HIT - SI

Aeronautics & Astronautics
University of Washington
College of Engineering

An overview of the HIT-SI research program and its implications for magnetic fusion energy

Derek Sutherland, Tom Jarboe, and

The HIT-SI Research Group

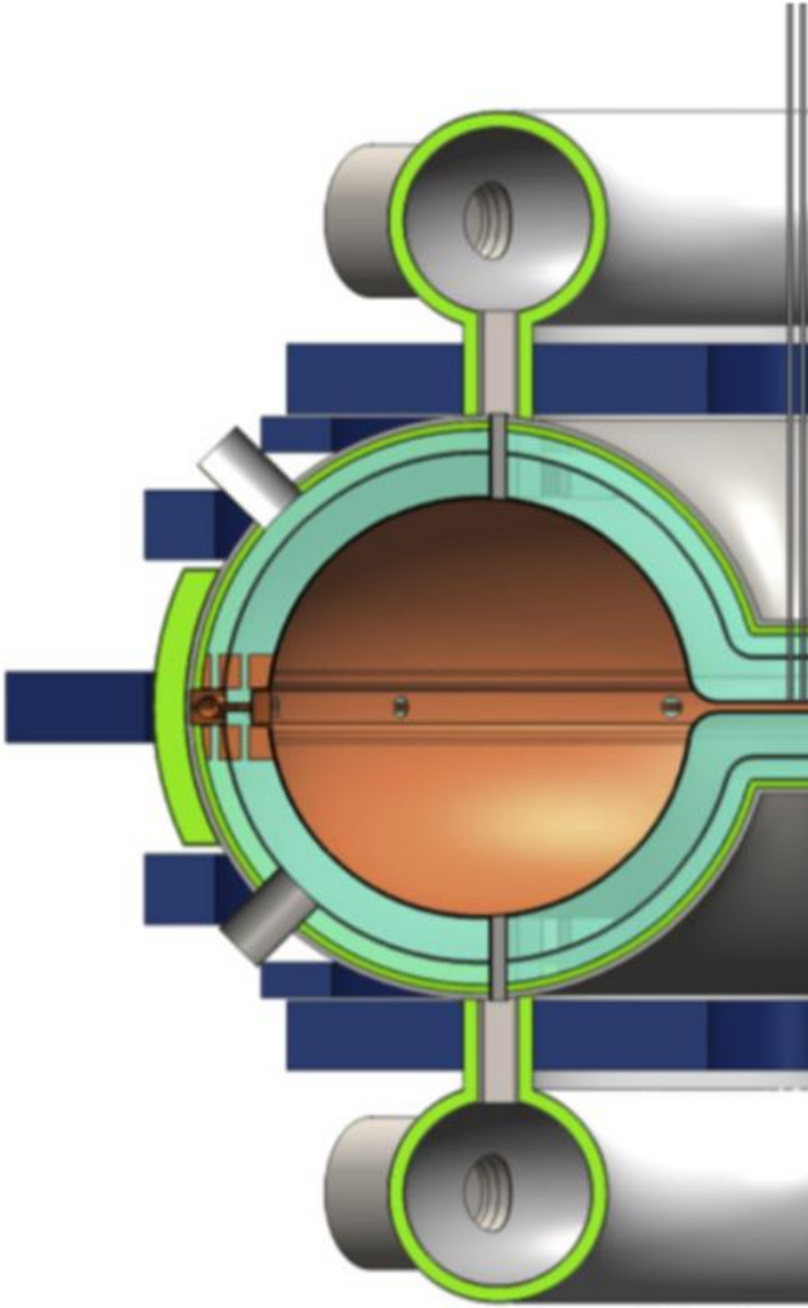
University of Washington

36th Annual Fusion Power Associates Meeting – **Strategies to Fusion Power**

December 16-17, 2015, Washington, D.C.

Motivation

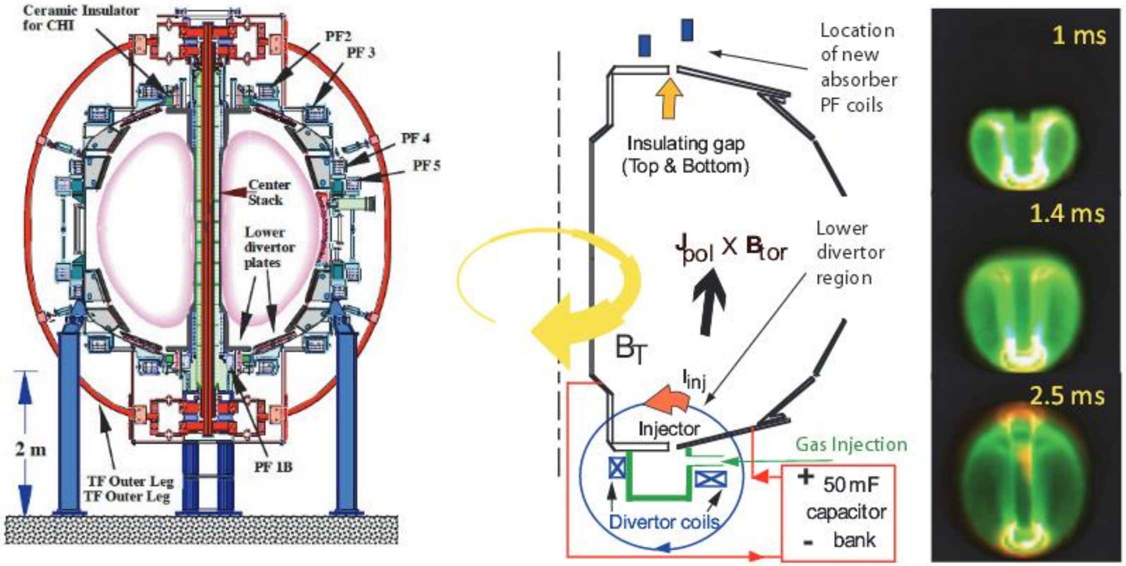
- Spheromaks configurations are attractive for fusion power applications.
- Previous spheromak experiments relied on coaxial helicity injection, which precluded good confinement during sustainment.
- Fully inductive, non-axisymmetric helicity injection may allow us to overcome the limitations of past spheromak experiments.
- Promising experimental results and an attractive reactor vision motivate continued exploration of this possible path to fusion power.



Outline

- Coaxial helicity injection NSTX and SSPX
- Overview of the HIT-SI experiment
- Motivating experimental results
- Leading theoretical explanation
- Reactor vision and comparisons
- Conclusions and next steps

Coaxial helicity injection (CHI) has been used successfully on NSTX to aid in non-inductive startup



Figures: Raman, R., et al., *Nucl. Fusion* **53** (2013) 073017

- Reducing the need for inductive flux swing in an ST is important due to central solenoid flux-swing limitations.
- Biasing the lower divertor plates with ambient magnetic field from coil sets in NSTX allows for the injection of magnetic helicity.
- A ST plasma configuration is formed via CHI that is then augmented with other current drive methods to reach desired operating point, reducing or eliminating the need for a central solenoid.
- Demonstrated on HIT-II at the University of Washington and successfully scaled to NSTX.

Though CHI is useful on startup in NSTX, Cowling's theorem removes the possibility of a steady-state, axisymmetric dynamo of interest for reactor applications

- Cowling* argued that it is impossible to have a steady-state axisymmetric MHD dynamo (sustain current on magnetic axis against resistive dissipation).

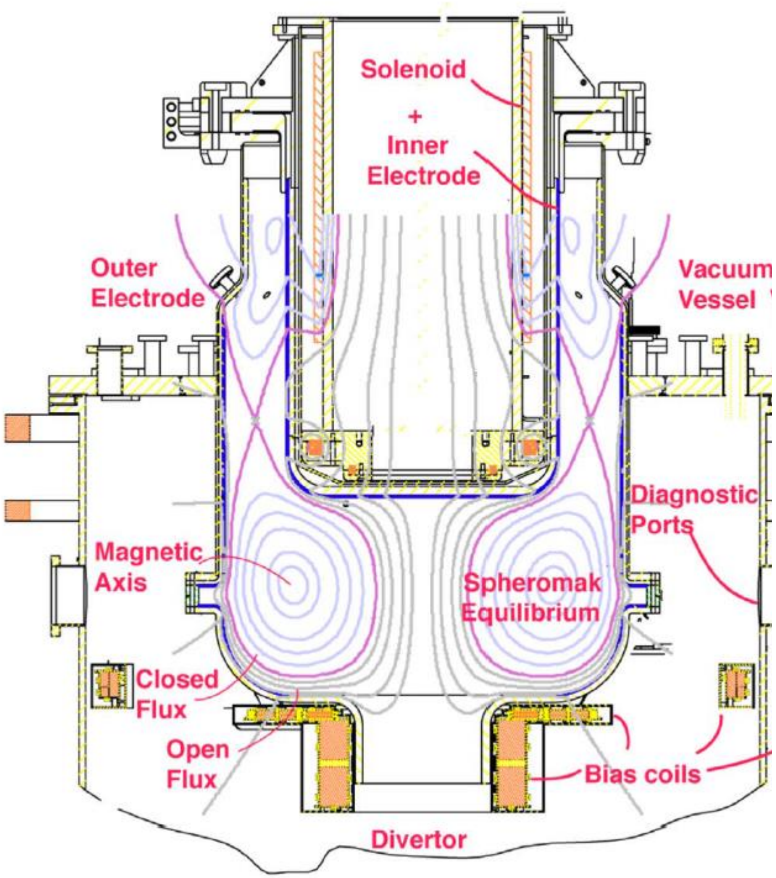
- At first glance, the requirement for non-axisymmetry seems to require the breaking of nested, closed-flux surfaces.

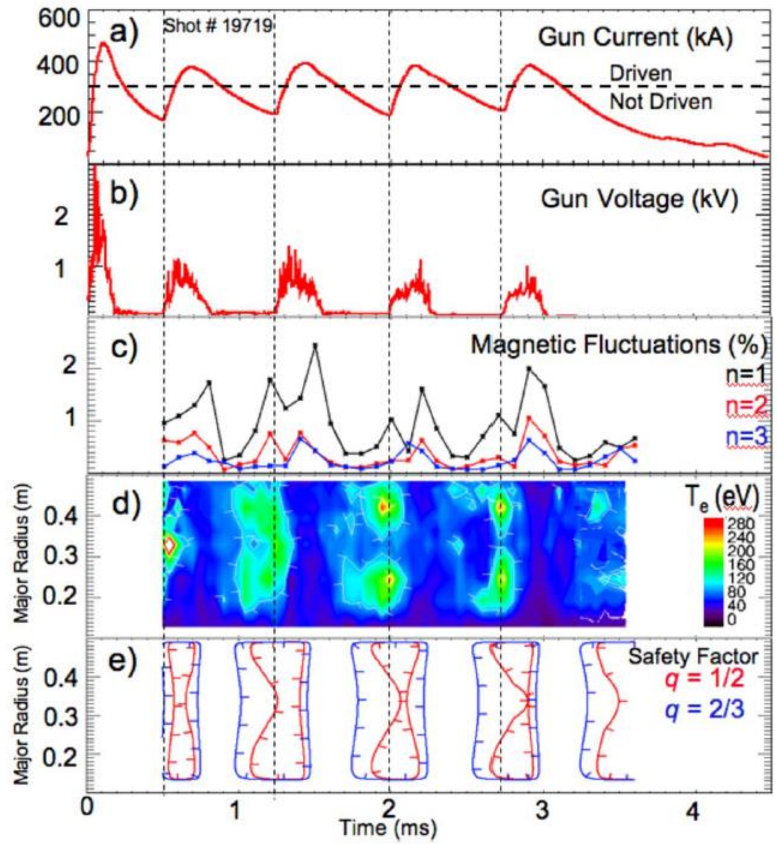
- In previous CHI-driven spheromak experiments, **instability** during sustainment was observed, leading to severe degradation in confinement quality.

- **From these results**, steady-state spheromak configurations did not look attractive for fusion power applications.

*Cowling, T.G., *Monthly Notices of Royal Astronomical Society* **94** (1934) 39-48.

Previous spheromak experiments used coaxial helicity injection (CHI) for current drive (SSPX shown*)

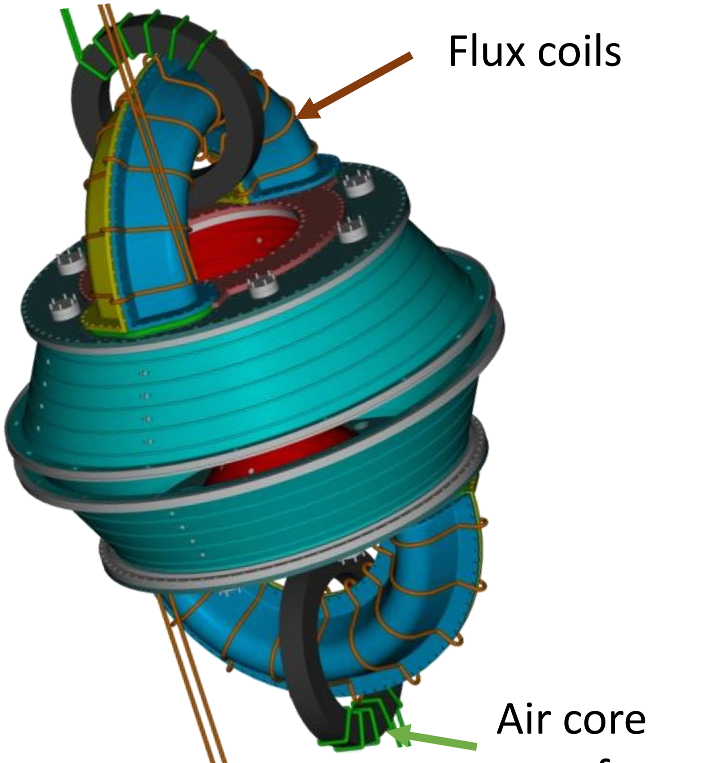




*B. Hudson, et al., *Phys. Plasmas* **15** (2008) 056112.

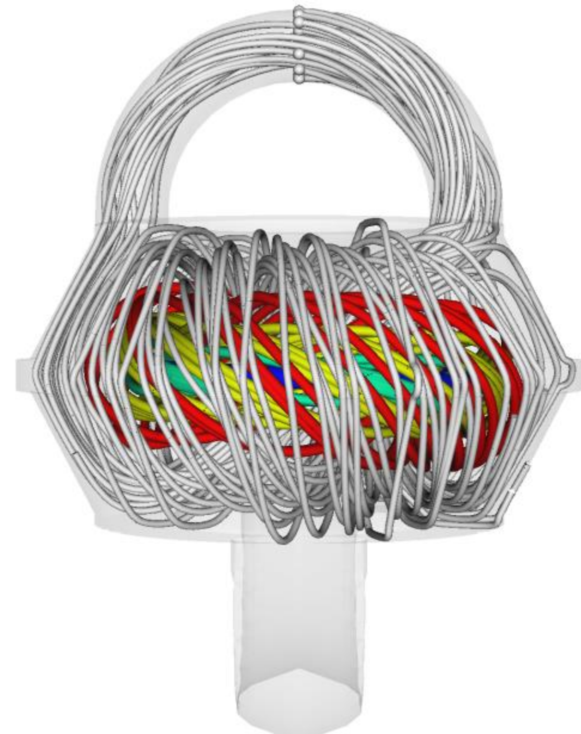
HIT-SI seeks to overcome the issues of CHI with fully-inductive, non-axisymmetric helicity injection

HIT-SI coils and geometry



Taylor state equilibrium

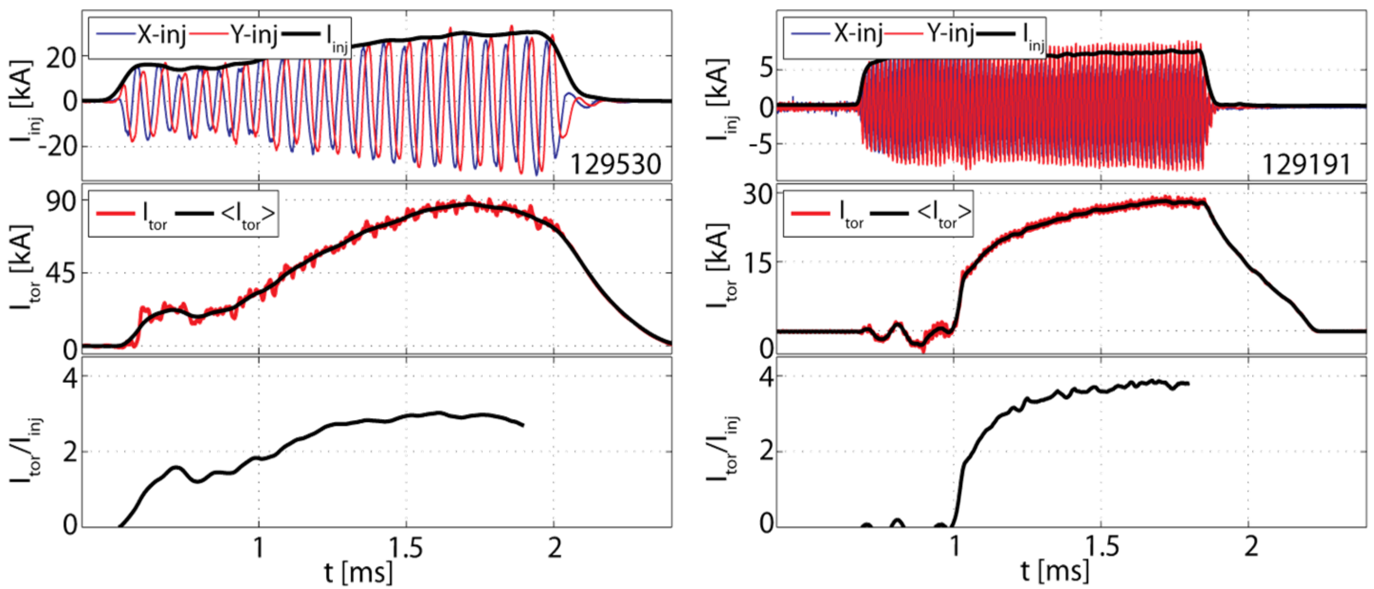
$\nabla \times \vec{B} = \lambda \vec{B}$, where $\lambda \equiv \mu_o \vec{J} / \vec{B}$



A spheromak forms after an ample amount of helicity is injected, and relaxation occurs. The spheromak is then sustained by continued injector operation.

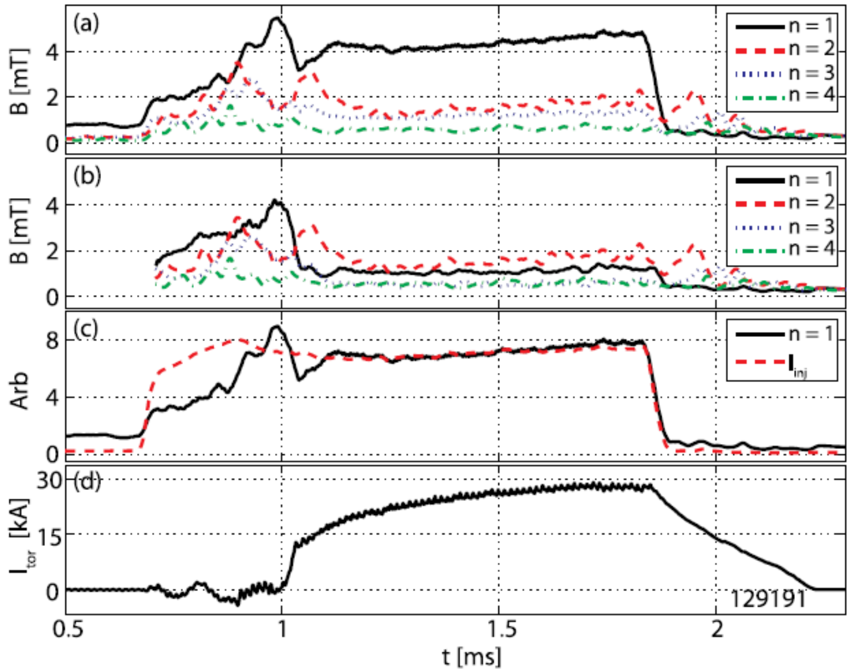
Record current gains are observed at higher injector frequencies

14.5 kHz results 68.5 kHz results



- Current amplification of 3.9 at high frequency, a new spheromak record.
- 90 kA of toroidal current at lower frequencies.
- Stable, sustained equilibria Ohmically heat to the beta limit, achieving the current drive goal of HIT-SI.

The only significant magnetic fluctuations observed are those that are imposed after relaxation*



Mode amplitudes vs time

Mode amplitudes minus the imposed perturbations vs time

n=1 amplitude and the injector current vs time

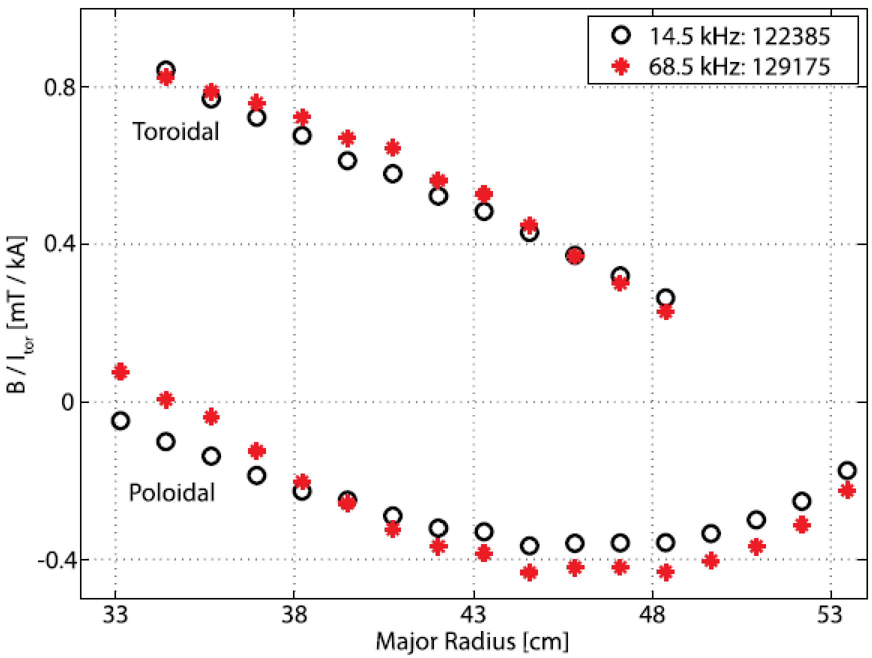
Toroidal current vs time

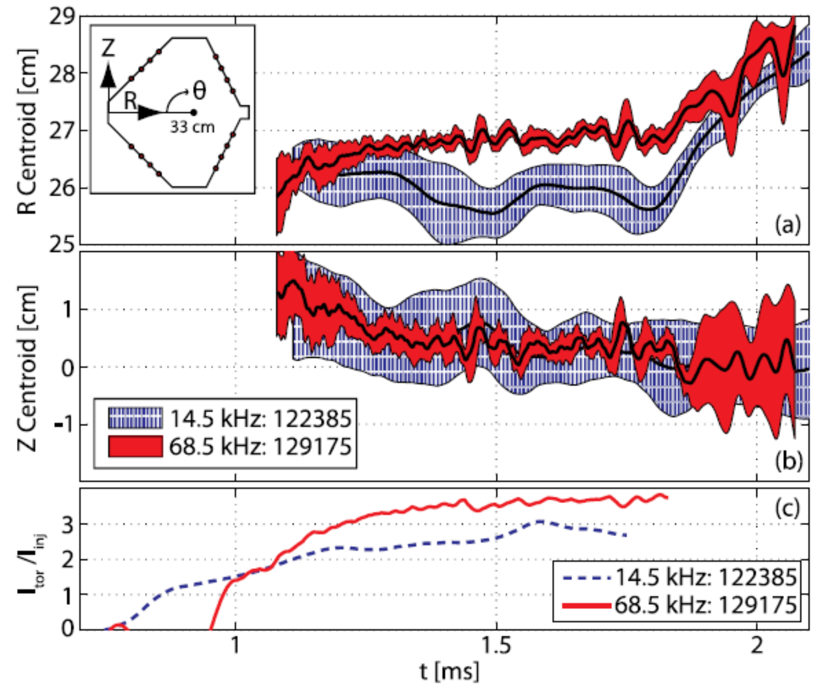
- During sustainment, the n = 1 component of the magnetic fields in the system is almost entirely imposed.

- HIT-SI is capable of testing MHD stability, which has been the problem with sustained spheromaks until now.

*B.S. Victor, et al., *Physics of Plasmas* **21** (2014) 082504.

HIT-SI sees a transition to higher β and increased stability as ω_{inj} is increased*



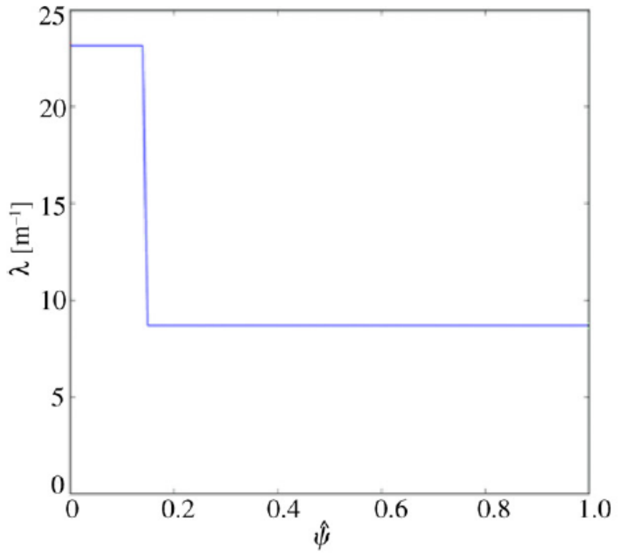


- Internal magnetic probes show larger Shafranov shift due to higher β (5% vs 25%) at high frequency.
- Centroid measurements at four toroidal locations show better symmetry and larger outward shift at high frequency.
- At high frequency, the imposed-fluctuations appear to be controlling the pressure driven modes (greater symmetry and running above β limit).

*B.S. Victor, et al., *Physics of Plasmas* **21** (2014) 082504.

Imposed-dynamo current drive (IDCD) is the leading theory to explain HIT-SI results

- IDCD* requires driving the edge-λ higher than the spheromak λ, while imposing non-axisymmetric, magnetic perturbations.
- The dynamo terms in Hall-MHD Generalized Ohm's Law leads to a dynamo electric field that drives current parallel to current.
- This dynamo electric field gives rise to an electrostatic field along the magnetic field that is able to drive current parallel to magnetic field.
- The dynamo electric field, by itself, does not sustain current parallel to B, complying with Cowling's theorem.**



IDCD 2-step λ model

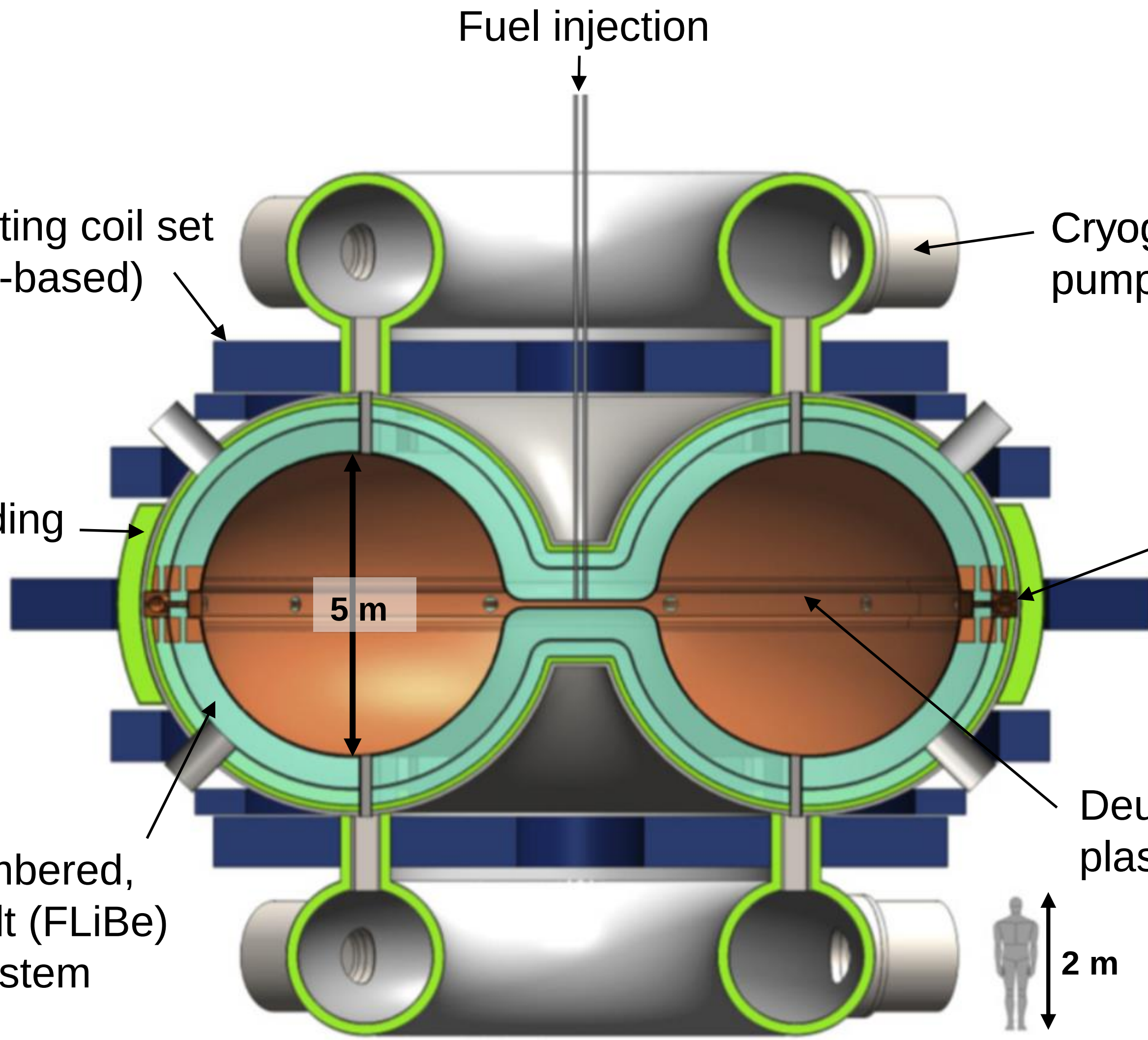
*T.R. Jarboe, et al., Imposed-dynamo current drive, *Nuclear Fusion* **52** (2012) 083017.

T.R. Jarboe, B.A. Nelson, and D.A. Sutherland, *Phys. Plasmas* **22 (2015) 072503.

Using the IDCD model, the dynomak reactor study was conducted to determine what a eventual reactor based on the HIT-SI experiment may look like

- Due to the favorable results from the HIT-SI experiment, a reactor concept study was performed based on a scale-up of HIT-SI.
- Due to the lack of a TF coil, the overall engineering of the reactor concept is simpler and more compact than a tokamak or stellarator system.
- The reactor vision based on an imposed-dynamo driven spheromak is called the *dynomak* concept.

An overview of the dynomak reactor concept*



* Extensive details and development path published in *Fusion Engineering and Design:*
Sutherland, D.A., et al., The dynomak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies, *Fus. Eng. Design* **89** (2014) 412-425.

The operating point of the dynomak reactor system

- 1 GWe scale fusion power plant based on a scale up of HIT-SI.
- Major radius of 3.75 m and a minor radius of 2.5 m.
- Tritium breeding ratio of 1.125 with un-enriched FLiBe.
- Total current drive power to sustain 42 MA toroidal plasma current is estimated from the IDCD model to be 58.5 MW.
- 41% experimental CD coupling efficiency used from HIT-SI experiment.

Parameter	Value
Major radius [m]	3.75
Aspect ratio	1.5
Toroidal I_p [MA]	41.7
Number density [10^{20} m^{-3}]	1.5
Wall-averaged β [%]	16.6
Peak T_e [keV]	20.0
Neutron wall loading [MW m^{-2}]	4.2
Tritium breeding ratio (TBR)	1.125
Current drive power [MW]	58.5
Blanket flow rate [m^3 s^{-1}]	5.2
Thermal power [MW]	2486
Electrical power [MW]	1000
Thermal efficiency [%]	$\geq$ 45
Global efficiency [%]	$\geq$ 40

Dynomak reactor concept is attractive when compared to other DEMO fusion reactor concepts

Parameters	Compact Stellarator*	Tokamak*	Spherical Torus*	Dynomak
R_o [m]	7.1	6.0	3.2	3.75
$A = R_o/a$ [m]	4.5	4.0	1.7	1.5
I_p [MA]	3.3	11.6	26.2	41.7
P_{fusion} [MW]	1794	2077	2290	1953
P_{aux} [MW]	18	100	60	58.5
Q_p - Plasma	100	20.8	38.2	33
Q_e - Engineering	6.5	3.4	2.8	**9.5**
$\langle W_n \rangle$ [MW m^{-2}]	2.8	3.0	3.4	**4.2**
$P_{electric}$ [MW]	1000	1000	1000	1000

*J.E. Menard et al. **Prospects for pilot plants based on the tokamak, spherical tokamak, and stellarator**. *Nucl. Fusion* 51 (2011) 103014 (13pp)

IDCD must be demonstrated in a larger, higher-temperature plasma

- IDCD has been demonstrated on the HIT-SI device successfully, but uncertainty lies in whether it will scale to reactor relevant plasmas.
- The next step of the development path (HIT-SIX) is devoted to answering this critical question.
- Currently, IDCD theory predicts successful scaling to reactor relevant plasmas, which must be demonstrated experimentally.

IDCD must be compatible with good confinement quality at high temperature

- Evidence of pressure confinement on HIT-SI suggests that IDCD may be compatible with good confinement quality.

- We must ensure the good confinement resulting from axisymmetric flux surfaces is not severely degraded by the magnetic fluctuations required to maintain a flat-λ profile for IDCD ($\delta B_r/B \approx 10^{-4}$).

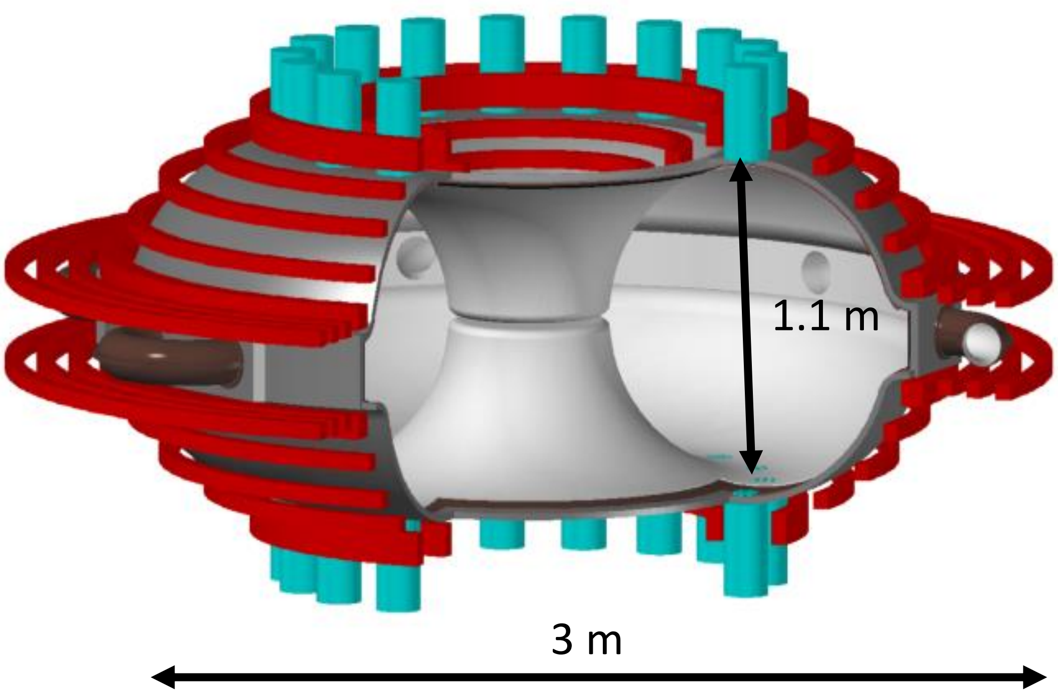
- This question will also be addressed in the HIT-SIX experiment as well.

- Should 100s of eV to 1 keV temperatures be reached, this is direct confirmation of high-temperature confinement with IDCD active.

The HIT-SIX experiment: Build a high-performance plasma experiment optimized for flat-λ and impose sufficiently large magnetic fluctuations to maintain the profile.

- In maintaining a flat-λ profile by applying sufficiently large magnetic perturbations, the free energy to drive instabilities is greatly reduced.
- In choosing a compact aspect ratio device, significant q-shear is still present to ensure good confinement characteristics → **optimized flux conserver geometry.**

Parameter	Value
R_o [m]	0.85
a [m]	0.55
I_p [MA]	1.35
T [keV]	0.5-1+
β_{wall} [%]	16
τ_{pulse} [s]	2
Cost [$M]	$\approx$ 35



HIT-SIX

Conclusions and next steps

- The spheromak configuration may provide a path to fusion power.

- Have evidence of sustainment with confined pressure via non-axisymmetric, inductive helicity injection without gross kink instabilities present.

- Imposed-dynamo current drive (IDCD) is the leading model of behavior in HIT-SI, and allows for the sustainment of current without breaking closed-flux surfaces.

- The dynomak, a compact-aspect-ratio reactor vision based on HIT-SI, has sufficient Q_E, high neutron wall loading ($/m^2), and relatively simple engineering requirements.

- The IDCD-driven spheromak is ready for a high-temperature test in the HIT-SIX experiment.

- Provided with a successful HIT-SIX experiment, the uncertainty in whether a spheromak could be a fusion relevant plasma configuration will be greatly reduced.

Key References

[1]T.R. Jarboe, et al., Imposed-dynamo current drive, *Nuclear Fusion* **52** (2012) 083017.

[2]B.S. Victor, et al., Sustained spheromaks with ideal n=1 kink stability and pressure confinement*, Physics of Plasmas* **21** (2014) 082504.

[3]D.A. Sutherland, et al., The dynomak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies, *Fusion Engineering and Design* **89** (2014) *4*, 412-425.

[4]T.R. Jarboe, B.A. Nelson, and D.A. Sutherland, A mechanism for the dynamo terms to sustain closed-flux current, including helicity balance, by driving current which crosses the magnetic field, *Phys. Plasmas* **22** (2015) 072503.

Backup Slides

Helicity injection fundamentally allows for the steady-state sustainment of a plasma configuration

- Helicity injection is described by the following expression:

$$\frac{dK}{dt} = 2\int_V \vec{E} \cdot \vec{B}\, dV$$

- Line integrating along the electric field linking magnetic flux provides another helicity injection equation form:

$$\frac{dK}{dt} = 2V\psi$$

- Thus, applying a voltage that links magnetic flux will lead to helicity injection into a plasma configuration.

- The central solenoid is a helicity injector in a tokamak.

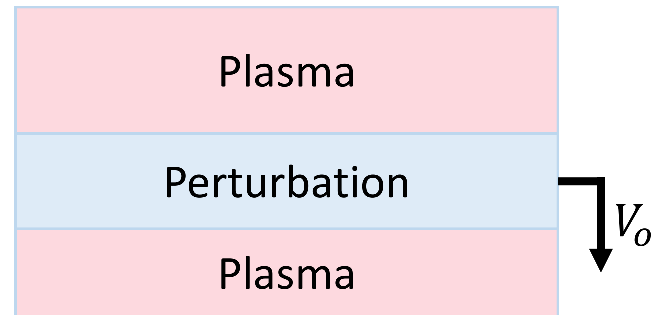
$$\frac{dK}{dt} = 2V_{ohmic}\Phi_{tor}$$

- Thus, **helicity injection is closely linked with current drive.**

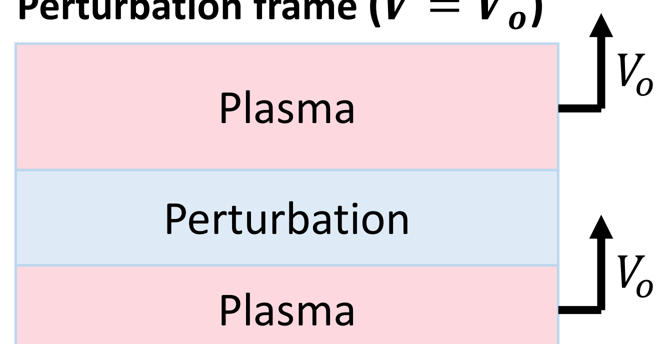
Key assumptions in the analysis of IDCD*

- An equilibrium and perturbative component of relevant quantities (e.g. $\vec{J}, \vec{B}$) are assumed.
- A n = 1, m > 0 magnetic perturbation is imposed and is frozen into the electron fluid.
- In the lab frame, the plasma is at rest (i.e. the plasma velocity is zero).
- In the lab frame, the electron fluid (which carries the current) is moving with a speed $V_o = J_o/ne$ since ions are assumed to be at rest.
- **The computations and pictures presented are done from the perturbation frame of reference (i.e. the plasma velocity is non-zero).**

Plasma frame ($\boldsymbol{V = 0}$)



Perturbation frame ($\boldsymbol{V = V_o}$)



* T.R. Jarboe, B.A. Nelson, and D.A. Sutherland, *Phys. Plasmas* **22** (2015) 072503.

The dynamo electric field drives current parallel to current

Assume $\vec{J} = \overrightarrow{J_o} + \delta\vec{j}, \vec{V} = \overrightarrow{V_o},\ \vec{B} = \overrightarrow{B_o} + \delta\vec{b}$, and that perturbation is small compared to equilibrium field.

Generalized Hall-MHD Ohm's Law

$$\vec{E} = -\vec{V} \times \vec{B} + \frac{\vec{J} \times \vec{B}}{ne} + \eta\vec{J}$$

Component of dynamo terms (Lorentz + Hall) in direction of perturbative portion of total current $\vec{J}$.

$$-\left[\overrightarrow{V_o} \times \left(\overrightarrow{B_o} + \delta\vec{b}\right)\right] \cdot \frac{\left(\overrightarrow{J_o} + \delta\vec{j}\right)}{\left|\overrightarrow{J_o} + \delta\vec{j}\right|} + \frac{\left(\overrightarrow{J_o} + \delta\vec{j}\right) \times \left(\overrightarrow{B_o} + \delta\vec{b}\right)}{ne} \cdot \frac{\left(\overrightarrow{J_o} + \delta\vec{j}\right)}{\left|\overrightarrow{J_o} + \delta\vec{j}\right|}$$

$$= \frac{-\left(\overrightarrow{V_o} \times \delta\vec{b}\right) \cdot \delta\vec{j}}{\left|\overrightarrow{J_o} + \delta\vec{j}\right|} = \frac{\left(\boldsymbol{\delta\vec{b}} \times \boldsymbol{\overrightarrow{V_o}}\right) \cdot \boldsymbol{\delta\vec{j}}}{\left|\boldsymbol{\overrightarrow{J_o}} + \boldsymbol{\delta\vec{j}}\right|} + \boldsymbol{O}(\boldsymbol{\delta^2})$$

A toroidal view of imposed magnetic perturbations and current crossing the magnetic field

An n = 1 perturbation is imposed.

Total $\vec{J}$

$\overrightarrow{B_o}, \overrightarrow{\mathrm{V_o}}$

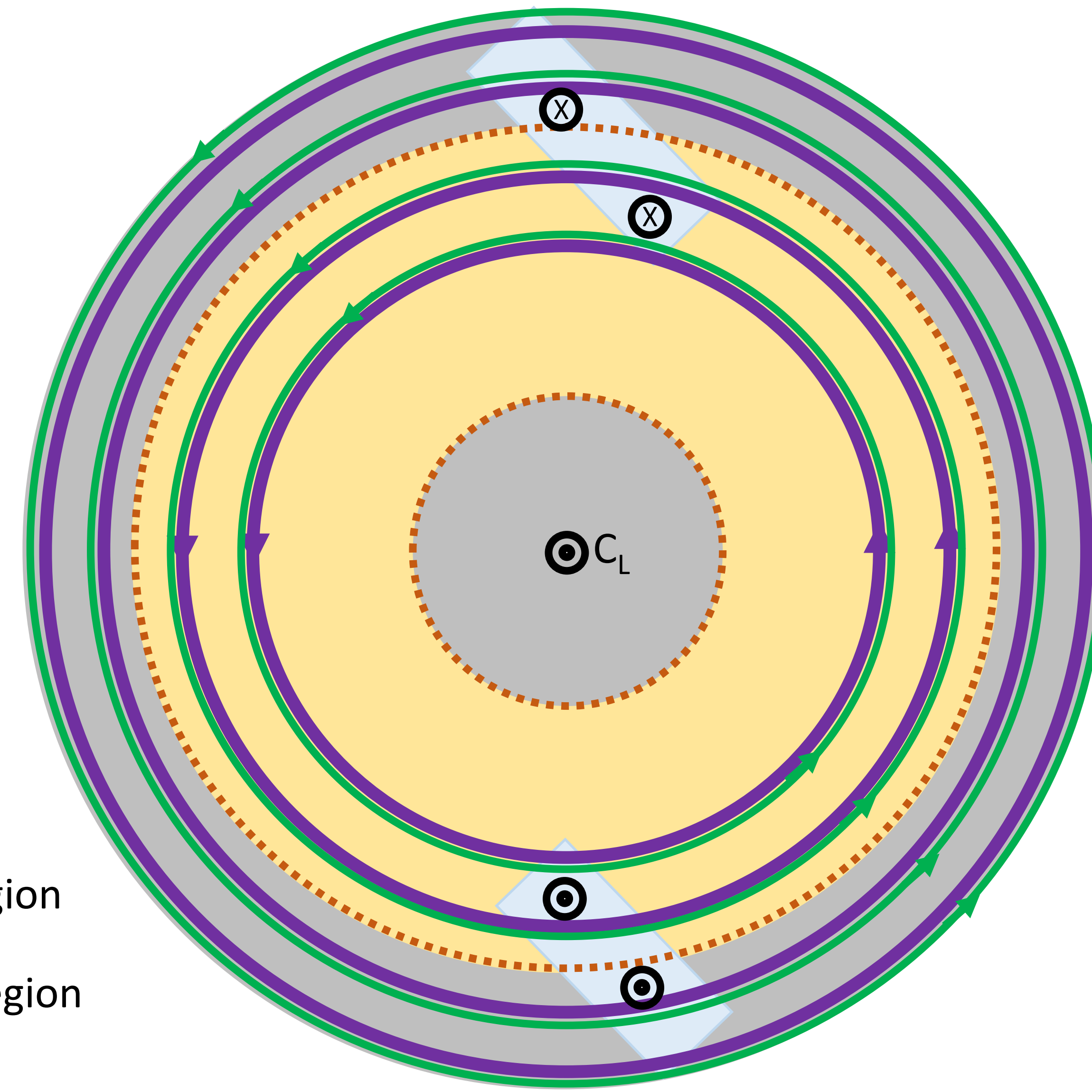
Separatrix

$\delta\vec{J}$

Perturbation region

Dynamo-driven region

Externally-driven region



This cartoon shows the critical ingredients for IDCD, magnetic perturbations and electron flow.

- The key acting dynamo term is $\delta\vec{b} \times \overrightarrow{V_o}$, which requires an electron flow velocity and a perturbative magnetic field.

- The dynamo electric field, $\delta\vec{b} \times \overrightarrow{V_o}$ has a finite component parallel to $\vec{J}$, which crosses the magnetic field

- Thus, the dynamo drives **current parallel to current**.

- A space charge is created by the dynamo electric field, which produces a electrostatic $\overrightarrow{E_V}$ is able to drive current parallel to $\vec{B}$.

- This electrostatic $\vec{E}_V$ field dotted with $\overrightarrow{B_o}$ also provides helicity injection.

- Thus, the electrostatic $\vec{E}_V$ field drives current parallel to $\overrightarrow{B_o}$, but the dynamo electric field **does not**.

- **Therefore, there is no need for the gross breaking of flux surfaces for steady-state dynamo current drive with the IDCD conditions met.**

Proposed development path and goals

Current stage → **HIT-SI3**: Advance understanding of injector physics, plasma rotation, power coupling.

Next step → **HIT-SIX**: IDCD scaling confirmation, confinement development, copper coils, 1 keV, 2 second pulse.

Optional: Dependent on HIT-SIX results → **HIT-PoP**: Confinement development, copper coils, 3 keV, 10 second pulse.

HIT-PX: Add HTSC magnets, steady-state operation, 8 keV, water cooling.

Active nuclear site → **HIT-FNSF**: Add tritium, FLiBe coolant, confirm TBR, 15 keV, materials testing.

HIT-Pilot: Add SC-CO_2 secondary cycle, 20 keV, electricity generation. (~ 20-250 MWe, depending on confinement quality)

Time ↓

An estimated overnight capital cost breakdown of the dynomak reactor concept

Component(s)	Est. Cost ($M)
Land and land rights*	17.7
Structures and site facilities*	424.3
Reactor structural supports	45.0
First wall and blanket	60.0
ZrH_2 neutron shielding	267.4
IDCD and feedback systems	38.0
Copper flux exclusion coils	38.5
Pumping and fueling systems	91.7
Tritium processing plant	154.0
Biological containment	50.0
Superconducting coil system	216.0
Supercritical CO_2 cycle	293.0
Unit direct cost	**1696**
Construction services and equipment*	288
Home office engineering and services*	132
Field office engineering and services*	132
Owner's cost*	465
Unit overnight capital cost	**2713**

***Asterisks indicate inflation adjusted figures from ARIES-AT.**

The dynomak reactor concept is cost-competitive with conventional energy sources

Energy source	$ (USD) for 1 GWe
Coal	≥ 2.8 billion
Natural gas + No CO_2 capture	≤ 1 billion
Natural gas + CO_2 capture	≥ 1.5 billion
Gen III+ nuclear plant	> 3-4 billion
Dynomak reactor concept	≈ 2.7 billion

Schlissel, D. et al. **Coal-Fire Power Plant Construction Costs**, *Synapse Energy Economics Inc.*, Cambridge, MA. July 2008. www.synapse-energy.com

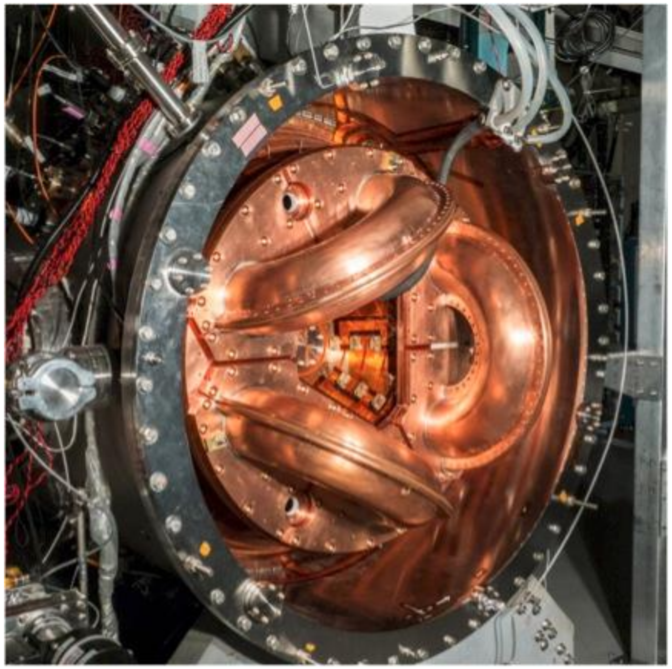
Schlissel, D. and Biewald, B. **Nuclear Power Plant Construction Costs.** *Synapse Energy Economics Inc.*, Cambridge, MA. July 2008. www.synapse-energy.com

Black, J. et al., **Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity**. *National Energy Technology Laboratory*, sponsored by U.S. DOE, November 2011.

Updated Capital Cost Estimates for Electricity Generation Plants, *U.S. Energy Information Administration: Independent Statistics and Analysis*, U.S. Department of Energy, November 2010.

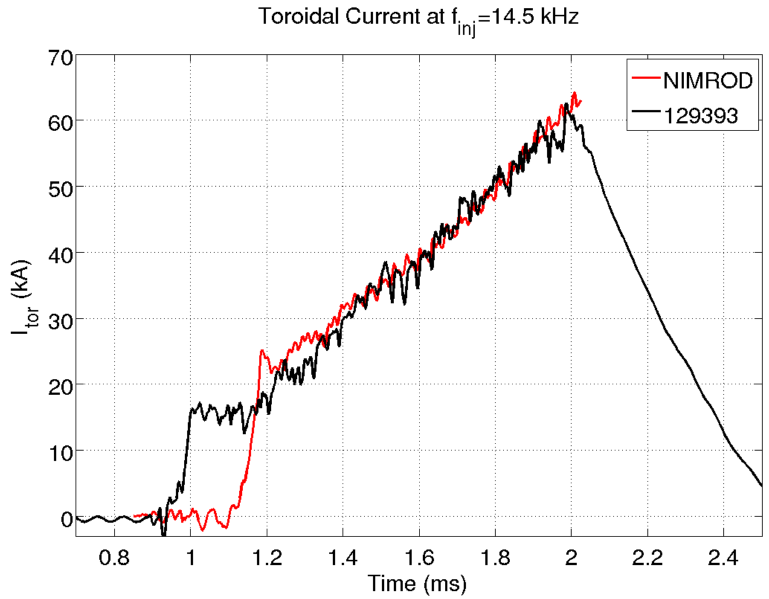
In summary, the successes of the HIT-SI research program

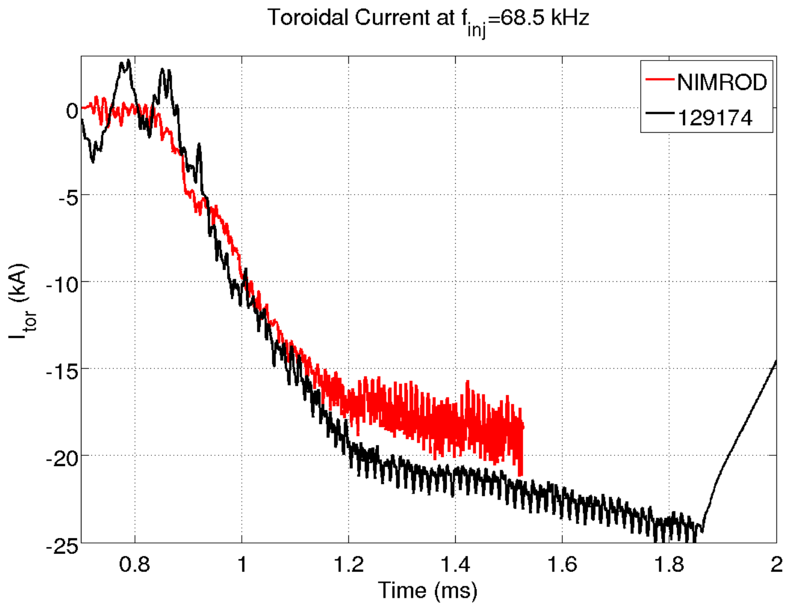
- Produced sustained kink-stable spheromaks with imposed-dynamo current drive (IDCD).
- Produced sustained spheromaks with pressure confinement.
- Imposed magnetic fluctuations required for IDCD appear compatible with sufficient confinement, likely due to plasma stability.
- Published an IDCD-driven spheromak (dynomak) concept study that is cost competitive.



The HIT-SI3 experiment, an upgrade of HIT-SI.

NIMROD simulations are approaching validation at low injector frequency, and are underway at high frequency





- NIMROD simulations indicate pressure confinement and better toroidal symmetry at higher frequencies ($f_{inj} > 40$ kHz).
- Validation has been achieved with the magnetic portion of the simulation at low frequency.
- High frequency validation is underway.