Highlights of Some Research Activities:

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

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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 $\beta$ 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 $B$, $n$; $\Rightarrow$ same $\omega_{pe}$, $\omega_{ce}$, $\omega$]

- **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.**

Porkolab_FPA_12.4.2008
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

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 $I_p$ 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

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

- Unfavorable $\nabla B$ drift direction; 
  increased $\delta, I_p$
  - 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

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

Levitated Dipole Confinement Concept:
Combining the Physics of Space & Laboratory Plasmas

- Akira Hasegawa, 1987
- Three key properties of active magnetospheres:
  - **High beta**, with ≈ 200% in the magnetospheres of giant planets
  - Pressure and density profiles are strongly peaked
  - And solar-driven activity increases peakedness

J. Spencer

Porkolab_FPA_12.4.2008
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 ($\beta \sim 26\%$) 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 ($\tau_E > 60$ msec), high peak $\beta \sim 26\%$, and anisotropic fast electron pressure, $P_{\perp}/P_{\parallel} \sim 5$.
- Stability of the high-beta fast electrons was maintained with sufficient gas fueling ($> 10^{-6}$ Torr) and plasma density.
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
Scientists

Rich Petrasso
PSFC Division Head,
Chair, OMEGA Laser
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14.7-MeV-proton radiograph
of an imploding cone-in-shell capsule
revealing fields inside & out.


Close collaborators and support:

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HEDP / ICF Division – Key Program Elements

ICF Physics on OMEGA and the NIF

– Shock and implosion dynamics
– $pR$ 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

several laser drive beams

Backlighter
Exploding pusher
Glass shell, $D^3He$ fill

$D + D \rightarrow T (1 \text{ MeV}) + p (3 \text{ MeV})$
$D + ^3He \rightarrow \alpha (3.6 \text{ MeV}) + p (14.7 \text{ MeV})$

CR-39 records species, positions and energies of individual particles
MG B-field reconnection has been observed and quantified at OMEGA with 14.7-MeV-proton radiography.

\[ \text{D} + \text{D} \rightarrow \text{T} (1 \text{ MeV}) + \text{p} (3 \text{ MeV}) \]
\[ \text{D} + ^{3}\text{He} \rightarrow \alpha (3.6 \text{ MeV}) + \text{p} (14.7 \text{ MeV}) \]

Laser beam

14.7-MeV protons

Laser on from 0 – 1 ns

0.04 ns 0.67 ns 1.42 ns

Reduced field strength where bubbles overlap

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/cm²) was measured by MIT-designed compact proton spectrometers.

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

primary reaction: \( \text{D} + \text{D} \rightarrow \text{n} (2.45 \text{ MeV}) + ^{3}\text{He} (0.8 \text{ MeV}) \)

secondary reaction: \( ^{3}\text{He} (0.8 \text{ MeV}) + \text{D} \rightarrow \text{\alpha} (6.6-1.7 \text{ MeV}) + \text{p} (12.5-17.4 \text{ MeV}) \)

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

*T. C. Sangster et al., PRL 100, 185006 (2008)

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

10 laser beams drive the hohlraum

21 laser beams drive the backlighter

15.0-MeV proton images

0.00 ns  0.37 ns  0.86 ns  1.28 ns  1.67 ns

3.3-MeV proton images

0.00 ns  0.52 ns  1.01 ns  1.43 ns  1.82 ns

C.K. Li et al., Invited talk, 2008 APS
During NIF start-up, MIT compact proton spectrometers* will diagnose ablator $\rho R$ and $\rho R$ asymmetries**

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)

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

www.PSFC.MIT.EDU