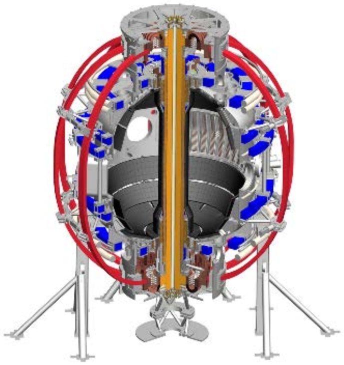
NSTX-U Q4/Year-End Review - Program

Jon Menard

S. Kaye, M. Ono, S. Gerhardt

For the NSTX-U Research Team

September 30, 2016



NSTX-U had very scientifically productive year

- Achieved H-mode on 8th day of 10 weeks of operation
- Surpassed magnetic field and pulse-duration of NSTX
- Matched best NSTX H-mode performance at ~1MA
- Identified and corrected dominant error fields
- Commissioned all magnetic and kinetic profile diagnostics
- Discovered 2nd NBI can suppress Global Alfven Eigenmodes (GAE) – may provide means of modifying fast-ion and central electron transport? (future/TBD)
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation
  - Important for ITER and all large tokamaks
- See NSTX-U results review for more details

Researchers were very scientifically productive
(see year-end report for more details)

- 49 papers + 2 book chapters published in FY16
  - 79 papers published or prepared/submitted
- 78 invited/oral conference/workshop presentations
- 25 seminars and colloquia from NSTX-U
- 17 scientific leadership positions, provided scientific and technical expertise in 52 additional positions
- 4 major awards by NSTX-U affiliated researchers:
  - Berkery & Sabbagh (CU) – Landau-Spitzer for kinetic restive wall modes
  - Gerhardt – Fusion Power Associates Excellence in Fusion Engineering for disruption warning, NSTX-U operations
  - Goldston – Nuclear Fusion Award for SOL heat flux width
  - Kolemen (PU) – DOE ECA - "Physics-Based Real-time Analysis and Control to Achieve Transients-Free Operations for the ITER Era"

NSTX-U Run Assessment held Wed, Sept 28th

- Many good ideas suggested as opportunities to improve NSTX-U operations in the areas of:
  - Communication, Program Coordination
  - Collaborator Support
  - Run Staffing/Equipment needs.
- Summary and action items in-preparation
  - Gerhardt, von Halle will provide in coming weeks

Outline

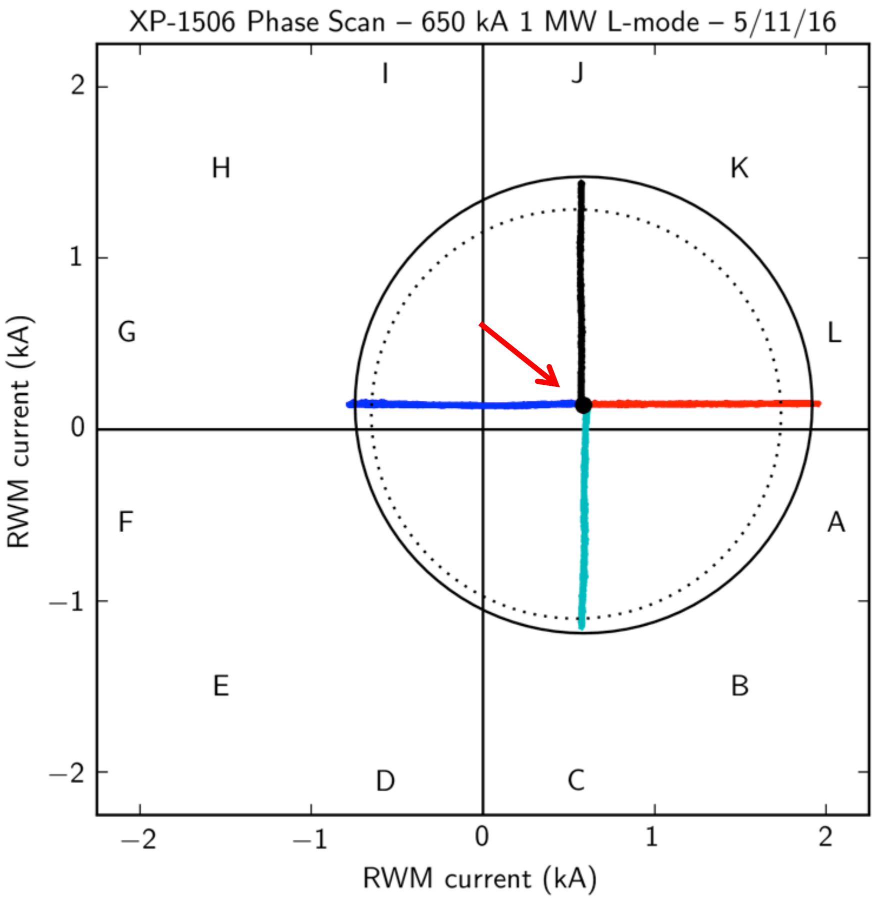
- Recent research highlights (Q3-Q4)
- Progress toward milestones
- FY2017 Collaboration Planning Status

Outline

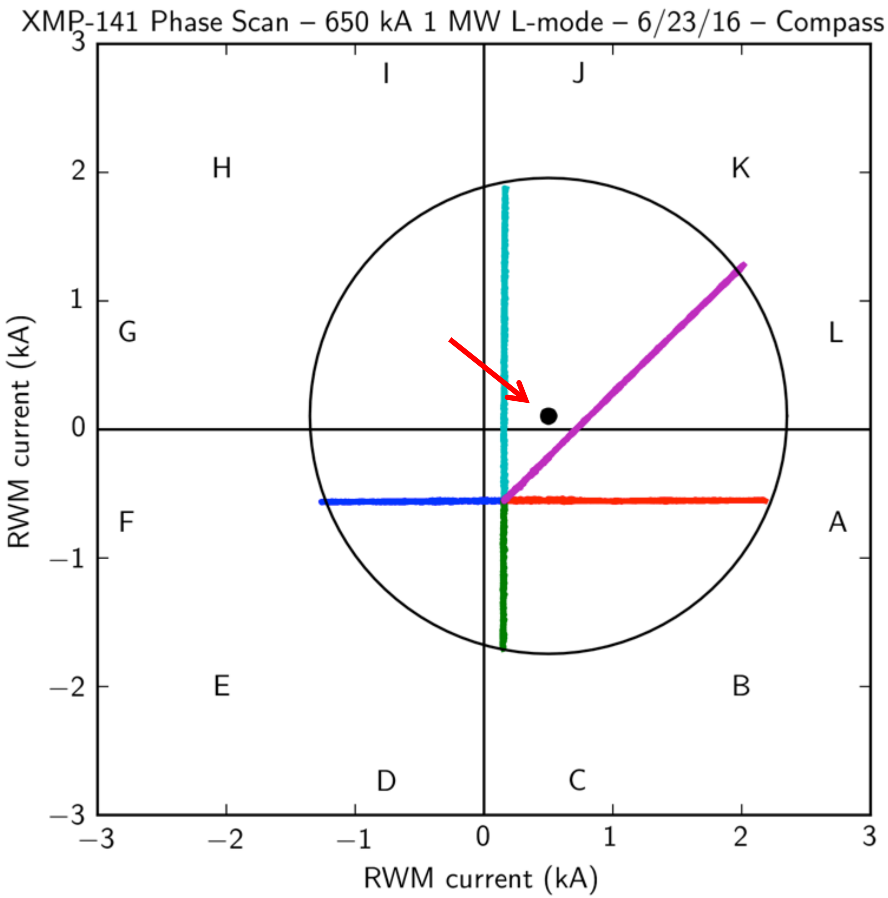
- Recent research highlights
  - MHD
  - Energetic Particles
  - Boundary Physics

Multiple compass scans confirm the optimum L-mode EFC phase and amplitude in the flattop

Higher density

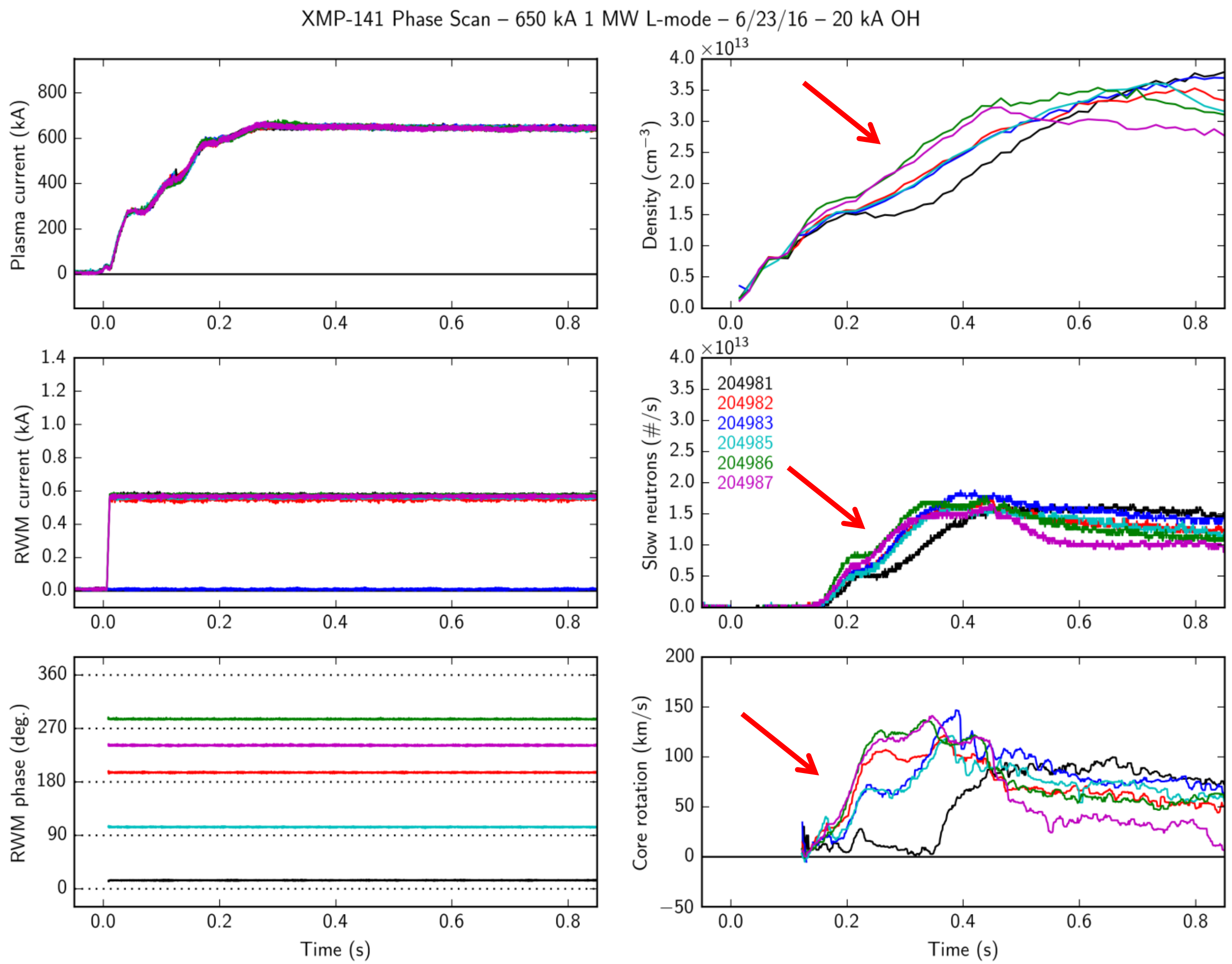


Different OH pre-charge (8 kA vs. 20 kA)



Static EFC scan early in time → different EFC phase

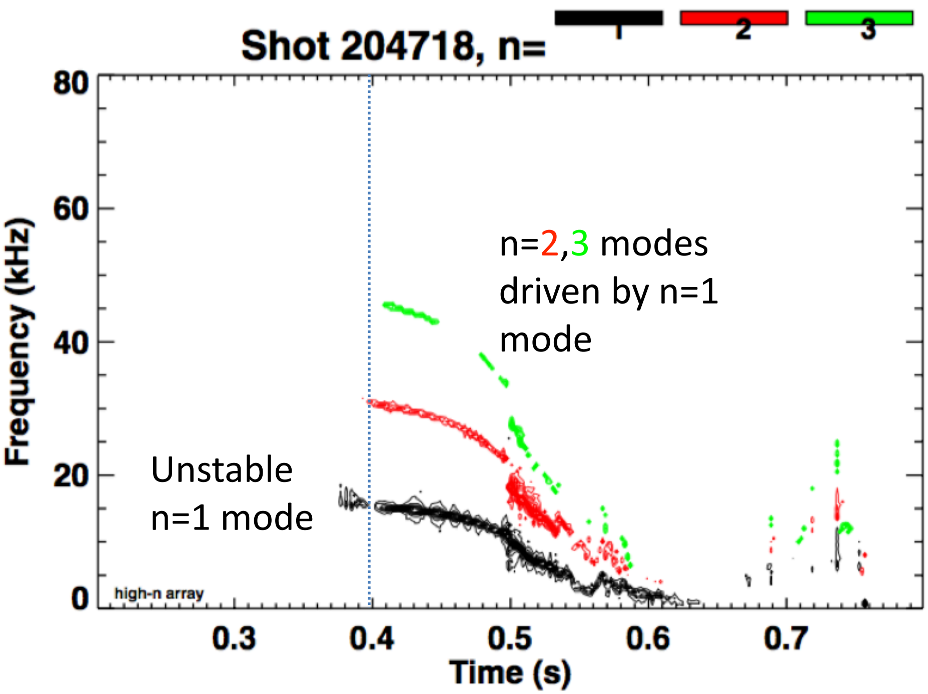
- Static EFC scan early in the discharge shows different optimum correction phase
- Flattop phase of 15° is counter-productive early on
- Phase asymmetry visible in density, neutrons, and core rotation
- Search for the time-evolving error field source is ongoing
  - Tilted TF, vessel currents?



MARS-F and new developed resistive DCON predict unstable tearing mode consistent with NSTX-U observation

Unstable n=1 tearing mode is observed in L mode NSTX-U discharge (204718).
Resistive DCON and MARS-F predict unstable n=1 tearing modes at q>2 singular surfaces.

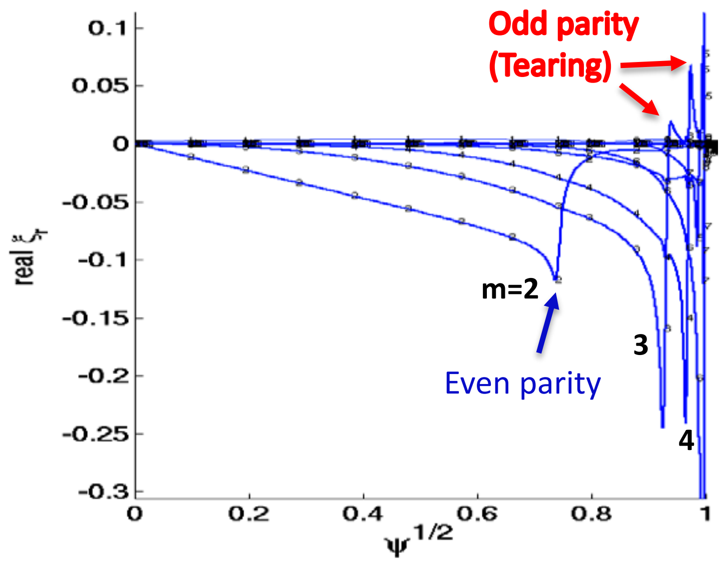
NSTX-U experiment observes n=1 unstable mode which drives n=2, 3 modes later



Diagonal terms of Δ' matrix solved by DCON (outer region) is positive at q=3 and 4 surfaces

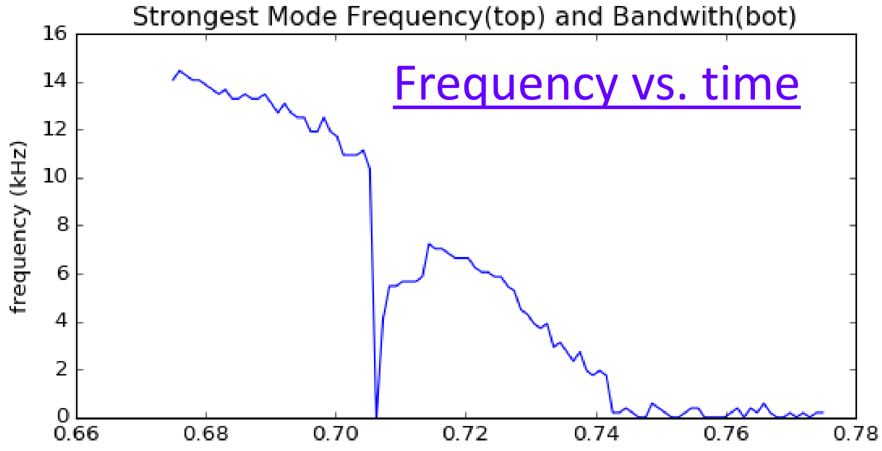
Δ'(q=2)	-4.29
Δ'(q=3)	10.0
Δ'(q=4)	3.18

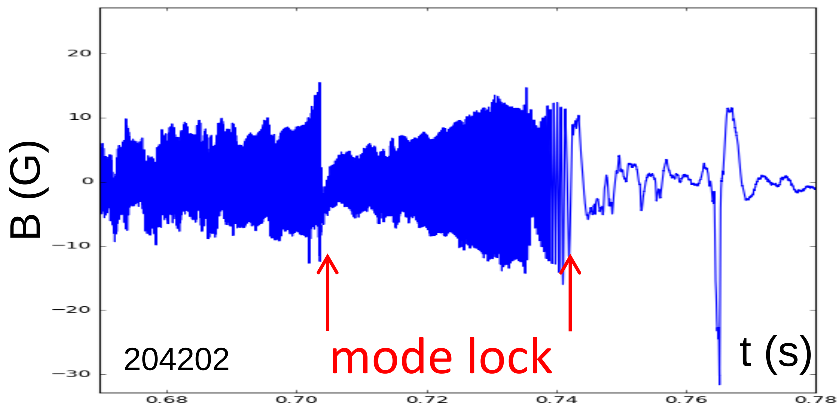
MARS-F finds unstable tearing mode at zero rotation, growth rate $\gamma = 1.7 \times 10^{-3}\omega_A$

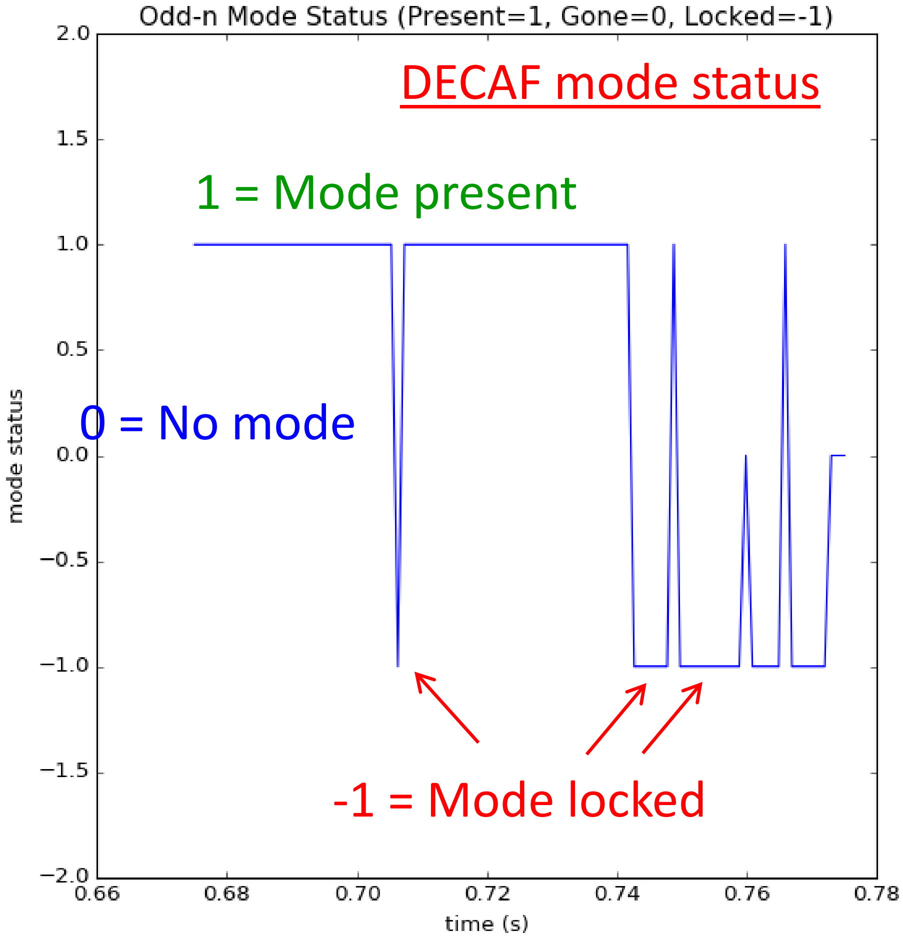


Continuing analysis of rotating MHD for DECAF includes accurate analysis of mode "status"

Odd-n magnetic signal / analysis (mode locking / unlocking)







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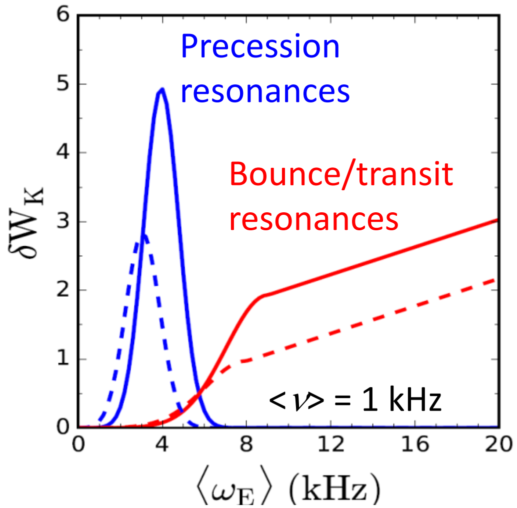
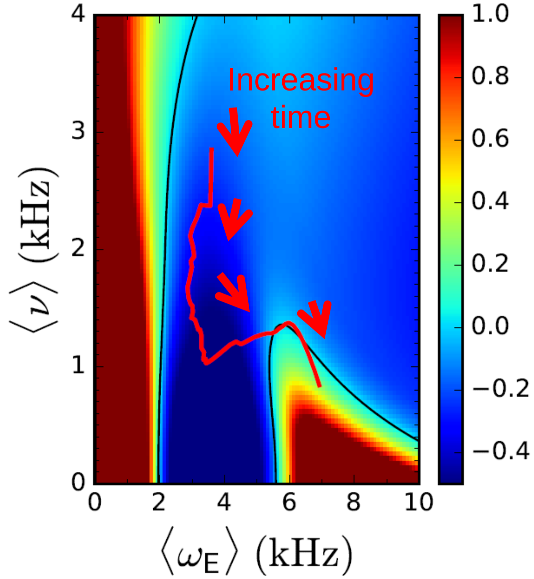
Reduced kinetic RWM model in DECAF results in a calculation of $\gamma\tau_w$ vs. time for each discharge

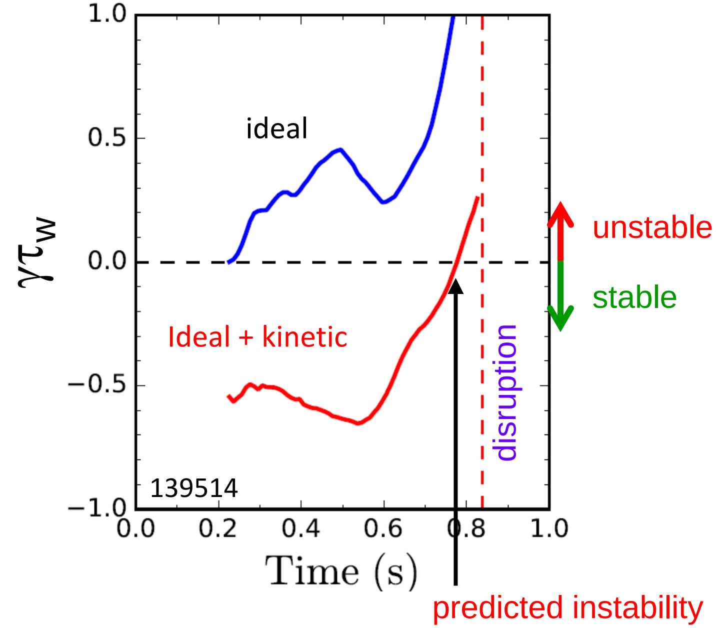
Kinetic component δW_K



$\gamma\tau_w$ contours vs. ν and ω_ϕ



Normalized growth rate vs. time



- Gaussian forms used to reproduce precession and bounce/transit resonances
- Height, width, position of peak depend on collisionality

- Favorable characteristics
  - Stability contours CHANGE for each time point (last time point shown left frame)
  - Possible to compute growth rate prediction in real time
- Initial tests on NSTX RWM database
  - 86% of RWM shots are predicted unstable

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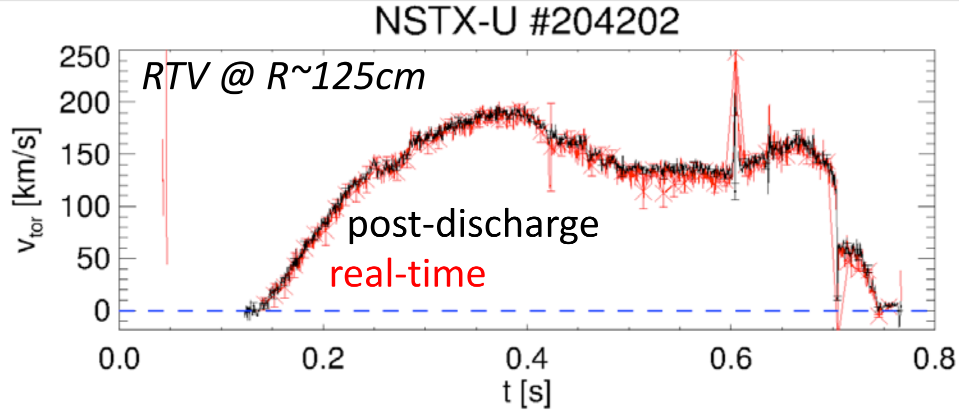
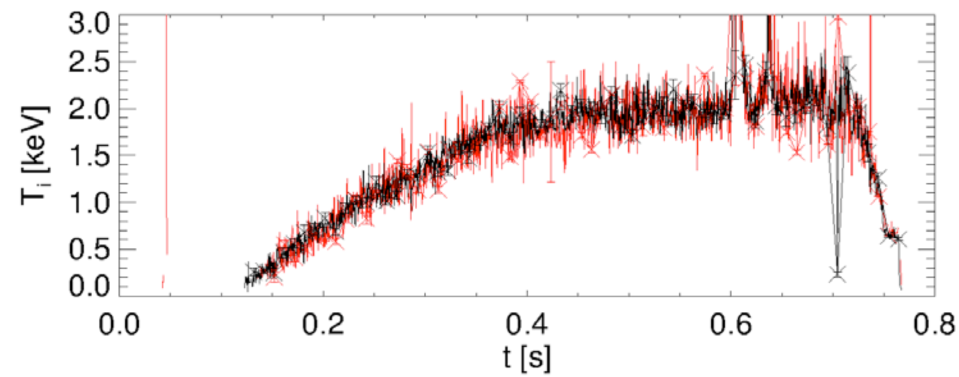
Real-time rotation analysis provides accurate data for rotation feedback (and physics studies)

- Good agreement with main CHERS system
- Good match for both v_ϕ and T_i between real-time and post-discharge analysis



> First RTV data from NSTX-U confirm achievement of design goals

> System is ready to support development & testing of v_ϕ control on NSTX-U



- Additional physics insight can be gathered from post-discharge analysis
  - E.g. effects of RMPs, MHD, ELMs, pellets/granules on v_ϕ, T_i, n_C
  - Complements high spatial resolution of CHERS with sub-millisecond time resolution at 4 radii

[M. Podestà, PPCF (submitted 2016)]

GPEC shows NCC can drive core-concentrated NTV while minimizing edge NTV, and vice versa

- GPEC gives self-consistent NTV torque matrix:

$$\tau_{NTV}(\psi) = \vec{\Phi}^{x\dagger} \cdot \overleftrightarrow{T}(\psi) \cdot \vec{\Phi}^{x}$$

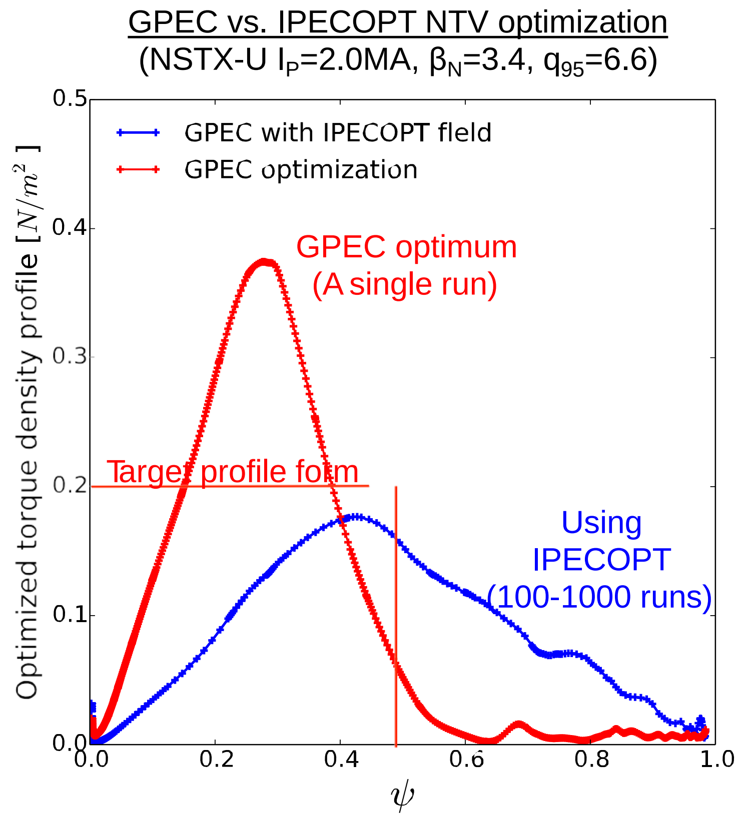
  - T is MxM matrix function (M: # of poloidal modes)

- Changing basis from $\mathbf{\Phi^x}$ to coil vector **C:**

$$\tau_{NTV}(\psi) = \vec{C}^{\dagger} \cdot \overleftrightarrow{T}_{C}(\psi) \cdot \vec{C}$$

  - NSTX-U NCC+MID: T_C is 3x3 for n=1-2 (for n=3, constrained 3x3)
  - KSTAR IVCC: T_C is 3x3 for n=1 (Studied for NTV)
  - ITER RMP+EF: T_C is 6x6 for n=1-2, 3x3 for n=3-4

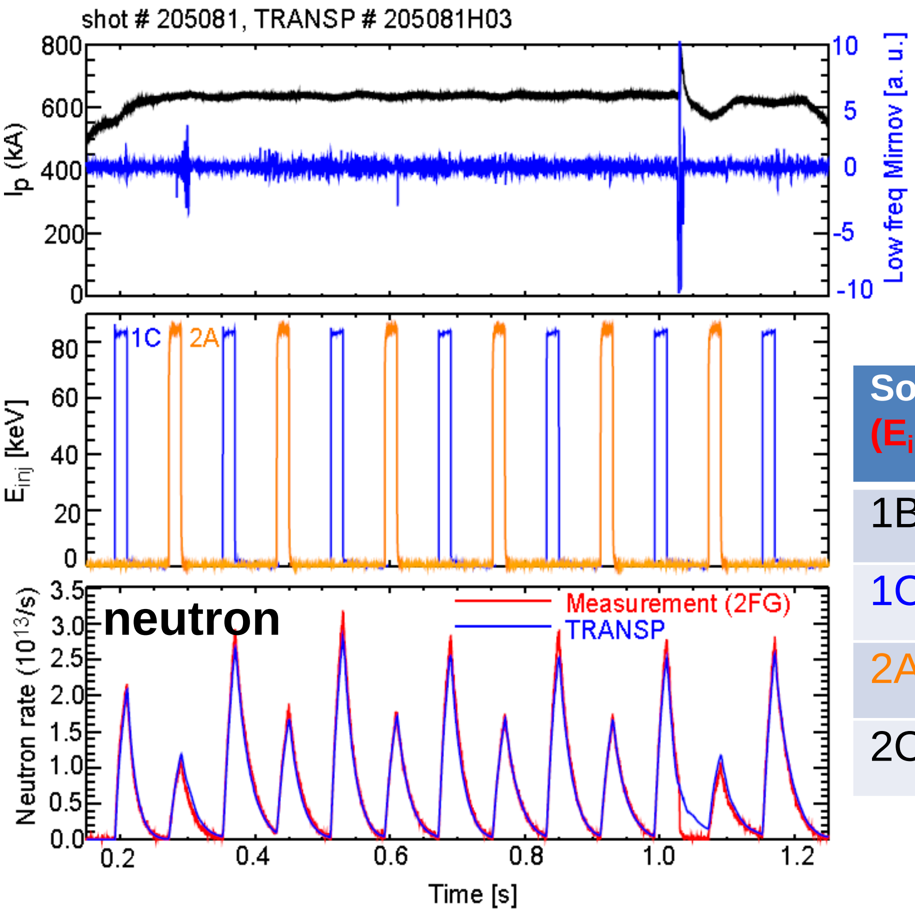
- Torque response matrix T contains all the information about self-consistent NTV torque that can be generated by external fields, or coils in a device



Outline

- Recent research highlights
  - MHD
  - Energetic Particles
  - Boundary Physics

At E_{inj}=85keV, neutron rise and decay rate agree with TRANSP modelling



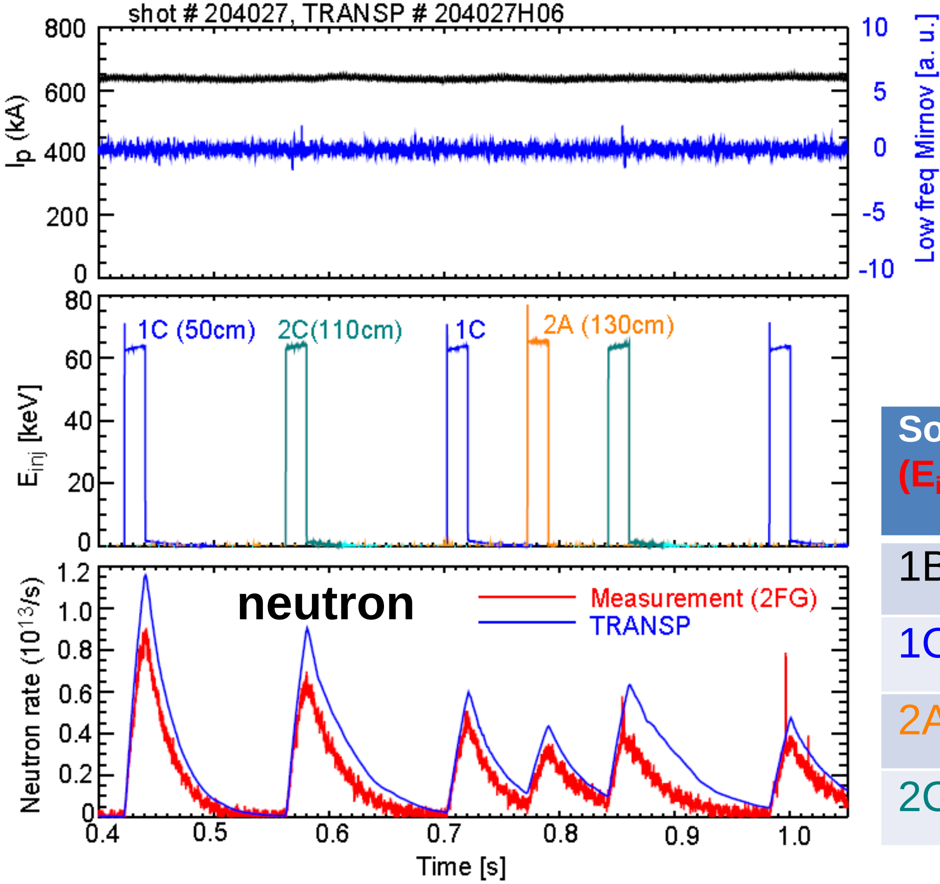
- Exclude bad blips with strong MHD
- TRANSP: Classical simulations (no ad hoc fast-ion diffusion), $T_i=T_e$, Z_{eff}=1.5, EFIT01
- 1C (R_{tan}=50cm), 2A R_{tan}=130cm

Source (E_{inj}=85keV)	Neutron Rise (Exp/TRANSP)	Neutron Decay (Exp/TRANSP)
1B (R_{tan} 60cm)	0.82 +/- 0.10	1.01 +/- 0.14
1C (R_{tan} 50cm)	1.05 +/- 0.07	1.05 +/- 0.13
2A (R_{tan} 130cm)	1.04 +/- 0.06	1.04 +/- 0.11
2C (R_{tan} 110cm)	0.83 +/- 0.09	0.94 +/- 0.17

- **For E_{inj}=85keV, beam Ions are well confined based on neutron decay**

UCIrvine
University of California, Irvine

At E_{inj}=65keV, discrepancy between measurements and TRANSP

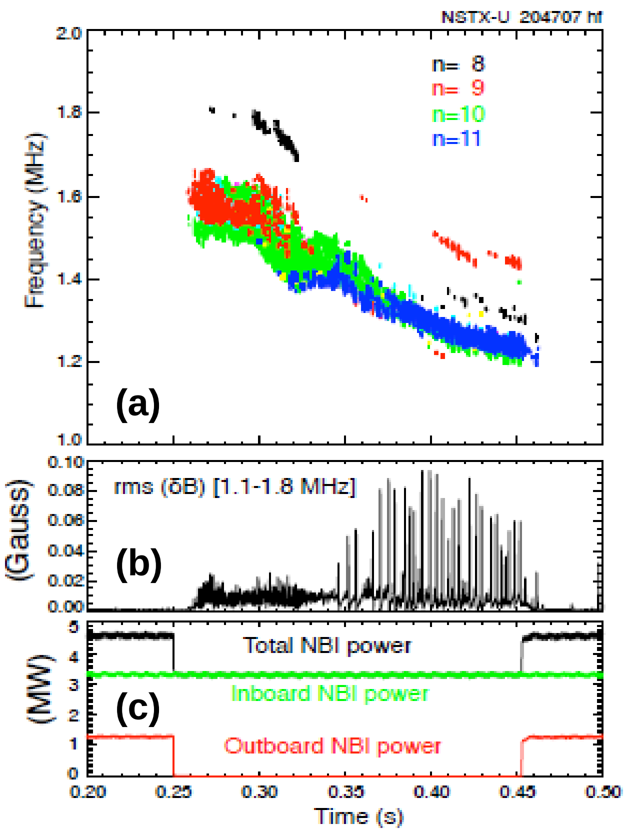


- TRANSP: Classical simulations, T_i=T_e, Z_{eff}=1.5, EFIT01
- Not much MHD
- Use "1de_zns" neutron signal cross calibrated to fission detector

Source (E_{inj}=65keV)	Neutron Rise (Exp/TRANSP)	Neutron Decay (Exp/TRANSP)
1B (R_{tan} 60cm)	0.48	1.01
1C (R_{tan} 50cm)	0.52 +/- 0.02	0.84 + /- 0.27
2A (R_{tan} 130cm)	0.47 +/- 0.02	0.94 +/- 0.04
2C (R_{tan} 110cm)	0.49 +/- 0.02	0.77 +/- 0.09

- **Large discrepancy in neutron rise, depends on absolute neutron rate**
- **~20% discrepancy in neutron decay**
- **Exploring multiple explanations, including NB source species mix**

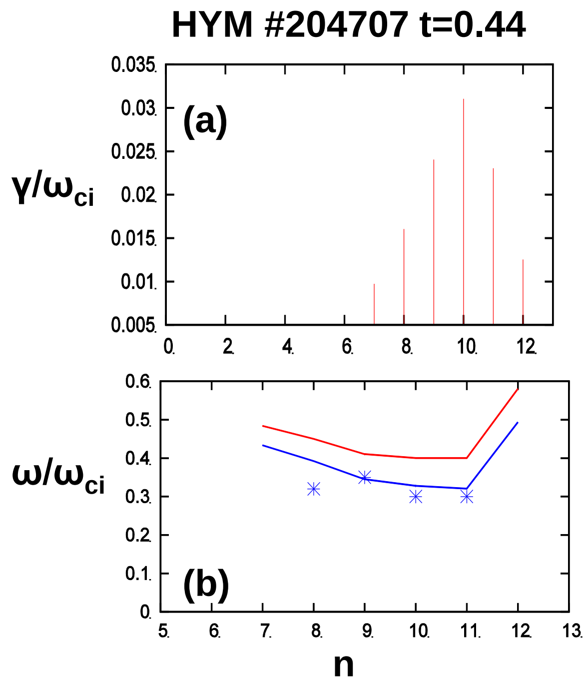
HYM code consistent with NSTX-U tangential 2nd neutral beam suppressing Global Alfven Eigenmode (GAE)



(a) Magnetic fluctuation spectrogram

(b) RMS magnetic fluctuations

(c) Injected beam power

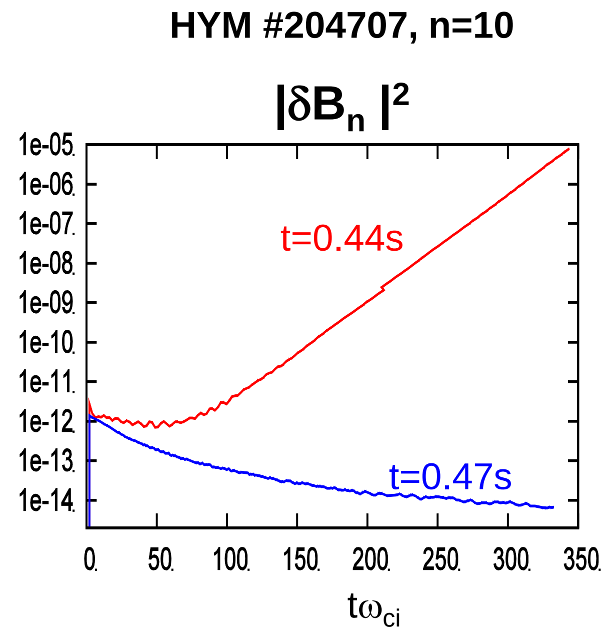


(a) Growth rates

(b) Frequencies of unstable counter-GAEs from HYM for t=0.44s.

- Blue line: Doppler-shift corrected ω
- Points/stars: experimental values

→ Data and simulation consistent



HYM shows suppression of n=10 counter-GAE by additional beam injection

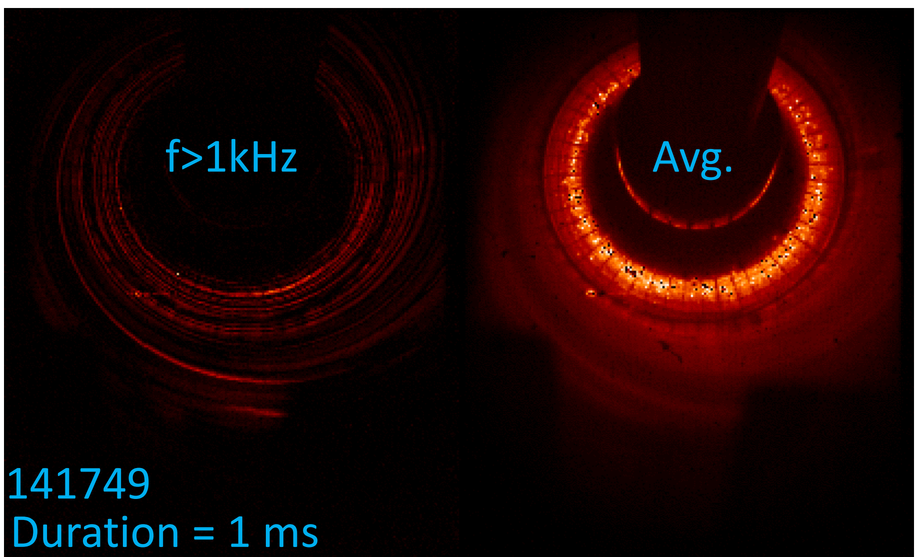
Future modelling and experiments: Explore impact on fast-ion and thermal electron transport

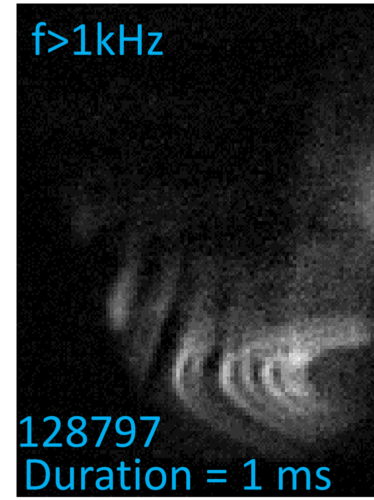
Outline

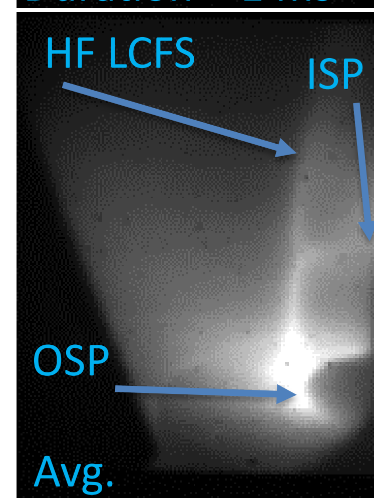
- Recent research highlights
  – MHD
  – Energetic Particles
  – Boundary Physics

Divertor intermittent filaments routinely observed in NSTX L-mode and H-mode discharges

- Understanding divertor turbulence is important to assess its role in setting divertor heat and particle flux magnitude and width
- Divertor intermittent filaments have been studied in NSTX L-mode (Scotti APS 2016) and H-mode discharges (Maqueda NF 2010)
- Most easily studied via neutral lithium imaging of filament footprint
  - Brightest line in NSTX (with Li), atomic physics provides surface localization
  - Brightness fluctuations can be understood as being ~ $\tilde{n}_e$
  - Tangential Dα imaging can complement with poloidal filament structure



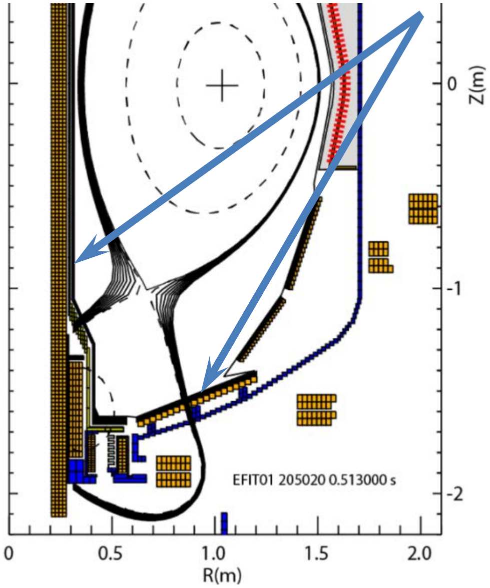


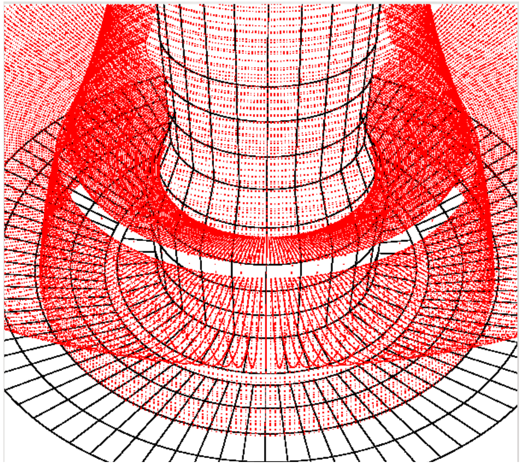


Lawrence Livermore National Laboratory

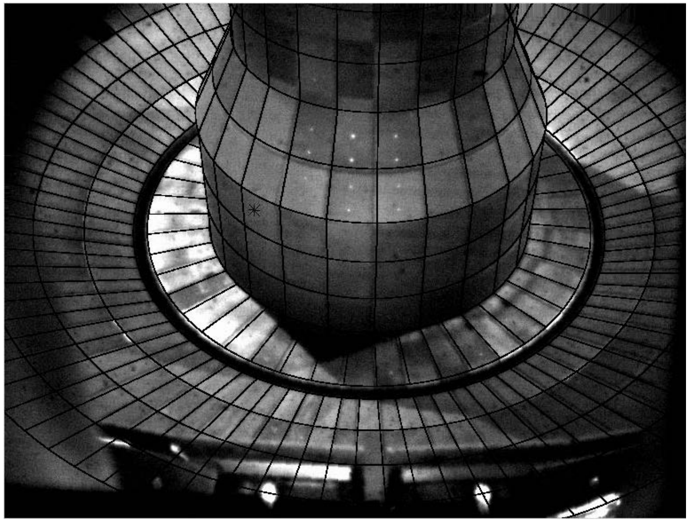
Throughput-optimized camera and high-X-point L-modes enabled near-separatrix turbulence imaging in NSTX-U

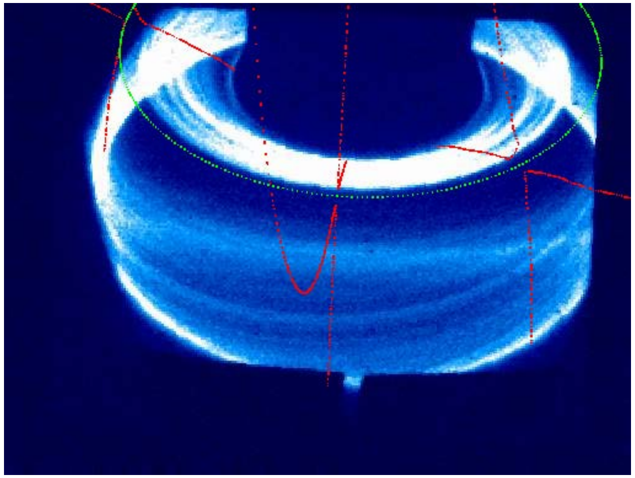
- Divertor turbulence imaging through different species/charge states provides information at different spatial locations
- Throughput-optimized setup enabled turbulence imaging via C III (up to 140kHz)
  - Filaments along divertor legs (vs. filament footprint on floor via Li I or Dα)





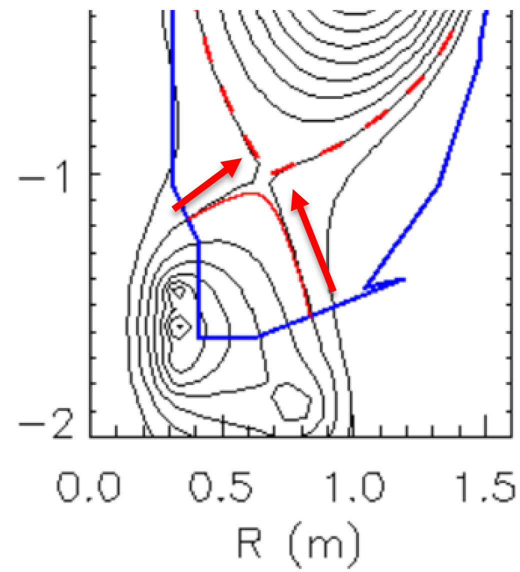
Reconstructed view + separatrix



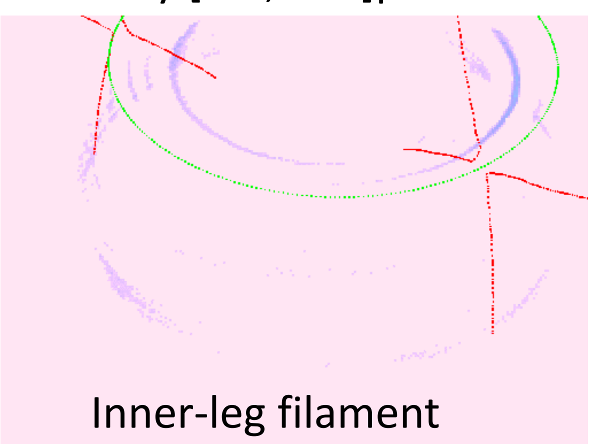


Time delayed cross correlation shows opposite toroidal rotation for inner/outer leg filaments

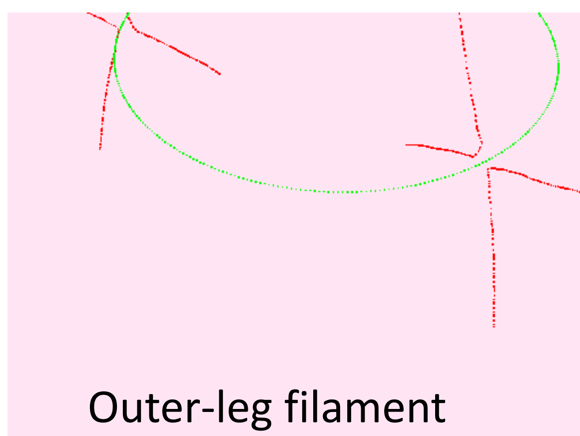
- Time-delayed cross correlation of single pixel with rest of image to show average filament propagation
- Apparent poloidal motion for both inner and outer leg filaments towards X-point
  - Or equivalently opposite toroidal directions
  - Inconsistent with flux tube rigid rotation (also in C-Mod, J. Terry JNME 2016)
- Poloidal velocity ~1km/s

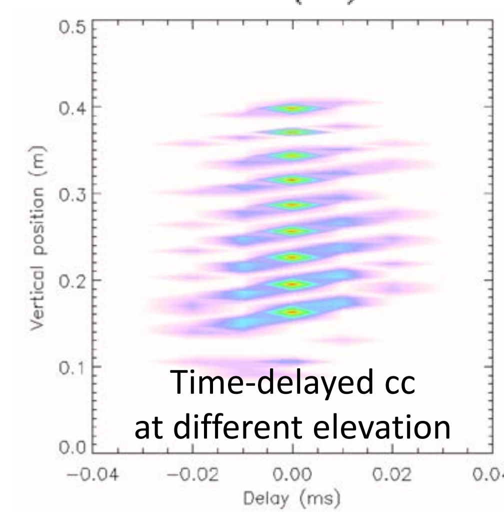


Delay [-30, +40]µs

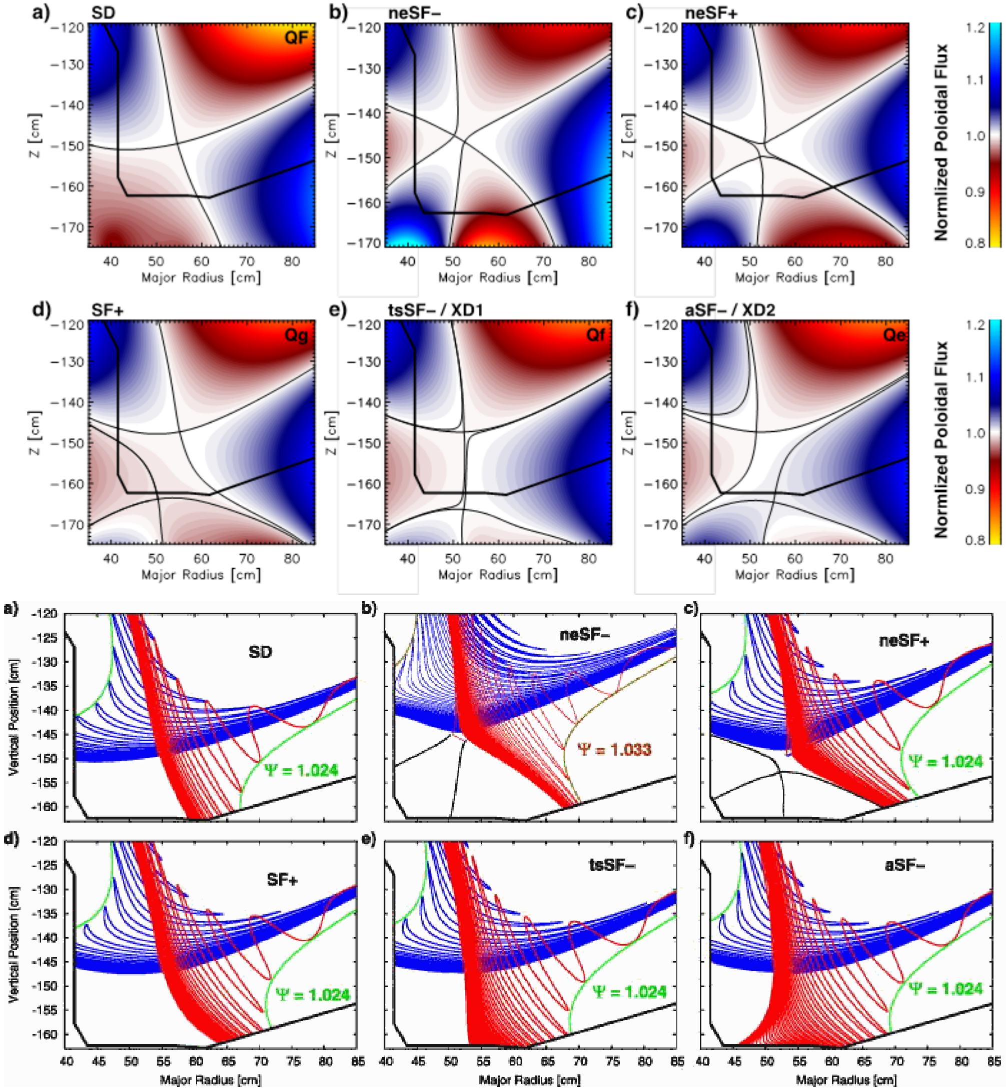


Delay [-40, +40]µs



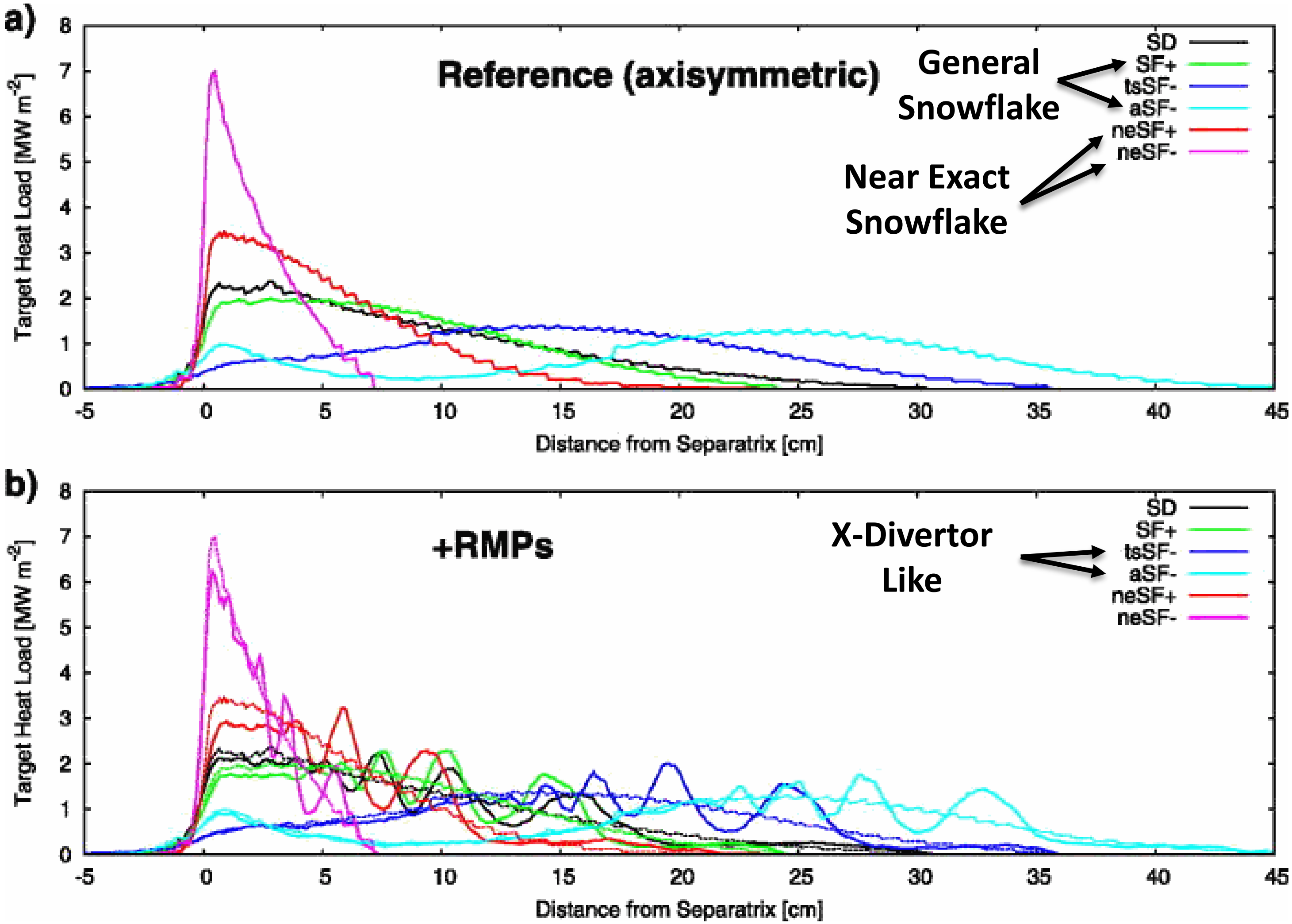


First systematic assessment of major advanced divertor configurations at NSTX-U with EMC3-EIRENE

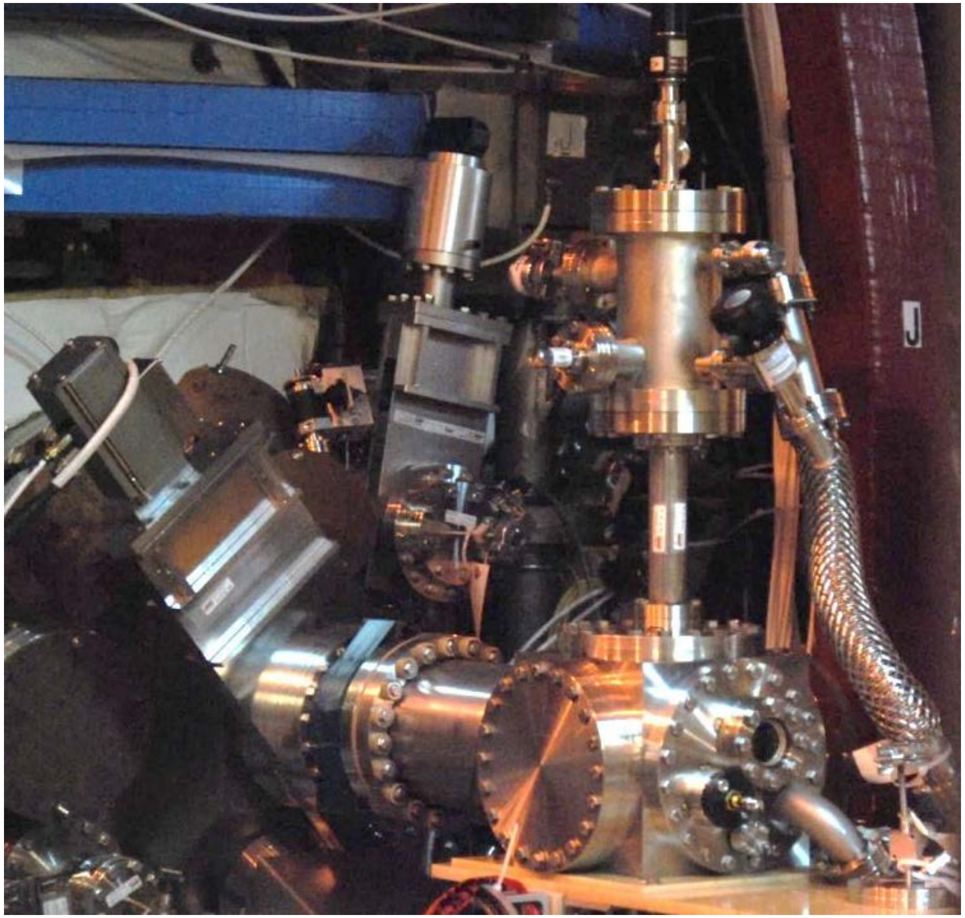


H. Frerichs et al Phys. Plasmas **23**, 062517 (2016); http://dx.doi.org/10.1063/1.4954816

Peaked heat loads in Near Exact Snowflake, lowest heat loads in X-Divertor-like configs, RMP fields don't impact toroidal average.



Granule Injector Commissioned on NSTX-U



NSTX-U Granule Injector

Granule sizes :
900μm, 700μm, 500μm, 300μm

Injection Species : Li, B_4C, C

Injection Velocity : 50 – 150 m/sec

Granule to Granule Injection Frequency : 50 – 500 Hz

Particle drop rates are controlled by a piezoelectric disk.

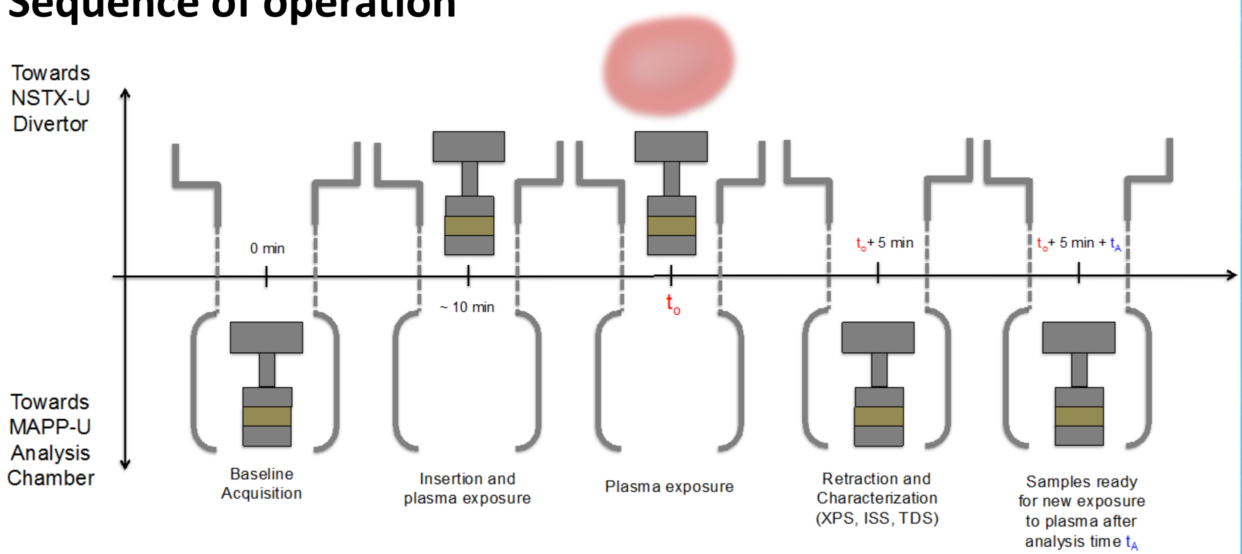
Granules driven into the plasma by a pneumatic rotary impeller

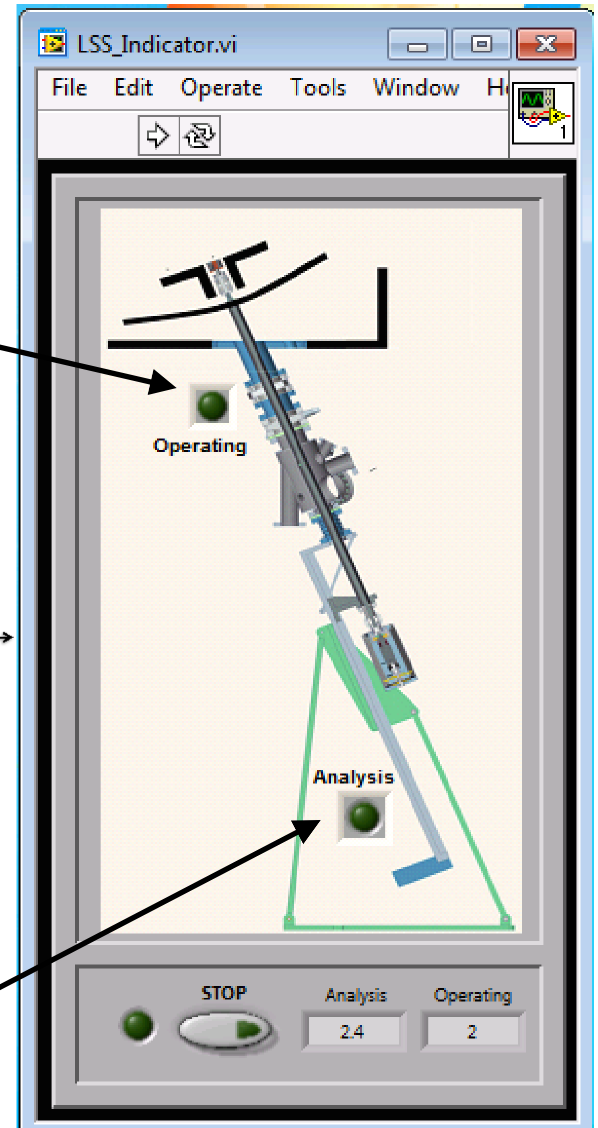
Materials Analysis Particle Probe fully commissioned

- Full remote operation (EPICS and LabView® Interface) now possible for in between plasma discharges measurements

Flush with LD tiles at bay J (boronization, lithiumization, D^+ plasma exposures)

Sequence of operation





XPS, ISS, DRS measurements

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MAPP used to track effect of boronization on PFCs

Supported PhD Thesis, will be vital to understanding Li surface chemistry

- **Boron oxidation due to plasma exposure measured with MAPP via X-ray Photoelectron Spectroscopy (XPS)**

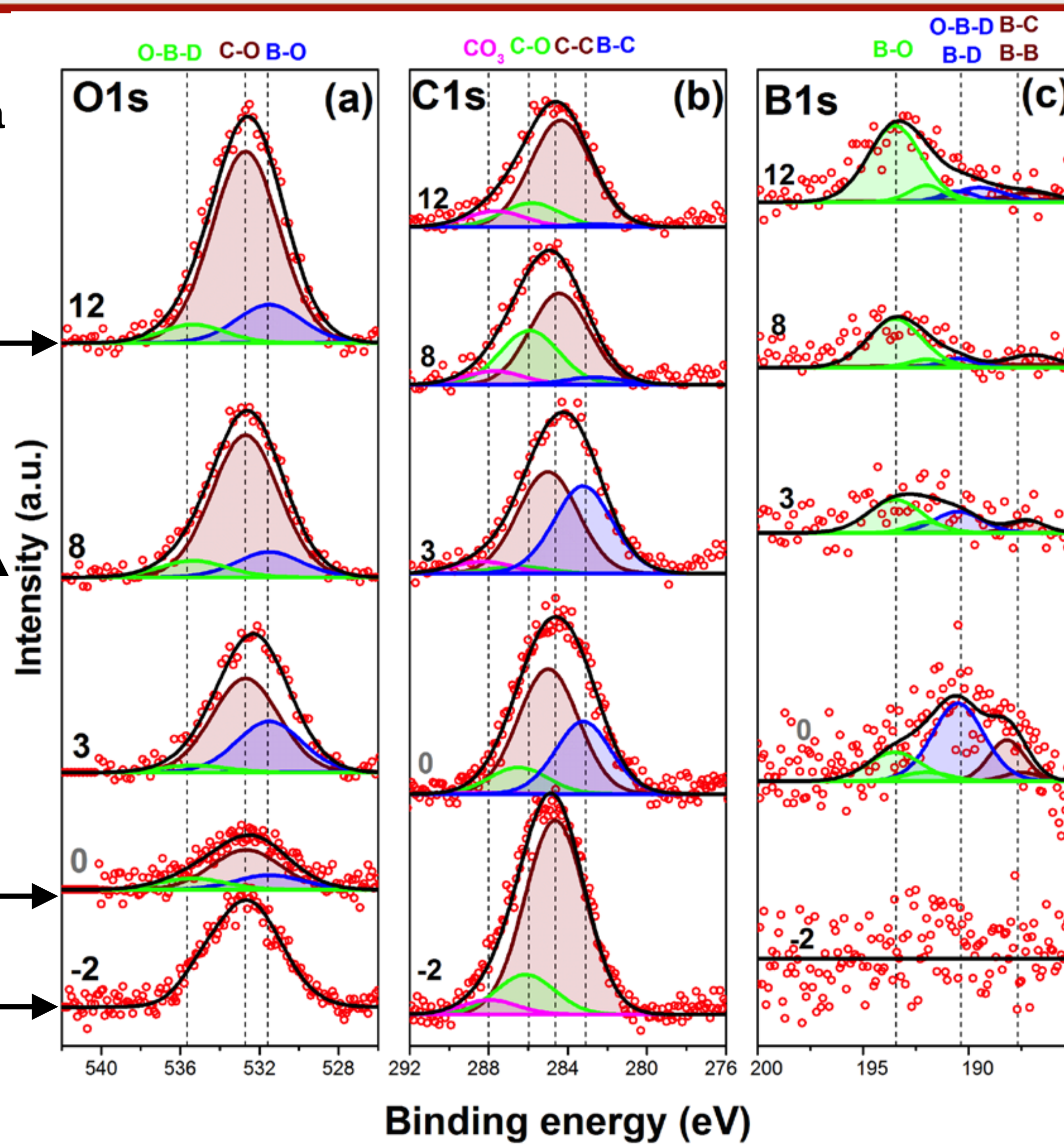
High oxygen %
Low % of B in metallic state ← **3.** ATJ post boronization post plasma exposure

XPS data obtained at the end of each plasmas operations day

Days after boronization D+ fluence increasing

Low oxygen %
High % of B in metallic state ← **2.** ATJ post boronization

1. ATJ graphite



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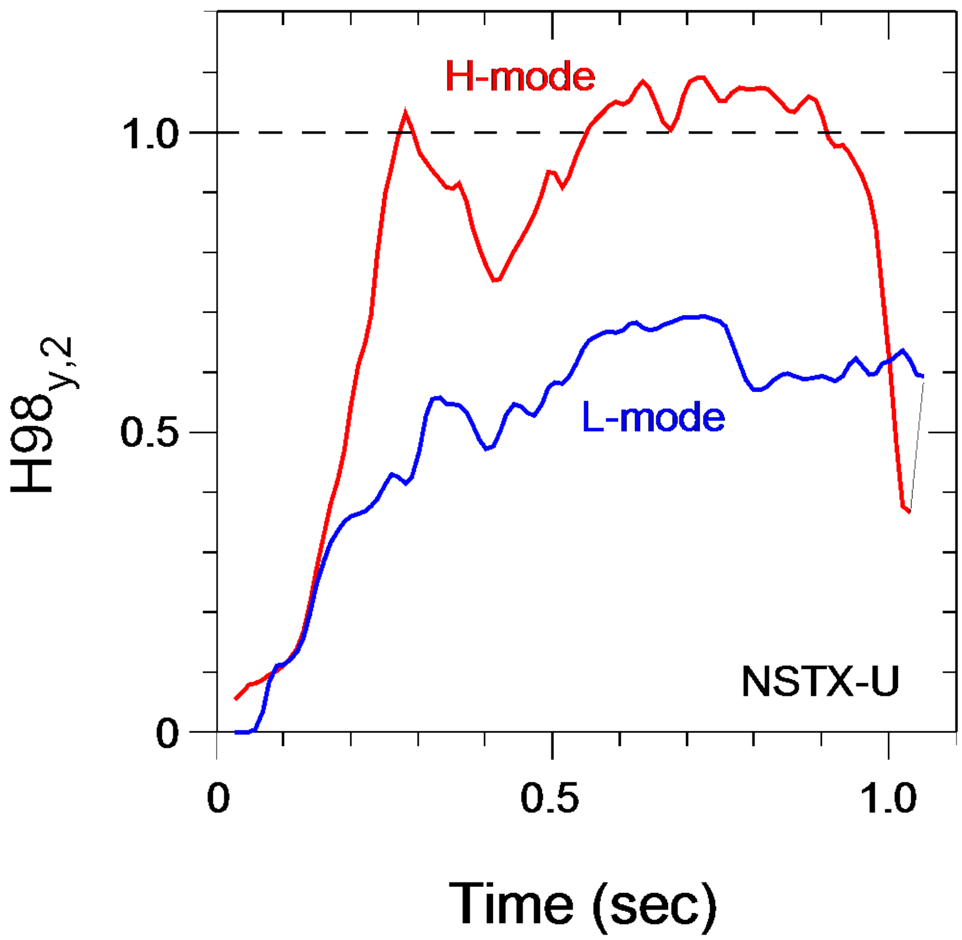
Outline

- Recent research highlights
- Progress toward milestones
- Future milestone discussion

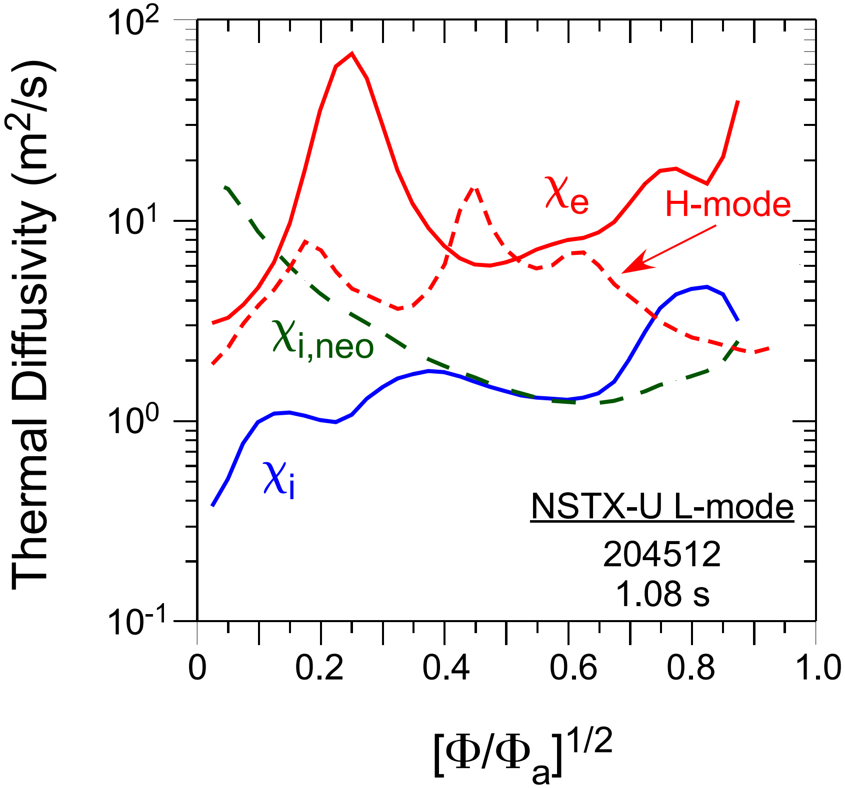
Progress toward Milestones (I)

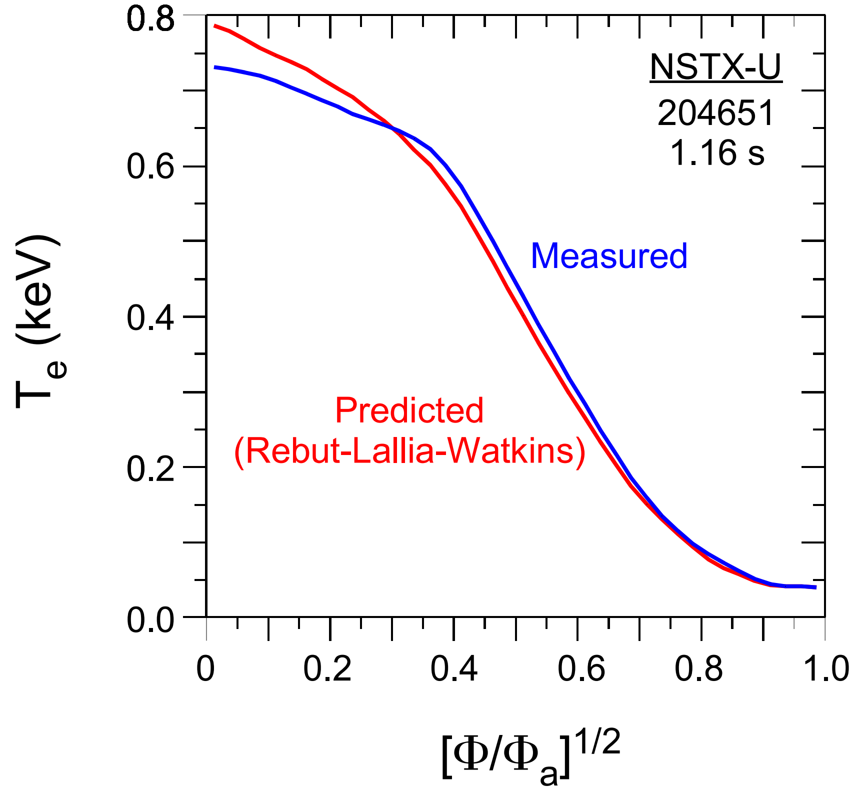
- **R16-1:** Assess H-mode energy confinement, pedestal, and SOL characteristics with higher B_T, I_P and NBI heating power
  - All key diagnostics took data, except MSE – was waiting for 90kV on NB1A – got to 90keV on 1A during final 2 weeks.
  - Checked data consistency via TRANSP
  - Next run → robust / longer-pulse higher I_P H-mode scenarios
- **R16-2:** Assess effects of NBI parameters on fast ion distribution function and neutral beam driven current profile
  - Neutron, FIDA, ssNPA functional (but no MSE data in FY16)
  - Started studies of fast ion confinement vs. R_{tan} and effect of NB#2 on *AE modes, NBI source scans in L-modes

H-mode confinement enhancement well above that of L-mode (and >=1)



Reduction in χ_e Going From L- to H-; RLW model consistent with T_e

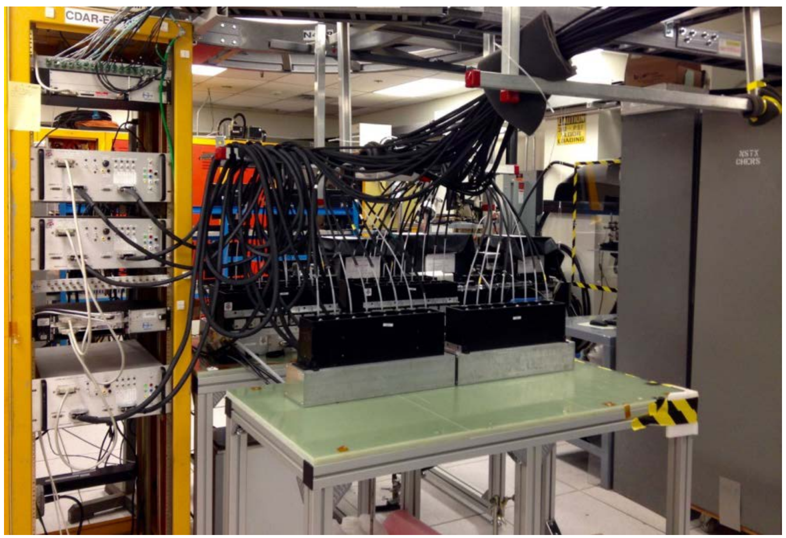


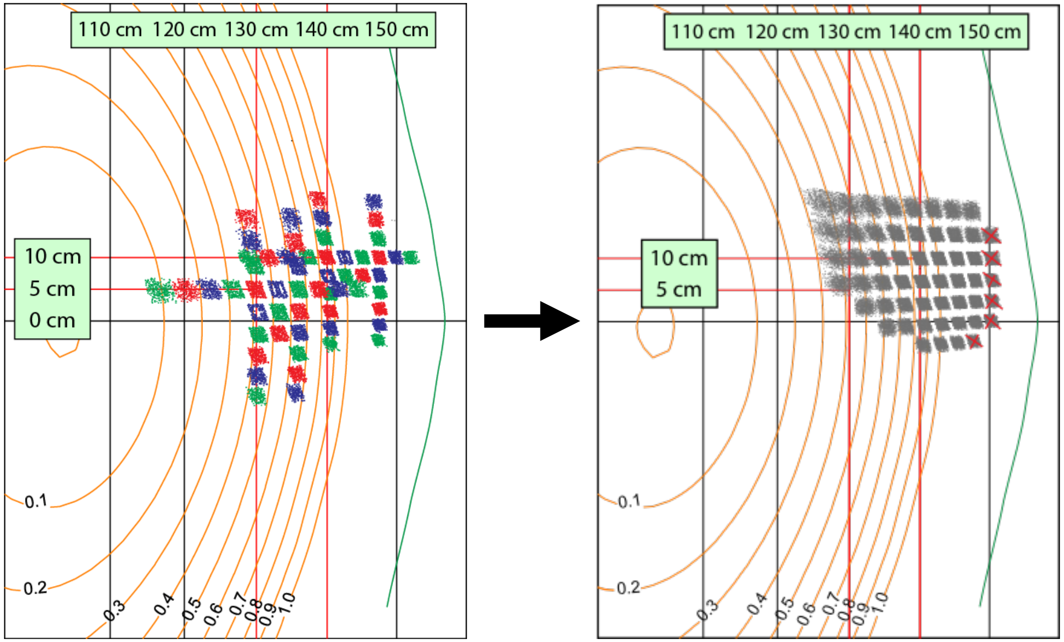


Caveat: Linear GYRO indicates microtearing is NOT dominant μ-instability

UW-Madison Beam Emission Spectroscopy (BES) system reconfigured+enhanced during Upgrade outage

- BES system expanded from 32 to 48 channels
  - 2D turbulence imaging
  - 2D flow analysis





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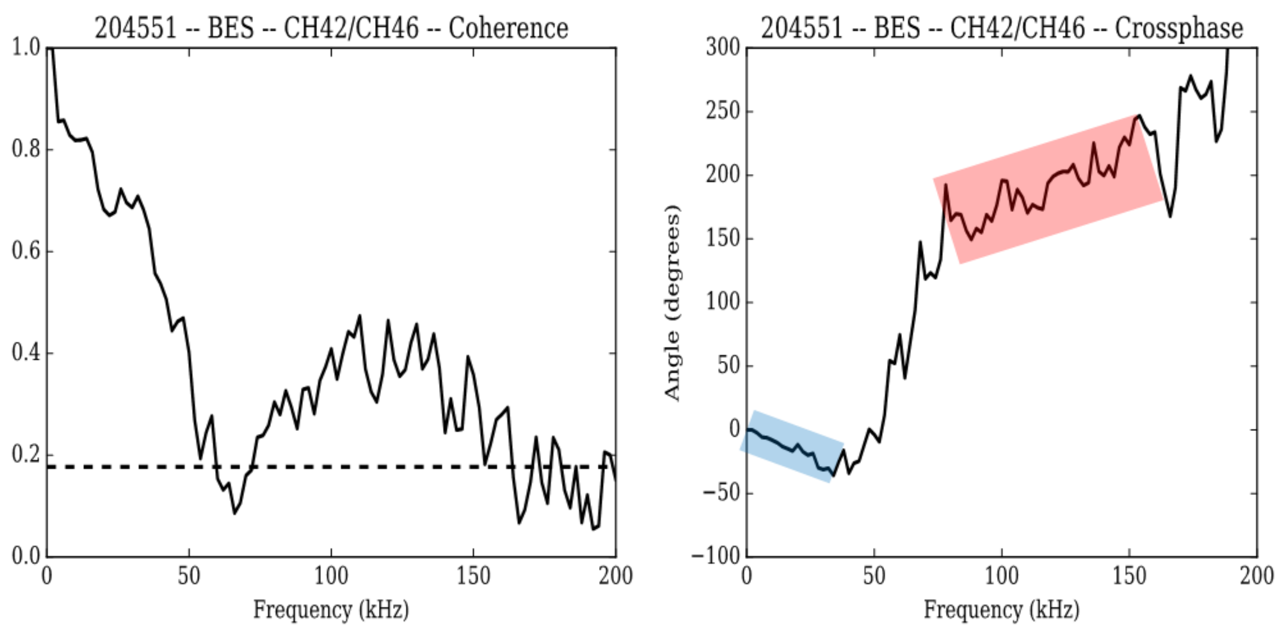
Bimodal turbulence seen in some L-mode shots



ΔZ = 3 cm
R = 142 cm
Δt = 24 ms

13 km/s in electron diamagnetic direction

11 km/s in ion diamagnetic direction

- Modes propagate in opposite directions
  - Similar spectra seen with DIII-D and TFTR BES
  - Potential link to grad B direction?
  - Gyro-kinetic modelling underway (ITG + MTM?)

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Progress toward Milestones (II)

- **R16-3:** Develop physics and operational tools for high-performance discharges.
  - Developed shape & vertical control, new inboard gap control, EFC, HFS & LFS fueling, automated shutdown
    - Early EF identified, important impact on ops, source not yet understood
  - Future: commission n=1 DEFC, RWM control, test LGI
- **Notable Outcome:** Perform experimental research …at magnetic field, I_P, pulse length beyond that achieved in NSTX….
  - NSTX-U pulse lengths (>2s) exceeded NSTX (< 1.8s) at field (0.65T) exceeding maximum NSTX field (0.55T)
  - Achieved I_P ~ 1MA – did not exceed max NSTX I_P = 1.3MA, will require early EFC + improved early H-mode scenarios

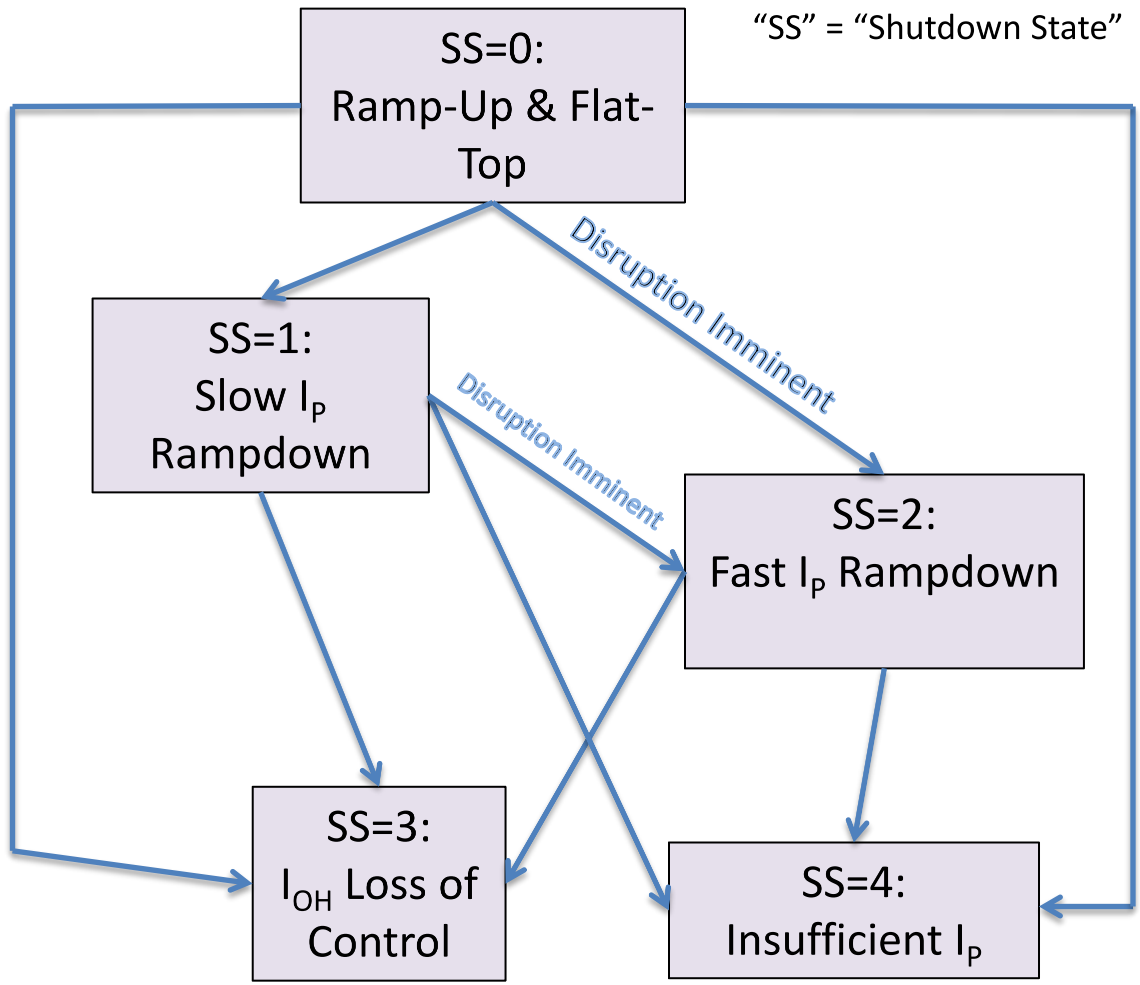
Progress toward Milestones (III)

- The JRT overlaps with a Notable Outcome:
  - **JRT:** Conduct research to detect and minimize the consequences of disruptions in present and future tokamaks
  - **Notable Outcome:** Conduct NSTX-U experiments and data analysis to support the FES joint research target ….
- Made good progress on this Notable:
  - Automatic shutdown algorithms developed
  - Detecting disruptions in real-time via the I_P error, vertical motion, and (soon) the n=1 locked mode signature.
  - DECAF code progressing toward real-time application
  - MGI using an electromagnetic valve similar to ITER design
    - 2 MGI valves installed on the machine, fully commissioned, but could not be tested into plasma due to PF1AU fault

NSTX-U Experiments Are Using a Significantly Expanded Plasma Shutdown Scheme

- **NSTX PCS**: No means of detecting a disruption, or ramping down the plasma current based on events.

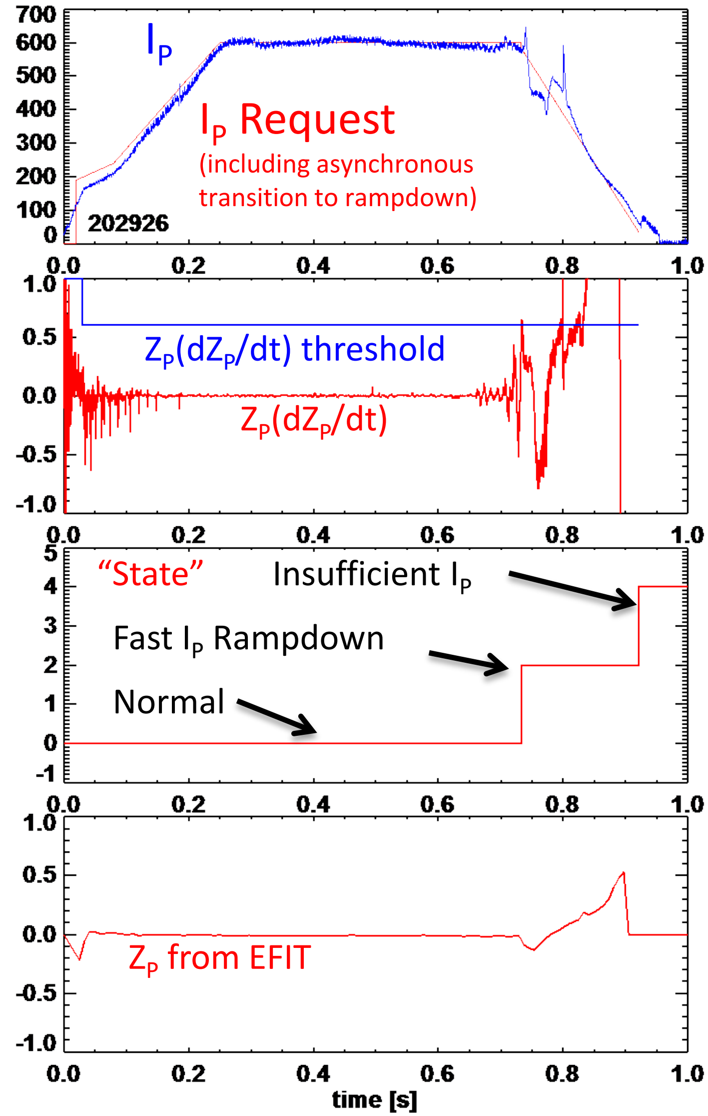
- **NSTX-U PCS**: State machine orchestrates the shutdown.



Example of automated ramp-down now used in routine operations

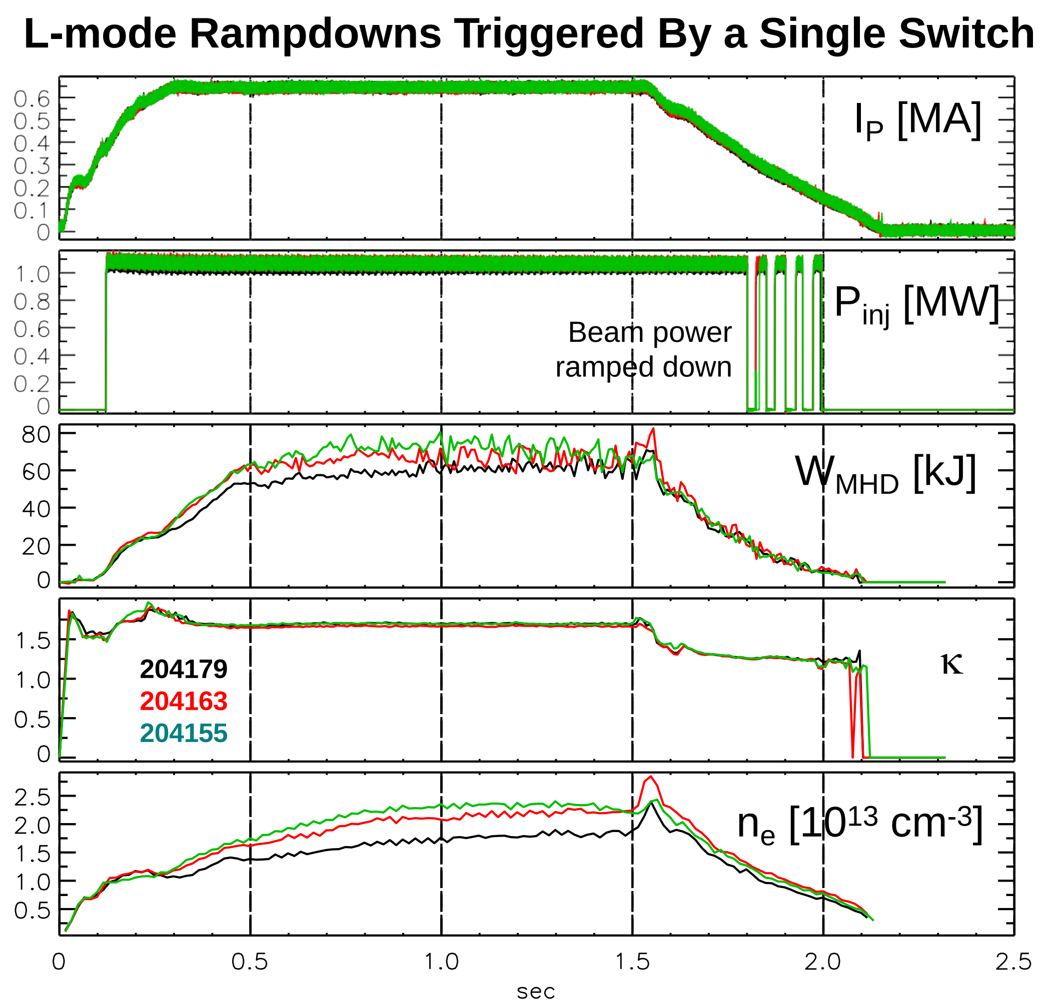
- Plasma control system detects loss of control
  - OH solenoid near maximum current
  - Vertical oscillations exceed threshold
  - ABS (I_p - $I_{p\ request}$) too large

- Feedback control switches to new "states" that attempt to gently end the discharge

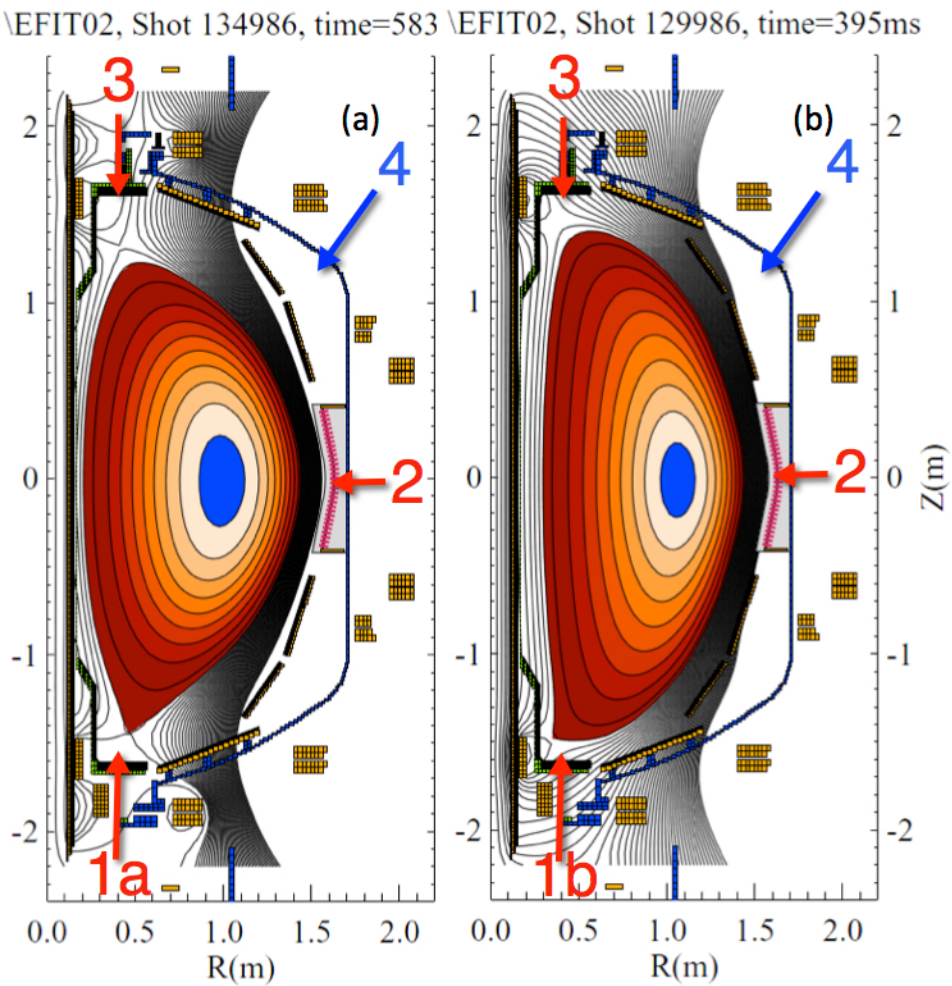


Shutdown handler used to create well-controlled L-mode ramp-down

- Three morning fiducials (April 2016)
- Single operator waveform modified at t=1.5 to start the ramp-down
- Ramp-down is inner-wall limited, with power and current slowly ramped off



NSTX-U MGI will study poloidal injection location variation using nearly identical MGI valves + gas lines



- In support of FY16 JRT, two MGI valves (at locations 1 and 2) were made fully functional on NSTX-U
- FY18 Goal: Assess benefits of injection into the private flux region & the high-field side region vs. LFS mid-plane

1a: Private flux region
1b: Lower SOL, Lower Divertor
2: Conventional mid-plane
3: Upper divertor
4: Future installation

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Beginning to coordinate FY17 collaborations to extend / complement NSTX-U results and plans

- DIII-D National Campaign for NSTX-U researchers
  - Coordinators/helpers: Kaye, Menard, Maingi
- EAST: Edge physics, plasma material interactions (high-Z, Li)
  - Maingi
- JET: Energetic particle studies and plasma ramp-down scenario development and modelling
  - Hawryluk, Poli
- KSTAR: Core MHD and rotation physics, plasma control
  - Sabbagh, Park
- MAST-U: Control, scenario modelling supporting 1st plasma
  - Menard, Battaglia
- W7-X: 3D confinement and stability
  - Gates, Neilson
- WEST: plasma start-up, RF physics, high-Z PMI
  - Hawryluk, Mueller, Le Blanc (maybe)

Summary

- Very productive year scientifically
  - Excellent first results on scenario development, H-mode access, error fields, fast-ion physics, transport
  - Strong publication and presentation record
  - Commissioned & utilized major heating and diagnostic systems
- Research Milestones:
  - Control tool development milestone largely completed
  - Transport and Energetic Particle milestones partially completed
  - Need to revisit and complete milestones requiring higher I_P
  - Several/most FY16 research milestones will shift to FY18
- Good support of FY16 JRT (control, DECAF)
  - Would have been nice to get 1st results from new MGI system
- FY17: strategic collaborations, prep for FY18 run