX research facility.

The goal of the proposed research is to understand the equilibrium, stability and confinement properties for a plasma that is confined in the field of a levitated dipole.

The proposed LDX experiments will yield new data on high-beta magnetic plasma confinement in a dipole magnetic field. They will be the first systematic investigations of the use of MHD compressibility to achieve stability with significant and highly-peaked plasma pressure. LDX will also provide the basis for understanding of (1) energetic particle confinement and stability in a dipole magnetic field, (2) the relation between edge plasma and a hot plasma core, (3) the possible elimination of drift-wave turbulence to produce plasmas with classical confinement, and (4) the circulation and adiabatic heating of plasma confined by closed, shear-free magnetic field lines. Finally, LDX has important outreach and educational goals. Because the dipole concept was motivated by observations of magnetospheric plasma, contributes basic understanding to the dynamics and confinement of plasma trapped by a dipole magnetic field, and incorporates superconducting magnets, LDX has attracted considerable public interest and the involvement of undergraduate and graduate students and visiting scientists from Japan and Germany.
Figure 1: Cross-section view (left) of LDX experiment showing the basic coil configuration and plasma equilibrium resulting from ring levitation. Magnetic field lines (solid) and $|B|$ contours (dotted) are shown. Photograph of experimental cell (right) showing the vacuum vessel and launcher system.

2 Synopsis of Research Plan

The LDX research plan is organized along two interconnected pathways. First, the plan is organized into three scientific tasks:

1. Experiments to test and understand compressibility stabilization.

2. Experiments to measure and control particle circulation and adiabatic heating.

3. Experiments to measure and understand dipole plasma confinement at high beta.

Each of these physics tasks involve active experiments where plasma control tools (e.g. shaping coils, multiple frequency electron cyclotron heating, and particle sources) are used to modify plasma conditions and where plasma diagnostics are used to measure local and global parameters. These physics tasks are strongly coupled to our theory and modeling efforts.

Second, our research plan is separated into three carefully planned facility stages that allow the safe and reliable operation of the LDX superconducting magnets and that allow the coordi-
nated installation and test of diagnostics and research tools. The three stages of LDX facility operation are:

1. Supported coil operation and investigation of the production of high beta energetic electrons with multiple-frequency ECRH.

2. Levitated coil operation and investigation of dipole confinement and compressibility stabilization in a high-temperature plasma.

3. Studies of high-density plasma created with fast gas and Li pellet injection.

The proposed three-year LDX schedule provides for all three of these operational phases and allows experimentation with both long-pulse, energetic electron plasmas produced by ECRH and for relatively transient plasmas produced by fast gas and Li pellet injection.

The first stage of our plan will begin this summer shortly after the arrival of the large, superconducting charging coil from St. Petersburg. Based on our previous experience with microwave heating of plasmas confined by magnetic mirrors and supported dipoles, we expect little difficulty with the production of relativistic electrons shortly after the start of plasma operation. The second stage begins during the first year of our proposed program. We will launch the first levitated coil experiments and begin the important research using hot electron plasmas to study high-beta equilibrium and stability and the maximization of stored energy by using multiple frequency ECRH. The study of high density plasma and confinement is the last stage, beginning in the second program year.

The LDX research plan achieves its scientific objectives by executing active experiments that directly test the physics of dipole stability and confinement. The pressure profile of high beta plasma will be adjusted by applying multiple frequency ECRH (with frequencies between 2.45 and 28 GHz). Magnetic compressibility will be adjusted by adjusting the shape of the outer boundary of the plasma with a low-current Helmholtz coil. A 50-fold increase in stored energy is predicted in LDX when the flux expansion increases as these shaping coils are adjusted. Convective cells will be measured and excited by edge probes. Finally, fast deuterium gas puff techniques or the injection of lithium pellets [20] will be utilized to thermalize the energy stored in the hot electrons and to raise the plasma density. We will use inner and outer fueling to modify the density profile of these thermal plasmas, test MHD limits, and investigate confinement. As appropriate for first-ever experiments, our strategy uses these active experiments to reveal limiting processes and to determine general and important features of high-beta, stability, and particle convection.

3 Specific Results and Deliverables

Our proposed LDX research program will answer two important questions needed to establish the dipole fusion concept and achieve several research objectives that advance our fundamental understanding of dipole physics.
1. First, LDX will answer the question: can a dipole magnetic field confine a high beta plasma with near classical energy confinement as suggested by theory?

2. Second, experiments with LDX will determine whether plasma confined by a dipole can circulate rapidly from the core to the edge without degrading energy confinement.

The answers to these two questions are necessary to evaluate the suitability of the dipole fusion concept to burn advanced fusion fuels.

Our LDX experimental program will also advance our fundamental understanding of several important areas of plasma physics and magnetic fusion science. These include:

- The study of high beta plasma stabilized by compressibility. The compressibility constraint will determine the coupling of the scrape-off-layer and the hot plasma core.
- The determination of the relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence.
- The investigation of strong plasma flows and convective cells in a large confined plasma without magnetic shear.
- The understanding of the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields.

By the end of the proposed research program, we will have had three years of systematic study of high beta dipole plasmas and be able to report on the feasibility of the dipole confinement concept as a potential route to an innovative fusion power source. These studies significantly benefit from especially strong interactions with theory and modeling efforts.

4 Dipole Fusion Concept and the Pathway to Practical Energy

The dipole fusion concept was first proposed in 1987 by Akira Hasegawa [21] who was motivated by observations of planetary magnetospheres [22]. Akira asked whether fusion energy could benefit from our knowledge of plasma trapped and confined naturally in the dipole fields of magnetized planets. Unlike traditional toroidal configurations in which field lines define irrational flux surfaces (which surround and include rational surfaces) the dipole has closed field lines. The dipole magnetic confinement concept is based on the idea of generating and maintaining pressure profiles near marginal stability for low-frequency magnetic and electrostatic fluctuations.

The start of fabrication of the LDX experiment has motivated a substantial theoretical development in the dipole physics including work at MIT, Columbia, UCLA, UCSD, U. Texas (Austin) and the Kurchatov Institute in Moscow. These more recent theory efforts have lead to the evolution of the dipole concept while also supporting the scientific validity of Hasegawa’s original concept. Recent theory has also guided our experimental program and improved the prospects for a practical dipole power configuration. We fully expect that continued theory work will aid in planning and interpreting of upcoming LDX experiments.
The recent theoretical efforts in dipole physics answered questions of MHD stability, thermal and convective transport, and fusion power configurations.

Several authors have explored the ideal [5, 23] and resistive MHD [42] properties of a high beta dipole confined in a dipole field. The stability of drift frequency modes has been explored by Hasegawa and co-workers [24] and recently by Kesner, Simakov, Hastie and others [25, 26, 27, 28]. Convective cells and flows in closed field line configurations has been studied by a number of groups [29, 30] including PIC simulations by Dawson’s group [31] and non-linear reduced MHD studies of Pastukhov and co-workers [32, 33, 34, 36].

Pastukhov and Sokolov [35, 37] have developed theories of thermal transport to the levitated ring when the surrounding plasma fully recycles neutrals and Mikhailovskii [38] has explored the effect of opening the field lines. Finally, the CTX device at Columbia University has illustrated the stability properties of collisionless energetic electrons confined by a dipole magnetic field [15, 16, 17, 18, 19]. This literature provides a strong physics basis for levitated dipole research.

Hasegawa, Chen, and Mauel [24, 39] have made initial explorations of dipole fusion power sources and Teller, Fowler, et al. [40] have developed a conceptual design of a levitated dipole space propulsion system. Kesner and co-workers have recently explored a dipole as a DD based power source that would eliminate both the difficulty of tritium breeding and the neutron damage and shielding requirements that follow from production of 14 MeV neutrons [41].

The remainder of this section describes the fundamental principles of dipole confinement and stability that underlie the dipole plasma confinement, and presents recent (but still preliminary) considerations for practical dipole fusion power sources.

### 4.1 MHD Equilibrium and Stability

**MHD Equilibrium.** We have developed an equilibrium code, DIPEQ [5] that can be run in either a predictive or interpretive mode to solve the Grad-Shafranov equation for arbitrary beta. Several plasma equilibria are shown in Fig. 2 (in Section 5). In practice, MHD interchange stability will limit the pressure gradient as indicated by Eq. 1 and so the peak beta obtainable depends on the edge plasma pressure and on the magnetic field flux expansion, \((V_{sol}/V_0)^\gamma\) with \(V(\psi) = \oint d\ell/B\) the volume of a tube of unit flux. As found in other toroidal equilibria, various integral conditions exist that aid the interpretation of experiment. For example, it can be shown that a consequence of MHD equilibrium is that the diamagnetic ring current of the plasma is equal to the integral of the pressure gradient, i.e. \(I_p = I_R - I_C = \int_{\psi_{min}}^{\psi_{max}} d\psi V(\psi)dp/d\psi\), with \(I_C\) the current in the floating coil and \(I_R\) the total current as measured by a Rogowski coil. For the expected profiles, \(I_R\), which can be directly measured with a Rogowski coil and is analogous to the Earth’s ring current, provides a measure of the plasma stored energy.

**High Beta Stability through Compressibility.** From ideal MHD, a plasma confined in bad curvature will be in a marginally stable state when the pressure profile, \(p(\psi)\) satisfies the adiabaticity condition,

\[
\delta(pV^\gamma) = 0 \rightarrow p_0/p_{sol} = (V_{sol}/V_0)^\gamma
\]

where \(\gamma = 5/3\) [2, 3]. Throughout the proposal, we have the designated core values, i.e. those
at the pressure peak, with a zero subscript and edge, or scrape-off-layer, values with a “sol” subscript. The stability requirement can also be written as $d \equiv -d\ln p/d\ln V < \gamma$. Importantly, this is a limit on the pressure gradient and not on the pressure. Thus a large enough dipole plasma can have arbitrarily large local beta values and at these high beta values the magnetic field is largely excluded from the region of the pressure peak on the outer dipole midplane. Recent calculations have shown that when a high beta dipole confined plasma is stable to interchange modes it will also be stable to ideal ballooning modes [5]. The stability of ballooning modes at high beta has also been shown for a point dipole [23]. The adiabaticity condition leads to pressure profiles that scale radially as $p(\psi) \sim 1/V(\psi)^{\gamma}$ and gyrokinetics lead to density profiles that scale as $n(\psi) \sim 1/V(\psi)$. Thus, for adiabatic profiles the value of $\eta \equiv d\ln T/d\ln n = \gamma - 1 = 2/3$. In a dipole magnetic field, $V(\psi) \sim r^4$, and the marginally stable pressure can increase rapidly with decreasing radius, $p(r) \sim r^{-20/3}$. The adiabatic density profile scales as $n \sim r^{-4}$ and the temperature scales as $T \sim r^{-8/3}$.

Simakov, et al. [42] have also examined the resistive stability of the high beta point dipole and shown that it remains stable to the usual fractional power resistive modes, $\omega_i \propto \eta^{1/3}$, with $\omega_i$ the growth rate and $\eta$ the plasma resistivity, although a weak mode $\omega_i \propto \eta$ can appear.

The stabilizing effect of compressibility has been observed experimentally in the large mirror ratio LAMEX experiment [43], supporting the dipole concept. The earlier levitron or “spherator” experiments provided a particularly illustrative contrast with a levitated dipole. In the levitron, the radial separation between the internal ring and the outer plasma boundary was determined by close-fitting limiters. When the toroidal field was strong, the flux tube volume was seen to scale with radius like a tokamak, $V \sim 1/q$, and stable plasmas could only be created when the applied vertical field was sufficiently strong to provide good average curvature. When the toroidal field was zero, the flux tube volume scaled approximately with radius as a hard-core z-pinch, $V \sim r^2$. Since the ratio of the plasma radius at the edge to the inner radius of the ring was typically less than two (about $1 - 1.5$), the ratio of the core pressure, $p_0$, to the edge pressure, $p_{sol}$, was limited by compressibility to $p_0/p_{sol} \leq (V_{sol}/V_0)^{\gamma} = (r_{sol}/r_0)^{10/3} \approx 1.5^{10/3} = 19$. In contrast, for the dipole, $r_{sol}/r_0$ can be made very large leading to $p_0/p_{sol} > 10^3$.

**Stability of Convective Cells.** Under many important circumstances such as strong local heating or fusion self heating, the pressure profile can be driven to violate the MHD marginal stability condition. Recent work indicates that in this event the plasma would develop large-scale convective cells which generate non-local energy transport of the required magnitude to prevent the pressure profile from significantly exceeding the critical gradient set by ideal MHD interchange [32, 33, 33, 36] (Eq. 1). The nonlinear cascade of interchange modes into large spacial scales is expected [44] because interchange modes are two dimensional and enstrophy is conserved in two dimensions, (in addition to energy). The MHD interchange criterion is therefore expected to impose a stiff limit on the pressure gradient. Convective cell formation has also been predicted by PIC simulations [31]. Such convective cells lead to rapid circulation of particles. Thus one can imagine that a dipole confined plasma can exhibit near classical confinement until the pressure profile obtains a critical gradient. Thereafter energy transport will prevent a further steepening of the pressure profile and it will be accompanied by rapid particle circulation. This process is quite favorable to a potential advanced-fuel fusion power...
Experiments in multipoles have indicated that convective cells can provide the dominant source of cross-field transport in shear-free systems. It is understood theoretically [45, 46] that zero frequency convective cells are closely related to interchange modes and they will grow in regions of bad magnetic well, i.e. where \( \delta(pV^\gamma) < 0 \). In addition it has been shown that convective cells will exist in regions of good curvature when the heating is non-uniform. In the Wisconsin octupole experiments the initial plasma was non-uniformly distributed and convective cells were observed in both good and bad curvature [47] regions. The convective cells were observed to decay slowly. These results lead one to suspect that uniform heating will be important in a levitated dipole if it is desirable to avoid the excitation of convective cells. These experiments also indicated that a small amount of shear eliminated convective cell formation. Additionally it was observed that small field errors can cause convective flow patterns in a shear-free configuration [49].

**Effect of Shear.** Mikhailovskii and Skovoroda [38] has called systems that satisfy the adiabatic stability condition, \( \delta(pV^\gamma) < 0 \), “well organized” systems. From ideal MHD the presence of magnetic shear will eliminate the compressibility term and give rise to ballooning modes at relatively low values of beta. Mikhailovskii et al. have recently shown that in the presence of weak shear, when the adiabatic stability condition is maintained, the destabilized Mercier modes give rise to weakly unstable sound waves. As a result the “ideal” instabilities that would arise from the presence of weak shear have relatively low growth rates and in principle, may be stabilized by non-ideal effects. In contrast, in systems which do not satisfy the adiabatic stability condition (i.e. in tokamak-like systems) fast Alfvén modes appear when the Mercier criterion is violated. It will be of great interest to observe the change in the plasma behavior in dipole confined plasmas with and without weak magnetic shear.

### 4.2 Drift Stability and Kinetic Theory

**Drift Stability in a Dipole Confined Plasma.** Since plasma loss from a levitated dipole results from cross field transport, (and not from scatter into a loss cone as in planetary magnetospheres) we expect the distribution function will become isotropic on a transport time scale. To lowest order the distribution function would be approximated by \( F_0 = F_0(\epsilon, \psi) \) with \( \epsilon = \mu_B + v^2_\parallel /2 \), the particle energy.

For a closed-field line system the MHD stability requirement is intrinsically related to the criteria for the stability of drift waves. We define the following frequencies:

\[
\hat{\omega}_{sp} = \frac{\vec{b} \times \vec{\kappa} \cdot \nabla p}{\Omega_i m_i n_i},
\]

\[
\hat{\omega}_d^{mhd} = \frac{2c}{\epsilon} \frac{R k_\theta T}{1 + \gamma(3)/2} \int \frac{d\ell \kappa / R B^2}{\int d\ell / B},
\]

with \( R \) the cylindrical radial coordinate, \( \kappa \) the field line curvature, \( k_\theta \) the azimuthal part of the perpendicular wave number \( (k^2_\perp = k^2_\theta + k^2_R) \) and \( k_\theta R = m \gg 1 \). One can show that \( d = \hat{\omega}_{sp} / \hat{\omega}_d^{mhd} \)
and therefore the MHD stability requirement, \( d \leq \gamma \), can be written as:
\[
\hat{\omega}_{sp} = \omega_{si}(1 + \eta) \leq \gamma \hat{\omega}_{d}^{mhd}.
\]
with \( \omega_{sj} \) the diamagnetic drift frequency, \( \omega_{sj} = T_j \vec{k} \times \vec{b} \cdot \nabla n_0 / (n_j m_j \Omega_j) \) and \( \eta = d \ln T / d \ln n \).

The inequality in Eq. (4) is opposite to the usual (tokamak) inequality and can lead to the stabilization of drift waves.

The outer "bad curvature" region of the dipole (between the pressure peak and the wall) can be subject to a drift-like instability known as the "entropy mode" when \( \eta < \frac{2}{3} \) [25, 26, 27]. This result holds for all regimes of collisionality that have been studied, including collisionless, semi-collisional (collisional electrons and collisionless ions) and collisional plasmas [26]. Furthermore, it has been shown that for a collisional plasma the entropy mode remains electrostatic at high \( \beta \) and the stability boundaries and not significantly modified by beta effects [28].

Near the marginal stability boundary (Eq. 4) the MHD and the entropy mode will couple and the separation of the plasma response into these two modes becomes impossible. In the inner (good-curvature) region the temperature and pressure will rise moving away from the coil but the density will fall (assuming complete recycle at the internal coil) and therefore \( \eta < -1 \). In this regime instability of the entropy mode becomes possible [27]. The level of plasma energy transported inwards toward the ring is of great importance and since it may be determined by turbulent transport of drift wave (i.e. entropy mode) origin it is important that it be studied experimentally.

**Drift Cyclotron Modes.** Drift cyclotron modes are high frequency unstable modes (\( \omega \sim \Omega_{ci} \)) modes that are driven by temperature and density gradients. Pastukhov and Sokolov have evaluated the transport from these modes in the good curvature region near the surface of the levitated dipole [35, 37]. They show that the resulting transport would be severely limited by particle recycling at the surface of the internal coil. Because the surface of dipole is completely surrounded by a dense plasma, the net particle flux to the ring must vanish. A cool, high-density sheath forms at the dipole surface which transforms the thermal flux into Bremsstrahlung radiation.

### 4.3 The Dipole as an Advanced Fuel Energy Source

Studies by Hasegawa, et al. [24] and by Teller, et al. [40] considered the application of a levitated dipole as a D-3^He based power source. Advanced fuel cycles (D-3^He, D-D) eliminate the need for tritium breeding and can eliminate most 14 MeV neutron production and the associated structural damage. A levitated dipole device would be intrinsically steady state (the floating coil could be designed to contain an internal refrigerator) and extract power from surface heating, permitting a thin walled vacuum vessel and eliminating the need for a massive neutron shield. The magnetic field is produced by a coil that is internal to the plasma and the plasma pressure falls off as the magnetic field falls off leading to a good utilization of the field. Therefore although the vacuum chamber envisioned is relatively large this does not lead to an unreasonably high magnetic field energy. There are no interlocking coil so that coil replacement would be routine.
The D-D cycle is particularly interesting since the only fuel required is the plentiful deuterium. We have recently considered a dipole based system as a fusion power source [41] utilizing a fuel cycle which we call the “Helium catalyzed D-D” cycle in which the secondary $^3$He is burned and the secondary Tritium is removed and the $^3$He decay product is reintroduced and burned. Whereas Nevins [51] found that a D-D cycle is precluded in a tokamak because of the long particle confinement time that accompanies the required energy confinement time and leads to ash accumulation, in a dipole the combination of high beta and high energy confinement with reduced particle confinement makes it ideally suited as a D-D based power source. In a recent study in which we developed a conceptual design for a dipole based D-D reactor [41] it was found that the ratio of plasma stored energy to magnet energy defined as $\beta_{\text{global}} = W_p/W_B$ is $\beta_{\text{global}} = 0.096$. For an tokamak reactor it is typically several times smaller: for the ARIES AT [52] advanced tokamak reactor study $W_B = 45$ GJ, $W_P = 0.75$ GJ and therefore $\beta_{\text{global}} = 0.017$. The ratio $\beta_{\text{global}}(\text{dipole})/\beta_{\text{global}}(\text{aries}) \sim 5.7$ indicates a substantially better utilization of magnetic field energy which results from the higher average beta that a dipole can support.

In the “Helium catalyzed D-D” power cycle approximately 94% of the fusion power is produced as Bremsstrahlung and particles leading to surface heating (with a relatively low wall loading). Nevertheless, although the ARIES AT wall loading (3.3 MW/m$^2$ from neutrons) exceeds the dipole reactor wall loading (photons and particles) by a factor of 40, the mass power density [53], i.e. the power per unit volume of structure (first wall and coil) for the dipole (1.1 to 1.75 MW/m$^3$) is comparable to the mass power density of ARIES, estimated to be 1.5 MW/m$^3$ (thermal power = 2 GW, system volume = 1300 m$^3$).

Although the D-T cycle is not desirable in a dipole power source due to excessive neutron heating of the internal coil, seeding with tritium may be useful in obtaining ignition in such a device. Furthermore the D-T cycle offers the possibility of a modest ignition experiment in which the internal coil is designed to have minimal shielding and to warm up inertially and float for up to 10 minutes after attaining ignition [41].

5 Elucidating the Principles of Dipole Physics

Our research program will provide a wide range of important information on magnetized plasmas and it may demonstrate an entirely new, very attractive development path for fusion using advanced fuels. The physics base for dipole confinement is distinct from a tokamak. The plasma is axisymmetric and toroidal but the magnetic field is poloidal with closed field lines and is shear-free. Using superconducting coils, the dipole configuration is intrinsically steady state, disruption-free and has a low divertor heat load. MHD stability results from compressibility and not from well and shear as in other toroidal confinement approaches. Micro-stability is attained when the precessional drift exceeds the diamagnetic drift, a condition that is not attained in a tokamak and as a result a dipole confined plasma may be free of drift frequency fluctuations. Coupled with the elimination of drifts off the flux surface (which in a tokamak results from the presence of a toroidal field), drift stability may produce classical confinement. The physics base is closely akin to the physics of magnetospheric plasmas, which provide examples of naturally occurring high beta plasma confinement. The dipole magnetic field is known to be capable of
supporting very high plasma pressures, such as those found in the Jovian magnetosphere with \( \beta > 1 \) [54].

This section summarizes the physics objectives which guided the design of the LDX device and research plan. These objectives address fundamental questions in magnetic plasma confinement while also providing a basis for the evaluation of the dipole concept as a fusion power source.

5.1 Magnetic Configurations of the Levitated Dipole Experiment

LDX has been designed to investigate the stability and confinement properties of both diverted and limited plasmas. In order to investigate the coupling between the edge plasma and the hot plasma core within a dipole-confined plasma as well as to observe the difference between limited and diverted plasmas, low-current copper shaping coils have been attached to the outside of the vacuum vessel to shape the outer flux surfaces. By energizing the shaping coils with respective currents \( I_{s1} \) and \( I_{s2} \), \(-50 < I_{s1}, I_{s2} < 50 \) kA, the position of the ring null divertor can be positioned from the outer vacuum chamber wall to a nearby radius of 1.2 m without significantly changing ring stability. Three examples of LDX equilibria for an edge pressure of \( p_{\text{sol}} = 0.25 \) Pa are shown in Fig. 2 and listed in Table 1. Recall the peak pressure, \( p_0 = p_{\text{sol}}(V_{\text{sol}}/V_0)^\gamma \). Figure 2a shows the equilibrium with the shaping coils off; \( \beta_{\text{max}} = 8\% \). Figure 2b shows an optimized equilibrium that produces a beta of \( \beta_{\text{max}} = 58\% \). Figure 2c shows an equilibrium in which the coil currents have been adjusted to reduce flux expansion leading to \( \beta_{\text{max}} = 1.5\% \). Thus the shaping capability of LDX will permit a systematic investigation of the role of flux expansion on plasma stability and confinement.

For the optimized equilibrium of Fig. 2b, \( I_{s1} = 1 \) kA and \( I_{s1} = 12 \) kA and the plasma fills the vacuum chamber. A small increase in the \( I_{s1} \) current, \( I_{s1} \rightarrow 3 \) kA, will expand the plasma so as to create a limited plasma configuration. Thus the shaping capability will also permit a direct comparison of limited and diverted discharges.

Additionally, a point null divertor configuration can be obtained with the field X-points located on the dipole axis above and below the midplane [55, 56]. In this case, the ring would be unstable to tilt and horizontal displacements. Tilt stabilization will require four low-power windings of approximate circular cross-section, and horizontal stability will require two larger quadrupole windings. Both windings will be made from appropriately sized insulated cable and wound on the outside of the vacuum vessel. Since this divertor option requires feedback control of four dynamical variables (instead of one), we do not plan to investigate point null divertor configurations until close to the end of our three-year research plan.

5.2 Coupling to the Scrape-Off Layer: The Compressibility Constraint

LDX has been designed to permit the flux expansion to be substantially varied. In Table 1 we consider three diverted configurations labeled A, B and C, which are illustrated in Fig. 2 and a diverted case labeled D. At marginal stability the peak plasma pressure and beta are proportional to the scrape-off layer pressure, \( p_0 = p_{\text{sol}}(V_{\text{sol}}/V_0)^\gamma \), and in these calculations \( p_{\text{sol}} \) has been set to a modest value of \( p_{\text{sol}} = 0.25 \) Pa. In equilibrium A the shaping coils are off
Figure 2: Examples of diverted LDX equilibria: (A) Shaping coils off, (B) Shaped for maximum $\beta$, (C) Shaped for low $\beta$.

and $\beta_{\text{max}} = 8\%$. In case B the shaping coils are adjusted so that the plasma fills the vacuum chamber and $\beta_{\text{max}} = 55\%$. In C we use the shaping coils to reduce the flux expansion and find $\beta_{\text{max}} = 1.5\%$. Thus we observe that a variation in plasma shape will change the peak pressure by a factor of $\sim 30$. When the plasma fills the vacuum chamber the ratio peak-to-edge pressure can be as large as $\sim 6000$. This experiment would indeed offer a dramatic indication that flux expansion will permit a strong buildup of beta and of plasma pressure.

Changing the magnetic topology to a limited as opposed to diverted plasma may substantially effect the parameters in the plasma edge. When the plasma is bounded by a magnetic separatrix a null appears on the separatrix causing $\oint d\ell / B$ to diverge. Consistent with MHD this divergence would permit the plasma pressure to fall sharply in the vicinity of the separatrix and create a pressure pedestal at the plasma edge while permitting a very low scrape-off layer pressure. Additionally a magnetic divertor can create good average scrape-off layer curvature by diverting the field. Equilibria B and D (Table 1) represent similarly shaped equilibria, one diverted and one limited. We expect that such an experimental comparison will provide a conclusive indication of the relative importance of the plasma-sol boundary.

While we expect to satisfy the MHD requirement $\delta(pV^\gamma) > 1$ within the closed flux surfaces, the scrape-off layer cannot be stabilized by compressibility for a limited plasma and in the simplest dipole magnetic geometry would be ideal MHD unstable. However, when the scrape-off layer width is of the order of one ion gyroradius, it may remain stable due to finite gyro radius (FLR) effects. FLR will not stabilize the $m = 1$ (rigid) mode (where $m$ is the azimuthal mode number), but this mode is a global mode and should be stabilized in the core by compressibility.

For a dipole plasma operating at the MHD stability limit the adiabatic pressure ratio limits the peak pressure, $p_0$, to a value set by the scrape-off layer pressure, i.e. for Table 1, case B, $p_0 / p_{\text{sol}} \sim (V_{\text{sol}} / V_0)^\gamma \sim 6000$. Assuming that a fraction, $f_R$, of power leaving the plasma is radiated, we can balance the power loss from the plasma with the flow in the scrape-off layer:
Table 1: Plasma equilibria parameters. (A) diverted, no shaping, (B) diverted, shaped for maximum beta, (C) diverted, shaped for minimum beta, (D) limited plasma.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Coil Currents; $I_{s1}$, $I_{s2}$ (kA)</td>
<td>0.0</td>
<td>1.12</td>
<td>50.50</td>
<td>3.12</td>
</tr>
<tr>
<td>Plasma Volume (m$^3$)</td>
<td>14</td>
<td>27</td>
<td>1.7</td>
<td>24</td>
</tr>
<tr>
<td>SOL Pressure (Pa)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>Max Pressure (Pa)</td>
<td>136</td>
<td>1530</td>
<td>45</td>
<td>472</td>
</tr>
<tr>
<td>Plasma Current (kA)</td>
<td>3.2</td>
<td>16.4</td>
<td>0.39</td>
<td>5.78</td>
</tr>
<tr>
<td>Stored Energy (J)</td>
<td>316</td>
<td>1450</td>
<td>27</td>
<td>516</td>
</tr>
<tr>
<td>$R(P_{max})$ (m)</td>
<td>0.76</td>
<td>0.76</td>
<td>0.77</td>
<td>0.79</td>
</tr>
<tr>
<td>$B(P_{max})$ (T)</td>
<td>0.088</td>
<td>0.088</td>
<td>0.088</td>
<td>0.088</td>
</tr>
<tr>
<td>$\beta(P_{max})$</td>
<td>0.08</td>
<td>0.55</td>
<td>0.015</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[
\frac{(1 - f_R) \oint pdV}{\tau_E} \approx 2p_{sol}A_{sol}c_s
\]  

with $c_s$ the scrape-off layer sound speed, $V_0$ the effective volume of hot plasma, and $A_{sol}$ the scrape-off layer cross-section area. Assuming that the minimum width of the scrape-off layer is an ion gyroradius, we take $A_{sol} \geq A_{min} \approx 2\pi R_{sol}\rho_{sol}$ with $\rho_{sol}$ the scrape-off layer ion gyro-radius at the outer radius of the scrape-off layer. We will define $\tau_E(A_{min}) = \tau_E^{crit}$. The scrape-off layer pressure, $p_{sol}$ is obtained assuming $p \propto V^{-\gamma}$.

When heating is applied to the core plasma and $\tau_E = \tau_E^{crit}$, sufficient energy and particles are supplied to the scrape-off layer to form a marginally stable equilibrium. When $\tau_E < \tau_E^{crit}$, there is more energy entering the scrape-off layer than can be accommodated and it is expected that the scrape-off layer will expand to accommodate a higher heat flow. However $\tau_E$ cannot exceed $\tau_E^{crit}$ because the peak pressure relative to the scrape-off layer is limited by the MHD interchange condition and the energy outflow must maintain the scrape-off layer (and the scrape-off layer cannot be narrower than an ion gyroradius). Convective and turbulent processes are expected to prevent $\tau_E$ from exceeding $\tau_E^{crit}$.

### 5.3 Stability of Hot Electrons in the Field of a Levitated Dipole

The combination of closed field lines and high beta makes the dipole an ideal geometry for creating a high beta, hot electron plasma by the application of ECRH. Such plasmas have been demonstrated in mirror machines with open field lines as well as in levitrons and in the non-levitated dipole CTX experiment [15, 16, 17, 18] at Columbia University. Additionally, as was first observed in the EBT experiments, hot electron $\beta_h$ can exceed the ordinary MHD beta limits whenever the energy of the “hot” component is sufficiently high and there exists a sufficient mass density of the cooler plasma component. The buildup of hot electron stored energy in CTX is
observed to be limited by both the application of strongly localized heating which results in the pressure gradient exceeding a critical value as well as thermal losses of warm electrons to the dipole’s mechanical support. The transport of thermal energy will fundamentally change for multiple frequency heating in the levitated dipole configuration. Unlike MFECRH in magnetic mirrors, the hot electrons created in a levitated dipole can only be lost by cross-field transport.

It is known that a hot electron population will decouple from the background plasma when the hot electron precessional drift frequency exceeds the MHD growth rate of the background plasma \([57, 58]\). The stability of the hot electron component depends on the density ratio of the warm to the hot electron plasma. For a sufficiently high hot electron fraction the hot electron interchange (HEI) mode (a high frequency version of an MHD interchange mode) can be excited. This mode results from the coupling of the negative energy precessional mode with the positive energy drift mode. HEI instability requires

\[ \Gamma_h^2 \equiv 1.5 \omega_{ci} \omega_{dh} \frac{\psi}{n_i} \frac{\partial n_{eh}}{\partial \psi} > m_\perp \omega_{dh}^2 \tag{6} \]

with \( \omega_{dh} \) the hot electron precession frequency. It will be seen that the HEI does not restrict the buildup of the hot electron population when the hot electron fraction is not high, i.e. \( n_{eh}/n_i < 0.5 \). When the thermal plasma has a significant beta, \( \beta_{th} > 2(r_p/R_c)/(1 + \beta_h) \) (with \( r_p \) equal to the characteristic radial scale-length), it has been shown that the decoupling condition is violated \([59]\) and the hot electrons can no longer exceed the usual MHD stability limit, \( \delta(pV^\gamma) > 1 \). However since in the dipole \( r_p/R_c \sim 1 \) this condition is not restrictive. Therefore, we expect that a stable high \( \beta \) hot electron population can be present in a dipole.

### 5.4 Convective Cells and the Pumping of Impurities

According to theory, attempts to exceed the critical pressure gradient imposed by ideal MHD in the outer bad curvature region between the pressure peak and the vacuum chamber wall can lead to the formation of convective cells. Convective cells are expected to grow as the non-linear consequence of interchange instability in the outer plasma region. At the marginally stable gradient, convective cells may be expected to transport particles without the transport of energy. As the pressure gradient exceeds the marginal values the convective cells would create sufficient non-local energy transport so as to create a stiff pressure profile and to prevent the pressure gradient from significantly exceeding the marginal value. In the inner, good curvature region between the pressure peak and the floating coil the plasma will remain stable to interchange modes and the formation of convective cells are not energetically favored. However, if convective cells formed in the outer plasma can penetrate into the inner region they would cause an undesirable inward transport of energy. This penetration of convective cells is theoretically not expected to occur \([33]\). An experimental verification of convective cell formation is of substantial importance for the understanding of dipole plasma confinement.

An important consequence of convective cell formation in a dipole is the capability for selectively removing impurities entrained in these flows. The ability to remove impurities and unwanted species (for example tritium in a DD reactor) from the plasma core is a unique capability of a dipole. As these species are convected out from the core into the edge region a
pumping method such as ion cyclotron heating must be selectively applied to the unwanted species. We expect to explore selective ion species pumping methods in the later phase of the proposed experimental program.

5.5 Confinement and Drift Wave Stability

We have seen that the plasma will be stable when \( p \propto V^{-\gamma} \) and that a particularly desirable density profile would be \( n \propto 1/V \). The temperature and density profiles are determined by the profiles of fueling, heating and thermal transport. In addition to MHD stability these profiles insure that the density profile will not be altered by convective cells and that \( \eta_i \approx 2/3 \), stabilizing entropy modes. These properties of a dipole plasma will be the subject of specific investigations. For example, if we exceed the critical pressure gradient, we would expect the plasma to expand unstably and broaden the pressure profile. If we exceed a critical value of \( \eta_i \), we would expect an onset of micro-turbulence and increased transport. This behavior is analogous to the operation of a tokamak except, in a dipole, the adiabatic pressure ratio between the edge and the core can be very much larger than in a tokamak. The determination of whether a dipole’s adiabatic profile comes about naturally will be an important research goal of the experiment.

We have observed that transport may be near classical in a levitated dipole. The dipole avoids drift frequency modes due to a relatively small diamagnetic drift, \( \omega_p < \omega_D \) (\( \omega_D \) is the bounce averaged curvature drift), coupled with strong compressibility. In addition, since the field is poloidal, there is no inherent drift off the flux surfaces and no “neo-classical” degradation of confinement. The proposed LDX experiment will have the capability of steady state operation using high frequency (28 GHz) gyrotrons which permit heating at density levels of up to \( 10^{19} \) m\(^{-3} \).

6 Description of the LDX Device

The LDX experimental device consists of three circular and co-axial superconducting magnets (the floating coil, the charging coil, and the levitation coil), a large cylindrical vacuum chamber, several common plasma diagnostics, five microwave ECRH heating systems, and several low current shaping and control coils. Although the basic configuration for a dipole experiment is simple, the design and fabrication of the LDX experiment has been a major undertaking. During the present grant period, the LDX research team has:

- Specified a first-of-a-kind experiment that meets our scientific goals and insures the safe charging and levitation of a 620 kg, 1.5 MA coil,
- Designed three superconducting magnets including the Nb\(_3\)Sn floating coil [7, 8] that must operate in a persistent mode at high current in order to achieve high plasma compressibility and, fusion’s first high-\( T_c \) magnet, the levitation coil [10],
- Supervised the manufacture and testing of the three superconducting magnets,
• Prepared the experimental hall including the construction of the vacuum vessel, the construction of coil handling systems, the installation of control and data acquisition systems, the design and assembly of basic diagnostic systems, and the full power testing of microwave heating systems, and

• Advanced the physics and understanding of the dipole fusion concept including the identification of free-boundary LDX equilibria that are stable to ideal MHD modes with \( \langle \beta \rangle > 1 \) [5], the development of new gyrokinetic theory for drift stability [25, 26] and for convective cells [36], and the suggestion of a new fusion fuel cycle applicable to the dipole concept [41].

The design and entire construction of the LDX device has been recorded month-by-month and posted on our website’s “Project News”: http://www.psfc.mit.edu/ldx/news.html. The website has 40 reports and numerous photographs showing the superconducting magnets under all stages of construction, the vacuum chamber and site preparations, and the hard work and active oversight of the LDX research team.

The main purpose of this section is to describe the LDX device as a scientific experiment. First, the daily operation of the superconducting magnets is described to explain how the floating coil will be energized, levitated, and returned to it’s docking or “charging station.” Next, we list the plasma heating and fueling systems that will be used to startup, heat, and adjust the density and pressure profile of confined plasma. Finally, we note how important plasma properties will be measured and analyzed. More details describing the superconducting magnets, the vacuum system, and the other support facilities are presented in the “Facilities and Resources” appendix, in our publications, and on our website.

### 6.1 The Daily Operation of LDX

In contrast to levitron devices that successfully operated with levitated coils several decades ago [12, 13, 20], a critical design goal of LDX was to maximize the expansion of magnetic flux. LDX requires a relatively small coil to be levitated within a large vacuum chamber. Although the large distance between the floating coil and the vessel and control magnets represented a design challenge, LDX does not require strong toroidal and vertical fields. This greatly simplifies the stability and control of the LDX floating coil. Our base case magnet configuration, shown in Fig. 1, achieves ring levitation using a single, high temperature superconducting magnet. The floating coil’s orientation is stable to tilt and horizontal displacements and, as a result, LDX only requires feedback control to stabilize a slow (\( \gamma \sim 4 \text{ s}^{-1} \)) instability in floating coil’s vertical position.

To achieve a large expansion of the magnetic flux, LDX uses a pneumatic “launcher”, designed at PPPL, to mechanically lift the floating coil from the bottom of the vacuum vessel (from the so-called “charging station”) to the center of the vacuum vessel. At this location, the coil’s weight is counterbalanced by the levitation coil located at the top of the vacuum vessel. In effect, the floating coil hangs like a pendulum.

Careful design of the floating coil’s cryostat and method to induce the coil’s very large current (\( > 1 \text{ MA} \)) was necessary. The floating coil’s cryostat borrows some of the ideas used
in the superconducting FM-1 ring built over 30 years ago at PPPL [12, 60]. The FM-1B coil was able to levitated for more than 10 hours a day. The method we've selected to charge the floating coil's large current is induction. As a consequence, there are no high-current electrical contacts that need to be made and broken on the floating coil.

Perhaps, the best way to appreciate the operation of LDX is to view an informative animation prepared by Andrew Unikowsky, an MIT undergraduate student. Andrew’s animation is located at http://www.psfc.mit.edu/ldx/ldx_daily_op.html, and it illustrates a “Day in the Life of LDX.” At the beginning of each day, the floating coil is resting within the charging station and precisely centered inside the bore of the large NbTi “charging coil”. The floating coil is connected to inlet and outlet cryogenic transfer tubes and a multi-pin temperature-monitoring connector. While the floating coil is resistive near 20 °K, the charging coil is energized to maximum current. Then, liquid Helium is used to chill the floating coil to approximately 4.5 °K at which time the charging coil current is gradually ramped down. The vacuum tubes and connector to the floating coil are withdrawn and the coil heat exchanger is evacuated and plugged. With the floating coil now fully charged and disconnected, the pneumatic launcher lifts the coil into position. The levitation coil current is switched on to balance the weight from the launcher. Eight lasers monitor the position of the floating coil, and a real-time digital feedback system controls the current in the levitation and control coils. The “catcher” that cradles the floating coil is now retracted, and plasma experiments begin. At the end of the day, the procedure is reversed, discharging the floating coil and reheating it to approximately 20 °K. Then the charging coil is discharged.

6.2 Plasma Formation, Heating, and Fueling

LDX high-beta plasma will be created using multiple-frequency electron cyclotron resonance heating (MFECRH) [11]. The dipole magnetic field is known to be stable to high-beta plasmas with energetic particles, and ECRH has proven to be a reliable and low-cost technique to create hot electron, $\beta \sim 1$, plasmas in magnetic mirrors. Furthermore, we have gained important experience from the successful production of hot electrons plasmas in Columbia’s CTX experiment [15, 18]. Additionally, MIT and Columbia University have made available five microwave power sources: four long-pulse or CW klystrons, at 2.45 GHz, 6.4 GHz, 10.5 GHz, and 18 GHz, and a 28 GHz Varian gyrotron (200 kW, 100 ms) which will be used for plasma production and hot electron profile control. The klystrons can be frequency modulated to improve the efficiency of energetic electron production. The wide range of microwave frequencies and very large variation of the dipole’s magnetic field strength allow scientists to alter the plasma pressure profile by localizing power deposition at specific electron cyclotron resonance layers.

Initially, neutral gas will be injected with fast piezo-electric puff valves as done in CTX. In order to investigate effects of density profiles, an inner, remotely triggered, gas valve and a Li pellet injector will be installed midway through the proposed project period. The floating coil’s limiter is placed on the outer midplane of the coil. Finally, localized impurity “sparks” will be used to seed the edge of the plasma with impurities that can be traced to investigate the rate of inward particle convection.
6.3 Diagnostics and Data Analysis

Common diagnostics will be used to measure global plasma equilibrium (including stored energy and pressure profile), plasma density, hot electron energy, plasma fluctuations and instabilities, neutral particle sources, and edge plasma characteristics. These diagnostics are relatively low-cost and take advantage of the good access provided by the dipole geometry and the LDX vacuum vessel. This approach is appropriate for first-ever investigations where limiting processes and general features of high-beta confinement and stability must be observed. Most of these diagnostics have already been designed, and many have already been built and will be installed during the present grant period.

A list of the LDX diagnostics are:

- Magnetic diagnostics will be used for equilibrium reconstruction and magnetic fluctuations. Included are nine flux loops, 18 magnetic field coils, and a Rogowski coil to measure the plasma’s diamagnetic current.

- X-ray diagnostics will be used to measure the energy, intensity, and profile of the energetic electrons. Included are pulse-height counters and an intensified x-ray imaging camera borrowed from the PPPL.

- Multi-cord microwave interferometry will be used to measure the density and estimate the density profile. The first cord to be installed operates at 50 GHz with a superheterodyne receiver.

- Adjustable Langmuir probes and probe arrays will be used to measure the edge plasma parameters and the electrostatic potential and potential fluctuations. These probes are mounted onto motorized bellows. Gate valves allow various probe types to be used without venting.

- Neutral particle energy analyzer will be installed midway through the proposed project year to measure $T_i$ in high-density plasma.

- Multi-cord doppler spectrometer will be installed during the third program year to measure the rate of impurity convection. We plan to make use of the novel, high-throughput line-spectrometer developed by S. Paul [50] that uses interference line filters.

- Visible light, with and without $D_\alpha$ filters, and photography will be used to view features of the plasma equilibrium, boundary, and gross dynamics.

These diagnostics will be digitized, processed, and archived using MDS-Plus and standard software tools convenient for students and scientists. The critical derived quantities result from magnetic equilibrium reconstruction, pulse-height analysis of the hard x-ray spectrum, and Abel inversion of line-integrated density.
Detailed Research Plan

The LDX research plan is organized into two interconnected activities: (1) the experimental, or scientific, plan and (2) the operations plan.

The experimental plan describes how we intend to achieve our project goals by executing active experiments that investigate (1) compressibility stabilization and high beta, (2) particle circulation and adiabatic heating, and (3) dipole confinement at high beta. Carrying out the experimental plan is the major activity of the next three years.

The operations plan describes the installation and use of plasma control tools and the transition from supported to levitated operation of the floating coil. Compared to the facility and fabrication work that was necessary to fabricate our three superconducting magnets during the current grant period, there will be less facility work and fewer and simpler installations during the proposed grant period. The most significant installations will begin after first plasma and after ECRH startup experiments. They include: (1) the systems needed to demonstrate reliable levitation of the floating coil, (2) the complete, multi-frequency ECRH system including a 28 GHz gyrotron originally used in the TARA tandem mirror, and (3) several density control tools including edge biasing probes. These installations are staged to coincide with important experimental campaigns. Because the levitation coil and real-time digital feedback system used to maintain the position of the floating coil are already in-hand, we will make the transition from supported to levitated coil operation within the first program year as soon as it is prudent to do so. Experiments with a supported coil will be used to establish ECRH startup, to optimize the production of energetic electrons, and to conduct preliminary investigations that demonstrate proper function of diagnostics and data analysis. Our broader scientific investigations will be conducted with a levitated coil.

This section describes our research plan in terms of scientific objectives of the LDX program and in terms of the schedule for the installation of research tools.

Overview

Fig. 3 presents an overview of the schedule for LDX experiments and operations. Our research plan is divided into three phases: (1) experiments with a supported coil, (2) experiments with a levitated coil, and (3) experiments with higher-density plasma. The three-year schedule sets a relatively rapid pace of scientific investigation. We believe this is appropriate for the first study of a new concept. Our strategy is to conduct active experiments that reveal limiting processes within LDX dipole-confined plasma and that determine gross (and relatively easy-to-measure) features of high-beta stability, confinement, and particle circulation. The installation of new microwave heating and density control tools are staged throughout the next three years so that important physics can be understood as new capabilities become available. We expect some interesting scientific surprises, and, for this reason, we anticipate that most investigations will span more than one program year. Many will become the subjects of doctoral dissertations.
7.2 Experiments with a Supported Coil

Supported-coil operation begins in the present grant period shortly after the arrival of the charging coil this summer. The floating coil will be supported by the “phase-one” catcher that suspends the coil by three high-strength spokes enclosed by narrow tubes of boron nitride. Initial experiments using a supported coil will provide important scientific results concerning creation and stability of high beta dipole-confined plasma with energetic electrons. However, the primary purposes of this phase are (1) to establish cryogenic procedures for the charging and discharging of the floating coil, (2) to demonstrate performance of the the 6.4 GHz and, then, the 2.45 GHz microwave heating systems, and (3) to verify the operation of diagnostics. These initial experiments with a supported coil do not require the use of the high-T<sub>c</sub> levitation coil nor the laser position detection and control system.

The initial ECRH startup experiments are likely to achieve a high beta even with a supported coil since trapped electrons can be heated to relativistic energies with very long collision times. These experiments build upon and extend the results already obtained using electron cyclotron
resonance heating to create energetic electrons at the Columbia CTX device [15, 16]. Since the large, high-field floating coil is suspended by three relatively small spokes, polar heat losses and particle recycling are reduced. Experiments in a supported configuration will permit a direct comparison with CTX and supply information on the size scaling of a supported dipole.

After establishing plasma startup, we will demonstrate the operation of all basic diagnostics. These include (1) magnetics for equilibrium reconstruction, measurement of total stored energy, and MHD instabilities, (2) x-ray imaging and pulse-height analysis, (3) visible photography, (4) steerable microwave interferometry, and (5) a variety of movable probes and probe arrays.

Preliminary scientific studies will focus on \( \langle \beta \rangle \) enhancement through optimization of neutral fueling and the use of two-frequency ECRH. Two-frequency ECRH heating at 6.4 GHz and 2.45 GHz will give scientists the ability to adjust the electron pressure profile in LDX. We hope to observe an early glimpse of the fundamental (and nonlocal) relationship between the stored energy and the pressure profile in a dipole. Multi-frequency ECRH also increases the efficiency of hot electron pressure production. Experiments in SM-1 [11] achieved a substantial increase of stored hot electron energy when multiple frequencies were applied probably due to the elimination of superadiabatic effects [61] which can create phase space barriers during single-frequency heating. The frequency of our 6.4 GHz klystron can be modulated at the bounce frequency of multi-keV electrons and will also interact with relativistic electrons created by the higher-power, but shorter-pulse, 2.45 GHz system. By the end of the supported-coil experiments, we will have (1) established efficient operating parameters as function of MFECRH power, frequency, and neutral pressure, (2) measured plasma stability and MHD beta limits, and (3) developed our diagnostic and data processing systems.

7.3 Demonstrating Reliable Levitation

Approximately half-way through the first project year, supported-coil experiments will end, and we will begin the levitation phase. The eight-channel, redundant, laser detection and position control system, the modified ("phase-two") catcher, and the tilt-slide-rotation (TSR) saddle coils will be installed. Our existing catcher was designed to remain in contact with the floating coil and to allow only limited vertical motion during the very first tests of the levitation control system. The "phase-two" catcher will replace the existing catcher and allow lift-off and gentle landing of the floating coil onto the pneumatic launcher system. The laser coil-position detection system is described elsewhere. The operation of the real-time digital control system was successfully tested with a permanent magnet more than a year ago. The TSR coils consist of eight (10-turn, 40 A) saddle-coils wound in-place on the LDX vacuum vessel.

Since all of the LDX magnets and control systems can operate when the vacuum chamber is vented, we plan a one-to-three month period where floating coil levitation is demonstrated without plasma (and with supplemental safety restraints.) The first plasma experiments with a levitated coil will occur in the summer of 2004. Experiments with a levitated coil constitute the remainder and the majority of the research plan.
7.4 Experiments with a Levitated Coil

The key physics experiments of the proposed LDX research plan will be conducted with a levitated coil. Our descriptions of these experiments are organized in terms of the three LDX science objectives: (1) experiments to test and understand compressibility stabilization, (2) experiments to measure and control particle circulation and adiabatic heating, and (3) experiments to measure and understand dipole plasma confinement at high beta. These objectives are obviously interrelated, and the experimental “campaigns” will overlap in time and produce data that will be integrated to form an overall assessment of dipole plasma confinement at high beta. Physics themes present throughout are research are the importance of pressure and density profiles, understanding edge parameters, and the important role of plasma density.

7.4.1 The Role of Density in LDX

Plasma density plays an important role in the LDX experiment since microwave electron cyclotron resonance heating (ECRH) is used to form and heat the plasma. Based on extensive experience with ECRH in magnetic mirrors, tandem mirrors, bumpy tori, and in the CTX device, plasma density is known as a critical operational parameter. Besides microwave accessibility, plasma density regulates the intensity of relativistic electrons. In LDX, the plasma density will initially be controlled by precisely pre-programming neutral gas puffs. Later, high-speed, fast-acting gas puffs, inner gas fueling, pellets, and edge plasma sources will be explored as techniques for density control. When the neutral pressure is either too large or too small, the density and temperature of trapped energetic electrons decreases.

We expect the rate of gas fueling that optimizes the production of energetic electrons and electron stored energy will be less during levitated operation than during supported operation. This is because levitated operation will eliminate polar losses and particle recycling that occurs on a pitch-angle collision time. During levitated operation, we expect particles to be very well confined in LDX. While proper adjustment of gas fueling will be important for a supported coil, the investigation of density and neutral gas control will become even more important during operation with a levitated coil. The well-confined plasma in a levitated dipole will likely be a better particle “pump” requiring reductions in the deuterium gas feed and operating pressures as compared with CTX experience. The care we have given to the quality of our vacuum chamber (base pressure < $10^{-8}$ Torr) will help insure that the plasma density doesn’t “run away” during levitated operation. The reduced polar losses should also increase the temperature of the warm (non-relativistic) electrons, further enhance the rate of hot electron production, and significantly increase plasma pressure.

As stated in Section 5, the stability and behavior of high-pressure dipole-confined plasma should also differ depending on whether the pressure is contained in the energetic electrons or a more thermalized, high-density plasma. Energetic electrons neutralized by colder ions have stable pressure gradients that exceed the MHD compressibility criterion. Furthermore, non-thermal electrons have rapid magnetic drifts that may influence convective cells and the symmetry of any electrostatic and density structures that may form in a dipole.

In order to study thermal, high-density plasma in a dipole, we plan to use fast gas puffs and Li
pellet injection to rapidly build-up overdense plasma by converting energy stored in the trapped energetic electrons. These studies will necessarily be transient, but, by the third program year, our 28 GHz gyrotron (100 kW, 100 ms) will be used to help sustain higher-density thermal plasma. The study of density and density profile effects will be a central activity throughout our research.

While we intend to investigate a wide range of parameters in LDX, Table 2 presents parameters representing our expectations for low-density energetic electron plasma and for high-density thermalized plasma. The scrape-off layer plasma parameters are estimated assuming $p_0 \propto V^{-\gamma}$ and $n_{e0} \propto 1/V$. The remaining parameters derive from the following considerations:

- For a hot electron plasma with $T_{eh} \approx 250$ keV, $n_{eh} \approx 3 \times 10^{16} \, m^{-3}$, $\beta_h \approx 0.55$ and with the pressure peak located at $R_0 = 0.76$ m, and $R_{sol} = 2$ m, $B_0 = 0.088$ T, assume a core background plasma with $T_{e0} \approx 5$ keV, $n_{e0} \approx 3 \times 10^{16} \, m^{-3}$ and $f_R \sim 0.5$. From Eq. (5), we obtain the thermal plasma’s critical energy confinement time $\tau_{E}^{crit} = 29$ ms.

- Consider a low-density, high-$\langle \beta \rangle$ hot electron plasma into which we rapidly increase the plasma density and transfer $\approx 50\%$ of the stored energy to the now denser thermal plasma. If the core density rises to $n = 1 \times 10^{19} \, m^{-3}$ at $\beta \approx 0.27$, then we would obtain $T_{i0} = T_{e0} = 240$ eV. If we further assume that radiation is insignificant ($f_R \sim 0.5$), we obtain from Eq. 5 an estimate for the critical energy confinement time, $\tau_{E}^{crit} = 98$ ms.

Since these parameters are consistent with computed free-boundary equilibria and MHD sta-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hot Electron</th>
<th>High Density</th>
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<tbody>
<tr>
<td>Levitated coil current (MA)</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td>Major radius of coil (m)</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Total usable flux (V·s)</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Total plasma volume (m$^3$)</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Core volume (m$^3$)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum, Maximum $B$ at core (T)</td>
<td>0.088, 3.3</td>
<td>0.088, 3.3</td>
</tr>
<tr>
<td>$B$ at edge (G)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Core hot electron density (m$^{-3}$)</td>
<td>$3.6 \times 10^{16}$</td>
<td>–</td>
</tr>
<tr>
<td>Core total electron density (m$^{-3}$)</td>
<td>$7.6 \times 10^{16}$</td>
<td>$10^{19}$</td>
</tr>
<tr>
<td>Core hot electron temperature (keV)</td>
<td>$\approx 250$</td>
<td>–</td>
</tr>
<tr>
<td>Core thermal electron temperature (keV)</td>
<td>5</td>
<td>0.24</td>
</tr>
<tr>
<td>Core thermal ion temperature (keV)</td>
<td>0.05-0.1</td>
<td>0.24</td>
</tr>
<tr>
<td>Peak core $\beta$ (%)</td>
<td>$\sim 55$</td>
<td>$\sim 27$</td>
</tr>
<tr>
<td>Edge density (m$^{-3}$)</td>
<td>$7 \times 10^{14}$</td>
<td>$5.3 \times 10^{16}$</td>
</tr>
<tr>
<td>Edge thermal temperature (eV)</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2: Expected LDX plasma parameters for both stages of plasma formation: (a) hot electron ECRH plasma and (b) high density deuterium plasma.
bility [5], they provide useful targets for our experiments, and they have guided selection of diagnostics and the order of our research plan. Achieving these parameters would both validate the dipole concept and the LDX experimental approach.

### 7.4.2 Compressibility Stabilization at High Beta

A major objective of the LDX experiment is to provide the first systematic investigation of the use of MHD compressibility to stabilize large pressure gradients in a high-temperature and high-beta plasma. As explained in Section 4, stabilization by compressibility requires the pressure gradient to satisfy the adiabaticity condition, \( \delta(pV^\gamma) < 0 \). Thus, the maximum \( \langle \beta \rangle \) and plasma stored energy occurs when the pressure gradient is nearly marginal from the hot core to the edge, when the flux-tube volume ratio, \( V_{\text{sol}}/V_0 \), is large, and when the edge pressure is large. The goal of our investigation of compressibility stabilization is to understand the relationship between plasma stored energy, pressure profile, the shape of the outer boundary, and the edge plasma.

Our compressibility experiments involve three elements:

1. Measurement of the pressure profile and stored energy by reconstructing the plasma equilibrium from measurements of the magnetic flux, local field, and Rogowski coil and by direct measurement of the edge plasma with movable probes.

2. The use of multiple ECRH heating frequencies to modify the pressure profile.

3. Systematically change the compressibility parameter by imposing large variations of the plasma shape by energizing the Helmholtz coils and causing significant changes in the flux-tube volume, \( V_{\text{sol}}/V_0 \).

The demonstration of plasma compressibility will follow clearly from the ability to show that we can reach a critical pressure profile and therefore a critical peak pressure that depends upon the ratio of \( V_{\text{sol}}/V_0 \). As shown in Fig. 2 and Table 1, we are able to change this ratio significantly. The peak pressure, stored energy, and plasma diamagnetic current change by more than a factor of 30 (and \( \langle \beta \rangle \) changes even more) as the Helmholtz coils are energized reducing \( V_{\text{sol}}/V_0 \).

The pressure profile and stored energy will be measured through reconstructed from magnetic measurements: nine flux loops, nine coils measuring the normal field at the vessel wall, nine measuring the tangential field, and the total current measured by summation of partial Rogowski coils. Our x-ray imaging camera and steerable interferometer will lend support to the magnetic reconstruction. The measurement of the maximum stored energy as a function of plasma edge pressure will lead directly to the measurement of the critical pressure gradient set by MHD. The comparison of the critical pressure gradient with the MHD interchange criterion will clearly elucidate the limits of compressibility stabilization.

Multiple frequency electron cyclotron heating will be used to adjust the plasma pressure profile. Langmuir probe measurements will permit direct measurements of the scrape-off layer characteristics. Fluctuations of the magnetics data will detect MHD instability.
7.4.3 Particle Circulation and Adiabatic Heating

Unlike toroidal plasma confined by nested magnetic surfaces that have magnetic shear, the dipole field permits rapid, adiabatic particle circulation that may make the dipole concept ideally suited to utilize advanced fuels in a fusion power source [41]. As discussed in Section 4, a fundamental property of magnetic topologies with closed field lines lies is the tendency of the field lines to charge up and generate large scale $\mathbf{E} \times \mathbf{B}$ convective flows. In the outer regions of the LDX plasma, this process is expected to impose a stiff limit on the pressure gradient, forcing the profile to be near the critical gradient predicted by ideal MHD interchange theory. Although particle circulation may be rapid, convective flows do not necessarily give rise to energy transport. Rapid particle circulation and adiabatic heating exists within Earth’s magnetosphere. Showing the existence of these flows within the laboratory is a critical part of our evaluation of the feasibility of the dipole configuration as a fusion concept.

Our investigations of large-scale convective cells and the axisymmetry of the electrostatic potential profiles will begin during the second program year. We will focus three active approaches. First, we will measure convection and the rate of circulation of impurities that move from the edge to the core following a short and spatially-localized impurity “spark”. The impurity flow patterns and resulting averaged inward impurity flux will be observed spectroscopically. Secondly, the symmetry of the electrostatic potential will be measured with probe arrays at the plasma edge. Finally, movable emissive probes will be used to measure the time-variation of the electrostatic potential at a particular toroidal location. We will also investigate their use to excite convective cells by modulating their bias.

Once we have successfully identified convective cells and measured the rate of inward particle convection, three other experiments will be conducted to further understand the formation of convective cells. These are:

1. First, the eight TSR saddle coils will be used to generate (and eliminate) small magnetic field errors that may cause stationary ambipolar potentials.

2. Secondly, we are able to easily drive up to 4 kA through the launcher cables creating a weak toroidal field (10-20 G) and allowing tests of the suppression of convective cells with magnetic shear [48].

3. Finally, the Li pellet injector, installed for transient density studies in the third year, will most likely create large, localized, and easy-to-measure density perturbations that will create large $\mathbf{E} \times \mathbf{B}$ convective flows.

7.4.4 Dipole Confinement Studies

The third scientific objective of the LDX experiment is to provide the basic understanding of energy confinement in a dipole magnetic field and to test conditions that may eliminate drift-wave turbulence and produce plasmas with classical confinement. LDX will enable the first observations and investigations of high-temperature plasma confinement for many collisions times in a large plasma with strong compressibility effects. As discussed in Section 4, when both
the pressure profile and the density profile are near adiabatic, theory suggests that electrostatic drift modes are stable. These adiabatic profiles have density profiles that scale with radius as \( n(\psi) \sim 1/V(\psi) \) and pressure profiles that scale as \( p(\psi) \sim 1/V^\gamma \). The gradient parameter, \( \eta = d\ln T/d\ln n \sim 2/3 \) is a constant. What distinguishes the dipole concept from others is its large variation in the flux-tube volume, \( V(\psi) \). When the dipole satisfies drift-wave stability criteria, both the pressure and density profiles remain sufficiently steep to be relevant for fusion energy.

Several active experimental studies will be made to investigate dipole confinement beginning with low-density plasmas containing significant energetic electrons and ending with high-density plasma with greatly reduced energetic electron populations. In all cases, we will measure global stored energy, pressure profiles, and the edge plasma. Equilibrium reconstruction using magnetic measurements is the primary diagnostic tool, but we will also use a multichord microwave interferometer to estimate the electron density profile and a neutral particle charge-exchange energy analyzer to indicate the ion temperature.

For plasma with large fractions of energetic electrons, the injected ECRH microwaves are strongly absorbed, and this makes estimations of global confinement times relatively easy. However, the rapid magnetic drifts of the energetic electrons allow pressure gradients to exceed the usual MHD interchange constraint. For energetic electron plasma, the global energy confinement times can be larger than the critical values, \( \tau_{E}^{\text{crit}} \), that balance scrape-off layer losses. For these plasmas, our confinement studies will emphasize edge plasma measurements, edge fluctuations, and maximizing the total stored energy by adjusting the pressure profile with MFECRH.

Perhaps, our most important confinement studies will occur upon study of high-density plasma created by fast gas and/or Li pellet injection into high \( \beta \), hot-electron target plasma. It is with these plasmas that we seek to create conditions that meet the dual adiabaticity constraints on (thermal) pressure and density. Our goal is to create high-beta plasma with large variations in the \( \eta \) profile parameter: ranging from peaked density to hollow. When \( \eta \approx 2/3 \), the profile should remain stable to drift-wave turbulence and simultaneously maximize energy confinement.

As already mentioned, modifications to the density profile will be made by fast gas injection, both from the edge and from the floating coil, and by pellet injection. Additionally, the plasma may “naturally” adjust its profile towards the condition \( \eta \approx 2/3 \) due to particle circulation and adiabatic heating. High density experiments with different shapes (i.e. compressibility parameters, \( V_{s} / V_{0} \)) will also be investigated.

While these experiments will focus on understanding the relationship between profiles and confinement, this research phase of the LDX program will also investigation techniques to increase plasma pressure and energy confinement and global performance.

### 7.4.5 Advanced Studies

We list here plans for several “advanced studies” of dipole physics that may be investigated during the end of the proposed project period. These include:

1. The use of an array of edge probes or an axisymmetric limiter to create an axisymmetric
radial electric field and excite axisymmetric rotational flows. We would test whether these flows might create an edge pressure pedestal.

2. The design and configuration of advanced diagnostics such as a heavy ion beam probe to measure the internal plasma potential and structure of convective cells.

3. The possibility of preferential removal of chosen species as they convect toward the outer region of the confined plasma region, possibly by the use of localized ion cyclotron heating.

4. The investigation of bottom levitation and the specification of the required enhancements to our feedback system. Bottom levitation produces the point-null configuration that may aid in the understanding of scrape-off layer parameters and reduce charge-exchange losses.

7.5 Installation and Facility Plan

Fig. 3 also shows the schedule for the installation and operation of equipment and the experimental facility. The installation of new equipment is staged to coincide with needs in the scientific program. In this section, we have listed the major installation and facility tasks planned for the next three years. These tasks are fewer and much simpler than those associated with the fabrication of our three superconducting magnets. When completed, they provide all of the research tools required for our physics objectives.

- **Year 1: November 2003 – October 2004**
  - Install coil levitation components: laser coil detectors, TSR coils, phase 2 catcher. Demonstrate reliable levitation of the floating coil.
  - Install gas valve near floating coil to be used to alter density profile
  - Install waveguide and utilities for existing 10.5 GHz and 18 GHz klystrons used for pressure profile control experiments.

- **Year 2: November 2004 – October 2005**
  - Install neutral particle charge-exchange energy analyzer.
  - Install additional cords for microwave interferometry.
  - Install impurity “spark” source.
  - Install and test edge bias probes to induce electrostatic particle convection.

- **Year 3: November 2005 – October 2006**
  - Install Li pellet injector.
  - Install waveguide and utilities for existing 28 GHz gyrotron.
  - Purchase impurity spectroscopy and imaging diagnostic.
7.6 Educational and Outreach Activities

As a new experiment in the U.S. fusion program, LDX has an important educational and outreach goal. The LDX experiments are closely related to the physics of magnetospheric plasma, and it contributes basic understanding to the dynamics and confinement of plasma trapped by a dipole magnetic field that may be relevant to space plasma. LDX also incorporates superconducting magnets. While magnetic levitation is now appreciated by many, never before has such a large magnet been levitated by a coil at such a great distance. As a consequence, LDX has already attracted considerable public attention, and we plan to take good advantage of this interest to promote fusion science with public tours and articles written for the public.

The research opportunities of the dipole concept has also attracted the involvement of several undergraduate and four graduate students at MIT and Columbia. LDX has also hosted a DOE undergraduate fusion fellow. MIT’s Department of Nuclear Engineering devoted a part of its innovative fusion engineering course to the dipole concept. LDX has hosted two visiting scientists from Japan and Germany and the proposed budget helps to continue these international collaborations.

8 Facilities and Budget

The LDX project is a joint project of Columbia University and the Plasma Science and Fusion Center (PSFC) at MIT. The project benefits from very strong institutional support from both Columbia University and MIT.

The LDX experiment is located in the south end of the west cell in MIT PSFC building NW21–adjacent to the Pulse Test Facility (PTF) and within the same building as Alcator C-Mod. The experimental hall occupies one-third of space previously used for the TARA experiment. Because this research space has in place power supplies, power and cooling utilities, cryogenic systems, and a large overhead crane, MIT’s PSFC is an ideal location for LDX.

During the assembly of the LDX device, motivated major investments have been made by PSFC and MIT to further enhance the site and benefit superconducting magnet testing and operation. A helium recovery system has been installed permitting low-cost purchase and re-use of liquid helium from MIT’s on-campus liquefier. At the present moment, MIT is completing the installation of new experiment access decking that incorporate supports for x-ray shielding and that permit scientists safe and convenient access to the large LDX vacuum vessel.

While the site and infrastructure at the MIT PSFC is particularly well-suited for the LDX experiment, without any doubt, the two most important capabilities of the LDX project are (1) the members of the LDX research team and (2) the three superconducting magnet systems. The appendix, entitled “Facilities and Budget” provide longer descriptions of the magnets and systems that will be used for the proposed experiment.

8.1 Personnel and Project Management

At the beginning of the previous grant period, a new team of scientists and engineers was assembled to design, assemble, and operate an entirely new experimental fusion device. The
LDX research team includes plasma scientists and magnet technology and cryogenics experts making it unique within the U.S. fusion science program. The present membership of the LDX team is listed in Table 3.

The LDX project is jointly directed by Drs. Mike Mauel and Jay Kesner. Project activities have been further organized into three key areas. Engineering and superconducting magnets have been directed by Dr. Joe Minervini. LDX has supports two leading magnet research engineers, Drs. Alex Zhukovsky and Phil Michael, and two full-time technicians, Rick Lations and Don Strahan. Experimental operations is directed by Dr. D. Garnier. During the design and assembly of LDX, Dr. Garnier assisted to Dr. Minervini in coordinating the installation of experimental systems. Dr. Garnier is assisted by Dr. Alex Hansen and four graduate students (Ishtak Karim, Eugenio Ortiz, Jennifer Ellsworth, and Alex Boxer). Dipole physics is directed by Dr. Kesner. The MIT theory group under Dr. Peter Catto has also been actively involved in the development of dipole related theory. Columbia University’s experience with the mechanically-

### Table 3: Members of the LDX Research Team.

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<thead>
<tr>
<th>Name</th>
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<tr>
<td>M. Mauel</td>
<td>Columbia</td>
<td>Co-PI</td>
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<tr>
<td>J. Kesner</td>
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<td>Co-PI</td>
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**Engineering and Superconducting Magnets**

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<tr>
<td>J. Minervini</td>
<td>MIT</td>
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<tr>
<td>A. Zhukovsky</td>
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<td>P. Michael</td>
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**Experimental Operations**

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<td>D. Garnier</td>
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<td>A. Hansen</td>
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<td>ECRH, Diagnostics</td>
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**Dipole Physics**

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**Technical Support**

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<td>D. Shahan</td>
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**Graduate Students**

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<td>E. Ortiz</td>
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<td>Edge Probes, Edge Potential Control</td>
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<td>J. Ellsworth</td>
<td>MIT</td>
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<td>A. Boxer</td>
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<td>Interferometry, Profiles</td>
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**Visiting Scientists**

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<td>IPP</td>
<td>Edge Arrays, Convective Cells</td>
</tr>
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</table>
supported CTX device [15]-[18] and with electron cyclotron resonance heating has guided the LDX design and research plans.

Two international collaborators have so far worked with LDX. These are (1) Prof. Yuichi Ogawa (University of Tokyo) who has interacted on many occasions sharing experiences during the construction of Mini-RT levitated dipole device, and (2) Dr. Olaf Grulke (IPP Greifswald) who is spending one year at LDX with support from a Humbolt Fellowship.

8.2 Budgets

The proposed budgets for LDX is adequate for the proposed three-year research plan. Approximately one-third is granted to Columbia University supporting the experimental research staff, one graduate student, and the LHe and LN$_2$ cryogens. Two-thirds is granted to MIT to support the engineering and technical staff, operational components, diagnostics, and control tools, and three graduate students.

All major components for LDX have now been purchased. Consequently, the proposed LDX three-year research budget reflects operating and personal costs and funds needed to install additional heating and diagnostic systems. The equipment and diagnostics budget is as follows: (FY04) the phase 2 (levitation) catcher, the laser detector system and microwave equipment, (FY05) the the pellet/gas fueling system, the edge biasing system, charge exchanger energy analyzer, interferometry channel upgrade and microwave and gyrotron components, and (FY06) multichannel visible spectroscopy system and interferometry channel upgrade.

Acknowledgement

This proposal represents important contributions, ideas, and suggestions, from a number individuals. We wish to gratefully acknowledge the advice and information provided by Stewart Zweben (PPPL), Allen Boozer (Columbia), Leslie Bromberg (MIT), Gerald Navratil (Columbia), Miklos Porkolab (MIT), Joseph Minervini (MIT), Alex Zhukovsky (MIT), Philip Michael (MIT), Joel Schultz (MIT) and Brad Smith (MIT).
Bibliography

A Facilities and Resources

The LDX project is a collaborative effort among several well-established groups within the fusion community. The LDX project has combined the PSFC’s technical capabilities and expertise with superconducting magnets with Columbia’s experience with energetic electron production using electron cyclotron resonance heating (ECRH) in a mechanically supported dipole experiment, the CTX device, which presently operates at Columbia University. PPPL has provided engineering assistance in the design of the pneumatic “launcher” and a further collaboration with a loan of a hard x-ray imaging diagnostic.

Significant resources and equipment are available to carry out the proposed research. This appendix gives a more detailed description of the LDX device including its three superconducting magnets, the vacuum vessel and fueling systems, and the multiple-frequency ECRH systems. It also describes the experimental hall where the LDX device is located and the onsite available resources.

A.1 Superconducting Floating Coil

The floating coil (F-coil) is a superconducting magnet comprised of a single 1.5 km length conductor carrying up to 1.5 MA turns in a persistent mode. The design of this conductor, coil and its cryostat was based on many of the advances in superconducting magnet technology made over the past 25 years and now widely used in large numbers of commercial MRI, NMR and other high field magnet systems in reliable, long term operating service worldwide.

The technologies utilized in the F-coil design include:

- High critical current density, low loss, high stability Nb$_3$Sn conductor,
- Inductive charging arrangement with one very low resistance joint,
- Very low heat loss cryostat design,
- High load, low heat leak laminated crash supports, and
- Indirect cooling by a flow heat exchanger with re-sealable helium transfer ports.

Optimum combination of these technologies will allow for up to an 8 hour levitation time.

Floating Coil Description. The F-coil, shown in Fig. 4, was designed by the MIT engineering group [8] and utilizes an advanced Nb$_3$Sn superconductor originally developed for ITER. The strand was fabricated at IGC (now Outokumpu), wound at Everson Electric and the cryostat was fabricated at Ability Engineering. Before being encapsulated in the cryostat the coil was tested at full current at MIT in July, 2000 and it performed up to specification.

The preliminary design of the conductor was based on pre-reacted 18 strand Rutherford cable, similar to that used in the D20 dipole, a very high-performance particle physics magnet developed at the Lawrence Berkeley Laboratory. The advanced Nb$_3$Sn strand, a successor to the ITER strand development, with a diameter of 0.75 mm and a relatively low copper fraction of 0.3, maximizes the current-sharing temperature at a given current, and therefore
Figure 4: Floating coil at Ability Engineering showing the outer vacuum vessel and a cut-away view of the radiation shield (January, 2003).

the experimental run time. The strand was then formed into a cable and heat treated to become a superconductor. The reacted cable was then soldered into a half-hard 8 mm × 2 mm copper channel for structural support and quench current sharing. The choice of reduced strand copper content with a hardened copper channel allows maximal superconductor performance at minimum coil weight, reducing the requirements on the external levitation coils and maximizing plasma volume.

The single 1.5 km long reacted cable was then insulated and carefully wound in a hybrid double pancake/layer wound fashion to form a continuous winding pack (714 turns) without internal joints. The winding pack is free standing with all thermal and magnetic stresses internally maintained. The combination of internal conductor stabilization and nominally steady state operation should minimize unexpected quenching of the magnet. In the event of a quench, however, the coil is designed with passive quench protection to ensure hot spot propagation allowing the magnetic stored energy to be safely dumped within the winding pack thermal mass. The winding pack was epoxy vacuum pressure impregnated and cured to provide structural integrity. After testing to full current in a liquid helium bath using current leads, a joint was made on the outer diameter of the coil so as to form a closed loop.

The cryostat consists of a toroidal shaped inconel helium pressure vessel surrounded by a 316L stainless steel vacuum vessel. Run time is also maximized by an optimized combination of helium ullage space providing inertial cooling below 12 °K in the inner helium pressure vessel and a lead shield at intermediate cryogenic temperature, similar in concept to the shield used in the Princeton FM-1 experiment [60]. The lead shield is wrapped with aluminized mylar multilayer
insulation to minimize the radiated thermal load from the outer vacuum vessel.

The inconel pressure vessel is pressurized at room temperature to 125 atm and contains roughly 1.5 kg of helium gas cryogen. Inconel 625 was chosen as the pressure vessel material because of its strength to weight ratio, high yield strength in its room temperature welds and known cryogenic properties. Over the operating temperature of the Nb$_3$Sn magnet from 4.7 to 10 °K, this small amount of helium provides the bulk of the thermal capacity of the 470 kg winding pack / inconel vessel cold mass. Utilizing a low heat leak cryostat design, the total heat leak to the cold mass is kept below 1 W, allowing an expected 8 hour levitation time.

The cryostat is cooled by a heat exchanger wrapped within the helium pressure vessel and on the surface of the lead shield. Liquid helium flows through the heat exchanger by a pair of bayonets that penetrate through the bottom of the charging station. After cooling, the heat exchanger is pumped out and o-ring sealed plugs are inserted into the warm ends of the bayonet ports to keep atmospheric or plasma gases from entering the cold the heat exchanger volume. In addition to these bayonet ports, an electrical feedthrough is fitted to allow monitoring of internally placed temperature sensors during cooldown and warmup.

The cryostat support system is built from 24 columns of powdered metal laminations to withstand up to 10 g overload at occasional crash collisions. The supports provide a very low heat leak at the normal operation of the magnet.

The magnet will be charged inductively in combination with the charging coil described below. The magnet is in a normal state during the excitation of the charging coil and thereafter is cooled so as to trap the flux threading the coil. After charging, the helium heat exchanger cooling is terminated and the bayonets removed leaving no contact.

### A.2 Superconducting Charging Coil

The charging coil [9] (C-coil), shown in Fig. 6 was designed and fabricated by the Efremov Institute (St. Petersburg, Russia) and was tested the week of March 3, 2003. It was found that the coil operated well up to 440 A at which current a quench occurred. This is 83% of the base case design value. Calculations indicate that operation at the 80% current level results in a factor of 2 reduction in peak plasma pressure and a reduction of peak beta from 60% to 42%. This degradation of plasma parameters is not expected to effect any of the physics program.
envisioned for LDX. In addition it was found that the pumping capacity was inadequate (for the vacuum region within the coil) which resulted in a higher than planned consumption of cryogens. As a result the pumping port on the coil is being enlarged. To increase the coil current up to the design value would require a repair that could be performed at a later date as part of a facility upgrade.

**Charging Coil Description.** The NbTi C-coil serves to charge/discharge inductively the floating superconducting magnet to/from 1650 A (2070 A nominal) when it is resting in the charging station at the bottom of the LDX vacuum vessel. The free standing solenoid magnet is installed in a low heat leak liquid helium bath cryostat with a warm bore of more than 1 m diameter. The magnet quench protection system has an external dump resistor, which dissipates most of the 12.5 MJ stored energy during a quench. A narrow gap between the top of the C-coil cryostat and the LDX vacuum vessel restricts the location of ports at the cryostat top and thus most feedthroughs are unusual being from the underside of the cryostat.

The conductor and C-coil were designed with the criteria that the maximum hot spot temperature after a quench shall remain below 150 °K, and the maximum voltage developed during a C-coil quench not exceed 3 kV. The coil was wound on a demountable mandrel and after winding the coil was vacuum-pressure impregnated with epoxy resin. Soldered praying-hands joints 0.6 m long were located outside of the winding pack. The C-coil is fixed inside a cryostat which consists of a liquid helium vessel designed so that the coil is fully immersed in liquid helium coil during operation. The helium vessel is supported by a structure consisting of 16 inclined thin wall G-10 CR tubes attached at one end to the outer wall of the helium vessel and at the other end to a stainless steel support ring. The ring is supported by four columns which are connected to the C-coil stand. The support system of the cold mass was designed to withstand the most severe combinations of electromagnetic and seismic loads.

An 80 °K thermal shield surrounds the helium vessel and consists of outer and inner stainless steel liquid nitrogen vessels connected by liquid and vapor tubes and by top and bottom copper disks. The basic support ring and some other supporting elements are cooled by direct liquid nitrogen flows. A vacuum can surrounds the thermal shield. The bottom location of all electric, instrumentation, and cryogenic feedthroughs is dictated by the restricted space at the C-coil cryostat top.

To reduce the radiation heat load, all the surfaces of the vessels and thermal shields of the
cryostat were covered with thin metal shim stock coated by a highly reflective 1-3 \( \mu \)m aluminum layer. A special surface treatment was used in which evaporated aluminum is deposited to form a mono-crystalline aluminum cover on the metal substrate which results in a surface with extremely low emissivity. The emissivity factor for such surfaces at temperatures of 80 to 4 \( ^\circ \)K can be less than 0.005. At this emissivity, the estimated radiation heat leak to the helium vessel is about 0.15 W. Cryo adsorption panels with a charcoal adsorbent have been installed on the liquid nitrogen vessel to maintain \( 10^{-6} \) torr operating vacuum in the cryostat. This vacuum is associated with a residual gas heat leak to the 4 \( ^\circ \)K level of about 0.15 W.

A quench protection system serves to protect the superconducting C-coil and the power supply in case of quench or a power supply failure. During the time when the F-coil is out of the charging station, the C-coil protection circuit must be open. To protect the C-coil from damage during a quench, the quench protection system provides a fast discharge through the dump resistor. During testing several quenches occurred and the quench protection system worked as designed. A four-quadrant 40 V and 600 A power supply, whose use is borrowed from the PTF, is used for powering the C-coil.

The main scenario of C-coil operation is as follows: At the beginning of the LDX working day, the C-coil is charged in about 30 minutes to the full current, while the F-coil is slowly cooled from an initial 20 \( ^\circ \)K. The F-coil is then cooled down to a superconducting state while the C-coil current is held constant. The C-coil is then discharged during 1/2 hour, inducing full current in the F-coil. We expect the total cycle time of the C-coil to be approximately 90 minutes after we gain experience with the coils, with a total time for F-coil cooling to be approximately 2.5 hours. After the F-coil is brought to 5 \( ^\circ \)K, the main C-coil circuit is then opened, but the quench protection dump resistor circuit remains closed. The C-coil is held at zero current when the F-coil is lifted out of the charging station in the vacuum vessel and during LDX experiments. It can also carry a small negative current during floating operation to boost the levitation coil (which supports the F-coil). At the end of the experimental run period the F-coil is lowered back into the charging station, the main C-coil circuit is closed, and the C-coil is ramped up in half an hour to discharge the F-coil. The F-coil is then heated above its critical temperature and the C-coil is discharged.

### A.3 High Temperature Superconducting Levitation Coil

This floating coil is supported by a levitation coil (L-coil) which is located on the top of the vacuum vessel. In addition to providing the magnetic force to levitate the 600 kg floating coil, the L-coil must also be modulated with a feedback signal to provide vertical stability. In the initial LDX machine design, the levitation coil was a water-cooled copper solenoid, and was a substantial continuous load on the available (0.6 MW) cooling water system. With the help of a SBIR with American Superconductor Corporation (ASC), we have designed and fabricated a high temperature superconducting (HTS) levitation coil, which will be the first HTS coil to be used in a US fusion program. The coil winding and cryostat was manufactured at Everson Electric Company, in Bethlehem, PA. The finished coil, now at MIT, is shown in Fig. 7.

**L-coil Description.** The L-coil is a disk-shaped solenoid magnet made from two single pancakes that sandwich a supporting disk that provides structural integrity and conduction cooling.
Each pancake contains roughly 1400 turns of stainless steel reinforced BSSCO-2223 superconducting tape provided by ASC. The conductor, designated by the ASC product literature as “Bi-2223 Narrow” is a state-of-the-art tape in terms of having the best combination of critical properties and strength for the application. The dimensions are 3.1 mm × 0.168 mm and available piece lengths ranged from 300 m to greater than 500 m. Approximately 34 internal joints were required in the conductor, before winding. The joints, developed by ASC, were 100 mm PbSn soldered lap joints, each with a room temperature resistance of around 100 nΩ.

The central support plate consists of a 9 mm think stainless steel disk to which are bonded thin copper sheets on each side that provide radial heat conduction. These copper sheets are given radial cuts to reduce eddy currents during in the AC operation of the coil. To wind the coil, the conductor was soldered to pre-assembled inner joint structure that links the upper and lower windings at the coil inner diameter. The conductor was then co-wound with a .102 mm thick nomex tape to provide turn to turn insulation. Terminations were then made at the outside of the winding. The winding pack is then sandwiched between upper and lower support plates and the entire assembly was epoxy vacuum pressure impregnated and cured.

At this point, the L-coil was tested in a liquid nitrogen bath to ensure the operation of the conductor and winding pack integrity. In June 2002, the coil was tested to a critical current of 62 A at 77 °K. The nominal operating point for the coil in the LDX experiment is 110 A at 20 °K. As the conductor modeling shows that the coil should obtain a 160 A critical current at the operating current, the coil is expected to easily exceed its design specification in operation.

The L-coil cryostat is a nearly cryogen free design. The coil is conduction cooled by a cold head inserted into the top of the cryostat. The Cryomech made cryocooler produces 25 W at 20 °K. High temperature superconducting leads are used to reduce the heat load to the cold
mass and a cooled copper thermal shield is used to intercept room temperature radiation. The shield is cooled by a liquid nitrogen (LN2) reservoir located in the top of the vacuum can. A fully cryogen free design was considered, but given the easily available LN2 on the LDX site, this solution was chosen to reduce cost and complexity. In operation, the LN2 reservoir is automatically re-filled to the desired level. As in design for the F-coil, multi-layer insulation is used to reduce the radiated heat load on the nitrogen reservoir and shield.

The power supply for the L-coil power supply was specifically designed for the LDX experiment. The 10 kW, 2 quadrant supply provides the 110 A DC current as well as the needed voltage to ramp the current for levitation feedback control. In addition, a secondary crowbar circuit was added to protect against an unmitigated upward loss of control event that could result in catastrophic damage to the floating coil.

A.4 Charging Station

The charging station consists of a moderate sized vacuum vessel and mechanical system for positioning the the floating coil within the bore of the charging coil and carrying out the routine daily servicing of the floating coil. Within the charging station, the F-coil rests on a special vacuum compatible rotary table that maintains radial alignment of the two coils and may be manually oriented to provide proper alignment of helium transfer bayonets and attachment of the temperature monitoring electrical umbilical. Stain gauges will installed in the legs of the rotary table to monitor any mechanical forces due to coil misalignment during the charging process.

The charging station also provides secondary interlock vacuum systems that allow the helium cooling bayonets and heat exchanger plugs to be inserted or removed without introducing atmosphere into the floating coil heat exchanger or allowing cryogen to contaminate the vacuum in the main plasma vacuum chamber.

A.5 Launcher/Catcher System

The launcher/catcher system, shown in Figs. 1 and 8, provides the transportation of floating coil from its initial position within the charging coil to its levitation position at the midplane of the main vacuum vessel. In addition, it must also enable the F-coil to be successfully caught in the unlikely event of a levitation system failure. To do so, it must limit the forces to less than
Table 4: Characteristic frequencies \((f, \text{ Hz})\) and growth rates \((\gamma, \text{ s}^{-1})\) for representative ring levitation configurations in LDX.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency, (\omega)</th>
<th>Vertical (\sqrt{2\pi a IB_{z,r}/M})</th>
<th>Horizontal (-\pi a IB_{z,r}/M)</th>
<th>Tilt (\sqrt{2\pi IB_{z}/M})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Base Case</td>
<td>(\gamma = 4.1)</td>
<td>(f = 0.5)</td>
<td>(f = 1.1)</td>
<td></td>
</tr>
<tr>
<td>B: Max Flux Expansion</td>
<td>(\gamma = 4.0)</td>
<td>(f = 0.5)</td>
<td>(f = 1.2)</td>
<td></td>
</tr>
<tr>
<td>C: Min Flux Expansion</td>
<td>(\gamma = 4.1)</td>
<td>(f = 0.5)</td>
<td>(f = 2.25)</td>
<td></td>
</tr>
<tr>
<td>P: Point Null</td>
<td>(f = 5.5)</td>
<td>(\gamma = 4.5)</td>
<td>(\gamma = 16)</td>
<td></td>
</tr>
</tbody>
</table>

the specified 10g load requirement of the F-coil inner support structure. The launcher/catcher was designed at PPPL and subsequently built by the LDX team.

The launcher/catcher consists of a large bellows operated crane connected to a basket like catcher fixture that internally cradles the F-coil vacuum vessel. The crane which is positioned above the LDX vacuum vessel provides the lifting force for the 600 kg floating coil by means of a 6-inch pneumatic cylinder. A pulley system with a 1-2 purchase is utilized to reduce the required throw of the cylinder. In addition, a secondary pair of gas spring cylinders are used to limit the maximum deceleration of the F-coil and launcher to less than 5g in event of a control system failure. Finally, a second bellows feedthrough is provided beneath the LDX device to provide tension to the lifting crane, easing issues of alignment and limiting transverse loading of the system in the crash situation.

A.6 Floating Coil Control System

In general, a coil that is magnetically levitated has six degrees of freedom: vertical motion, horizontal translation, tilt and precession about its axis. In the dipole confinement approach there are no toroidal or vertical fields and the superconducting ring must only be levitated against its own weight (in our case, equal to 600 kg). In LDX, we have located the levitation coil 1.55 m above the superconducting ring, and, thereby, we have selected for our base-case configuration a simple levitation scheme which is stable to translation and tilt. Only a single low power feedback system is required to stabilize the vertical mode. This approach works for limited plasmas and for ring null diverted configurations (Fig 2a).

We have solved the linearized equations of motion of a rigid ring current to obtain the characteristic frequencies and growth rates of the levitated ring [62]. Table 4 shows the stability results obtained, where we have taken the ring radius \(a\), the mass, \(M\), and the ring current, \(I\). The first order expressions for the characteristic frequencies can be written in terms of the applied vertical field at the ring, \(B_z\), and its first radial gradient, \(B_{z,r} = \partial B_z/\partial r = \partial B_r/\partial z\). Instability is indicated by the growth rate, \(\gamma\) and stability by a real frequency \(f\). Characteristic frequencies and growth rates are typically < 5 Hz. The stability of configurations with ring null divertors are similar to that of the non-diverted configurations. In the Helmholtz configuration
(case C) the shaping coils create a uniform field near the axis and therefore the field derivative, $B_{z,r}$, does not change.

A further example is presented (case P) illustrating the possibility of creating a point null configuration using lower levitation. In this case, the system is stable to vertical motion but unstable to horizontal translation and tilt modes. Due to the increased requirements for stabilization, it is likely that an upgrade of the tilt-slide-rotate system would be required to reliably achieve this configuration.

We plan to monitor the position of the ring optically in a manner similar to FM-1 [60]. A cylindrical ring will be attached to the floating coil outer cryostat that will occult ribbon-shaped laser beams that pass horizontally through the plasma chamber. A 1-D position sensitive photo-diode detector will be used to determine how much of the beam is blocked and thus what the position of the coil is. Eight beams will be used to redundantly determine the 5 degrees of freedom of the coil. (Axisymmetric rotation of the coil will determined with a separate reflecting system.)

These signals will then be digitized and processed using a digital feedback control system. A digital system, enabled by recent advances in computer speed and advances in operating systems, was chosen to simplify system development and maximize system flexibility. As implemented, the digital feedback control system consists of a 950 MHz industrial Pentium III based computer running the QNX/Neutrino real-time operating system (RTOS) with analog and digital signal interface boards. With 32 analog input, 16 analog output, and 64 multipurpose digital channels, the system is capable of making a complete input/process/output control cycle at up to 20 kHz. The system is programmed using Opal-RT RT-Lab and Matlab Simulink/Stateflow. This system allows rapid implementation of new feedback algorithms without resorting to direct lower level programming normally required for real-time control. The digital control system has been successfully tested on a small desktop levitation model with roughly 10 times the required frequency response of the full experiment.

The digital feedback system will control the current in the levitation coil, typically changing the current of order 1% to maintain vertical stability. In addition to the L-coil, eight low power...
saddle coils will be installed on the vacuum vessel exterior to provide damping for the stable tilt, slide and rotational modes (tilt-slide-rotate coils).

A.7 Plasma Systems

The LDX vacuum vessel, shown in Fig. 9, is a 5 m diameter by 3 m high non-magnetic, 304L stainless steel vessel. It was fabricated using two ASME flanged and dished heads with an interconnecting cylinder and is 1.9 cm (3/4-inch) thick. The vessel is supported below the cylindrical section by six aluminum 6061-T6 legs. Two 1.25 m diameter axial ports, one on the top and one on the bottom, are provided for installing the floating coil and other large internal structures. As illustrated in Fig. 10, the vessel also incorporates an array of ten 16.5-inch diameter radial diagnostic ports on the cylindrical section and a set of four 10-inch diameter ports on the top and bottom heads. A separate 10-inch port is located on the top axial port cover for mounting the launcher catcher. In addition two 24-inch diameter ports provide ports for manned access and large cryopumps. The large size of the vacuum vessel provides excellent access for a variety of plasma heating and diagnostics systems.

Vacuum Systems and Particle Control. The vacuum pumping system consists of a gate
valve for isolation, a 1000 l/s turbo pump with a 60 CFM backing pump. In addition, a 300 CFM roughing pump and 1000 CFM Roots blower is available for initial system pumpdown. Two 22-inch cryopumps are used to maintain a base-pressure without plasma to $< 10^{-8}$ Torr. Numerous pressure gauges are included to monitor vacuum throughout the system and a residual gas analyzer is installed to aid in system debugging. Much of the system is controlled by a programmable logic controller (PLC) for remote and automated operation and monitoring.

Glow discharge cleaning will be performed in the usual manner. A single electrode, 7 kW DC glow will be used with D2 and/or He backfill.

A.8 Microwave Systems for ECRH

We have selected resonant microwave heating of electrons as the plasma heating and formation technique best suited for the production of high beta plasmas in LDX. Multiple frequency electron cyclotron resonance heating (MFECRH) allows scientists to adjust the radial location microwave heating and to enhance the production of energetic electrons. LDX will generate relativistic electrons, and harmonic absorption should be strong. The cyclotron resonance surfaces are shown in Fig. 11.

Five microwave sources are available to the LDX experiment. These include a 28 GHz Varian gyrotron (200 kW, 100 ms and 5 kW CW) originally used for the Tara tandem mirror experiment, an 18 GHZ Varian klystron (20 kW CW) also used for Tara, a 10.5 GHz klystron (10 kW CW) originally used in the Constance mirror experiment, a 6.4 GHz Varian klystron (3 kW CW) originally used at Columbia University for plasma processing and a 2.45 GHz klystron (50 kW for 100 ms) that is used in the VTF experiment (located next to LDX in the Tara cell). The 6.4 GHz klystron is ready for use, and all components of the 10.5 GHz klystron are present; these will be used during the initial plasma operation.

We have used these microwave sources successfully in previous plasma experiments, and we expect little difficulty adapting them to LDX. As in the Constance mirror and CTX dipole experiments, the 2.45 and 6 GHz microwave power will be coupled into the vacuum chamber near the midplane through quartz windows and using single mode waveguide (Fig. 10), using antennas with a broad emission pattern. For these frequencies, we intend to rely on “cavity heating” to maintain uniformity during microwave heating. This will limit the plasma density to approximately one-half of the...
Figure 12: Photographs of microwave tubes used for multiple-frequency ECRH.

cut-off density for each frequency. Since the stationary density profile scales as $r^{-4}$ while the
cutoff density scales as $r^{-6}$ along the dipole midplane, microwave accessibility to the fundamen-
tal and second harmonic electron cyclotron resonance will probably determine the maximum
density compatible with hot electron formation. The higher frequencies will be applied at ports
in the charging station, and will be directed to high-field regions within the ring. The 10.5 and
18 GHz klystrons will use single-mode waveguide and standard-gain horns. For the 28 GHz
gyrotron, we intend to use the same Vlasov antenna used in Tara which couples the TE$_{02}$ mode
to a gaussian beam.
A.9 Facilities and Organization

The LDX experiment occupies one-third of the experimental hall previously used for the TARA experiment. Besides the usual electrical, water and HVAC services already provided within the building, the LDX experiment takes advantage of significant additional experimental equipment already in place, including: (1) several TARA power supplies (each rated 800 V, 4 kA), (2) a large 1000 A, 50 V regulated power supply to be used to charge the superconducting charging coil, (3) 10 ton overhead crane, and (4) 10,000 gallon LN2 storage tank and vacuum insulated transfer line. PSFC machine and electronics shops are available to LDX engineers and technicians, and (at appropriate and opportune times) members of the Alcator technical staff have assisted in LDX assembly. Presently, MIT is constructing a dedicated mezzanine in the LDX area that will effectively double the available experimental space surrounding the LDX and greatly simplify access to the midplane vacuum vessel ports.

Adjacent to the LDX experimental area within the same experimental hall is the Pulse Test Facility (PTF) that was used for ITER superconductor cable and joints testing. The superconducting Nb$_3$Sn floating coil was successfully tested at 1.52 MA using the PTF. The LDX project has benefited from parts of the PTF data acquisition and control system computers and software that have been incorporated into a data acquisition system, a PLC control system, and a fail-safe, real-time levitation control system each dedicated for LDX use. The LDX project will take advantage of an available PTF power supply for charging the floating coil.