MIT C-Mod/PSFC Magnetic Fusion Collaborations

Fusion Power Associates

Annual Meeting

December 14, 2016

C-Mod Team has always been strongly engaged in collaborations

- When C-Mod operating, many collaborations both at C-Mod and at other facilities
  - Internationally, ITPA provides strong foundation, direct connections to research in support of ITER design and planned operations
  - Group to group and individual investigator joint work
  - Experiments, theory and modeling
- Subsequent to completion of C-Mod operations in 2016, the group is increasing and strengthening outgoing collaborations
  - New 5 year cooperative agreement (2015-19)
    - Biggest current efforts focused on DIII-D and NSTX-U
    - more modest funding for European collaborations (JET, WEST)
  - With delays in NSTX operations, also planning to redirect some of that effort to additional European collaborations during 2017-2018 (JET, WEST, TCV, ASDEX-U, MAST-U)
  - Grants to work with ASDEX-U, W7-X
  - Part of multi-institutional grants focused on EAST and KSTAR

C-Mod team increased its engagement with JET in FY16

- ITPA experiments, eg Low Z seeding effects on pedestal, particle pinch
- Participated in US planning for JET Internationalization workshop in July, and attended the meeting, including proposals for joint work on ICRF
- Proposed, planned and participated in an experiment (suggested by Loarte, ITER Organization) to find if I-mode could be accessed with 'favorable' drift in other conditions which have very high L-H threshold
  - Hydrogen campaign on JET provided a unique opportunity, since P(L-H) at >3 T was expected to be very high.
  - Experiment ran very well technically, with up to 17 MW auxiliary heating. P(L-H) was even higher, and no I-mode was evident. Implies that the 'unfavorable' configuration per se may be necessary.

Planned activities for JET, FY 2017:

MIT team will use this year to become well integrated to JET team, contributing to analysis and planning activities.

This should position us to propose and participate in many key experiments in 2018 and then, importantly, in the DT campaign planned for 2019.

Analysis of recent experiments:

- I-mode attempts in hydrogen: any changes in turbulence, profiles?
- **Pedestals and scenarios with ILW.** What factors made the difference between past, poor performance and recent apparently better performance? (power, density, fueling….?). Can we further optimize?
- Analysis of ITPA experiments, including low Z seeding effects on pedestal, particle pinch

ICRF physics, technical assessments in preparation for D-T

- Control of core W impurities.
- Increase total heating power, supplementing NBI.
  - Provide bulk ion heating for enhanced DT fusion.

Planned activities for JET, FY 2017 (2):

Based on results and analysis, we will do preparatory work, and develop proposals for, new experiments in 2018. Ideas so far include:

- I-mode, in reversed B_T and I_p configuration. This could flush impurities while keeping density low, eliminating ELMs.
  - JET has been resistant to trying this configuration as it has not been used with ILW. We have proposed *(in web forum and at planning meeting 11/25)* to help with needed analysis, determine safe power levels.
  - Simulations of likely I-mode performance in DT could help make the case.
- Use of boronization or other low Z coating to reduce W influx.
- Increased ICRH (resulting from RF task) to flush W, and increase fusion rate.

Will closely collaborate with EU JET team, and with other US colleagues, for greater impact. *How should US effort be coordinated?*

New opportunities for I-mode collaborations in EU

Recently increased interest in I-mode (and QH-mode) across EU program.

- Hubbard gave a EURO-fusion seminar last spring on 'no-ELM regimes in view of DEMO'.
- They have now been adopted as a 2017 task for 'Medium Sized Tokamaks' (AUG, TCV, MAST-U). Potential increase in available run time.

Planned experiments include:

- **TCV**: An MIT proposal had already been accepted in 'internal' program (winter 2017, plus expected extra MST runs in summer 2017)
- **AUG:** Has been main experiment (apart from C-Mod) studying I-mode. MST program will push to higher density, try beta control. Summer 2017.
- **MAST-U:** Will study I-mode access in ST, ~2018.
- **WEST:** has accepted an MIT proposal, scheduled for 2018.

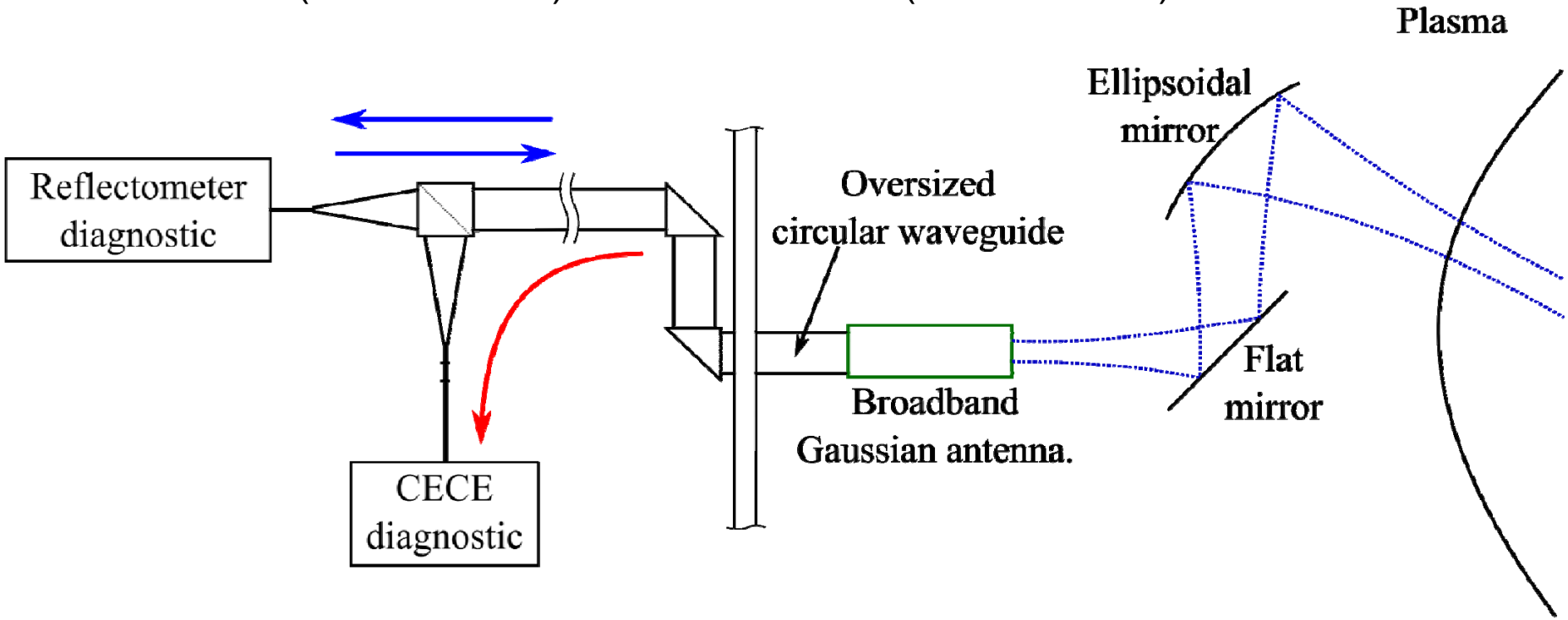
New CECE n-T cross phase measurements on AUG and validation of nonlinear gyrokinetic simulations

S.J. Freethy*, G.D. Conway, **A.J. Creely (PhD student)** *, T. Happel, **A.E. White*** and the ASDEX Upgrade Team

*MIT/PSFC and MIT research affiliates

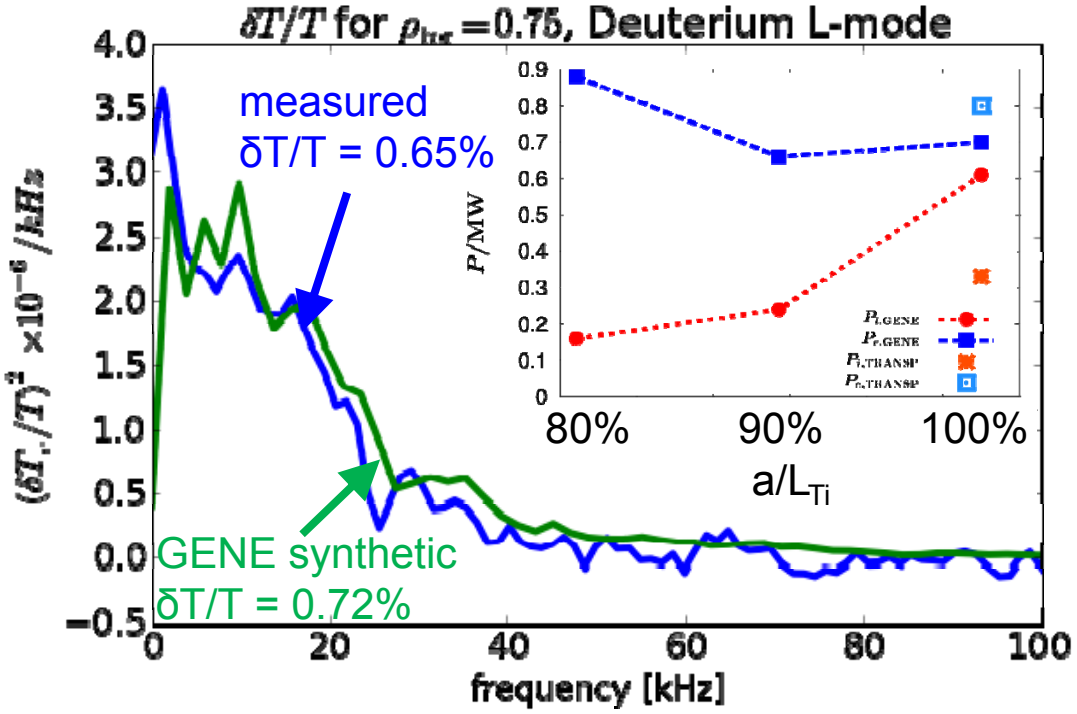
Correlation Electron Cyclotron Emission (CECE) and nT-phase diagnostic allow for detailed turbulence measurements in AUG

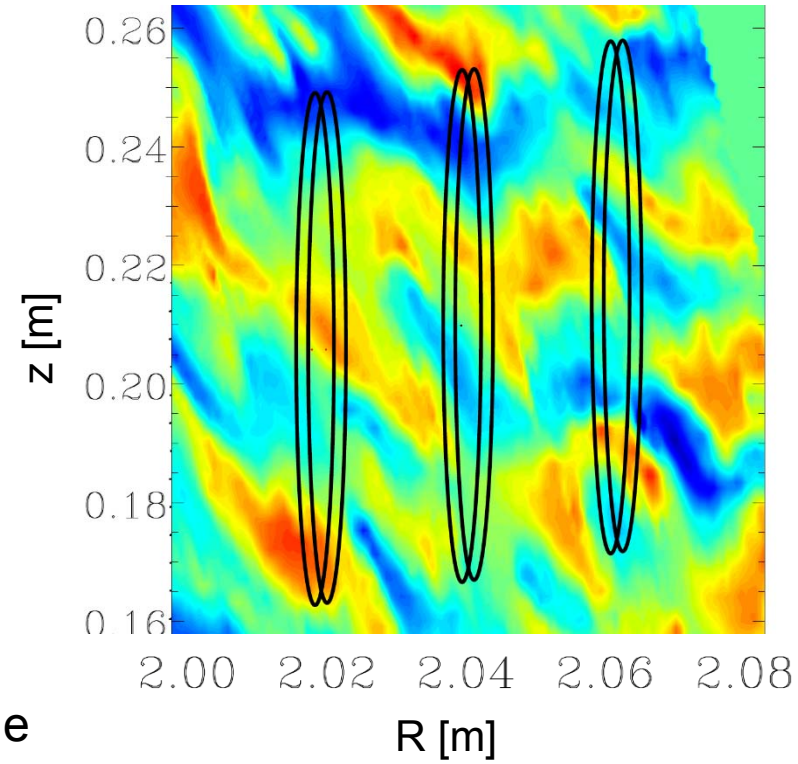
- New ECE radiometer for turbulence measurements was developed at AUG via MIT collaboration.
- System was successful last campaign, measuring $\delta T_e/T_e$ profiles in Deuterium L-mode plasmas and for the first time in Helium plasmas.
- Successful prototype nT cross-phase demonstrated correlation between radiometer (T-fluctuations) and reflectometer (n-fluctuations)



[S. Freethy, *RSI*, **87** 11E102 (2016)]

Comparing Te fluctuation spectra at AUG to theory is underway, results revealing interesting differences with C-Mod

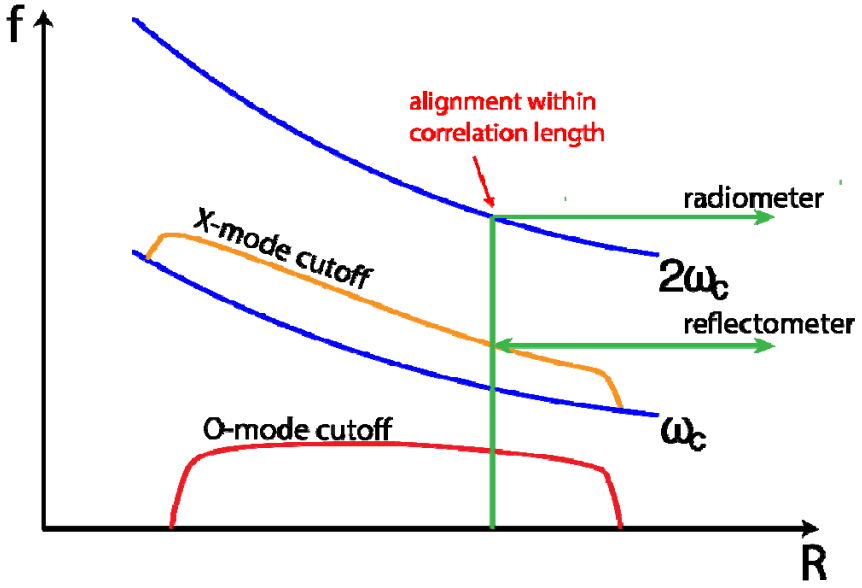




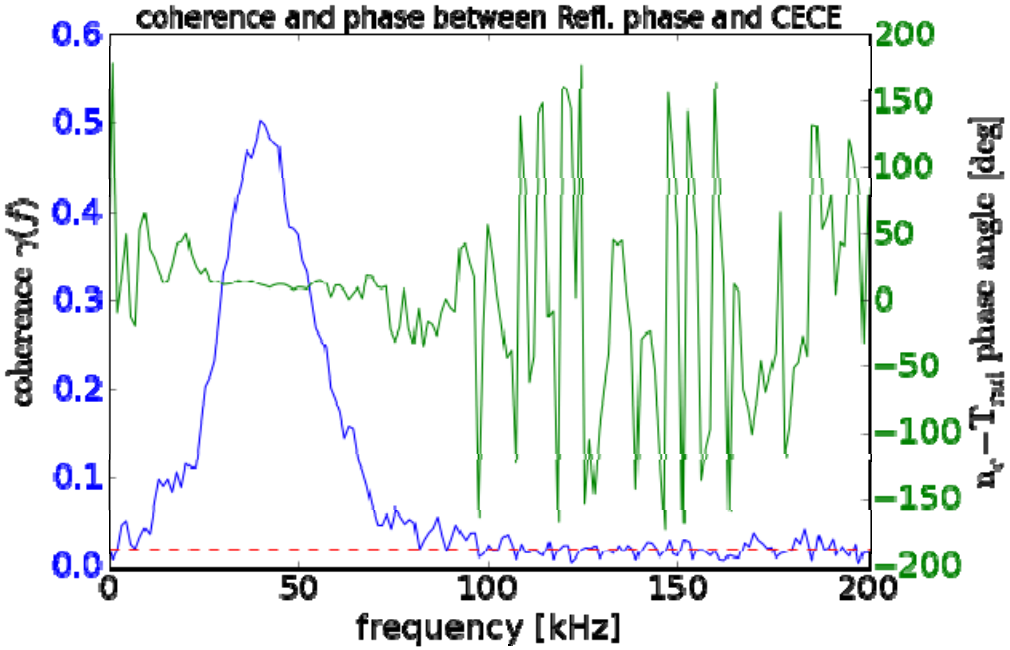
- $\delta T_e/T_e$ measured by CECE on ASDEX Upgrade
- Non-linear GENE code [1] simulations match both ion and electron heat flux
- Excellent agreement between fluctuation spectra for Deuterium L-mode plasma.
- Contrasts with C-Mod where same physics model does not match experiment! [2]

[1] www.genecode.org [2] Alex Creely APS Invited 2016

Working prototype n-T cross-phase diagnostic



- Coupling CECE with reflectometer allows for n-T cross-phase measurement
- Phase angle between turbulent fields is critical parameter for testing transport models

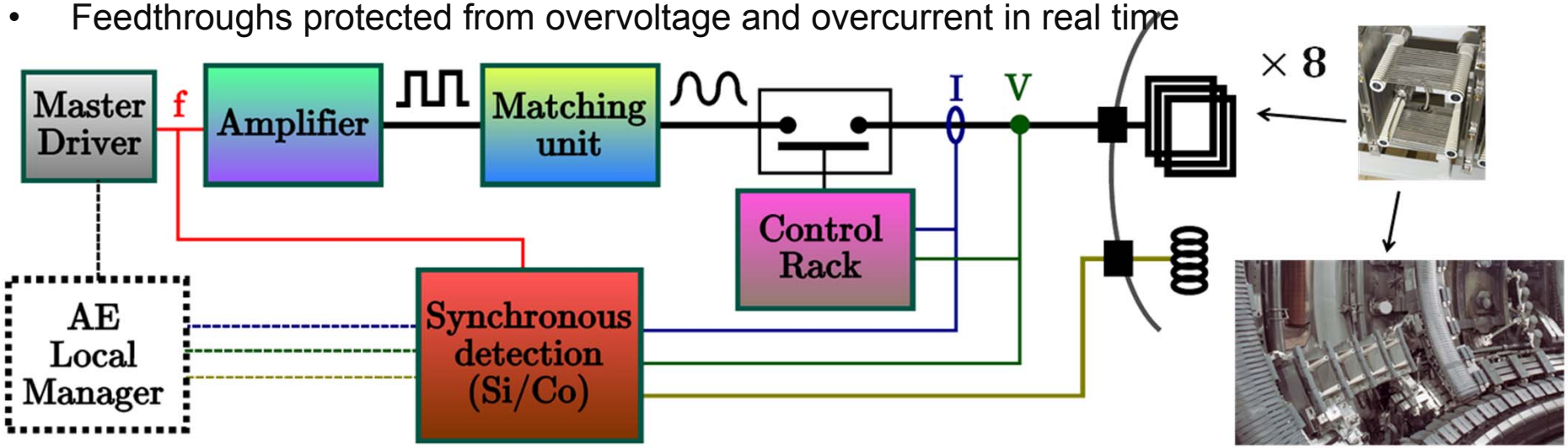


- Measurement shown at r/a = 0.9
- Pedestal fluctuations of great interest, but low optical depth makes measurements difficult (not impossible) to interpret

TAE Antenna and Transmitter Upgrade Project on JET to Measure AEM Damping and Growth During the D-T Phase

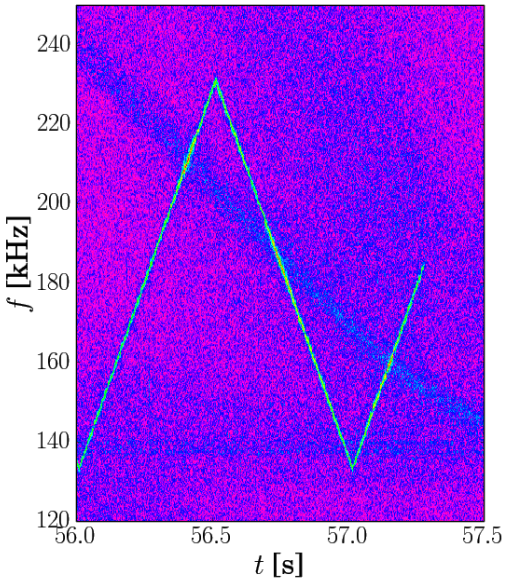
M. Porkolab, V. Aslanyan, and P. Woskov

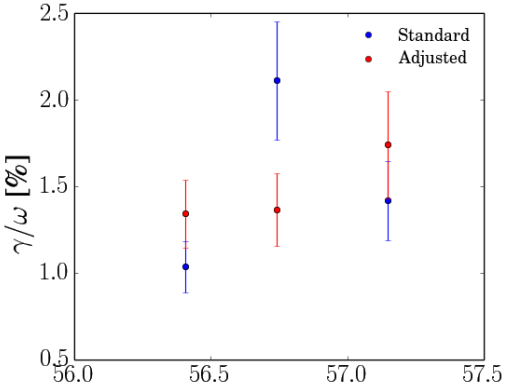
- Master Driver creates reference signal for up to 8 antennas, separated into 2 groups, toroidally opposite below the outer midplane
- A single switching amplifier drives each antenna; harmonics filtered and large impedance changes are smoothed by matching units and master driver control algorithm
- Signals from magnetics (+ optionally interferometry) digitized synchronously
- Frequency controlled in real time to track modes of interest
- Independently controlled amplifiers allow arbitrary phasing – crucial to couple to modes with high toroidal number *n*
- Feedthroughs protected from overvoltage and overcurrent in real time



First Damping Rate Measurements

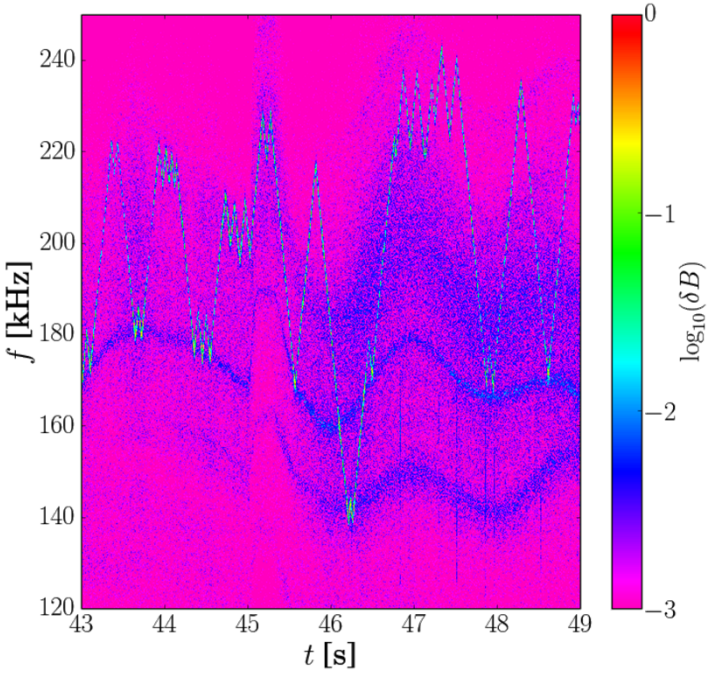
JET pulse 91747



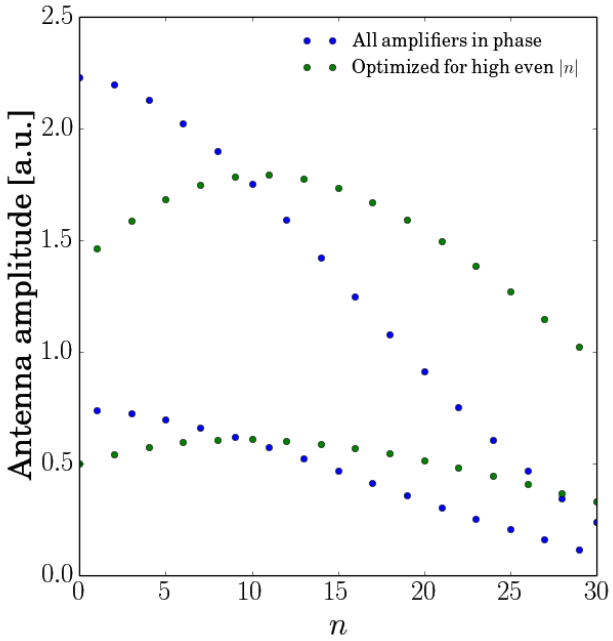


Real-time mode number identification and damping rate estimation allow mode tracking during pulse

JET pulse 92087



- Phasing sufficient to excite $|n|<20$
- High $|n|$ measurements require replacement of JET magnetics



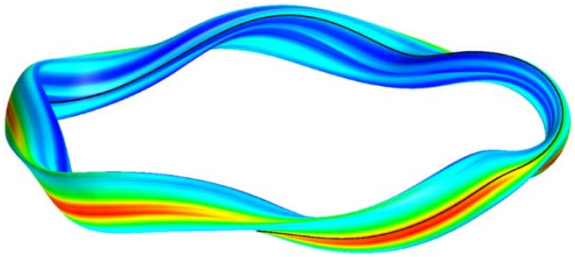
Massachusetts Institute of Technology

PSFC

Phase Contrast Imaging for Wendelstein 7-X

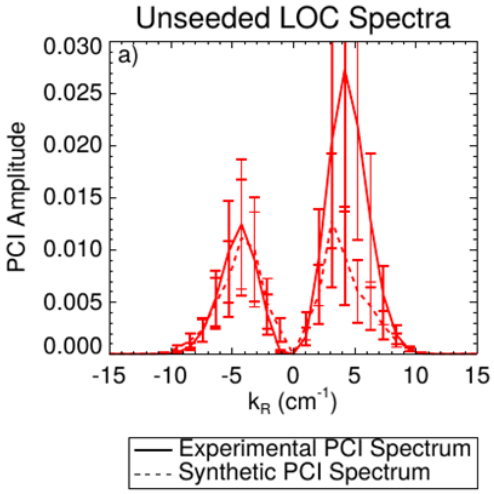
Miklos Porkolab, Eric Edlund, MIT
in collaboration with Olaf Grulke and Lukas Böettger, IPP Greifswald

- Understanding the role of turbulence in stellarators and its significance in determining particle and energy transport above neoclassical is of critical importance.



GENE calculations of fluctuations in the electrostatic potential due to ITG modes.
From Xanthopolous *et al.*, PRL **113**, 155001 (2014).

- The PCI system will be able to detect fluctuations over a broad range of spatial and temporal scales:
  - Frequency range: 10 kHz to 2 MHz.
  - Wavenumber range: 1.0 cm^{-1} to 20 cm^{-1}



Fluctuation power spectrum measured with the PCI diagnostic at Alcator C-Mod, from Ennever *et al.*, PoP **23**, 082509 (2016).

- A dual-detector system will allow for the measurement of poloidal and radial correlations of core TEM-range turbulent fluctuations.

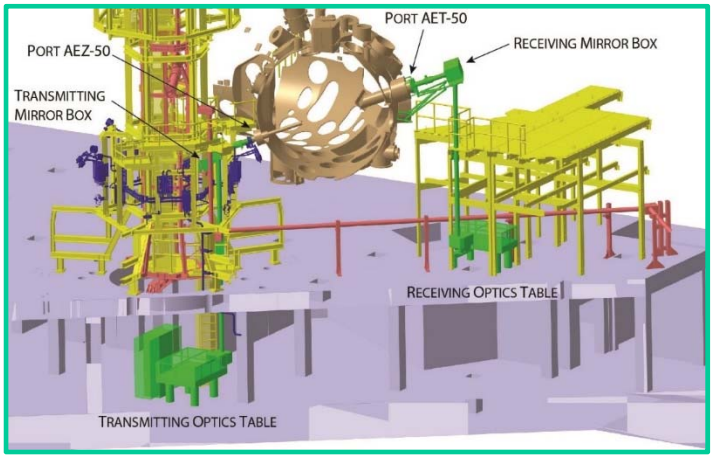
- The diagnostic will be ready for the beginning of OP1.2 in 2017.

Massachusetts Institute of Technology

The PCI project is entering the installation phase

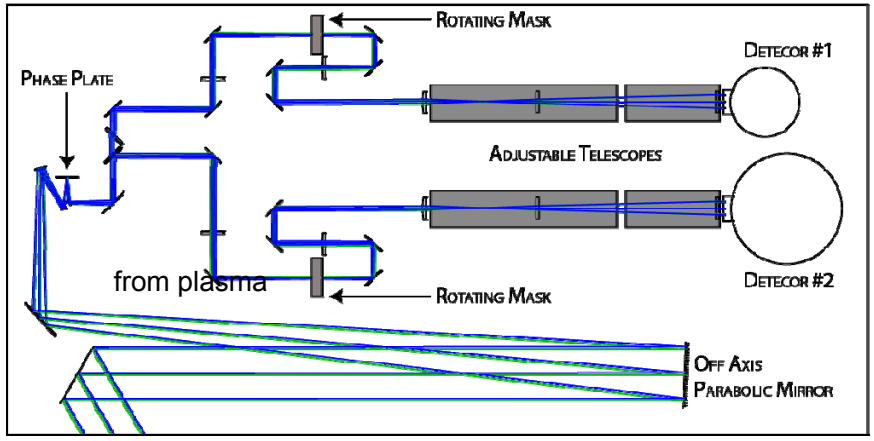
PSFC

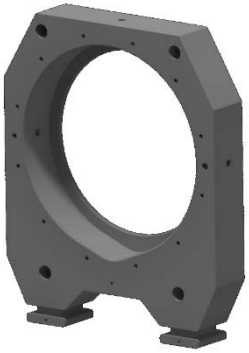
- Optics and mechanical design is complete and includes multiple elements for remote operation.
- About $200k of equipment has been purchased.
- First equipment to Germany in January 2017.



Torus Hall layout with PCI shown in green.

Optical layout for the receiving optics table.





Custom optical mounts for large diameter steering mirrors will provide excellent optical stability.

Remote control mirrors will provide for remote alignment during restricted access to the torus hall.

MIT-W7X collaboration on GPI will provide fast-imaging of edge fluctuations during OP 1.2

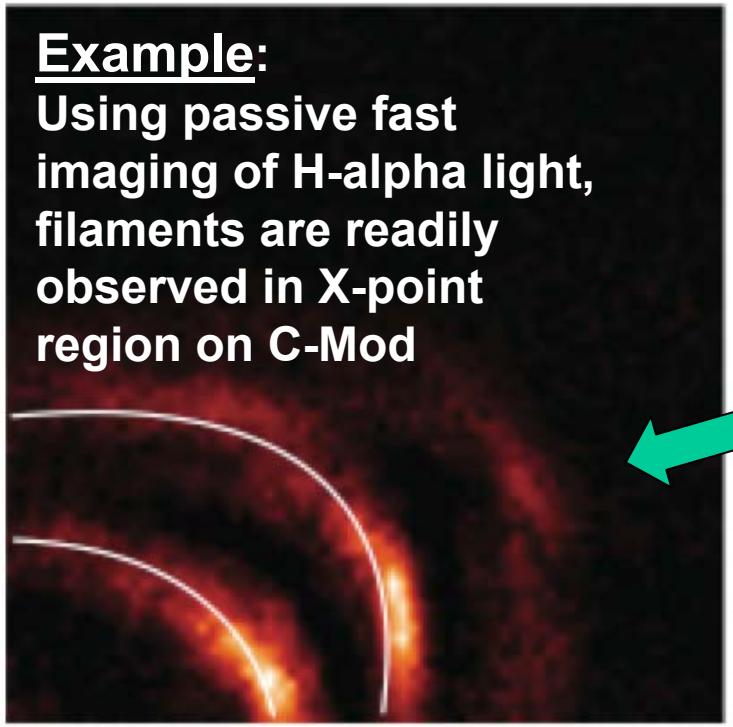
J.L. Terry, S.G. Baek, S. Ballinger (MIT), & O. Grulke (W7-X)

Fast-imaging of plasma fluctuations in divertor region: Passive and Powerful

[Terry, PSI 2016]

Motivation:
Study of fluctuations and plasma structure in the edge and near island-divertor region is critical for boundary physics understanding, and heat exhaust control in W7X

Example:
Using passive fast imaging of H-alpha light, filaments are readily observed in X-point region on C-Mod



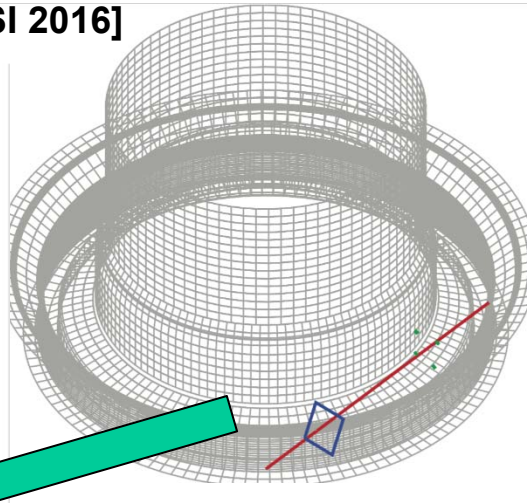


Diagram of X-point view at C-Mod tokamak

MIT - fast-camera imaging on W7-X during OP 1.2

Status:

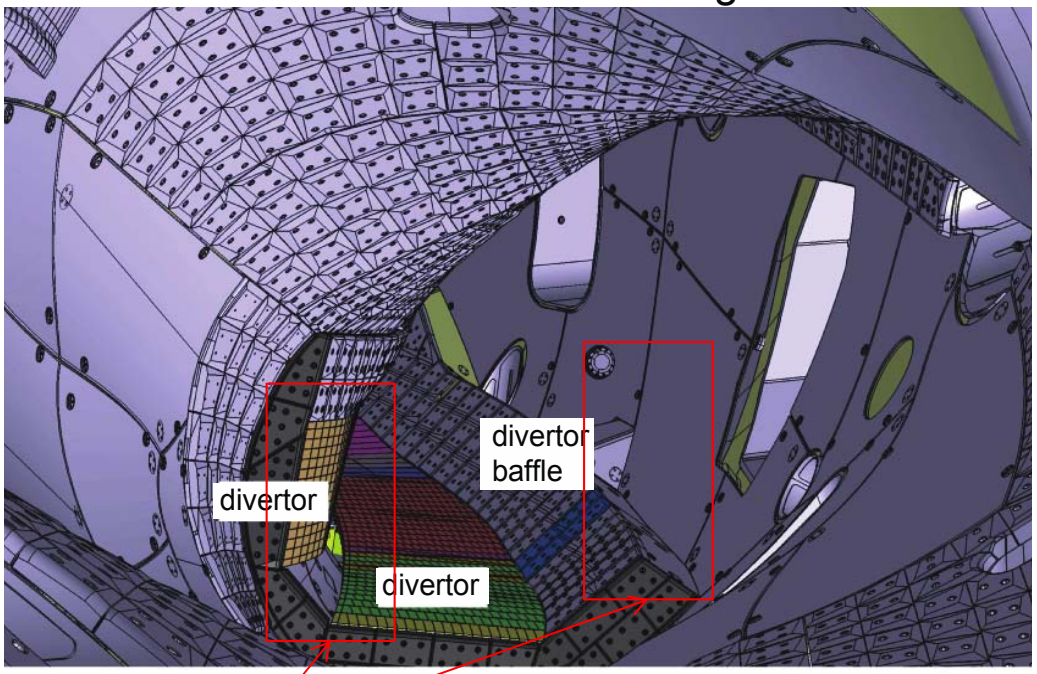
- Thanks to Aug. ’16 supplemental funding, added **MIT graduate student Sean Ballinger** (w/ Baek & Terry)
- Secured a fiber-coupled view of the W7X X-section
- View to be shared with slow camera used for plasma monitoring
- Shared viewing scheme designed and tested

Plans:

- Provide fast-imaging of passive Hα light as it responds to plasma fluctuations & turbulence, especially in the divertor region
- Fast-camera and optics to be shipped to W7-X late in ’16
- Install camera and optics at W7-X in 1st quarter of ’17 (site visits)
- Participate fully in OP 1.2 with Sean on-site in summer of ‘17

Optical setup allows fast-camera to image full X-sect. or to examine any portion of view

CAD reconstruction of view from image-fiber AEQ 30

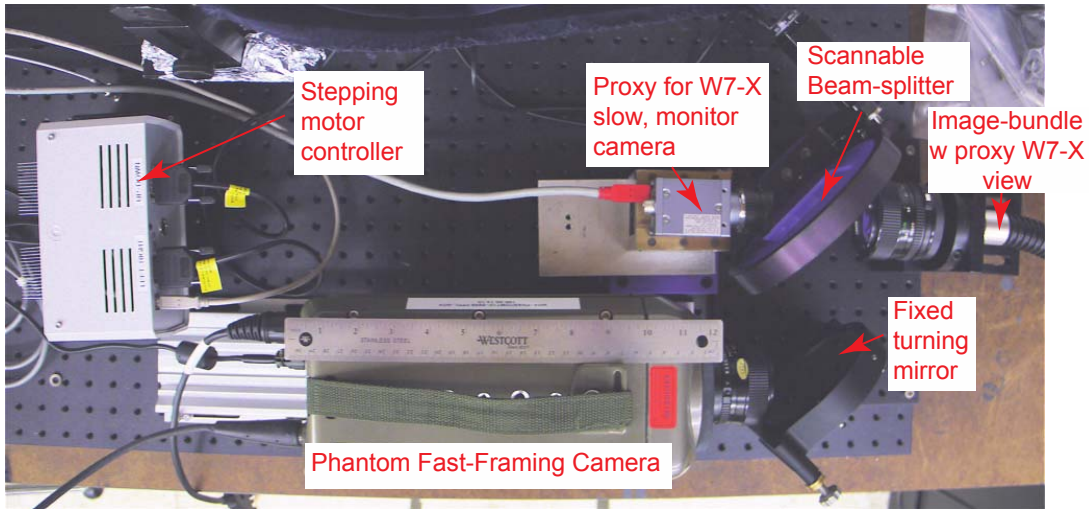


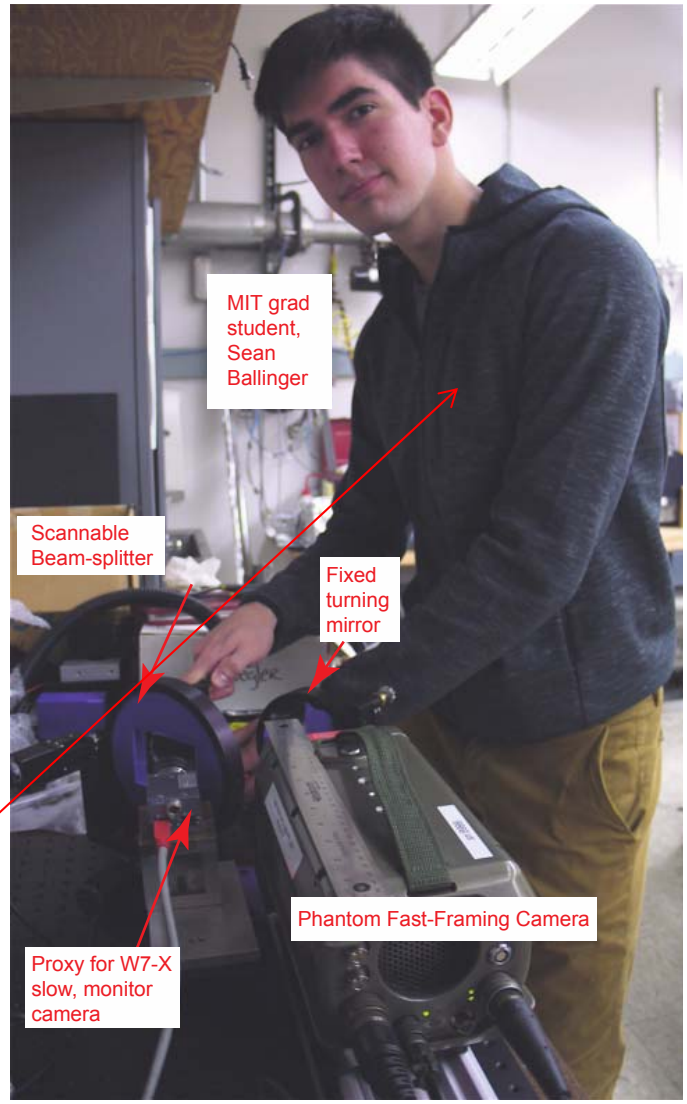
128x64 pixel sub-window can be moved anywhere within full view & recorded at up to 390000 frames/s

- unlike true GPI, this is fast passive imaging of Hα light
- spatial resolution: ~0.5 cm per pixel in plane at front edge of divertor as shown
- time resolution: down to 2.6 μs (*if* there is enough light coming thru the image-fiber – this is a risk that is NOT in our control)

Motorized beam-splitter used to scan fast-camera view & to share view with (slow) plasma-monitor camera

working optical setup on bench at MIT





student involvement is important & valuable!

MIT/WEST Collaborations

- LHCD and ICRF operation in advanced confinement regimes, with high Z wall
- Edge sources and core transport of high Z wall materials
- X-ray imaging spectroscopy for T_i and V_ϕ profiles (no CXRS on WEST)
- RF rotation drive (no NBI)
- I-Mode operation (should have large operating window at 3.7 T)
- Discussing other diagnostic participation (e.g. Thomson scattering)
- C-Mod LHCD physics program maps well to WEST.
  - Off-axis current drive
  - LHCD Density Limit
  - Simulation Validation
  - Role of Parametric Decay, Interactions with SOL
  - Possible candidate for high-field side LHCD?

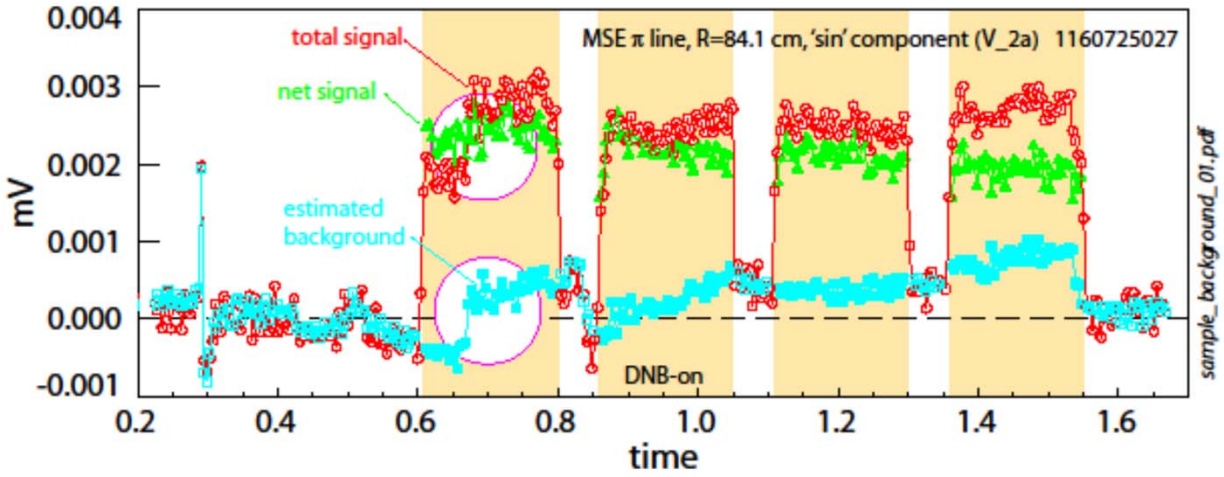
Disruption Prediction and Avoidance in High-beta, Long-pulse KSTAR Plasmas

- Objective: *forecasting and avoidance of disruptions in a long-pulse, superconducting tokamak*
  - *at high stability parameters (e.g. normalized beta)*
  - *with direct, quantifiable figures of merit (plasma disruption rate)*
  - *and its reduction based on improved stability physics and control*
- Apply physics-based paradigm: disruption event characterization and event chain analysis
- Codes: DECAF, MISK, DCON, M3D-C, TRANSP.
- Relevant KSTAR capabilities: low error field (allows low q_{95}); non-axisymmetric field coils (IVCC) → rotation control and global mode control, beams → pressure, q-profile control.
- PSFC + PPPL contribution: improved MSE q-profile measurement based on existing C-Mod 'background polychrometer' to accurately measure background light. Also Thomson improvement.

PPPL PRINCETON PLASMA PHYSICS LABORATORY COLUMBIA UNIVERSITY PSFC MIT

Recent performance validation with DNB on C-Mod

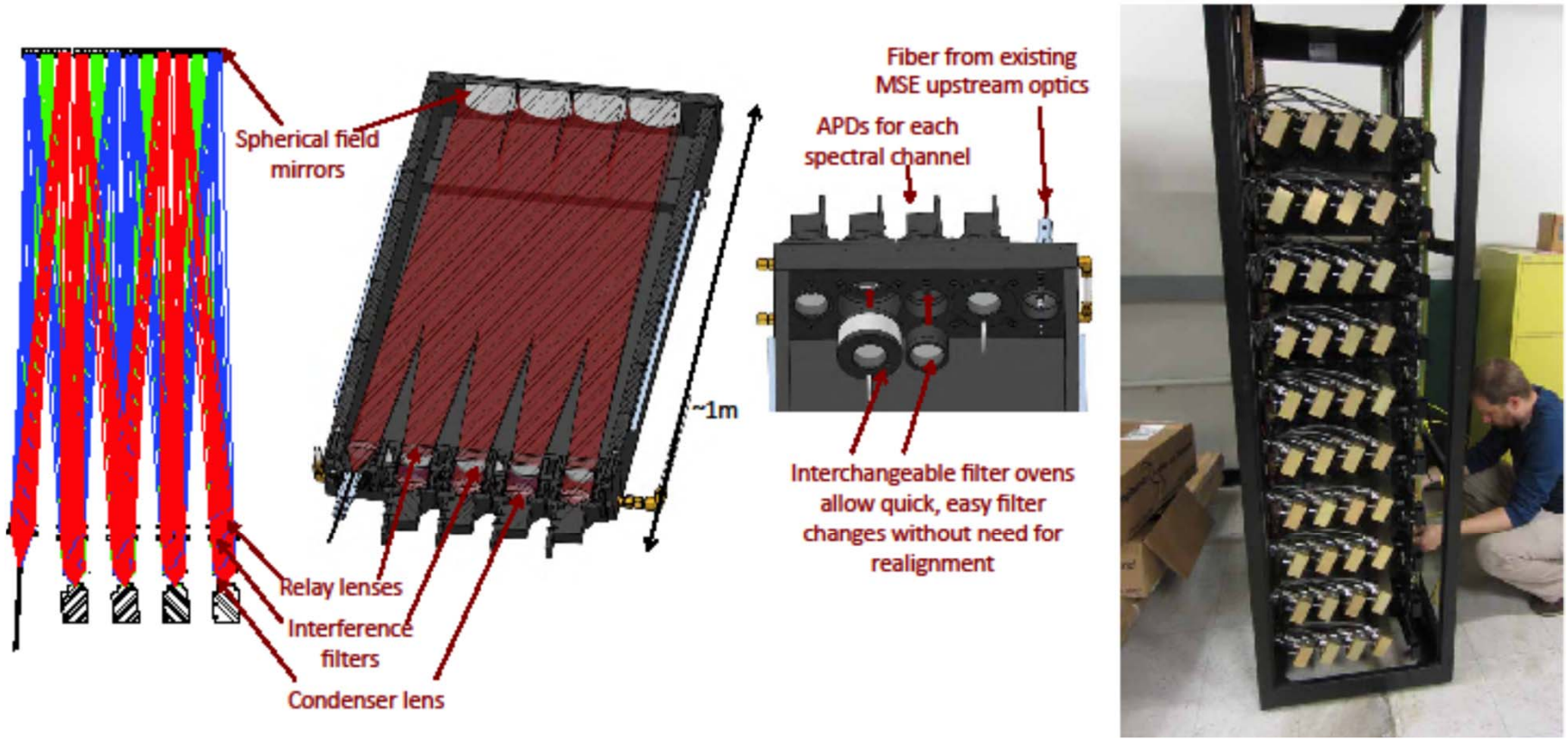
Operation of MSE background polychrometer with recently-repaired DNB confirms that hardware & software properly estimate rapidly-changing background



* Background and total signal experience rapid change but net signal does not (as expected).
* System is expected to be used for LHCD experiments in early/mid August.

PPPL Princeton Plasma Physics Laboratory · Columbia University · MIT PSFC

A 10-channel polychrometer fabricated by PPPL/PSFC to *simultaneously* measure MSE σ and π lines + 2 nearby background wavelengths



Easily portable to ASDEX (single channel; 2014) and KSTAR (10 channels, 2017): only filters need to be changed

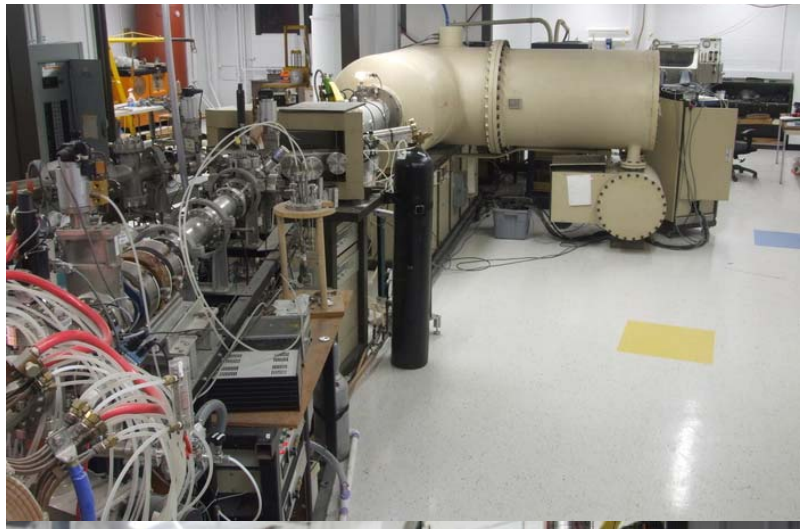
Control and Extension of High Performance Scenarios to Long Pulse (EAST)

- Disruption warning algorithms using large databases on C-Mod, DIII-D and EAST
  - Several parameters (I_p-error, v_{loop}, P_{rad}/P_{in}) have been identified so far that each individually can warn of a significant fraction of impending disruptions, with few false positives.
  - Have created databases consisting of candidate parameters sampled at many times during disruptive and non-disruptive shots on several tokamaks:
    - C-Mod 2015 campaign (~2000 shots; > 165,000 time slices)
    - EAST 2015 campaign (~3000 shots; > 117,000 time slices)
    - DIII-D 2015 campaign (~2100 shots; > 500,000 time slices)
- LHRF actuator development for EAST
  - Analysis of "two-frequency" and current profile broadening experiments in EAST
    - Find improvement in LHCD effect when LH source frequency is changed from 2.45 GHz to 4.6 GHz
      - Investigating the explanation – linear wave propagation?, PDI?

Plasma-materials interaction studies on EAST

- Multi-institutional grants (with PPPL, LANL, ORNL, Johns Hopkins U., U. Illinois, U. Tennessee)
- MIT focus:
  - Use of MIT accelerator CLASS facilities for characterizing plasma-surfaces in EAST
  - Developing novel depth-marking technique for erosion/deposition studies in high-Z metals
  - Preliminary tests in DIONISOS linear plasma being planned

CLASS Tandem Accelerator



DIONISOS Linear Plasma Device