NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

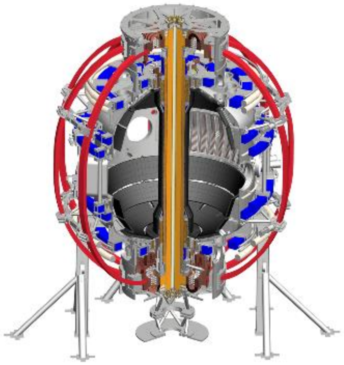
NSTX-U Research
FY2017 Q3 Quarterly Review

J. Menard, S. Kaye, S. Gerhardt - PPPL

For the NSTX-U Research Team

August 21, 2017
FES, PSO, and PPPL

PPPL



NSTX-U Research Overview

- Research Contributions to Recovery
- FY2017 Milestone Progress
- Additional Research Highlights
- Collaboration Status and Plans

NSTX-U researchers actively engaged in Recovery efforts

- Aided Extent of Condition reviews:
  - Aided in System Design Description (SDD) formulation, edits
  - Design Validation and Verification Reviews (DVVRs)
    - Aided in preparation of presentations, chit submission, chit response
- New PFC requirements working group (next slide)
  - Extent of Condition review process identified PFC power handling issues that must be addressed
    - Narrower SOL width not incorporated in GRD (2009-2012)
    - Increased halo peaking on IBDH → T-bar design insufficient
  - Extensive equilibrium & heat-flux scans performed, more to come
- Topical Science Group contributions:
  - Re-assessed scenario needs: first 2yrs of ops + 5/7 year plan
    - Magnetic balance and δ variations influence PFC design considerations
  - Assessed impact of polar region mods on research plans

New Working Group formed for NSTX-U PFC performance and monitoring requirements

- Leader / deputy:
  - Matt Reinke (ORNL) / Mike Mardenfeld (PPPL engineering)
- Working Group charges: (click here for more info)
  - Define which (additional) parameters need to be specified in an updated requirements document for the NSTX-U PFCs
  - Facilitate generation of updated requirements utilizing:
    - Available reduced models, empirical scalings, boundary simulations
    - Ultimately, a validated model for specifying heat loads to all plasma facing components for arbitrary NSTX-U scenarios
  - In preparation for operations, develop:
    - Instrumentation plan for intra and inter-shot PFC monitoring
    - A reduced model for heat loading for pre-shot planning
    - Guidance on how to best integrate monitoring with operations
    - Control, diagnostic requirements for real-time heat-flux control
  - Work w/engineers/analysts to develop/implement requirements

Use Conservative Approach: Assume Narrow λ_q

Three scalings of heat flux width, λ_q, with eng. parameters

- **Heuristic Drift Scaling [Eich, PRL 2011]:** **(7), (9-10) results in** $\boldsymbol{\lambda_q \sim B_T^{-7/8} q_{cyl}^{9/8}}$ — **1.95 [mm]**
- MAST scaling [Thornton, PPCF 2014]: $\lambda_q[mm] = 1.84(\pm 0.48) B_{pol,omp}^{-0.68(\pm 0.14)} P_{SOL}^{0.18(\pm 0.07)}$ — 4.09 [mm]
- Eich Scaling [Eich, NF 2013]: $\lambda_q[mm] = 1.35 \varepsilon^{0.42} R_{geo}^{0.04} B_{pol,omp}^{-0.92} P_{SOL}^{-0.02}$ — 2.96 [mm]

2 MA, 1 T, 10 MW Scenario

- **PFC Requirements developed assuming Heuristic Drift Scaling**

- **PFC requirements assume 30% radiated power fraction based on best-fits to scalings (small data set)**

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FY2017 NSTX-U Milestones

- **JRT-2017:** FES Joint Research Target (led by DIII-D)
  - Conduct research to examine the effect of configuration on operating space for dissipative divertors
- **Research Milestones**
  - R(17-1): Simulation-based projection of divertor heat flux footprint
  - R(17-2): Advanced divertor operating scenario modeling for NSTX-U
  - R(17-3): Identify, mitigate, and develop correction strategies for intrinsic error field sources in NSTX-U
  - R(17-4): Assess high-f Alfvén Eigenmode stability & associated transport
  - R(17-5): Analysis & modelling of I_P ramp-up dynamics in NSTX/NSTX-U
- **Diagnostic Milestone**
  - D(17-1): Complete installation and preliminary commissioning of the pulse burst laser system

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TODAY

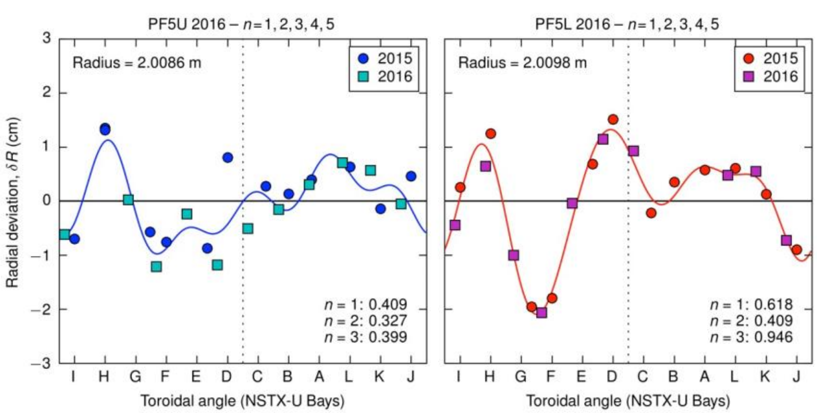
- **Diagnostic Milestone**
  - D(17-1): Complete installation and preliminary commissioning of the pulse burst laser system → **COMPLETED**

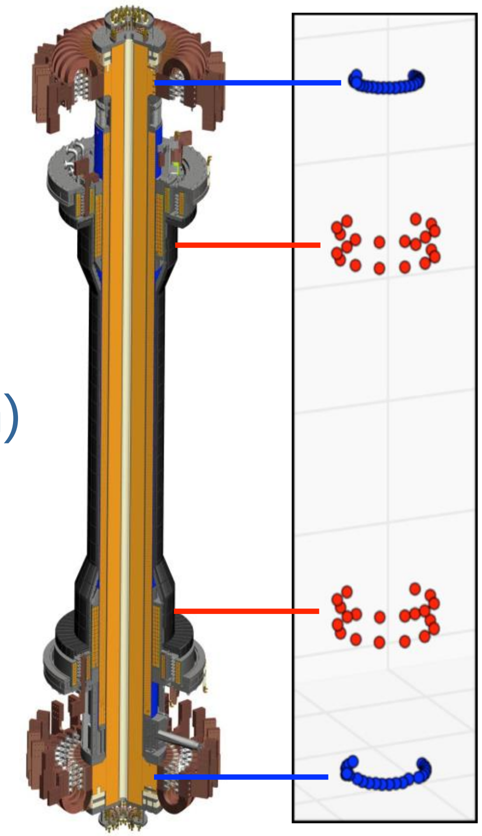
R17-3: Identify, mitigate, and develop correction strategies for intrinsic error fields

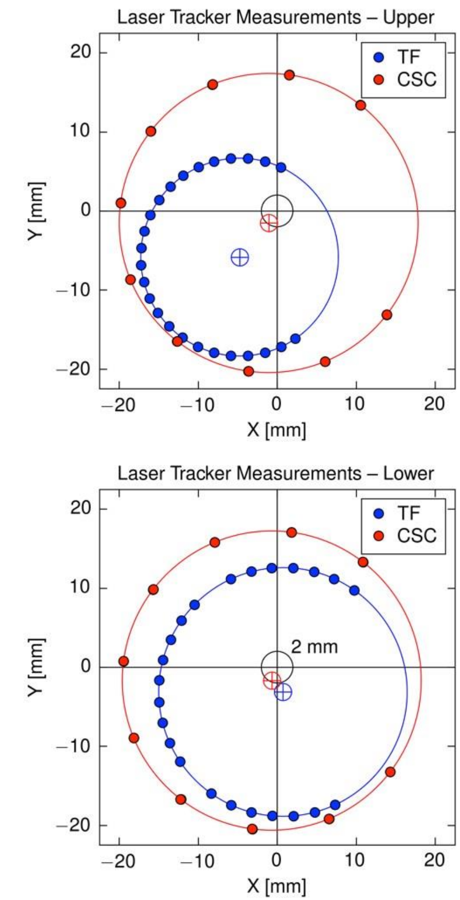
- **Goals:** Complete characterization of coil positions, shapes, model plasma response, provide guidance on TF bundle re-alignment requirements
- **Tools:** IPEC, M3D-C1, metrology (FARO arm, laser tracking)
- **Impact:** Minimize intrinsic error fields, access high performance more rapidly during next ops
  - Critical to highest performance
  - Responsive to FY2016 PEMP concern

Coil metrology conducted on TF rod, center-stack casing (CSC), and PF5 coil

- Combine metrology techniques: ruler, ROMER arm, laser tracker
- PF5 $n = 1$ amplitude and phase:
  - $\delta R \sim 6$ mm at $\phi = 16°$
- TF rod shift and tilt:
  - Shift = 4.9 mm at $\phi = 246°$
  - Tilt = 1.2 mrad at $\phi = 206°$ (6 mm)

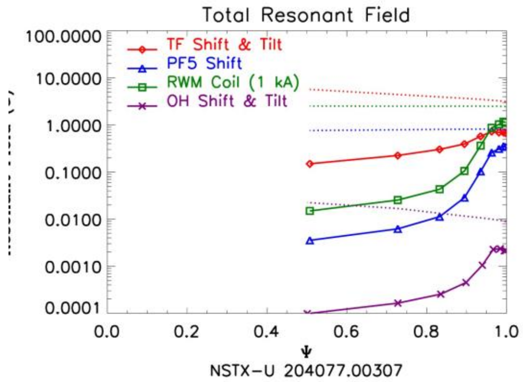


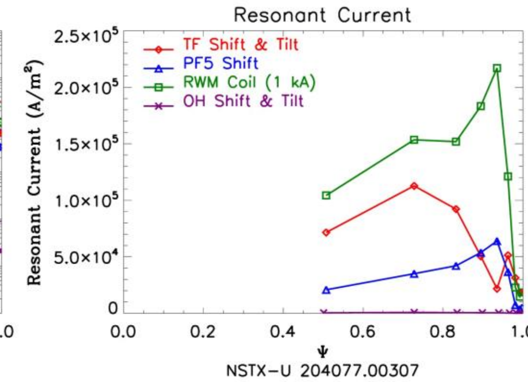


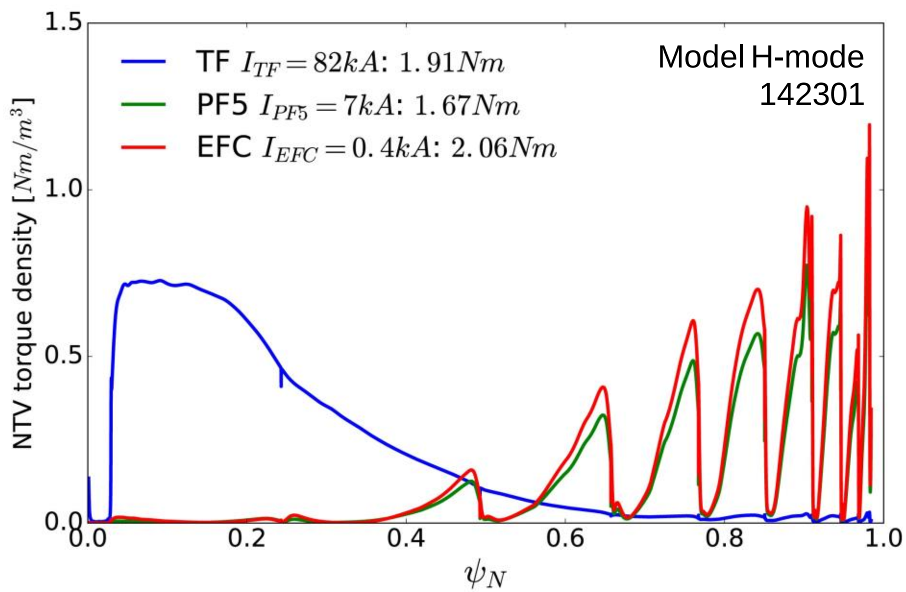


Modeling results → need to impose 2 mm tolerance for TF alignment to mitigate TF error field effects

- Metrology → coil shape models
  - Feed to IPEC & M3D-C1
- Resonant fields and currents:
  - TF error field is dominant
  - TF EF phase not constant
  - Difficult to correct
- Neoclassical toroidal viscosity:
  - RWM coils are poorly matched to TF NTV spectrum
- Tolerance of 2 mm:
  - Resonant fields below locking threshold without EFC
  - Reduces TF NTV by 10×







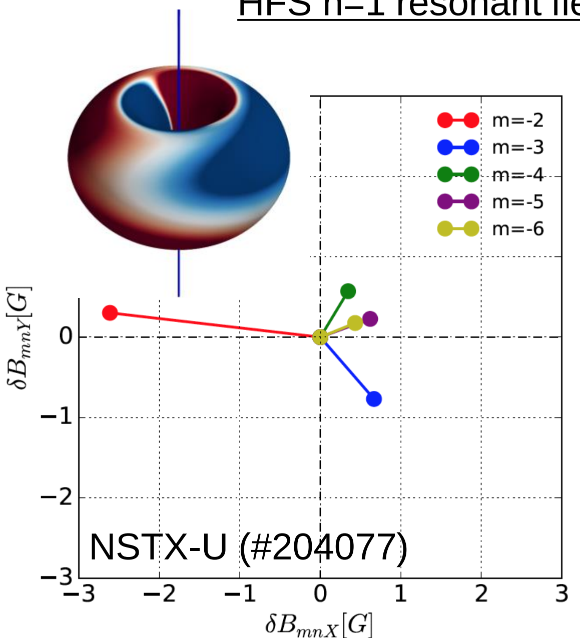
R(17-3) milestone progress to-date

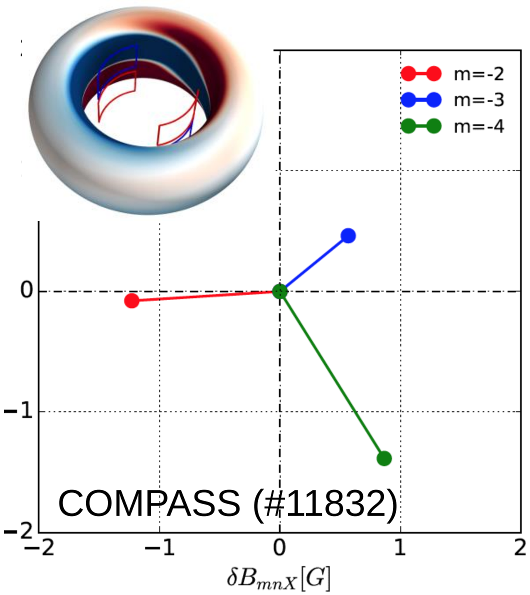
- Error field assessment report:
  - Report issued to Recovery Project on 30 April
  - Recommend TF alignment tolerance of ≤ 2 mm (×3 reduction)
- Additional metrology and magnetic measurements:
  - Ex-vessel metrology of PF5 → coil plane w.r.t. ROMER arm
    - Completed last week
  - Define the vertical axis to which the TF should be aligned
  - In-vessel B-measurements during outer PF validation testing
- Reinstallation and realignment planning:
  - Shim / post-machine CS casing to ensure TF bundle centered
  - Repeat CSC / TF metrology to verify alignment
  - Design flexibility into end flanges to facilitate CS alignment (?)
  - Use ROMER arm to quantify CS alignment upon installation

NSTX-U TF error field (EF) presents a challenge to single-mode approaches to ITER EF correction

- NSTX-U TF EF effects vary significantly depending on equilibrium evolution
- Collaboration in COMPASS confirms multi-modes characteristics of HFS EF
- Also, HFS non-resonant field is not easily correctable by LFS control coils

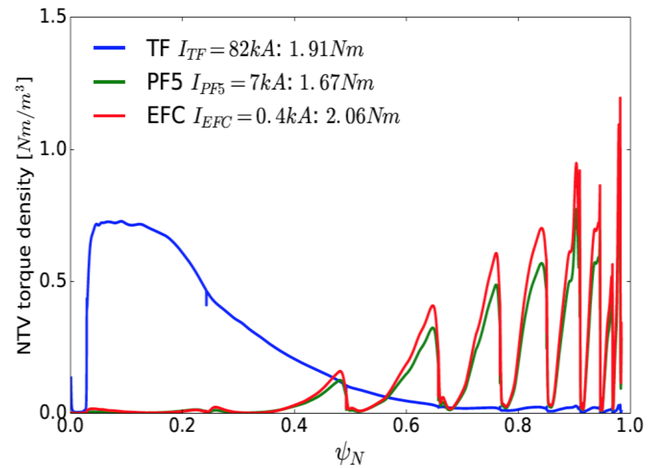
HFS n=1 resonant fields driving islands (IPEC)





HFS non-resonant field driving NTV torque

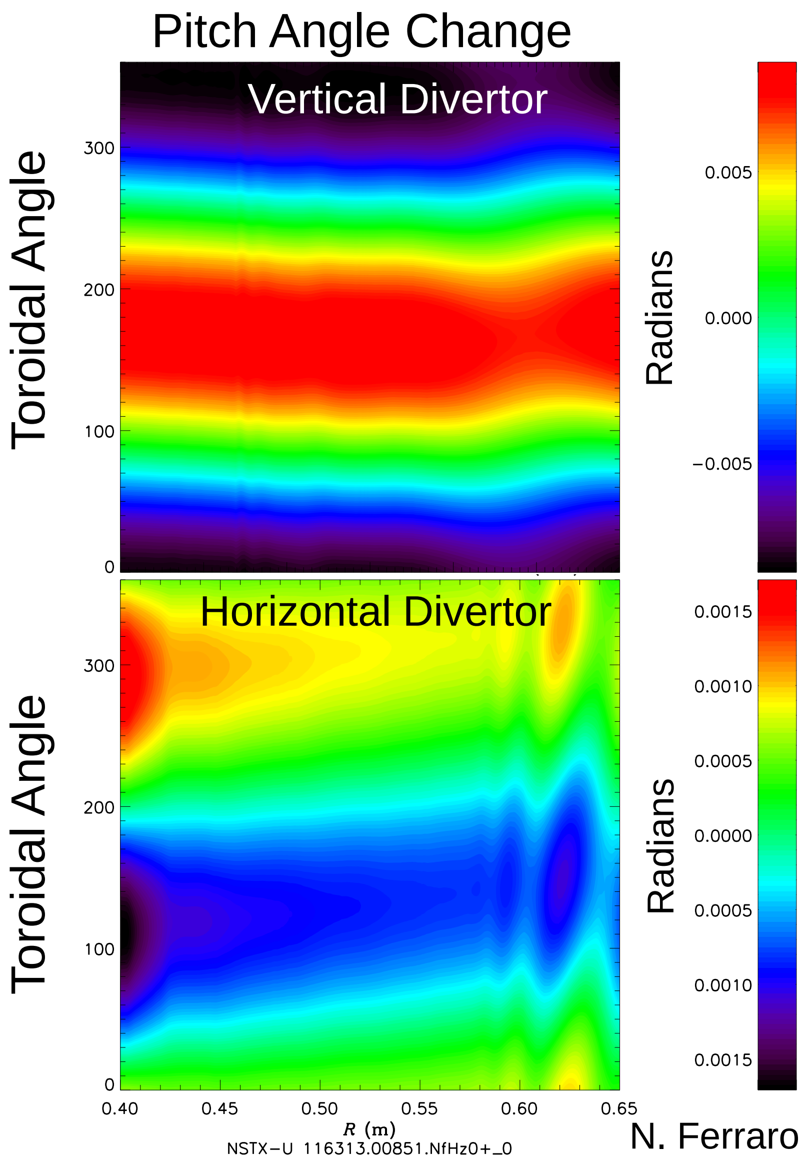
NSTX-U high-β modeling



Progress and remaining challenges on ITER error field correction for ITER are reviewed in J.-K. Park et al., 2017 ITPA MHD MDC-19 Report

Error Field modeling informing PFC design

- Error fields may significantly affect heat flux to divertor PFCs
  - Change incidence angle of B-field
  - Cause radial and toroidal variations in the heat flux due to magnetic lobes
- Effect of error fields on magnetic pitch angle calculated with M3D-C1 for high-performance model NSTX-U equilibria
- Largest known error field in NSTX-U (TF error) would cause pitch angle changes of up to 0.5°
  - This is significant, but likely not large enough to cause concern after improved TF realignment



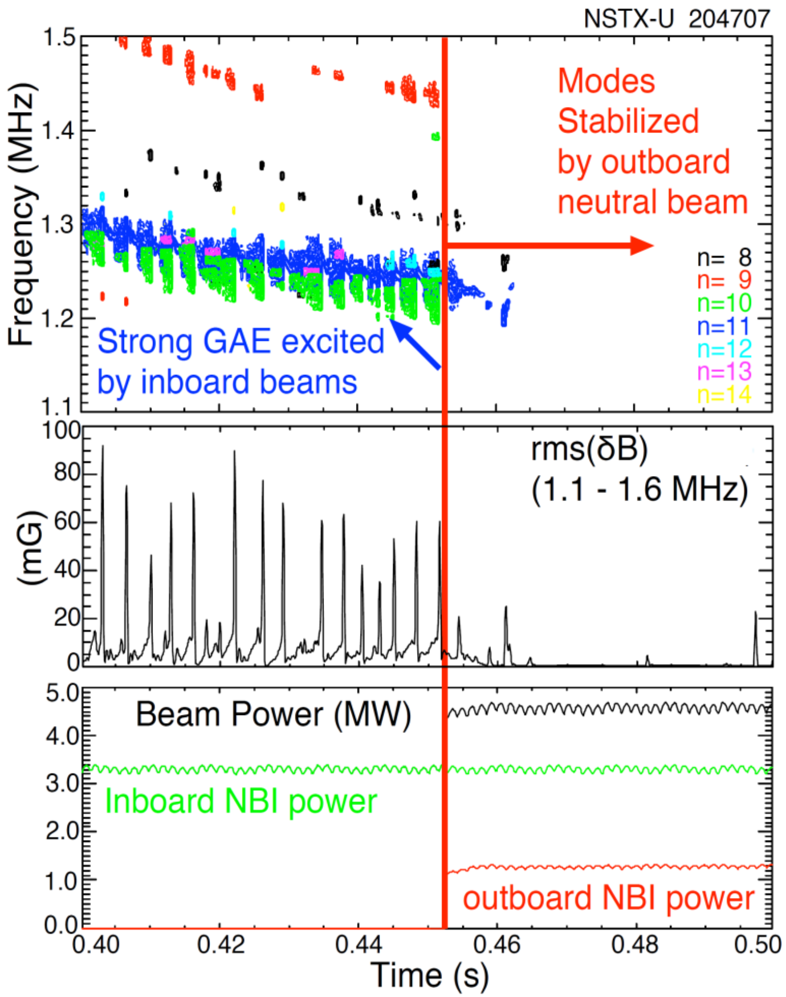
N. Ferraro

R17-4: Assess high-frequency Alfvén Eigenmode stability, associated transport

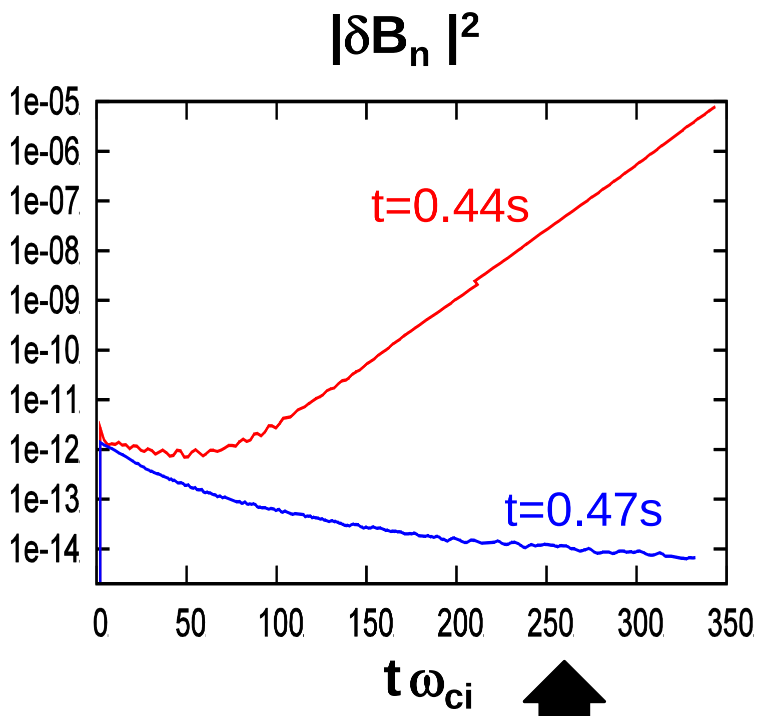
- **Goals:** (1) Extend simulations of NSTX-U CAE/GAE to high heating power, plasma current, toroidal field, (2) Further validate simulations, (3) initial assessment of Ion Cyclotron Emission (ICE) observations from NSTX-U
- **Tools:** HYM code, DIII-D National Campaign XPs
- **Impact:** Project fast-ion, thermal electron transport from CAE/GAE, ICE for inferring ITER $f_{fast}(v)$
  - Builds on new physics discovered during FY16 NSTX-U run campaign
- **Related Activities:**
  - Analyzing high-k data for evidence of CAE coupling to kinetic Alfvén waves
  - High-f AE experiment on DIII-D (planned July 2017)
    - Some data from single source, B_T ramp shots obtained in piggyback
    - Useful data about CAE stability vs P_{NB}, V_{inj}, R_{tan}, n_e, B_T

NSTX-U: Tangential 2nd neutral beam suppresses Global Alfven Eigenmode (GAE) – consistent with simulation

Published in PRL in June 2017 - E. Fredrickson et al.



HYM code simulation of #204707, n=10



- HYM code: growth of n=10 counter-GAE from 1st NBI
- HYM: suppression of n=10 counter-GAE by 2nd NBI
- Most unstable *n*-number, mode ω consistent with HYM

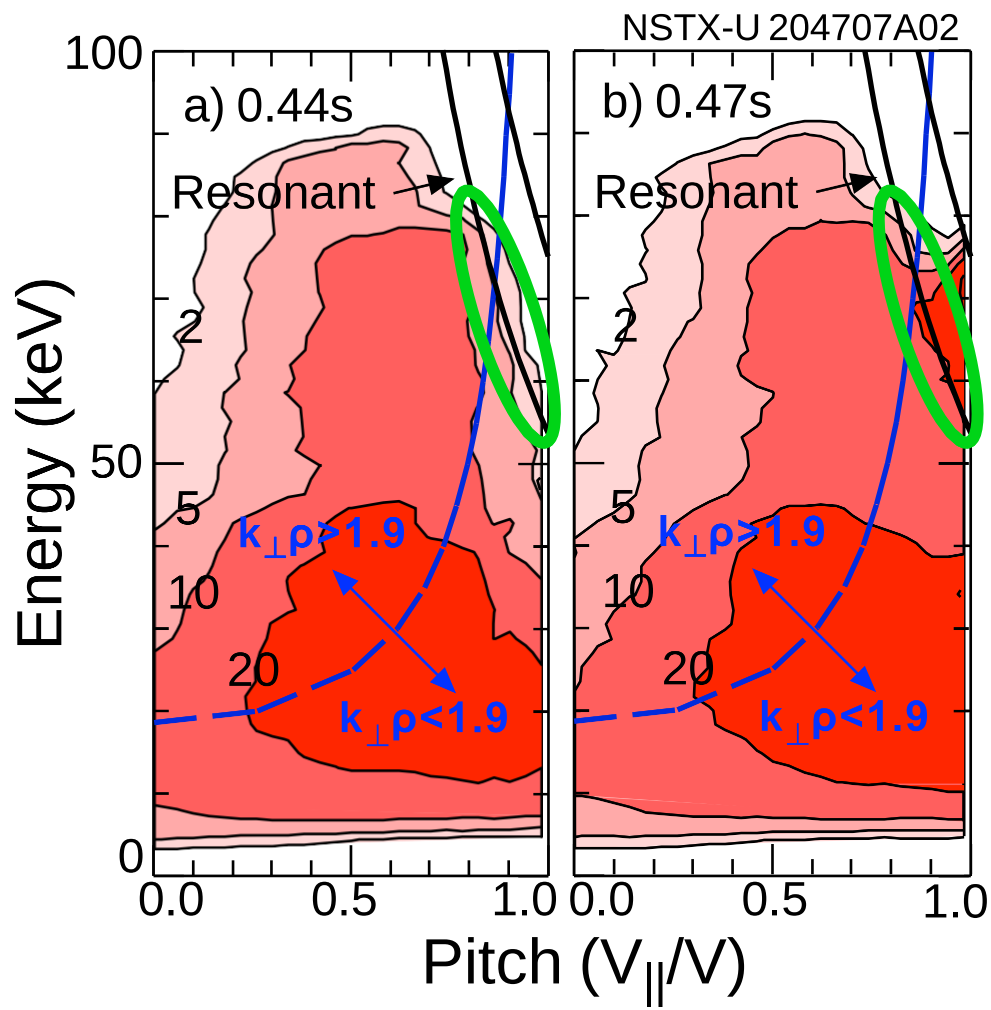
Analytic theory providing insight into HYM simulations of GAE stability

- Fast ions can be stabilizing/ destabilizing depending:

  Stable : $0 \le k_{\perp}\rho_{\perp} \le 1.9$

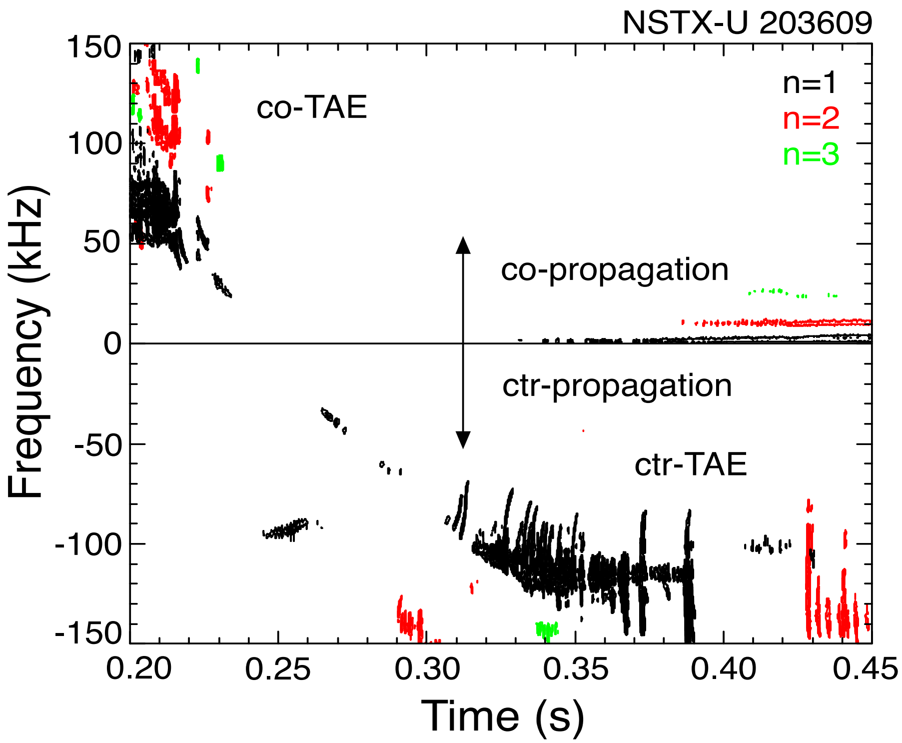
  Unstable: $1.9 \le k_{\perp}\rho_{\perp} \le 4$

- Resonant outboard beam ions with pitch > 0.9 have small $\rho_{\perp}$, are stabilizing by this theory.
- Estimates based on dispersion relation and resonant condition suggest that 65keV outboard beam ions might be just marginal to reach resonant condition.
- NSTX (low field) parameter regime *might* be very different.



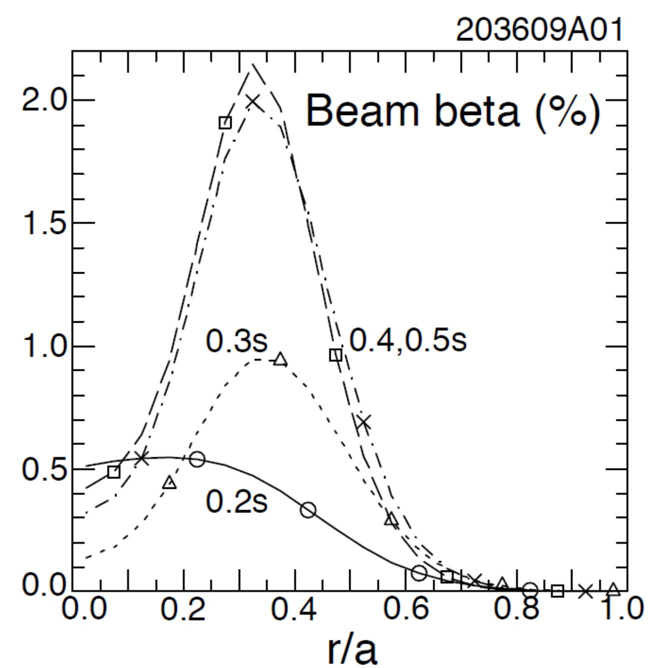
(Gorelenkov, NF 2003)

NSTX-U: Off-axis co-NBI destabilizes counter-propagating Toroidal Alfvén Eigenmodes (TAEs)



- Hollow fast ion profile reduces stabilization of counter-propagating TAEs
  - *H.V. Wong, H. Berk, Phys. Lett. A* ***251*** *(1999) 126.*
- Preliminary analysis reveals important role of large orbit width, FLR effects

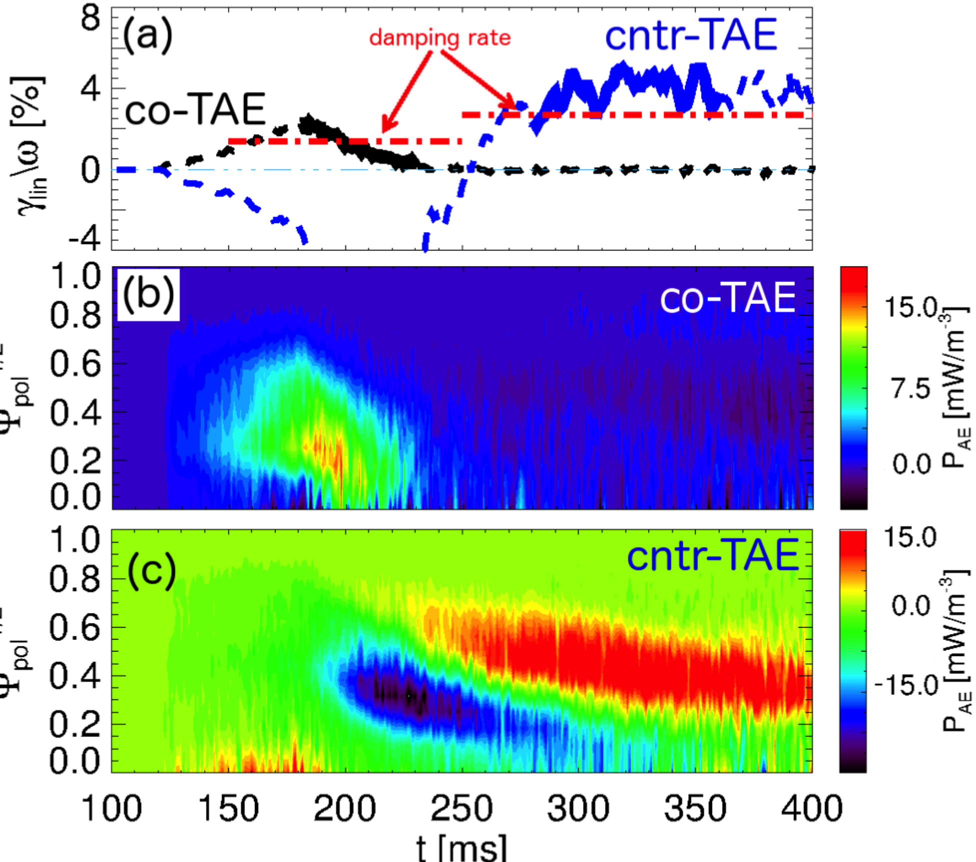
- TRANSP: as current builds up, fast-ion beta profile predicted to become hollow
  - ✓ **1st evidence of off-axis NBI in NSTX-U**
- Co-TAEs are stabilized, but cntr-TAEs become unstable with only 1MW NBI



Linear TAE stability vs time from TRANSP + *kick model* is consistent with NSTX-U experiments

- Compute power from fast ions to mode
  - Infer growth rate [Podestà, PPCF 2017]
  - Using damping rate from NOVA-K
- Timing of most unstable |n|=1 TAE modes compares well with experiments
- Stability related to gradients in both radius & energy
  - Not the usual "universal drive"

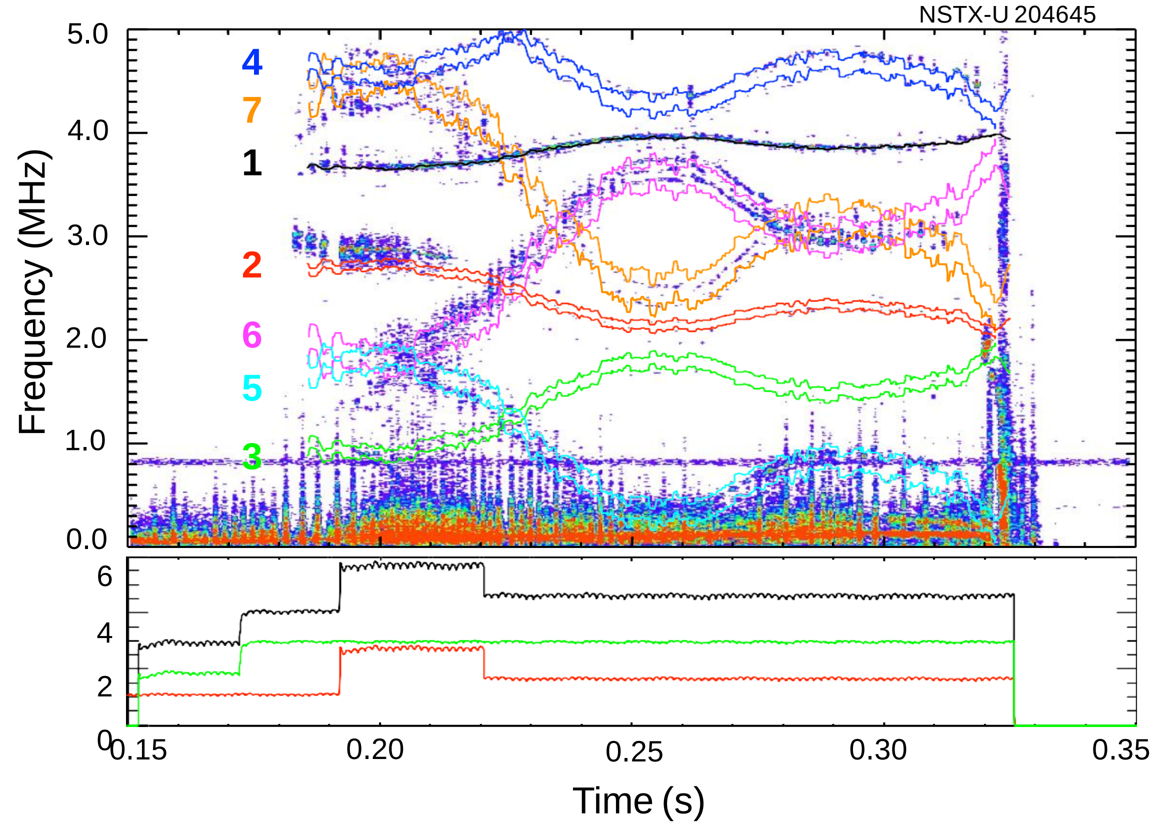
[Podestà, PRL 2017 (submitted)]



- *Flexibility of TRANSP + kick model approach enables scenario development for realistic geometry*
  - Example: ~0.5MW "blips" with 1st NBI predicted to stabilize cntr-TAEs

Investigating newly observed Ion Cyclotron Emission (ICE) from NSTX-U discharges

- Spatially coherent → argues for mode
- Bursty rather than CW → unstable mode - what defines mode *f*?
- Doesn't follow Alfvénic scaling - not Alfvén eigenmode?
- Like conventional ICE, higher harmonics largest amplitudes



- Strongest ICE correlated with source 1C – the most perpendicular source
- Amplitude decreases with increasing density
- TRANSP runs started to study β_{fast} dependence
- **Can ICE be correlated with confined fast-ion distribution parameters?**
- **Needs theory support**

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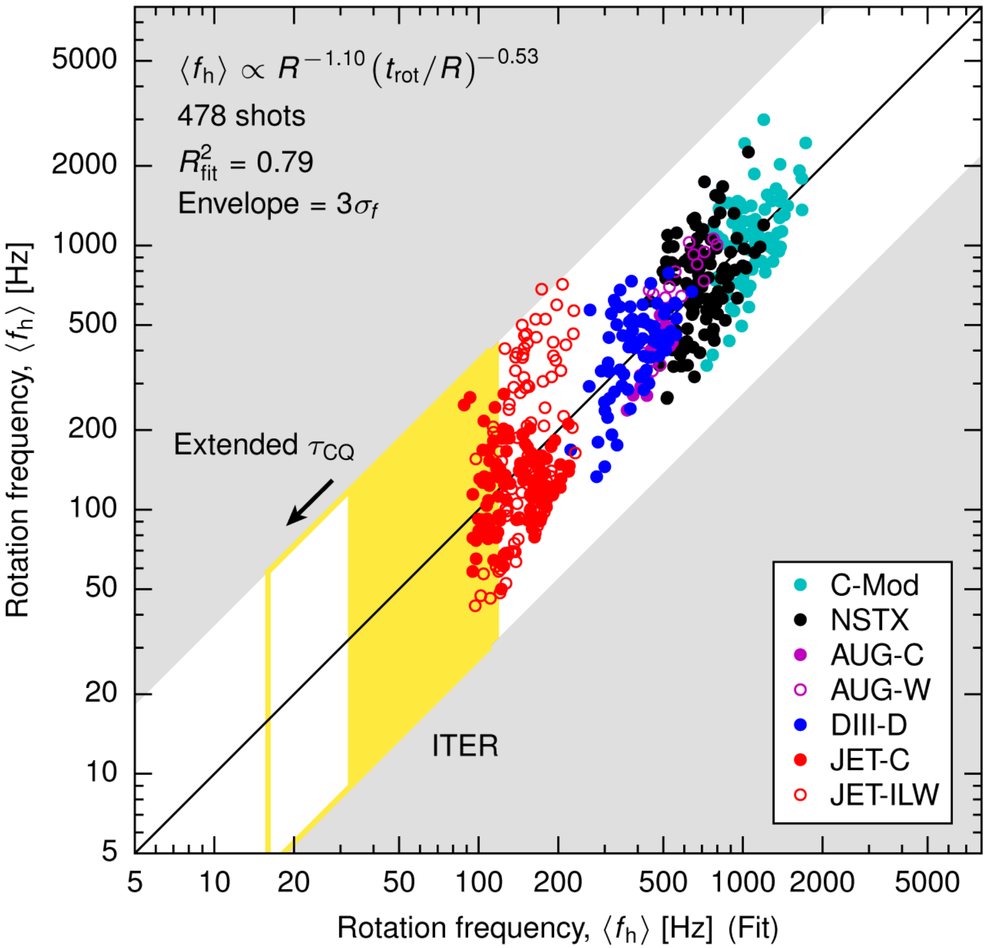
Leading halo current propagation studies

C. Myers (PPPL)

- The concern for ITER:
  - Concern is for asymmetric halo currents during unmitigated disruptions
  - Forces are dynamically amplified if $N_{rot} > 2\text{-}3$
  - Critical mechanical resonances in the 3-8 Hz range [Schioler FED 2011]
  - Overall response is broader (10-20 Hz) [Bachmann FED 2011 & Lehnen]
- **Could halo current forces be dynamically amplified in ITER?**
  - **Could the halo currents rotate at frequencies below 20 Hz?**
  - **Could the rotation last long enough to complete 2-3 rotations?**
- Substantial halo current rotation observed in a number of devices:
  - JET Noll 1996, Riccardo 2004 & 2009, Gerasimov 2014 & 2015
  - C-Mod Granetz et al. *Nucl. Fusion* **36**, 545 (1996)
  - DIII-D Evans et al. *J. Nucl. Mater.* **241-243**, 606 (1997)
  - AUG Pautasso et al. *Nucl. Fusion* **51**, 043010 (2011)
  - NSTX Gerhardt *Nucl. Fusion* **53**, 023005 (2013)

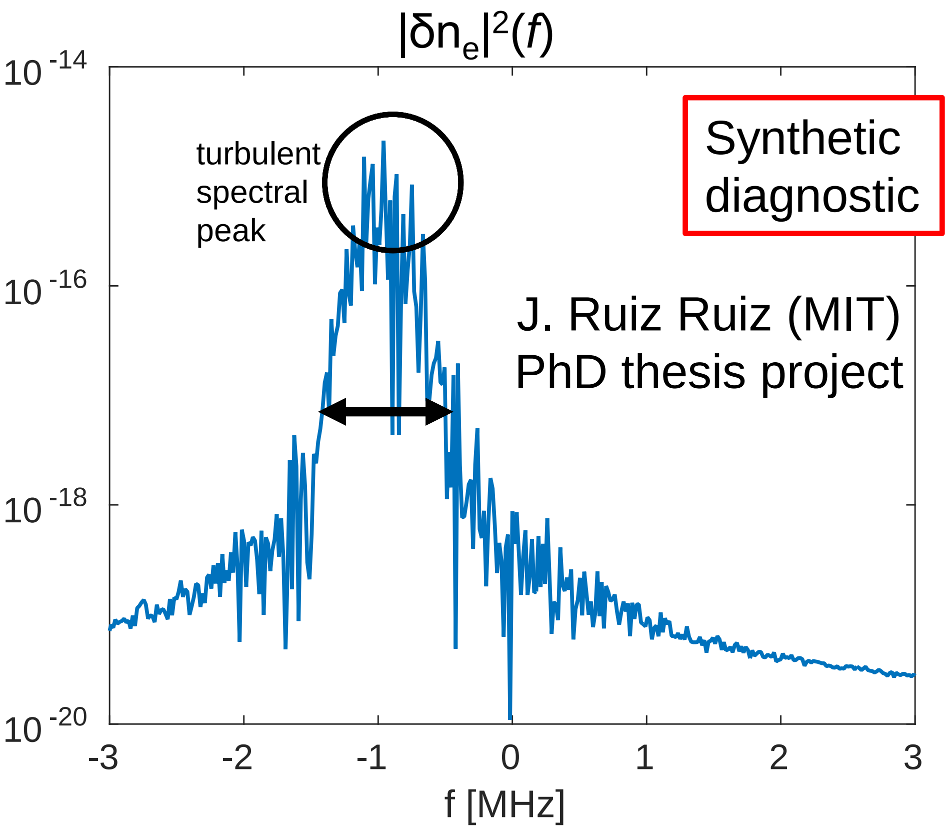
Simple rotation frequency scaling: $\langle f_h \rangle \sim 1/R$
Cannot rule out dynamic force amplification in ITER

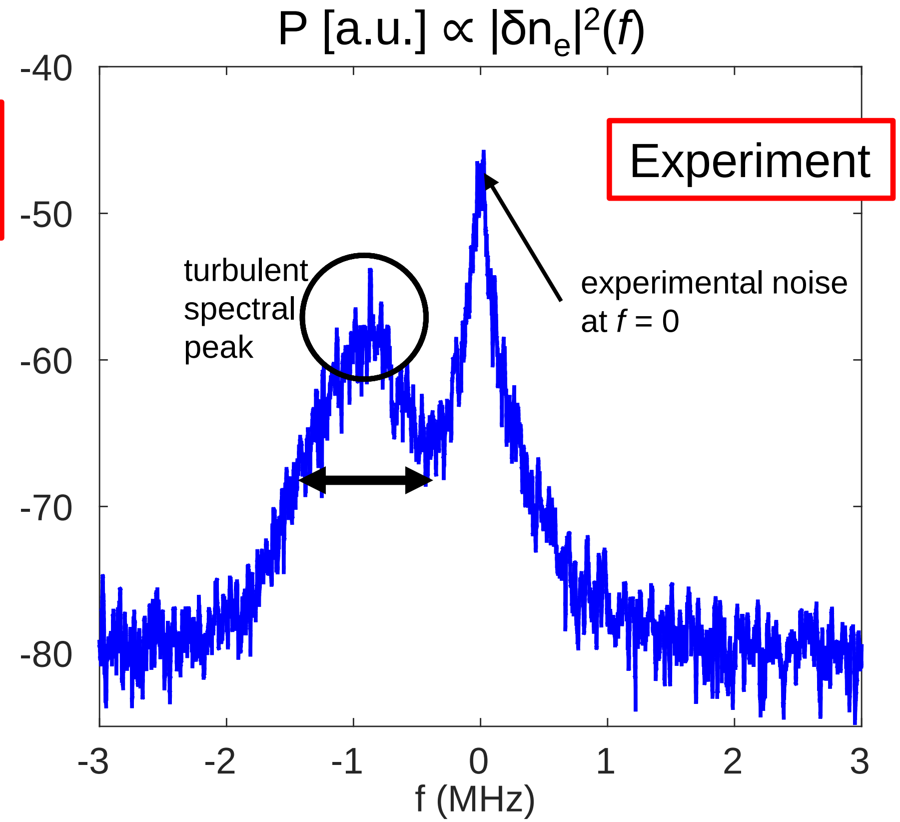


- Key quantities:
  - N_{rot} = number of rotations
  - t_{rot} = rotation duration
  - $\langle f_h \rangle = N_{rot} / t_{rot}$ = rotation frequency
- Carry out regression using two parameters → R, t_{rot}
- Additional parameters do not improve regression (e.g., I_p, B_T)
- $\langle f_h \rangle \sim 1/R \sim$ constant $\langle v_h \rangle$
- ITER projection:
  - Rotation at $\langle f_h \rangle < 20$ Hz probable
  - Rotation duration analysis → Cannot rule out dynamic force amplification in ITER

C. E. Myers, et al. (Manuscript submitted to *Nuclear Fusion*)

Developing high-k synthetic diagnostics for quantitative comparison of ETG plasma turbulence spectrum



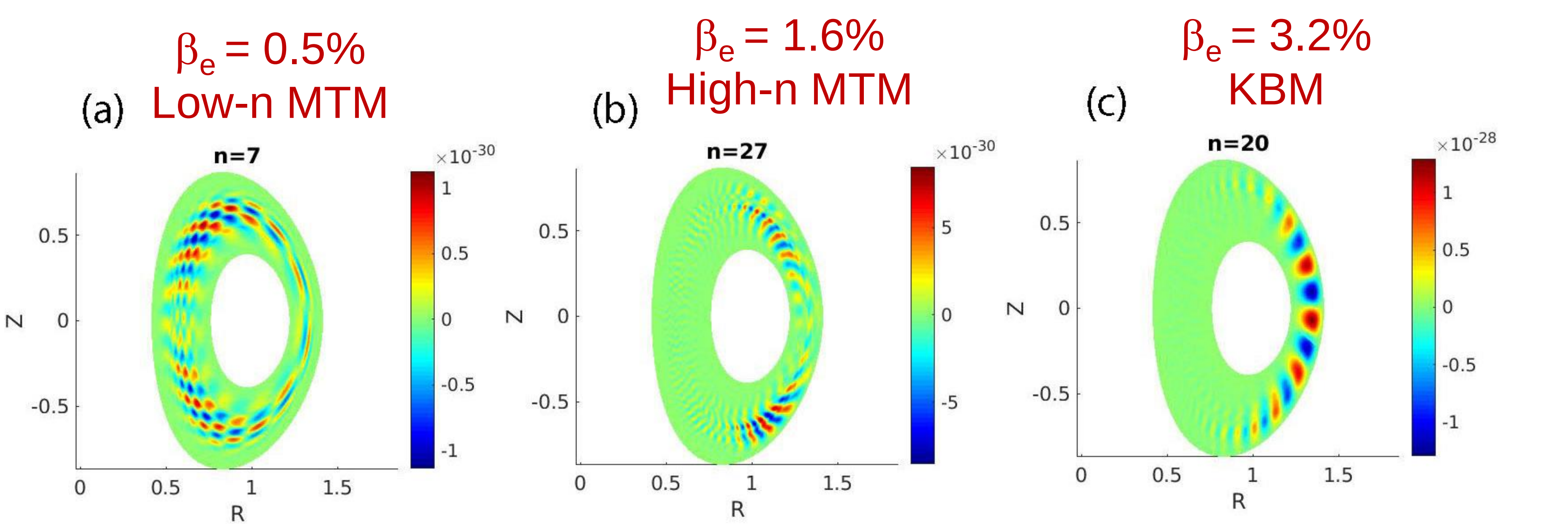


- Recovered spectral peak, spectral width.
- **NOTE**: a quantitative comparison is not yet available: correct experimental units determining the amplitude are not included in Synthetic diagnostic.

Developing of electromagnetic capabilities in GTS relevant to NSTX / STs

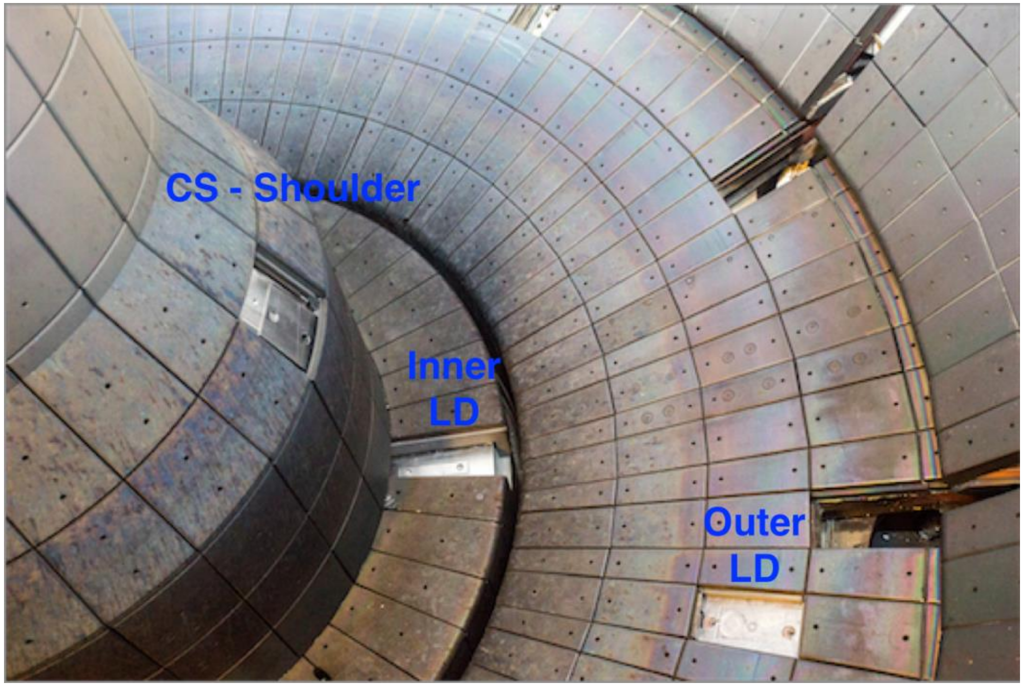
- Startsev-Lee EM scheme to include toroidal effects, simulate ion-temperature-gradient (ITG), kinetic ballooning mode (KBM) transition, tearing and micro-tearing modes (MTM) with new electromagnetic version of GTS code (EM-GTS)
- Recently extended to enable shaped plasmas like NSTX

ES potential φ in poloidal plane of NSTX



PFC conditioning techniques and their correlation with plasma performance (Allain)

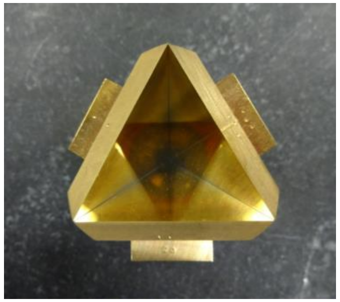
- F. Bedoya (U. Illinois) completed his PhD thesis on MAPP analysis of NSTX-U PMI
- Also completed NSTX-U PFC post-run analysis



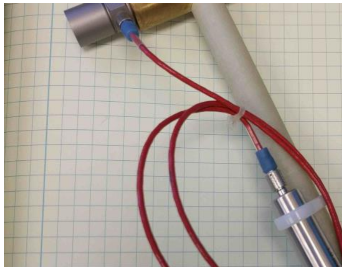
- Core C18 – OSP
- Core B17 – ILD
- Core a18 - ISP

Adaptive filter approach prototyped to provide vibration compensation for FIReTIP*

- Implementation of FIReTIP for real-time density control motivated development of active noise cancellation by digital adaptive filtering
- Use Kalman filter as adaptive method that takes prior system state to predict next state based on state-space model of system



- In-vessel retroreflector for FIReTIP probe beam sensitive to vibrations suggested test of concept with vacuum vessel model



- Model system response determined from “carefully controlled” striking of vacuum vessel with brass hammer

**Work performed by University of California at Davis doctoral student Evan Scott for thesis entitled “Interferometry and Vibration Compensation on the National Spherical Torus Experiment – Upgrade“*

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NSTX-U / DIII-D Campaign MPs and status
(Process coordinated by S. Kaye)

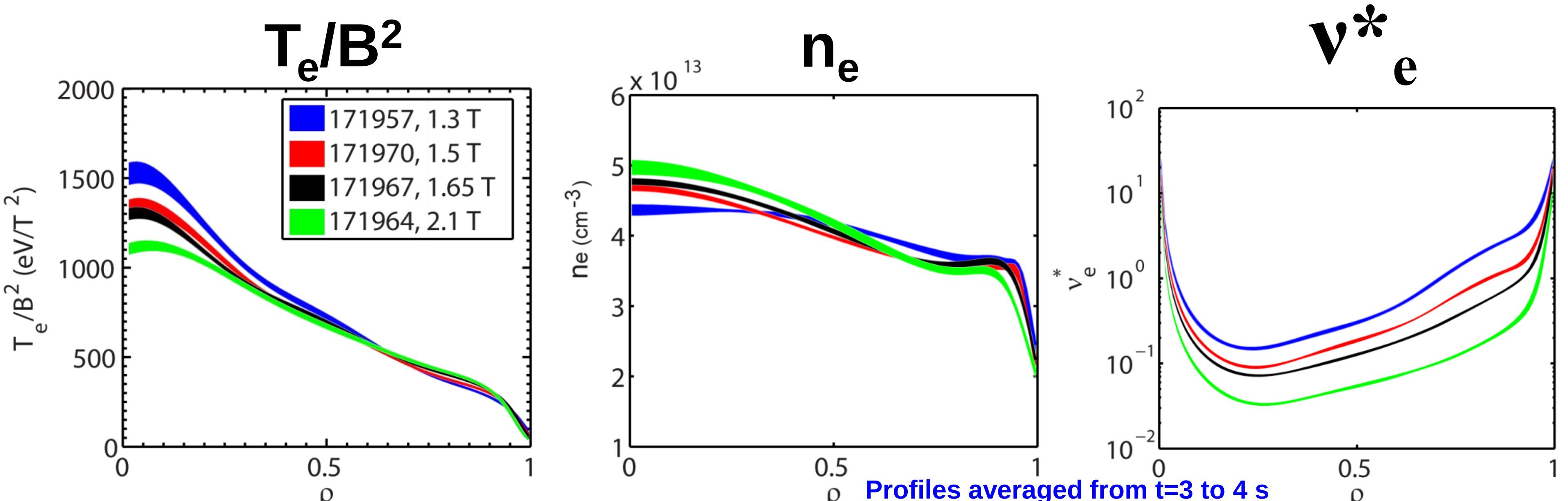
- Boundary Studies (3 days)
  - Impurity transport in response to Li aerosol injection (R. Lunsford; FY18)
  - Divertor detachment: JRT2017 (V. Soukhanovskii, 6/21)
  - Enhancement of divertor radiation in SAS divertor (A. Bortolon; FY18)
- Core Studies (4.5 days)

TODAY

  - Collisionality dependence of ion- and electron-scale turbulence in hybrid scenarios with ST-relevant q_{95} (Y. Ren; 7/10)
  - Studying electromagnetic effects on transport in high performance plasmas (W. Guttenfelder; 7/18)
  - Impact of resonant vs non-resonant applied 3D fields on n=2 locking (C. Myers, N. Ferraro; 6/22)
  - CAE frequency and wavenumber dependence on beam pitch angle and energy (S. Tang – UCLA; 7/11)
  - Scaling of SPI penetration in high temperature plasmas (R. Raman – U. Wash; 7/31)
- Scenarios and control (evening control session + 0.5 days)
  - Feedback control of stored energy and rotation, combined with stable ramp-down control (D. Boyer; 7/11,19)

Collisionality Dependence of H-mode Energy Confinement Scaling was Studied in the DIII-D/NSTX-U National Campaign

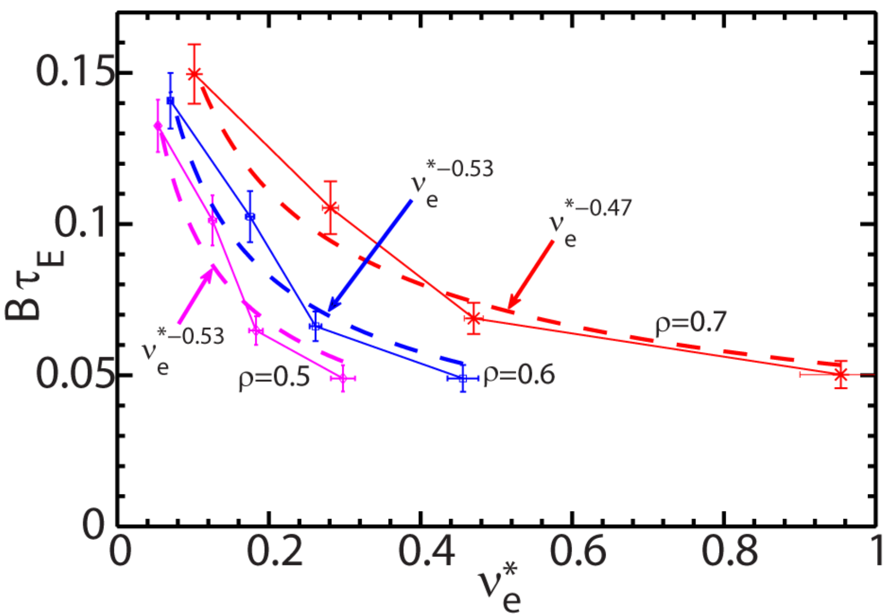
- ν* dependence of H-mode confinement scaling not understood
  - Strong inverse dependence on collisionality ($\propto \nu_e^{*-1}$) in STs
  - A weaker dependence observed on DIII-D ($\propto \nu_e^{*-0.5}$)
- An experiment was successfully carried out on DIII-D
  - Using advanced inductive hybrid scenario with ST-relevant q_{95}~6.6
  - Achieved reasonable profile matching for a dimensionless collisionality scan
    - E.g. T_e/B^2 and n_e matched to keep β_e and ρ* nearly constant
  - Achieved a factor of about 7 change in the electron collisionality

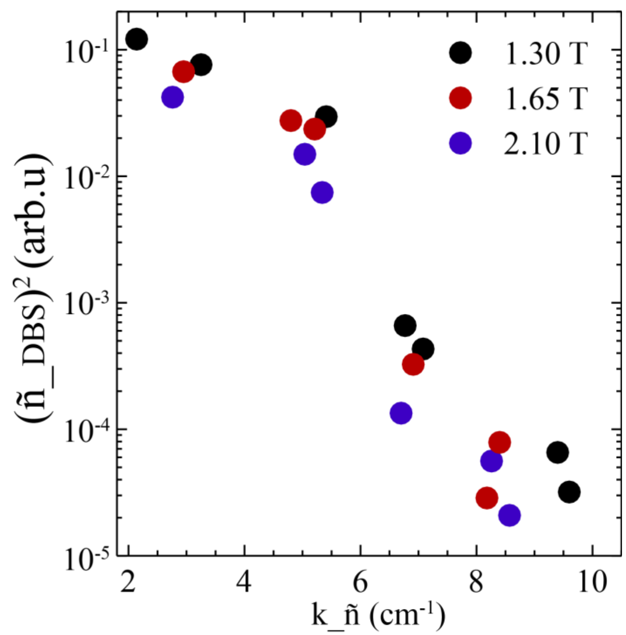


Profiles averaged from t=3 to 4 s

Collisionality Dependence of H-mode Energy Confinement Scaling was Studied in the DIII-D/NSTX-U National Campaign

- Observed confinement scaling ($\propto \nu_e^{*-0.5}$) consistent with the previous DIII-D result (Luce et al., PPCF, 2008)
- DBS measurement showing turbulence spectral power reduction with the increase in B_T (decrease in collisionality), consistent with energy confinement improvement
- Further analysis is ongoing

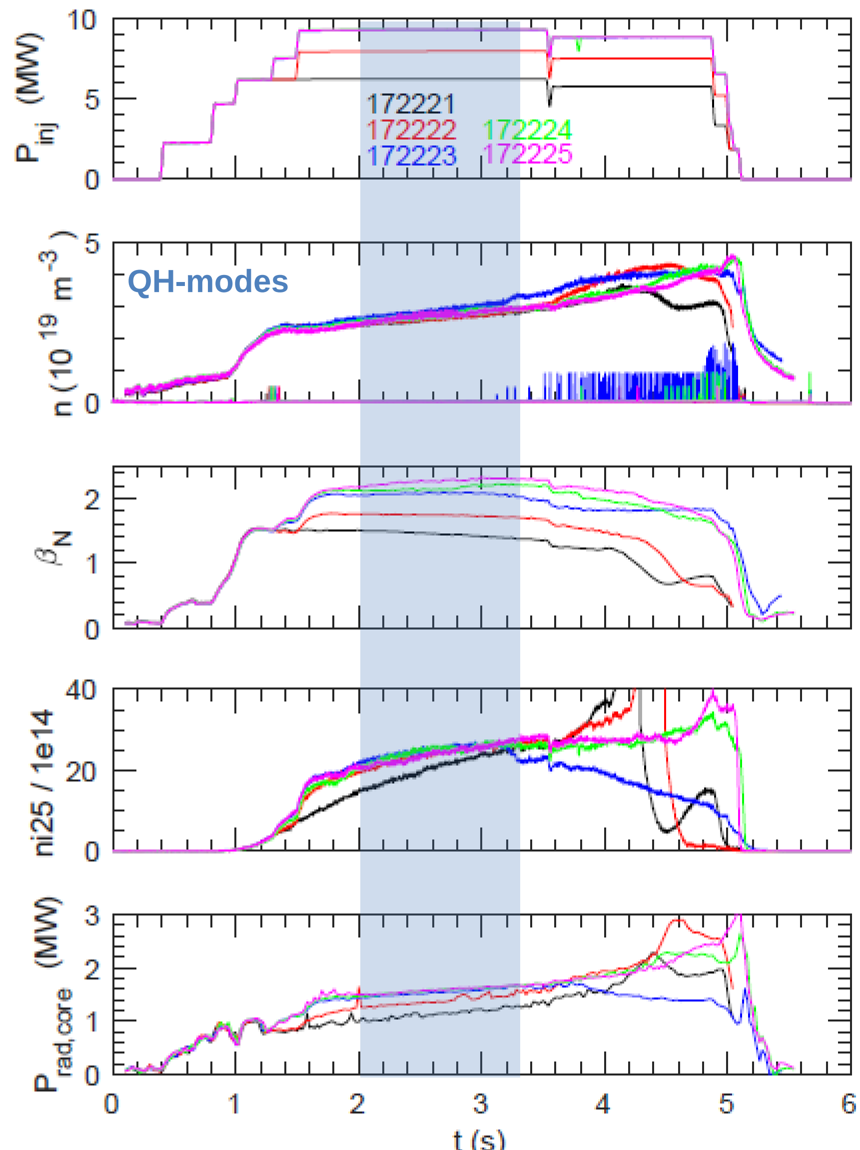




DBS measurement at ρ~ 0.55-0.65, averaged for t=3.75-4 s

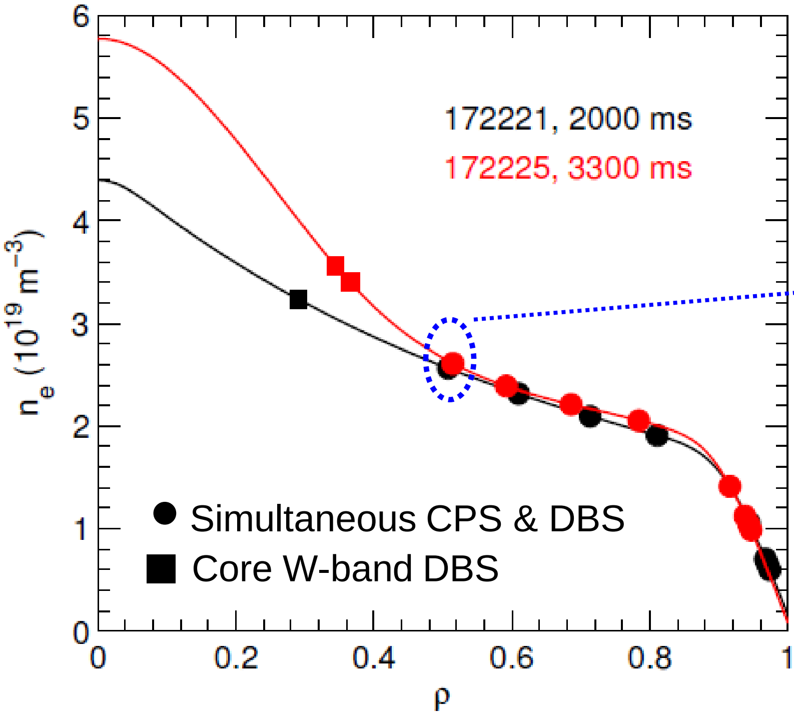
DIII-D "NSTX-U campaign" MP to measure core CPS (~δB) to validate electromagnetic microturbulence effects

- EM effects important in spherical tokamak (ST) H-modes *and* deep core (ρ<0.5) tokamak H-mode
  - Increasing β stabilizes ITG, TEM
  - Can lead to EM instabilities: MTM, KBM
- Obtained β_N scan (1.5-2.3)
  - Large impurities, performance evolving throughout day
- Goal: measure δB using UCLA cross-polarization scattering (CPS) to validate GK predictions (*plans to install CPS on NSTX-U*)



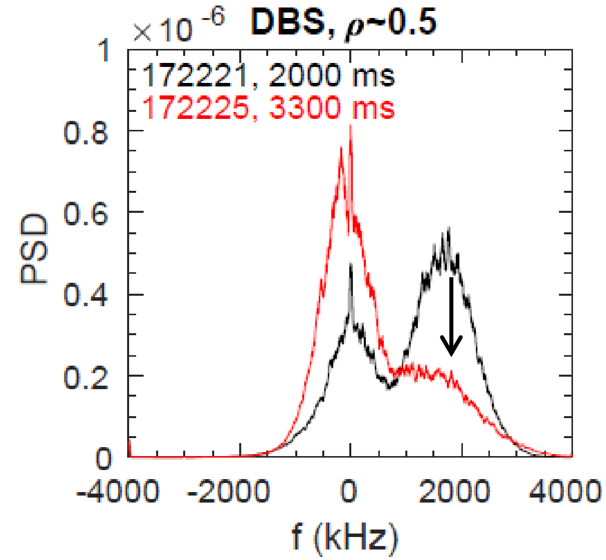
Initial results: core (ρ~0.5) CPS measurement distinct from DBS, both change with increasing power

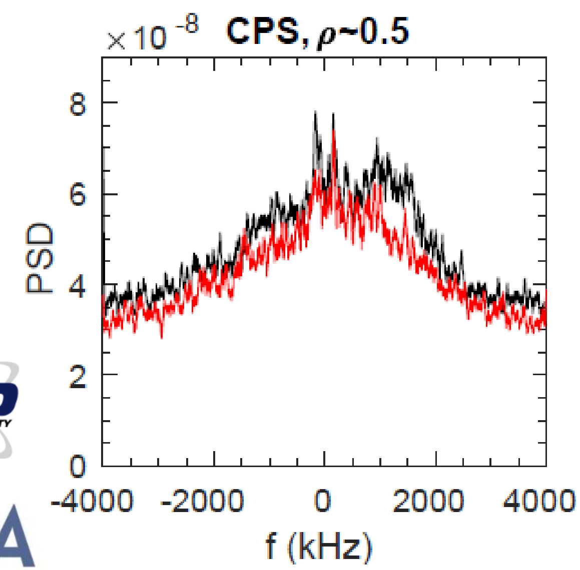
- Broad range of locations and wavenumbers:
  - CPS ($k_r\rho_s$=1.2–6), DBS ($k_\theta\rho_s$= 0.3–3)
- Will require extensive ray tracing + synthetic diagnostics for comparison & gyrokinetic validation



β_N=1.5

β_N=2.3 (higher T_i/T_e, n_{beam}/n_e, …)





Two of three DBS systems (W- & V-band) on loan from UCLA/NSTX-U

DIII-D NATIONAL FUSION FACILITY

UCLA

Enhancing NSTX-U / DIII-D collaboration on access to high non-inductive fraction scenarios

- Background / Motivation:
  - NSTX-U next ops will focus on partial inductive ramp-up and understanding/optimizing early H-mode access
    - Provide elevated low-l_i, high κ, elevated q_{min}, and access to MHD-stable high I_P plasmas for confinement and stability studies
  - DIII-D has related interest in physics of how to access advanced (i.e. high-β_P non-inductive) scenarios predictably
    - NSTX-U / STs interested in non-inductive sustainment and ramp-up
    - Follow up on previously performed NI ramp-up experiments on DIII-D
- Collaboration focus: Analyze, simulate, control high q_{min} scenarios – improve access, performance
  - J. Ferron (GA), C. Holcomb (LLNL), E. Schuster (Lehigh), …
  - Grierson / Poli (TRANSP), Boyer (control), Diallo (pedestal), Guttenfelder (transport), Park, Wang, Menard (MHD stability)

MAST-U areas of collaborative opportunities (1)
(coordinated by S. Kaye)

- Startup development – LRDFIT for null, wall modeling, vertical shape control, real-time EFIT and PCS upgrade:
  - D. Battaglia spending 2 ½ months at MAST-U – through August
    - Also engaging D. Boyer, K. Erickson both from PPPL
- Core physics
  - Transport and confinement: TRANSP, expts (S. Kaye)
  - Core turbulence using BES, DBS (Y. Ren)
  - MHD stability
    - Error fields and tearing modes (N. Ferraro, C. Myers)
    - Equilibrium reconstruction and MHD stability (S. Sabbagh, J. Berkery)
- Energetic particles
  - TAE modes, NB characterization (M. Podesta, E. Fredrickson, E. Belova, N. Gorelenkov)
  - High-frequency AE (N. Crocker)

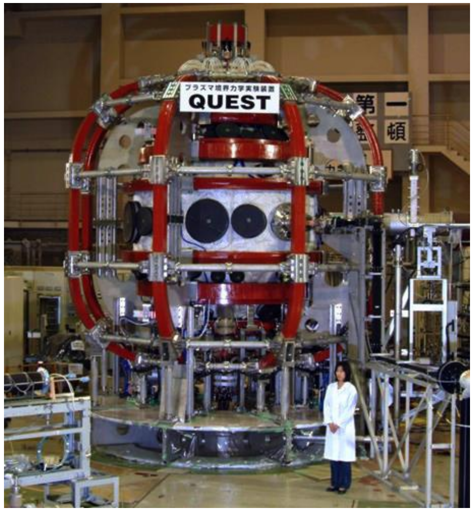
MAST-U areas of collaborative opportunities (2)
(coordinated by S. Kaye)

- Pedestal physics
  - Turbulence, pedestal structure (A. Diallo – continuing active collaboration, T. Rhodes)
  - Gas puff imaging (S. Zweben)
  - Pedestal & ELM stability modeling: (possibly G. Canal)
- Exhaust physics
  - Bolometry, radiative divertor physics (M. Reinke – already funded)
  - Divertor IR: TBD (J.-W. Ahn, T. Gray)
  - Divertor spectroscopy, turbulence, snowflake divertor ops (V. Soukhanovskii)

Major goal of the QUEST program is to generate steady-state fully non-inductive plasmas

- QUEST will ultimately use a combination of 2.45, 8.2, 8.56 and 28 GHz heating to generate steady-state, fully non-inductive plasmas with 3 MW of RF power:
  - *Present capability:*
    ~ 50 kW of 2.45 GHz
    ~ 400 kW of 8.2 GHz
    ~ 250 kW of 28 GHz

- The QUEST CHI system has been commissioned by University of Washington team and will be used with 28 GHz heating later this year

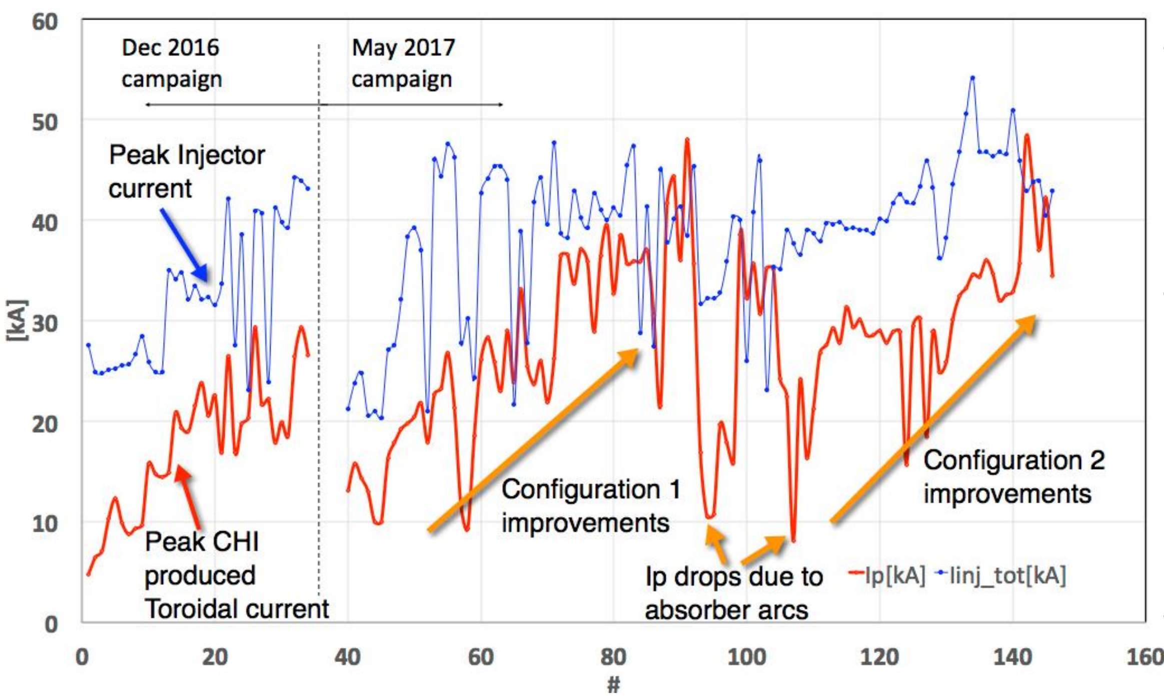


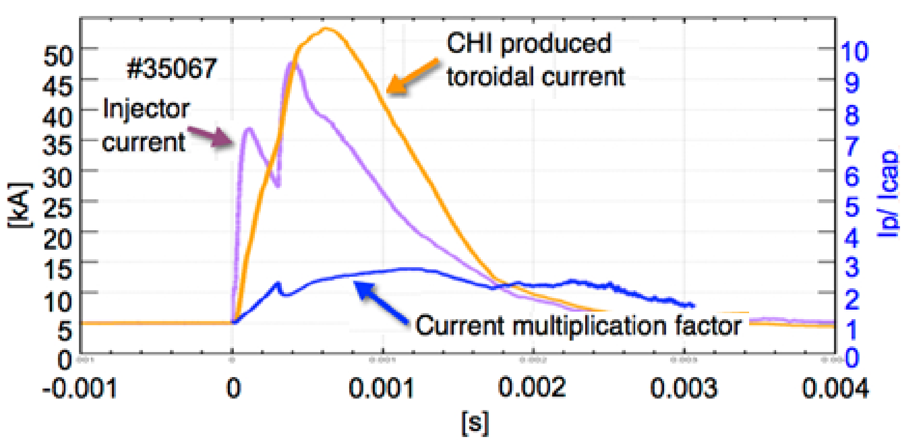
QUEST Spherical Tokamak

Major Radius	0.68 m
Minor Radius	0.40 m
Aspect Ratio	1.70
Vacuum Chamber Radius	1.4 m
Vacuum Chamber Height	2.8 m
Toroidal Magnetic Field	0.25 T (steady state), 0.5 T (pulse)
Plasma Current	100 kA (current) → 300 kA (target)
Heating Power	8.2 GHz + 8.56 GHz + 28 GHz: 3 MW (target)

QUEST Parameters

QUEST: Steady progress increasing plasma current using Coaxial Helicity Injection (CHI)





- Increased peak toroidal current from 29 kA (Dec 2016) to 48 kA
- CHI produced toroidal current exceeded injector current during this campaign
- Config. 2 used VF & narrower flux footprint
- Considerable amount of magnetics data to be analyzed to further improve discharges during Campaign 3

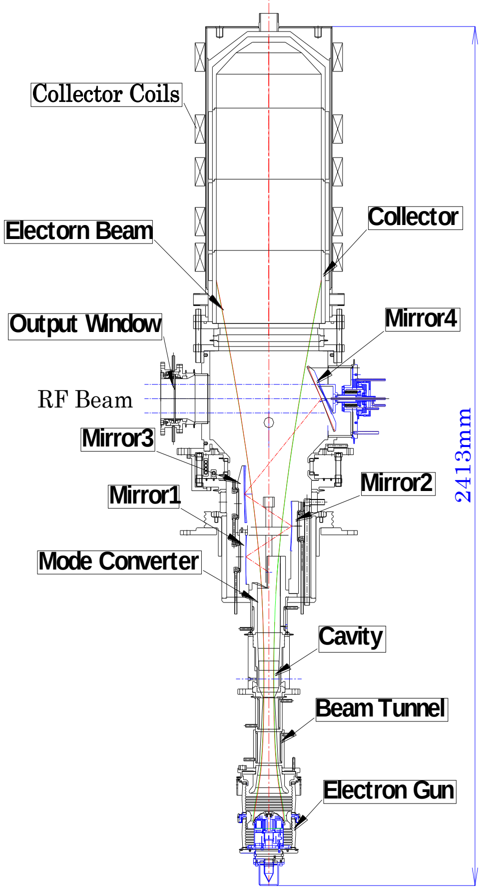
Initiated Work on TSC Simulations of CHI on QUEST & Physics Design of High-Current Transient CHI System for PEGASUS

PEGASUS	QUEST
High injector flux >60 mWb (I_p ~400kA)	Low injector flux ~28mWb (I_p ~100kA)
B_T to be upgraded to 0.6T, with 0.9T enabled by larger power supply in future Quite important for injecting large quantities of poloidal flux	B_T on QUEST is 0.25T
ECH heating needed to support sustained current operation	QUEST has access to high power ECH capability
Plan to test multiple electrode materials and also change the electrode location to improve understanding of CHI system optimization for larger fusion experiments	QUEST is an all metal machine, and the CHI electrodes are metallic Provides early supporting data on operation of CHI with metal electrodes
Will use double biased electrode configuration to more clearly define current path	QUEST is testing a new, single biased configuration

- Detailed QUEST vessel model developed for simulations with TSC
- Comparative studies using simplified vessel model is in progress
  - With insulators in NSTX-like configuration, and coils close to the CHI break
  - With insulator as in QUEST, and the coils much farther away, as on QUEST

R. Raman, M. Ono

QUEST uses 28GHz Gyrotron developed by Tsukuba (similar to gyrotron proposed for NSTX-U)



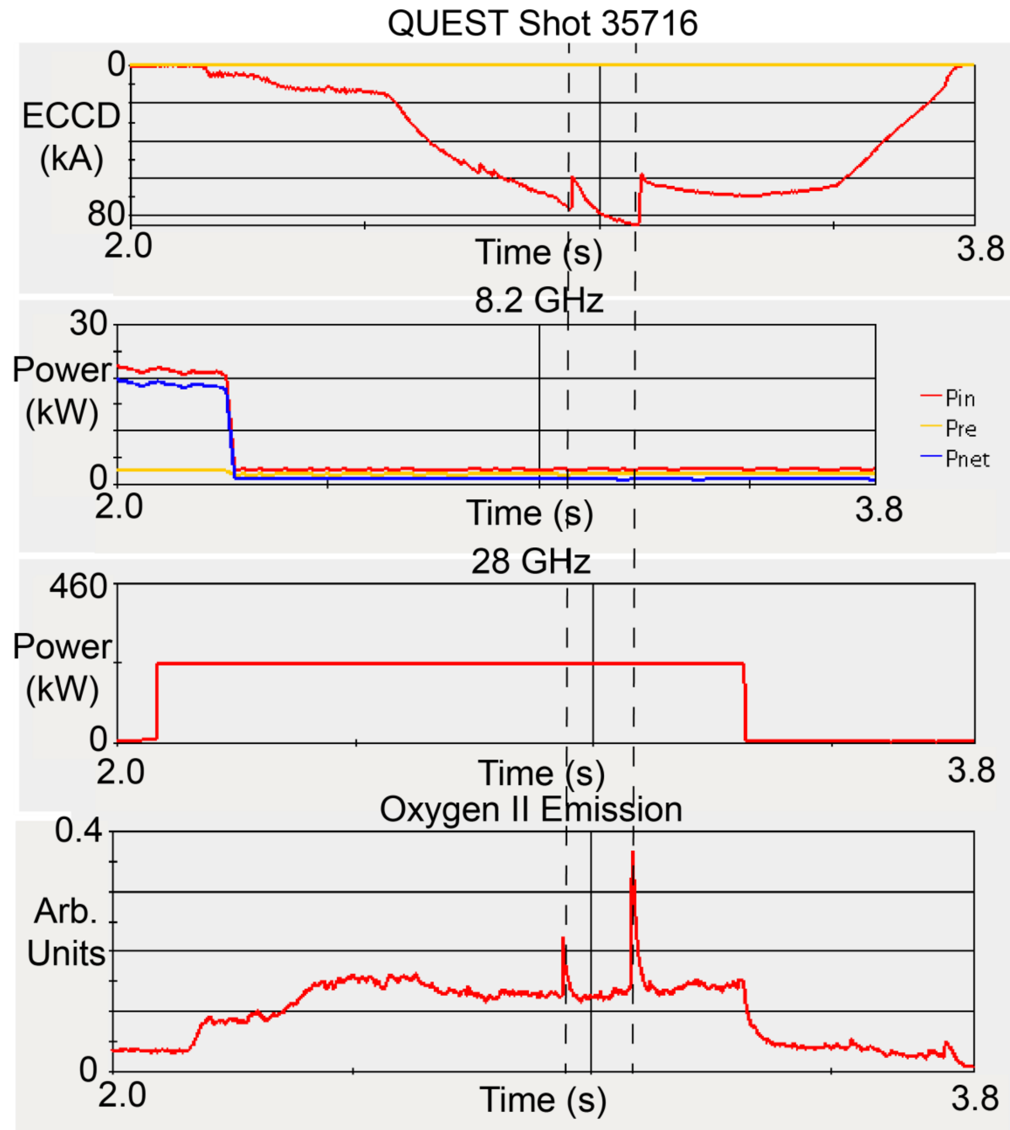
- 28 GHz gyrotron had been developed for Gamma-10/PDX projects at Tsukuba University

28 GHz Gyrotron Design Parameters	
Frequency	28GHz
Output Power	1 MW
Pulse Width	1 s
Output Efficiency	35% (W/O CPD)
Beam Voltage	80 kV
Beam Current	40 A
Cavity Oscillation mode	$TE_{8,3}$
Output mode	Gaussian like
Output Window	Sapphire Single Disk
Aperture diameter	112 mm

Generated up to 85 kA with 230 kW

- Limited by large drops in generated current, coincident with bursts in the Oxygen-II emission
- Analysis ongoing to investigate cause
- Also collaborating on kinetic modelling of energetic electron population and current drive (Bertelli - PPPL)

G. Taylor (PPPL)



NSTX-U researchers also actively engaged in generating input for National Academy panel

Workshop Info

- Agenda
- Meeting Venue
- Remote Connection (Zoom)
- Upload Presentation / File
- View / Download Presentations / Files
- Submit Chit (Comment / Recommendation)
- View / Download Chits
- Discussion Session Groups
- Discussion Session Guidance
- Discussion Session Questions
- Registration
- View / Download Whitepaper
- Whitepaper Guidance & Template
- Announcement PDF
- Overview
- Hotel Information
- Workshop Governance & Process
- Program Committee
- MFR Report Archive
- Sitemap

NAS Study Info

- NAS Charge and Schedule
- NAS Committee

Agenda

US Magnetic Fusion Research Strategic Directions Workshop

University of Wisconsin – Madison

July 24 – 28, 2017
Last updated July 20, 2017

Zoom URL (only available during plenary presentations):
https://zoom.us/j/5669851878 or here
PLEASE MUTE YOUR MICROPHONE!

To download this agenda click here

Monday, July 24

Plenary Session: Workshop Goals / Strategic Planning Perspectives / Program Health

(Chair: M. Wade)

8:30 O. Schmitz: Welcome and Workshop Logistical Details (10)

8:40 J. Menard: Overview of Goals and Organization of Workshop (15+5)

9:00 M. Mauel: A Strategic Plan for US Burning Plasma Research (15+5)

9:20 M. Greenwald: Community Planning For Fusion Energy and Plasma Science (25+5)

9:50 M. Shochet: Overview of P5 Planning Process: Lessons Learned (20+10) (Remote via Zoom)

10:20 T. Carter: The Current Status and Health of US Magnetic Fusion Energy research (15+5)

10:40 Coffee break

Plenary Session: Strategic Directions / Vision for the Future

Thank you!

Any questions?

Backup - milestone progress

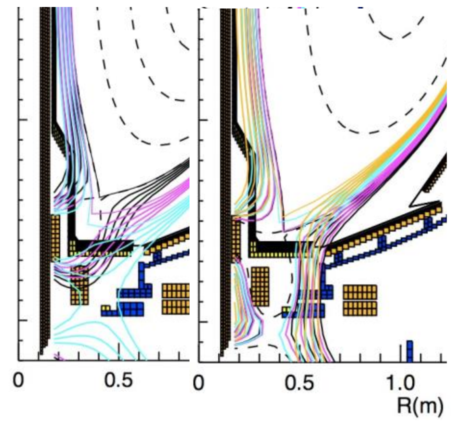
Scope of JRT-2017 contribution from NSTX-U

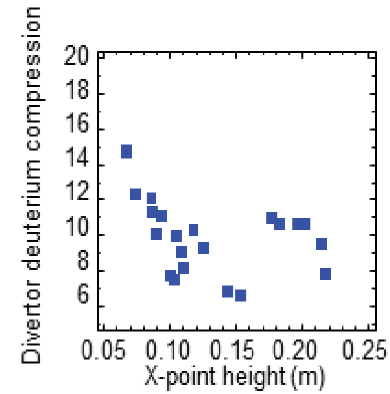
- **JRT-2017 deliverable**: "…data will be used to assess the impact of edge magnetic configurations and divertor geometries on dissipative regimes, as well as their effect on the width of the power exhaust channel"
- No divertor experimental data from NSTX-U, so are utilizing additional / new analysis of NSTX divertor experiments:
  - Summarize partially detached divertor operating space, characteristics
  - Analyze how detachment depends on divertor flux expansion
  - Analyze how the radial extent of the partially detached region depends on divertor scrape-off layer width and gas seeding
  - Compare to multi-fluid transport model predictions
- Large experimental NSTX database:
  - XPs: 605, 708, 814, 816, 826, 1045, 1050
    - But, only later XPs had full complement of divertor diagnostics

Assessing how detachment depends on flux expansion, how detachment width depends on SOL width

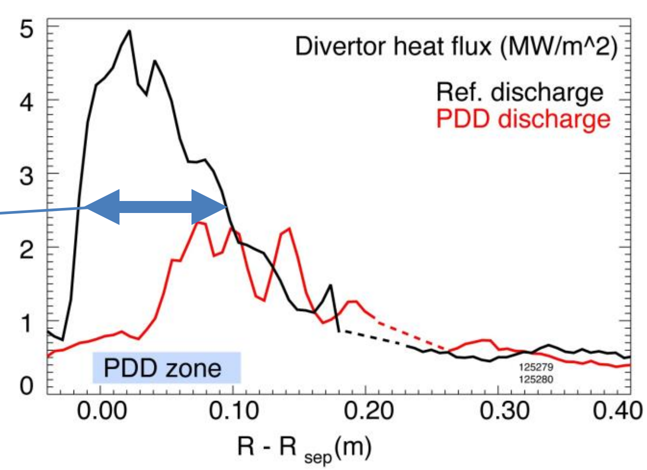
- New analysis of NSTX divertor detachment onset as function of standard divertor geometry ($l_{||}$, f_{exp}, R_{SP}, etc)
  - UEDGE modeling underway for 6 different configurations with charge-state resolved carbon and n_e scans
  - National campaign: 1 run day MP on divertor detachment similarity to NSTX / NSTX-U

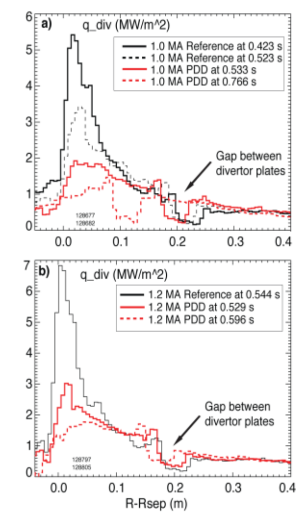
Scenario	Coils	X-pt height	OSP major radius	Flux expansion
#1	PF1AL	6-23 cm	0.30-0.39 m	6-26
#2	PF1AL & PF1B	4-11 cm	0.42-0.45 m	14-35





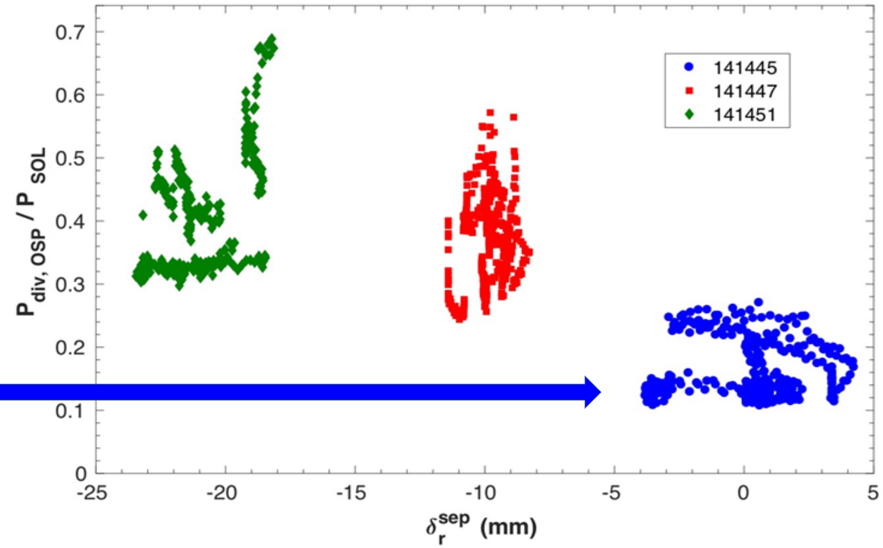
- Can extent of detachment be linked to radial transport via λ_q?
  - Initiated analysis of the radial detachment region extent as function of divertor scrape-off layer width and gas seeding (0.8, 1.0, 1.2 MA)



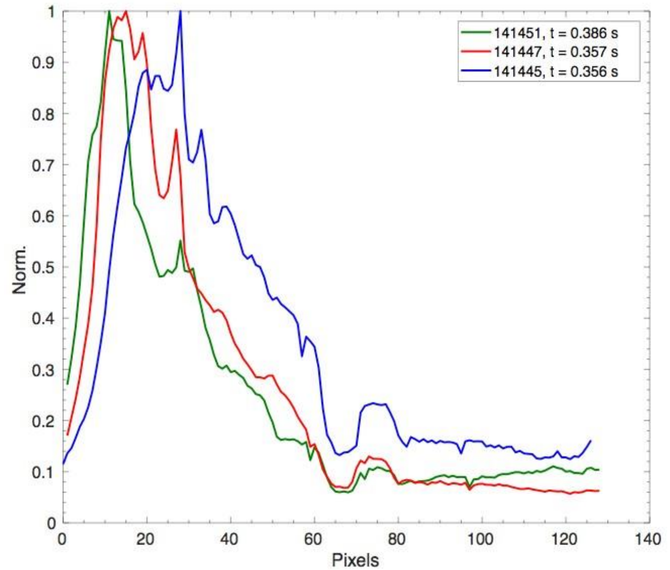


New result from data mining: Inter-ELM power to lower-outer strike point is reduced as $dR_{sep} \rightarrow 0$

- dR_{sep} = radial distance at the outer midplane between the flux surfaces connected to the upper and lower X–points
- Near double-null:
  - $10\% \leq P_{div,\ OSP/PSOL} \leq 30\%$

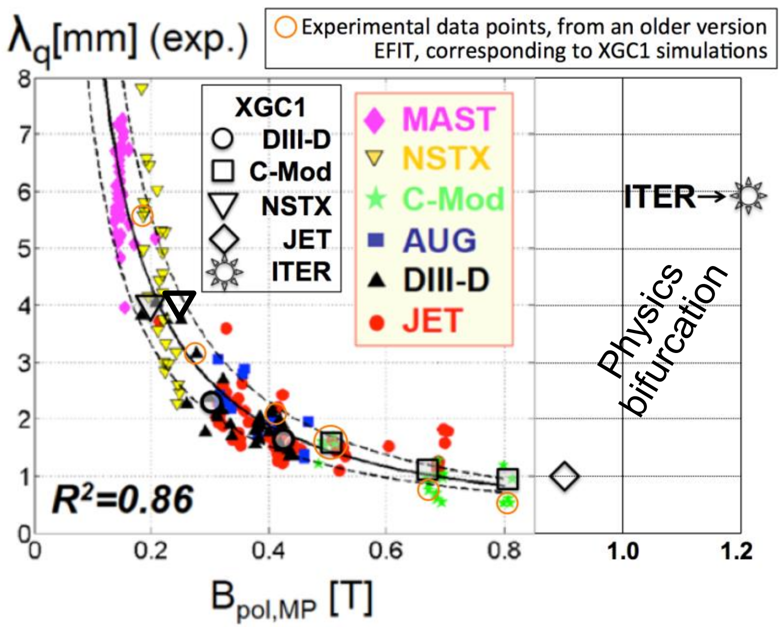


- λ_q broadens as $dR_{sep} \rightarrow 0$
- Next steps in analysis:
  - Use Langmuir probe data to estimate power deposition at other strike points without IR data
  - Quantify changes in λ_q with dR_{sep}
- **May impact expected heat fluxes in NSTX-U DND?**



R(17-1): Simulation-based projection of divertor heat flux in NSTX-U

- **Goal:** Extend SOL heat-flux width simulations up to 2MA, 10MW NSTX-U scenarios – make prediction for NSTX-U
- **Tools:** XGC1 – including magnetic drift of warm ions across separatrix, cross-field E×B-drift heat-flux from edge turbulence
- **Impact:** Understand neoclassical vs turbulent SOL transport
  - Important to NSTX-U heat flux mitigation, ITER power exhaust challenge
- **Progress:**
  - Completed 1MA NSTX
    - 11% of 29 peta-flop Cori Xeon-Phi nodes at NERSC, 3 days
  - 1 and 2MA NSTX-U cases now running on Cori
  - Will report final results Q4

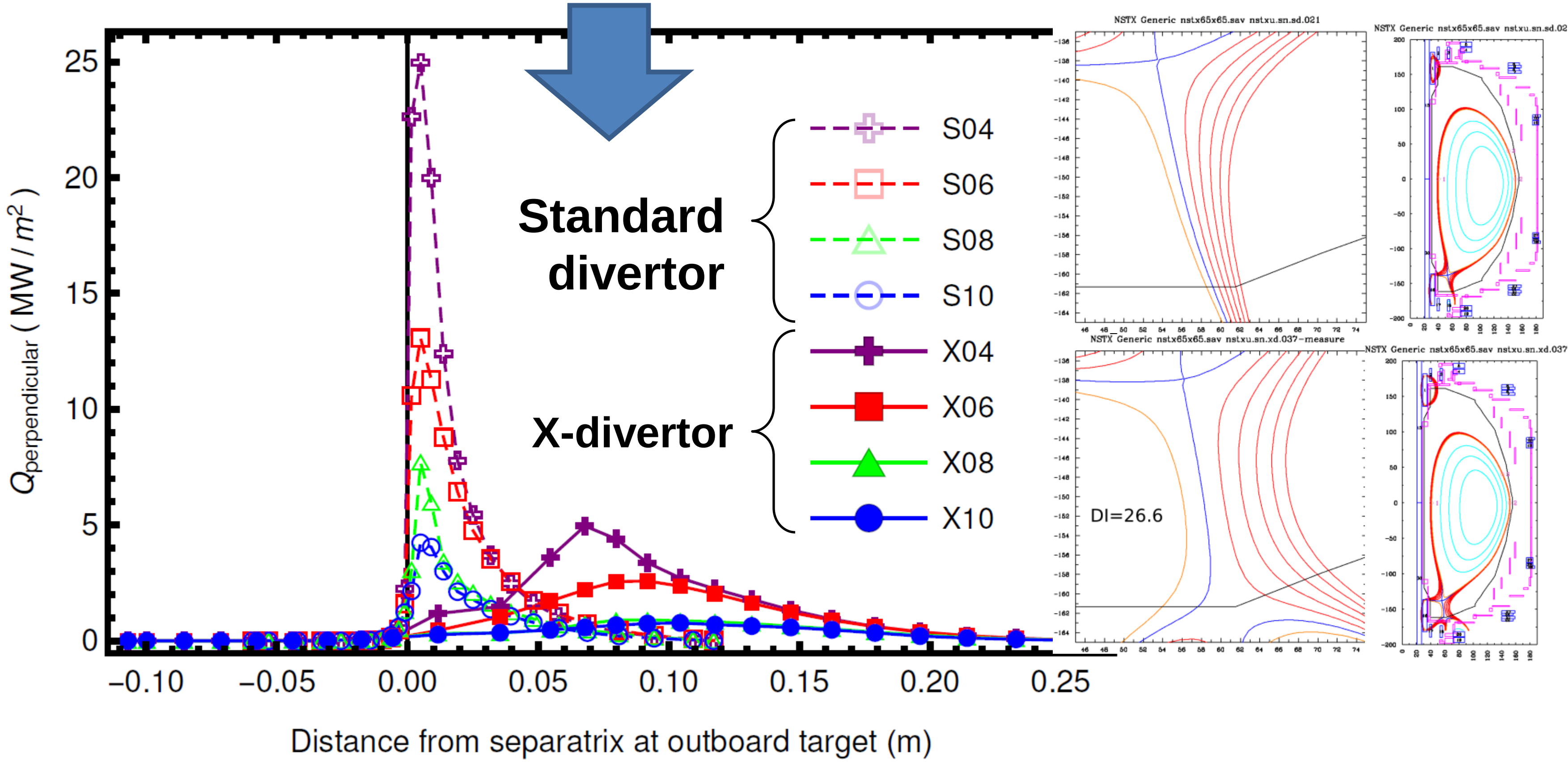


R17-2: Advanced divertor operating scenario modeling for NSTX-U

- **Goals:**
  - Assess dependence of advanced divertor vs solenoid and PF currents, perturbed 3D fields (could increase local peaking)
  - Assess divertor radiation & heat fluxes vs current, input power, density, and seeded impurities
- **Tools:** ISOLVER, CORSICA, SOLPS, UEDGE, GINGRED, M3D-C1, EMC3-EIRENE
- **Impact:** Define advanced divertor operational space
  - Responsive to Recovery Project issue / concern
- **Progress:**
  - Extensive heat-flux reduced modelling vs. OH, PF1 currents for PFC requirements specifications and PF1 coil design
    - Reported at several FES Thursday meetings, EoC (not repeated here)

Designed controlled experiment for NSTX-U to assess heat flux and detachment vs. flaring (UT Austin)

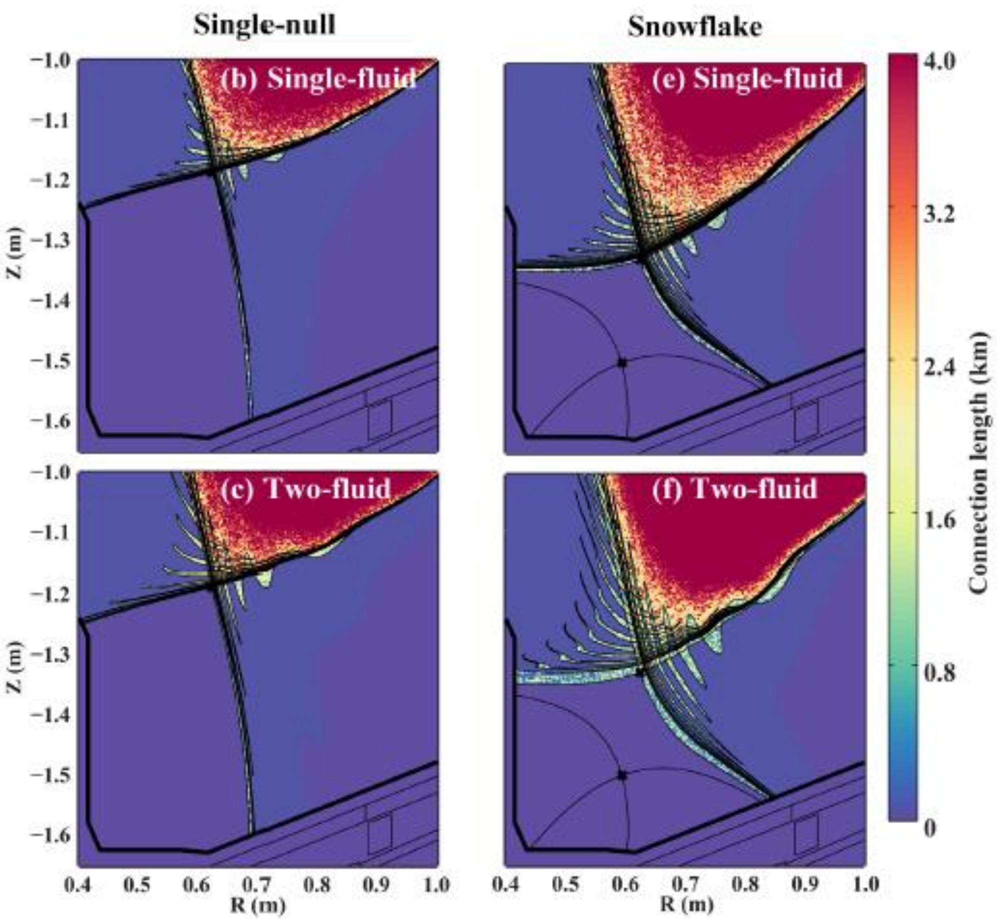
- Can hold core fixed while varying divertor (CORSICA+SOLPS)
  - I_P = 1.1MA, B_T = 0.74T, A~1.73, q_{95}~6, κ=2, δ_L = 0.47, P_{SOL} = 2.9MW
- X-divertor (2nd x-point under target plate) promotes detachment
  - Gas-puff scan: 4, 6, 8, 10 $\times 10^{21}$ particles / second



Assessing impact of 3D fields on advanced divertors incorporating different plasma response models

- Lobe structure and connection length both sensitive to divertor type, plasma response model
  - Snowflake has larger/longer lobe structure than conventional single-null divertor
    - May result in stronger asymmetries at divertor target (?)
  - Plasma response stronger from 2-fluid model than from single-fluid model

n=3 RMP using mid-plane RWM/EF coils



G. Canal, et al., recently published in Nuclear Fusion 2017

R17-5: Analysis and modelling of current ramp-up dynamics in NSTX and NSTX-U

- **Goal:** Understand, optimize evolution and global stability of current ramp-up phase to lower inductance, access high current scenarios to support wide-range of NSTX-U research goals
- **Analysis:** L-H transition vs. density, shape, current, vertical growth rate (LRDFIT, TOKSYS), TRANSP, DCON/RDCON
- **Impact:** Accelerate access to high plasma current, power scenarios when NSTX-U operation resumes
  - Responsive to FY2016 PEMP, supports entire research program

Specific goals for R17-5

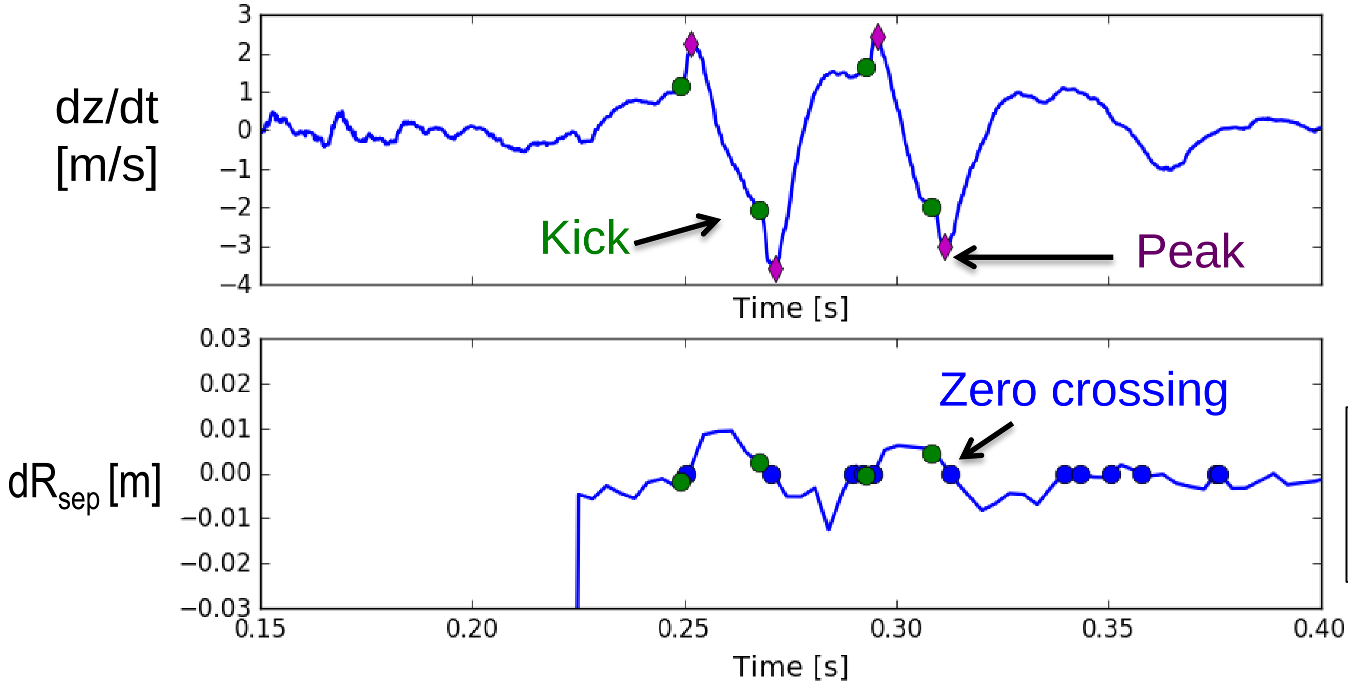
- Evaluate elongation limits during ramp-up phase using data and calculations
  - What factors limit the elongation before, during and after diverting?
  - Identify growth rate of vertical instability to predict controllability of high-κ shapes

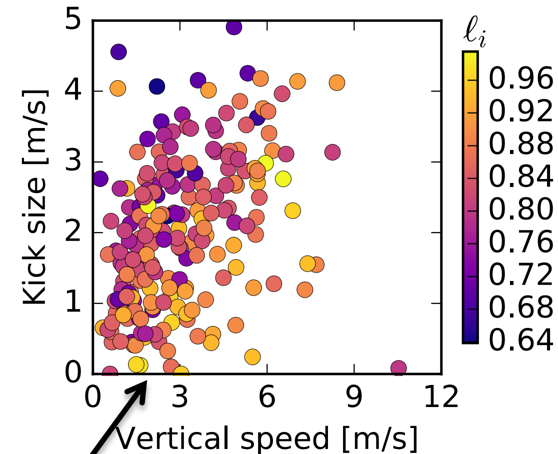
- Establish the dependence of the L-H transition on density, plasma shape, etc. to inform modeling of threshold criteria and scenario targets

- Perform stability analysis of experimental and modeled discharges to identify MHD limits during ramp-up

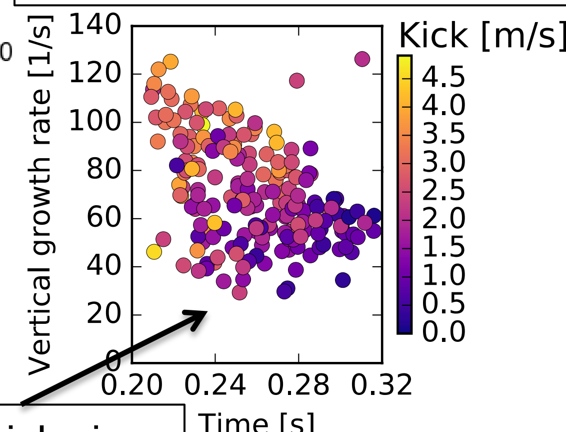
- Prepare for FY2018: establish TOKSYS framework for testing and optimizing control

Oscillations often observed just after diverting on NSTX-U appear to be sustained by ‘kicks’ that occur when crossing dRsep=0 with velocity/growth rate dependent magnitude that decreases in time





Kick size increases with vertical speed, larger at low li (early in time)



Given growth rate, kick size appears to decrease in time

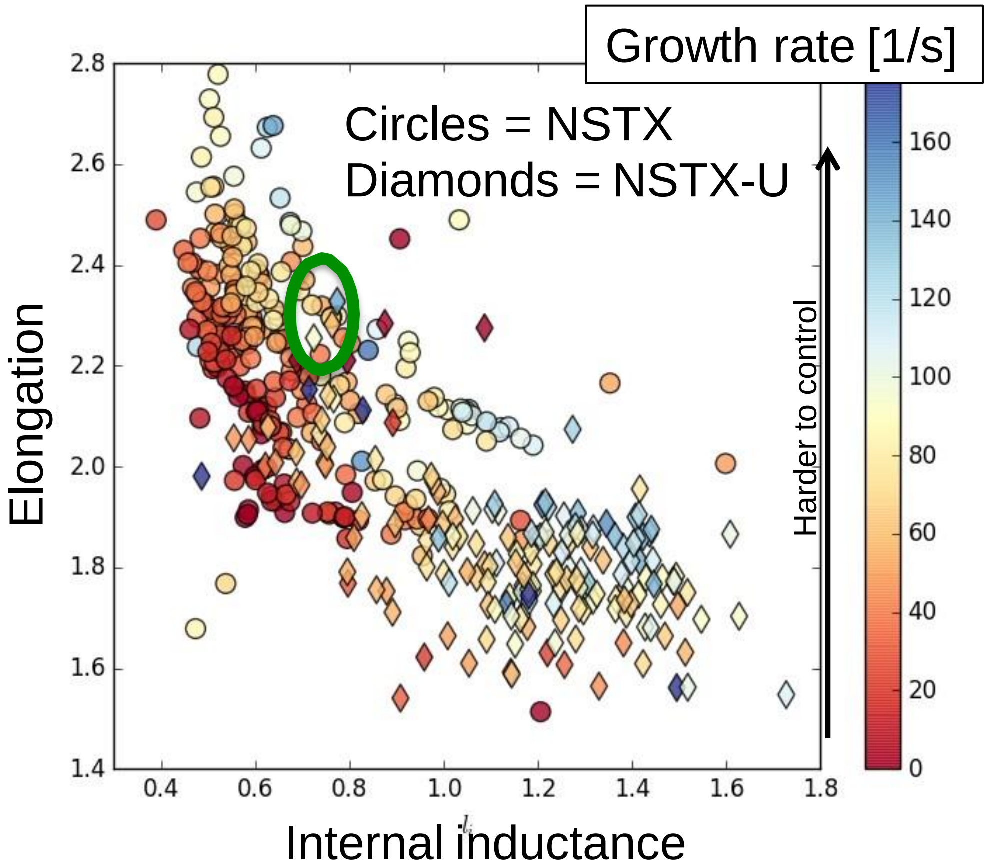
- Should try to avoid vertical motion and high growth rate just after time of diverting
- Should avoid crossing drsep=0 near time of diverting
- Will study ways to make controller less sensitive to kicks (Filtering, time/equilibrium dependent gains)

Flat-top growth rate calculations will allow projection of NSTX-U limits to lower l_i

- Calculations within LRDFIT quantify open loop vertical growth rate
  - Evaluate growth rate just prior to VDE time

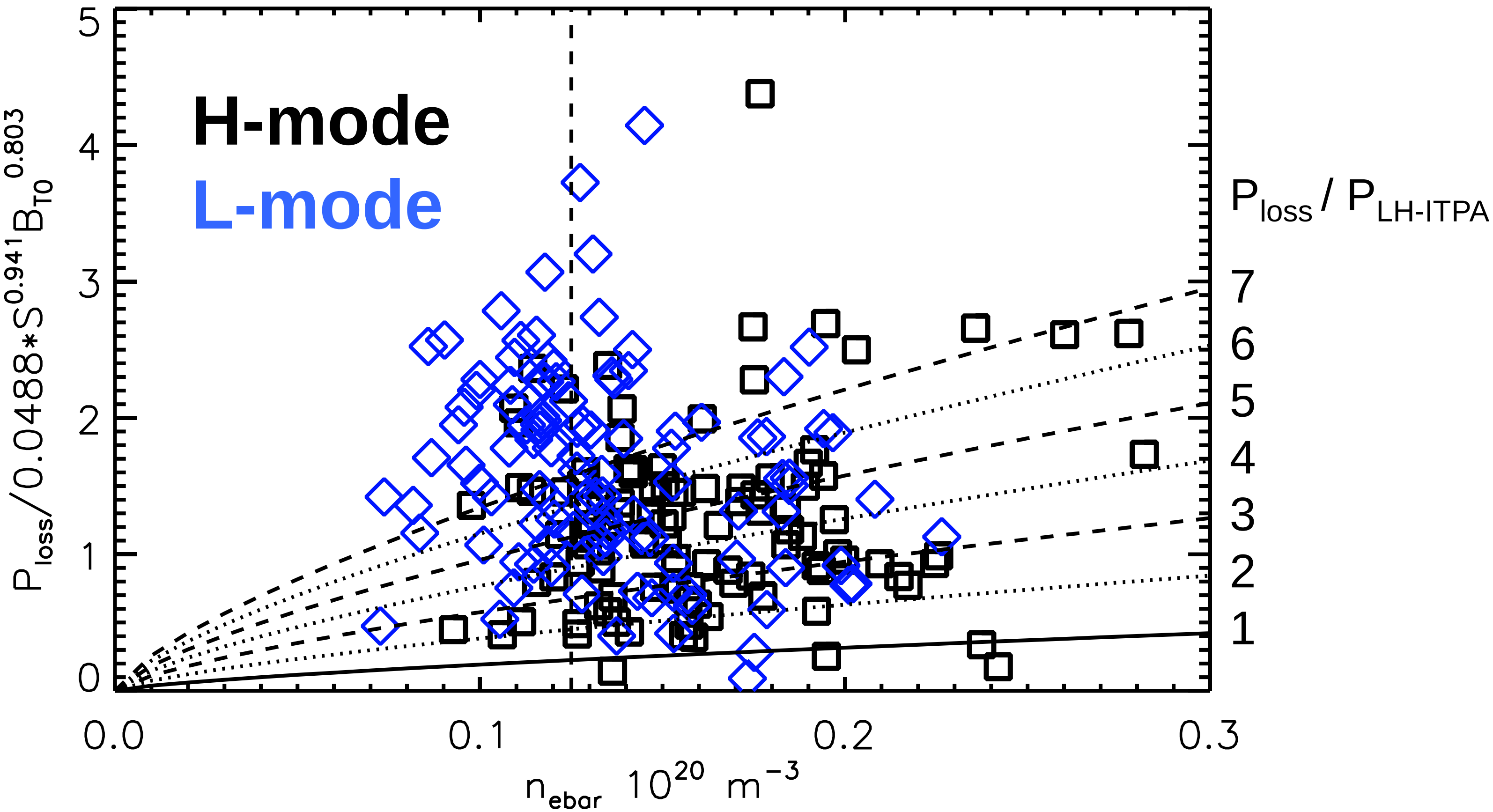
- Maximum growth rates for NSTX-U, NSTX similar
  - Implies NSTX-U κ can approach NSTX κ at low l_i

- Many 'VDEs' occur below limit ~ 120-140 s^{-1}
  - Probably have different triggers, e.g., locked modes
  - Will refine filtering of VDE database (DECAF)



Database of normalized P_{loss} vs line-averaged n_e

- Some discharges stay in L-mode despite $P_{loss} >> P_{LH-ITPA}$
  - While some shots enter H-mode with $P_{loss} \sim P_{LH-ITPA}$



Identify parameters that isolate L-H time points from L-mode timepoints

- Restrict database such that all L-mode database points are excluded

  Above a minimum density: $\mathbf{n_{ebar}} > 1.25 \times 10^{19}\ m^{-3}$

  Low surface V (pause I_p ramp): $\mathbf{V_{surf}} < 1.15$ V

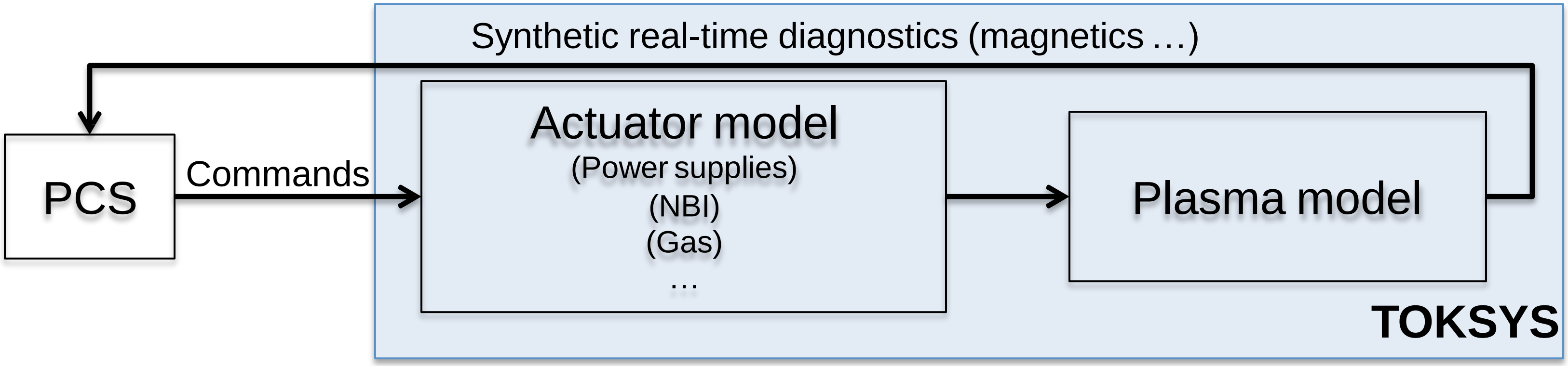
  Near double null: $|\mathbf{d_{rsep}} - 0.2\ cm| < 0.6$ cm

  Clean wall conditions: $\mathbf{O\ II_{LD} / D_{\gamma LD}} < 1.1$

- About half (36 / 68) of the H-mode database points satisfy this criteria
  - Most L-H points with lowest P_{loss} satisfy this criteria

- Informs operational targets for improved reliability in L-H timing

Modeling framework aims to accelerate ramp-up scenario and control development



- TOKSYS: Matlab code used to develop actuator and plasma models for testing PCS algorithms (supported by GA)

- Two major development efforts
  - Design and validate plasma model using experimental data and simulations (i.e. TRANSP, DCON)
  - Develop non-linear models and/or switching between linear models
    - Flattop modeling typically uses linearized model around a reference case

- Ultimate goal: develop, test and optimize scenarios and control in the ramp-up phase in offline simulations

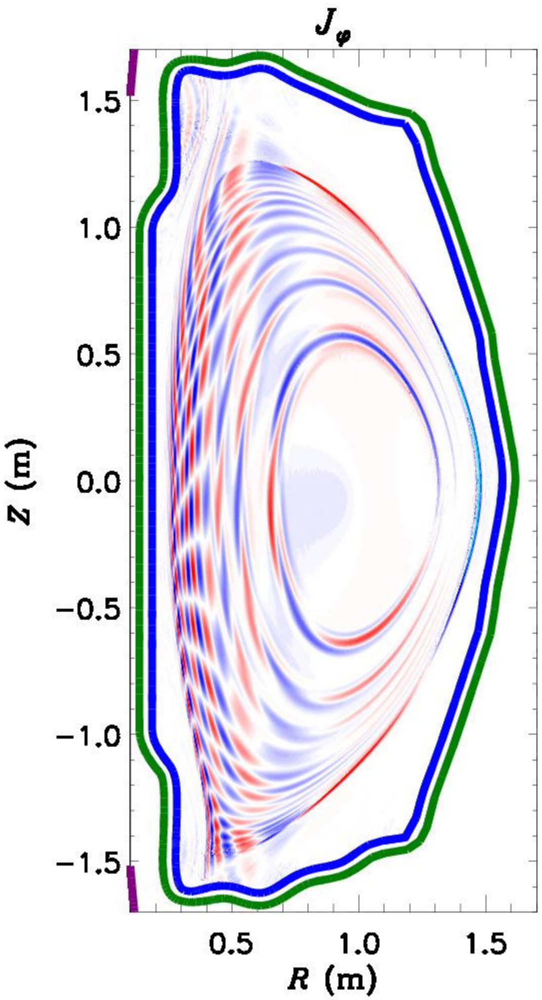
Progress in establishing TOKSYS simulations for NSTX-U

- Vessel current model, linearized plasma response model, synthetic magnetic signals generated
  - Supports snowflake control development and testing
  - Validation of plasma response model will begin soon
- Power supply models have been developed
  - Model includes simplified bridge rectifier model
  - Working toward end-to-end optimization of vertical stability
- Recently demonstrated coupling between PCS and the models within TOKSYS

Backup - Core

Modeling Finds that Resistive Modes May Explain ELMs in STs

- Ideal-MHD models of ELM stability have not been accurate in STs
  - Ideal-MHD model often finds ELMing plasma to be stable
- New modeling with M3D-C1 shows that ELMing discharges in NSTX are unstable to resistive peeling-ballooning modes
- *This may resolve longstanding question about ELM stability in STs*



G. Canal

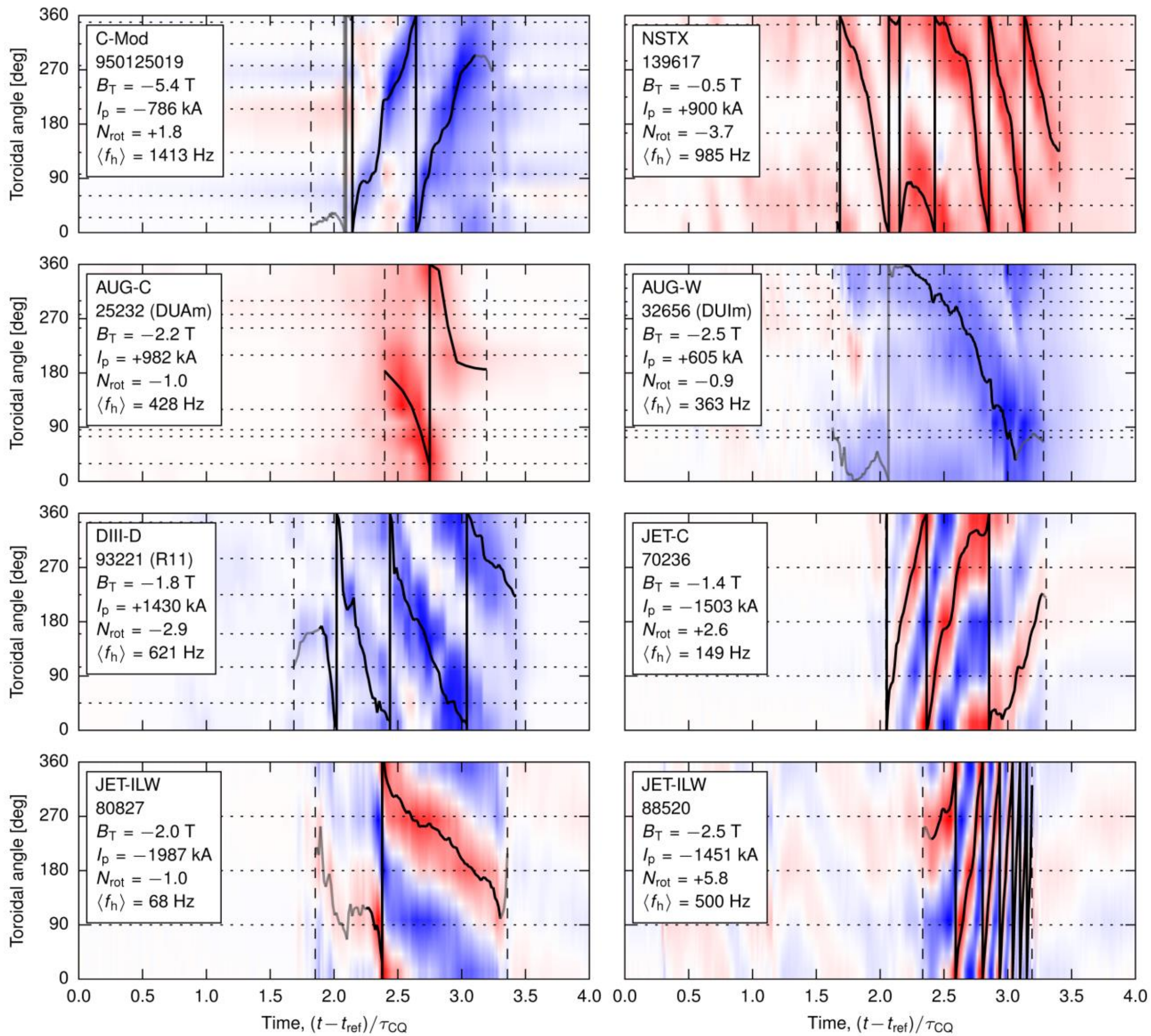
Create an ITPA halo current rotation database: C-Mod, DIII-D, AUG, NSTX, and JET

C-Mod | NSTX

AUG-C | AUG-W

DIII-D | JET-C

JET-ILW | JET-ILW



Energetic-particle-modified GAEs

- Self-consistent simulations reveal strong energetic particle modifications to high frequency global Alfvén eigenmodes (GAEs)
- Demonstrates that the nonperturbative regime for these modes was routinely accessed in NSTX operating conditions
  - Challenges assumption that GAEs in NSTX(-U) are well described by perturbative models
- May indicate existence of a new, previously unidentified energetic particle mode (EPM)
  - Observable in future NSTX-U experiments
- Potential implications for understanding the anomalously flat electron temperatures observed in NSTX at high beam power (correlated with CAE/GAE excitation)
  - Magnitude of energy channeling and orbit stochastization effects may be modified when incorporating these modes vs traditional GAEs

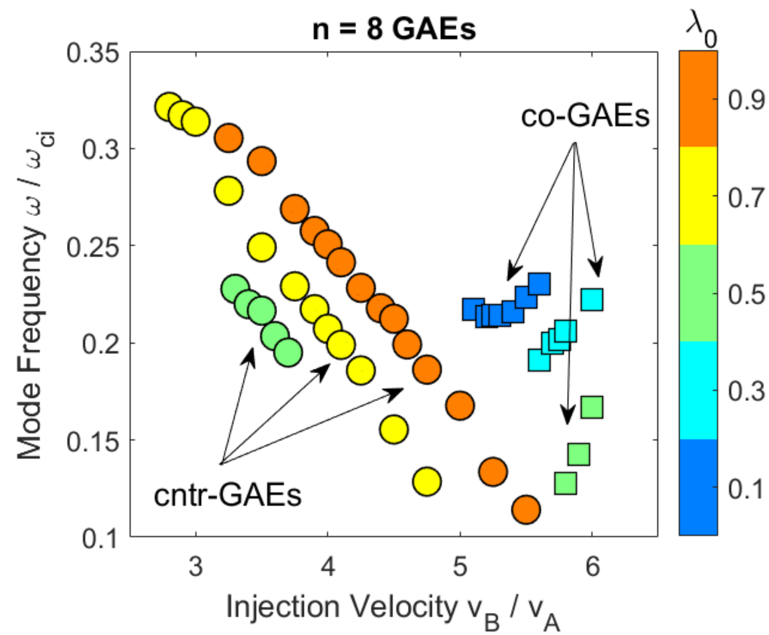
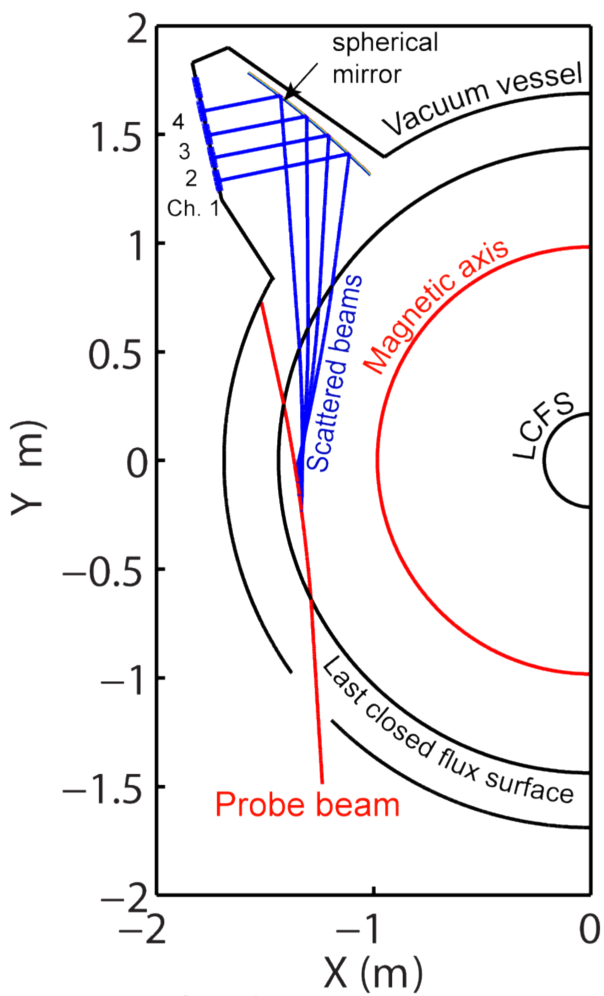


Figure: Change in frequency for |n|=8 GAEs as a function of the normalized injection velocity v_b/v_A. Cntr-GAEs are marked by circles, co-GAEs by squares. Color denotes the central pitch $\lambda_0 = \mu B_0/\varepsilon$ of the beam distribution in each simulation. The on-axis cyclotron frequency is 2.4 MHz.

Probe Plasma Turbulence at NSTX using a High-k Scattering Diagnostic

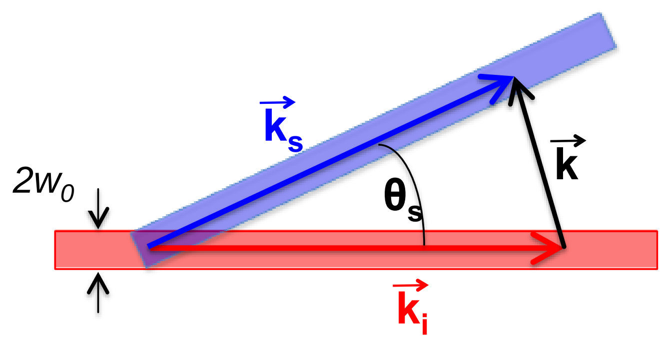


View from top of NSTX

- Scattered Power $P_s \propto \left(\frac{\delta n}{n}\right)^2$
- ***Three wave-coupling*** between incident beam $(\mathbf{k_i}, \boldsymbol{\omega_i})$ and plasma $(\mathbf{k}, \boldsymbol{\omega})$

$$\vec{\mathbf{k}}_s = \vec{\mathbf{k}} + \vec{\mathbf{k}}_i \qquad \boldsymbol{\omega}_s = \boldsymbol{\omega} + \boldsymbol{\omega}_i$$

- $\boldsymbol{\omega}_i, \boldsymbol{\omega}_s >> \boldsymbol{\omega}$ imposes Bragg condition

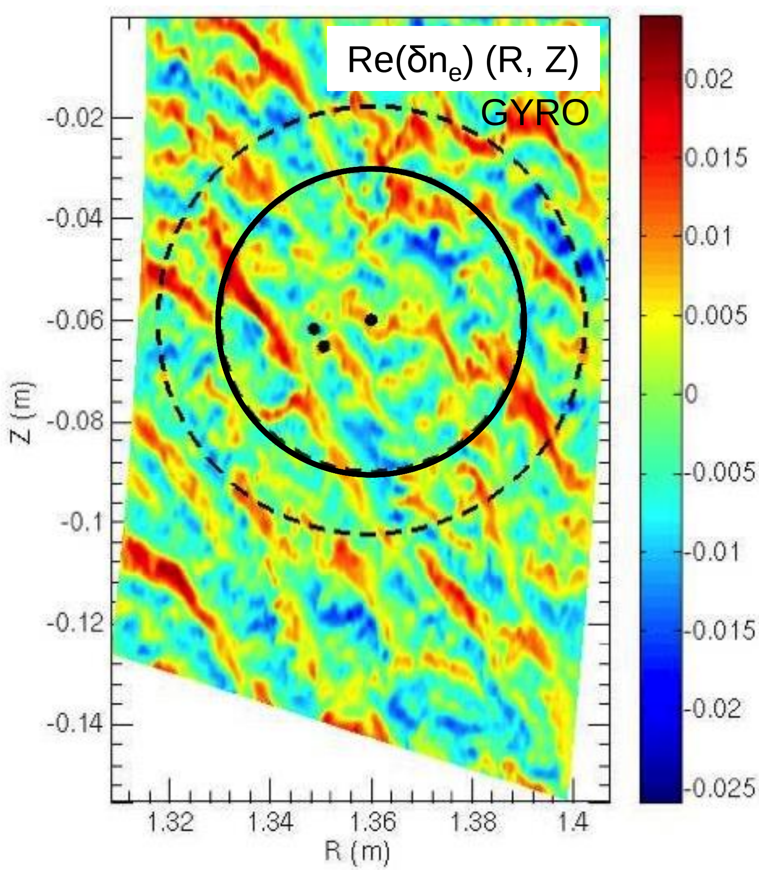


$$\mathbf{k} = 2\mathbf{k}_i \sin(\theta_s/2)$$

- k of the turbulence is selected by geometry.

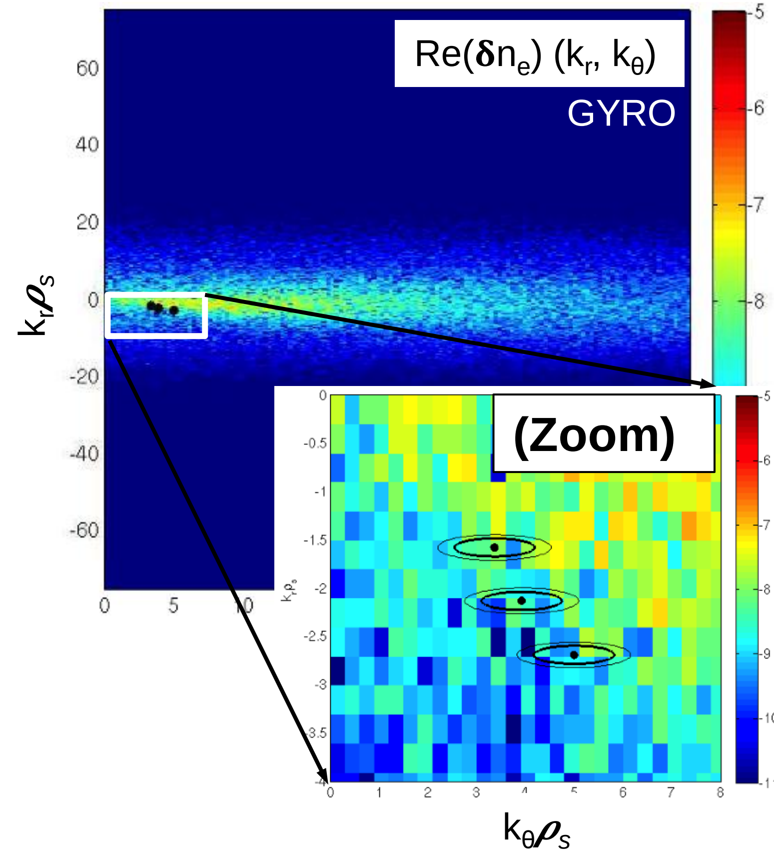
Two Equivalent Ways to Perform a Synthetic Diagnostic for High-k Scattering at NSTX Using Gyrokinetic Simulation

Filter fluctuations in real space



Scattering system is *spatially* localized (R, Z, φ)

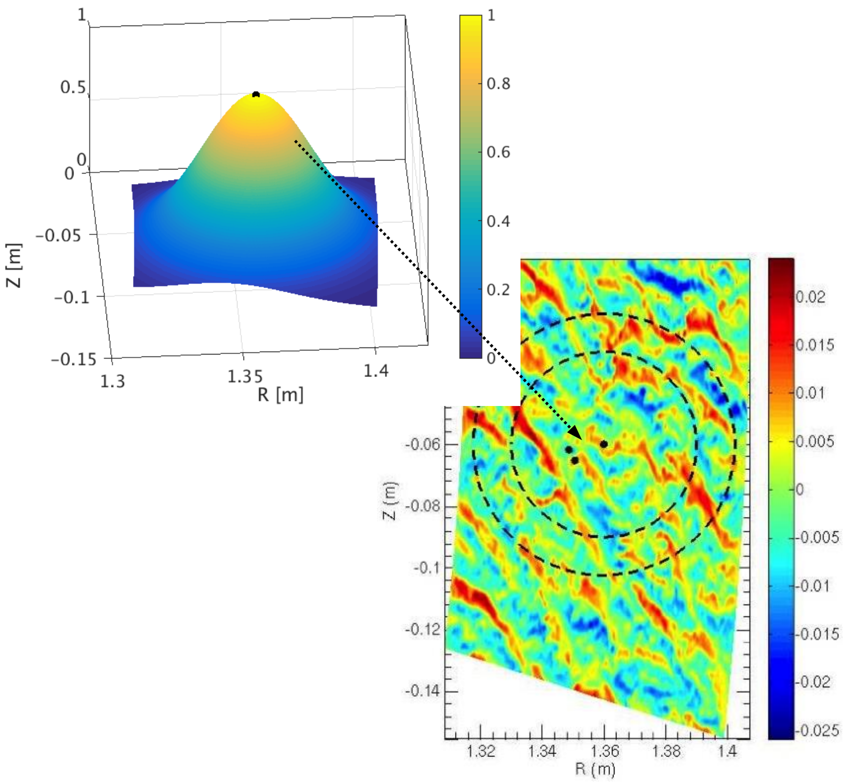
Filter fluctuations in k-space



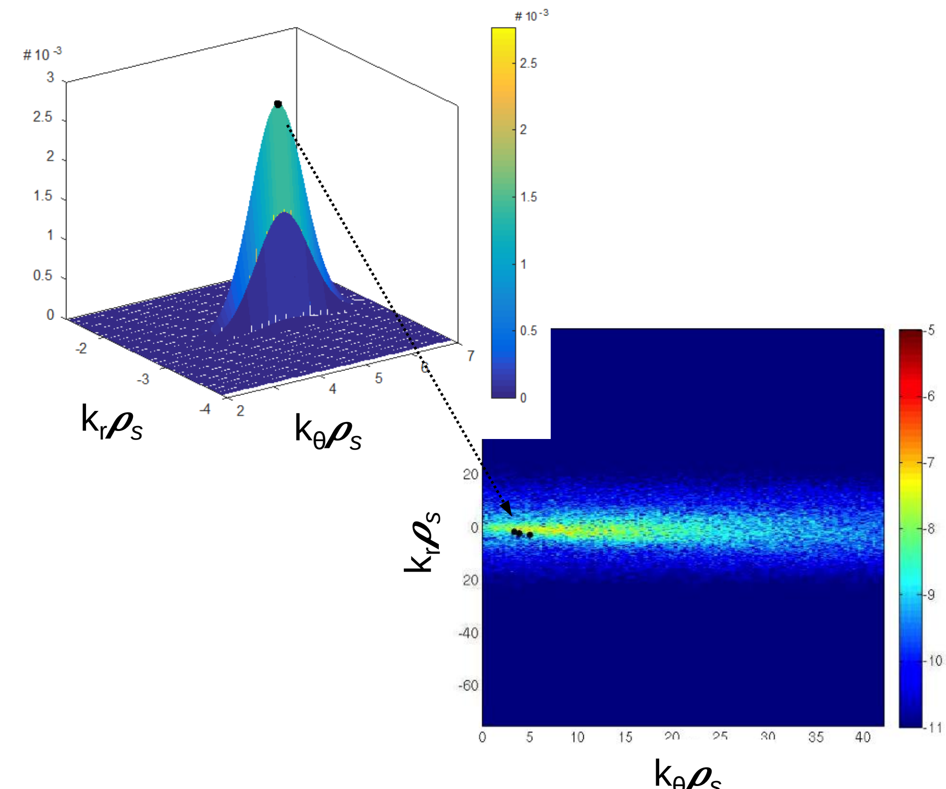
Scattering system is *wavenumber* selective (k_r, k_θ, k_φ)

Filter Turbulent Fluctuations in Real and Wavenumber Space to Obtain a Synthetic Signal

Filter in real space: $\boldsymbol{\psi}_{\mathrm{R}}(\vec{r})$



Filter in wavenumber space: $\boldsymbol{\psi}_{\mathrm{K}}(\vec{k} - \vec{k}_0)$



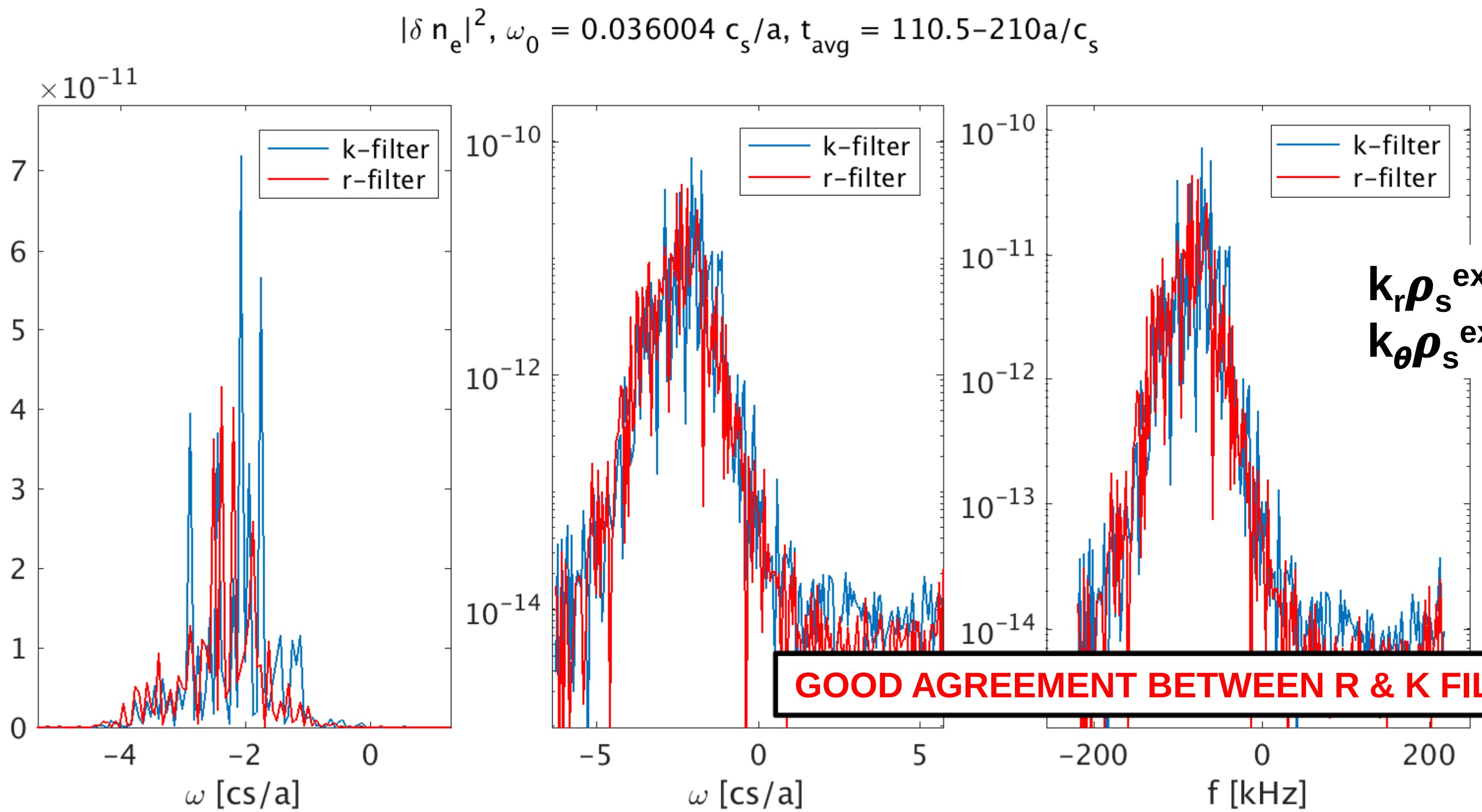
$$\delta\hat{n}_e{}^{syn}(t) = \int \tilde{n}_e(\vec{r},t)\boldsymbol{\psi}_{\mathrm{R}}(\vec{r})e^{-I\vec{k}_0\cdot\vec{r}}\, d^3\vec{\mathbf{r}}$$

$$\delta\hat{n}_e{}^{syn}(t) = \frac{1}{(2\pi)^3}\int \tilde{n}_e(\vec{k},t)\boldsymbol{\psi}_{\mathrm{K}}(\vec{k}\text{-}\vec{k}_0)\, d^3\vec{\mathbf{k}}$$

Obtain a time series of turbulent density fluctuations $\boldsymbol{\delta\hat{n}_e{}^{syn}(t)}$

Synthetic diagnostic applied to the cyclone base case: direct comparisons with experiment not yet available

Proof of principle showing equivalence between real space filtering and wavenumber space filtering



$k_r \rho_s^{exp}$ = 0.27
$k_\theta \rho_s^{exp}$ = 0.42

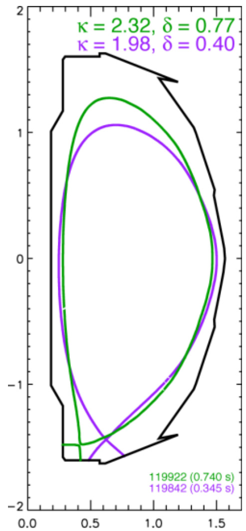
GOOD AGREEMENT BETWEEN R & K FILTERS

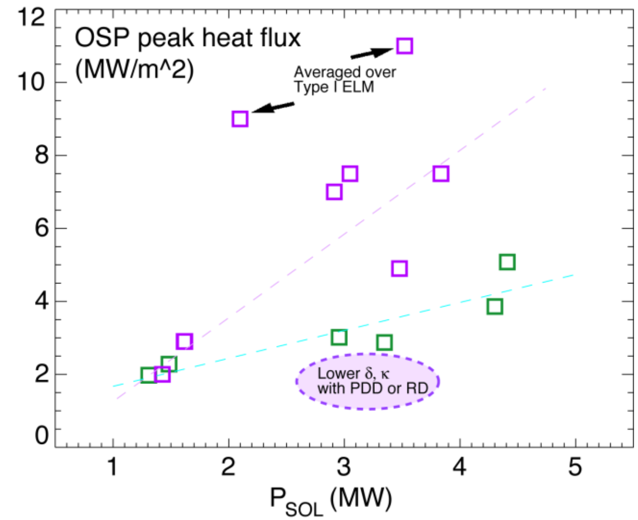
Direct comparisons between both synthetic diagnostic methods and experiments require additional big box electron scale simulations – to be computed at NERSC Edison/Cori supercomputers

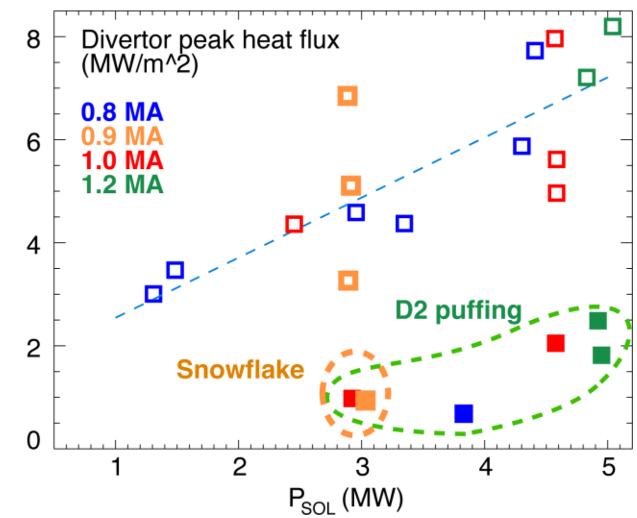
Backup - Boundary

Partial detachment operating space in NSTX

- Only no lithium data (2004-2008)
- Standard divertor configuration
  - Compact (small geometric area - ST)
  - High divertor power and peak heat flux
  - Never reaches detachment naturally at high n_e~0.9 n_G
  - Detachment onset strongly depend on
    - Magnetic flux expansion
    - Gas puffing location
    - Plasma current (B_p, λ_q ?)



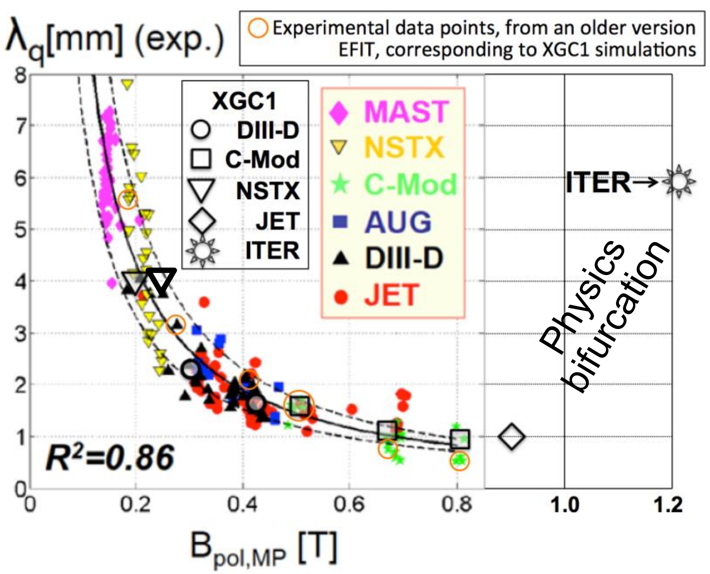


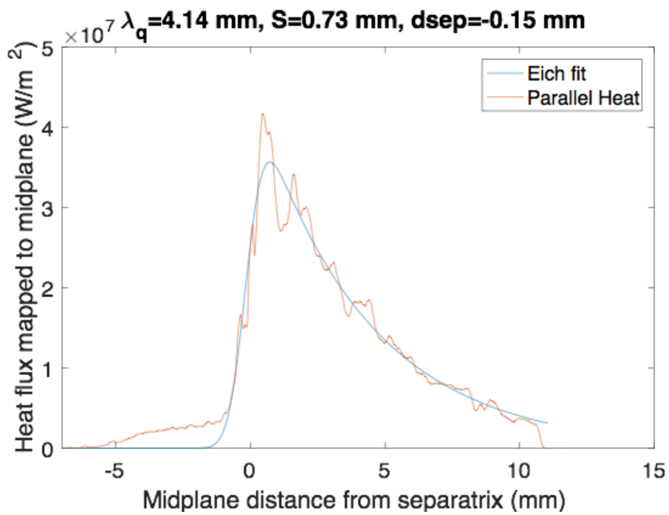


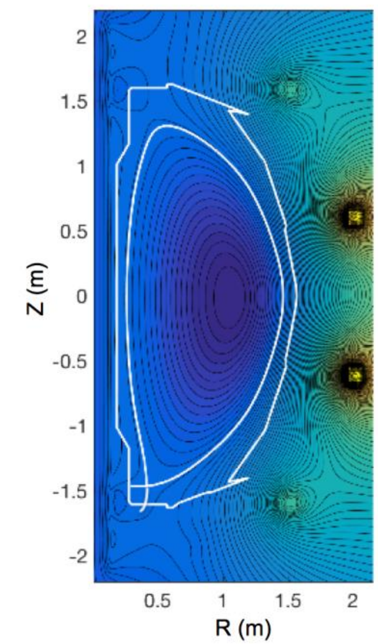
	NSTX high κ,δ	Tokamak
Aspect ratio	1.3	2.7
In-out SOL area ratio	1:3	~ 2:3
Parallel connection length $L_{\|\|}$, midplane to target (m)	8-12	30-80
$L_{\|\|}$, X-point to target (m)	5-8	10-20
Angle at target (deg)	5-15	1-2

Heat-load width for lower inboard divertor in NSTX

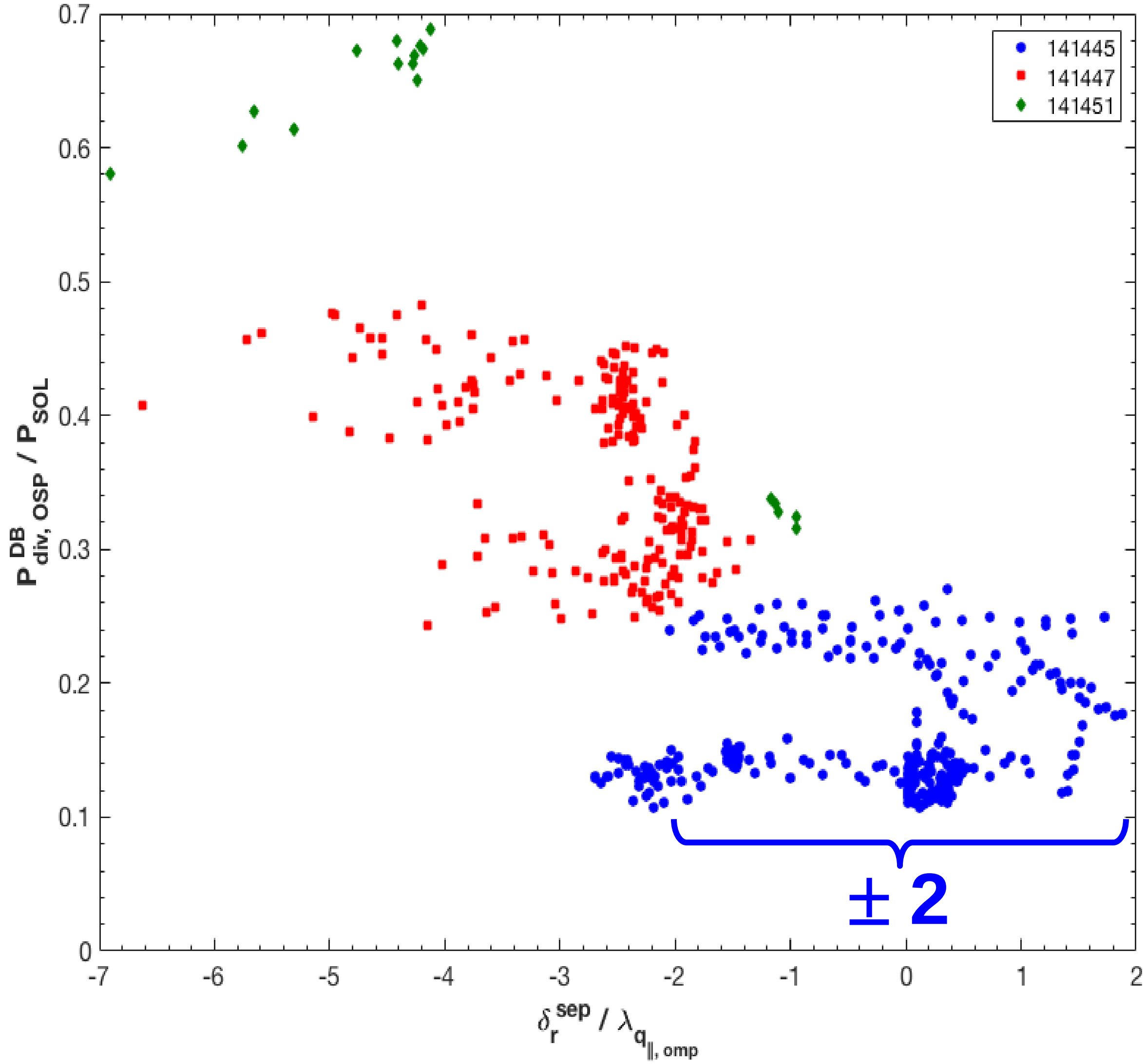
- Large-scale XGC1 gyrokinetic simulation used 11% of 29 peta-flop Cori Xeon-Phi nodes at NERSC for 3 days
- NSTX #139047, $B_{p,mid}$=0.25T, Heat input=3.8MW
- XGC1 finds that the heat-flux width for lower inboard divertor discharge in NSTX still follows the Eich-Goldston scaling
- XGC1 also finds that $P_{outer\ leg}/P_{inner\ leg} \approx 2.3$
- Prediction for heat-load width and density in NSTX-U will be reported in Q4.







Analysis of outboard power fraction vs. dR_{sep} / λ_q



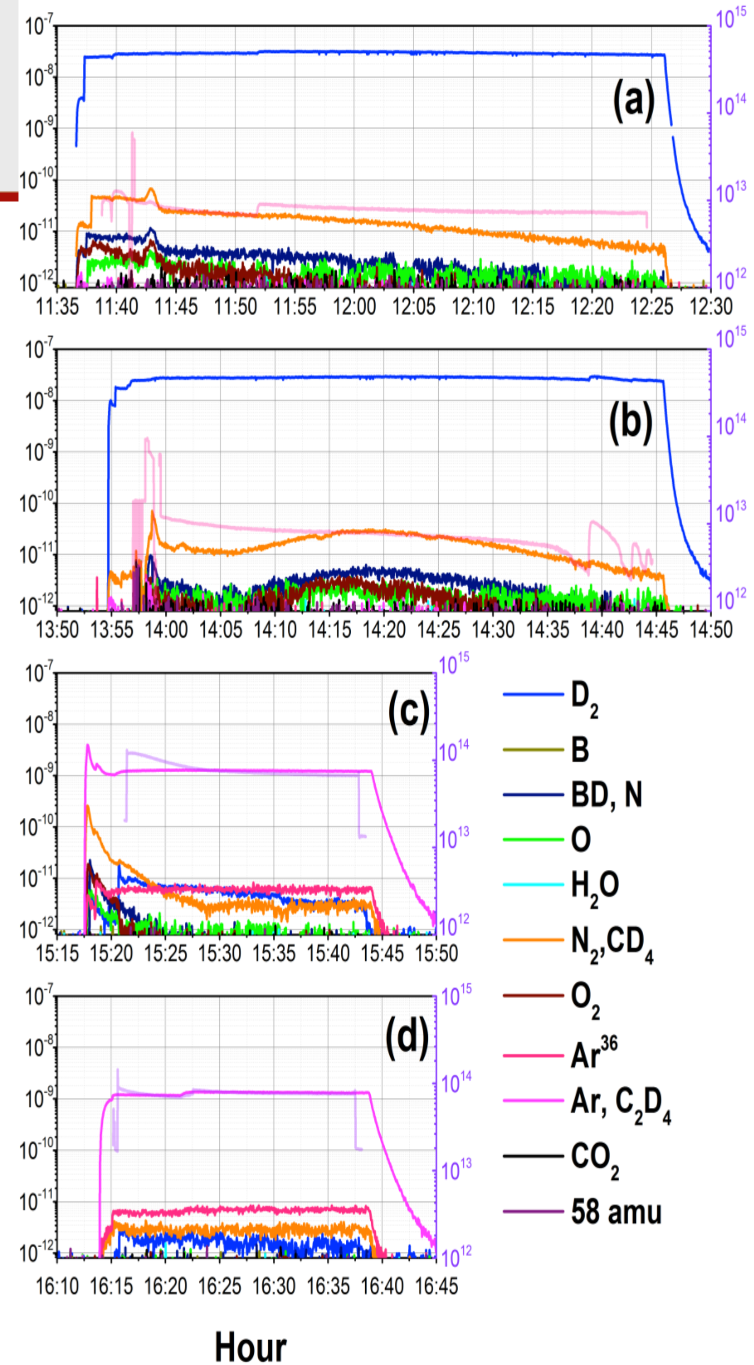
PFC impurity emission during irradiations (post-mortem analysis)

Impurity emission during irradiations

- Different *m/q* , shown as PP (left axis)
- Ion flux (Ar+(pink) or D^+(purple) (right axis)

D+ and Ar+ Irradiation of Core A17

- Two D+ ((a) and (b)) and two Ar+ ((c) and (d)) irradiations.
- D_2 dominated (a) and (b) as expected, so did Ar in (c) and (d)
- D_2 is visible in (c) and (d) !!
- D_2 signal in (d) is lower than that in (c) (decreasing with increasing Ar+ fluence)
- **Evidence of D_2 retention by the boron coatings !!**

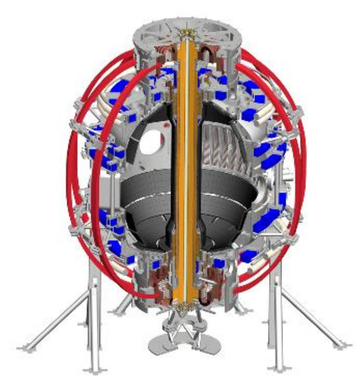


NSTX-U Surface Science Research*

R. Kaita and M.A. Jaworski, Princeton Plasma Physics Laboratory
B.E. Koel, Dept. of Chemical and Biological Engineering, Princeton University

USDOE Budget Planning Meeting
June 15, 2017

*Work supported by US Department of Energy Contract DE-AC02-09CH11466



Surface science on NSTX-U – multi-institutional collaborative effort

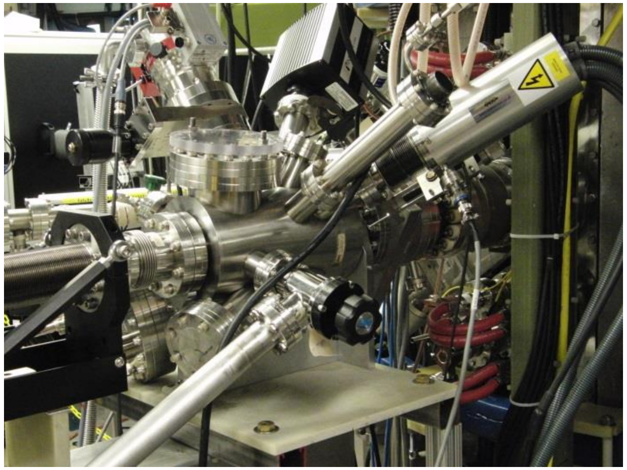
- J.P. Allain (University of Illinois at Urbana-Champaign)
  - F. Bedoya – PhD student
  - H. Schamis – first-year graduate student
- D. Donovan (University of Tennessee at Knoxville)
  - A. Maan – PhD student
  - S. Lee – visiting graduate student in summer of 2017
- M.A. Jaworski, R. Kaita and C.H. Skinner (PPPL)
  - J. Nichols – PPPL PhD student
- B.E. Koel (PU Chemical & Biological Eng. Dept. - CBE)
  - L. Buzi – PPPL postdoctoral research fellow
  - M. Hofman – PU CBE PhD student
  - A. (“Oak”) Nelson – PPPL first-year graduate student
  - Y. Yang – PU CBE PhD student
- P. Krstic (Stony Brook University)
  - F. Javier Domínguez-Gutiérrez – postdoctoral research fellow

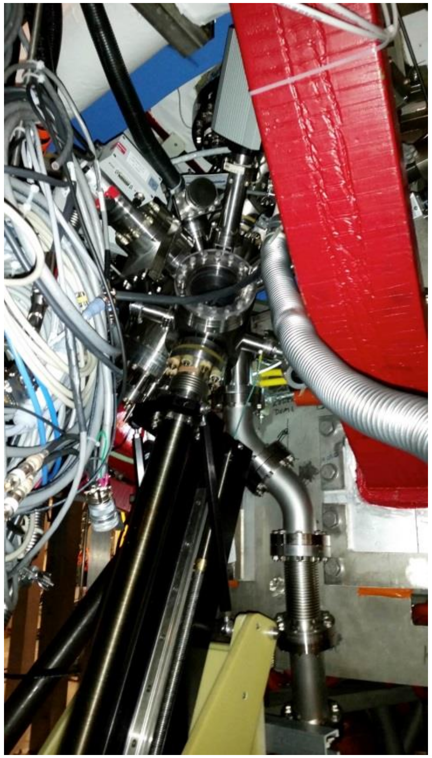
Extensive experimental and computational capabilities leveraged for NSTX-U mission

– PPPL
  - Facilities including ALISS (Alkali Ion-Scattering Spectroscopy) and (SAM) Scanning Auger Microprobe operated jointly with PU CBE Dept.
– Princeton University
  - High-resolution X-ray and ion and electron beam instrumentation at IAC (Imaging and Analysis Center)
– University of Illinois at Urbana-Champaign
  - Facilities including IIAX (Ion-surface InterAction eXperiment) and IGNIS (in-situ, in operando modification and analysis)
  - Development of Materials Analysis and Particle Probe – MAPP
– University of Tennessee at Knoxville
  - Facilities including ion exposure stage for materials analysis
– Stony Brook University
  - LI-red cluster with multiple Cray compute nodes for 100 teraflop capability and access to ORNL NCCS supercomputing facility

Development during NSTX-U outages permit efficient implementation of new capabilities

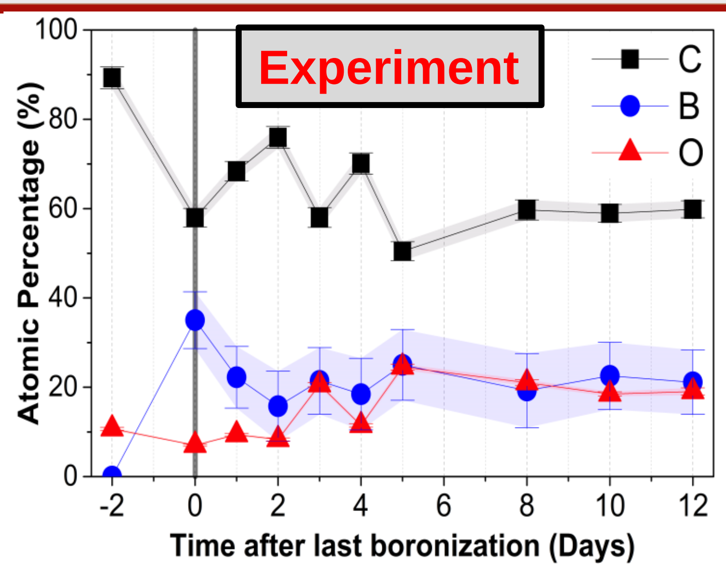
- Materials Analysis and Particle Probe – MAPP – tested and commissioned on LTX
  - M. Lucia, *Material Surface Characteristics and Plasma Performance in the Lithium Tokamak Experiment,* PhD thesis, Princeton U. (2015)



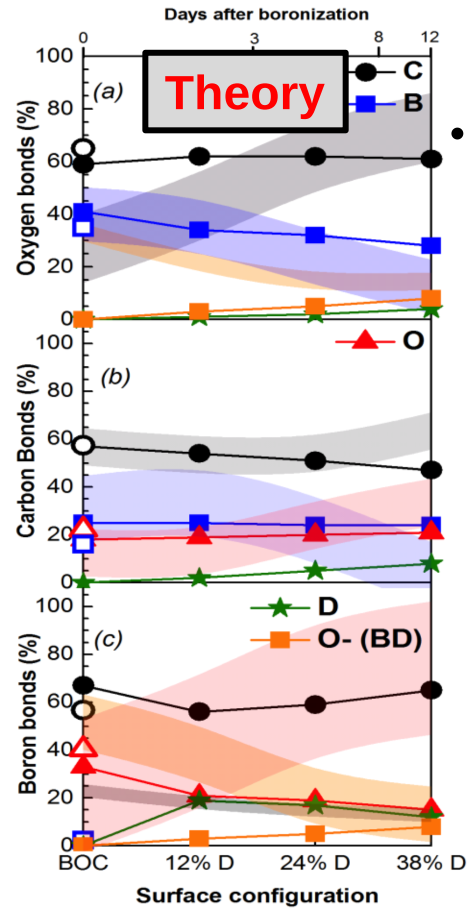


- Successfully installed and operated for first *in vacuo* boronization studies of plasma-facing components on NSTX-U
  - F. Bedoya, *Plasma Facing Components Conditioning Techniques and their Correlation with Plasma Performance in the National Spherical Torus Experiment Upgrade (NSTX-U)*, PhD thesis, U. of Illinois at Urbana-Champaign (2017)

First quantitative agreement between boronization chemistry theory and experiment demonstrated*



- Concentrations of O, B and C in boronized graphite sample with time – and increasing plasma exposure – measured *in vacuo* with MAPP



- Quantum-classical molecular dynamics calculations follow experimental evolution of percentage of bonds of O, C, and B to other surface constituents as D concentration increases with plasma exposure

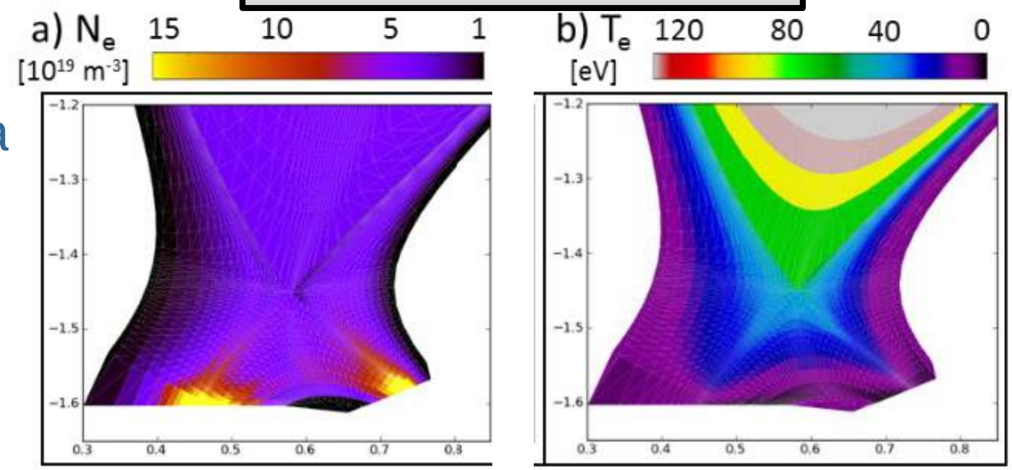
- Continuing laboratory experiments and development of computational tools during outage can enhance surface science for future NSTX-U operations

*F. Javier Domínguez-Gutiérrez *et al., Unraveling the plasma-material interface with real time diagnosis of dynamic boron conditioning in extreme tokamak plasmas, in press* Nuclear Fusion

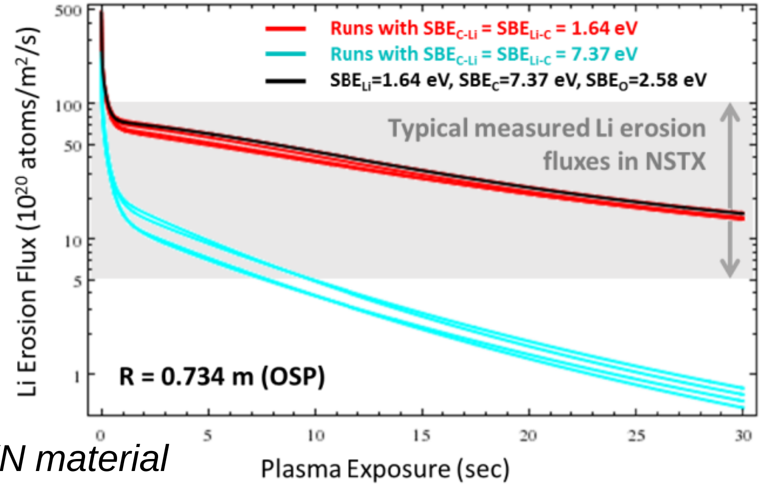
Building toward whole-device models with surface science advancements

- NSTX-U mixed-material environment is complex
  - Plasma redistribution of materia
  - Multiple, chemically reactive species
  - Complex plasma-surface interactions impact machine
- Computational efforts underway to integrate new surface science
  - PhD student J. Nichols implementing WallDYN
  - **Mixed-material erosion models can continue to be improved by surface science**

NSTX Divertor conditions



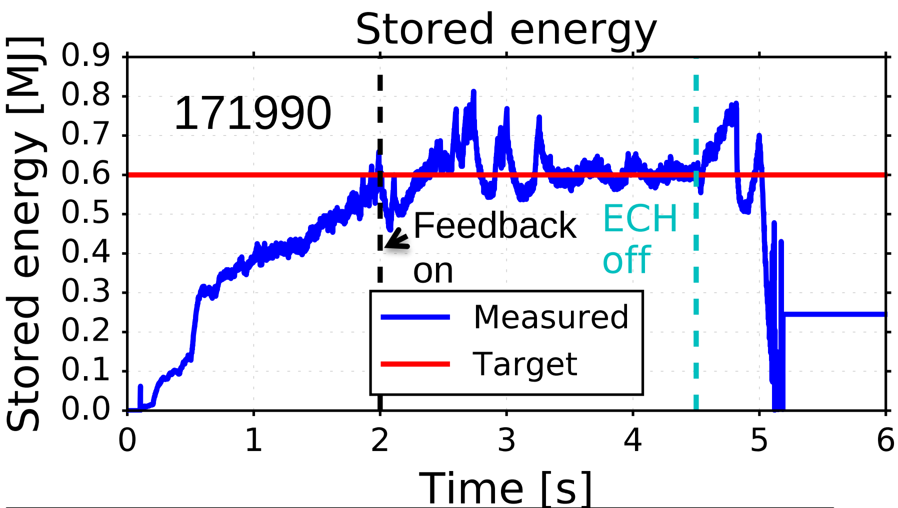
Comparison of erosion models

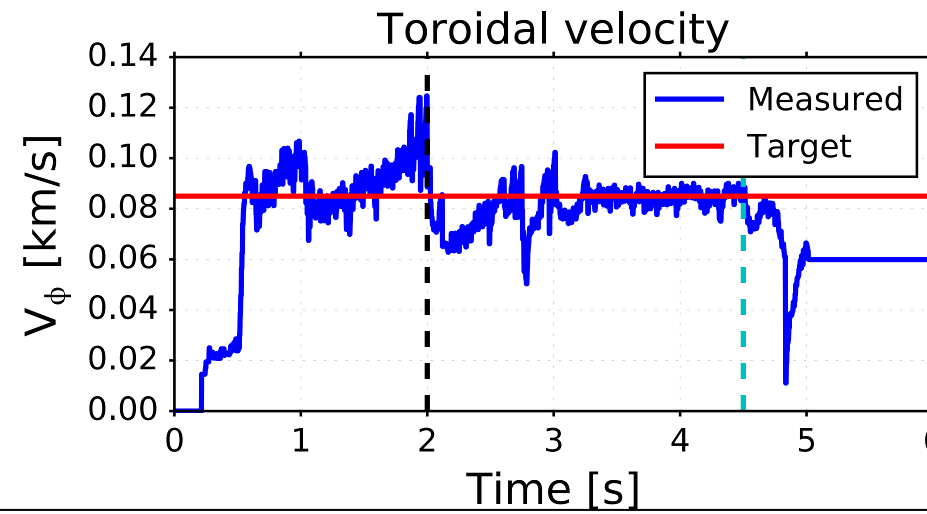


J. Nichols, M. Jaworski and K. Schmid, *Sensitivity of WallDYN material migration modeling to uncertainties in mixed-material surface binding energies, in press* J. Nucl. Materials

Backup - Scenarios

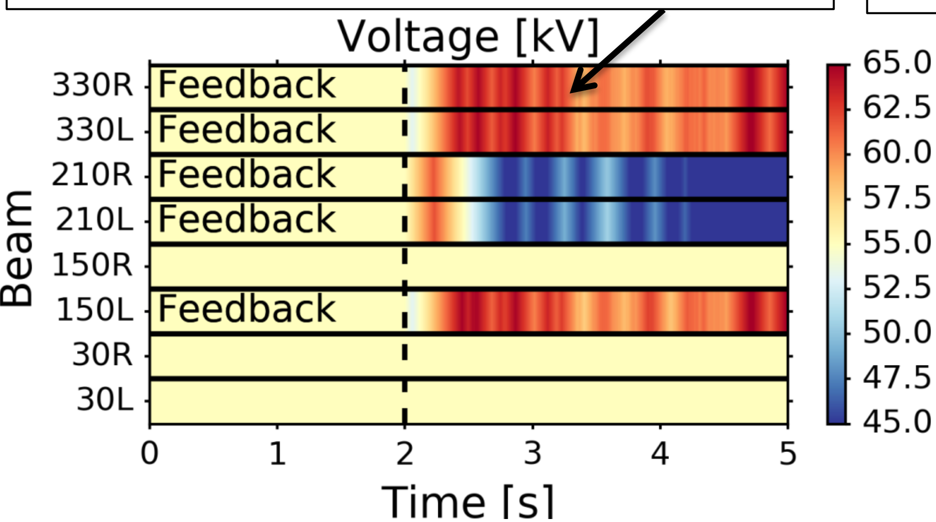
First feedback algorithm using DIII-D's variable beam voltage/perveance tested in DIII-D/NSTX-U National Campaign, demonstrated energy/rotation control

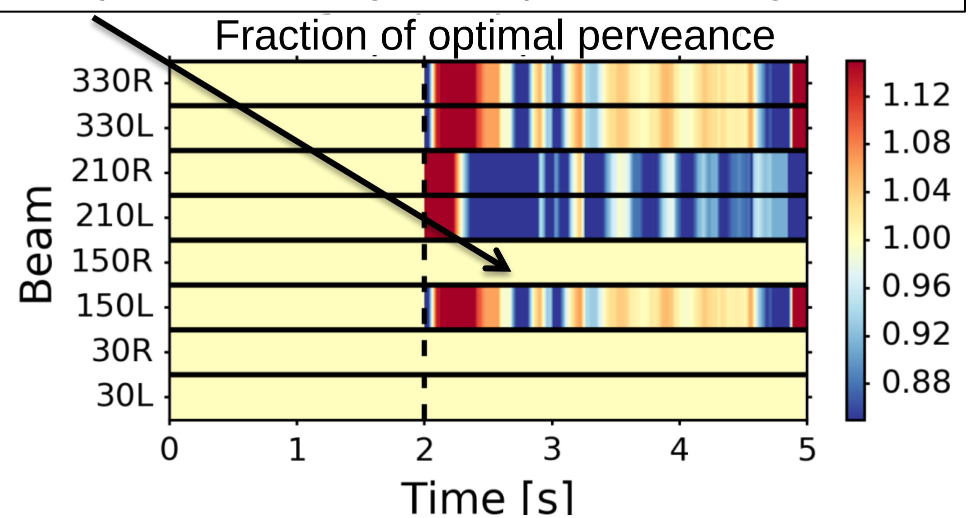




Voltage in co- and cntr- beams adjusted to achieve required torque and power

Fast changes in perveance used to compensate slow response of voltage to requested change





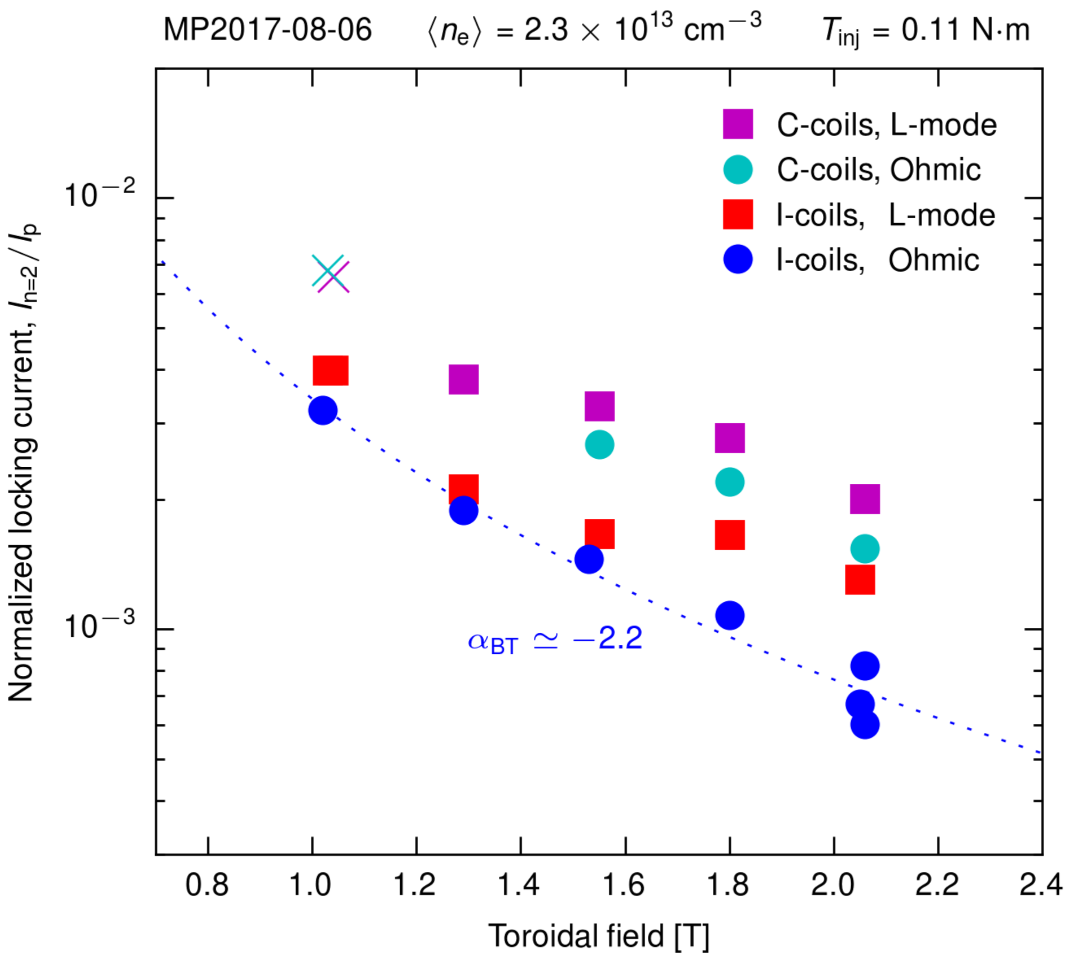
Backup - Collaborations

Motivation for n=2 locking studies

- High-level motivation:
  - Expand DIII-D n=2 locking database
    - Physics understanding of n=2 locking (B_T dependence, etc.)
    - ITPA MDC-19 → EFC strategy for ITER
  - Inform n=2 EFC strategy in NSTX-U
    - NSTX-U EFC (RWM) coils similar to C-coils → mixed resonance
    - Possible Non-axisymmetric Control Coil (NCC) facility enhancement → motivate control of resonance spectrum

- Specific goals of MP2017-08-06 (1 day):
  - Touch base with MP2016-23-01 (Lanctot)
  - Primary scans: n=2 field resonance spectrum, B_T, and density

Obtained 22 point B_T scan (L-mode + ohmic) Locking threshold decreases with increasing B_T

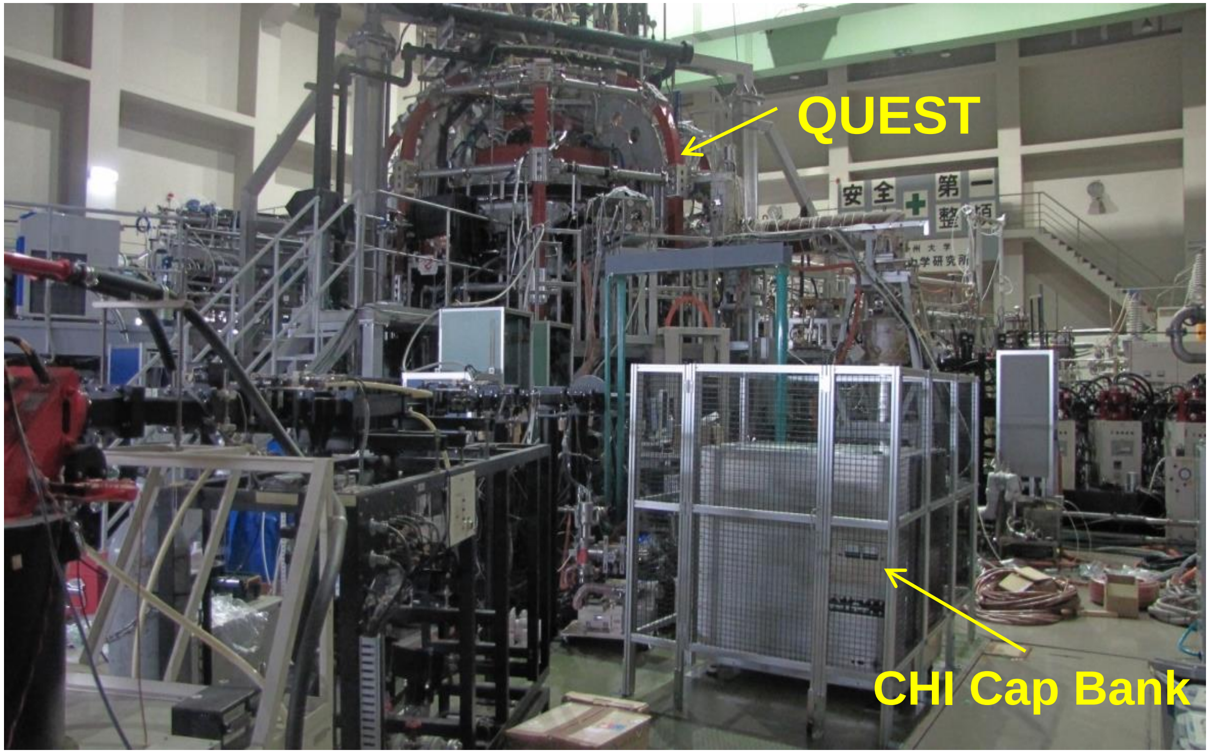


- Easier to lock the plasma with max resonant fields (I-coils only)
- Able to lock with mixed resonant / non-resonant fields (C-coils only) at all points except B_T=1T
- Locking threshold declines with increasing B_T in all cases
- A little bit of NBI goes a long way → L-modes harder to lock than ohmic

Enhanced collaborations during NSTX-U outage Targets NSTX-U research goals

- **EAST**: edge physics, plasma materials interactions (high-Z, Li)
  - R. Maingi + collaborators leading expts
- **JET**: EP studies, plasma ramp-down scenarios and modeling
  - M. Podesta, D. Darrow, F. Poli
- **KSTAR**: Core MHD, rotation physics, plasma control
  - Columbia Univ (Sabbagh, Berkery, Park et al.), J-K Park, J-W Ahn (ORNL)
- **MAST-U**: Control, scenario modeling supporting first plasma
  - D. Battaglia (on-site for several months), D. Boyer
- **W7-X**: wall conditioning using boron powder dropper
  - R. Lunsford
- **WEST**: ~~Start-up,~~ RF physics, high-Z PMI, real-time wall protection
  - Mueller (?), M. Reinke (ORNL), RF physicists
- **QUEST:** Coaxial Helicity Injection (CHI) + ECH/EBW heating
  - R. Raman (UW), M. Ono
- **LAPD**: RF coupling and heating physics, cavity modes
  - R. Perkins
- **DIII-D, HL-2A (China)**: Dedicated campaigns (see following vgs)

First CHI experiments carried out on QUEST



QUEST

R = 0.68 m
a = 0.4 m
B_T = 0.25T
V_{plas} ~3.8m^3

CHI

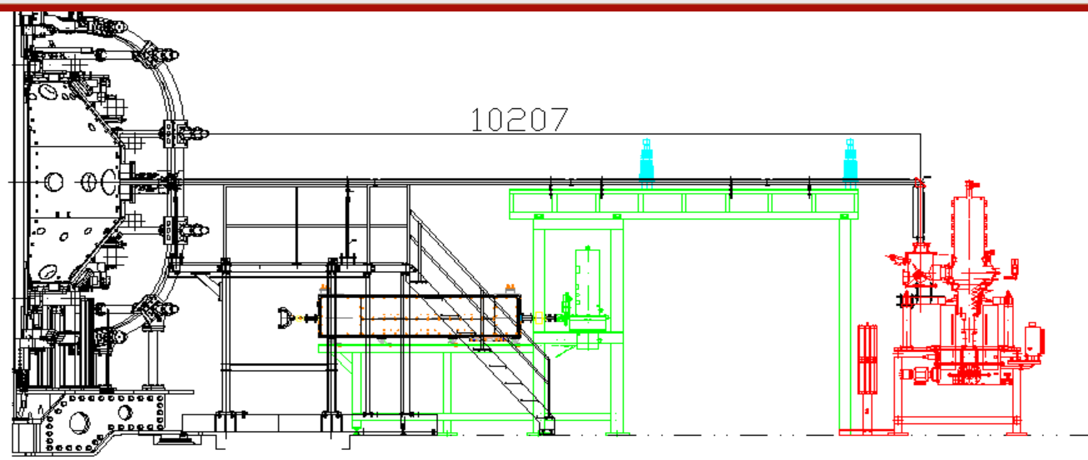
V = 2 kV
C = 30 mF
Inj. Flux ~28mWb
Electrodes: metal

Goals:

- Commission all CHI hardware
  - Cap bank, gas injectors, snubbers, vessel safety resistors, fast voltage monitors on vessel
- Establish reliable gas breakdown using 2kV CHI power supply
- Measure toroidal current generation

28 GHz gyrotron system has been upgraded with a focusing mirror launcher and polarizer

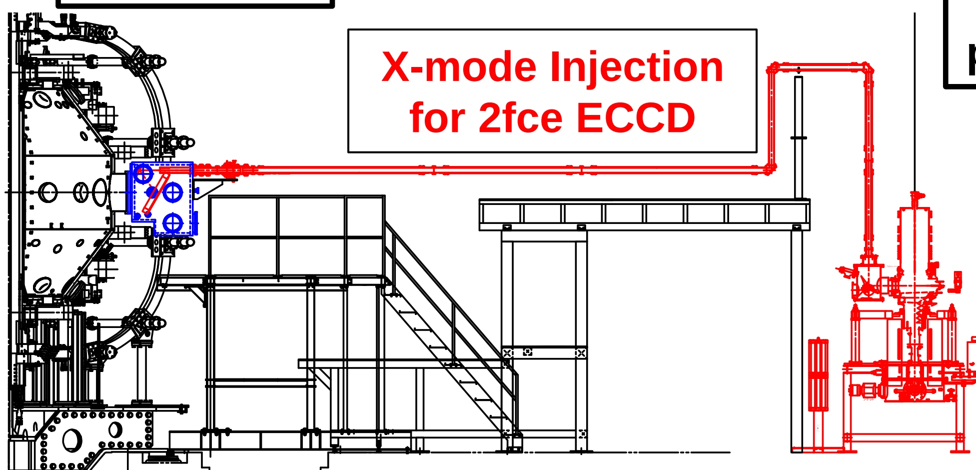
- Added quasi-optical polarization control to provide the desired X-mode polarization to obtain good single pass absorption
- Added focusing mirror launcher to obtain a narrow beam
- This new 28 GHz transmission line was commissioned in July



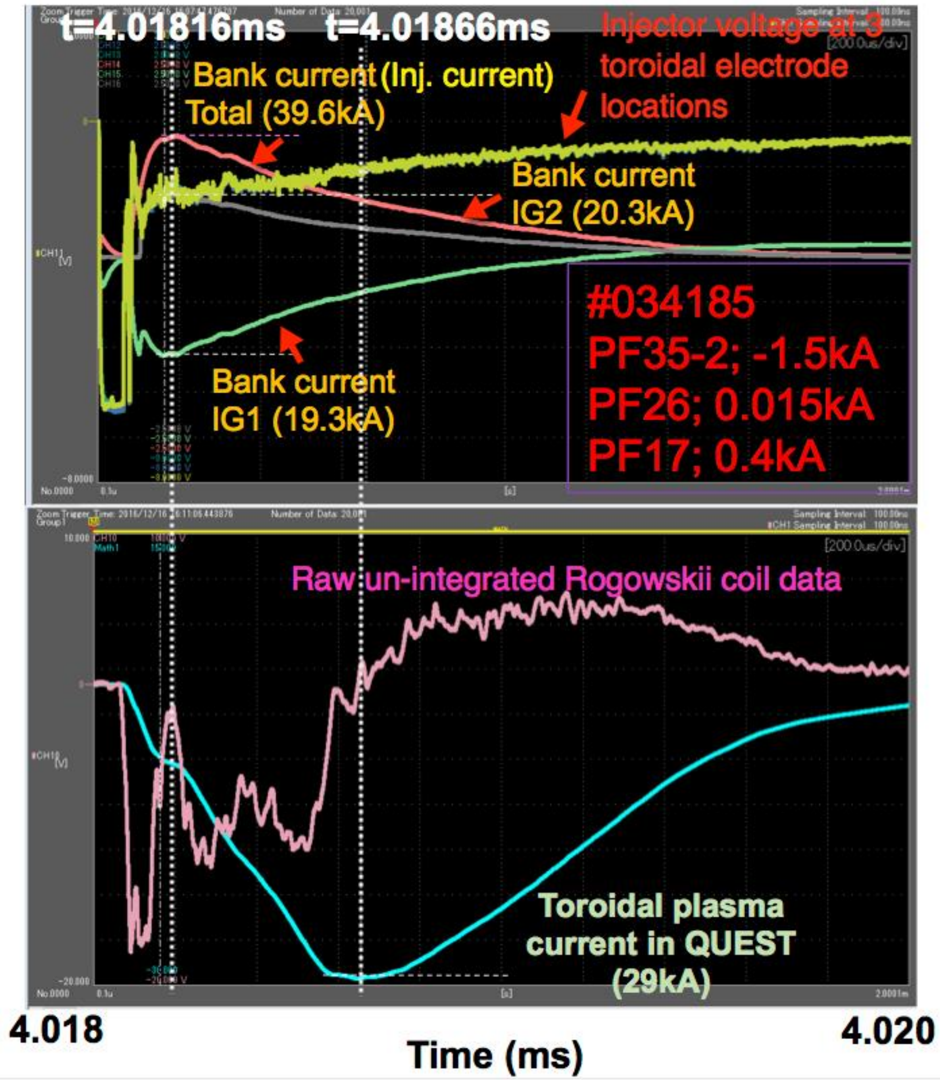
Launcher with a focusing mirror

λ/4 polarizer

λ/8 polarizer



QUEST: 29kA Toroidal Current Generated
by operating Injector coil at 30% of full capability (1.5kA)



- Injector current ~39kA is high due to very low B_T
- Peak in Ip (~29kA) occurs after injector current is ~20kA
  - Not enough information to know if absorber arching is occurring, but it is not keeping the plasma discharge from forming
  - QUEST CHI should be more prone to absorber arcs
- Electrode voltage at 3 toroidal current injection locations overlaps – good no toroidal asymmetries
- All CHI capacitor bank monitor signals and vessel voltage monitors worked well