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The efficient sustainment of a stable, high-β spheromak: opening a path to economical fusion power (fusion cheaper than coal)

By
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To

Doe Office of Fusion Energy Sciences town meeting

July 1, 2015

Outline

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- Introduction to the spheromak
- HIT-SI results
- Ready for next step
- Summary

Spheromaks promise economical fusion power

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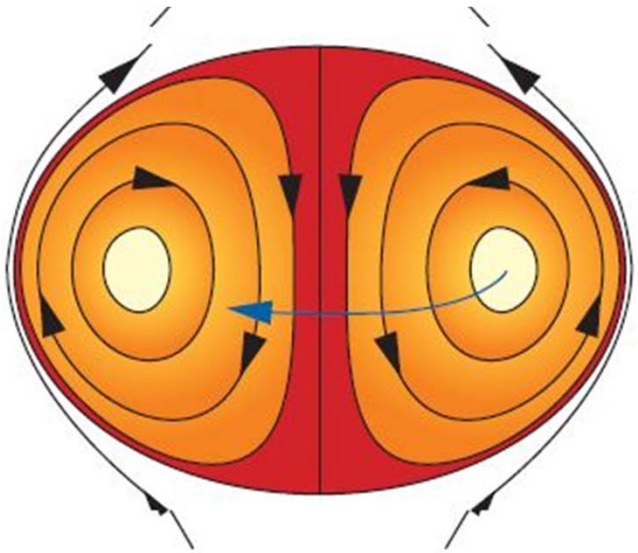
- Spheromaks are compact toroidal plasmas that rely on plasma currents for both poloidal and toroidal magnetic flux.
- Due to their compact size and simple engineering requirements, spheromaks provide the possibility of economical fusion reactors. (DOE started spheromak research in 1979.)
- Provided with a method to sustain large plasma currents (i.e. 5-8 times more than tokamaks) efficiently, a spheromak-based magnetic fusion reactor may be possible.
- The HIT-SI experiment provides a basis for efficient current sustainment with imposed-dynamo current drive (IDCD).



Toroidal and poloidal plasma currents provide helical magnetic fields for confinement of plasma.

Spheromak research had considerable success in the past

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- Most spheromak experiments have relied on coaxial formation and sustainment.
- CTX experiment at Los Alamos, and more recently SSPX at LLNL utilized the coaxial gun method of formation and sustainment.
- Spheromaks to date have shown the ability to Ohmically heat to the pressure limit at temperatures of several 100eV, while decaying.
- Spheromaks were not able to be sustained without a nearly complete loss of thermal energy due to instabilities → **we seek to overcome this problem with imposed-dynamo current drive (IDCD).**

Instabilities in CHI experiments precluded good confinement quality during sustainment due to instabilities (SSPX* most recent)

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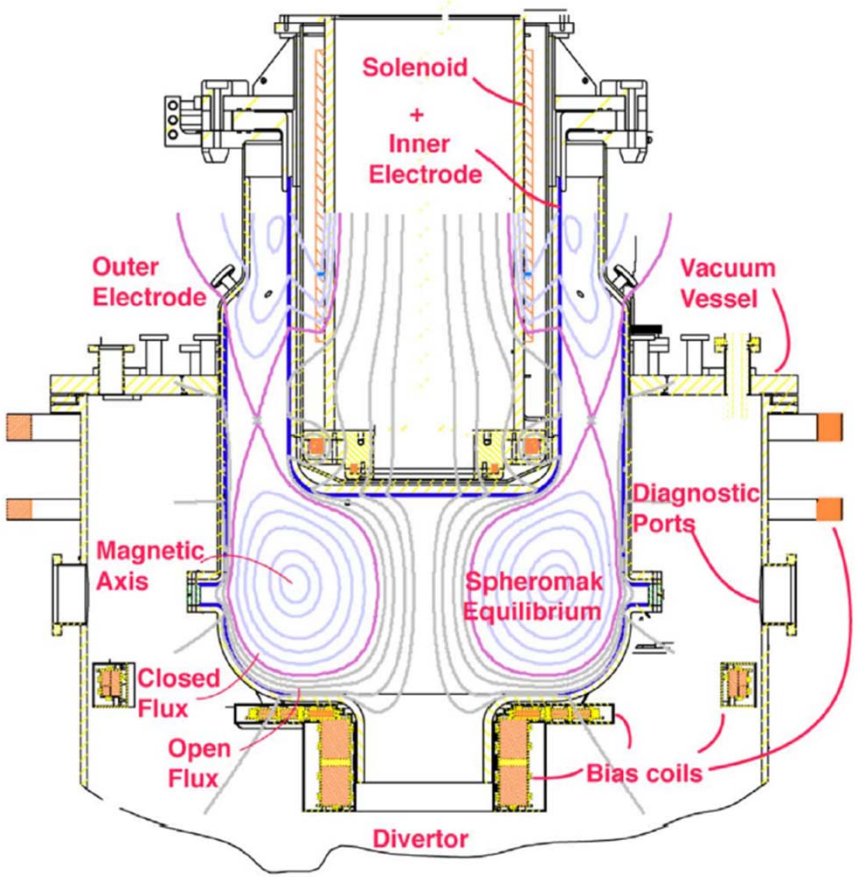

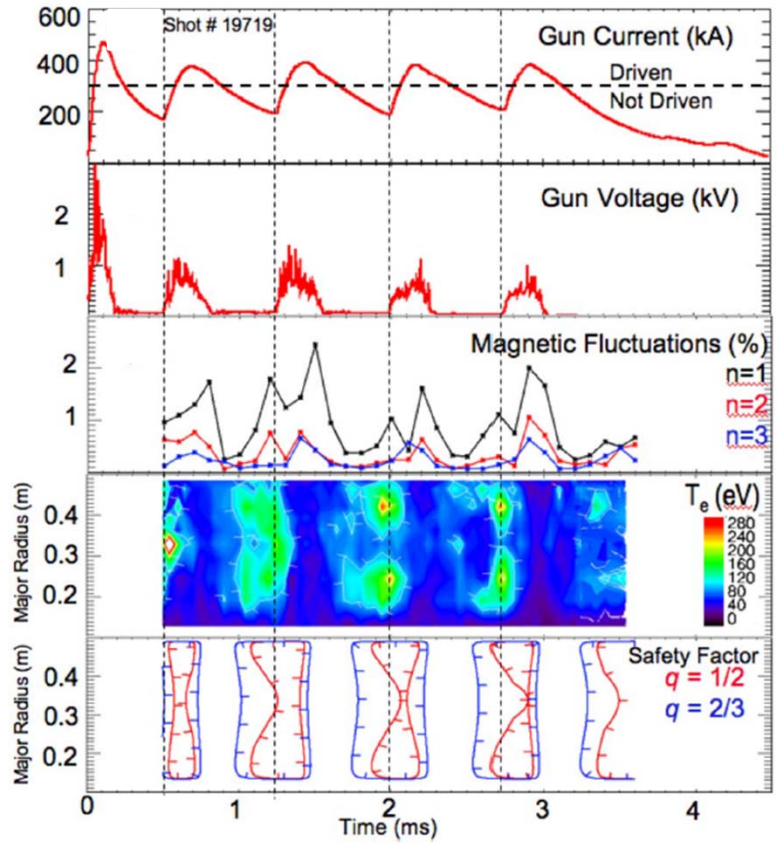

*B. Hudson, et al., *Phys. Plasmas* **15** (2008) 056112.

The HIT-SI experiment seeks to overcome the issues with CHI-driven spheromaks with fully inductive, non-axisymmetric helicity injection.

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- In imposing non-axisymmetric magnetic fluctuations with inductive helicity injection, we're able to sustain a spheromak without the need for plasma instability while still satisfying Cowling's theorem.

- We have produced sustained spheromaks with evidence of pressure confinement, **something that previous spheromak experiments have failed at doing.**

- Without the requirement for plasma instabilities or reconnection for cross-field dynamo current drive, **confinement expectations for sustained spheromaks are far better than ever before.**

IDCD is a new relaxation mechanism for making j/B uniform in a <u>stable</u> symmetric equilibrium

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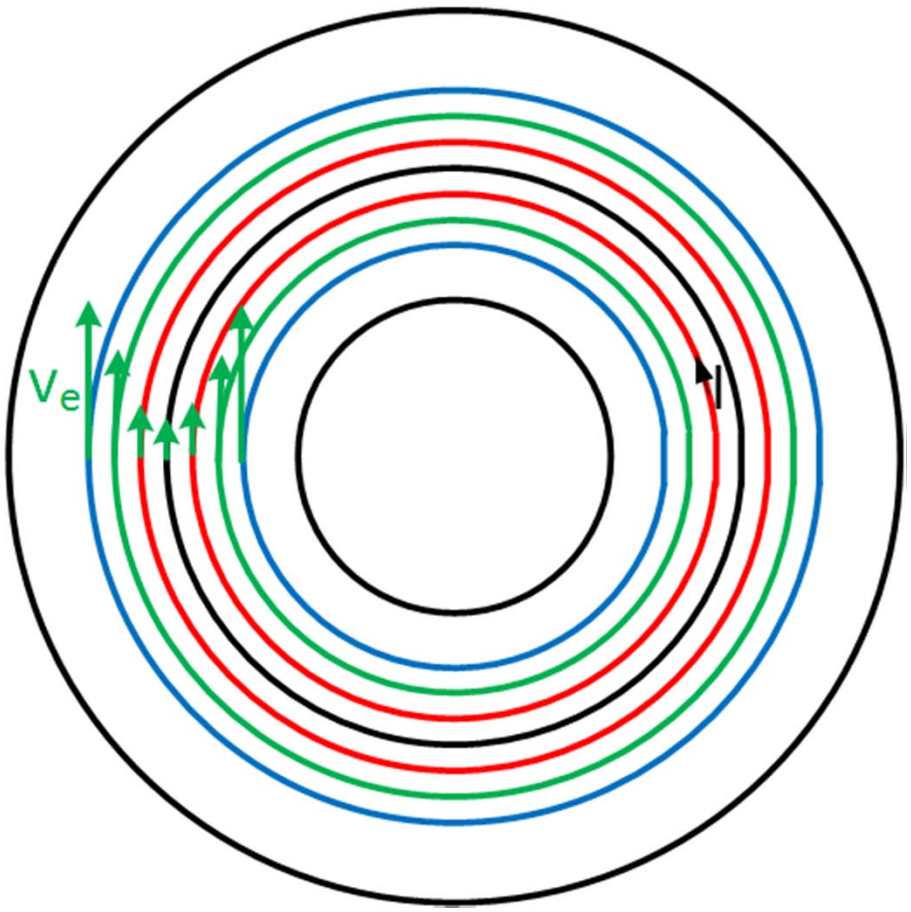
This mechanism provides an explanation for:*

- The level of field error ($\delta B/B = 10^{-4}$) that spoils tokamak performance.
- The rate of poloidal flux loss in Argon induced disruptions in DIII-D.
- The change in plasma rotation direction with LHCD in the edge on C-mod.
- The toroidal current versus time, the injector impedance, and the current profile of HIT-SI.

*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", to be published July 15, 2015 in Physics of Plasmas

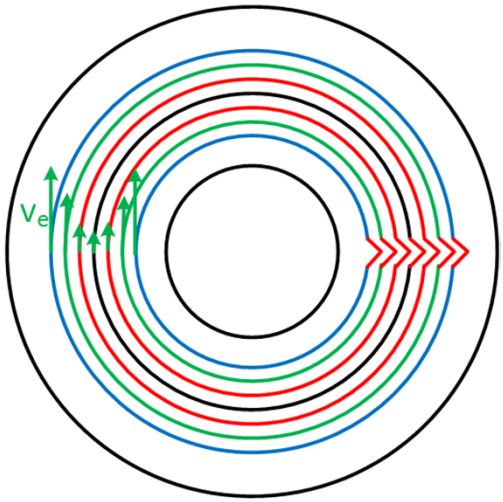
An explanation of effect of perturbations on current starts with symmetric current

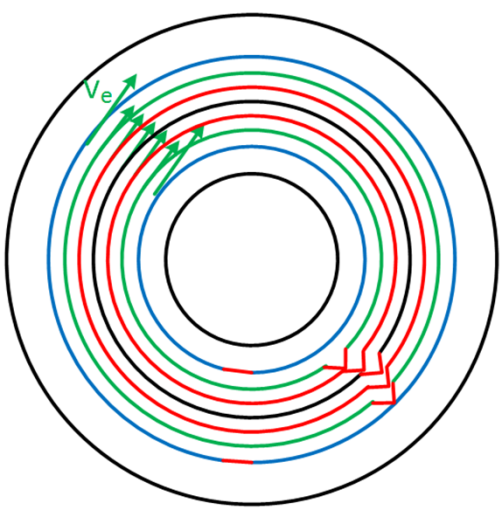


Toroidal current in a torus with a hollow current profile

- Electron fluid is frozen to magnetic fields. (Two-fluid MHD)
- Current flow is also magnetic field flow.
- For a stable equilibrium the magnetic structure is rigid. It resists deformation.
- Toroidal 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





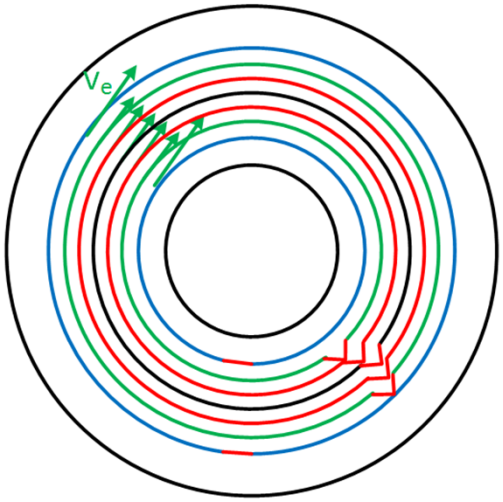
- Now add a magnetic perturbation (red) and differential flow is no longer free.
- If the perturbation is large enough the flow locks across flux surfaces (inner flux surfaces).
- If the perturbations are small enough the differential flow can symmetrize the perturbation and differential flow continues.
  - 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_{tor}/B_{tor}.
- HIT-SI data indicate that the viscosity-like 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)

Gradients in j/B may inhibit instability



- Imposed perturbations cause a force that inhibit differential motion of rigid shells.
- Conversely, differential motion of rigid shells cause a force that inhibits perturbations, including eigenmodes of instabilities, preventing instability growth and turbulence.
- The gradient in j/B is maintained at the current separatrix by keeping the injector j/B high.
- Differential current flow at the separatrix enforces symmetry and stability in the region.

HIT-SI uses imposed fluctuations and an externally driven edge current to sustain the equilibrium

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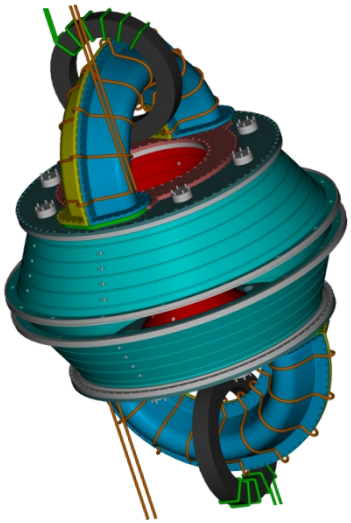

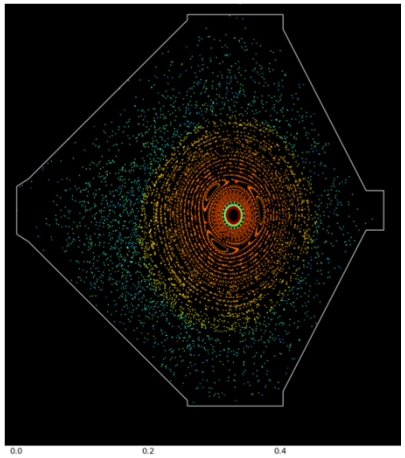

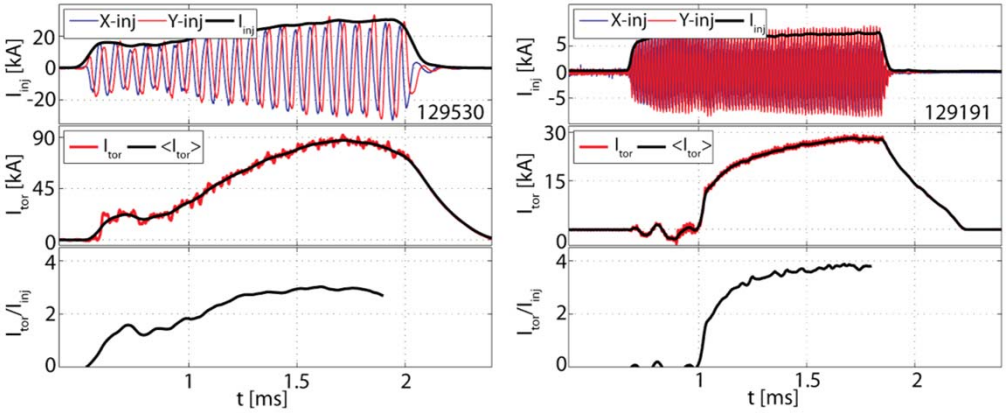

- Current amplification of 3.9, a new spheromak record
- 90 kA of toroidal current
- Stable sustained equilibria ohmically heat to the beta limit,*achieving the current drive goal

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

HIT-SI produces equilibria stable to current driven modes

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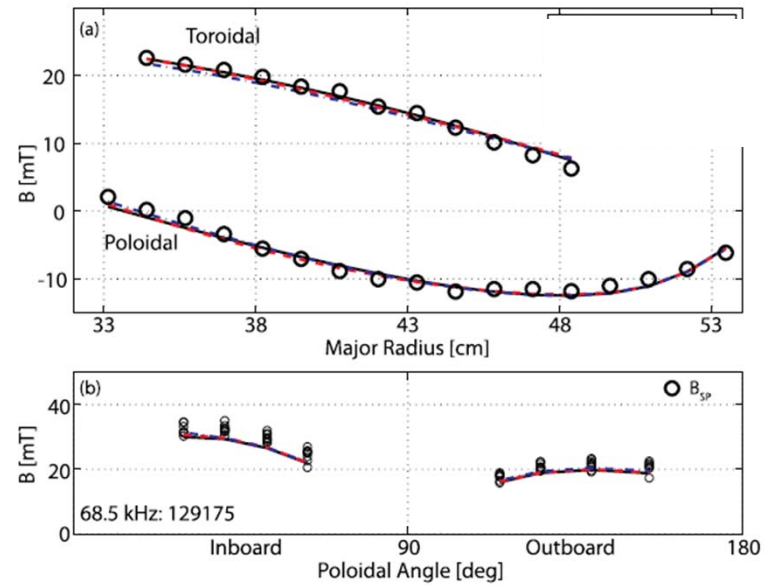
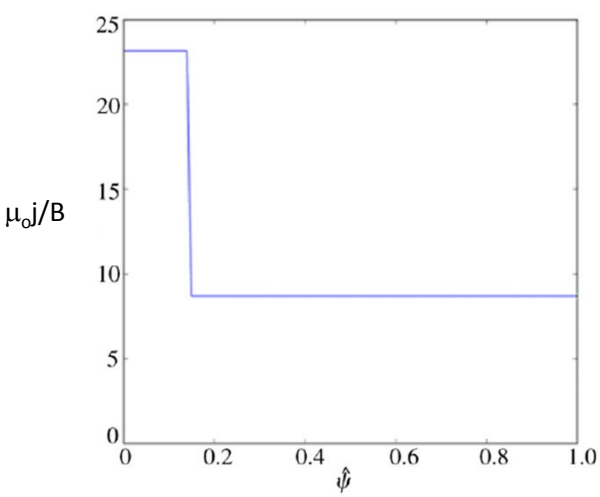
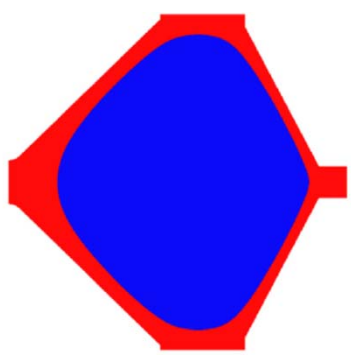
- Data matches a very flat two step profile
  - First step is at the injector j/B and wide enough to hold injector current.
  - Second step is high enough to hold the toroidal current.



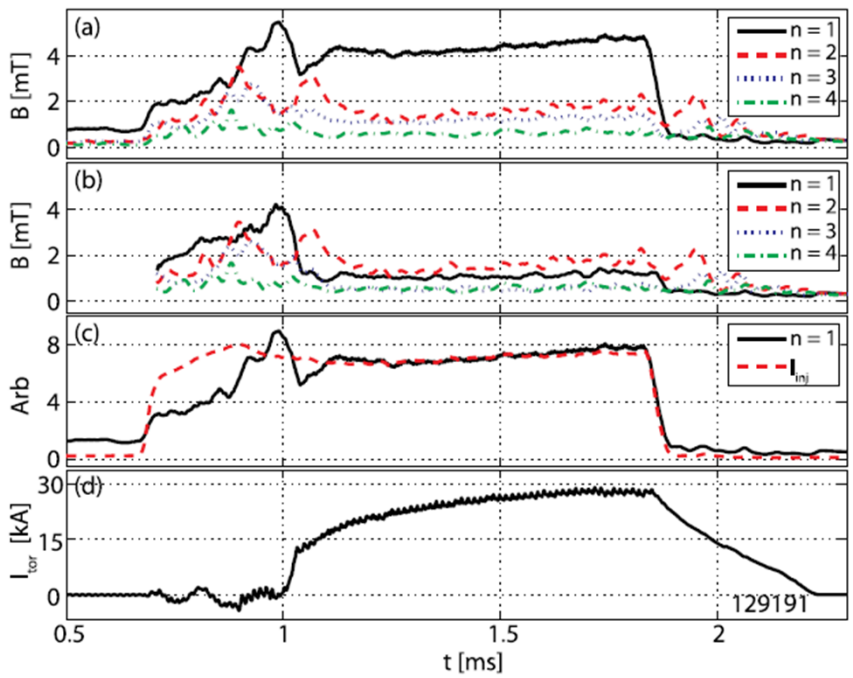
(a) Internal probes. (b) surface probes





- Equilibria are stable.
- The only significant fluctuations observed are imposed.
- The toroidal current versus time, the injector impedance scaling with *j/n* of the spheromak, and the current profile data of HIT-SI are predicted by the IDCD model.

The only significant fluctuations observed are imposed



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 is almost entirely imposed and the equilibrium is stable.
- HIT-SI is capable of testing MHD stability, which had been the problem with sustained spheromaks until now.

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

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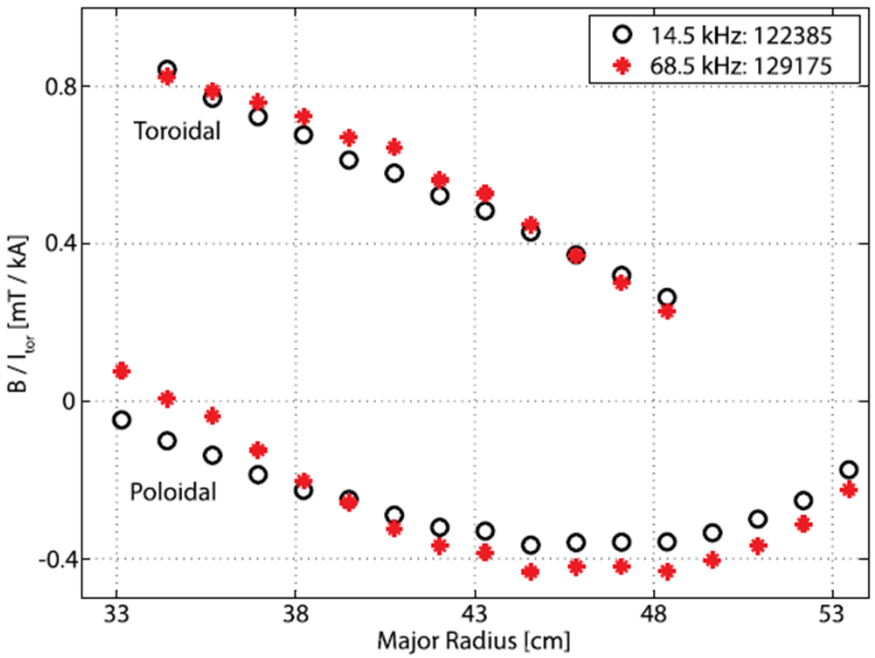

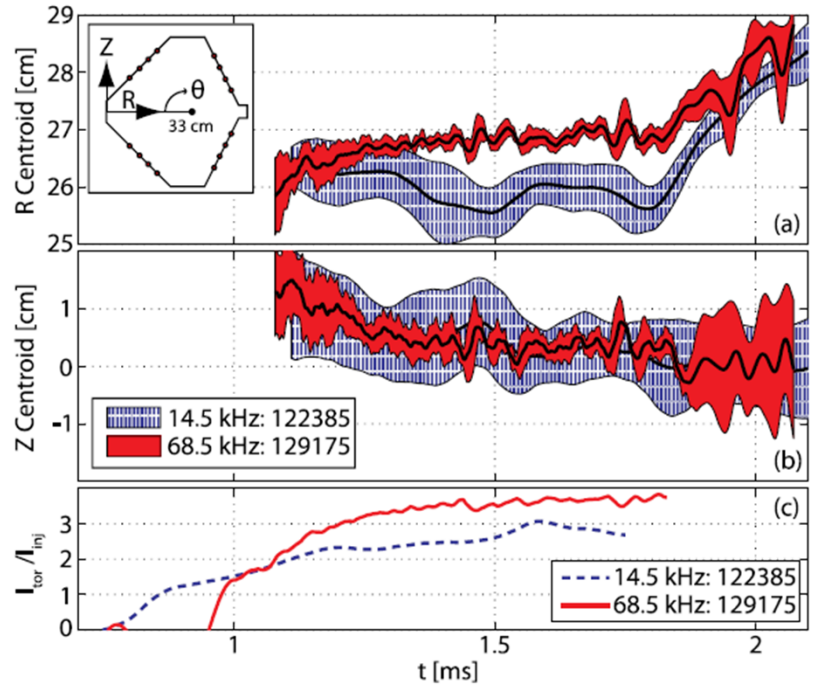

- Internal magnetic probes show larger Shafranov shift due to higher β (5% vs 25%) at high frequency.
- Centroid measurements at four toroidal locations show better symmetry and larger outward shift at high frequency.
- At high frequency the imposed fluctuations appear to be controlling the pressure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

A higher S (larger, hotter) experiment is needed for studying the stabilizing nature of IDCD

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- HIT-SI can accurately assess ideal MHD stability since: $\tau_{Alfv} << \tau_{L/R}$ (the breakthrough is in this stability)
- Slower growing but important instabilities like the resistive interchange and temperature gradient modes may be resistively stabilized on HIT-SI because: $\tau_{growth} \sim \tau_{L/R}$
- A larger hotter machine will have $\tau_{growth} << \tau_{L/R}$ and the stabilizing effect of IDCD can be studied.

HIT-SIX represents a paradigm shift: design experiment for flat j/B and impose enough fluctuations to keep it flat

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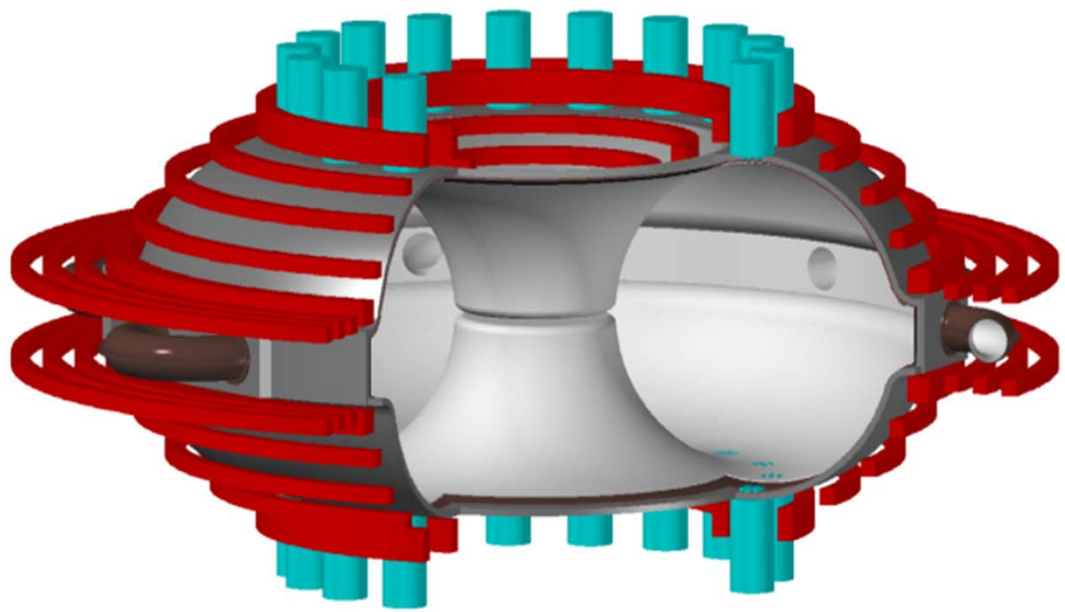
- Becomes possible to maintain an equilibrium rock-stable to current driven modes.

a = 0.55 m
I = 1.35 MA
τ_{pulse} = 2 s
T = keV range
β_{wall} = 16%



3 m

Next step

Summary

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- HIT-SI uses IDCD to sustain a stable equilibrium by directly driving the edge j/B and imposing perturbations.
- The uniform-j/B profile is compatible with a high performance spheromak, which makes an economically attractive reactor.
- Needs to be tried in a confinement experiment!
- The experiment will also increase our understanding of the effects of perturbations and develop more efficient current drive.
- Next step to economical fusion power (fusion cheaper than coal*) is a strong spheromak program.

*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.