Status of
MFE Alternate Concepts

Innovative Confinement Concepts

FPA Symposium on Fusion & Energy Policy

Oct. 12, 2005

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LA-UR-05-7679

Innovative Confinement Concepts
Why do we have an ICC Program?

- There may be "better" solutions to confining a plasma
- Arguably, the US program leads the world in plasma confinement innovation.
- It allows cutting-edge plasma science across the nation, in a distributed, cost-effective manner.
- It's focus on small-scale experiments as the premier method to train the next generation of plasma researchers (more than 100 students/year)
- It provides outstanding venues to test ideas for implementation on mid and large scale fusion devices.
- ICC's are the "Skunkworks" of the fusion program

Innovative Confinement Concepts
What kind of science & engineering issues are addressed*?

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?
T11. How do electromagnetic waves interact with plasma?

T8. How do hydrodynamic instabilities affect implosions to high energy density?
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?
T12. How do high-energy particles interact with plasma?

T13. How does the challenging fusion environment affect plasma chamber systems?
T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

* From the FESAC Priorities Panel Report, April 2005

U.S. Fusion Program Participants

ANL	Argonne National Laboratory
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PPPL	Princeton Plasma Physics Laboratory
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory

● NATIONAL LABORATORY ● UNIVERSITY ● INDUSTRY ● INTER-GOVT AGENCY

MARCH 8, 2005

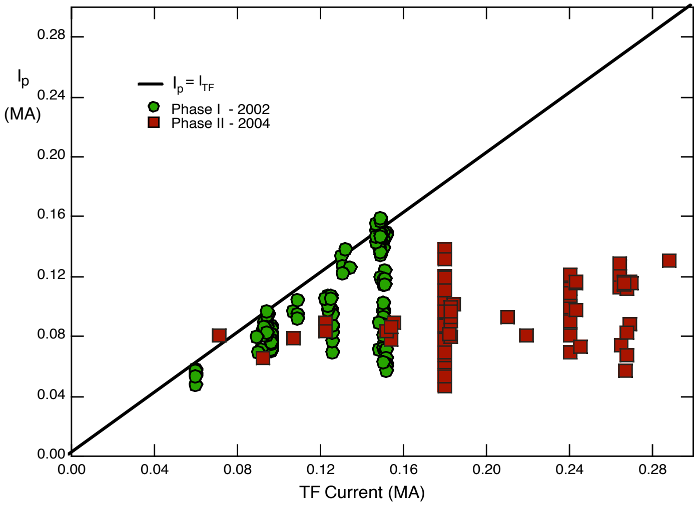
ICC – CE Program supports many concepts ($20.8M)

"Strong External B field"		"Advanced Toroidal and Other"		
Tokamak innovations & physics	**Stellarator**	**Self-organized**	**high-pressure and high-B**	**Other**
HBT-EP Resistive-wall stab. Tokamak trans. phys. Divertor innovation Pegasus HIT-II LTX	HSX CTH QPS	Spheromak (SSPX, HIT-SI, CalTech) FRC (TCS-rotomak, Odd-parity RMF, SSX, Theory & Misc.)	Magneto-Inertial Fusion (FRX-L, Solid liner, theory, stand-off driver) Inverse Z-pinch Accelerated FRC Flow Pinch (ZAP) CT Accel Plasma jets	LDX Mary. Centr. Exp. Magneto-Bern. Exp. Inert. Elect. Conf. ICC Center
$3.9M	**$3.4M**	**$6 M**	**$4M**	**$3.5M**

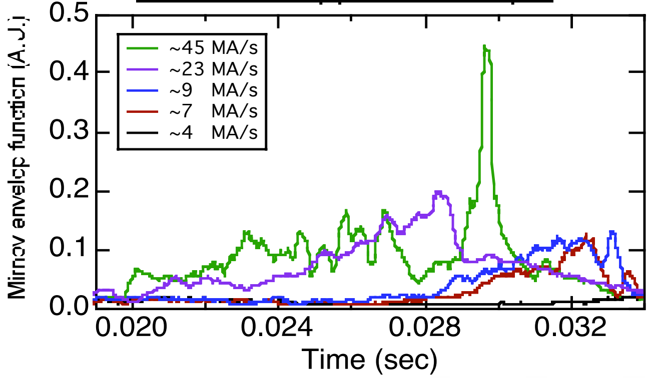
PEGASUS Spherical Tokamak: Explore plasma limits as A → 1

- Stability and confinement at high I_p/I_{TF}: Limits on β_t and $I_N \sim 6I_p/I_{TF}$ (kink) as A→1
  - Low field, OH and HHFW → high I_N & β_t

- Recent Accomplishments:
  - Almost all-new laboratory facility built
    - Programmable & controllable coil currents
    - New low-L TF system
  - First plasma with new facility
    - Low-power OH
    - Extend TF operating range
    - Recovered earlier low-A, low-l_i regime
- Present campaign:
  - New high-power OH system deployed
  - Employ new control tools to suppress MHD
  - Extend operating space to move to $I_p/I_{TF} > 1$



1st MHD suppression expts



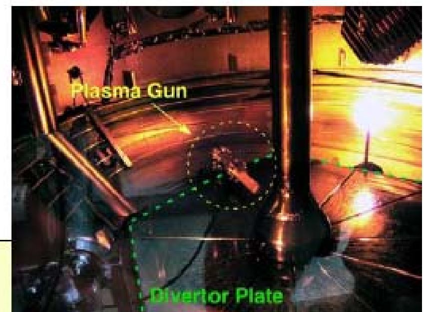
PEGASUS FY06: High I_N, Noninductive ST Formation, Heating, CD

- **FY06: a 3-pronged campaign proposed**

1) Use new tools to explore low-A, high I_N, high β_t regime

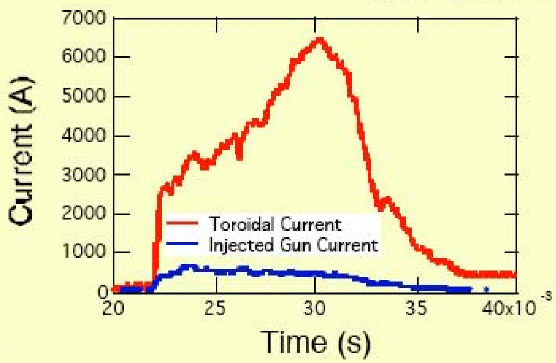
2) High-power ST EBW tests at 2.45 GHz (w/PPPL)

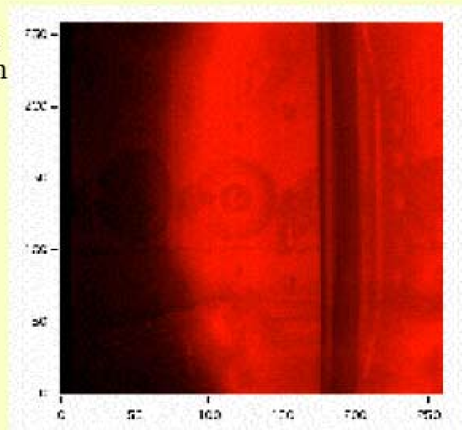
3) Extend non-inductive startup with local plasma current gun array

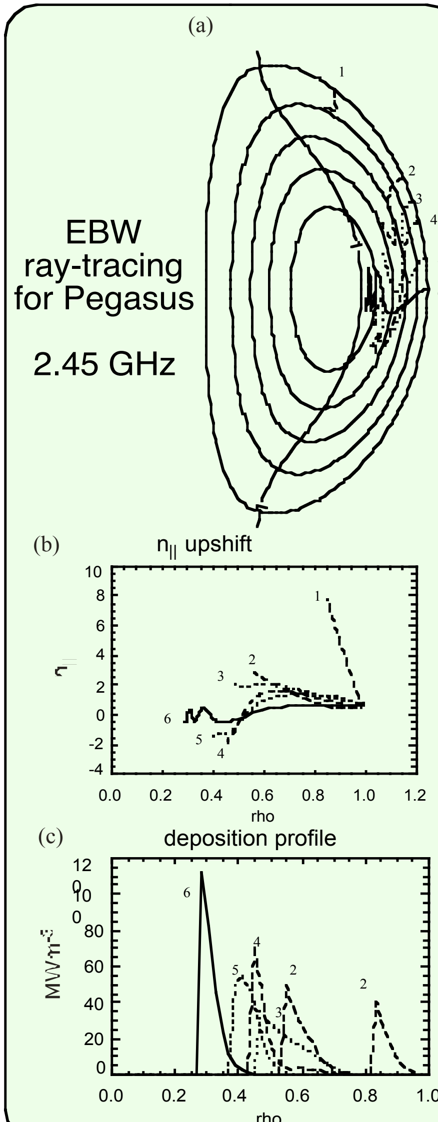


SN 24438 Vbias = 400 V
Single gun in lower divertor region:

High current => Filaments Merge
Net amplification







Results from the CDX-U/LTX lithium program

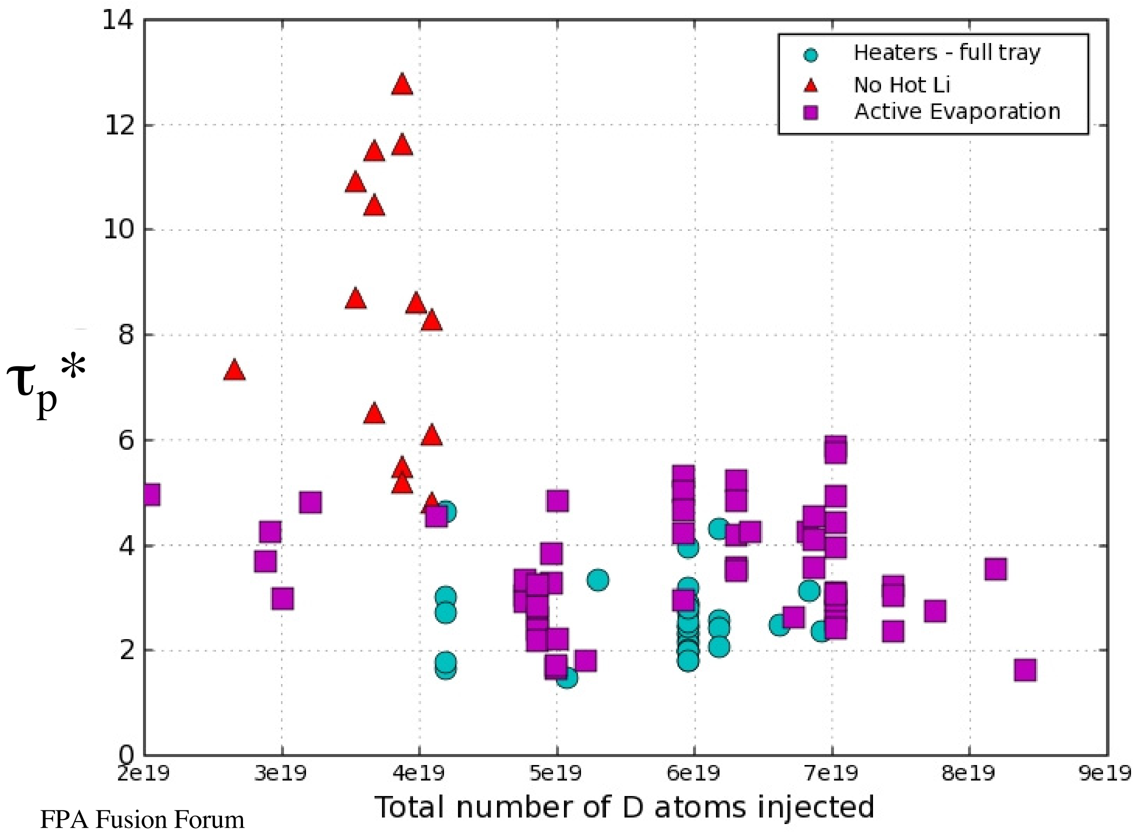
CDX-U

- The Lithium Tokamak program on CDX-U and LTX is designed to investigate very low recycling regimes. Offers a *fundamental change* in magnetic confinement:
  - Elimination of electron conduction losses, control of the density and temperature profiles through fueling, improved stability.
- CDX-U experiments with a 2000 cm^2 liquid lithium filled limiter complete. **Results:**
  - Recycling is greatly reduced.
    - » Factor-of-eight increase in gas puffing is required to maintain density.
    - » Plasma density pumps out in ~ 1 τ_E without strong gas puffing.
  - Record low loop voltages for ohmically driven small tokamaks.
    - » Resistive loop voltage at constant plasma current only 0.3 - 0.5V.
      - ***6 - 10 ×*** reduction in V_{loop} compared to nonlithium operation.
      - Comparable to ***TFTR*** ohmic loop voltage.
  - 10 × reduction in oxygen radiation.
  - 2.5 × increase in ion temperature.
  - 50% increase in edge electron temperature.
  - Broader current profiles. 2 × reduction in internal inductance.
  - *No ejection of lithium,* due to design of the limiter (lithium surface, currents ‖ **B**).
- Progress towards LTX:
  - Lithium coating systems undergoing first tests.
  - Conformal shell (main LTX component) is in fabrication.

Record low recycling achieved in CDX-U

CDX-U

- The effective particle confinement time with recycling, $\tau_p^* \equiv \tau_p/(1\text{-}R)$, where R is the recycling coefficient, is reduced dramatically with liquid lithium limiters and wall coatings
- Lowest τ_p^* corresponds to <50% recycling
  - Previous record (TFTR) 70-85%



- CDX-U particle pumping rate is 1 - 2 × 10^{21} part/sec.
- Sufficient to pump a TFTR supershot
  - But the active wall area in CDX-U is only 0.4 m^2
  - *~Two orders of magnitude* less than the active wall area in TFTR during lithium wall conditioning.
- Note that shots with bare walls (no lithium at all) have τ_p^* too long to measure

Helicity Injected Torus (HIT) Program

- The goal of the HIT program is to develop helicity injection current drive, which has the potential of being a very efficient steady state current drive. Presently, we are studying steady inductive helicity injection on a high-beta spheromak.
- Recent achievements with CHI on the ST HIT-II
  - Achieved 100 kA of closed flux current with transient CHI. This is a solenoid free startup with no time variations in the flux boundary conditions.
  - Discovered criteria for poloidal flux amplification and the possibility of closed flux sustainment with steady state CHI. Requires:

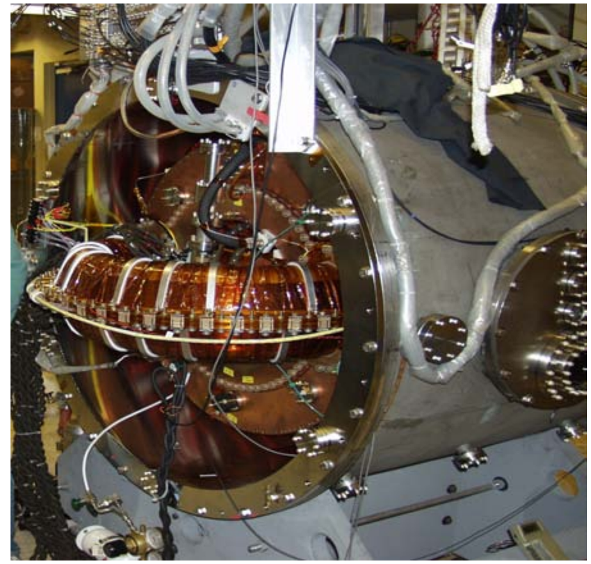
$$I_{TF} < 27 I_{inj}$$

  - Achieved 350 kA in this regime
  - Demonstrated edge profile control
  - Application of CHI on NSTX

HIT-SI experiment

Recent accomplishments on HIT-SI experiments

- Diagnostics
  - Installed HIT-SI on HIT facility ⇒
  - Interferometry
  - Spectroscopy
  - Magnetic probe arrays
- Machine improvements
  - Changed from parallel to series resonance driving circuit. (better voltage control)
  - Baked to 110 °C (base 3×10^{-8} torr)
  - Retractable RF glow electrodes
- Measurements:
  - Density ~ $10^{19} m^{-3}$
  - Injector current ~ 10 kA
  - Peak magnetic fields in spheromak region ~ 0.4 kG
  - Structure of magnetic field to be determined



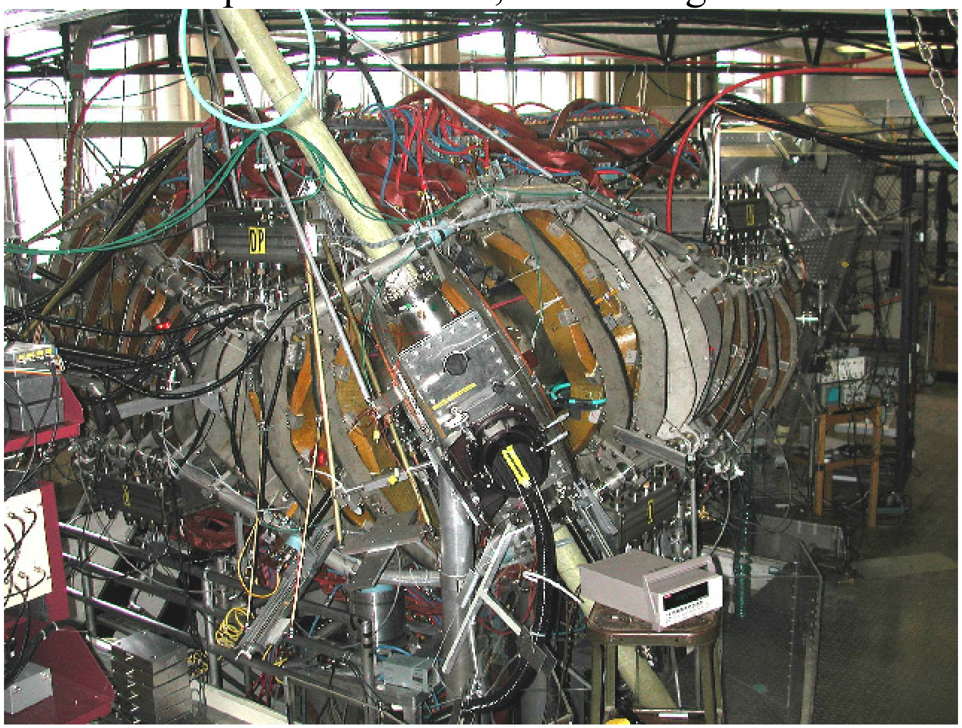
HIT-SI experiment

The HSX Program: World’s First Experimental Test of Quasi-symmetry

Mission: Explore Improvement of Neoclassical Transport in Stellarators

Quasihelical stellarators have high effective transform, $\iota_{eff} \sim 3$ (q~1/3)

- Reduced particle drift
- Small neoclassical transport
- Low plasma currents; robust magnetic surfaces



R=1.2m, <a>=0.15m B = 1.0 T
4 periods, ECH 28GHz 200 kW

- **First experimental verification of reduced flow damping with quasi-symmetry**
- **Confirmation of high effective transform and reduction of direct loss orbits**
- **Fast particle effects on MHD modes observed due to improved confinement**
- **Observation of reduced neoclassical thermodiffusion**
- **Experimental verification of 3D neutral code DEGAS**

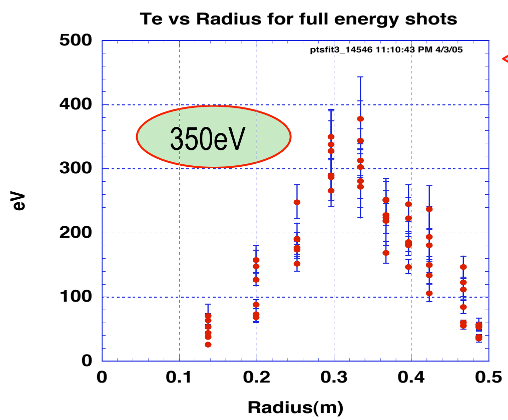
Near-term Plans

Operation at B =1.0 T

Heating power up to 400 kW

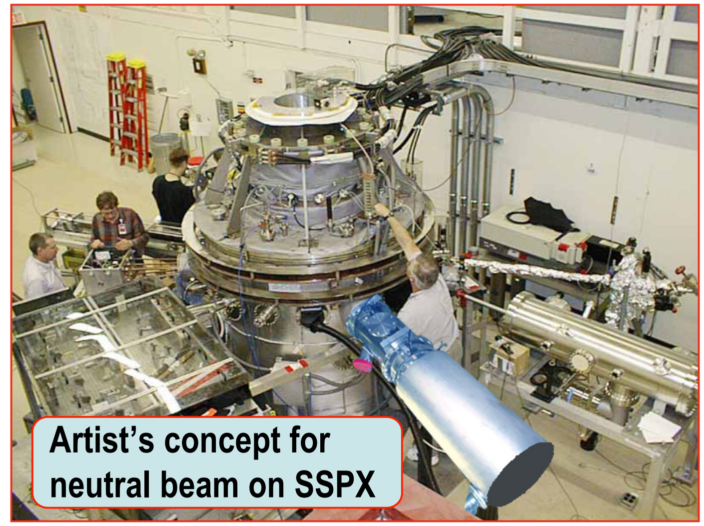
Measurement of core fluctuations and radial electric field

High electron temperatures in SSPX open new regimes for studying energy transport in driven spheromak plasmas



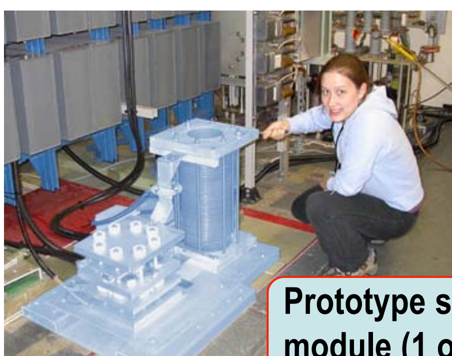
Recent results motivate adding neutral beam heating to SSPX: transport & pressure limit studies.

Beams (1.8MW total) from the Budker Institute in Russia.

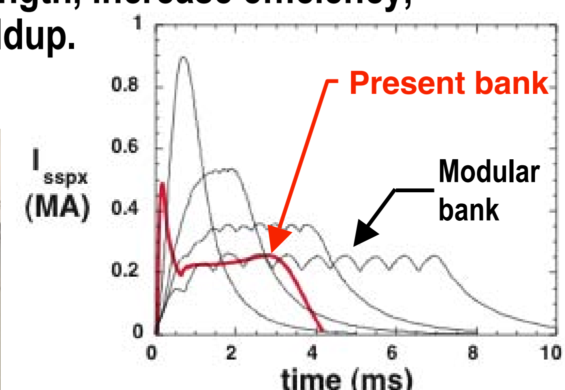


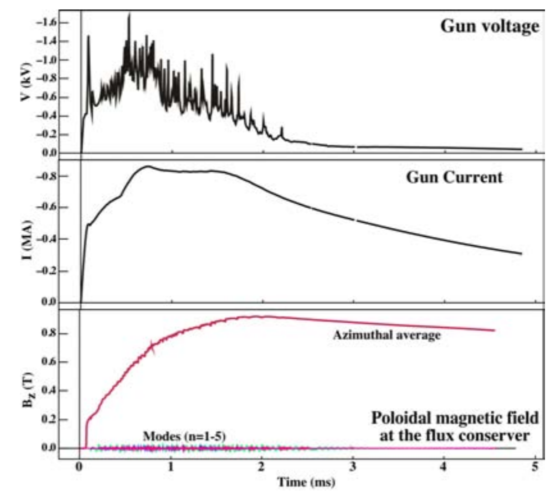
Artist's concept for neutral beam on SSPX

Now installing a solid-state modular capacitor bank to extend pulse length, increase efficiency, explore multi-pulse buildup.



Prototype solid-state module (1 of 30 required)





NIMROD 3D MHD code simulates buildup with SSPX modular bank.

Caltech ICC Program   PI: Paul Bellan

"Determining how spheromak self-organization works"

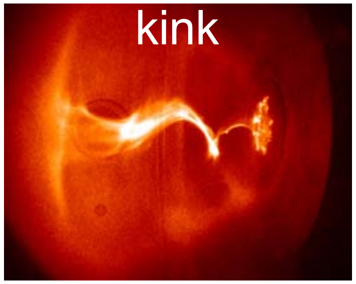
Method: Use planar magnetized plasma gun experiment designed to reveal essential spheromak formation physics, diagnose with high speed photography, magnetic probes, spectroscopy, interferometry, x-ray detectors

Issues being addressed:

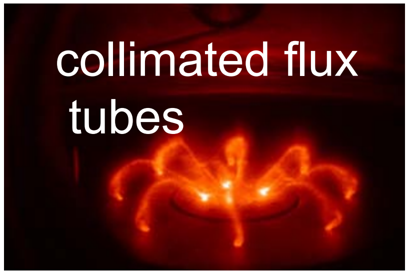
- Plasma is just "there" (but how did it get in?)
- Taylor relaxation assumes zero beta, but need pressure gradients for confinement
- Taylor relaxation assumes symmetry, but Cowling's theorem shows that symmetry must be broken to create poloidal flux
- Relaxation changes topology, but how does topology evolve?

Results obtained so far:

1. **Kink instability found to be fundamental to both relaxation process and topological evolution**
   - toroidal to poloidal flux conversion observed to result from kink instability
   - this is essential basic mechanism for relaxation to spheromak
   - ref: S. C. Hsu and P. M. Bellan, Phys. Rev. Letters **90**, article 215002 (2003)

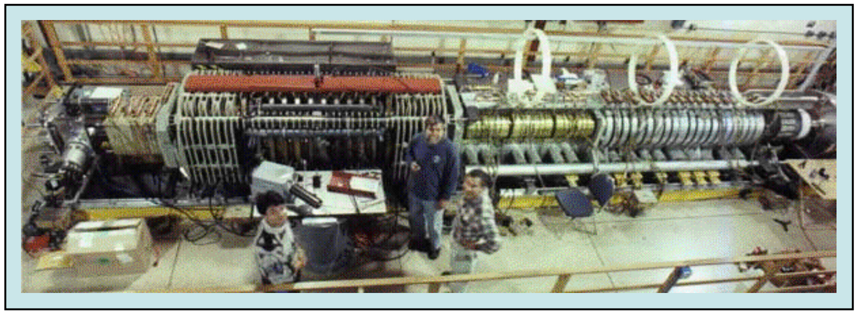


2. **High-speed plasma inflows (jets) are found to be a critical feature**
   - driven by **J**x**B** forces which *ingest* plasma from *wall source*
   - fast inflow velocity ~v_A observed, 10-50 km/s
   - gas source geometry critically affects plasma geometry
   - closely related to astrophysical jets
   - magnetic field geometry dictated by inflow behavior (magnetic flux convected with flow)
   - ref: S. You, G. S. Yun, and P. M. Bellan, Phys. Rev. Lett. **95**, art. 045002 (2005)



3. **Uniform plasma, zero beta assumption is found to be inappropriate**
   - stagnation of flow gives jet collimation and high, localized density
   - get bright, dense, *collimated* flux tubes
   - ref: P. M. Bellan, Phys. Plasmas **10** Pt 2, 1999 (2003)

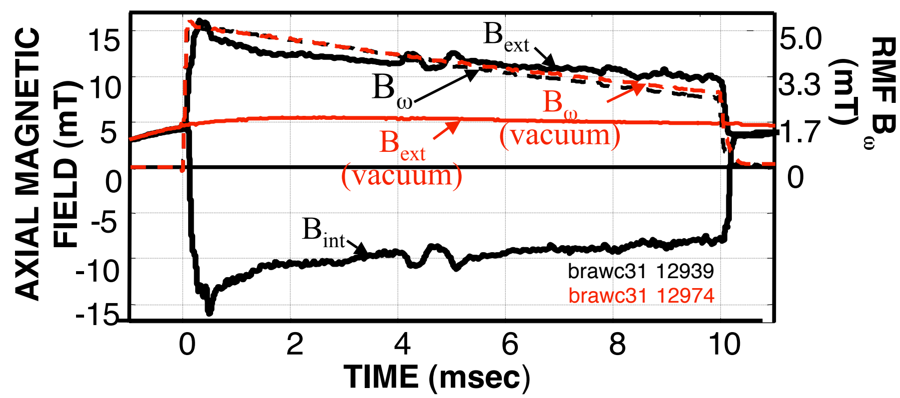
TCS FRC Sustainment Experiment



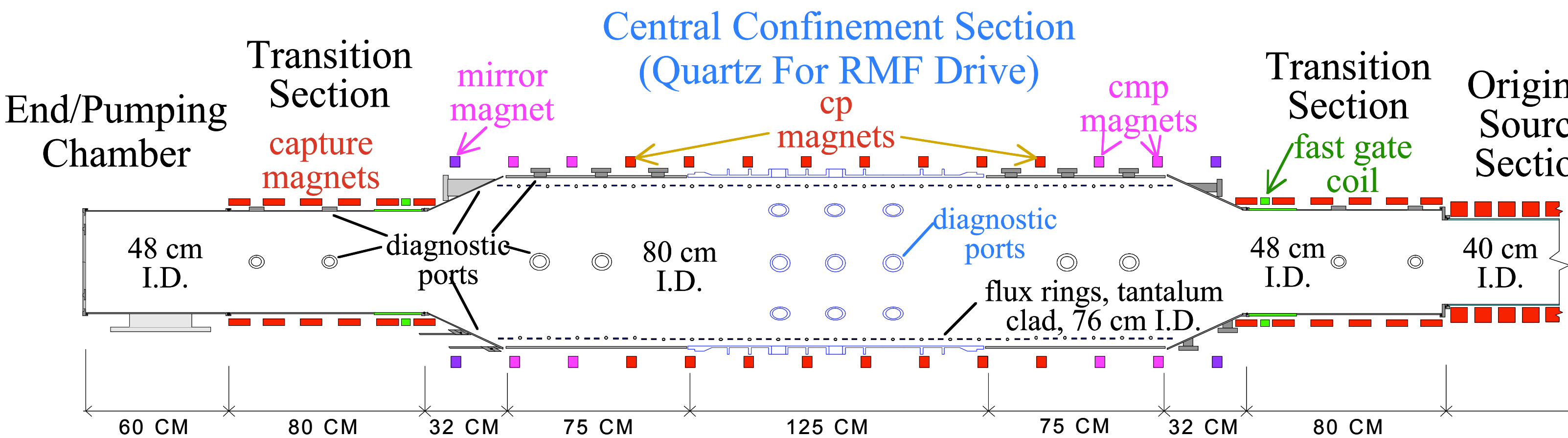
- The overall objective is to produce and sustain hot FRCs using technology that can be extended to large sizes. FRC formation and sustainment using RMF has been demonstrated, in agreement with a comprehensive supporting theory that has been developed.
- Currently building a clean, bakable, UHV chamber as required to form and sustain hot FRCs.
- Additional heating and current drive methods will be developed in the future to produce large s.

Notable Achievements

- Sustained FRCs in quasi-steady state with no sign of destructive instabilities.
- Developed theory & demonstrated strong RMF stabilization of high β plasmas.
- Observed natural relaxation to high β compact toroid in both translated and stationary FRCs with enhanced τ_{conf}.
- Key demonstration of closed field line confinement enhancement using anti-symmetric RMF drive, as previously postulated.
- Quality of energy confinement has been improved by a factor of 5 over the last three years in terms of the electron thermal diffusivity
- 2005 Physical Review Letter on translating FRC stability against n=2 mode



FY07 Plans & Budgets for TCS/upgrade



- TCS/upgrade will be run in a clean, high vacuum environment with a baked, discharge cleaned, and wall-conditioned plasma chamber.
- Anti-symmetric RMF current drive will be applied to maximize temperatures and energy confinement times.
- Multi-point Thomson scattering will be employed to measure $T_e(r)$.
- Additional heating and current drive methods will be developed towards production of large s.

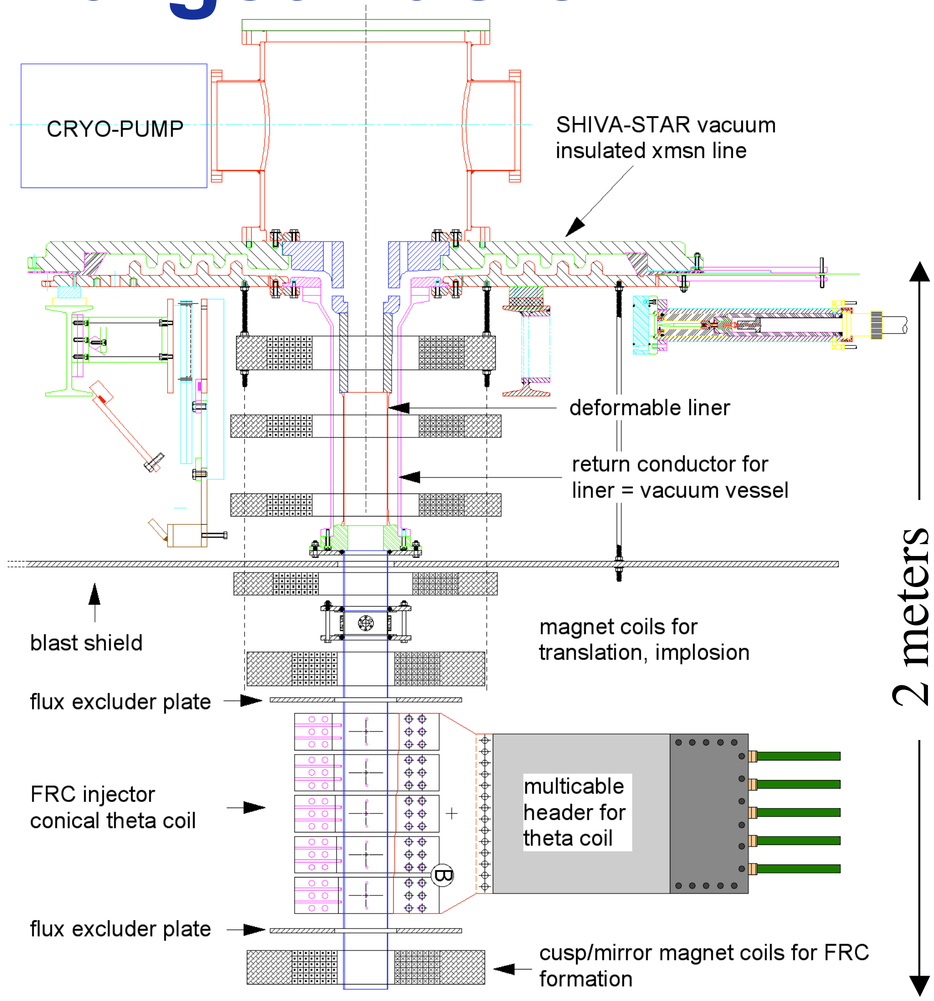
- Personnel & lease yearly costs ~ $1,250,000.
- Operational and equipment costs ~ $250,000
- University Overhead ~ $250,000
- Total Cost ~ $1,750,000

Magnetized Target Fusion

Proposed

"liner on plasma experiment"

- FRC formation in conical theta coil
- Robust translation v≈12cm/msec
- compression with tested deformable liner
- Integration of LANL front end with AFRL Shiva-Star implosion bank
- FY 2007 schedule for liner on plasma shots



integrated liner on plasma design
- FRC formation with conical theta coil
- translation region
- tapered, deformable 30 cm tall liner, tested 2004, 2005 shots

FRX-L newest results: double previous parameters

Improved crowbar switch decreases main bank modulation

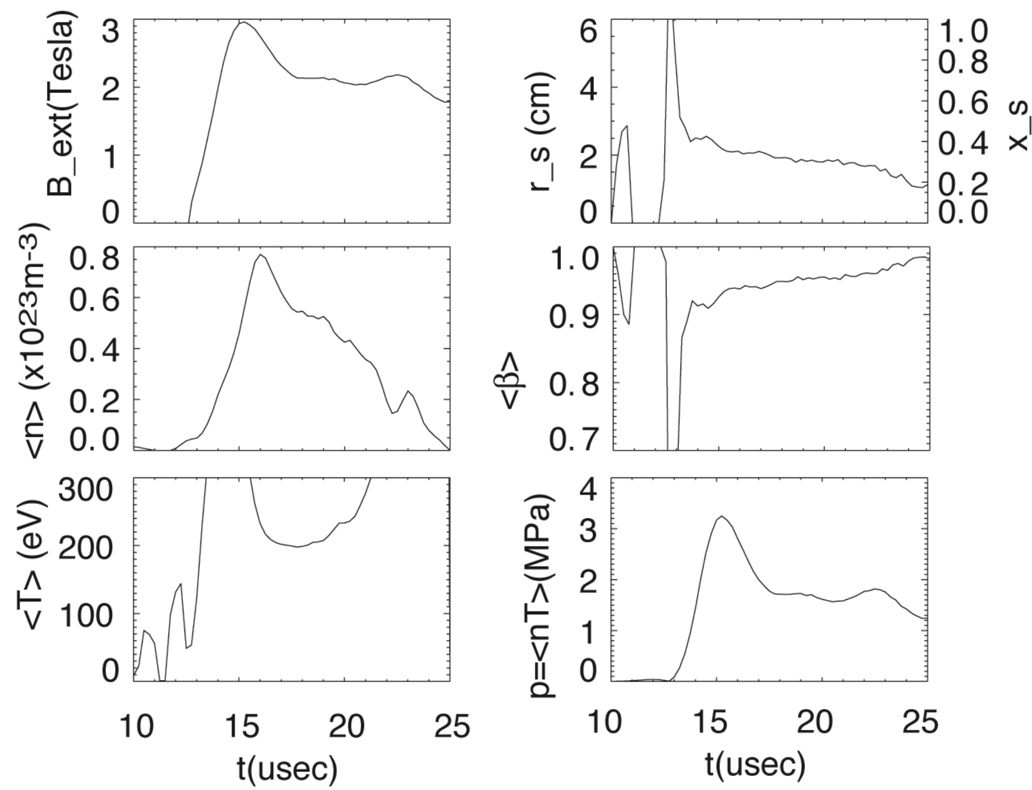
- Pressure

$\langle nT \rangle \approx$ 20-30 atm

- Lifetime $\tau_\Phi \approx$ 6 μsec

*Longest lifetime ~15 μsec

- Density n ≈ $5\text{x}10^{16}\text{cm}^{-3}$
- $T_e + T_i \approx$ 220 eV
- Axial position diagnostics indicate most apparently "short lifetime" FRC's are instead already translating out of the central theta-coil region



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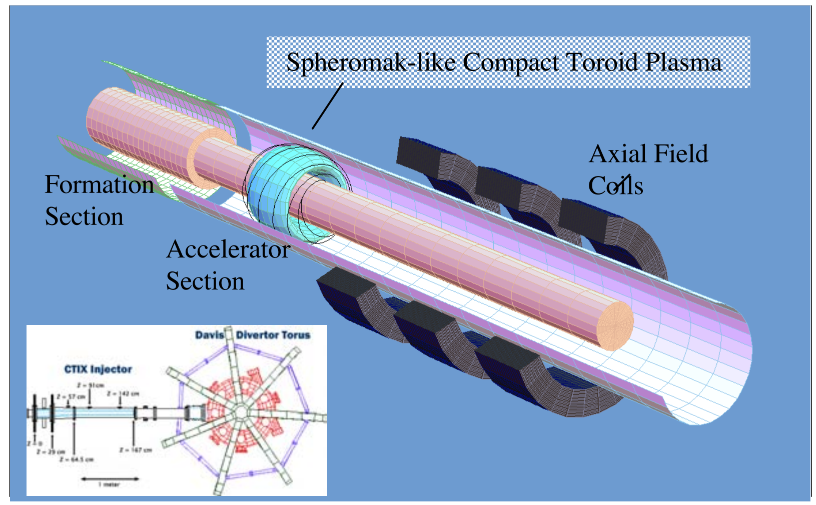
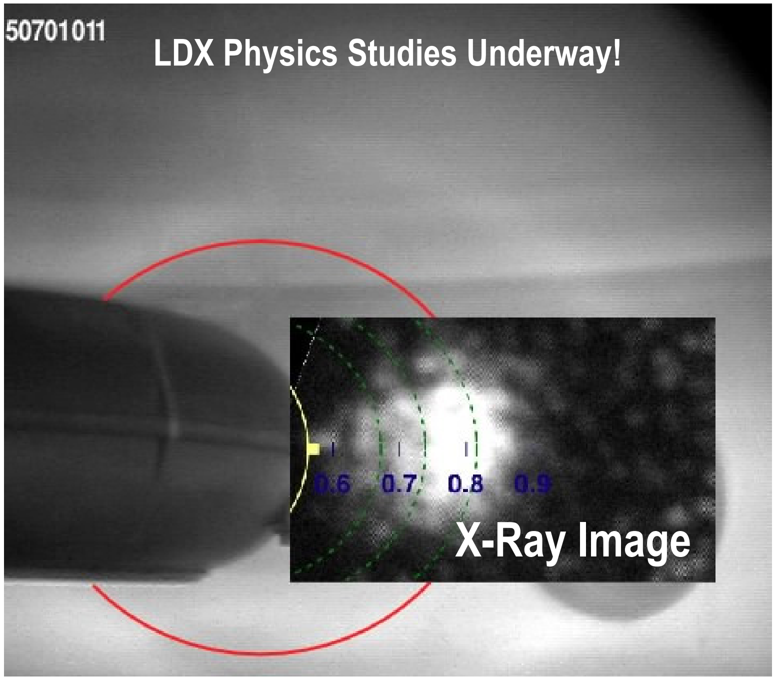
Compact Toroid Injection Experiment (CTIX)
UC Davis/Livermore, Livermore CA

- **Program Goals:**
  - Central refueling of magnetically confined plasmas
  - Passive switching for rep-rate SCT accelerator
  - Improve formation and acceleration
  - Increase overall efficiency of the accelerator
  - Increase final SCT density and velocity
- **FY05 Budget: $350K**



Levitated Dipole Experiment



- Can high-beta (β ~ 1) plasma be stabilized by dipole compressibility?
- Are high-temperature plasmas well-confined by the dipole field?
- Can adiabatic convection of plasma, confined *without* rotational transform, cause rapid removal of impurities and fusion products?

See *Nuc. Fusion*, **44**, 193 (2004): Dipole fusion without tritium-breeding or fast neutron damage.

A partnership of innovative plasma science with magnet technology experts.

Can fusion benefit from nature's way to confine high-beta plasma and advance understanding using the US Fusion Program's only operating experiment with superconducting magnets?

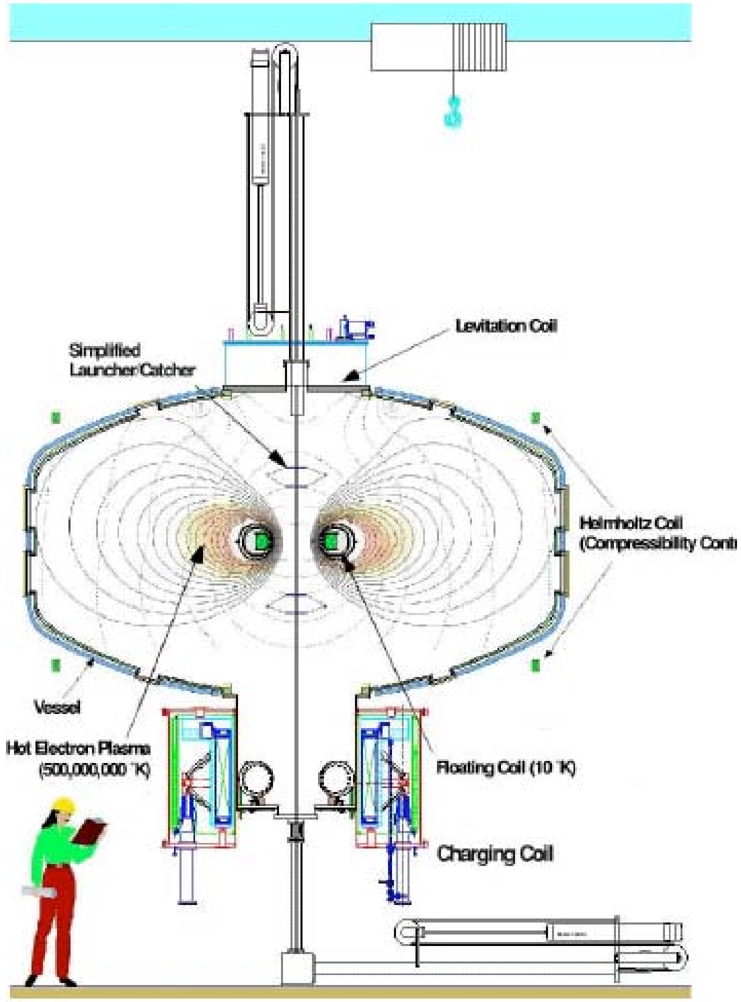
FY04-05 Achievements

- **Completed fabrication and integrated testing of high-field superconducting magnets.**
- **Phase 1: Experiments with "nearly levitated" coil (now).**
  - ✓ **Quasi-steady state plasmas** created with more than 10 s multi-frequency ECRH (6 kW).
  - ✓ ECRH creates **central torus of energetic electrons** (~ 100 keV) supported by a cooler plasma.
  - ✓ Equilibrium reconstruction using arrays of flux loops and magnetic coils show **high beta (> 25%)** with peaked profile.
  - ✓ Interferometry and edge probe measurements consistent with **peaked density profile**, beneficial to dipole concept.
  - ✓ **External coils** modify plasma boundary, compressibility.
- **Phase 2: Experiments with fully levitated coil on-track.**

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 Campaign

- **Continue basic physics explorations of high-beta, high-temperature plasma confined by levitated dipole magnet.** Use magnetic, optical, x-ray, microwave, and probe diagnostics to study and understand equilibrium and dynamical processes within a high-beta dipole plasma. Edge studies. Investigate effects of convective flows. Continue to develop understanding of dipole particle and energy confinement.
- **Install additional ECRH sources and expand operational parameters to higher density and β.** Test ability to control pressure profile with high power, multiple-frequency ECRH. Study higher-density thermalized plasmas.

FY07 Campaign ("Full Use Budget")

- 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 questions to evaluate the potential for attractive dipole fusion with advanced (non D-T) fuels.
- **Funding reduction (-10%): would limit purchase of cryogens needed to run superconducting magnets and eliminate support for a graduate student.**

Sheared Magnetofluids and Bernoulli confinement

Roger Bengtson, Prashant Valanju, and H. Quevedo
University of Texas at Austin

- Motivation for MBX
  - Create plasma conditions for transitions to Bernoulli states
- MBX program accomplishments
  - Observations made so far
    - Created and observed sonic velocity profile penetration to mirror center
    - Rotation bistability with hysterisis
    - Chiral (reflection) asymmetries
  - Theory developed for MBX
    - Two-fluid theory of rotated plasma bifurcations
  - One M.S. student graduated, one Ph.D. student near completion
- MBX limitations to overcome
  - Need to create higher density plasmas to reduce Alfven speed and decrease neutral fraction

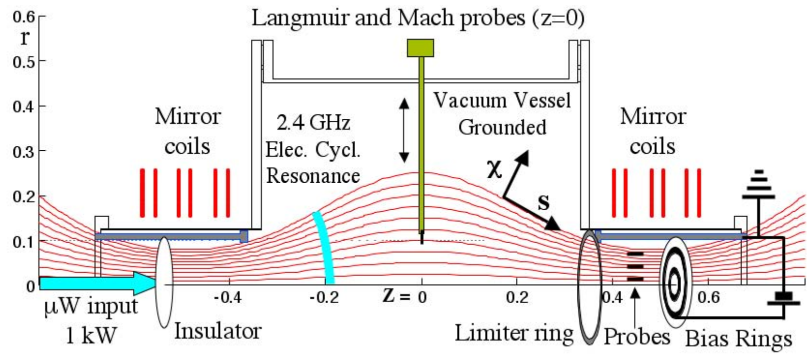


Fig.1 MBX Schematic showing end bias rings.

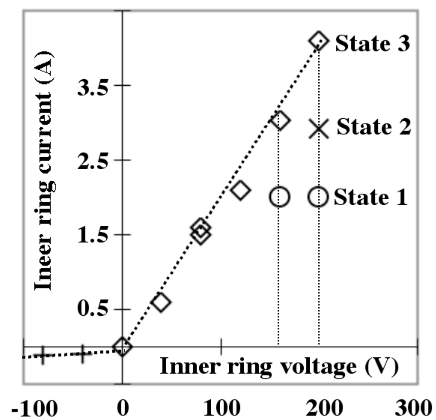


Fig.2 Multiple, stable rotation states (1,2,3) are observed in MBX at high rotation speeds, i.e., at high end ring voltages.

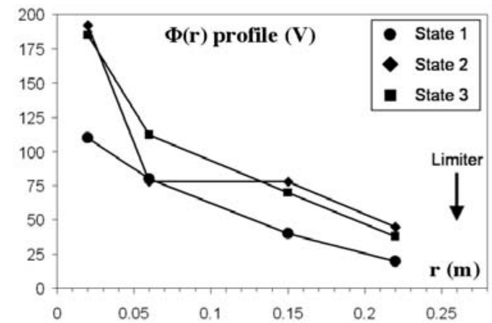


Fig.3 Rotation profiles of the multiple stable states observed with Mach probe in MBX center show spontaneous jumps in radial velocity shear

MARYLAND CENTRIFUGAL EXPERIMENT

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

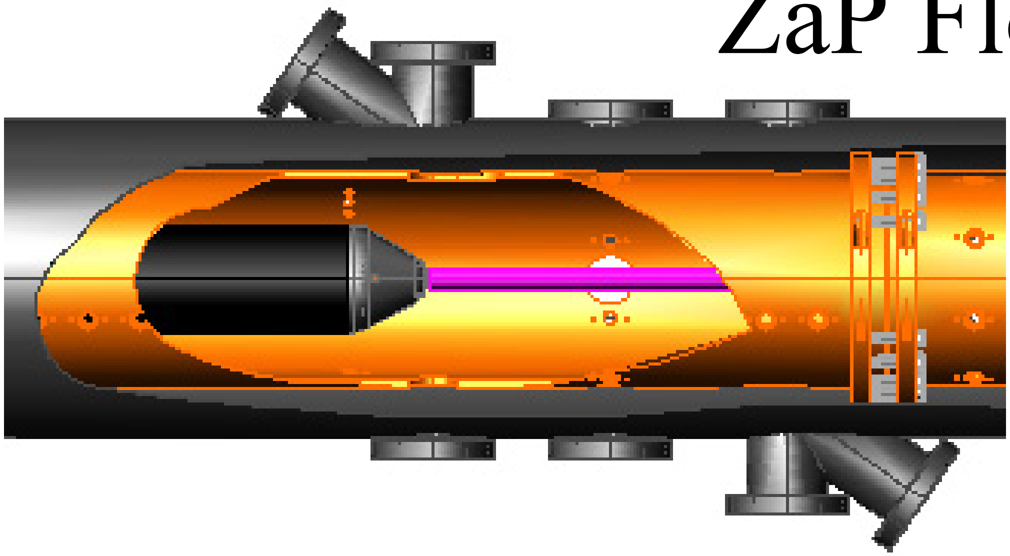
Achievements(March 2005, FY 2005 budget 480 K$)

- **Supersonic Rotation**: ***ExB*** *rotation to 250 km/s (Mach 3),* $T_i \sim 20\text{-}40$ *eV*
- **No destructive MHD modes** : *Stationary to 8ms,* τ_{MOM} *to 300μs,* $\tau_{MHD} \sim 10$*μs*
- **Detached Plasmas :** *HR mode(x2 Mach #,* τ_{MOM}*) – indicates detachment and centrifugal confinement.*
- **Basic Physics :** *First confirmation of MHD dielectric constant; rotation beyond Alfven ionization limit*

FY 06 Goals(budget request 511 K$)

- **HR mode performance :** *use new diagnostics to optimize HR mode; extensively explore parameter space.*
- **Understand MHD stability**: *measure rotation profiles, magnetic modes - correlation with plasma parameters*
- **Assess centrifugal confinement :** *new diagnostics will be implemented*
- **Plasma jet injection** *: experiments on momentum fueling (with HyperV Corp.)*
- **MCX upgrades** : *wall conditioning, higher voltage cap bank, increased midplane B to ~ 1T, mirror B to 2.7 T*

ZaP Flow Z-Pinch Project



Project/Concept Description:

ZaP Flow Z-Pinch Project generates a long-lived Z-pinch plasma stabilized only with sheared axial flow

PI: U. Shumlak, U of Washington

Goals:

1. **Advance the fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through the comparison of well-diagnosed experiments, theory and simulation.**
2. **Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.**

Objective of currently funded project is to investigate sheared flow stabilization of macroscopic plasma modes in a magnetically-confined, hot Z-pinch plasma and evaluate the potential of the flow Z-pinch concept for magnetic fusion

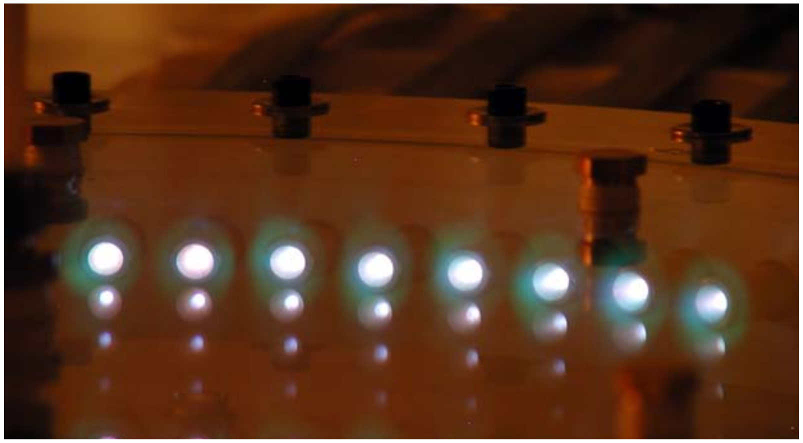
Applications include fusion space thruster, power production, & neutron generation

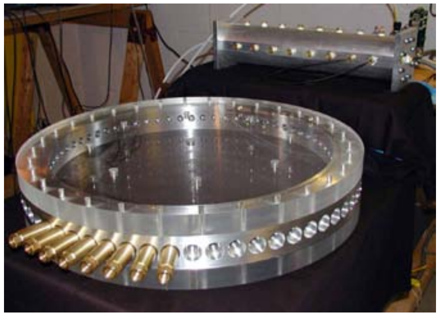
Research on Plasma Jets for Applications in Innovative Confinement

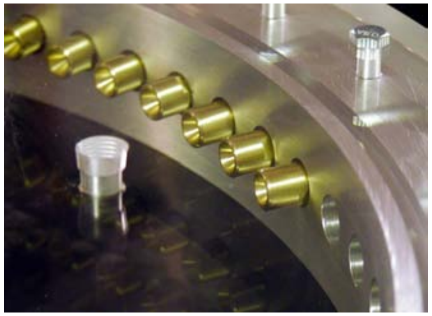
- **Goals:** Experimental plasma research tdevelop high momentum-flux-density plasma jets.
- **Applications:** Refueling, driving rotations, disruption mitigation in fusion devices, high energy density physics, magneto-inertial fusion.
- **PI:** Dr. Doug Witherspoon
- **HyperV Technologies Corp.**, Chantilly, VA (moved into new facility on 10/1/05)
- **Principal project objective** in this phase: Develop operational high mach number (>10) plasma jets, supported by a scientific knowledgebase for scalability
- **Status:**

- 8 plasma injectors fired with ~100 ns jitter
- 64 plasma injector planar array under construction - to be test fired Oct 2005
- Mach2 modeling identified two electrode profiles which suppress blow-by instability.
- Optical/spectroscopic diagnostics under construction.

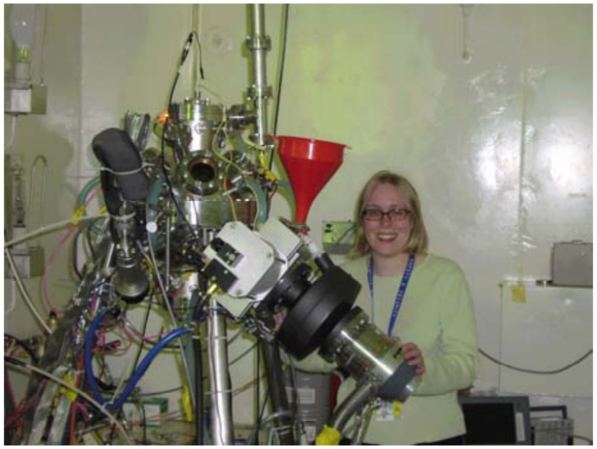
- **Approach**: highly collisional armature, preformed plasma with high speed injection from electrothermal discharge
- **Technical challenges**
  - Plasma injector
  - Blow-by: a dynamical instability
  - MHD instabilities: filamentation, Raleigh-Taylor



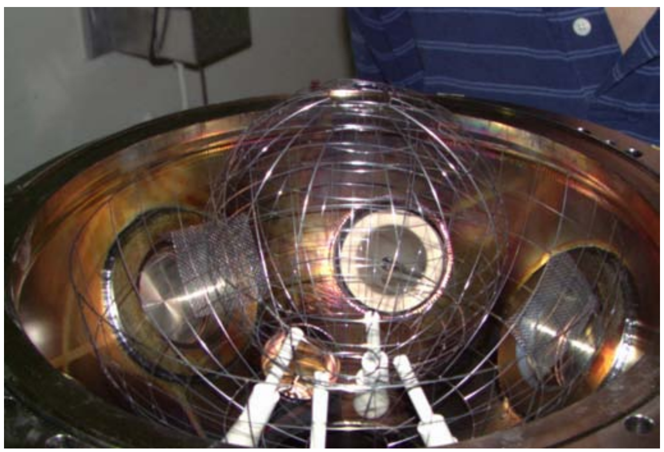




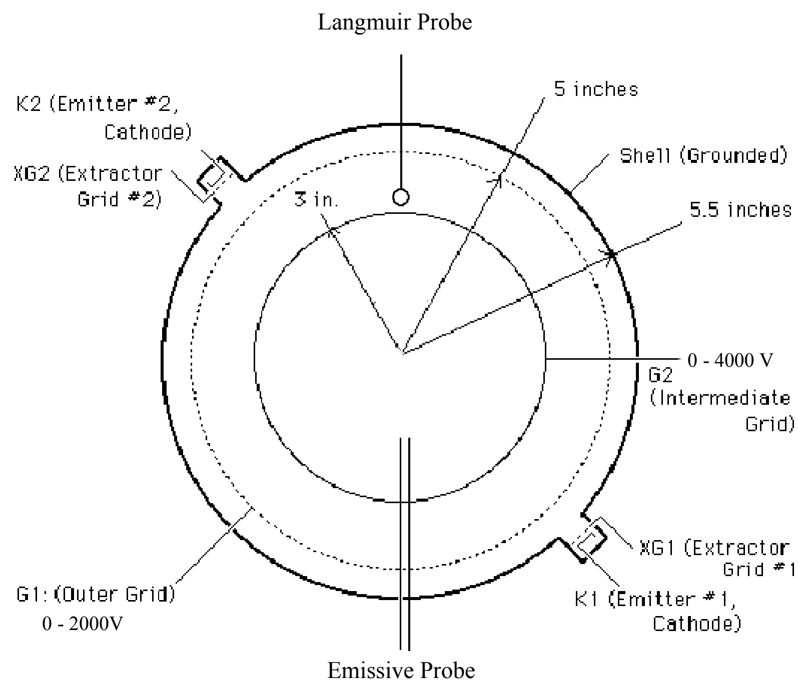
Inertial Electrostatic Confinement



Intense Neutron Source-Electron device



Recently installed highly
transparent grids (~ 90%)



- Harmonic potential created by electron injection.
- Extractor grid and outer grid bias controls electron injection current
- Inner grid bias controls the well depth
- Plasma potential measured by emissive probe.

NNSA

Los Alamos

Goals of Plasma Science and Innovation Center (PSI-Center)

- In concert with smaller innovative plasma physics experiments, refine and optimize existing MHD codes to achieve significantly improved predictive capability.
- Areas of refinement of NIMROD and MH4D:
  - Two fluid / Hall physics
  - Kinetic and FLR effects
  - Reconnection, relaxation physics
  - Transport, atomic physics, and radiation
  - Boundary conditions and geometry
- Initial experiments to validate and calibrate codes: FRX-L, MBX, SSPX, SSX, HIT-SI, PHD, TCS, ZaP, and Caltech experiments.
- Funding "started" March 05

PSI-Center accomplishments

- All personnel on board.
- NIMROD and MH4D running on the Center's code-development computer.
- Computational grids generated for eight experiments.
- Implementation of insulating boundary conditions is underway.
- Strategy in place to develop a model for neutrals and ionization.
- Simi-collisionless transport coefficients under development
- Begun characterizing nature of linear two fluid FRC tilt to compare to analytic model.
- Non-linear n=0 two-fluid calculation started for FRC

Steady, but incremental, progress is being made in ICC's

- **ICC results are constrained by the breadth of fielded diagnostics**
- **There is constrained manpower available to each of the experiments**
- **Theory and modeling could contribute considerably more***
  ***(but a new center started in FY05!)**
- **Many experiments take 3 or more years to construct, and many years to complete, because the funding levels limit the pace & sophistication necessary for a state-of-the-art fusion experiment**
- **No experiments even approach the $5M level called for when the ICC program was established**
- **Tight funding makes it difficult to turn-over the portfolio of projects for new ideas (competition is stiff)**

Summary

- ICC's are engaged in vibrant, world-class scientific research, focused on improved confinement ideas & understanding.

- ICC's form the experimental foundation of US plasma science & training (majority of US students).

- ICC participants are united to support the American domestic fusion program, including ITER, but fear becoming an appetizer to ITER's budget needs.