70 YEARS OF CREATING TOMORROW

Los Alamos NATIONAL LABORATORY

LANL Fusion Energy Sciences Research

G. A. Wurden

Fusion Power Associates Meeting

Washington DC

Dec. 11, 2013

LA-UR-13-29463

Abstract / Outline of this talk

FES funding at LANL has been shrinking, especially due to the near elimination of FES funded HEDP research. Nevertheless, we conducted theoretical and experimental research on a variety of topics:

•Basic plasma and astrophysical plasma experiments @ Magnetized Shock Experiment (MSX), Reconnection Scaling Experiment (RSX), and the Plasma Liner Experiment (PLX).

•Three-lab collaboration (LANL/PPPL/ORNL) on the W7-X stellarator in Greifswald, Germany, principally edge plasma control & diagnostics in 3D magnetic geometry.

•Magnetized Target Fusion (MTF) experiment at the Air Force Research Lab in Albuquerque. We conducted our final implosion experiment on Oct. 23, 2013. We are hopeful that ARPA-E might become involved in magneto-inertial fusion.

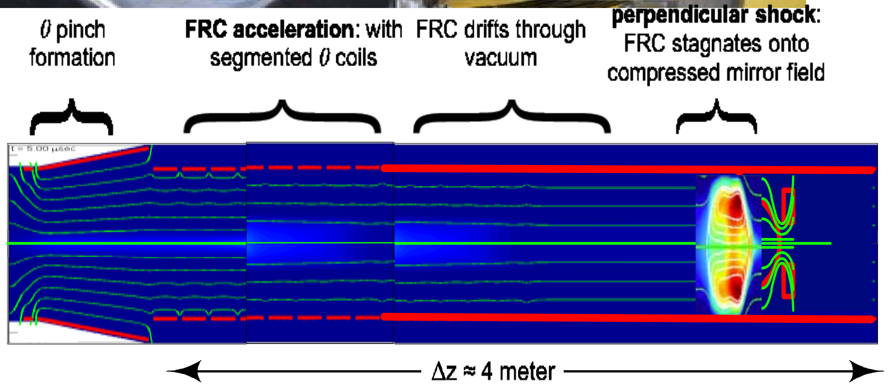
•Plasma theory in a number of topics, tokamak and alternate (RFP) transport modeling.

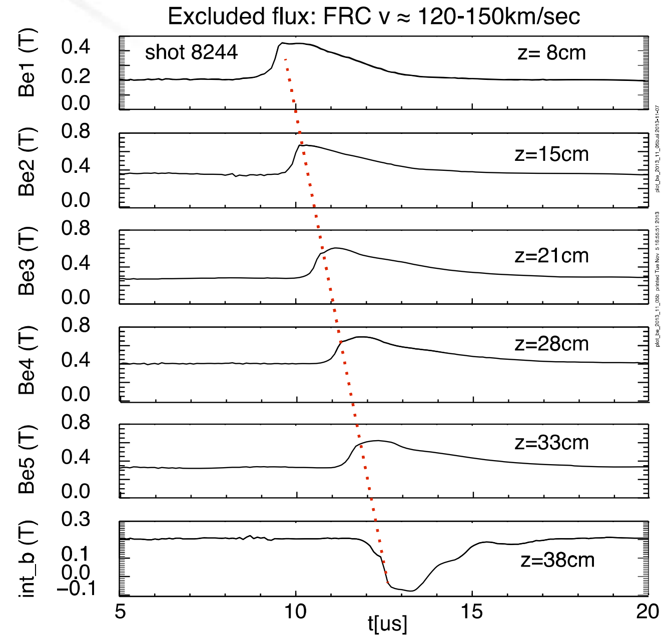
•Paper studies for ITER: eg, a neutron source for diagnostic calibration (ITER-IO), study of high speed dust injection for disruption mitigation (US-ITER)

Magnetized Shock Experiment MSX

T.P. Intrator
T.E. Weber
R.J. Smith

- Super Alfvenic FRC $M_A \approx 3$, *threshold for critical shock* onset
- Perpendicular, parallel, oblique shocks
- Large size >> ion inertial & gyro size
- internal probe measures field reversal





external B probe array data shows FRC speed

<u>Perpendicular shock</u>
propagates backward through FRC

UNCLASSIFIED

Pulsed Polarimeter Instrument on MSX

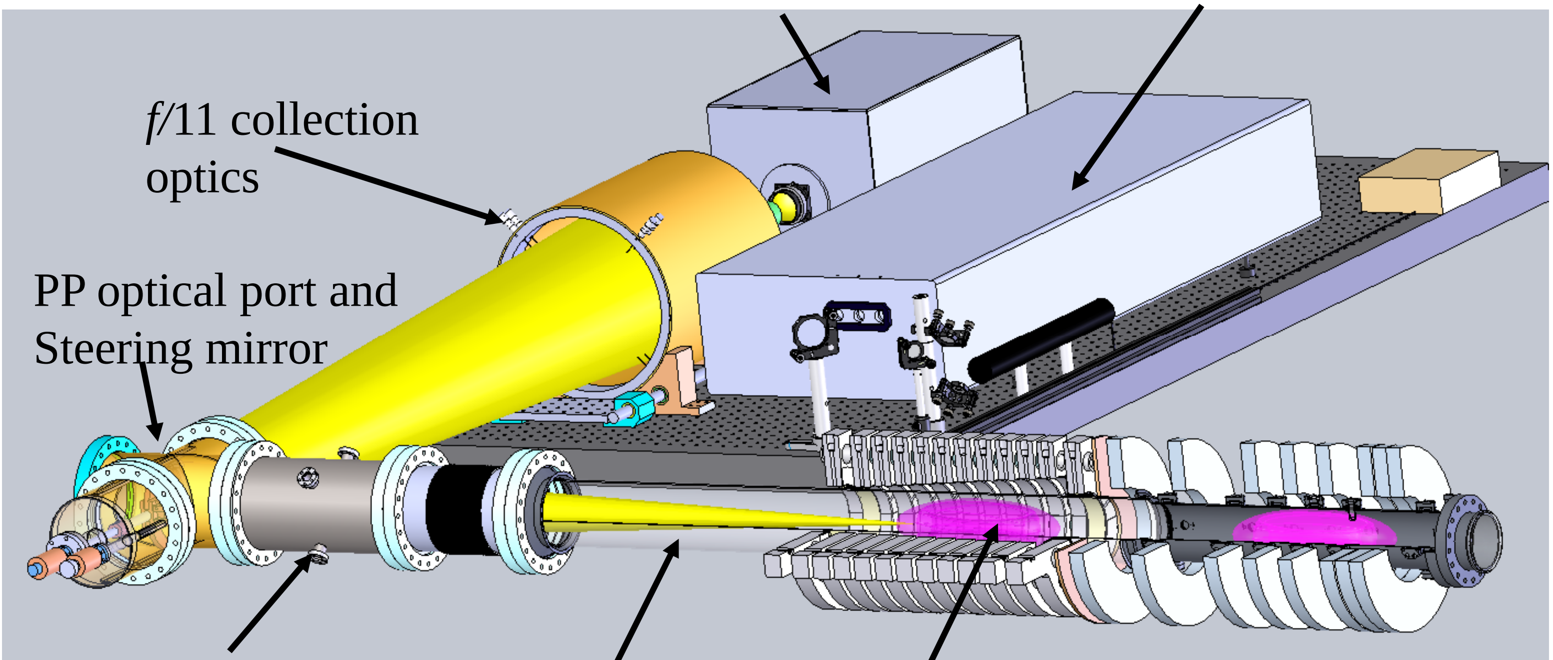
R.J. Smith
T. Hutchinson

Measures electron temperature, density, magnetic field

Spatially resolved internal measurements at an instant of time

20 ps pulse, 60mJ, 532nm NdYag laser

Streak camera



plasma guns

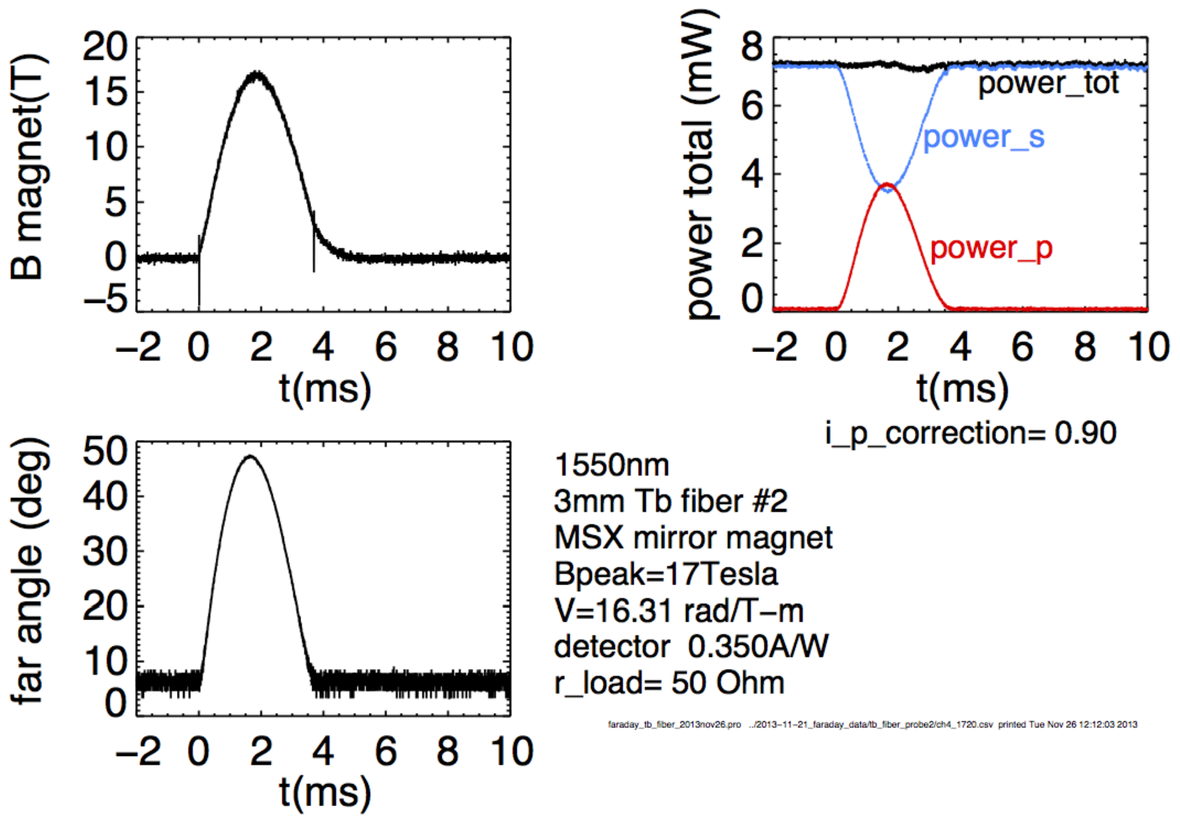
Thomson Backscatter

FRC in MSX

Faraday fiber measures B field for MagLIF, MSX

Terbium doped Faraday fiber test on MSX at LANL

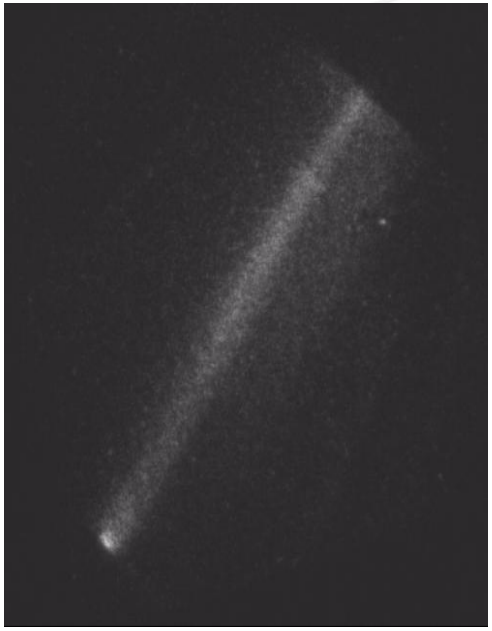
T.P. Intrator, T. Weber, D. Bliss, R. McBride

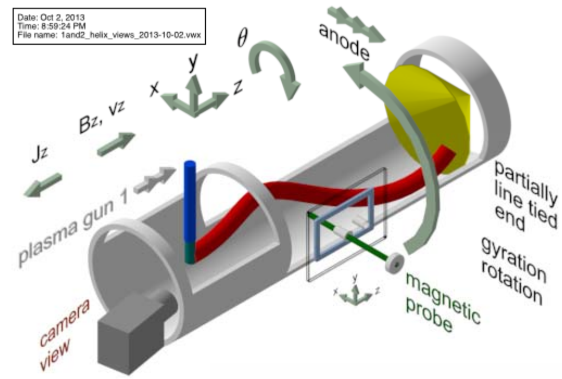


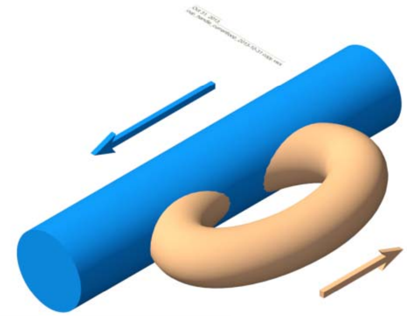
UNCLASSIFIED

A single flux rope nonlinearly self-stabilizes its kink behavior

T.P. Intrator, Y. Feng, J.Sears, H. Swan

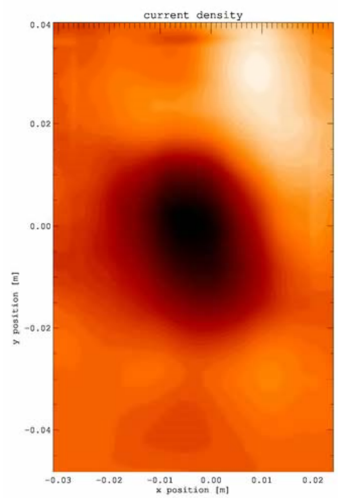


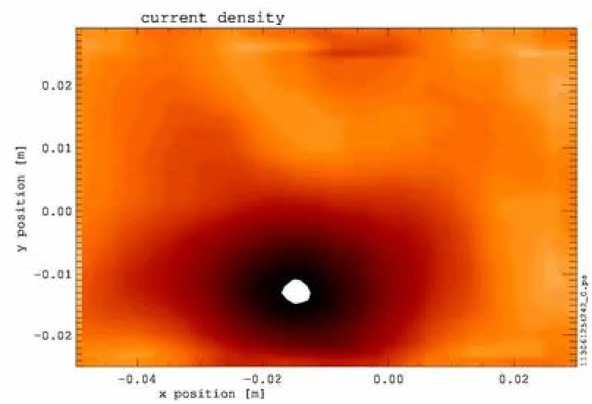




Z=25cm from plasma gun Jz(x,y)

flux rope (black) & reversed (white)

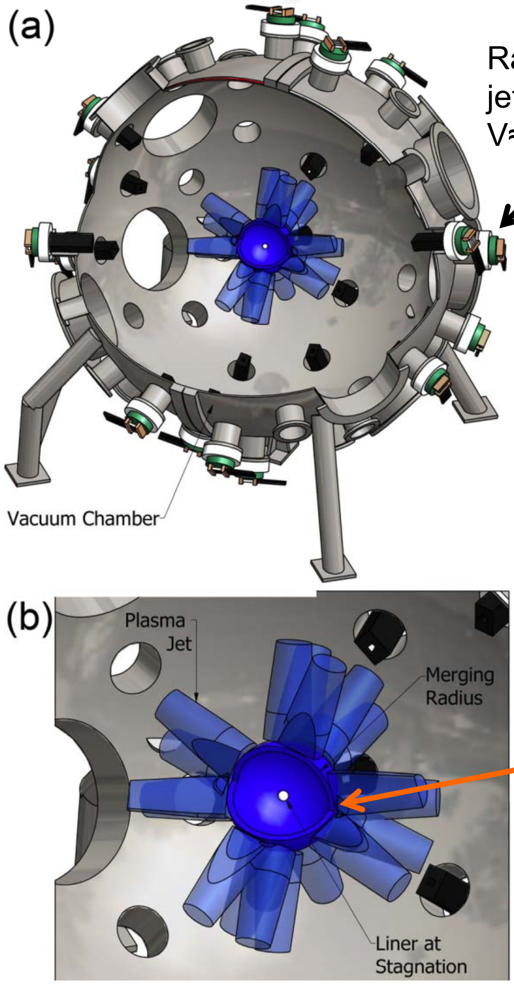




Z=40cm from plasma gun

No obvious induced -Jz

Plasma Liner Experiment (PLX) was designed to generate imploding spherical plasma liners via thirty merging supersonic plasma jets



Railguns produce argon jets with $n \approx 10^{17}$ per cc, $V \approx 50$ km/s, mass≈8 mg

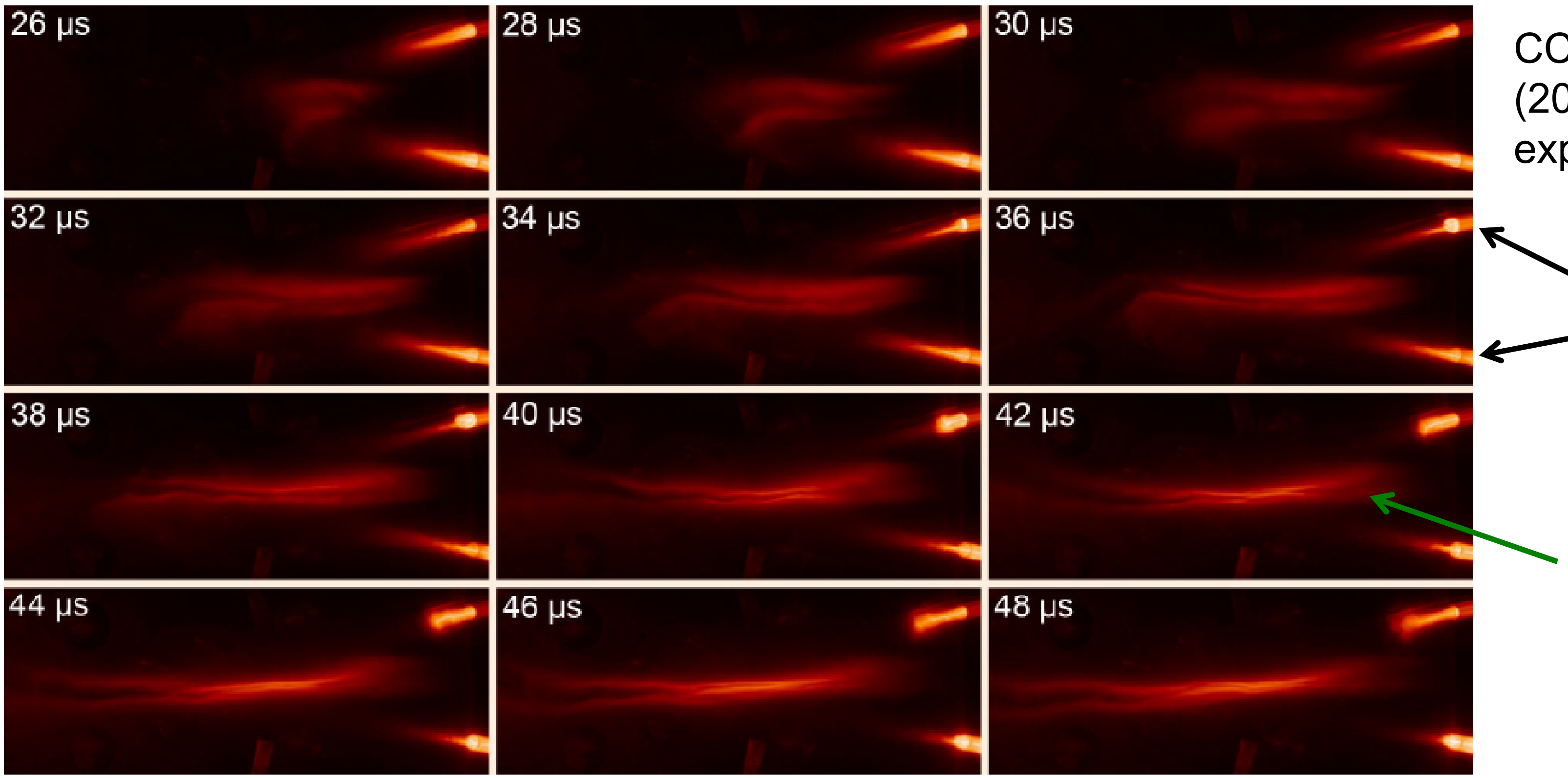
Imploding spherical plasma liner formed by 30 merging jets

- Potential standoff compression driver for magneto-inertial fusion[1]
- PLX facility now studying collisional and collisionless shock physics via head-on merging of two plasma jets[2]
- Simulations/modeling predict peak liner ram pressures ~1 Mbar using ~1 MJ of capacitive stored energy

[1]S. C. Hsu et al., IEEE Trans. Plasma Sci. **40**, 1287 (2012).
[2]A. L. Moser, S. C. Hsu et al., manuscript in preparation (2013).

UNCLASSIFIED

PLX team characterized the stagnation layer between two obliquely merging supersonic plasma jets



- Highest-spatial-resolution measurements of a plasma shock (via spectroscopy and interferometry) → observations consistent with two-fluid plasma shock[1,2]
- Reduction in Mach # not observed → encouraging for imploding plasma liner formation using array of merging plasma jets[2]

[1]E. C. Merritt, A. L. Moser, S. C. Hsu et al., Phys. Rev. Lett. **111**, 085003 (2013).
[2]E. C. Merritt, A. L. Moser, S. C. Hsu et al., submitted to Phys. Plasmas (2013) [APS-DPP invited paper].

Materials testing at GLADIS in Germany

- GLADIS is the **(Garching LArge DIvertor Sample test facility), a neutral beam test stand**

  The GLADIS heat flux test facility serves for investigating the thermo-mechanical behavior of components subjected to extreme thermal loading. The facility is equipped with two 1 MW hydrogen ion beam sources. The components to be investigated are subjected to power densities of 5 – 50 MW/m² in the vacuum chamber. It is possible to load and characterize samples of one size with a length in the region of a few cm to ~ 1 m.

Technical data

Beam:

- Power: 2 x max. 1.1 MW
- Heat flux: 1 - 50 MW/m²
- Pule length: 10 ms - 30 s
- Repetition rate: ~ 100 /h

Vacuum chamber :

- Base pressure: < 1·10-6 mbar
- Dimension: Diameter: 1.5 m
  Length 4.5 m
- Six turbo pumps
- Side insertion manipulator, with water hookups

Sample water cooling:

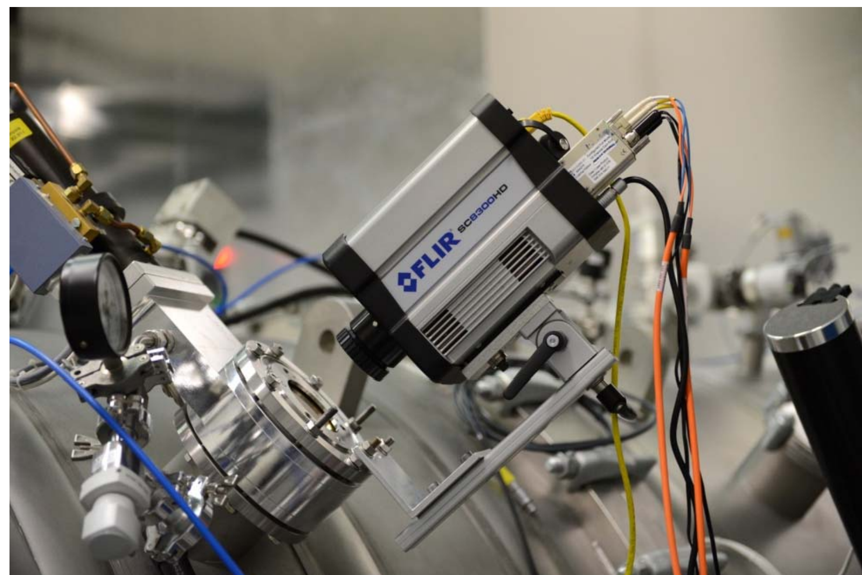
- Static pressure: < 1.6 MPa
- Pressure loss: < 1.5 MPa
- Throughput: < 8.5 l/s

Photo: Dr. Henri Greuner putting protective covers on the end-flange O-ring seal of GLADIS

UNCLASSIFIED

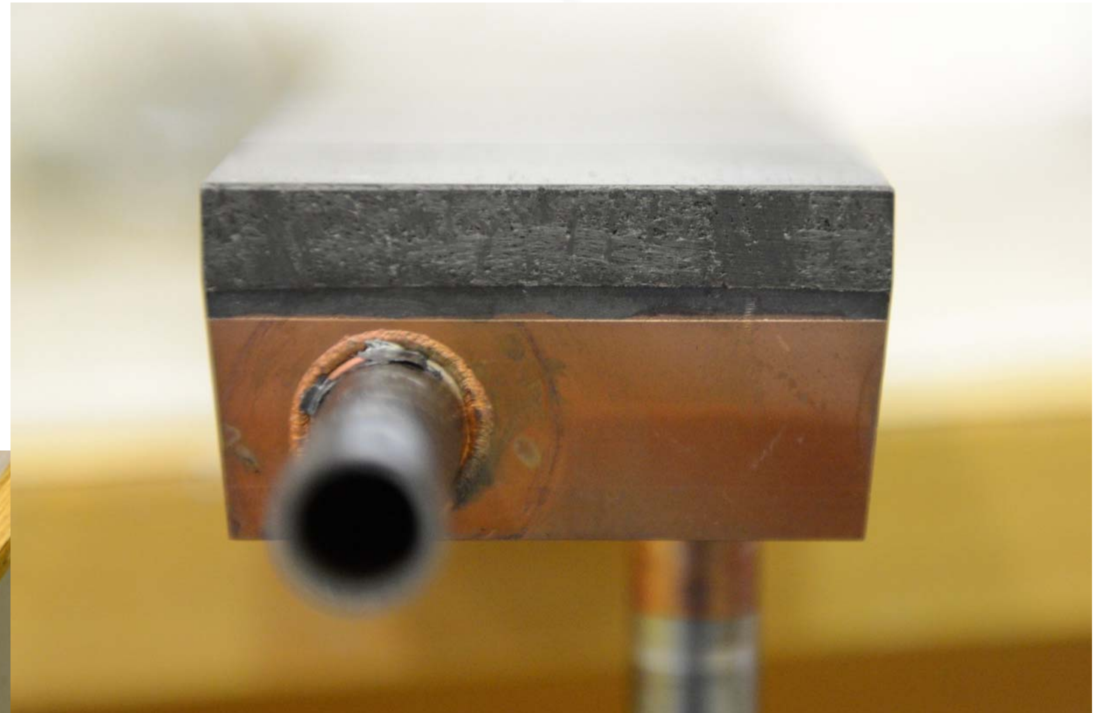
We brought an American FLIR IR camera system from Greifswald to Garching

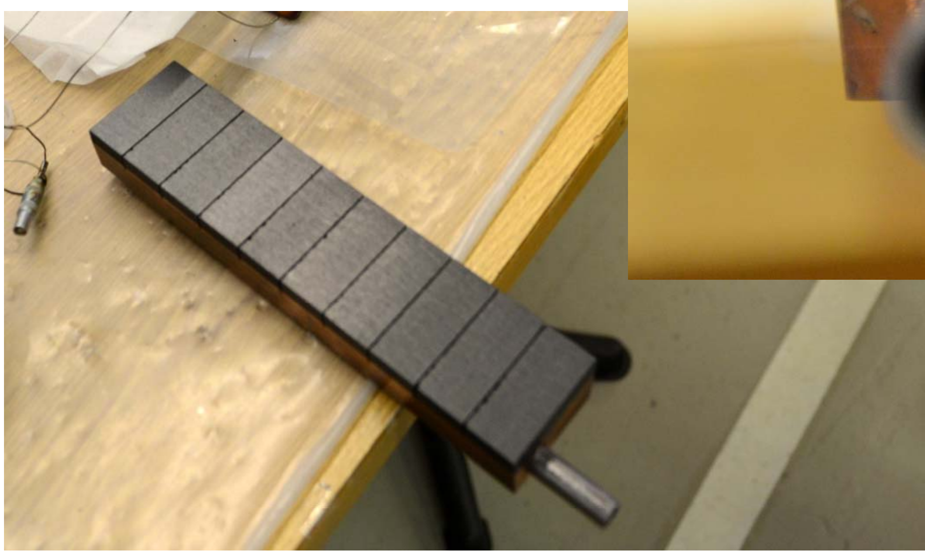
- Alex Rodatos (MPI-Greifswald grad student), and Glen Wurden (LANL)
- We set-up the camera control computer in the GLADIS control room, put on a viewing window (uncoated ZnSe) and used a mount provided by Dr. Henri Greuner (head of GLADIS). The hydrogen atomic beam produces no neutrons, and there are no magnetic fields around the chamber, so installation is straight-forward with 100-m fiber optic cabling.



Views of the carbon fiber composite graphite tile assembly on the work bench

Below: The neutral beam will strike about 3 of the 10 tile elements seen below at any one time

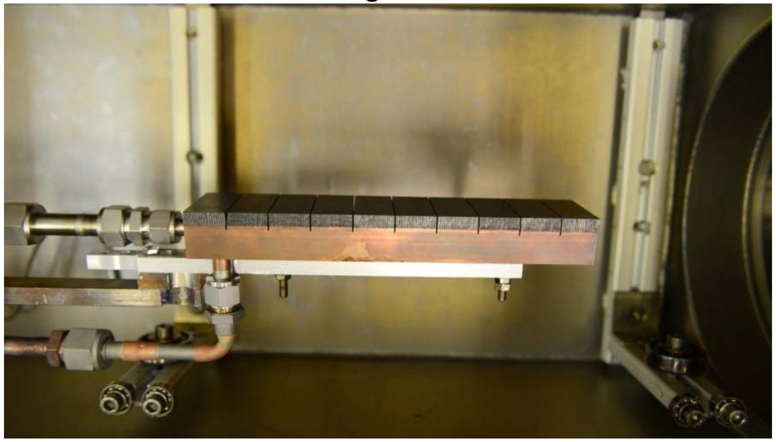




Above: The CuCrZr bonding layer is visible between the CFC graphite and copper substrate.

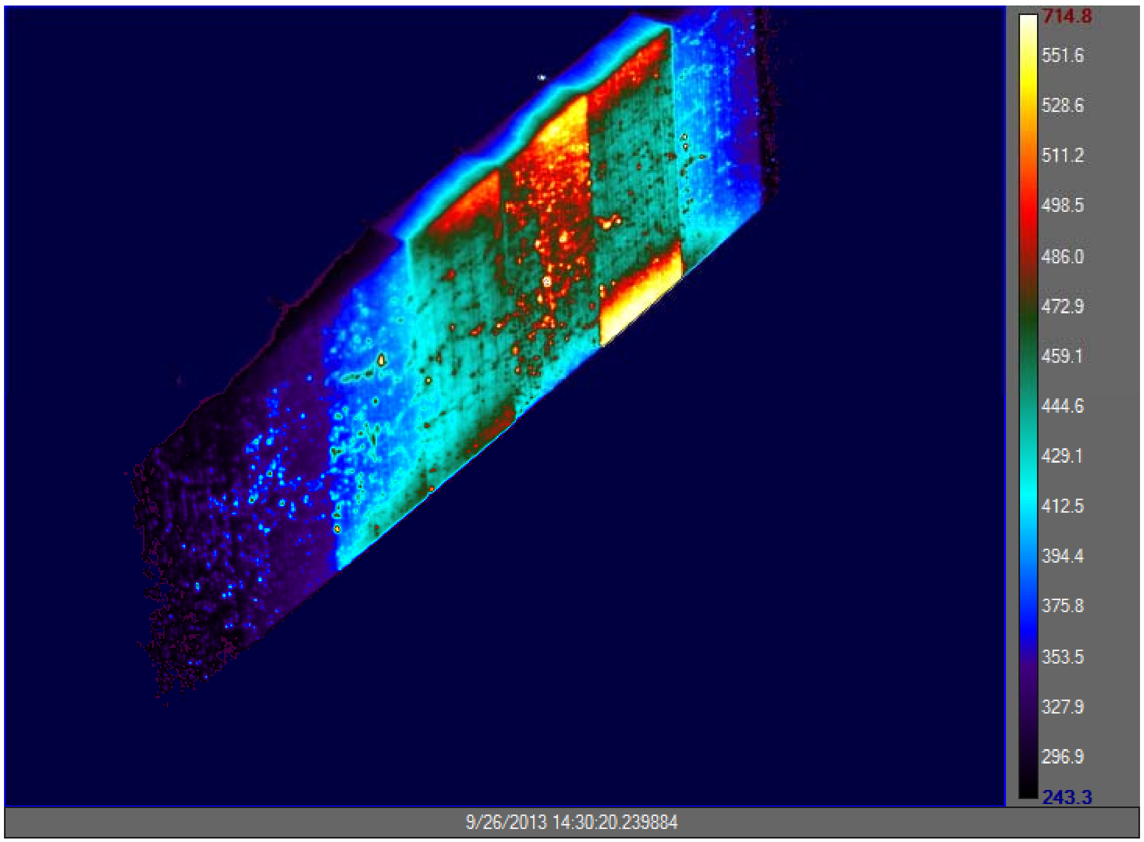
Loading a water-cooled armor sample

- We started with an early set of water-cooled W7-X graphite tiles, with known delamination defects. This W7-X CFC graphite-bonded-to-copper water-cooled divertor tile set is shown in the insertion chamber (Alex's smiling face), and also viewed from above (in visible light). I am holding a 30-cm long ruler for scale. The insertion arm carries with it a flexible set of water cooling lines, in vacuum.

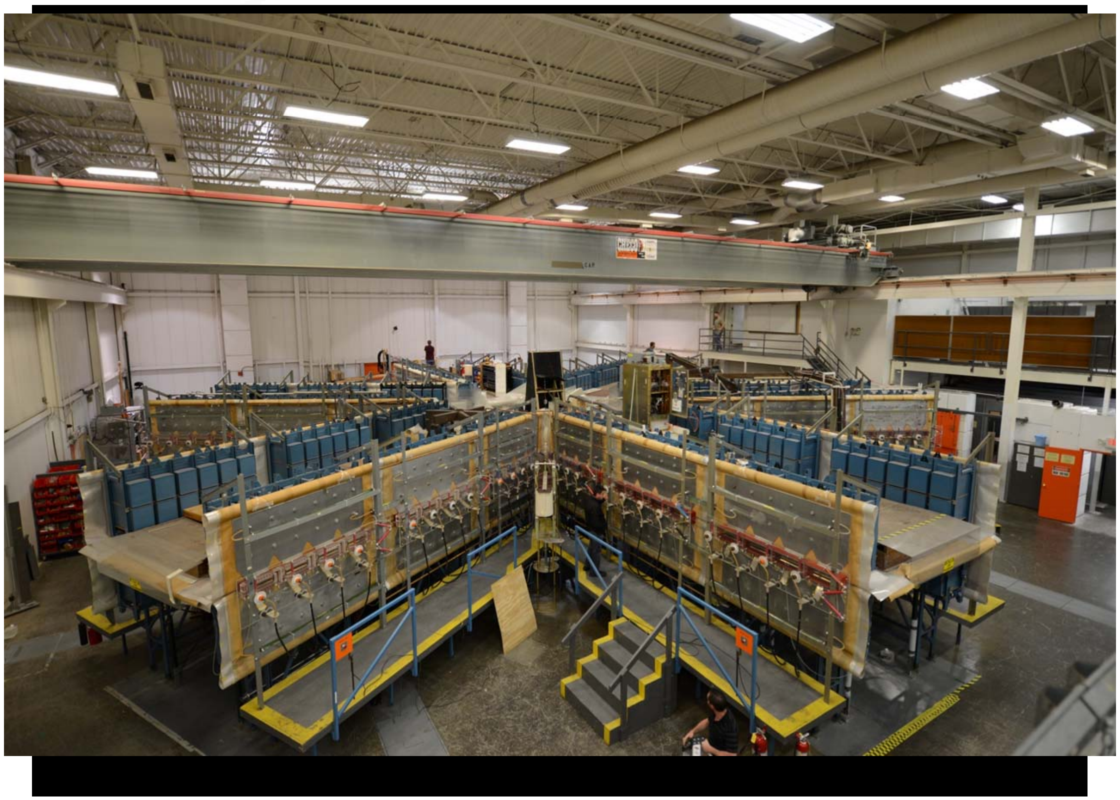


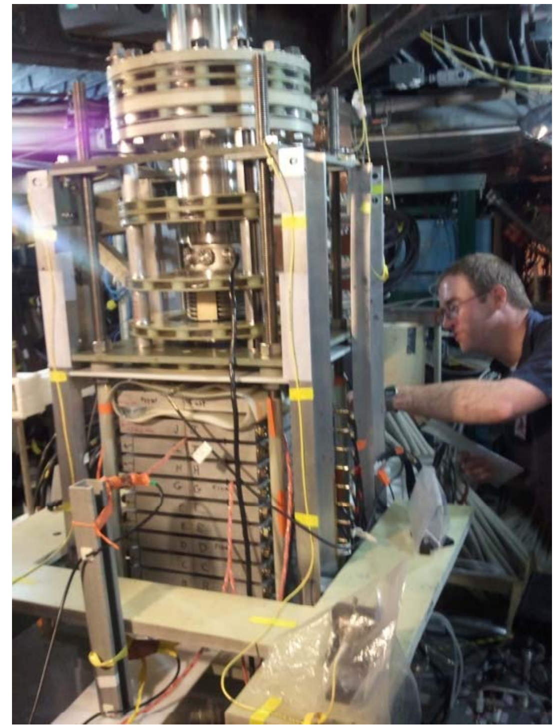
UNCLASSIFIED

A single IR frame from an 8 MW/m^2 shot. Increased temperature due to CFC delamination of the ends of several tiles is visible (scale is °C)



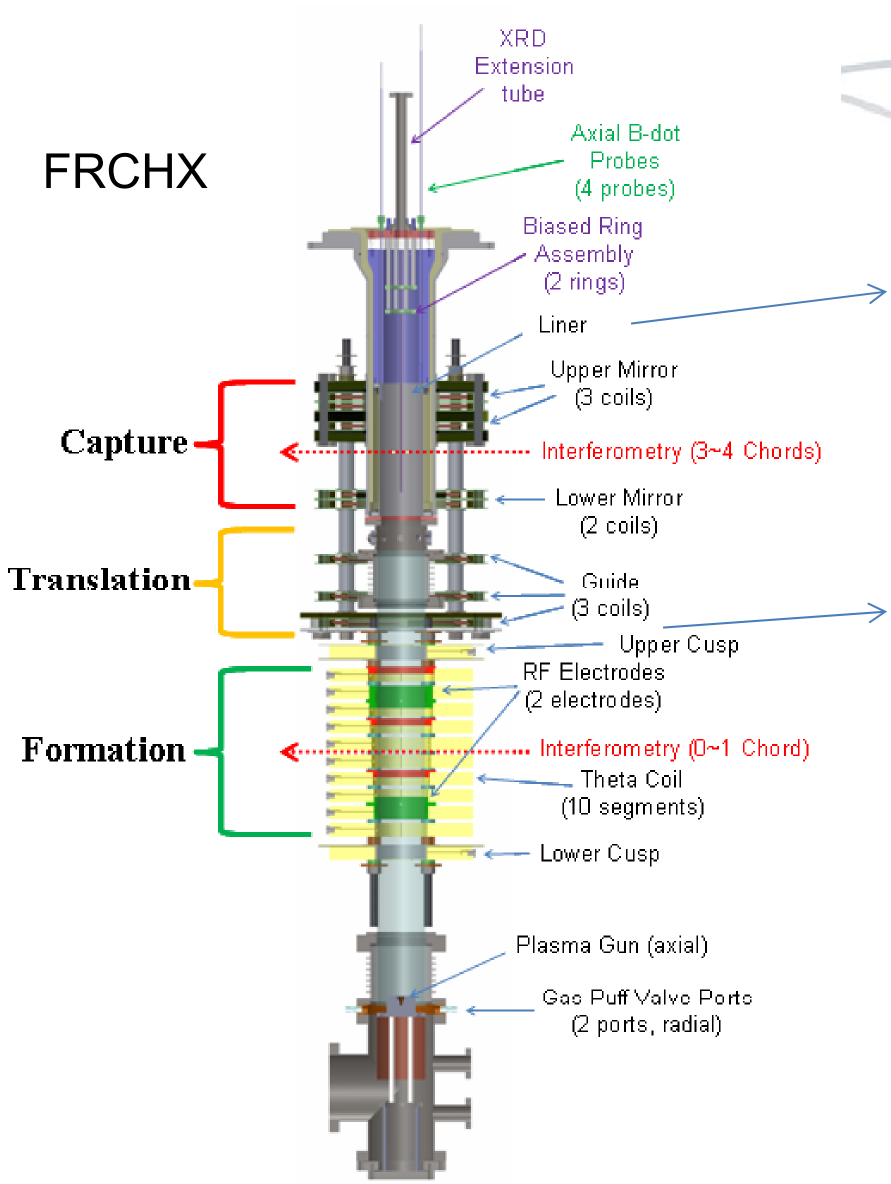
Shiva Star is an Air Force pulsed power facility where we conduct Magnetized Target Fusion (MTF) experiments



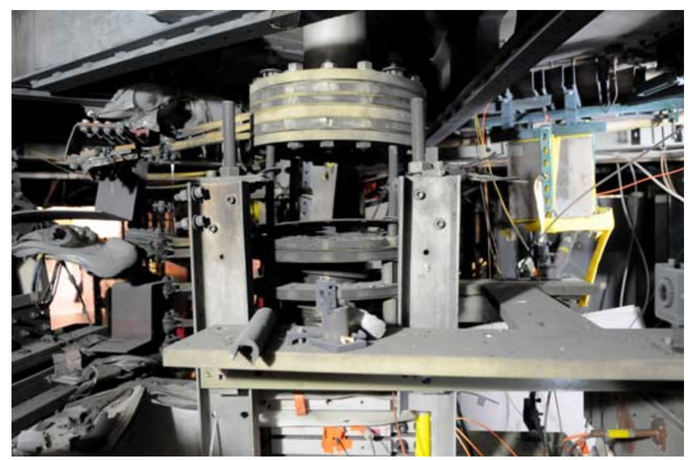


Shiva Star (left) can store 9 MJ of energy with 1.3 mF of capacitors, at up to 120kV. More typically, at 4.5 MJ, it delivers 11.4 MA of current to crush a 30-cm tall, 10 cm diameter, 1 mm thick, 270 gm Aluminum cylindrical liner load in 25 microseconds. The FRCHX load assembly (right) is located under the center of Shiva Star.

FRCHX



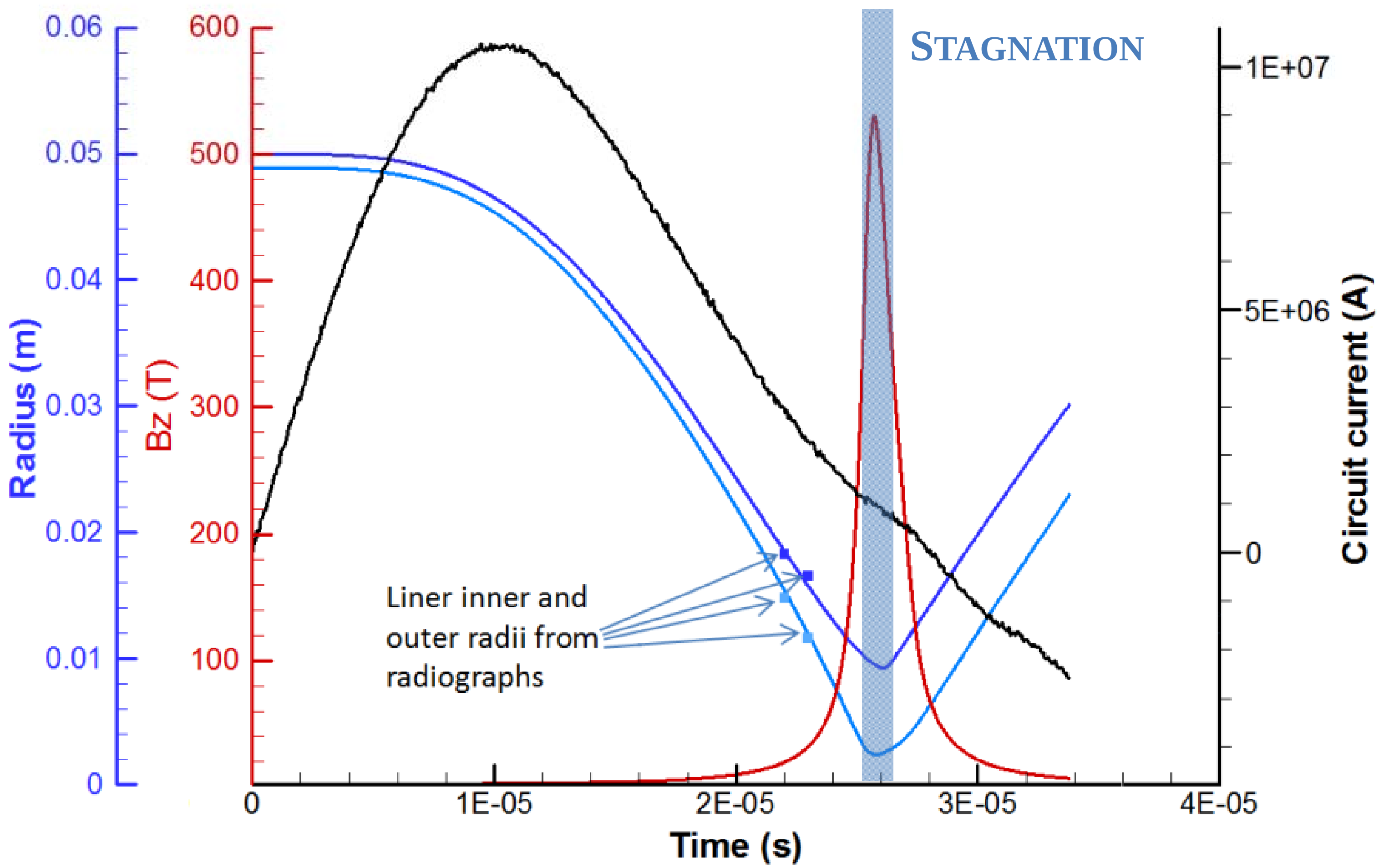
Before



After

UNCLASSIFIED

MACH2 results for solid liner compression, ~1.36 T initial axial field and 79 kV charge on the Shiva bank ("FRCHX #2"). Modeling suggest final fields > 500 Tesla.

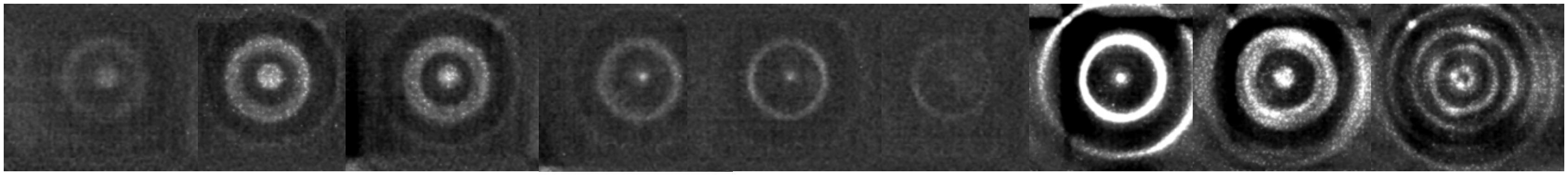


Note: The "bump" in the current trace (black) was predicted by modeling, and is observed in the experiments. It is caused by the rebound of the liner off of the magnetic field.

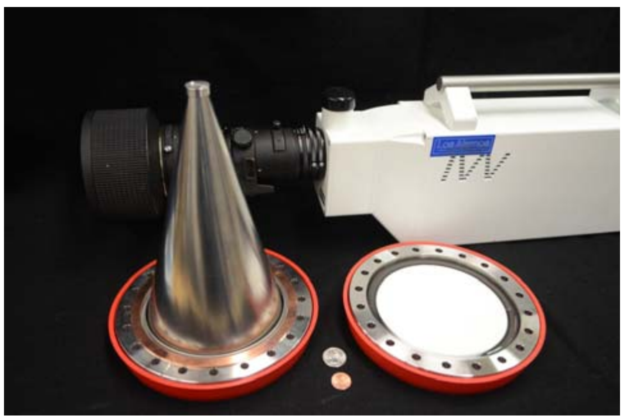
UNCLASSIFIED

Soft x-ray pinhole camera framing images show the plasma compression

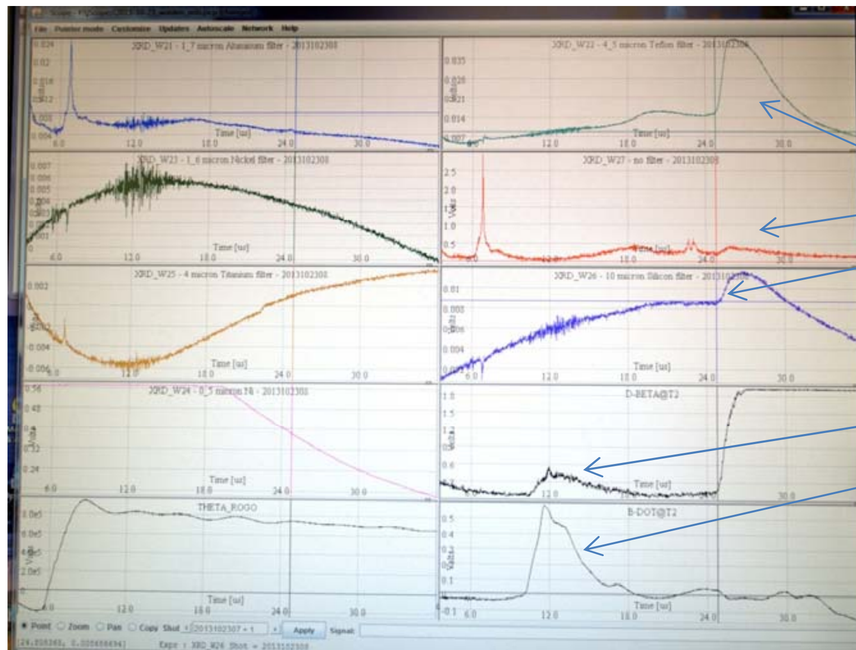
11.8 usec 13.8 usec 15.8 usec 17.8 usec 19.8 usec 21.8 usec 23.8 usec 25.8 usec 27.8 usec



The FRC plasma is the central feature, the middle ring is a reflection from half-way down the column. It certainly compresses, but also fades until the 7th frame (stagnation time). Expansion (rebound) is seen in the last two frames shown here.



A P46 phosphor converts VUV and soft x-ray light into visible light, imaged by a telephoto lens on the Hadland camera (2 usec exposure for each frame)



Filtered XRD photodiodes take off at 24.8 usec

H-beta and magnetics located below the capture region show the passage of the FRC just before it enters the capture region

UNCLASSIFIED

Preliminary FRCHX Shot Details

- We waited 5 μsec after the start of the liner implosion to inject a longer-lived FRC into the capture region. The FRC arrived when the liner was at 80% of its initial radius (at 12 usec). The pre-compression FRC plasma had an excluded flux lifetime in the capture region of 14-17 μsec. Peak compression/stagnation was observed at ~25 usec.
- The entry mirror field was reduced for the implosion shot, to compensate for the expected compression of the fields, at the time the plasma first transited the mirror location.
- From interferometry prior to injection, the density was $4x10^{16}$ cm^{-3} , while a Stark broadening measurement (100 nm FWHM broadening of the D-beta line) at a time of 16-20 μsec (5 usec before peak) suggests a minimum density of ~$6x10^{17}$ cm^{-3} at 18-20 μsec in the colder regions of the deuterium plasma.
- The broadband soft x-ray imaging clearly shows the plasma being compressed. But it also shows that while in the liner prior to peak compression, the plasma was still getting dimmer, until the last microseconds, when it finally got brighter. Taken with the previous point, we can infer that the electron temperature was NOT increasing during most of the compression (until the very end).
- Several filtered soft x-ray diodes (4.5 um Teflon, and 10 um Silicon) saw a large jump in their signals starting at 24.8 μsec, suggesting heating in the last few microseconds. A diagnostic monitoring D-beta radially at the T2 location (just below the liner) also showed a large jump at the same time (probably reflected light). However the overall magnitude of the signals were much smaller than anticipated.
- Only our most sensitive neutron detector (a 25 cm diameter Arsenic activation system, which is loaded with 8.4 kg of arsenic powder embedded in epoxy at a distance of ~90 cm from the center of the liner) showed signals above backgrounds. It recorded 38 counts (backgrounds are 5), corresponding to ~3x 10^6 DD neutrons from the source. This was a factor of 1000x or more below what we were hoping for from the shot, consistent instead with 300-400 eV temperatures.
- Conclusion: The compression was not adiabatic (not even isothermal) for the majority of the implosion. Only at the very end did we see net heating….and then most likely from too low of a starting point. We need a better target plasma….one with lifetimes longer than the implosion/heating timescale.

FRCHX Shot Summary

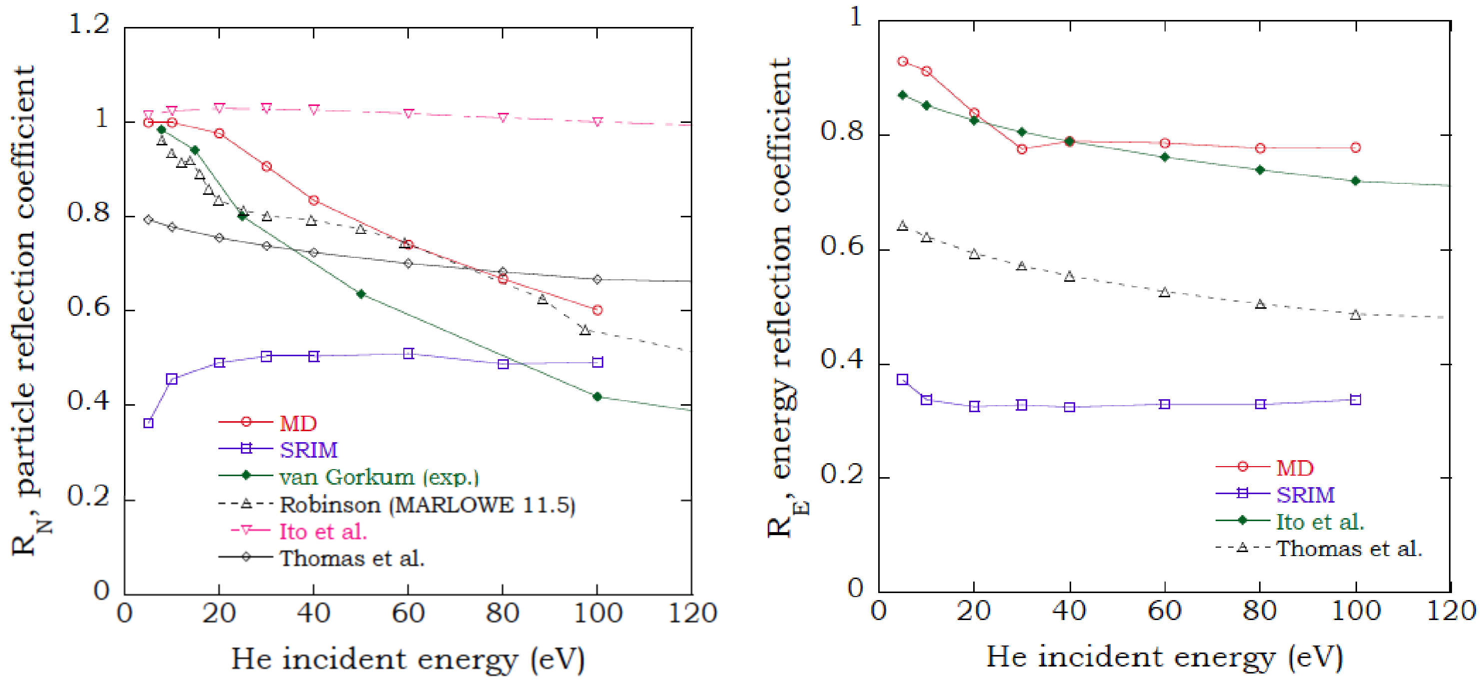
- We compressed an FRC plasma a factor of 10x or more (to < 0.5 cm diameter). This was the highest density (in the range of 10^18 to 10^19 cm^-3) FRC plasma ever created.
- The plasma cooled for most of the compression, until the final microsecond, where liner heating won out. The DD neutron yield was 3x10^6, consistent with an ion temperature in the range of 300-400 eV. We did not achieve keV temperatures.
- Rebound of the liner was observed, at a time and rate consistent with the generation of ~ 5 Megagauss fields, and ~ 1 Megabar stagnation pressure.
- For a future experiment, one should start with a plasma having 2-3*x* longer lifetime, relative to the compression timescale.
- We could do this with double-sided FRC injection/merging (as shown by Tri-Alpha at much lower densities), using a split FRC bank, and simplified theta-coil driven liner compression on Shiva Star.

LANL's theory/modeling of magnetic & inertial fusion

- **OFES supports a fusion theory program in the Theoretical Division: the T-5 Plasma Physics Team (team leader: Xianzhu Tang)**
  - Team has nine staff plasma physicists, six postdocs, three students
- **Magnetic fusion research**
  - Plasma-materials interaction in a tokamak environment: material focus is tungsten
    - Helium recycling at W surface: molecular dynamics calculation of He reflection;
    - Impact on boundary plasma via the sheath energy transmission coefficients
  - Sheath/Scrape-off layer of a tokamak with low-recycling and high-recycling walls :
    - Parallel transport in the presence of magnetic trapping.
    - Magnetic sheath modeling including energy conservation (full Bragniskii equations).
    - Dust motion/survivability near a tokamak divertor/first wall.
  - Interaction between turbulence and macro-stability:
    - Turbulence modification of neoclassical bootstrap current.
- **Inertial fusion research:** Plasma physics effect in ICF target performance:
  - Fuel ion separation by baro-, electro-, and thermo-diffusion
  - Inverse Knudsen layer effect of yield recovery in the cold fuel layer due to tail ion loss from the hot spot, which is known to reduce hot-spot fusion reactivity.

Recycling at tungsten wall & impact on boundary plasma

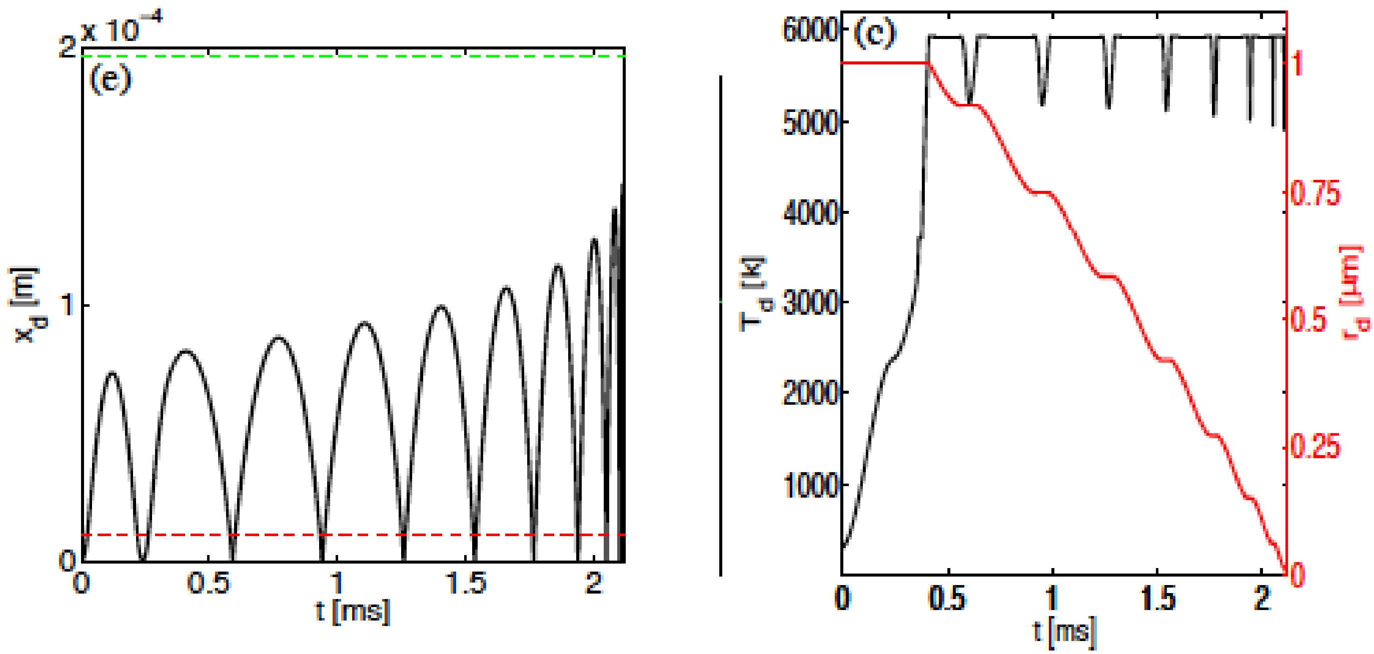
In sharp contrast to carbon tiles, recycling of light ions such as helium on tungsten wall/divertor is dominated by reflection. Molecular dynamics simulations show that both the particle and energy reflection coefficients are near unity. This implies that the ion channel of the sheath energy transmission suffers considerable blockage. Exhausting the plasma heat flux requires a large separation in electron and ion temperature, and a more significant role of radiation loss seeded by impurities.



Tang, Guo, Borovikov, Voter (2013)

Dust survivability in a tokamak

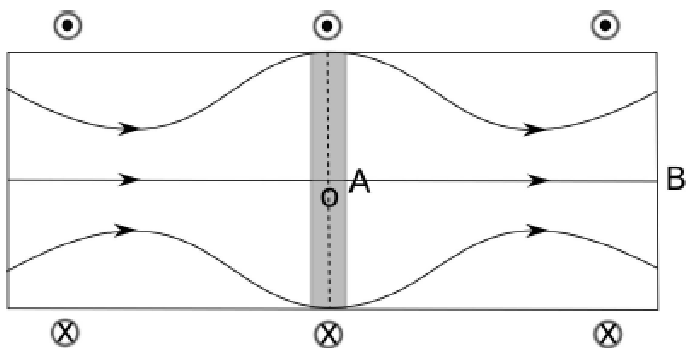
Dust generation and transport is a key Plasma-Materials Interaction (PMI) issue for tokamak reactor since it can drastically impact the local balance of erosion and redeposition. The dust survivability hinges on the competition between its poloidal transition across the divertor in the neighborhood of the plasma sheath, and the balance between plasma heat collection and radiative cooling of the dust. We find that micron size dust, although can survive the current tokamak condition of 1 MW/m^2, will be mostly nonlocally redeposited in a reactor of ~10 MW/m^2.

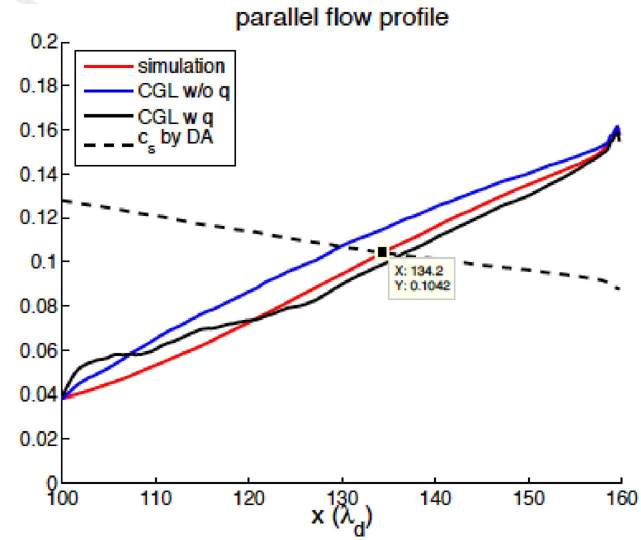


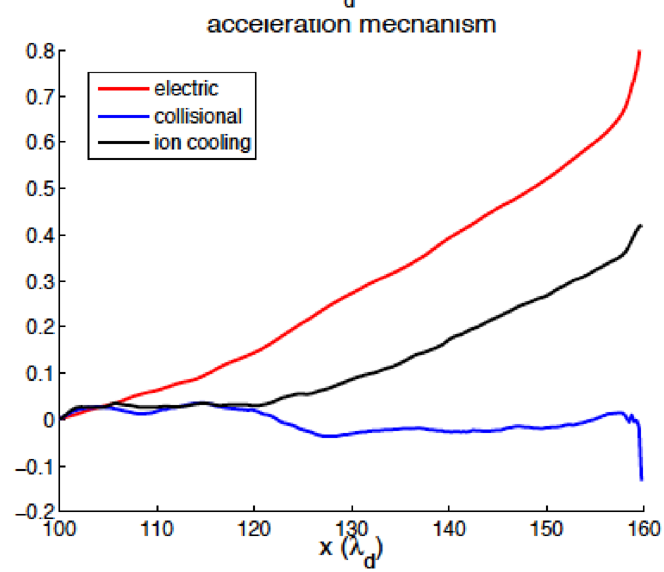
Delzanno & Tang (2013)

Parallel flow at the presence of magnetic trapping

Parallel flow acceleration in the scrape-off-layer is complicated by magnetic trapping, and the ensuring temperature anisotropy. Using a combination of kinetic simulations in simply mirror geometry and analytical model based on an extension of the CGL model that includes parallel heat flux, we find that (1) parallel flow is accelerated from subsonic to supersonic, with the transonic point around the B maximum; (2) ambipolar potential dominates flow acceleration in low collisionality; while (3) ion cooling has an increasing role at high collisionality.







Guo, Tang, McDevitt (2013)

UNCLASSIFIED

Ion separation dominated by thermo-diffusion

$k_T^{(i)}$

- **In an unmagnetized plasma or along the direction parallel to the magnetic field, different ion species can diffuse against each other. This can cause fuel ion separation in an ICF target or impurity penetration in the SOL of a tokamak.**
- **We find that in a plasma of most interest, thermo-diffusion tends to play a dominate role compared with baro- and electro-diffusion.**

$$c \equiv \rho_l / \rho = \rho_l / (\rho_l + \rho_h)$$

$$\rho \partial c / \partial t + \rho \vec{u} \cdot \nabla c + \nabla \cdot \vec{i} = 0$$

Kagan & Tang, PoP & PRL (2012)

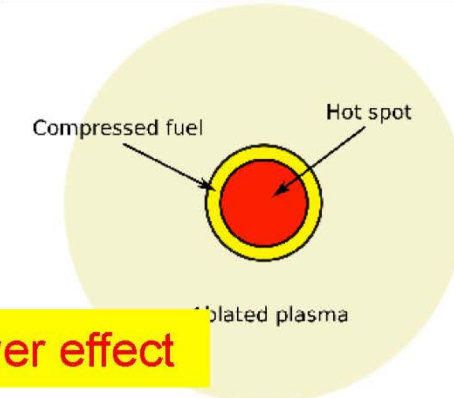
$$\vec{i} = -\rho D \left(\nabla c + k_p \nabla \log p_i + \left(e k_E / T_i \right) \nabla \Phi + k_T^{(i)} \nabla \log T_i + k_T^{(e)} \nabla \log T_e \right)$$

Kagan & Tang (2013)

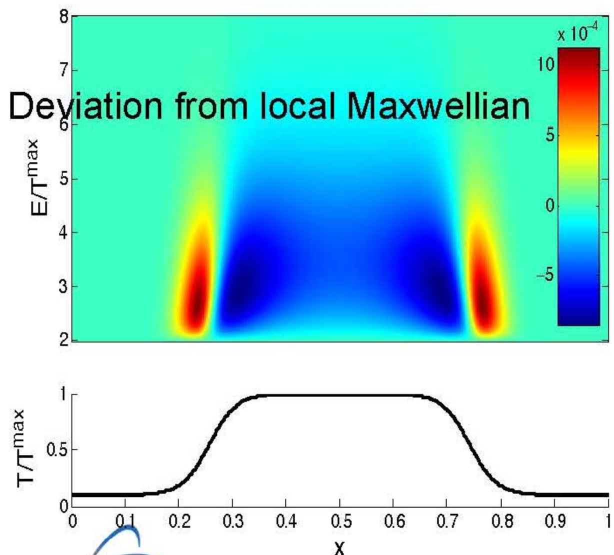
Tail ion loss and fusion reactivity

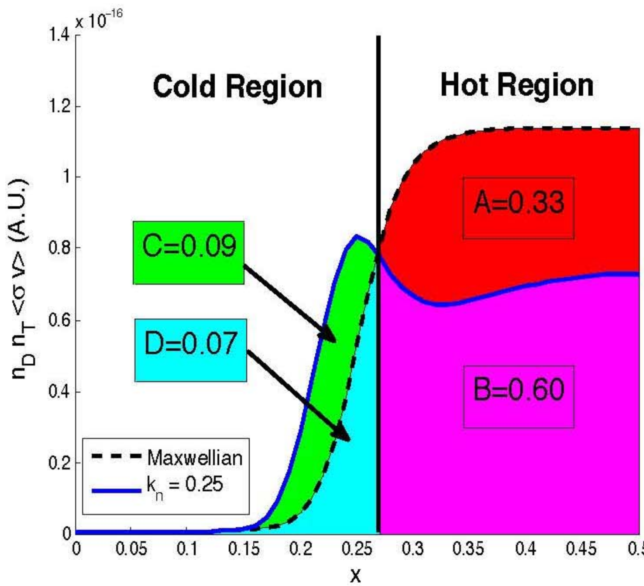
- *Fusion reactivity dominated by suprathermal (fast) ions at Gamow peak ← DT cross section (nuclear physics)*
- *Knudsen layer effect: fast (tail) ions escaping from hot spot → tail ion depletion → reduction in hot spot $\langle \sigma_{DT} v \rangle$*
- *Inverse Knudsen layer effect: escaping ions fuse in cold fuel ice – resulting yield recovery ($\beta = Y_{shell}/Y_{hot\text{-}spot}$)*

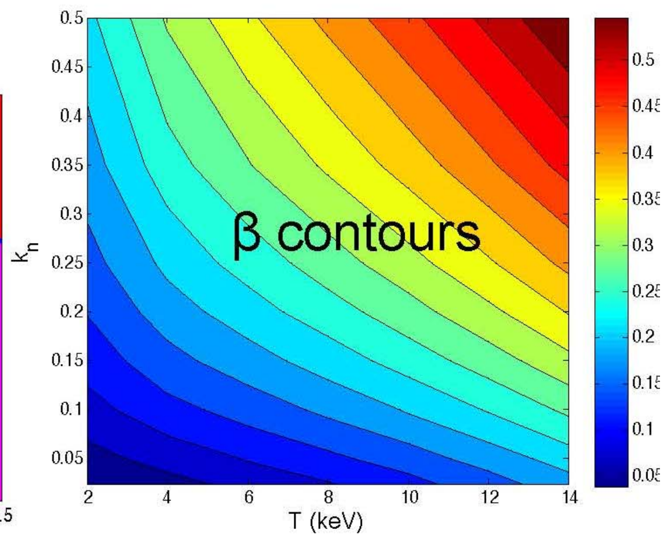
Knudsen number $Kn=\lambda_{ii}/L$



LAPS Fokker-Planck module quantifies (inverse) Knudsen layer effect







McDevitt, Tang, Guo, & Berk (2013)

0<β<0.5

LANL Theory Collaborations

•PPPL collaboration (John Finn, C. L. Ellison, grad student; H. Qin; W. Tang) – PhD thesis of Ellison: variational integrator for guiding center equations with adaptive time steps

•U. Wisconsin CMSO (Finn, Z. Billey, grad student; E. Zweibel; W. Daughton, LANL) – development of field line diagnostics for PIC data and quasi-separatrix layers. Paper submitted for special issue on flux ropes of *Plasma Phys. Contr. Fusion*

•Columbia U., U. Wisconsin (Finn, A. Cole, Columbia; C. Hegna, UWM, P. Terry, UWM) – momentum transport by Reynolds stress and Maxwell stress in resistive layers in RFPs and tokamaks; tearing layer computations by Pade' approximants

•Princeton, GA (Finn, D. Brennan, R. White, A. Turnbull) – m=1 mode localized inside radius of minimum of *q* in reversed shear discharges and coupling to MHD continuum. Coupling with energetic particles using PEST and NIMROD

•Princeton (Finn, D. Brennan, K. Sassenberg) – Feedback stabilization of tearing modes in RFPs; paper appeared in *Plasma Phys. Contr. Fusion*. Toroidal geometry (PEST-III) feedback studies for tokamaks underway

For the future: A “new” in-situ runaway electron diagnostic for tokamak research

G. Wurden
J. Oertel

- It has been suggested for a number of years that runaway electrons in tokamaks could be detected by employing inverse Compton scattering of a laser pulse off of the relativistic electrons. Runaway current densities of MeV electrons are ~ 1 MA/m^2 in tokamaks.
- When a visible to near IR photon scatters off of a 5-50 MeV electron, forward directed soft x-ray photons are generated (1 keV to 40 keV).
- An experiment was attempted on JT-60U in 2006-2007 (Y. Kawano), but not completed due to the shutdown of JT-60U for construction of JT-60SA. To date, no one has made successful measurements in a tokamak.
- We believe that newly available laser technology (1 Joule at 1064 nm, in a 20 picosecond pulse) and gated x-ray detectors (used by P-24 at NIF) could be employed to greatly improve the S/N ratio of the detected soft x-rays (by narrowing the time gating window to reject plasma & disruption noise sources), while also enabling time of flight localization of the emitted soft x-rays to give spatial profiles of the runaway electrons along a single tangential laser chord.
- This proposed diagnostic would enable studies of the energy and spatial distribution development of runaway electrons in today’s large tokamak facilities.

Summary

- LANL continues to be engaged and interested in a wide range of Fusion Energy Sciences research.
- We would like to see an HEDLP FES program restored from the drastic FY13-FY14 cuts.
- We hope and believe that after all the budget uncertainties are said and done for FY14-FY15, that there will still be opportunities for innovation in solving critical issues to achieve fusing plasma conditions while using magnetic fields.