Alternative pathways to fusion energy (focus on Department of Energy Innovative Confinement Concepts)

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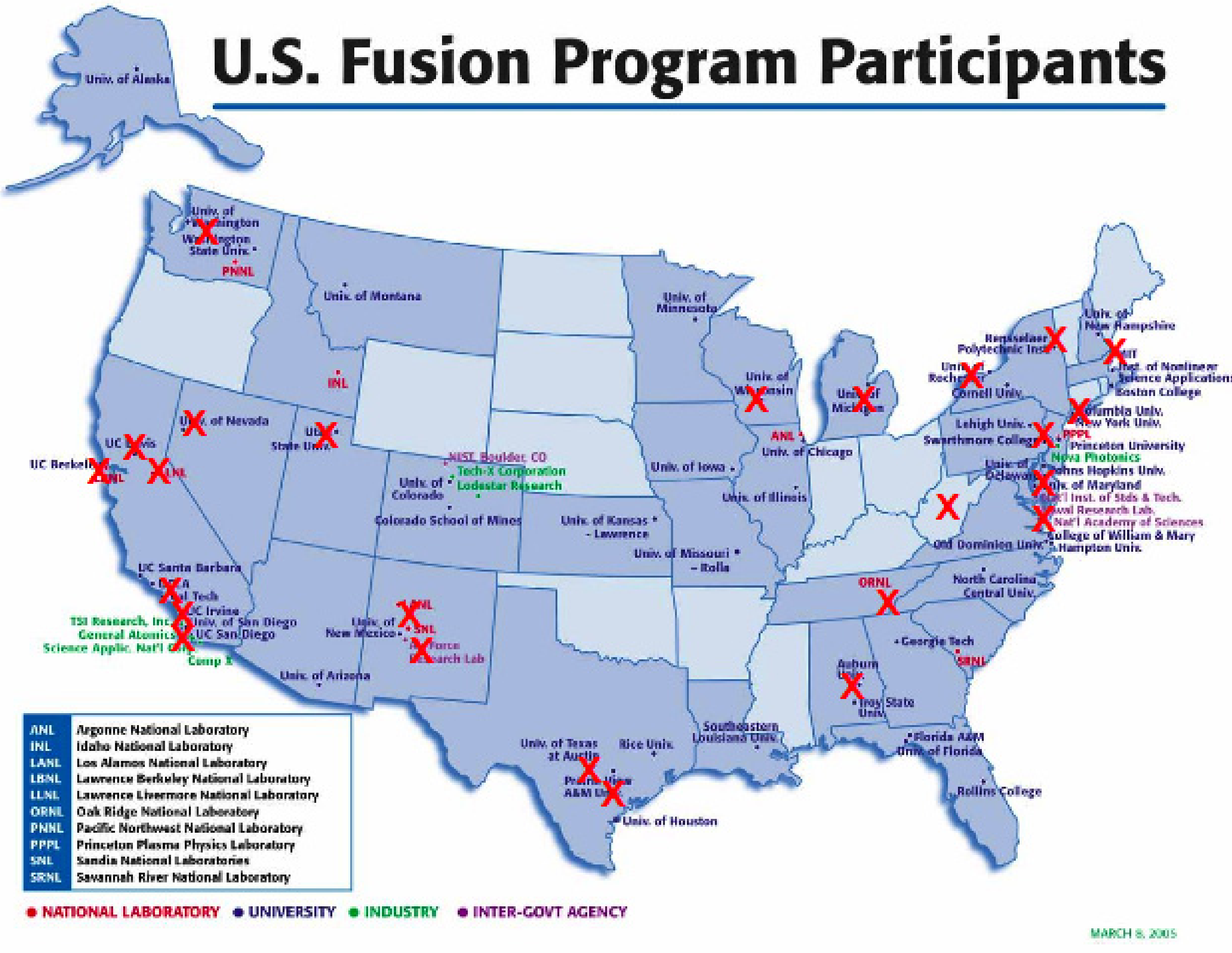
September 28th 2006

Outline:
1. Motivation
2. ICC experiments, and theory support
3. Summary

Fusion Power Associates Meeting, Washington DC

U.S. Fusion Program Participants

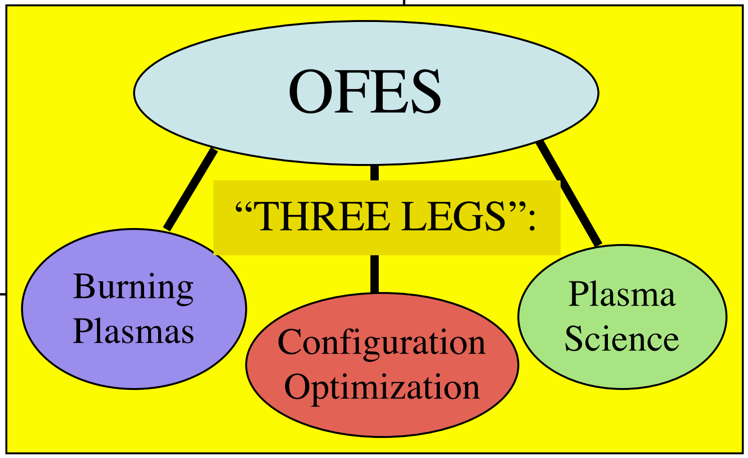


OFES Mission and 15 years of program planning outline the role of alternates.

MISSION: The mission of the Fusion Energy Sciences (FES) program is to provide the national basic research effort to advance plasma science, fusion science, and fusion technology—the knowledge base needed for an **economically** and environmentally **attractive fusion energy source**.

1992	FEAC advises program strategy, suggests program for Innovative Concepts [1]
1995	OTA TPX and the Alternates [2]
1995	PCAST (given flat budgets, what is the plan?) [3]
1996	FEAC: A restructured fusion energy science program [4]
1996	Conference report accompanies Energy and Water Subcommittee conference [4]
1996	OFES Strategic Plan for a restructured fusion energy science program [5]
1996	FESAC: Opportunities in Alternative Confinement Concepts [6]
1997	First ICC Workshop [7]
1999	Snowmass I (Barnes leads EC discussion) [8],
1999	Davie's Policy for ICCs [9]
2000	Integrated Program Planning Activity (IPPA) [10]
2002	Snowmass II [11]
2002	Goldston 35 year plan [12]
2005	FESAC Priority Panel Report [13]

Table 1. Main policy documents relating to the alternates.



Innovative Confinement Concepts address fusion energy science objectives by:

1. Working within a broad range of plasma and fusion energy sciences, including **cross fertilization** with other fields of plasma science;

2. Seeking concepts and innovations that work better or **change the paradigm** for fusion energy;

3. Broadening the physics of toroidal magnetic confinement by **operating in parameter regimes inaccessible by the tokamak**;

4. Strengthening university plasma science and technology programs, **engaging faculty** by providing opportunities to contribute to plasma and fusion science **with small-to-medium size experiments**; and

5. **Attracting bright, young talent** with the vision of unlimited energy for mankind while providing the opportunity to participate in experiments they can "get their hands around."

--Snowmass 2002

Innovative Confinement Concepts address **science** objectives in the broader program:

T1. How does magnetic field structure impact fusion plasma confinement?
T2. What limits the maximum pressure that can be achieved in laboratory plasmas?
T3. How can external control and plasma self-organization be used to improve fusion performance?
T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?
T5. How are electromagnetic fields and mass flows generated in plasmas?
T6. How do magnetic fields in plasmas reconnect and dissipate their energy?
T7. How can high energy density plasmas be assembled and ignited in the laboratory?
T8. How do hydrodynamic instabilities affect implosions to high energy density?
T9. How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?
T11. How do electromagnetic waves interact with plasma?
T12. How do high-energy particles interact with plasma?
T13. How does the challenging fusion environment affect plasma chamber systems?
T14. What are the operating limits for materials in the harsh fusion environment?
T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

--FESAC Priorities Panel 2005

ICC development path is staged to address **performance** metrics.

Progress

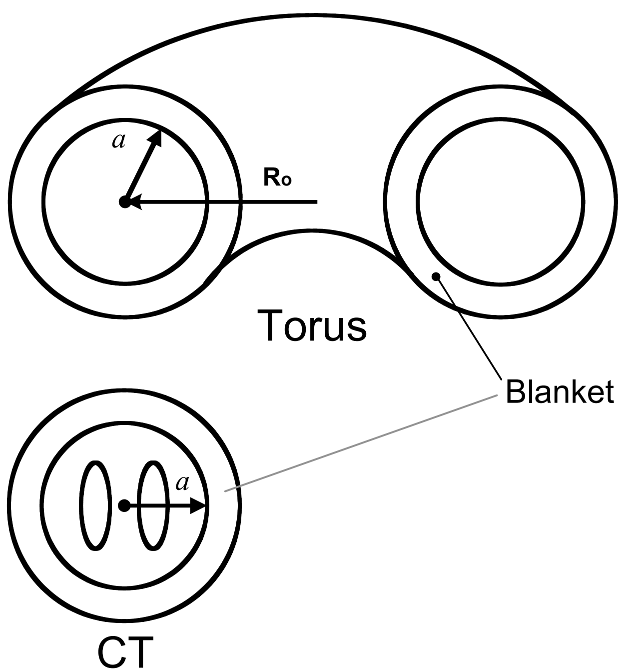
	Qualitative Metrics (advancement requires a science-based prediction that the next-level metrics can be met)	Target Quantitative Metrics for MFE*	Target Budget ($M/yr)
Concept Definition	• Defines a CE experiment that addresses uncertain physics or tech issues of the concept • At a minimum, theory indicates that the CE experiment will be grossly stable • A fusion application is defined	$\tau > \tau_A$	0.3
Concept Exploration	• Obtains sufficient theoretical, computational, & experimental knowledge & understanding of the science to confidently describe the current CE experiment and predict the next PoP experiment • Gross stability is demonstrated • A competitive fusion reactor is supported by the physics & technology	T = 0.4 keV $n\tau = 10^{17}$ s/m^3	< 3.0
Proof of Principle	• Establishes most of the experimental & theoretical physics bases and validity for fusion application • Can confidently describe and predict the performance extension experiment • An improved fusion reactor is supported by the physics & technology	T = 2 keV $n\tau = 10^{19}$ s/m^3	<15.0

How to fundamentally change the paradigm?

- Aim to reduce cost of ultimate device.
- 'Simply connected' may be a virtue.

Doubly: structure links plasma

Simply: nothing links plasma



Total cost

Direct cost	65%
indirect cost	25%
Contingency	10%
	100%

Direct cost

Reactor	50-60%
Conventional plant	35-30%
Structures	15-10%
	100%

Reactor Cost

Coils	30%
Shield	10%
Blanket	10%
Heat Transfer	15%
Auxilliary power	15%
Other compnents	20%
	100%

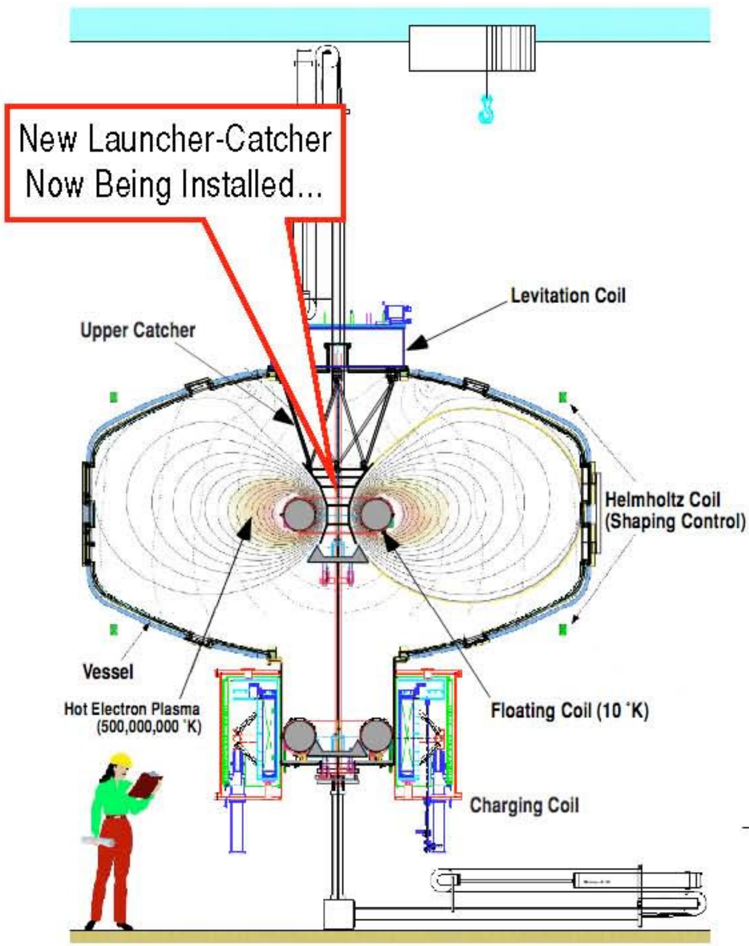
ICC experiments fall into broad categories.

"Doubly connected"		"Simply connected"	
Tokamak / stellarator	**Non-tokamak /stellarator**	**Closed**	**Open**
HBT-EP Resistive-wall stab. Tokamak trans. phys. Divertor innovation Pegasus LTX HSX CTH QPS	**Reversed field pinch** (MST) **Dipole** LDX	**Spheromak** (SSPX, HIT-SI, SSX, CalTech) **FRC** (TCS-rotomak, Odd-parity RMF, SSX, PHD, PFRC, Theory) Magneto-Bern. Exp. **Magneto-Inertial Fusion** (FRX-L, Solid liner, theory, stand-off driver) Accelerated FRC CT Accel Inverse Z-pinch	**Mirror** Mary. Centr. Exp. **Flow Pinch** (ZAP) Plasma jets
$7M	**$7M**	**~$10M**	**~$3M**

Levitated Dipole Experiment

Space observations, nonlinear numerical simulations, and basic laboratory experiments show high-beta, good confinement, and rapid adiabatic convection of plasma is possible in dipole-confined plasma.

Can we produce well-confined, high-beta plasma with a levitated dipole and understand large-scale adiabatic convection that maintains energy confinement while allowing rapid removal of impurities and fusion products?



FY06-07 Campaign

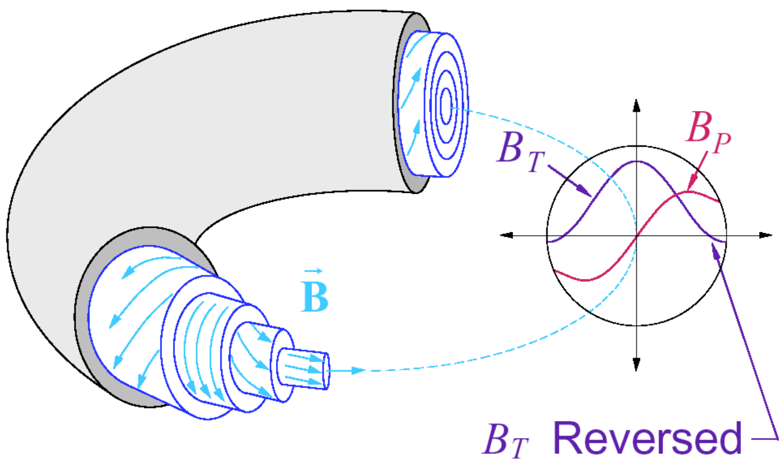
- **Complete testing of levitation systems.**
  Complete installation (*in progress*) and tests of new launcher-catcher system and levitation control systems.
- **Initiate investigation of confinement and stability of plasma confined by levitated dipole and heated with higher-power ECRH.**
  Investigate quasi-steady-state plasmas produced by multiple-frequency ECRH. Study higher-density thermalized plasmas.
- **Funding reduction (-8%): will eliminate support for two graduate students**.

FY08 Campaign

- Expanded diagnostics for detailed physics observations, and allow increased run time of LDX experimental facility.
- Investigate the unique capability of a dipole for high plasma beta, high energy confinement, and adiabatic convective flows.
- Answer critical questions to evaluate the potential for attractive dipole fusion with advanced (**non D-T**) fuels.

Research Staff: 2 scientists (Drs. Garnier and Hansen),
4 graduate students, PI's (Kesner & Mauel)

The Reversed Field Pinch toroidal plasma configuration.



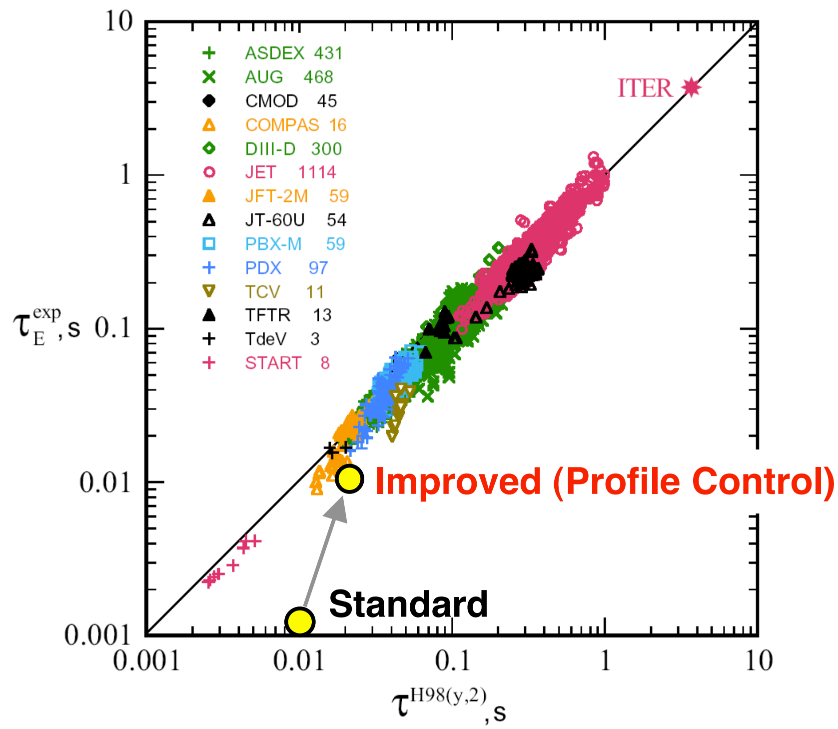
Potential Advantages:

- compact, high beta configuration
- low magnetic field requirement
- single-piece maintenance

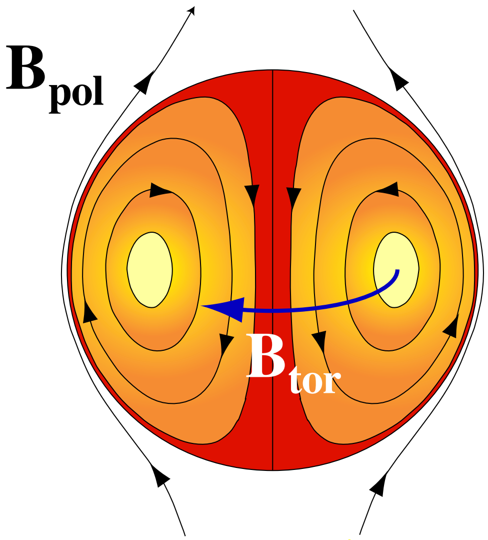
Madison Symmetric Torus (UW)

R=1.5 m, a=0.5 m, I_p ≤0.55 MA

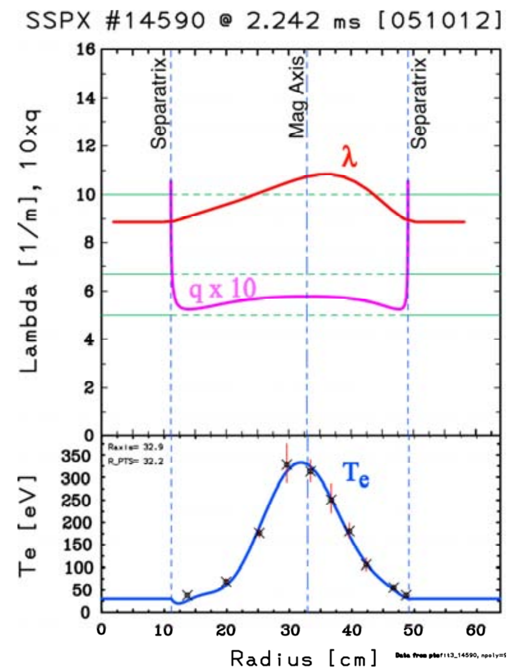
Tokamak-like Confinement (Transiently)

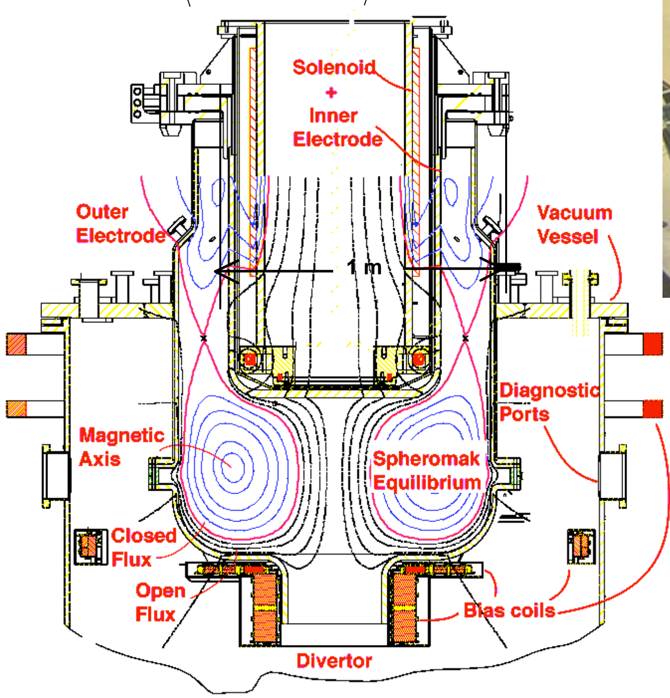


Sustained Spheromak Physics Experiment.



Investigates magnetic field generation and confinement in high temperature spheromaks.



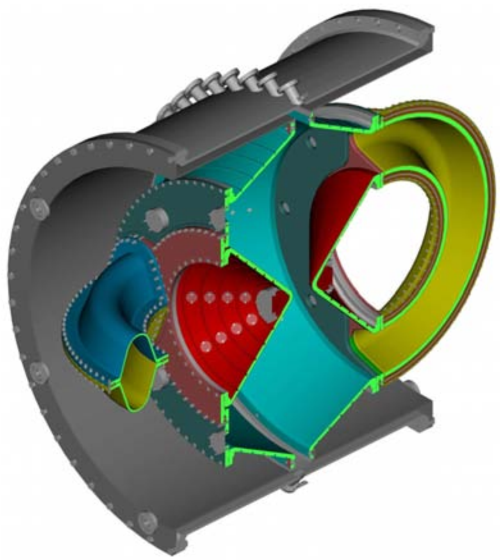


- **Low magnetic fluctuations with low edge λ —> no low-order rational surfaces**
- **T_e = 350 eV**

Potential Advantages:

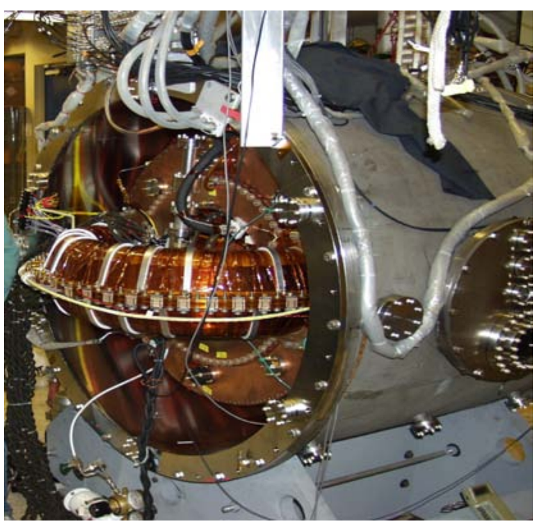
- compact, low aspect ratio
- no linked coils – no coils along geometric axis
- easy to disassemble and maintain

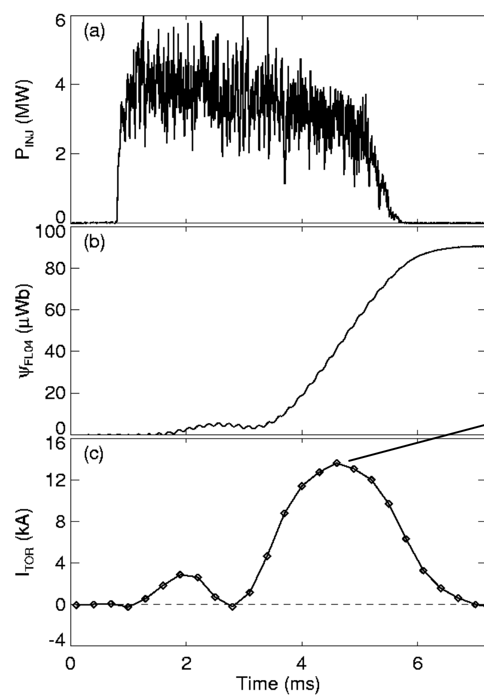
HIT-SI is making progress towards its goal of inductively sustaining a closed-flux, high-β, spheromaks



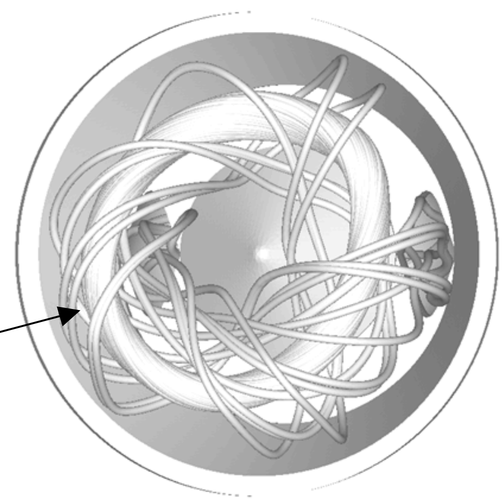
Novel current drive scheme being explored to form spheromaks more efficiently.

Flux conserver shaped to obtain high beta spheromaks.

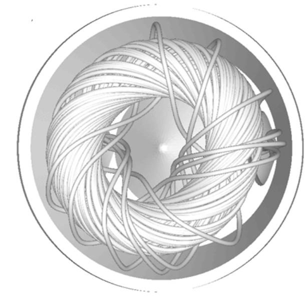




Modeling



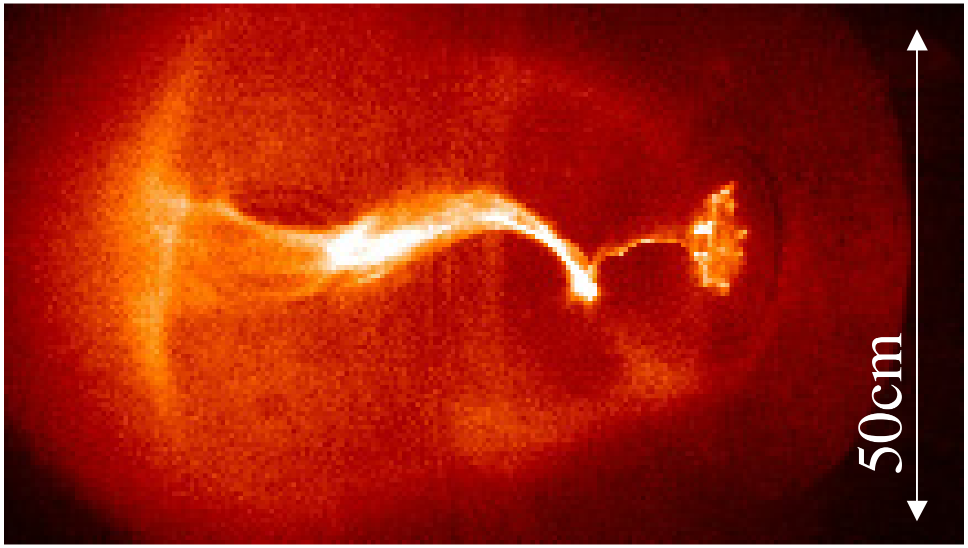
Taylor State, $I_p = 1.5\ I_{inj}$



Goal

$I_p = 5\ I_{inj}$

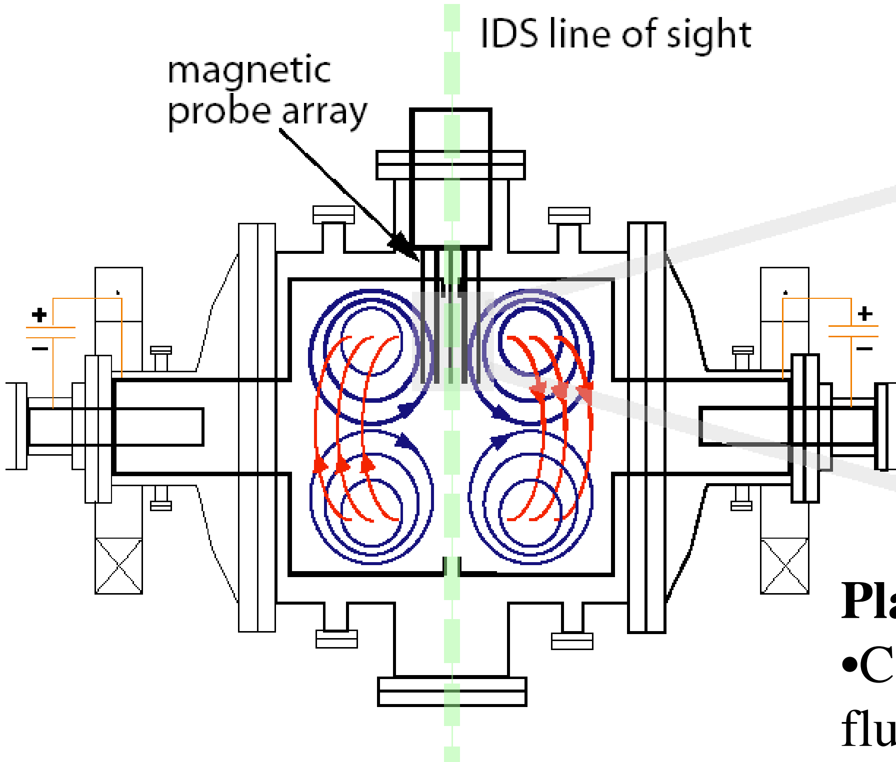
Caltech spheromak identifies a spheromak formation sequence & astrophysical jet physics

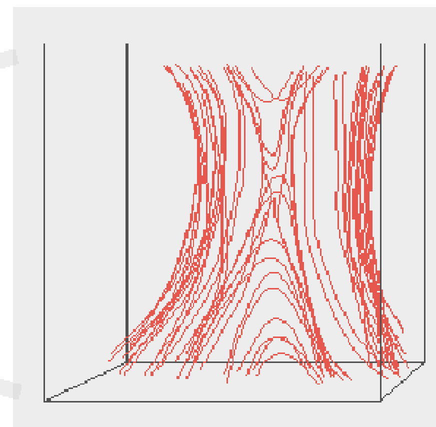


- JxB force creates plasma-filled filamentary loops like solar prominences [1]
- Loops merge to form axial jet which accelerates plasma, frozen-in toroidal flux [1]
- Jet kinks [2], kinking identified as a source of spheromak poloidal flux amplification [3]
- (New textbook [4]).

[1] Bellan, Phys. Plasmas 10, 1999 (2003)
[2] Hsu and Bellan, Monthly Notices Royal Astron. Soc. 334, 257 (2002)
[3] Hsu and Bellan Phys. Rev. Lett. 2004
[4] Fundamentals of Plasma Physics, P. M. Bellan 2006

The Swarthmore Spheromak Experiment

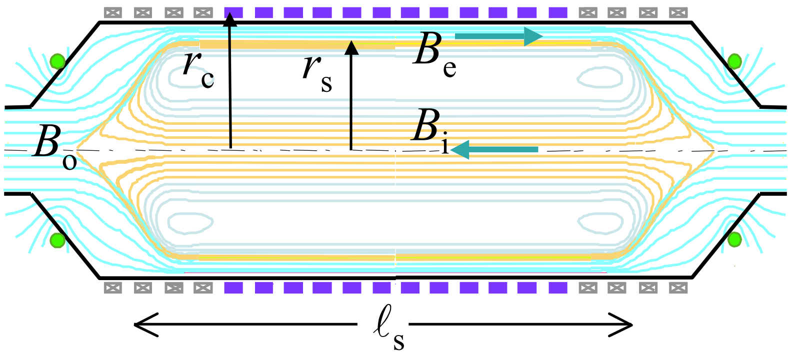




Achieved:
•Dynamical measurement of 3D magnetic geometry in merging experiments.
•Measurement of bi-directional jets with 1.33 m ion Doppler spectrometer.

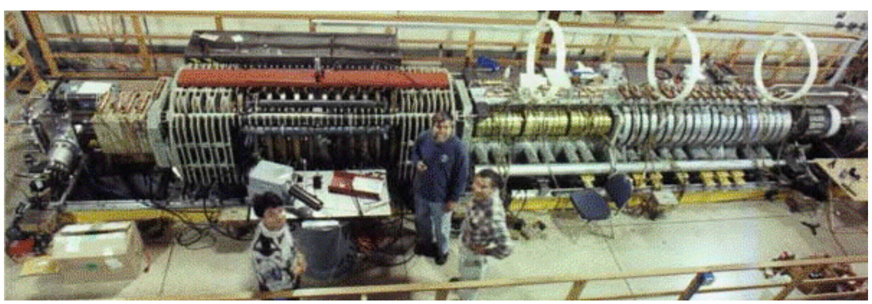
Plans:
•Continued study of doublet FRC, flux-core dipole-trapped spheromak, and other novel CT configurations
•Comparison of IDS flow measurements with 3D simulation (HYM, NIMROD, MH4D, etc)
•Merged spheromaks in oblate flux conserver (tilt stable)

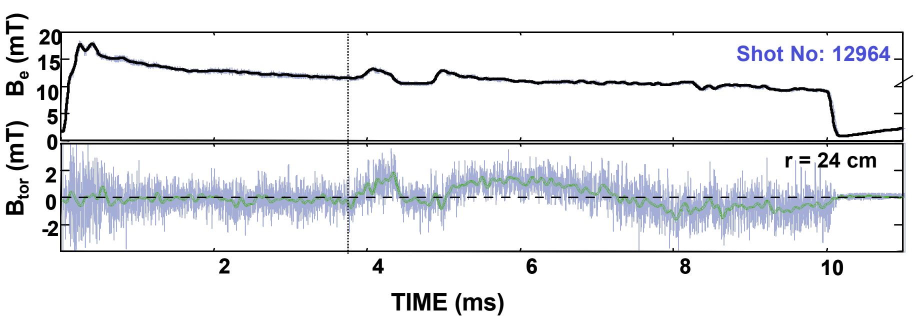
The TCS Field Reversed Configuration (FRC)



U. Washington TCS Experiment
(Translation, Confinement, Sustainment)

$r_c = 0.42$, $\ell_s = 2.5$ m





Potential Advantages:

- Very high β.
- Simple linear geometry.
- Natural divertor: unrestricted flow out ends.

True steady-state operation with rotating magnetic field (RMF) current drive

Greatly enhanced stability

Calculations point way to complete stability

High temperatures produced by fast formation should be achievable with slow formation in new improved vacuum system

A UW / PPPL collaboration using RMF & TNBI could result

Princeton FRC Experiment

Program: test theoretical predictions that odd-parity RMF can form, confine, heat, and stabilize FRC plasma

FY06 accomplishments

Plasma formation at sub-mT fill pressures

Added capabilities: Hall effect probe, diamagnetic loops, 170 GHz interferometer, 2 divertors

Characterization of internal flux conservers

New method to measure RMF penetration

Operation of components at full design parameters:

B_v to 400 G; RMF power to 10 kW;

Pulse length 5 ms; 1% duty factor

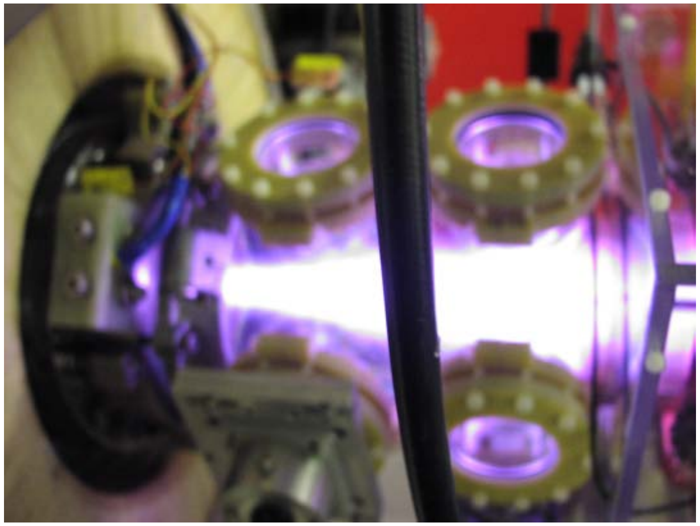
B_{RMF} to 15 G; Density to 10^{13} cm^{-3}

Phys. Rev. Lett. on ion heating theory

PhD produced: A. Landsman

Graduate students: N. Ferraro, D. Fong, D. Lundberg, A Roach   Undergraduate: D. Olivan

Collaborators: A. Glasser (LANL), E. Scime (WVU), G. Zaslavsky (CIMS)



Plasma well separated from Pyrex vessel

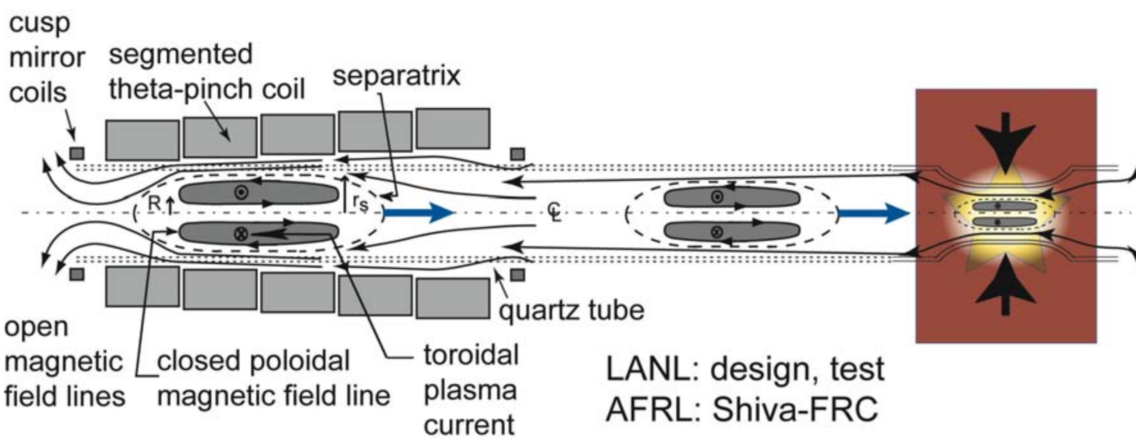
Goal: Research aimed at the development of a clean, compact, steady-state, reliable, and practical fusion reactor.

- Operation at 100 kW RF power
- Superconducting components to extend pulse length

LANL/AFRL Magnetized target fusion physics compression of FRC

Los Alamos

Formation: LANL Translation Compression



- The plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- The plasma density is high ~10^{19} cm^{-3}
- The current density can be 1000 MA/m^2
- The magnetic field confining the plasma is 500 Tesla !
- The auxiliary heating power level is ~ 1000 Gigawatts !

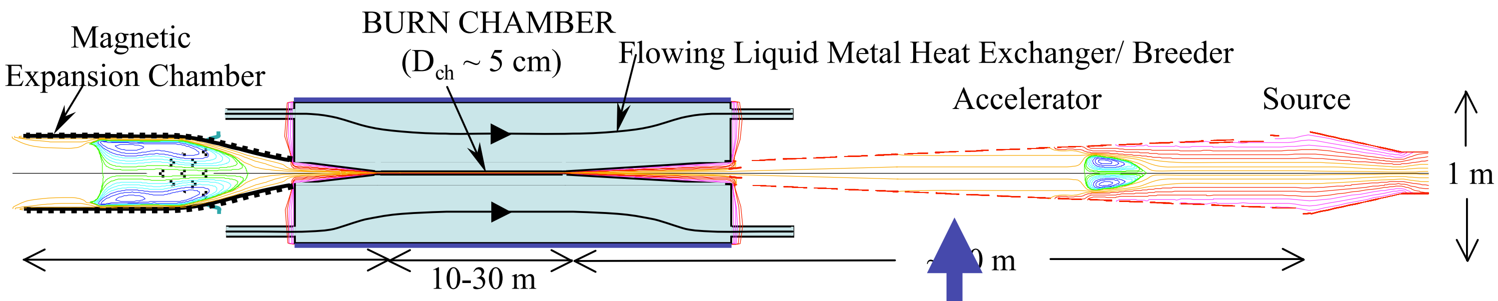
Potential Advantages:

- Pulsed, high pressure. No materials issues with liquid walls.
- Simple geometry
- Hybrid of inertial and magnetic confinement

NNSA

MSNW

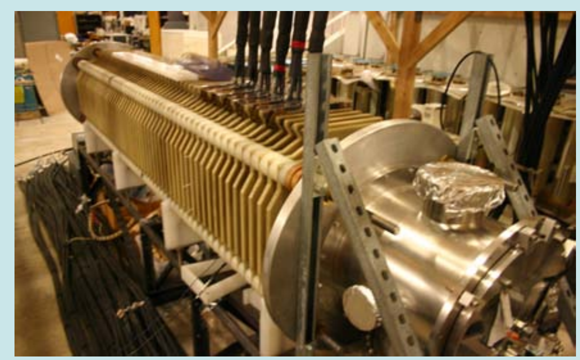
Pulsed High Density (PHD) Experiment



Potential advantages

- Minimum B field at highest plasma pressure (β~1)
- Simple linear system.
- Variable output power ~ 10-100 MW not multi-GW
- Burn chamber well separated from plasmoid formation/heating.
- Direct electric power conversion with expansion of fusion heated plasmoid
- Low mass system directly applicable to space propulsion
- Key physics and scaling have been demonstrated
- Potentially, lower development cost.

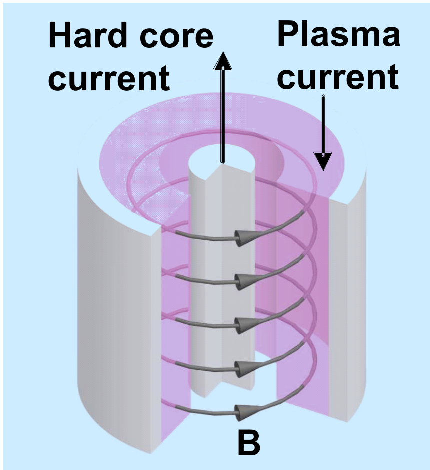
Energy required to achieve fusion conditions is transferred to FRC plasmoid from array of axially sequenced coils.

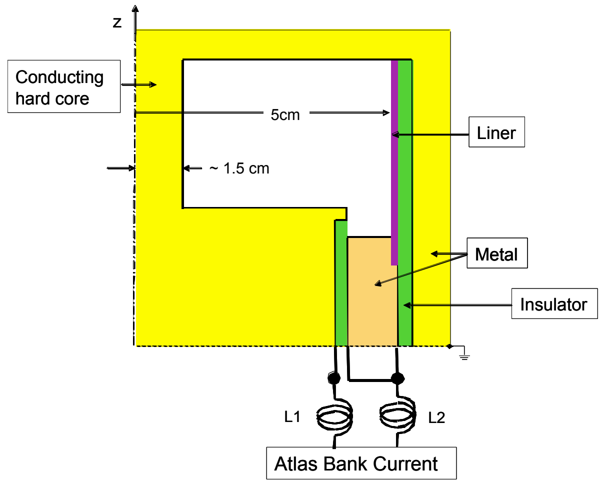


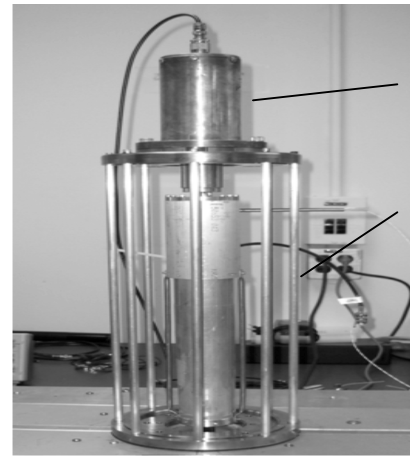
Current experiment to create initial FRC plasmoid.

UNR

Diffuse pinch experiment studies wall-plasma interactions & confinement



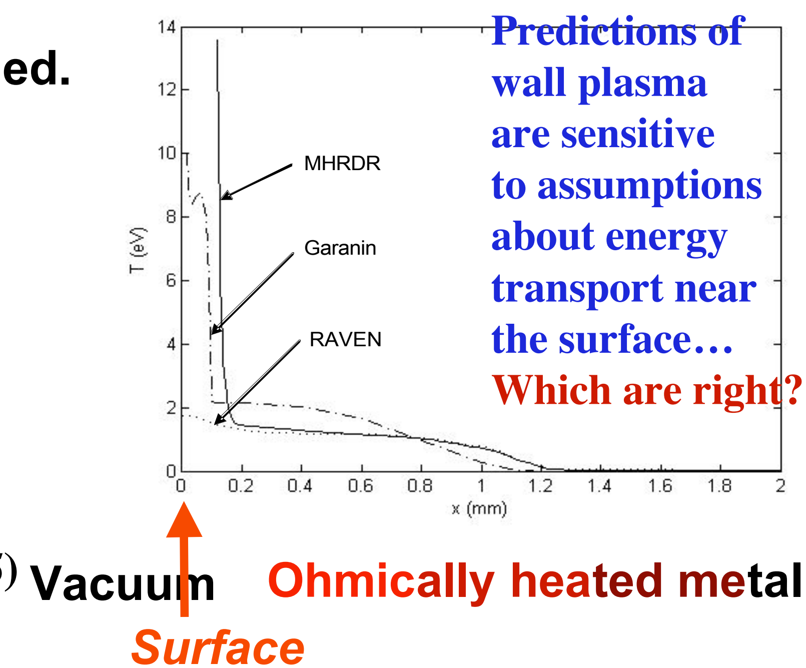




Initially flux-compression experiments planned.

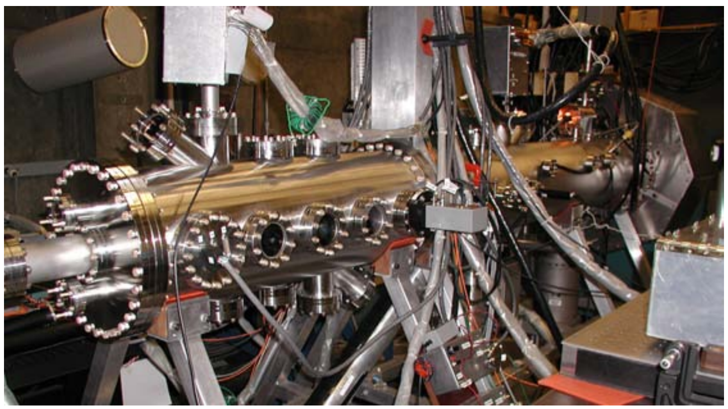
Follow-on experiments to use plasma pinch.

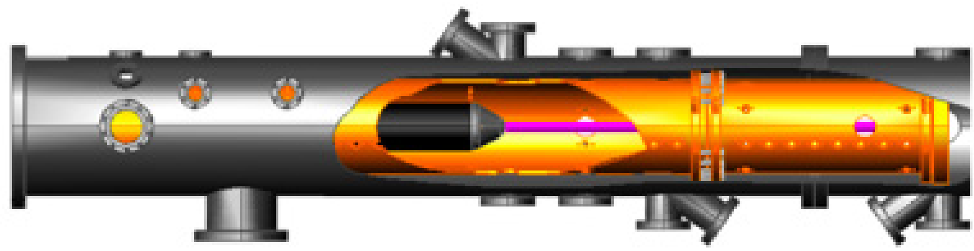
1. **Self-organization observed numerically**
   Makhin et al., Phys. Plasmas 12, 042312 (2005)
2. **Potential for fusion reported at IAEA**
   Siemon et al., Nuc. Fusion 45, 1148 (2005)
3. **Experimental design presented at APS**
   Siemon et al., Makhin et al., 47th APS-DPP (2005)

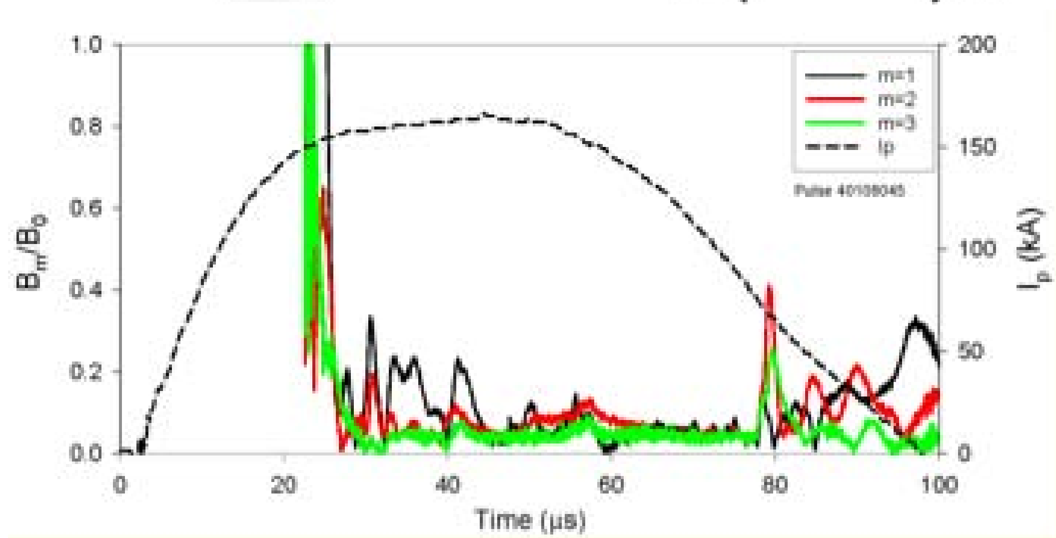


ZAP Z-pinch produces a stable column by providing a shear in the velocity.

To generate a Z-pinch configuration with an embedded axial flow the ZaP experiment couples a coaxial accelerator with a pinch assembly region.







Potential Advantages:

- linear system
- no coils
- natural exhaust.

[1] U. Shumlak et al PHYSICS OF PLASMAS VOLUME 10, 2003

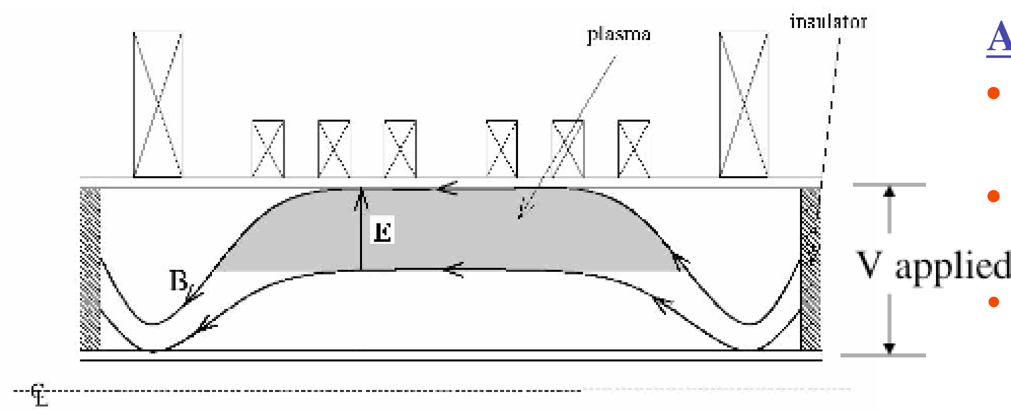
[2] R. P. Golingo and U. Shumlak REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 74, NUMBER 4 APRIL 2003

MARYLAND CENTRIFUGAL EXPERIMENT

Mission *Create a supersonic rotating plasma to augment magnetic confinement by centrifugal force and stabilize flute modes with velocity shear.*

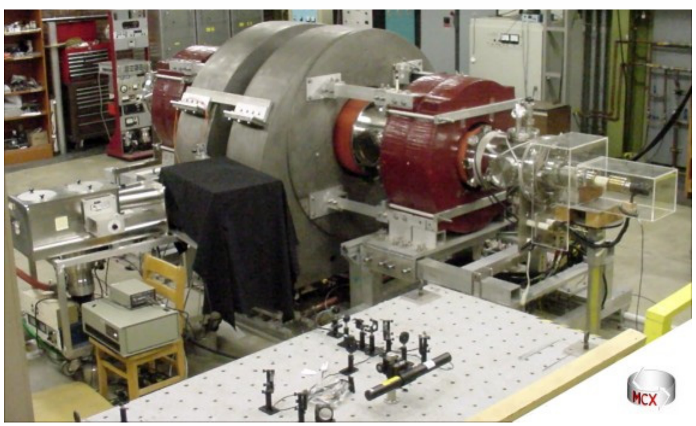
Potential Advantages:

- Simple linear geometry
- Natural divertor: unrestricted flow out ends.



Achievements

- **Supersonic Rotation**: ***ExB*** *rotation up to Mach 2.5, T_i ~ 40 eV*
- **"HR-mode"**: *High rotation mode discovered, x2 better confinement*
- **V' Shear measured**: ***exceeds theoretical criterion (multi-chord spectrometer)***



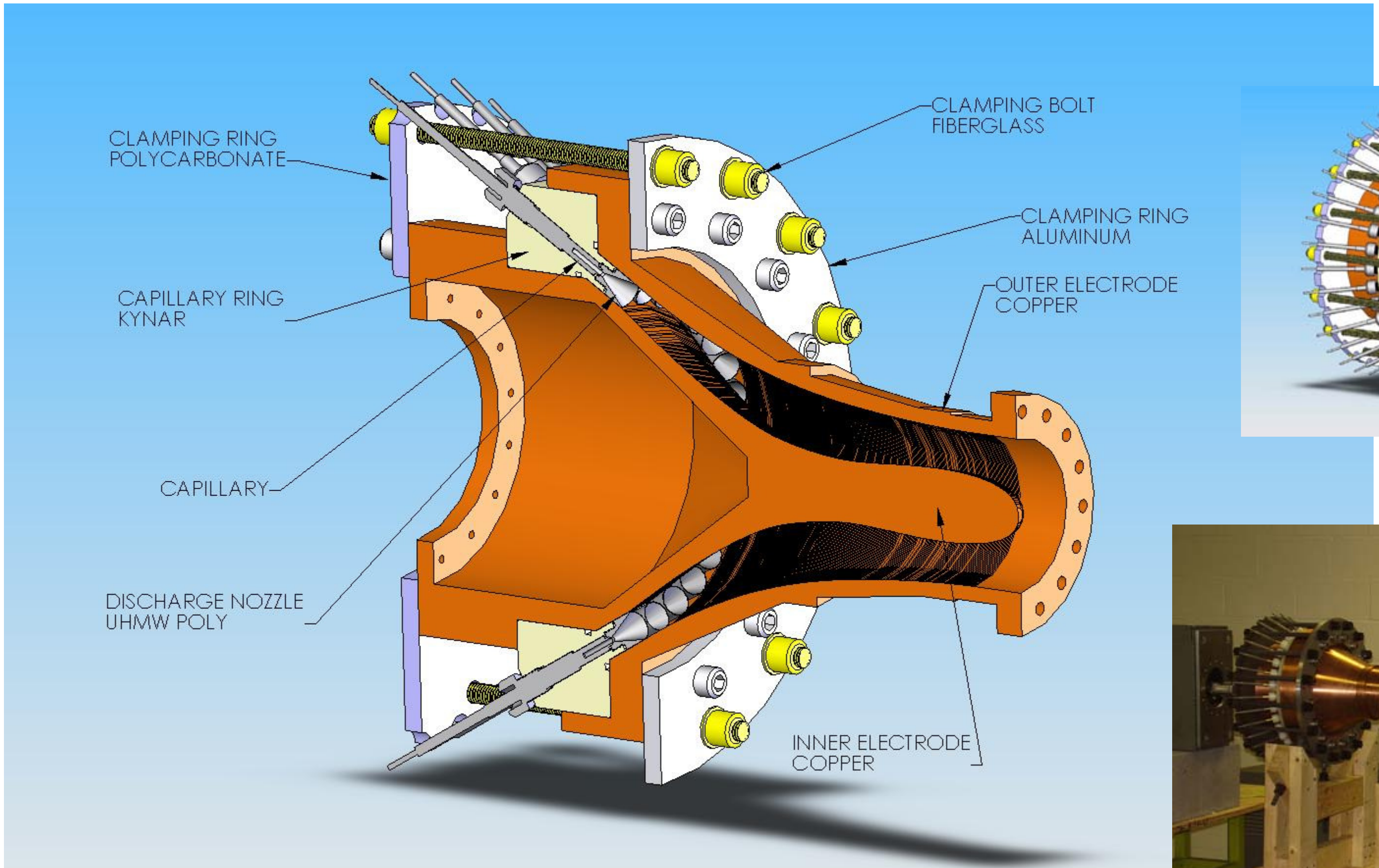
Plans

•**Confinement scalings:** *parametric scans, optimize and hold HR mode*

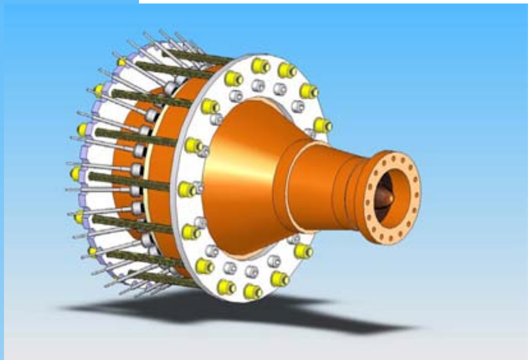
•**Plasma jet injection**: *off-axis momentum input (with HyperV Corp.)*

Plasma Jet Using Capillary Discharge Injectors

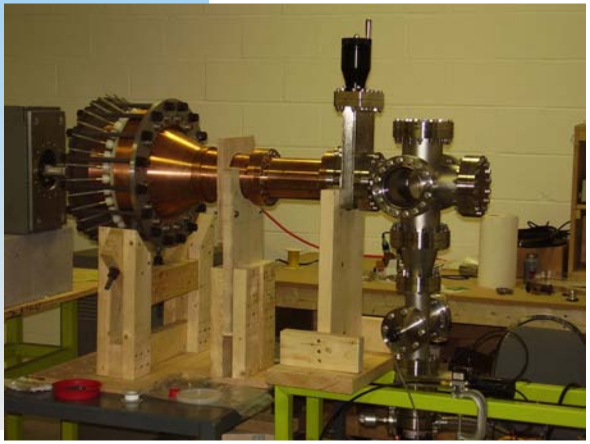
Initial Use on MCX uses Ablative Polyethylene Capillaries



Cutaway View of Accelerator



Exterior View



<u>Technical Objectives</u>:

- > 200 km/s
- > 100 microgram
- > Mach 10
- 10^{16} - 10^{17} cm^{-3}

<u>Nominal Injection Parameters</u>:

- 10^{19} cm^{-3}
- 1 - 5 eV
- 10-20 km/s
- few kA in each of 32 capillaries
- 100-200 kA main discharge

Theory efforts support ICC experimental programs.

FRC Theory and Modeling
PI: Belova, Davidson,
H. Ji, M. Yamada (PPPL)

Develop and apply state-of-the-art numerical simulations to provide an improved understanding of FRC formation and stability properties; validate the theoretical models, and improve agreement between theory and existing experimental results; provide theoretical support and guidance for FRC experiments.

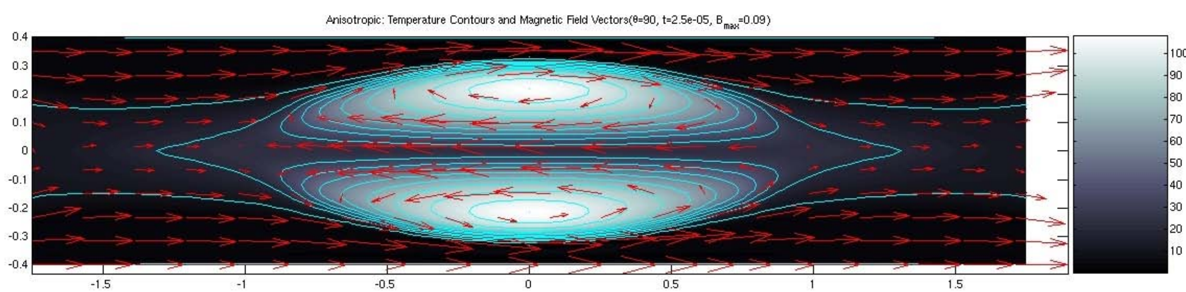
NIMROD Team
U.Wisc - PI: Sovinec

3D resistive MHD simulations with the NIMROD code address fundamental physics in many ICC and tokamak expts.

Team encompasses collaborators from LLNL, LANL, UWs, GA, MIT, SAIC…

PSI Center - U. Washington PIs: Jarboe, Milroy

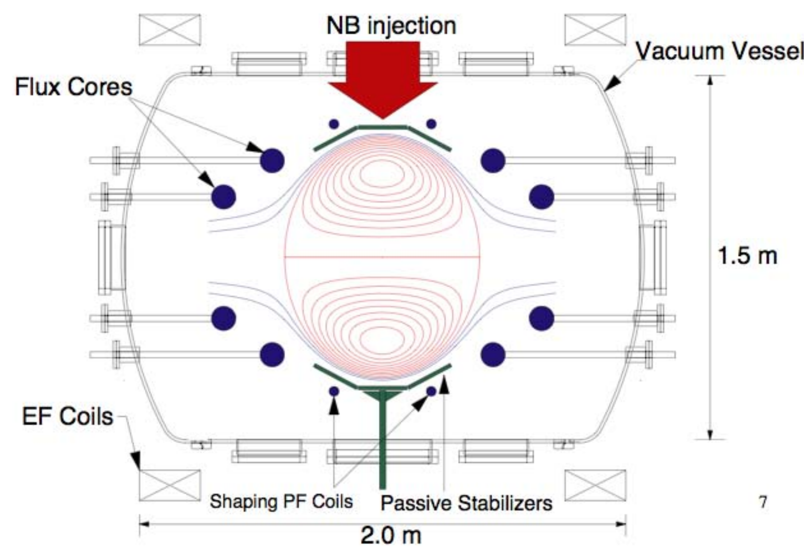
In concert with experiments refine present computational tools with sufficient physics, boundary conditions, and geometry to be calibrated with experiments and achieve improved predictive capabilities.



Annual ICC conference:
This year, the Innovative Confinement Concept workshop hosted by the University of Texas, Austin entailed 115 contributed papers, 37 oral presentations on most of the ICC concepts in the US (plus one from Italy, one from Russia), organized into six sessions --> Special edition of JoFE.

Fusion Skunkworks: new ideas, including patents.

New Proposals, e.g.:
SPIRIT - Ji *et al* PPPL
Flux-Core ST - Hsu *et al* LANL



Collaborations with new NSF Centers (e.g. CMSO @ UW)

Summary

- **Cutting-edge** plasma science across the nation (20 research groups at national labs and universities).
- Experiments are fundamentally **changing the paradigm**: confinement and current drive results are encouraging.
- Premier method to **train the next generation** of plasma researchers (more than 100 students/year).
- The US program **leads the world** in concept innovation.
- Small-scale experiments (1-2M/year) address important scientific questions in the national program.