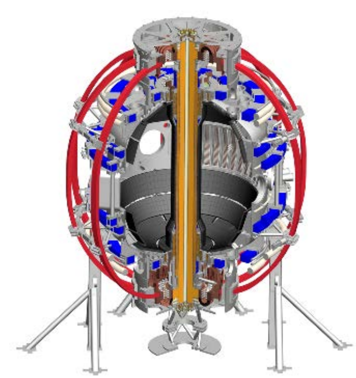
Progress and Plans on NSTX-U

Jonathan Menard (PPPL)
On behalf of the NSTX-U Research Team

Fusion Power Associates
37th Annual Meeting and Symposium
FUSION POWER DEVELOPMENT: AN INTERNATIONAL VENTURE

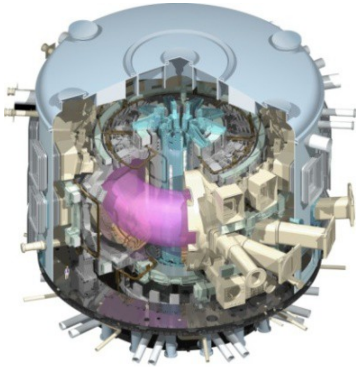


Outline

- NSTX-U mission
- Research highlights
- Goals for next run
- Summary

NSTX-U Mission Elements:

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



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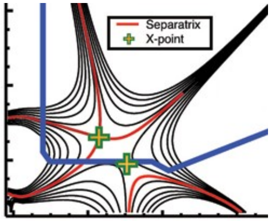
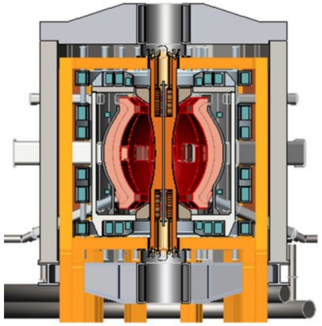
- Develop solutions for plasma-material interface (PMI)



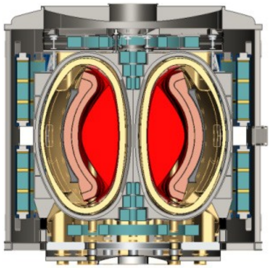
Snowflake/X

Liquid metals / Li

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant

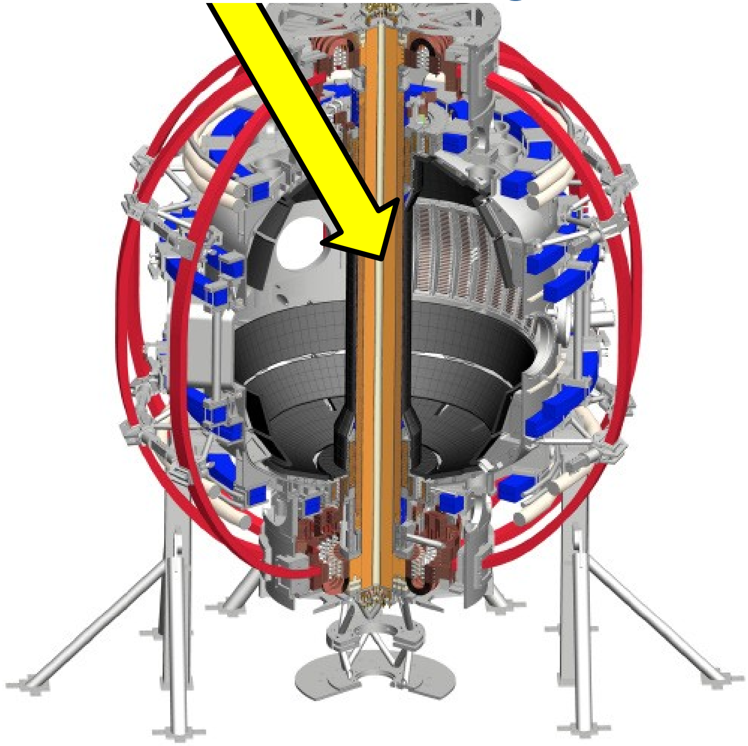


ST-FNSF / Pilot-Plant



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

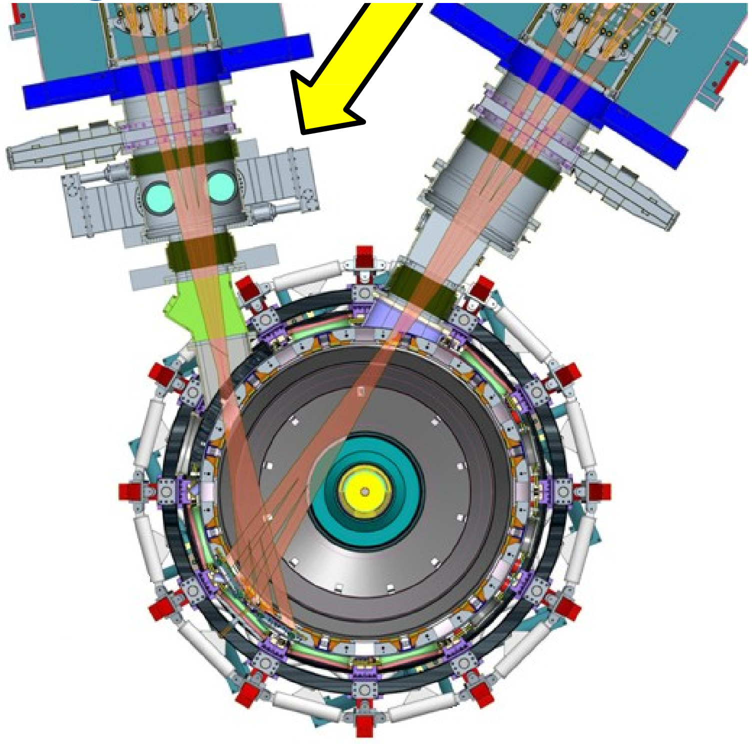
1. New Central Magnet



Higher T, low ν^* from low to high β

→ Unique regime, study new transport and stability physics

2. Tangential 2nd Neutral Beam



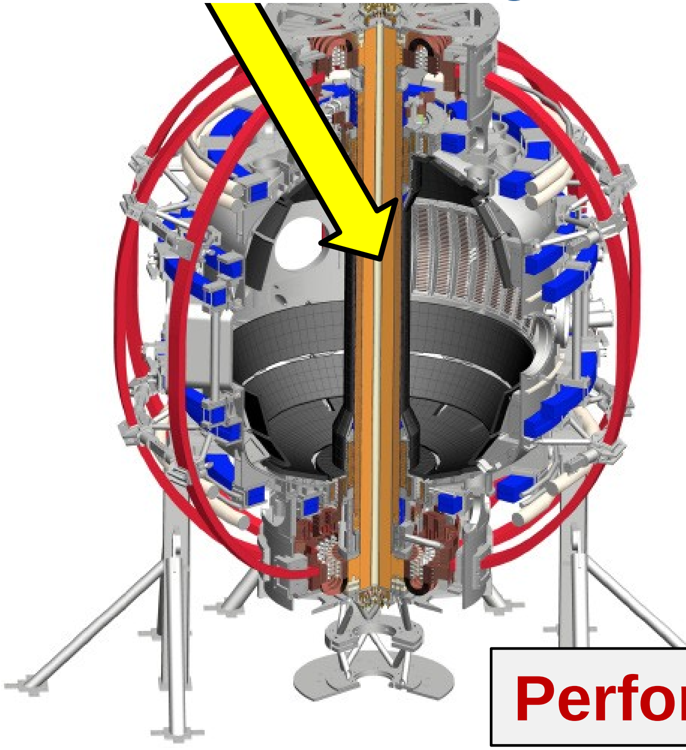
Full non-inductive current drive

→ 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



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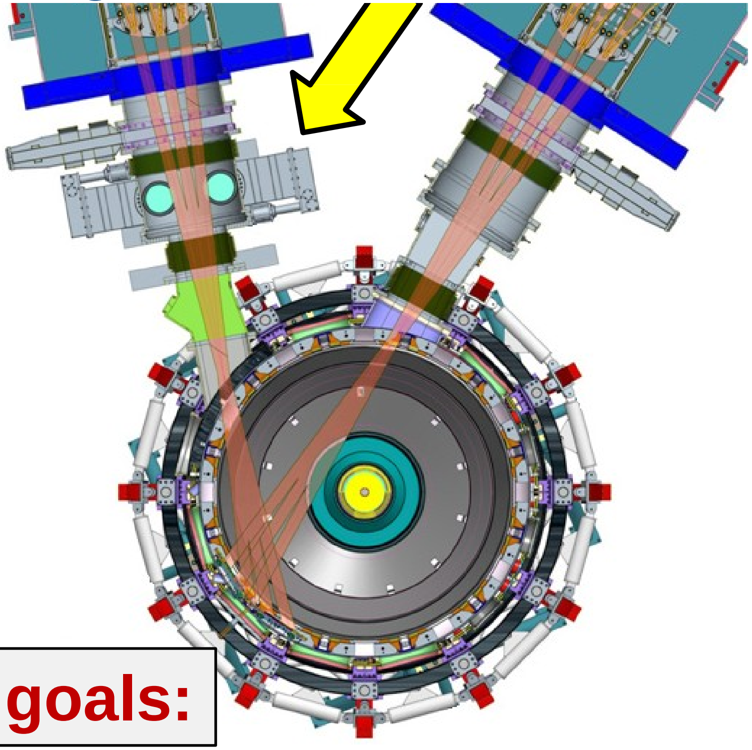


Performance goals:

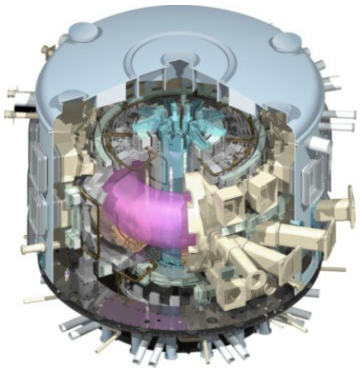
- 2× toroidal field (0.5 → 1T)
- 2× plasma current (1 → 2MA)
- 5× longer pulse (1 → 5s)
- 2× heating power (5 → 10MW)
  - Tangential NBI → 2× current drive efficiency
- 4× divertor heat flux (→ ITER levels)
- Up to 10× higher $nT\tau_E$ (~MJ plasmas)

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



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Topical science areas:

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

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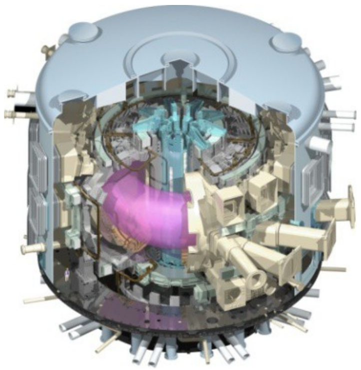

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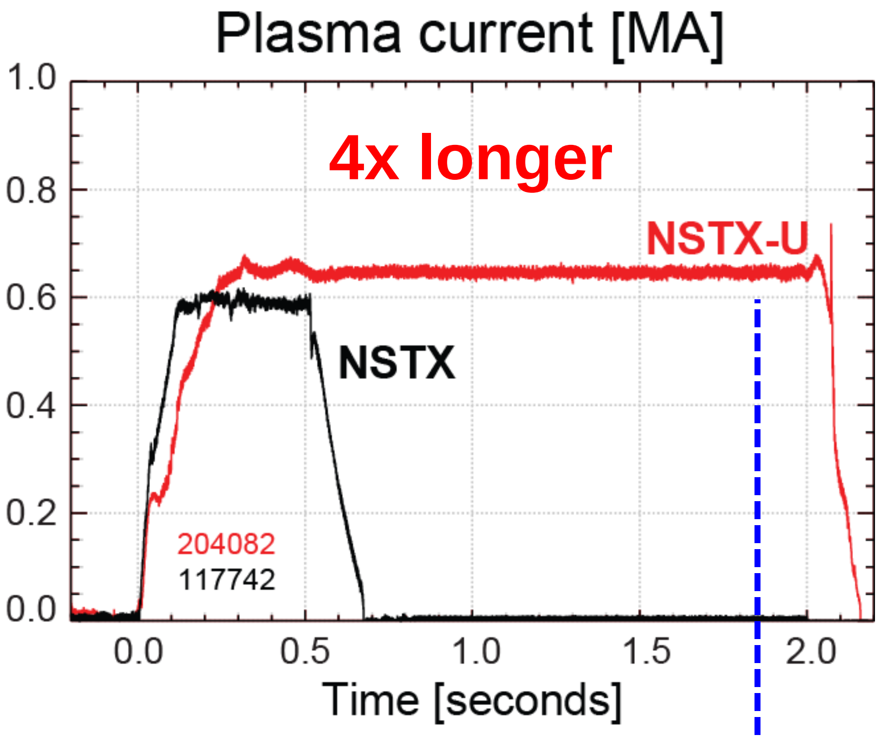
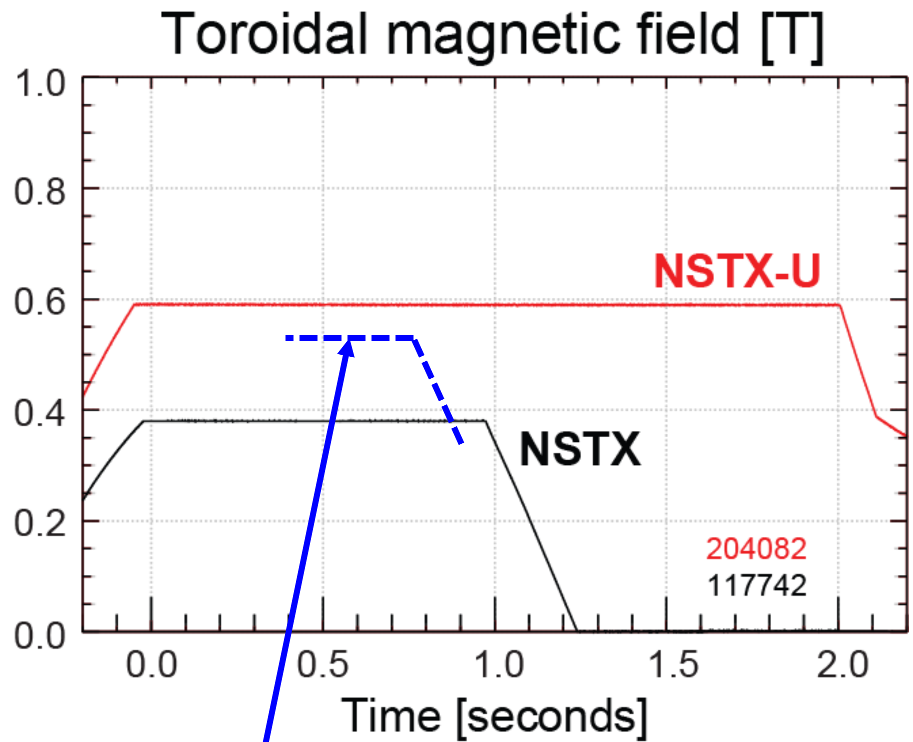
NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

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



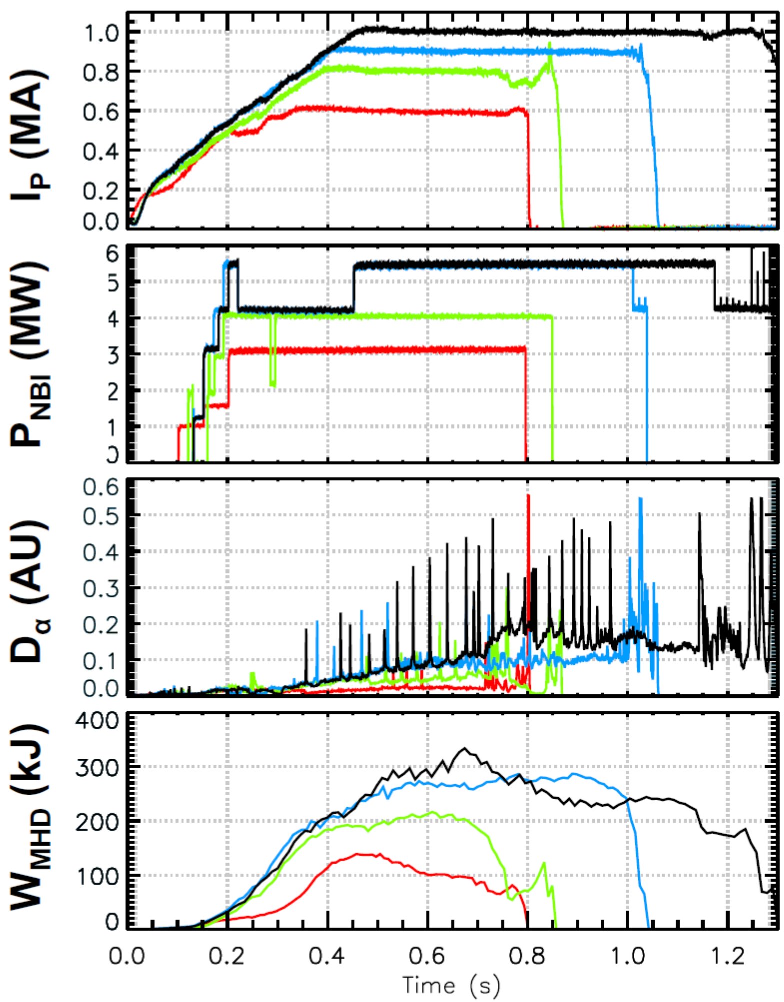


NSTX-U L-mode duration exceeds longest NSTX H-mode

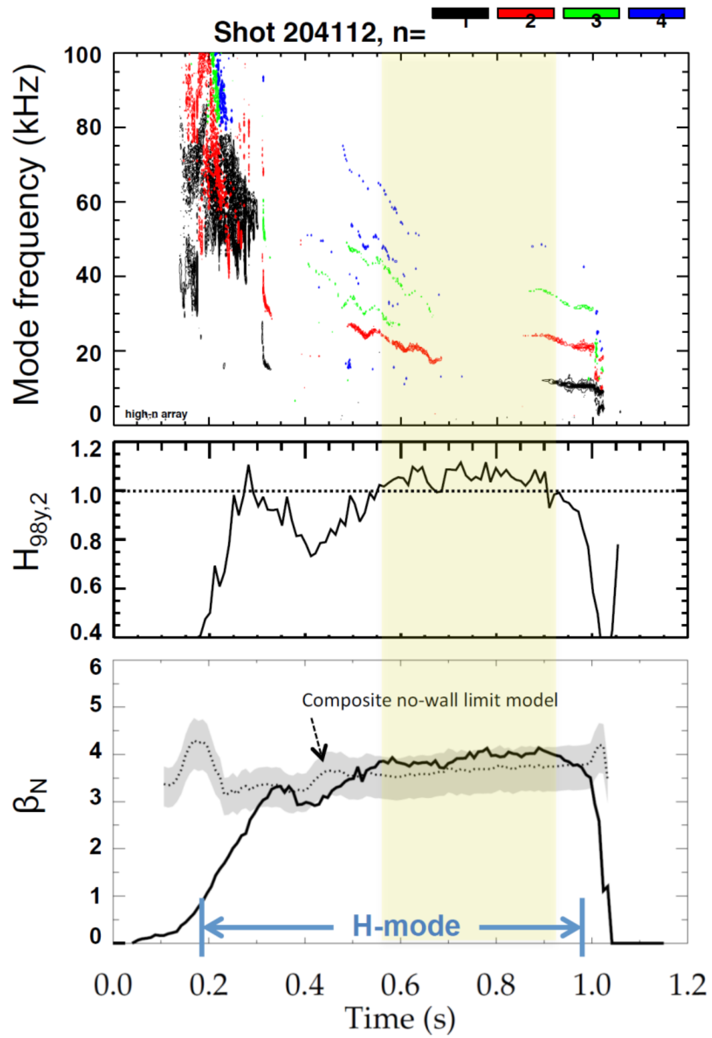
NSTX-U B_T > highest NSTX B_T

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

202946 – no EFC 204112 – EFC v2
203679 – EFC v1 204118 – EFC v2



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



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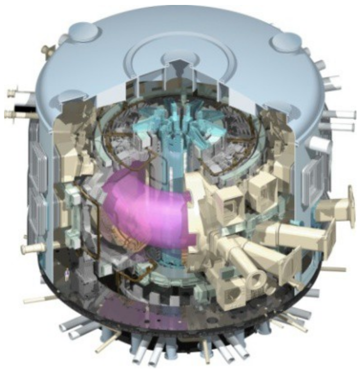
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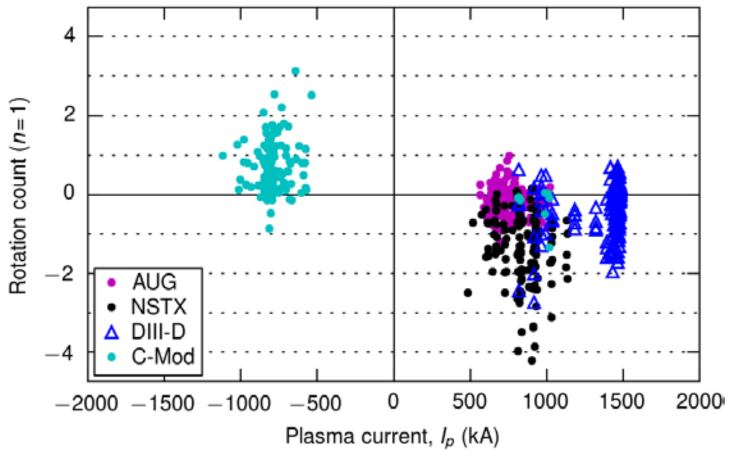
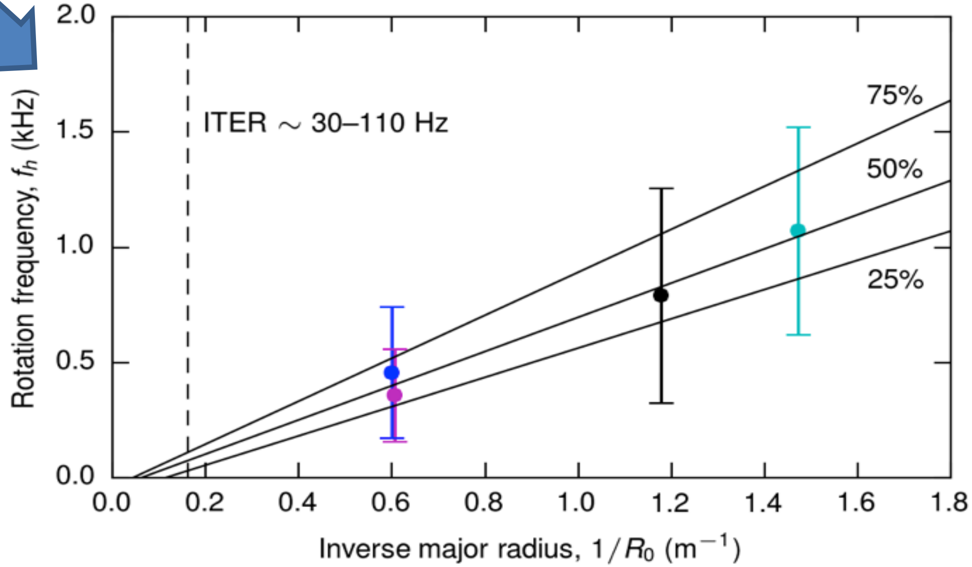
Leading studies of rotating halo currents through ITPA multi-machine analysis and M3D-C1 numerical simulations

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

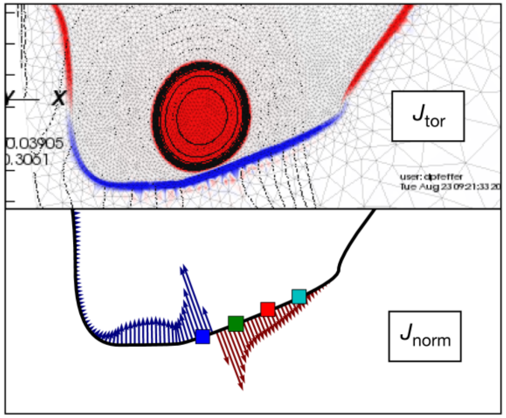
- Halo current data from C-Mod, DIII-D, AUG, NSTX
- All measurements in lower divertor (> 400 shots)
- Halo current rotation is predominantly counter-I_p
- Consistent rotation velocity, v_h ~ 5 km/sec

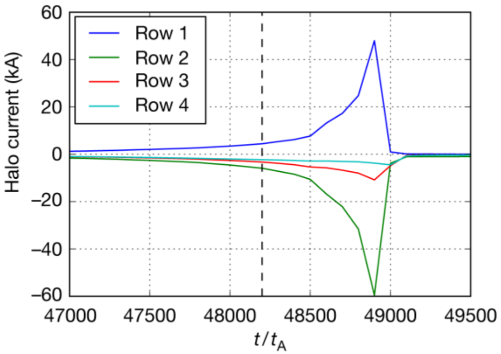




M3D-C1 simulations:

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



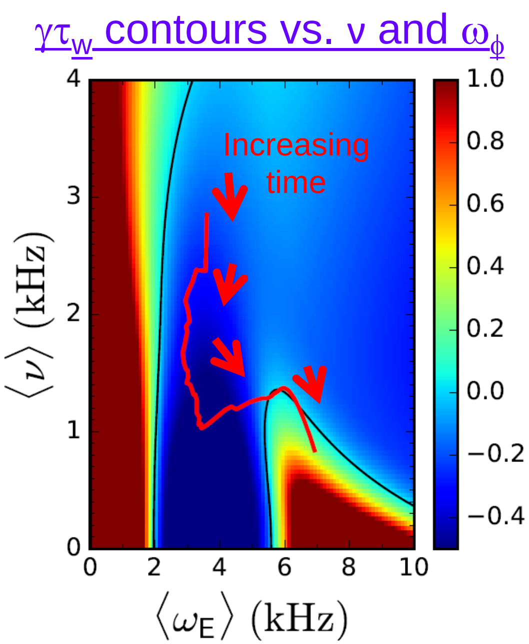


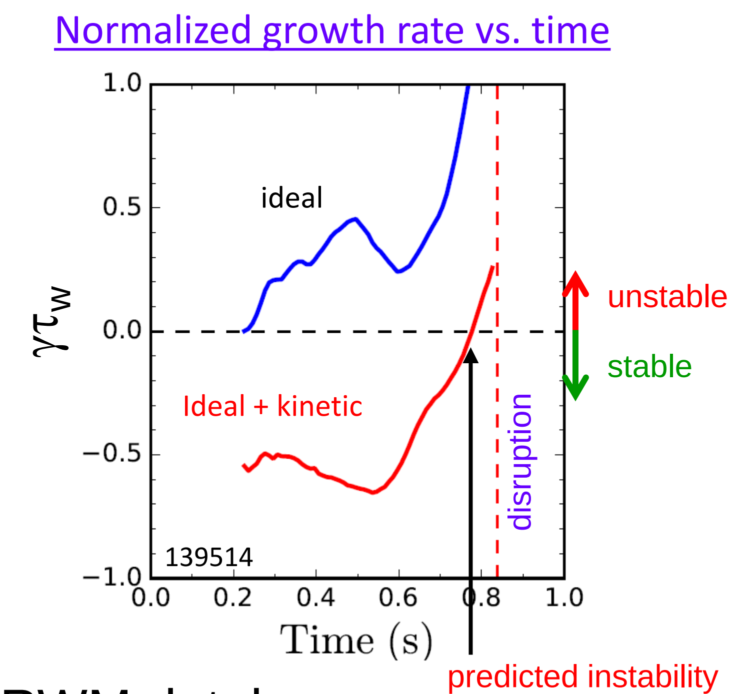
Disruption characterization and forecasting capability started for NSTX-U as part of disruption avoidance plan

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





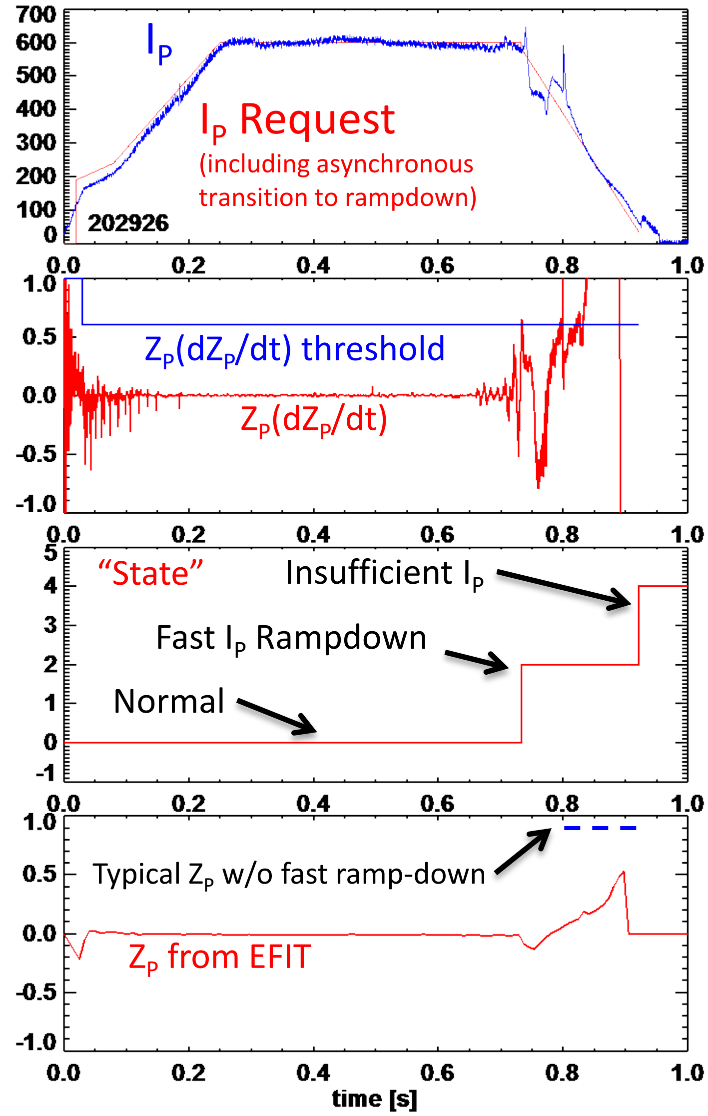
- Initial tests on NSTX RWM database
  - 86% of RWM shots are predicted unstable
- Possible to predict growth rate in real time

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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

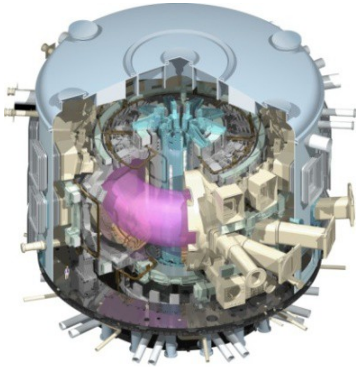
- Plasma control system detects loss of control
  - OH solenoid near maximum current
  - Vertical oscillations exceed threshold
  - ABS (I_p - $I_{p\ request}$) too large

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



NSTX-U Mission Elements:

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



ITER

Topical science areas:

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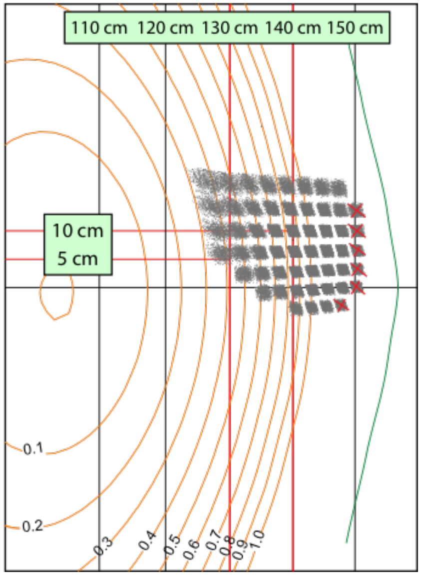
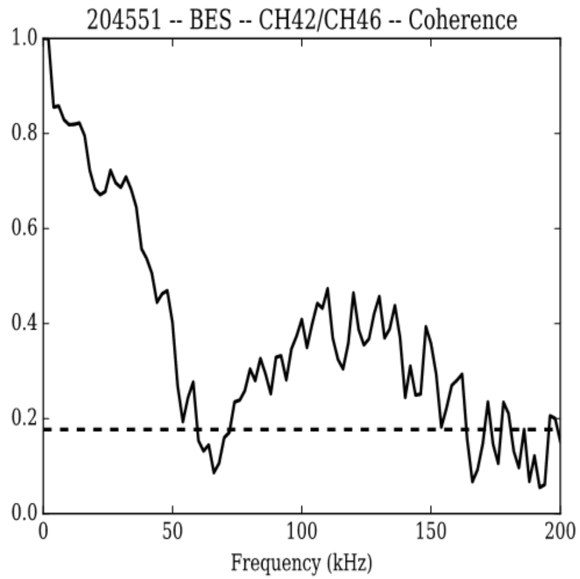
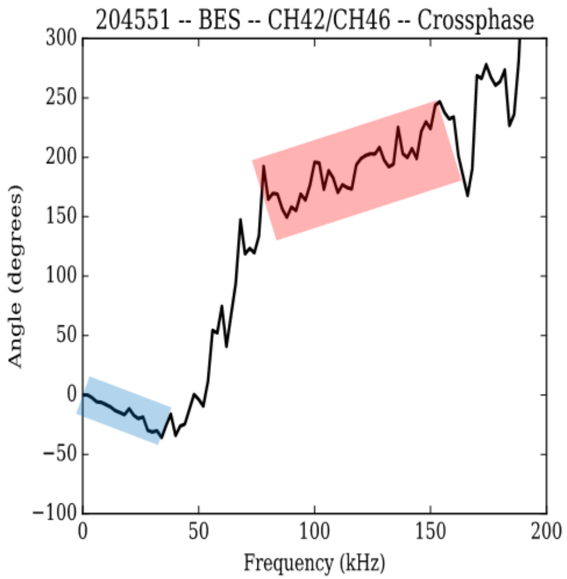
NSTX-U: Bimodal turbulence seen in some L-modes
using upgraded 48 channel Beam Emission Spectroscopy (BES) system







ΔZ = 3 cm
R = 142 cm
Δt = 24 ms

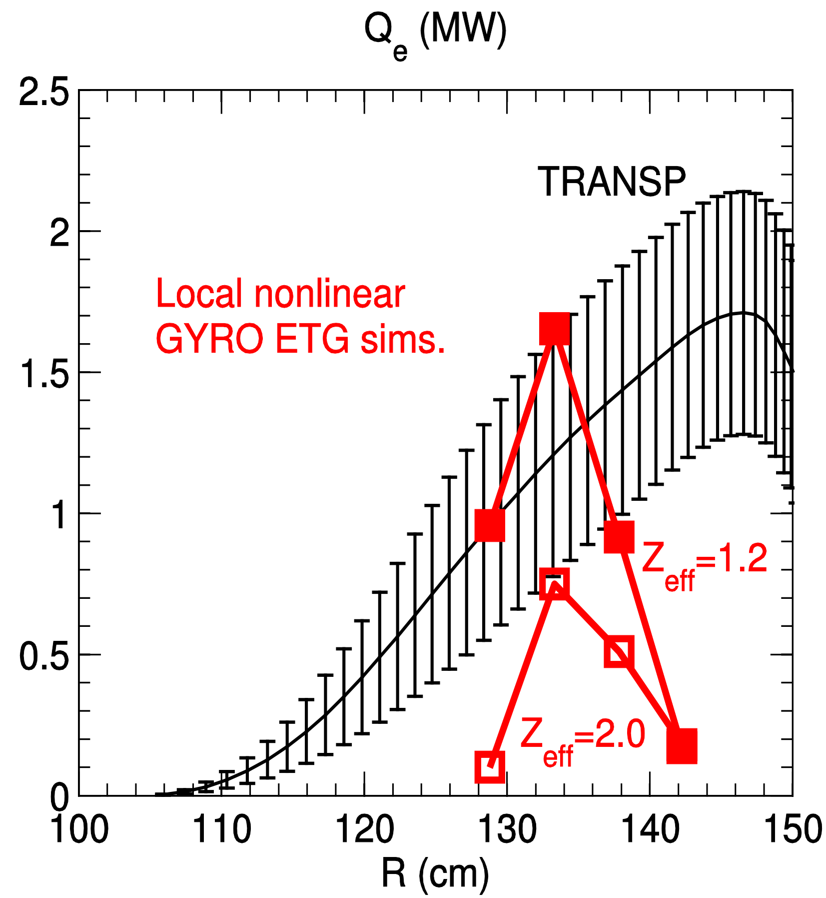
11 km/s in ion diamagnetic direction

13 km/s in electron diamagnetic direction

- Modes propagate in opposite directions
  - Similar spectra seen with DIII-D and TFTR BES
  - Gyro-kinetic modelling:
    - Ion-temperature-gradient (ITG) mode unstable – propagates in ion direction
    - Micro-tearing mode (MTM) also unstable - propagates in electron direction

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 $Z_{eff}=Z_{eff,c}\approx1.2$
  - Larger Z_{eff} (VB $Z_{eff}\leq2$) → lower $Q_{e,etg}$
- New high-k microwave scattering diagnostic (2018 run) will be ideal for probing region of ETG turbulence
- *May require multiscale simulations for validation*



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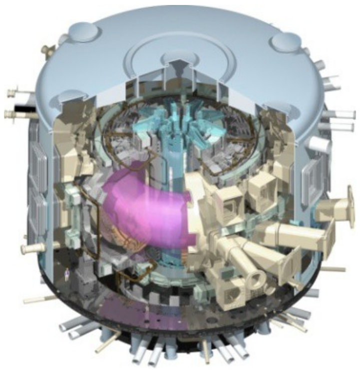
ITER

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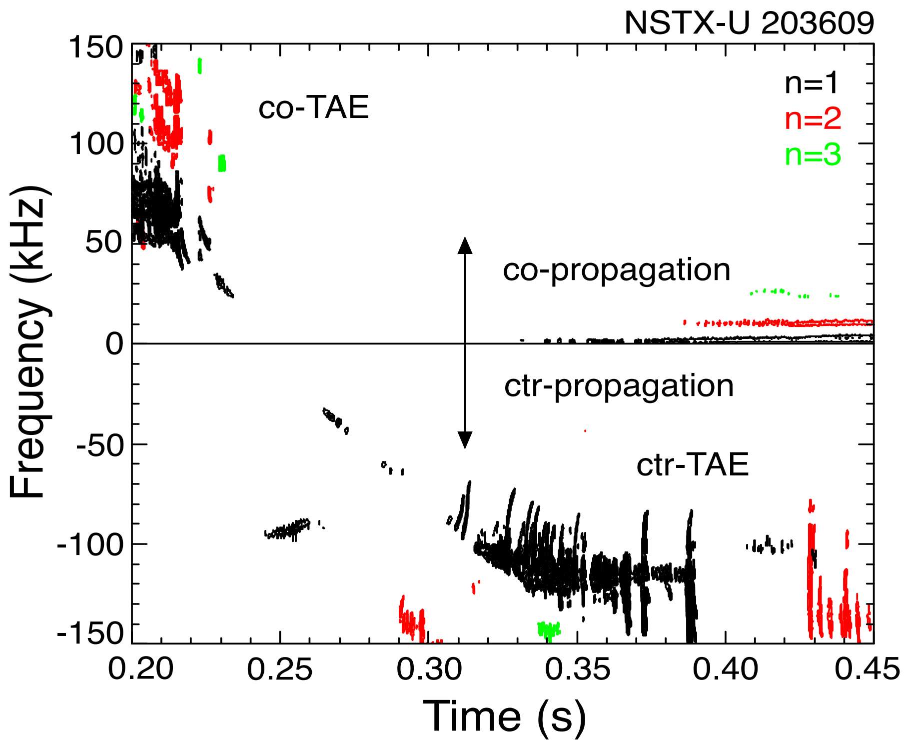
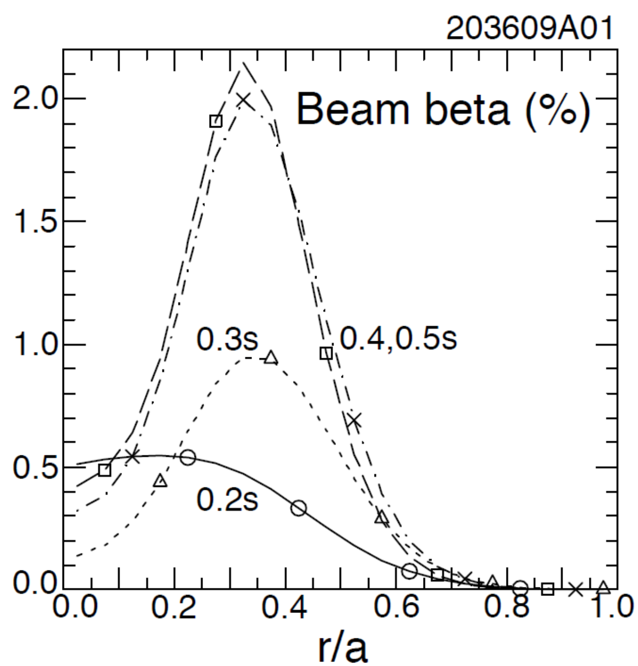
NSTX-U: Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)



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

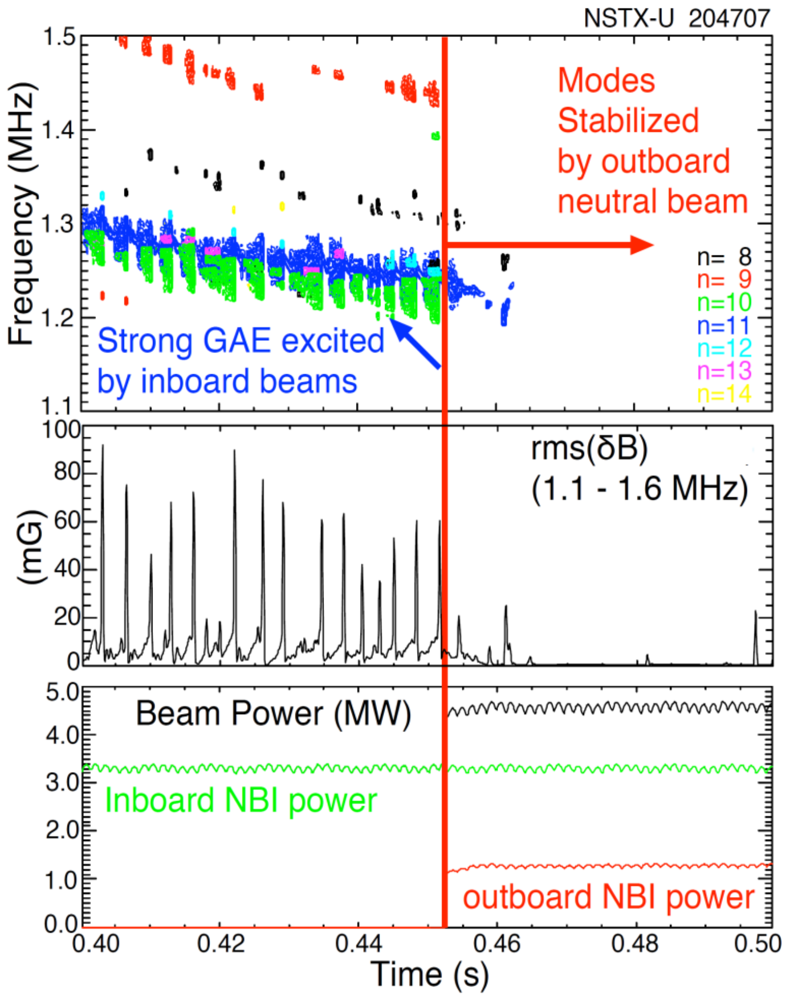
*H.V. Wong, H. Berk, Phys. Lett. A **251** (1999) 126.*

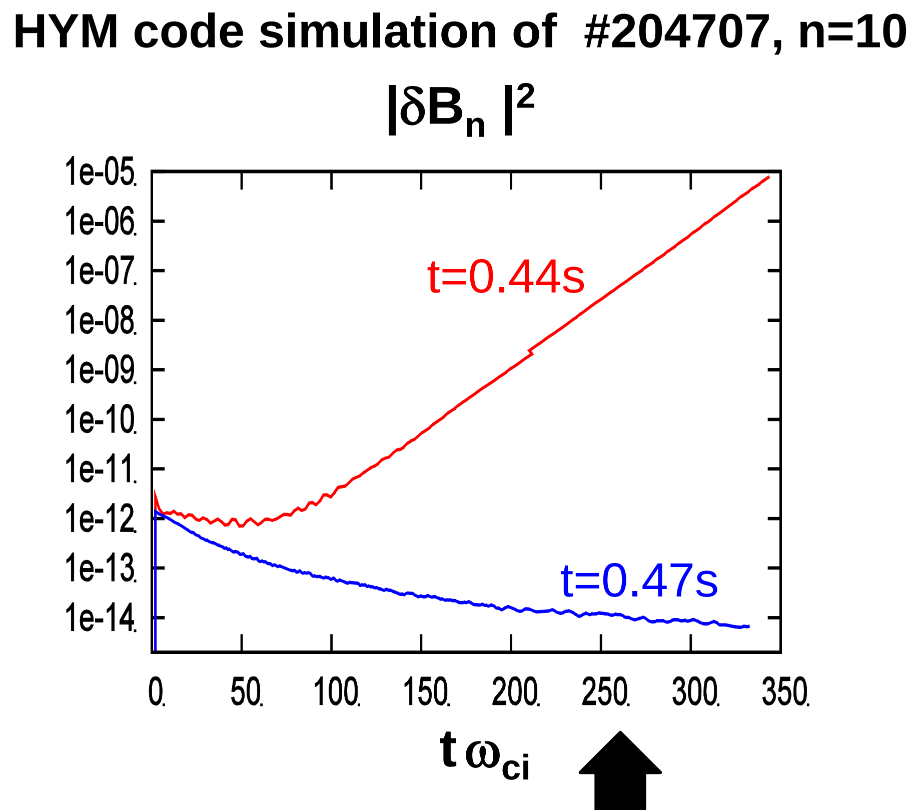
- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow



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

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





- 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

New 2nd NBI already powerful tool for fast ion, AE physics

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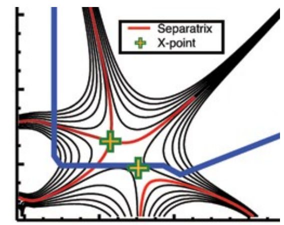
ITER

- 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

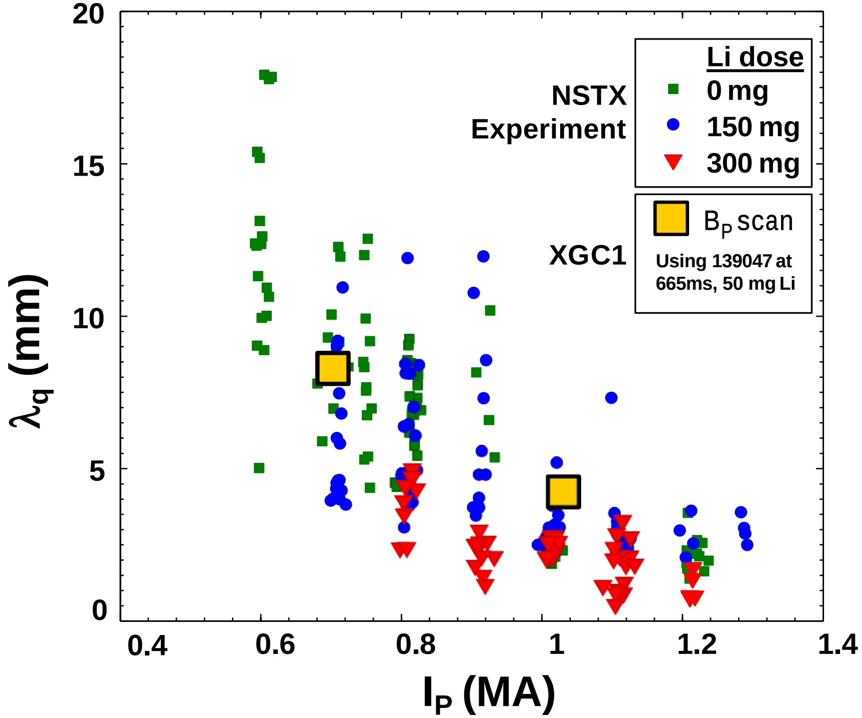
XGC-1:

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

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

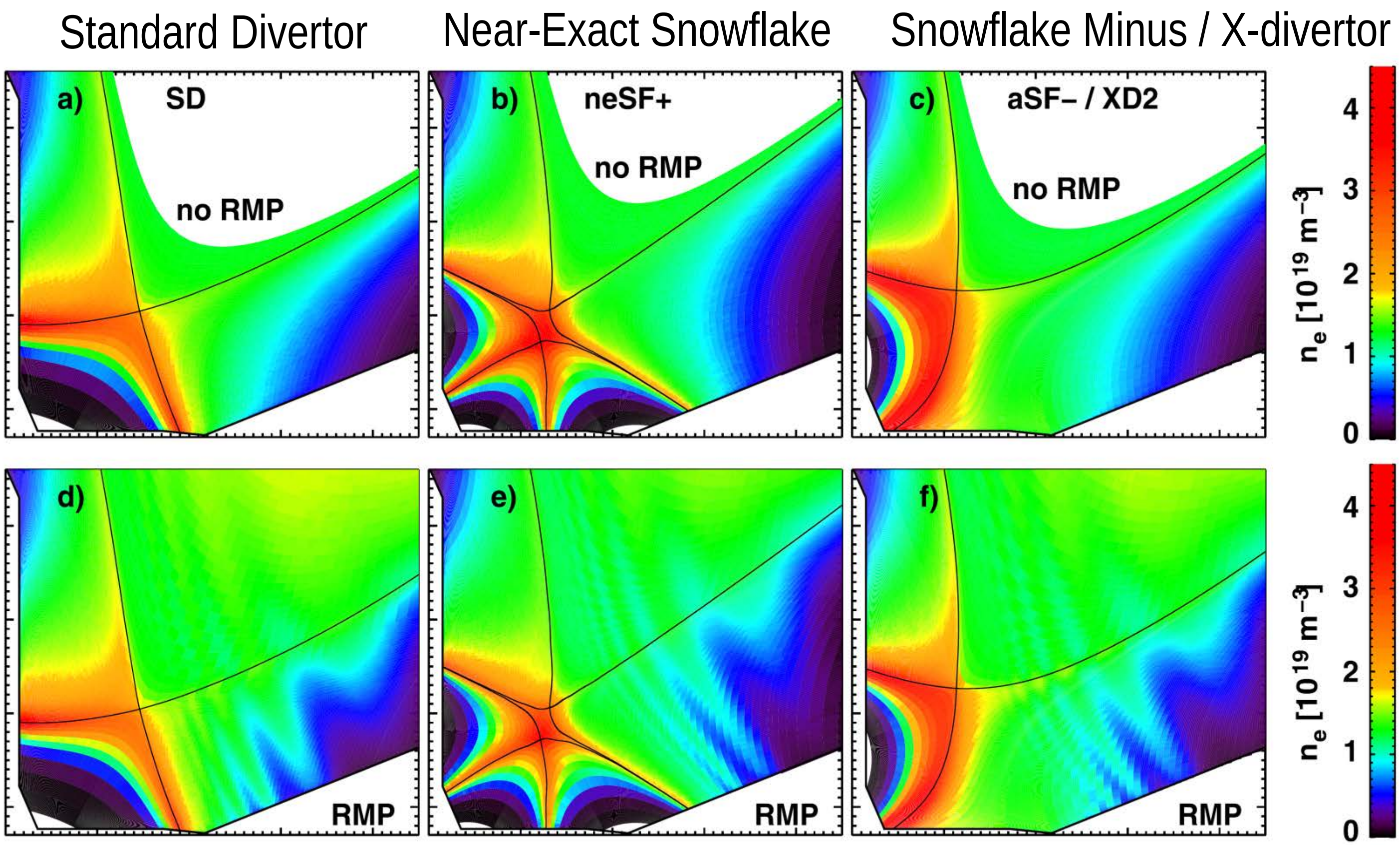
- Simulations for ITER presented at IAEA-FEC 2016 (C.-S. Chang) indicate turbulence can play significant role in setting heat-flux width
  - **Will SOL turbulence become important in NSTX-U at high current?**

XGC1 w/ collisions → similar trends



Heat flux width set primarily by neoclassical processes

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



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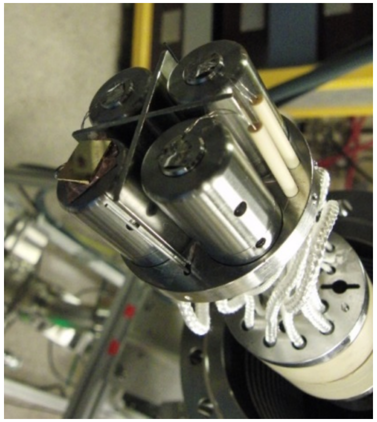
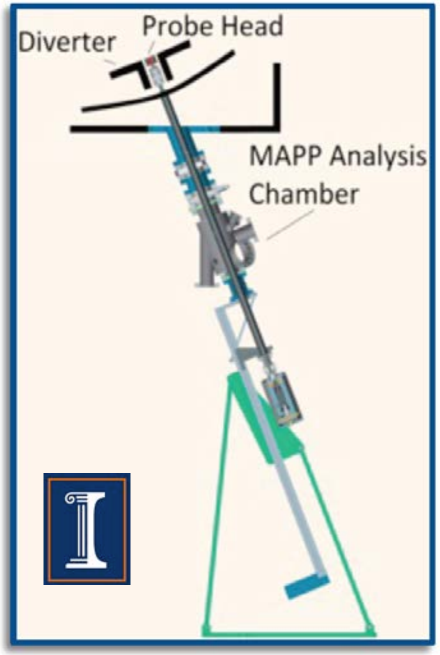
GENERAL ATOMICS

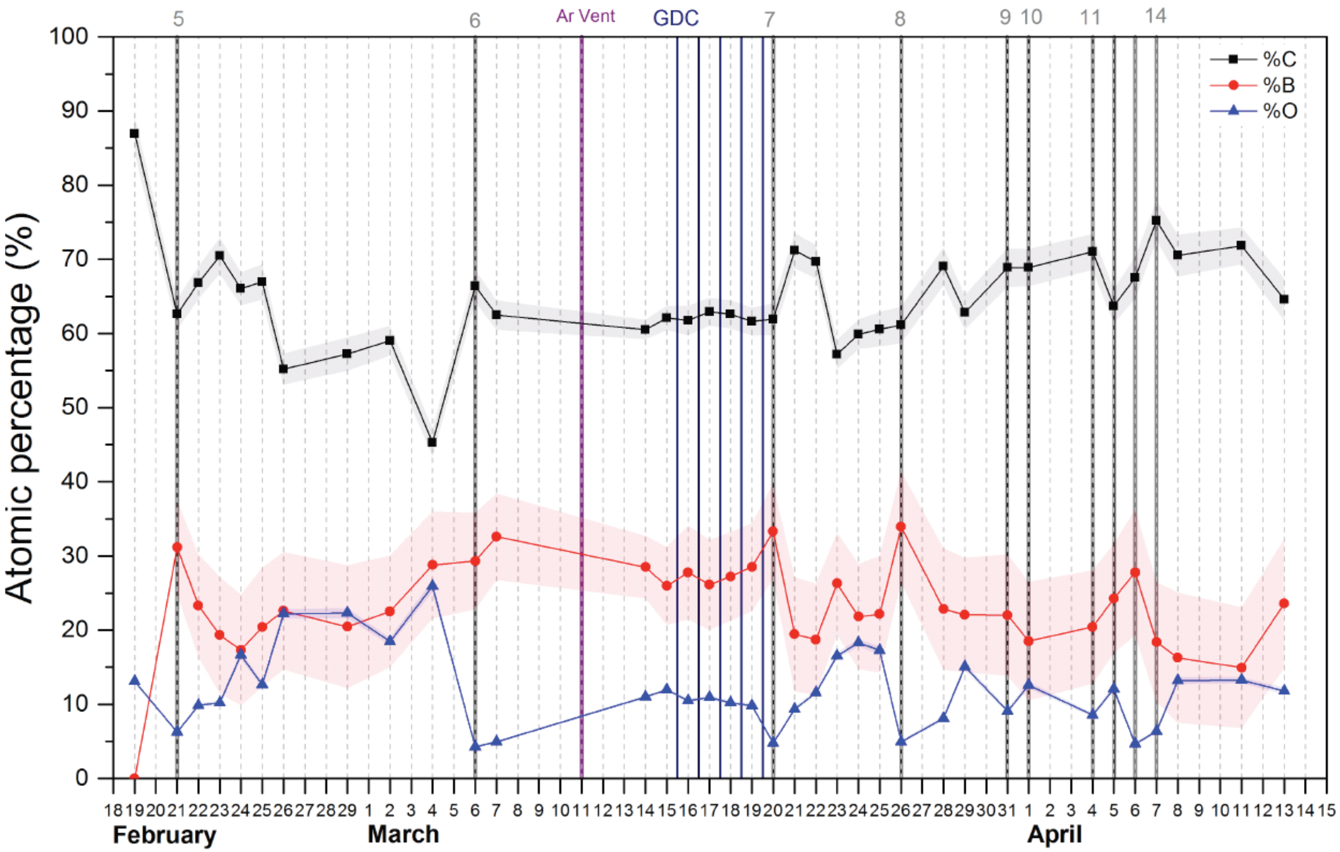
Lawrence Livermore National Laboratory

- **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

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

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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
- Further 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}
  - Informs collisionality scaling of low-A confinement and stability
- Complete assessment of effects of NBI parameters on fast ion distribution, neutral beam driven current profile
  - Informs goal of full non-inductive operation
- Key physics and operational tools for sustained high-β_N

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Liquid metals / Lithium

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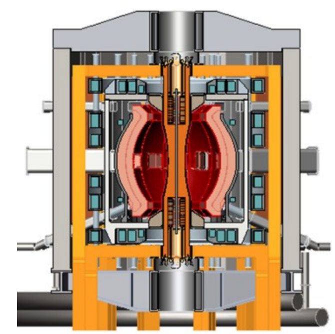
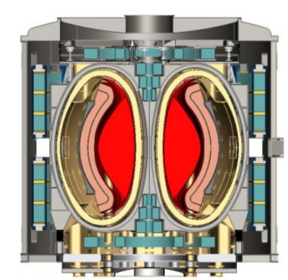


ST-FNSF / Pilot-Plant



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

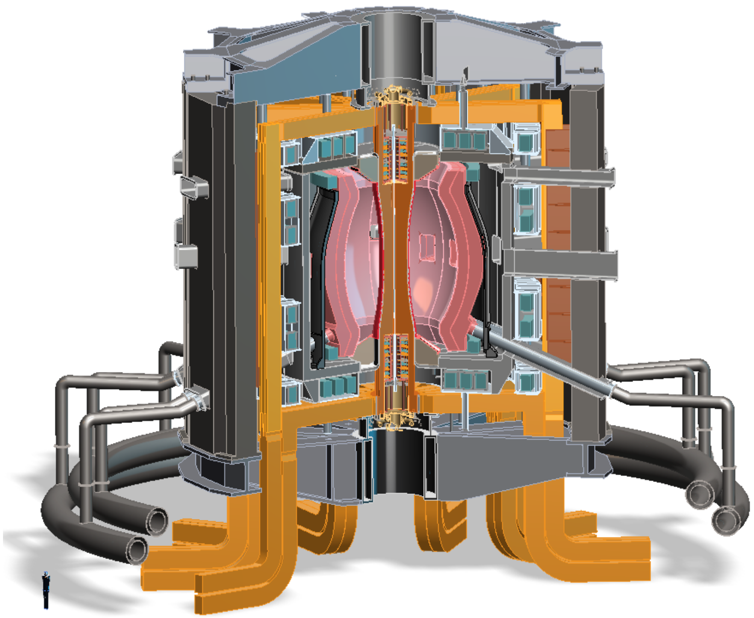
FNSF: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

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

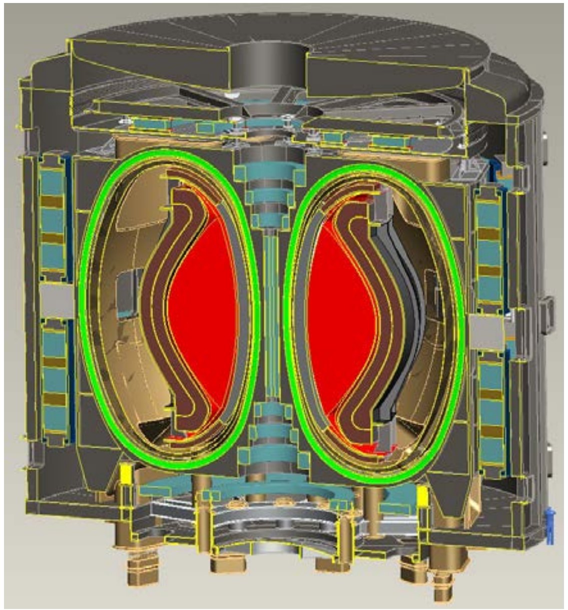
Fluence = 6MWy/m^2, TBR ~ 1



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

Summary: NSTX-U strongly supporting advancing predictive capability, ITER, PMI solutions, next-steps

- **Productive first year of operations on NSTX-U**
- **Developing advanced predictive capability**
- **Developed attractive ST FNSF, Pilot Plant concepts**
- **2017: Recovery, collaborations, write 5 year plan**
- **Aim to resume NSTX-U physics operation in CY2018**