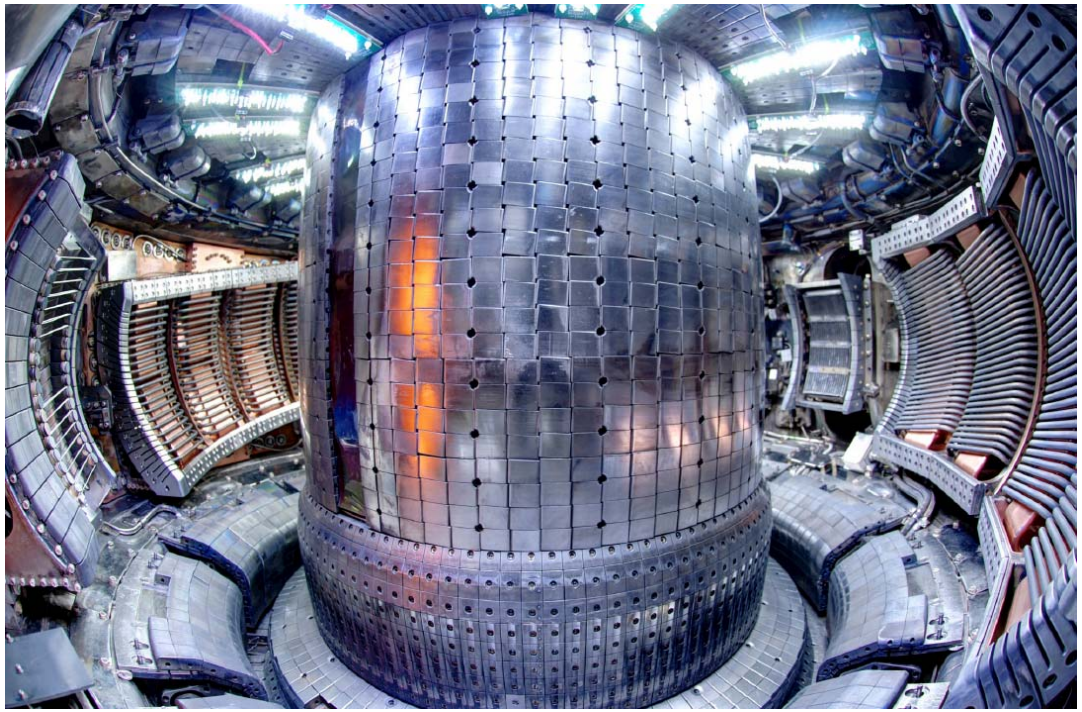
Alcator C-Mod – Current status and plans



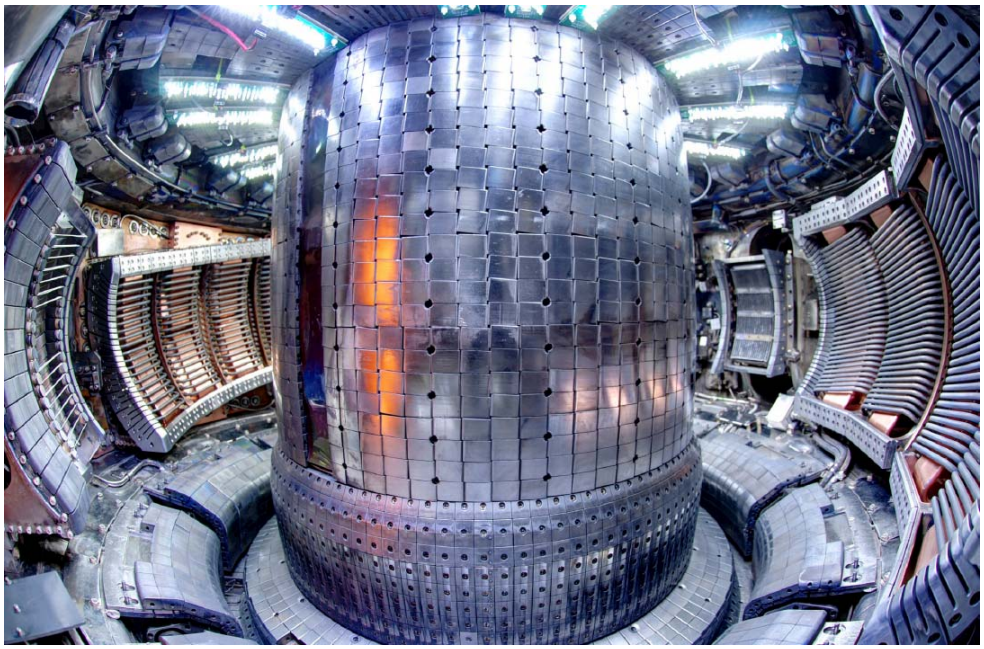
Collaboration ideas for NSTX-U

Presented by B. LaBombard for the Alcator Team

NSTX-U Research Forum, Feb. 24, 2015

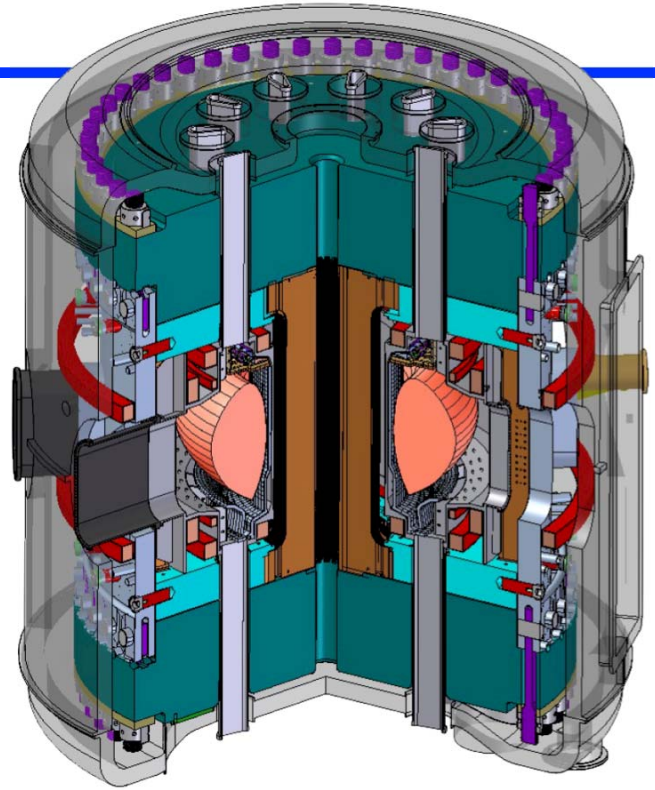
Alcator C-Mod will operate for 12 run weeks in FY15

- April: plasma operations
- May – Sept: physics expts.
- Currently up-to-air, refurbishing in-vessel components



- Upgrades: Accelerator-based In-situ Materials Surveillance (AIMS); Shoelace antenna (x4 power); Lower hybrid wave $k_{//}$ spectrum diagnostic; MSE: multi-spectral line polarization system using imaging polychromators; ski-ramped divertor cassettes (ITER-like)

Some Highlights for FY15 Campaign



- 2015 JRT: impact of off-axis LH current drive on stability and confinement
- Exploit upgraded AIMS
- High-power dissipative divertor experiments with feedback control
- I-mode studies at 8 T
- ICRF Plasma-edge interactions with field-aligned antenna: impurity control and antenna characterization
- Exploit “shoelace” antenna – for study and control of active short-wavelength electromagnetic modes in pedestal
- Look for signatures of ETG with new PCI detector and compare with multi-scale gyrokinetic simulations
- Early run time for 2016 JRT: Disruptions

Alcator Team in Transition – long term outlook

- Guidance: operate C-Mod 5 run weeks FY16, shut down FY17
- Transition to collaborative activities
  - DIII-D and NSTX-U
  - International
- **MIT Team is presently assembling a 5-year Cooperative Agreement proposal to fund domestic and international collaborations**

MIT Team sees NSTX-U as having excellent opportunities for collaborative work in a number of areas.

Timing: FY16-FY17: Ramp down of C-Mod research
FY17+: Ramp-up of collaborations

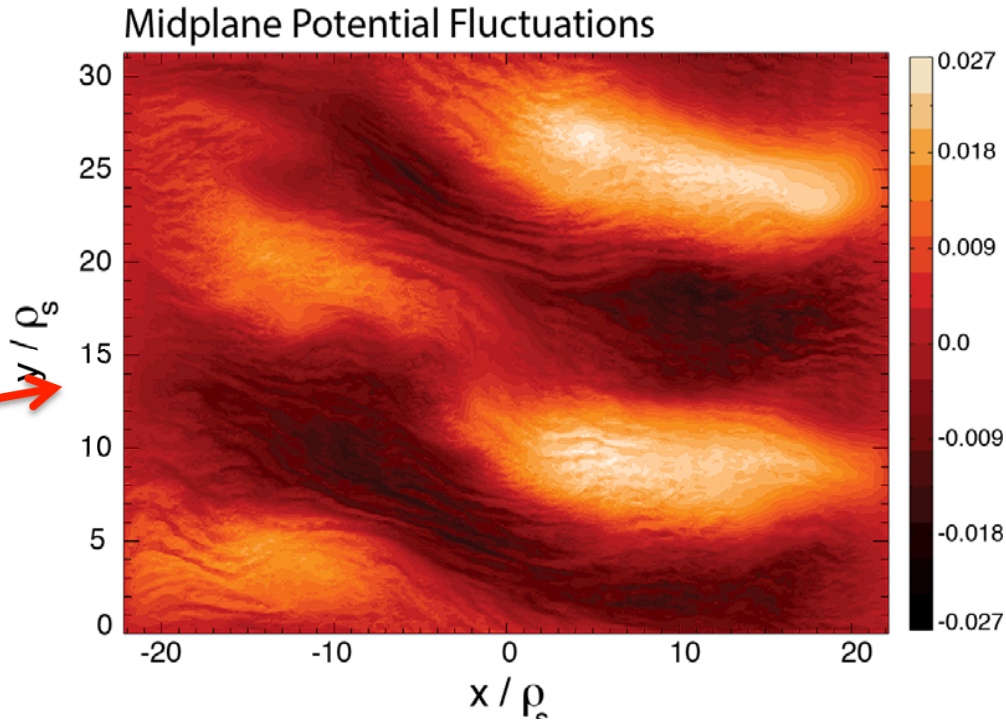
Alcator C-Mod – Current status and plans; Collaboration ideas for NSTX-U

Outline

- C-Mod Research Highlights and Ideas for Collaboration with NSTX-U
  - Core Transport
  - Pedestal
  - RF Heating and Current Drive
  - MHD – Disruptions
  - Boundary Plasma Physics and PMI (5 topics)

C-Mod Research Highlights: Core Plasma Transport

- Multi-channel transport studies; focus on impurity, particle and momentum transport
- Beta scaling of transport in ITER-relevant plasmas
- **Multi-scale transport model validation**; effects of high-k (ETG) on electron heat transport in L-mode plasmas; configure PCI for high-k /int-k measurements to test new predictions
- Most planned experiments supported by pre-experiment nonlinear gyrokinetic code *predictions*, as well as extensive post-experiment gyrokinetic analysis/ validation efforts



N. Howard *et al*, PoP 2014

Nonlinear GRYO simulation of C-Mod L-mode plasma resolving $k_\theta \rho_s$ up to 48 ($k_\theta \rho_e < 0.8$)

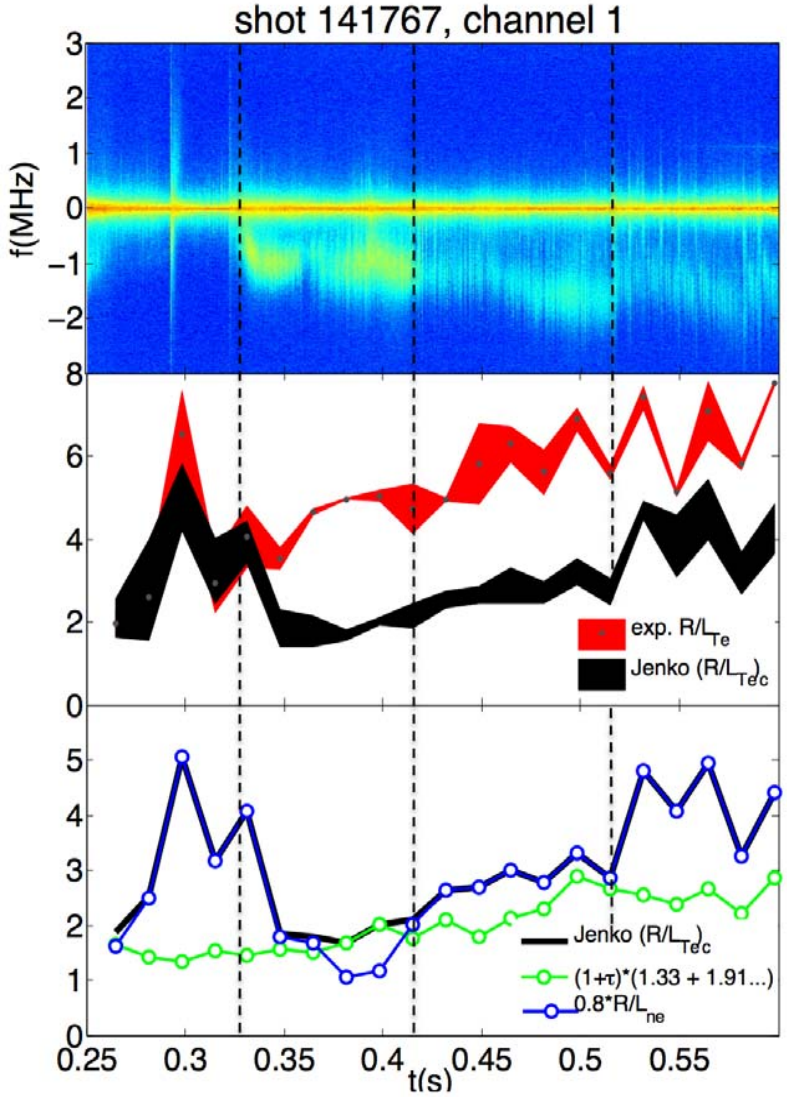
Ion and electron heat flux at r/a=0.6 matches experiment only when electron scale turbulence is included.

Contacts: Anne White, Martin Greenwald

NSTX-U Collaboration Ideas: Electron Heat Transport

Build on recent work -- Evidence for density gradient stabilization of high-k turbulence in NSTX

- J. Ruiz Ruiz and A. White, collaboration with Y. Ren, W. Guttenfelder and S. Kaye
- Evidence for density gradient stabilization of high-k turbulence in NSTX (Ruiz Ruiz, APS 2014). *Phys. Plasma* manuscript in preparation (Ruiz Ruiz)
- Work has focused on high-k turbulence data analysis and linear GS2 simulations only
- **Future plans for TRANSP and nonlinear GYRO simulations, new experiments with upgraded high-k system (2016) to examine similar plasmas in NSTX-U.**

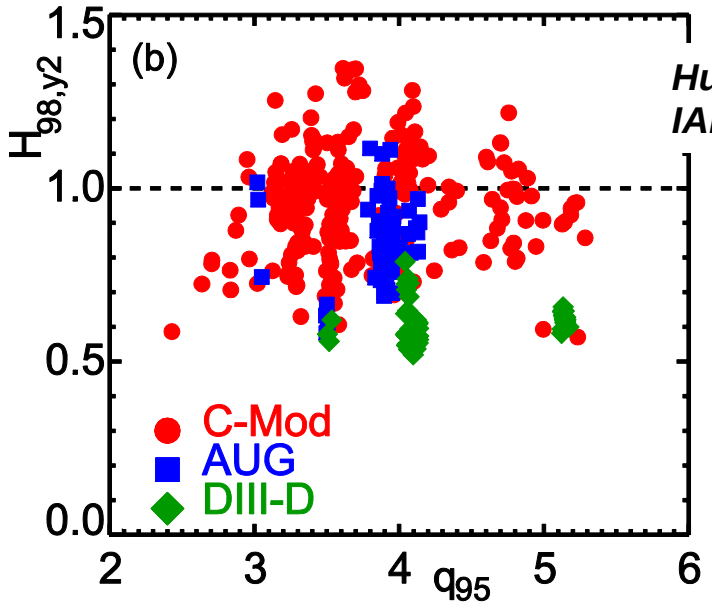


Timescale: FY15 + MIT/NSTX-U collab. plan

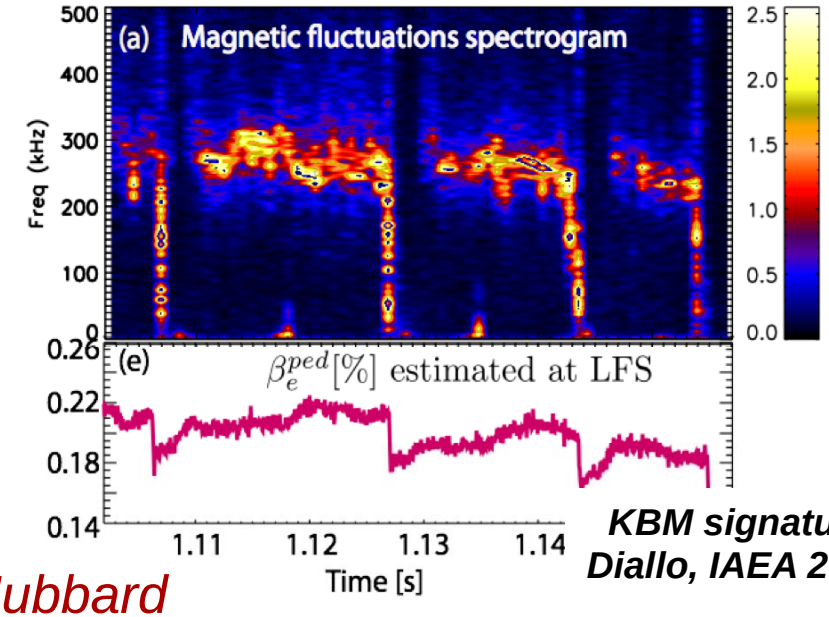
C-Mod FY15/16 Research Highlights: Pedestal Physics

- **Access and sustainment of desirable high-confinement regimes**
  - Expanding studies of I-mode to 8T, exploring divertor power handling
  - Influence of divertor geometry on H-mode, I-mode power threshold
- **Modeling activities for enhanced understanding of transport + stability determining pedestal structure**
  - EPED predictions for super H-mode tested at high B_T, n
  - Gyrokinetic simulations of measured kinetic ballooning modes between ELMs
  - Turbulence modeling of I-mode pedestals with gyrokinetic codes and BOUT++

Range of I-mode performance, safety factor



Hubbard, IAEA 2014

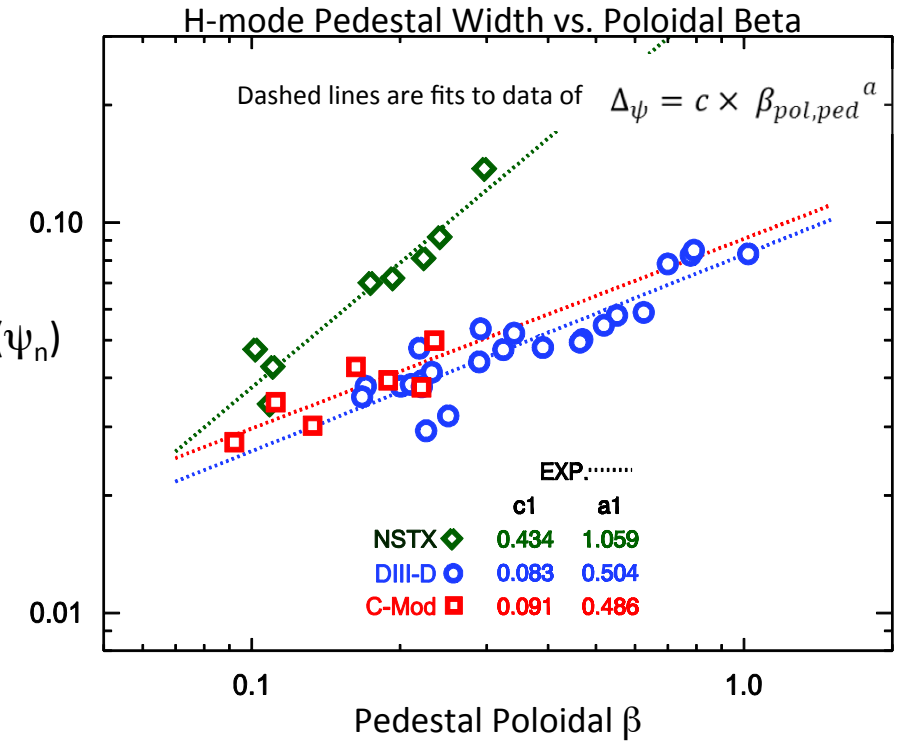


KBM signatures Diallo, IAEA 2014

Contacts: Jerry Hughes, John Walk, Amanda Hubbard

Pedestal: Ideas for Collaboration on NSTX-U

- **Development of stationary high-confinement regimes**
  - I-mode experiments (FY15/16)
    (proposal submitted to Research Forum)
- **Aspect ratio dependence of pedestal structure (i.e. height + width)**
  - Multi-machine study can utilize high resolution pedestal data from C-Mod, DIII-D, NSTX-U, state-of-the-art modeling tools
  - Work toward predictive capability for next-step devices
- **Transients and pedestal dynamics**
  - Utilize new multi-pulse Thomson system (FY16)
  - Study implications for fast flux perturbations (e.g. sawtooth heat pulses) on transitions between confinement regimes, pedestal stability



Hughes, APS 2012

Timescale: FY15 + MIT/NSTX-U collab. plan

Contacts: Jerry Hughes, John Walk, Amanda Hubbard

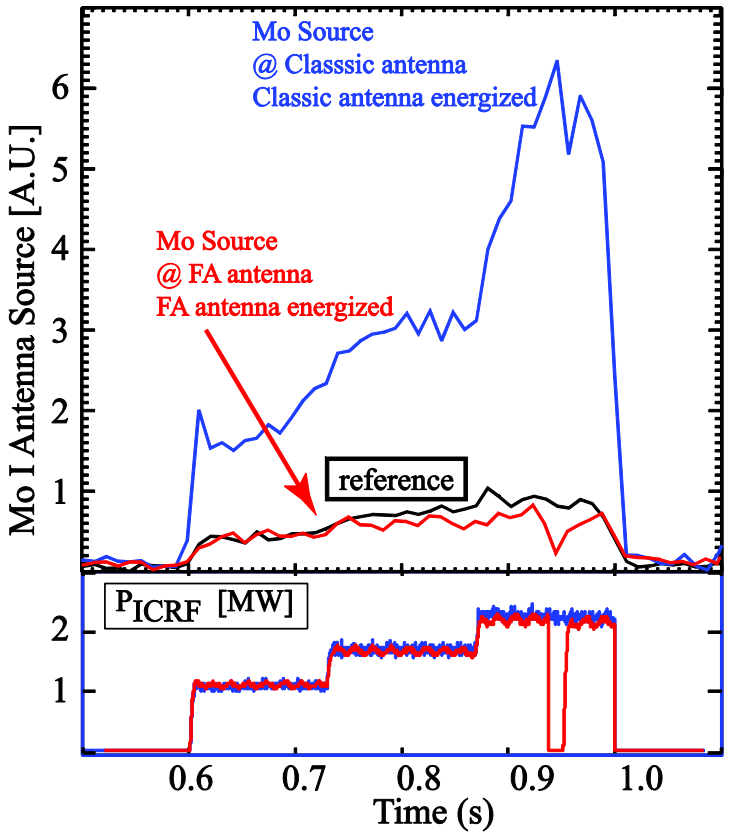
C-Mod Research Highlights: LH Current Drive; RF Wave Physics; ICRF Actuator Development

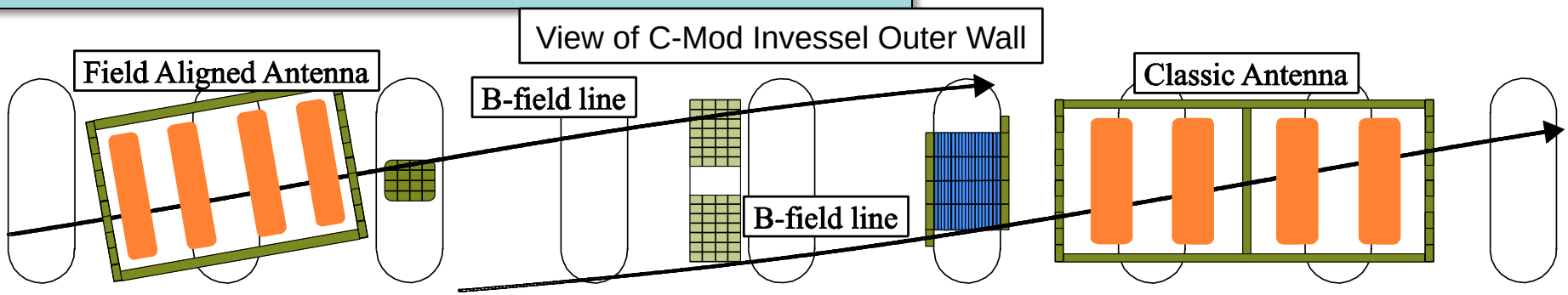
Lower Hybrid

- Current profiles and effect on plasma stability and confinement (JRT 2015)
- Current drive optimization: high single-pass absorption scenarios (8 tesla, I-mode)
- LH wave–boundary plasma interaction physics
- Direct measurements of LH $k_{//}$

ICRF

- Mode conversion physics, flow drive
- Field-aligned antenna physics:
  - Mechanisms behind local impurity source reductions ICRF-induced impurity penetration physics
  - Mechanisms behind observed enhancements in load tolerance



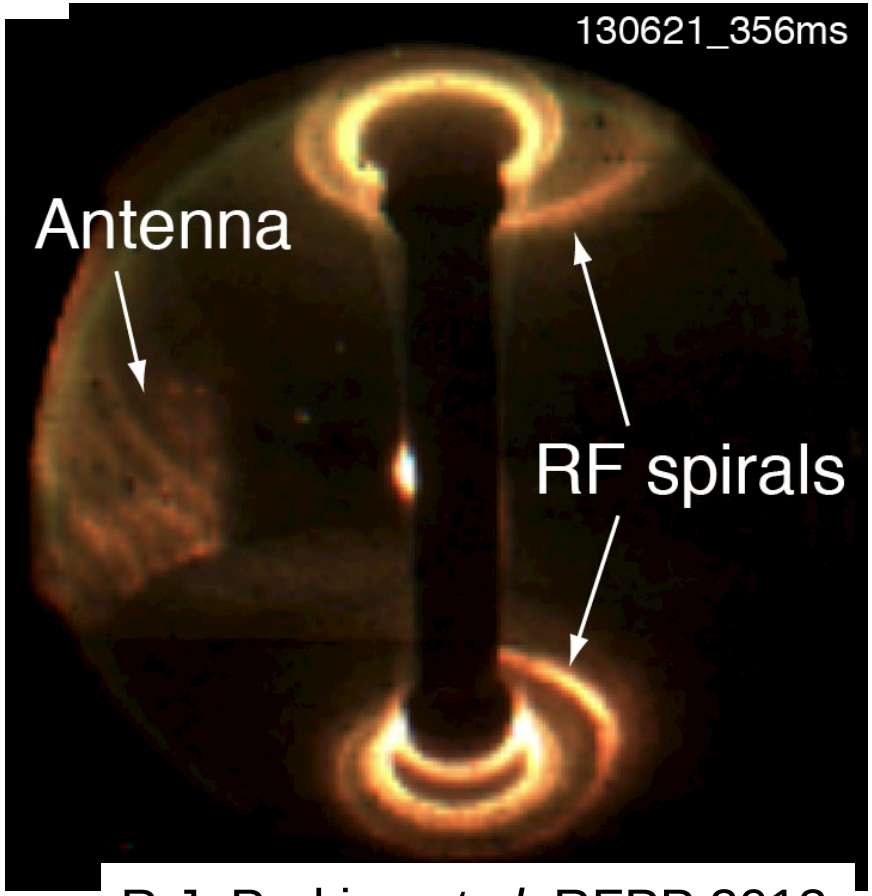


Contacts: Steve Wukitch, Greg Wallace

RF: Ideas for Collaboration on NSTX-U

Topic: Field-aligned antenna physics

- **Assess and develop technological and physics solutions to RF antenna–plasma interactions**
  - Develop warm plasma dielectric tensor solver to identify waves that can be excited by antenna
  - Analyze antenna geometries that can minimize parasitic absorption
  - Can field aligned antenna ameliorate edge RF absorption?
- **Develop tools to assess HHFW core absorption, particularly in fusion reactor grade scenarios**
  - High harmonic fast waves interaction with beam ions could be used as proxy for fusion alphas



R.J. Perkins *et al*, RFPP 2013

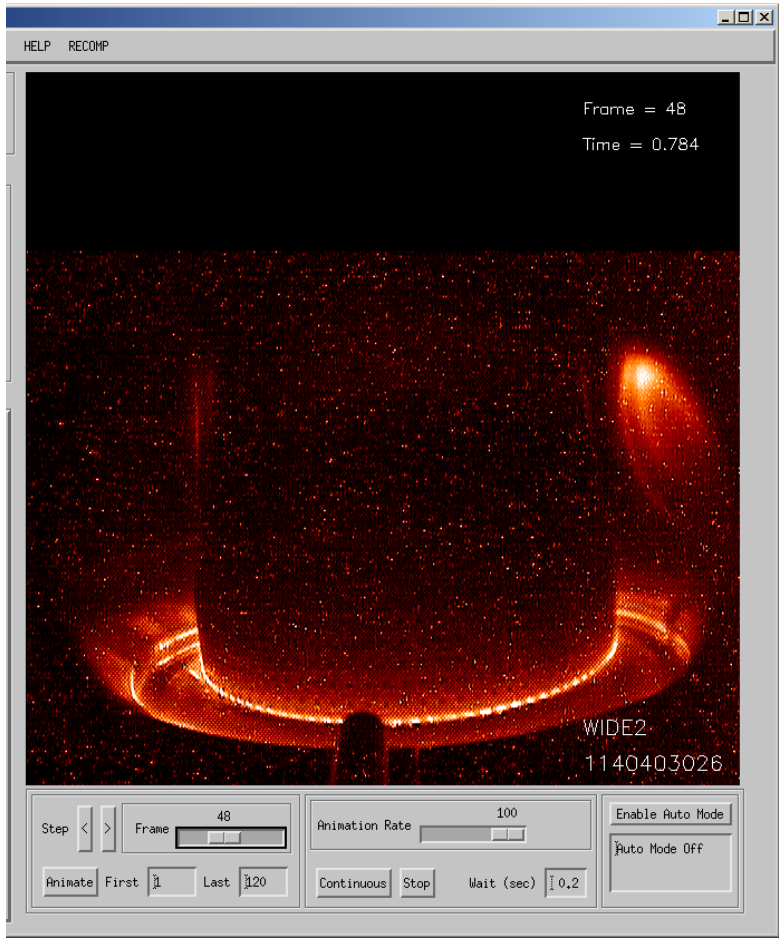
Topic: ECH/EBW for NSTX-U – MIT has a strong interest in this area

Timescale: FY15 + MIT/NSTX-U collab. plan

Contacts: Steve Wukitch, Greg Wallace

C-Mod Research Highlights: Disruptions

- **FY2016 JRT: *"Disruption avoidance, detection, and mitigation"***
- Experiments planed for C-Mod in FY2015-16
  - Mitigation and asymmetry of MHD-"sick" plasmas (large 2/1 and/or locked) with two MGI valves
  - Impurity injection as a tool to mitigate runaway electrons in flattop of very-low-density discharges
- Video imaging and new spectrometers will record forward-peaked synchrotron emission spectrum (300-800 nm) from highly-relativistic runaways
  - energy, pitch angle, spatial structure, number density, and temporal evolution
  - provide data to outside groups for RE theory and modeling
- Development of universal disruption warning algorithms based on S. Gerhardt's physics-based method, using data from C-Mod, DIII-D, and NSTX-U



Visible light images provide a wealth of information on RE beam shape, size, evolution, ...

Contact: Robert Granetz

Disruption Physics: Ideas for Collaboration on NSTX-U

- **JRT2016: NSTX-U disruptions to be included in the development of universal disruption warning algorithm(s)**
  - **Idea: Set up an SQL database of disruptions for NSTX-U**. We have a disruption database on C-Mod, have recently created one on EAST, and are currently setting one up on DIII-D. If this has not been set up yet for NSTX-U, we propose to do it. The database would be populated automatically after each disruptive shot.

- **Participate in executing and/or analyzing disruption experiments**
  - basic characterization: dI/dt, P_{rad} fraction, halo currents
  - mitigation: P_{rad} fraction enhancement, halo current reduction, toroidal asymmetries [NOTE: we could transfer the two fast MGI valves on C-Mod to NSTX-U]
  - Development of high-temperature halo/eddy current sensors?

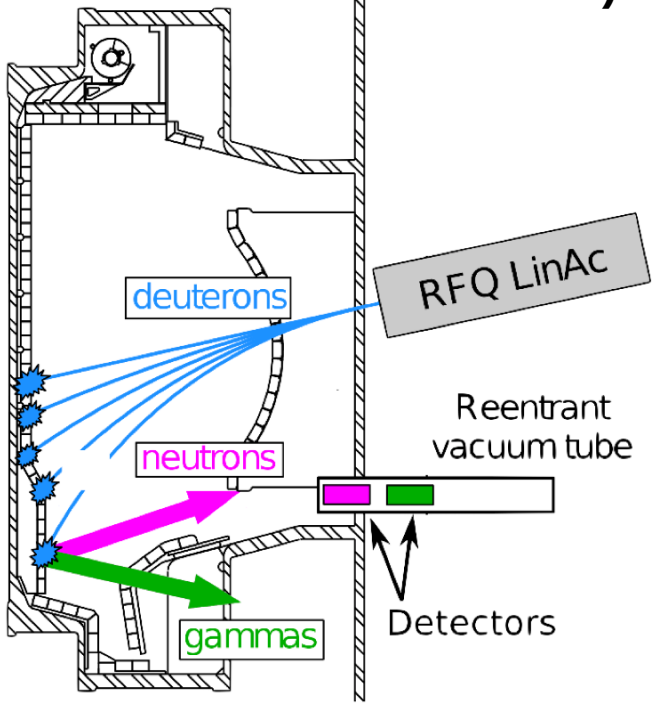
Timescale: FY15 + MIT/NSTX-U collab. plan

Contact: Robert Granetz

C-Mod Boundary Research in FY15/FY16

- **Boundary plasma turbulence & transport**
  - External probing/excitation of boundary modes
  - Improved confinement via LHRF boundary modification
  - Physics of the heat flux channel width
  - SOL transport and turbulence in inner-wall limited discharges
  - Effect of magnetic shear on turbulence
  - n, T_e, Φ fluctuation statistics and blob propagation models
- **Divertor Physics**
  - Optimized plasma performance; seeding via feedback control
  - Detachment in I-mode
  - Magnetic topology: vertical target, snowflake, X-divertor
  - X-point turbulence
- **Density Limit Physics**
  - Experiments in support of simulation validation
  - Heat flux widths, edge gradients and EM turbulence
  - Impact of LHRF on MARFE onset and density limit
- **RF-Boundary Interactions**
  - Physics of impurity penetration during ICRF-heated L-modes
  - LHCD driven fast electrons in the boundary plasma
  - High-field side / low-field side impurity screening asymmetries
- **Plasma-Material Interaction Physics (AIMS)**
  - Boron erosion, deposition and migration
  - ICRF-induced boron erosion studies
  - Between shot and daily tracking of wall condition evolution

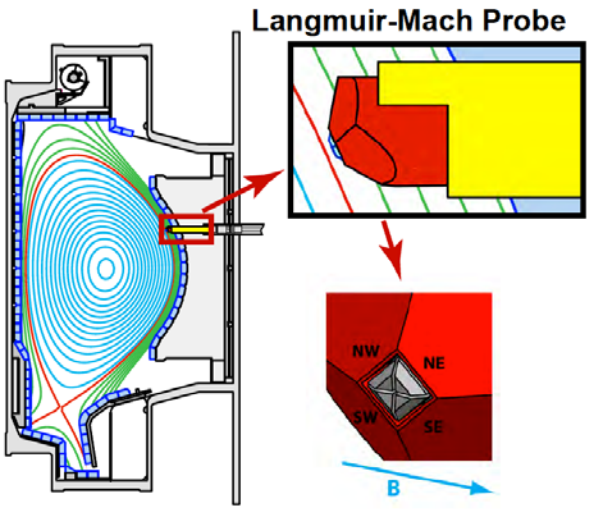
AIMS (Accelerator-based In-situ Materials Surveillance)



- **New Tools**
  - AIMS
  - X-point turbulence imaging (GPI)
  - Multispectral divertor imaging
  - Advanced scanning probe
  - Upgraded Shoelace Antenna

Contacts: Brian LaBombard, Jim Terry

C-Mod Highlight: Unfolding boundary physics with a scanning Mirror Langmuir Probe



MLP simultaneously measures $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$ on all 4 electrodes (~1 μs)

Enables new capabilties:

- High resolution n, T_e, Φ profiles
- Fluctuations and transport

Particle flux

$$\Gamma_r = \langle \tilde{n}\tilde{E}_\theta \rangle / B$$

Heat fluxes

$$Q_{er} = (5/2)\langle \tilde{P}_e \tilde{E}_\theta \rangle / B = (5/2) T_e \Gamma_r + (5/2) n \langle \tilde{T}_e \tilde{E}_\theta \rangle / B$$

convection conduction

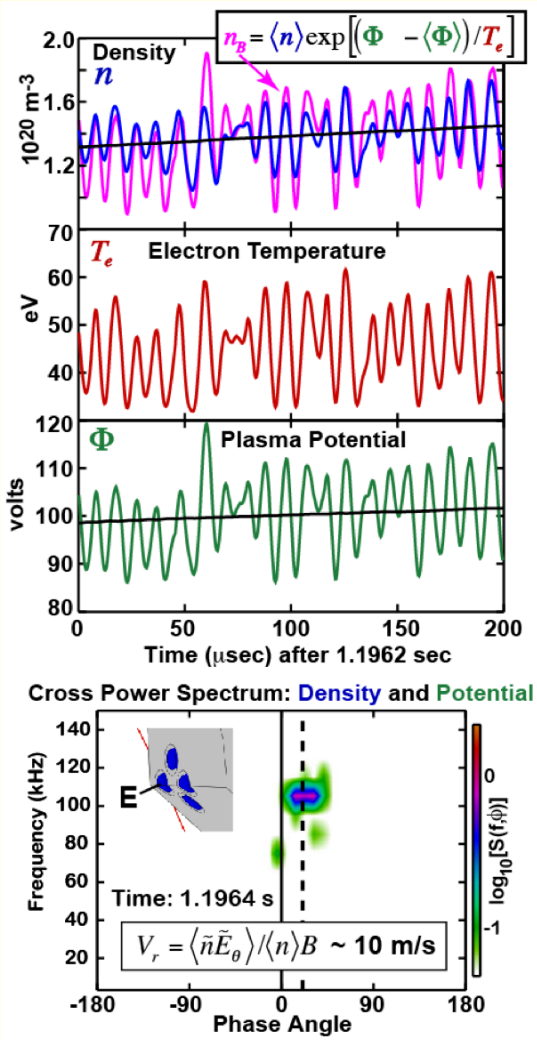
Turbulence mode stucture

k_θ- resolved $\tilde{n}$, $\tilde{T}_e$, $\tilde{\Phi}$ and relative phase angles

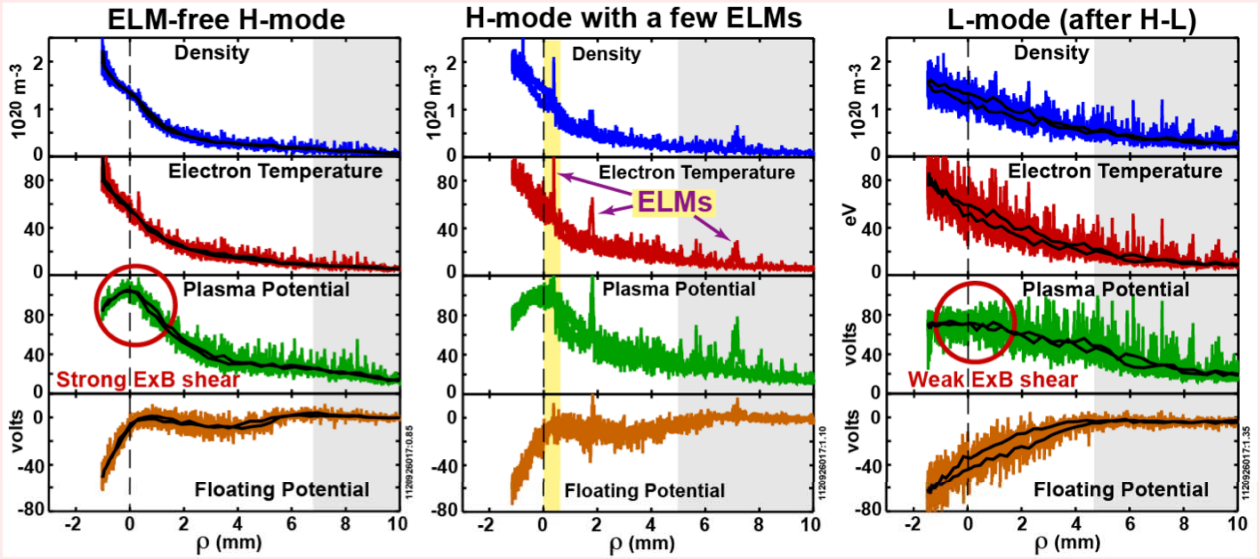
Momentum fluxes

$$\langle \tilde{V}_r \tilde{V}_{//} \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_{//} \rangle \quad \langle \tilde{V}_r \tilde{V}_\theta \rangle \quad \langle \tilde{n} \tilde{V}_r \tilde{V}_\theta \rangle$$

Resolves physics of Quasi-Coherent Mode



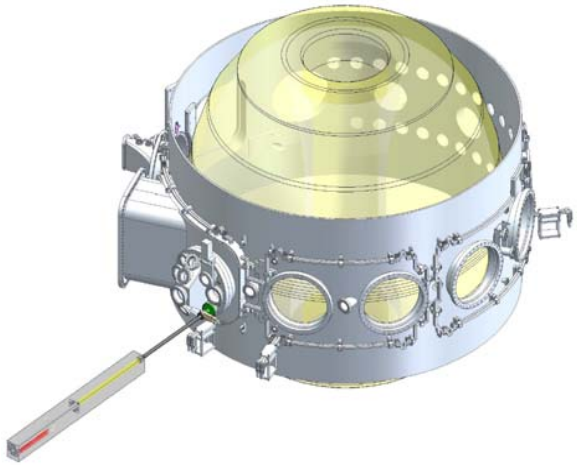
High-resolution profiles (one electrode:18,000 points)



LaBombard, B., Phys. Plasmas **21** (2014) 056108

Collaboration Idea: Implement an advanced scanning probe system on NSTX-U

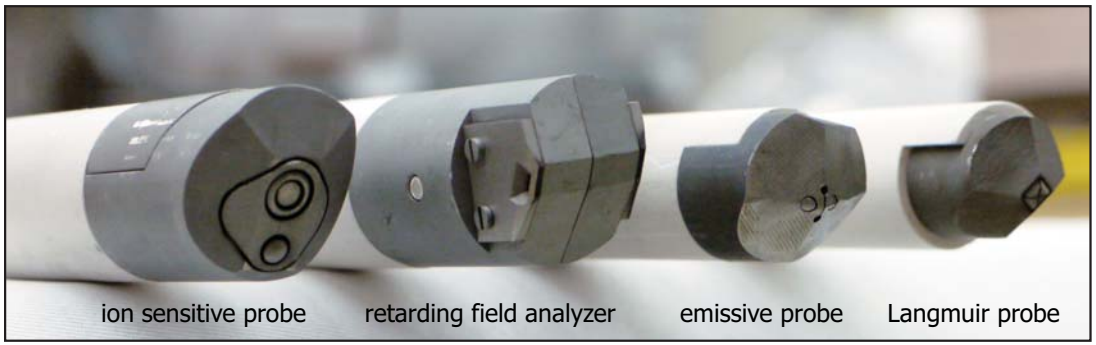
- **MIT is developing a next generation, scanning probe system**
  - Mirror Langmuir Probe bias for real-time I_{sat}, V_f, T_e measurements
  - Linear Servomotor drive -- *Sets plunge depth based on local plasma conditions*
- **High heat flux probe heads would access NSTX-U pedestal**

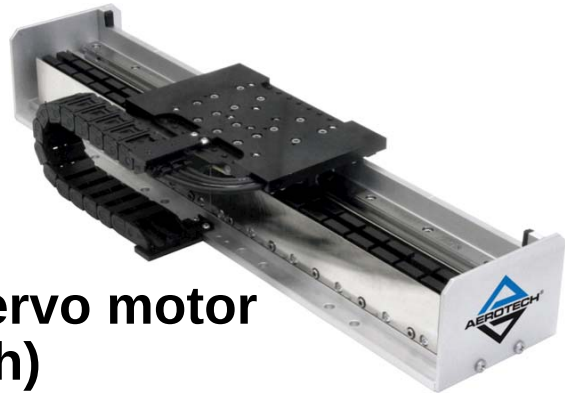


Plan

- **Prototype in C-Mod (FY15-FY16)**
- **Build, install on NSTX-U (FY16-FY17)**
- **Experiments FY17+**

Advanced probe heads:





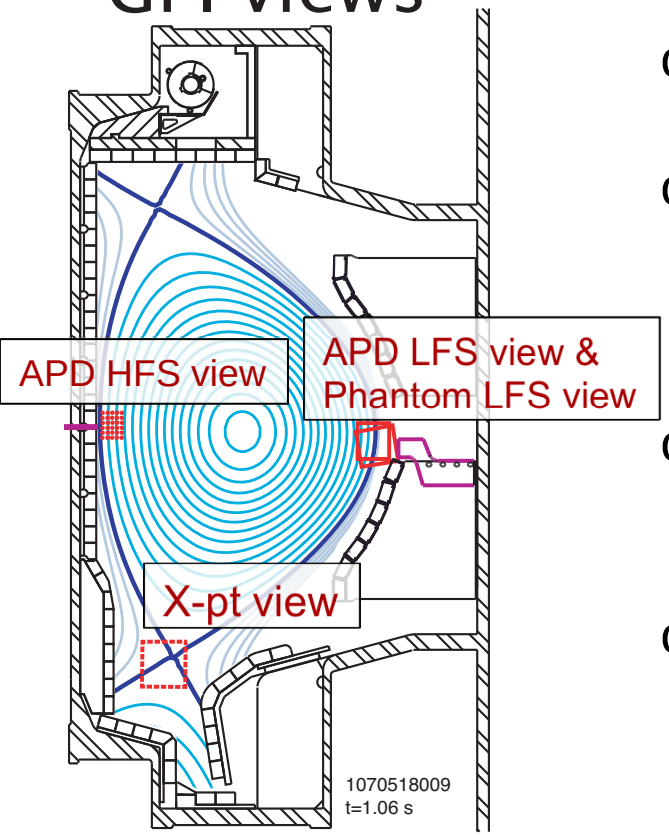
Linear servo motor (Aerotech)

Contacts: Dan Brunner, Brian LaBombard

C-Mod Highlight: Edge/divertor turbulence research enabled by GPI

- PPPL and MIT have had a long-standing fruitful collaboration on GPI
- Use C-Mod's 4 GPI systems for research into:

C-Mod's 4 GPI views



- Turbulence at the X-pt – "churning" mode? (X-pt view)
- RF-Induced convection (both LFS midplane views)
- Edge coherent modes (Quasi-coherent mode, Weakly coherent mode, KBM-like mode, GAMs) (APD LFS midplane view)
- Effects of high-shear region, e.g. near-X-pt region, on blobs (X-pt view and LFS midplane views)
- Spatial dynamics of detachment (X-pt view)

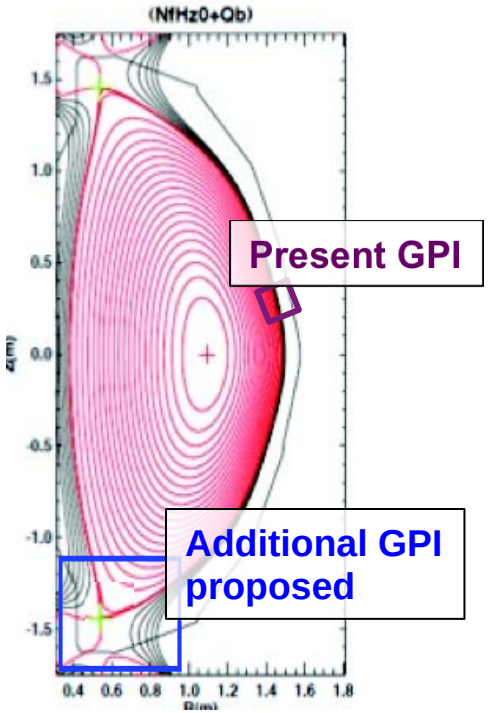
Collaboration Idea: Advanced GPI on NSTX-U

Enhance NSTX-U GPI systems (in stages)

(1) Implement APD-based GPI on existing view of the existing gas-puff manifold

(2) Transfer C-Mod HFS APD-based system to NSTX-U, viewing a plasma-fueling gas puffer on center stack, enabling new HFS turbulence measurements

(3) Add new view of the X-pt region, enabling X-pt turbulence measurements & fast 3D diagnosis of edge turbulence - employ two existing quartz coherent fiber bundles



Physics:

- Edge/SOL turbulence and relationship to SOL heat-flux width;
- L-H transition trigger (coupling between turbulence and sheared flows);
- Pedestal modes (EHO, GAMs, ELMs);
- Effect of 3D fields (RMP) on edge and SOL turbulence;
- SOL convection induced by HHFW RF heating;
- Edge, SOL, and private flux region turbulence in different divertor configurations;
- X-point turbulence dynamics in standard and snowflake configurations -- "churning" modes;
- 3-D turbulence structure and parallel dynamics -- midplane to divertor

Timescale: FY16+ as part of MIT/NSTX-U collab. plan

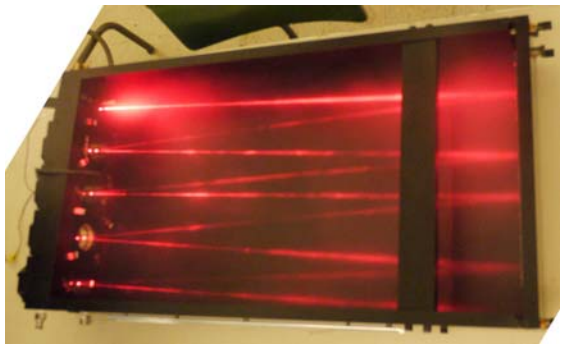
Contact: Jim Terry

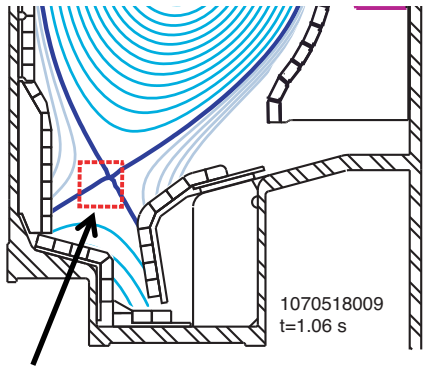
C-Mod Highlight: Development of multi-spectral imaging for atomic line ratios in the divertor

- **PPPL-Alcator collaboration has developed high-throughput imaging polychromators for multi-spectral MSE**
  - 20-30x etendue of typical Thomson scattering polychromators – *optically fast*
  - New filter technologies and design– *spectral resolution of 10^{-4},full visible range*
  - Little degradation of each additional image –*many filtered images w/ same view*

10 polychromator system for Multi-spectral MSE

- **FY15-16: Proof-of-principle and workflow development on C-Mod**
  - Helium line ratios and Stark broadening for n_e, T_e images
  - Balmer line ratios for recombination images
  - Multi-wavelength GPI (Cziegler)
  - Mo, N, Ne lines for impurity influx and seeding



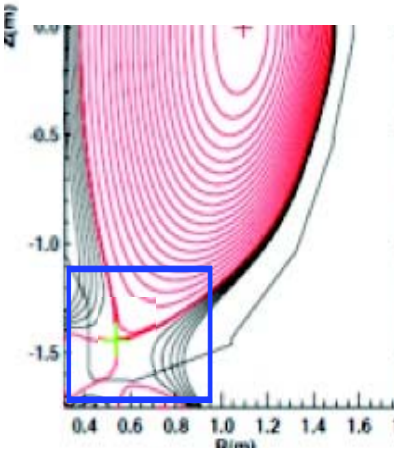


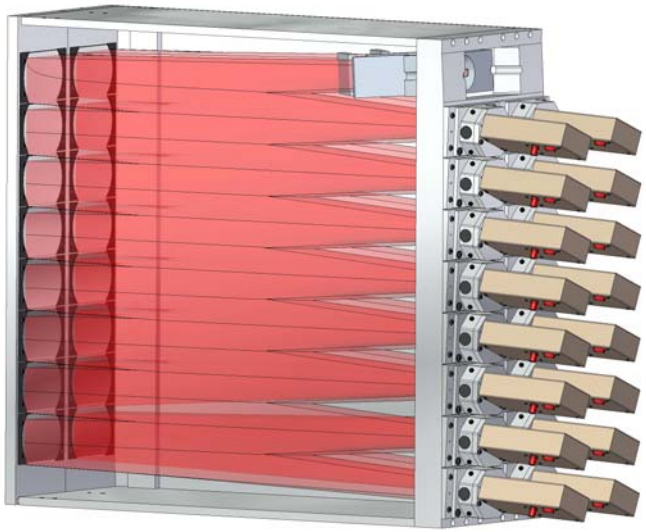
Existing prototype hardware used for imaging the x-point through coherent fibers

Collaboration Idea: Multi-spectral imaging of the NSTX-U divertor for T_e, n_e, recombination and impurities

- **Take lessons learned and workflow from C-Mod and apply technique to image divertor region on NSTX**
  - Refined polychromator layout with 10-16 ports –*populate as funding allows*
  - Invert images or compare directly to synthetic diagnostics in simulations

Proposed view
(share with GPI?)





Line	Wavelength [nm]	Purpose
D Balmer	410, 434, 486, 656	Volume recombination
High n D	370-385	
C I	494, 538, 833	Impurity transport, erosion from ELMS
C II	392, 427, 514, 658, 678	
C III	407, 465, 570	
He I	389, 447, 588, 668, 707, 728	n_e, T_e images
He II	320, 468, 541	Higher temps
Continuum	-	Background subtraction
N I	746	Seeding experiments
N II	400, 463, 501, 568, 648, 661	
Ne I	640, 693, 703, 717, 724, 743	
Ne II	357, 366, 371, 373	
Dβ wide	486	Stark broadening for n_e
Dβ narrow	486	
Li I	323, 413, 460, 610, 670	Monitoring LLD and Li propagation
Li II	320, 325, 468, 478, 549	
Li III	516	
W I	361, 386, 401, 407, 429	High Z upgrade erosion
Mo I	380, 386, 390, 551, 553, 557	

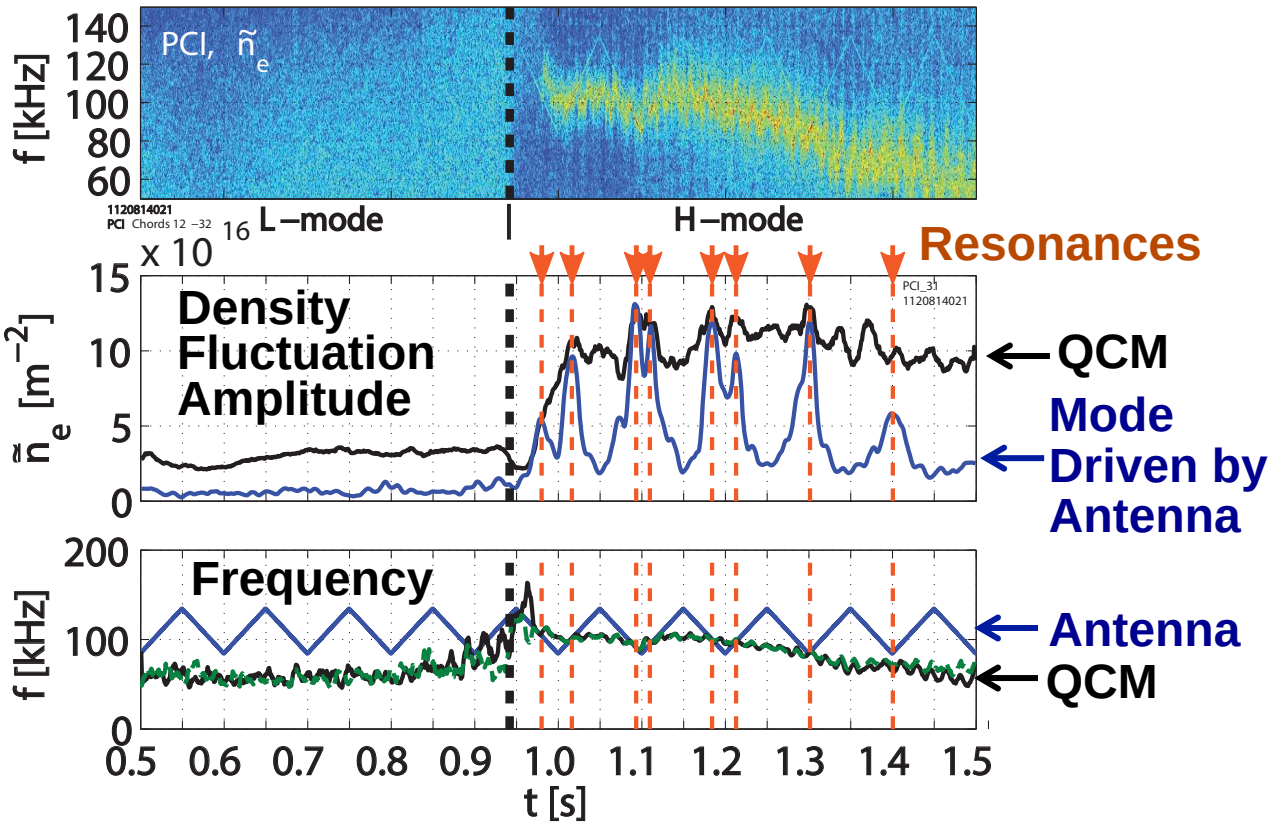
1-window: many lines, same view

Plan

- **Prototype in C-Mod (FY15-FY16)**
- **Install view and upgraded system on NSTX-U (FY16-FY17)**
- **Experiments FY17+**

Contacts: Bob Mumgaard, Jim Terry

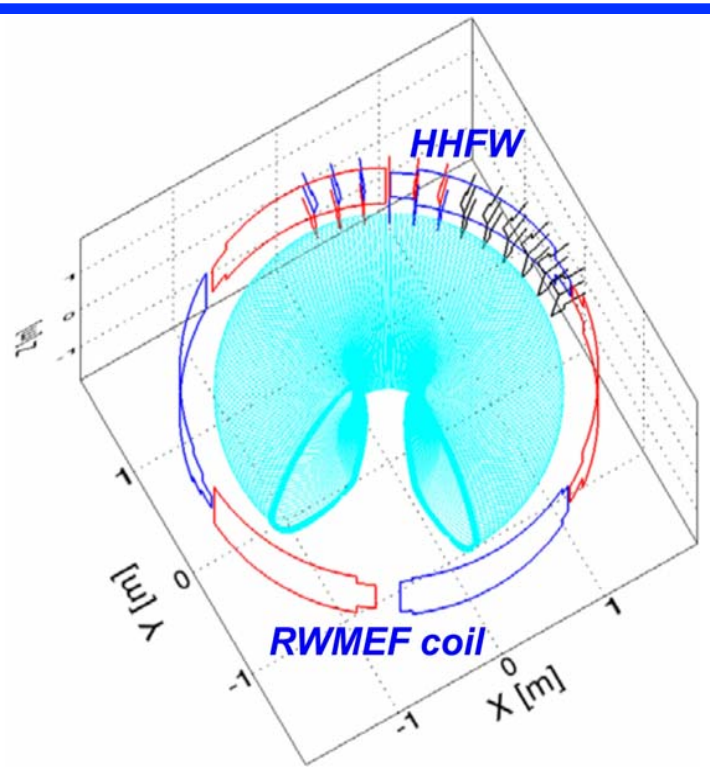
C-Mod Highlight: Exploring Active Edge Control with the Shoelace Antenna

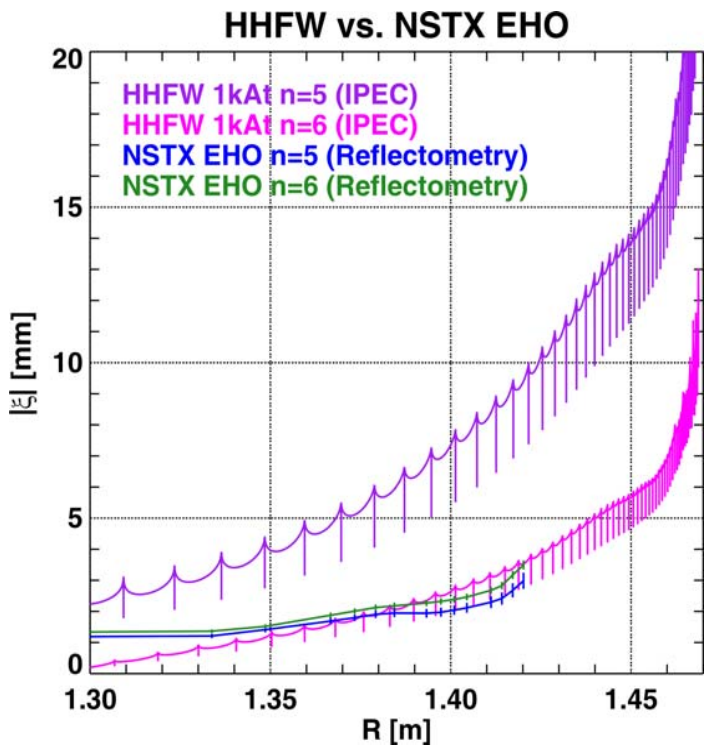


- **Active Edge Control** (AEC): perturb coherent edge fluctuations by external means to exhaust impurities, sustain high-performance confinement mode
- **Shoelace Antenna** drives resonance at f, $k_\perp$ of Quasi-Coherent Mode (QCM), which enables EDA H-mode; also matches WCM
- FY2015 experiments to make measurements of antenna-driven transport, utilizing Mirror Langmuir Probe and ≥4× power upgrade

T. Golfinopoulos, Phys. Plasmas **21** (2014) 056111; T. Golfinopoulos, Rev. Sci. Instrum. **85** (2014) 043510

Collaboration Idea: Active Edge Control on NSTX-U
Target – Edge Harmonic Oscillation





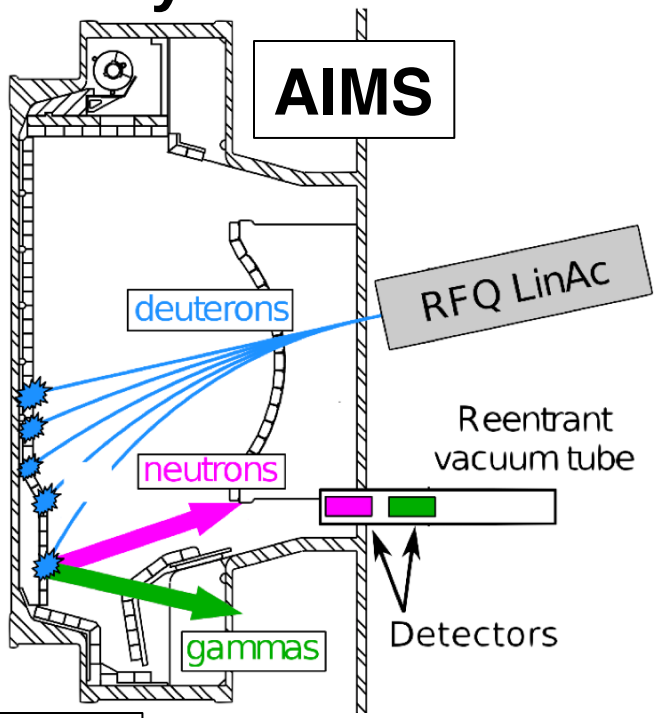
- J.K. Park *et al.* have proposal to use HHFW straps to excite Edge Harmonic Oscillation (EHO) [Park *et al.*, Nucl. Fus. 2014] of Quiescent H-mode
- **Plan:**
  - **FY15+: Investigate low-*f* (1-10 kHz) amp. modulation, with HHFW antenna RF as carrier, to excite EHO (idea submitted to Research Forum)**
  - **FY16+: Work with NSTX-U on follow-on experiments -- power sys., antenna, and experimental design; supporting diagnostics; interpretation of data**

Contact: Ted Golfinopoulos

C-Mod Highlight: Developing Advanced Tools for Plasma-Material Interaction Science

- **AIMS (Accelerator-based In-situ Materials Surveillance) is being enhanced for intershot *in-situ* PFC ion beam analysis**
  - Upgrades to detectors and RFQ LinAc will enable between-shot analysis, including B erosion/deposition and D retention
  - AIMS NRE is ideal for carbon/lithium – NSTX-U

  An AIMS system at NSTX-U will be explored as part of MIT/NSTX-U collaboration plan, FY16+



- **"Traditional" ion-beam analysis (IBA) tools at MIT (CLASS) are also used to interrogate C-Mod PMI in the usual *ex-situ* mode**

Cockroft-Walton tandem

DANTE tandem

Contacts: Zach Hartwig, Graham Wright

Collaboration Idea: Leverage Materials Analysis Particle Probe capabilities to expose custom targets for ex-situ IBA

- Ion Beam Analysis (IBA) techniques reveal material distributions below the surface complimenting the surface-focused diagnostics of MAPP.
  (Idea submitted to NSTX-U Research Forum, Materials & PFC Group)

- Two main thrusts:
  1. Traditional IBA (RBS, NRA, ERD) to measure Li-layer thickness, oxide layer thickness, D retention and Li-C intermixing in targets exposed in NSTX-U.

  2. Implement low-Z *implanted* depth markers to track net deposition/ erosion of targets.

IBA will simulate AIMS capabilities and refine AIMS detection techniques for the NSTX-U environment.

Timescale: FY15, and part of MIT/NSTX-U collab. plan

Contacts: Zach Hartwig, Graham Wright

The Alcator Team is looking forward to fruitful collaborative work with PPPL scientists on NSTX-U in a number of areas.

- **C-Mod operations -- FY15: 15 weeks, FY16: 5 weeks, FY17: 0**
- **Presently assembling 5-year Cooperative Agreement proposal to fund collaborative research**

FY16-FY17: Ramp down of C-Mod research
FY17+: Ramp-up of collaborations