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

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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.

- 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.

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

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

HIT-SI coils and geometry

Taylor state equilibrium
\[ \nabla \times \mathbf{B} = \lambda \mathbf{B}, \text{ where } \lambda \equiv \frac{\mu_0 j}{B} \]

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

- 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*.

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.

HIT-SI sees a transition to higher $\beta$ and increased stability as $\omega_{\text{inj}}$ is increased.*

- Internal magnetic probes show larger Shafranov shift due to higher $\beta$ (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 $\beta$ limit).

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

- IDCD* requires driving the edge-\(\lambda\) higher than the spheromak \(\lambda\), 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.**


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*

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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Major radius [m]</td>
<td>3.75</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Toroidal $I_p$ [MA]</td>
<td>41.7</td>
</tr>
<tr>
<td>Number density [$10^{20}$ m$^{-3}$]</td>
<td>1.5</td>
</tr>
<tr>
<td>Wall-averaged $\beta$ [%]</td>
<td>16.6</td>
</tr>
<tr>
<td>Peak $T_e$ [keV]</td>
<td>20.0</td>
</tr>
<tr>
<td>Neutron wall loading [MW m$^{-2}$]</td>
<td>4.2</td>
</tr>
<tr>
<td>Tritium breeding ratio (TBR)</td>
<td>1.125</td>
</tr>
<tr>
<td>Current drive power [MW]</td>
<td>58.5</td>
</tr>
<tr>
<td>Blanket flow rate [m$^3$ s$^{-1}$]</td>
<td>5.2</td>
</tr>
<tr>
<td>Thermal power [MW]</td>
<td>2486</td>
</tr>
<tr>
<td>Electrical power [MW]</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal efficiency [%]</td>
<td>≥ 45</td>
</tr>
<tr>
<td>Global efficiency [%]</td>
<td>≥ 40</td>
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</table>
Dynomak reactor concept is attractive when compared to other DEMO fusion reactor concepts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Compact Stellarator*</th>
<th>Tokamak*</th>
<th>Spherical Torus*</th>
<th>Dynomak</th>
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<tbody>
<tr>
<td>$R_0$ [m]</td>
<td>7.1</td>
<td>6.0</td>
<td>3.2</td>
<td>3.75</td>
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<tr>
<td>$A = R_0/a$ [m]</td>
<td>4.5</td>
<td>4.0</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>$I_p$ [MA]</td>
<td>3.3</td>
<td>11.6</td>
<td>26.2</td>
<td>41.7</td>
</tr>
<tr>
<td>$P_{fusion}$ [MW]</td>
<td>1794</td>
<td>2077</td>
<td>2290</td>
<td>1953</td>
</tr>
<tr>
<td>$P_{aux}$ [MW]</td>
<td>18</td>
<td>100</td>
<td>60</td>
<td>58.5</td>
</tr>
<tr>
<td>$Q_p$ - Plasma</td>
<td>100</td>
<td>20.8</td>
<td>38.2</td>
<td>33</td>
</tr>
<tr>
<td>$Q_e$ - Engineering</td>
<td>6.5</td>
<td>3.4</td>
<td>2.8</td>
<td>9.5</td>
</tr>
<tr>
<td>$&lt;W_n&gt;$ [MW m$^{-2}$]</td>
<td>2.8</td>
<td>3.0</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td>$P_{electric}$ [MW]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

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-$\lambda$ 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-$\lambda$ and impose sufficiently large magnetic fluctuations to maintain the profile.

- In maintaining a flat-$\lambda$ 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 $\rightarrow$ **optimized flux conserver geometry.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$R_o$ [m]</td>
<td>0.85</td>
</tr>
<tr>
<td>a [m]</td>
<td>0.55</td>
</tr>
<tr>
<td>$I_p$ [MA]</td>
<td>1.35</td>
</tr>
<tr>
<td>T [keV]</td>
<td>0.5-1+</td>
</tr>
<tr>
<td>$\beta_{wall}$ [%]</td>
<td>16</td>
</tr>
<tr>
<td>$\tau_{pulse}$ [s]</td>
<td>2</td>
</tr>
<tr>
<td>Cost [$M$]</td>
<td>$\approx$ 35</td>
</tr>
</tbody>
</table>
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


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

- Helicity injection is described by the following expression:
  \[ \frac{dK}{dt} = 2 \int \overrightarrow{E} \cdot \overrightarrow{B} \, dV \]

- 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.
  \[ \frac{dK}{dt} = 2V_{\text{ohmic}}\Phi_{\text{tor}} \]

- 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. $J, B$) 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).

The dynamo electric field drives current parallel to current

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

Generalized Hall-MHD Ohm’s Law

$$\vec{E} = -\vec{V} \times \vec{B} + \frac{\vec{j} \times \vec{B}}{n_e} + \eta\vec{j}$$

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

$$- \left[ \vec{V}_o \times (\vec{B}_o + \delta\vec{b}) \right] \cdot \frac{(\vec{j}_o + \delta\vec{j})}{|\vec{j}_o + \delta\vec{j}|} + \frac{(\vec{j}_o + \delta\vec{j}) \times (\vec{B}_o + \delta\vec{b})}{n_e} \cdot \frac{(\vec{j}_o + \delta\vec{j})}{|\vec{j}_o + \delta\vec{j}|}$$

$$= - \frac{(\vec{V}_o \times \delta\vec{b}) \cdot \delta\vec{j}}{|\vec{j}_o + \delta\vec{j}|} = \frac{(\delta\vec{b} \times \vec{V}_o) \cdot \delta\vec{j}}{|\vec{j}_o + \delta\vec{j}|} + O(\delta^2)$$
A toroidal view of imposed magnetic perturbations and current crossing the magnetic field

An n = 1 perturbation is imposed.

- **Total \( \vec{j} \)**
- **\( B_o, V_o \)**
- **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 $\delta \vec{b} \times \vec{V}_o$, which requires an electron flow velocity and a perturbative magnetic field.

- The dynamo electric field, $\delta \vec{b} \times \vec{V}_o$ 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 $\vec{E}_V$ is able to drive current parallel to $\vec{B}$.

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

- Thus, the electrostatic $\vec{E}_V$ field drives current parallel to $\vec{B}_o$, 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-CO₂ secondary cycle, 20 keV, electricity generation. (~ 20-250 MWe, depending on confinement quality)
An estimated overnight capital cost breakdown of the dynomak reactor concept

<table>
<thead>
<tr>
<th>Component(s)</th>
<th>Est. Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land and land rights*</td>
<td>17.7</td>
</tr>
<tr>
<td>Structures and site facilities*</td>
<td>424.3</td>
</tr>
<tr>
<td>Reactor structural supports</td>
<td>45.0</td>
</tr>
<tr>
<td>First wall and blanket</td>
<td>60.0</td>
</tr>
<tr>
<td>ZrH₂ neutron shielding</td>
<td>267.4</td>
</tr>
<tr>
<td>IDCD and feedback systems</td>
<td>38.0</td>
</tr>
<tr>
<td>Copper flux exclusion coils</td>
<td>38.5</td>
</tr>
<tr>
<td>Pumping and fueling systems</td>
<td>91.7</td>
</tr>
<tr>
<td>Tritium processing plant</td>
<td>154.0</td>
</tr>
<tr>
<td>Biological containment</td>
<td>50.0</td>
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<tr>
<td>Superconducting coil system</td>
<td>216.0</td>
</tr>
<tr>
<td>Supercritical CO₂ cycle</td>
<td>293.0</td>
</tr>
<tr>
<td><strong>Unit direct cost</strong></td>
<td><strong>1696</strong></td>
</tr>
<tr>
<td>Construction services and equipment*</td>
<td>288</td>
</tr>
<tr>
<td>Home office engineering and services*</td>
<td>132</td>
</tr>
<tr>
<td>Field office engineering and services*</td>
<td>132</td>
</tr>
<tr>
<td>Owner’s cost*</td>
<td>465</td>
</tr>
<tr>
<td><strong>Unit overnight capital cost</strong></td>
<td><strong>2713</strong></td>
</tr>
</tbody>
</table>

*Asterisks indicate inflation adjusted figures from ARIES-AT.*
The dynomak reactor concept is cost-competitive with conventional energy sources

<table>
<thead>
<tr>
<th>Energy source</th>
<th>$ (USD) for 1 GWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>≥ 2.8 billion</td>
</tr>
<tr>
<td>Natural gas + No CO₂ capture</td>
<td>≤ 1 billion</td>
</tr>
<tr>
<td>Natural gas + CO₂ capture</td>
<td>≥ 1.5 billion</td>
</tr>
<tr>
<td>Gen III+ nuclear plant</td>
<td>&gt; 3-4 billion</td>
</tr>
<tr>
<td>Dynomak reactor concept</td>
<td>≈ 2.7 billion</td>
</tr>
</tbody>
</table>


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 \( f_{inj} > 40 \text{ kHz} \).

- Validation has been achieved with the magnetic portion of the simulation at low frequency.

- High frequency validation is underway.