PLASMA CONFINEMENT IN A MAGNETIC DIPOLE*

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Abstract

A dipole fusion confinement device is stable to MHD interchange and ballooning modes when the pressure profile is sufficiently gentle. The plasma can be confined at high beta, is steady state and disruption free. Theory indicates that when the pressure gradient is sufficiently gentle to satisfy MHD requirements drift waves will also be stable. The dipole approach is particularly applicable for advanced fuels. A new experimental facility is presently being built to test the stability and transport properties of a dipole-confined plasma.

1. INTRODUCTION

The dipole fusion concept was first proposed by Hasegawa [1, 2] who was motivated by observations of high β, energetic plasma within planetary magnetospheres. Active magneto-spheres, such as that surrounding Jupiter, can have plasma pressures exceeding the magnetic pressure, $\beta > 1$. A dipole fusion confinement device takes advantage of these properties by operating with plasma profiles that have sufficiently gentle gradients to be stable to interchange and ballooning modes at high beta. This stability derives from plasma compressibility. The dipole confinement concept is fundamentally different from other fusion concepts since the diamagnetic frequency, ω_*, proportional to the radial gradient of plasma pressure, is small relative to the magnetic drift frequency, ω_d, proportional to the radial gradient of the magnetic field. The condition $\omega_*/\omega_d \leq 2$ characterizes a unique regime in magnetic plasma confinement. It corresponds to MHD stability and the possible elimination of drift wave instabilities [3].

In this paper, we will present (1) the theoretical basis for the dipole approach to plasma confinement, (2) the design and research goals of a new experimental facility that is presently being built as a joint project of Columbia University and MIT, and (3) the potential of dipole confinement for magnetic fusion energy. The dipole approach is particularly applicable for advanced fuels, *i.e.* DD and D^3He, since good confinement and stability at high-β might eliminate the need for a tritium breeding blanket and since convection cells may purge fusion-product ash without energy confinement degradation.

2. THEORETICAL BASIS FOR DIPOLE CONFINEMENT

For a plasma confined in the field of a levitated dipole, MHD interchange stability is determined by the requirement that compressibility balance the energy of expansion. As a result, the plasma pressure must fall-off gently on flux surfaces of increasing separation from the internal ring. Ideal MHD determines marginal stability to occur when the pressure profile, p, satisfies the condition, $\delta(pV^\gamma) = 0$, where V is the flux tube volume ($V = \oint dl/B$) and $\gamma = 5/3$. This requirement leads to the result that the peak pressure within a dipole is related to the edge pressure and the flux-tube geometry, $p_{max}/p_{edge} \leq (V_{edge}/V_{max})^\gamma$. Dipole plasma confinement requires a large expansion of magnetic flux, and a dipole confinement device would consist of a relatively small ring levitated within a large vacuum chamber. Since the peak plasma pressure depends on the edge pressure, dipole energy and particle balance is governed, in part, by the physics of plasma flowing along open field lines into a limiter.

* Work supported by DOE Grants DE-FG02-98ER54458 and DE-FG02-98ER54459.

The ignition of a fusion power source burning advanced fuel requires extremely good energy confinement (For example the ignition of D^3He requires 10 times the confinement required for DT ignition). Since the magnetic field of a dipole is poloidal, there are no charged-particle drifts off of magnetic flux surfaces and, therefore, no "neo-classical" degradation of confinement as seen in a tokamak. It has been shown that a plasma that satisfies the MHD interchange stability requirement $\delta(pV^{\gamma}) \geq 0$ may be intrinsically stable to drift frequency modes [3]. Stability of low frequency modes can be evaluated using kinetic theory and a Nyquist analysis permits an evaluation of stability boundaries with a minimum of simplifying assumptions [4]. It can be shown that when $\eta \equiv d\ln T / d\ln n = 2/3$ the interchange stability requirement (for small Larmor radius) becomes, in the low β limit, $\omega_* \leq 2\ \omega_d$. This result is consistent with MHD. Physically, plasmas stabilized by compressibility have a pressure gradient scale length which exceeds approximately one-half the radius of curvature. This physical property distinguishes dipole confinement from other confinement approaches to magnetic fusion. Importantly, when $\omega_* \leq 2\ \omega_d$, drift-type modes such as the η_i-mode can be shown to be stable. For example [4], the instability of the η_i.-mode requires $\omega_* > 3\ \omega_d$ (for $\eta_i = 2$) and therefore the η_i-mode is expected to be stable when the plasma is MHD stable. This behavior is typical of dipole confined plasmas and indicates when the pressure gradient must be sufficiently gentle for interchange stability, then drift-type modes are also stable.

When a small vertical field is added to the dipole field a magnetic separatrix will form (Fig 2). The separatrix will contain a field null and depending on the direction of the vertical field the null can occur at the outside of the plasma (Fig 2a) or on the magnetic axis (Fig 2b). The presence of the separatrix may change the stability properties of the scrape-off layer plasma. Additionally the presence of a magnetic field null on the flux tube that bounds the plasma is expected to effect the core plasma stability. Lane and co-workers [5] have studied the stability of interchange modes in a low β unstable mirror plasma bounded by a magnetic separatrix. They show that, whereas in the core plasma where both ions and electrons are magnetized and the plasma can be interchange unstable, in the vicinity of the separatrix one species can be unmagnetized and this leads to a local drift-wave response. The azimuthal electric fields of the interchange mode are effectively short-circuited in the vicinity of the field null and the interchange modes driven by the core plasma are forced to form a node at the separatrix flux tube. Therefore a core interchange mode would (1) have an increased FLR stabilization due to the requirement that the eigenfunction have a node at the separatrix and (2) could only transport energy up to a Larmor radius of the separatrix (since the eigenfunction amplitude is zero at this location). Experiments performed in the Tara tandem mirror confirmed that the bounding of an interchange unstable plasma by a magnetic separatrix produced a significant stabilizing effect [6]. The unstable drift waves that may be present near the separatrix could, in principle, transport energy. However it is believed that drift waves can be stabilized by the flow shear that tends to develop at the plasma edge due to such processes as preferential scrape-off of the large gyro radius ions and this leads us to conjecture that we may observe an H-mode-like phenomenon in a separatrix-limited levitated dipole. Since the peak pressure is directly related to the edge pressure, an edge pedestal would be extremely useful in permitting a reduction in the required flux expansion and therefore in the required vacuum chamber size.

When the interchange stability criterion is violated convective cells are expected to become unstable. For plasmas that are marginally stable $\delta(pV^{\gamma}) = 0$ and furthermore when $\eta = 2/3$ an interchange of flux tubes does not transport net energy and leaves the temperature and density profiles unchanged. The convective cells transport cool fuel ions inward from the edge and transport thermalized fusion products outward from the hot plasma core. The fuel ions heat adiabatically as they convect inwards, and the core plasma cools at the same rate as it convects outward. Thus this process would provide an ideal mechanism for the steady fueling and ash removal of a burning plasma [7].

2. THE LEVITATED DIPOLE EXPERIMENT (LDX)

We are in the process of constructing a small laboratory levitated dipole, called LDX to investigate the possibility of steady-state, high-beta dipole confinement with near classical energy confinement. The experiment will utilize a persistent Nb_3Sn superconducting ring of approximately 0.8 m diameter and levitated within a 2.5 m radius vacuum chamber as shown in Fig. 1. The experiment is designed to maximize the flux expansion and we expect p_{max}/p_{edge} =

LDX - Base Case Parameters

Levitated Mass	452 kg
Net Ring Current	1.28 MA
Compression Ratio:	512
Adiabatic Pressure Ratio:	32,768
Minimum B at Ring:	0.24 T
Maximum B at Ring:	3.95 T
Linear Ring Stability:	
Axial Growth Rate:	5 1/s
Horizontal Wobble:	0.5 Hz
Tilt Wobble:	1.6 Hz
Hot Electron Parameters:	
Hot Electron Temp:	250 keV
Peak Density:	1-5E11 cm^{-3}
Core Field Strength:	1.7 kG
Hot Electron Beta:	> 20%
Plasma Parameters:	
Peak Density:	> 1E13 cm^{-3}
Plasma Beta:	> 10%

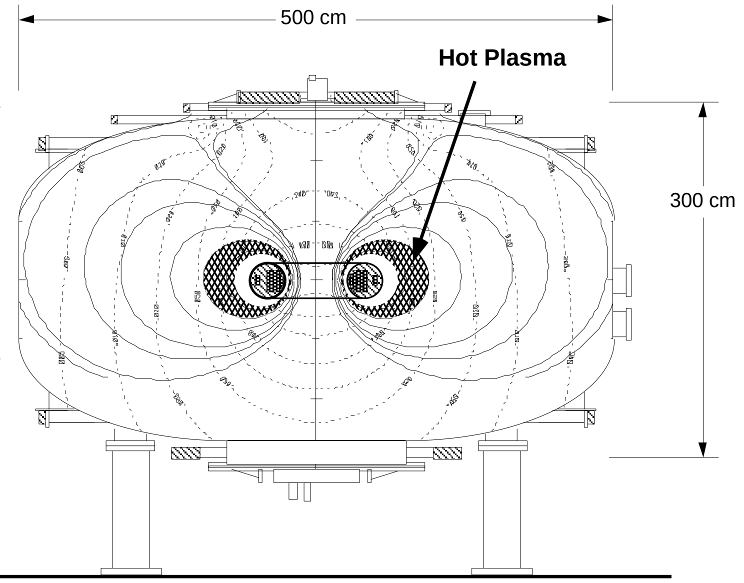

FIG. 1. The configuration and basic parameters of the proposed LDX experiment.

$(V_{edge}/V_{max})^{\gamma} > 2\text{x}10^4$. A pair of Helmholtz coils will enable the experiment to form a magnetic separatrix as seen in Fig. 2. As the magnetic separatrix moves inwards (toward the floating coil) the flux expansion decreases and this capability should permit a direct test of MHD stabilization due to compressibility. Since, in a dipole, the peak-to-edge pressure ratio depends sensitively on the flux expansion, the variation of flux expansion should lead to a strong variation of the core plasma pressure. In addition the separatrix-limited dipole plasma should provide a test of dipole h-mode as discussed above. The Helmholtz pair also permits the formation of a second limited magnetic configuration in which the “x-points” fall on the symmetry axis (Fig. 2b). This configuration may exhibit improved plasma properties due to a reduced penetration of neutrals into the vicinity of the core plasma.

In LDX the floating coil is unstable and a feedback-control system is being designed to stabilize of the floating coil. The floating coil can either “hang” from a coil located above the

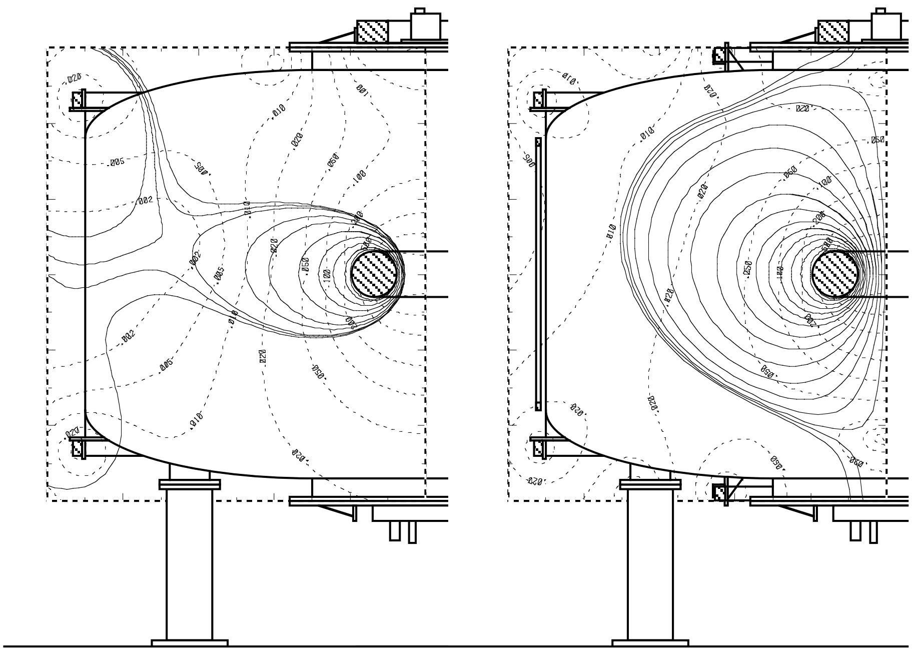

FIG. 2. The outer boundary of the levitated dipole plasma can be adjusted with low-field coils: (a) Outside diverted, (b) Inside diverted.

vacuum chamber or be held up by a coil located below the vacuum chamber. In the former case the ring is stable to tilt and horizontal translation and only unstable to vertical perturbations. As a result the control system will utilize only axisymmetric fields and is a particularly simple system. The latter arrangement is necessary to form the on-axis x-point configuration shown in Fig 2b.

The LDX experiments will investigate (1) high beta plasma stabilized by compressibility, (2) the relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence, and (3) the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma. High-β plasma will be formed by multiple-frequency ECRH since this heating technique has proven effective in magnetic mirrors and in a mechanically-supported dipole [7]. In the initial electron heating experiments, we expect to form hot electron plasmas with $T_e \sim$ 200-300 keV, $n_e \sim$ 1-5x10^{11} cm^{-3}. Higher density thermalized plasmas will be studied by using fast gas puffing and Li-pellet injection into the hot electron annulus. The thermalized plasma is expected to have $T_e \sim T_i >$ 100-400 eV, $n_e > 10^{12}$ cm^{-3}.

3. POTENTIAL OF DIPOLE CONFINEMENT FOR MAGNETIC FUSION ENERGY

Concepts for dipole based fusion power sources are being developed, both for electricity production as well as for non-electrical applications such as space propulsion. The dipole power source is characterized by a sophisticated coil, easy to replace, inside a large vacuum vessel. In order to increase the power density at the first wall, several concepts are being studied. They include the following: (1) Use of a higher order field, *i.e.* a quadrupole created by combining the floating dipole coil with a supported (opposing) dipole coil, (2) High temperature first wall operation ($T_{wall} \sim$ 1100 K) to radiate the power back into the vacuum chamber cavity from a large fraction of the first wall surface in combination with a small area heat exchanger that will then operate at a relatively high power density, and (3) H-mode like plasma pressure pedestal to increase the allowed edge plasma pressure and therefore decrease the size of the vacuum chamber.

The dipole plasma is steady state and high beta with no current-drive requirements. In order to operate in steady state, the surface thermal loads (x-rays, particle convection [9]) and the volume thermal loads (neutrons and gamma rays) need to be radiated away to cooler vacuum vessel walls. The ring needs to be suspended without electrical leads, mechanical support or pipes, to avoid loss cones and the creation of asymmetries. The energy dissipated in the cryogenic region of the coil needs to be transferred to the surface of the ring to be radiated at the high surface temperature. To do this, internal refrigerators, coupled with internal generators, are needed. Concepts for thermo-ionic generators are being developed, operating across a temperature gradient that is expected to develop at the ring surface. Typically at the outer midplane, the ring will be 1800-2000 K and at the inner midplane it will be 1200-1500 K. Multiple refrigerators, driven with homopolar motors and spanning several (three) temperatures ranges, are envisioned.

In addition to high beta, good confinement and unique fueling, a levitated dipole may have other advantages as compared to tokamak confinement devices. These include simplification of the divertor problem due to the large flux expansion, elimination of current driven instabilities and disruptions, elimination of interlocking coils and intrinsic steady state operation.

ACKNOWLEDGMENTS. The authors gratefully acknowledge the efforts of the engineering design team including J. Minervini, P. Michael, S. Pourrahimi, A. Radovinsky, J. Schultz, B. Smith, P. Wang and A. Zhukovsky of the PSFC, L. Myatt of MTechnology and S. Kochan of M.I.G. Designs.

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