National Spherical Torus eXperiment Upgrade

Non-Milestone Research Results; Collaborations/Public-Private Partnerships

NSTX-U PAC-40 – Sept. 11, 2019

A. Diallo for NSTX-U Team

Non-Milestone research results that can impact NSTX-U, ITER and tokamak research

- NSTX-U scientists are involved in NSTX-U-related research activities as well as collaborations during the Recovery outage
  - PPPL researchers carrying out research in both areas
  - Collaborator research funding primarily through collaborations
- Collaborations can be on topics that can impact future NSTX-U operations
  - NSTX-U can capitalize on the DoE investment in research that is independent of NSTX-U

Researchers are actively engaging in other domestic and international collaborations during Recovery

- **LTX-β (PPPL):** Spectroscopy, plasma surface interaction, impurity transport
- **DIII-D (US):** Pedestal physics, 3D physics, plasma materials interactions
- **EAST (China):** edge physics, plasma materials interactions, effect of lithium
- **ASDEX-U**, **W7-X (Germany):** wall conditioning using boron powder
- **QUEST (Japan):** Full non-inductive startup (CHI, ECCD)
- **Urunia (UW):** CHI
- **HL-2A (China):** LH stabilization of ELMs, effects of NTMs on fast ions
- **KSTAR (S. Korea):** Core MHD, rotation physics, plasma control
- **MAST-U and ST40 (UK):** See next slide
- **MST (WIPPPL):** ME-SXR for profiles and impurity transport
- **New collaborations (recent International proposal awards - JET, WEST, KSTAR, and COMPASS-U)**

Collaboration on MAST Upgrade will afford opportunities with direct connection to the NSTX-U research program

- Plasma startup, rampup and control
- Confinement and transport, including TRANSP and gyrokinetic analyses, L-H threshold (PPPL), turbulence (UCLA)
- Equilibrium and stability including EF and tearing physics (PPPL), RWM, disruptions, equilibrium codes (Columbia U.)
- Divertor physics – diagnostics and data analysis (ORNL, LLNL)
- Energetic particles, modeling, FIDA support, ssNPA, fusion products (PPPL, UC Irvine, Florida Int. Univ., UCLA)
- Pedestal physics (PPPL)

- **First physics campaign planned for Spring 2020**

ST40 collaboration has been approved and will be funded in FY20

- **Public-private partnership with Tokamak Energy Ltd., UK**
  - Collaboration funded for three years through CRADA (Cooperative Research and Development Agreement)
  - PPPL, ORNL, UC Irvine, U. Washington, Columbia U.
- **ST40 is a high-TF (up to 3 T) Spherical Tokamak with Business Milestone by end of third year to "establish fusion conditions" ($T_i(0)>10$ keV, $n_e>10^{20}$ m^{-3})**
  - 2-4 MW NBI
  - Will not have full diagnostic set; research, and time for it, will have limitations
- **Areas of collaboration include:**
  - Pedestal physics – PBLS (PPPL), Divertor physics (ORNL)
  - Confinement scaling, TRANSP, EP physics, EF and tearing physics (PPPL, UC Irvine)
  - Disruption prediction algorithm development (Columbia U)
  - RF modeling for startup/rampup (EC/EBW), possible ICRH (PPPL, ORNL)
  - Scoping for turbulence diag. (PPPL), CHI (U. Washington), Li injection (PPPL)

This talk addresses PAC-40 charge #1

1. Please comment on the quality and importance of recent research results, including collaborative activities, and how they advanced the NSTX-U Mission and Milestones

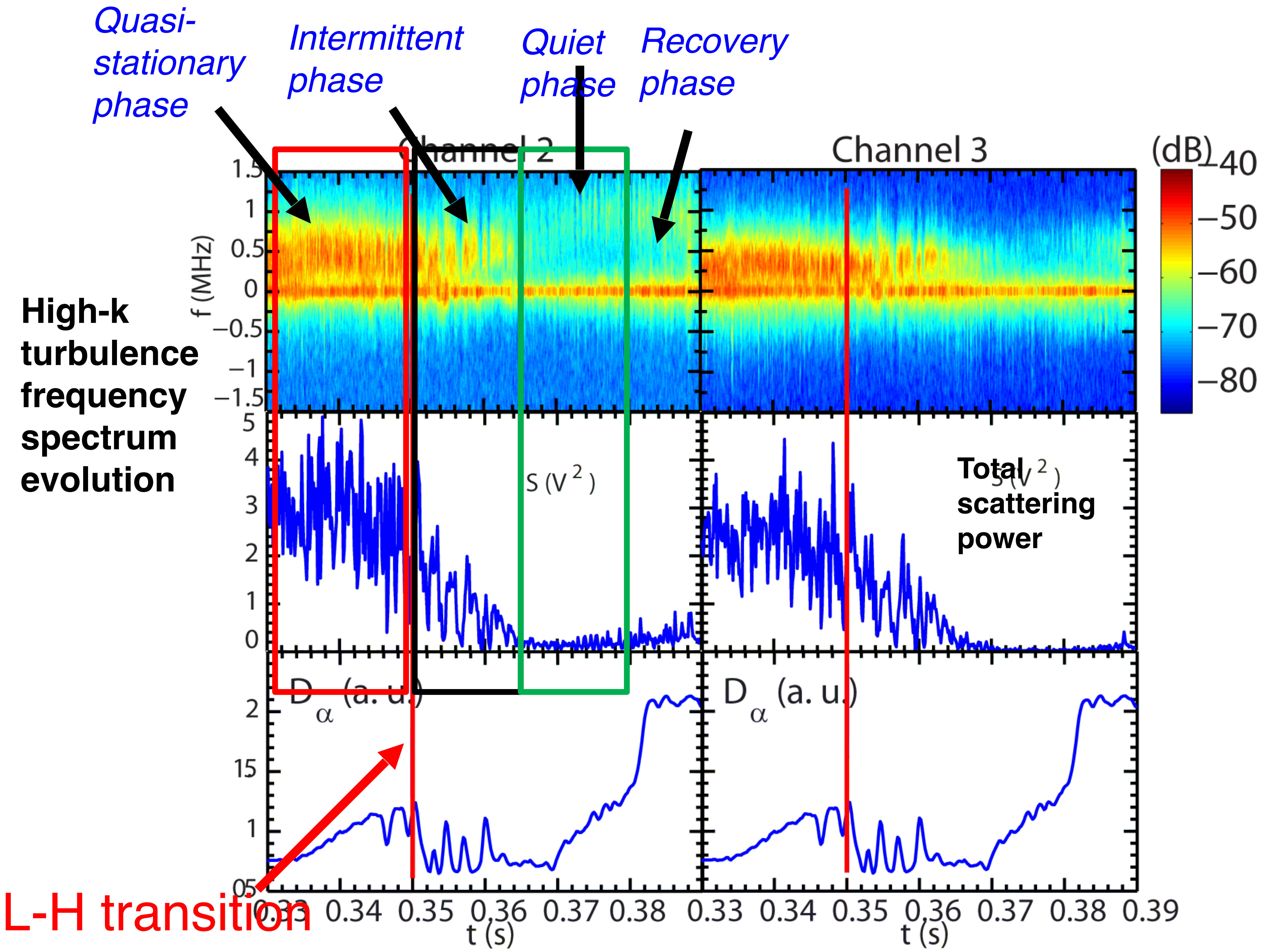
- Edge/pedestal physics
- Energetic particle physics
- Macrostability
- Scenario development
- Diagnostics development

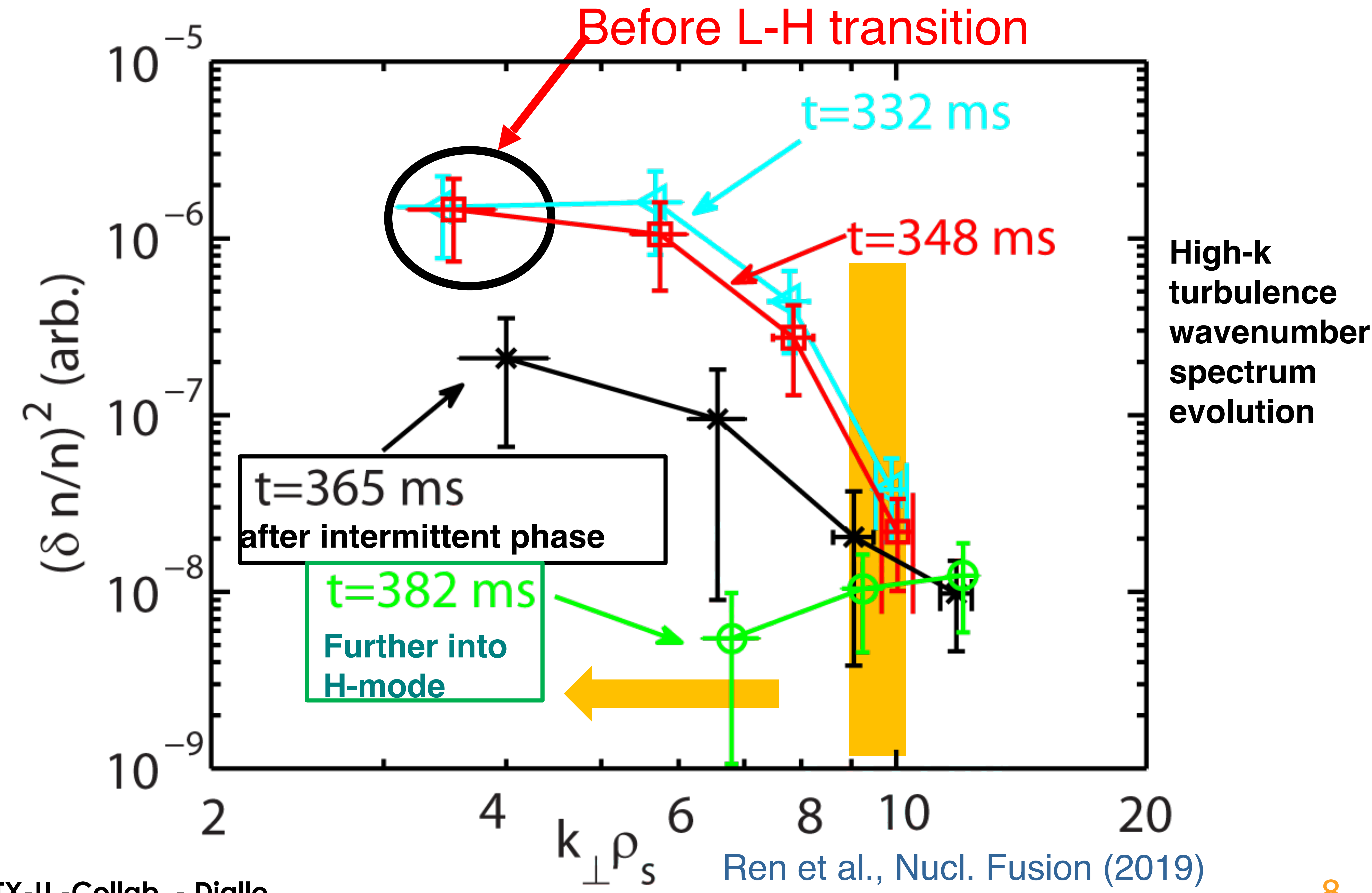
Outline

- Edge/pedestal physics
  - Explore dynamic processes in the edge region for understanding pedestal/SOL structure (NSTX/NSTX-U)
  - Utilize different wall conditioning techniques to optimize plasma performance (EAST, DIII-D, AUG, KSTAR)

First detailed measurements of high-k (electron-scale) turbulence across L-H transition in NSTX reveal broad spectral changes

- **Multiple turbulence phases are identified across the L-H transition**
- **Suppression of high-k turbulence at lower wavenumbers, i.e. $k_\perp \rho_s \leq$ 9-10 (higher wavenumbers unaffected); similar with turbulence changes at ion scale (BES)**





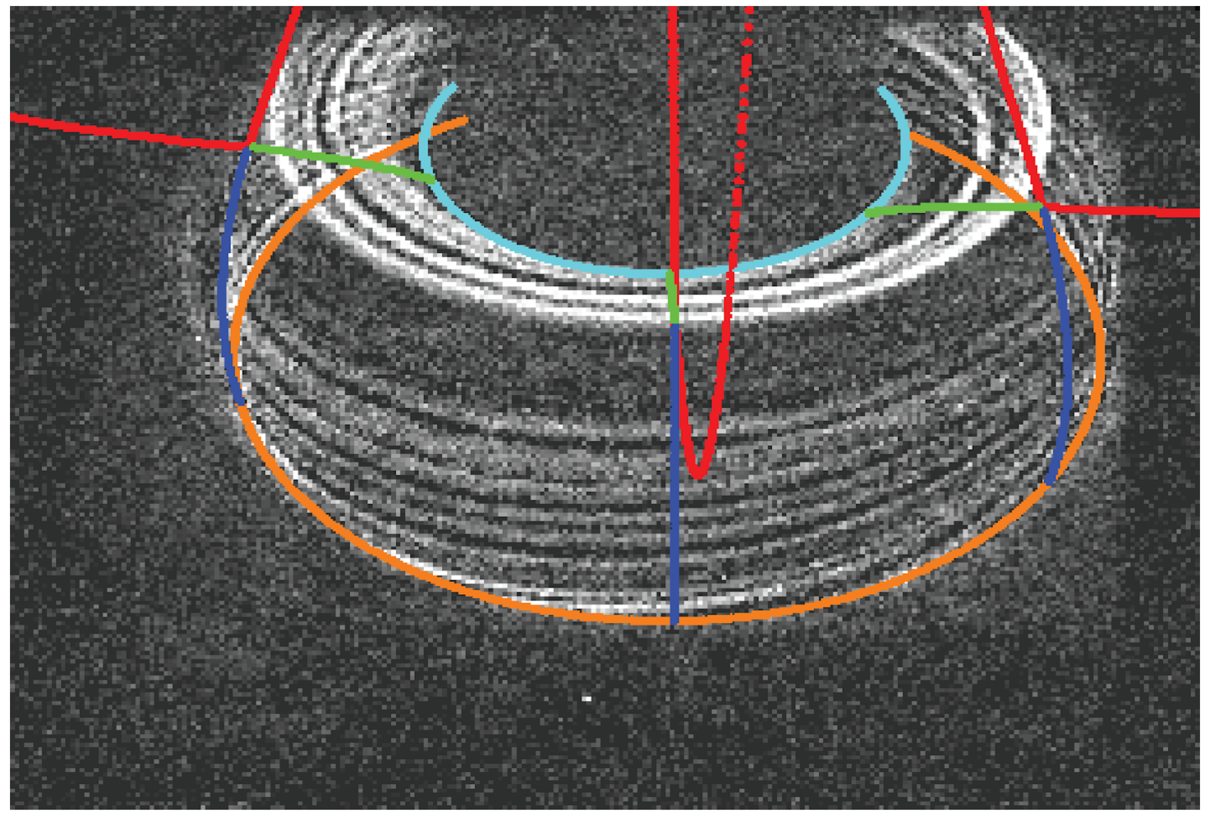
Ren et al., Nucl. Fusion (2019)

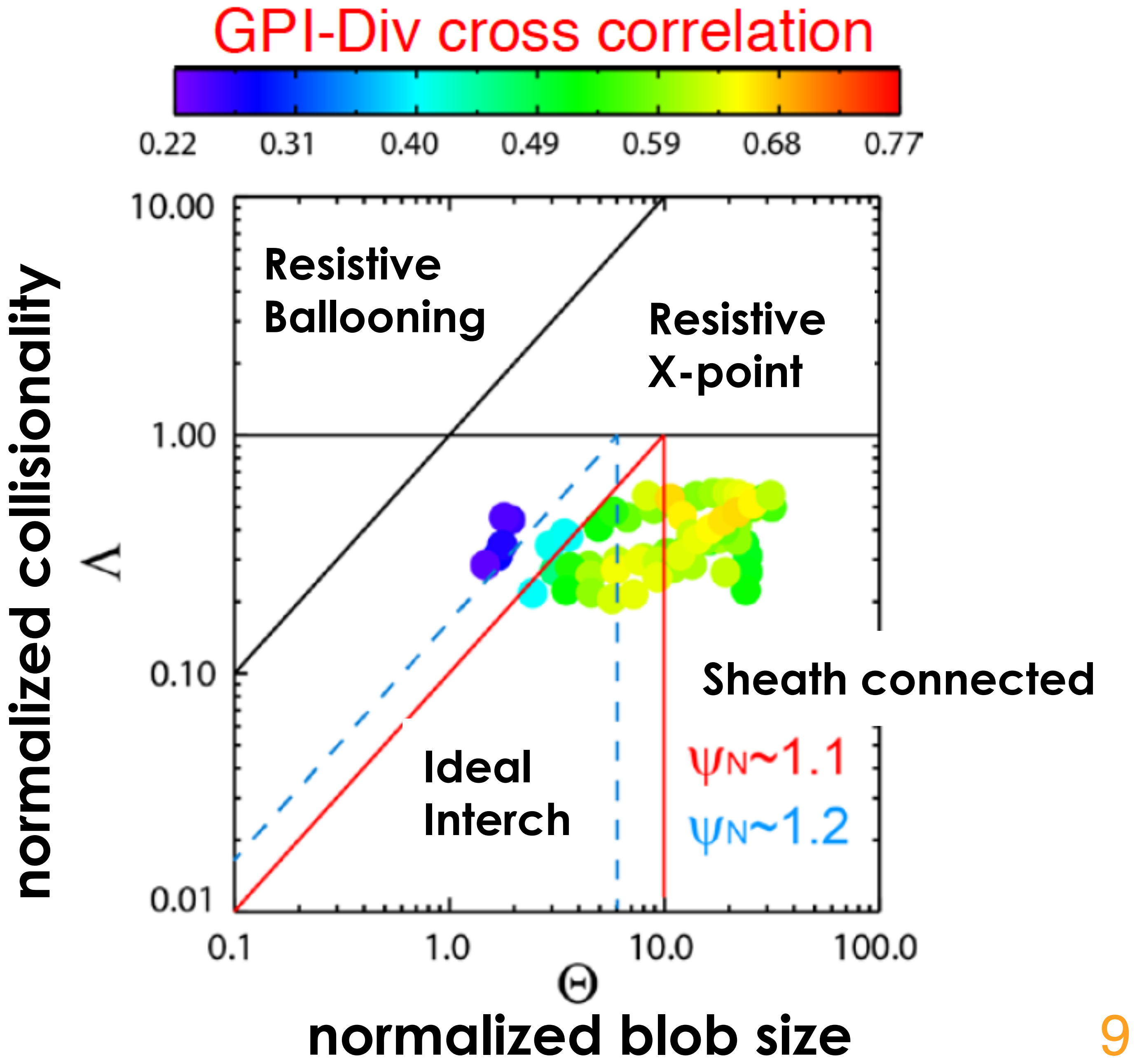
Fast camera imaging of the divertor provides new insights into SOL turbulence

- **Divertor leg fluctuations observed by fast imaging in NSTX-U** **[Scotti, Nuc. Fusion (2018)]**
  - Intermittent; localized to bad curvature side
    - Simulations with ArbiTER code find unstable resistive ballooning mode **[Baver, CCP (2016)]**

- **Disconnection of midplane turbulence from divertor plate due to X-point**
  - Consistent with expectation from two-region blob model **[Myra, PoP (2005)]**

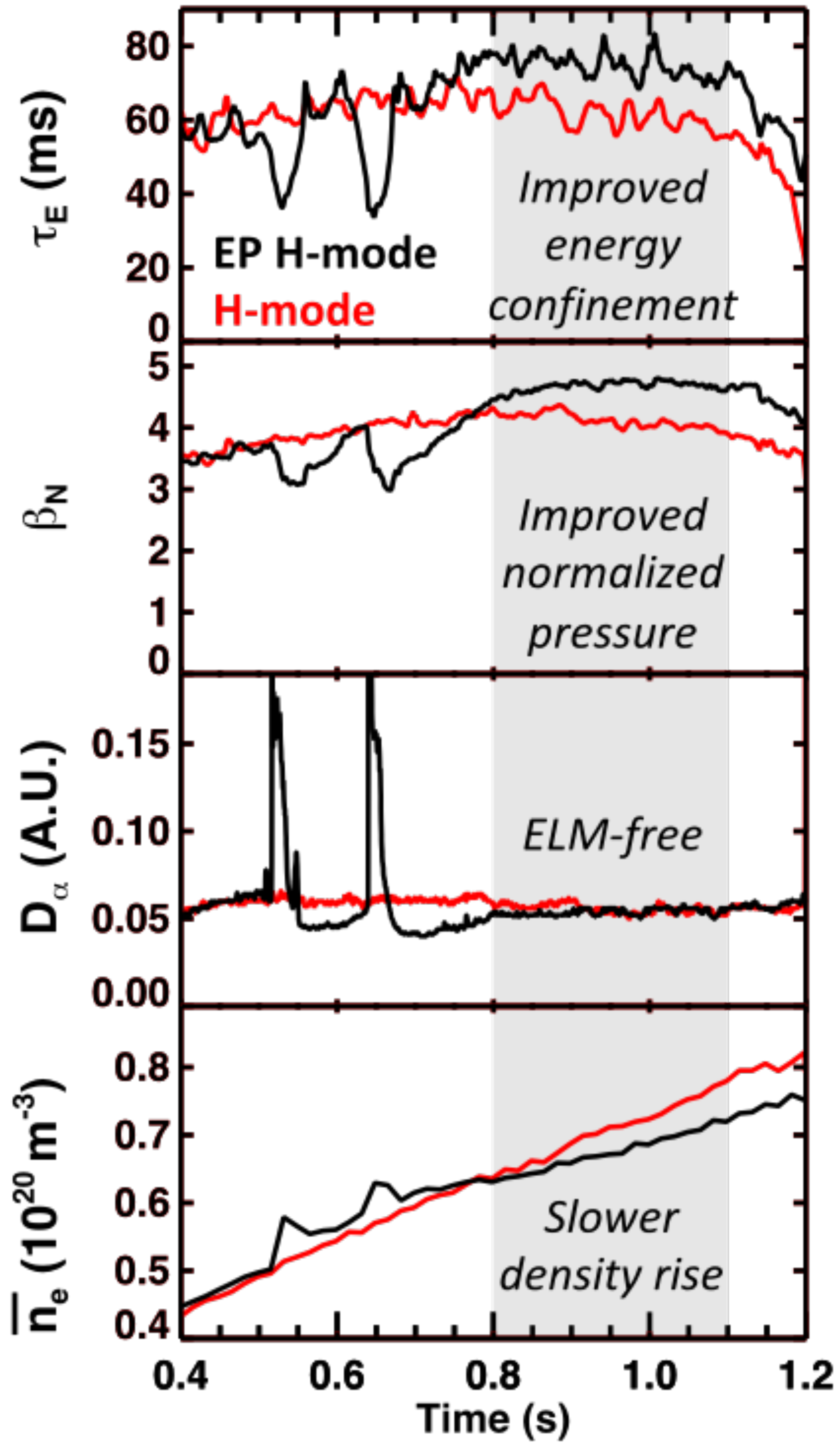
Images in CIII emission





Mechanisms leading to Enhanced Pedestal (EP) H-mode are being better understood

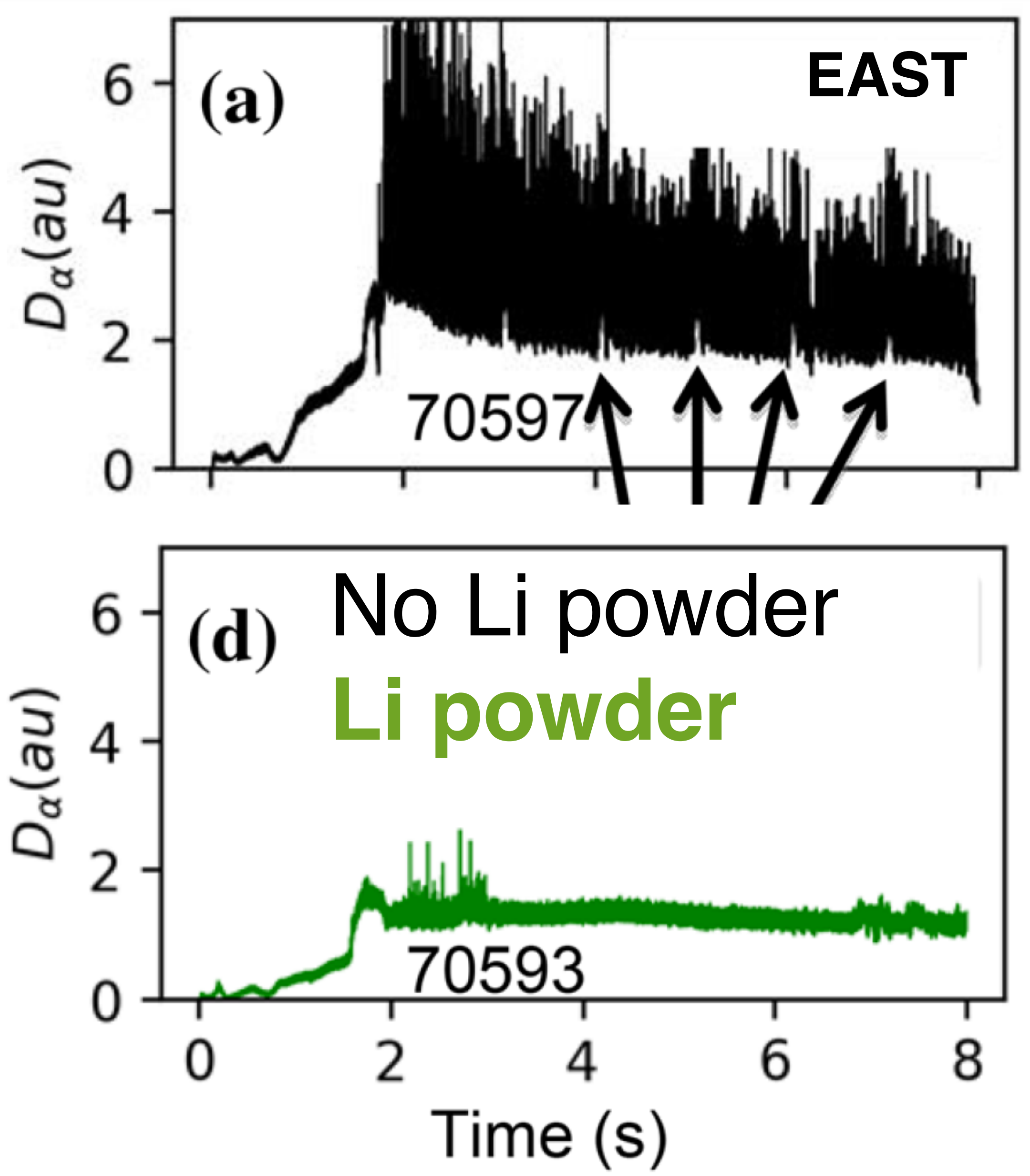
- **EP H-mode is an attractive ELM-free regime for compact reactors**
  - $H_{98y,2}$ typically 1.5
  - Slower density and impurity accumulation
- **Reduced edge ion collisionality drives reduction in neocl. ion energy and momentum transport**
  - Decrease in edge density following an ELM initiates a period of reduced edge ion collisionality
  - Positive feedback loop: Improved neo. **energy confinement compensates** for larger anom. particle transport **loss**
    - Faster loss of colder ions, slower loss of hotter ions
  - "Locks in" lower collisionality
- **Access to lower collisionality may enable routine access to EPH for NSTX-U**



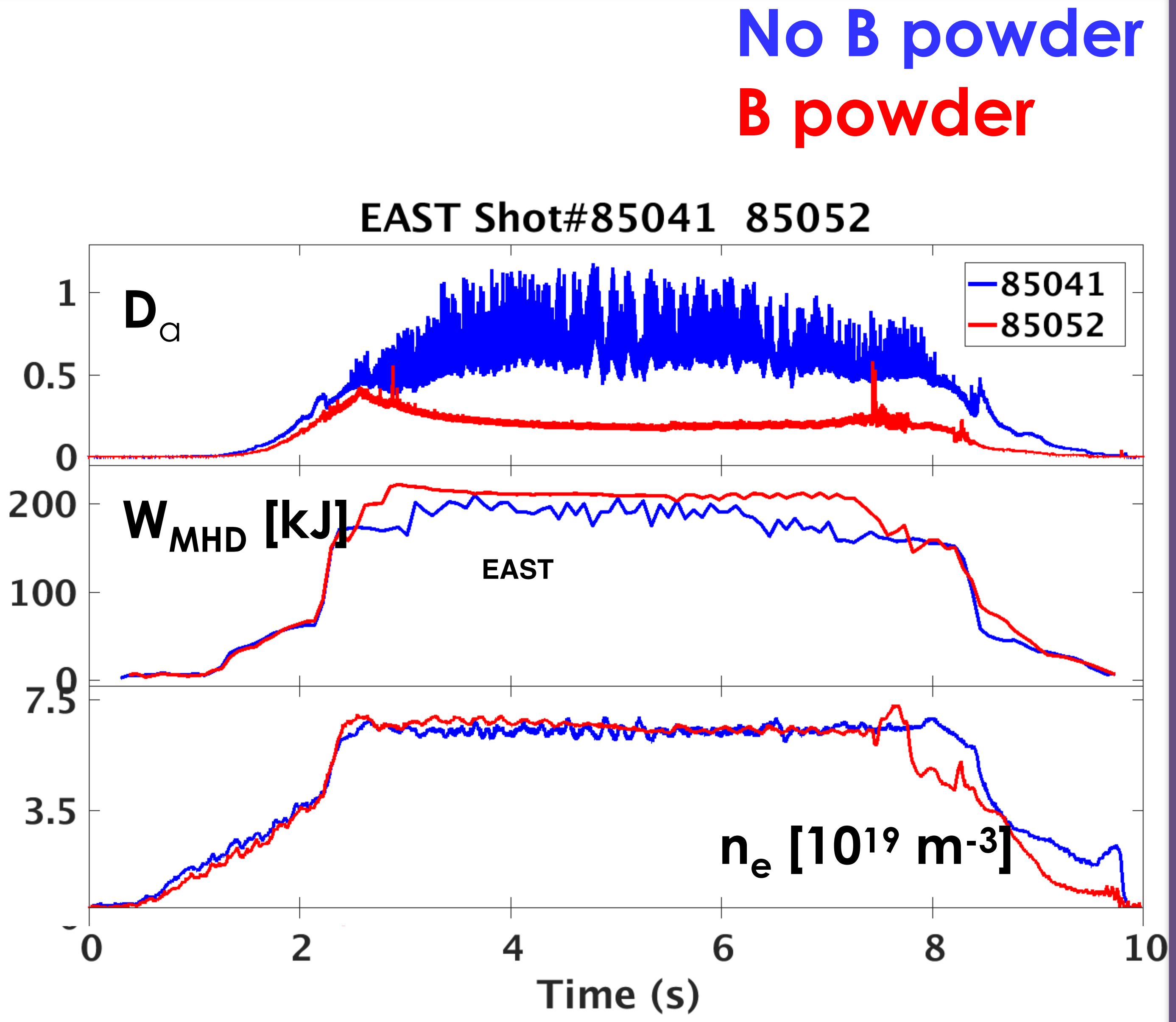
Battaglia, 2019 APS invited, PoP to be submitted

Wall conditioning and ELM control studied with low-Z impurity powder injection on EAST and DIII-D

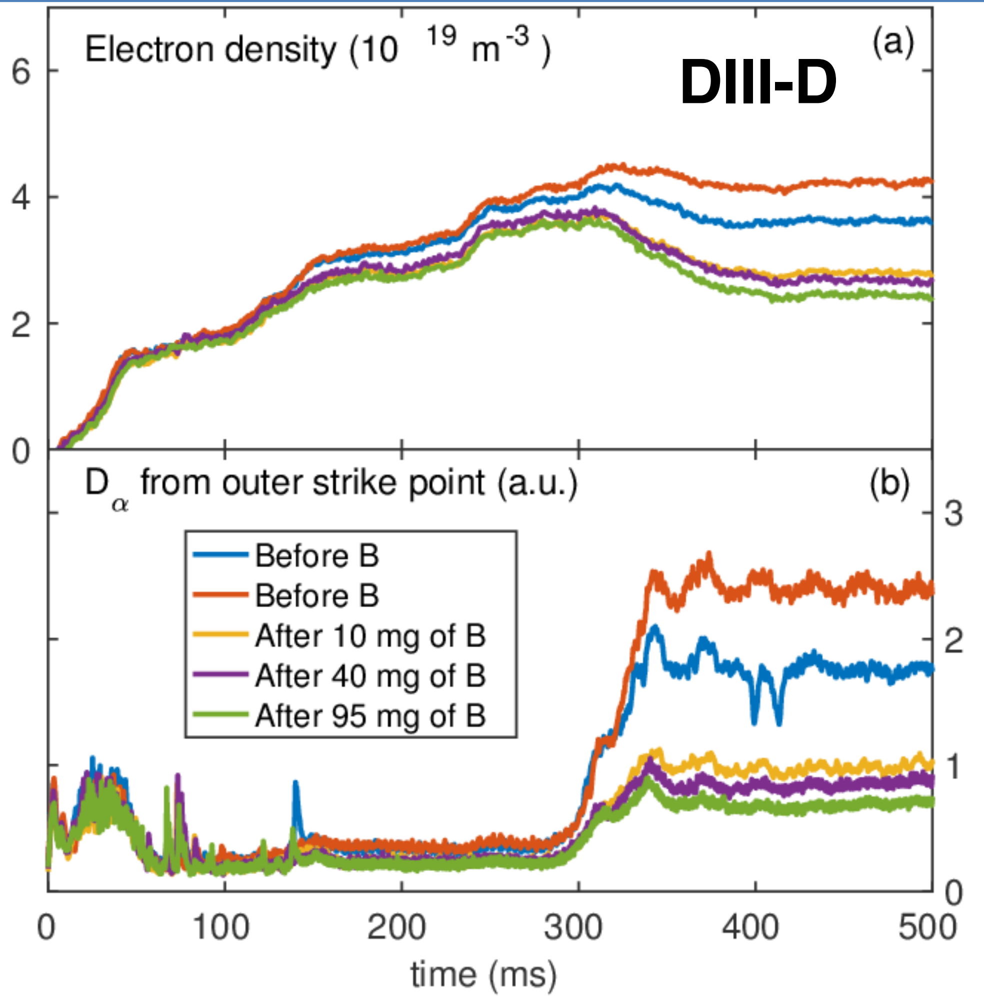
- **Impurity powder dropper compatible with many materials deployed on EAST & DIII-D**
  - Original version using Li was first deployed on NSTX
- **EAST: compare ELM suppression with Li powder injection (reduced recycling) with B powder (low freq. edge mode)**
- **DIII-D: B powder injection successfully used for wall conditioning to reduce recycling and density**



R. Maingi, Nucl. Fusion 58 (2018) 024003



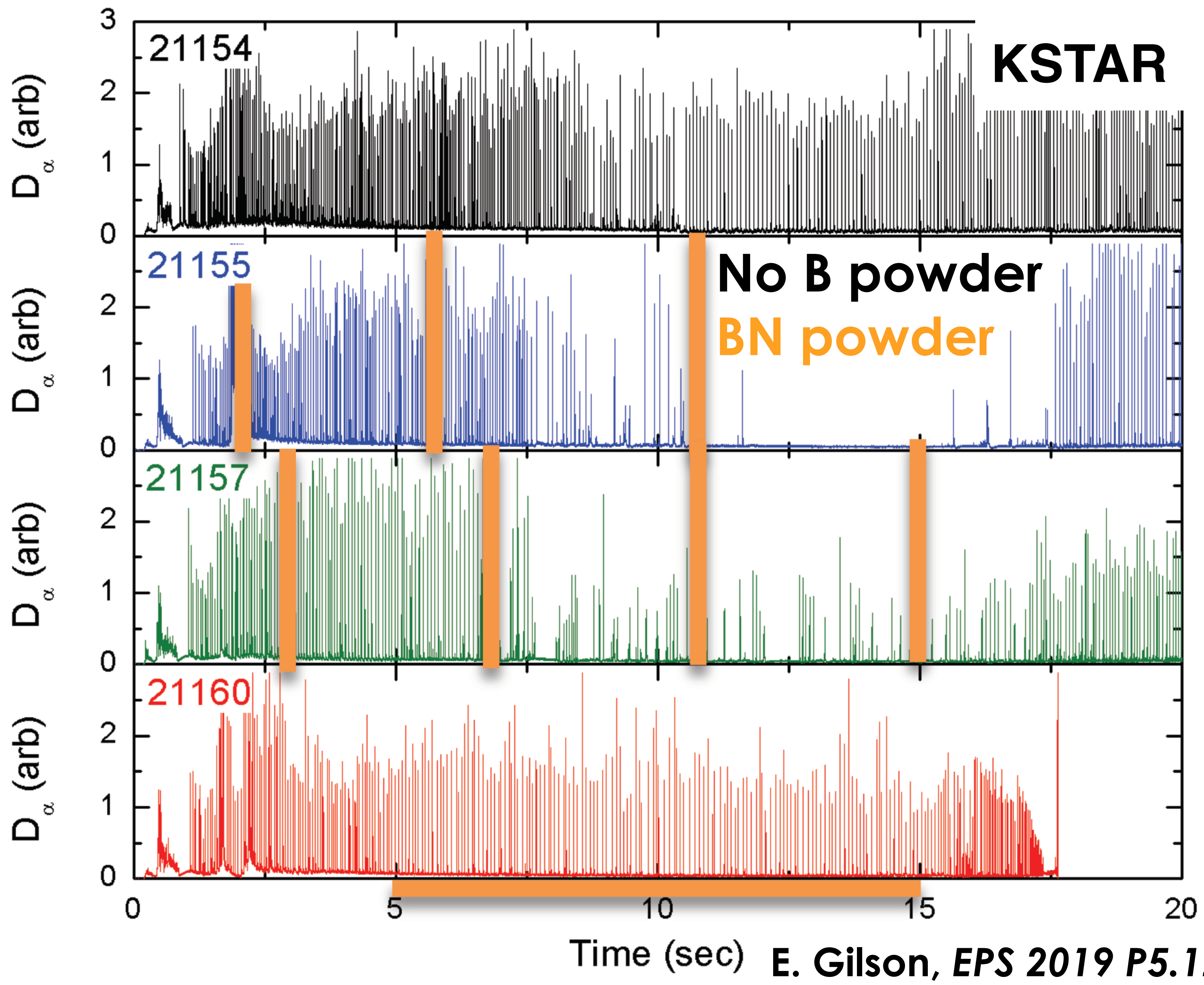
A. Diallo, H-mode workshop 2019



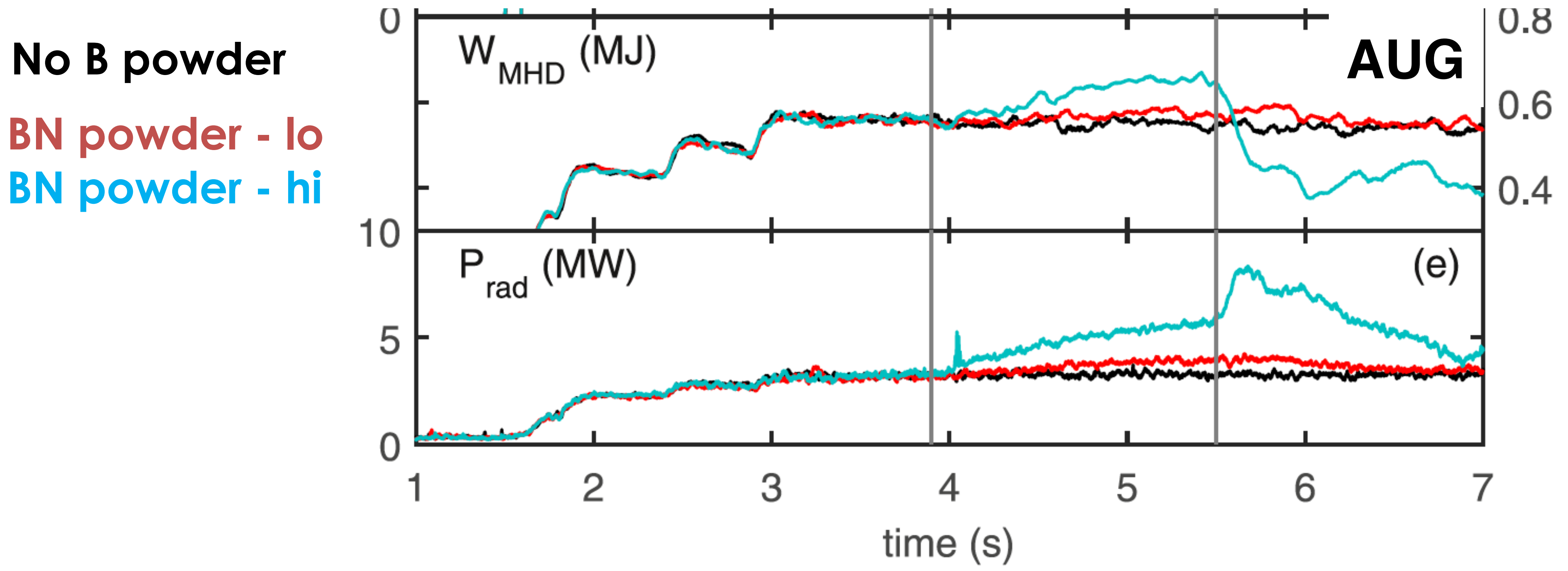
A. Bortolon, APS 2018, NME in prep

ELM control and enhanced power exhaust studied with low-Z impurity powder injection on KSTAR and AUG

- **KSTAR: BN powder injection led to periods of ELM quiescence**
  - Dependence on injection rate
- **AUG: BN powder injection led to enhanced radiated power, reduced heat flux, improved stored energy**
  - Similar to N_2 gas injection
- **Powder dropper is being considered for early deployment in NSTX-U**



E. Gilson, *EPS 2019 P5.126*



A. Bortolon, *Nucl. Mater. Energy* 19 (2019) 384

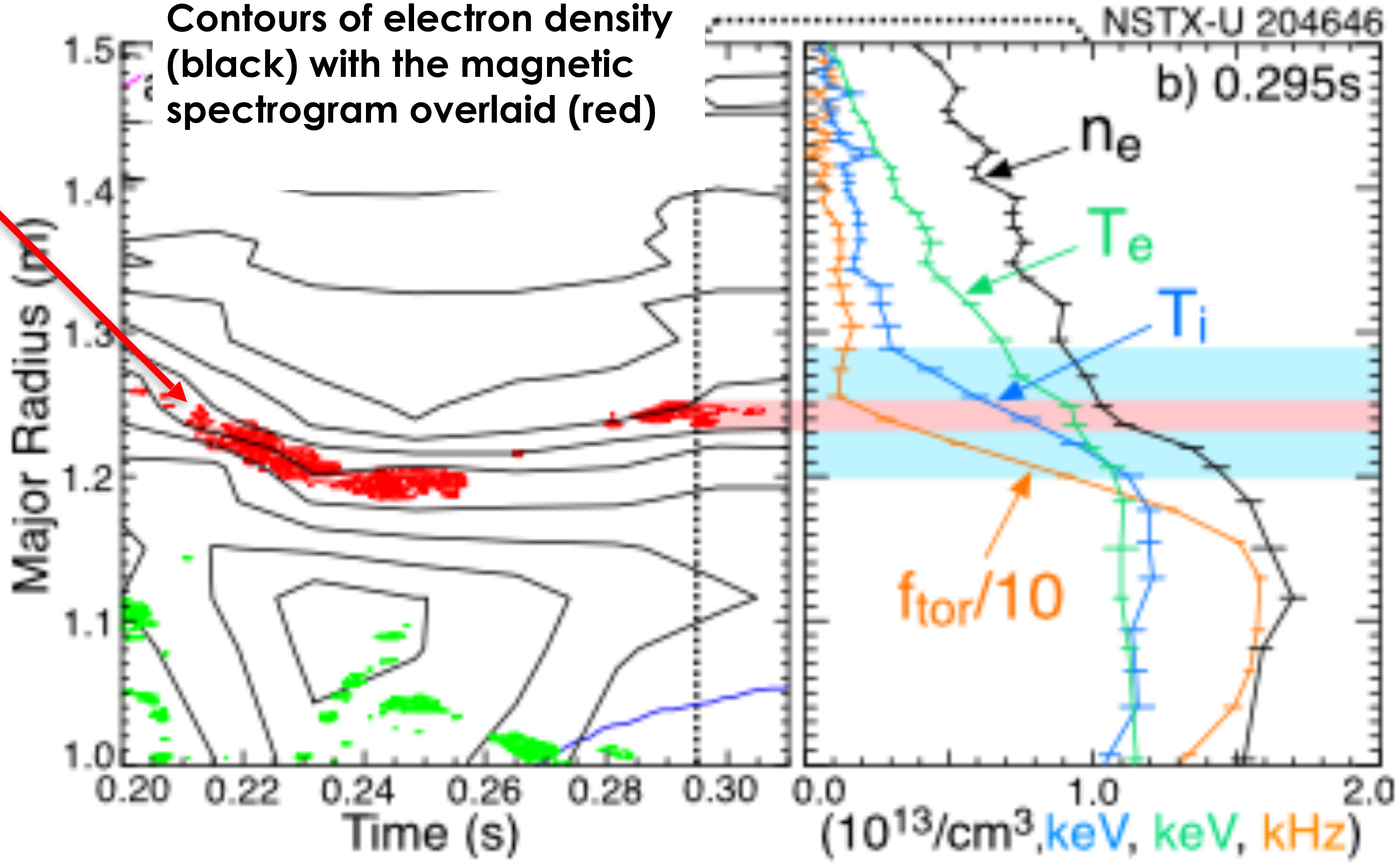
Outline

- Energetic particle physics
  - Novel ICE observation on NSTX-U
  - Effect of EP on NTV on DIII-D
    - Potential effects on plasma rotation/performance
  - Effect of RF on EP distribution
    - Impact on NB heating and current drive

Ion Cyclotron Emission (ICE) from NSTX/NSTX-U scenarios shows features uncommon in larger R/a devices

- **NSTX(-U): ICE frequency maps to f_{ci} deeper in the core**
  - ICE maps to a region of **strong local density gradient**
  - Frequency doesn't follow Alfvénic scaling (but scales with *B*)
- **Understanding ICE would provide a reactor-relevant fast ion diagnostic for ITER and beyond**
  - Neutron rate generally proportional to ICE amplitude [JET]
  - Simple measurements (coils)
  - ICE typically associated with fast ions

Contours of electron density (black) with the magnetic spectrogram overlaid (red)



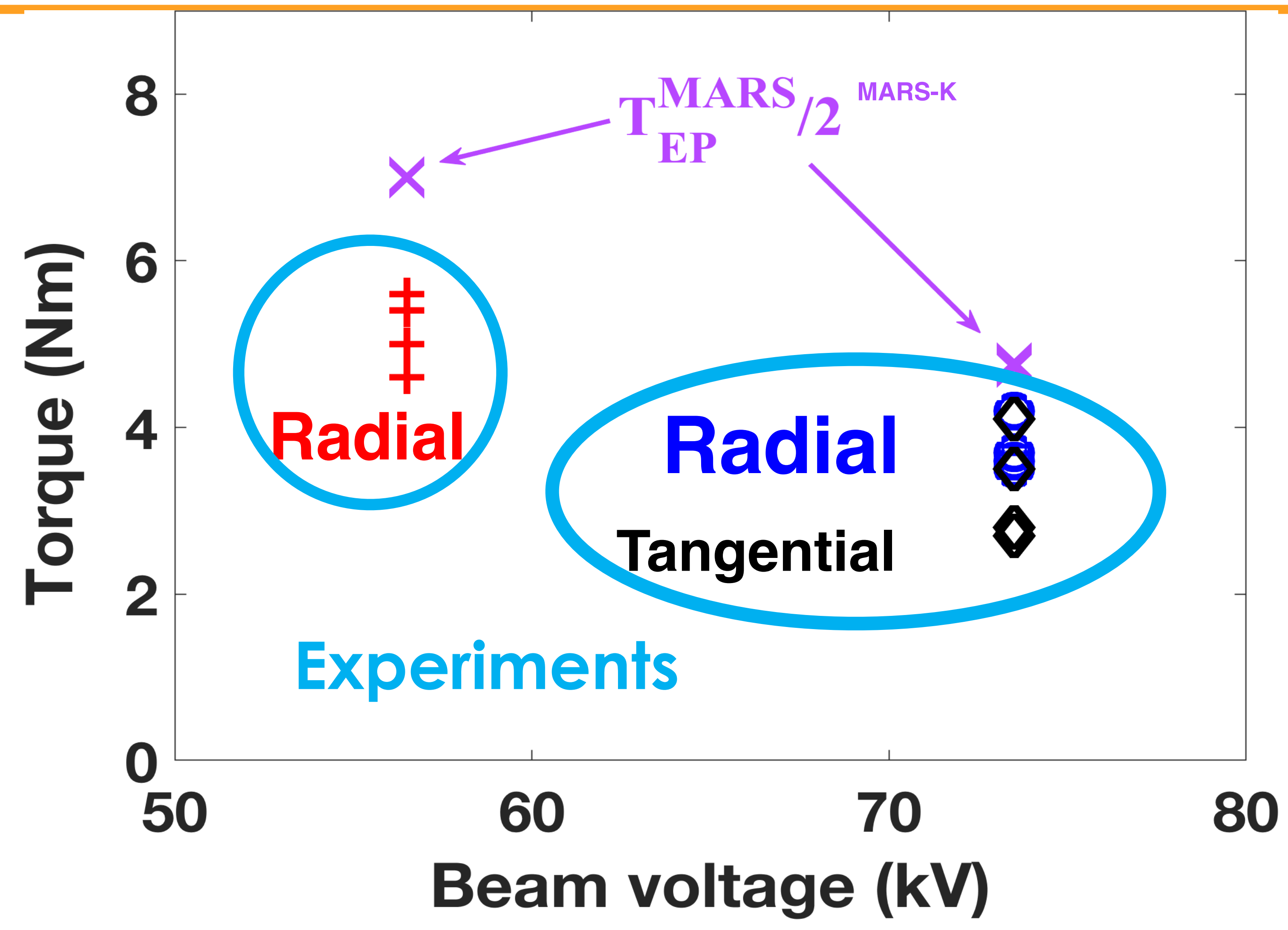
– ***Complement data from larger R/a devices***

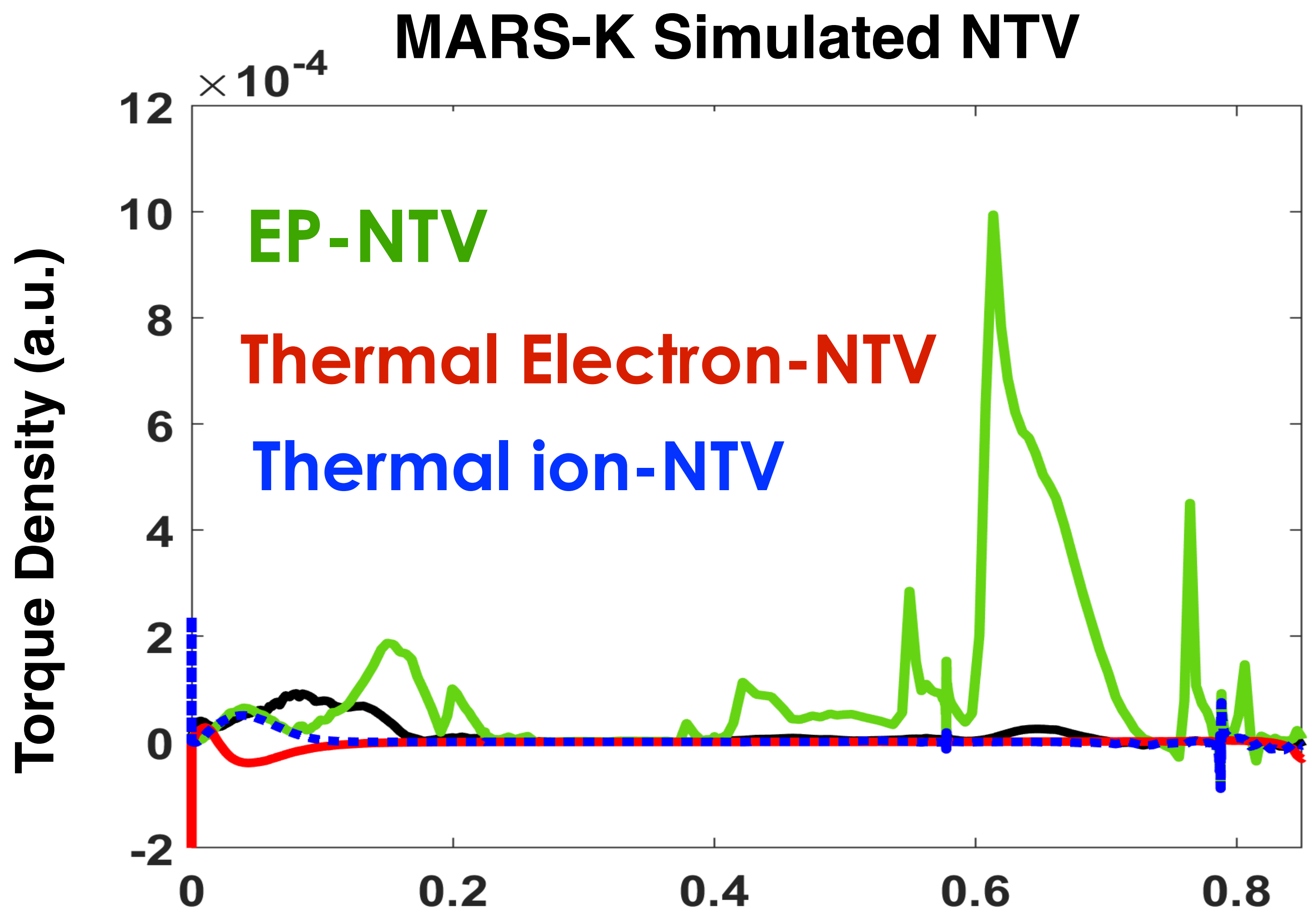
– ***More theory work needed to explain the observations***

[E. Fredrickson, PoP 2019]

Energetic Particles found to Induce neoclassical toroidal viscosity on DIII-D

- **EP-induced NTV, predicted by theory was verified in n=1 DIII-D plasma response experiments**
  - Experimental measured NTV torque is varied with beam voltage and injection angle
  - Simulated EP NTV agrees with experiments
- **EP NTV, due to precession resonance, can be much stronger than thermal NTV**, <u>when ExB rotation is comparable to the precession frequency</u>
- **Energetic particles, as one of major plasma species, may contribute significant NTV torque in NSTX-U and ITER operation**
  - Can impact plasma rotation and thus confinement and stability
- **NSTX-U flexible beams can help to further verify EP NTV and improve NTV modelling**

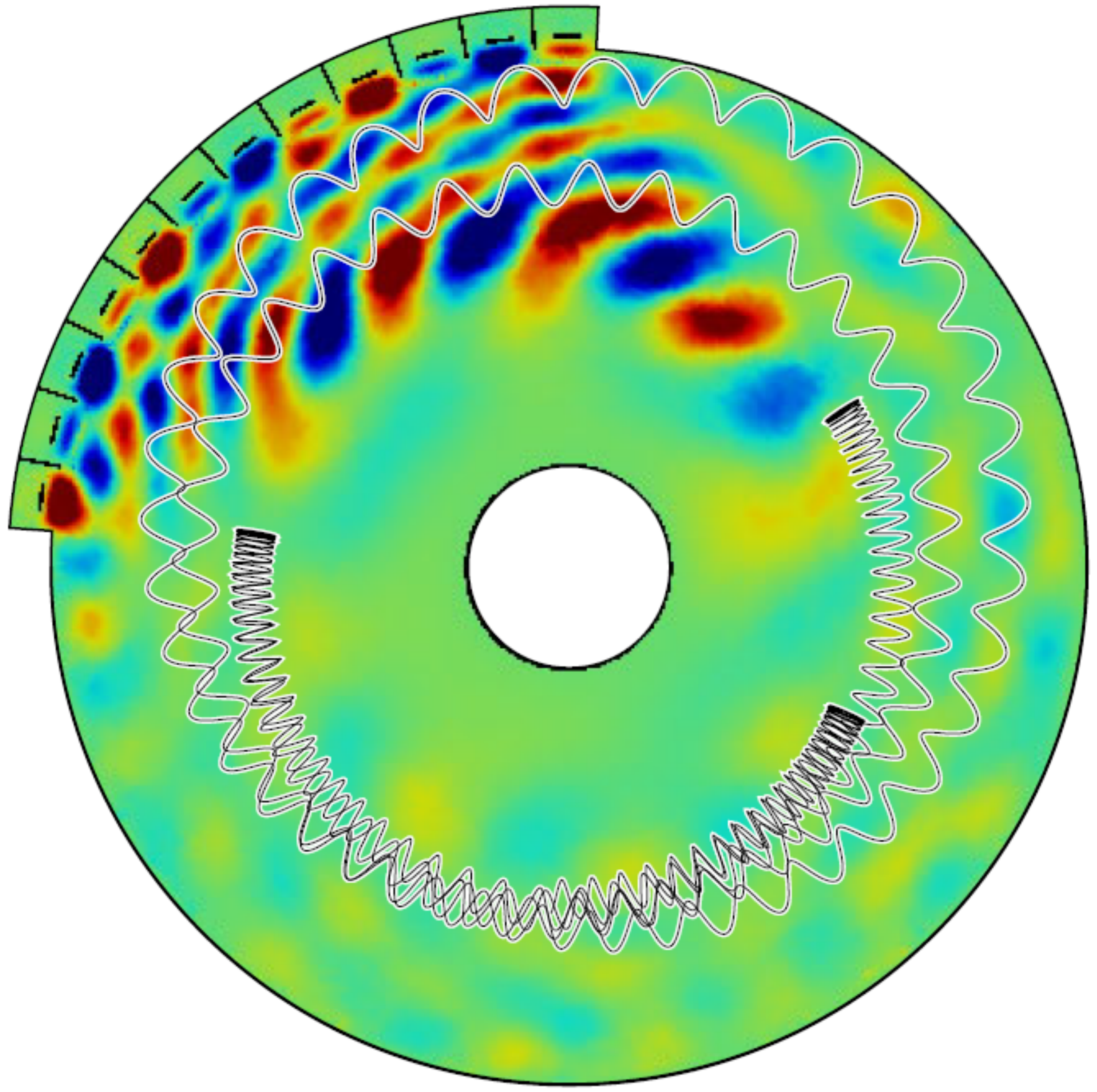


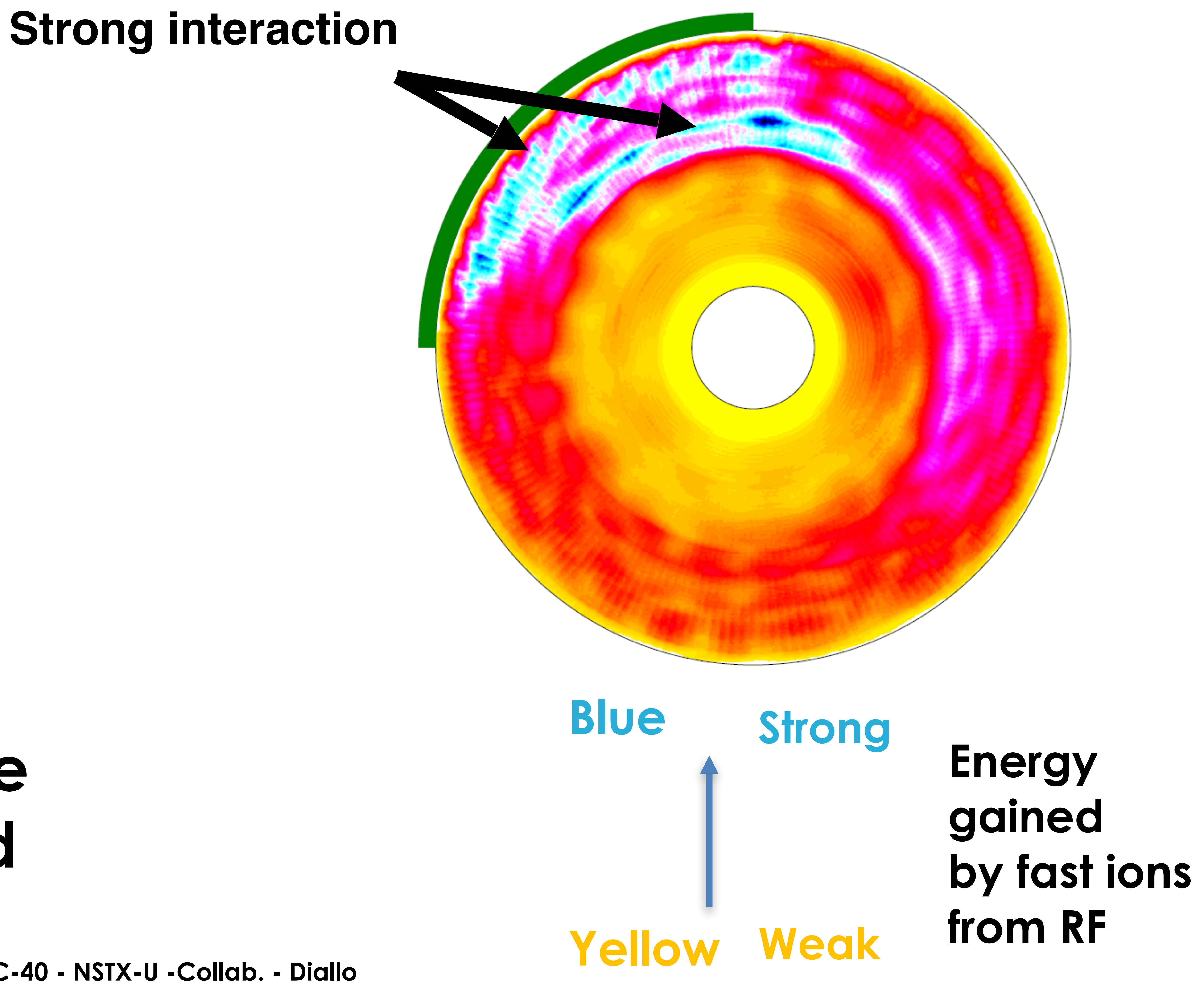


Z.R. Wang, EPS 2019

3D RF field (from Petra-M) combined with following particle code SPIRAL to study the interaction of FW with fast ions

Extending to 3D enables accurate core-edge coupling with the antenna





3D vs. 2D field can affect the interaction between FW and fast ions

Outline

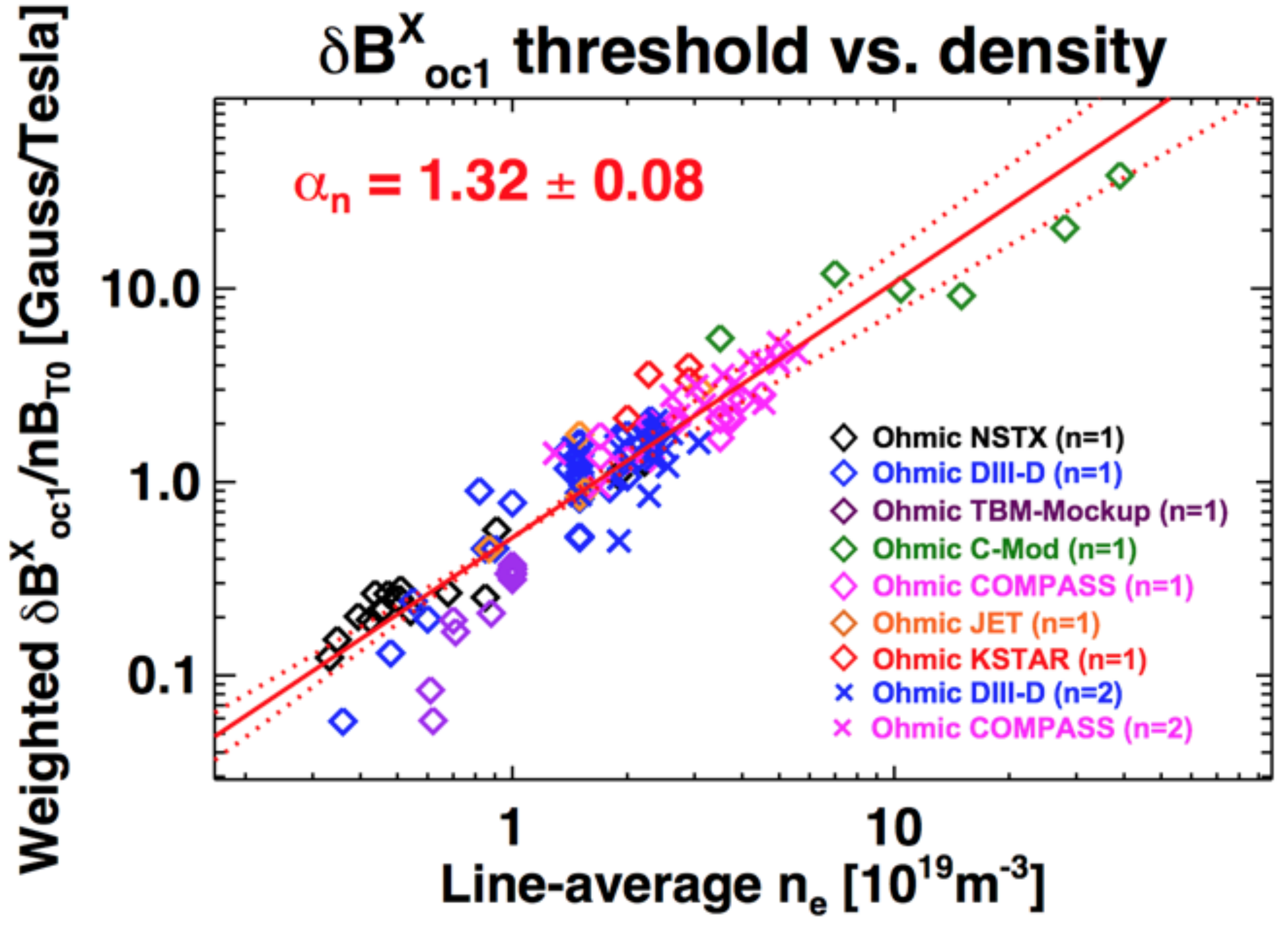
- **Macrostability: Study being performed to understand and mitigate processes that impact plasma stability**
  - EF correction (KSTAR and ITER)
  - Impact on the magnetic footprints on the divertor plates due to the misalignment of NSTX-U equilibrium coils
  - RWM and effect of wall (MAST - no wall, NSTX - wall)
  - Disruptions and VDEs

NSTX-U researchers continue to develop and test error field correction (EFC) strategy in tokamaks and for ITER

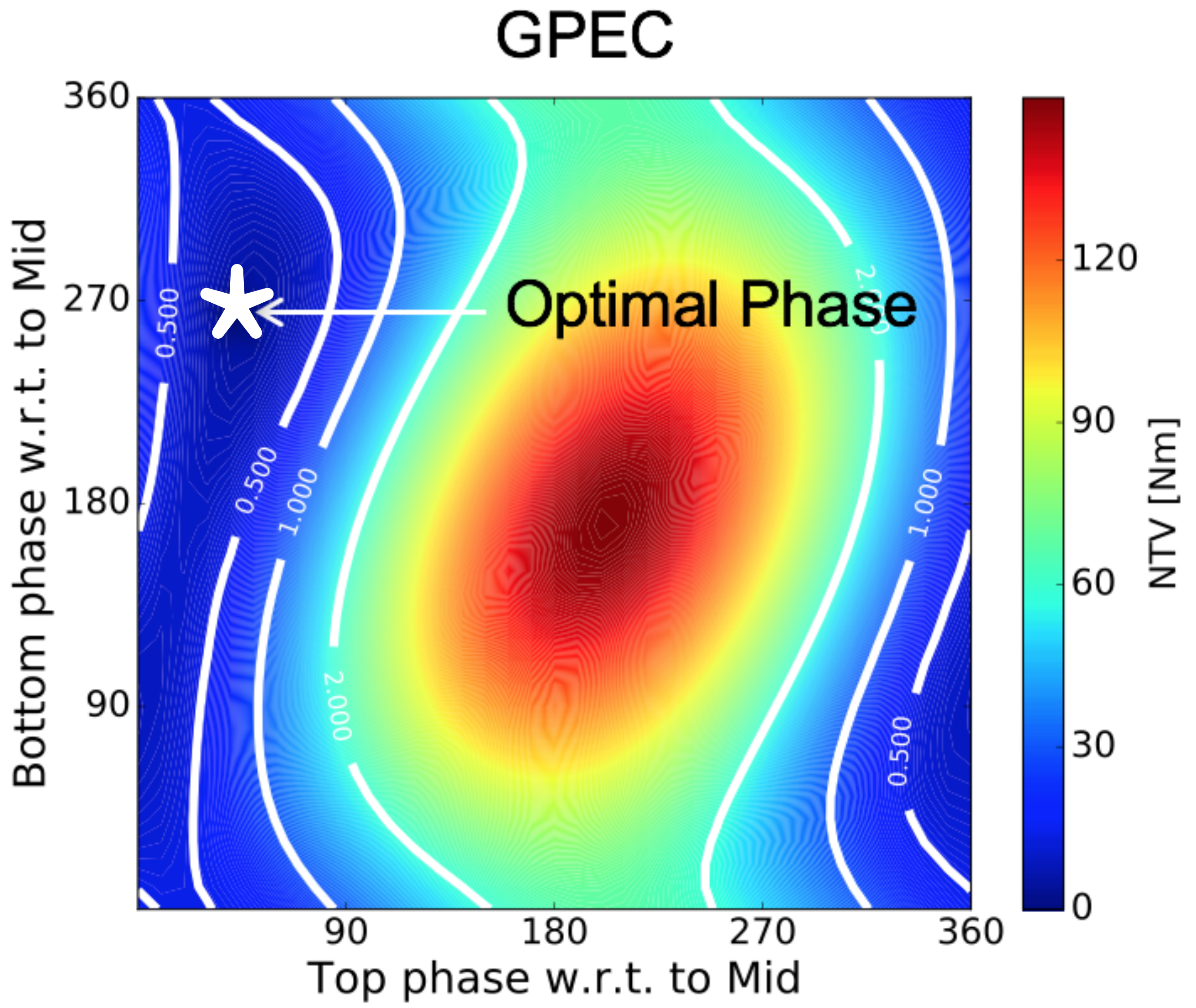
- **Developing unified n=1+2 <u>resonant</u> EFC criteria to avoid disruptive MHD modes***
  - Using **IPEC to** calculate **resonant field threshold** for locked modes
  - Investigating multi-modal aspects of HFS EF effects as seen with NSTX-U TF errors and COMPASS HFS coils
- **Predicting <u>non-resonant</u> NTV correction capabilities of existing and designed coils**
  - Using self-consistent NTV response matrix in GPEC
  - **Assessing** Top/Bottom coil utilities in ITER*, and **designing** coils to couple NTV dominant response structure in KSTAR

** As a part of ITPA MHD activity (MDC-19)*

<u>n=1+2 resonant EF scaling in tokamaks</u>



<u>ITER T/B coil correction against NTV by mid-coils</u>

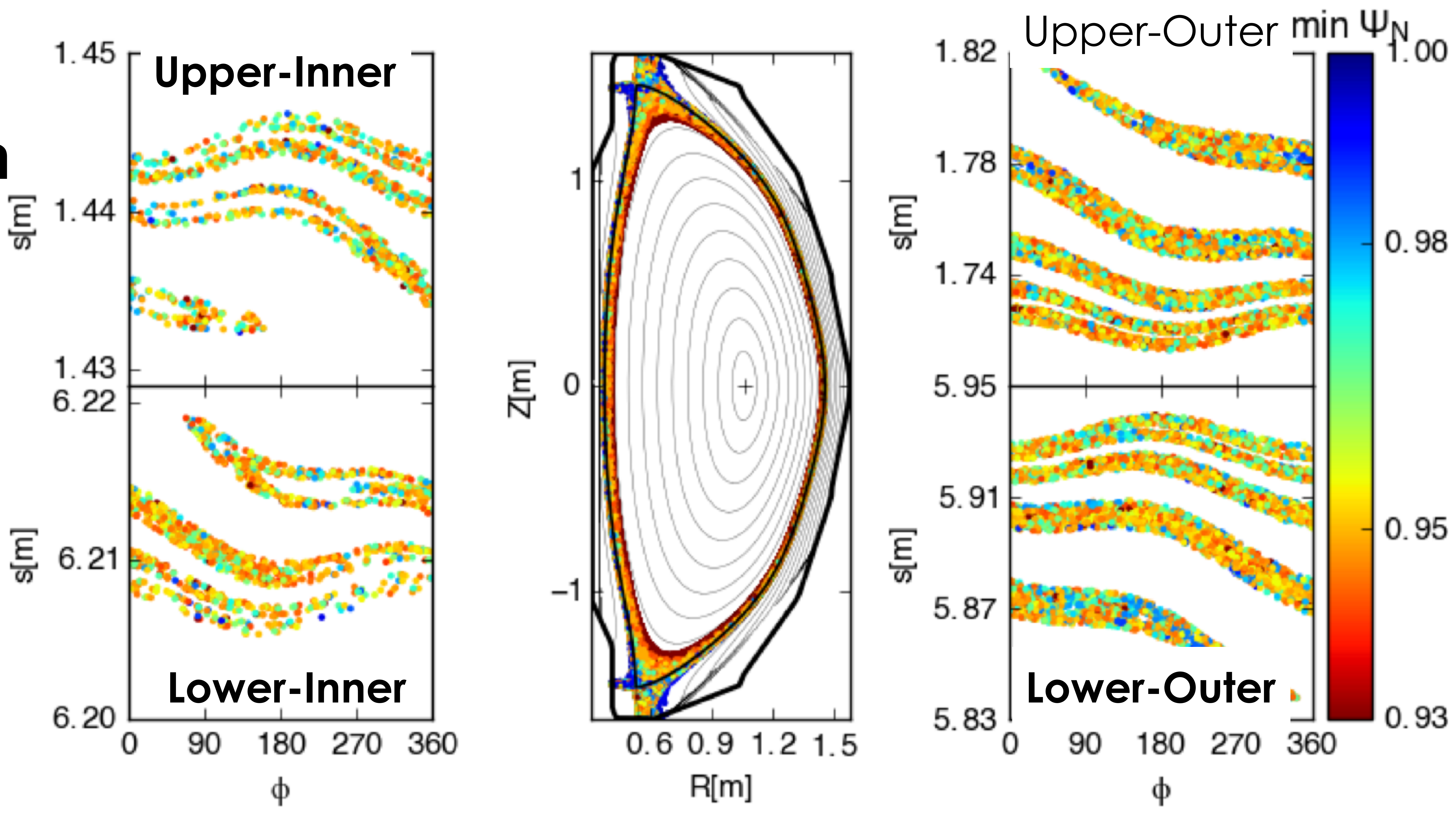


Study the precision needed to install the equilibrium coils of NSTX-U in terms of plasma footprints on the divertor plates

- **A 5 mm shift of the TF coils produces 10 cm wide footprints on the outer divertor plates**

  "s" is defined as the distance from inner midplane along the wall clockwise

- **The footprint size is linearly proportional to the misalignment magnitude of TF and PF5.**



- **Study predicted that error fields in NSTX-U will not expand footprints outside of divertor PFCs**

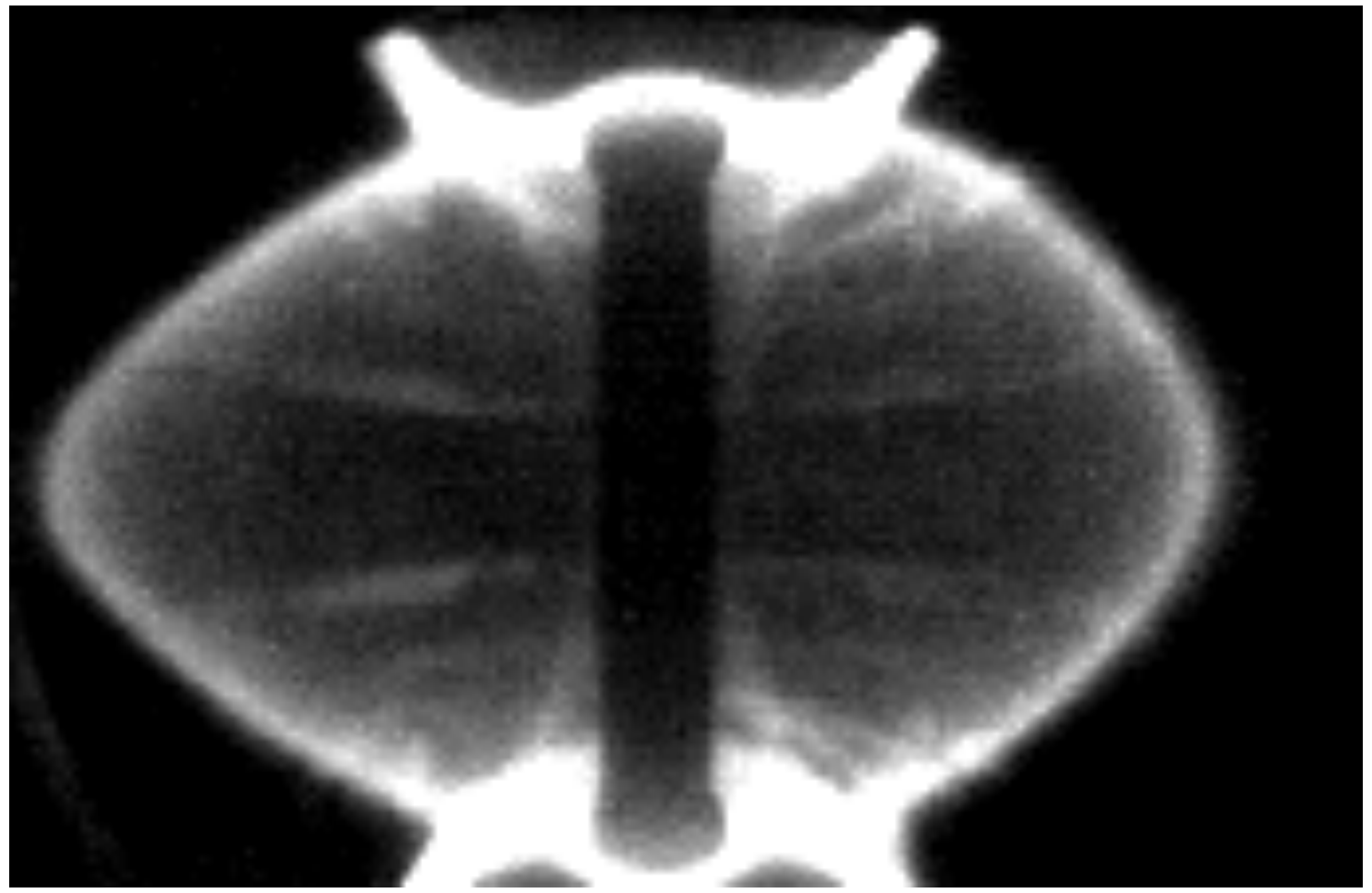
Munaretto Nucl. Fusion 59(2019) 076039

Studies of observed global modes in MAST & NSTX allow for understanding the effect of wall proximity on mode structure

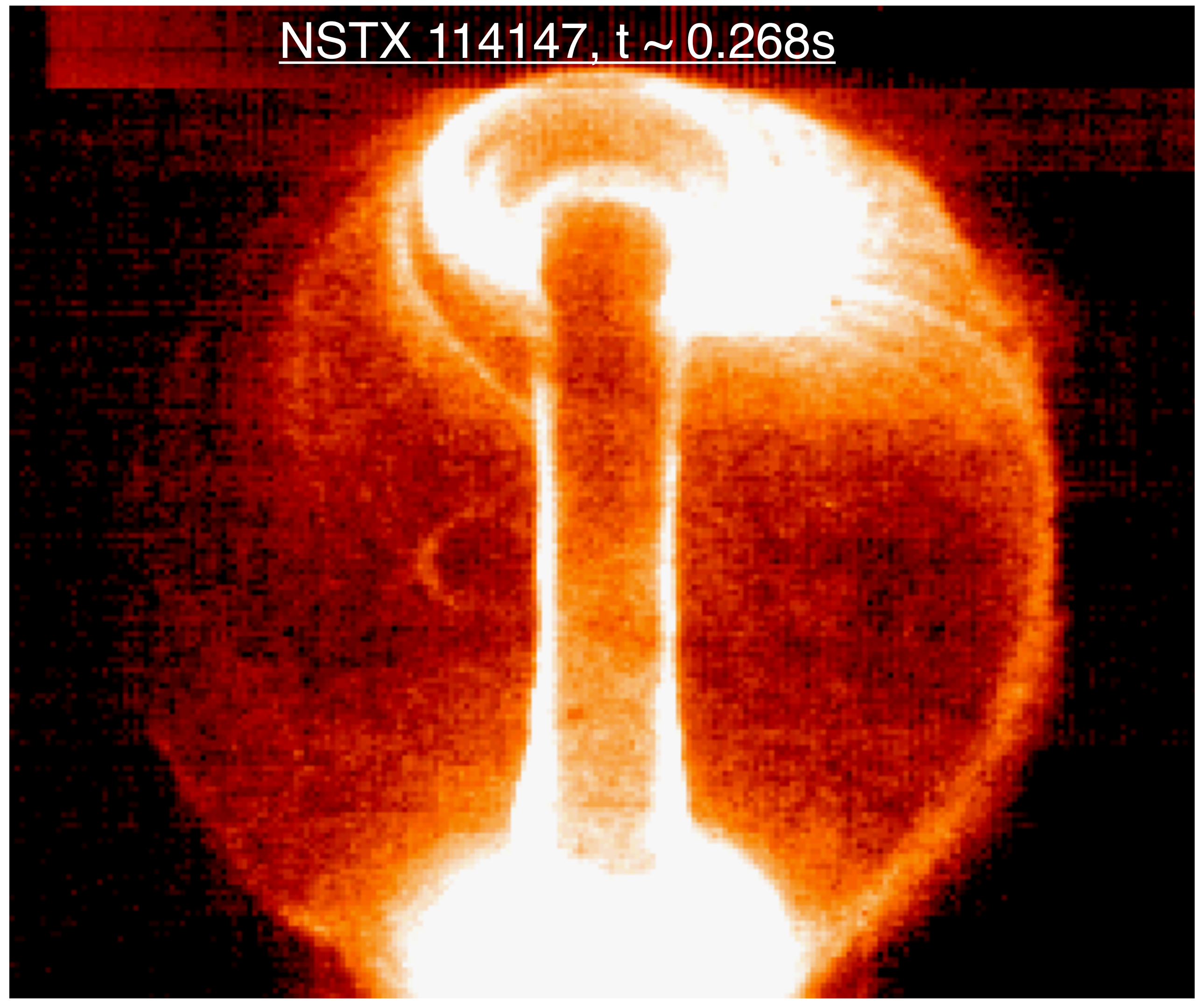
“egg shape event”

Fast camera image
(MAST 21436, t ~ 0.280s)

MAST

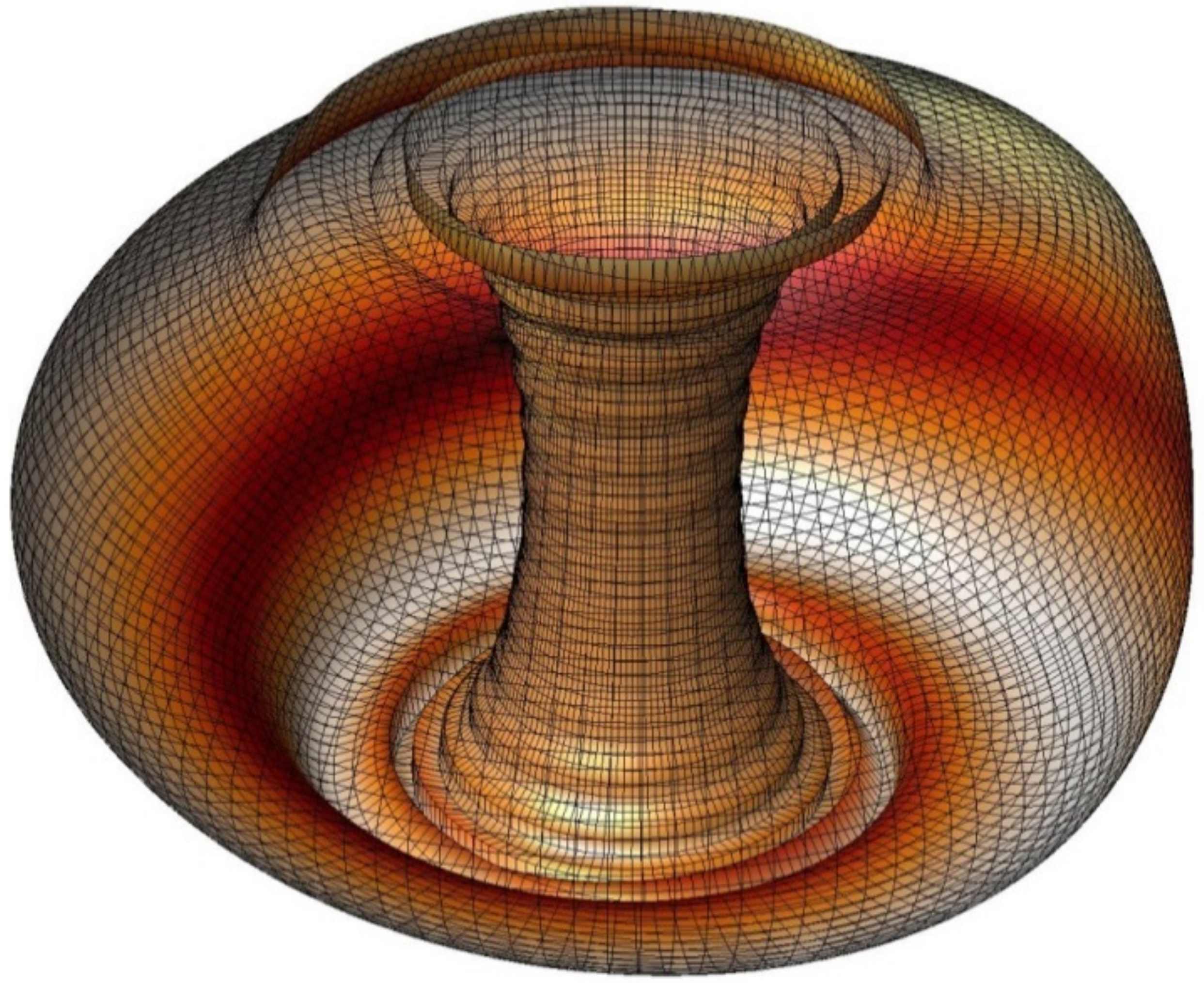


Images of plasma distortion due to global modes

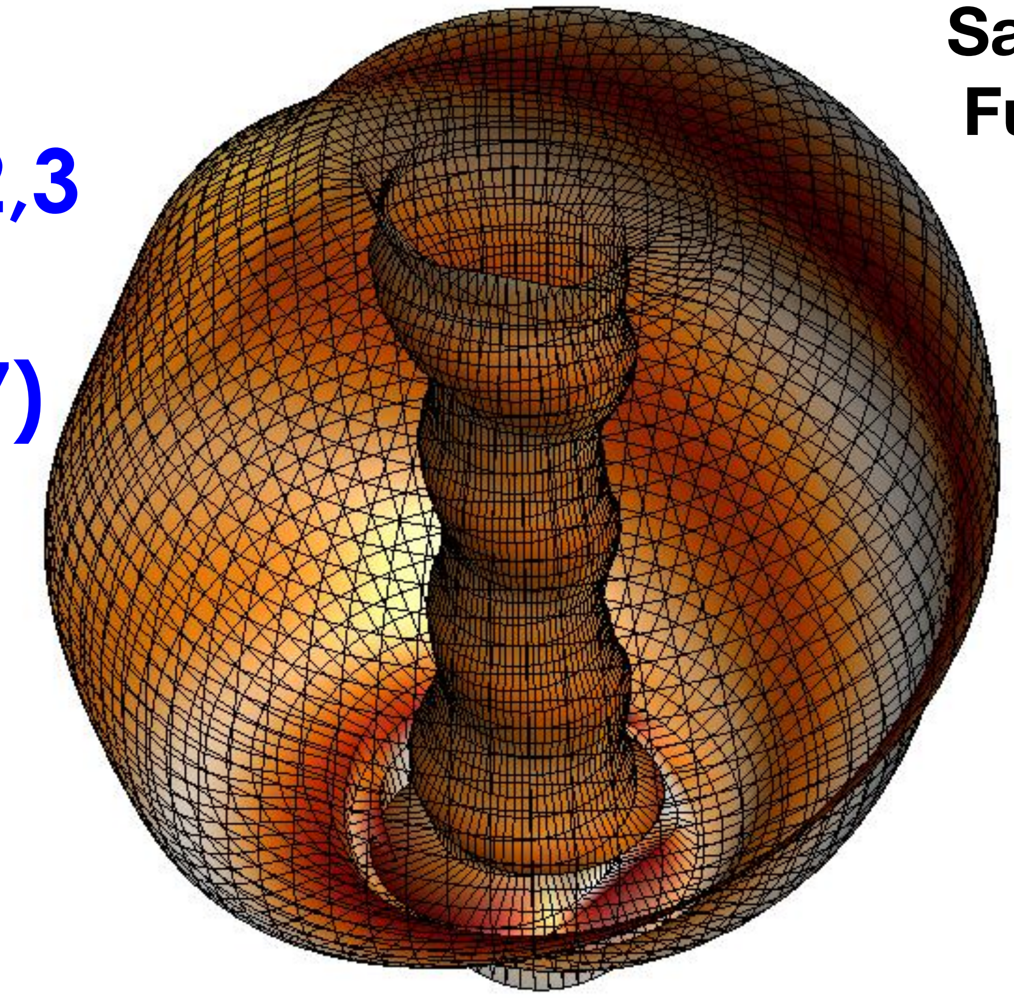


NSTX

**VALEN analysis (n = 1 RWM)
(using MAST 7090)**



**VALEN analysis (n = 1,2,3 RWM)
(reconstructed 114147)**

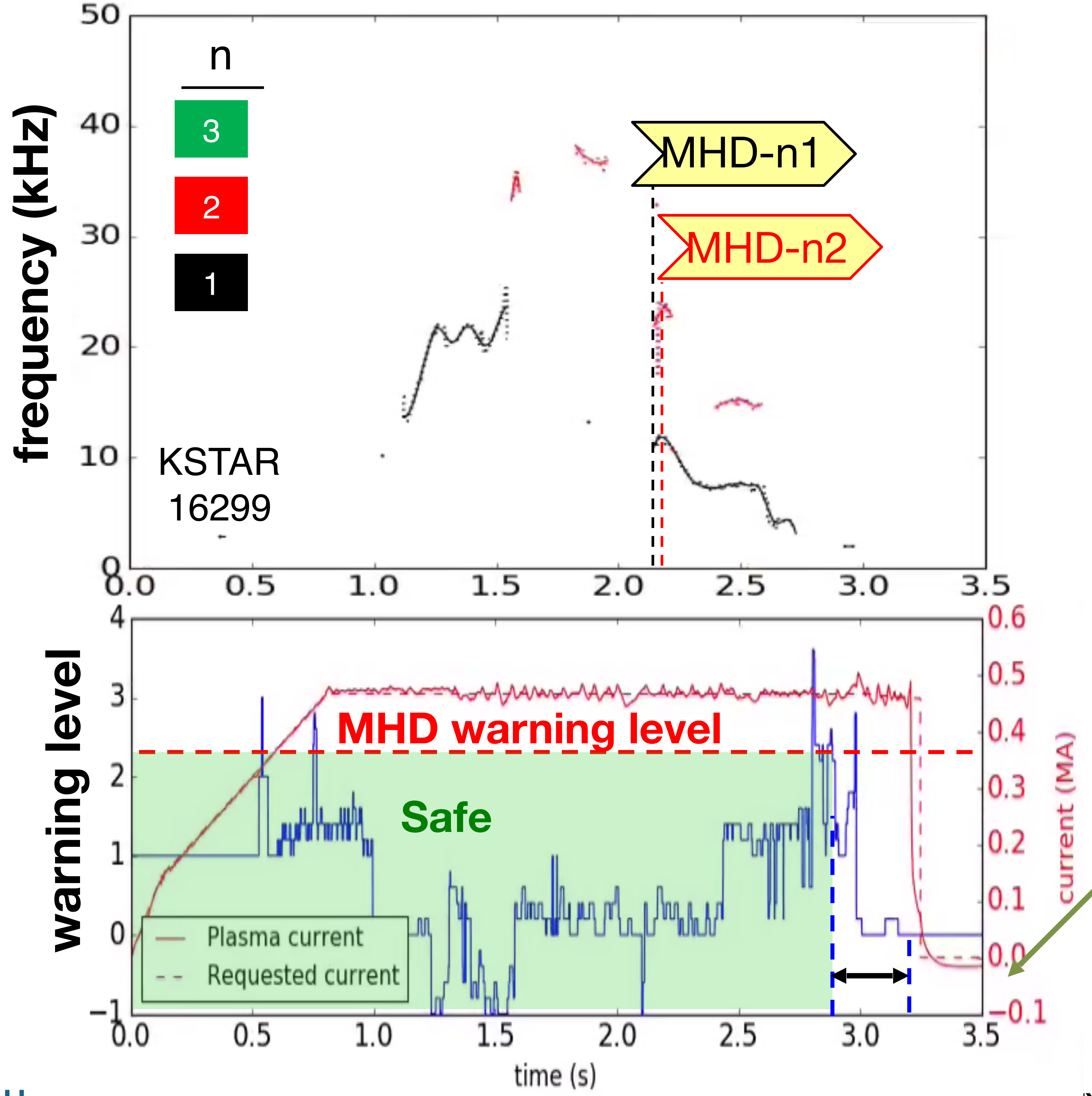


Sabbagh, et al., Nucl. Fusion 46 (2006) 635

VALEN code analysis produces similar distortions to MAST and NSTX observations

DECAF MHD events are now producing early disruption warnings for KSTAR

DECAF automated MHD objects



- **DECAF* is a physics-based disruption algorithm**
- **Mode locking at reduced plasma rotation**
- **Key notables of MHD warning**
  - "Safe"/"unsafe" MHD periods
  - Early disruption warning (300 ms) → on transport timescale

***D. Humphreys, et al., PoP 22 (2015) 021806**
S.A. Sabbagh, APS DPP Invited talk (2018)

Outline

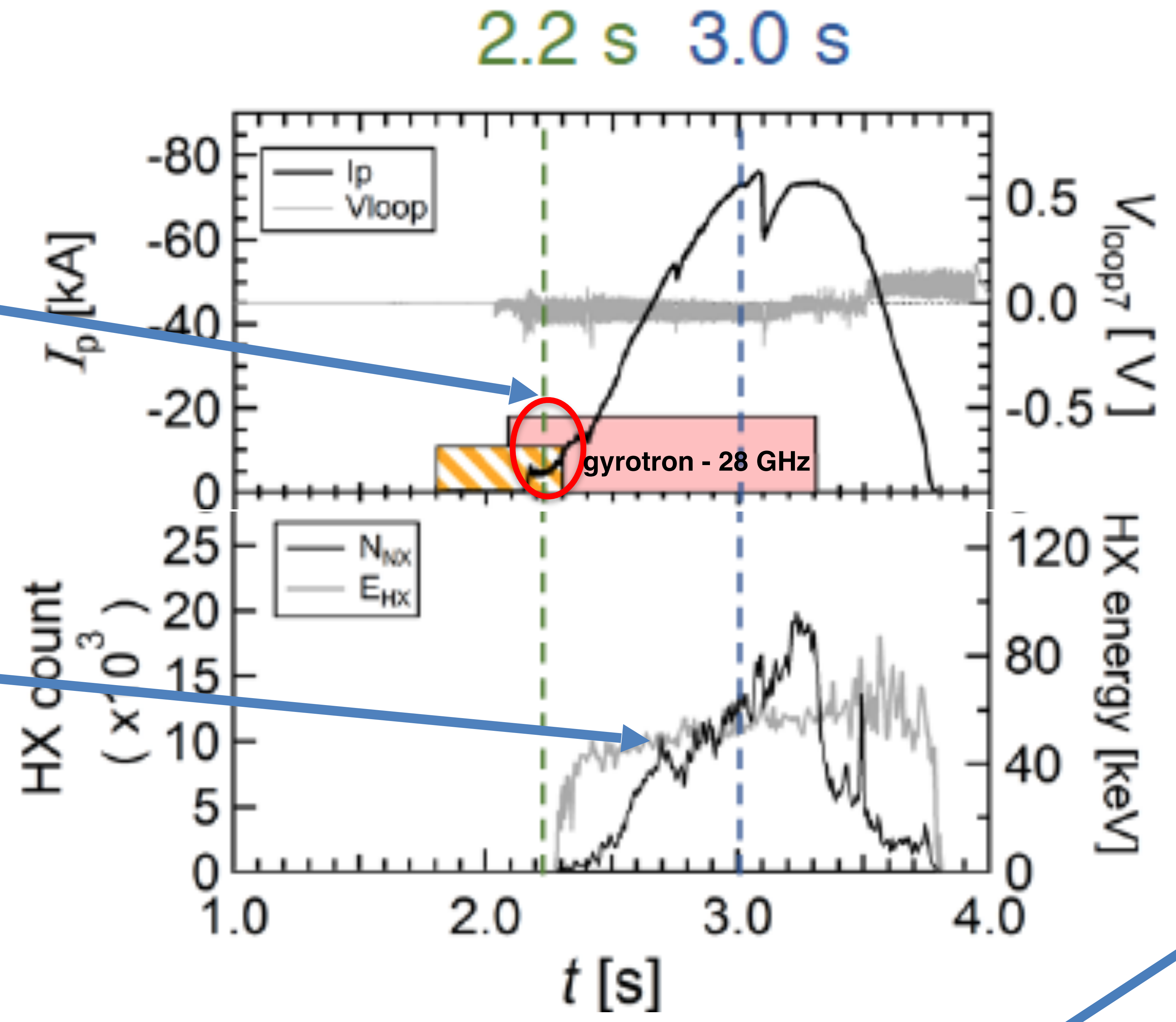
- Scenario development
  - Optimize non-inductive startup and ramp up, including active controls plasma (QUEST, URANIA, MAST (+U), NTSX(+U), KSTAR, DIII-D)
  - Assess impact of H species in HHFW heated plasma

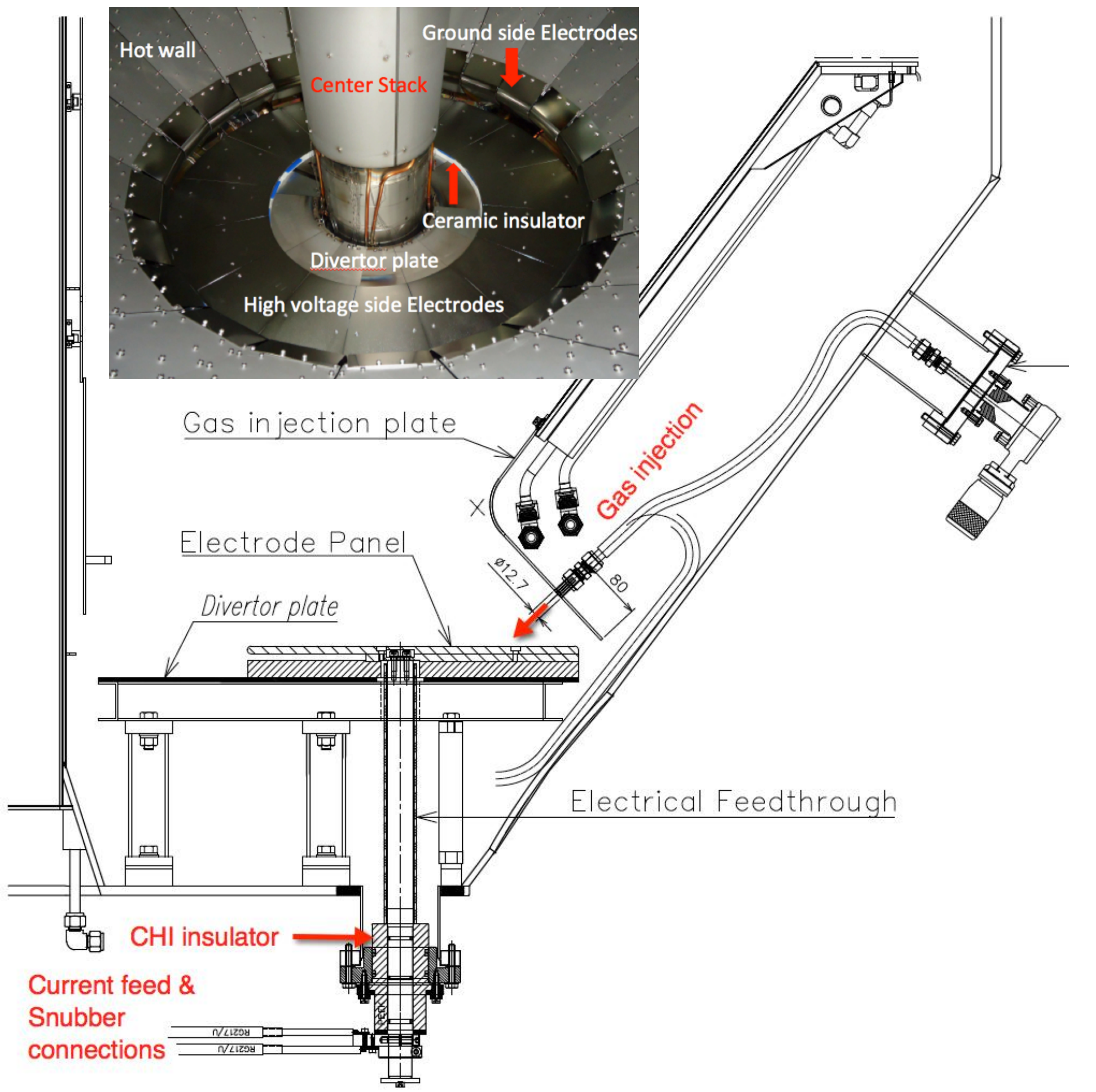
QUEST ECH provides unique opportunity to understand and optimize ECH based tokamak/ST start-up/ramp-up concept

- **Experiment and modeling of 2nd harmonic electron cyclotron heating and current drive solenoid-free start-up in QUEST**

Initial pressure driven current phase
- No X-ray
- No ECCD

ECCD Phase
- Increasing X-ray – energetic electrons
- $I_p \propto I_{X\text{-}ray} \propto n_{eh}$
- Minority energetic particle population





- **Transient CHI on QUEST has shown reliable discharge initiation, and plasma growth in biased electrode configuration**
  - **CHI to be tested also on URANIA**

N. Bertelli, invited talk at the 23rd Topical RF Conf. (China, 2019)

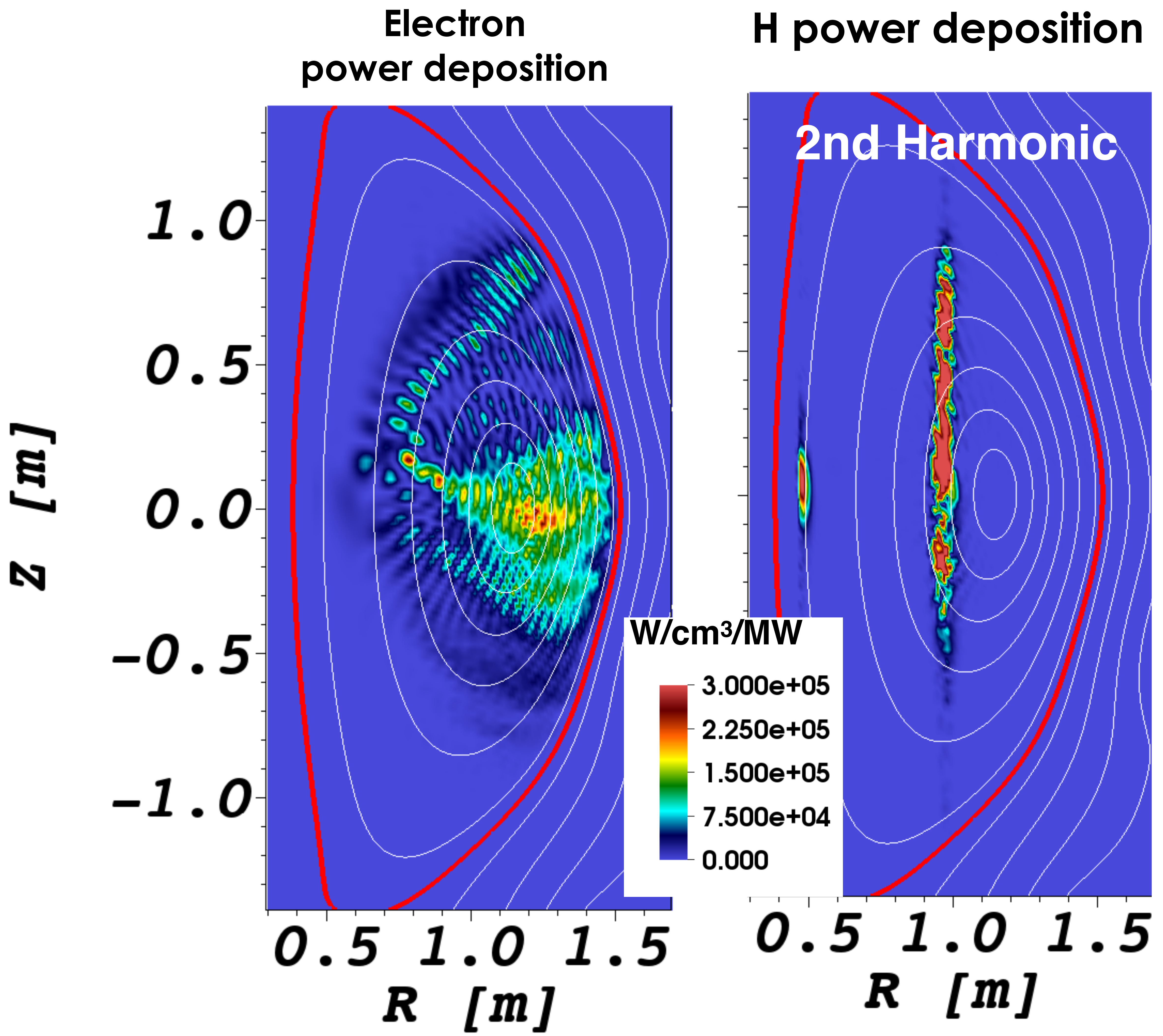
Exploring optimized HHFW with H species

Performed through the RF SciDAC collaboration

2D power deposition obtained by AORSA full wave code

10% H concentration case & $n_{\varphi} = -12$, f=30MHz, and B_T = 1T

Could provide an attractive path for 2nd harmonic H minority heating in NSTX-U (perhaps in the ramp-up phase)



N. Bertelli, invited talk at the 23rd Topical RF Conf. (China, 2019)

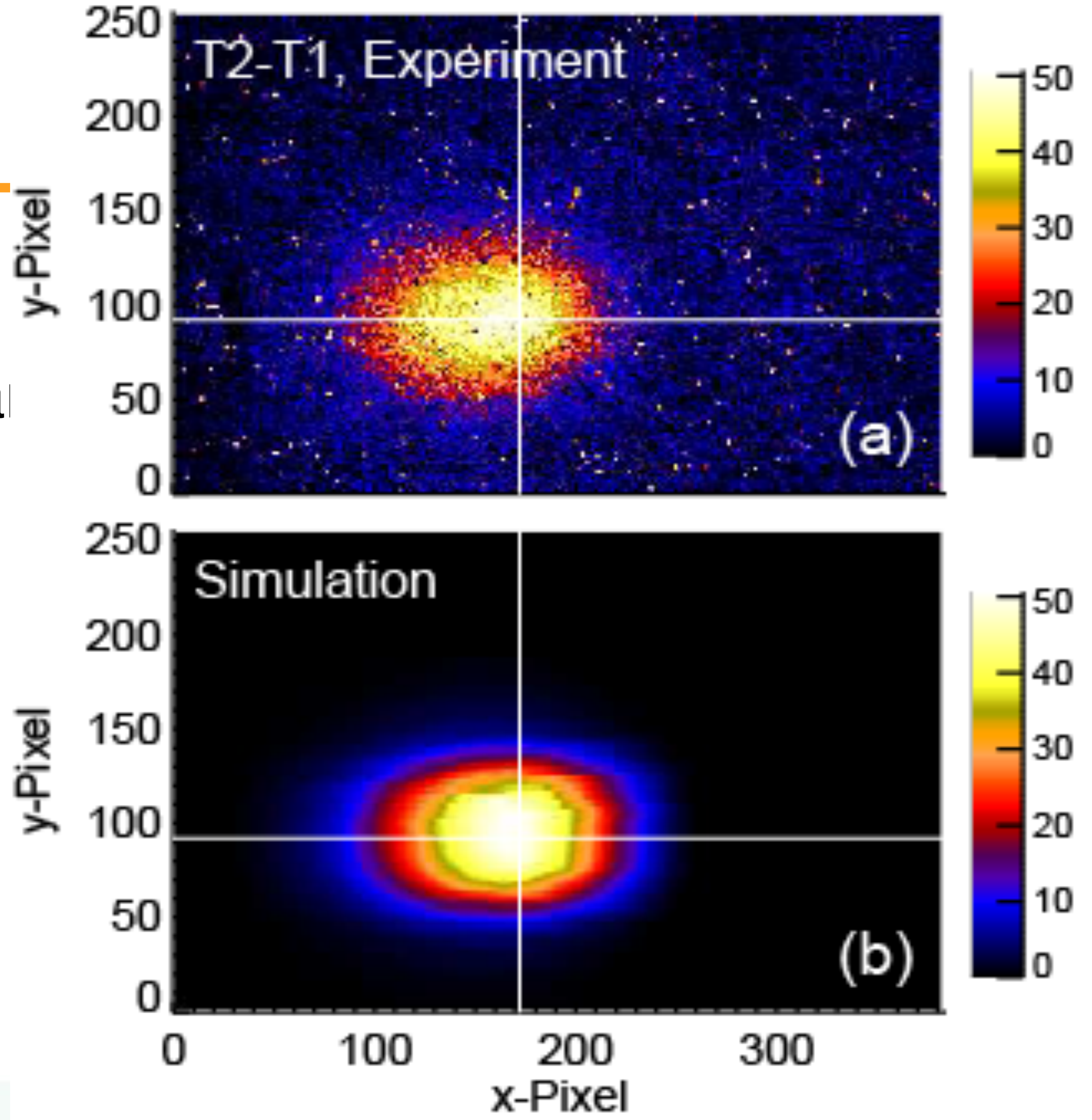
Outline

- Diagnostics development
  - Comprehensive measurements for EP distribution and impurity studies
  - Implementation of real-time capable DECAF

New/Upgraded Fast Ion Diagnostics/Tools to Improve Phase Space Coverage and Accuracy

- **Fast-Ion D-Alpha Imaging**
  - Much better spatial resolution
  - Simultaneously get FIDA energy spectra with beam splitter

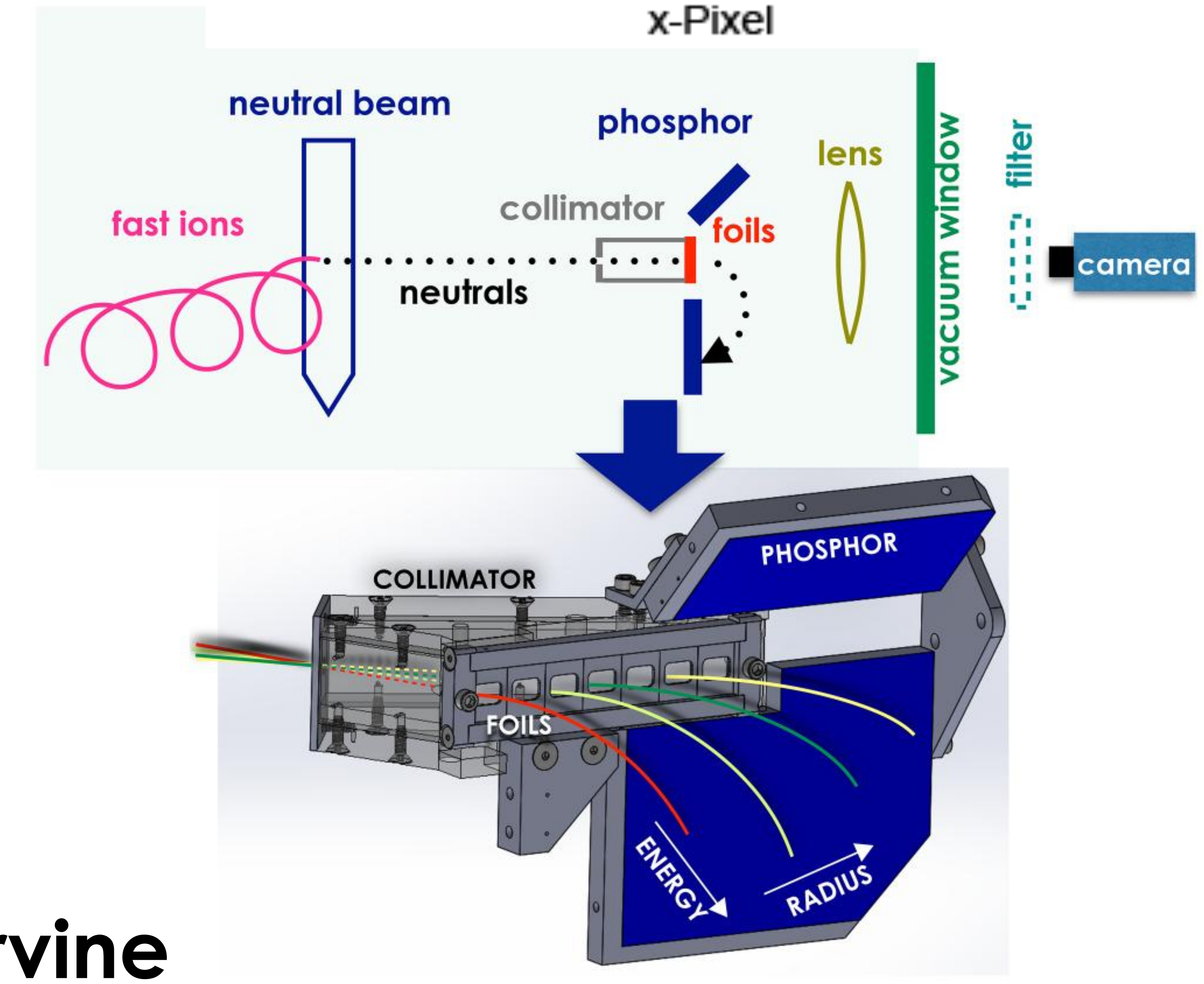
FIDA Imaging On DIII-D
M. A. Van Zeela
PPCF (2009)



- **Imaging Neutral Particle Analyzer (INPA) provides radially resolved image**
  - Gyroradius ➡ energy
  - Line-of-sight ➡ radius

- **Test NSTX-U neutron electronics at DIII-D**

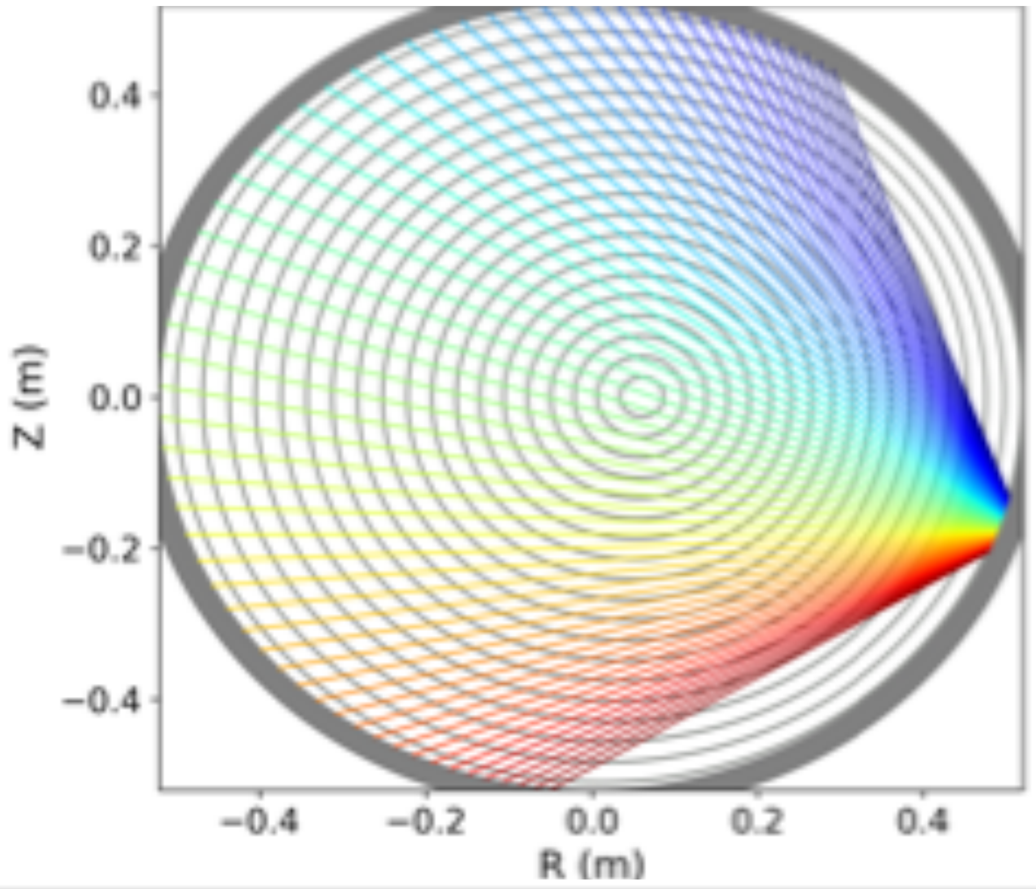
- **Inference of fast-ion distribution function with all available fast-ion diagnostics (software development)**

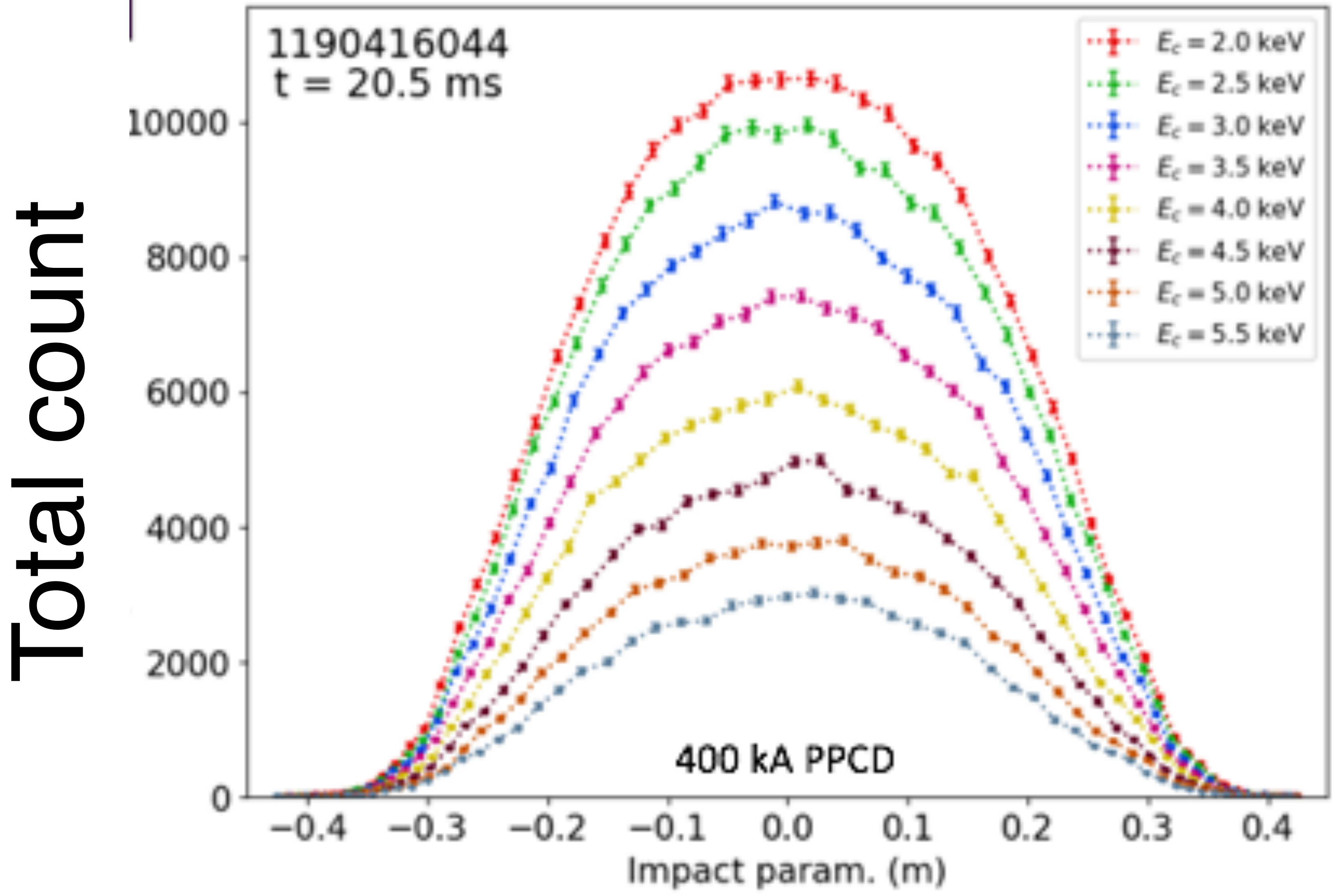


UC Irvine
INPA on DIII-D X.D. Du NF(2018)

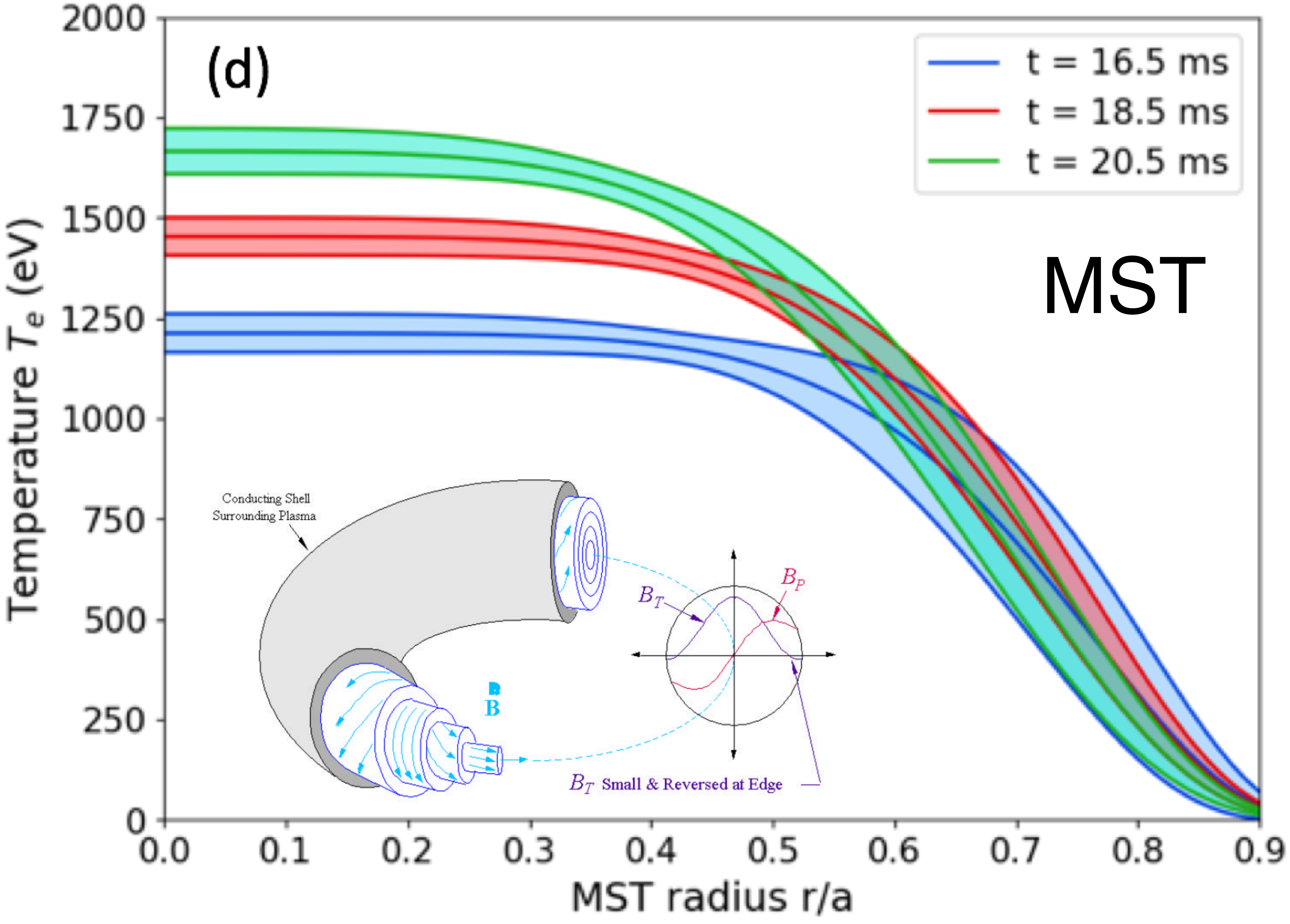
ME-SXR diagnostic tested at MST: originally designed to be installed on NSTX-U for impurity transport experiments

Large # of viewing chords & high energy resolution





SXR-inferred $T_e(r,t)$ measurement @ MST

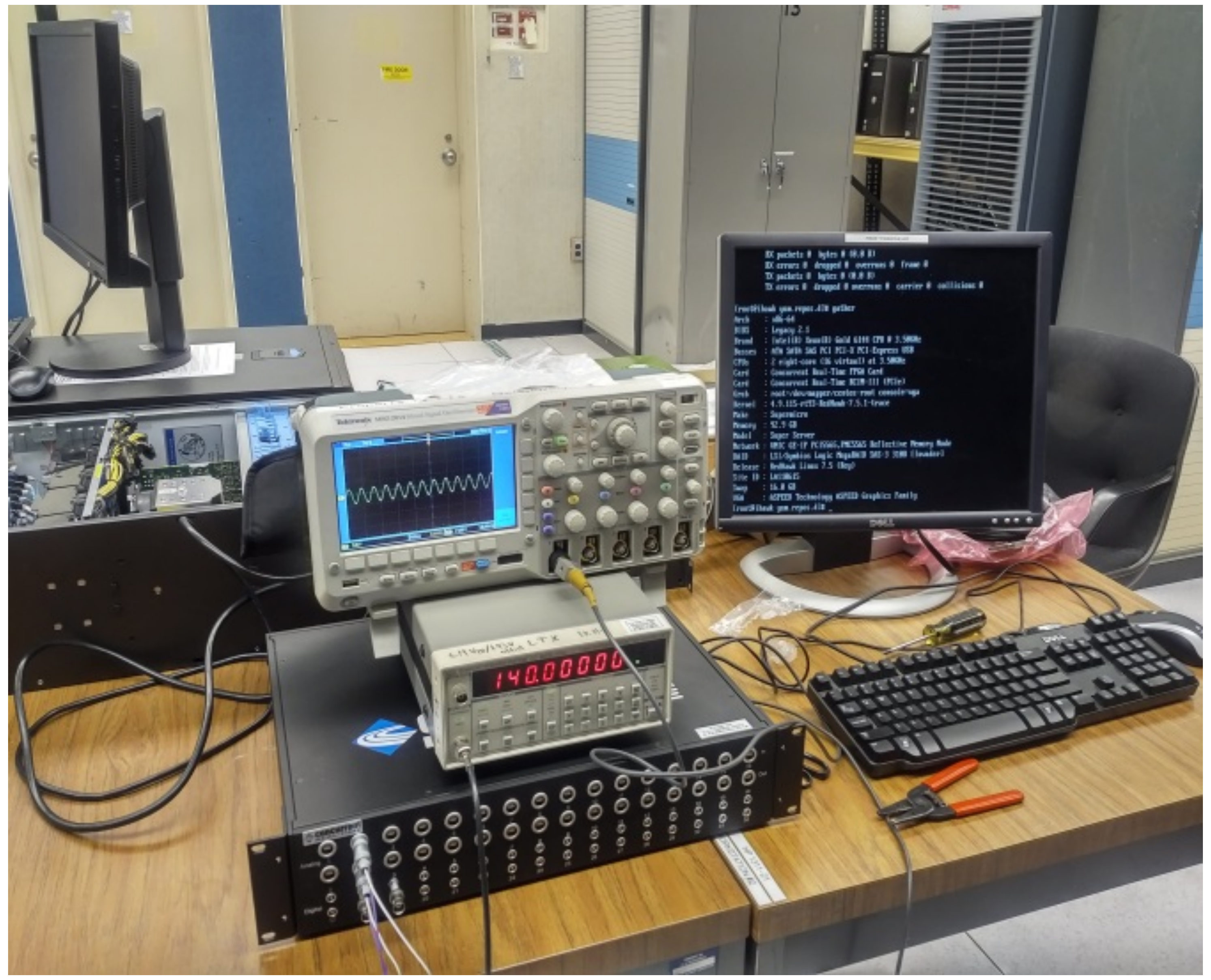


Disruption prediction and avoidance research on KSTAR moving to real-time application in 2019

S.A. Sabbagh, et al.

<u>Disruption Prediction</u>
First real-time computation of DECAF MHD analysis planned for 2019

<u>New</u> KSTAR r/t MHD computer and test stand (Columbia U. / PPPL)



- <u>Real-time computer now online at KSTAR</u>; r/t DAQ tests start on 9/10/19

- <u>Plasma Stability and Disruption Avoidance</u>
  - Resistive wall mode active control system with required r/t sensor compensation completed, ready for initial use in 2019
  - <u>New</u> U.S. DOE funding granted to greatly expand real-time capability

Summary

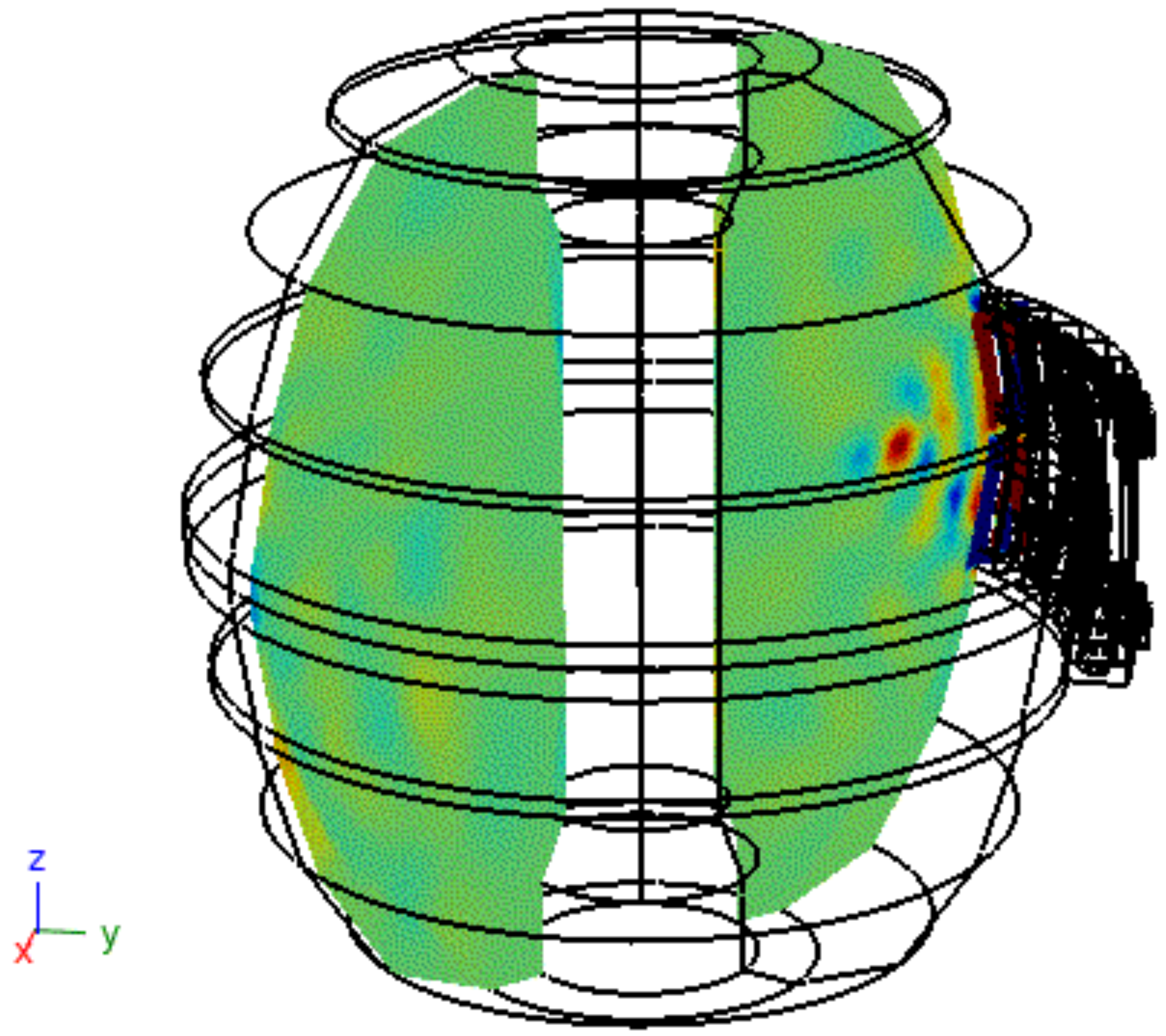
- During the recovery, NSTX-U Team remains actively engaged in research activities on NSTX/U and other devices
- Ongoing activities and collaborations address many issues common to NSTX-U and conventional aspect ratio tokamaks
- ST collaborations (MAST-U, URANIA, QUEST, ST40) can target ST specific issues necessary to advance tokamaks physics as well as impact and facilitate NSTX-U research

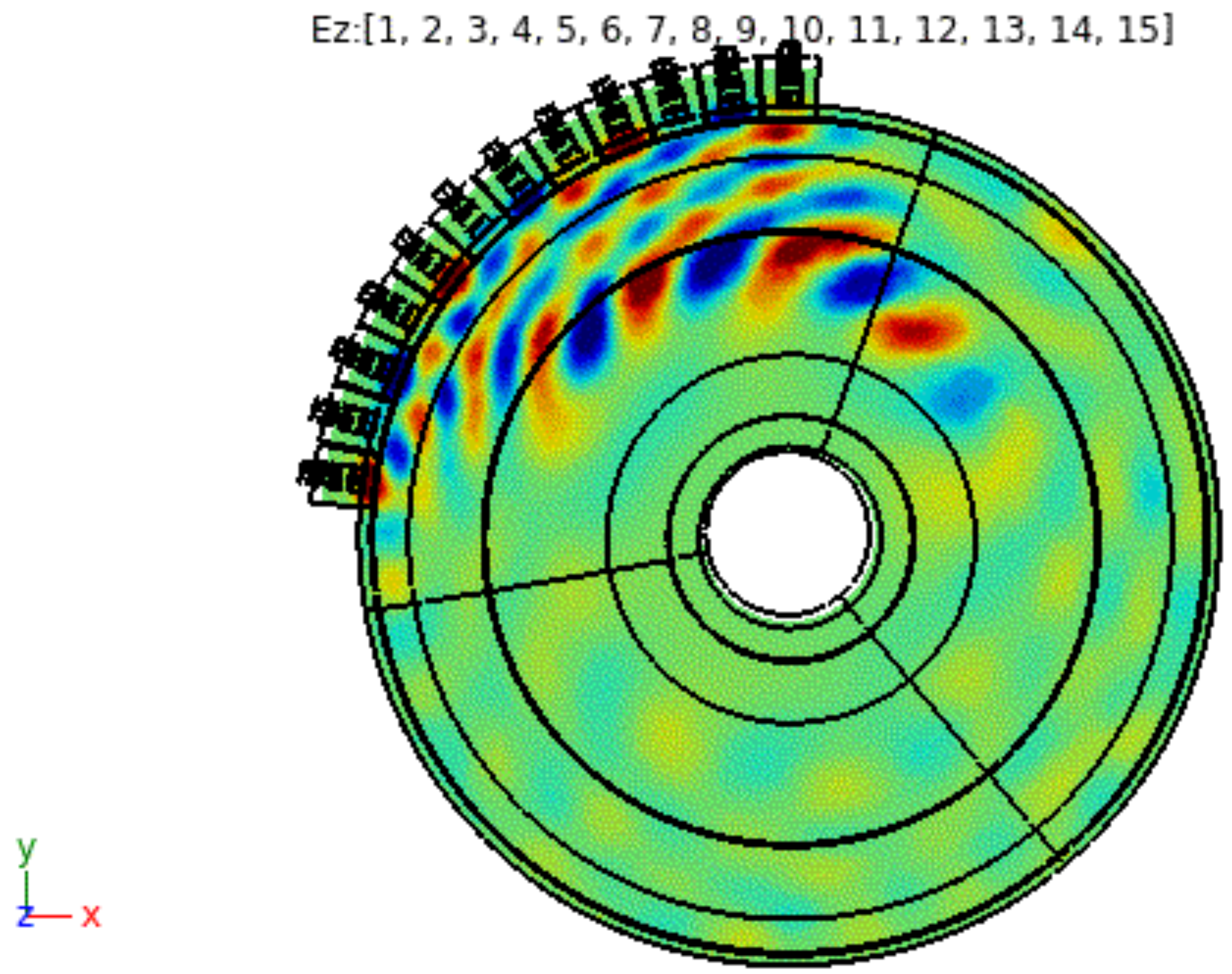
Backup

First full 3D torus simulation including realistic antenna geometry

- Performed using the Petra-M code developed by RF SciDAC team
- Extending to 3D enables accurate core-edge coupling with the antenna

E_z component for 90 degree antenna phasing





N. Bertelli, invited talk at the 23rd Topical RF Conf. (China, 2019)

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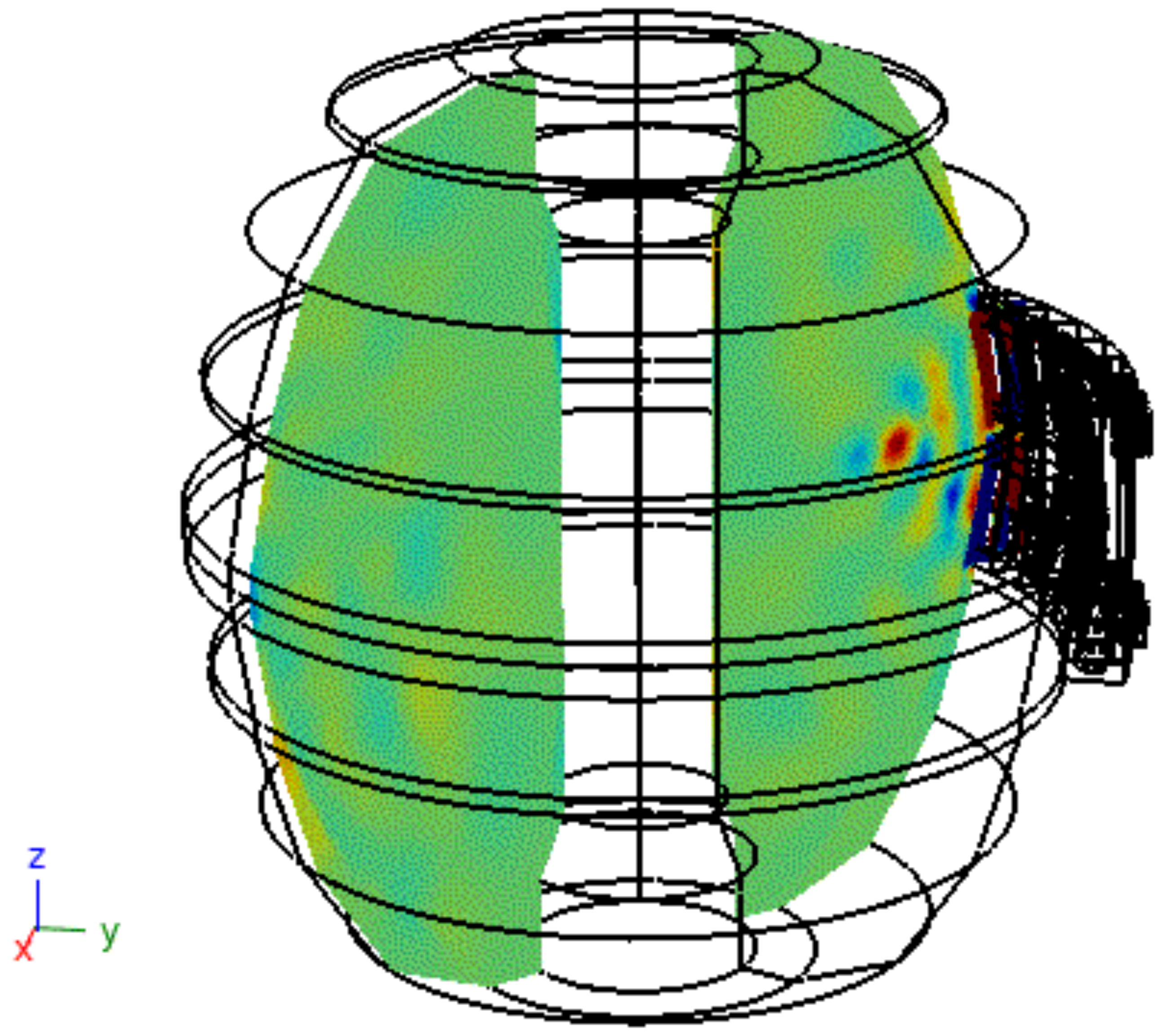

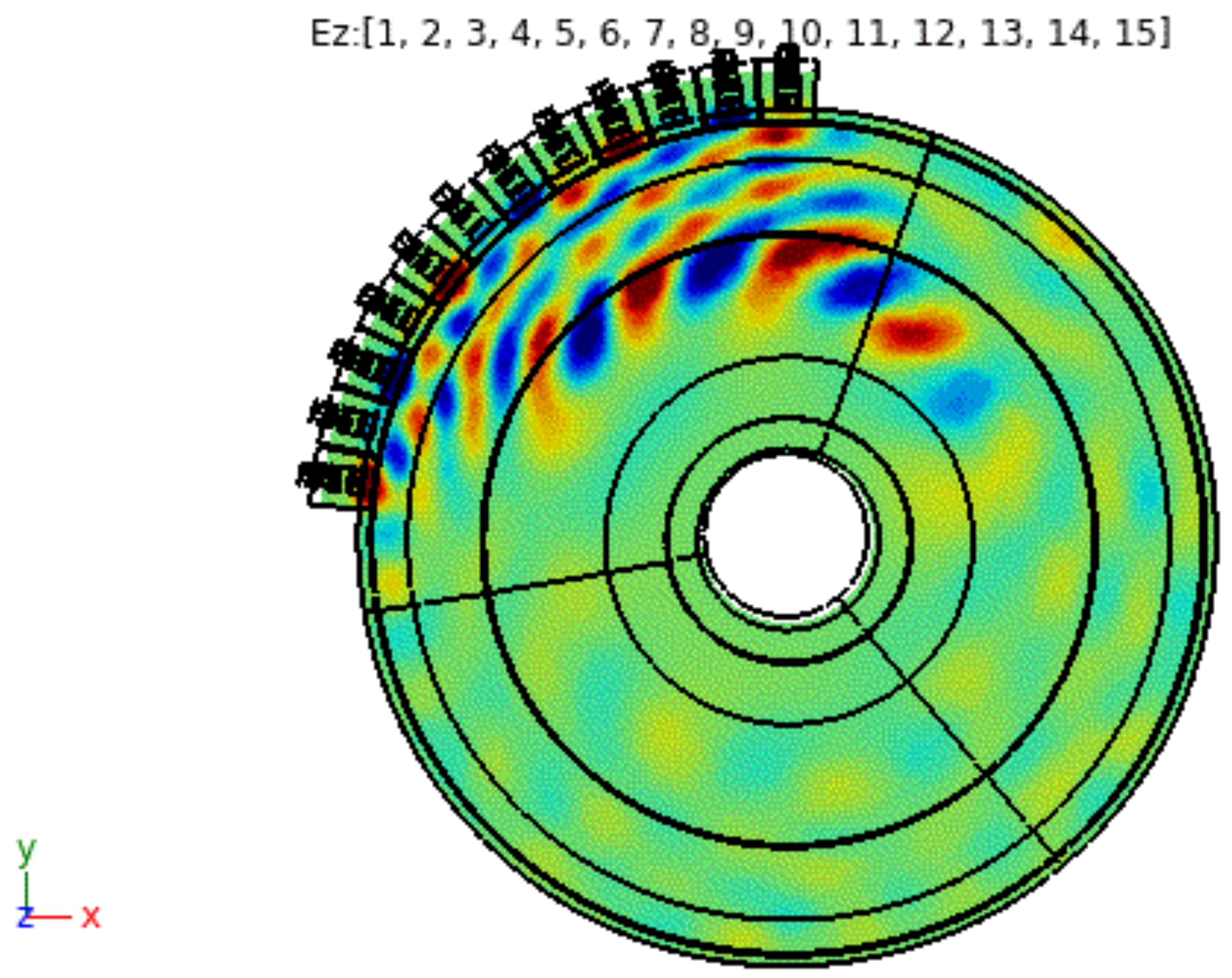

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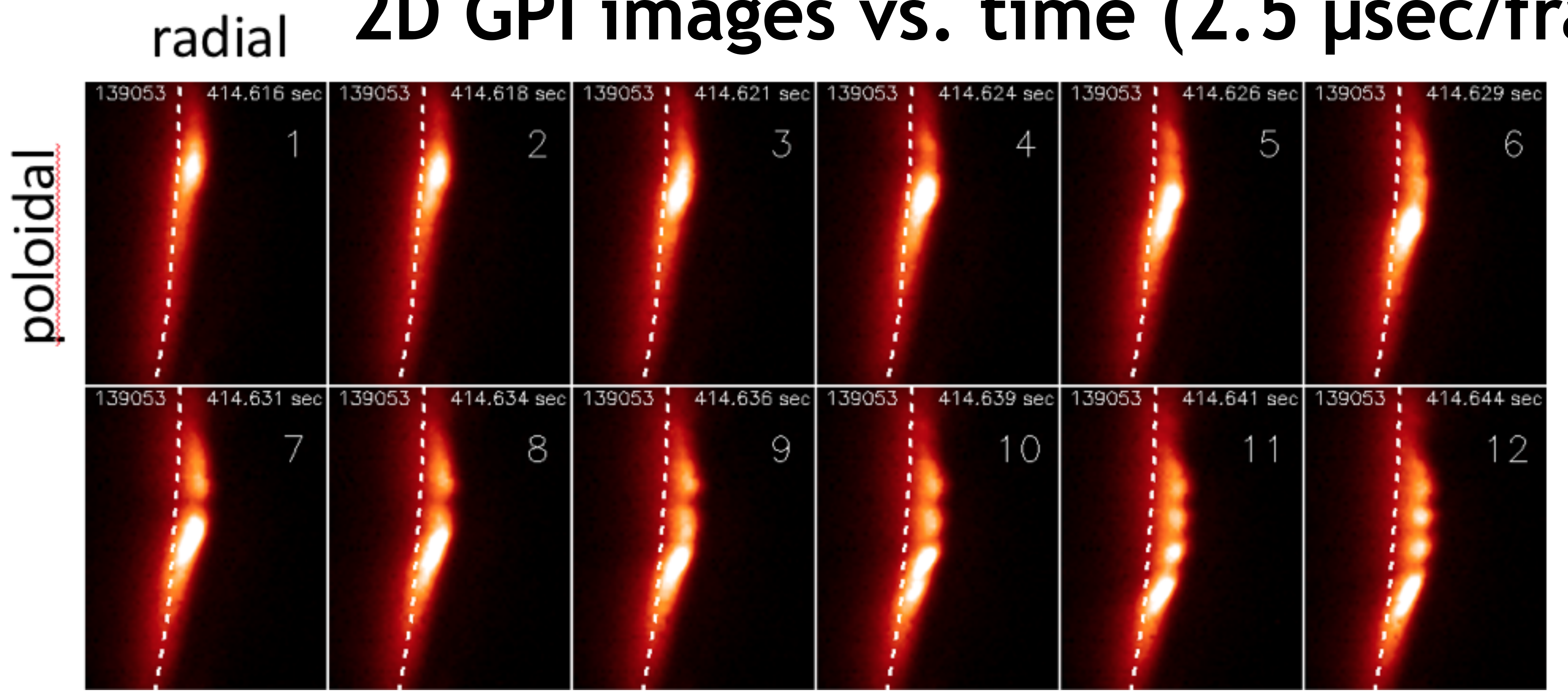
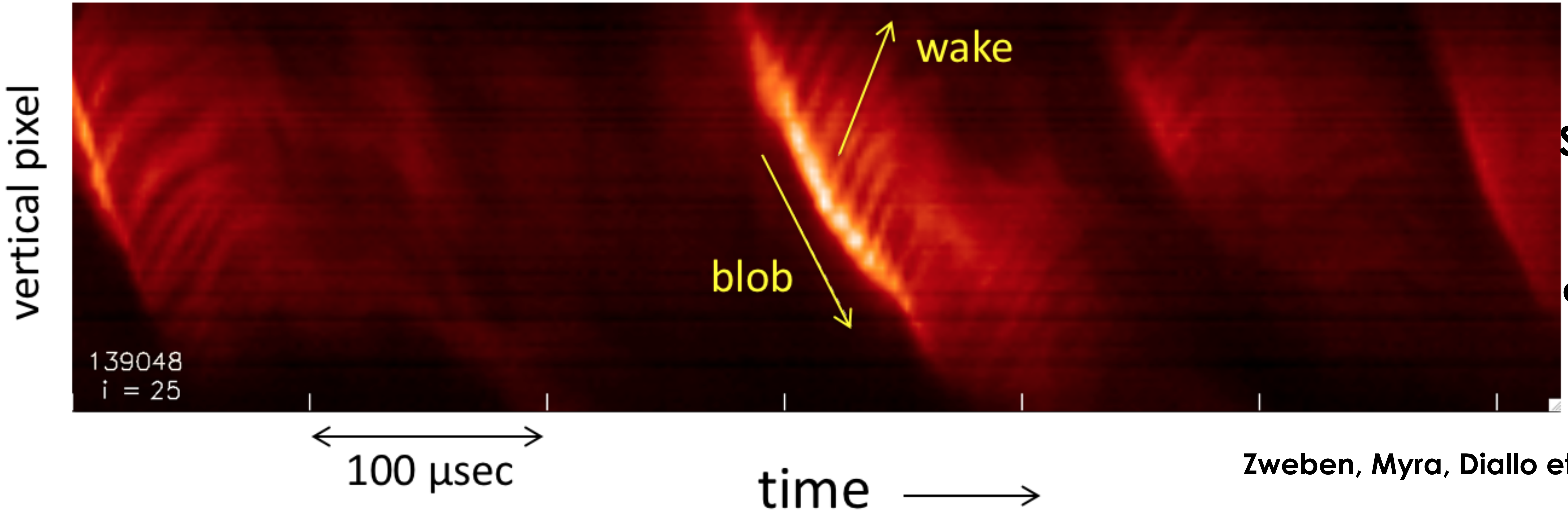
Novel Phenomenon: Blob Wakes in NSTX

- **Blobs sometimes break up into trailing small-scale "wakes"**
  - Direction: poloidally in the opposite direction to the blobs (i.e. wakes move in electron diamagnetic direction)
- **Theory : blob wakes consistent with to drift or drift-Alfven waves instabilities**

2D GPI images vs. time (2.5 μsec/frame)



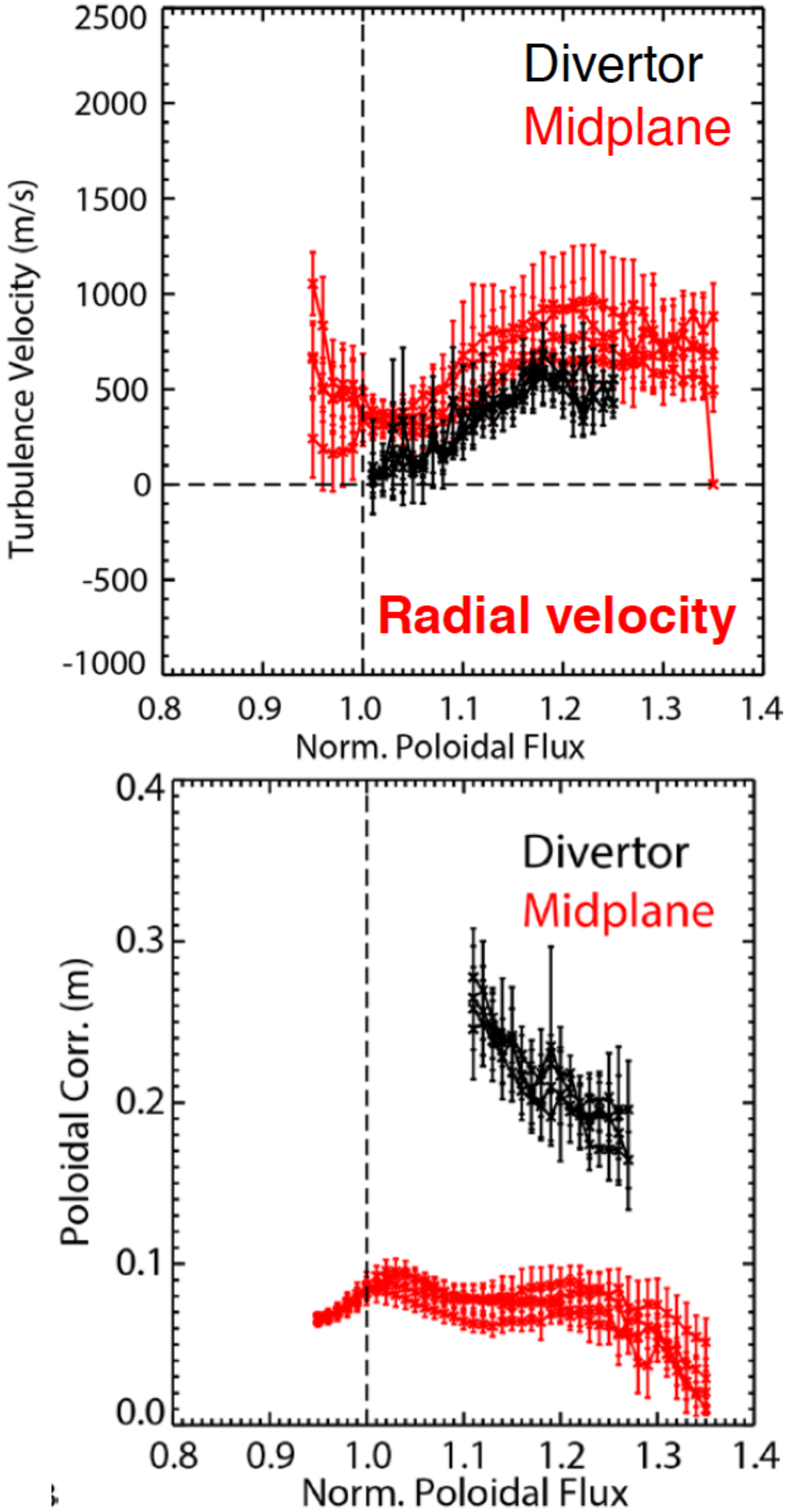


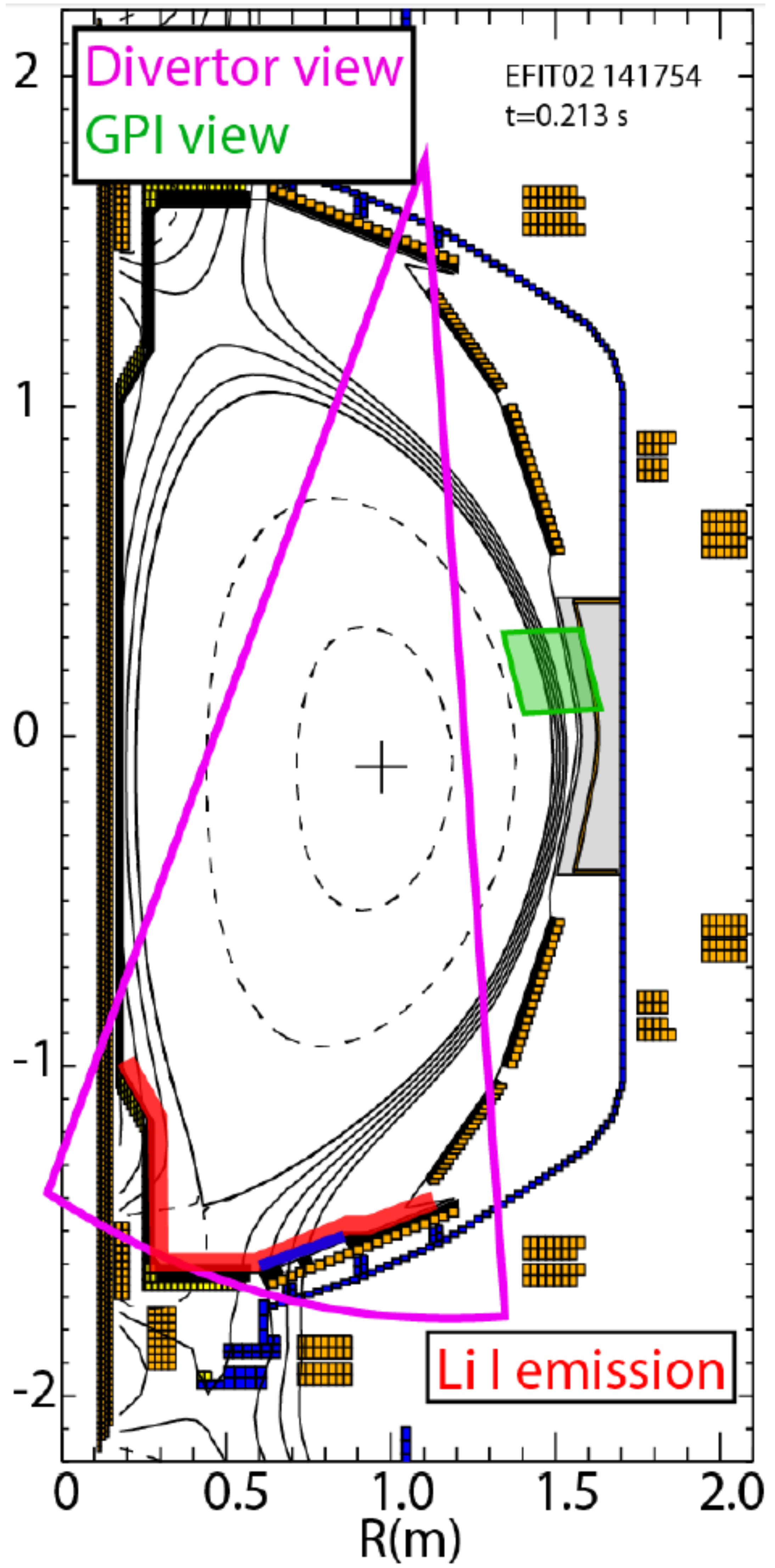
Single column of 2D data vs. time showing poloidal propagation of wakes (upward) vs. blobs (downward)

Zweben, Myra, Diallo et al, Phys. Plasmas 26, 072502 (2019)

Characterization of SOL and divertor turbulence in NSTX/NSTX-U via imaging of divertor fluctuations

- **Reduction in V_{rad} with respect to upstream V_{rad} approaching separatrix in disconnected region**
  - Midplane poloidal velocities in agreement with target filament velocity
- **~2x larger poloidal corr. length on divertor target**
- **Radial velocity reduction consistent with reduction in polarization drive due to X-point**
- **Imaging of diverter localized intermittent field-aligned filamentary structures is support by modeling**
  - Consistent with unstable resistive ballooning modes (ArbiTER code)



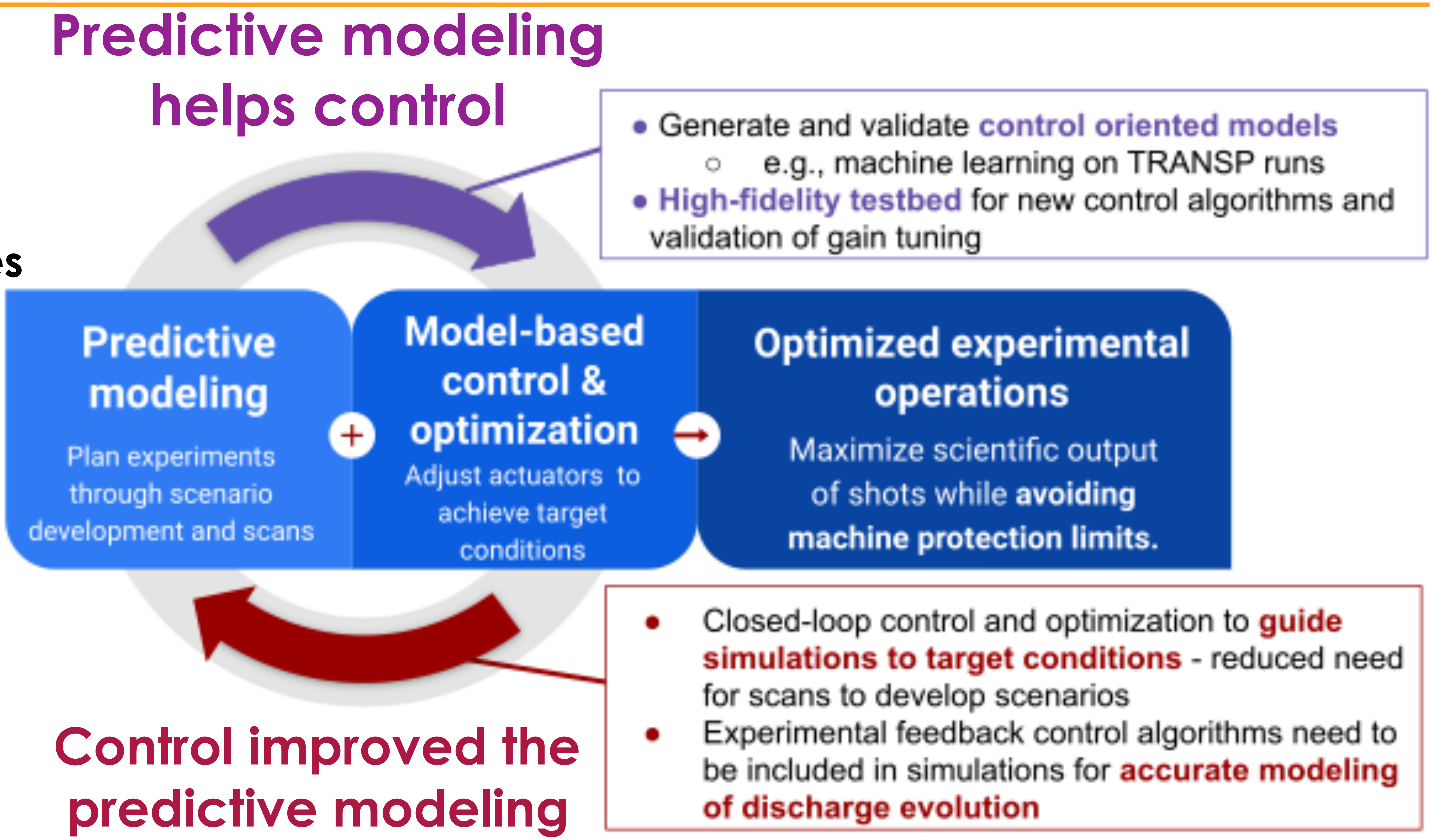


Scotti, Nucl. Fusion 58(2018) 126028

Enable external steering of TRANSP for control and scenario development

- Socket connection for TRANSP enables passing of information between actuators (NTV, beam, shape, ne, etc…) and controlled parameters (q, li, betaN etc..)

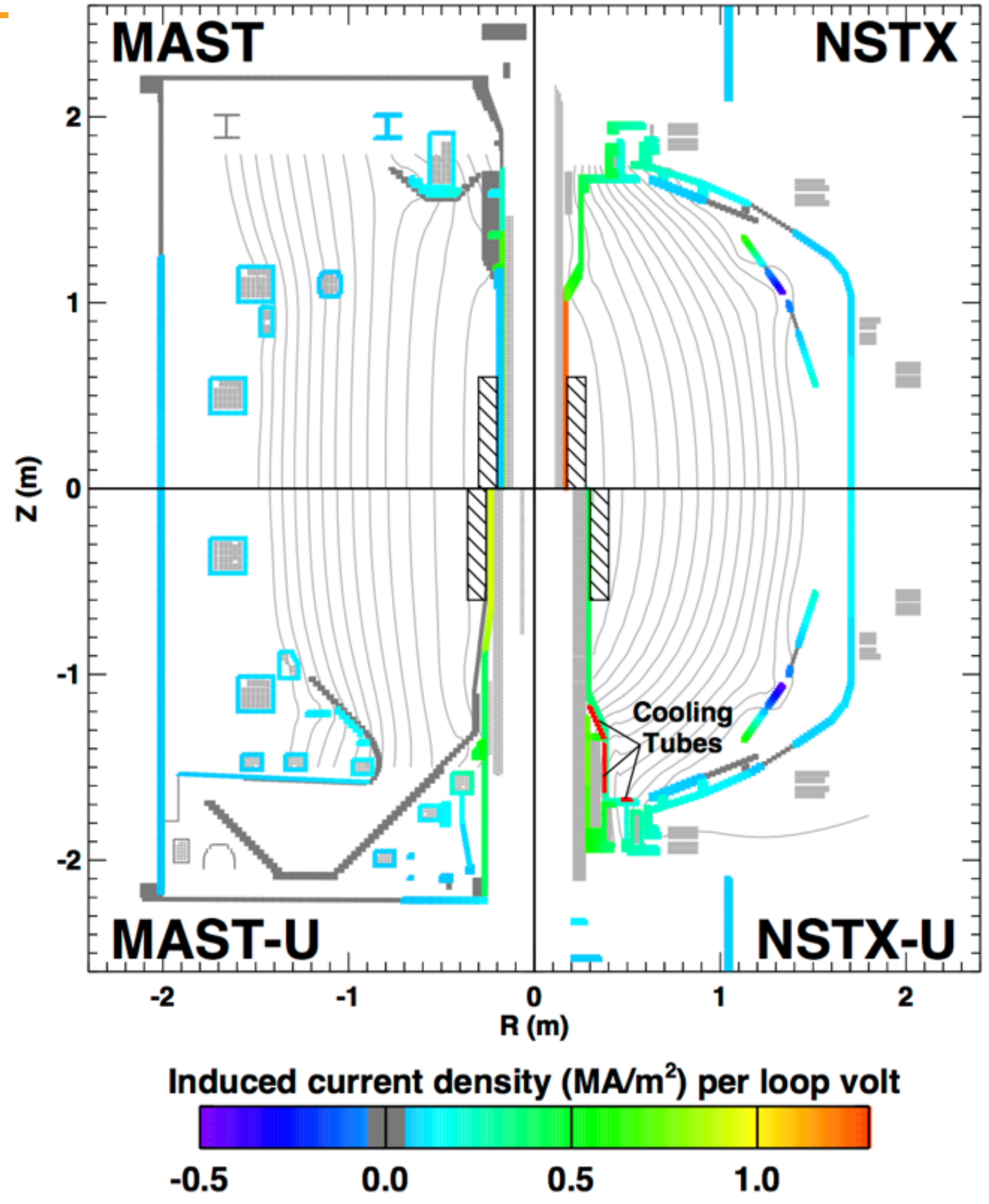
- Builds upon previous work on NSTX-U as well as KSTAR collaboration



e.g., Boyer, et al., Nuclear Fusion 2017.

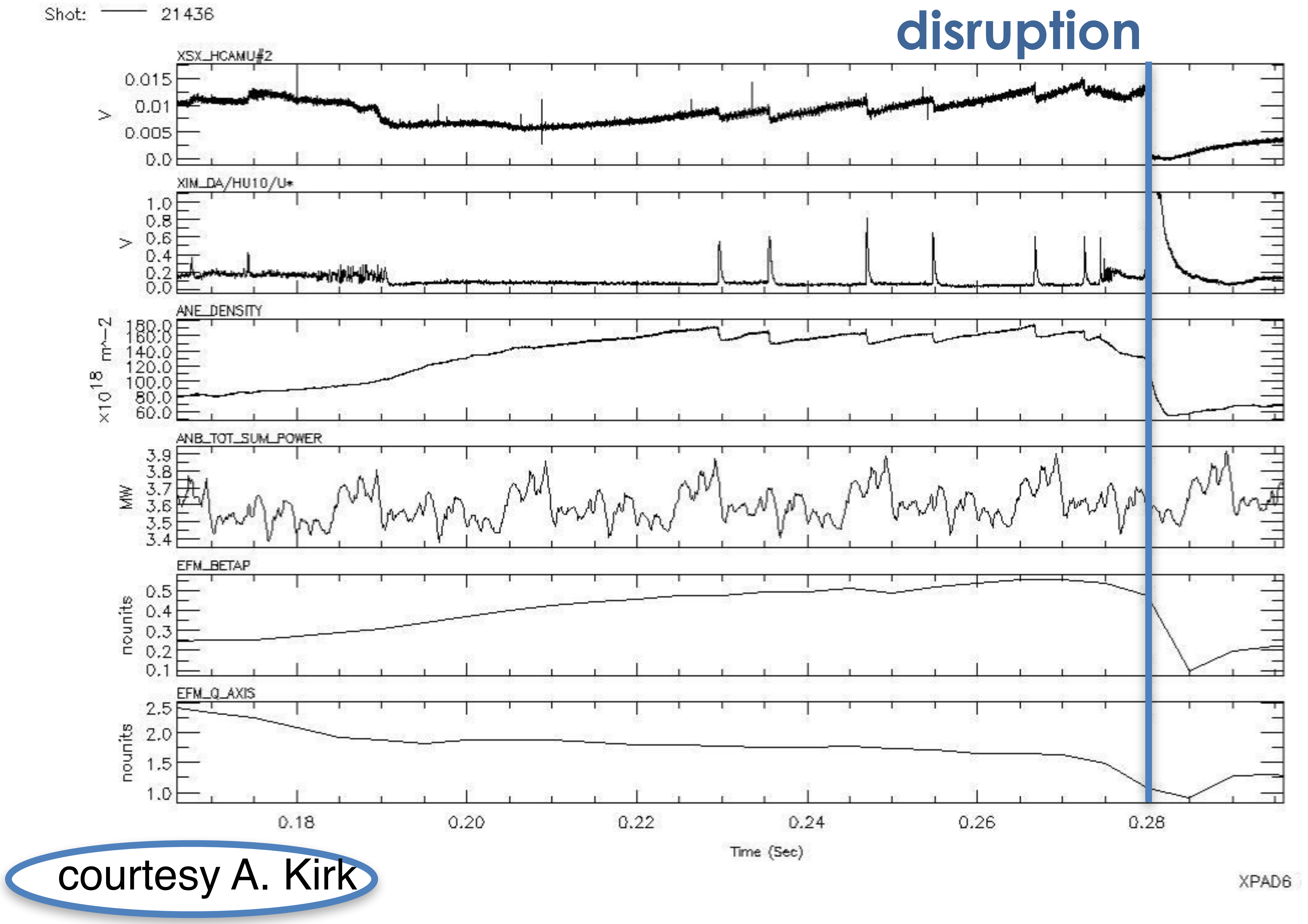
Collaboration with MAST-U led to development of novel, time-dependent model for evaluating startup on Spherical Tokamaks

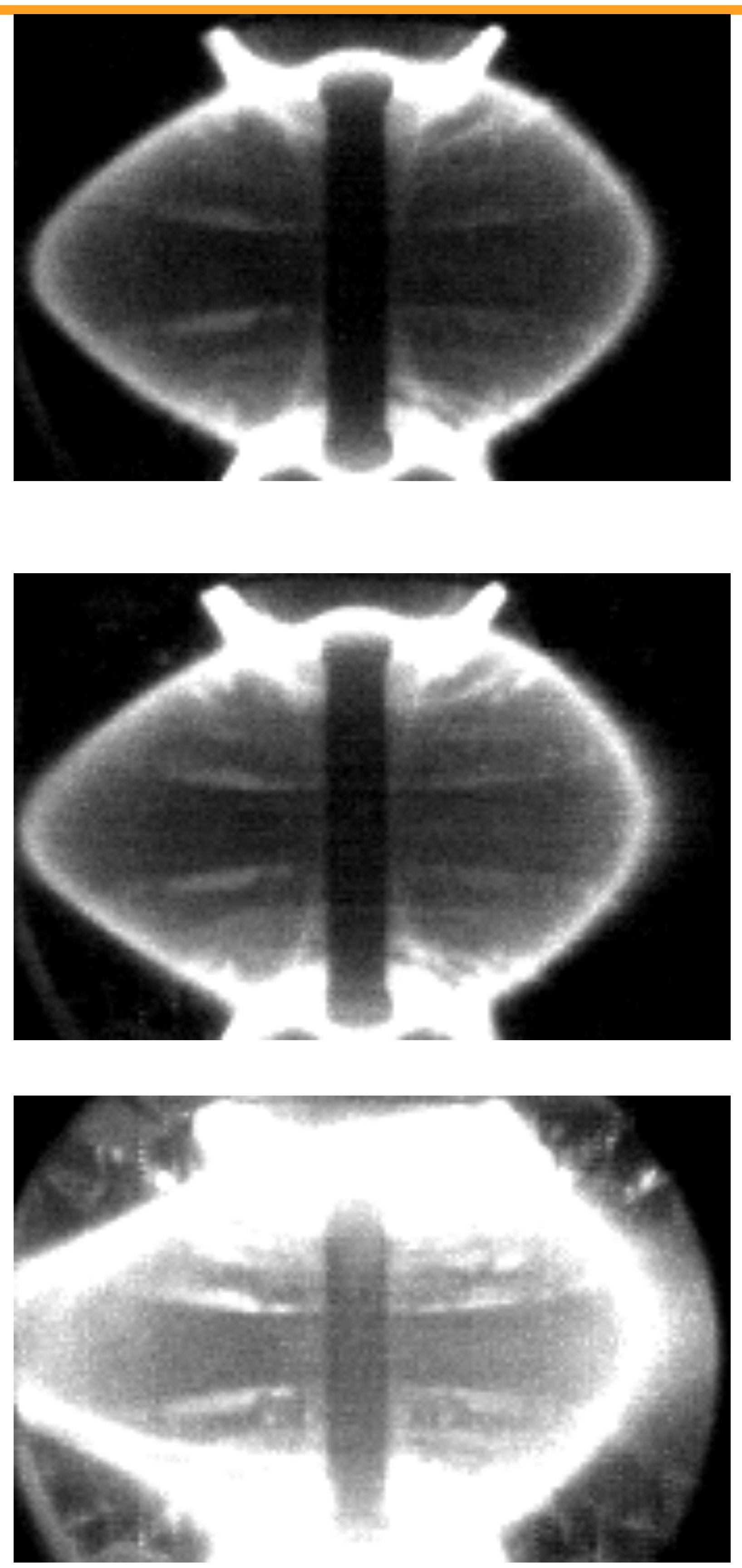
- **Vacuum calculation producing 2D, time-dependent E, B able to predict timing of startup in MAST-U and NSTX-U**
  - Includes reduced models describing Townsend Avalanche as well as particle loss on open field lines
  - Model developed and tested against shared database of MAST and NSTX(-U)
  - Applied model to scenario development to assist in MAST-U commissioning activities during summer 2018 appointment at CCFE
- **Supports broader effort to develop startup models for future tokamaks, such as ITER and is supporting experiments on DIII-D (summer, 2019)**



Battaglia, D. J. accepted, 2019 Nucl. Fusion

Apparent global mode "egg shape event" has been noted by A. Kirk regarding loss of H-mode → RWM on MAST





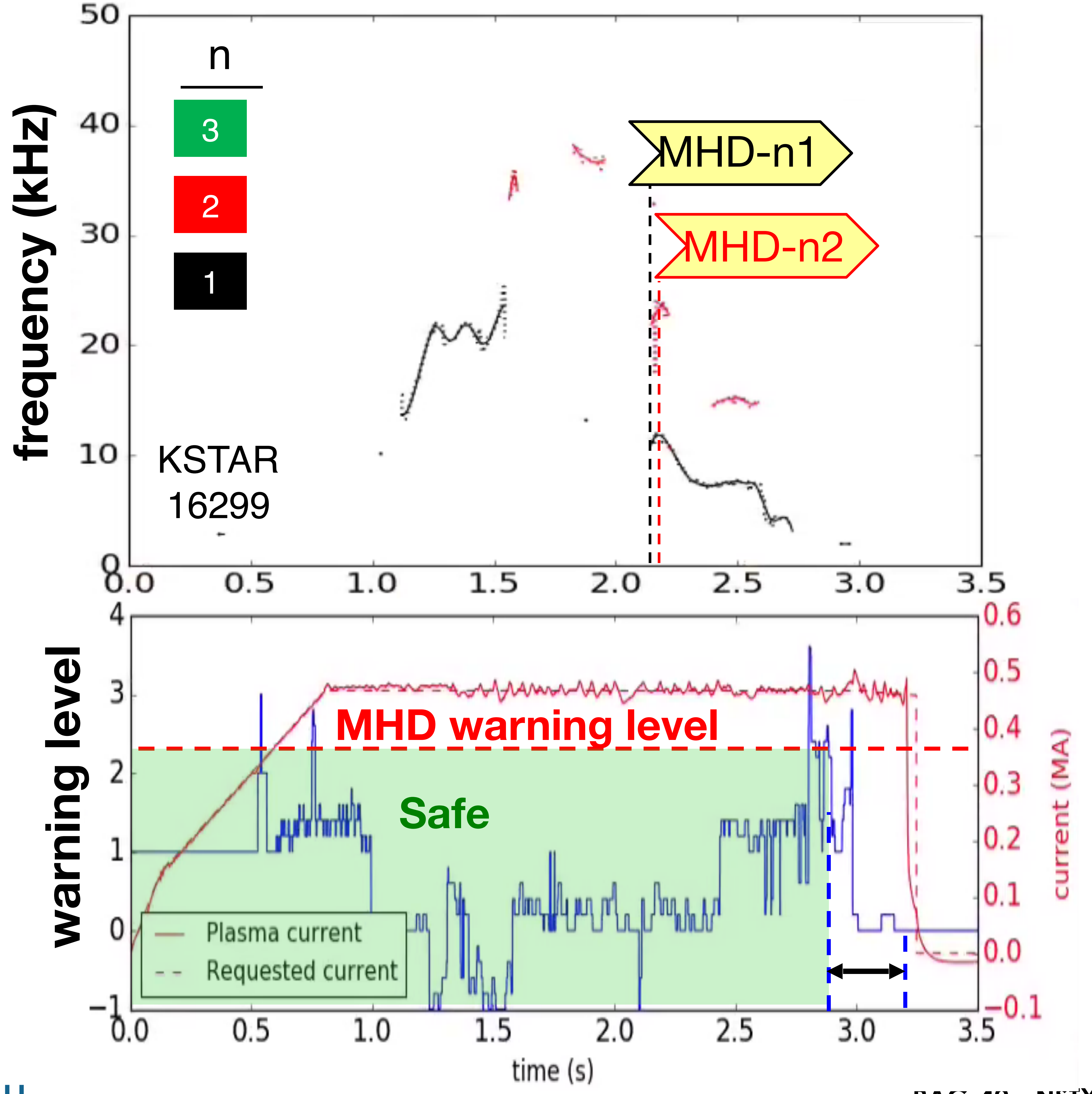
Fast camera images (21436, t ~ 0.280s)

- **Several shots display asymmetric, global events**
  - Consider that the "egg shape events" are global MHD →kink/ballooning/resistive wall modes (RWM)
    Q: does this follow "standard" theory? A: yes

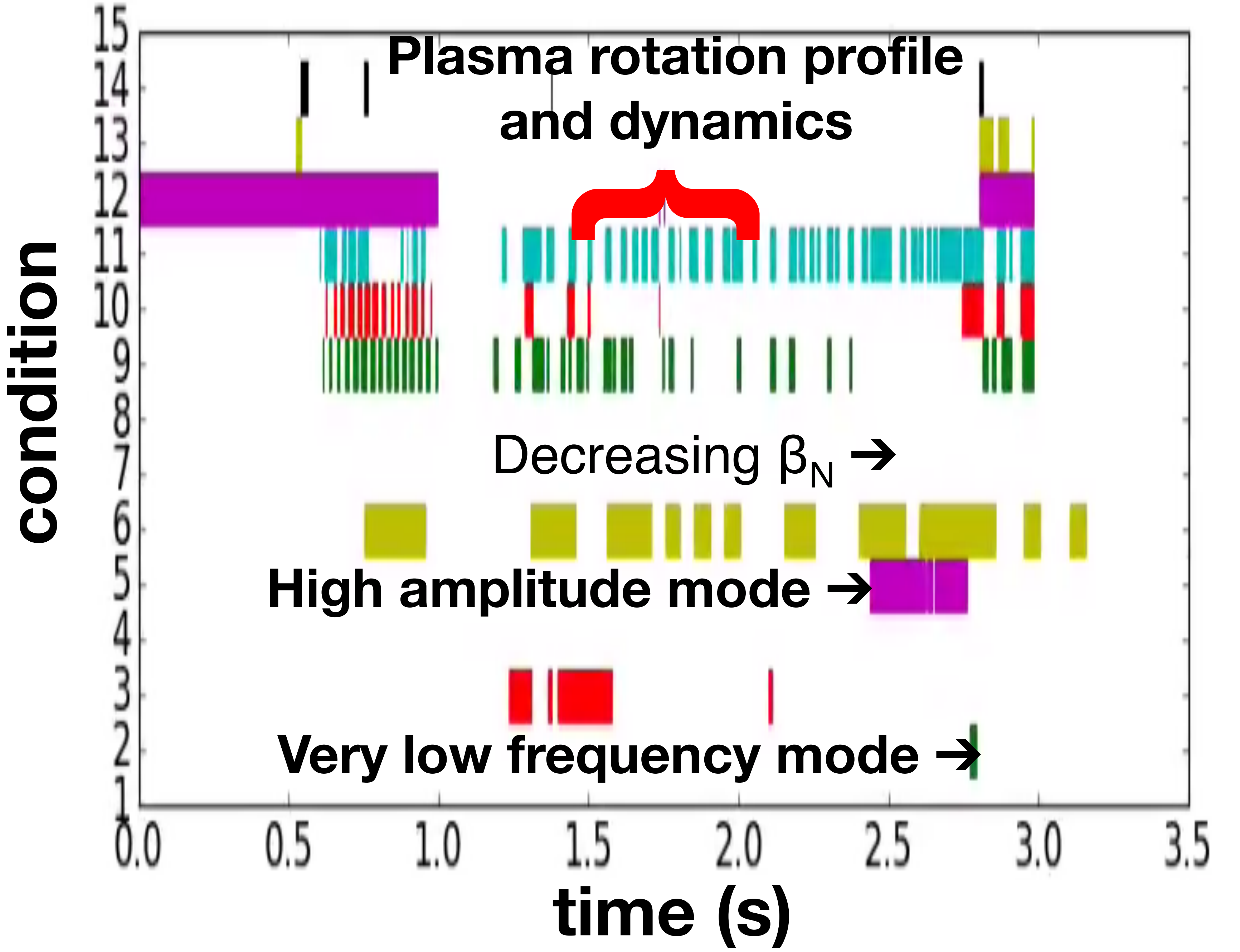
Mode locked toroidally, expands radially

DECAF MHD events are now producing early disruption warnings for KSTAR

DECAF automated MHD objects



DECAF "heat map" (for MHD)



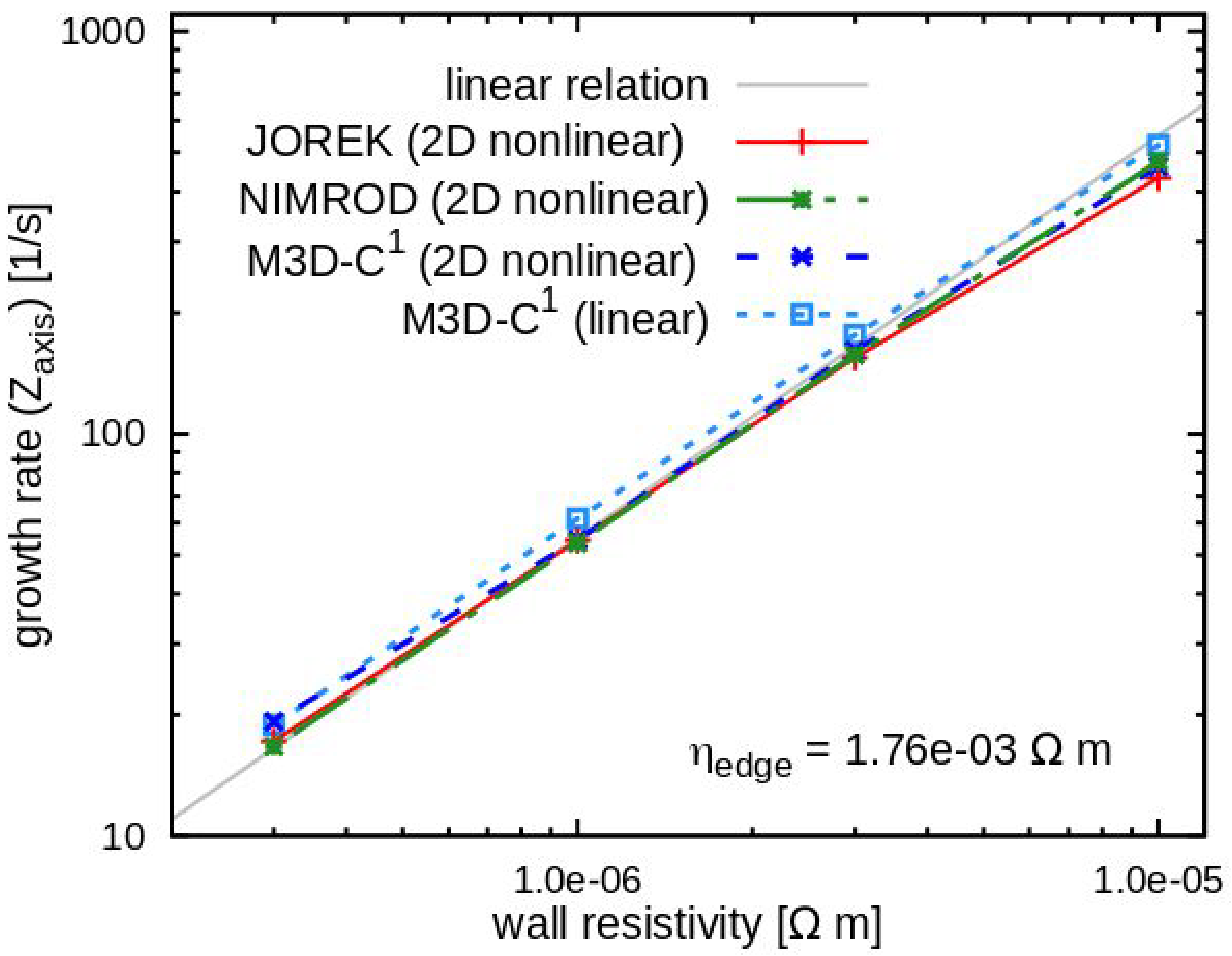
- **DECAF* is a physics-based analysis paradigm that meets all disruption predictor requirement metrics**
- **Mode locking at reduced plasma rotation**
- **Key notables of MHD warning**
  - "Safe"/"unsafe" MHD periods
  - Early disruption warning (300 ms) → on transport timescale

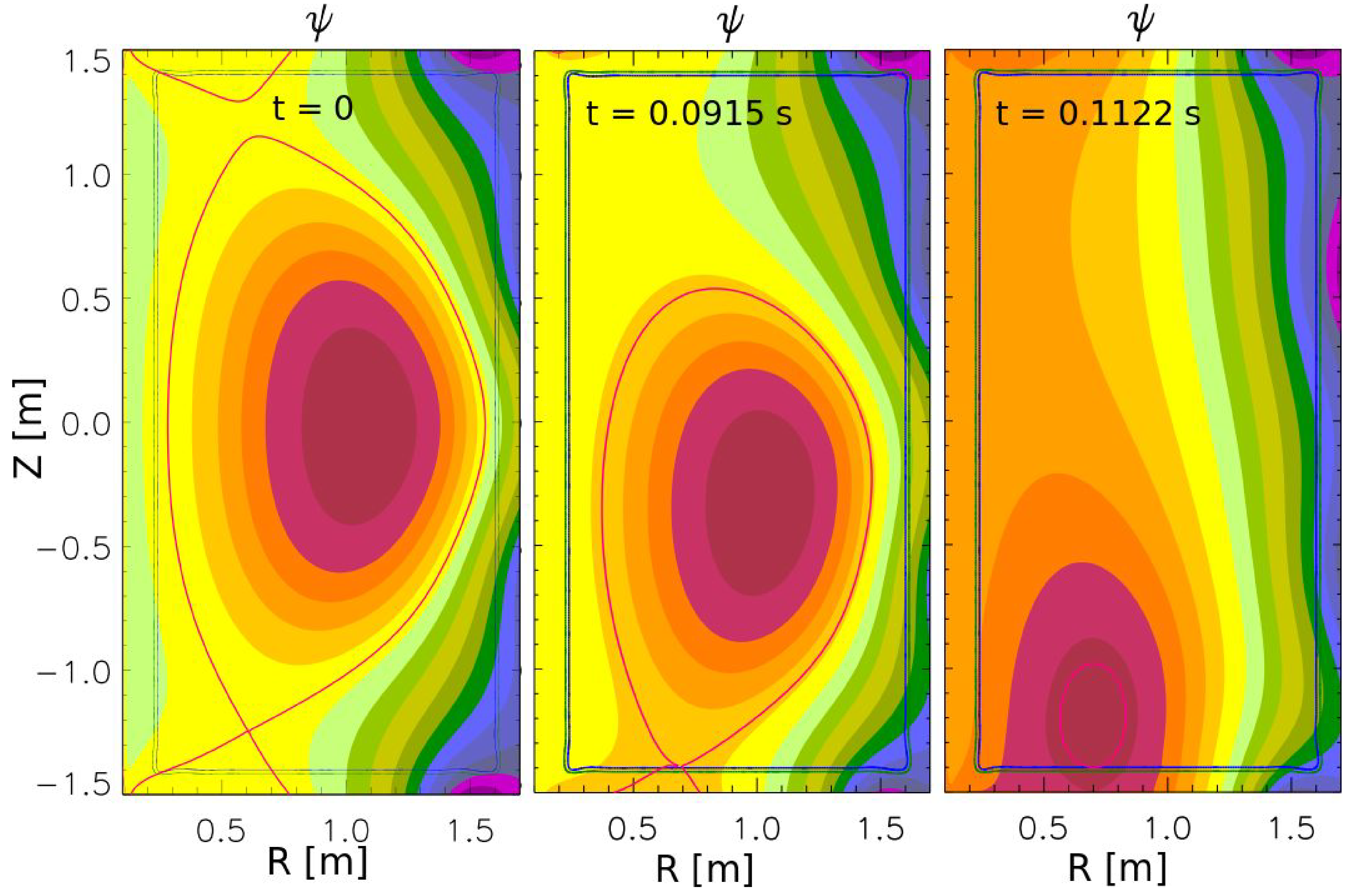
*D. Humphreys, et al., PoP 22 (2015) 021806
S.A. Sabbagh, APS DPP Invited talk (2018)

Successful benchmark of nonlinear MHD codes based on NSTX Vertical Displacement Event

- Axisymmetric VDE simulations with M3D-C1, NIMROD &
  - Based on NSTX #139536 with simplified resistive wall
  - Excellent agreement of linear growth rates & nonline halo currents between all three codes

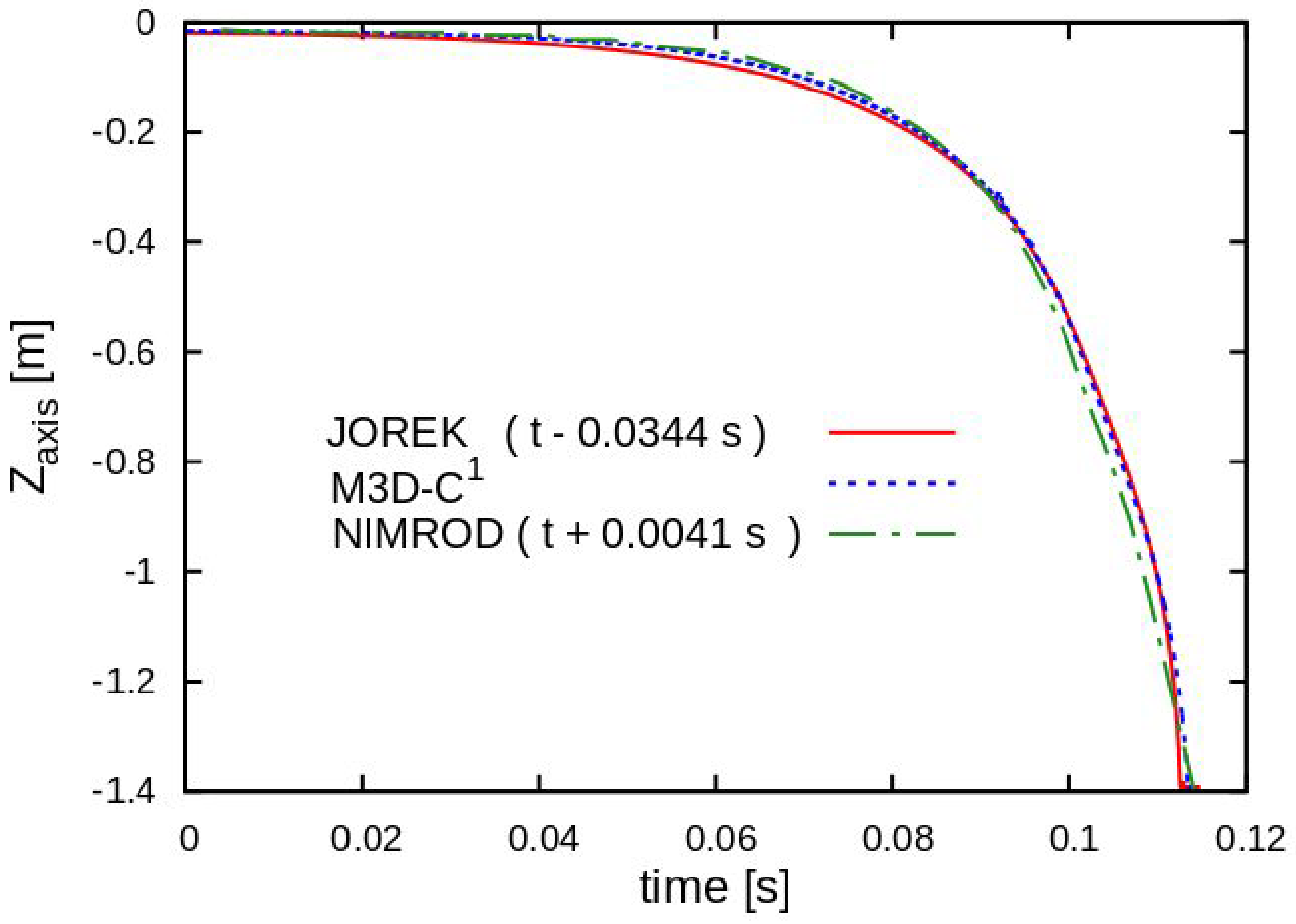
VDE growth rates



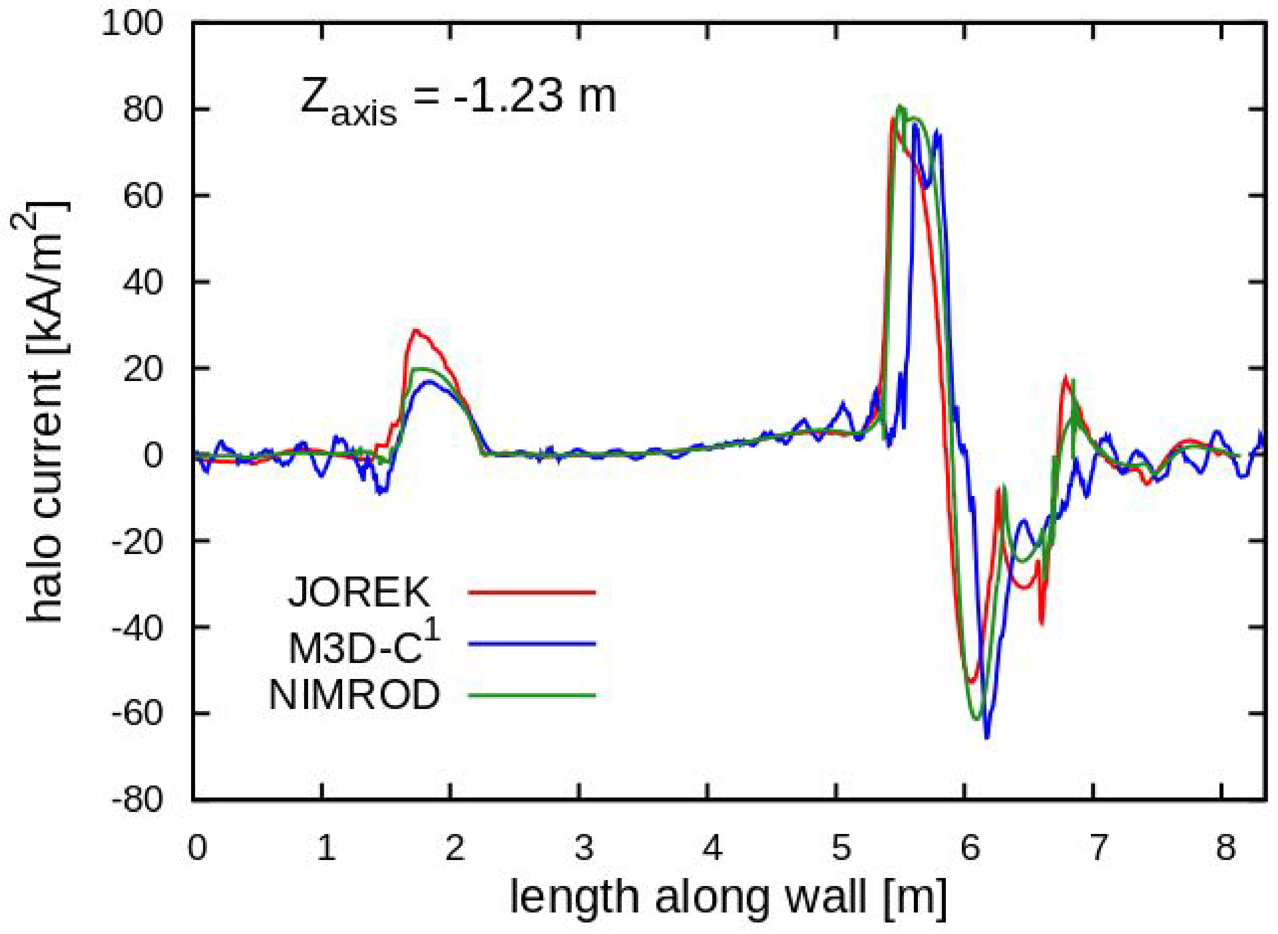


Poloidal magnetic flux (M3D-C1)

Vertical position



Halo current



Krebs to be submitted; http://arxiv.org/abs/1908.02387]