**Facilities needed for the development of economical fusion power**: T. R. Jarboe, D.A. Sutherland, C. Akcay, R. Golingo, C. J. Hansen, A. C. Hossack, G. J. Marklin, K. Morgan, B. A. Nelson, R. Raman, B. S. Victor, and S. You, *University of Washington, Seattle WA 98195*

**Summary:** This is a proposal to use a newly discovered dynamo mechanism for steady-state sustainment of a plasma-confining magnetic configuration where the current-driving fluctuations are not generated by plasma instability but rather are imposed by the helicity injectors[1]. Instability and relaxation were erroneously considered a necessary part of dynamo current drive until now. In the new experiment, the fluctuations are imposed on a stable plasma configuration using asymmetric injectors. This shaking of a stable plasma is not as damaging to confinement as instability. The equilibrium can be efficiently sustained using imposed fluctuations, and the current profile can, in principle, be controlled by controlling the imposed fluctuation profile. Both are large steps for controlled fusion that lowers the development and reactor costs of fusion power by an order of magnitude. The present experiment (HIT-SI) is a current drive experiment with size and capabilities too limited to study and demonstrate good confinement. A program is outlined that includes a minor and major facility in the 2014-24 time frame: the major facility ($200M) is a high performance DD steady-state experiment that later becomes a FNSF and Pilot. It is based on the physics results from the new minor facility that will allow the development and achievement of sufficient confinement for controlled fusion as outlined in ReNeW report (Fig. 2 of Thrust 18). The technical discussion will focus on this next-step facility.

In Imposed Dynamo Current Drive (IDCD), currents are driven parallel to a magnetic field that become juxtaposed and aligned with the fields of the equilibrium being sustained. Magnetic fluctuations then act across the aligned fields to couple the electron flows so the injector driven electrons couple to and drive the electrons of the equilibrium. The same process occurs with adjacent flux surfaces, sustaining the entire stable equilibrium. Previous dynamo sustainment experiments lacked the stability and size needed for achieving relevant confinement, whereas, the proposed experiment can succeed.

For the first time, a two-fluid MHD simulation by NIMROD has been quantitatively validated using HIT-SI. Extrapolating to a larger and hotter similarly shaped simulation shows IDCD driving a stable equilibrium with periods of closed flux when the gain ($I_{tor}/I_{inj}$) reaches 7. The simulation shows that if and only if the equilibrium is stable does the flux become closed, further suggesting the reason for poor confinement in previous dynamo experiments was due to the lack of equilibrium stability. HIT-SI ramps up and sustains stable equilibria.

The Dynomak device proposed is a spheromak with the aspect ratio of a spherical tokamak and shaped like a reversed field pinch. It is driven with only IDCD. The six inductive handle-shaped drivers use low-cost AC (≈ 40 kHz) power. Resistively heated to a few keV, the experiment has a 3.2 MA, 5 second pulse with a 2.5 s plasma current ramping duration. Its minor radius is 1.0 m with aspect ratio 1.5. There is no toroidal field coil or anything linking the torus yet it has an engineering beta-limit as high as 16%. As a design-class project its reactor potential was assessed to be competitive with conventional power sources, undercutting coal and on par with natural gas with carbon capture[2]. Costing using several ITER-developed components gave $1.2B.

In addition to studying and developing confinement physics during sustainment with IDCD, the experiment will study the effects on transport, rotation and current drive of low frequency ($\lambda v_A < \omega < 1/\tau_{L/R}$ ; $\lambda \equiv \mu_o j/B = 2.4/a$) magnetic fluctuations in stable plasmas, similar to the effects of resonant magnetic perturbations. MHD codes will be validated in this new regime.

**Concept is ready to initiate design and construction:** Based on breakthrough results and understanding coming from the HIT-SI experiment and validated NIMROD simulations a new experiment is proposed. With the achievement of greatly improved parameters on HIT-SI came the discovery of Imposed Dynamo Current Drive[1] (IDCD) a method of efficiently sustaining a stable equilibrium with the possibility of current profile control. Toroidal currents up to 58 kA and up to 3 times the injector current (the spheromak record) and separatrix current of 40 kA[3] are achieved using IDCD on HIT-SI. These new results justify a Proof of Principle (PoP) program to study and develop the confinement of high beta spheromaks sustained with IDCD. IDCD also applies to tokamaks. Conventional RF and neutral beam current drive are very power-inefficient leading to an unacceptably high recirculating power fraction in a fusion reactor.[4] Lack of profile control causes disruptions,[5] a major weakness of the tokamak configuration. Developing this efficient current drive and profile control method enhances the tokamak and enables the RFP and spheromak as viable alternatives for fusion reactors is world-leading science.

The key assumption in projecting to very attractive devices, leading to competitive fusion power with limited technical developments, is that the confinement is sufficient. Namely, the plasma will Ohmically heat to the Mercier β-limit on each flux surface. The primary purpose of the minor facility is to validate this key assumption. There is strong evidence that this will happen. a) Decaying spheromaks have been observed to Ohmically heat to the β-limit.[6] b) Stable equilibria have been produced transiently that have good confinement at temperatures in the keV range on the RFP[7] and the spheromak[8,9,10,11,12,13]. The proposed geometry is a stabilized high-β spheromak. c) It can be shown that classical cross-field transport and plasma resistivity scale such that the transport β-limit only depends on and is proportional to $\lambda a$, which is 2.4 for spheromaks such as the proposed experiment and 0.5 for tokamaks. Therefore, spheromaks can heat to the Mercier β-limit. While there might be anomalous resistivity and transport, the net effect on heating will need to be determined experimentally. d) The fluctuations needed for the reactor are projected to be acceptably low ($\delta B/B \sim 10^{-4}$). e) Previous attempts at sustaining small spheromaks had the oscillation amplitude of the plasma about a mean flux surface, $\delta r_{plasma}$, orders of magnitudes too large for good confinement.[1] The proposed development path avoids this fatal flaw. f) Much better density control will be used than was used in previous spheromaks. g) A five second pulse will allow time for good confinement to develop. h) The fluctuations will be controlled to be only as large as necessary and to impose the current profile needed for the stable equilibrium. i) IDCD sustains a stable equilibrium with controlled fluctuations that are at a low enough level to allow acceptable confinement. A NIMROD simulation of a scaled up HIT experiment clearly shows that, while subject to severe imposed fluctuations ($\delta B/B = 10\%$), a stable equilibrium forms closed flux surfaces and flux surfaces dissolve when the equilibrium goes unstable. Thus the proper interpretation of the observation that poor confinement is correlated with fluctuations is that instability causes them both, but fluctuations **do not** cause poor confinement. All previous dynamo sustainment experiments failed because they drove the equilibrium unstable to produce the required fluctuations needed for dynamo current drive. This proposal has a new paradigm of dynamo current drive where the fluctuations are imposed on a stable equilibrium and HIT-SI has demonstrated the ramp up and sustainment of a stable equilibrium.

**A flagship confinement facility is needed:** A new flagship facility plus reorganization of the present research is necessary to produce a program leading to efficient current sustainment and possibly economical TF-coil-free fusion power. Figure 1 shows the conceptual design of the proposed first experiment. The injectors are placed on the outboard mid-plane. The PoP has the plasma parameters given in Table 1. The color contours on the right are the plasma pressure normalized by the average wall magnetic pressure, which reaches over 20%. In this case, a Grad-Safranov equilibrium is found for inside the outer most shown flux contour having constant $\lambda$ (like produced with IDCD in HIT-SI) with the maximum pressure gradient at the Mercier-limit. The dark blue edge, between the red wall and outer most flux surface, is at zero pressure and $\lambda$. The gray and white lines are the flux surfaces.

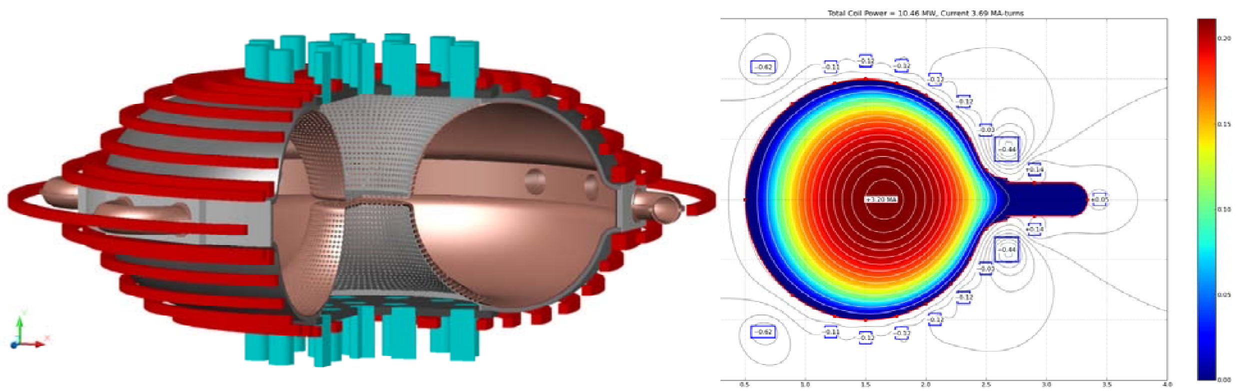


**Figure 1 On the left: Engineering conceptual design, the teal cylinders are cyro-pumps. All surfaces in the vacuum will be covered with an insulating ceramic. On the right: Physics conceptual design, the contours are beta engineering = $2\mu_o p/B^2_{wall}$ where $B_{wall} = \mu_o I/2\pi a$. Table 1 gives parameters of this PoP experiment.**

The proposed experiment is designed to overcome the limitations with HIT-SI and to be capable of studying magnetic energy confinement. HIT-PoP will overcome those limitations as follows: a) the uniform-$\lambda$, $\beta_{wall}$ increases from 3% to 15%; b) the areas around the injector openings, that over heat by a factor of 4 on HIT-SI, is increased by a factor of 8; assuming the same injector power as HIT-SI the wall loading will be a factor of two below the empirical limit; c) $\delta r_{plasma}/r_{gi}$ will decrease from 66 to 3; d) active gas pumping during the discharge will increase from less than 0.1 $m^3/s$ to about 184 $m^3/s$ on HIT-PoP; and e) HIT-PoP will have $na = 5 \times 10^{19} m^{-2}$ a factor of 2.5 higher than the estimated density needed to prevent neutral penetration. HIT-SI has $na = 5 \times 10^{18} m^{-2}$. HIT- SI is at the Greenwald-limit. HIT-PoP will stay below it by a factor of 2, and have enough plasma current to reach keV temperatures, all required for studying magnetic confinement. Thus, HIT-PoP will meet all requirements with factor of 2 margins, which is not too high considering the uncertainties in the requirements. Costing of the $30M device is shown next to Table 1. A $10M-$20M/year operations budget would also be required. A five year research and development, construction, and first-plasma program is suggested with a few addition years of development as needed.

The proposed device is 0.4 scale of a commercial 1 GWe reactor and full size of a FNSF. In an aggressive development plan, results from the major performance extension DD facility (HIT-PX) and DT results from ITER will lead to an FNSF experiment. A successful PoP experiment, showing sustainment with good confinement and beta, leads to the HIT-PX, which is the size of HIT-PoP but with conditions closer to a reactor scenario while demonstrating steady-state operation. This facility would have a high-temperature superconducting YBCO coil set and a water cooled, 316SS and Cu, blanket structure of HIT-Pilot and be built in the 2014-2024 time frame. The cost of HIT-PX would be about $200M ($0.4^2 \times$ $1.2 B cost of the reactor). A successful HIT-PX experiment coupled with data from ITER should allow for an FSNF by replacing the water coolant with FLiBe and adding tritium recovery for another $100M.

Successful blanket testing and development leads to a Pilot by adding a power conversion secondary cycle for another $100M. The proposed developmental program is shown in Figure 2. Table 1 shows some projected parameters of the sequence of experiments. The beta wall is the pressure divided by the magnetic pressure of $B_{wa}(= \mu_o I_p/2\pi a)$. The total equipment cost for the proposed development path is roughly $500M, about half the cost of the reactor, which is economically attractive. It is economically discouraging to pursue a developmental path that will require orders of magnitude more investment than an acceptable power plant cost to compete with conventional power sources (> $2B). It is imperative to pursue an economically viable commercial concept to ensure a reasonable developmental cost; this proposal seeks to develop such a concept. It is our best chance for practical fusion power.

**Table 1**

| Parameter | HIT-SI | PoP | PX | Pilot/DEMO | 1 GW reactor |
|---|---|---|---|---|---|
| Minor radius (m) | 0.25 | 1.0 | 1.0 | 1.0 | 2.5 |
| Major radius (m) | 0.25 | 1.5 | 1.5 | 1.5 | 3.75 |
| $T_{peak}$ ($2T_{ave}$ keV) | 0.015 | 3.0 | 16 | 30 | 30 |
| $I_{tor}$ (MA) | 0.055 | 3.2 | 9.0 | 17.0 | 41.7 |
| Density ($10^{19}m^{-3}$) | 2.5 | 5.0 | 7.5 | 15 | 15 |
| j/n ($10^{-14}$ Am) | 1.1 | 2.0 | 3.8 | 3.6 | 1.4 |
| Beta wall | 0.073 | 0.15 | 0.15 | 0.16 | 0.16 |
| $I_{injector}$ (kA) | 17 | 8.2 | 5.1 | 6.3 | 16 |
| $V_{inj}$ (V) | 500 | 540 | 600 | 694 | 750 |
| Freq. inj. (kHz) | 14.5 | 48 | 48 | 60 | 47 |
| $\delta B/B$ | 0.15 | 0.001 | .0003 | 0.0002 | 0.0002 |
| $\delta r_{plasma}/r_{gi}$ | 66 | 2.4 | 3.4 | 3.4 | 2.0 |

| item | cost ($k) | |
|---|---|---|
| Vacuum | | |
| Turbo pump | 61 | Alcatel ATH3200M |
| cryo-system | 618 | 39 (2 spares) Austin Scientific CT10 Cryoplex |
| Vacuum tank | 833 | GNB through Joe Gray (Palmborg Associates, Inc) |
| Cu spraying tank | 278 | MBI coatings, Sam |
| Perforated center | 463 | estimate |
| plasma spraying first wall | 972 | from our exp. |
| Flanges ports | 463 | |
| support structure | 93 | |
| **Vacuum and tank SubT** | **3781** | |
| Injector ring | 2543 | hit exp. |
| 6 injectors | 4166 | HIT expr. |
| **Injectors subtotal** | **6709** | |
| **Coils subtotal** | **2291** | Daniel J. Marisseau, New England Techni-coil |
| Power supply &SPAs | | |
| 500 SPAs | 2000 | Our experience |
| 5000 48 V modules | 5623 | Ajay Saini Maxwell |
| **PS and SPAs subtotal** | **7623** | |
| **Building prep subtotal** | **1666** | Realestate office UW |
| **Total** | **22071** | |
| Contingency | 7283 | |
| **Total** | **29354** | unassembled hardware and no diagnostics or data aqu no control system, no feedback design and fab. |

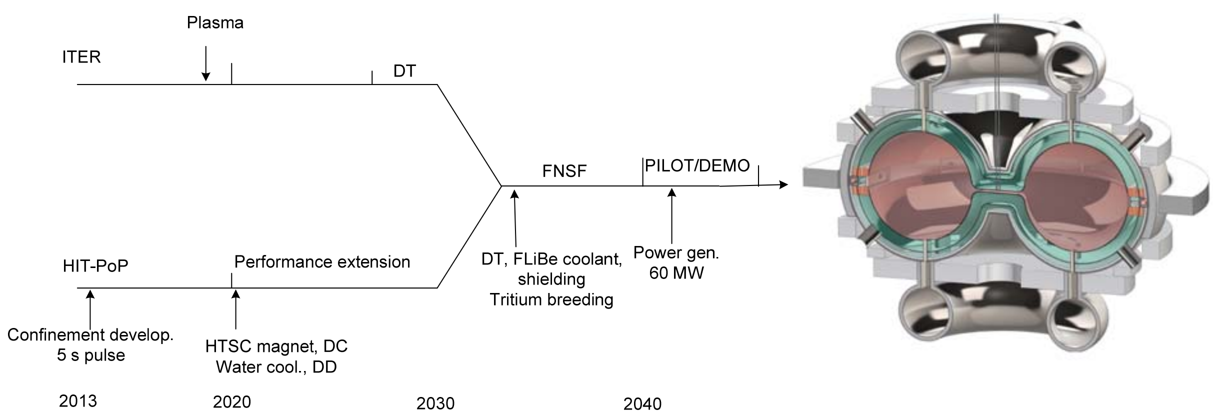


**Figure 2. Time line to fusion power generation. HIT-PX, FNSF, and Pilot/DEMO are the same facility with the plasma the size of HIT-PoP. The FNSF has the parameters of Pilot/DEMO in Table 1. The drawing on the right is of the 1 GW reactor[2] with parameters given in Table 1. The entire first wall is the limiter.**

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