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SUSTAINED SPHEROMAK PHYSICS EXPERIMENT*

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Abstract

The Sustained Spheromak Physics Experiment, SSPX, will study spheromak physics with particular attention to energy confinement and magnetic fluctuations in a spheromak sustained by electrostatic helicity injection. In order to operate in a low collisionality mode, requiring $T_e >$ 100 eV, vacuum techniques developed for tokamaks will be applied, and a divertor will be used for the first time in a spheromak. The discharge will operate for pulse lengths of several milliseconds, long compared to the time to establish a steady-state equilibrium but short compared to the L/R time of the flux conserver. The spheromak and helicity injector ("gun") are closely coupled, as shown by an ideal MHD model with force-free injector and edge plasmas. The current from the gun passes along the symmetry axis of the spheromak, and the resulting toroidal magnetic field causes the safety factor, q, to diverge on the separatrix. The q-profile depends on the ratio of the injector current to spheromak current and on the magnetic flux coupling the injector to the spheromak. New diagnostics include magnetic field measurements by a reflectometer operating in combined O- and X-modes and by a transient internal probe (TIP).

1. INTRODUCTION

SSPX is motivated by the achievement on a decaying plasma in CTX of T_e = 400 eV [1] and peak betas > 0.2 [2], and the subsequent recognition [3, 4] that the core energy confinement was consistent with magnetic fluctuation dominated transport which should scale favorably as T_e is increased. The experiment is designed to study confinement in a discharge sustained by electrostatic helicity injection [5, 6]. The experimental geometry is shown in Fig. 1a along with flux surfaces calculated in the ideal MHD approximation. A large-diameter coaxial injector has been chosen and calculations shown below predict that it will operate closely coupled to the spheromak. Both conditions are expected to optimize both operational flexibility and the efficiency of the dynamo current drive. The experiment has been designed for high vacuum cleanliness to minimize current and energy losses to impurities. The flux conserver (1 m diameter) is constructed to a 1 mm accuracy to control field errors. The goals of the experiment

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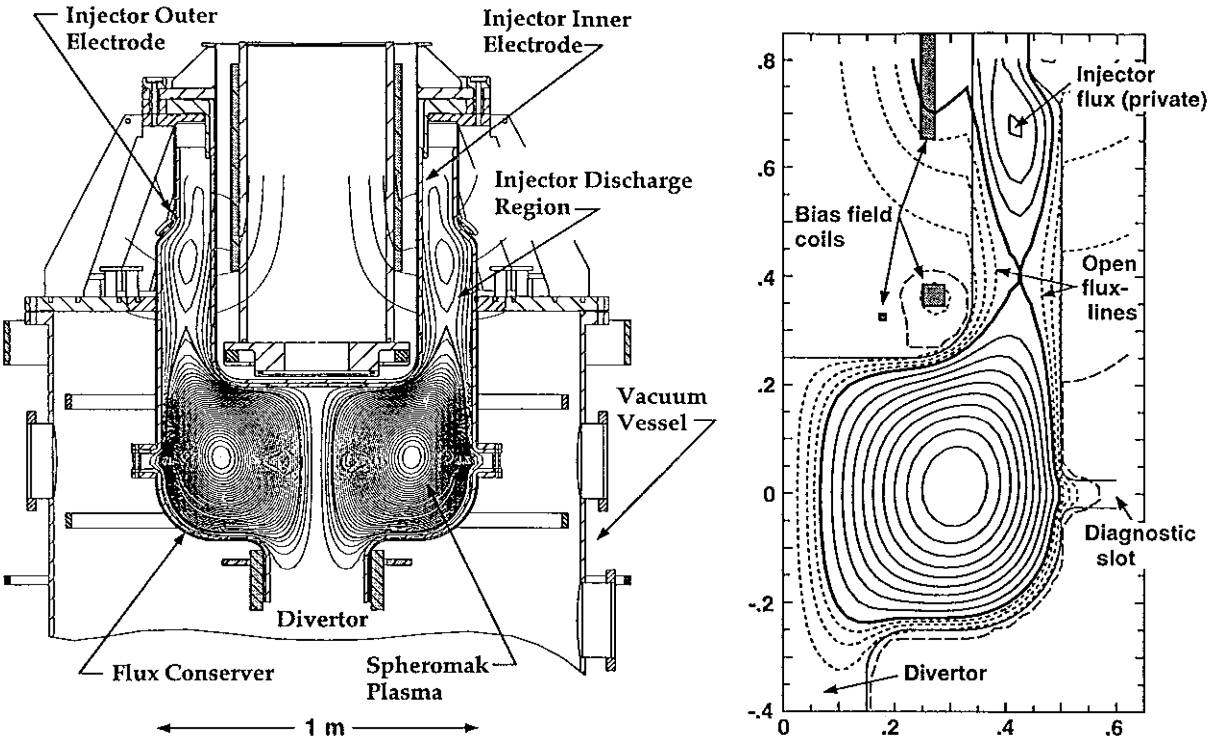

(a) (b)

Fig. 1: (a) SSPX flux conserver installed in the vacuum vessel, showing bias field coils and magnetic geometry. The injector bias magnetic flux, up to 34 mWb generated by a solenoid, is distributed on the injector walls by two small coils in the inner electrode and the top coil external to the vacuum vessel. Other coils are available for bias fields linking the injector and flux conserver. Impurities will be controlled by tungsten coating of the copper flux conserver, with baking, discharge cleaning, and boronization to condition the walls. A magnetic divertor will allow impurities in the edge flux boundary to be pumped (inertially) into the vacuum vessel. Primary diagnostic access is through a slot on the midplane of the flux conserver. (b) Expanded magnetic equilibrium (typical), including the flux surfaces in the coaxial helicity injector.

include n = 0.5-3×10^{20} m^{-3}, $T_e \approx T_i$ = 0.1-0.5 keV, B = 0.5-1.5 tesla, and I_p = 0.5-1.5 MA, yielding a Lundquist number $S = \tau_R/\tau_{Alfvén} \sim 10^6$. Initial experimental operation is planned in 1998.

2. MHD MODEL OF SSPX

The lowest order description of the experiment is the MHD equilibrium (evaluated using the TEQ package in the CORSICA code [7]) of the coupled spheromak and coaxial helicity injector, including the effects of currents on the open fieldlines; c.f. Fig. 1b. The flux conserver shape gives a margin of safety for low-order, ideal MHD modes as determined using the GATO code; for example, as shown in Fig. 2, the tilt and shift modes are calculated to be stable for flux conserver radii up to 60 cm, compared to the actual radius of 50 cm. Depending on current profiles, the configuration is Mercier stable for beta-poloidal < 0.24. The precise shape of the flux conserver is nearly tangent to the magnetic flux surfaces generated by coils outside the flux conserver, available to generate the divertor or a bias (vacuum) field, thus minimizing field errors.

To model the injector, the magnetic flux from the injector bias coils is considered frozen into the discharge walls. Current is assumed to flow at constant $\lambda = d(RB_\phi)/d\psi$ ($= j_\parallel/B$ at zero pressure on the open field lines); its distribution on the walls is thus determined by the injector bias flux. We take λ constant across the separatrix, but as shown in Fig. 3 allow a distribution inside

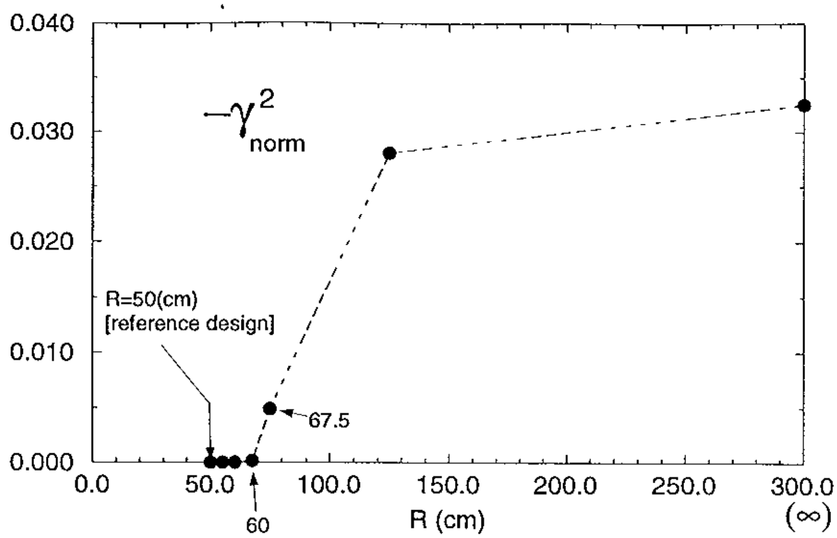

Fig. 2. Growth rate for tilt and shift modes in SSPX as a function of flux-conserver radius. The external current is zero in this calculation.

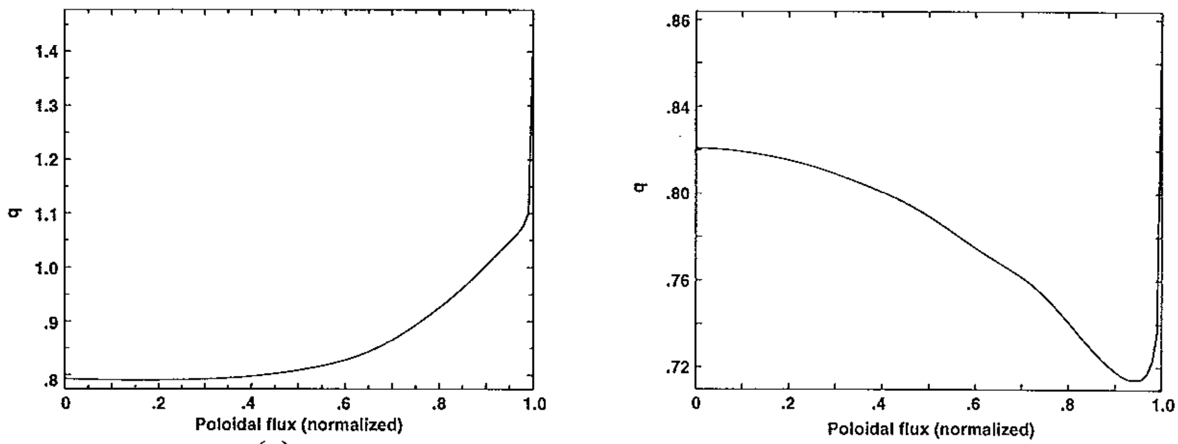

Fig. 3. Safety factor, q, profiles for two λ-profiles; λ in the edge plasma is constant at the value at the separatrix. In (a), $\lambda \sim 1 + (\psi/\psi_{edge})^{10}$. In (b), $\lambda \sim 1 + 0.6(\psi/\psi_{edge})^2$.

the separatrix parameterized by $\lambda = \bar{\lambda}\left(1 + \sum_1^3 a_n \psi^n + a_4 \psi^{nasp}\right)$. The value of λ on axis can reach unity if the current density on axis drops too low, e.g., in profiles like Fig. 3(b), presumably leading to strong instability. For both profiles, current along the flux conserver symmetry axis results in $q = 1$ in the logarithmic divergence layer near the plasma separatrix.

The close coupling between the spheromak and helicity injector allows operation somewhat below the eigenvalue for current density in a coaxial injector, $\lambda \approx \pi/\Delta$, with Δ the width of the gap. The q-profiles also have significant implications for the dynamo, as there are no internal $m = 1$ rational surfaces. Thus, internal helicity transport is expected to be due to resistive modes with $m > 1$, which should be relatively localized in the magnetic profile.

3. EXPERIMENTAL PLANS AND DIAGNOSTICS

The goals of the experiment require that the plasma be hot enough that the current dynamo can be driven by as small a ratio of $\lambda_{edge}/\lambda_{core}$ as can be sustained. This will require that resistive losses be as low as possible, and thus that the plasma have as low Z_{eff} and high T_e as possible. Experimental "knobs" include the injector flux which determines the diameter of the flux "hole" along the geometric axis, injector current which determines λ_{edge}, the gas injection rate which determines the fueling rate, the divertor magnetic configuration, and the bias magnetic field in the flux conserver. The spheromak power will be provided by an initiation capacitor bank (0.5 MJ at 10 keV) and a sustainment pulse-forming network (1.5 MJ at 5 kV, configured for 2 ms pulse). The voltage and impedances of these systems can be varied independently, offering additional control over spheromak operation.

Study of transport under these conditions will need external measurements of plasma profiles, including density, temperatures, and magnetic fields. Initial diagnostics include magnetic probe arrays in the flux-conserver walls, Rogowski probes to measure currents in the jumpers across the diagnostic slot, flux loops, a camera to view discharge behavior, H-alpha diodes, and visible and ultra-violet spectroscopy. As soon as possible, mm-wave reflectometry, Thomson scattering, and a CO_2 interferometer will be added. Probes will be used in the edge and boundary plasmas.

Critical to understanding the coupling between the current drive and energy losses is the measurement of magnetic fluctuations and their relationship to resistive MHD, including current (and pressure) driven tearing modes. The amplitude and behavior of magnetic fluctuations will be measured by an Ultra-Short-Pulse Reflectometer [8] operating in both the O- and X-modes; it will also used to measure the density and magnetic field profiles. Coupling between the two reflectometer modes is generated by magnetic shear, and thus will yield the vector direction of the field. The coupling is also expected to be sensitive to magnetic tearing modes in the plasma, and experiments are planned for using it to evaluate the level of the fluctuations presumed to drive the dynamo. Modeling using computational spheromak equilibria has been used to develop techniques for inverting the data [9]. As the measurement is indirect, a transient magnetic probe [10] will be installed to measure the magnetic field locally from the Faraday rotation in a sapphire "bullet" injected across the plasma. This field measurement will be used to validate the reflectometer measurements.

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