Highlights of Some Research Activities:

- Alcator C-Mod
- Levitated Dipole Experiment :LDX
- ICF/HEDP Activities

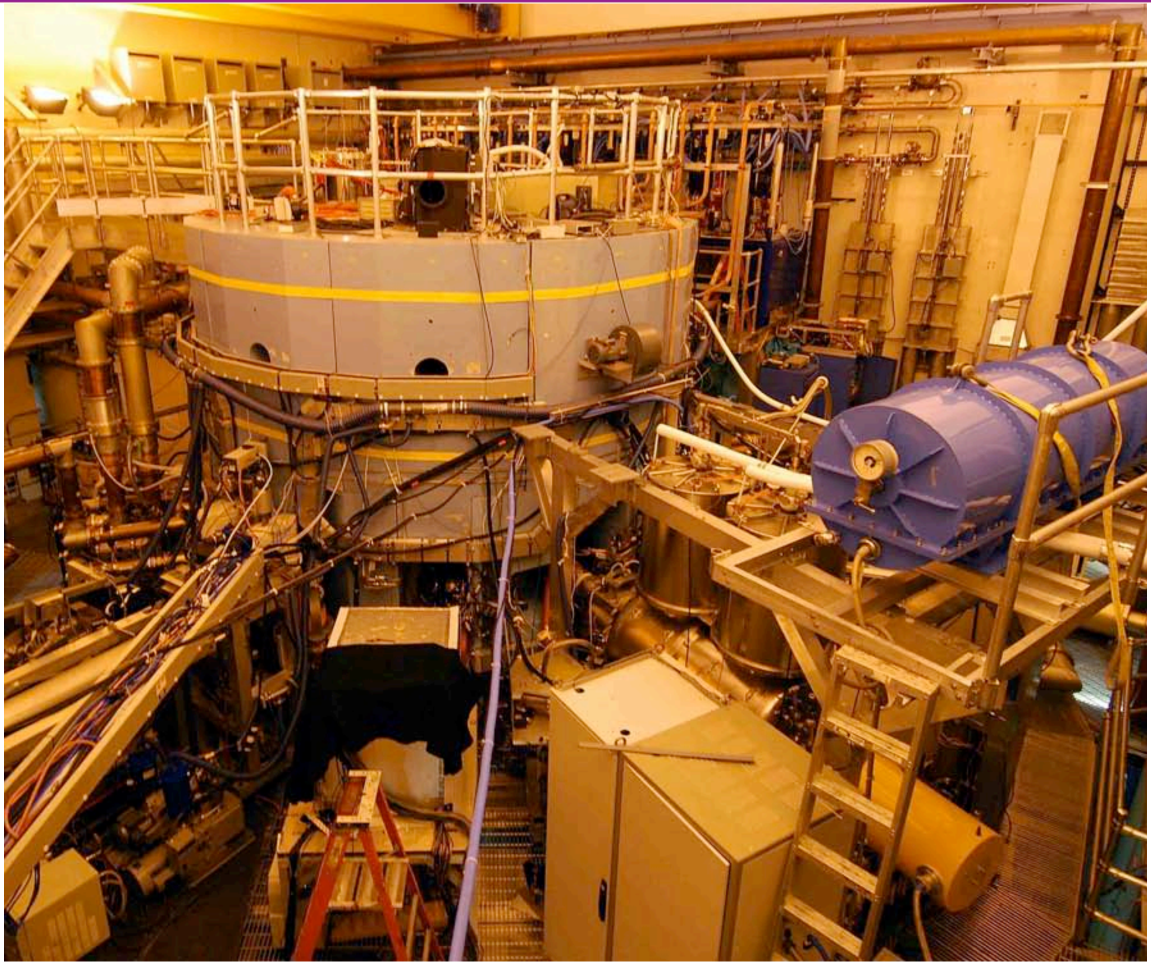
Miklos Porkolab

With input from Earl Marmar (C-Mod), Jay Kesner (LDX), Mike Mauel (LDX), Rich Petrasso (ICF/HEDP)

Fusion Power Associates Meeting
Livermore, CA, 12.04.2008

Alcator C-Mod Program Overview

Earl Marmar and the C-Mod Team

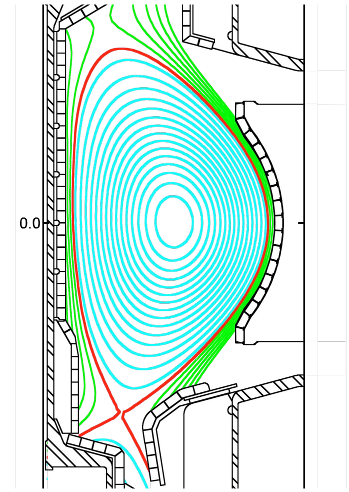


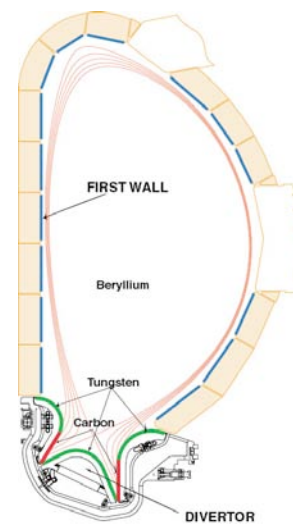
Compact high-performance divertor tokamak research to establish the plasma physics and engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors.

Developing the "steady state", high-Z wall, high-field tokamak for ITER and beyond

C-Mod physics regimes, machine capabilities and control tools uniquely ITER-relevant

- **Edge and Divertor:** All high-Z solid plasma facing components (key for D retention, effects on core). Divertor characteristics similar to ITER (power flow, neutral and radiation opacity)
- **Core Transport:** Equilibrated ions and electrons. No core fuelling or momentum sources
- **Macro-stability:** Can access ITER β range, as well as same B_T and absolute pressures
- **Wave Physics:** Similar to ITER: ICRF bulk plasma heating; FWCD; Critical test of LHCD profile control for ITER AT operation [same B, n; => same ω_{pe}, ω_{ce}, ω]
- **Pulse length:** $\tau_{pulse} >> \tau_{CR}$ Relevant non-inductive CD capability , *important for Steady State scenarios*
- **Combination of these features is unique and enables integrated studies of many key questions.**





Recent C-Mod Results Indicate Potential Improvements in ITER Design and Operation

- Intrinsic Rotation and Mode Conversion Flow Drive
- Lower Hybrid Current and Flow Drive
- Hydrogenic Retention in All-Metal Plasma Facing Materials
- ICRF Impurity/Sheath Effects
- Disruptions and Runaways
- High Performance L-Mode

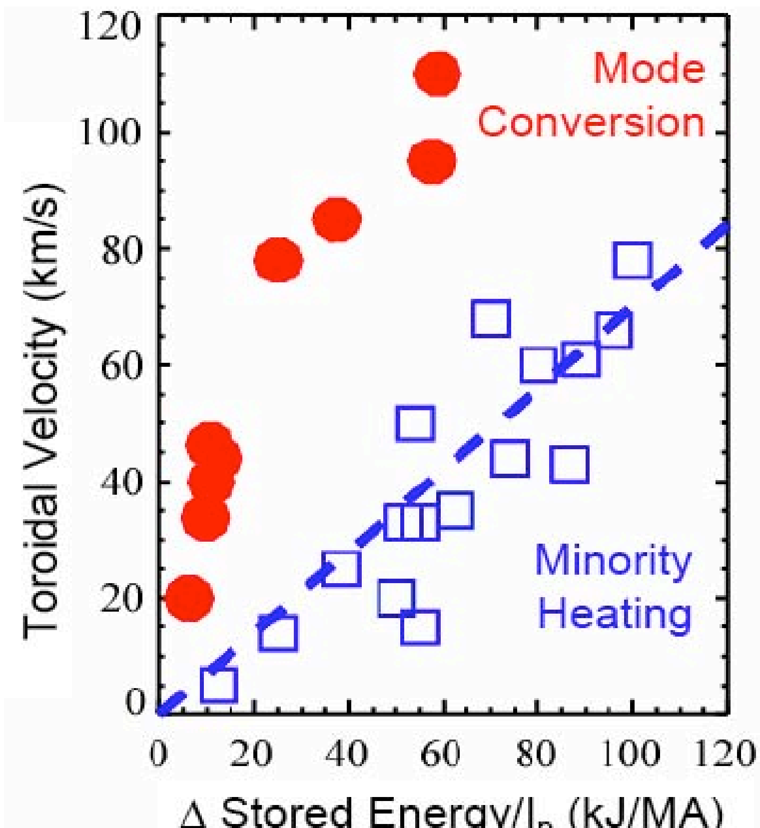
Discovered Flow Drive in recent ICRF *mode conversion* experiments which is twice as efficient as *intrinsic rotation*

Potentially Applicable to ITER

- Active ICRF Flow Drive
  - At least a factor of 2 above the usual scaling seen with pressure/current
- Use multi-frequency capability
  - 80 MHz, proton minority
  - 50 MHz, ^{3}He mode conversion
  - Both layers near the axis
- Near-axis conversion to Ion Cyclotron Wave (ICW)
  - propagates back toward low field side
  - damps and drives flow at ^{3}He cyclotron layer

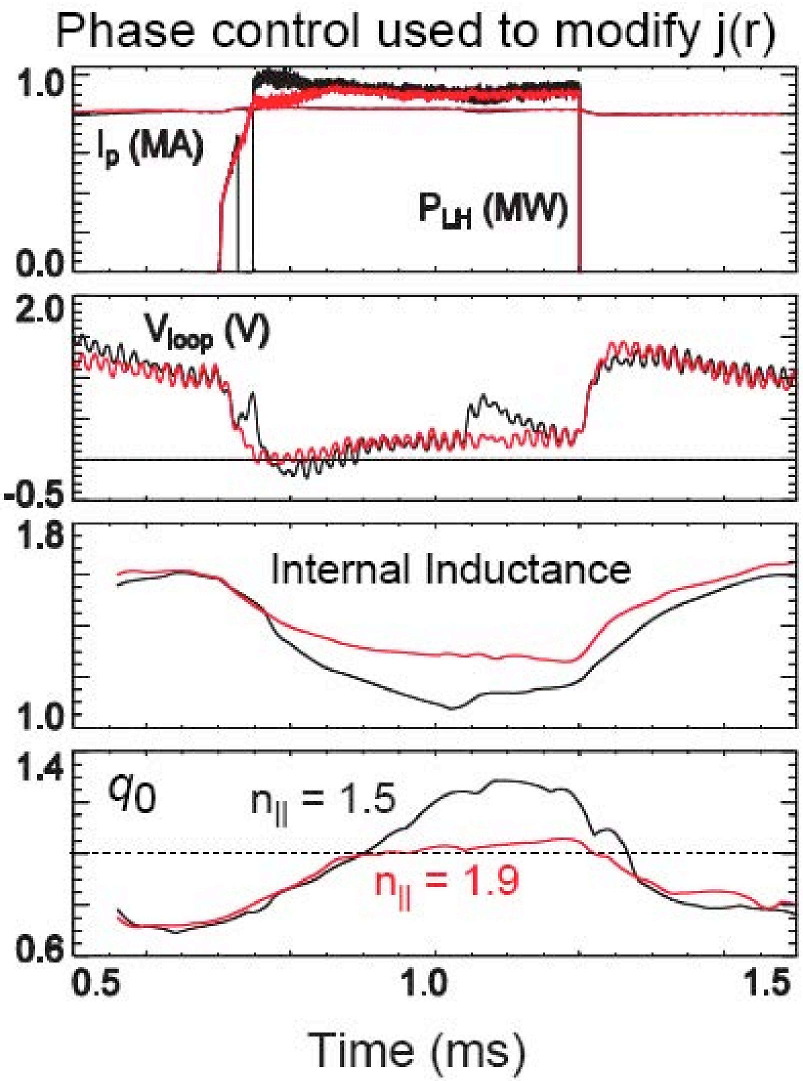
Mode Conversion Flow Drive

$B(R_0)$ = 5.1 Tesla; ^{3}He fraction ~ 10%



Y. Lin et al, PRL, 101, 235002 (2008)

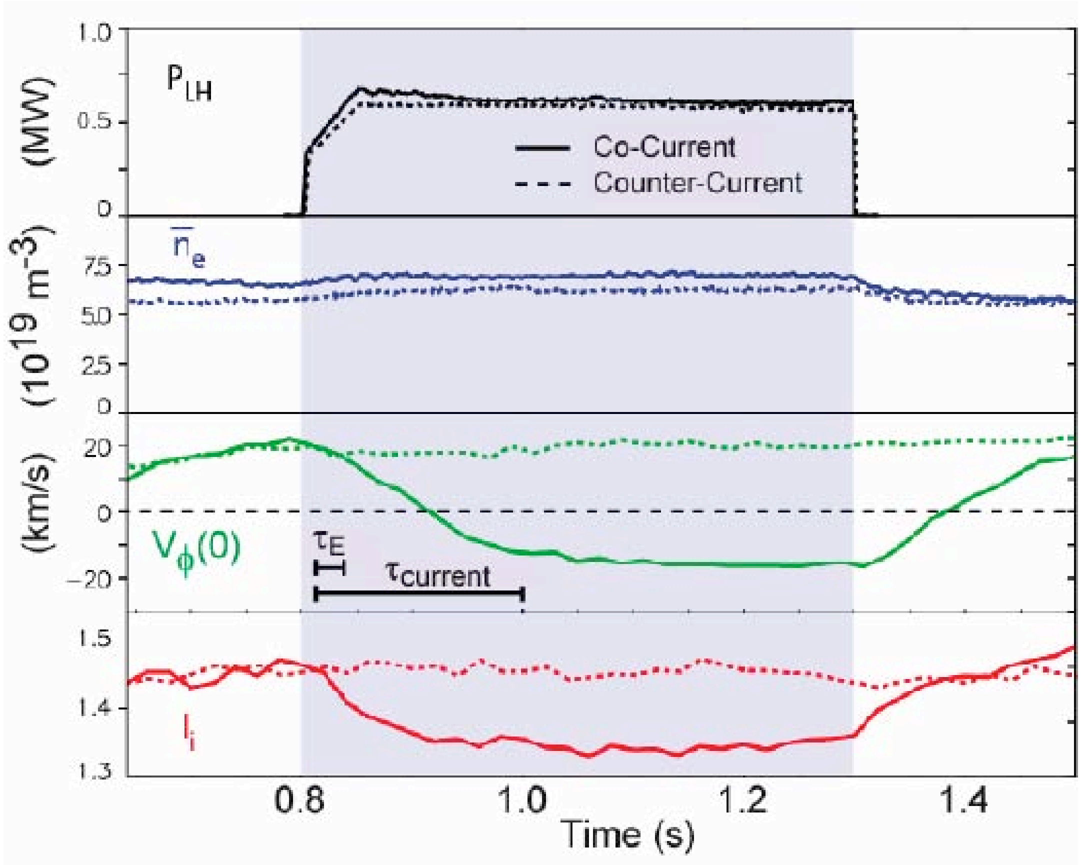
Lower Hybrid Waves Used to Control Current Profile by Variable Grill Antenna Phasing



- Magnitude of CD in agreement with Fisch-Karney theory
- Current is driven off axis, q(0)>1 (profiles from MSE-constrained EFIT)
- Largest magnitude of current driven by fastest waves
- Results being used to validate modeling
  - GENRAY/CQL3D + TORIC-LH)

Strong Counter Current Toroidal Flow Drive Observed with co-Current LHCD

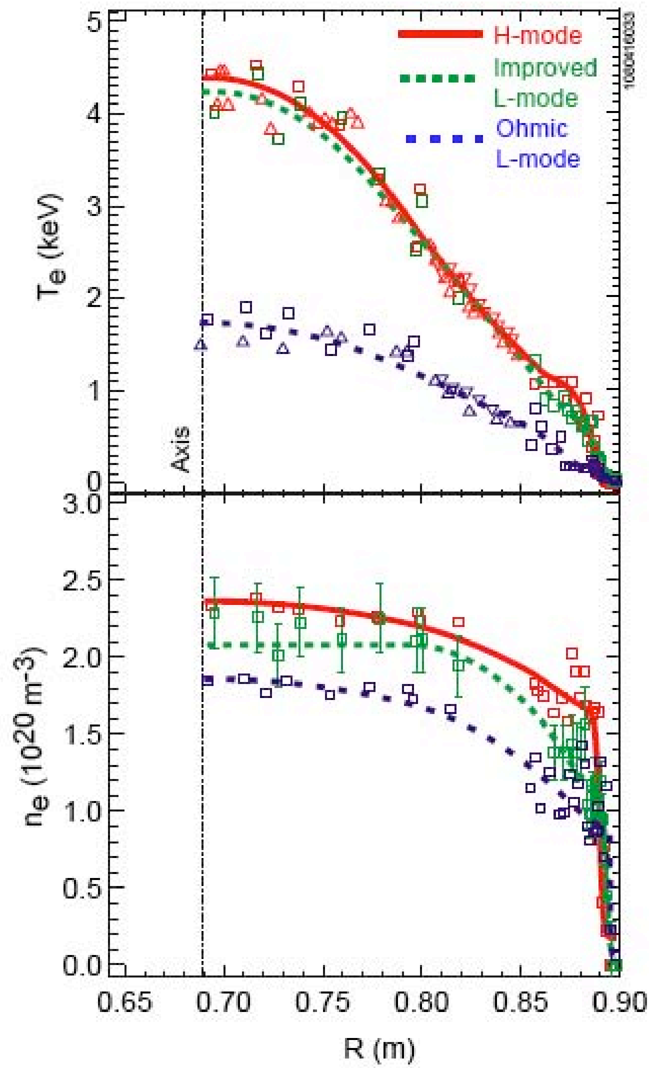
- **Toroidal plasma flow observed in the counter Ip direction and only in the presence of Co-Current drive with Lower Hybrid waves (co-LHCD)**
- **New opportunity to explore momentum confinement and plasma rotation**
- **Opportunity to tailor rotation shear when combined with ICRF flow drive**



Rice, Parker, Wilson, et al, IAEA, Geneva, 2008

Improved L-Mode: H-mode Confinement with L-mode Particle Transport - A New Possibility for ITER ?

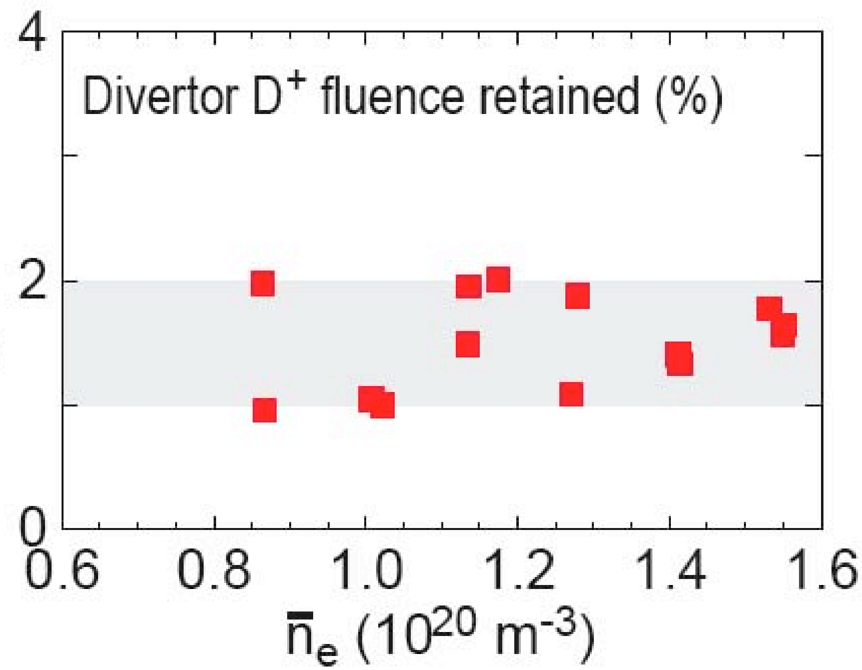
- Unfavorable ∇B drift direction; increased δ, I_p
  - Very high H-mode threshold (at least x3)
- H-mode confinement
  - (H-ITER-98y2 ~ 1)
- T_e barrier, little or no additional n_e barrier
  - No ELMs, no impurity accumulation
- Interesting potential as LHCD target for Advanced Scenarios
- Possible application to ITER?



E. Marmar, A. Hubbard, et al, IAEA, Geneva, 2008

Hydrogenic Ion Retention in all Metallic C-Mod Walls Surprisingly Similar to Carbon PFC Tokamaks

- Serious concern about tritium retention in ITER (with or without carbon)
  - –Tungsten proposed for ITER
- With clean Mo PFCs on C-Mod
  - –Retention can be a large fraction (few %) of the injected gas
- Surprisingly similar to carbon PFC tokamaks
- Retention is approximately independent of plasma density
- Independent of heating or confinement mode



B. Lipschultz, D. Whyte, et al, IAEA, Geneva, 2008

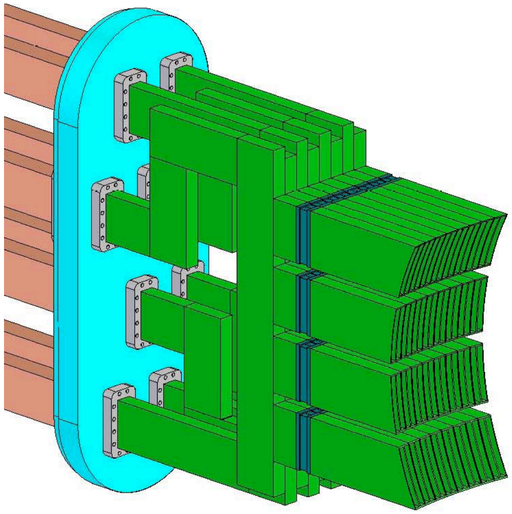
Near Term Upgrades of the RF Wave Launchers, Power Systems, Controls and Diagnostics in Progress

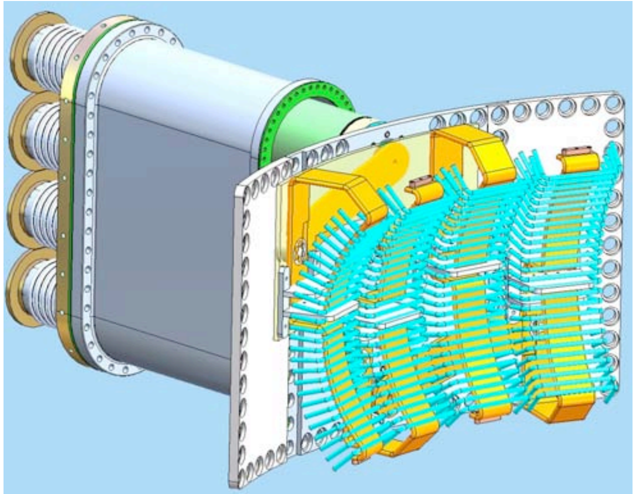
➢ Lower Hybrid upgrades
- Add second launcher with innovative power splitter design

➢ ICRF upgrades
- New 4-strap antennas (x2)
- Fast-Ferrite Tuners for all 4 transmitters (real time tuning)
- Tuneability (40 – 80 MHz) added for 3rd and 4th transmitters

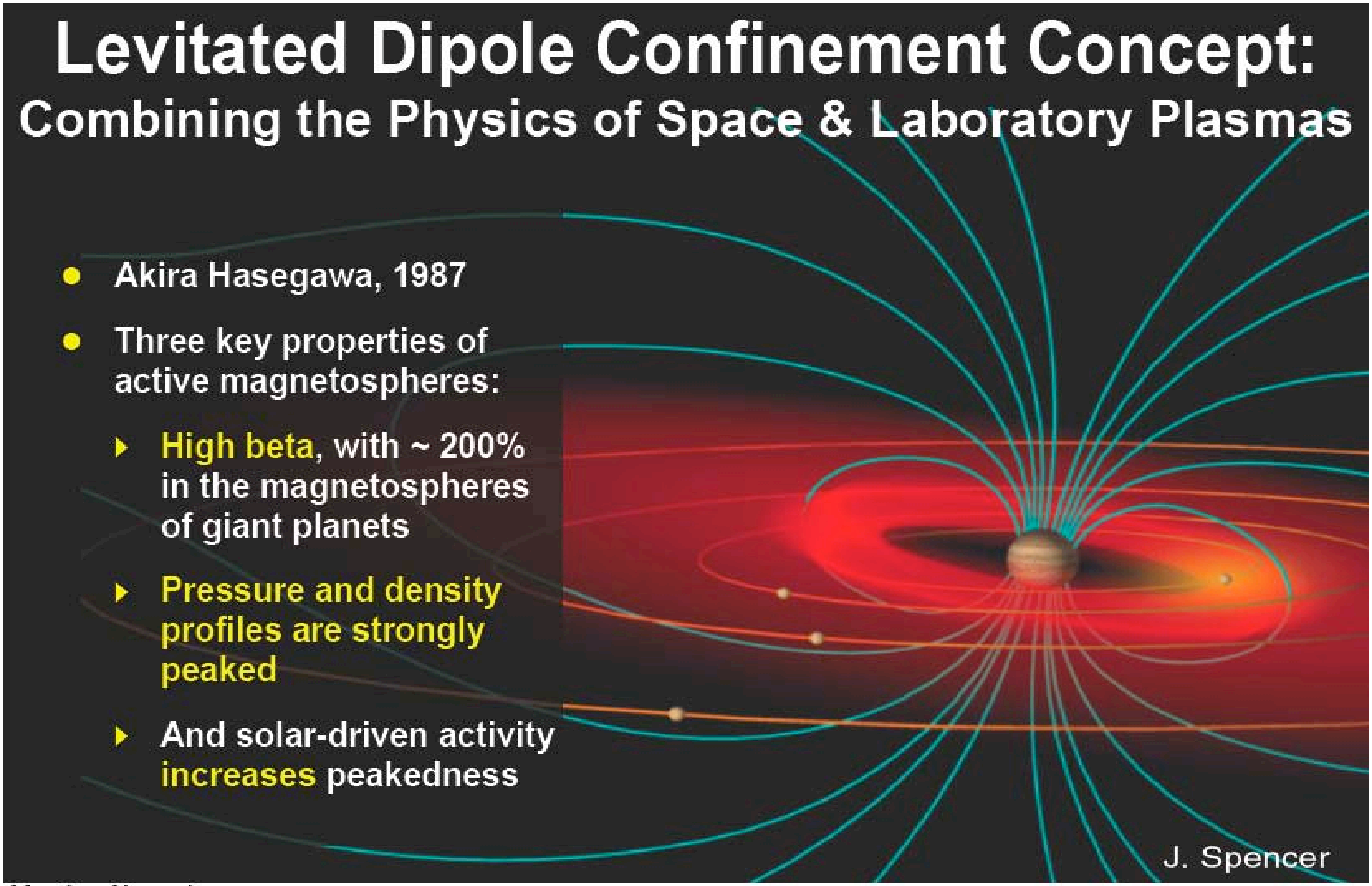
➢ Diagnostic upgrades

➢ DEMO like divertor
- solid metal, actively heated to 600 C



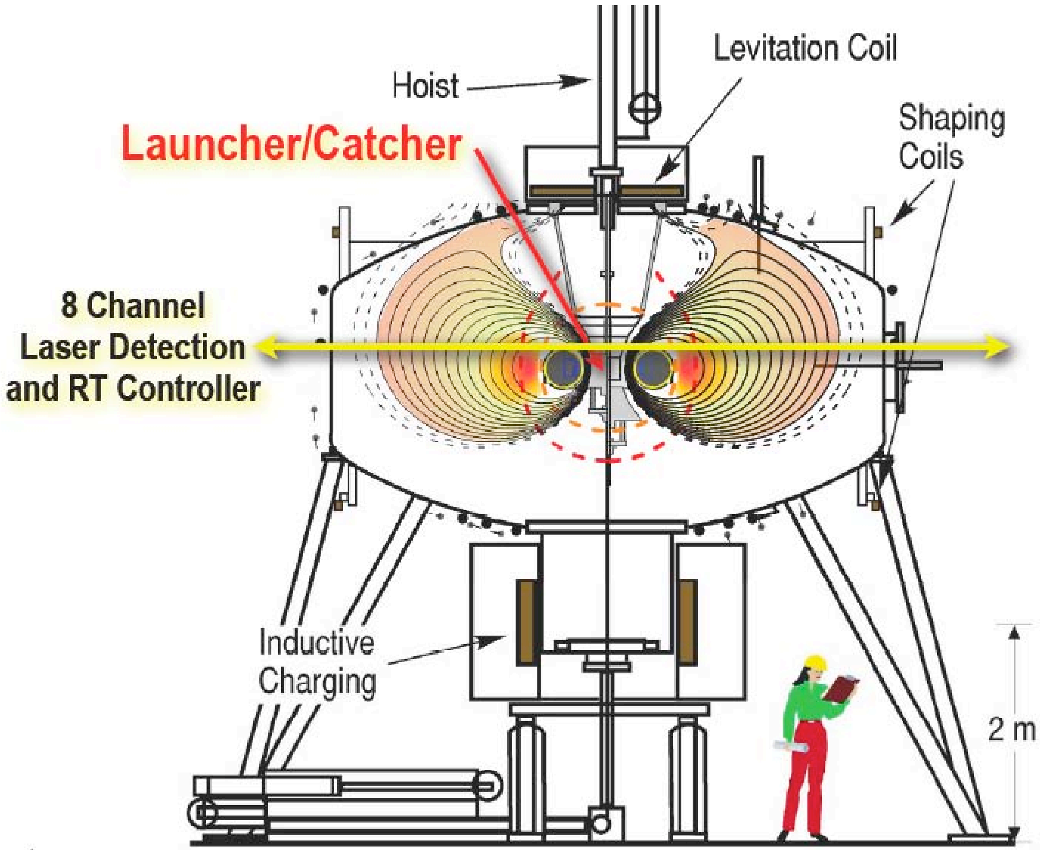


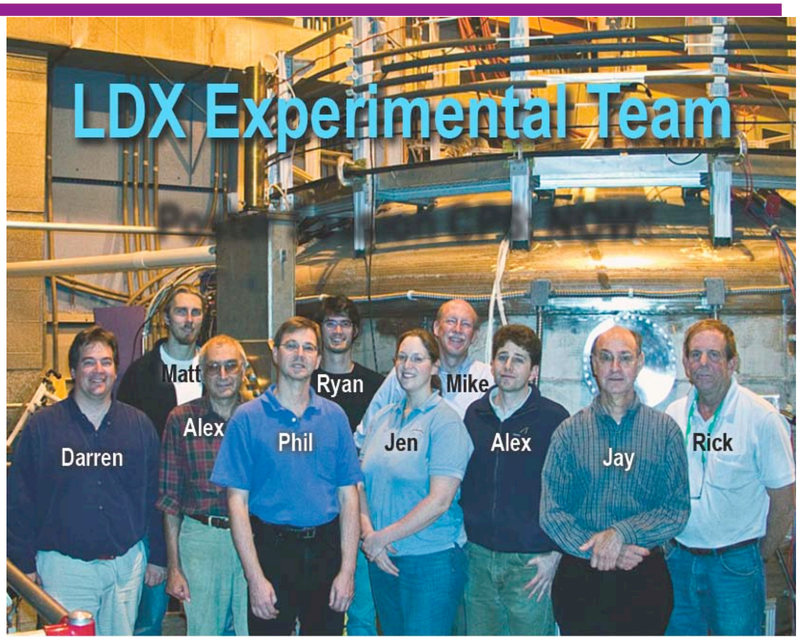
Artist Conception of Jupiter's Plasma Ring fuelled by the Vulcanic Activity of the moon Io

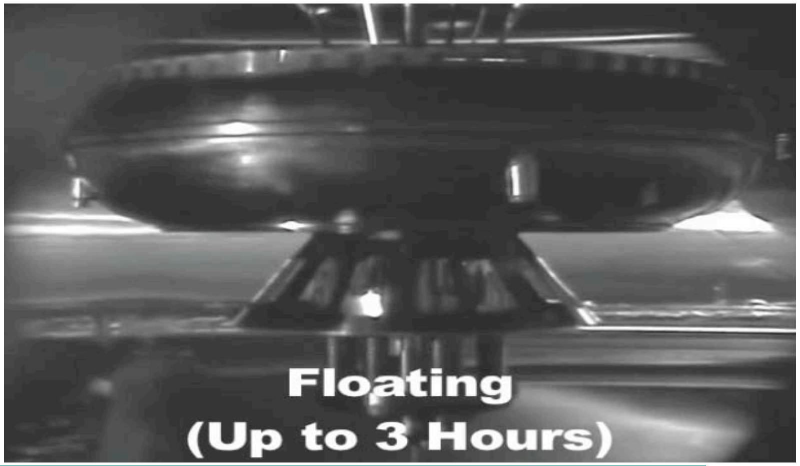


The LDX Team is Led by PIs Jay Kesner (MIT), Mike Mauel (Columbia), and Chief Scientist Darren Garnier

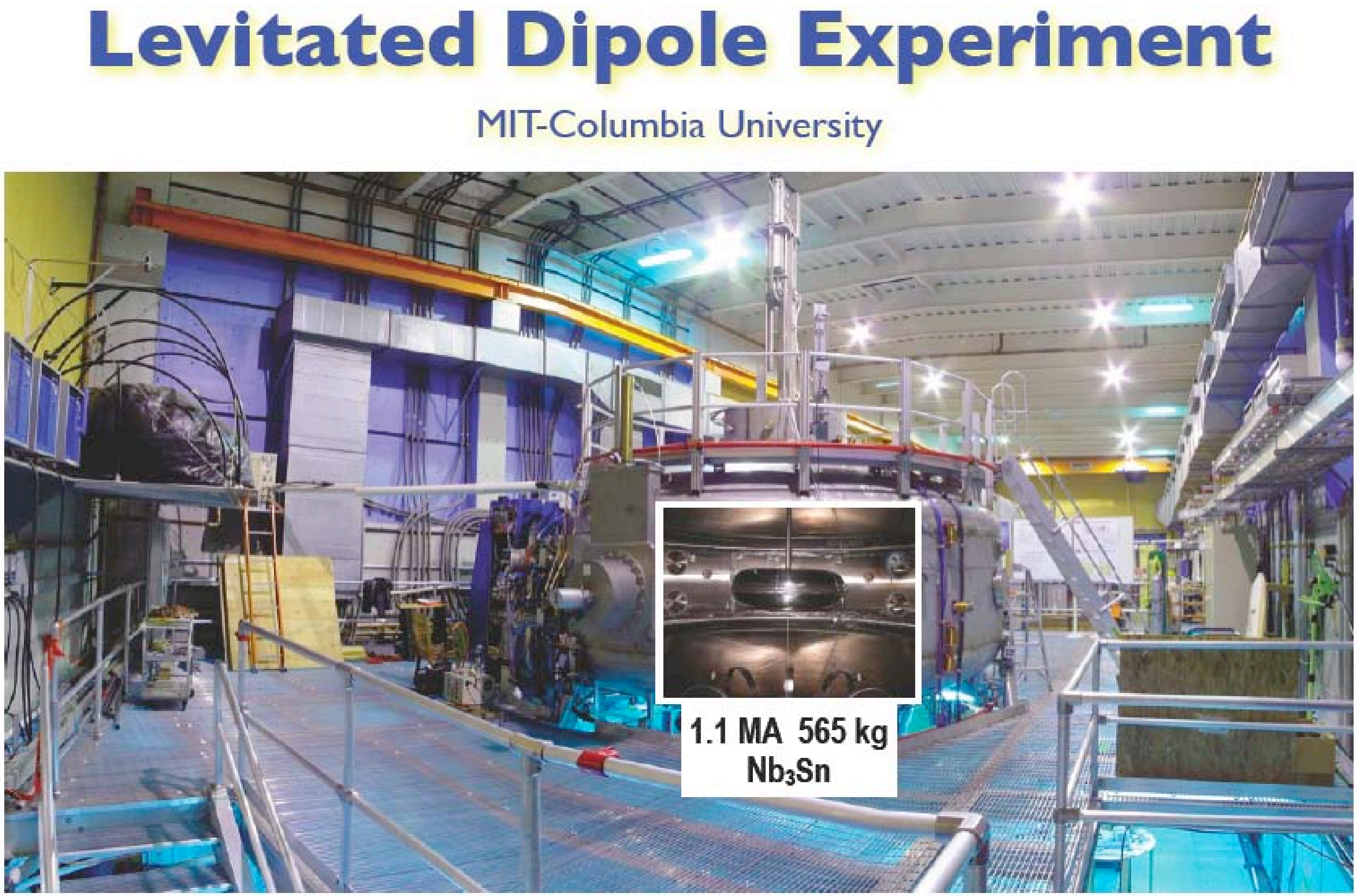
Additional team members include 2 engineers, 1 technician and 4 graduate students





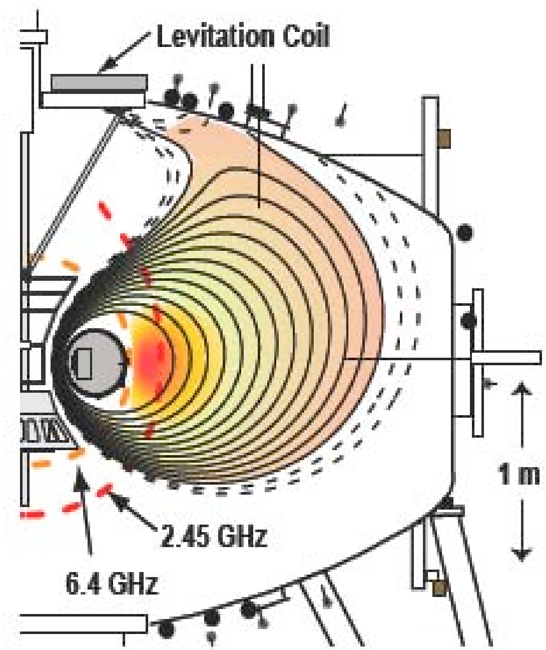


The LDX is located at MIT in the TARA cell; shown is an artificial cut in the chamber to display the levitated ring



Previous Results up to 2007 with a Supported (non-Levitated) Dipole in LDX

High-beta (β ~ 26%) plasma created by multiple frequency ECRH with sufficient gas fueling



- Using 5 kW of long-pulse ECRH, plasma with trapped fast electrons (E_h > 50 keV) were sustained for many seconds.

➡ Magnetic equilibrium reconstruction and x-ray imaging showed high stored energy > 300 J (τ_E > 60 msec), high peak β ~26%, and anisotropic fast electron pressure, $P_\perp/P_\|$ ~ 5.

- Stability of the high-beta fast electrons was maintained with sufficient gas fueling (> 10^{-6} Torr) and plasma density.

- D. Garnier, *et al.*, *PoP*, (2006)

Levitation of Current Ring (Routine up to 3 hrs) on LDX Greatly Improved Plasma Performance in 2008

(M. Mauel, Invited talk, November 2008 APS Meeting, Dallas, TX)

- The mechanics of magnetic levitation is proven reliable.
- Levitation eliminates parallel particle losses and allows a dramatic peaking of central density.

  LDX has demonstrated the formation of natural density profiles in a laboratory dipole plasma.
- Improved particle confinement improves hot electron stability and creates higher stored energy.

[Twice that of the supported ring case for the same input power]

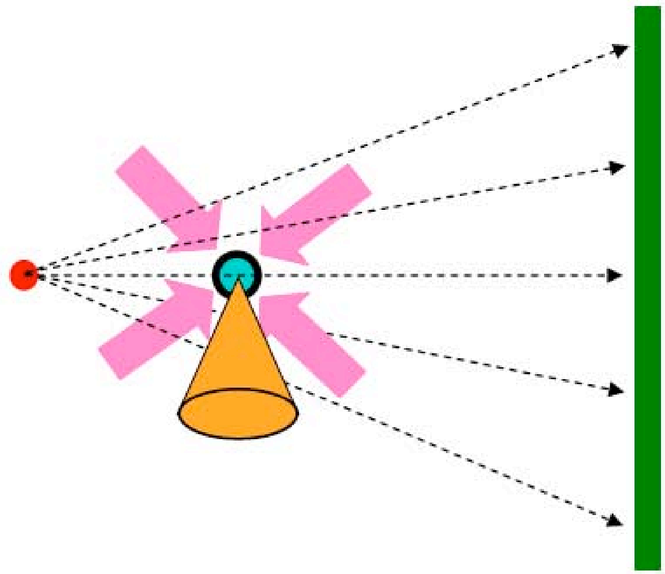
- Fluctuations of density and potential show large-scale circulation that is the likely cause of peaked profiles.

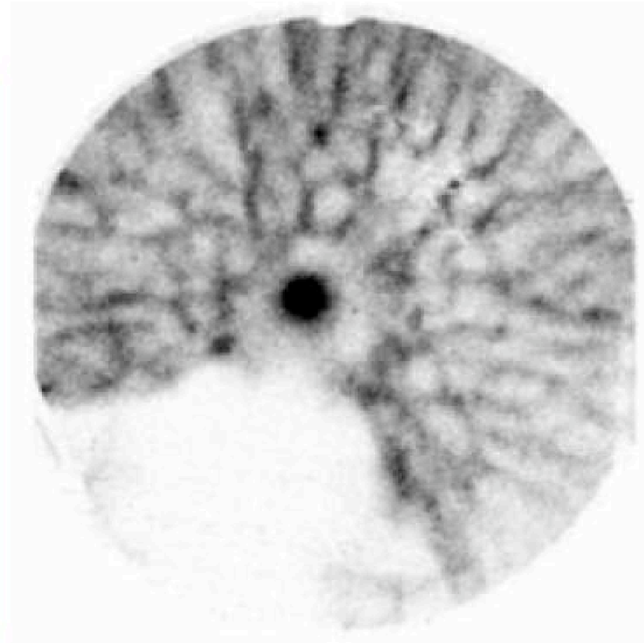
Next Step : Install additional heating (0.5 MW ICRH and 20 kW 28 GHz ECH) to heat bulk plasma and test beta limit; improve physics understanding with more diagnostic

MIT PSFC ICF/HEDP Division

Scientists

Rich Petrasso
PSFC Division Head,
Chair, OMEGA Laser Facility Users Group
Johan Frenje
Chikang Li
Fredrick Séguin





PhD Students

Dan Casey
Mario Manuel
Hans Rinderknecht
Mike Rosenberg
Nareg Sinenian

14.7-MeV-proton radiograph of an imploding cone-in-shell capsule revealing fields inside & out.

J. R. Rygg *et al.*, Science <u>319</u> 1223 (2008)

Close collaborators and support:

HEDP / ICF Division – Key Program Elements

ICF Physics on OMEGA and the NIF

- – Shock and implosion dynamics
- – **ρR and burn asymmetries***
- – Fuel-shell mix
- – Ablator burn-through
- – Hydrodynamic instabilities
- – Mass assembly for Fast Ignition
- – **External E & B fields***
- – **Fields in Hohlraums***

HED Physics

- – **Laser-generated E & B fields***
- – **Magnetic reconnection***
- – Particle slowing in warm, dense matter
- – Astrophysical jets

Nuclear diagnostics for OMEGA, the NIF, and HEDP

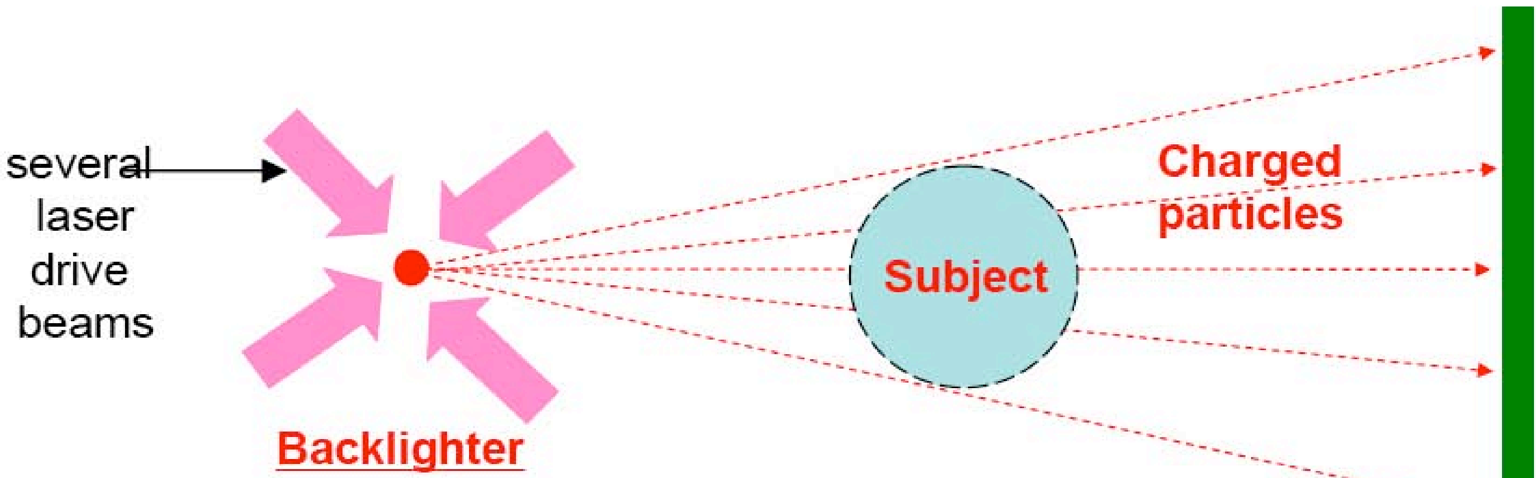
- – **Monoenergetic proton radiography***
- – Nuclear burn time history
- – 3D nuclear burn imaging
- – Charged-particle spectrometry
- – **Neutron spectrometry***
- – **Ablator diagnostics for the NIF***

–Theory and computation

- – Electron beam interactions with plasmas
- – Charged-particle slowing in plasmas
- – Nuclear reactions in ICF & astrophysics

*** Examples to follow**

Monoenergetic charged particle radiography setup at OMEGA



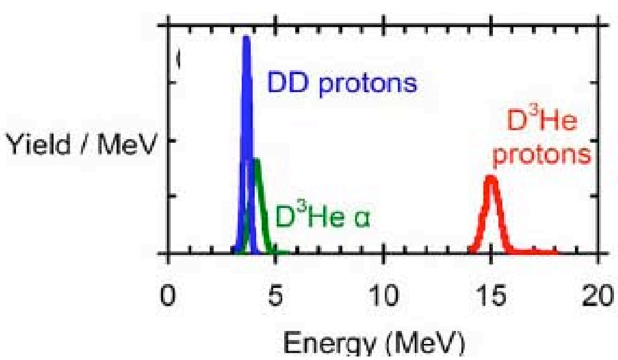
Exploding pusher
Glass shell, D^3He fill

Imaging Detector

CR-39
records species, positions and energies of individual particles

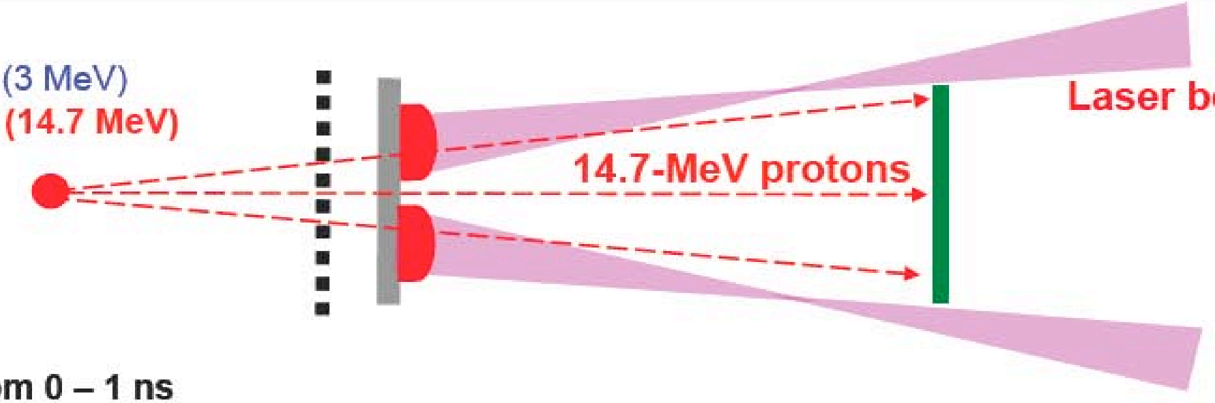
$D + D \rightarrow T$ (1 MeV) + **p (3 MeV)**

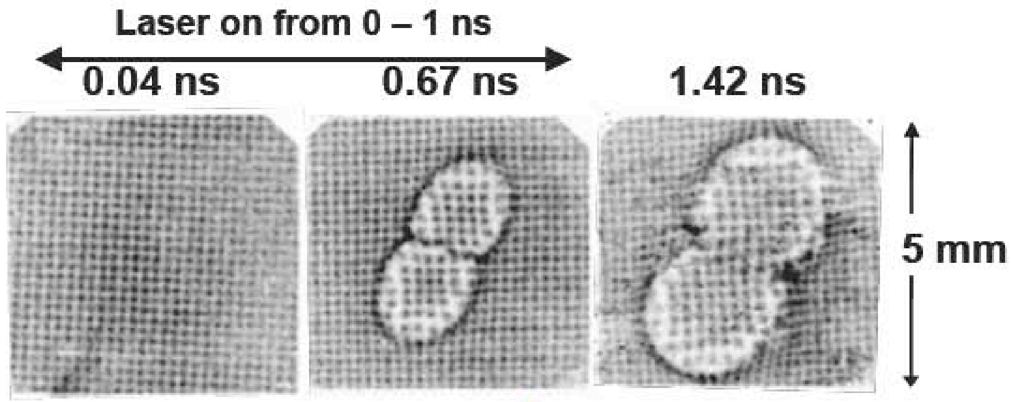
$D + {}^3He \rightarrow \alpha$ **(3.6 MeV)** + **p (14.7 MeV)**

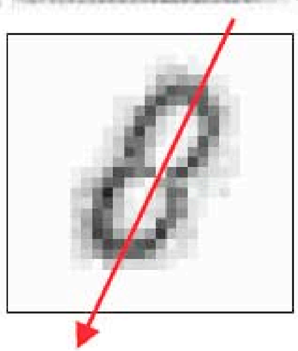


MG B-field reconnection has been observed and quantified at OMEGA with 14.7-MeV-proton radiography

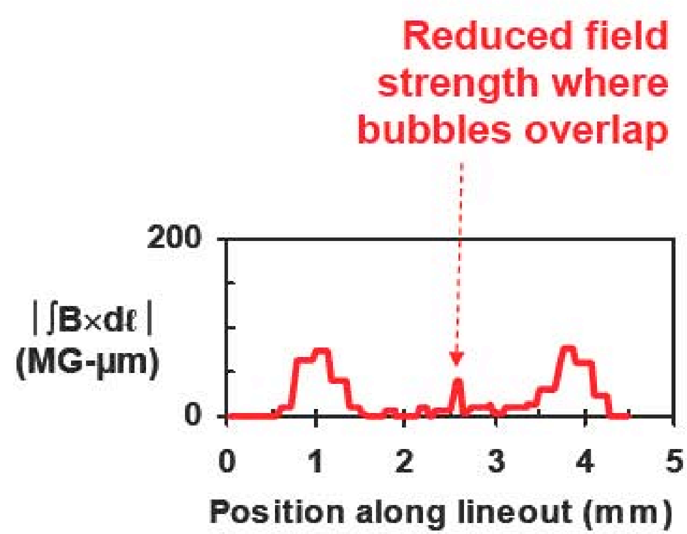
D+D → T (1 MeV) + p (3 MeV)
D+^{3}He→ α (3.6 MeV) + p (14.7 MeV)





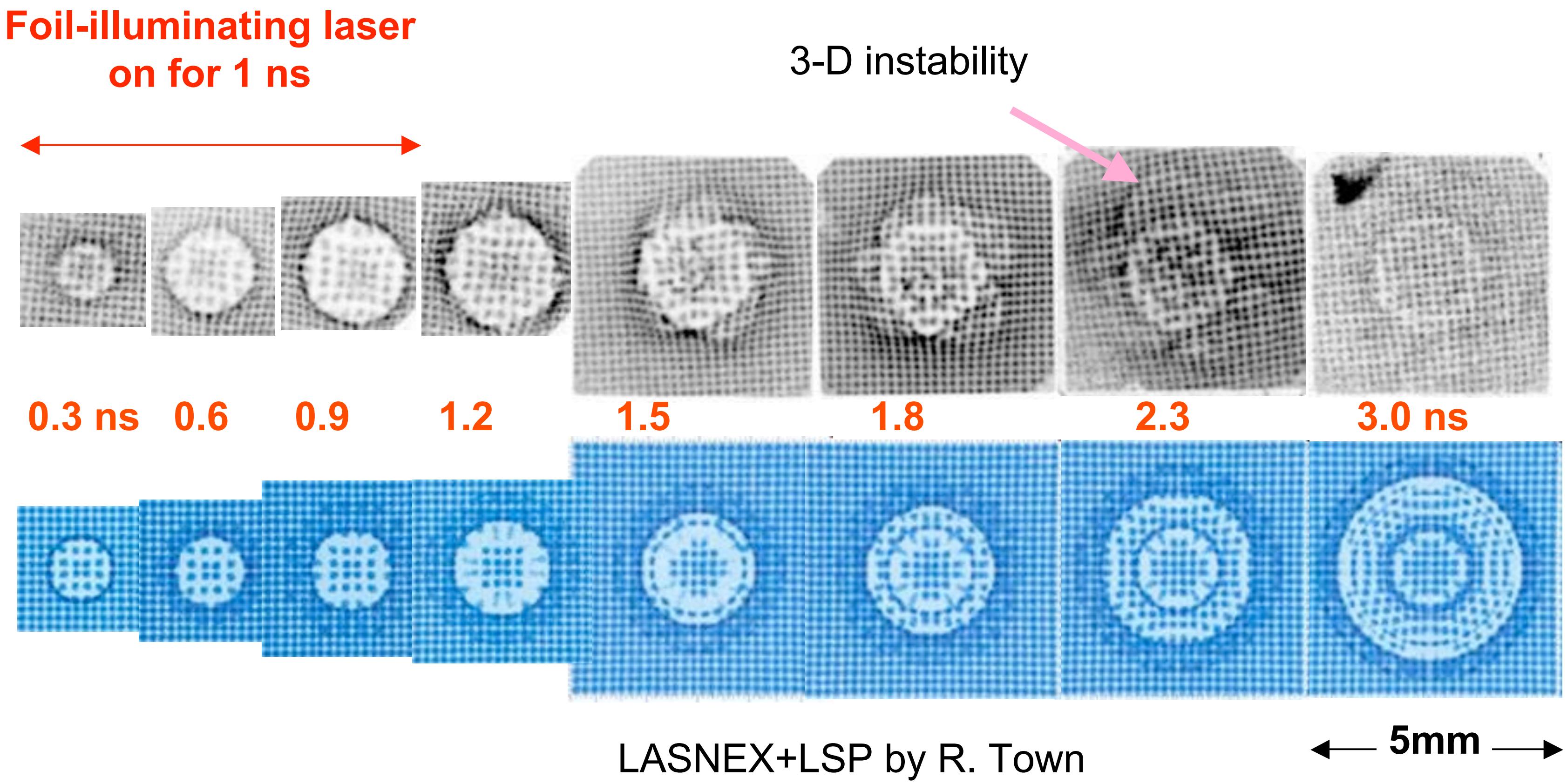


Field map calculated from beamlet deflections



Li *et al.*, PRL 99, 055001 (2007).

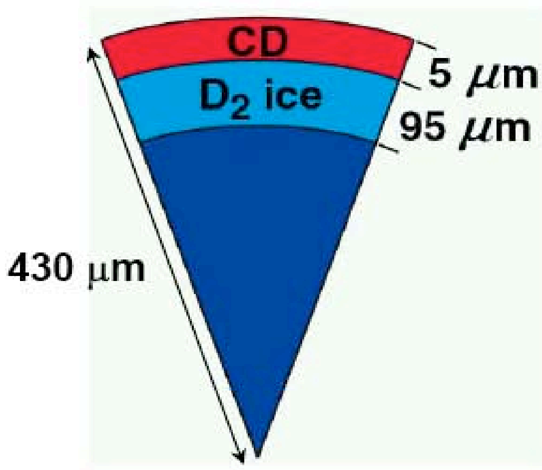
Mega-Gauss B-field generation, evolution, & instabilities have been studied with 14.7 MeV proton radiography at OMEGA

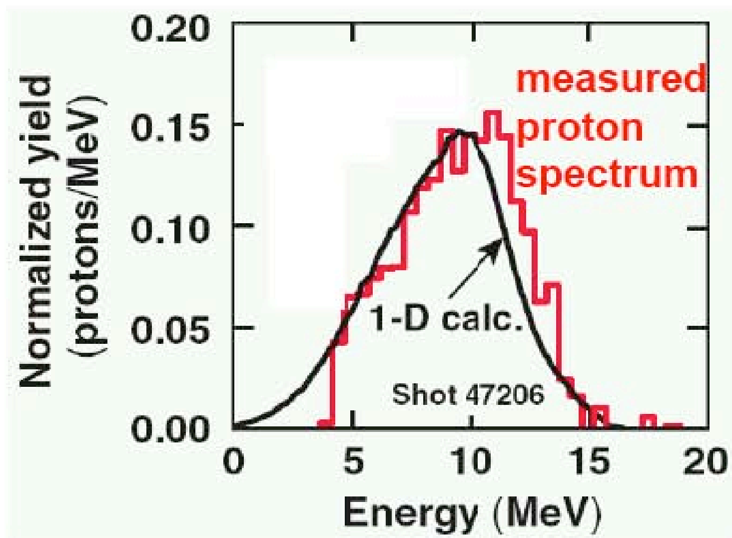


2-D code LASNEX produces credible simulations of hydro and fields while the laser is on, failing when 3-D instabilities appear.

C. K. Li *et al*., PRL 99, 015001 (2007)

Record areal density at OMEGA (202 ± 7 mg/cm^2)* was measured by MIT-designed compact proton spectrometers**





(1) Secondary fusion reactions produce 12.5-17.4 MeV p:

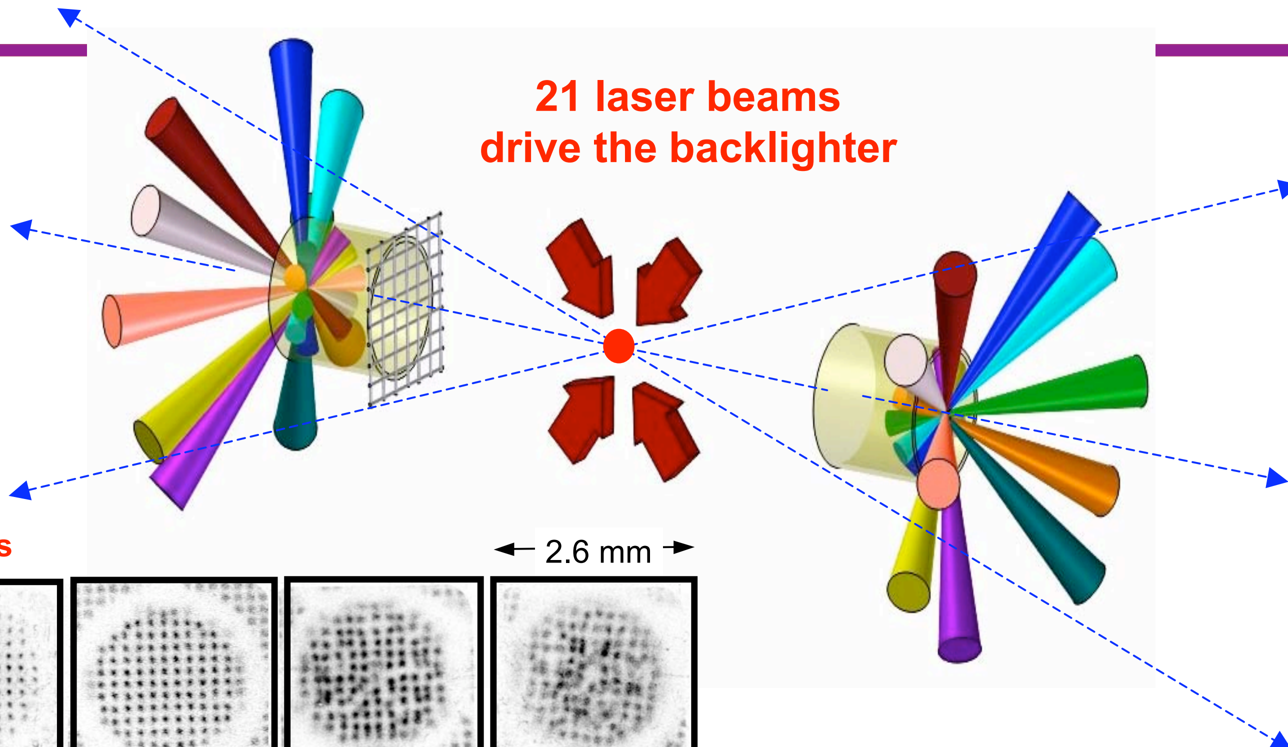
primary reaction: D + D → n (2.45 MeV) + ^{3}He (0.8 MeV)
secondary reaction: ^{3}He (0.8 MeV) + D → α (6.6-1.7 MeV) + **p (12.5-17.4 MeV)**

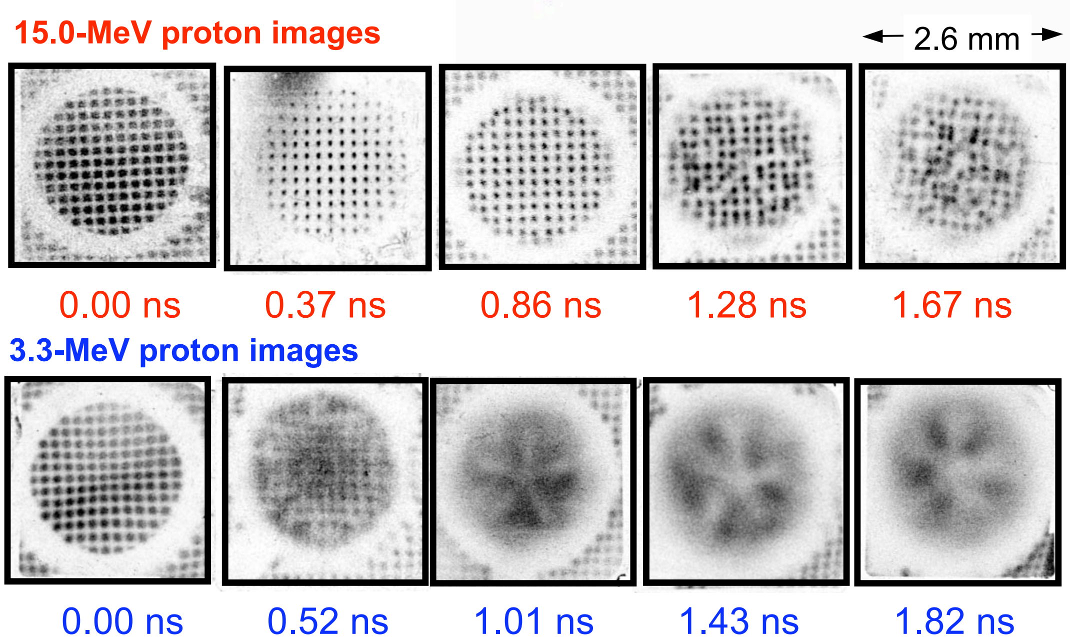
(2) Areal Density of imploded capsule is determined by measuring the energy lost by the secondary D^{3}He protons as they escape from the capsule

*T. C. Sangster *et al*., PRL 100, 185006 (2008)
** F.H. Seguin *et al*., Rev. Sci. Instrum. 74, 975 (2003)

Proton radiography of laser-irradiated vacuum Au hohlraums at OMEGA reveals fields and hydrodynamic flows

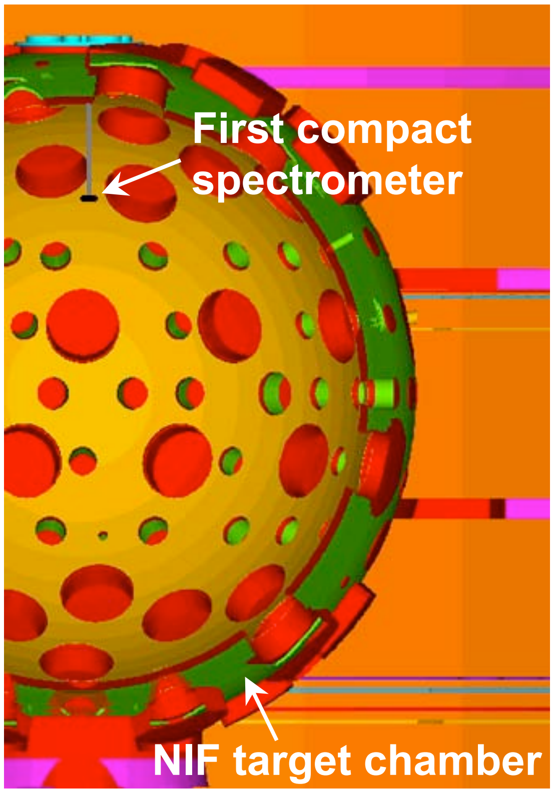
10 laser beams drive the hohlraum



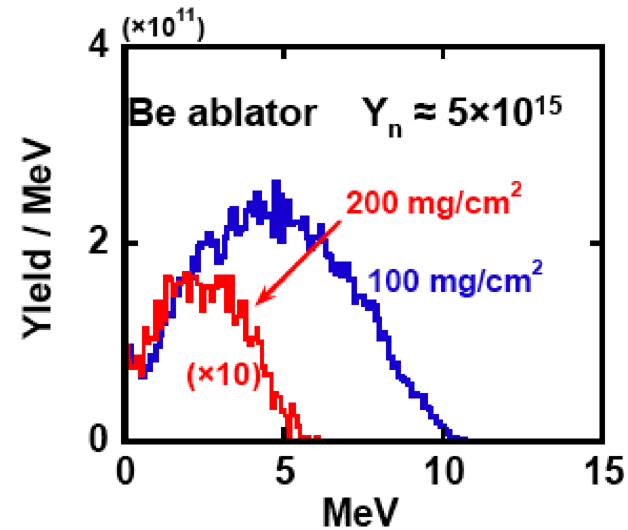


C.K. Li *et al.*,
Invited talk, 2008 APS

During NIF start-up, MIT compact proton spectrometers* will diagnose ablator ρR and ρR asymmetries**



Two simulated "failure-mode" proton spectra



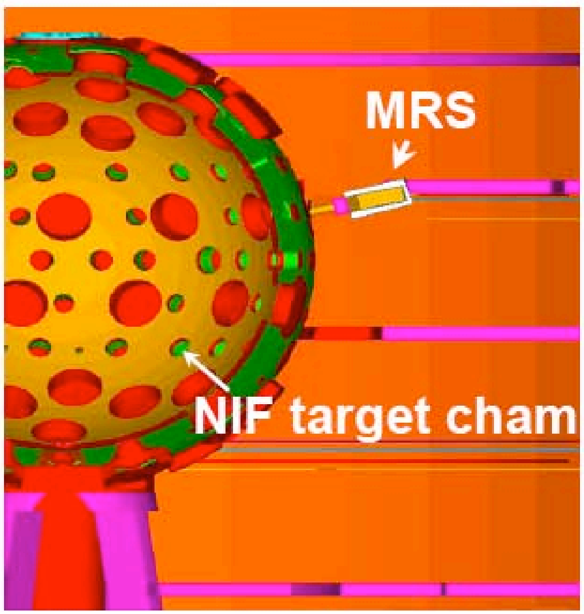
Ablator areal density is measured through the energy loss of knock-on protons

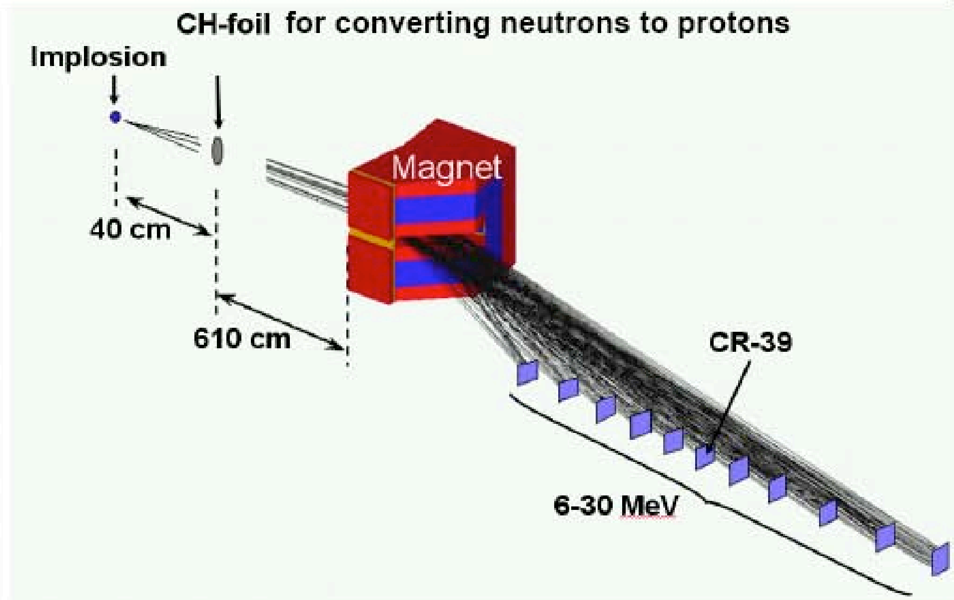
(n + p → n' + p')

* F.H. Seguin *et al*., Rev. Sci. Instrum. 74, 975 (2003).
** J.A. Frenje *et al*., accepted for publication in Phys. Plasmas (2008).

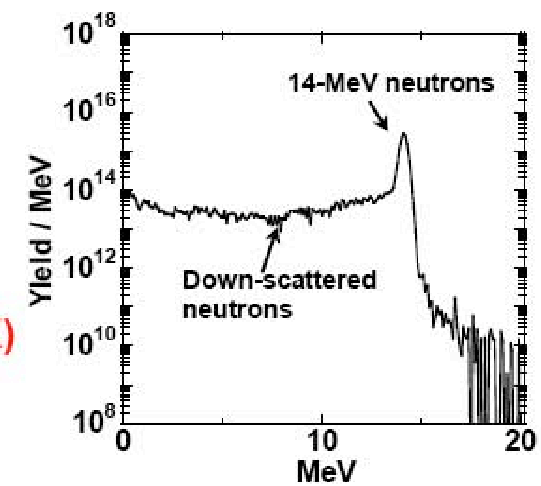
The MIT-designed neutron spectrometer (MRS – Magnetic Recoil Spectrometer) will measure areal density, ion temperature, and yield on the NIF

LLE and MIT successfully implemented an OMEGA MRS





Simulated NIF neutron spectrum in Hydrogen-rich startup phase (Hatchett, LASNEX)



J.A. Frenje *et al.*, Rev. Sci Instrum. 79, 10E502 (2008).

PSFC Program Overview

Other exciting program elements, including educational programs, movies, etc, may be found at the PSFC website

www.PSFC.MIT.EDU