U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Progress and plans for Research on NSTX Upgrade

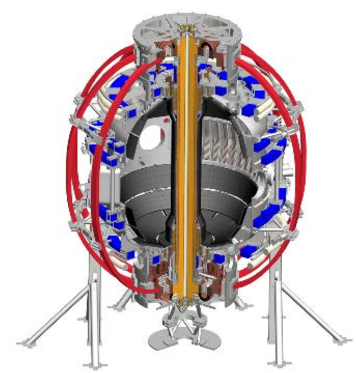
Jonathan Menard (PPPL)

On behalf of the NSTX-U Research Team

MIT Plasma Science and Fusion Center

December 9, 2016

PPPL

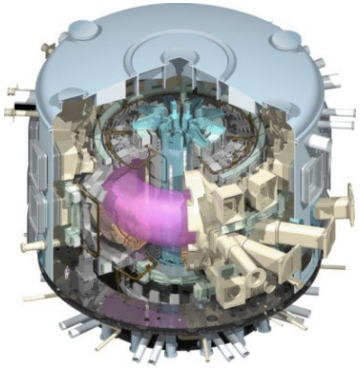


Outline

- NSTX-U mission
- Research highlights
- Progress on next-step ST concepts
- Goals for next run
- Summary

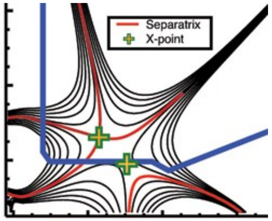
NSTX-U Mission Elements:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond



ITER

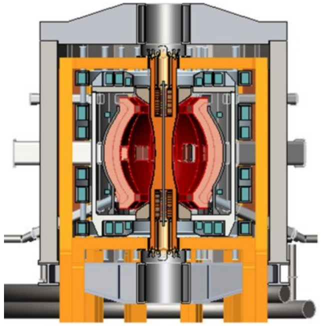
- Develop solutions for plasma-material interface (PMI)



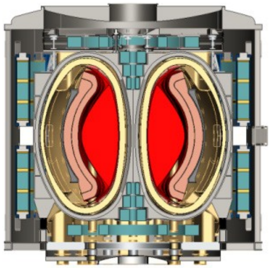
Snowflake/X

Liquid metals / Li

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant

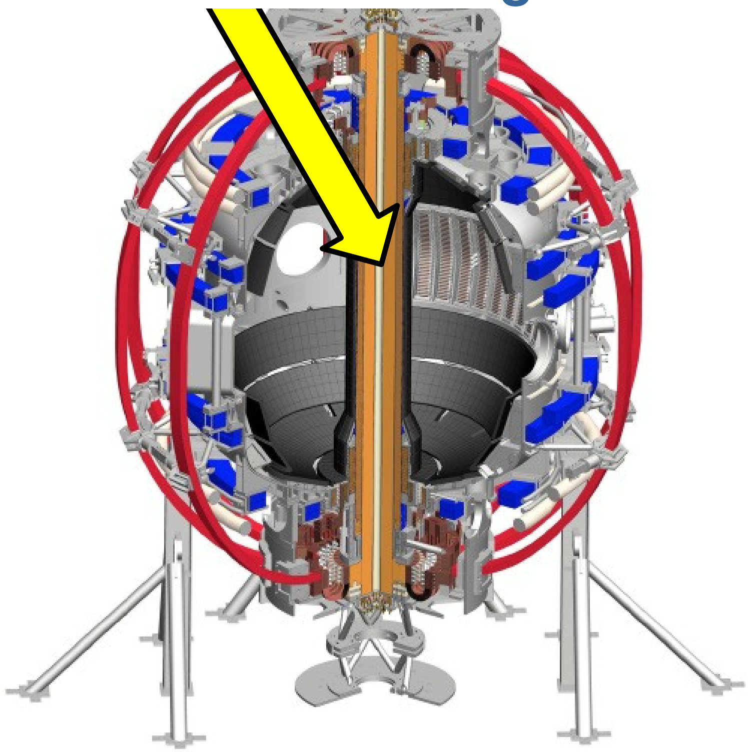


ST-FNSF / Pilot-Plant



NSTX-U will access new physics with 2 major new tools:

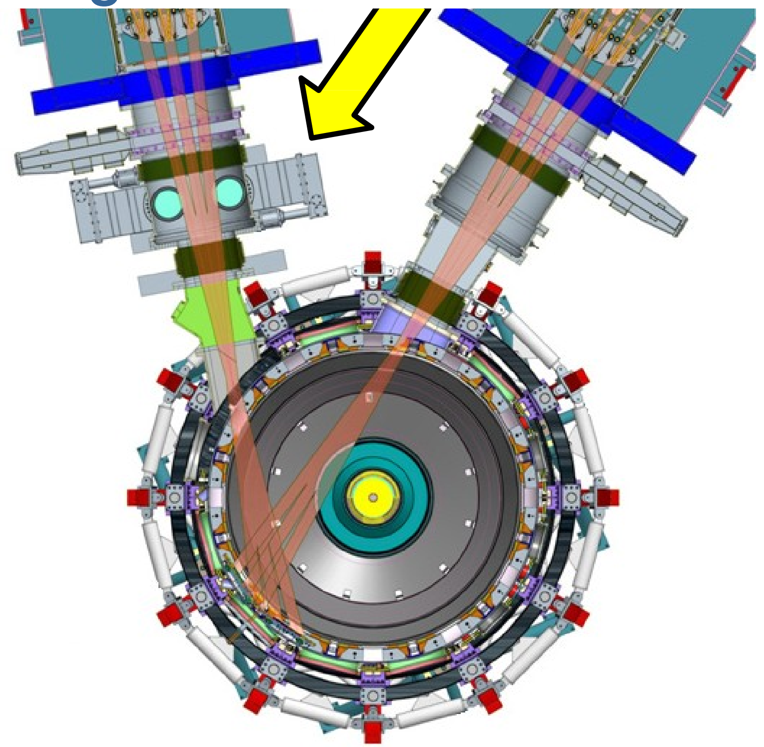
1. New Central Magnet



Higher T, low ν^* from low to high β

→ Unique regime, study new transport and stability physics

2. Tangential 2nd Neutral Beam



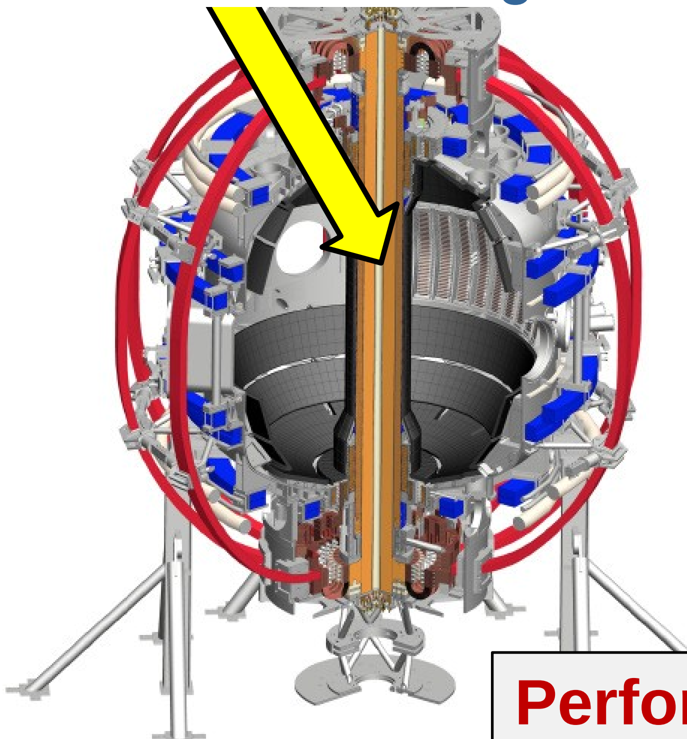
Full non-inductive current drive

→ Not demonstrated in ST at high-β_T

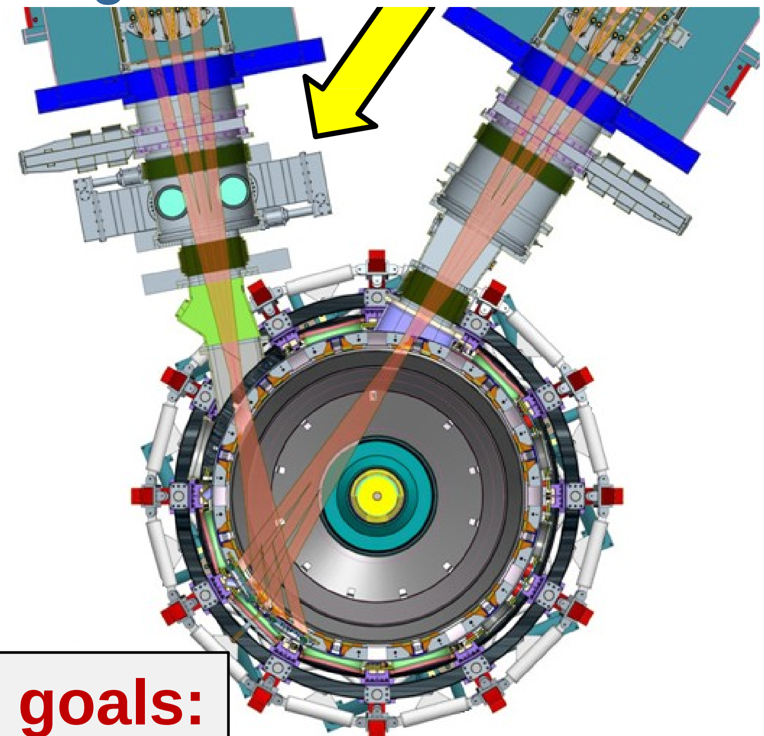
Essential for any future steady-state ST

NSTX-U will have major boost in performance

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Performance goals:

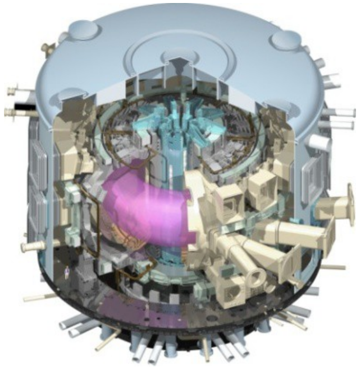
- ➢2× toroidal field (0.5 → 1T)
- ➢2× plasma current (1 → 2MA)
- ➢5× longer pulse (1 → 5s)
- ➢2× heating power (5 → 10MW)
  - Tangential NBI → 2× current drive efficiency
- ➢4× divertor heat flux (→ ITER levels)
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)

NSTX-U had scientifically productive 1st 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
- New 2nd NBI suppresses Global Alfven Eigenmodes (GAE)
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation
- 2016 run ended prematurely due to fault in divertor PF coil
  - Coil + other issues → major reviews of design, fab, procedures
  - Coil forensics complete, prep for new coil fab underway
  - Aim to resume plasma operation during CY2018

NSTX-U Mission Elements:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond



ITER

Topical science areas:

- Scenario Development
- Macroscopic Stability
- Transport and Turbulence
- Energetic Particles

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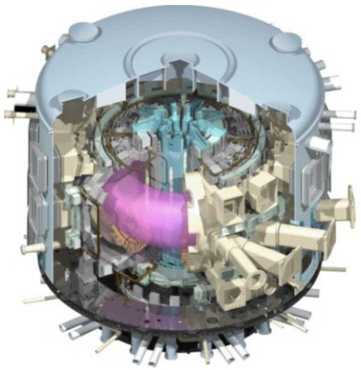

ITER

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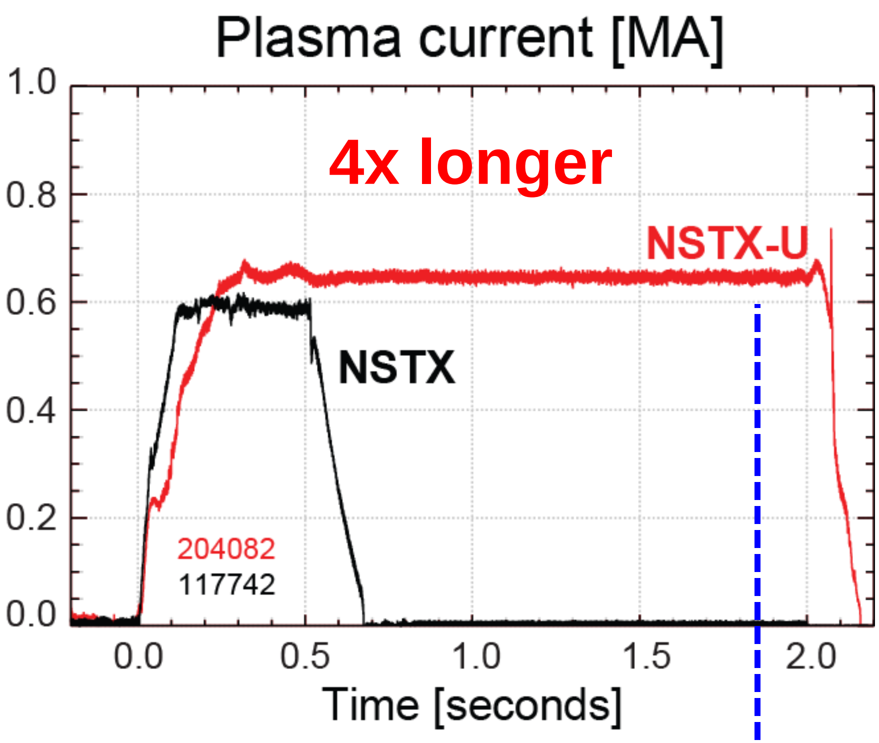
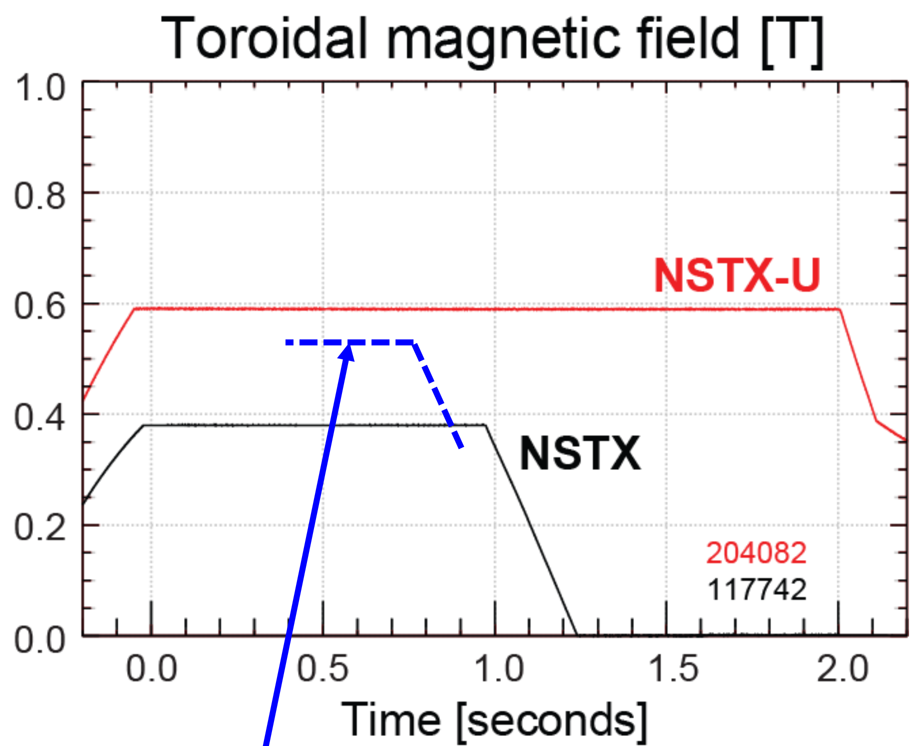
NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

Compare similar **NSTX** / **NSTX-U** Boronized L-modes, P_{NBI}=1MW



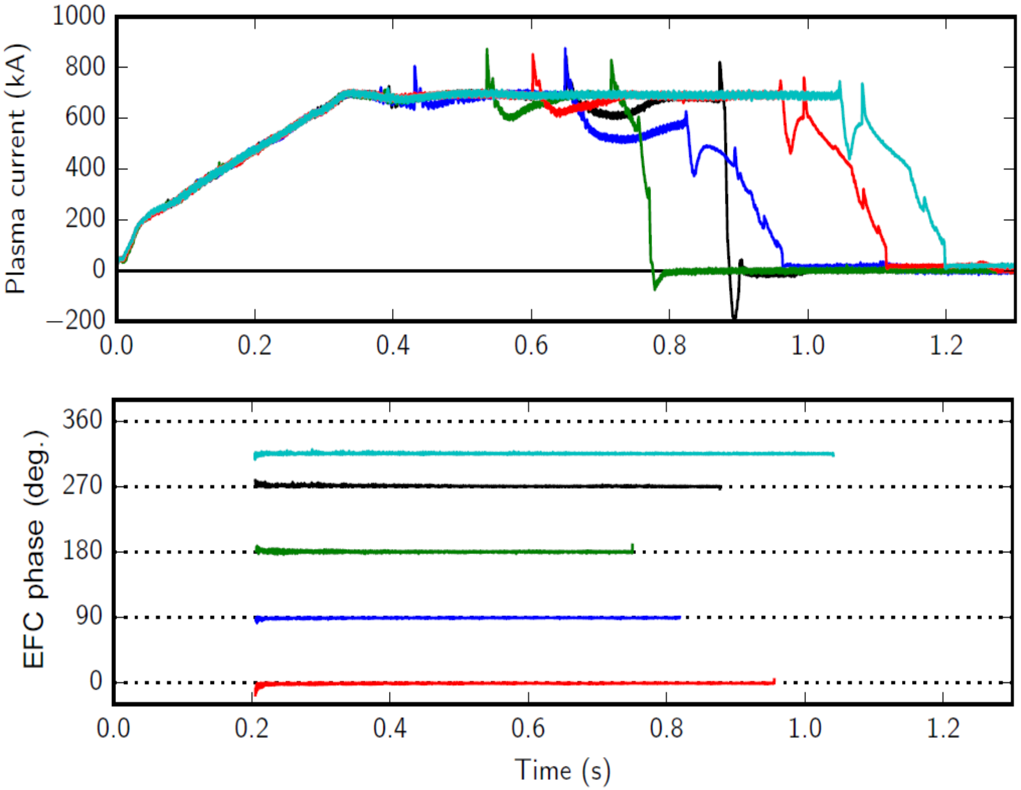


NSTX-U L-mode duration exceeds longest NSTX H-mode

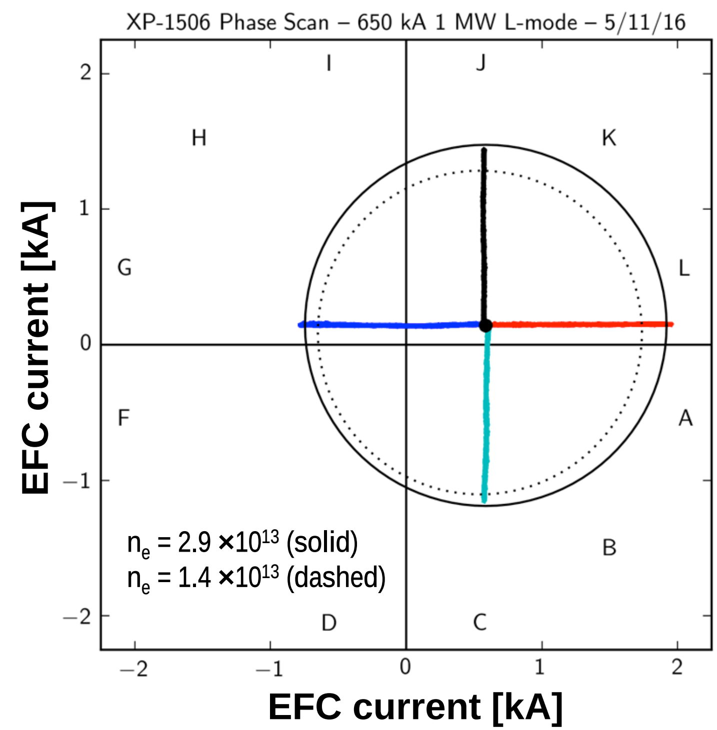
NSTX-U B_T > highest NSTX B_T

n=1 error field correction (EFC) optimized to maximize pulse length, discharge performance

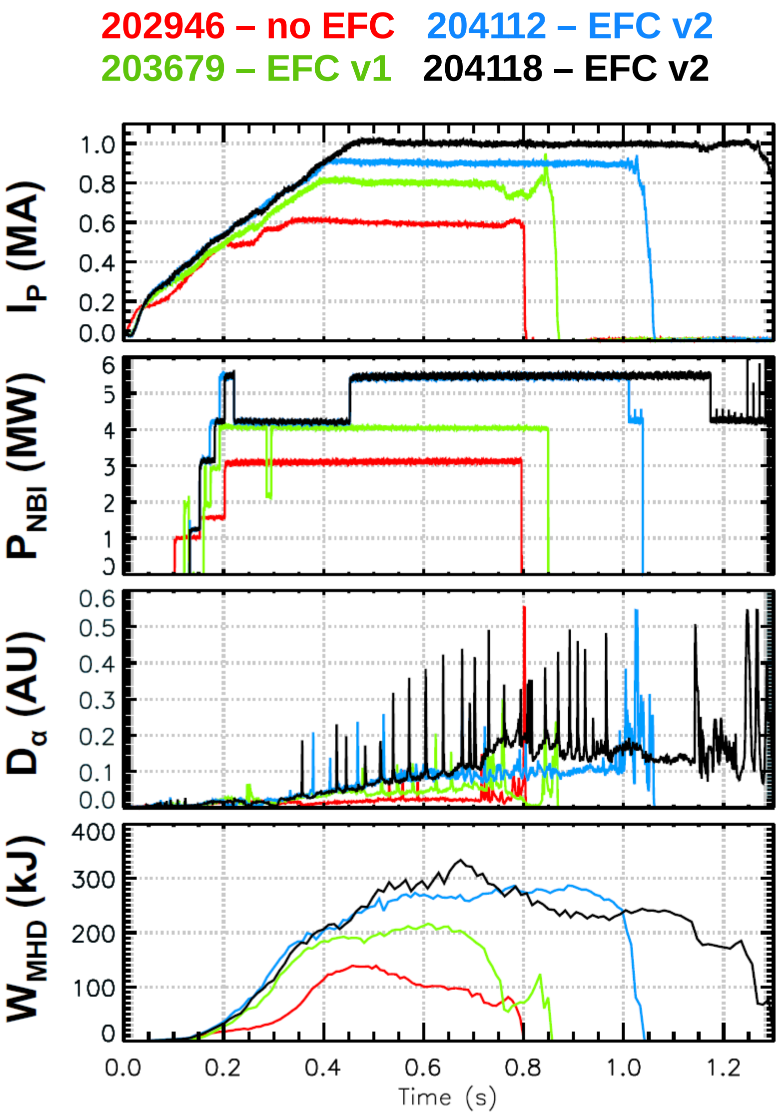
- L-modes used to identify optimal correction amplitude, phase



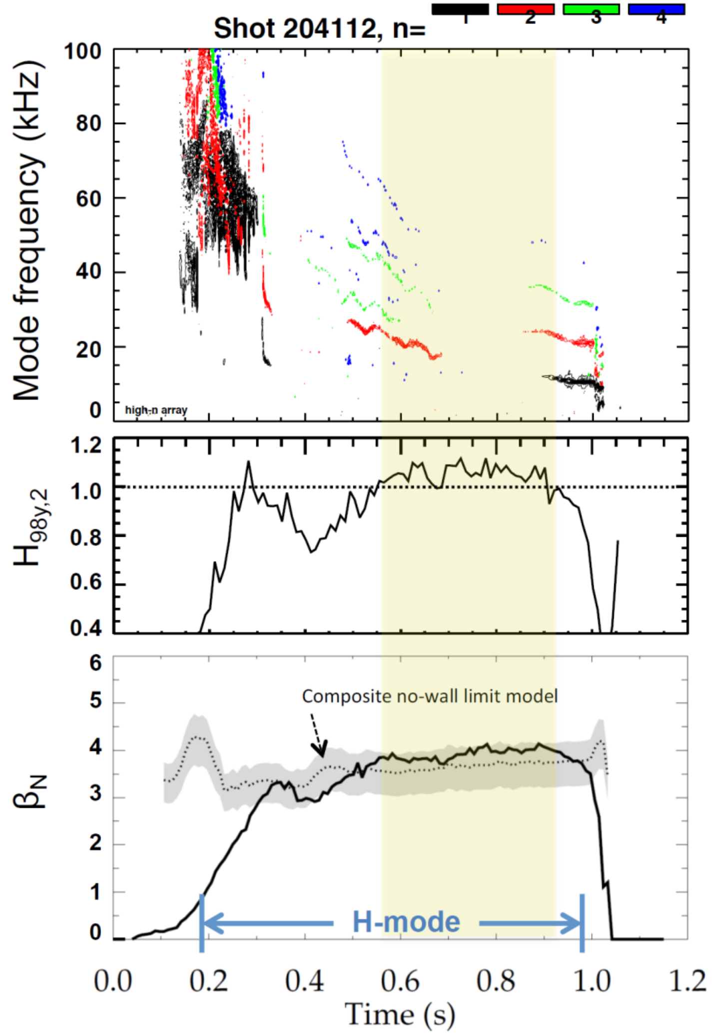
- Multiple compass scans confirm optimal L-mode EFC in flattop



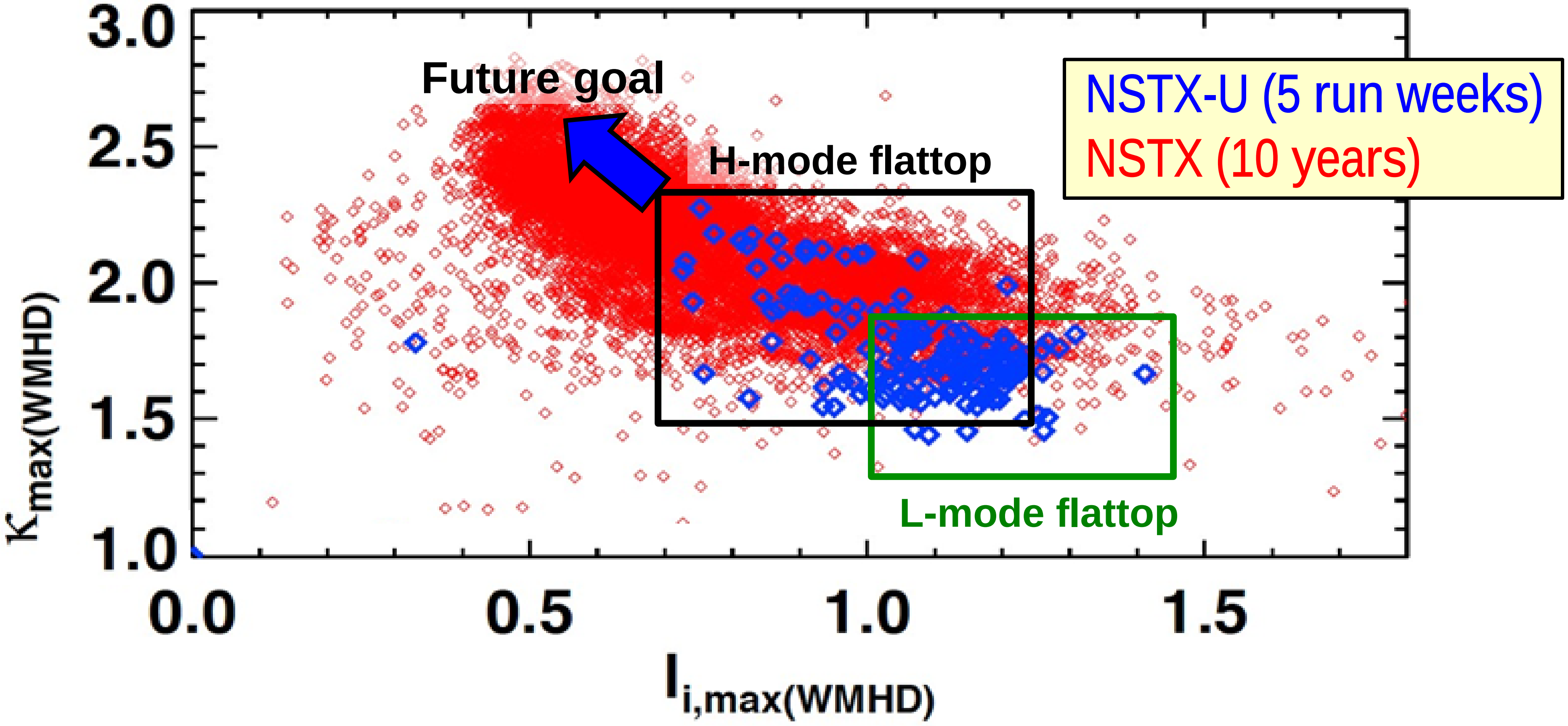
Recovered ~1MA H-modes with weak/no core MHD



$H_{98} \geq 1$, $\beta_N \geq$ n=1 no-wall limit



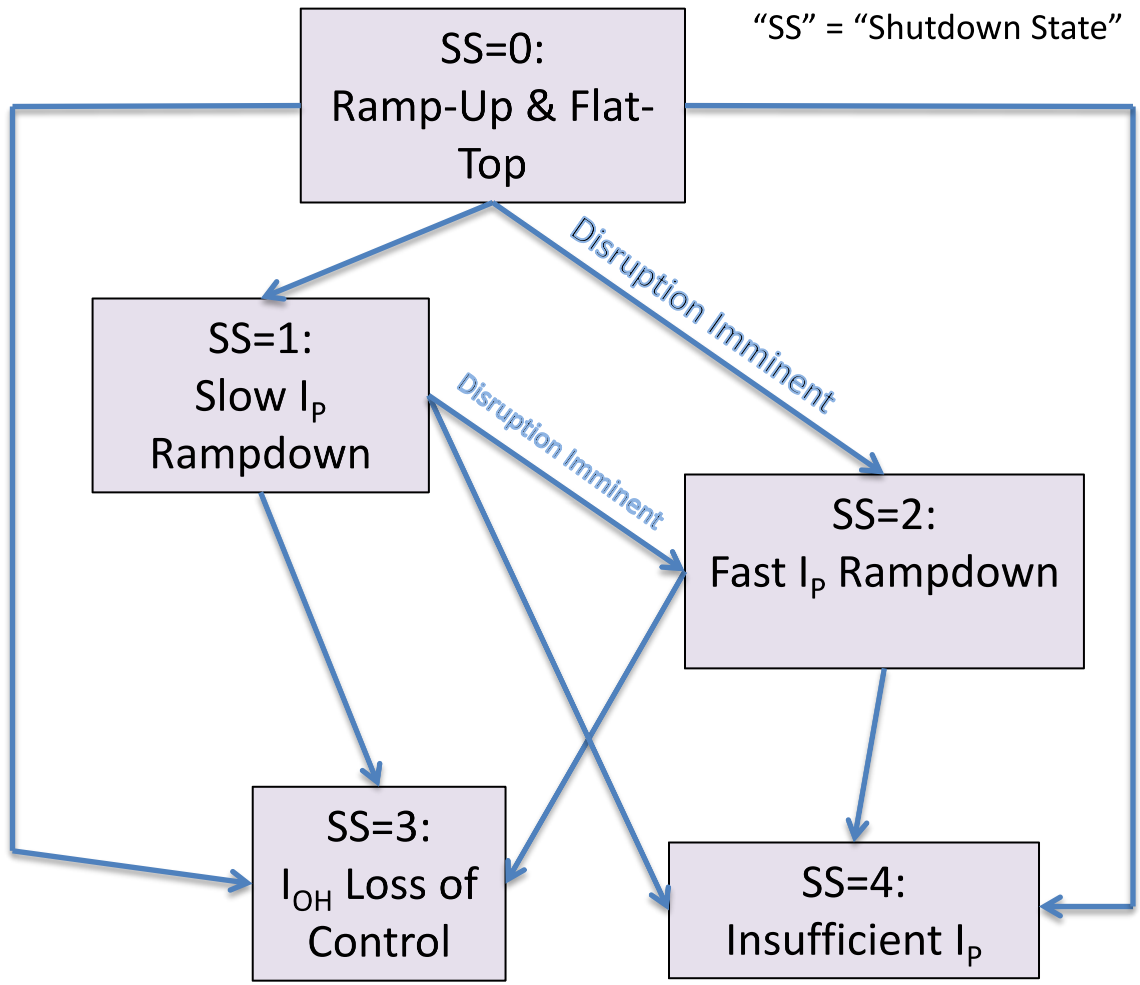
Accessed low l_i and high κ using progressively earlier H-mode and heating + optimized EFC



- **NSTX-U: Additional sensors improve estimation of Z, dZ/dt**
- **Goals for next run:**
  - **Access l_i = 0.5-0.7, κ=2.4-2.7, B_T = 0.75-1T, I_P = 1.5-2MA**

NSTX-U experiments are using a significantly expanded plasma shutdown scheme

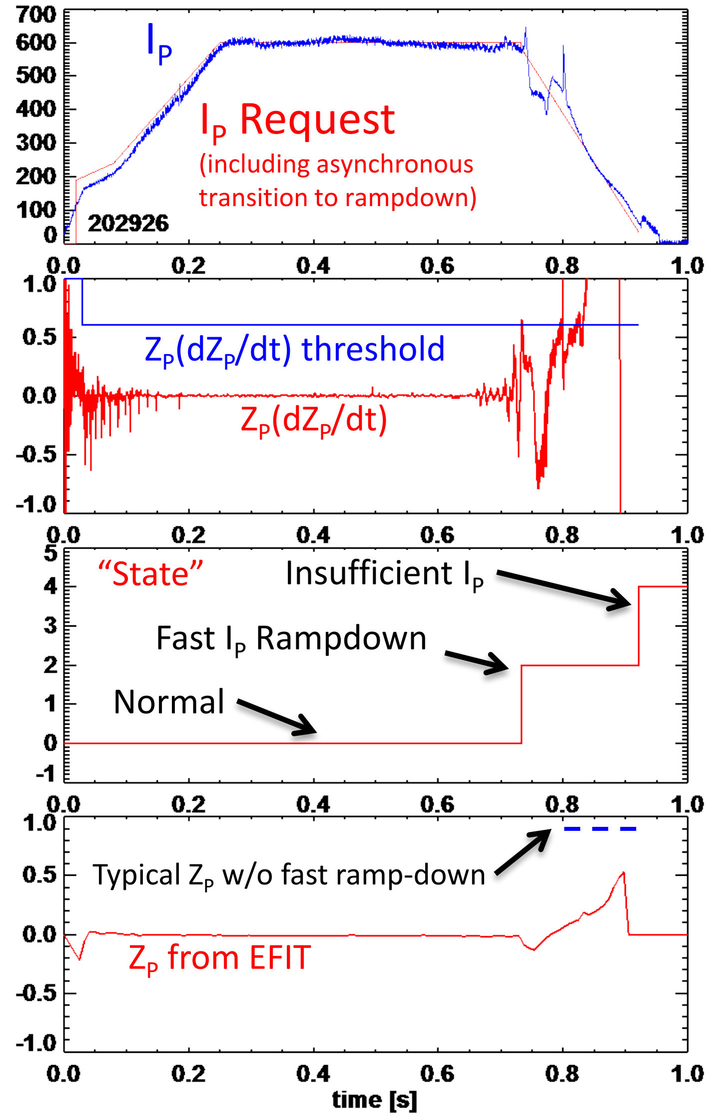
- **NSTX PCS**: No means of detecting a disruption, or ramping down the plasma current based on events.
- **NSTX-U PCS**: State machine orchestrates the shutdown.



“State-machine”-based automated ramp-down now used routinely during operations

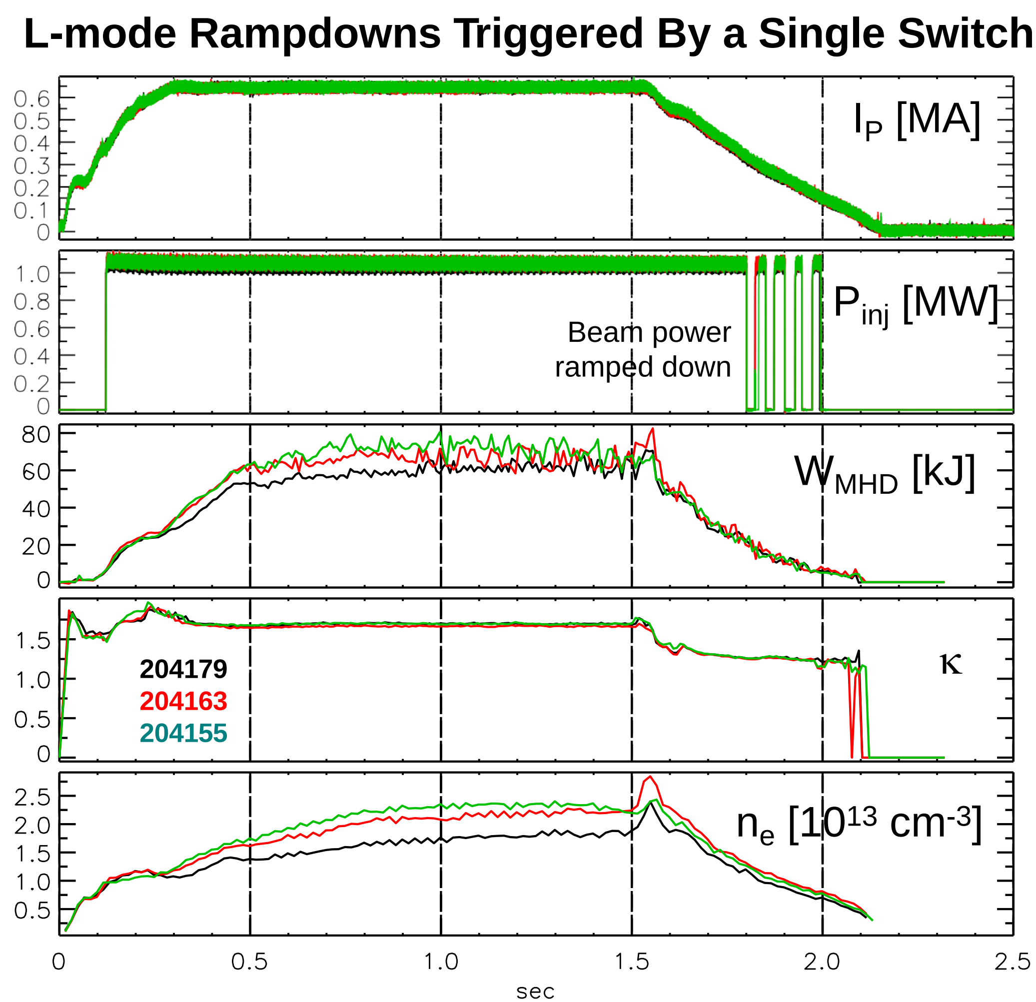
- Plasma control system detects loss of control
  - OH solenoid near maximum current
  - Vertical oscillations exceed threshold
  - ABS (I_p - $I_{p\ request}$) too large

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



Shutdown handler used for well-controlled disruption-free L-mode ramp-down

- Three morning fiducials
- One operator waveform used to start ramp-down at t=1.5s
- Ramp-down is inner-wall limited, power and current slowly ramped off



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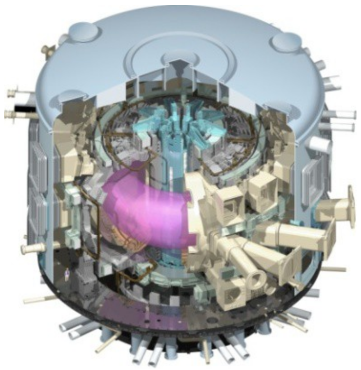

Topical science areas:

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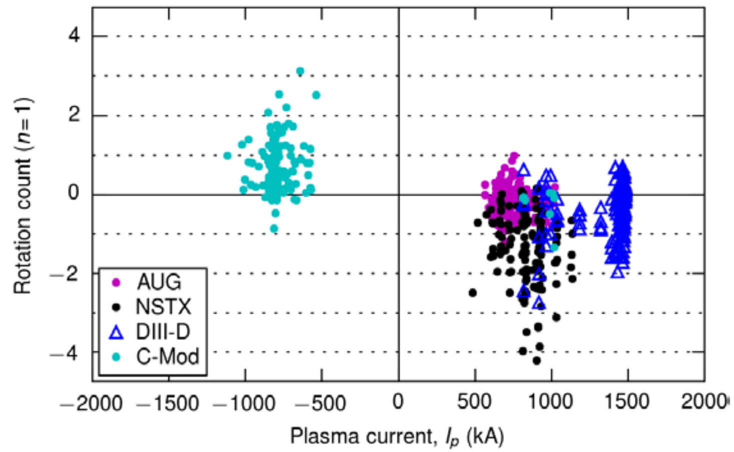
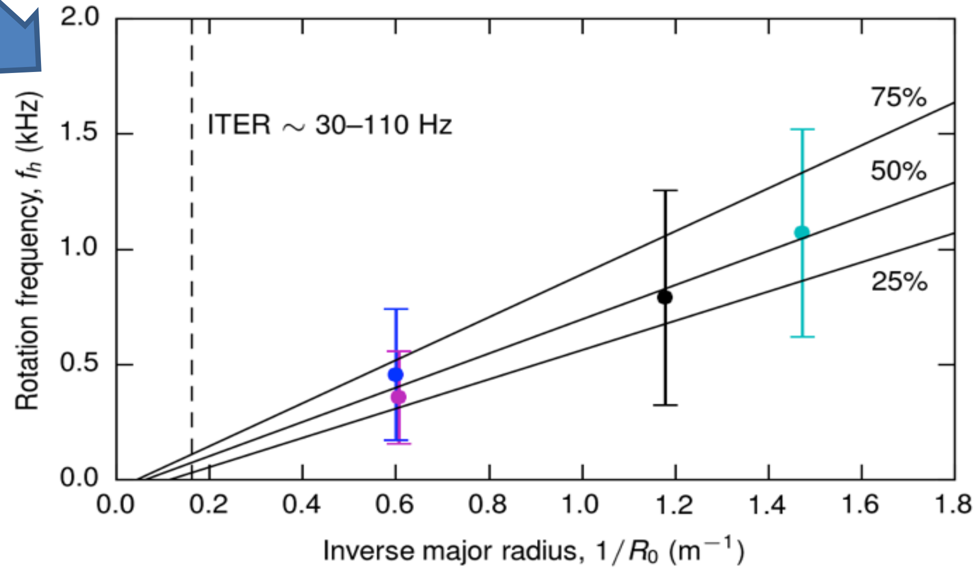
Leading studies of rotating halo currents through ITPA multi-machine analysis and M3D-C1 numerical simulations

ITPA multi-machine analysis (MDC WG-6):

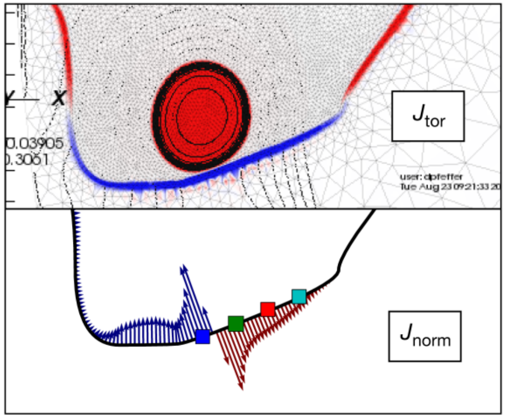
- Halo current data from C-Mod, DIII-D, AUG, NSTX
- All measurements in lower divertor (> 400 shots)
- Halo current rotation is predominantly counter-I_p
- Consistent rotation velocity, v_h ~ 5 km/sec

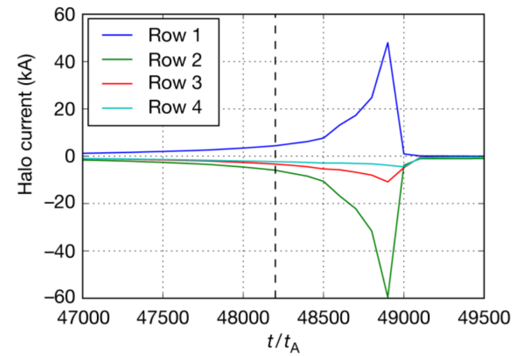




M3D-C1 simulations:

- NSTX(-U) geometry
- Simulate in 2D while q >2
- Switch to 3D to resolve halo rotation (in progress)
- *D. Pfefferlé et al. (PPPL)*





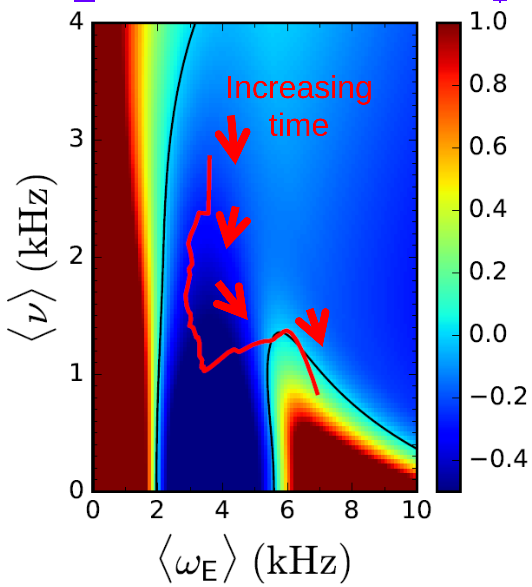
Disruption characterization and forecasting capability started for NSTX-U as part of disruption avoidance plan

New DECAF (Disruption Event Characterization And Forecasting) code written

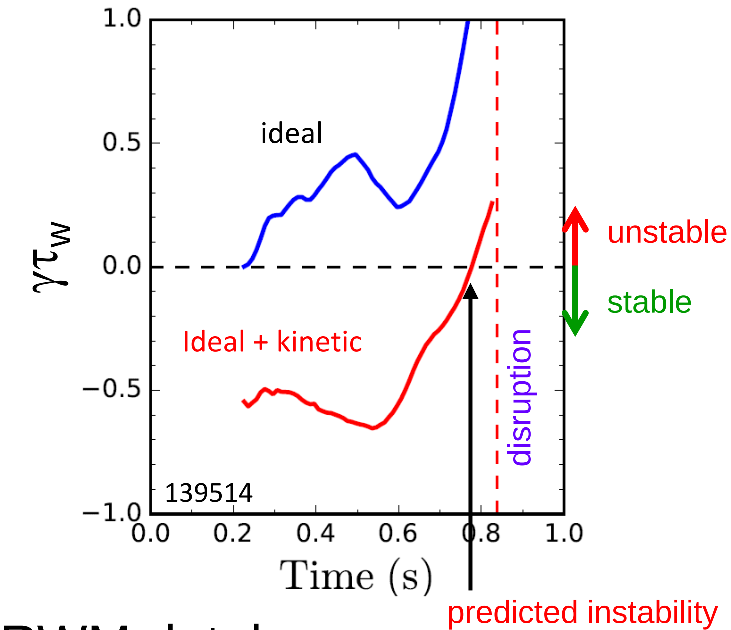
- Identify disruption event chains and elements
  - ex: vertical displacement, pressure peaking, tearing modes…
- Predict events in disruption chains
- Cues disruption avoidance system

Example: Reduced kinetic resistive wall mode (RWM) model developed for calculating growth rate vs. time

$\gamma\tau_w$ contours vs. ν and ω_ϕ



Normalized growth rate vs. time

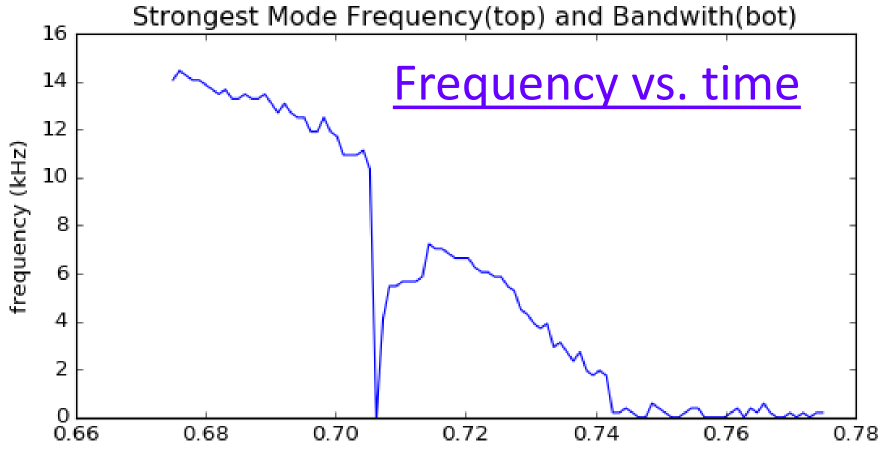


- Initial tests on NSTX RWM database
  - 86% of RWM shots are predicted unstable
- Possible to predict growth rate in real time

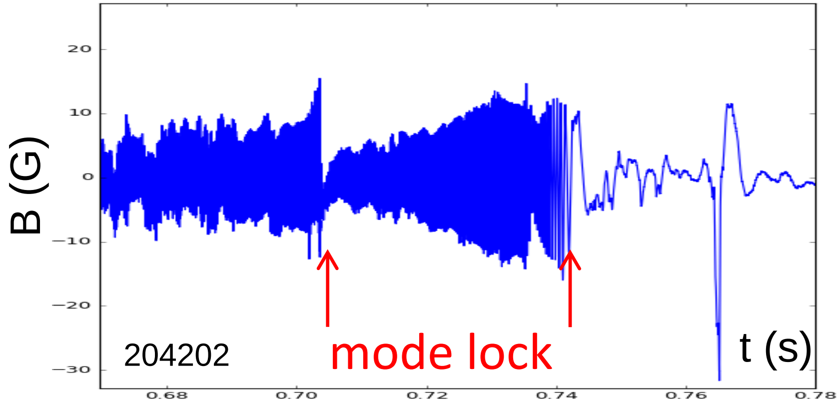
J.W. Berkery et al., Poster EX/P4-34, Wednesday afternoon

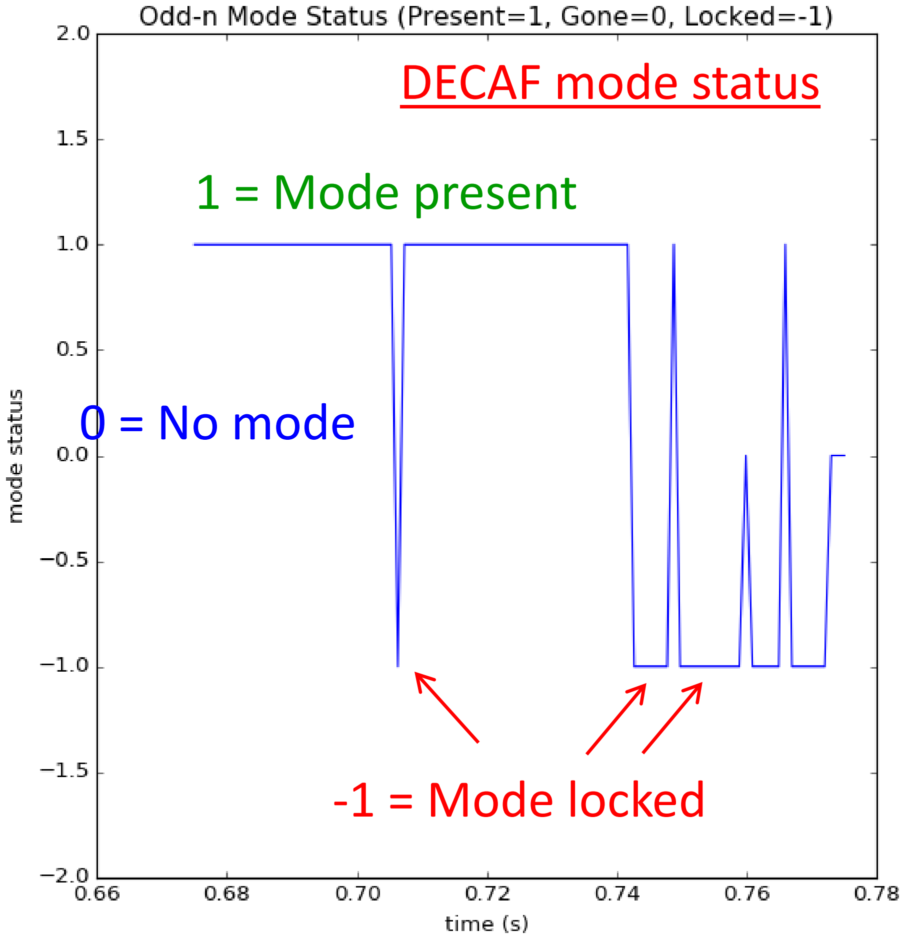
Continuing analysis of rotating MHD for DECAF includes accurate analysis of mode "status"

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



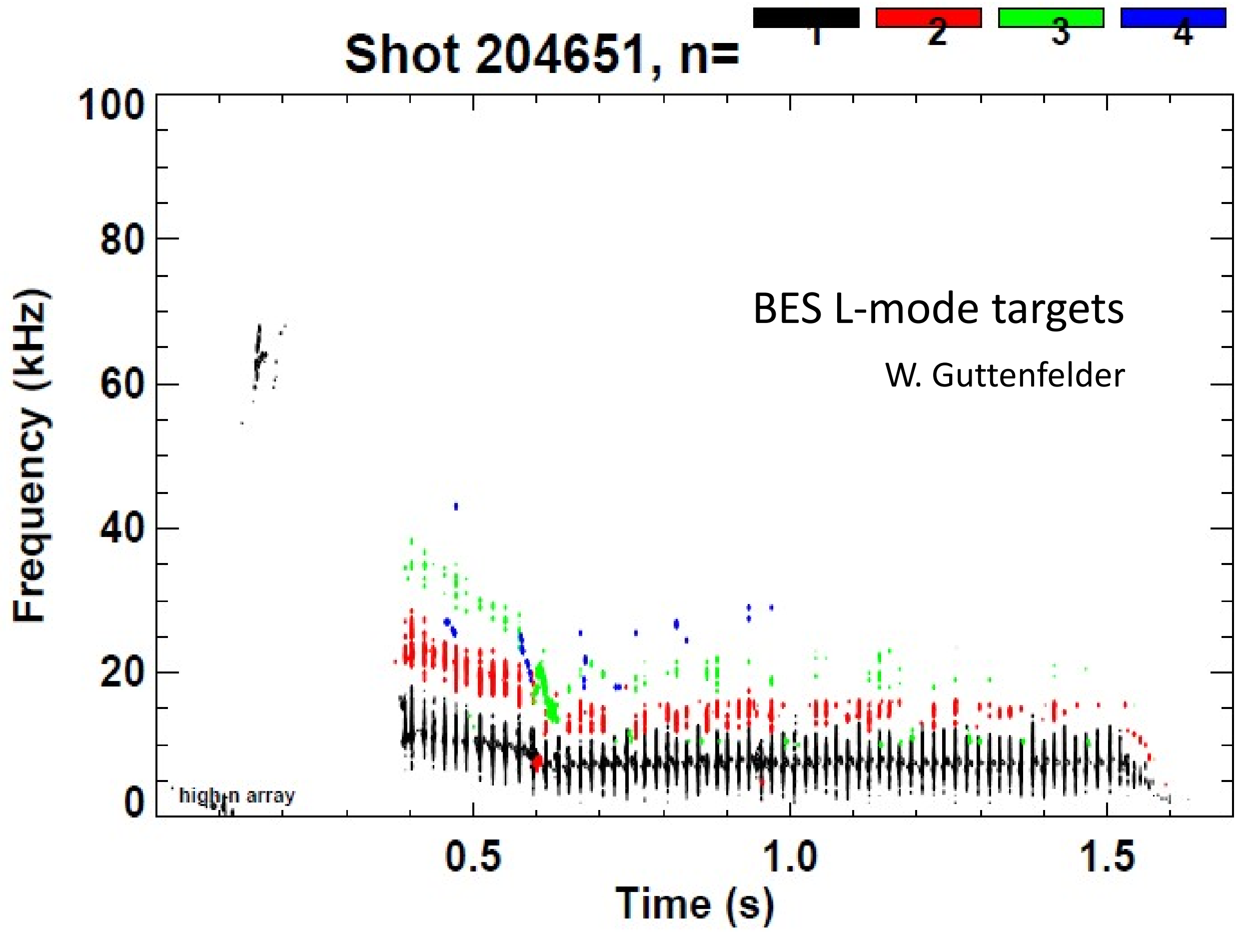
Signal





COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

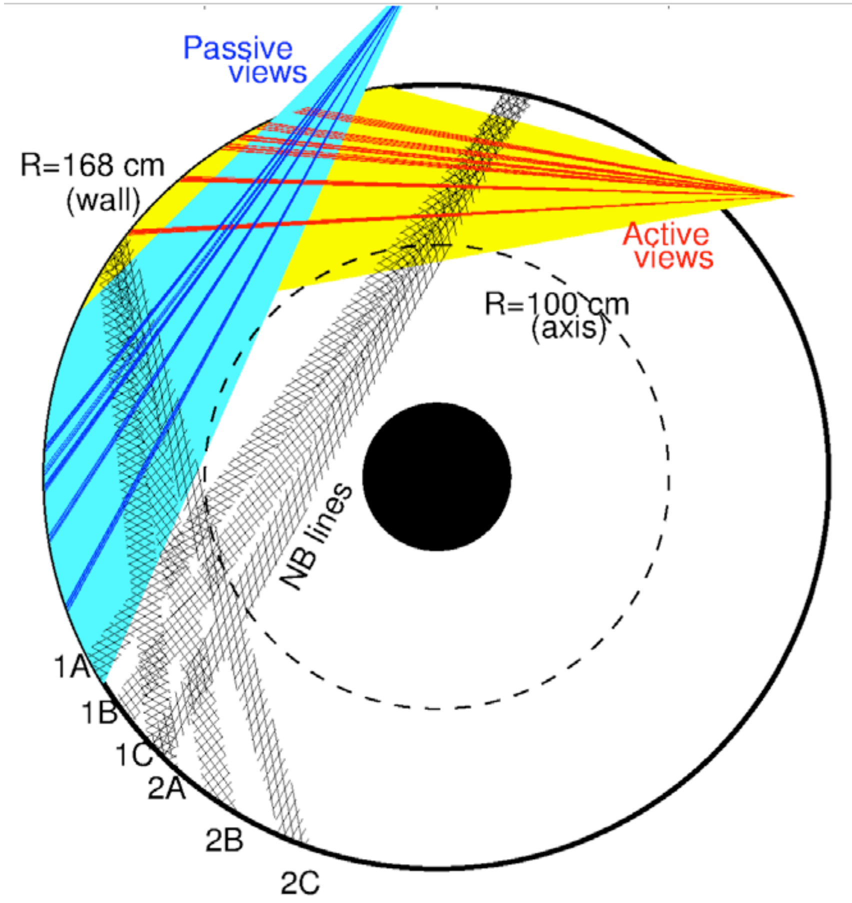
NSTX-U: Long-lived stationary sawtoothing discharges generated with core rotation f~15kHz



Previously very difficult to achieve in NSTX due to limited flat-top

Real-Time Velocity (RTV) is a fast (up to 5kHz) system based on active spectroscopy

- System based on active charge-exchange spectroscopy (NB1 line)
- Monitor C VI, n=8-7 line @ 5291nm
- RTV views interleaved with CHERS views at midplane
- 4 views available
  - R=112, 125, 132, 140cm



M. Podestá

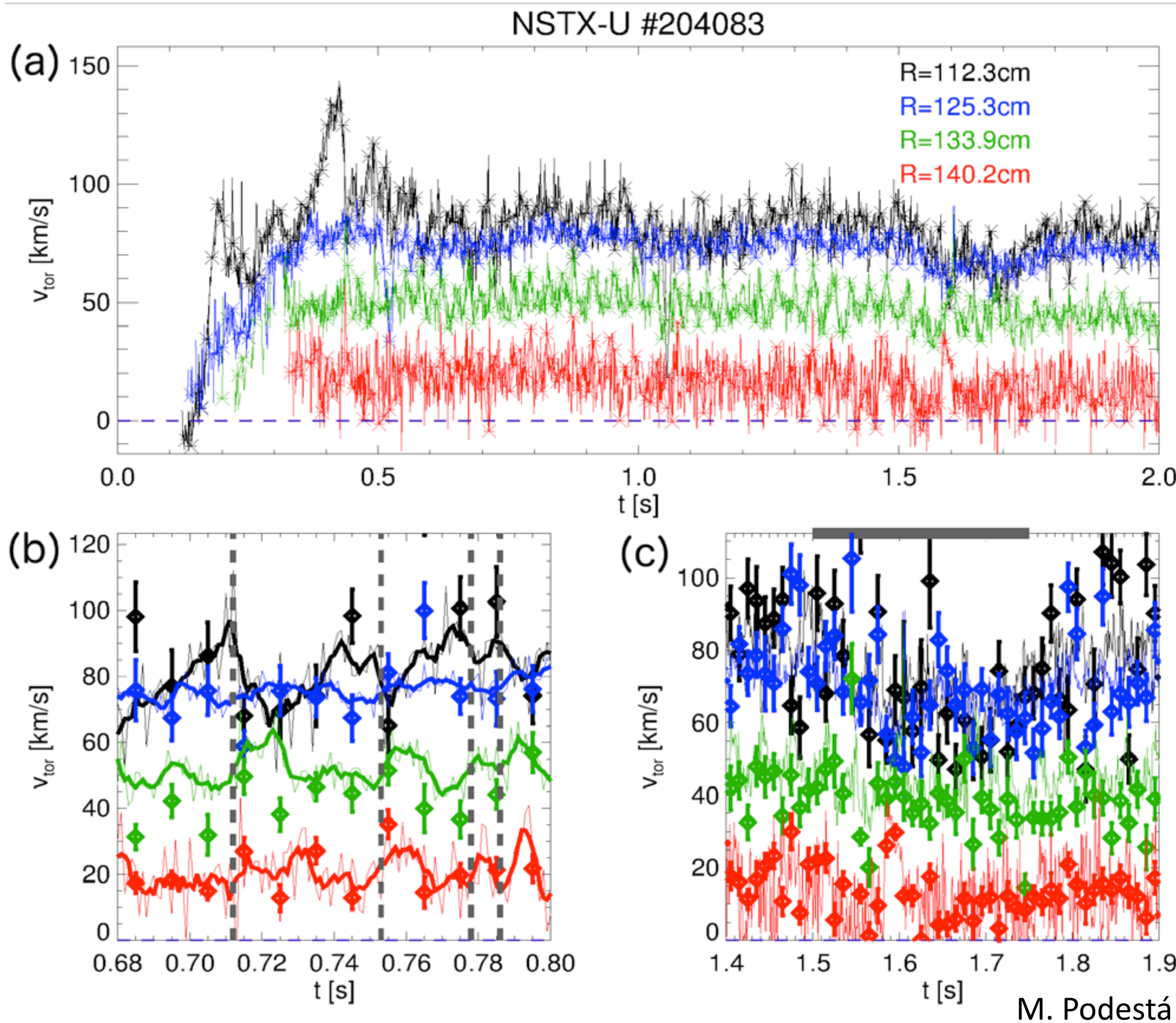
Sawteeth redistribute momentum, core v_ϕ decreases by ~20%

L-mode, P_{NB}~1MW

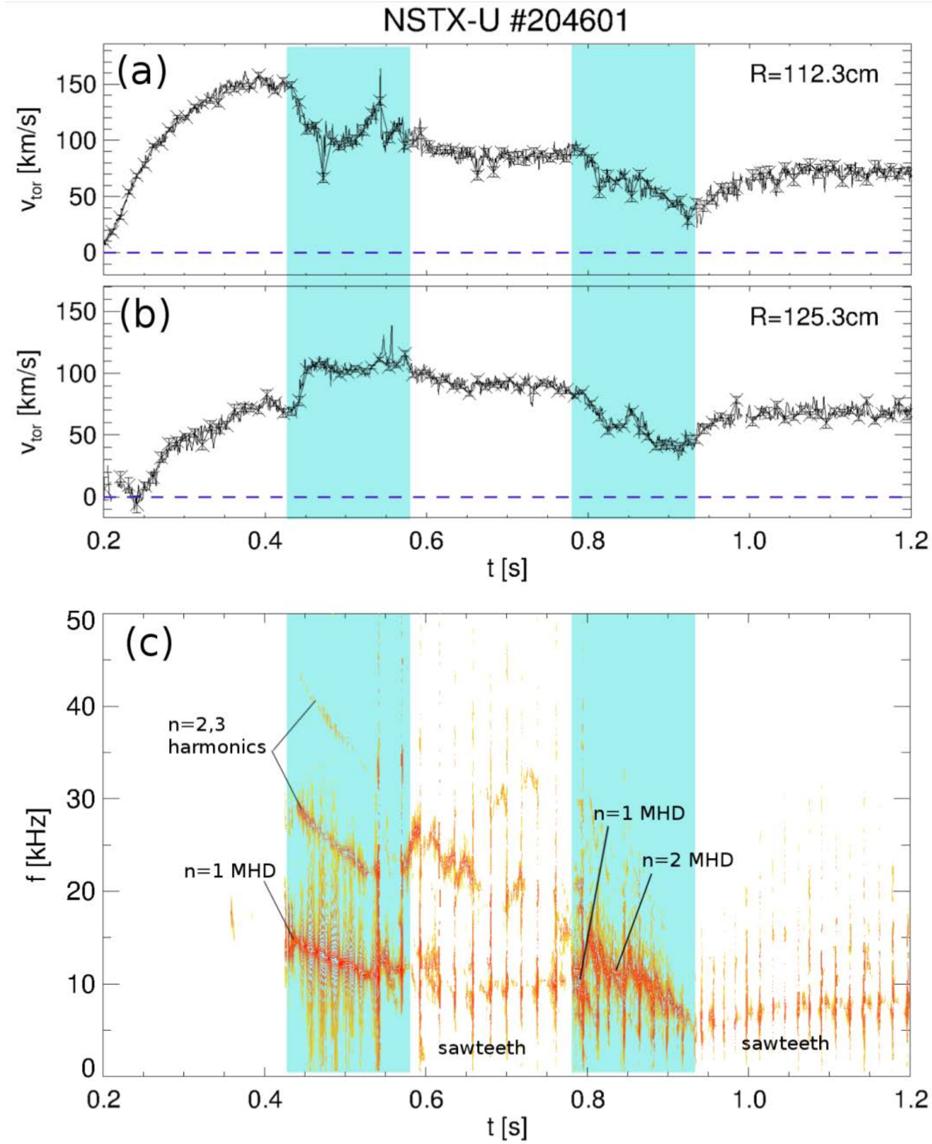
a) Sawteeth seen after t=0.5s

b) Crashes visible on $v_\phi(0)$, anti-correlate with increased v_ϕ at R>130cm

c) Large RMP pulse at 1.5s captured by RTV, CHERS



MHD, sawteeth compete in v_ϕ redistribution; different time scales, high f_{samp} or RTV enables separation



- Complex scenario
  - MHD n=1,2 modes act on ~10ms time scale
  - Sawteeth act on ~1ms time scale
- High f_{samp} of RTV allows to differentiate time scales
- Complements high spatial resolution CHERS profiles

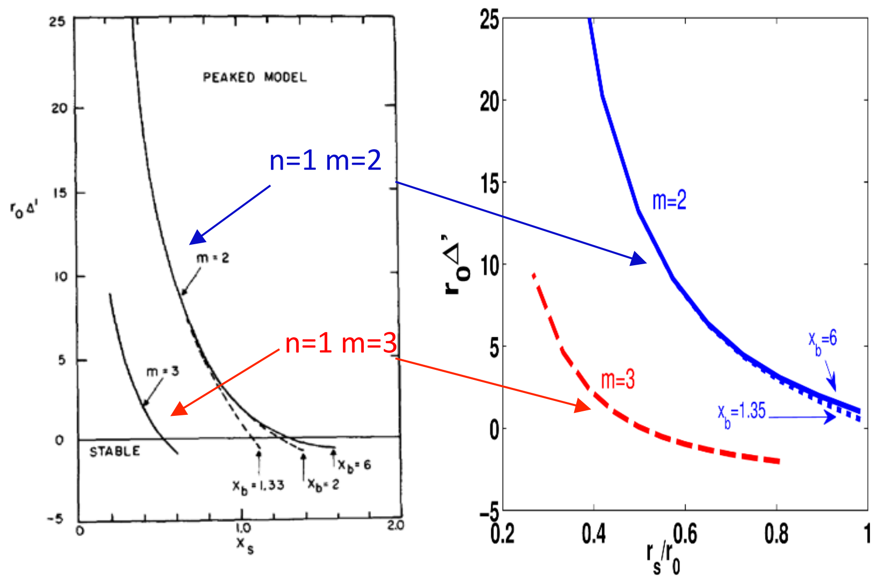
M. Podestá

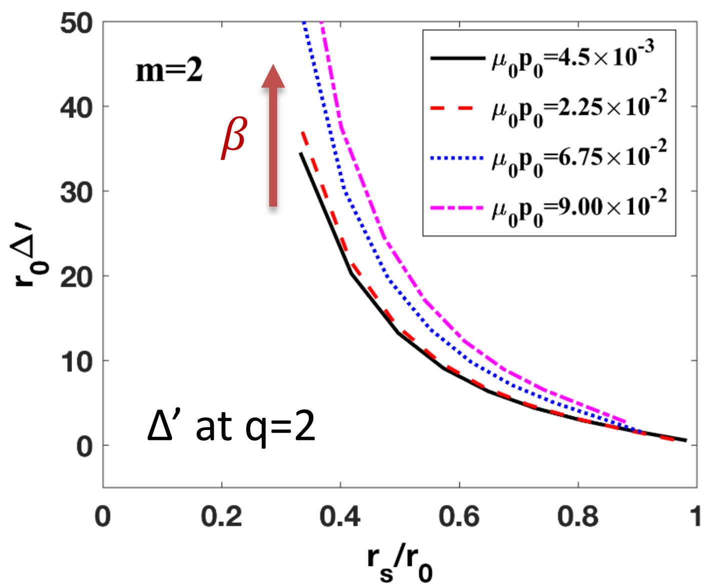
Resistive DCON Solves Reliable Outer Region Δ′ and Indicates Δ′ is Destabilized by Plasma Pressure

Resistive DCON reproduces Δ′ behavior in Furth, Rutherford and Selberg, Phys. Fluids 16, 1054(1973).

Higher β → Increase Δ′ at q=2,3
→ More unstable tearing mode

Resistive DCON solves Δ′ in full toroidal geometry.





First resistive DCON paper has been published.
Glasser, Wang and Park, Phys. Plasmas **23**, 112506 (2016)

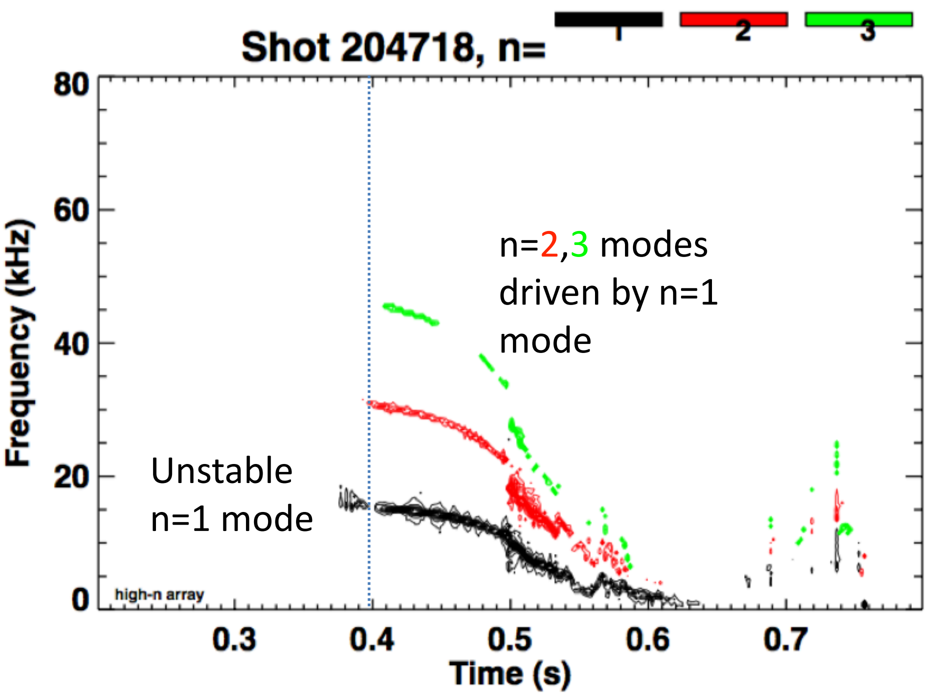
Z. Wang

Preliminary result: Resistive DCON and MARS-F predict unstable n=1 tearing mode as observed in NSTX-U experiments

- 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≥3 singular surfaces.

CAVEATS: No MSE, n=1 mode may be 1/1 mode?

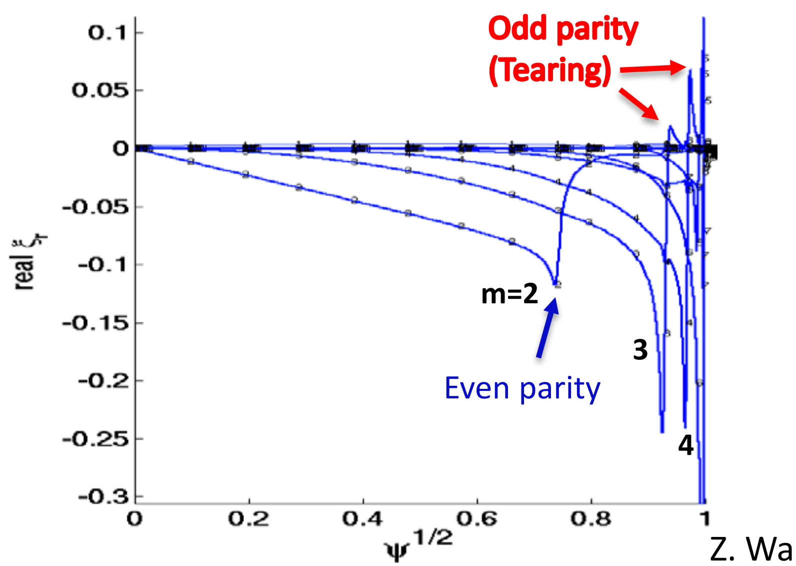
NSTX-U experiment observes n=1 unstable mode which drives n=2, 3 modes later



Diagonal terms of Δ' matrix from 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 $\gamma = 1.7 \times 10^{-3}\omega_A$



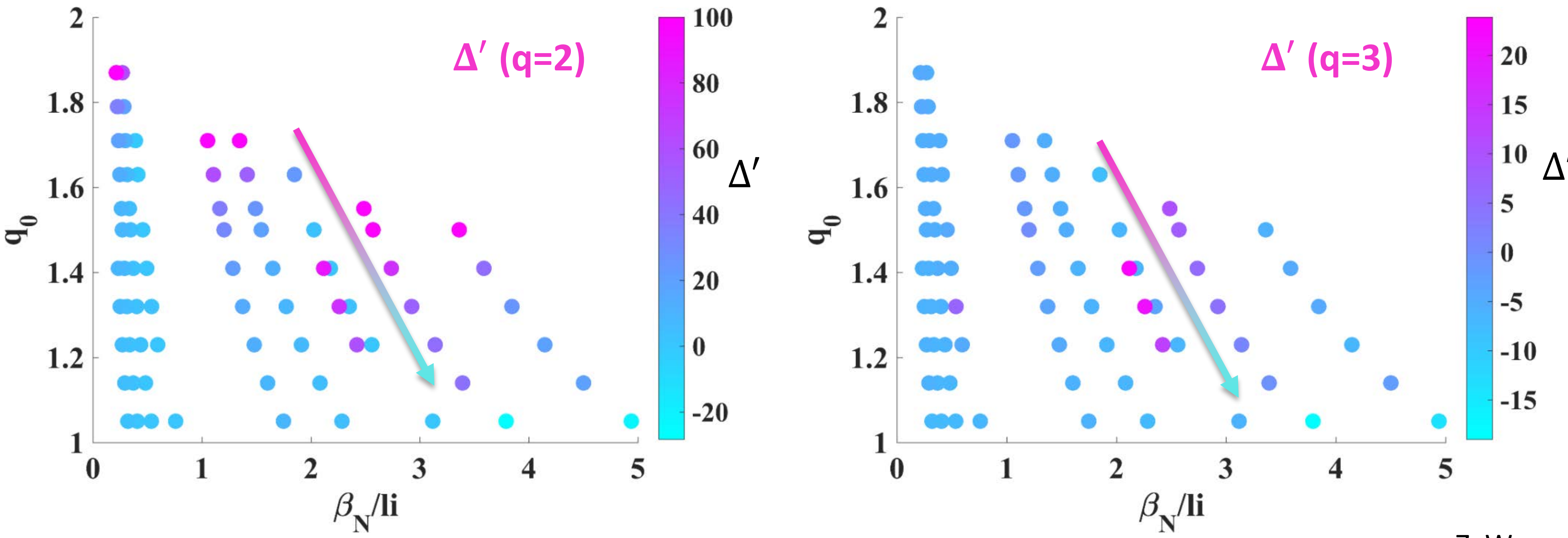
Z. Wang

RDCON: Δ' Optimization of NSTX-U L-Mode discharge to stabilize n=1 tearing mode ($q_0 \downarrow$ and $\beta_N/l_i \uparrow \rightarrow \Delta' \downarrow$)

Resistive DCON is applied to optimize NSTX-U equilibrium to avoid tearing instability (varying equilibrium parameters to minimize Δ').

A sequence of equilibria are generated by scanning current and pressure profiles with CHEASE code, where plasma boundary of discharge 204718 is used.

For this scenario, reducing q_0 and increasing β_N/l_i $\rightarrow$ Decrease in Δ' at q=2,3



Z. Wang

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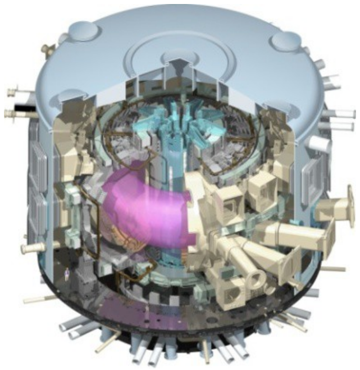

ITER

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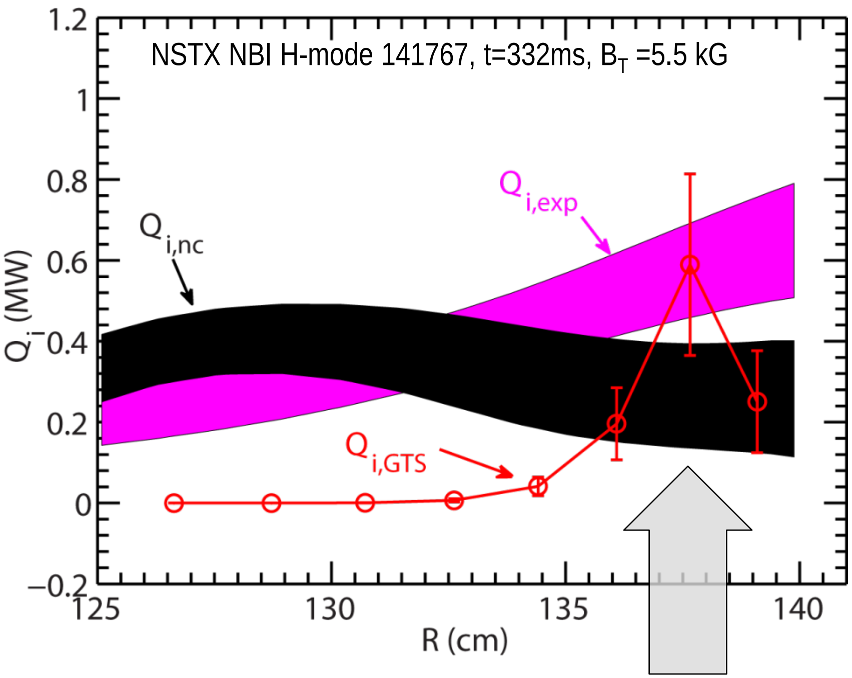
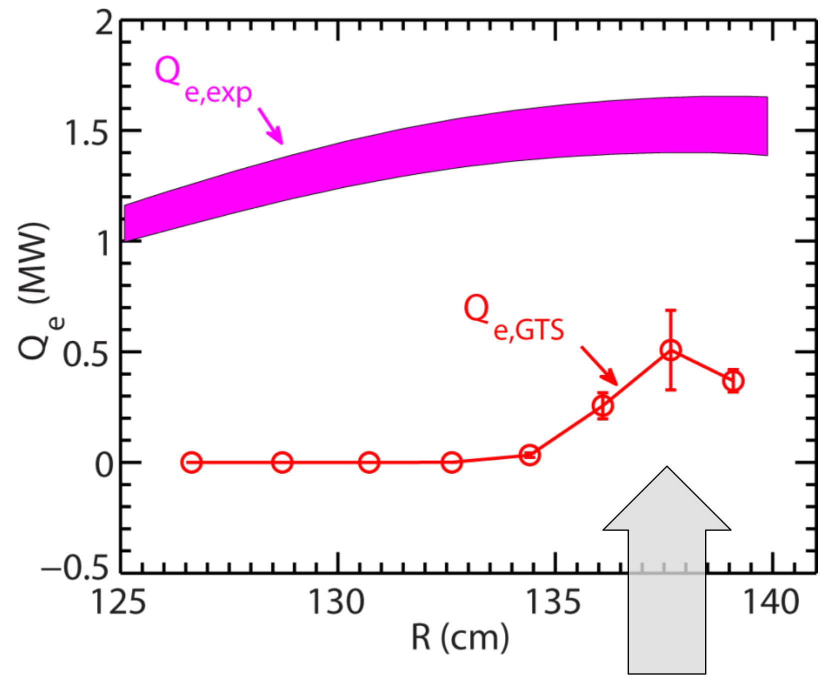
NSTX: Using global non-linear GTS gyrokinetic code to study multiple low-k turbulent transport mechanisms

Ion Temperature Gradient, Kelvin-Helmholtz modes + neoclassical, treat larger ρ*~0.01 of NSTX





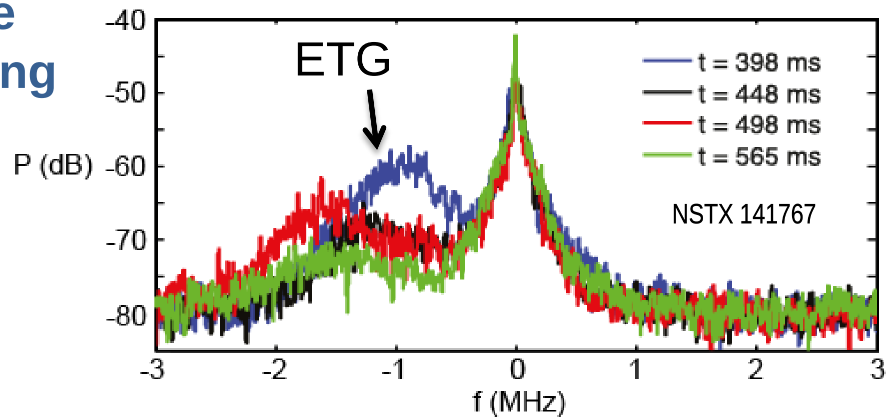
- Low-k turbulence contributes significantly for R > 135 cm
  - Turbulence later suppressed by ExB shear
- Total ion energy flux from GTS in agreement with experiment

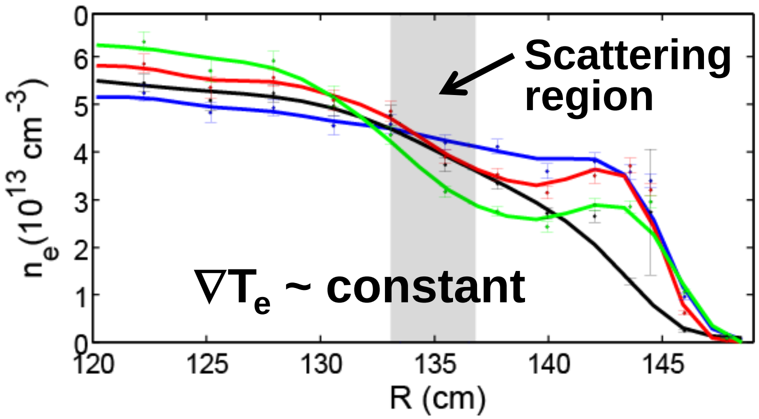
- GTS electron energy flux from only significant at R > 135 cm, and much smaller than experiment
- Electron Temperature Gradient (ETG), electromagnetic effects important?

Linear and non-linear gyrokinetic simulations of Electron Temperature Gradient (ETG) modes show ∇n_e can be stabilizing

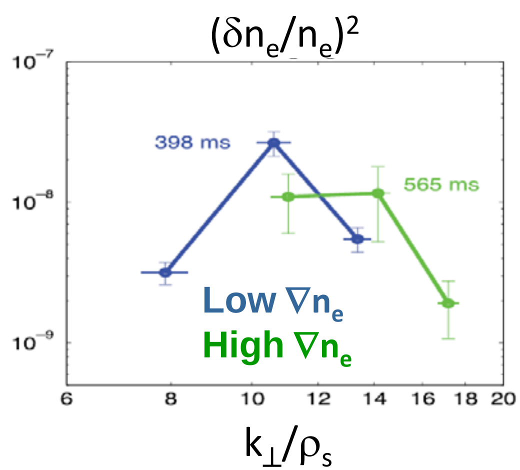
NSTX: Decrease in ETG turbulence amplitude w/ increasing ∇n_e

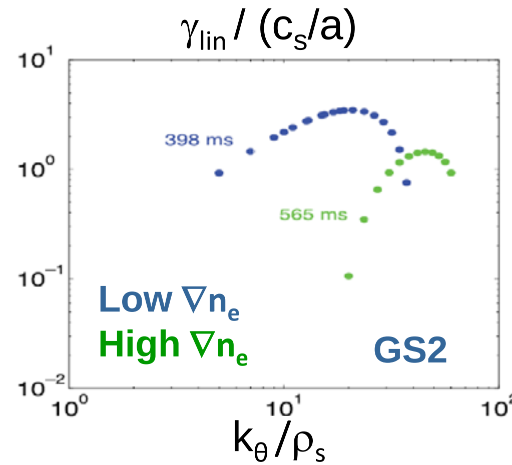
μ-wave scattering

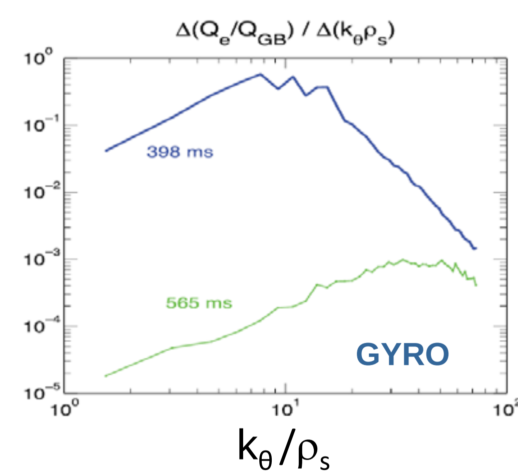




Measured $\delta n/n$, linear growth rates, non-linear Q_e all reduced by higher ∇n_e

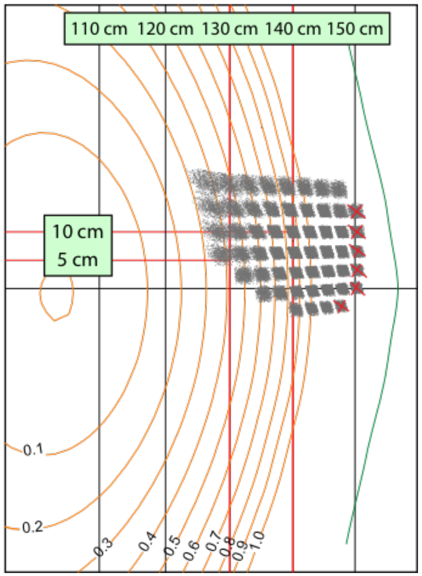


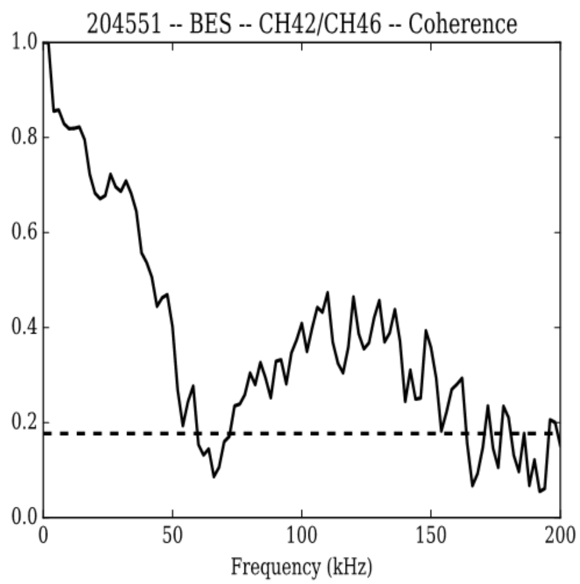


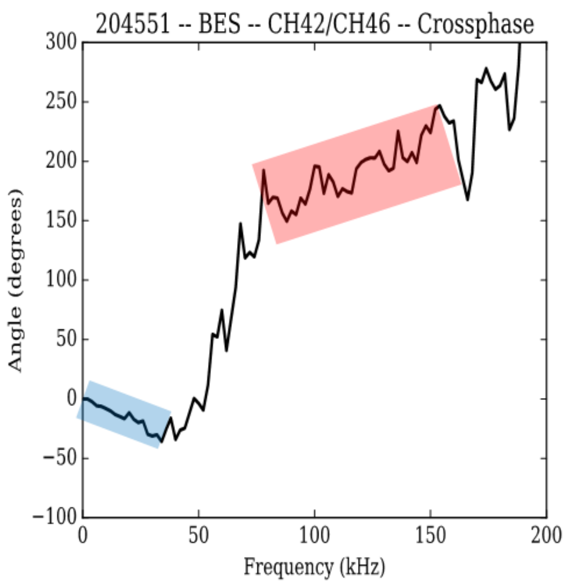


Non-linear GYRO under-predicts Q_e by 70-100% – need multi-scale GK?

NSTX-U: Bimodal turbulence seen in some L-modes
using upgraded 48 channel Beam Emission Spectroscopy (BES) system







ΔZ = 3 cm
R = 142 cm
Δt = 24 ms

11 km/s in ion diamagnetic direction

13 km/s in electron 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

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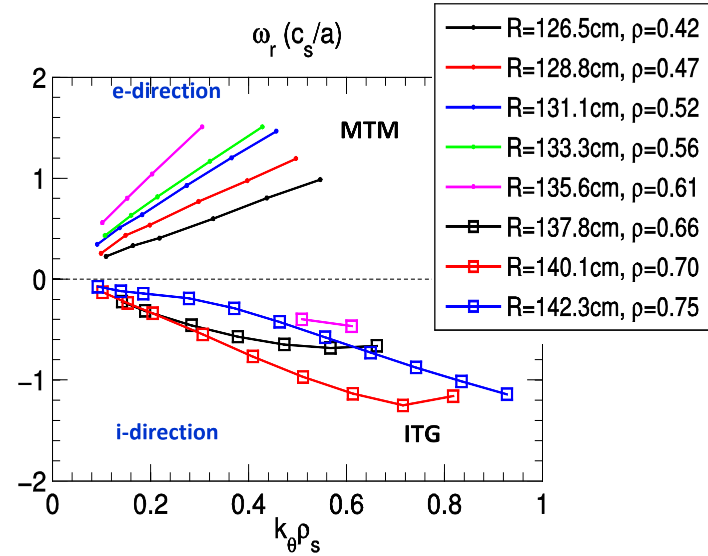
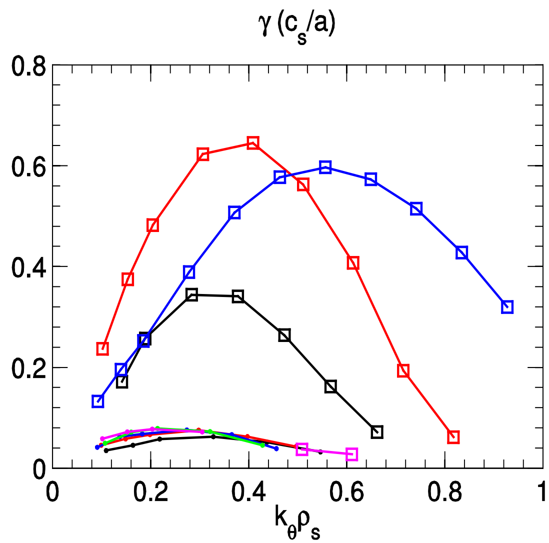
At ion scales ($k_\theta \rho_s$<1), linear GYRO* simulations predict unstable spectra of ITG and microtearing modes (MTM)

- ITG unstable R>135 cm, propagates in ion direction
  - Propagation direction consistent with BES ion mode (need to consider Doppler shift, although also in ion direction)

- MTM also unstable R>127 cm, propagates in electron direction
  - Surprised to find MTM unstable ⇒ sufficient beta (4.1%) and large collisionality enhances MTM





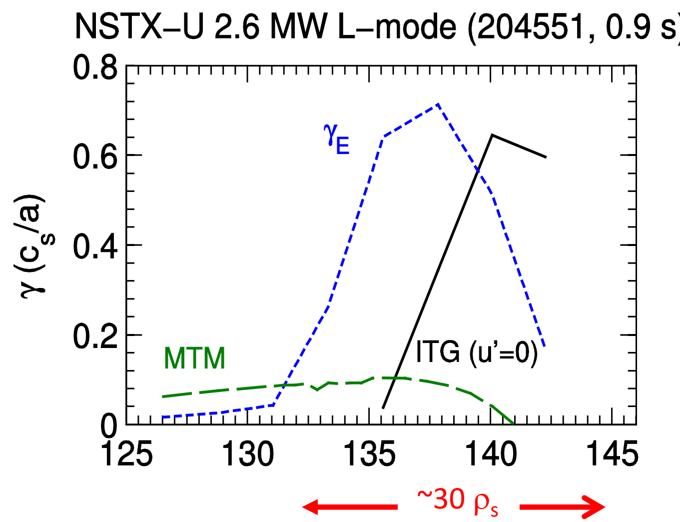
*GYRO (Candy, Waltz, 2003)

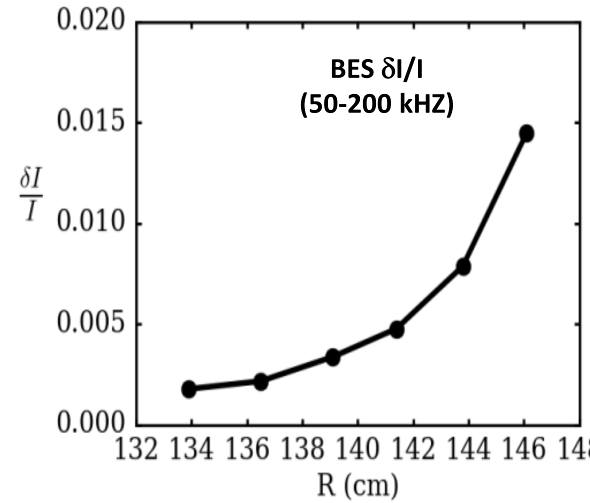
Strong variation in turbulence, stability and E×B shear over ≤ 30 ρ_s ⇒ *motivates the need for global simulations*

- Strong *local* E×B shearing rates ($\gamma_E > \gamma_{ITG}, \gamma_{MTM}$ at R=135 cm)
  - BES amplitudes increasing where $\gamma_{ITG} > \gamma_E$

- Significant variation over ~30 ρ_s ($\rho_* = \rho_s/a$ ~ 1/120, ρ_s / L_T ~ 1/35)

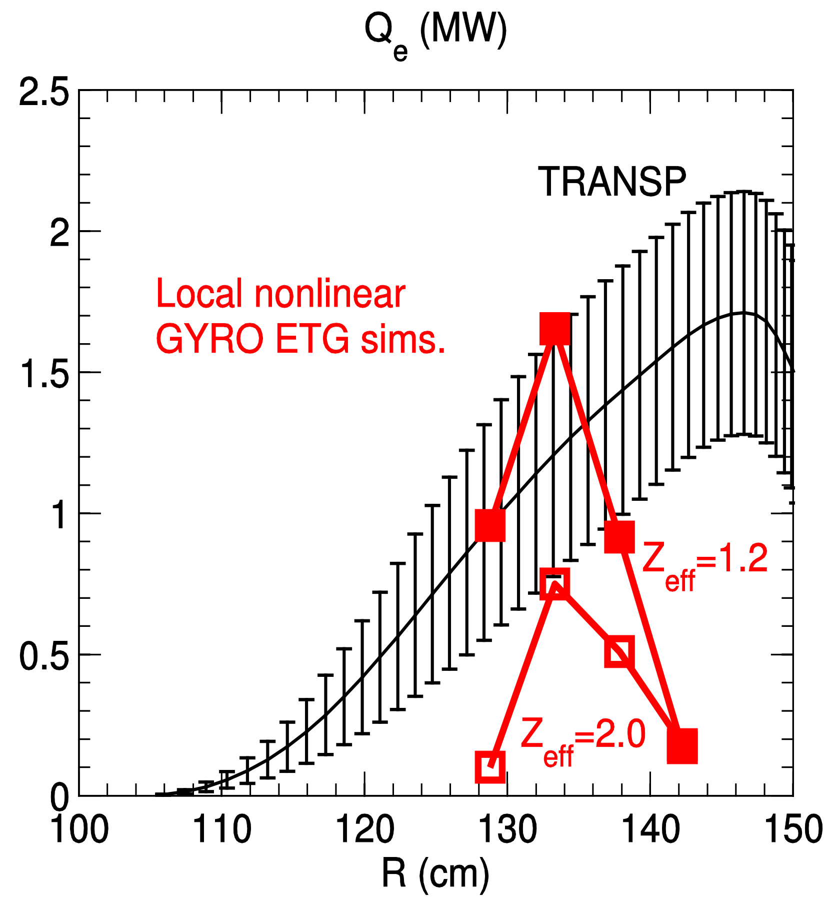
⇒ *Motivates the need for global simulations*





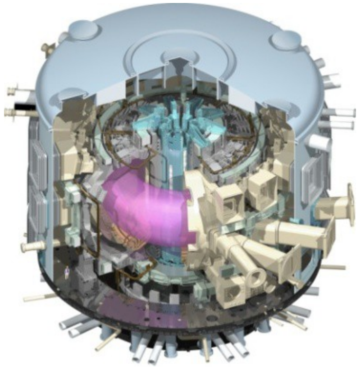
Same NSTX-U L-modes: Nonlinear ETG simulations give significant transport (R=129-140 cm, r/a=0.47-0.67)

- $Q_{e,etg}$ large enough to account for $Q_{e,exp}$ if $Z_{eff}=Z_{eff,c}\approx 1.2$
  - Larger Z_{eff} (VB $Z_{eff}\leq 2$) → lower $Q_{e,etg}$
- New high-k microwave scattering diagnostic (for 2018 run) will be ideal for probing region of ETG turbulence
- *May require multiscale simulations for validation*



NSTX-U Mission Elements:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

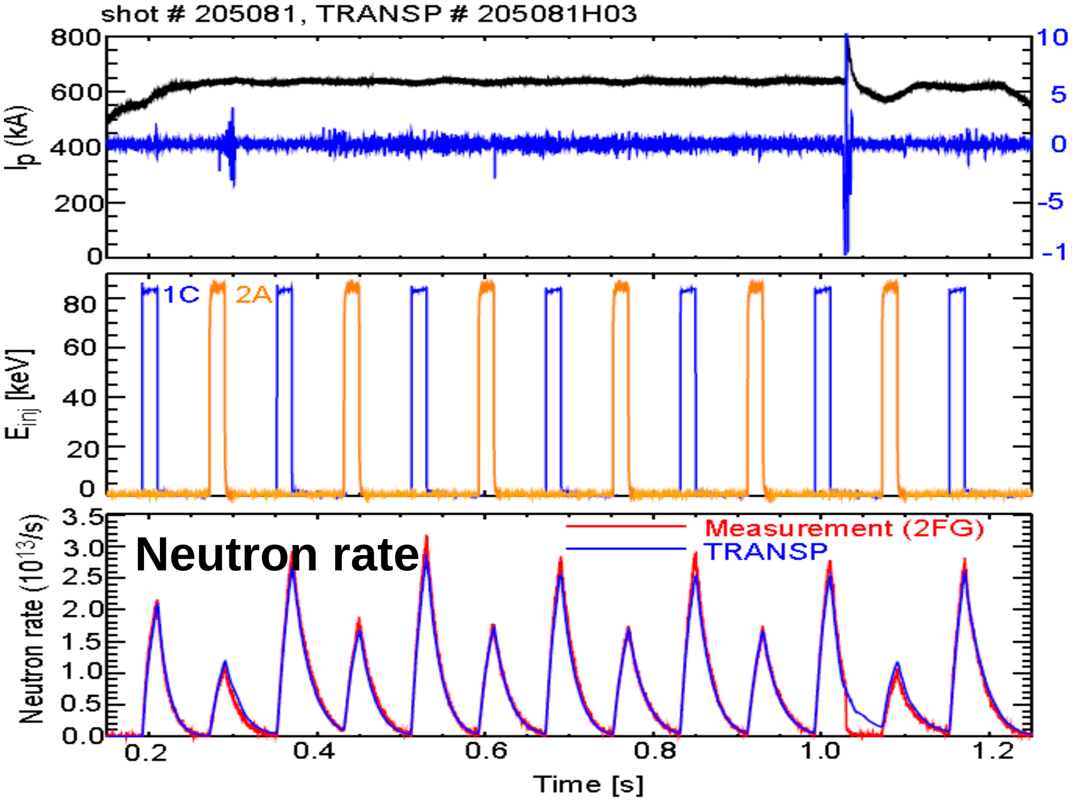

ITER

Topical science areas:

- Scenario Development
- Macroscopic Stability
- Transport and Turbulence
- Energetic Particles

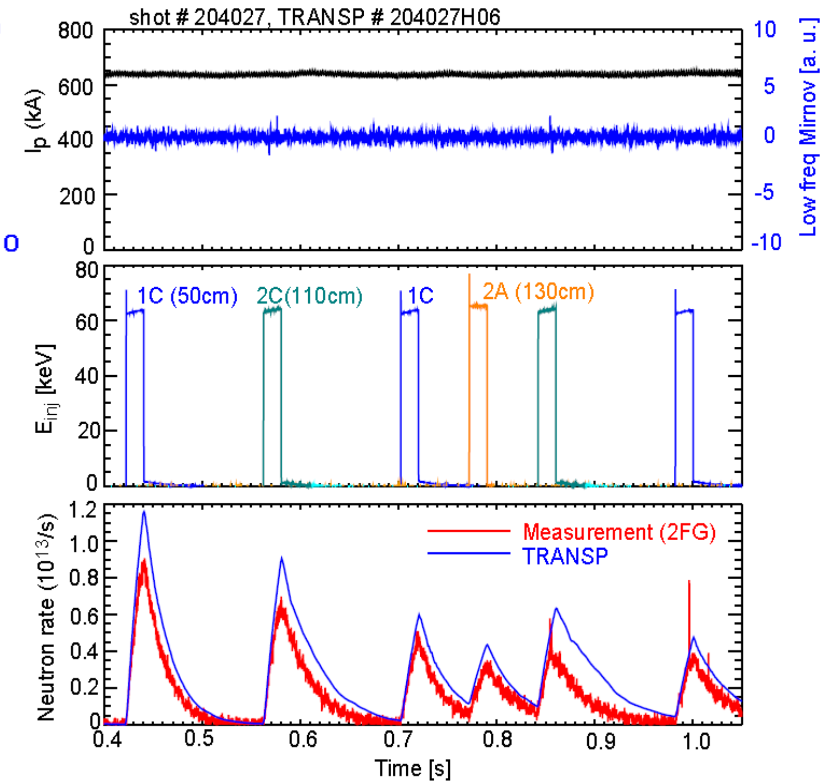
Explored fast-ion behavior with original and new NBI via beam blips with different NBI energies

E_{NBI} = 85keV



- Good agreement between neutron measurement and TRANSP prediction

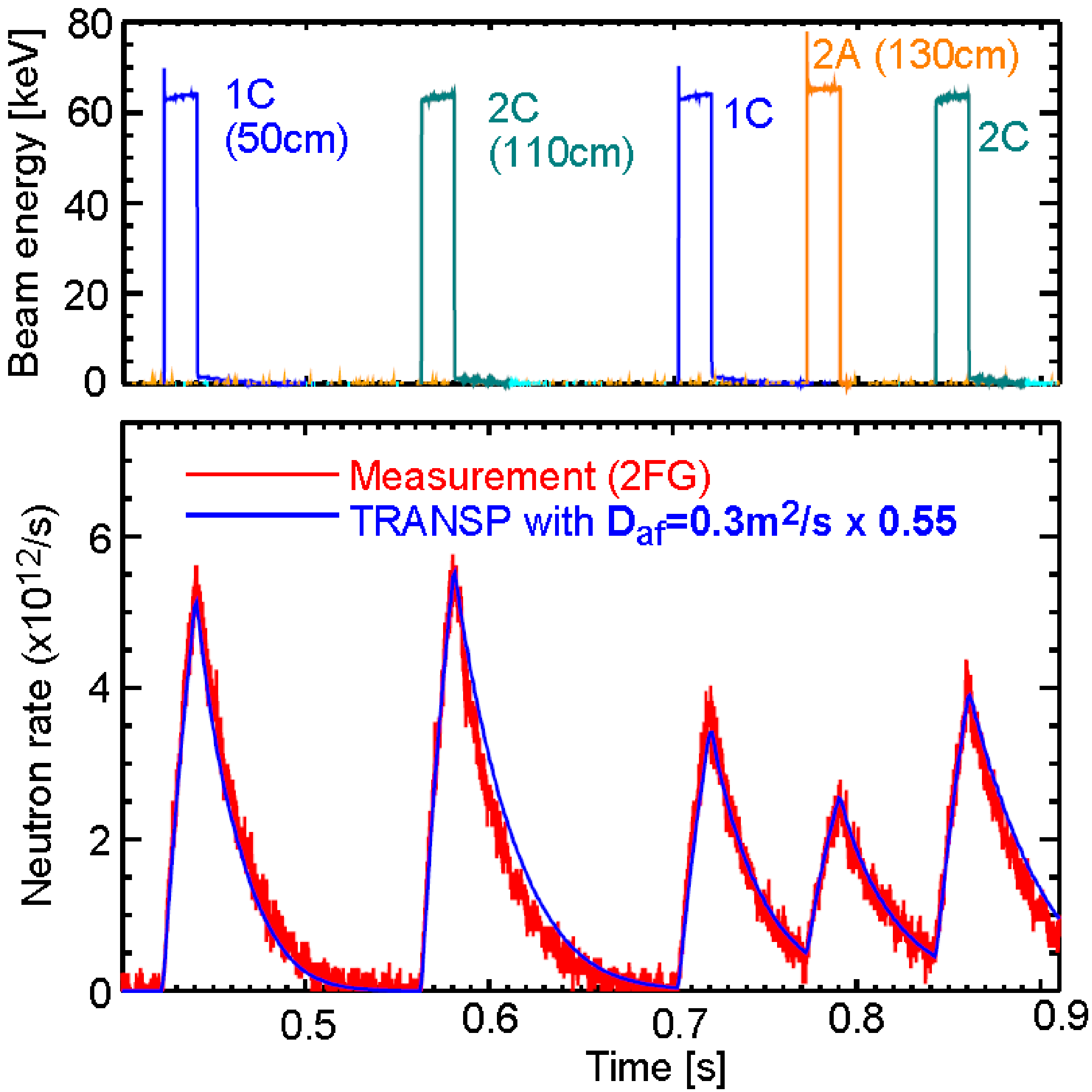
E_{NBI} = 65keV



- ~20% discrepancy between data and TRANSP predictions

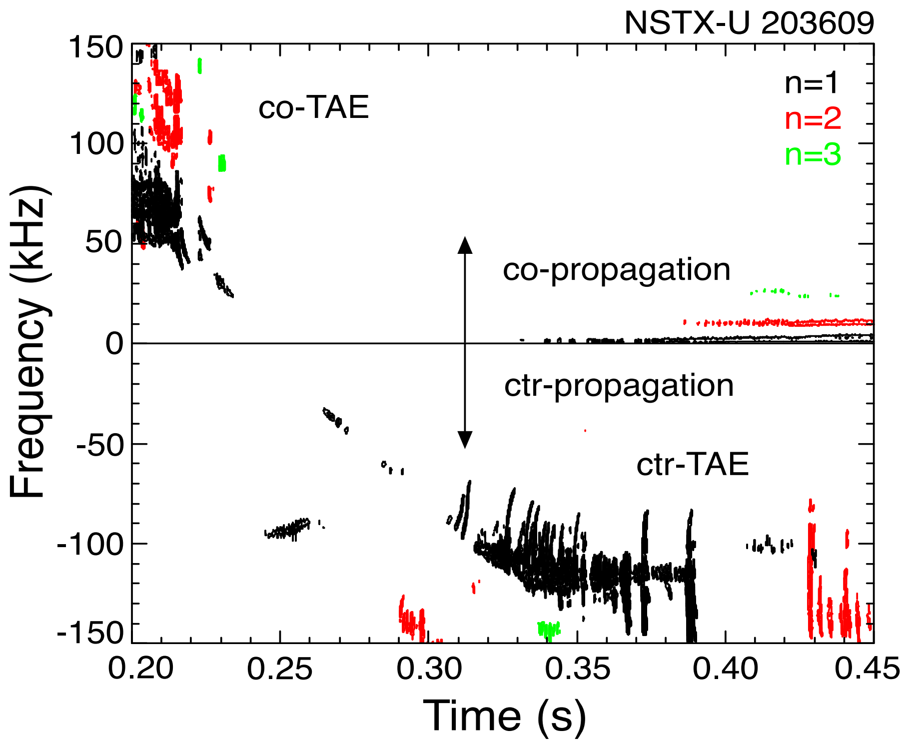
▪ Exploring possible causes, including NBI source energy split

Agreement improved for E_{inj} = 65keV using small anomalous fast-ion diffusion



- TRANSP decay time gets reasonable agreement with data when a small anomalous fast ion diffusivity (D_{af}=0.3m²/s) is used
- → Beam ion behavior is still close to classical theory

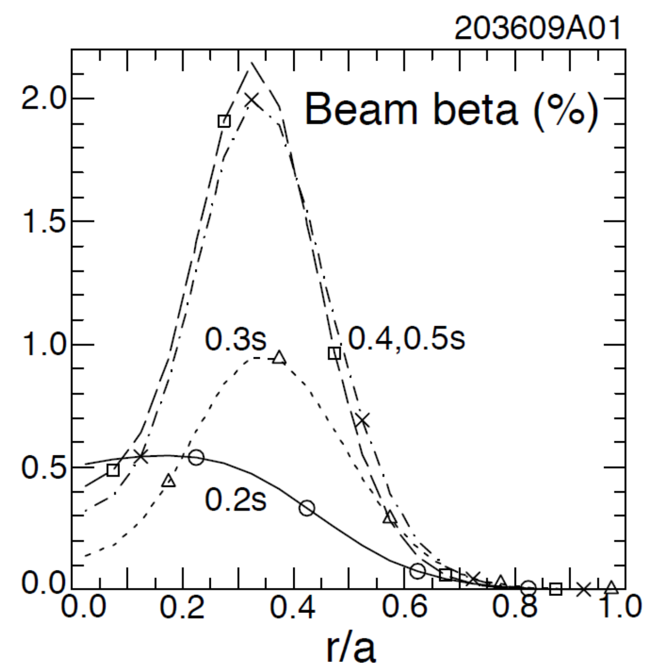
NSTX-U: Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)



- Counter-propagating TAE predicted for **hollow** fast-ion profiles

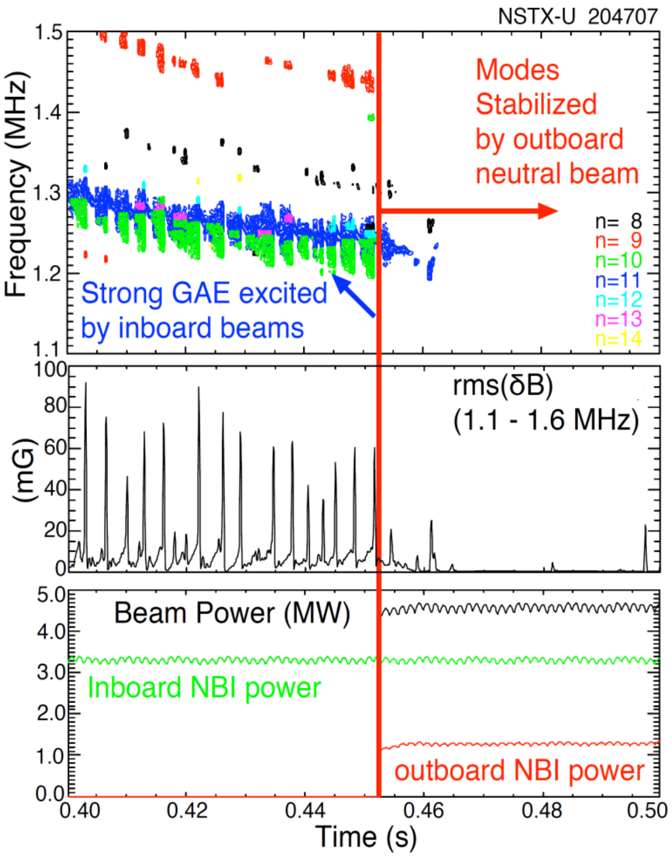
H.V. Wong, H. Berk, Phys. Lett. A ***251*** *(1999) 126.*

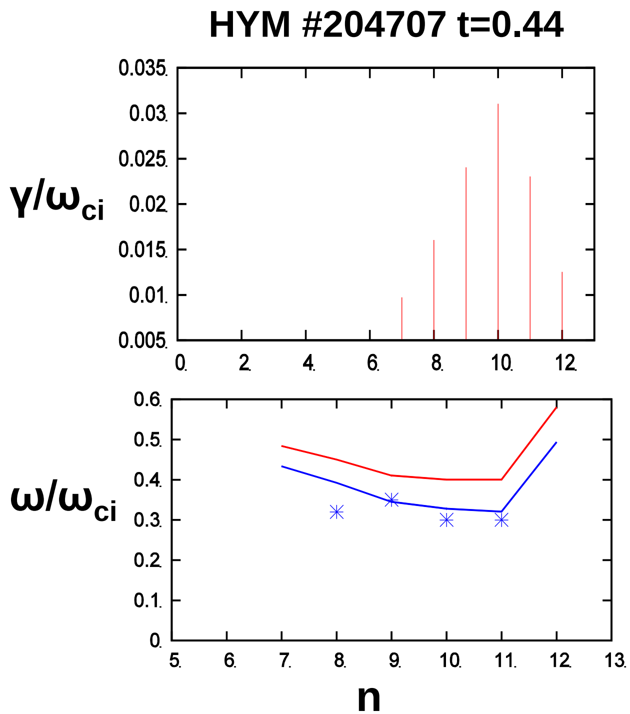
- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow

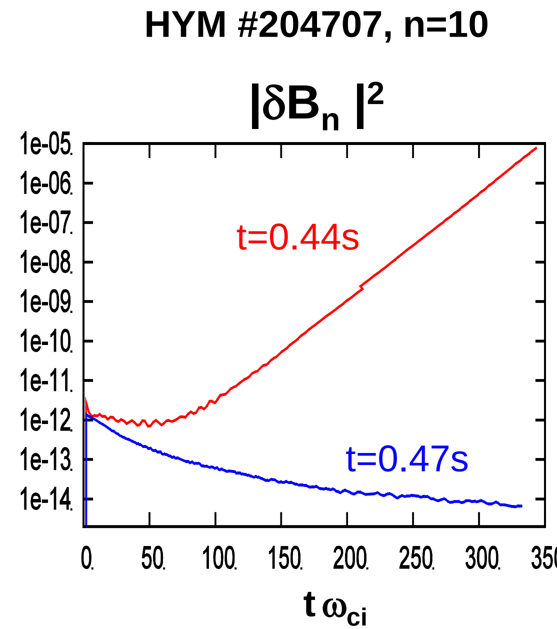


- **1st evidence of off-axis NBI in NSTX-U**

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







- 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

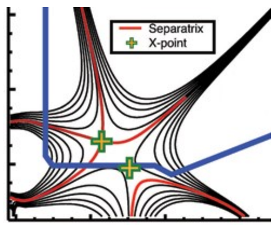
Future modelling and experiments:
Explore impact on fast-ion and thermal electron transport

NSTX-U Mission Elements:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

ITER

- Develop solutions for plasma-material interface (PMI)



Snowflake/X

Liquid metals / Li

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant

ST-FNSF / Pilot-Plant

Improving understanding of SOL heat flux width trends in NSTX using XGC1 simulations

- Experiment shows contraction of SOL heat flux width at midplane with I_p as well as influence of Li conditioning

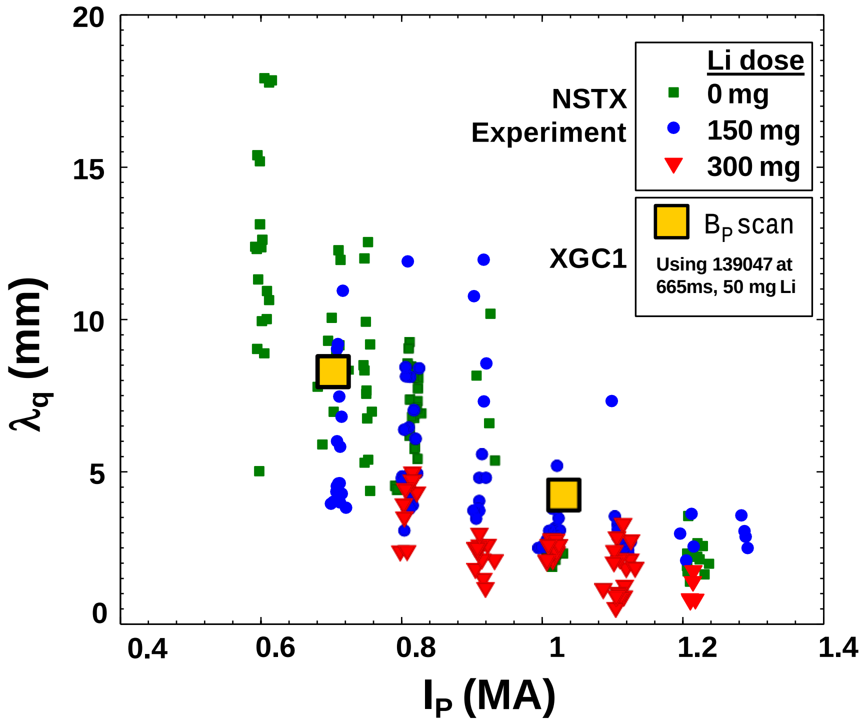
XGC1 w/ collisions → similar trends

XGC-1:

- Full-f, global PIC, kinetic ions and electrons

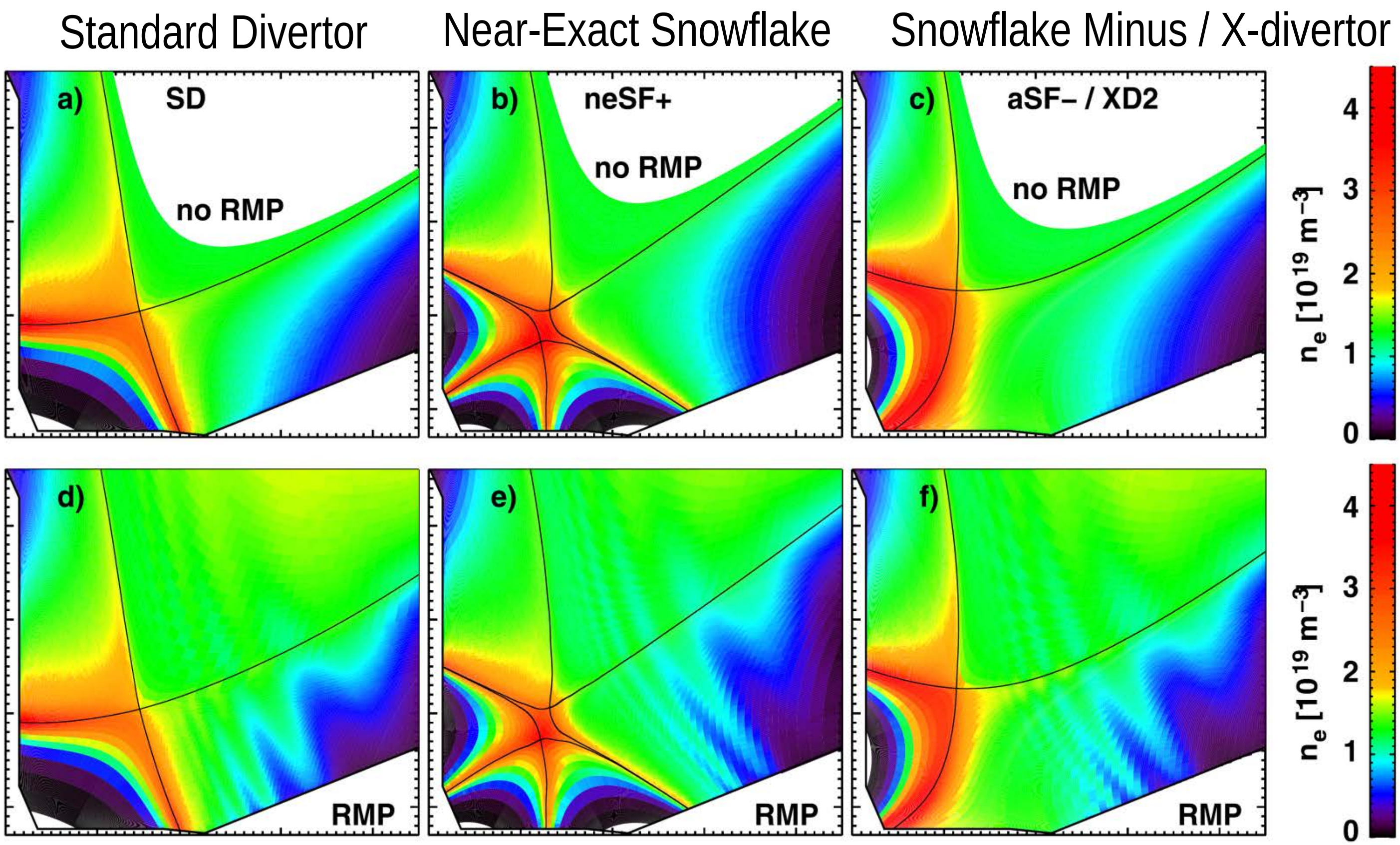
- **NSTX data and XGC-1: $\lambda_q \sim 1 / I_P^{1.5}$**

- Simulations for ITER presented at IAEA-FEC 2016 (C.-S. Chang) indicate turbulence can play significant role in setting heat-flux width
  - **Will SOL turbulence become important in NSTX-U at high current?**



Heat flux width set primarily by neoclassical processes

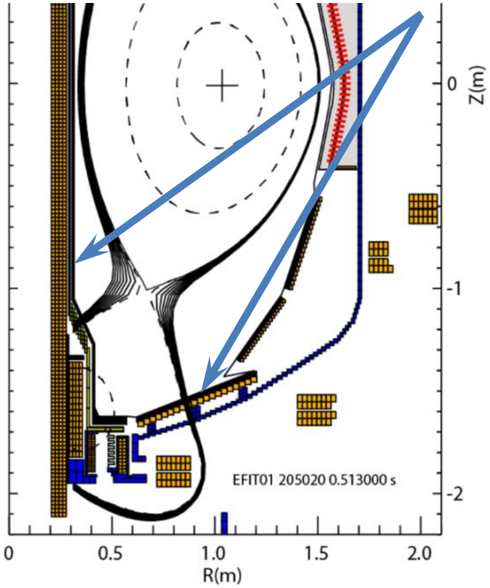
NSTX-U: First systematic simulations of advanced divertors combined with 3D fields using EMC3-EIRENE

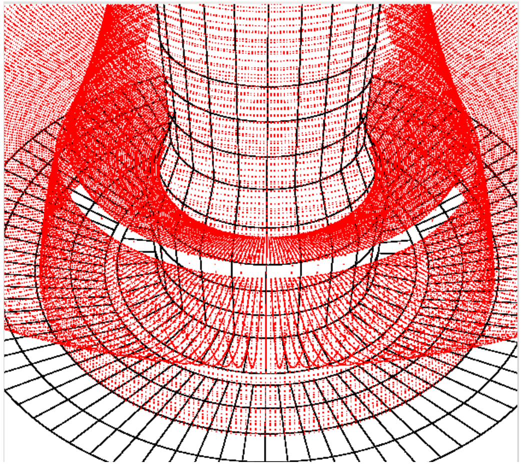


- **Divertor heat-flux trends:**
  - Peaked heat loads in Near Exact Snowflake
  - Lowest heat loads found for X-divertor-like configurations
  - RMP fields do not significantly impact toroidal average heat-flux

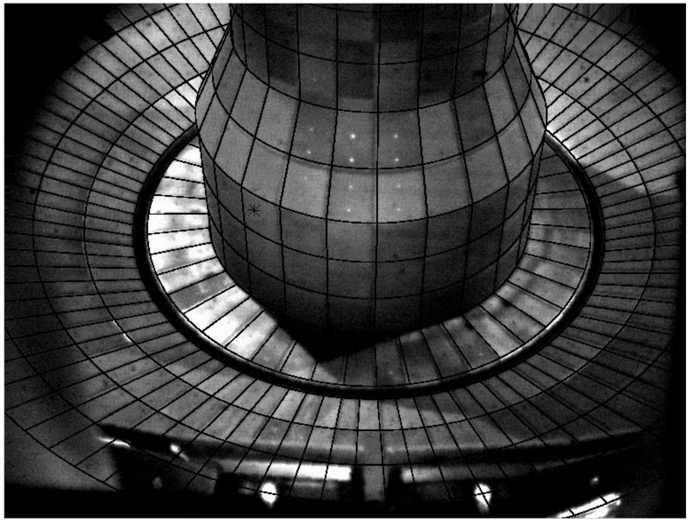
Throughput-optimized camera and high-X-point L-modes enabled near-separatrix turbulence imaging in NSTX-U

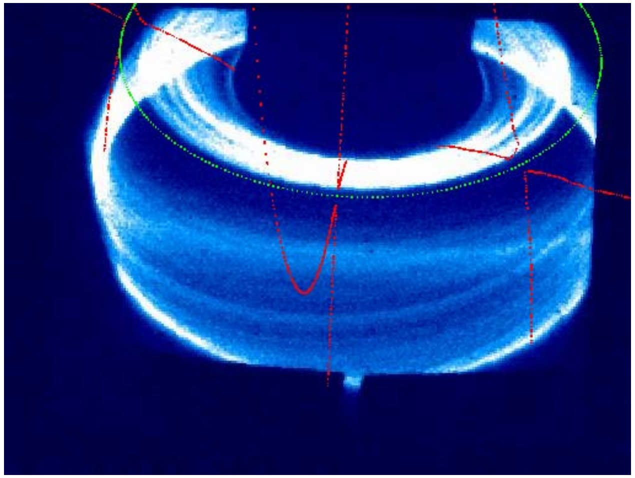
- Divertor turbulence imaging through different species/charge states provides information at different spatial locations
- Throughput-optimized setup enabled turbulence imaging via C III (up to 140kHz)
  - Filaments along divertor legs (vs. filament footprint on floor via Li I or Dα)





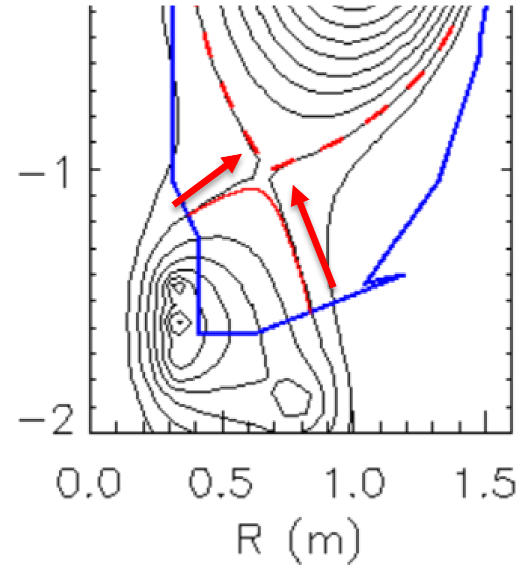
Reconstructed view + separatrix

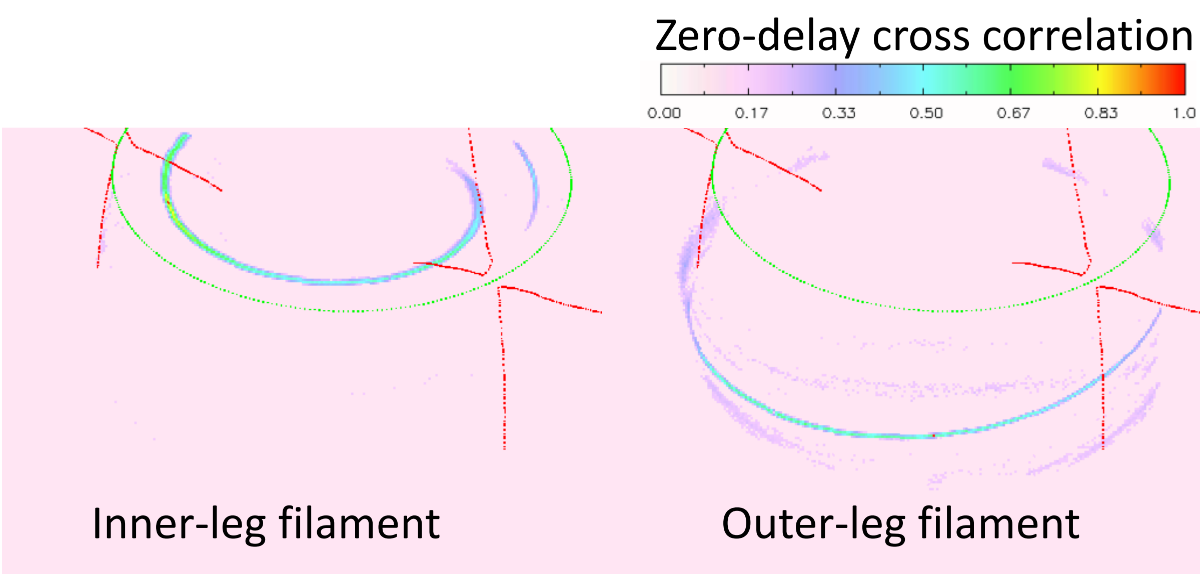


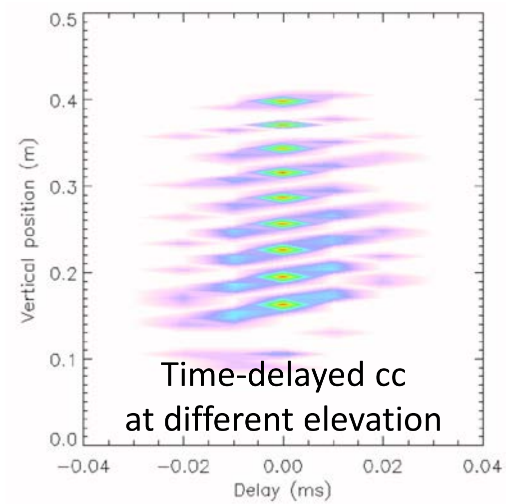


Time delayed cross correlation shows opposite toroidal rotation for inner/outer leg filaments

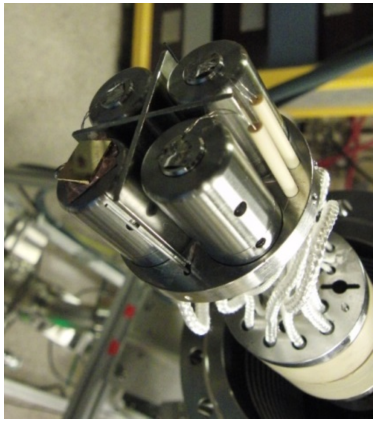
- Time-delayed cross correlation of single pixel with rest of image to show average filament propagation
- Apparent poloidal motion for both inner and outer leg filaments towards X-point (also in C-Mod, J. Terry, JNME 2016)
  - Or equivalently opposite toroidal directions
  - Inconsistent with flux tube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

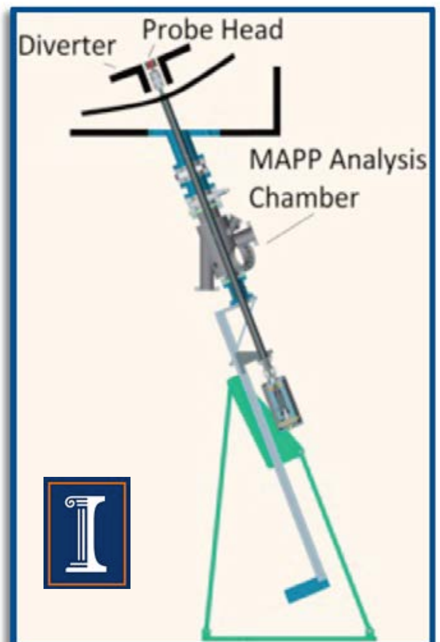


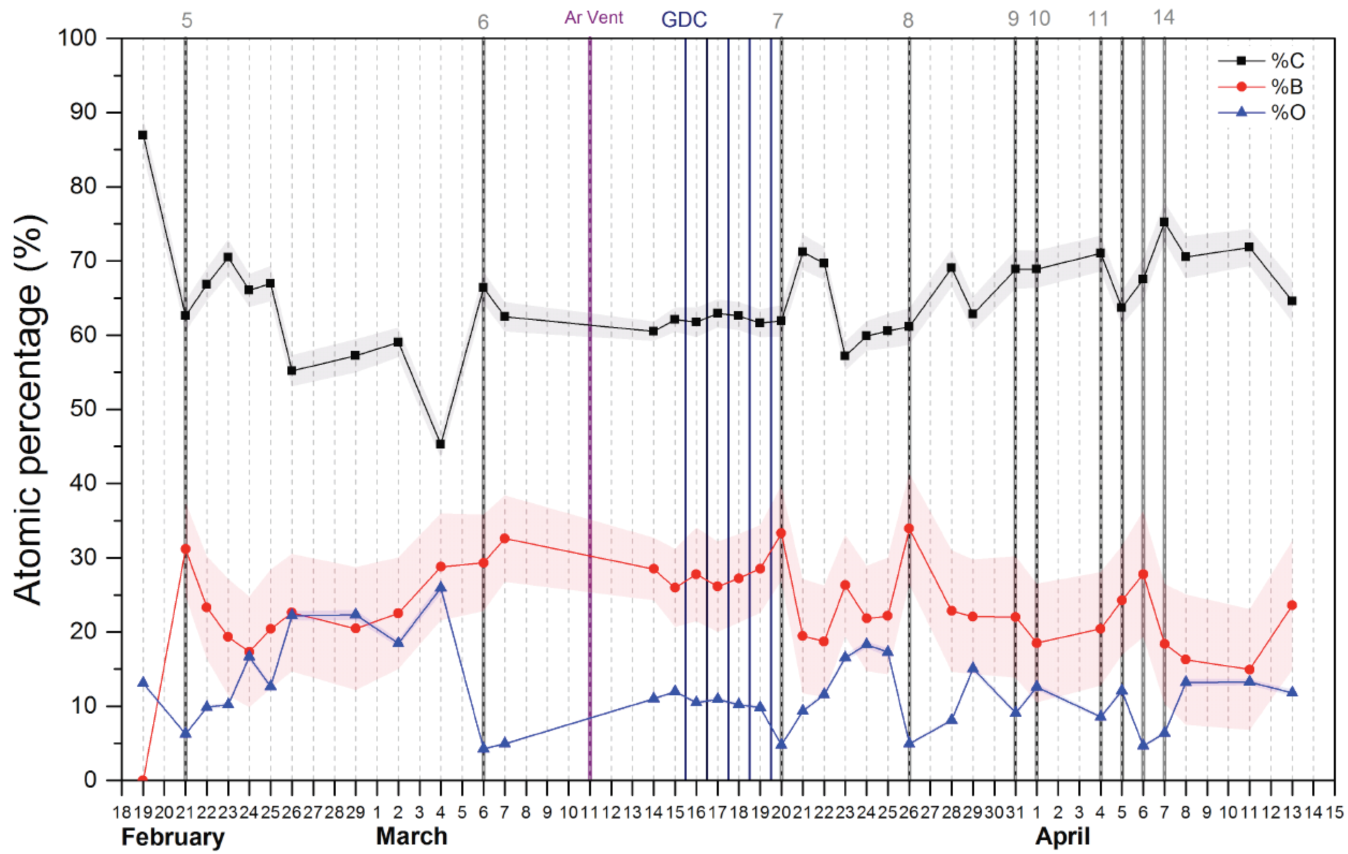




Material Analysis & Particle Probe (MAPP) providing new measurements of surface evolution in NSTX-U







- Tracked C/B/O evolution, correlated with plasma performance
- Implemented remote-control + between-shot MAPP analysis
- Future: Use with Li, understand complex Li chemistry/evolution

NSTX-U Mission Elements:

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

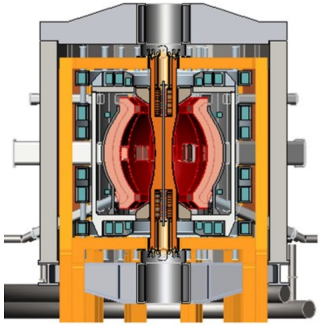
ITER

- Develop solutions for plasma-material interface (PMI)

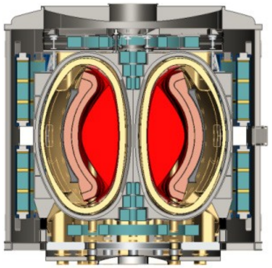
Liquid metals / Lithium

Snowflake/X

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant



ST-FNSF / Pilot-Plant



Recent design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) and Pilot Plant

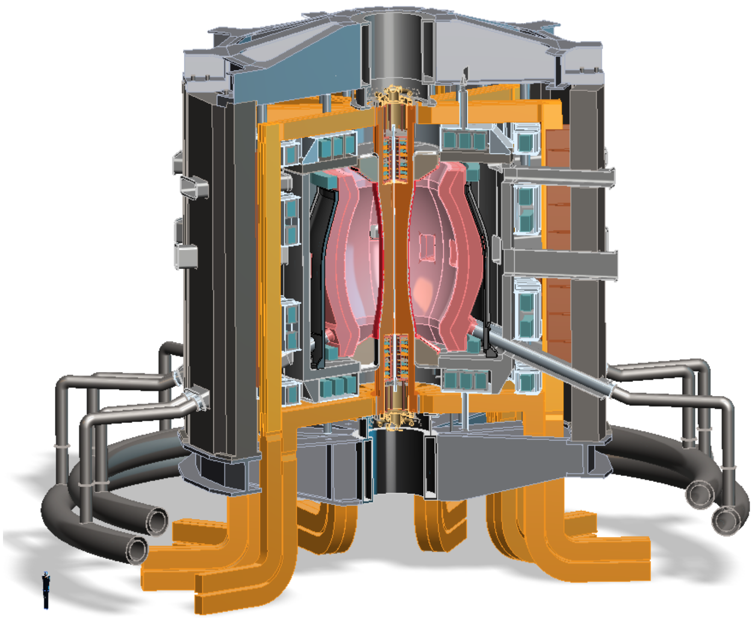
FNSF: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

Pilot Plant: Electrical self-sufficiency: $Q_{eng} = P_{elec} / P_{consumed} \geq 1$ (+ FNSF mission?)

FNSF with copper TF coils

A=1.7, R_0 = 1.7m, κ_x = 2.7, B_T=3T

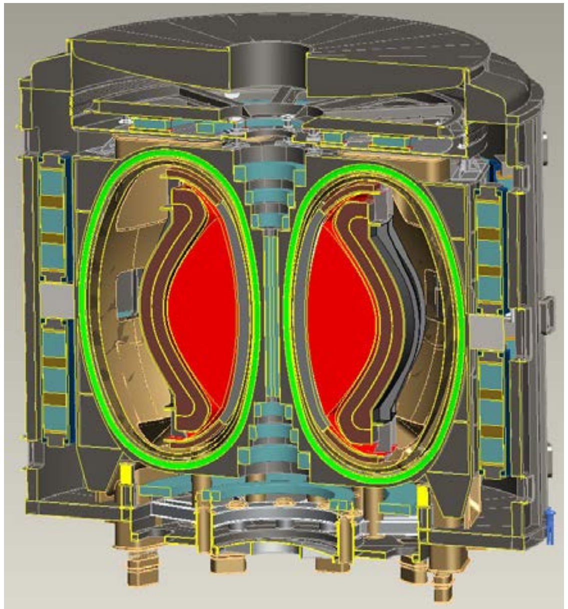
Fluence = 6MWy/m^2, TBR ~ 1



FNSF / Pilot Plant with HTS TF coils

A=2, R_0 = 3m, κ_x = 2.5, B_T = 4T

6MWy/m^2, TBR ~ 1, Q_{eng} ~ 1



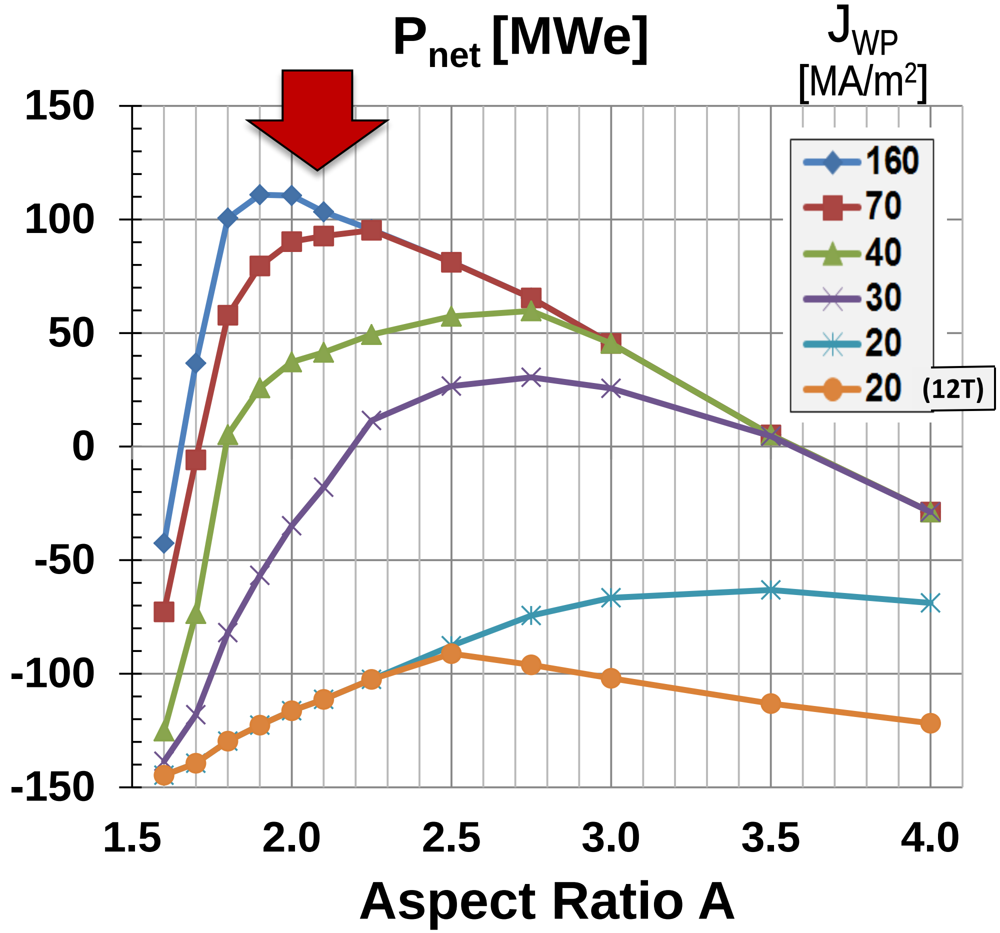
Designs integrate ST higher κ , β_N and advanced divertors (+ HTS TF for Pilot Plant)

J.E. Menard, et al., Nucl. Fusion 56 (2016) 106023

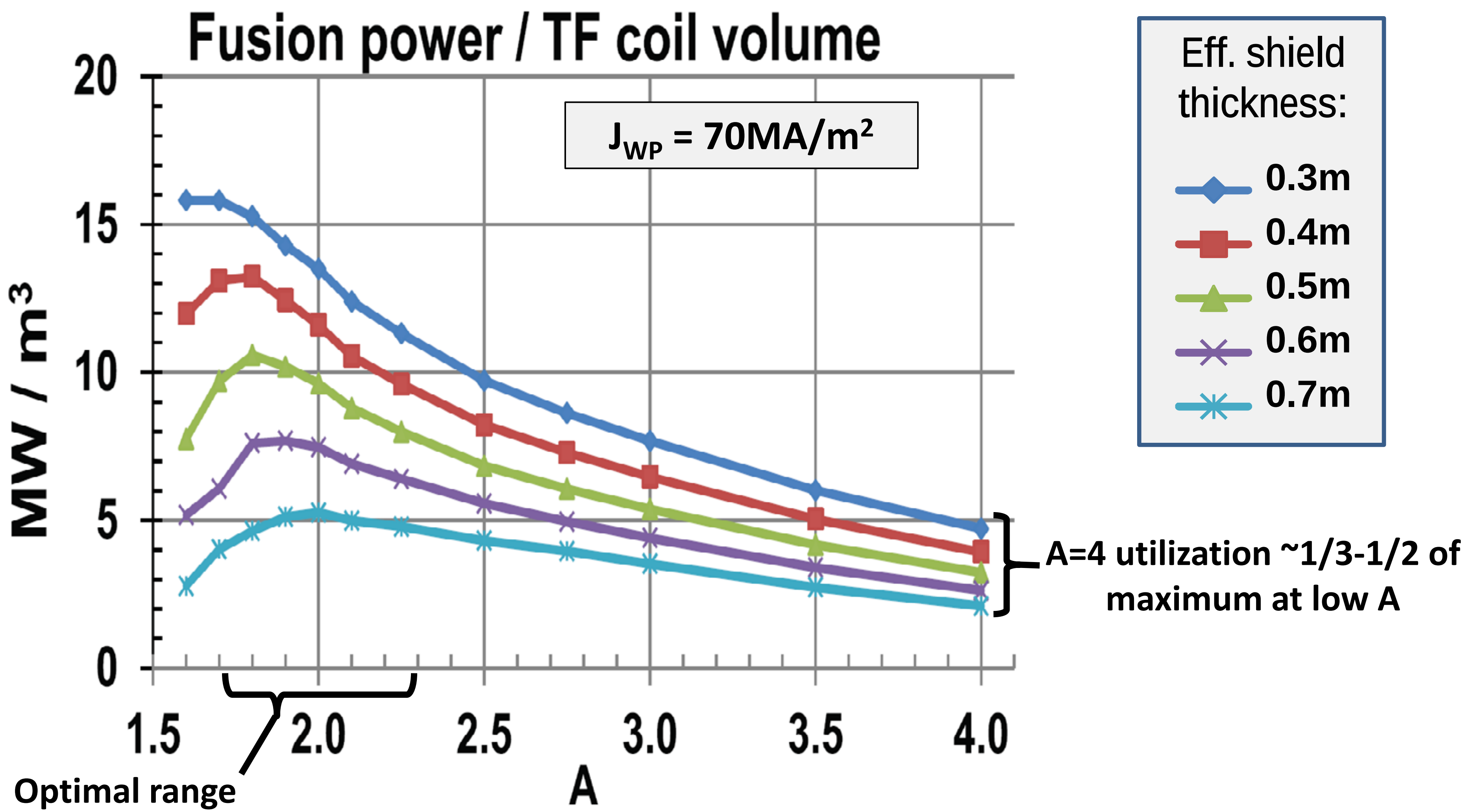
High current density HTS cable motivates consideration of lower-A tokamak pilot plants

- ITER-like TF constraints:
  - J_{WP}=20MA/m^2, B_{max} ≤ 12T
  - P_{fusion} ≤ 130MW, P_{net} < -90MW
- J_{WP} ~ 30MA/m^2, B_{max} ≤ 19T
  - P_{fusion} ~ 400MW
  - Small P_{net} at A=2.2-3.5
- J_{WP} ≥ 70MA/m^2,B_{max} ≤ 19T
  - P_{fusion} ~500-600MW
  - **P_{net} = 80-100MW at A=1.9-2.3**

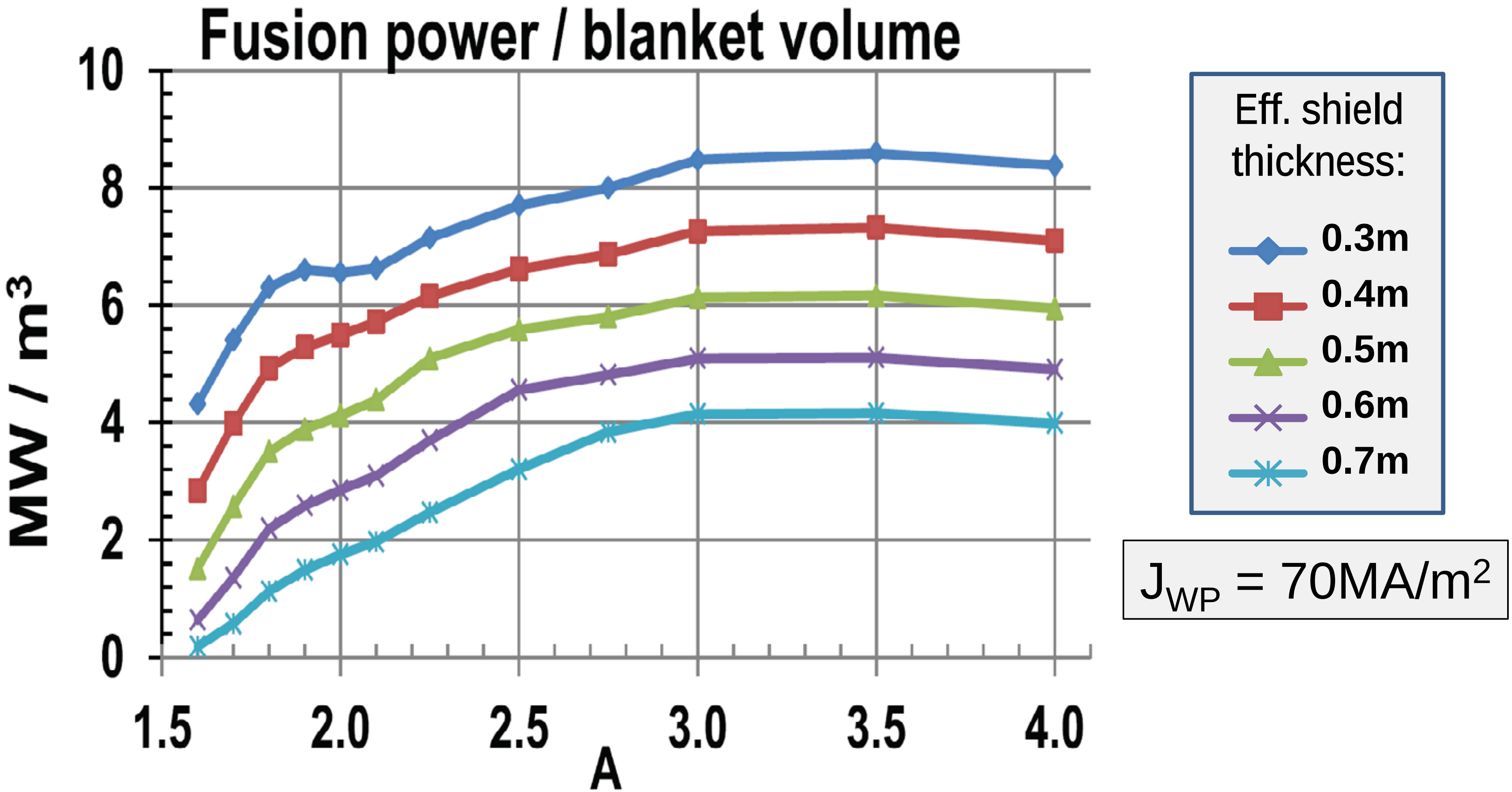
A ~ 2 attractive at high J_{WP}



A = 1.8-2.3 maximizes TF magnet utilization, and TF will be significant fraction of core cost



A ≥ 3 maximizes blanket volume utilization



Is blanket volume vs. TF volume a good relative cost metric for liquid metal blankets?

Outline

- NSTX-U mission
- Research highlights
- Progress on next-step ST concepts
- Goals for next run
- Summary

Goals for next NSTX-U run campaign

Only a subset, and will decide as a team via next Research Forum

- Increase field to 0.8-1T, current to 1.6-2MA
- Develop early H-mode / low-l_i / high-κ scenarios
- Assess H-mode energy confinement, pedestal, and SOL characteristics with higher B_T, I_P, P_{NBI}
- Complete assessment of effects of NBI parameters on fast ion distribution, neutral beam driven current profile
  - Expand upon new physics already observed w/ tangential NBI
  - Increase NBI current drive, non-inductive fraction
- Key physics, operational tools for high-performance
  - Developed shape & vertical control, new inboard gap control, EFC, HFS & LFS fueling under PCS, automated shutdown
  - Need to commission: n=1 dynamic EFC, RWM control
  - Test Impurity Granule Injector (IGI), MGI, Li evaporation

Expanding collaborations for outage period
Building upon and informing NSTX-U research

- DIII-D: National Campaign – 2-3 weeks in multitude of research areas
- EAST: Edge physics, plasma material interactions (high-Z, Li)
  - Maingi + collaborators leading experiments this month / early next year
- JET: Energetic particle studies and plasma ramp-down scenario development and modelling
  - Podesta, Darrow, Poli
- KSTAR: Core MHD and rotation physics, plasma control
  - Sabbagh (Columbia) + group, J-K Park, J-W Ahn (ORNL)
- MAST-U: Control, scenario modelling supporting 1st plasma
  - Battaglia (+Boyer) tentatively planning visits/stays summer/fall 2017
- W7-X: 3D confinement and stability
  - Lunsford - alternate wall conditioning using boron powder dropper
- WEST: start-up, RF physics, high-Z PMI, real-time wall protection
  - Mueller going in spring, Reinke (ORNL) in fall, possibly PPPL RF physicists
- LAPD at UCLA - RF coupling and heating physics, cavity modes
  - R. Perkins leading RF development efforts
- HL2A in China offering significant run-time
  - Y. Ren will present capabilities/opportunities on 12/12

NSTX-U Program wants and needs MIT collaborator input on the upcoming 5 year plan

- May have only 10 run weeks (mostly commissioning) for FY14-18 5YP
- FY19-23 plan due spring 2018, peer-reviewed summer 2018
- Begin brainstorming early 2017, then writing in summer / fall
- Need to generate research goals, prioritize facility enhancements

Mission Elements and Present 5 Year Plan 5 Highest Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Study energetic particle physics prototypical of ITER/FNSF burning plasmas
  2. Understand energy confinement and MHD stability at high normalized pressure
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / DEMO
  5. Form and sustain plasma current without transformer for steady-state ST

Are these still the best missions and priorities for the next 5 year plan?

NSTX-U strongly supporting advancing predictive capability, ITER, PMI solutions, and next-step STs

- Productive first year of operations on NSTX-U
  - Rapid H-mode access, scenario development, error field correction
  - Surpassed NSTX maximum magnetic field and pulse-duration
  - New fast-ion physics with 2nd NBI – GAE stabilization, counter TAE
  - Commissioned new advanced PMI diagnostics – MAPP
- Developing advanced predictive capability
  - New models for tearing stability, reduced models for RWM
  - Global ion-scale turbulence (GTS), ∇n ETG stabilization
  - GAE stabilization from 2nd NBI consistent with simulation
  - Exploring SOL widths, advanced divertor interactions with 3D fields
- Developed attractive Cu, HTS ST-FNSF, Pilot concepts
- In 2017 will emphasize collaborations, 5YP prep
- Aim to resume NSTX-U physics operation in CY2018