An Imposed Dynamo Current Drive experiment: studying and developing efficient current drive with sufficient confinement at high temperature:


1. Executive Summary
This paper addresses the issue of confinement compatibility of a new energy efficient current drive and profile control method, recently discovered by the HIT program, called Imposed Dynamo Current Drive (IDCD). A new spheromak experiment, with a minor radius 0.55 m, an aspect ratio 1.5 that is rated for 1.35 MA of toroidal current and 1 keV peak temperature is proposed. Previous spheromak research achieved transient plasmas that self-heated (from resistive heating) to the pressure limit, demonstrating sufficient confinement in the several 100 eV temperature range. However, attempts to sustain them with coaxial helicity injection relied on kink instability to produce the fluctuations necessary for helicity injection current drive, resulting in poor confinement. IDCD imposes the fluctuations while doing inductive helicity injection, sustaining a kink-stable equilibrium. Above a threshold frequency (\( \sim 30 \text{ kHz} \)) these sustained spheromaks self-heat (from input current drive power) to the pressure limit, demonstrating sufficient confinement but at low temperature (<50 eV). The primary goal of this new experiment is to study and develop IDCD further by using it to sustain a pressure-limited spheromak at several 100 eV, combining the previous and recent achievements. Success on this higher temperature experiment opens the path to an economical fusion power reactor. The experiment has the controls and capabilities to achieve formation, sustainment, equilibrium, stability, and confinement. The estimated fabrication cost of the experiment and power supplies is $6 M.

2. Introduction
Motivation: This proposal contributes to the goal of reducing operational and maintenance complexity of toroidal confinement and Thrust 18 of the ReNeW planning workshop: “Achieve high-performance toroidal confinement using minimal externally applied magnetic field”. Presently the tokamak has three coil sets and a toroidal vacuum chamber that are interlinked. The coil sets are the transformer solenoid, the toroidal field coils and the equilibrium coils. The transformer is used for current drive on present tokamaks and works very well since the plasma current is almost purely toroidal. However, since it is only used for startup in a reactor and other current drive must be developed anyway, it can be eliminated and indeed recent ARIES reactor studies do not have this coil. Of the remaining two coil sets only the equilibrium coils are fundamental for toroidal confinement and stable equilibria have been produced transiently that have sufficient confinement at temperatures in the kilovolt range using very little or no externally produced toroidal field. Sufficient confinement allows the current-drive power to heat the plasma to its stability \( \beta \)-limit. Decaying spheromaks, that have no toroidal field coil, have been observed to Ohmically heat to the \( \beta \)-limit. Until now, there was no known method for efficiently sustaining the spheromak current profile with sufficient confinement. With Imposed Dynamo Current Drive (IDCD) efficient steady-state current drive with sufficient current profile control and sufficient confinement has been demonstrated (at low temperature) and the toroidal field coil can be eliminated. Now a simple vacuum vessel can be used, which is less expensive. The capital cost is low enough that high thermal efficiency requiring very high operating temperatures (>800\(^\circ\)C) is not necessary and structural materials presently used by the nuclear industry (at ~580\(^\circ\)C) can be used, lowering the development cost and time. The simple geometry allows a higher tritium breeding ratio so FLiBe can be used as the coolant and breeding medium lowering the maintenance cost. These features lead to economically competitive fusion power.

This program contributes to FES mission because understanding and developing efficient current drive is helping to “build the scientific foundation needed to develop a fusion energy source” and validation work is helping with “creating theoretical and computational models to resolve essential physics principles”.

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This program contributes to FES goals 1 and 4. This research applies to all five top tier thrusts identified by the FESAC priorities panel. The proposal contributes to the study and application of 3D B-fields.

Based on breakthrough results and understanding coming from the HIT-SI experiment and NIMROD simulations, a new experiment is needed. With the achievement of greatly improved parameters on HIT-SI came the discovery of IDCD. Toroidal currents up to 90 kA and up to 3.9 times the quadrature sum of the injector currents (the spheromak record) are achieved using IDCD on HIT-SI. Langmuir probe temperature measurements indicate $T_e$ of 6 eV to 20 eV. Ion Doppler spectroscopy measurements of carbon lines indicate $T_i$ of 20 eV to 40 eV. Fitting the Grad-Shafranov equilibrium to the internal magnetic probe data shows a flat $\lambda$-profile that is stable to the confinement-destroying long wavelength kink modes and the sustained equilibrium is observed to be stable. In addition, above a frequency threshold of about 30 kHz, the imposed fluctuations seem to control the pressure driven interchange leading to sustainment with sufficient confinement. These new results justify an experiment to study and develop the confinement of high $\beta$ spheromaks sustained with IDCD in the keV temperature regime.

**HIT-SI experiment:** HIT-SI consists of an axisymmetric spheromak containment flux conserver and two inductive injectors (x-injector and y-injector) mounted on each end as shown in Figure 1. The voltage, current, and axial flux of each injector are oscillated in phase at 5.8 kHz to 68.5 kHz. The two injectors are 90 degrees out of phase. The injectors are purely inductive. The power and helicity injected by the sum of the two injectors is approximately constant in time during the discharge. A slowly varying, compared to the injector frequency, spheromak is formed and sustained.

![Figure 1. Drawing of HIT-SI. On the left shows the electrical connections to the machine. On the right shows a cutaway of the vacuum vessel. The plasma facing vacuum wall is alumina coated copper. The green wires drive the primary of the injector loop voltage $V_{inj}$ driving the plasma secondary current $I_{inj}$. The brown wires supply the injector flux $\psi_{inj}$.](image)

IDCD becomes a dominant process on HIT-SI after mean toroidal current forms in the confinement volume. (The details of the initial formation of toroidal current are still under investigation.) Two key functions of the injectors are to impose magnetic perturbations at the flux surfaces and maintain a high electron fluid velocity at the edge. The function of the injectors relative to the mean flux surfaces can be visualized in Figure 2. The gray lines link the injector and the electrons on these edge field lines are driven by the injector loop voltage they link. As the toroidal object grows, the cross-sectional area of the injector current flow decreases and the velocity increases to maintain the velocity shear. The injectors have $n=1$ symmetry and impose perturbations onto the $n=0$ spheromak. The two injectors take turns inductively driving edge current and imposing perturbations. IDCD was discovered on this first experiment where the injectors do both functions. (Previous helicity injection experiments maintained the high electron fluid velocity at the edge with $n=0$ symmetry and instability produced the fluctuations.)
HIT-SI results: Figure 3 shows the data from a high current (14.5 kHz) and a high current gain (68.5 kHz) discharge. The discharge time is limited because of overheating of the wall and excess density late in time. Still, the pulse lengths are much longer than an injector period, and thus this method is steady state.

HIT-SI has run at 5.8 kHz, 14.5 kHz, 36.8 kHz, 53.5 kHz, and 68.5 kHz. All data at gains greater than 2.5 fit very well to the two-step λ (=µlj/B) profile defined in reference 1 which is a flat, kink-stable profile. For this discussion a “kink” is a long wavelength current driven instability. IDCD seems to be causing the current penetration because: a) all fits to the data require this extremely flat j/B profile of IDCD; b) profiles are too n=1 kink-stable to be caused by kink modes; c) pressureless 2-fluid simulation show an extremely hollow profile that is unstable to n=1 kink modes further suggesting that the flat profiles in the experiment are not caused by kink modes.

Figure 3. Injector current, toroidal current, and their ratio for a 90 kA discharge at 14.5 kHz and for a discharge at 68.5 kHz with a current gain approaching 4.

Pressure driven modes can lower the q-profile (q is the safety factor) giving current penetration and their role in relaxation is under investigation.11 For this proposal, the experimentally observed two-step profiles are assumed. In addition, at higher frequencies the imposed fluctuations appear to control the pressure driven modes because: a) as the injector frequency is raised, a transition occurs near ωinj ≈ γ (where γ = νl/size, the transit time of the pressure driven mode); b) the high frequency equilibria have much higher beta and show sufficient confinement (Figure 4); and c) at high frequency, δn/⟨n⟩ ∝ τinj indicating the pacing of the pressure driven mode and the slope of δn/⟨n⟩ vs τinj agrees with the measured helicity

Figure 2. HIT-SI Taylor state equilibrium magnetic field lines when the left injector is at peak current and loop voltage. The gray edge field lines link the injector. The colored field lines are on different nested flux surfaces inside the separatrix. Itor/Iinj = 6
The decay time $\tau_k$. $(\delta n/n_0 \approx \delta p/p_0 \approx \delta W_{plas}/W_{plas} \approx \tau_{inj}/\tau_E \approx 3\beta\tau_k/2)$ Thus, IDCD seems to cause a current penetration that keeps the equilibrium stable to the destructive kink modes, while at high frequency the imposed fluctuations limit the damage from interchange and allow sufficient confinement. At high frequency there appears to be a paced pressure release while maintaining high $\beta$. Low frequency allows time for the full development of the pressure driven mode that apparently destroys pressure confinement. Figure 5 shows the q profiles for a high and low frequency shot, two NIMROD simulations, and the Taylor state. The experimentally observed profiles are kink stable. The pressureless simulations are not kink stable, but adding pressure to the simulation allows the sustainment of kink-stable equilibria. The key is keeping the profile away from the kink-unstable regions, that destroy confinement, and at the same time limit the damage from the pressure driven mode. In the correct range of injector frequencies this appears to happen on HIT-SI giving sustained sufficient confinement. The goal is to achieve this at higher parameters.

![Figure 4: Toroidal (x) and poloidal (*) equilibrium magnetic fields measured by the internal magnetic probe normalized by toroidal current. Error bars are smaller than the data points. The solid lines show the Grad-Shafranov profile of the fit to the data. $\beta_{14.5} = 0\%$, $\beta_{68.5} = 28.9\%$, $t_{14.5} = 1.50$ ms, $t_{68.5} = 1.65$ ms.](image)

**Compatibility of nested flux surface with imposed fluctuations:** A pressureless two-fluid NIMROD simulation of a 2.5 times larger, hotter (100 eV) plasma with the HIT-SI geometry showed that large $n=1$ fluctuations ($\delta B/B = 10\%$ at a current gain of 10) imposed on a stable equilibrium do not open flux surfaces, while $n=1$ instabilities do. If the equilibrium is kink-stable, imposed $n=1$ fluctuations do not open the closed flux. See Figure 6. Thus, imposed fluctuations may allow sufficient confinement. Previous spheromak dynamic current drive and refluxing experiments produced the current drive through the $n=1$ kink-instability resulting in poor confinement.

In addition to the potential of efficiently sustaining the spheromak with sufficient confinement on a larger hotter plasma, IDCD also has the potential to solve other fusion issues. The controlled interchange will interchange the edge and central plasma giving impurity and ash removal from the core and refueling of the core from the edge. Because the pressure driven instability is the highest in the hierarchy of instabilities, imposing fluctuations with the frequency and amplitude needed to control it should stabilize practically all other instabilities.
Development strategy and DEMO/reactor vision: The current profile imposed on HIT-SI is a two-step \( \lambda \) profile with the outer \( \lambda \) that of the injectors and the inner that required for the current amplification\(^1\). The profile is robust and fits HIT-SI data at all frequencies. With the large current gain of the reactor essentially all the volume is inside the inner \( \lambda \) region. An optimization of the plasma boundary was done for uniform \( \lambda \) and no external toroidal field using the Mercier criteria. \( \int \rho^2 \text{dvol} \) is maximized at constant blanket area and constant maximum B-field on the boundary. The result is a maximum very close to that of a 1.5 aspect ratio circular cross section torus. Figure 7 shows a cross section of the reactor vision and the equilibrium. There are several reasons the injectors are on the mid-plane unlike HIT-SI. a) At this position less extra current is required to exclude the equilibrium fields from the injectors with axially symmetric bucking coils. These coils prevent equilibrium fields from interfering with injector operation. b) At the mid-plane position the injectors are parallel with the bucking coils allowing the coils to be closer to each other with better symmetry for excluding the equilibrium fields from the injectors. c) The perimeter is largest here allowing more injectors with less power each and less local wall loading. d) The mounting ring for the injectors is in axial compression and toroidal tension which are easier to hold than the bending forces on the plate in the present position. Experiments have not been run this way but models are expected to predict the performance and the proposed experiment will test this method.

Figure 7 shows a reactor system designed with an overnight capital cost that is economically competitive with coal-fired power plants.\(^15\) This reactor system utilizes a molten-salt (FLiBe) blanket system for first-wall cooling, neutron moderation and tritium breeding. Currently available materials and ITER developed cryogenic pumping systems were implemented in this design on the basis of technological feasibility. A tritium-breeding ratio (TBR) of greater than 1.1 has been determined using a Monte Carlo N-Particle (MCNP) neutron transport simulation. High temperature superconducting tapes (YBCO) were used for the equilibrium coil set, substantially reducing the recirculating power for this reactor system. Using ZrH\(_2\) for neutron shielding, a limiting equilibrium coil lifetime of greater than thirty full-power years has been achieved. The primary FLiBe loop was coupled to a supercritical CO\(_2\) Brayton cycle due to attractive economics and high electrical conversion efficiencies. With these advancements, an electrical output of 1000 MW from a thermal output of 2486 MW has been achieved, yielding an overall plant efficiency of 40%. The structural material is stainless steel with the flux conserver being, yet to be tested, oxide dispersion strengthened Cu bonded to stainless steel since Cu is not an acceptable structure material at reactor temperatures.\(^18\) See Table 1 for 1 GW parameters.

A simple development path may be possible. A successful proposed confinement experiment (HIT-SIX), followed by a proof of principle experiment showing sustainment with sufficient confinement and beta at temperatures of a few keV leads to a performance extension DD experiment (HIT-PX). HIT-PX may be twice the size of HIT-SIX where conditions are closer to a reactor and true steady state is demonstrated.
will form the required confinement. The primary goal is to study and find the requirements for efficient current drive having sufficient confinement at high temperature using IDCD. The two important supportive goals are 2) to study and find the requirements for enough current gain in the absence of a magnetic separatrix that such a separatrix will form and 3) to study and find the requirements for the formation of a high enough edge temperature. A reactor vision. A reactor geometry with 1000 MWe output and 4.2 MWm⁻² neutron wall loading. Shown are the flux surfaces lines and pressure contours colors for the steady-state equilibrium (no currents in the flux conservor). The pressure shown in color contours is normalized by the magnetic pressure of \( B_{\text{ew}} = \mu_i \sqrt{2m} \). The numbers on the edge are distance in meters. The figure on the right is a drawing of the reactor vision. The vacuum pumping manifolds top and bottom are 2 m in minor diameter.

HIT-PX would have the high temperature super conducting magnet and a water cooled blanket structure. A successful HIT-PX plus data from ITER should allow for an FSNF by replacing the water coolant with FLiBe and adding tritium recovery. Successful blanket testing and development leads to a HIT-Pilot by adding a generator. Table 1 shows some projected parameters of the sequence of experiments. The beta wall is the rms pressure divided by the magnetic pressure of \( B_{\text{ew}} \).

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hit-SI</th>
<th>Hit-SIX</th>
<th>Hit-POP</th>
<th>Hit-PX</th>
<th>Pilot/DEMO</th>
<th>1 GW reactor</th>
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<tr>
<td>Minor radius (m)</td>
<td>0.25</td>
<td>0.55</td>
<td>1.0</td>
<td>1.0</td>
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<td>2.5</td>
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<tr>
<td>Major radius (m)</td>
<td>0.25</td>
<td>0.825</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>3.75</td>
</tr>
<tr>
<td>( T_{\text{peak}} ) (keV)</td>
<td>0.030</td>
<td>1.0</td>
<td>3.0</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>( T_{\text{edge}} ) (eV)</td>
<td>10</td>
<td>67</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>( I_{\text{tor}} ) (MA)</td>
<td>0.03</td>
<td>1.35</td>
<td>3.2</td>
<td>10.0</td>
<td>17.0</td>
<td>41.7</td>
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<td>Density ( (10^{19} \text{ m}^{-3}) )</td>
<td>1.5</td>
<td>7.0</td>
<td>4.0</td>
<td>7.5</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>( j/n ) ( (10^{18} \text{ Am}) )</td>
<td>1.1</td>
<td>2.0</td>
<td>2.6</td>
<td>4.0</td>
<td>3.6</td>
<td>1.4</td>
</tr>
<tr>
<td>( \beta_{\text{wall}} )</td>
<td>0.1</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>( I_{\text{injector}} ) (kA)</td>
<td>7</td>
<td>11</td>
<td>6.9</td>
<td>7.4</td>
<td>11</td>
<td>25</td>
</tr>
<tr>
<td>( V_{\text{inj}} ) (V)</td>
<td>680</td>
<td>620</td>
<td>1100</td>
<td>1800</td>
<td>2200</td>
<td>2400</td>
</tr>
<tr>
<td>( \delta B/B )</td>
<td>0.12</td>
<td>0.004</td>
<td>0.001</td>
<td>0.0004</td>
<td>0.0003</td>
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</tr>
</tbody>
</table>

3. **The proposed experiment, HIT-SIX:**

The proposed experiment has four goals. (HIT-SIX is an extension of HIT-SI and has six injectors.) 1) The primary goal is to study and find the requirements for efficient current drive having sufficient confinement at high temperature using IDCD. The two important supportive goals are 2) to study and find the requirements for enough current gain in the absence of a magnetic separatrix that such a separatrix will form and 3) to study and find the requirements for the formation of a high enough edge temperature.
so that the current drive power is acceptable. The fourth goal is 4) to make HIT-SIX meet these requirements if possible. HIT-SIX is sized so it is small enough that state-of-the-art XMHD codes can help with the two supportive goals yet large enough to achieve the fourth goal.

The experiment shown in Figure 8 is designed to overcome the limitations of HIT-SI and to be capable of studying energy confinement. HIT-SIX will overcome those limitations as follows: a) the uniform-\(\lambda\), \(\beta_{\text{wall}}\)-limit increases from 3% to 16%; b) the area around the injector opening that overheats on HIT-SI is increased by a factor of 3.6, allowing 9 MW of steady-state injector power; c) active gas pumping during the discharge will increase to allow steady-state operation below the Greenwald limit; d) HIT-SIX will have \(na = 4 \times 10^{19}\text{m}^{-2}\), a factor of 10 higher than HIT-SI and twice the estimated density needed to prevent neutral penetration; and e) enough plasma current to reach keV temperatures, all necessary for studying magnetic confinement. Thus, HIT-SIX will be magnetic confinement capable.

The gap in the central column is a desirable construction feature and an essential plasma physics feature because of a corollary to the minimum energy principle: If a volume is driven with a boundary condition \(\lambda_{\text{min}}\) greater than the lowest eigenvalue then all of the magnetic energy exists in the lowest eigenmode except for the minimum energy needed to satisfy the boundary condition. With the gap the lowest eigenvalue is 2.4/\(\rho\) and the eigenmode is symmetric. Without the gap the lowest eigenvalue is 3.1/\(\rho\) and the eigenmode has \(m=1\) symmetry. The construction is that of two deformed disks, simpler than a torus, and a connected small central column would tend to suffer high stress. HIT-SIX has the plasma parameter goals given in Table 1. Pumping, fueling, equilibrium coils, and injector voltage, flux, and phases are feedback controlled using IGBT switching power amplifiers (SPAs).

![Figure 8. Conceptual drawing of the experiment. HIT-SIX has minor radius of 0.55 m and major radius 0.825 m. Design plasma current is 1.35 MA with peak temperature of 1 keV. (Equilibrium coils are shown in red, and pumping access locations are shown in cyan.) The vessel is stainless coated with 5.5 mm of Cu for a 0.12 s L/R time. Equilibrium control has a 15 ms response time, requiring 58 SPAs. The Cu is plasma sprayed with a ceramic insulator. Cost break down is at the right. The total budget is $30M over 5 years.](image)

**Startup and ramp up:** To assess the feasibility of startup and the power and pumping requirements a 0D model is used. Constant \(\beta\) and \(\eta/n\) and a temperature profile self-similar to Figure 10 (with \(n = 7 \times 10^{19}\text{m}^{-3}\)) are assumed. Figure 9 shows a result. Because of the likely importance of pressure driven activity for current penetration without kink modes, the ramp rate is limited to the rate at which Ohmic heating can heat the central plasma to the \(\beta\)-limit. Central \([B] = 1.6 B_{w0}\) and \(\eta = 10^{-3}/T^{3/2} \Omega\text{m} (T \text{ in eV} \text{ and } \text{Zlog} \Lambda = 20)\) is used.\(^9\) The current drive is assumed to be 41% power efficient, based on HIT-SI experience. The injectors must power the rise in magnetic field energy and supply the Ohmic dissipation and ionization losses. It is assumed the relaxation energy will be interchanged out, keeping the interchange active. The
density is controlled to keep \( j/n = 2.0 \times 10^{-14} \text{Am} \) and the \( \lambda \)-profile is constant. Assuming an even distribution of energy the first wall copper would raise 28\(^\circ\) C the hottest coil would raise 5\(^\circ\) C, both are acceptable.

One of the difficulties with startup is achieving the current gain necessary for a large separatrix to form, as in Figure 6, in the face of parallel heat loss. Computer models indicate significant magnetic separatrix formation begins at gains of 6. (HIT-SI has achieved gains of nearly 4 and may have closed flux confinement with the high density, beta-limiting the temperature.) Assuming uniform wall loading, constant current drive efficiency, constant beta, parallel thermal conduction \( k_B \propto T^{-5/2} \), and resistivity \( \eta \propto T^{-3/2} \) and using:

\[
P_{inj} \propto p_w a^2 \propto \eta j f \lambda^4 \propto \frac{k_B}{a} \frac{T}{a^2} \quad \text{and} \quad j \propto \frac{I_{lw}}{a^2}; Z_{inj} \propto \alpha; P_{inj} \propto Z_{inj} I_{inj}^2
\]

Where \( p_w \) is the power per unit area gives:

\[
\frac{I_{lw}}{I_{inj}} \propto a^{17/14} P_{w}^{3/14}
\]

Thus, scaling from HIT-SI (gain=3.8, \( p_w = 1.2 \text{MWm}^{-2} \) \( a = 0.233 \text{m} \)) for \( a = 0.55 \text{ m} \) and \( p_w = 0.5 \text{ MWm}^{-2} \) a gain of 9 is possible without a separatrix. For short times HIT-SIX will have the power to achieve a projected gain of over 11. Even with 15 MW of power, HIT-SIX is limited to a gain of 5. An important goal of the proposed experiment is to understand the requirements for forming nested flux surfaces. HIT-SIX is a minimum size experiment for this goal.

The equilibrium: Conceptually, the sustained equilibrium consists of three regions: the magnetic confinement region, the region driven directly by the injectors, and the wall contact region. The temperature and density profile in the magnetic confinement region are expected to be the result of controlled pressure driven interchange activity limiting the pressure build up from Ohmic and viscous heating. The actual profile will need to be measured. The profile will be optimized for maximum \( \beta \) and minimum current drive power. Thus a high edge temperature and/or a high edge temperature gradient will be a goal. Measurements and simulations on HIT-SI show that this region has uniform \( \lambda \) giving the whole plasma a kink-stable magnetic structure that can be distorted by the oscillating injector driven channels to drive current without destroying magnetic confinement. The dynamic impedance is much higher than the resistivity of the low temperature plasma and the successful injector operation in the low temperature wall-contact plasma is expected to be similar to that on HIT-SI. The injector driven channels always move into the plasma, minimizing the material plasma interaction by sweeping the plasma away from the wall. The magnetic fluxes in the injectors are reduced by bringing in fluxes of the opposite sign. Thus the injector flux and current can oscillate but the flow is always away from the wall. The edge of this region is the separatrix. The power and plasma passing through the separatrix is carried to the walls by the plasma on stochastic fields outside the separatrix, including some directly driven field lines from the injectors. Where and if the stochastic fields penetrate the wall is a control parameter for the distribution of the wall loading. The result is similar to a diverted plasma with a large number of divertors and the entire first wall the divertor plates. The separatrix moves closer to the wall as the current gain increases.

Figure 10 shows an equilibrium. The injectors are placed on the mid-plane for the reasons given above. The color contours are the plasma pressure normalized by the average wall magnetic pressure, which exceeds 20%. In this case, a Grad-Shafranov equilibrium is found for the region inside the flux conserver (red wall), the colored region is at constant \( \lambda \) (like that produced with IDCD in HIT-SI) with the
maximum pressure gradient at the Mercier-limit. The black and white lines are the flux surfaces. The symmetric equilibrium coil set provides the surface fields. On the two-second time scale the symmetric coils provide equilibrium fields and exclude most of steady-state fields from the injector region. The wall contact region with no pressure gradient is between the wall and the first shown internal flux surface (dark blue region).

**Figure 10.** Flux surfaces (lines) and pressure contours (colors) for the steady-state equilibrium (no currents carried by the flux conserver) for HIT-SIX. The pressure shown in color contours is normalized by the magnetic pressure of $B_{\text{sep}}$. The numbers on the coils are kA-turns in the coils. The amount of flux between the flux conserver surface and the injector surface and the location of the x-point will be optimized experimentally. The goal is to achieve a high edge temperature to minimize the power required to drive the current. Edge is defined as where magnetic pressure confinement begins. This equilibrium, Mercier stability, and Ohmic power analysis shows: a) the experiment will confine interesting plasma pressure; b) driving current at low temperature (< 10 eV) is prohibited because of the Ohmic power required; c) the equilibrium field can be excluded from the injector region to ensure satisfactory injector operation; d) the equilibrium coil set is modest with the coils shown to scale; and e) the Amp-turns (1.34 MA) and power of the coil set (1.8 MW) are attainable. The final coil set design may use more coils to limit the flux that penetrates the injector wall to less than $10^{-7}$ Wb.

**Stability:** With the stabilizing effect of imposed fluctuations and rotation induced by imposing rotating fluctuations, a stable spheromak is possible. The external tilt and shift modes are stabilized by the flux conserver. The internal kink modes are stabilized by the robustly flat $\lambda$-profile produced by IDCD controlling the pressure driven interchange described above. As stated before, because imposed fluctuations seem to control this powerful instability many other instabilities may also be controlled by the imposed fluctuations. In addition, controlled rotation may be available to help control the rest of the instabilities and to obtain the high edge temperature.

The resistive wall modes can be stabilized by feedback, but with the very conductive wall a small rotation should do it easier. By approximating the shearing rate as $v_{\text{rot}}/a$, the stability condition can be estimated as $1 < \omega_{\text{rot}} \tau_{\text{imb}}$ where $\omega_{\text{rot}}$ is the rotation frequency and $\tau_{\text{imb}}$ is the growth time of the instability. A lower bound on $\tau_{\text{imb}}$ is the L/R time of the flux conserver. Because the spheromak is only shear stabilized it is susceptible to the weak resistive interchange modes which should be stabilized by two-fluid effects, by a low amount of sheared flow, or by imposed fluctuations. There are only weak neo-classical effects to excite the neo-classical tearing modes. See Table 2 for a stability summary.

Temperature gradient driven modes may be stabilized by the sheared flow resulting in internal transport barriers (ITBs). “Most theoretical models for ITB formation ultimately rely on the suppression of micro-instability induced transport by sheared $E \times B$ flows, supported by experimental observations of these near ITBs.”^21 HIT-SIX will have an x-point in the edge, large $\lambda$-gradients in the edge, and controlled plasma rotation, which are the ingredients for ITBs. The optimum rotation and x-point placement are to be empirically determined. Codes will help with the optimization.
Table 2. Summary of the stabilization of instabilities for an IDCD sustained device

<table>
<thead>
<tr>
<th>Instability</th>
<th>Estimated growth time</th>
<th>Method of stabilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>External kink</td>
<td>$\tau_A$</td>
<td>Flux conserver</td>
</tr>
<tr>
<td>Internal kink</td>
<td>$\tau_A$</td>
<td>IDCD profile control</td>
</tr>
<tr>
<td>Resistive wall mode</td>
<td>$\tau_{L/R}$ of the flux conserver</td>
<td>Rotation $\omega &gt; 300$ Hz, feedback</td>
</tr>
<tr>
<td>Ideal pressure driven mode</td>
<td>$\tau_{\text{sound}}$</td>
<td>Imposed fluctuations</td>
</tr>
<tr>
<td>Resistive interchange</td>
<td>$(\tau_A\tau_{L/R})^{1/2}$</td>
<td>Rot. $\omega &gt; 13$kHz, 2-fluid eff., IDCD</td>
</tr>
<tr>
<td>Temperature gradient modes</td>
<td>Many electron transit times</td>
<td>Sheared flow</td>
</tr>
<tr>
<td>Neo-classical tearing modes</td>
<td>Not present</td>
<td>Small neoclassical effect</td>
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</tbody>
</table>

**Confinement:** If the experiment succeeds in achieving the described equilibrium with an effective edge temperature of 67 eV then it will require 2.5 MW of Ohmic power delivered with 41% efficiency for 6.2 MW of sustainment power. Dividing this into the plasma energy yields an 18 ms total energy confinement time. However, just achieving sustained sufficient confinement at 200 eV with 12 MW of injected power would be considered a successful demonstration of the concept. The required field line length for open confinement to reach a temperature $T$ is about $\kappa_T T/Q$ where $\kappa_T$ is the parallel thermal conduction and $Q$ is the heat flux. With Spitzer $\kappa_T$, $T= 200$ eV, and $Q = 0.66$ MWm$^{-2}$ the required field line length is 250 km. Thus, sustaining a temperature of 200 eV demonstrates a sustained separatrix and magnetic confinement.

4. **Summary**

Previous transient experiments showing sufficient confinement at several 100 eV with no external toroidal field coil$^{7-10}$, recent results on HIT-SI showing sustainment with sufficient confinement$^{11}$, the potential of IDCD of solving other fusion issues, and a very attractive reactor concept$^{12}$ justify a confinement experiment for a high-$\beta$ spheromak sustained by IDCD. (Sufficient confinement meaning the current-drive power can heat the plasma to its stability $\beta$-limit.) A 1.35 MA experiment with temperature of 1 keV, density of $7 \times 10^{19}$m$^{-3}$, minor radius of 0.55 m, major radius of 0.825 m, and a beta relative to the wall B-field of 16% is envisioned. Density control, acceptable wall loading, equilibrium control, and rotation control were design considerations. With this control and the stabilizing effects of IDCD, heating to the beta-limit with current-drive power heating is expected.

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11. Victor B. S. et al., (submitted for publication)
13. R. Rosner presentation to FESAC, “Although not explicitly called out as a high priority thrust, we note that research supporting steady-state scenarios is cross-cutting and has connections to each of the high priority thrusts.”
17. Morgan K. D. et al., (to be published)