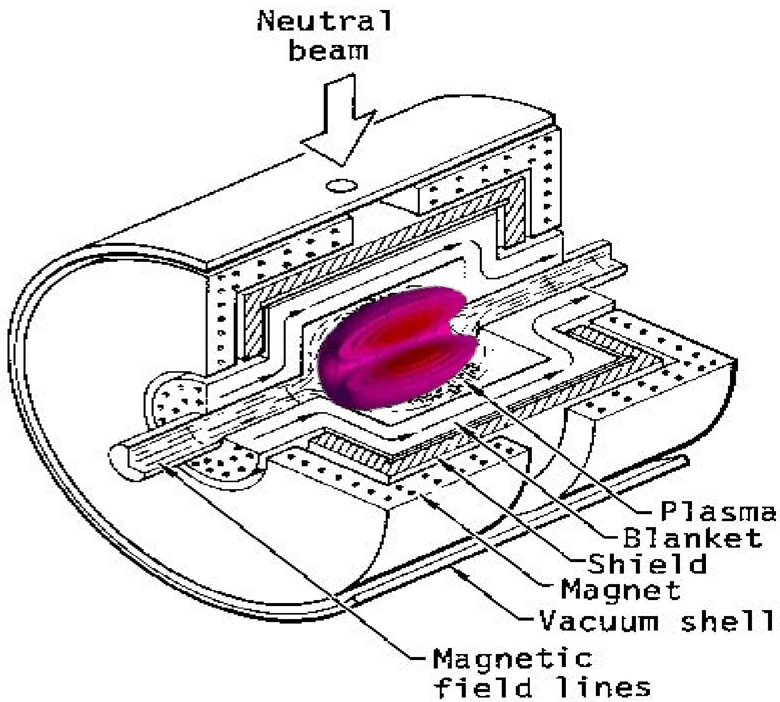
Steady-State Compact Toroids (CT)

Toroidal Confinement in a Singly-Connected Geometry



- Linear or spherical external vacuum chamber with closed field line plasma configuration.
- Exhaust plasma flows out ends to unrestricted ‘divertor’.
- High Beta, disruptions not a problem.
- Reactor cost an order of magnitude lower than for multiply connected systems with large toroidal field coils.

The old Field Reversed Mirror concept should be revisited based on recent favorable results on low power formation of hot CTs, steady-state maintenance, stability, and transport.

Small But Successful Programs

(steady-state efforts)

- FRCs
  - U. Washington: RMF creation & sustainment $1,536,000
  - LANL: Facility & diagnostic support $180,000
  - PPPL: Odd parity RMF heating $260,000
- Spheromaks
  - U. Washington: Inductive helicity injection $752,000
  - Swarthmore: Merging spheromaks $172,000
  - Woodruff Scientific: Spheromak pulsed buildup (SBIR) $320,000
- Theory & Computational Support
  - PPPL: FRC kinetic calculations incl. beams $192,000
  - Science Center: U.W.s. U.S. (CT portion of ICCs) ~$400,000

Total $3,812,000

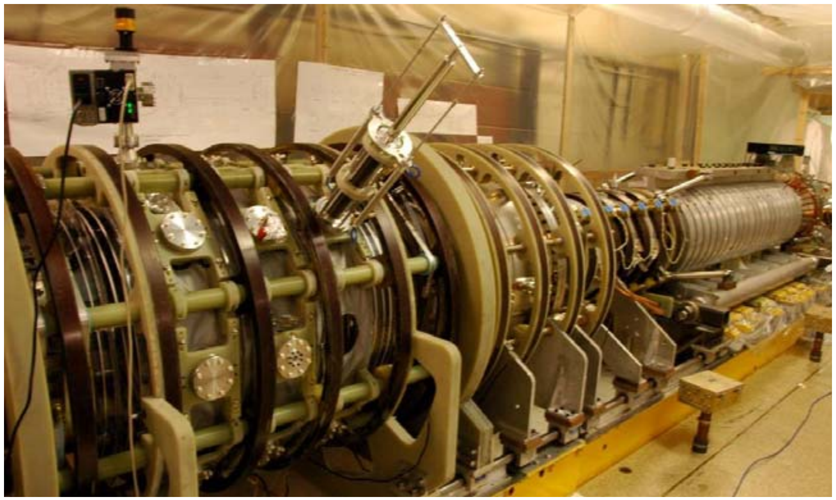
SSPX shut down at end of 2007, with only data analysis in 2008

(*Much additional interest including large, privately funded effort)

TCS-upgrade

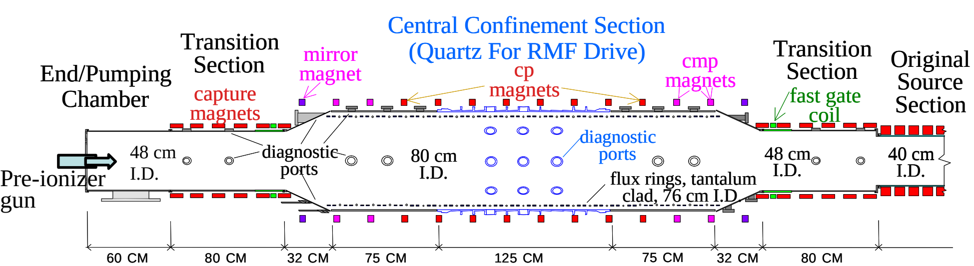
~2 MW RMF Power Input

U. Washington

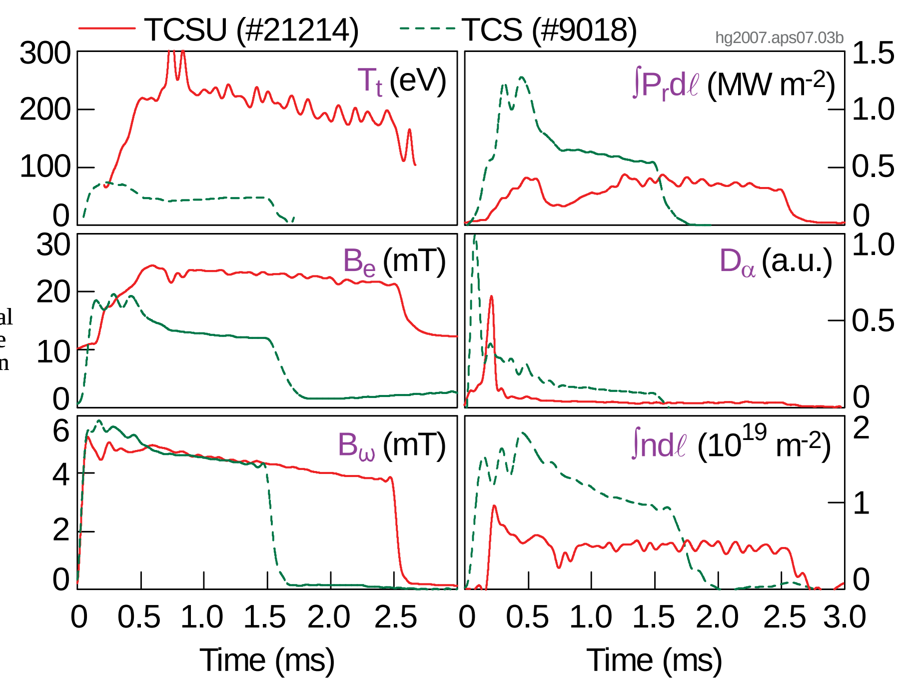


Completed early 2007

- Bakable (to 200°C), mostly all-metal construction, with base vacuum pressure reduced from ~10^{-7} Torr to ~10^{-10} Torr.



Form & sustain high temperature FRCs



Research Plans

U. Washington

- FY2008: Operate with internal rings – expect $B_e/B_\omega > 8$. Siliconization. Measure internal field structure.

- FY2009: 10% reduced budget – limited T.S. measurements.

  $1,567,720 budget – multipoint T.S. measurements, end flow exhaust characterization.

  Optimal budget - extra $500,000 – begin design studies for National Compact Toroid Facility (NCTF)

  - FY2010: 10% reduced budget – limited operation, end flow studies.

    $1,567,720 budget – varied RMF antenna configurations

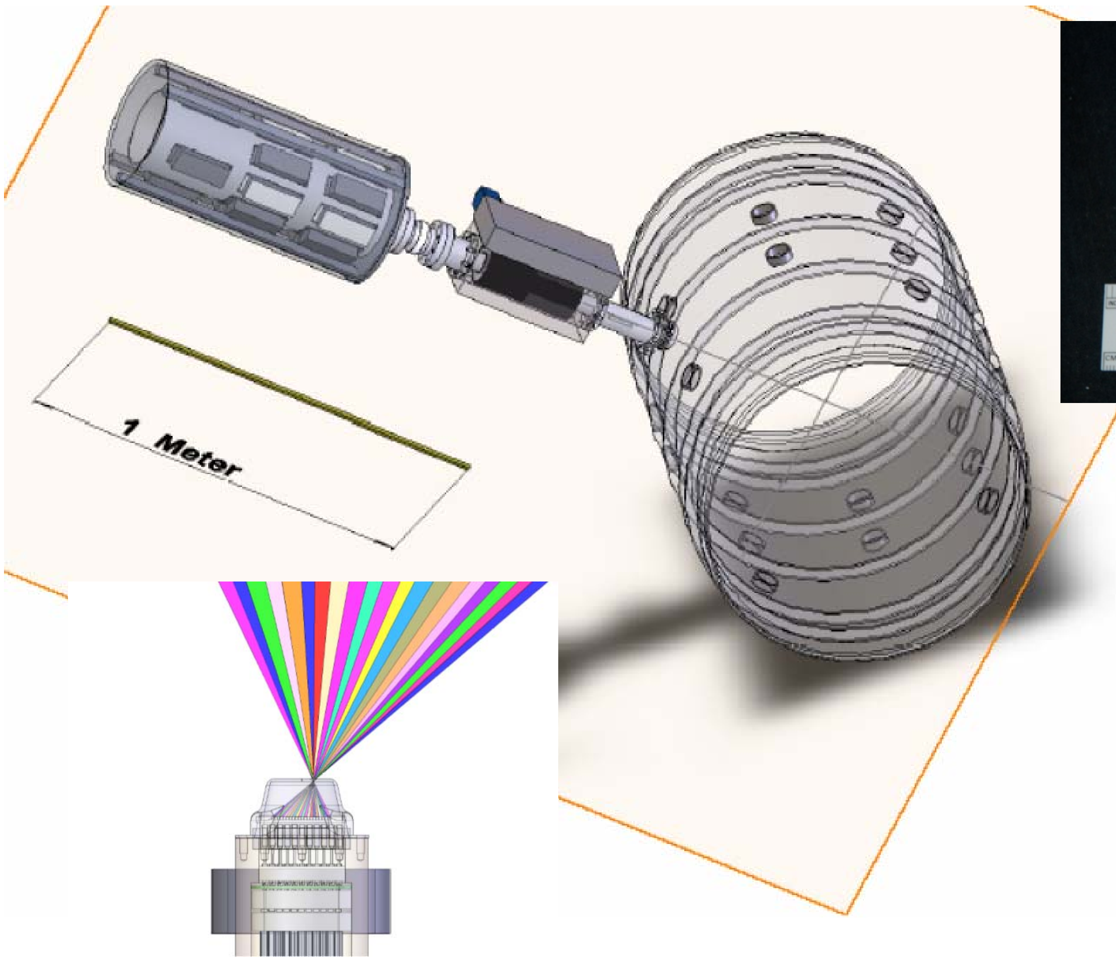
    Optimal budget – extra $1,000,000 – continue NCTF design & begin IGBT-based RMF upgrade and chamber construction studies.

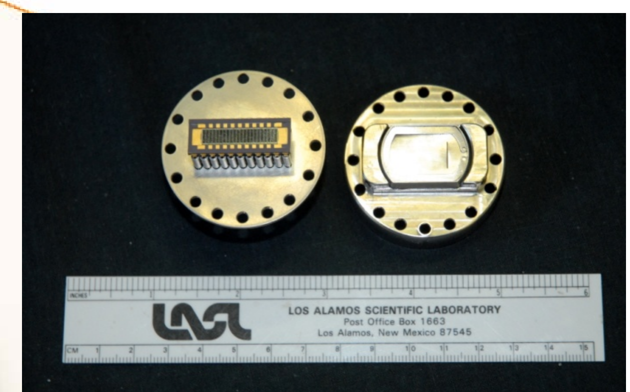
Los Alamos collaboration with TCS-U (G. Wurden, M. Kostora)

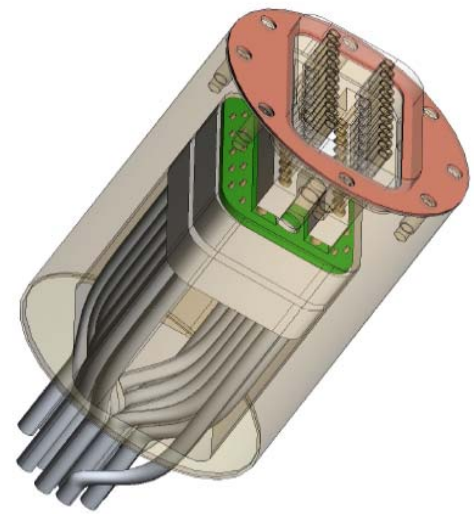
- In FY08 we completed construction of a 20-channel bolometer system, designed for re-entrant, wide angle operation in the hot TCS-U vacuum vessel. The unit is high-vacuum compatible, and has an all glass/metal set of components. The AXUV photo-diode array is amplified by variable gain 100 MHz preamps, is battery powered, and the entire unit is hardened against the RF noise environment of TCS-U. A 12-bit 16-channel Joerger TR digitizer with MDS+ driver will acquire the data. Active air cooling of the chip socket, enables survival in the TCS-U operating temperature of >100 °C.
- Bench testing at LANL is complete, and the system will be shipped to Seattle in the next 2 months.
- LANL scientists will conduct experiments at the TCS-U FRC, and begin efforts to field a soft x-ray array to look at fluctuations in the >100 eV TCS-U plasmas in FY10

Budget: FY08 $180k/year, assumed flat thru FY10

Los Alamos collaboration with TCS-U (G. Wurden, M. Kostora)

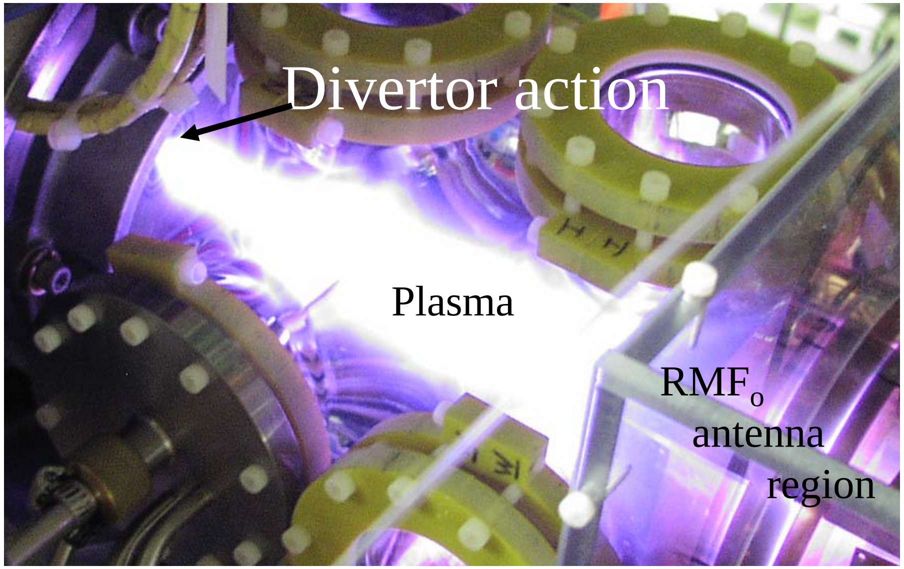






Mounting a simple chip onto a plasma experiment is more complicated than one would think at first glance. SolidWorks views of the 20-channel bolometer for the TCS-U FRC experiment (not all to same scale).

Princeton FRC: Odd-parity RMF (RMF_o)   PI: Sam Cohen

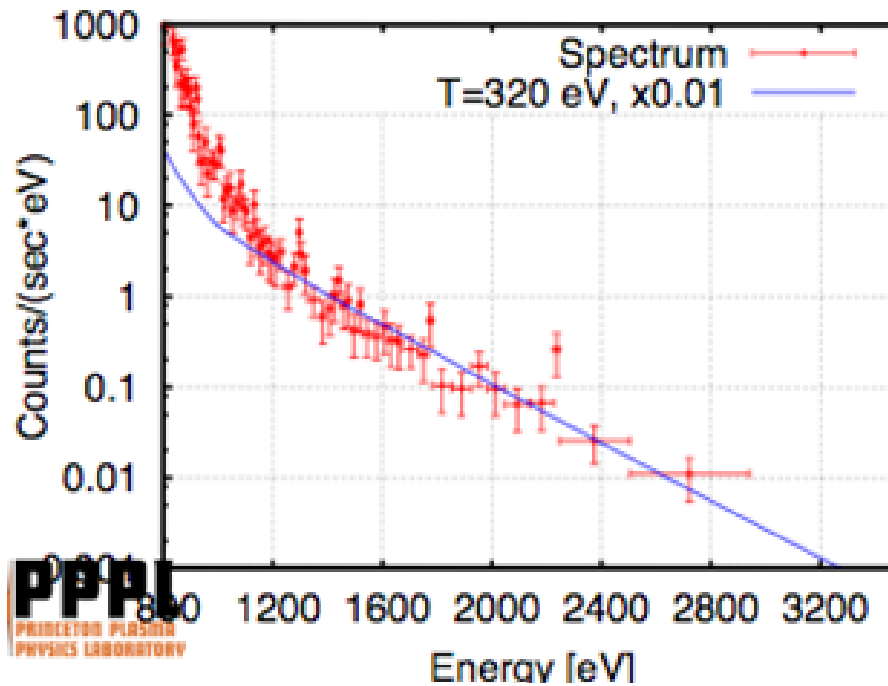


RMF_o research areas

- Closed field lines & τ_E
- Electron heating: $\omega_R << \omega_{ce}$
- Ion heating: $\omega_R \sim \omega_{ci}$
- Divertors & Hi-T superconducting (SC) internal flux conservers (FC)
- Stabilization
- Design of **small** D-He^3 reactor

FY08 Accomplishments

1. $T_e > 300$ eV at $B_R/B_a < 0.1$, P to 20 kW
2. Reactor relevance: $\nu^*_c < 10^{-3}$
3. Full penetration of RMF_o to major axis
4. First divertors in an FRC
5. First Ta & Hi-T SC FC tests
6. In-shot fueling
7. 2% duty factor (enable X-ray measurements)



PFRC FY2009/10 Budget scenarios

Three scenarios: Baseline 260 k$/year; -10%; Optimal: + 2M$

Technical activities | **Budget scenarios**

- Plasma radius to 4 cm, B = 120 G, T_i = 1 eV, T_e = 300 eV
- Ta flux conservers, RF power = 20 kW, 5 ms pulse — -26 k$
- RF power = 100 kW — Baseline
- Superconducting flux conservers, 1/2 s long pulse
- Improved X-ray, magnetic, particle and optical diagnostics
- Plasma radius to 6 cm, B > 1 kG
- Feedback control of operations — +2 M$

Scientific goals

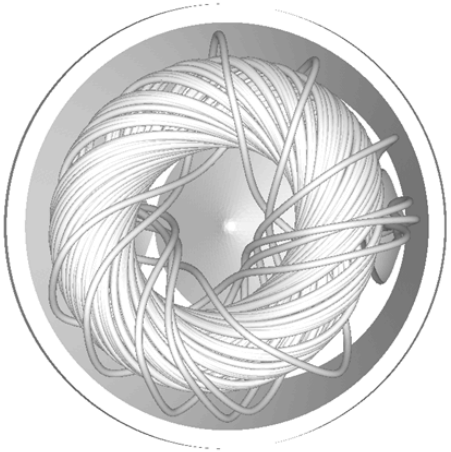
- Study electron heating physics — -26 k$
- Study axial plasma flow & oscillations *vs* mirror ratio — Baseline
- Measure internal field structure, radiated power, magnetics
- Heating physics at ω_R/ω_{ci}~ 5: T_i > 100 eV, T_e > 1.5 keV, $n_e > 10^{13}$ cm^{-3}
- Kinetic 3-d modeling of plasma, including RMF_o penetration
- Address stability issues
- Small (0.3 m radius) D-He^3 FRC reactor design — +2 M$

Recent results from the 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.

- Magnetic data (internal and surface probes) agree with Taylor state model. Helicity balance correctly predicts the toroidal spheromak current I_{sph}.
- Have produced a 29 kA spheromak with $I_{sph} \cong 1.4\ I_{inj}$ (Threshold for separatrix: $I_{sph} \cong I_{inj}$)
- Confirming results from computational study of non-linear relaxation and reconnection

Selected field lines of presently achieved HIT-SI equilibrium.



HIT-SI goal: $I_{sph} = 5I_{inj}$

HIT Goals

FY 08:

- Achieve 100 kA and/or 100 eV and improved MHD modeling agreement.
- Build inductive helicity injector that also stabilizes RWM.

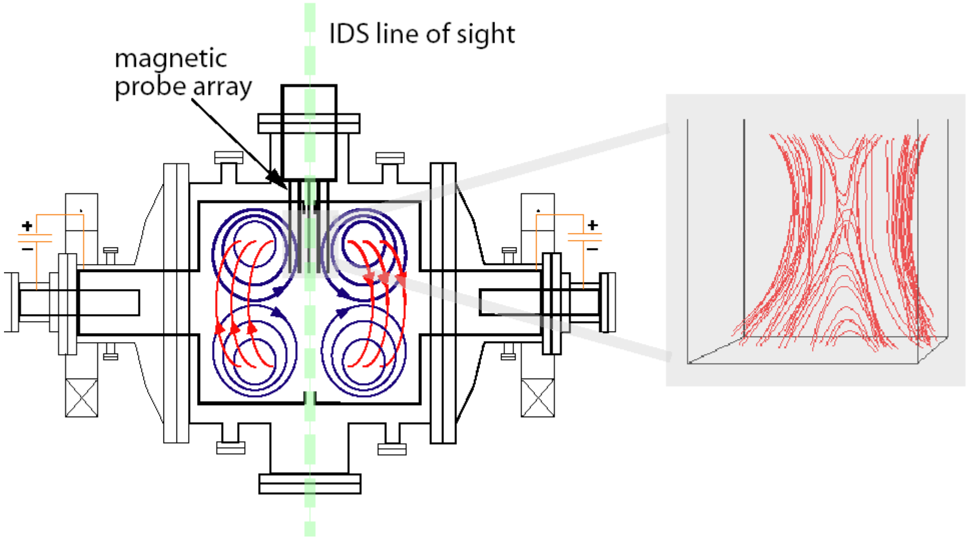
FY 09:

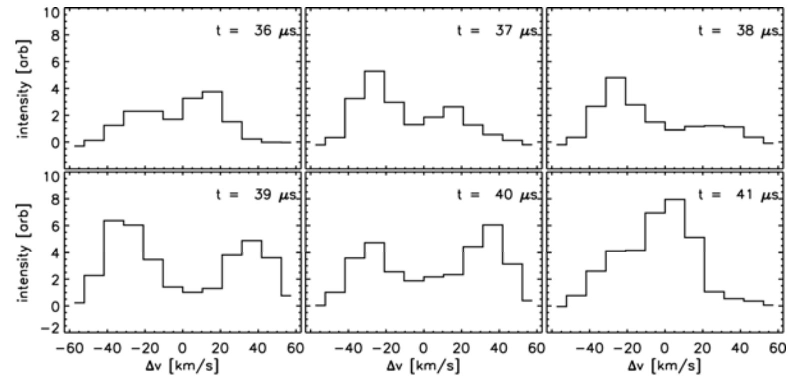
- Build equilibrium and stability control coil sets for 0.1 s pulse.
- Improve the spheromak fields and do MHD modeling to higher accuracy.
- -10%: lose the postdoc, slow progress.
- Dream Budget: Extra $700 k: Increase HIT-SI effort. Build power supplies for 0.1 s pulse. Begin design of inductive spheromak front end for NCTF. Begin design and construction of NCTF.

FY 10:

- Stabilize resistive wall modes and achieve 100 kA, 100 eV spheromak for 0.01 s.
- Improve MHD modeling to higher accuracy.
- -10%: lose the postdoc, slow progress.
- Dream Budget: Extra $1000 k: Design and begin construction of spheromak front end for NCTF. Achieve 100 kA, 100 eV spheromak for 0.1 s.

SSX-FRC achievements to date





- merge spheromaks to form FRC (above left), also trap single spheromaks in dipole field, new flux conserver 2008
- spectroscopic measurements: bi-directional jets with 1.33 m ion Doppler spectrometer (above right), vacuum ultra violet and soft x-ray determination of Te
- trained dozens of undergraduates in plasma physics research… several at PPPL, U Wisc, Berkeley, etc.

SSX-FRC plans for FY09/10

• study reconnection and merging in our new 0.5 m oblate copper flux conserver with spectroscopy and probes

• merged spheromaks form an oblate FRC in trapezoidal oblate flux conserver (tilt stable)… map out equilibrium and stability

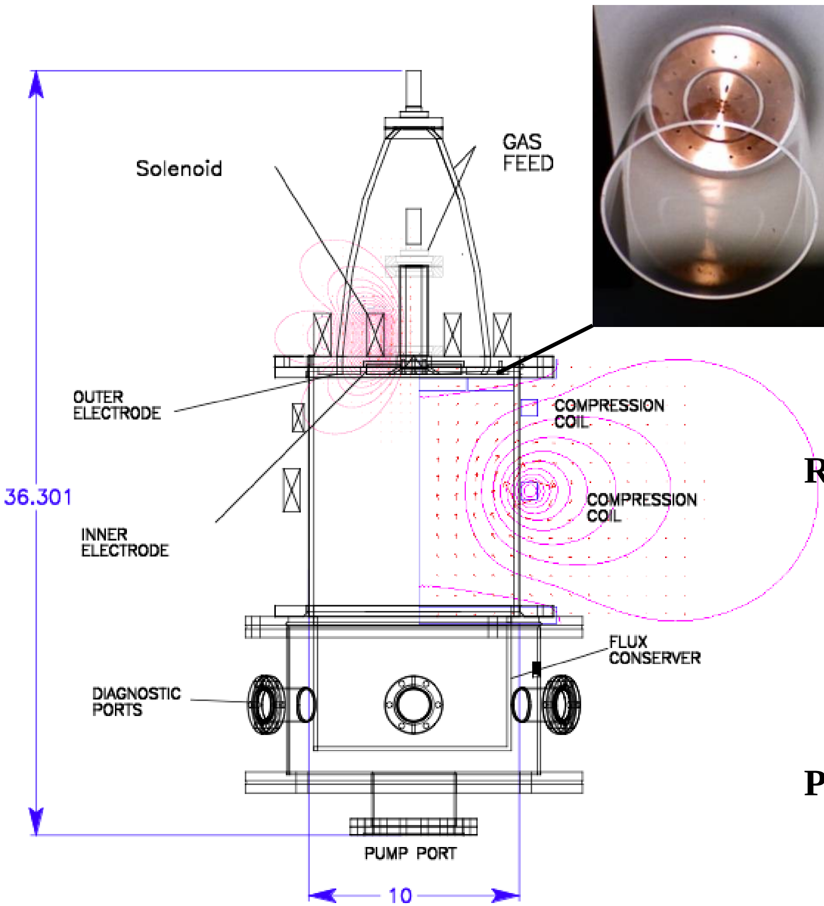
• comparison of IDS flow measurements with 3D simulation (HYM, NIMROD, MH4D, etc)… Yu Lin and Elena Belova

• one post-doc (Tim Gray, recently hired) and three undergraduates supported for summer 2008

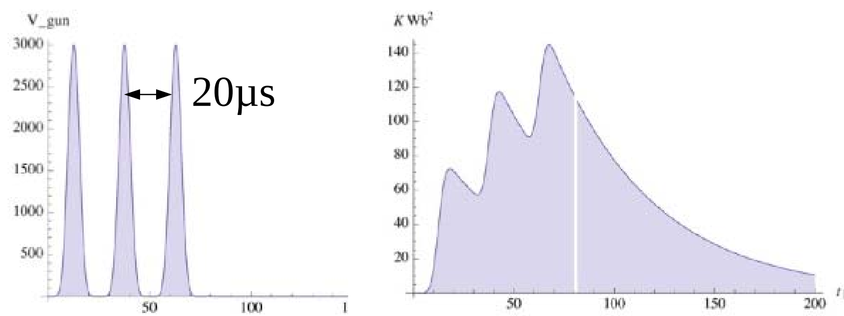
• *Changes in budget will determine how much time PI can devote to project*

WOODRUFF SCIENTIFIC, LLC

Pulsed **B**uild-up E**x**periment (**PBX**) --> explores the generation of strong magnetic fields in compact tori.



WS aims to demonstrate high frequency merging of CTs to generate strong magnetic fields in a spheromak.



Recent Accomplishments:

- New laboratory built (last 3 months).
- Bank, Vacuum, DAQ components tested.
- Simulation and analytic theory capability developed, NERSC time allocated.

Present Work:

- Building out all subsystems, testing.
- First discharges to be reported by ICC.

Work supported by DOE SBIR contracts DE-FG02-07ER84924 and DE-FG02-06ER84449

WOODRUFF SCIENTIFIC, LLC

PBX budget and schedule (FY09), research plans.

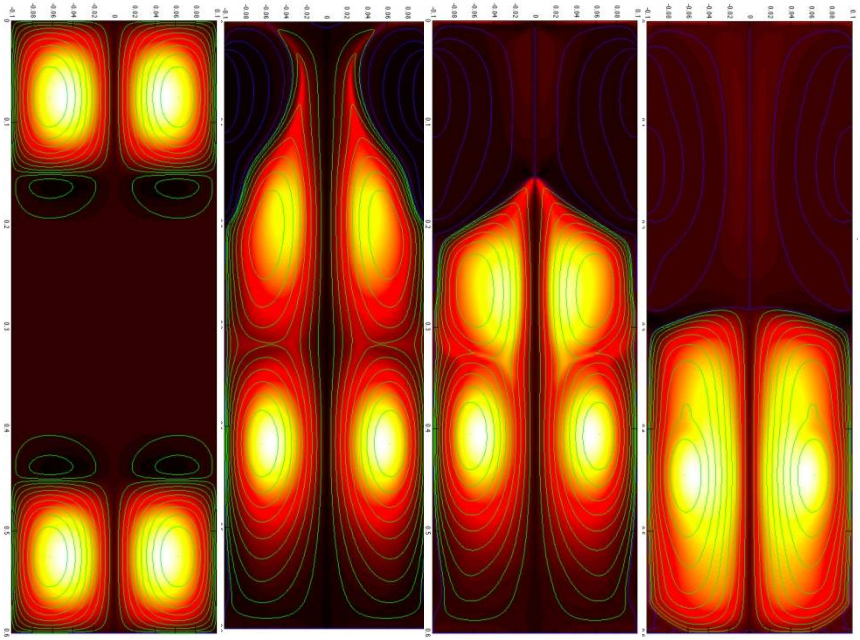
Baseline budget is 320k

FY09 tasks:

- Multi-pulsed operations, extending to higher field energies.
- Complete diagnostic set.
- 3D MHD simulations with realistic geometry and boundary conditions.
- Analytical modeling to scale physics.

+20% increment would allow us to improve vacuum conditioning (Ti getter, He glow, bake), and use a RGA.

-10% would mean inability to do repairs in the event of a failure.



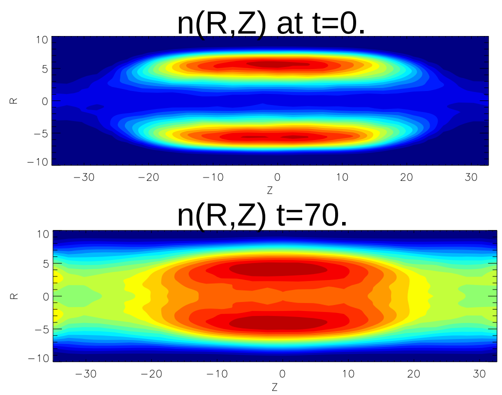
3D MHD simulations of co-helicity merging of spheromaks: starting with two equilibria, and compressing with a high current coil in ~5μs, comparable with the time-scale for the experiment.

Work supported by DOE SBIR contracts DE-FG02-07ER84924 and DE-FG02-06ER84449

FRC Theory and Modeling (PPPL)

Main Objectives:

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



Change in plasma density contours due to applied even-parity RMF from 3D self-consistent hybrid simulations using HYM code.

FY 2008 plans:

- Perform 3D simulations of rotational mode and ion spin- up in collaboration with the FRX-L experiment at LANL.

- Provide theoretical support for MRX-FRC experiments focused on spheromak merging, reconnection and FRC stability properties.

- Carry out initial 3D studies of the effects of rotating magnetic field (RMF) on FRC properties using the parallelized HYM code.

FY 2009-2010 Research Plan

FY 2009

- Carry out advanced 3D simulations to identify optimum operating regimes of the MRX-FRC and SSX-FRX experiments.
- Complete detailed 3D studies of the effects of rotating magnetic field (RMF) on FRC stability behavior using the parallelized HYM code.

For -10% reduced budget: delayed execution of second objective.

FY 2010

- Develop numerical model for self-consistent inclusion of electron kinetic effects in the HYM code.
- Implement a drift-kinetic description for the thermal electrons in the HYM code.
- Perform initial simulations of FRC stability properties using the HYM code with a drift-kinetic model for the electrons.

For -10% reduced budget: delayed execution of FRC simulations with kinetic electrons.

Funding Request	FY 2009 - 10 Guidance	FY 2009 Increment*	FY 2010 Increment*
	$195 K	$75 K	$75 K

Incremental funding request restores funding to FY07 level and provides support for 1 FTE graduate student.

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

- 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.
- Areas of refinement of NIMROD and MH4D-like: Two fluid / Hall physics, kinetic and FLR effects, reconnection, relaxation physics, transport, atomic physics and radiation and boundary conditions and geometry
- Experiments to test and calibrate codes: SSPX, SSX, HIT-SI, FRX-L, PHD, TCSU, ZaP, MST, Pegasus, HIT-II, LDX, and Caltech experiments.
- Testing handling two fluid effects with reasonable time step.
- FRC spin up modeled, small B_{tor} plus Hall physics stabilizes n=2 as observed
- Beginning implementation of self-consistent boundary conditions.

Goals for PSI-Center

Plans for FY08: Continue to validate NIMROD; Develop true 3D code; Develop self-consistent boundary conditions.

Plans for FY09:

- Finish atomic physics package.
- Compare NIMROD to many experiments, improve predictability.
- True 3D, implicit, higher order element, code compared to experiments.

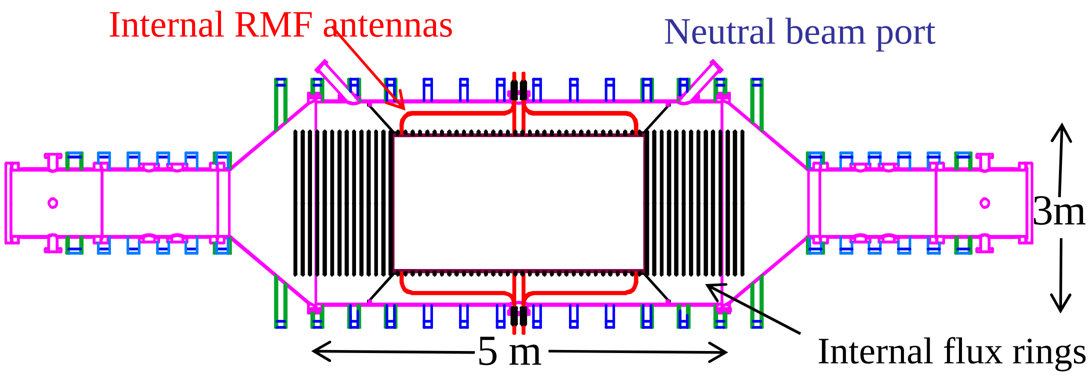
- At -10% lose post-doc, slow progress.
- Dream budget: as originally proposed, $2M/yr present progress is manpower limited.
  - Begin using CAD to interface to experiments.
  - Increase by a factor of four the effort in collaborating with experiments.
  - Double code development effort (including more grad students).
  - Sponsor workshops for users, physics, and outreach.
  - Fund Center activities in Computer Science and Earth & Space Sciences Departments.

Plans for FY10:

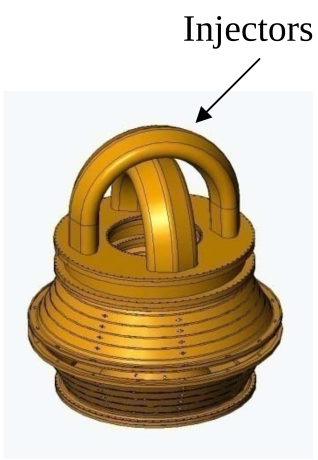
- Validate NIMROD and true 3D code against experiments.
- Modify codes for improved predictability.
- Begin using codes to help design NCTF experiments.

- At -10% lose post-doc, slow progress.
- Dream budget: as originally proposed, $2M/yr: Maintain effort described in this scenario for FY09

National CT Facility



FRC Front End



Spheromak Front End

- Common power supplies and diagnostics for FRC & spheromak studies.
- Large enough to achieve $v_{de}/v_{ti} < 1$ to minimize micro-turbulence and $\phi_p > 25$ mWb to trap fast ions.
- Principal new additions are ~10 MW RMF/HI 0.1 sec power supply and ~2 MW, ~20 keV, 0.1 sec neutral beams.
- Total cost ~ $28M over 4 years
- Proponents: A. Hoffman, T. Jarboe, G. Wurden, M. Brown …