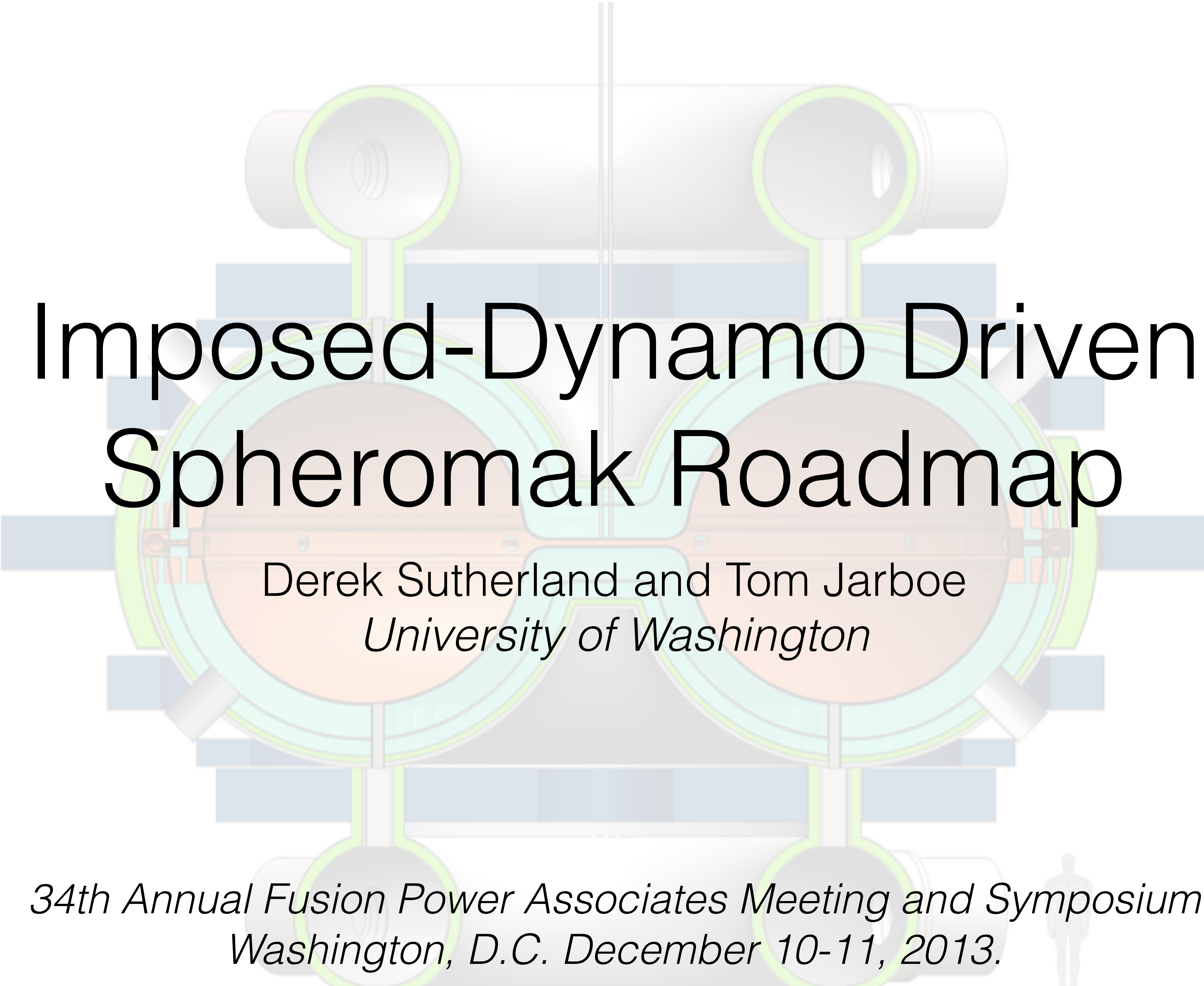

Imposed-Dynamo Driven Spheromak Roadmap

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Outline

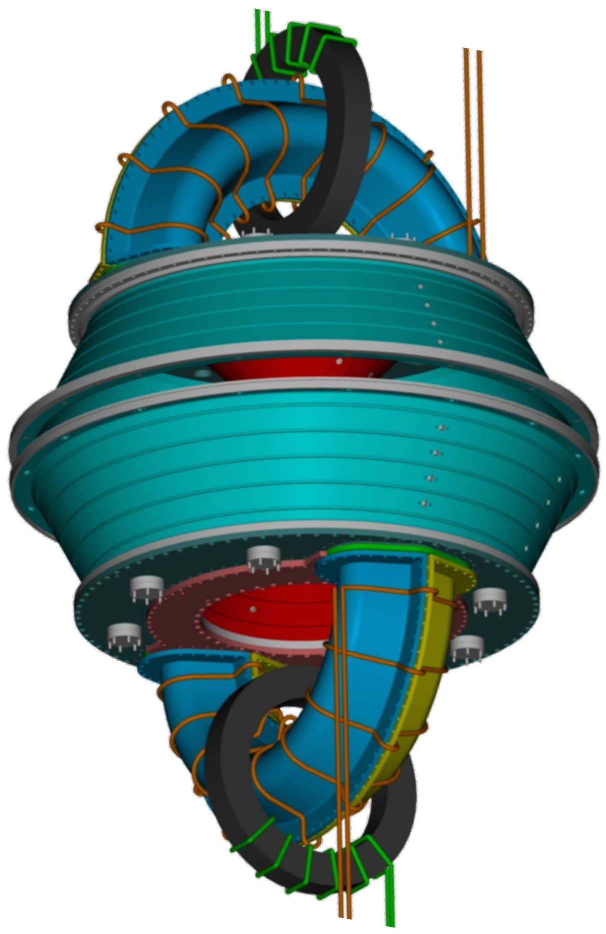
- Current drive requirements for magnetic fusion.
- HIT-SI experimental results — suggest sustained spheromak with pressure.
- NIMROD simulations indicate existence of closed flux with large, imposed magnetic fluctuations.
- The Dynomak reactor system — realization of economical fusion enabled by Imposed-Dynamo Current Drive (IDCD).
- IDCD-enabled spheromak development path.
- Conclusions and discussion.

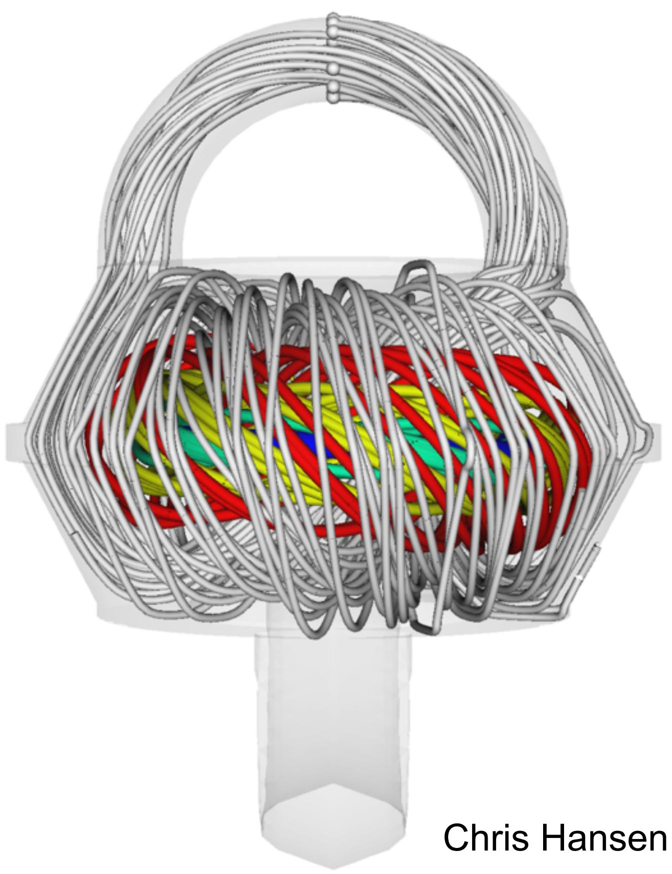
Efficient current drive is required for magnetic fusion energy

- RF and NBI current drive have $P_{ohmic}/P_{CD} \sim 10^{-3}$ in a reactor.
- High CD efficiency improves tokamak.
- 30% CD efficiency enables the spheromak —> high TBR and economically competitive with coal.
- HIT-SI, a cold (~10-20 eV) concept exploration experiment, has demonstrated such efficient sustainment with adequate confinement. (Reaches stability beta-limit with current drive power) —> IDCD

HIT-SI

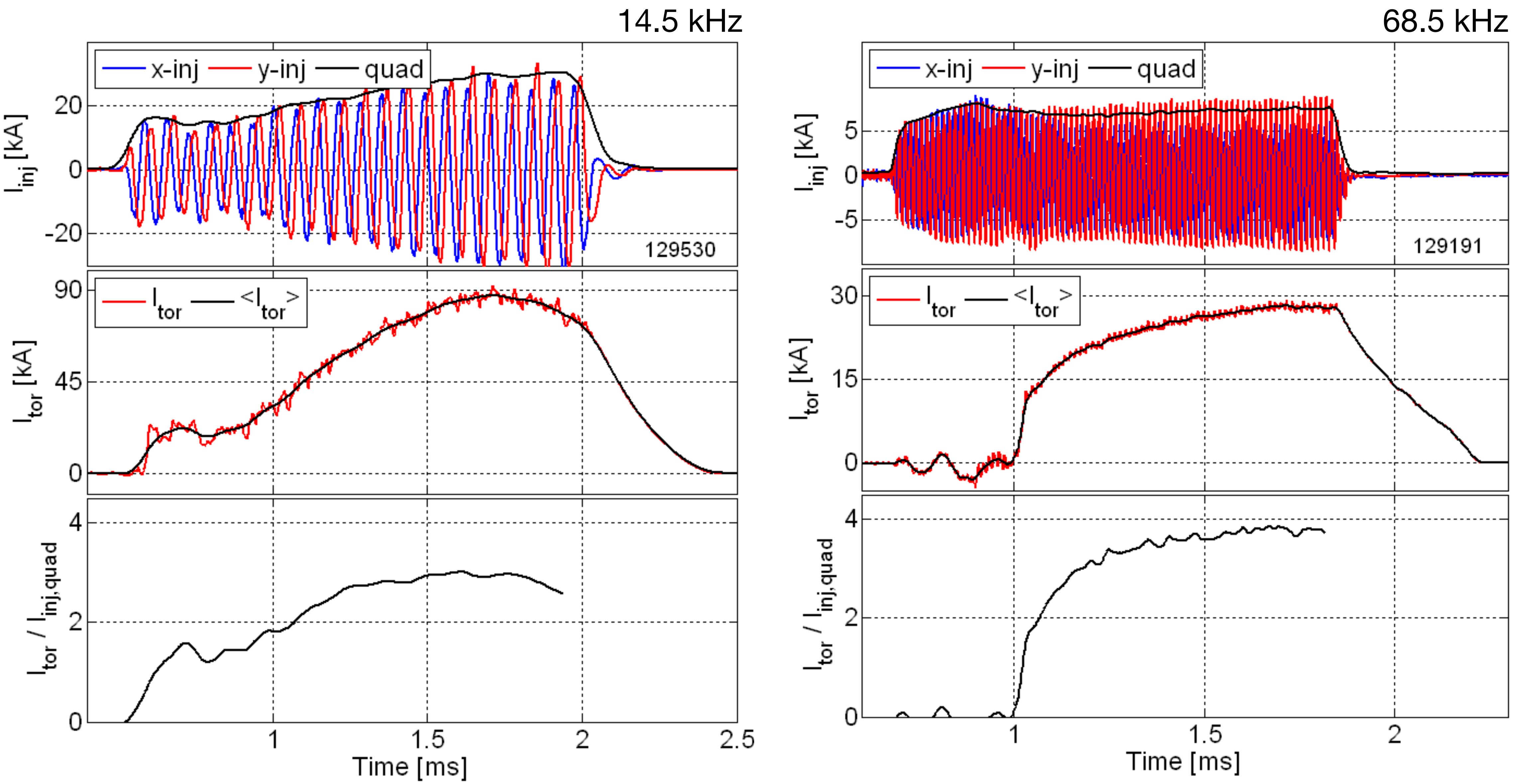
- Injectors form a spheromak equilibrium in the confinement volume.
- Spheromak is grown and sustained from continued injector operation.





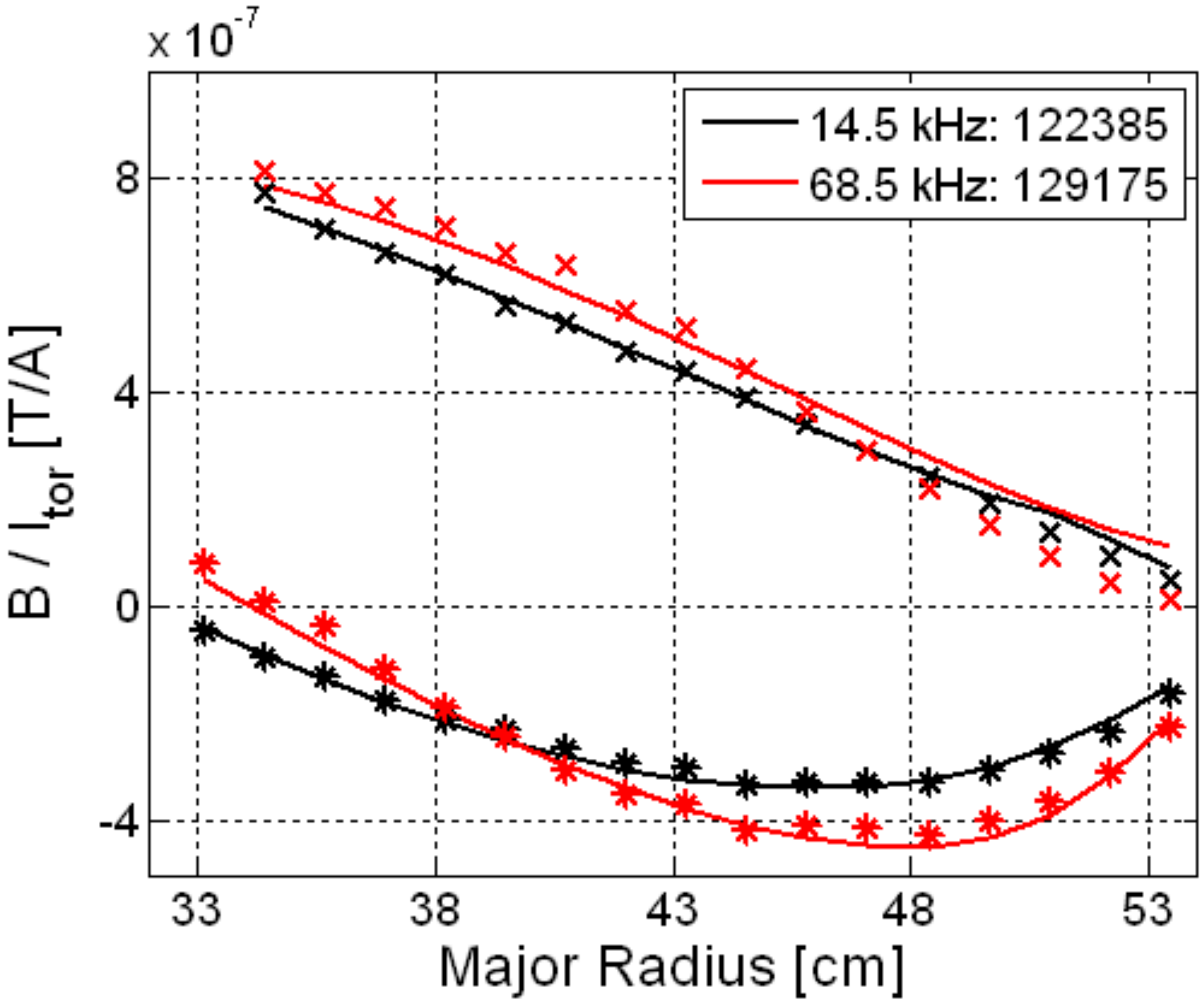
Chris Hansen

The Steady Injective Helicity Injection method has achieved 90 kA toroidal current and current gains approaching 4



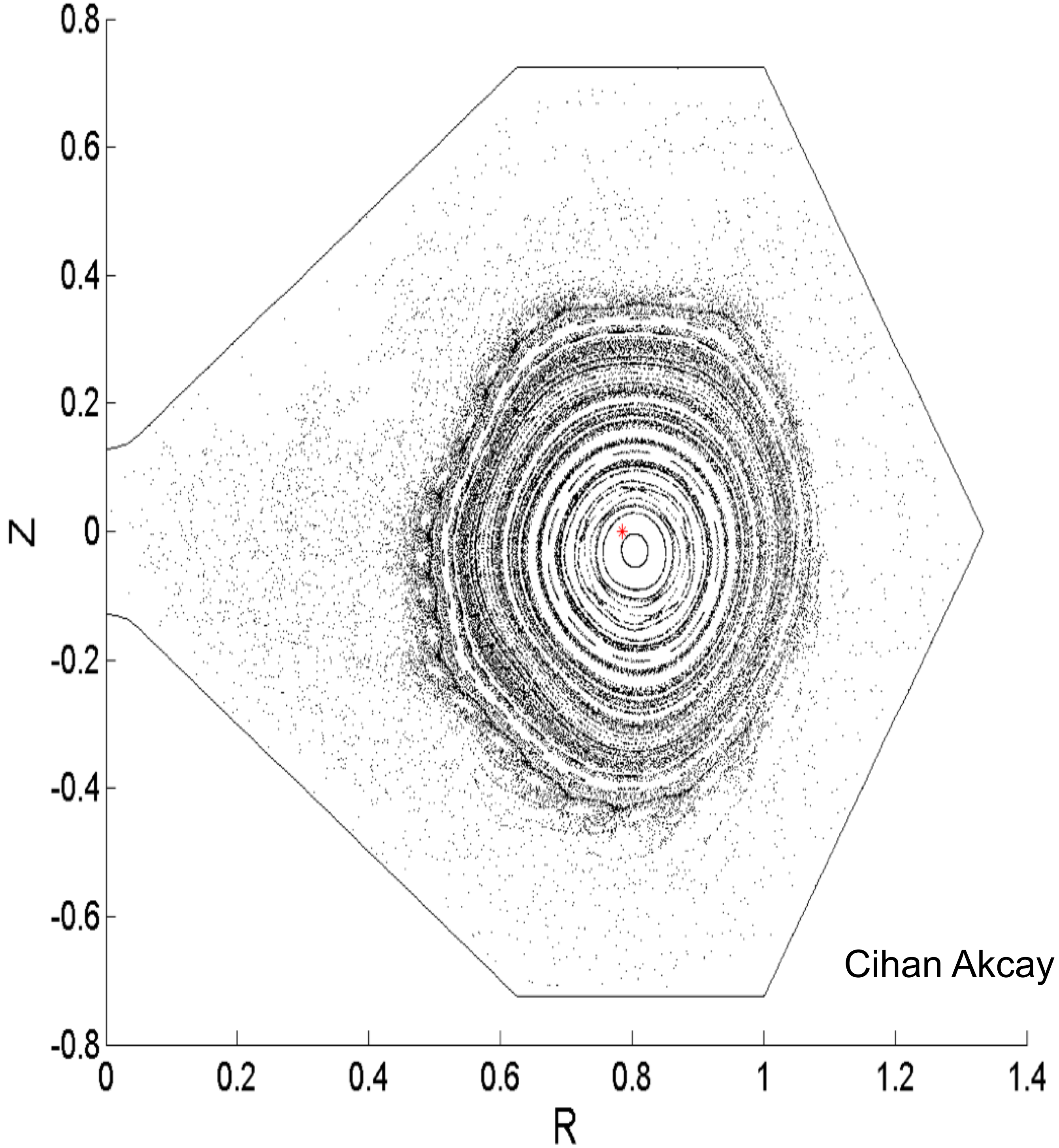
HIT-SI forms and sustains stable equilibria.

Magnetic axis is shifted toward the outer wall for high frequency shots



- Measured toroidal (x) and poloidal (*) equilibrium magnetic fields from internal magnetic probe.
- Solid lines indicate Grad-Shafranov fit to the data.
- $\beta_{14.5}$ = 0%, $\beta_{68.5}$ = 28.9%, $t_{14.5}$ =1.50 ms, $t_{68.5}$ = 1.65 ms.

NIMROD simulations of a bigger and hotter HIT show fluctuations may not break flux surfaces of stable equilibria



2-fluid MHD simulation a = 0.62 m, T = 100 eV, Zero pressure

- During stable periods, closed flux is observed in NIMROD calculations with $\delta B/B$ of 10% (amplification 9).
- Closed flux exists up to 20 injector cycles and grows only during stable times.
- Closed flux rapidly disappears when the equilibrium becomes unstable.
  - Only **imposed** fluctuations can be used for current drive for compatibility with adequate confinement.
  - All previous spheromak sustainment experiments failed to have good confinement because kink-instabilities were used to make the necessary fluctuations.

The following results justify HIT-PoP experiment

- Large amplitude fluctuations do not open the closed flux of a stable equilibrium.

- HIT-SI data show a stable current profile being sustained with adequate confinement.

- High frequency ($\omega_{inj} > \gamma_{interchange}$) density and profile data indicate:
  - A paced pressure driven interchange is doing the current penetration **(q-profile is kink-stable)**.
  - Imposed oscillating fluctuations control the pressure driven modes leading to high-beta confinement.

- Transient spheromaks and RFPs in the several 100 eV regime have Ohmically heated to the stability β-limit as expected for classical transport.

The Dynomak Reactor System Highlights

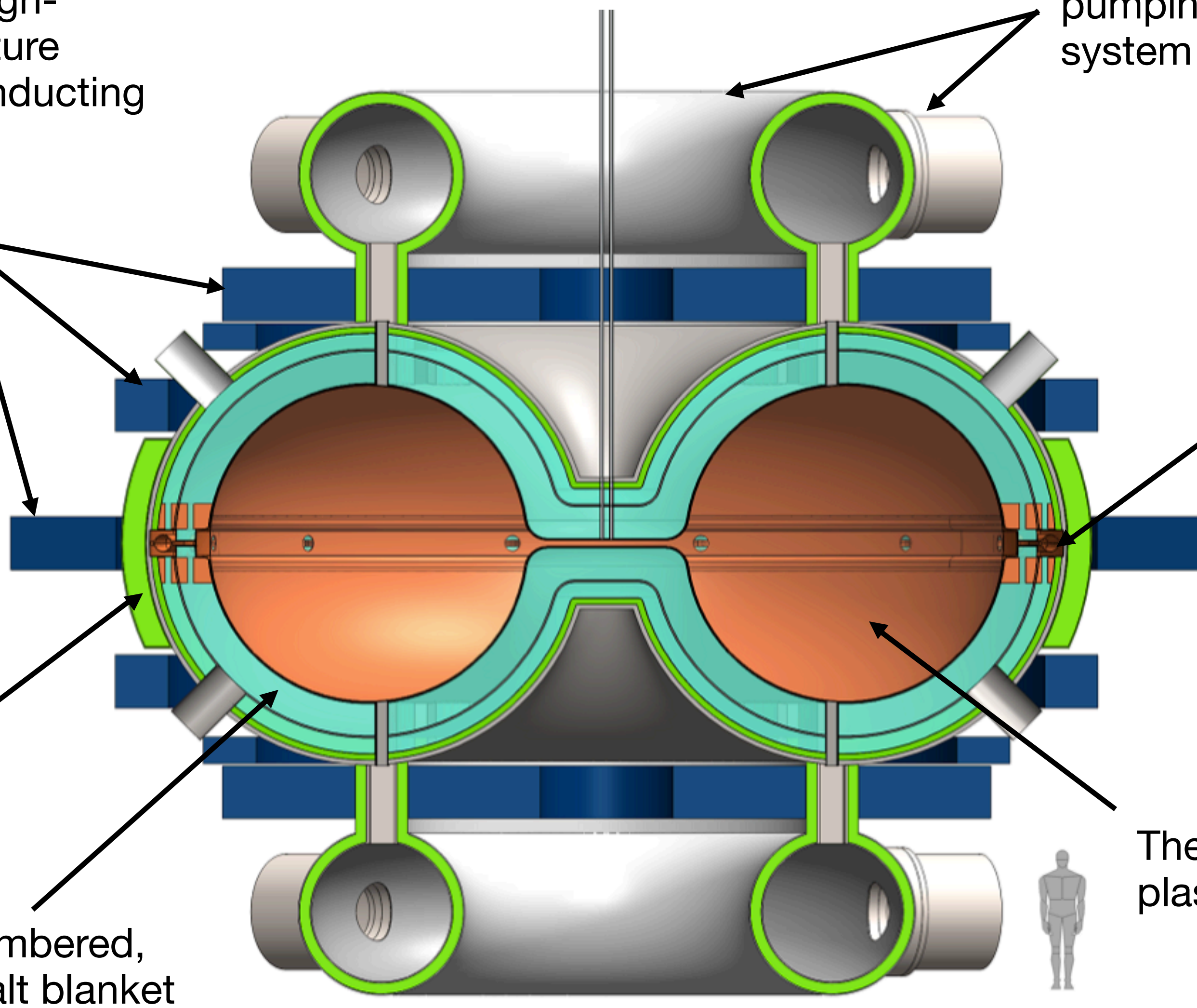
- Energy efficient IDCD for sustainment of a high-beta spheromak configuration.

- Immersive, molten-salt blanket system for first wall cooling, tritium breeding, and neutron moderation.

- YBCO high-temperature superconductors for PF coil set.

- SC-CO_2 secondary cycle (reviewed favorably by Westinghouse).

Dynomak Reactor System



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)	1.12
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

Overnight capital cost breakdown of Dynomak reactor

Subsystem	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	267.3
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
YBCO superconducting coil set	216.0
Supercritical CO_2 cycle	293.0
Unit direct cost	1696

Subsystem	Cost ($M)
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

- Dynomak reactor system overnight capital cost is ~$2.7 billion
- Overnight capital cost undercuts fission and is competitive with coal.
- Natural gas is cheaper, though fuel cost increases and carbon taxes may increase cost in future.

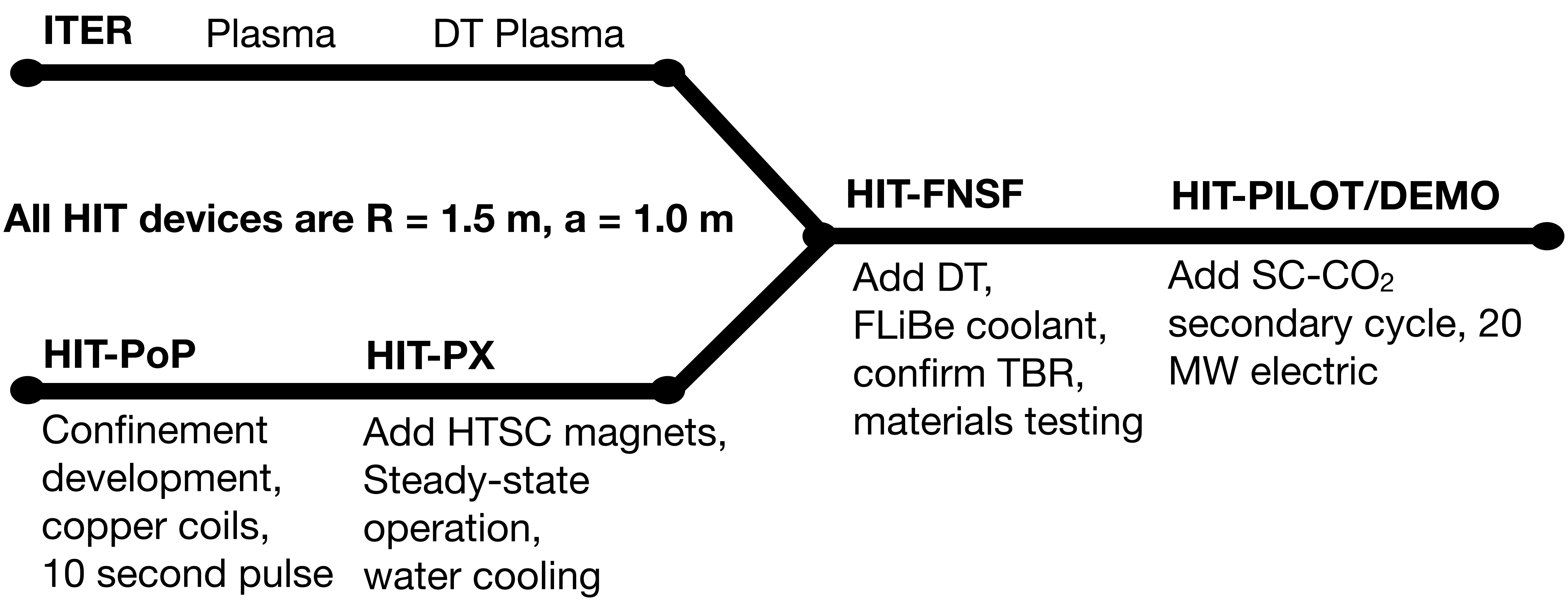
An economical fusion development path is proposed to reach Dynomak scale device

- Promising results from HIT-SI and NIMROD and an economical conceptual reactor design justifies Proof-of-Principle (PoP) experiment.

- PoP seeks to demonstrate adequate confinement at high temperature with IDCD on an inexpensive, pulsed machine.

- With successful PoP, the development path includes steady-state operation and nuclear engineering.

Development path uses same sized machine with various upgrades



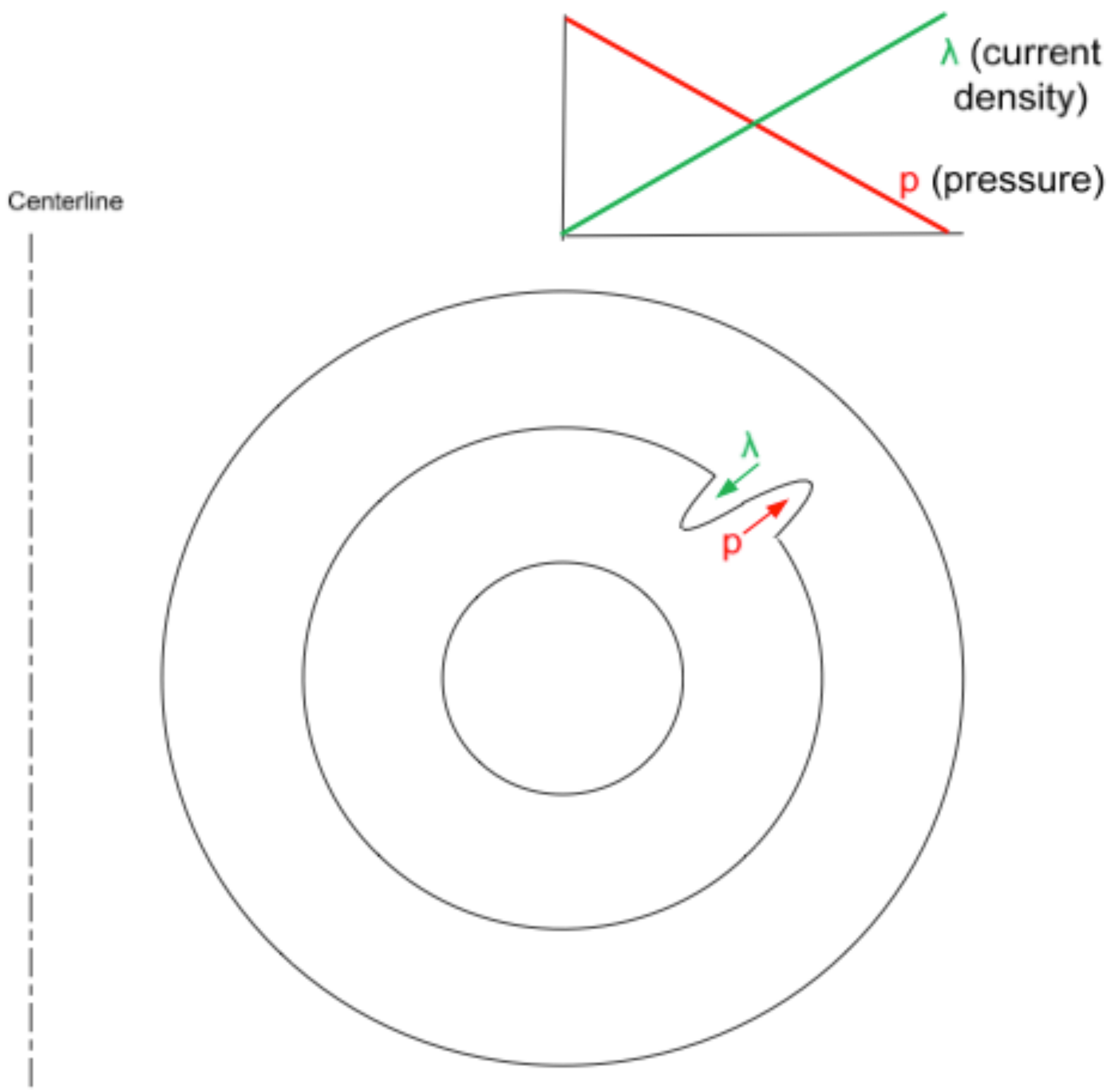
Conclusions

- HIT-SI results indicate sustained spheromaks with pressure.
- Computer simulations indicate closed flux with large magnetic fluctuations.
- An IDCD driven spheromak enables economical fusion power —> The Dynomak
- Encouraging spheromak and RFP results and economical conceptual reactor justifies Proof-of-Principle experiment.
- IDCD driven spheromak development path may provide a cost effective approach to fusion energy.

Questions and Discussion

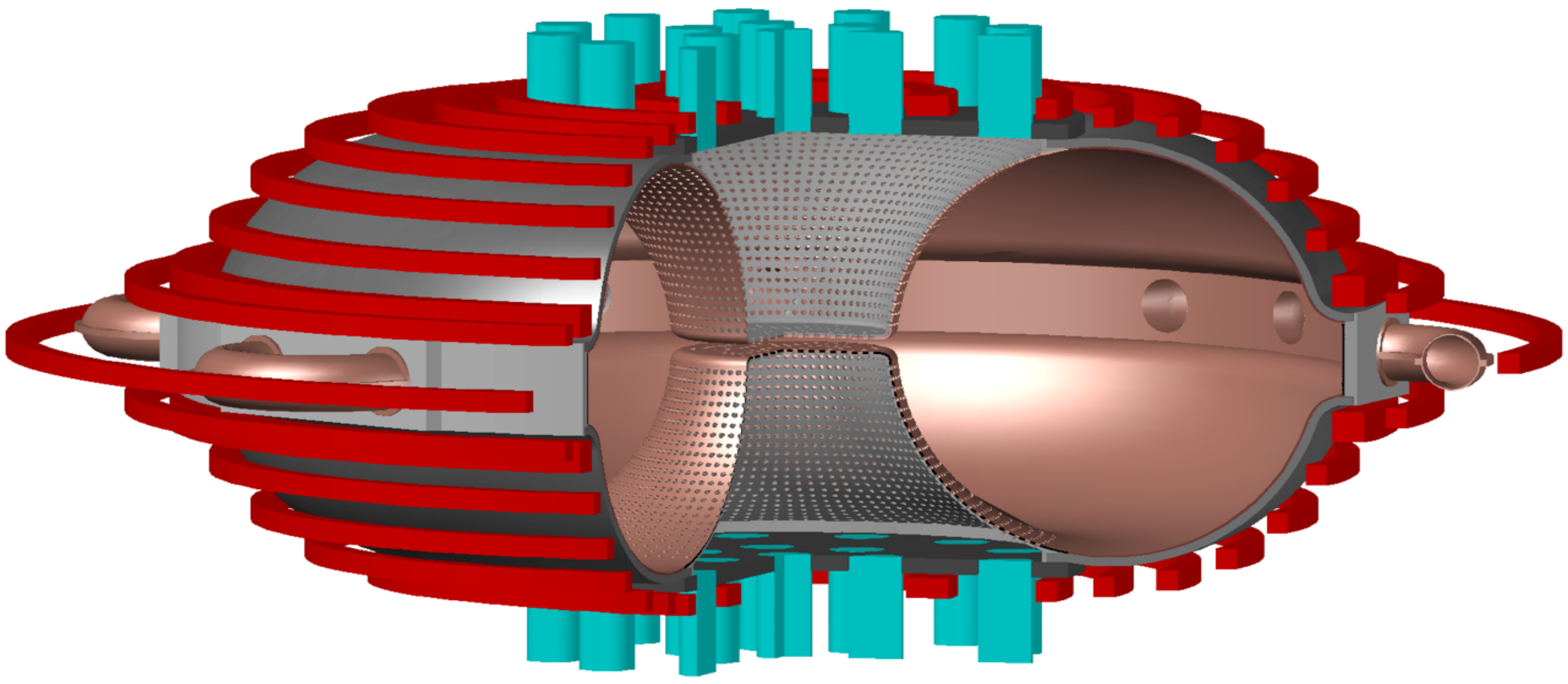
Backup Slides

Pressure modes may be responsible for current penetration



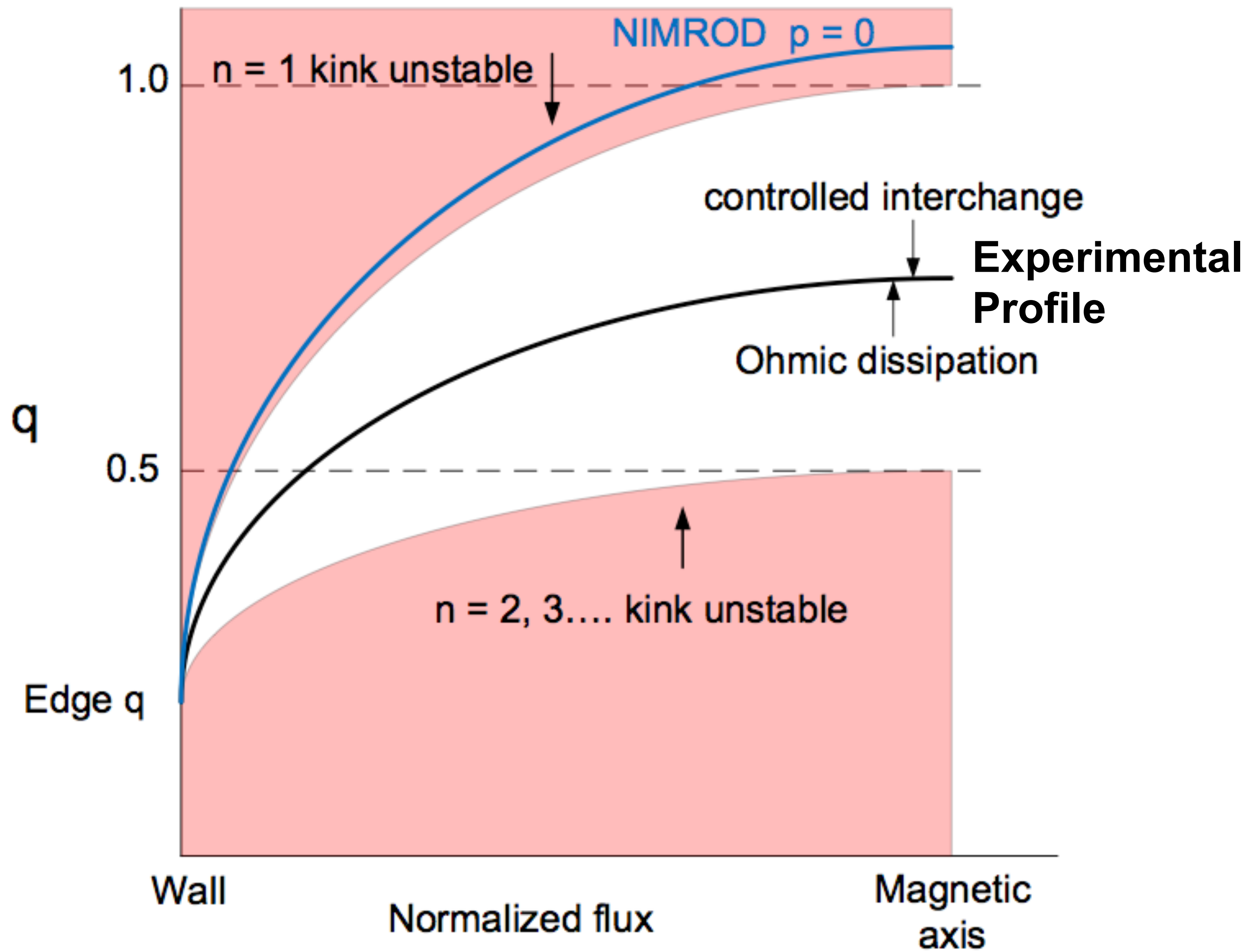
- Taming ELMs with injectors do not eliminate PDMs, but does reduce their average amplitudes.
- Forced, pressure driven interchange may cause current penetration.
- High frequency imposed fluctuations keep interchange local and encourages relaxation ($p' = 0$, $\lambda = \text{const.}$)
- Enables ash removal and power removal without global pressure loss.

Development path begins with PoP experiment



Parameter	Value
Major radius [m]	1.5
Minor radius [m]	1.0
Toroidal I_p [MA]	3.2
Number density [10^{19} m^{-3}]	4.0
Peak T_e [keV]	3.0
Shot Length [s]	10.0
Coil material	Cu
Plasma Type	D

Imposed fluctuations may control pressure-driven interchange to give kink-free cross-field current drive that balances Ohmic dissipation



Achieving sufficient confinement is expected

- A stable equilibrium maintains closed flux in the presence of fluctuations, unlike previously sustained unstable configurations.

- HIT-SI shows that a stable equilibrium with good confinement can be sustained with IDCD.

- The current is sustained with a stable flat j/B profile.

- Decaying spheromaks and transient RFPs have shown good confinement. Even some aspects are classical.*

- Spheromaks and RFPs in the several 100 eV regime have Ohmically heated to the stability β-limit as expected for classical transport.

- Pressure driven modes are controllable.

- A larger long pulse machine will allow the development of good confinement at keV temperatures.

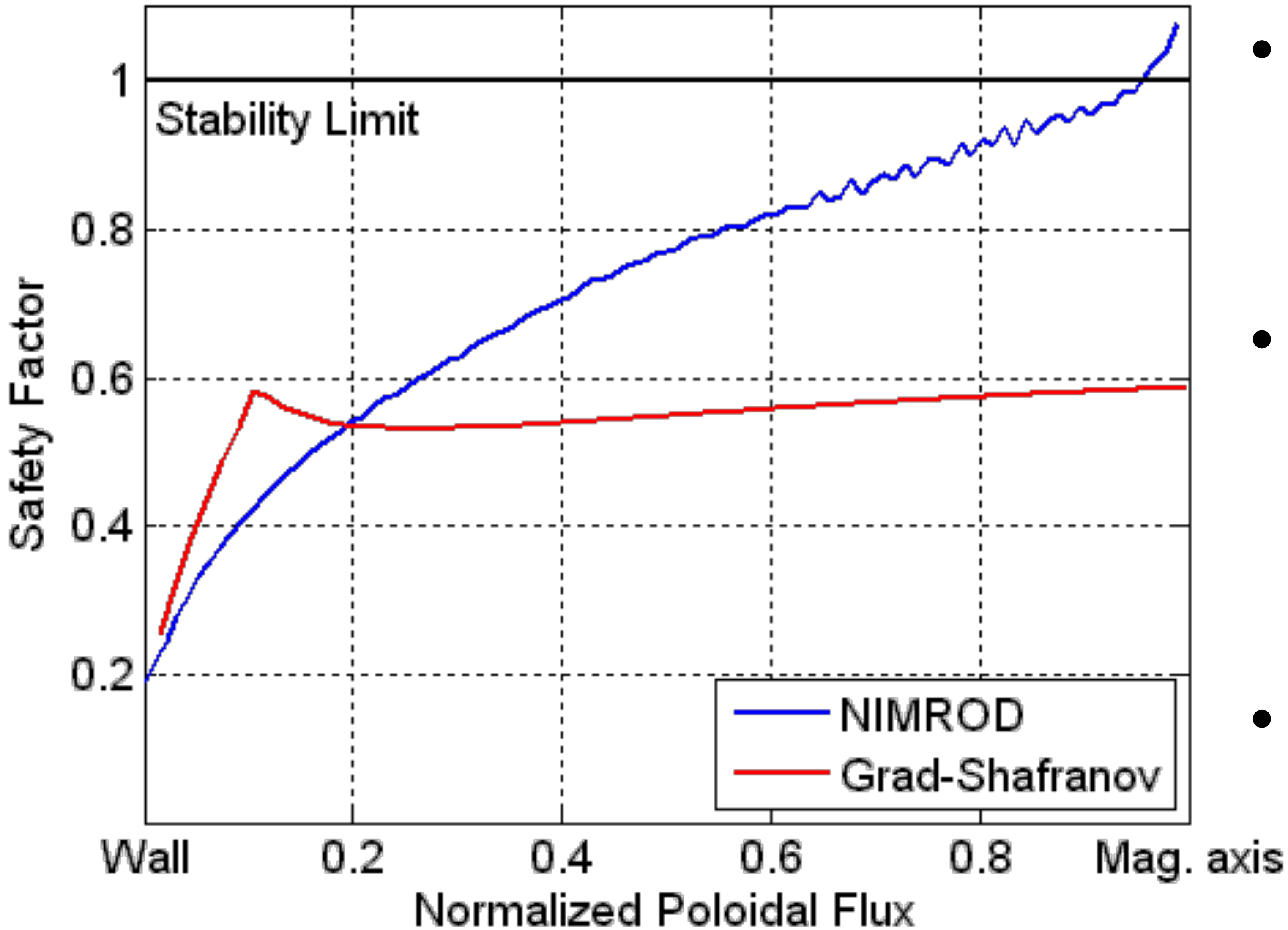
*S. T. A. Kumar et al.,PRL 108, 125006 (2012)

HIT-PoP experiment cost analysis

- HIT-PoP provides next critical step towards economical fusion power for a reasonable price.

Component	**Cost ($M USD)**
Vacuum tank assembly	3.8
Injectors and mounting ring	6.7
Copper equilibrium coils	2.3
Power supply and controls	9.2
Building preparations	1.7
Contingency	7.8
Total Experiment Cost	**31.5**

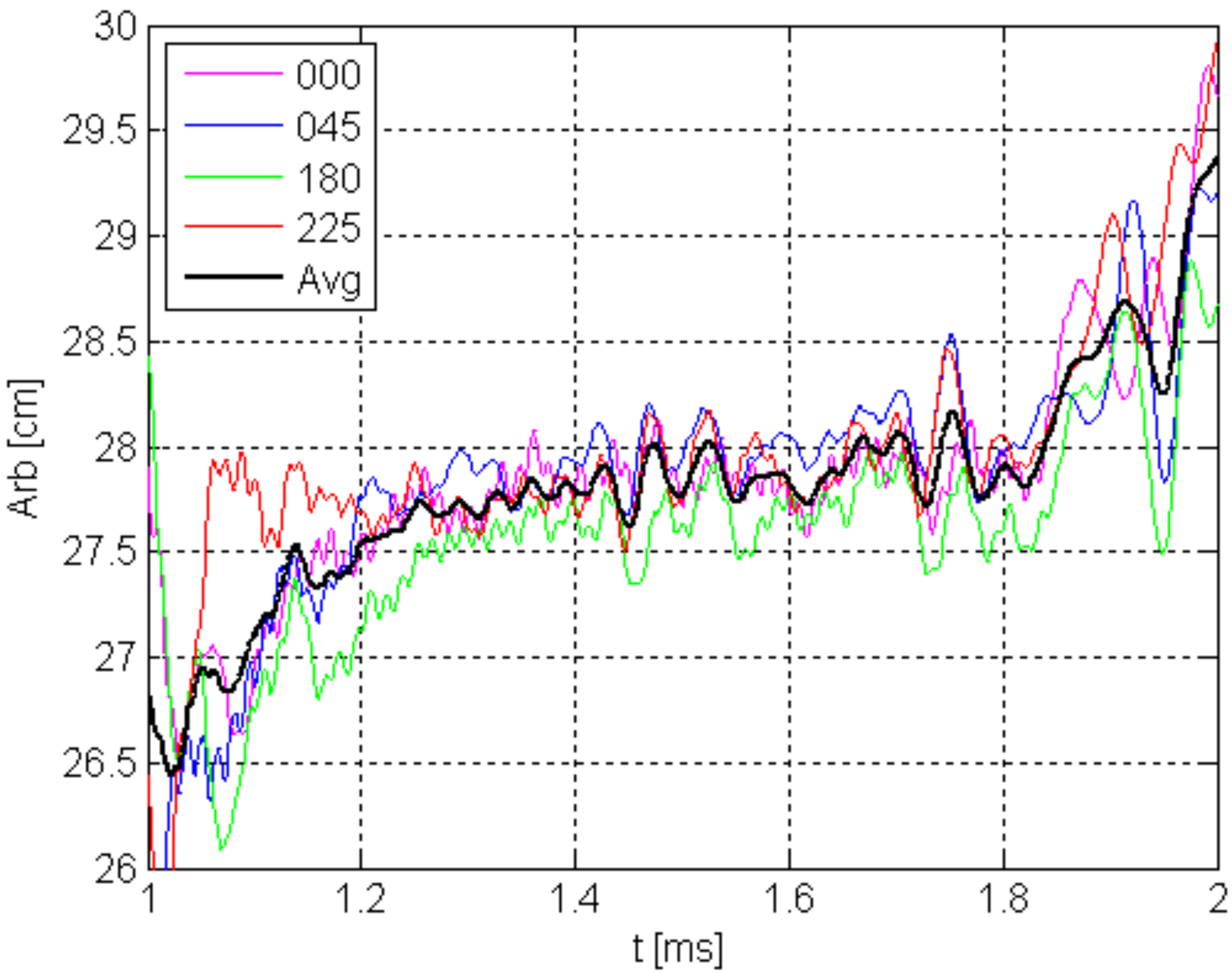
Deep stability suggested by internal magnetic field profile



Courtesy of C. Hansen and K. Morgan

- Spheromaks are kink stable with $q < 1$
- Grad-Shafranov fit to experimental data is well below the stability limit
- Simulations show closed flux when $q < 1$

Toroidal symmetry shown by surface probe arrays



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

HIT-SI limitation	**A PoP solution**
For uniform λ β-limit is 3%	Uniform-λ β-limited is 16%
Wall loading around injector is 4 times too high	Area around injectors increased by 8
$\omega_{injector} = \omega_{rotation}$	Frequencies are independent
No long pulse density control	High speed pumping
$na = 5 \times 10^{18} m^{-2}$, too low to screen neutrals	$na = 5 \times 10^{19} m^{-2}$, high enough to screen neutrals
$j/n = 10^{-14}$Am is marginal	$j/n = 2 \times 10^{-14}$Am

Comparisons with conventional energy sources indicate Dynomak is cost competitive

Energy Source	$ USD for 1 GWe	Fuel Energy Density (MJ/kg)	Annual Fuel Costs for 1 GWe
Coal Fire	> 3 billion	24	$267 million
Natural Gas + No CO_2 Capture	< 1 billion	53	$175 million
Natural Gas + CO_2 Capture	~1.5 billion	53	$175 million
Gen III+ Nuclear Plant	> 3 – 4 billion	79.5 million	$67 million
Dynomak Reactor System	**2.7 Billion**	**330 million**	**$0.85 million**

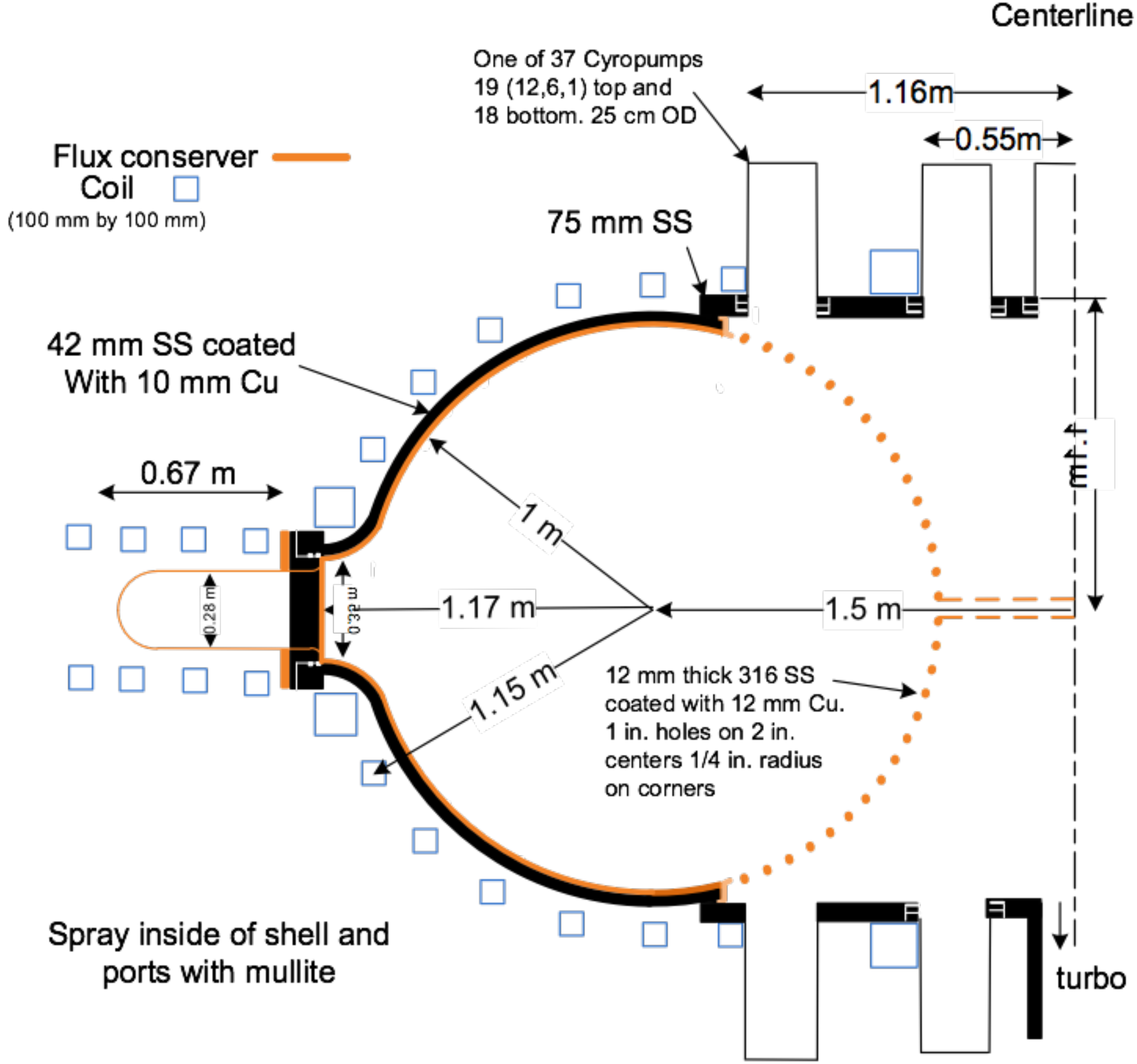
Schlissel, D. et al. **Coal-Fire Power Plant Construction Costs**, *Synapse Energy Economics Inc.*, Cambridge, MA. July 2008. www.synapse-energy.com

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

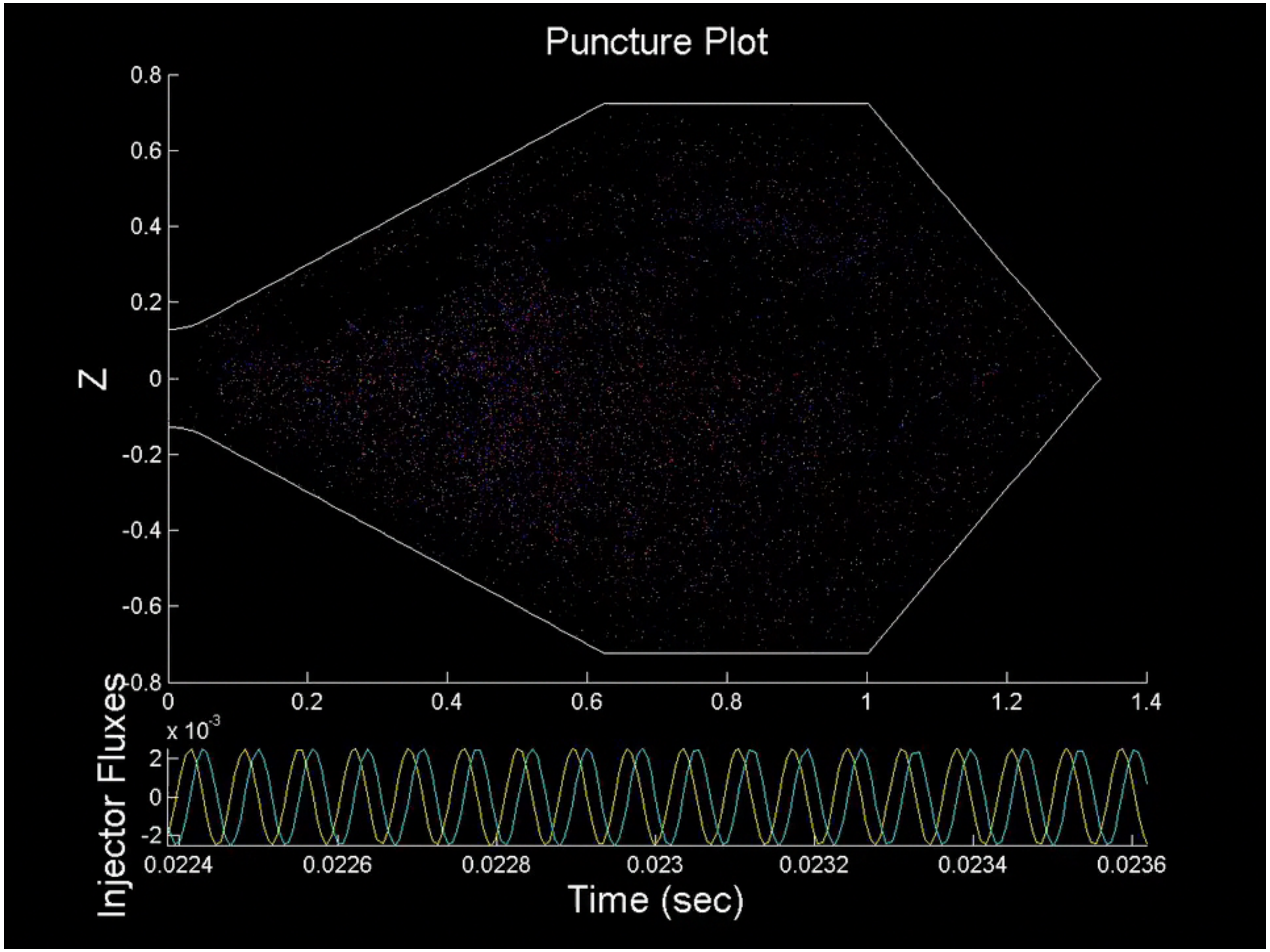
Black, J. et al., **Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity**. *National Energy Technology Laboratory*, sponsored by U.S. DOE, November 2011.

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

HIT-PoP experiment. The geometry and pumping. SS is for 316 stainless steel.



Big HIT Simulations



Big HIT Simulations