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

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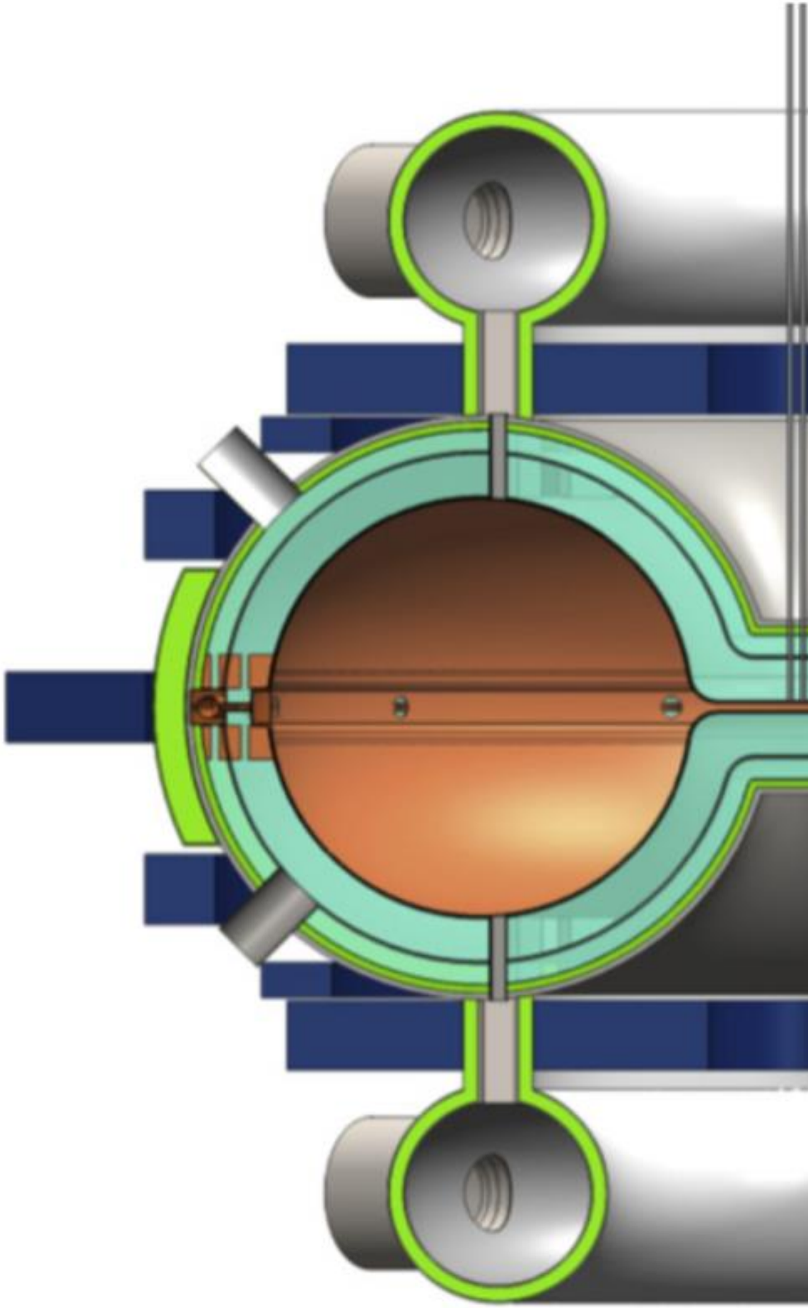
ISTW 2015 Workshop
November 6, 2015

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 economically 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
- Simulation capabilities and results
- Reactor vision and comparisons
- Conclusions and next steps

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

- Helicity injection is described by the following expression:

$$\frac{d\boldsymbol{K}}{d\boldsymbol{t}} = 2\int_{V} \vec{E} \cdot \vec{B}\, dV$$

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

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

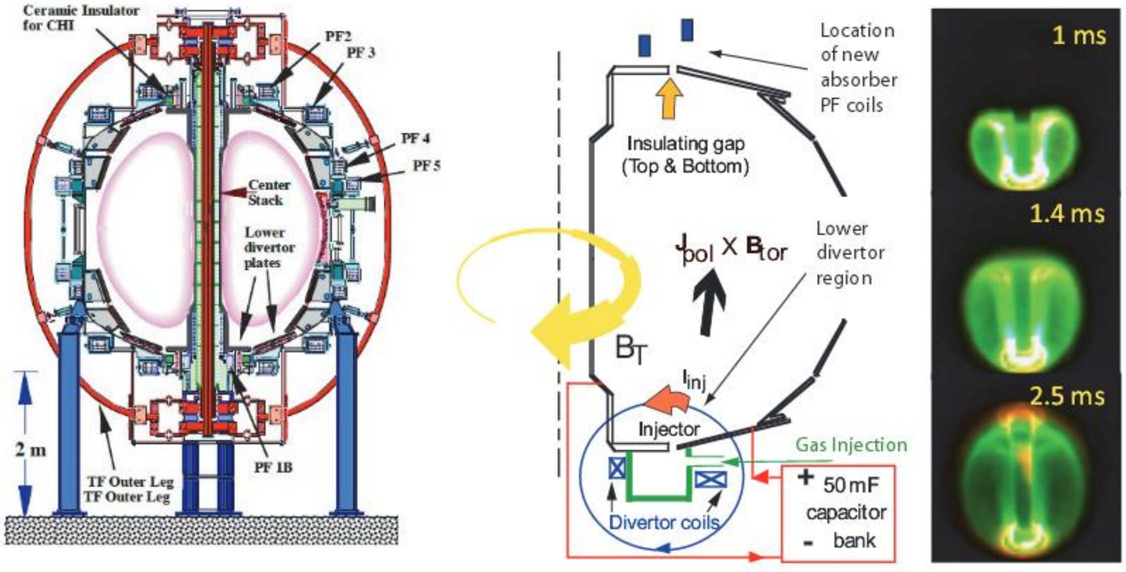
- Thus, applying a voltage that links magnetic flux will lead to helicity injection into a plasma configuration.

- 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.**

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

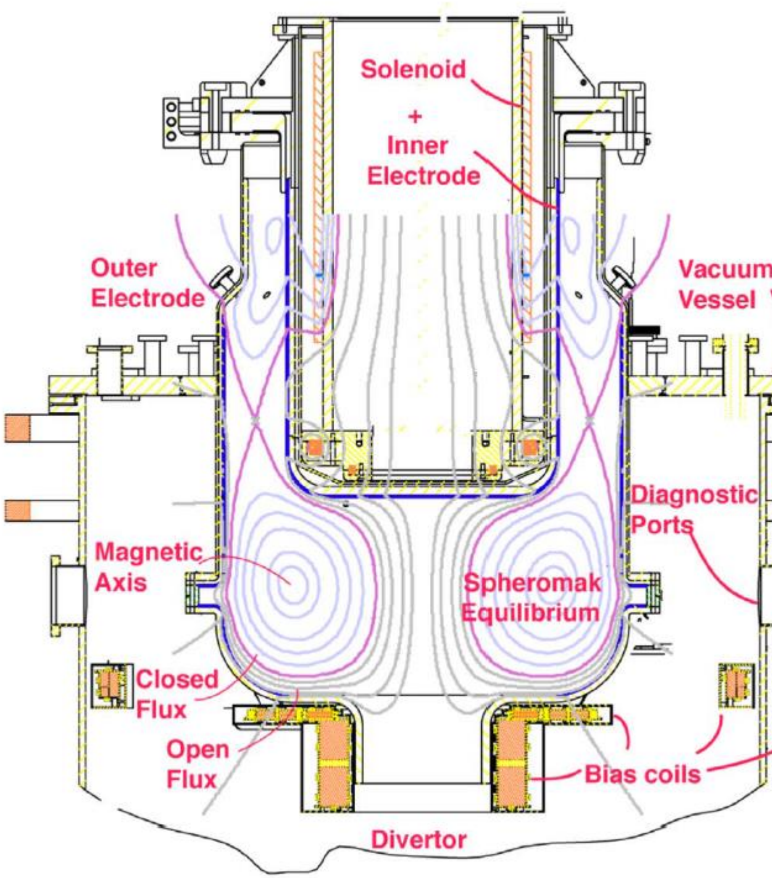
- Reducing the need for inductive flux swing in an ST is important due to central solenoid flux-swing limitations.
- Biasing the lower divertor plates with ambient magnetic field from coil sets in NSTX allows for the injection of magnetic helicity.
- A ST plasma configuration is formed via CHI that is 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.

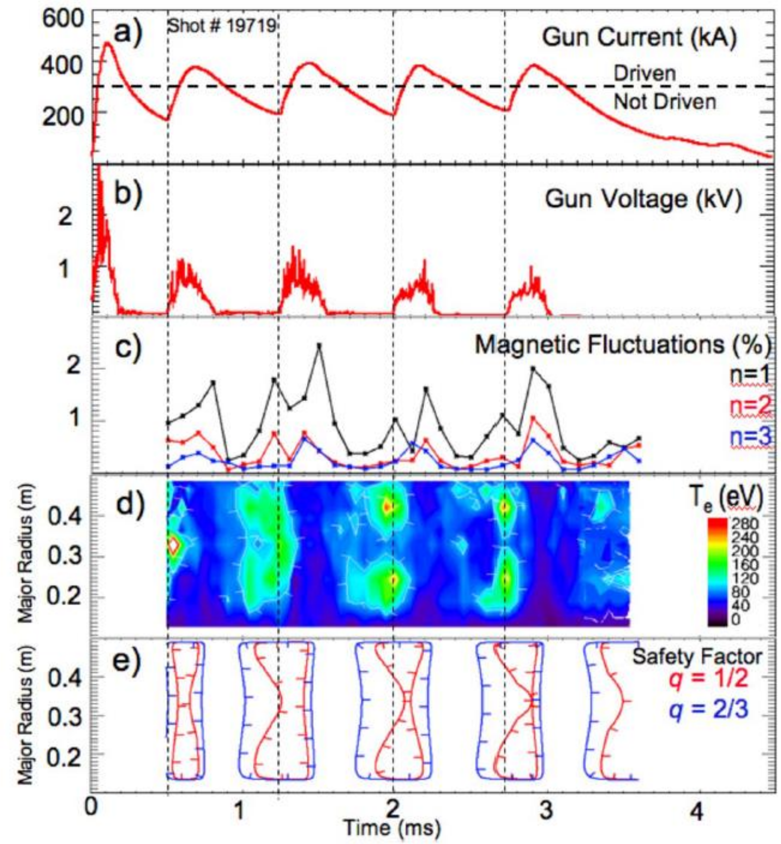
Though CHI is useful on startup in NSTX, Cowling's theorem removes the possibility of a steady-state, axisymmetric dynamo of interest for reactor applications

- 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*)

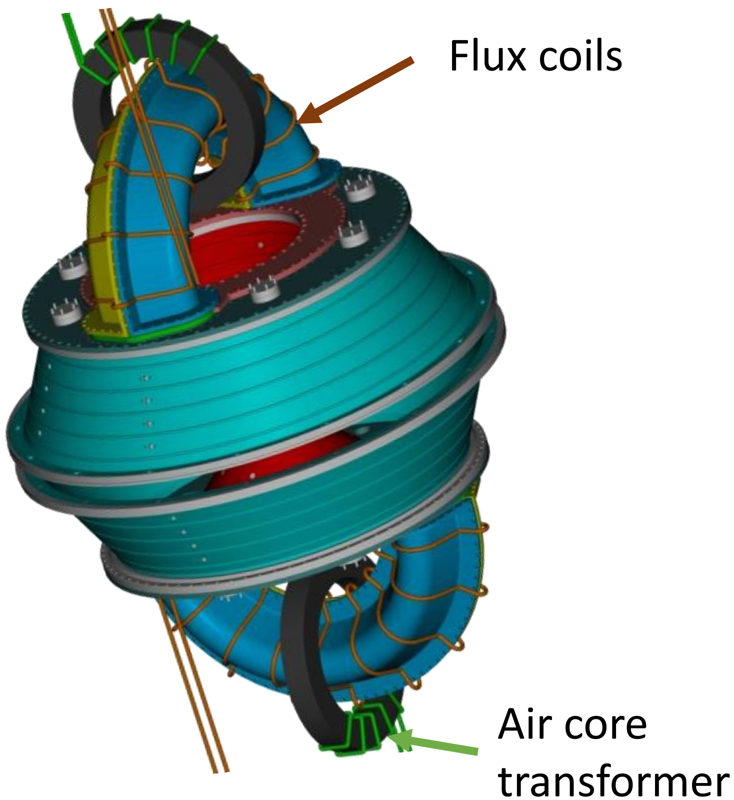




*B. Hudson, et al., *Phys. Plasmas* **15** (2008) 056112.

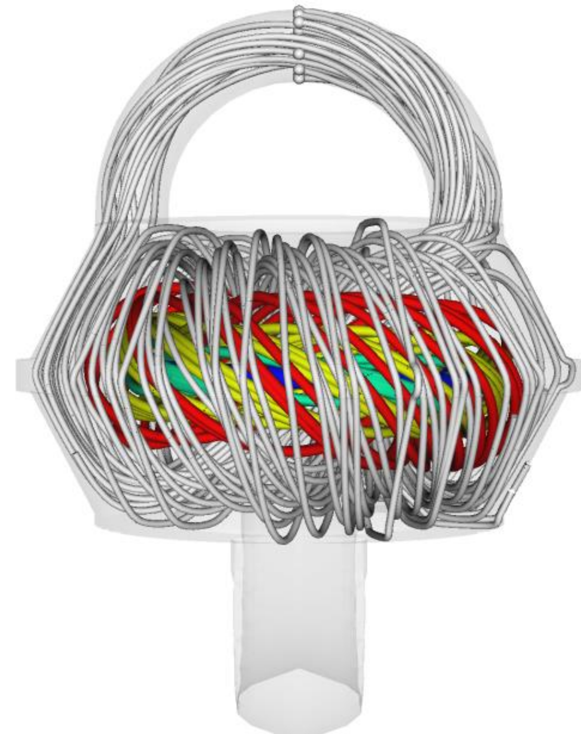
HIT-SI seeks to overcome the issues of CHI with fully-inductive, non-axisymmetric helicity injection

HIT-SI coils and geometry



Taylor state equilibrium

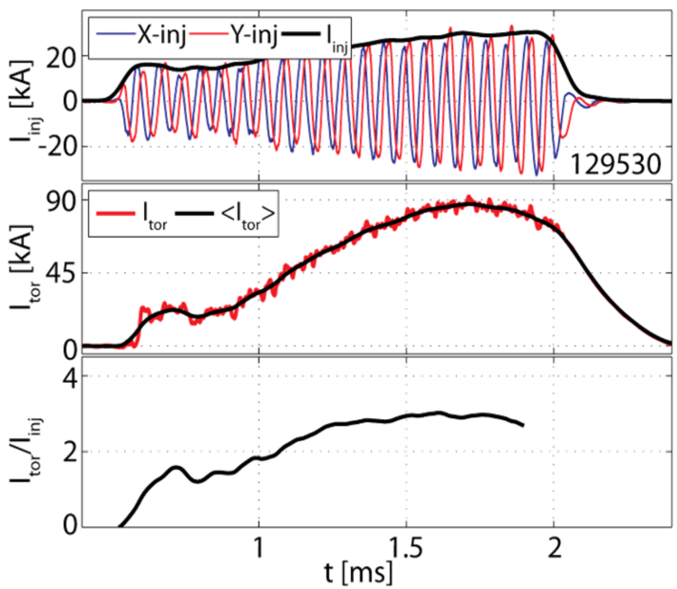
$\nabla \times \vec{B} = \lambda \vec{B}$, where $\lambda \equiv \mu_o \vec{j}/\vec{B}$



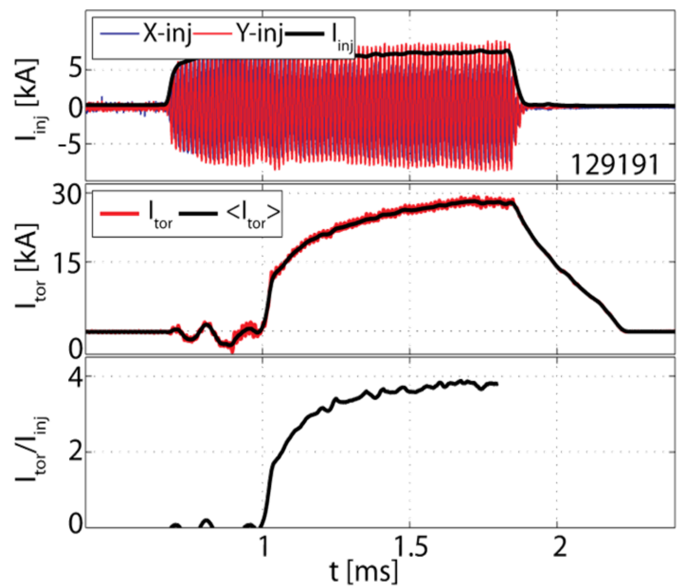
A spheromak forms after an ample amount of helicity is injected, and relaxation occurs. The spheromak is then sustained by continued injector operation.

Record current gains are observed at higher injector frequencies

14.5 kHz results

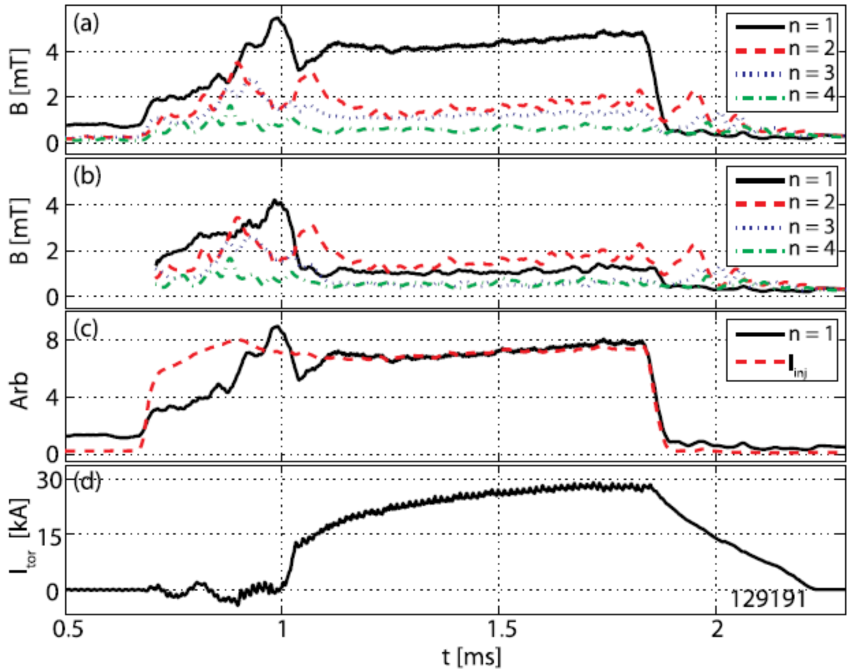


68.5 kHz results



- 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

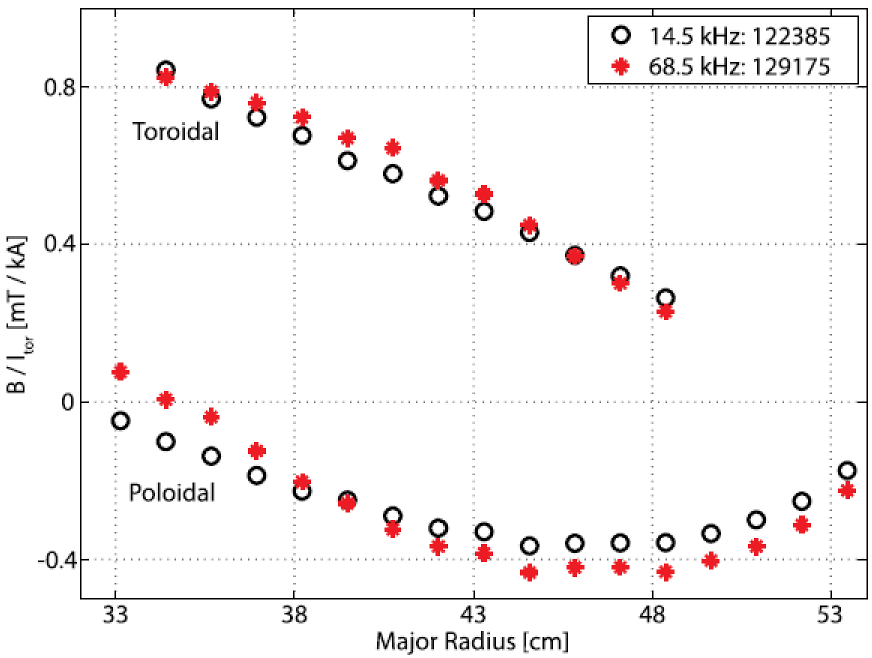
Toroidal current vs time

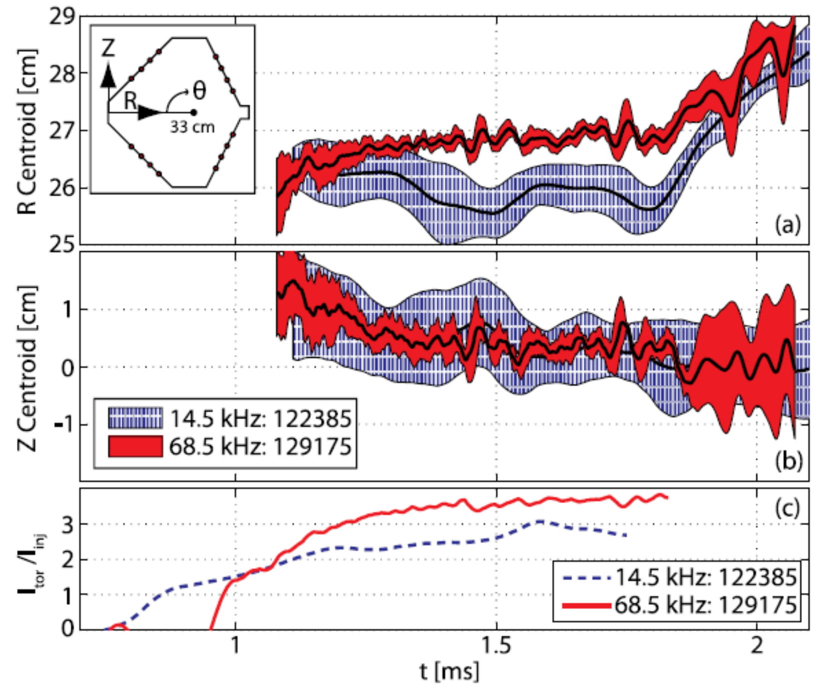
- During sustainment, the n = 1 component of the magnetic fields in the system is almost entirely imposed.

- 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.

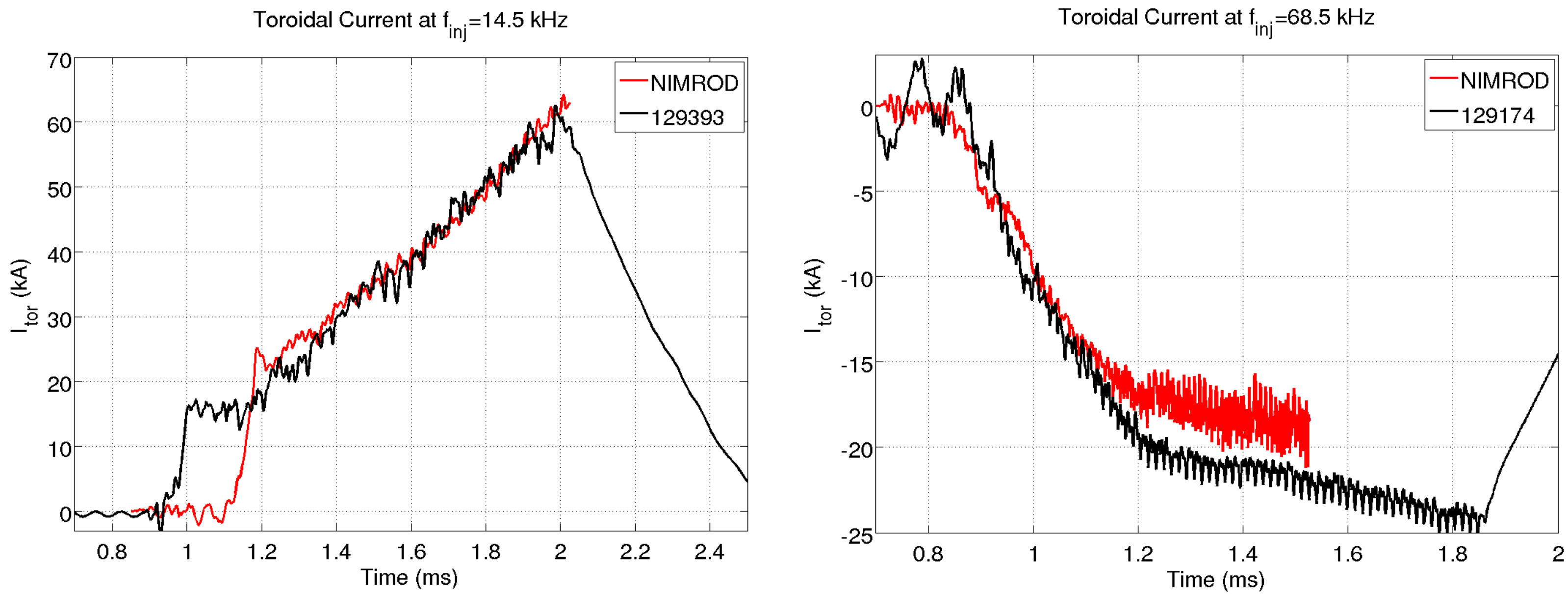
HIT-SI sees a transition to higher β and increased stability as ω_{inj} is increased





- 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).

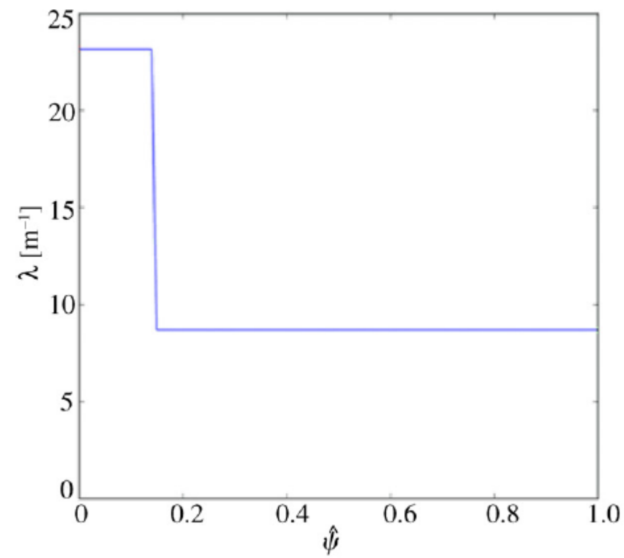
NIMROD simulations are approaching validation at low injector frequency, and are underway at high frequency



- 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.

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.**

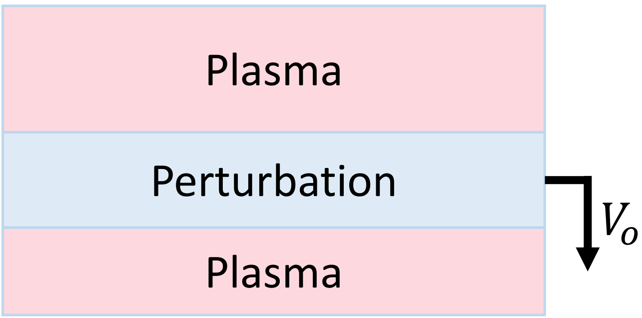


IDCD 2-step λ model

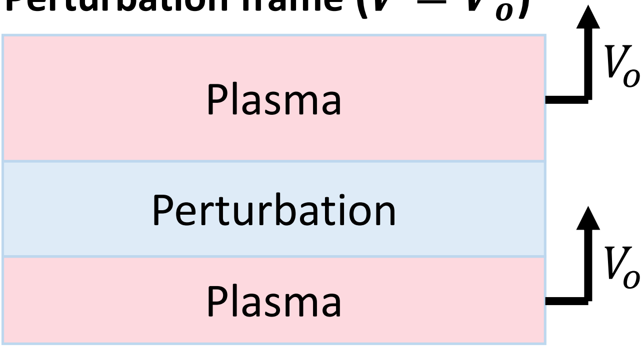
Key assumptions in the analysis of IDCD*

- 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 perception 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

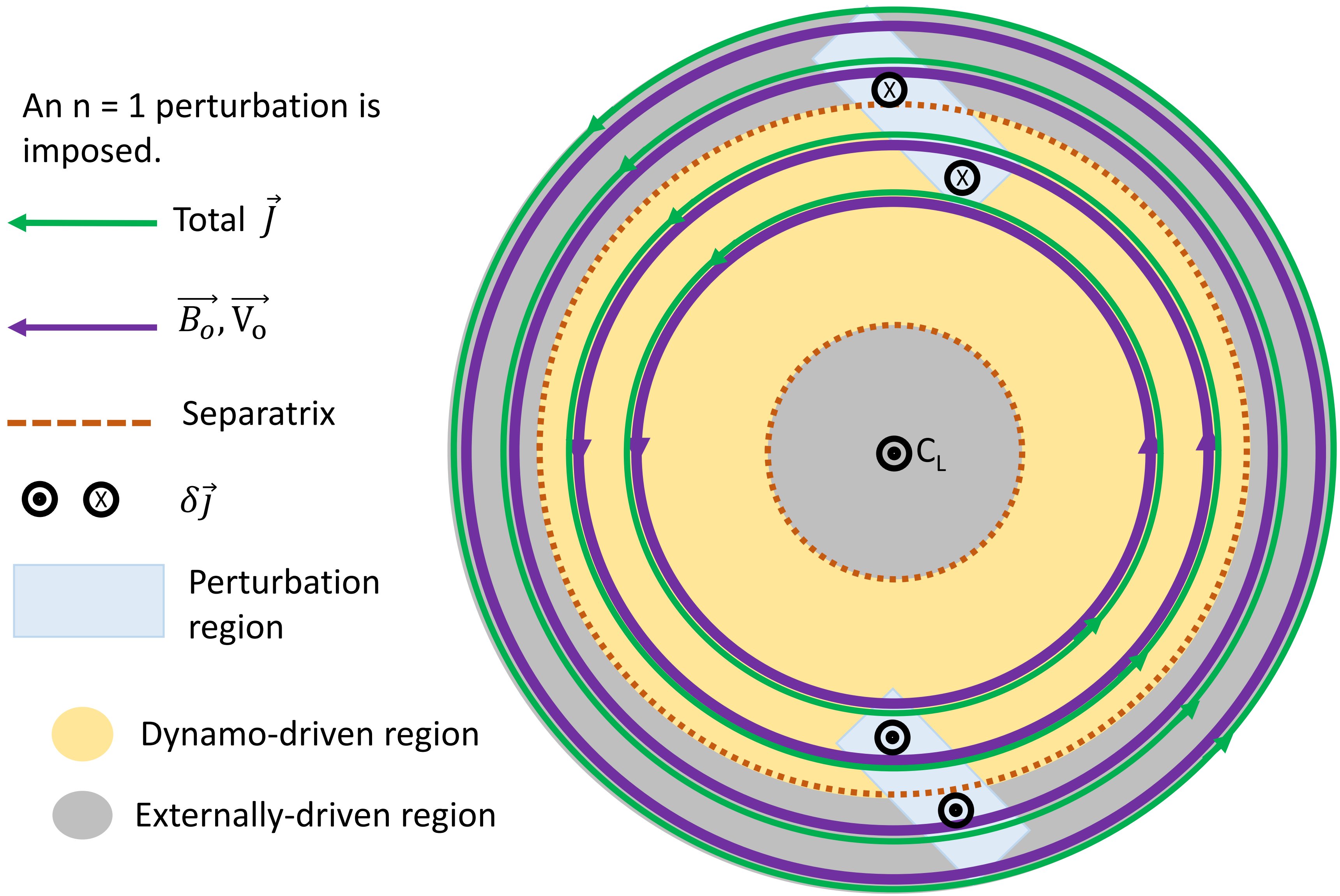
$$\vec{E} = -\vec{V} \times \vec{B} + \frac{\vec{J} \times \vec{B}}{ne} + \eta\vec{J}$$

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

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

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

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



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 $\vec{B}$.

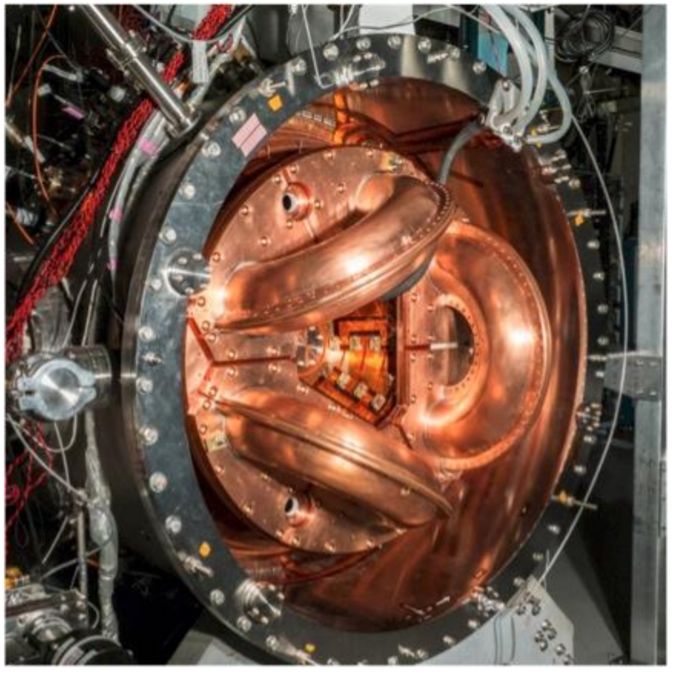
- This electrostatic $\vec{E}_V$ field dotted with $\overrightarrow{B_o}$ also provides helicity injection.

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

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

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.

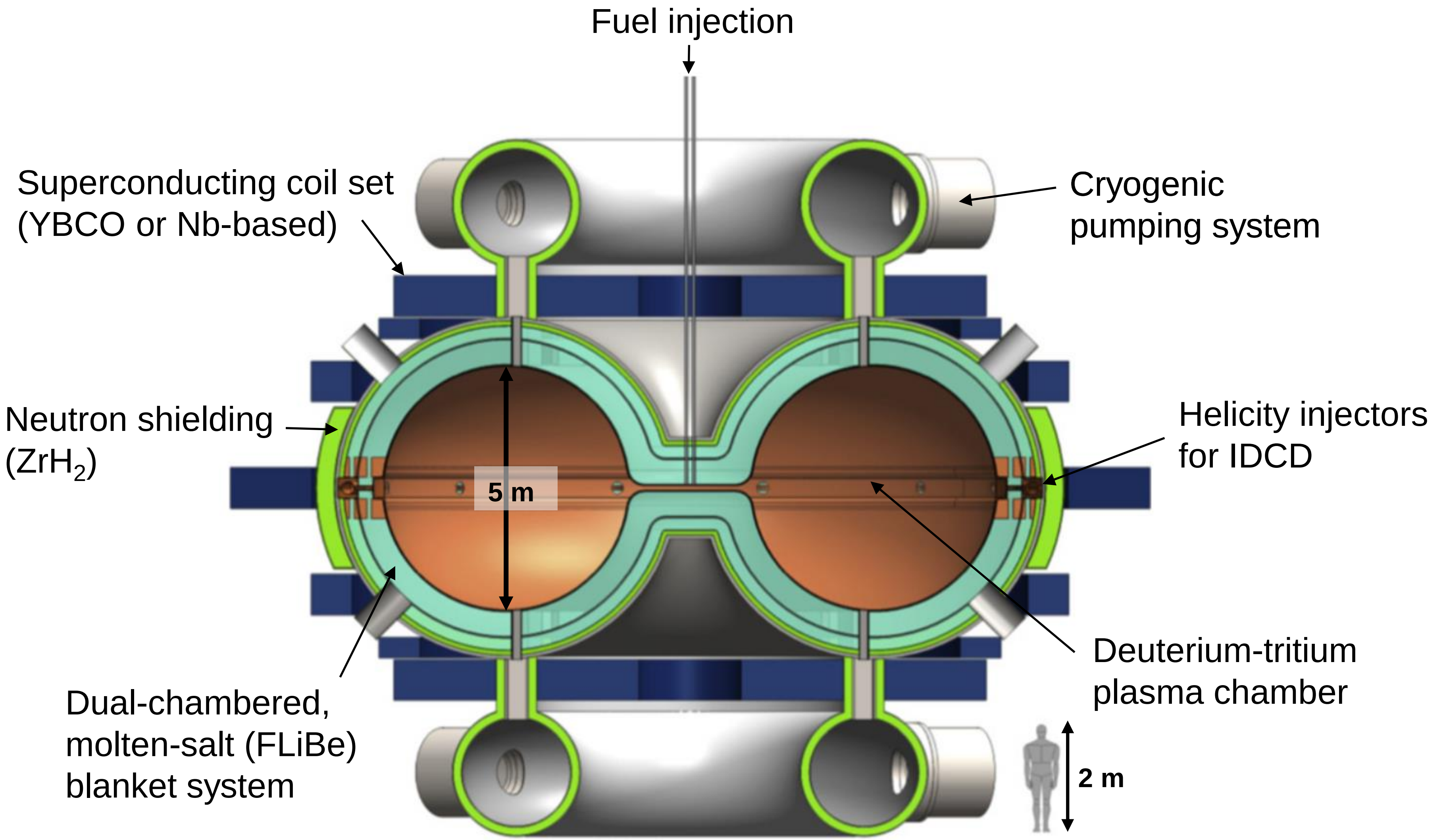
Using the IDCD model, the dynomak reactor study was conducted to determine what a eventual reactor based on the HIT-SI experiment may look like

- 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)

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	$\geq$ 2.8 billion
Natural gas + No CO_2 capture	$\leq$ 1 billion
Natural gas + CO_2 capture	$\geq$ 1.5 billion
Gen III+ nuclear plant	> 3-4 billion
Dynomak reactor concept	$\approx$ 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.

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.

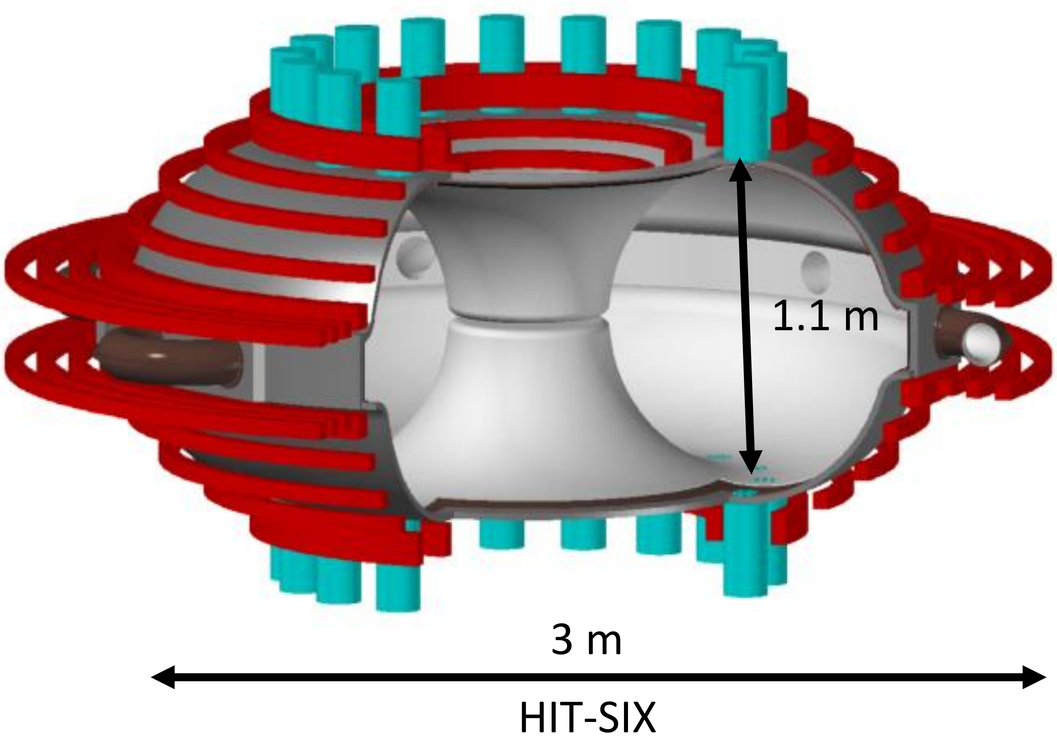
IDCD must be compatible with good confinement quality at high temperature

- 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]	≈ 35



Conclusions and next steps

- The spheromak configuration may provide an economical path to fusion power.
- Found evidence of sustainment via inductive helicity injection without gross plasma instabilities present.
- Found evidence of pressure confinement during sustainment is a spheromak first.
- Imposed-dynamo current drive (IDCD) is the leading model of behavior in HIT-SI, and a heuristic derivation shows the ability to sustain current without breaking closed-flux surfaces via dynamo action.
- The dynomak concept, a reactor vision based on HIT-SI, overnight capital cost is competitive with conventional energy sources.
- 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.

Pertinent 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

New experiment will overcome HIT-SI limitations as a confinement experiment

HIT-SI limitation	**HIT-SIX solution**
For uniform-j/B β-limit is 3%	Uniform-j/B β-limit is 16%
Too small for proper plasma spraying surfaces	Designed so all surfaces are properly plasma sprayed
Limited control of Imposed fluctuations mode structure	Linear combinations of n = 1, 2, 3, and 6 are available
No long pulse density control	High speed pumping
$na = 5 \times 10^{18} m^{-2}$, too low to screen neutrals	$na = 4 \times 10^{19} m^{-2}$, high enough to screen neutrals
$j/n = 10^{-14}$ Am is marginal	$j/n = 2 \times 10^{-14}$ Am

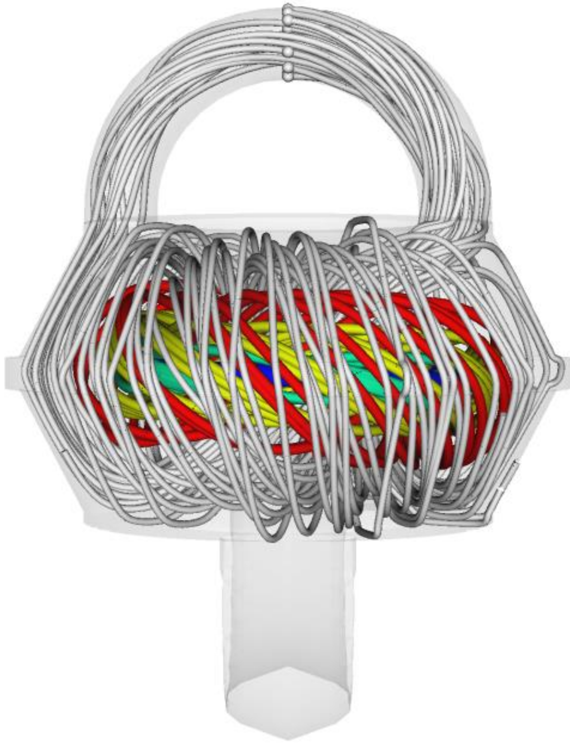
New experiment will overcome SSPX limitations

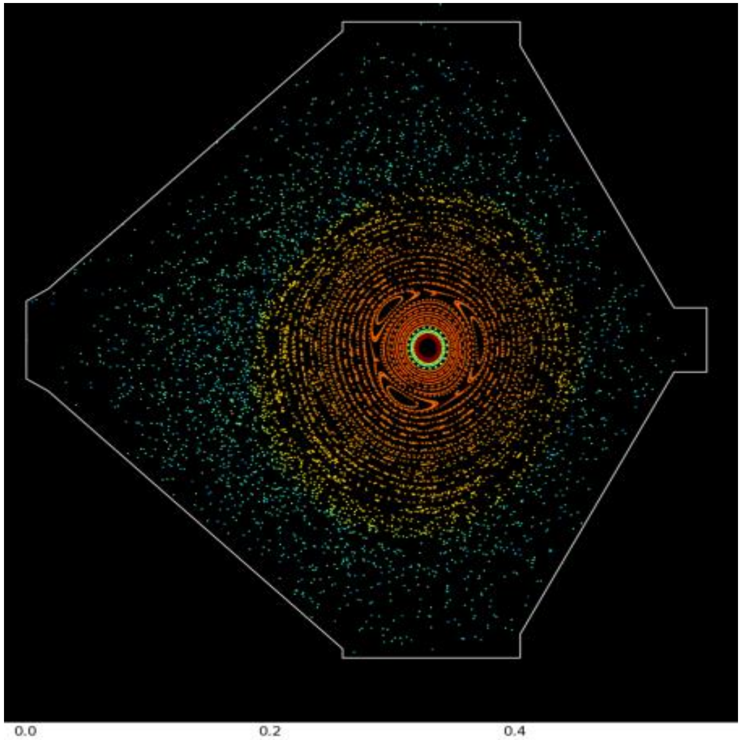
SSPX limitation	**HIT-SIX solution**
For uniform-j/B β-limit is 1%	Uniform-j/B β-limit is 16%
Fluctuations are produced by confinement degrading instabilities	Fluctuations are imposed on a stable equilibrium
Limited control of fluctuations mode structure	Linear combinations of n = 1, 2, 3, and 6 are available
Open field lines connect to the injector electrodes, cooling plasma	No open field lines to the wall due to inductive drive
Low injector fuel utilization of 1	Injector fuel utilization of 26

Poincare plot of Taylor state equilibrium showing closed-flux surfaces at a current gain of six

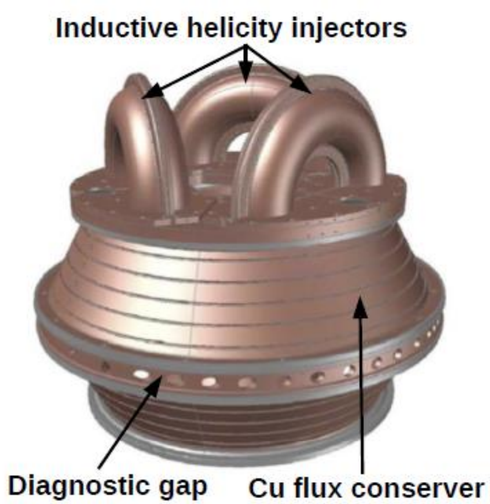
Taylor state equilibrium

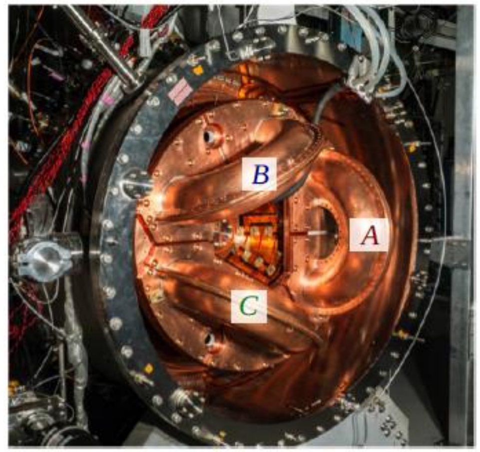
$(\nabla \times \vec{B} = \lambda \vec{B})$

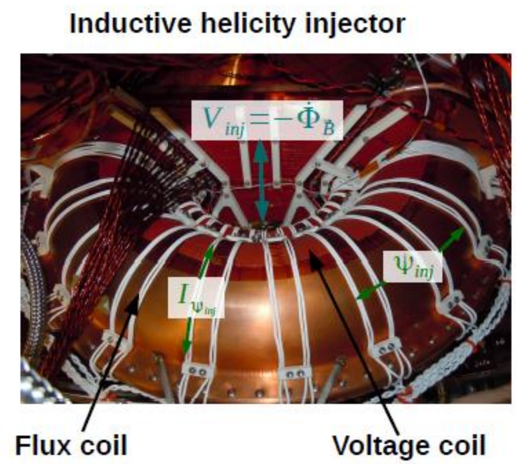


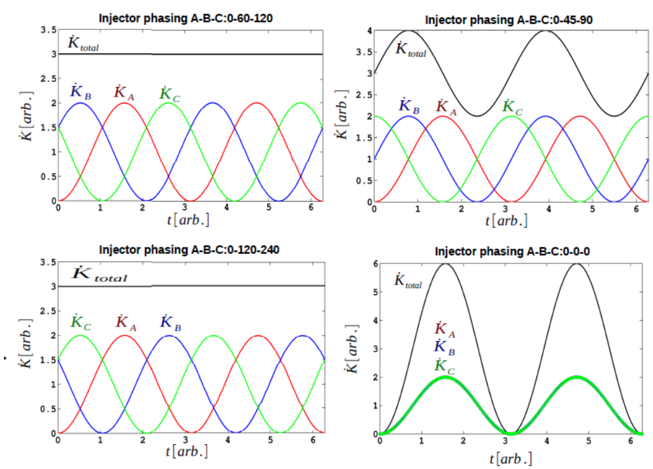


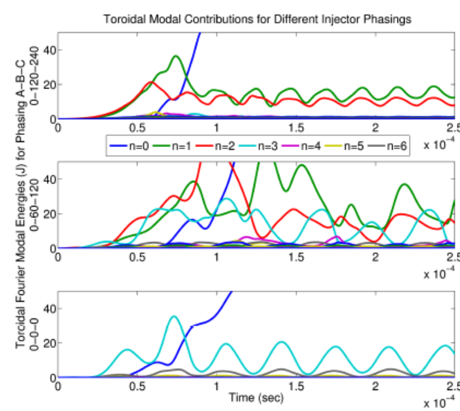
Current HIT-SI3 experiment allows for flexibility in phasing to modify magnetic fluctuation profile

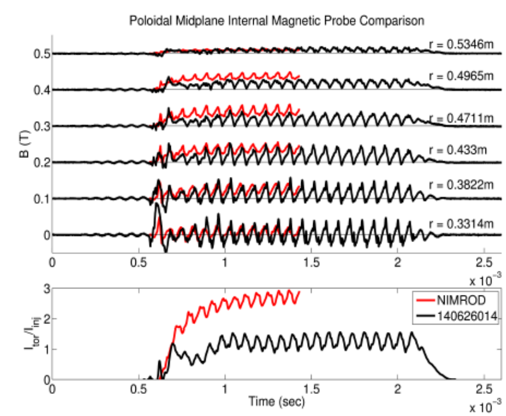




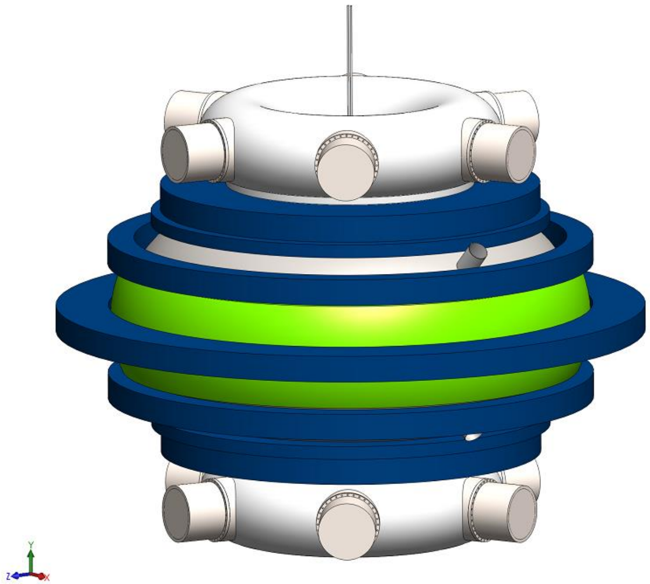


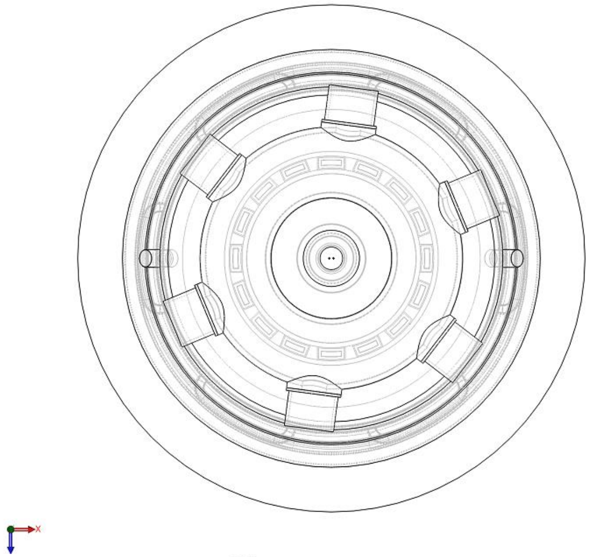


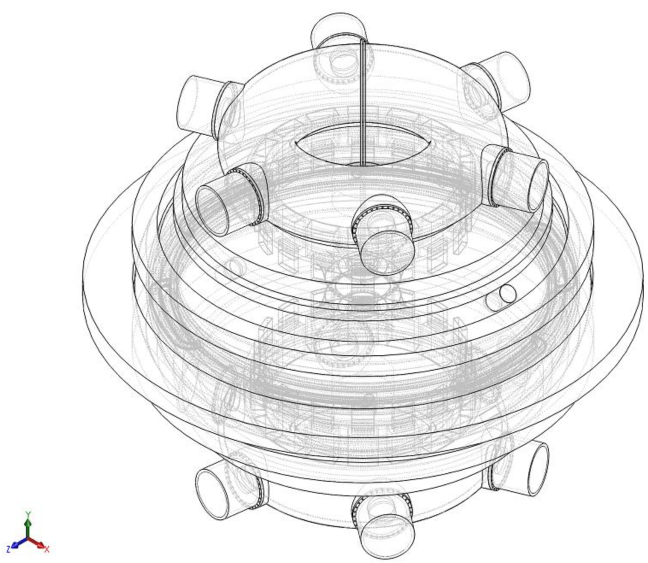


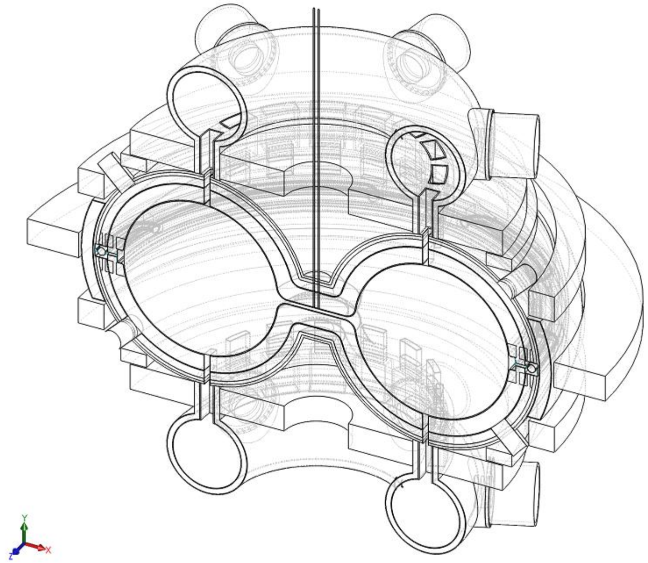


Additional views of the dynomak

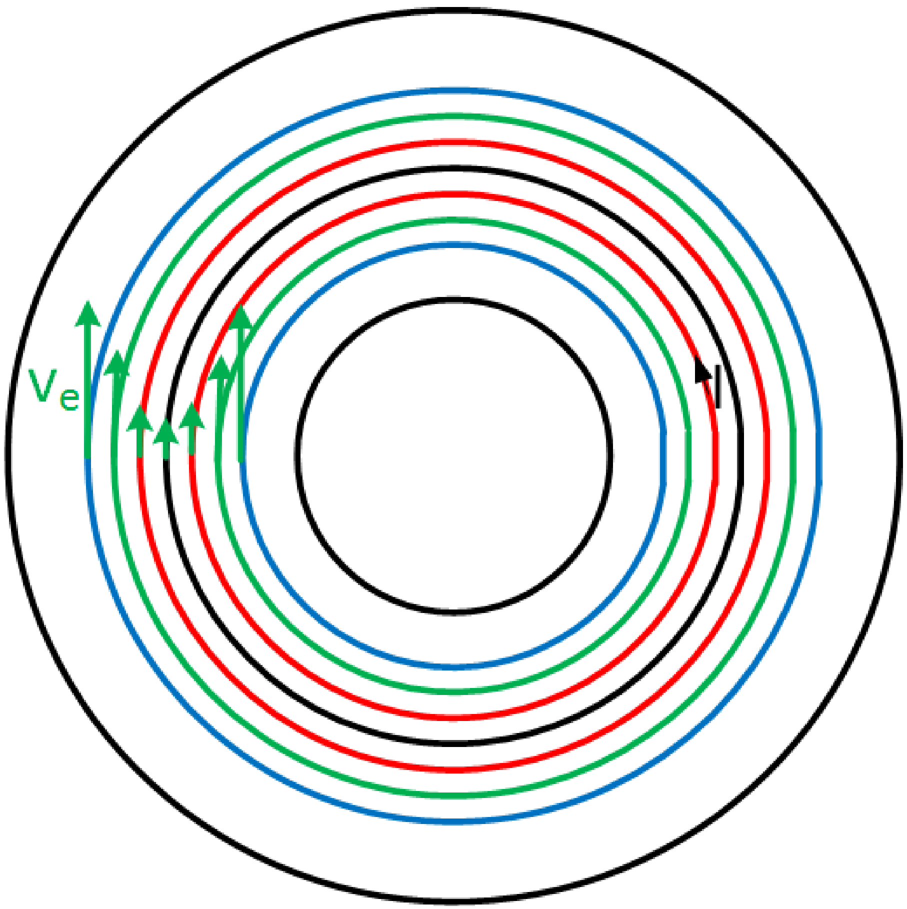








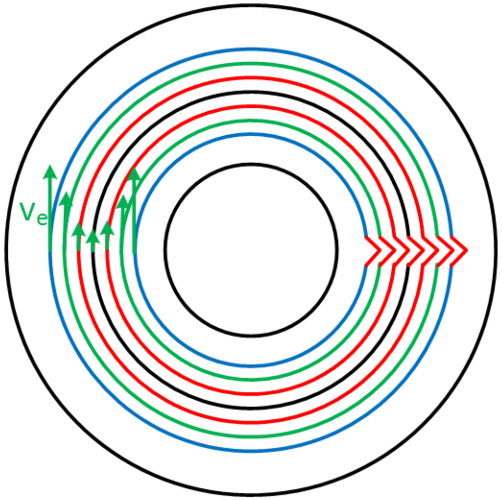
An explanation of effect of perturbations on current starts with symmetric current

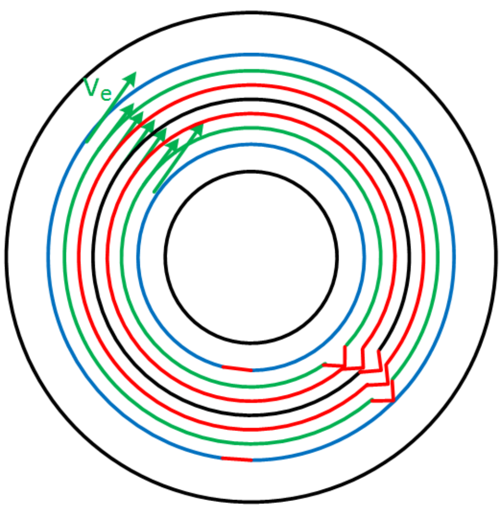


Toroidal current in a torus with a hollow current profile

- Electron fluid is frozen to magnetic fields. (Two-fluid MHD)
- Current flow is also magnetic field flow.
- For a stable equilibrium the structure is best thought of as a solid. It resists deformation.
- Current is from electrons frozen in nested solid shells that are rotating at different speeds.
- Symmetric flux surfaces allow free differential current flow.(Free means unobstructed by magnetic interference.)

Sheared electron flow plus perturbations give current drive across closed flux surfaces





- Now add a magnetic perturbation (red) and differential flow is no longer free.
- If the perturbation is large enough the flow locks across flux surfaces (inner flux surfaces).
- If the perturbations are small enough the differential flow can symmetrize the perturbation and differential flow continues.
    - A viscosity-like drag force will drive the current inside the symmetrize closed flux surface.
- Both effects are current self-organizing across closed flux surfaces towards uniform j/B.
- HIT-SI data indicate that the force per unit area needed to symmetrize is $\frac{(\delta B_\perp)^2}{2\mu_o}$.
- Externally driving the edge results in Imposed Dynamo Current Drive (IDCD).*

*T. R. Jarboe *et al*., Nucl. Fusion, **52,** 083017 (2012)

IDCD effect is simple to estimate

Viscous force on the flux surface area = force require to drive the current throughout that flux surface volume.

$$\int \left[\frac{(\delta B_{\perp})^2}{2\mu_o}\right] \mathrm{dA} = \int ne(\eta j_{\parallel} - E_{\parallel})\,\mathrm{dV}$$

$$\frac{\left(\delta B_{\perp,rms}\right)^2}{2\mu_o} \cdot 2\pi R_o \cdot 2\pi r = ne(\eta j_{\parallel} - E_{\parallel}) \cdot \pi r^2 \cdot 2\pi R_o$$

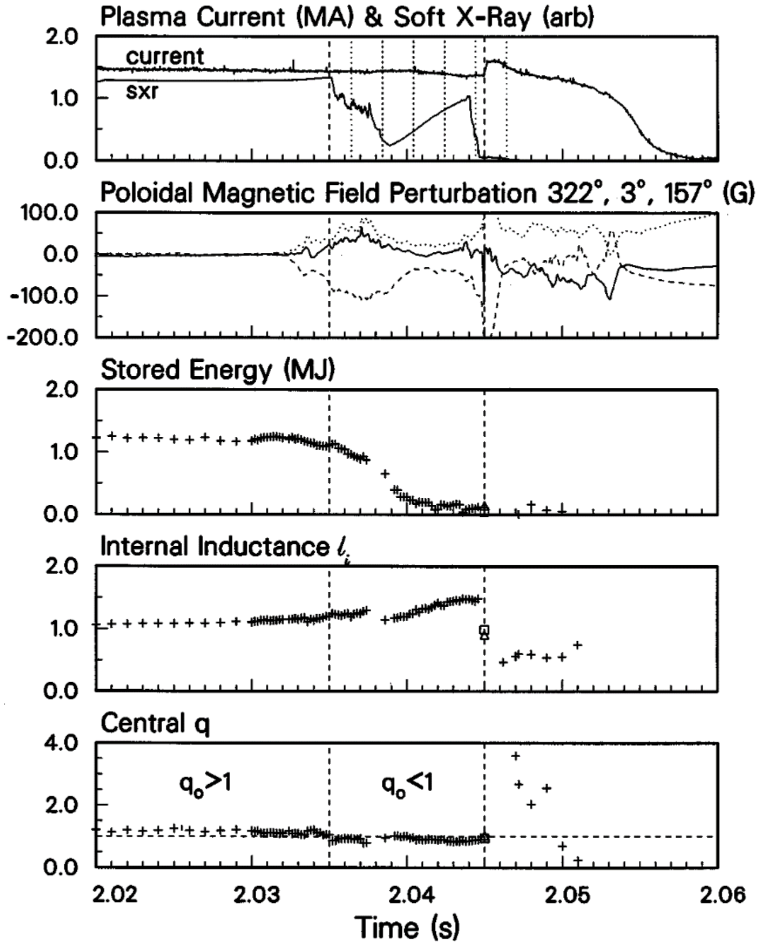
$$\frac{\left(\delta B_{\perp,rms}\right)^2}{\mu_o} = (\eta j_{\parallel} - E_{\parallel})ner$$

$$\frac{d(LI)}{dt} = \frac{\mu_o}{4\pi} \cdot 2\pi R_o \cdot \frac{d(l_i I)}{dt} = V_{loop};\ \frac{V_{loop}}{2\pi R_o} = -E_{\parallel} = \frac{\mu_o}{4\pi} \cdot \frac{d(l_i I)}{dt}$$

$$\boldsymbol{\delta B_{\perp,rms} = \left(\frac{\mu_o^2}{4\pi} \cdot \frac{d(l_i I)}{dt} \cdot ner\right)^{1/2}} \textbf{ when } \boldsymbol{E_{\parallel} \gg \eta j_{\parallel}} \textbf{ during transients.}$$

$$\boldsymbol{\delta B_{\perp,rms} = (\mu_o \eta j_{\parallel} ner)^{1/2}} \textbf{ when } \boldsymbol{E_{\parallel} \ll \eta j_{\parallel}} \textbf{ during steady} - \textbf{state.}$$

IDCD equation agrees with radiative disruption* perturbations



- Disruption created by Argon injection.
- Cold edge peaks the current until it is unstable. Instability cools plasma.
- The low edge current is maintained by the Argon and drags down the plasma current:

$$\delta B_{\perp,rms} = \left(\frac{\mu_o^2}{4\pi} \cdot \frac{d(l_i I)}{dt} \cdot nea\right)^{1/2}$$

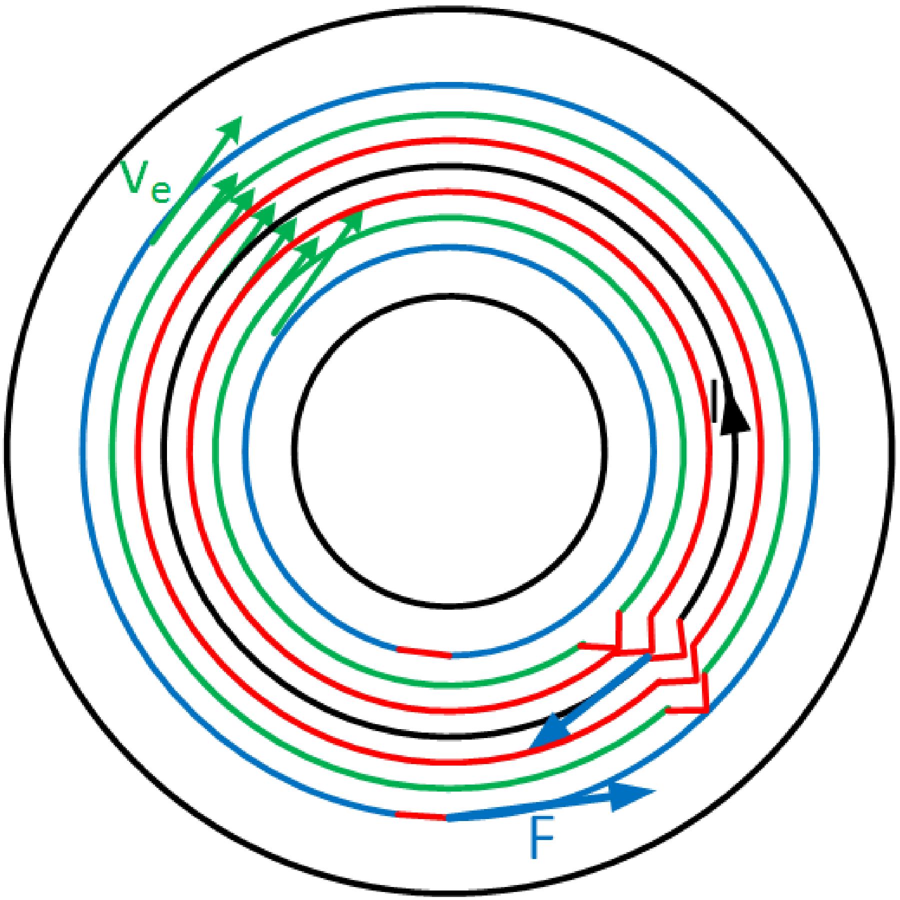
- 1.5 MA profile is flattened in 1.2 ms

$$\frac{d(l_i I)}{dt} \approx -0.92 \text{ GA/s}$$

IDCD requires $\delta B_\perp$ of 190G (at 2.045-6 s)

*P. L. Taylor *et al.*, *Phys. Rev. Lett*, **76**, 916-919 (1996)

Perturbations crossing flux surfaces give rotation



- In the externally driven regions the drag force (blue) brakes electrons so the force is in the direction of the current giving plasma velocity in that direction.
- In the dynamo driven regions the force is with the electron flow resulting in plasma flow against the current.
- Thus, the core plasma rotates with current in normal tokamak because the core is externally driven and against the current when LHCD is used in the edge because the core is dynamo driven (seen on C-mod).*

*J. E. Rice *et al.,* Nucl. Fusion **49** 025004 (8pp) (2009)

On a reactor and ITER the perturbation levels required to drive the current are a little higher than considered acceptable (which may confirm the effect).

Parameter	Present tokamaks	ARIES-AT	ITER
I_{tor} (MA)	4.5	12.8	15.
Temp. (keV)	2	18	8.1
a (m)	1	1.3	2
$\tau_{L/R}$ (s)	15	605	454
$\delta B_{\perp rms}/B$	0.0004	0.0001	0.0001

- Current driving perturbations can also flatten the j/B profile which flattens the q-profile leading to poor performance.

- In the face of such a powerful flattening effect it is not surprising how difficult it is to maintain a high-performance profile often ending in disruption.

Solutions

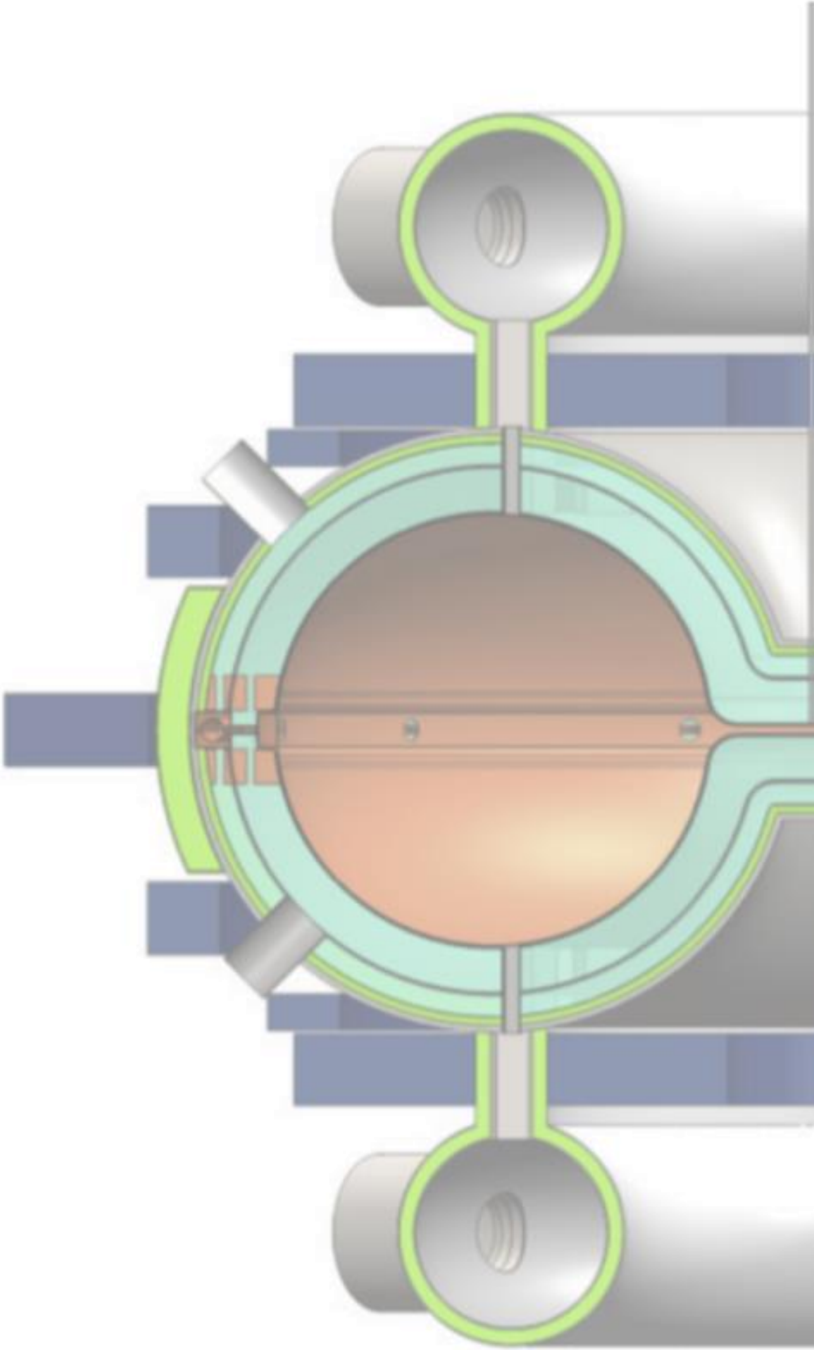
1. Drive the edge current high and impose a perturbation profile that sustains the desired reversed-shear current profile.

2. Select a high performance equilibrium that has a uniform j/B (low aspect ratio)
   - Rigorously sustain the rock-stable profile by edge current drive and repeated application of non-resonant perturbations of IDCD.
   - The method has been demonstrated on HIT-SI.

- Solves the sustainment problem. (IDCD is much more efficient on a reactor than RF or NBI.)

- High edge current prevent the edge from using perturbations to drag down the current in disruptions.

Core design



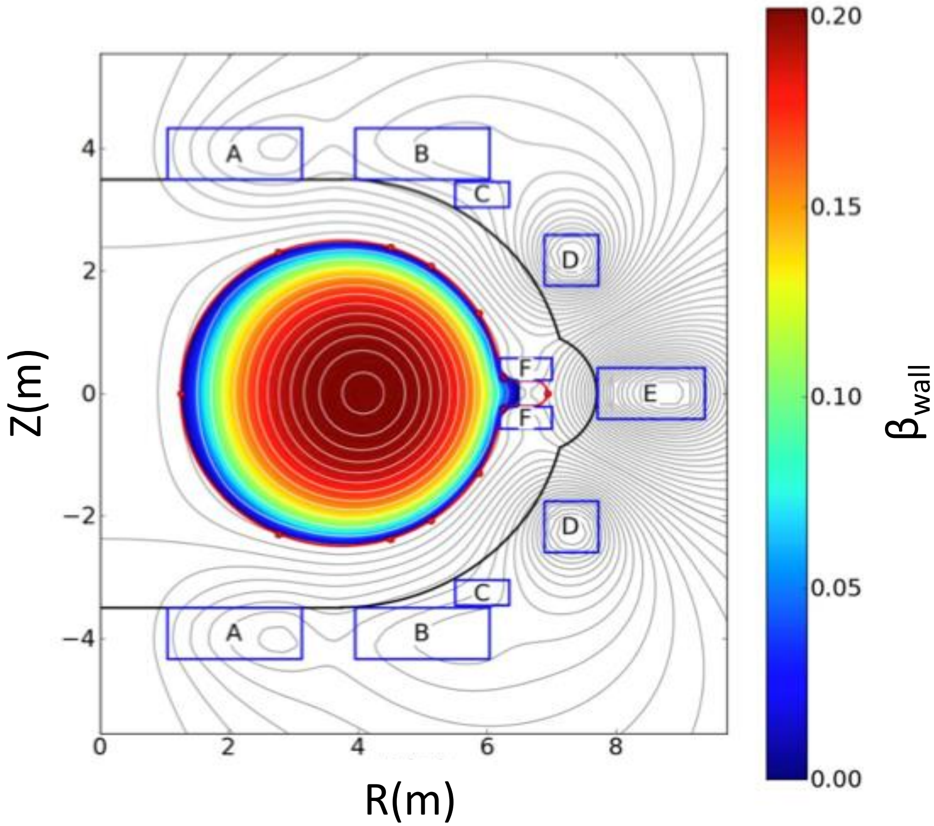
IDCD provides a complete current drive solution with low input power requirement

- Imposing small magnetic perturbations with non-axisymmetric helicity injectors on a **kink-stable** equilibrium provides current drive without plasma instabilities.[2]

- IDCD drives the plasma current profile towards a minimum energy state (flat-λ) above a particular value of $\delta B/B$.
  - Flat-λ may be compatible with good confinement in compact aspect ratio devices .
  - Rely on toroidal effects for q-shear instead of varying current density profile.

- IDCD could be a more efficient current drive mechanism than RF or NBI, such that 42 MA of toroidal current can be sustained with only 60 MW of input power when scaled to reactor plasma temperatures.[3]

A plasma equilibrium code was used to determine optimal coil set to provide desired plasma shaping during steady-state operation



Coil Set	MA-turns	Coil Set	MA-turns
A	-16.3	B	-5.2
C	0.4	D	-11
E	16.8	F	2.6

- Toroidal plasma current of 41.7 MA.
- Equivalently sized poloidal plasma current to provide stabilizing toroidal magnetic field.
- Modest peak field on coil of 6.5 T
- Copper coil set F in blanket to exclude equilibrium magnetic flux from injector region.

Use of YBCO superconducting (SC) tapes allows for lower cooling requirements and recirculating power fraction

- YBCO tapes operate a relatively high temperatures when compared to other SC candidates

Superconductor Type	Superconducting Temperature (K)	Maximum Field (T)
Nb_3Sn (i.e. ITER)	18.3	14
NbTi (i.e. ITER, W7-X)	9.2	7
Bi-2212	20	15
YBCO tapes	**92**	**25-30**
MgB_2	30	3

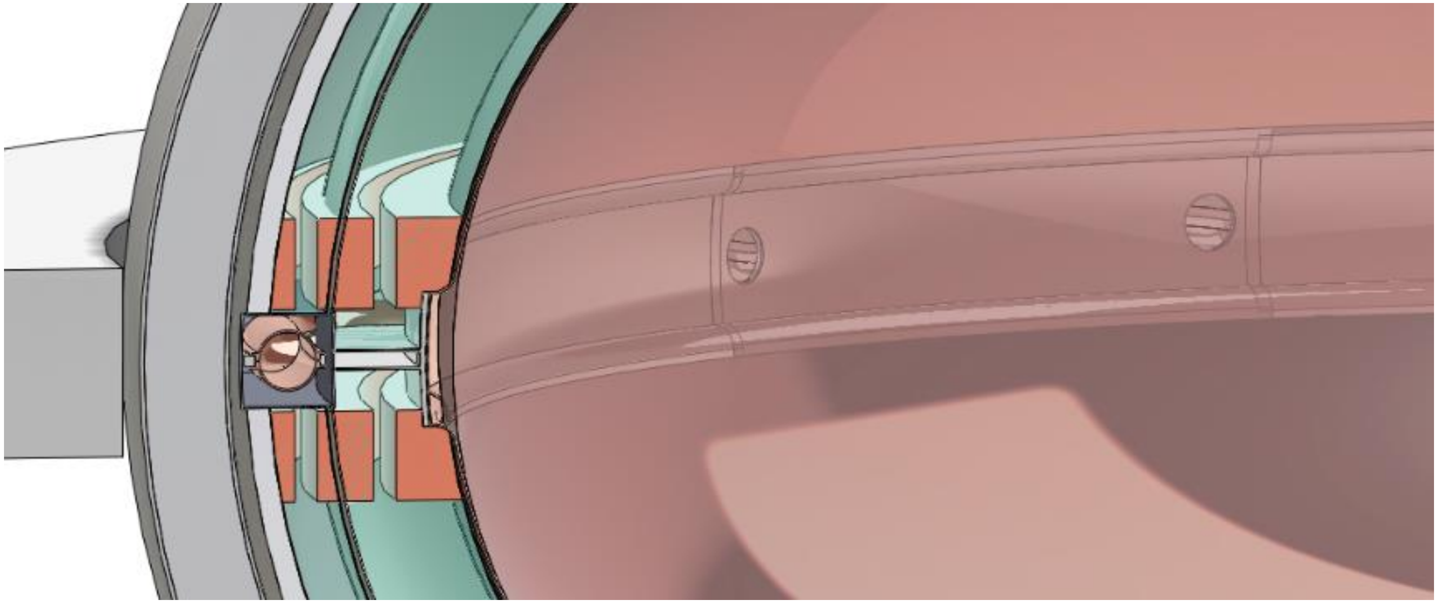
- Tape form of YBCO enables relatively easy coil manufacturing and winding.

- **However, if YBCO is still expensive or in-development at time of dynomak construction, we can certainly use Nb_3Sn and possibly even NbTi.**

Outboard mid-plane copper coils are required to exclude equilibrium magnetic flux from the injector region

- Inductive magnetic helicity injectors for IDCD are placed on the outboard mid-plane.

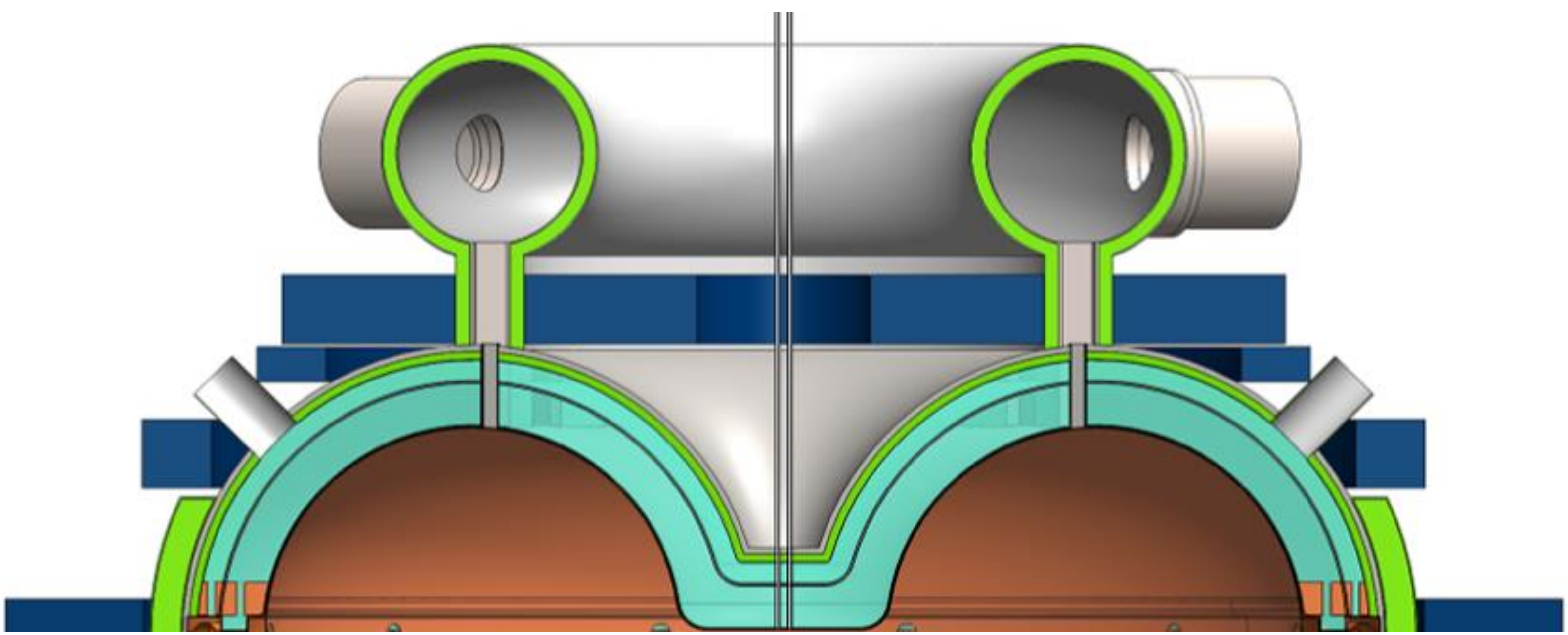
- Segmented copper coils exclude flux from the helicity injector region while allowing for poloidal blanket flow.



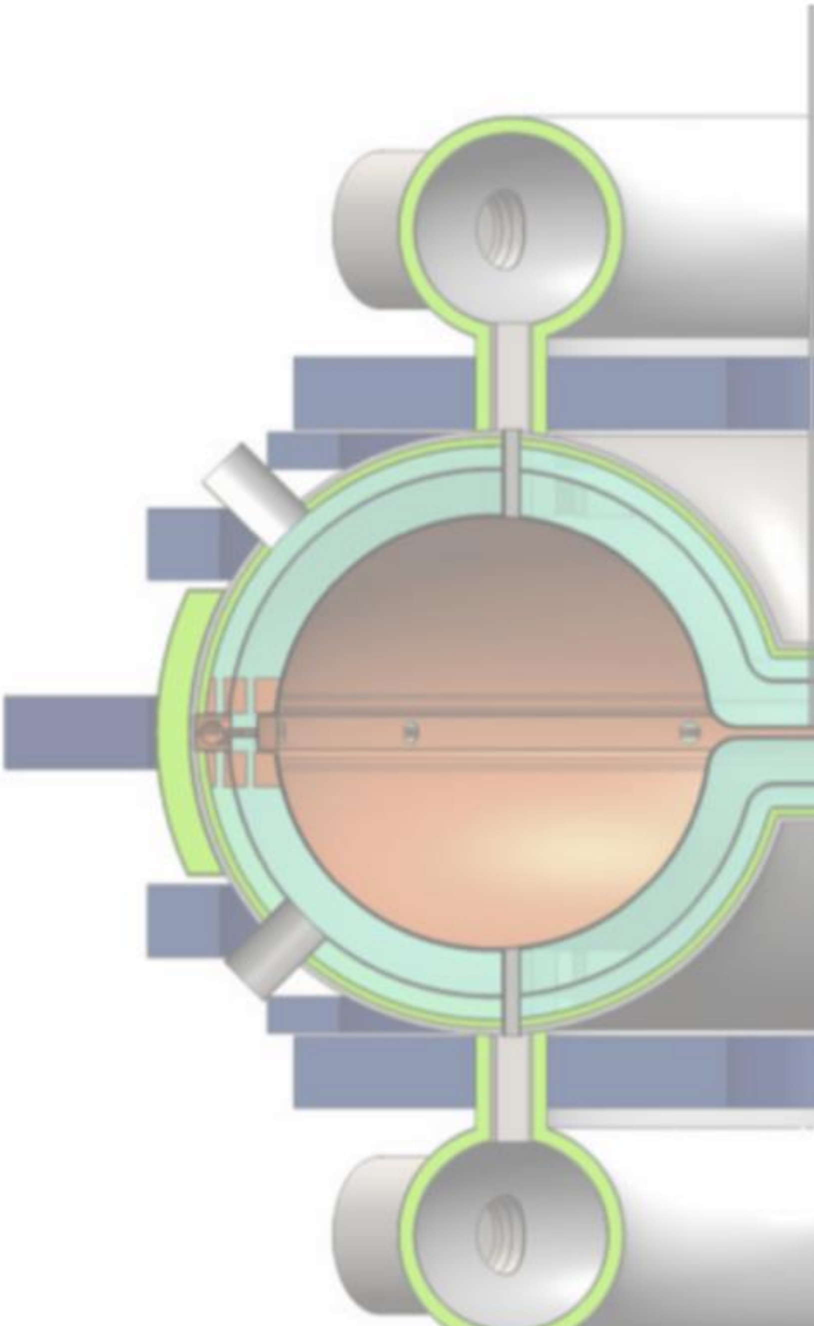
ITER developed cryopumps are used to limit helium concentration to 3%

- Fueling occurs from the inboard size of the vacuum vessel through a gas injection system.

- 12 ITER cryosorption pumps connect to shielded manifold that is connected to 24 blanket-penetrating pumping ducts



Blanket design

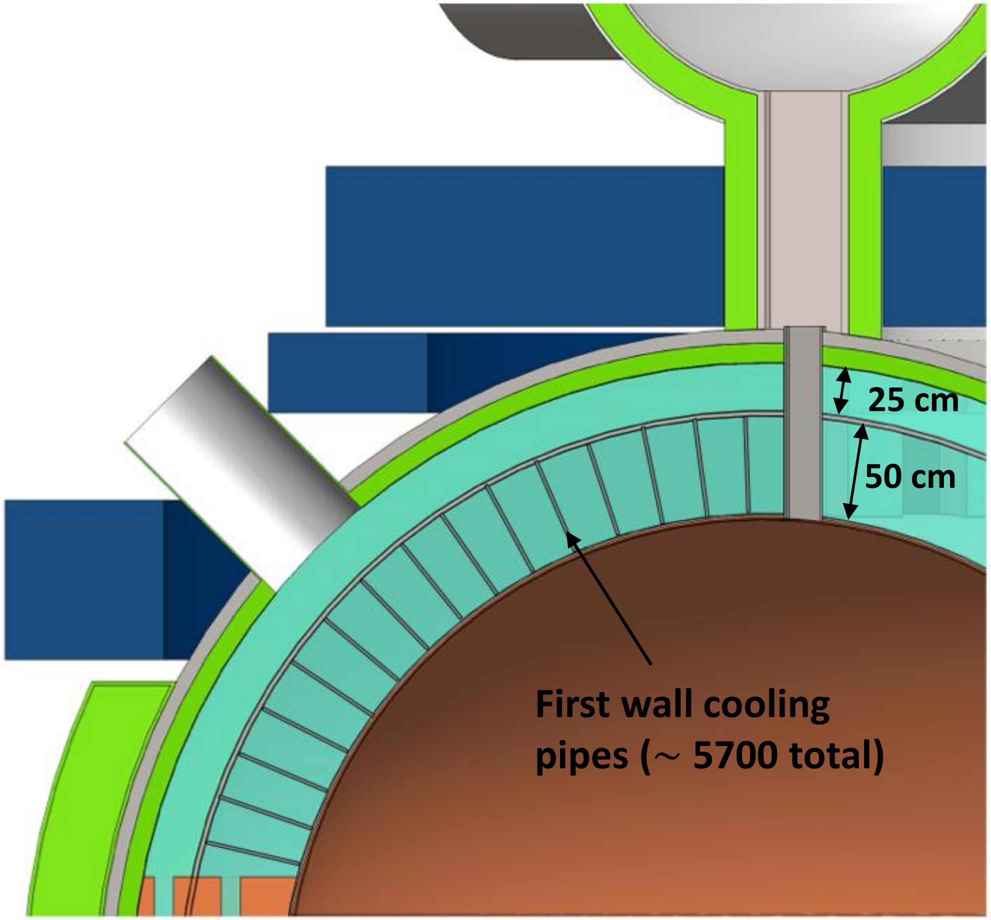


FLiBe was chosen as the liquid blanket material due to its favorable moderation capabilities and reasonable tritium breeding characteristics

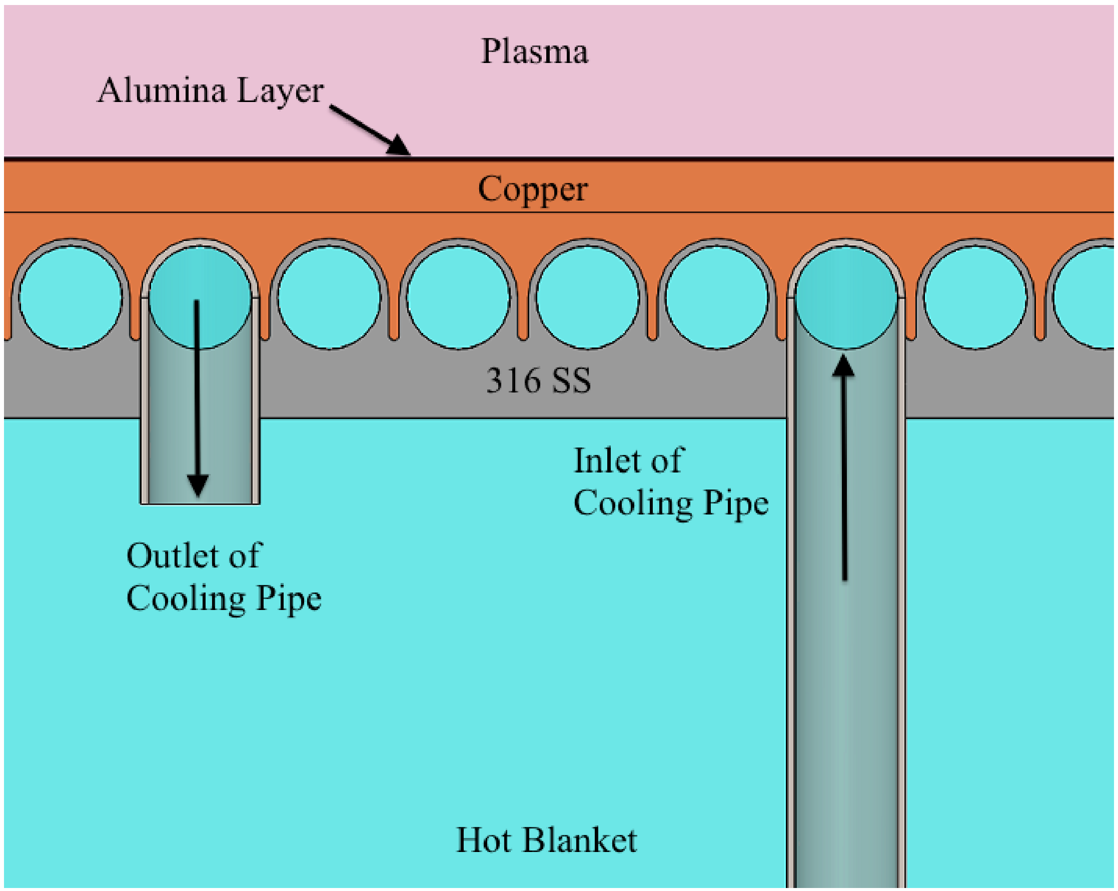
- FLiBe is a molten-salt eutectic composed of LiF and BeF_2 with a relatively high melting point of 460 ^{o}C.
- Nearly all fast neutrons are moderated in the first 50 cm of FLiBe (low-Z blanket).
- Presence of Be provides neutron multiplication required to achieve sufficient TBR.
- Varying enrichment is also another way to change TBR, depending on the blanket thickness.

Dual-chambered, pressurized blanket system provides single working fluid design with sufficient TBR

- Monte Carlo N-Particle (MCNP5) neutron transport simulation provides TBR of $\sim$1.12 without enrichment.
- Outer 25 cm blanket is pressurized to 125 psi, with an inlet temperature of 480 ^{o}C.
- Volumetric flow rate of blanket is 5.17 m^3s^{-1}.
- Global primary cycle temperature change is 100 ^{o}C.

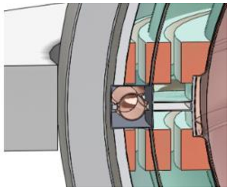


First-wall cooling (FWC) system provides structural strength and couples with bulk blanket system

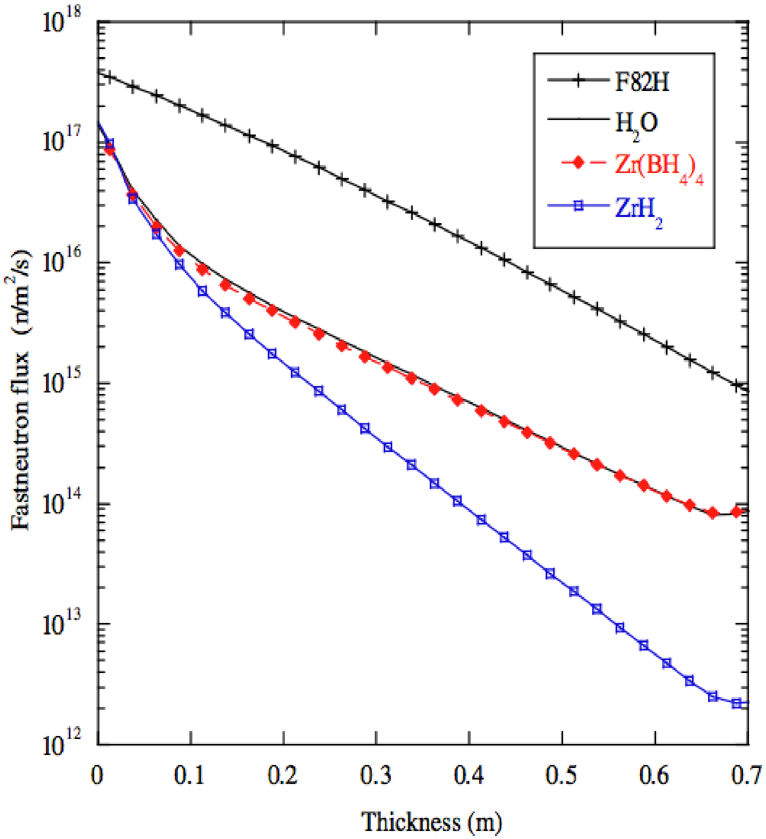


Parameter	Value
Plasma heat flux [MWm^{-2}]	1.05
FWC flow velocity [ms^{-1}]	8
FWC inlet temperature [^{o}C]	480
FWC outlet temperature [^{o}C]	509
Pipe diameter [mm]	12
Toroidal pipe length [m]	4.3
Peak wall temperature [^{o}C]	674

ZrH_2 provides ample neutron shielding to enable limiting YBCO lifetime of 30 FPY



- SC lifetime limiting un-attenuated 14.1 MeV neutron beam through the outboard, mid-plane injector mouths.
- 50 cm of ZrH_2 shielding provides fast neutron attenuation ratio of 10^{-5}.*
- 5×10^{22} nm^{-2} taken as YBCO lifetime.**
- **29.3 FPY limiting lifetime of outboard, mid-plane SC coil.**

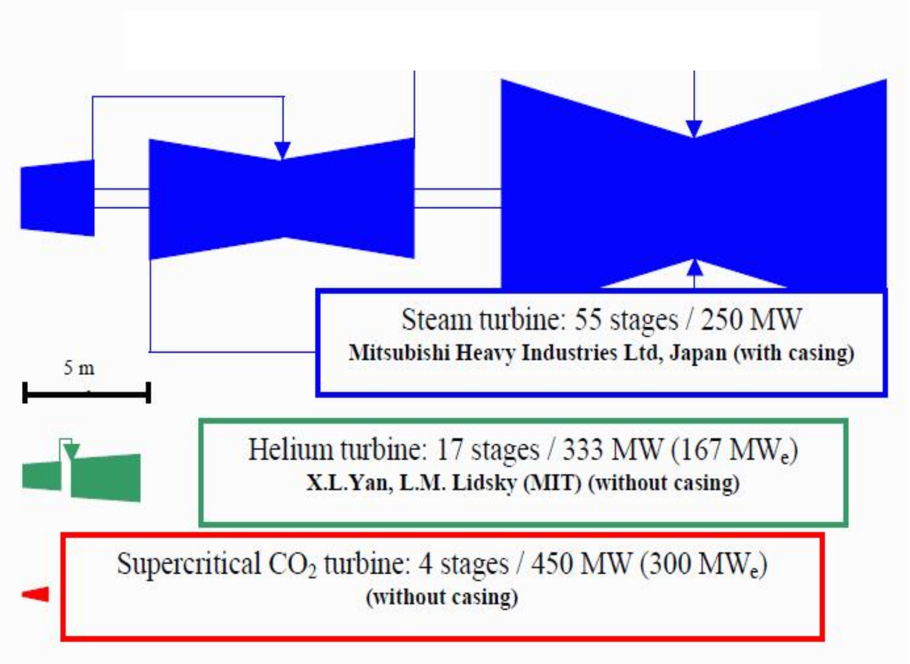


* Hayashi,T. et al., **Advanced neutron shielding material using zirconium borohydride and zirconium hydride**, *Journal of Nuclear Materials,* **386-388**, pp. 119-121, 2009.

** Bromberg, L. **Options for the use of high temperature superconductor in tokamak fusion reactor designs.** Fusion Eng. & Design, **54**, pp. 167-180, 2001.

A supercritical-CO_2 (SC-CO_2) Brayton cycle is used for secondary cycle due to high-efficiency at medium temperatures and small physical footprint

- Thermal efficiency of around 45% at dynomak operating temperatures.[*,**]
- Small components result in small physical footprint.[*,**]
- PCHEs are compact and cost effective for molten-salt/SC-CO_2 coupling.[**]



[*] Dostal, V. **A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors**, MIT Department of NSE Doctoral Thesis, 2004.

[**] **Westinghouse Electric Company,** personal correspondence.

Assuming IDCD scales to reactor relevant plasmas with sufficient confinement, the remainder of development needs are *relatively* lower risk

- Steady-state material testing of plasma facing first wall components is required to experimentally quantify expected longevity → **the insulating boundary requirement is something new, and may be maintained through recycling.**

- Once tritium is introduced in the system, one must conduct nuclear materials testing to ensure materials last as long as desired in a DT neutron environment → **use of copper flux conserver a concern, though different deposition methods may increase longevity.**

- Additionally, the tritium breeding ratio calculated with MCNP5 must be confirmed once the reactor starts burning tritium with the FLiBe blanket implemented.

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.

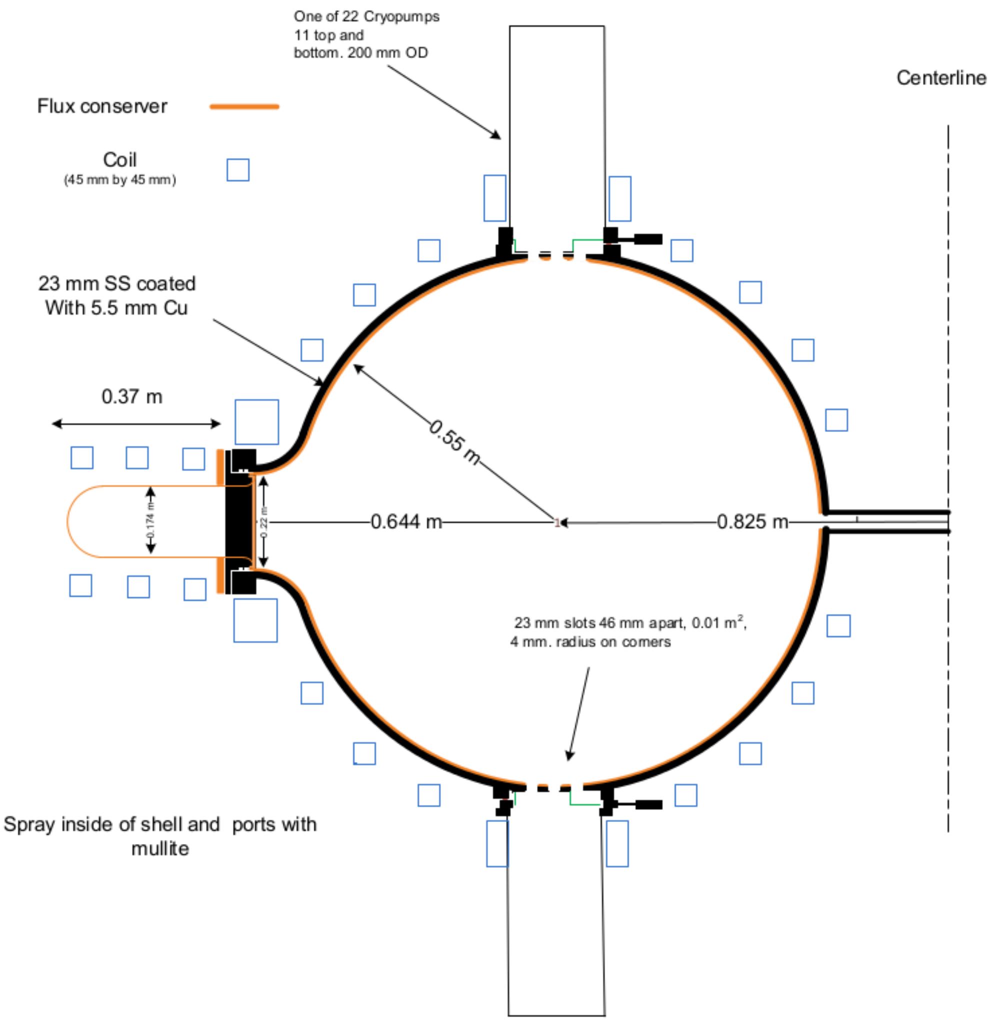
Active nuclear site → **HIT-FNSF**: Add tritium, FLiBe coolant, confirm TBR, 15 keV, materials testing.

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

Time

HIT-SIX cost estimates include construction, diagnostics and operating costs

- Total construction and diagnostics cost, including a \$1.6 million contingency: **\$8.6 million.**
- Total program cost (including construction and diagnostics cost): **\$32.2 million distributed over 5 years**.
- Detailed cost breakdowns and cost timelines are available.
- Currently in process of refining designs and getting concrete quotes.



Cross section of HIT-SIX