Compact, spheromak-based pilot plants for the demonstration of net-gain fusion power

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Outline

• Why spheromaks?
• HIT-SI experiment overview
• Revisit Dynomak concept
• Dynomak pilot plant study
• Summary
• Next steps
Spheromak configurations are conceptually enticing for fusion energy

- Compactness and simplified engineering allows for lower projected capital costs than equivalently-scaled tokamak or stellarator configurations.*

- No toroidal field coils or a central solenoid allows for efficient utilization of DT neutron flux for tritium breeding.

- Simply connected geometry allows for blanket, shield, and wall-loading to be optimized for cost.

- Requires power efficient current drive to enable high engineering gains $Q_E$ – imposed-dynamo current drive (IDCD) is a possible solution.

The main challenge for steady-state spheromak configurations has been the issue of energy confinement during sustainment

• Previous spheromak experiments were able to Ohmically heat to the beta limit and approached L-mode level thermal diffusivities during decay, with plasma temperatures up to 500-600 eV.*

• However, during sustainment with coaxial helicity injection (CHI), energy confinement was severely degraded due to the excitation of plasma instabilities.*

• Fundamentally, these instabilities were required by Cowling’s theorem** to perform dynamo current drive since the system was nominally axisymmetric.

A new method of current drive (imposed-dynamo current drive (IDCD)) decouples instability from current sustainment, which may allow for steady-state, spheromak fusion plasmas

- Helicity injection is fully inductive on the HIT-SI device.

- The semi-toroidal injectors operate in AC, and with appropriate phasing can provide steady helicity injection.

- IDCD removes the need for plasma instabilities to perform dynamo current drive by:
  1. Imposing non-axisymmetric magnetic perturbations.
  2. Externally driving the edge plasma current.

Taylor state equilibrium
\[ \nabla \times \vec{B} = \lambda \vec{B} \], where \( \lambda \equiv \mu_0 j / \vec{B} \)
Plasma currents approaching 100 kA and current gains ($I_{\text{tor}}/I_{\text{inj}}$) approaching 4 have been achieved in the HIT-SI experiment.

- Current amplification of 3.9 at 68.5 kHz injector frequency, a new spheromak record.
- 90 kA of toroidal current at 14.5 kHz injector frequencies.
- Stable, sustained equilibria Ohmically heat to the beta limit, thus achieving the current drive goal of HIT-SI.
If IDCD can sustain stable toroidal plasmas, it may be able to do so with satisfactory confinement quality for a relatively low-cost

• If gross plasma instabilities are no longer a necessary feature of the system, dynamo current drive may be able to be used in steady-state with satisfactory energy confinement quality.

• The effects of spatially and temporally varying imposed magnetic perturbations on confinement quality will need to be addressed in larger, higher temperature plasmas.

• Low-frequency (kHz), kA and kV-scale, AC electrical hardware is used for the current drive system, which is relatively inexpensive compared to other current drive technologies (such as NBI or RF current drive).
The Dynomak reactor concept study was performed in 2013-2014 based on a scale-up of the HIT-SI device.

- This reactor was designed to be a 1 GWe, commercial-scale fusion power plant to compare with other fusion concepts, and conventional power sources.

- The size of 1 GWe is often used as a good baseline of comparison since it is the maximum size for any single power plant allowed in the U.S.

- Larger reactors often benefit from decreasing costs per watt since the power output scales so strongly with size, whereas many costs of the plant scale weakly, or not at all, with size.
Key features of the Dynomak reactor system

• Liquid, immersive FLiBe blanket used for first-wall cooling, neutron moderation and tritium breeding.

• Fully inductive, non-axisymmetric helicity injection is used to fully sustain the spheromak equilibrium, and the configuration is assumed to Ohmically heat to the Mercier beta limit.

• Only one superconducting coil set is used (e.g. PFCs) that can be either high or lower temperature superconducting since the peak field on coil is modest ($\approx 6.5$ T).
The Dynomak reactor is concept based on promising results and scaling from the HIT-SI device.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_o$ [m]</td>
<td>3.75</td>
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<tr>
<td>$A$</td>
<td>1.5</td>
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<tr>
<td>$I_p$ [MA]</td>
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</tr>
<tr>
<td>$n_e [10^{20} \text{ m}^{-3}]$</td>
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<td>$\beta_{\text{wall}}$ [%]</td>
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<td>Peak $T_e$ [keV]</td>
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<td>$W_n$ [MW m$^{-2}$]</td>
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<td>TBR</td>
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<td>$P_{\text{CD}}$ [MW]</td>
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<td>Blanket $\dot{V}$ [m$^3$ s$^{-1}$]</td>
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<tr>
<td>$P_{\text{th}}$ [MW]</td>
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<tr>
<td>$P_e$ [MW]</td>
<td>1000</td>
</tr>
<tr>
<td>$\eta_{\text{th}}$ [%]</td>
<td>$\geq 45$</td>
</tr>
<tr>
<td>$\eta$ [%]</td>
<td>$\geq 40$</td>
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Compared with mainline fusion approaches, the Dynomak reactor concept looks quite appealing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Compact Stellarator*</th>
<th>Tokamak*</th>
<th>Spherical Torus*</th>
<th>Dynomak</th>
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<tr>
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<td>1.5</td>
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<td>1953</td>
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<td>100</td>
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<td>$Q_e$ - Engineering</td>
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<td>3.4</td>
<td>2.8</td>
<td>9.5</td>
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<td>3.0</td>
<td>3.4</td>
<td>4.2</td>
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<tr>
<td>$P_{\text{electric}}$ [MW]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
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</table>

*J.E. Menard et al. **Prospects for pilot plants based on the tokamak, spherical tokamak, and stellarator.** *Nucl. Fusion* 51 (2011) 103014 (13pp)
Two, small-scale Dynomak-based fusion concepts have been evaluated for their nuclear viability

- Two pilot plants are being designed to operate both as fusion nuclear science facilities and pilot power plants.

- Though these devices are viewed purely as fusion nuclear science or demonstration facilities, it may end up being the eventual product depending on market demands.

- I believe we must be prepared for the reality that these smaller units might be the eventual product in demand for electricity production rather than a 1 GWe unit that will likely be the lowest $/kWe out of all three sizes.

- **This type of market makes the need for economical fusion concepts even more important!**
The two pilot plant sizes are used due to uncertainties in confinement quality

- Both pilot plants are simulated using MCNP6 to assess the nuclear viability.

- The large pilot plant is approximately 64% the linear size of the Dynomak, whereas the smaller unit is 40% in linear size than the Dynomak.

- Instead of having discrete injectors like the Dynomak, a helicity injector manifold is implemented to provide more flexibility in the magnetic perturbation spectrum applied for IDCD.

- Two different ranges of operation are targeted, FNSF wall loadings, and scaling with constant wall magnetic field from the Dynomak design point.
Both pilot plants have a lower operating point to target a 1 MW/m$^2$ DT neutron wall loading, and an higher operating point of scaling at constant $B_{wall}$ self-similarly to the Dynomak.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Large Pilot Plant Operating Range</td>
<td></td>
<td>Small Pilot Plant Operating Range</td>
<td></td>
</tr>
<tr>
<td>$R$ [m]</td>
<td>2.4</td>
<td>$R$ [m]</td>
<td>1.5</td>
</tr>
<tr>
<td>$a$ [m]</td>
<td>1.6</td>
<td>$a$ [m]</td>
<td>1.0</td>
</tr>
<tr>
<td>$A$</td>
<td>1.5</td>
<td>$A$</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_{fusion}$ [MW]</td>
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<td>$P_{fusion}$ [MW]</td>
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<td>$P_{thermal}$ [MW]</td>
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<td>$P_{thermal}$ [MW]</td>
<td>94.1 – 159</td>
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<tr>
<td>$&lt;W_n&gt;$ [MW m$^2$]</td>
<td>1.0 – 2.7</td>
<td>$&lt;W_n&gt;$ [MW m$^2$]</td>
<td>1.0 – 1.7</td>
</tr>
<tr>
<td>$&lt;\beta_{wall}&gt;$ [%]</td>
<td>16.6</td>
<td>$&lt;\beta_{wall}&gt;$ [%]</td>
<td>16.6</td>
</tr>
<tr>
<td>$S_p$ [m$^2$]</td>
<td>151.6</td>
<td>$S_p$ [m$^2$]</td>
<td>59.2</td>
</tr>
<tr>
<td>$V_p$ [m$^3$]</td>
<td>121.3</td>
<td>$V_p$ [m$^3$]</td>
<td>29.6</td>
</tr>
<tr>
<td>$P_{fusion}/V_p$ [MW/m$^3$]</td>
<td>2.5-4.2</td>
<td>$P_{fusion}/V_p$ [MW/m$^3$]</td>
<td>2.5-4.2</td>
</tr>
</tbody>
</table>
The Dynomak used a copper flux conservener and 316 SS since they are well-established materials and low cost

- The Dynomak chose to use these materials to allow for easy costing, and also because people have extensive experience with them.

- Unfortunately, DT neutrons activate Cu, which produces low-level radioactive waste that would have to be stored for 50-100 years before being reprocessed.

- Storage costs and other regulatory expenses due to the generation of this waste would not be helpful in taking away market share from natural gas and coal power plants.
Additionally, the use of Cu and 316 SS makes it more challenging to obtain a sufficient TBR (TBR > 1.1) with natural, or even enriched FLiBe in the pilot plants.

• In the Dynomak, a sufficient TBR was obtained due to the thickness of the blanket and the lack of a large helicity injector manifold volume.

• In both pilot plants, thinner blankets had to be used due to less space, and both Cu and 316 SS was replaced with a Beryllium flux conserver and radiation resistant ferritic steels to reduce generation of radioactive waste and also reduce the fraction of neutrons being lost to absorption.

• Also, Be is a neutron multiplier that doesn’t activate like Cu does.

• Additionally, Be flux exclusion coils were used instead of Cu ones as was used in the Dynomak.
A representative MCNP model of the large pilot plant is shown at various scales.

- Pink is the neutron-producing DT plasma, blue is the beryllium flux conserver, cyan is radiation resistant ferritic steel, orange is Cu or Be (Be in the final version, but Cu above), and green is either ZrH$_2$ or TiH$_2$.
Representative radial build at $\theta = 45^o$ of pilot plant concepts
The simulations are run to calculate TBR, DPA in the first wall, and other parameters of interest such as fast neutron flux exiting the reactor.
With the material changes, the reactors generate the same or more tritium per neutron than the Dynomak with Be or Cu flux exclusion coils

- The first wall (flux conserver) thickness was changed to observe the effects on the TBR.
- Also, either Be or Cu flux exclusion coils were used in the simulation.
- With these geometry and material changes fixed, the enrichment of the FLiBe was varied from natural to nearly 100% Li-6.
- Enrichment would likely be required for all reasonable first wall thicknesses to be above 1.1, but not when using Be flux exclusion coils.
The TBR is sufficiently large in both the large reactor and small reactor with reasonable first wall thicknesses, and Be flux exclusion coils.

- A thicker beryllium flux conserver is required in the small reactor to achieve comparable values to the larger reactor for enrichments < 30%.

- The TBR with Be flux exclusion coils as a function of enrichment is more than sufficient for a closed-fuel cycle.

- Additionally, at approximately 32% enrichment, increasing the enrichment further decreases the TBR.

- Li-7 plays a role in generating tritium at high neutron energies, more so than Li-6.
Higher energy neutron multiplication or tritium breeding reactions are more important in smaller reactors because of less moderation

- The Li-6 tritium breeding reaction has the highest cross section at neutron energies below 1 MeV.

- But, the Li-7 reaction dominates for neutron energies above \( \approx 4.5 \) MeV.

- So, in thin blankets where once would expect the average neutron energy to be higher than in a thicker blanket, the Li-7 plays an increasingly larger role relative to the Li-6 reaction.

- Additionally, the Be and/or Pb neutron multiplying reaction switches on for high neutron energies \( \rightarrow \) put neutron multipliers close to DT source.
In short, both size pilot plants can make more than enough tritium with appropriate material choices and with natural FLiBe

• For a spheromak-based fusion reactor like these pilot plants, the ability to use the inboard neutron flux completely for tritium breeding instead of losing them to a shield protecting the TF coil allows for a sufficient TBR, even at small size. (STs have no such luxury).

• Higher fast neutron fluxes leaving the reactor will negatively effect the surrounding superconducting coil set in the pilot plants

• Preliminary estimates with appropriately applied neutron shielding suggest a reasonable superconducting lifetime (8-15+ full-power years).
At reasonable shield thicknesses, 10-20 cm, coil lifetimes between 10-39 FPY can be achieved.
Summary

• The spheromak configuration is an enticing prospect for economical fusion power because of their compactness and less demanding engineering requirements than tokamaks or stellarators.

• A new method of current drive (IDCD) may provide a path forward that could overcome the previous issue of current sustainment with good energy confinement quality.

• Two, small-scale FNSF/Pilot plants (R = 2.4 m and R = 1.5 m, both with A = 1.5) are viable from a tritium breeding and coil set shielding perspective.

• Thus, the main uncertainty with this pathway to fusion power is whether the confinement will scale favorably to allow for either size pilot plant, and the eventual Dynomak to produce the desired fusion powers.
Next step: IDCD is ready to be demonstrated in larger, higher temperature plasmas to further address viability

• It is necessary to demonstrate IDCD operating in higher temperature plasmas that allow for a greater separation of timescales of potential instabilities (e.g. tearing modes).

• The larger spheromak experiment would have <$10 million total hardware cost and, if successful, move this technology from a TRL of 2-3 to 4+.

• Additionally, we would like to implement one, or multiple inductive helicity injectors on a tokamak to study plasma current profile control and address high temperature viability as well.