Overview of First Results from NSTX-U and Analysis Highlights from NSTX

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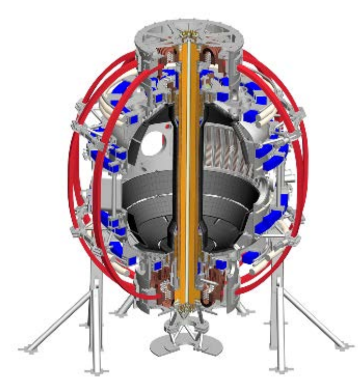
On behalf of the NSTX-U Research Team

26th IAEA Fusion Energy Conference
Kyoto, Japan
17–22 October 2016



NSTX-U Program is Highly Collaborative

Domestic (33)

College of William and Mary
Columbia University
CompX
Florida International Univ.
General Atomics
Idaho National Laboratory
Johns Hopkins University
Lawrence Livermore Nat. Lab.
Lehigh University
Lodestar Research Corporation
Los Alamos National Laboratory
Massachusetts Institute of Tech.
Nova Photonics, Inc
Oak Ridge National Laboratory
Old Dominion University
Princeton Plasma Physics Lab
Princeton University
Purdue University
Sandia National Laboratory
Tech-X Corporation
U. of California - Davis
U. of California - Irvine
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U. of California - San Diego
U. of California - Space Sci. Lab.
University of Colorado
University of Illinois
University of Maryland
University of Rochester
University of Tennessee
University of Texas
University of Washington
University of Wisconsin

350+ data users
55 institutions
22 US Universities

International (22)

ASIPP
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Hiroshima University
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IPP-Czech Republic
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JAEA
KAIST
Kyoto University
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NFRI
NIFS
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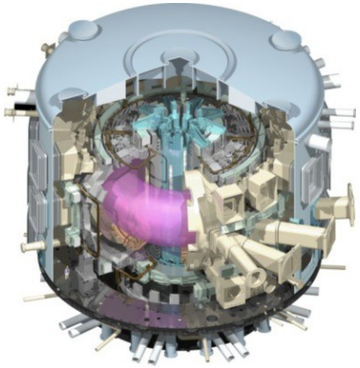
Tokamak Energy, LTD
TRINITI
UNIST
University of Costa Rica
University of Hyogo
University of Tokyo
University of York

Outline

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

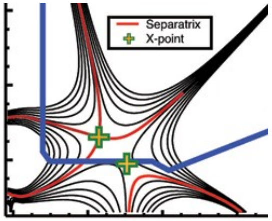
NSTX-U Mission Elements:

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



ITER

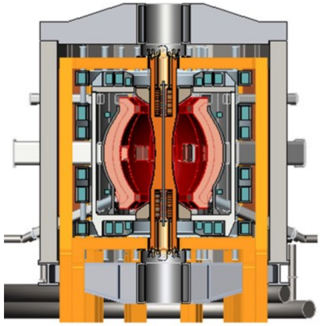
- Develop solutions for plasma-material interface (PMI)



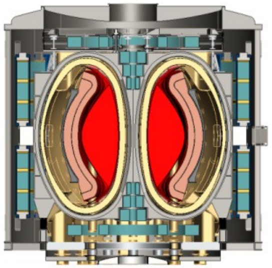
Snowflake/X

Liquid metals / Li

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant

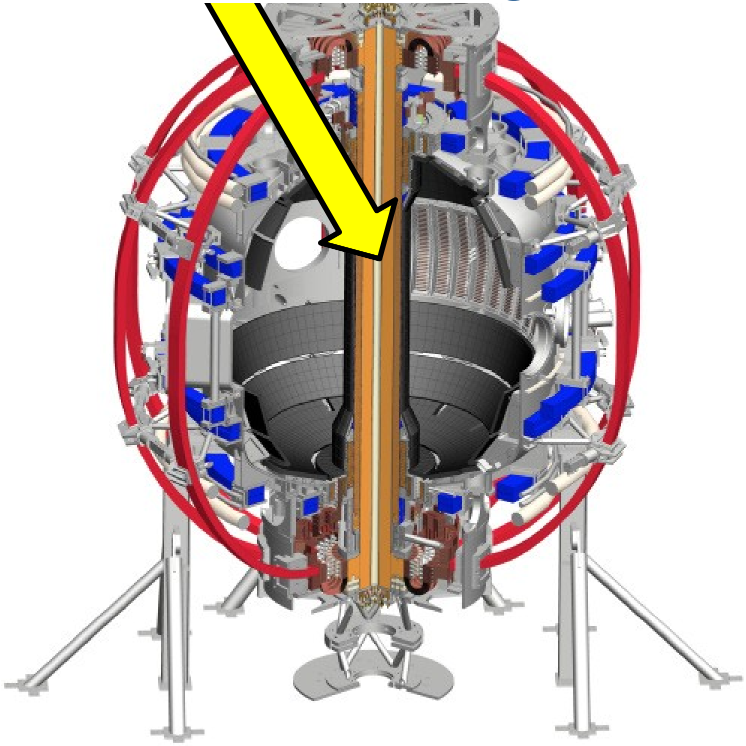


ST-FNSF / Pilot-Plant



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

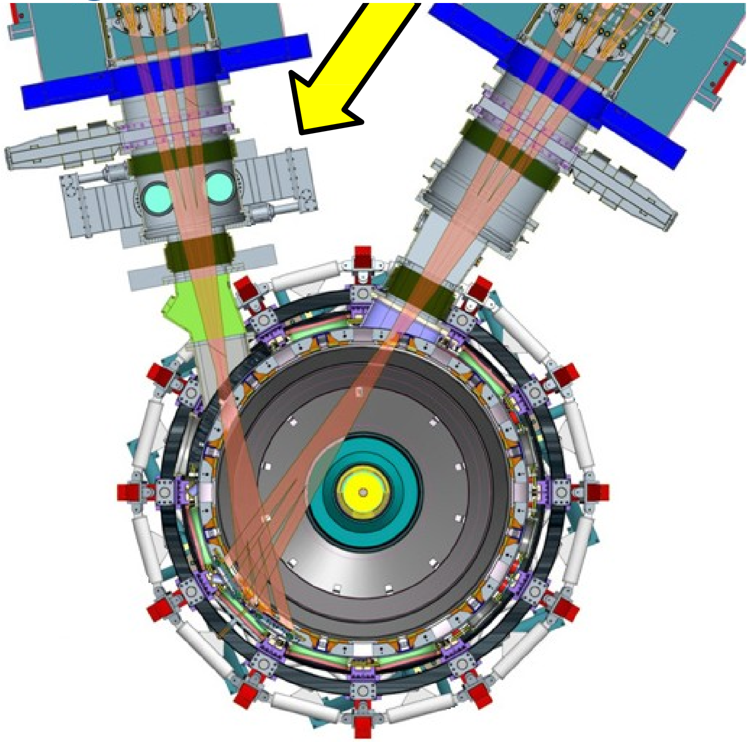
1. New Central Magnet



<u>Higher T, low ν* from low to high β</u>

→ Unique regime, study new transport and stability physics

2. Tangential 2nd Neutral Beam



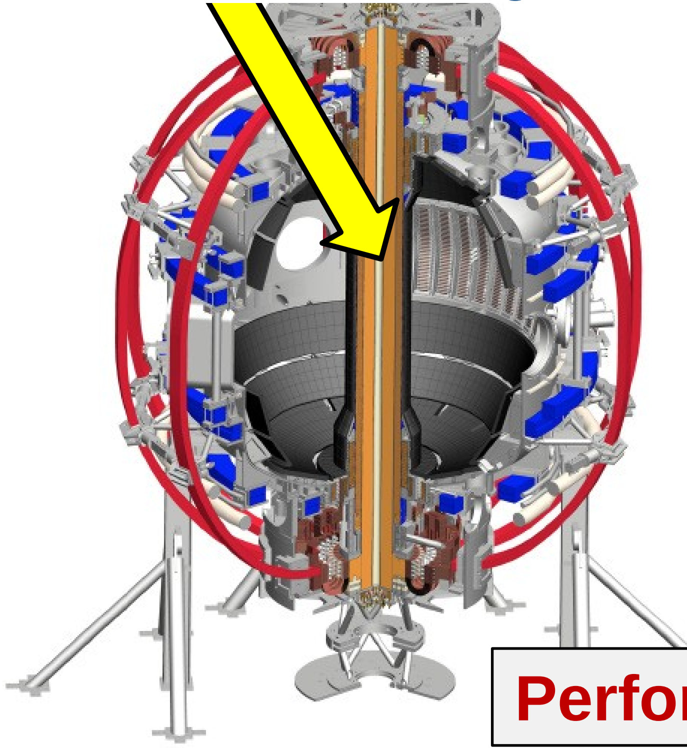
<u>Full non-inductive current drive</u>

→ Not demonstrated in ST at high-β_T

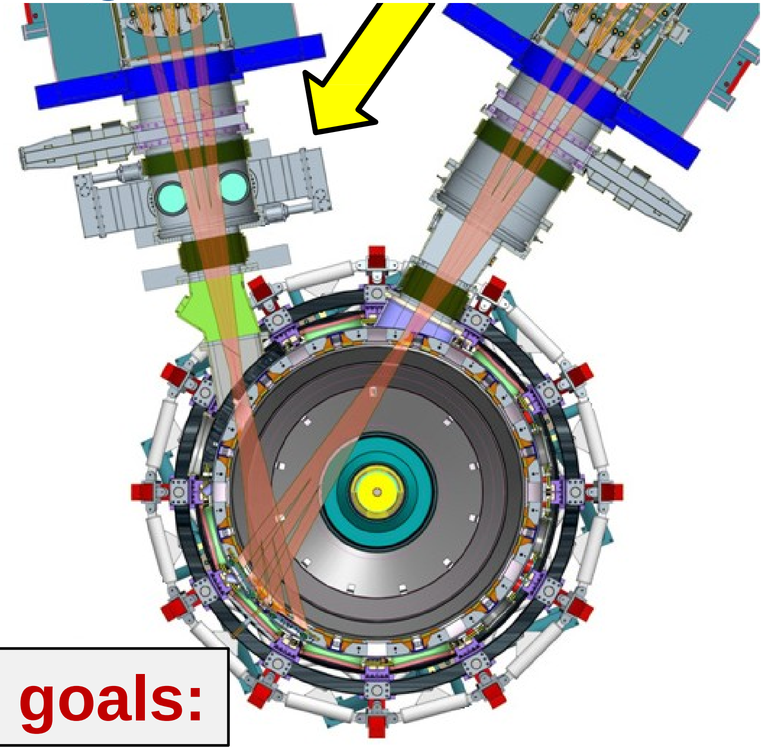
Essential for any future steady-state ST

NSTX-U will have major boost in performance

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Performance goals:

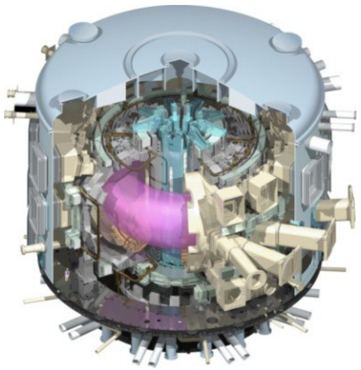
- 2× toroidal field (0.5 → 1T)
- 2× plasma current (1 → 2MA)
- 5× longer pulse (1 → 5s)
- 2× heating power (5 → 10MW)
  - Tangential NBI → 2× current drive efficiency
- 4× divertor heat flux (→ ITER levels)
- Up to 10× higher $nT\tau_E$ (~MJ plasmas)

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 forensics, design (re)-reviews, preparing for new coil fabrication
  - Aim to resume plasma operation end of 2017 / early 2018

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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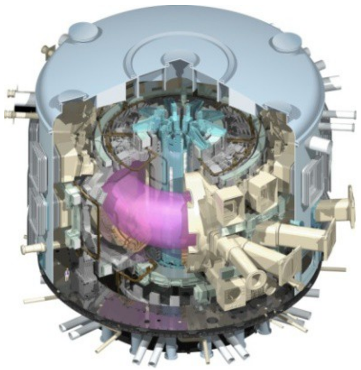

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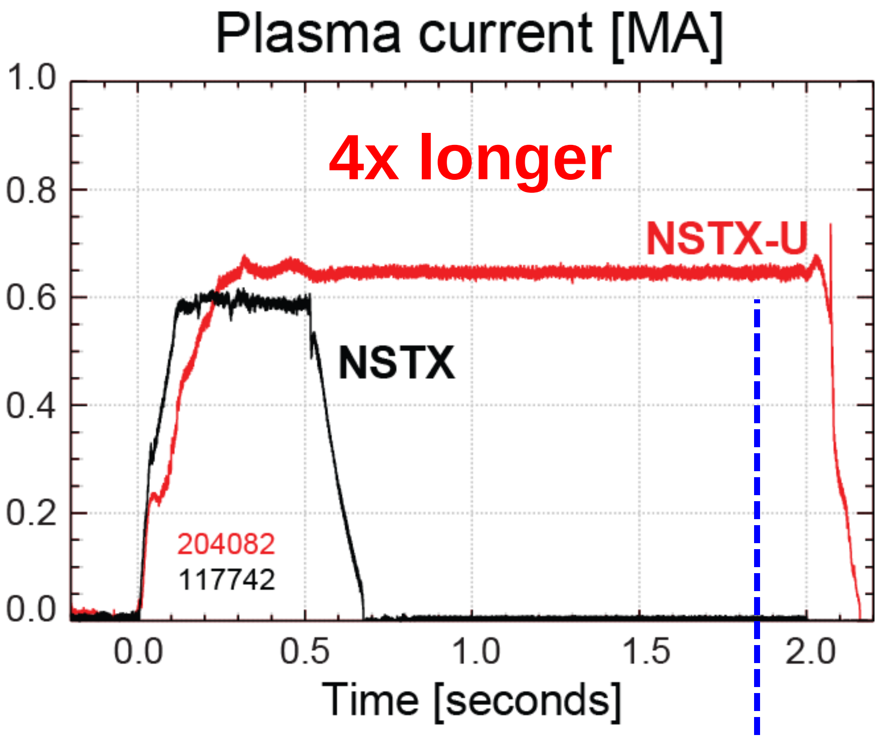
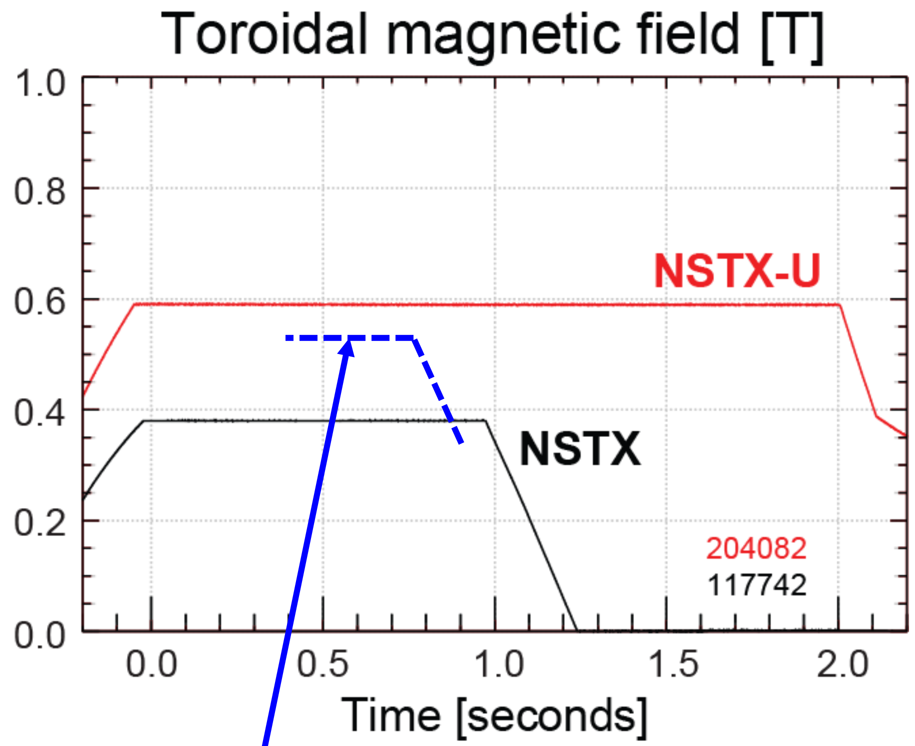
NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

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



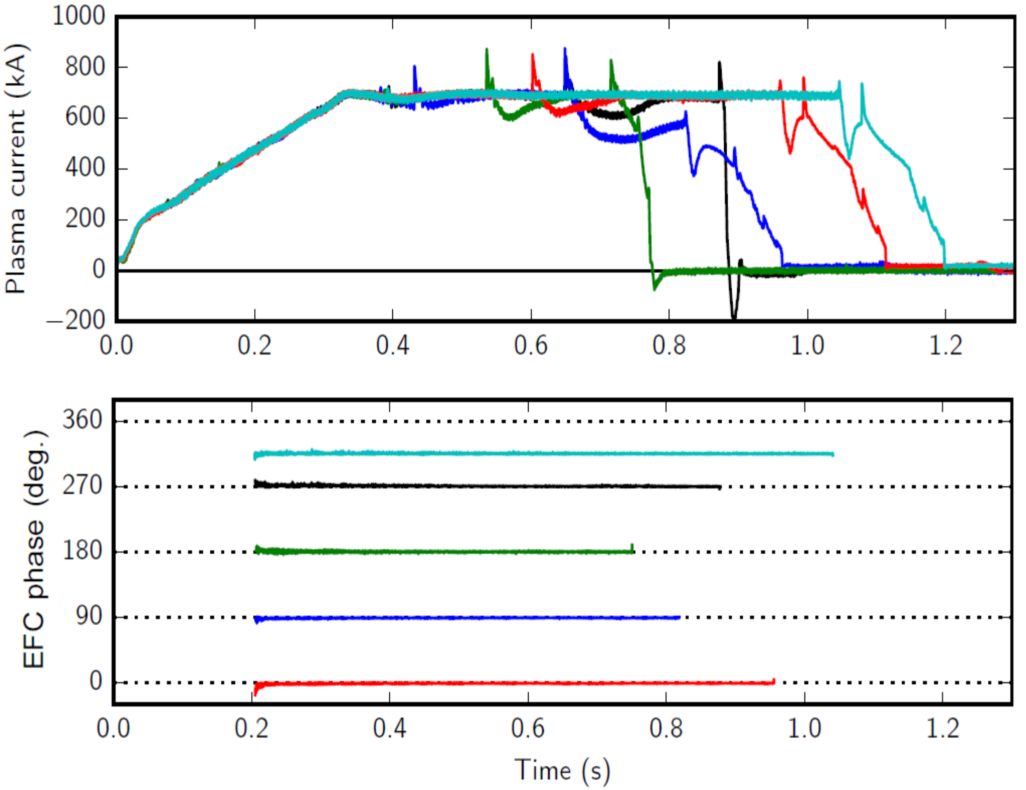


NSTX-U L-mode duration exceeds longest NSTX H-mode

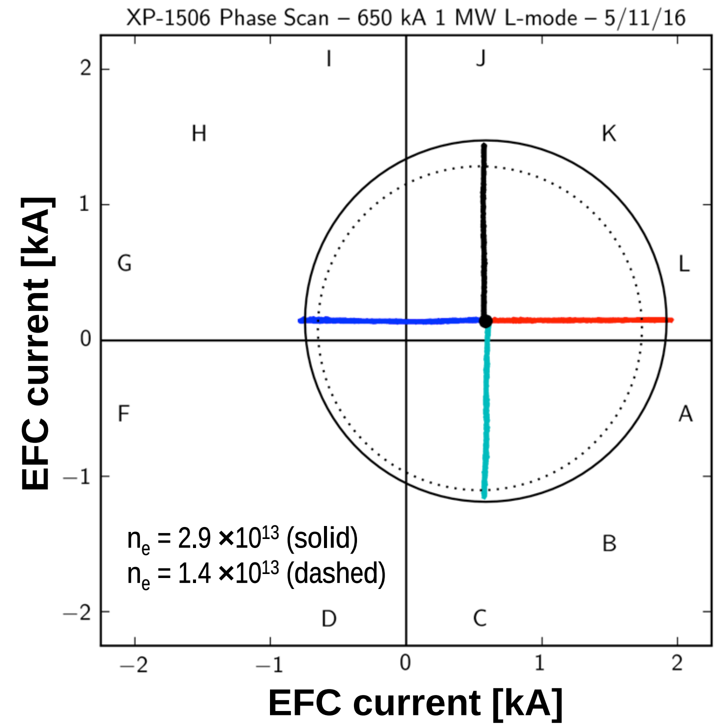
NSTX-U B_T > highest NSTX B_T

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

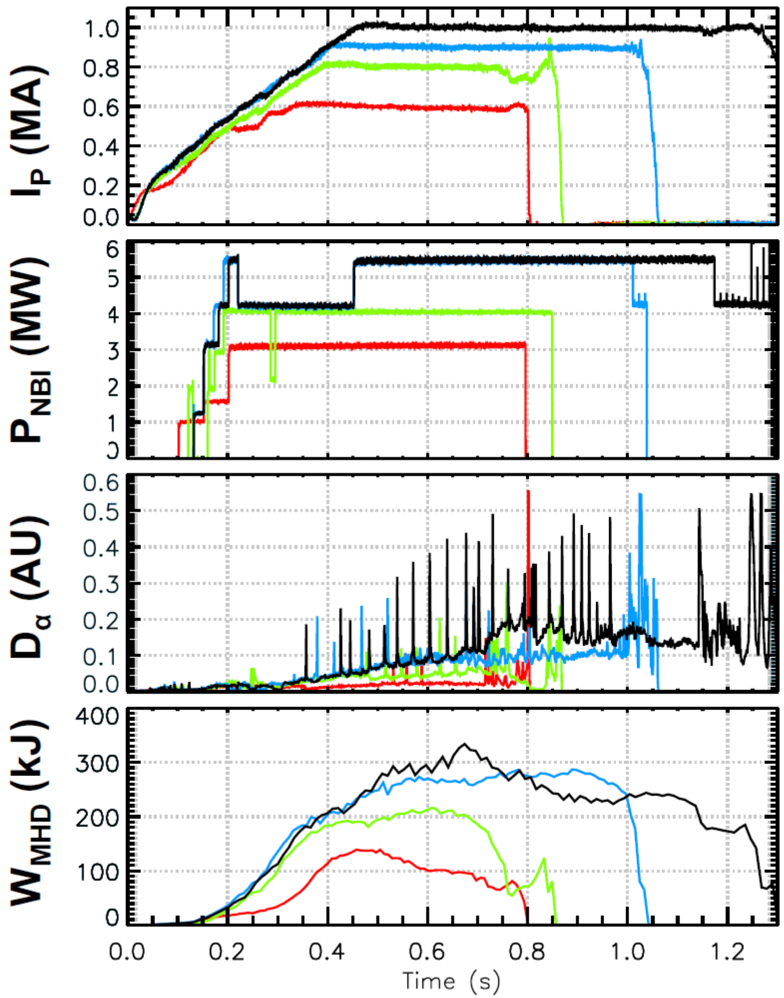
- L-modes used to identify optimal correction amplitude, phase



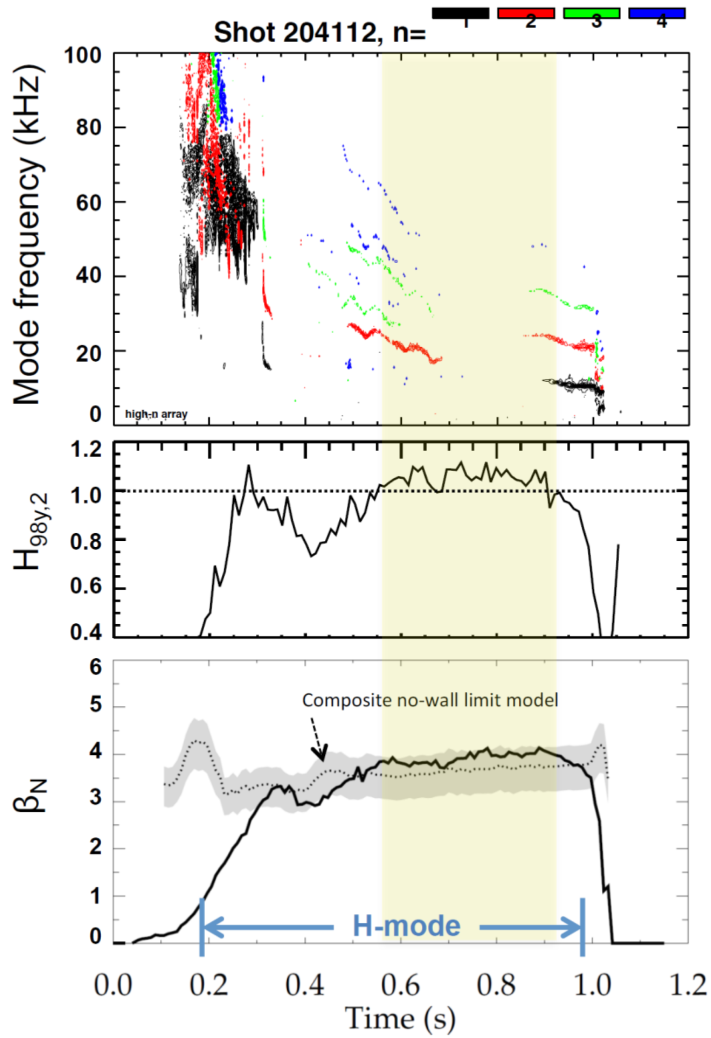
- Multiple compass scans confirm optimal L-mode EFC in flattop



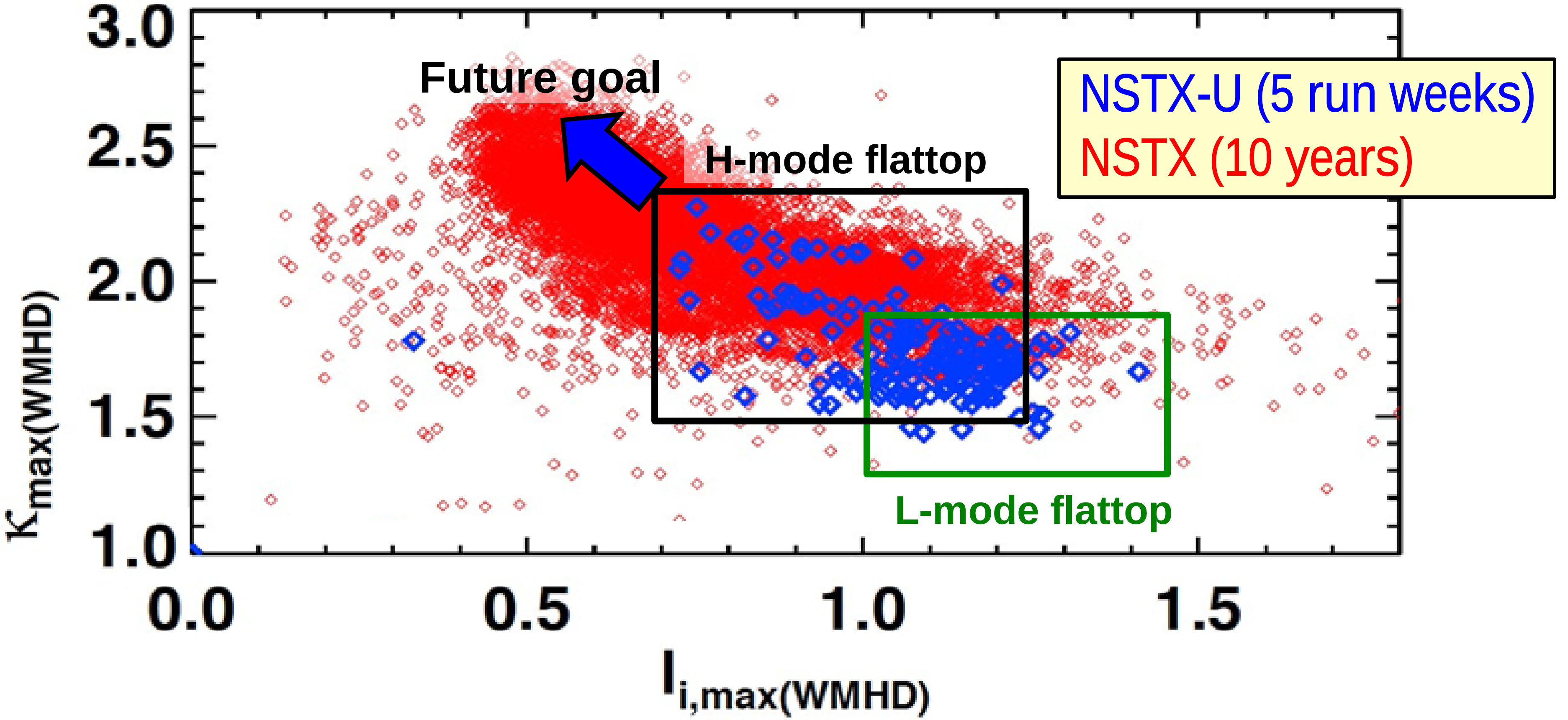
Recovered ~1MA H-modes with weak/no core MHD
(comparable to best NSTX plasmas at similar plasma current)



$H_{98} \geq 1$, $\beta_N \sim 3.5$-$4 \geq$ 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**

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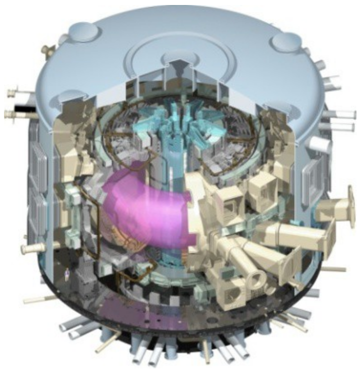

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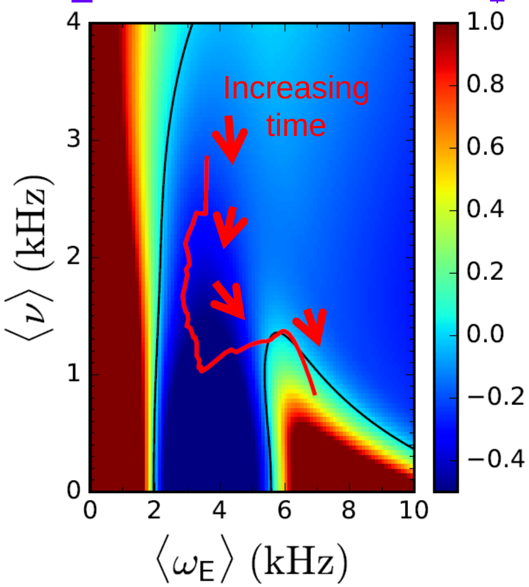
Disruption characterization and forecasting capability initiated for NSTX-U as part of disruption avoidance plan

New DECAF (Disruption Event Characterization And Forecasting) code written

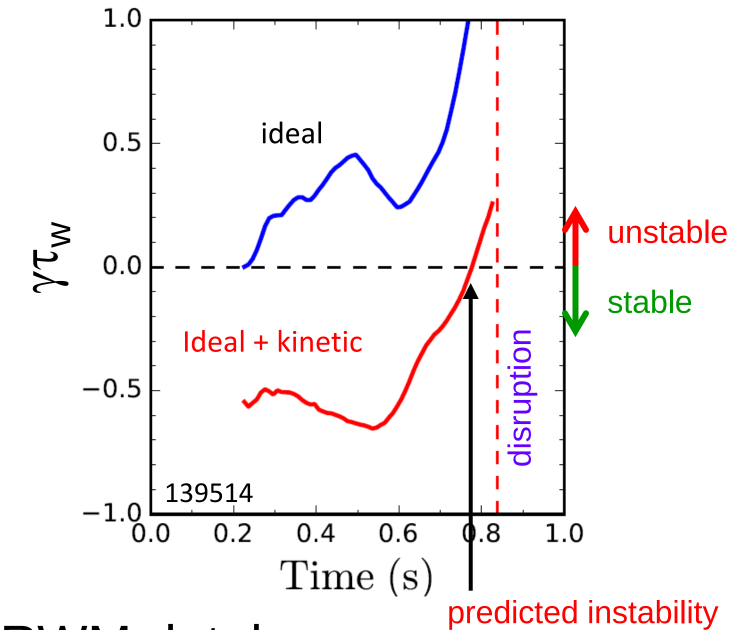
- Identify disruption event chains and elements
  - ex: vertical displacement, pressure peaking, tearing modes…
- Predict events in disruption chains
- Cues disruption avoidance system

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

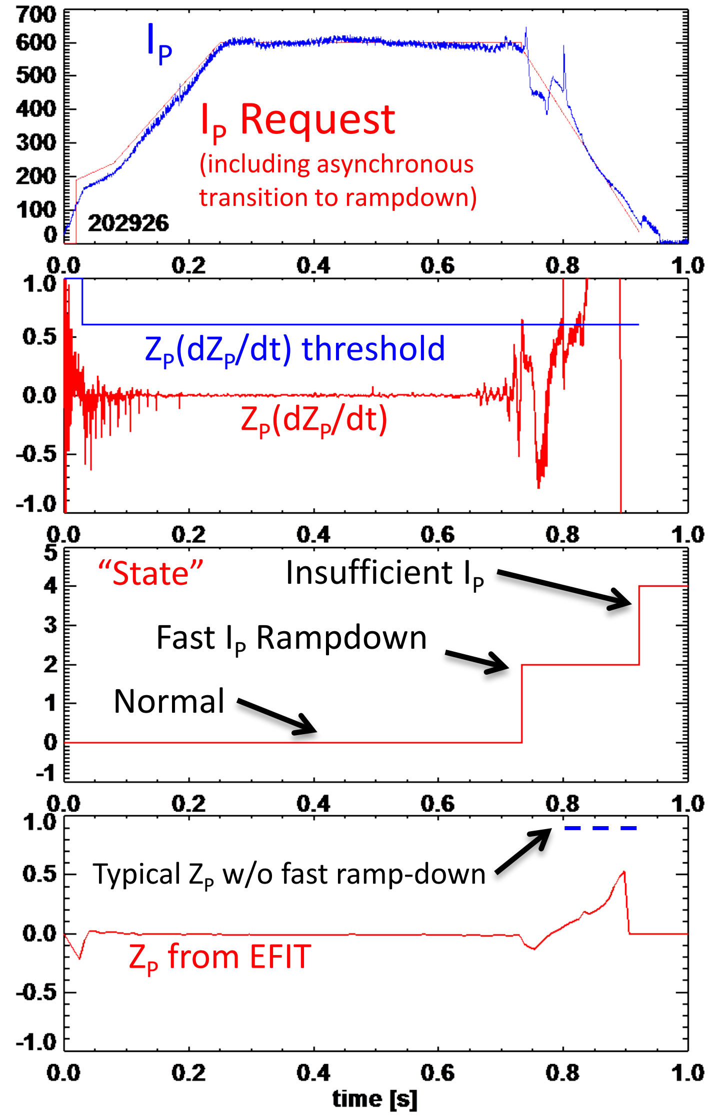


- Initial tests on NSTX RWM database
  - 86% of RWM shots are predicted unstable
- Possible to predict growth rate in real time

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

Implemented automated ramp-down for NSTX-U

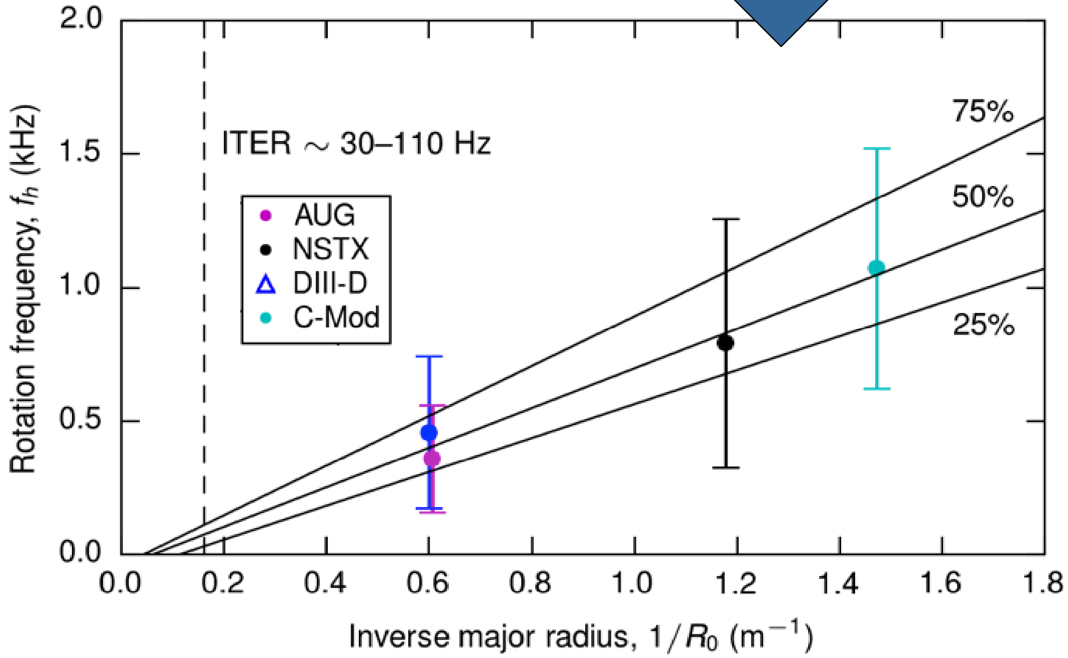
- Plasma control system detects loss of control
  - Central solenoid coil near maximum allowed current
  - Vertical oscillations exceed threshold
  - **ABS**(I_p–$I_{p\ request}$) above threshold
- "State-machine" based:
  - Feedback control switches to new "states" that attempt to stably ramp-down the plasma



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

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

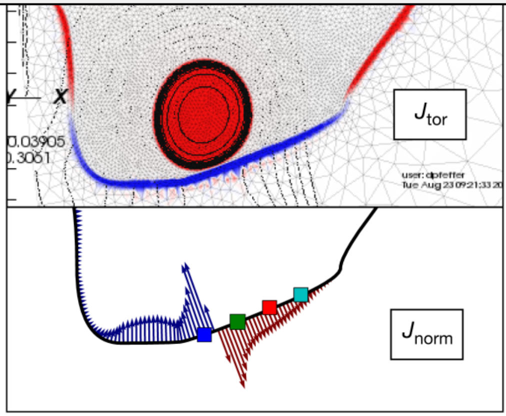
- Halo current data from C-Mod, DIII-D, AUG, NSTX
- All measurements in lower divertor (> 400 shots)
- Halo current rotation predominantly counter-I_p (not shown)
- **Consistent rotation velocity, v_h ~ 5 km/sec**

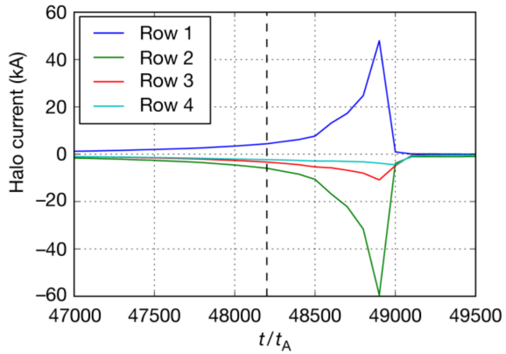


C.E. Myers et al., Poster EX/P6-46, Thursday afternoon

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)*





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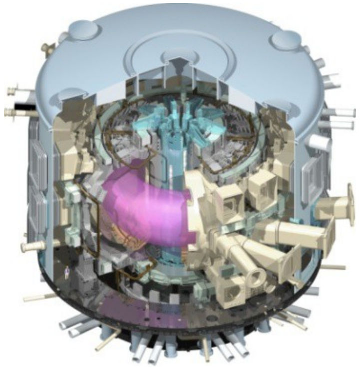

ITER

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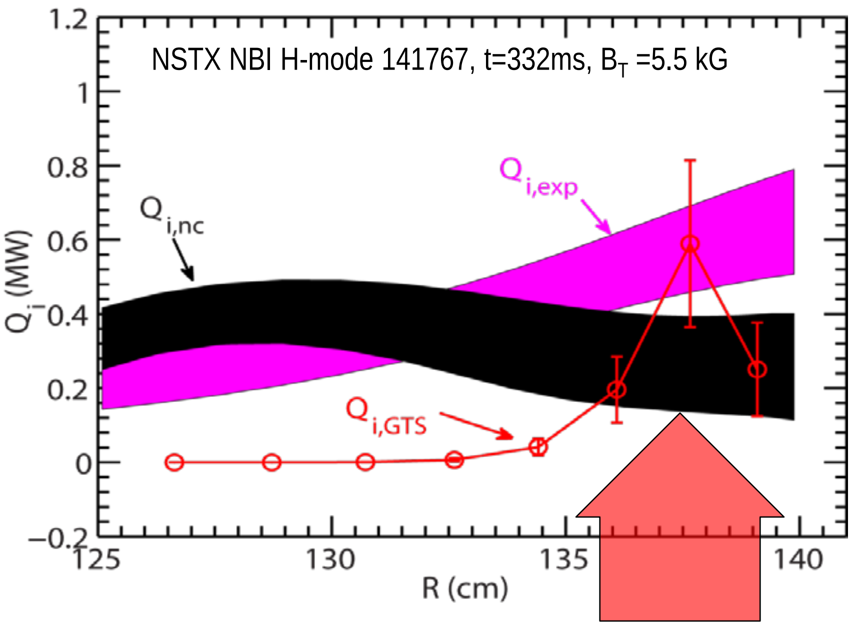
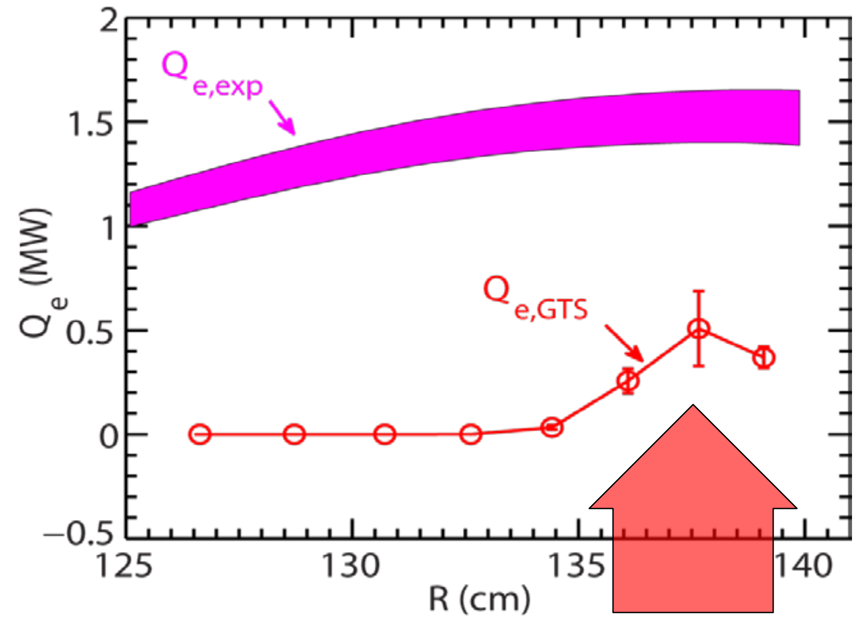
NSTX: Using global non-linear GTS gyrokinetic code to study low-k ion and electron transport

GTS global capability important for treating larger ρ*~0.01 of NSTX





- Low-k turbulence for r/a~0.7-0.85
  - Turbulence later suppressed by ExB shear
- **Total ion energy flux Q_e from GTS generally agrees with experiment**

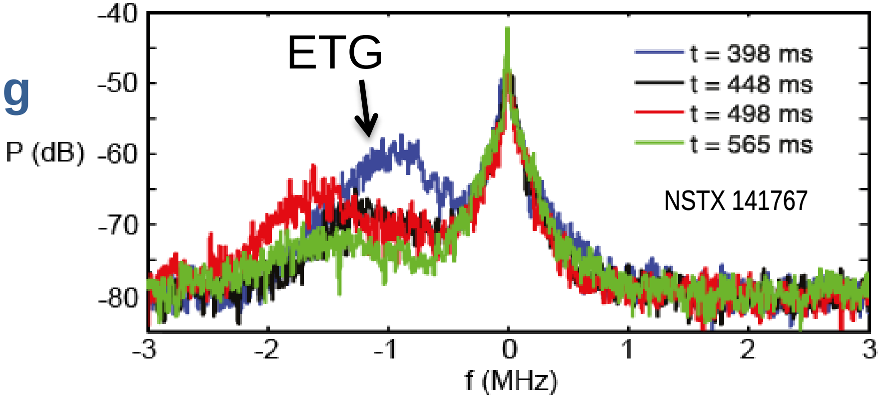
Y. Ren et al., Poster P4-35, Wednesday afternoon

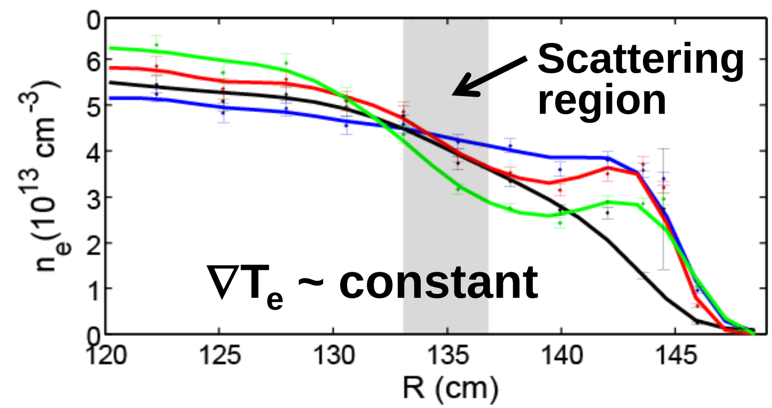
- Electron energy flux Q_e from GTS only significant for r/a~0.7-0.85
- **But GTS Q_e << experimental Q_e**
  - Electron Temperature Gradient (ETG) or electromagnetic (EM) effects important?

GYRO simulations of high-k Electron Temperature Gradient (ETG) turbulence find ∇n_e stabilizing

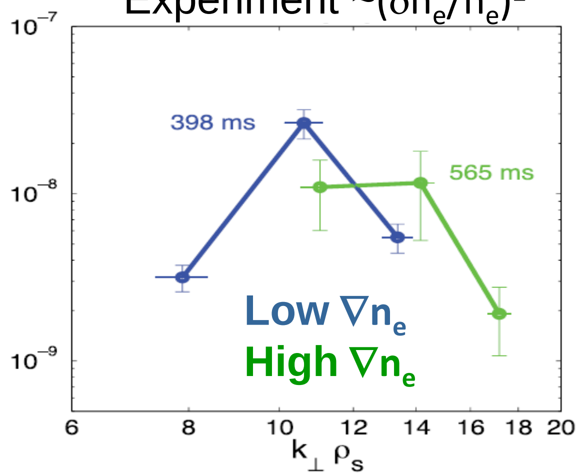
High-k μ-wave scattering

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

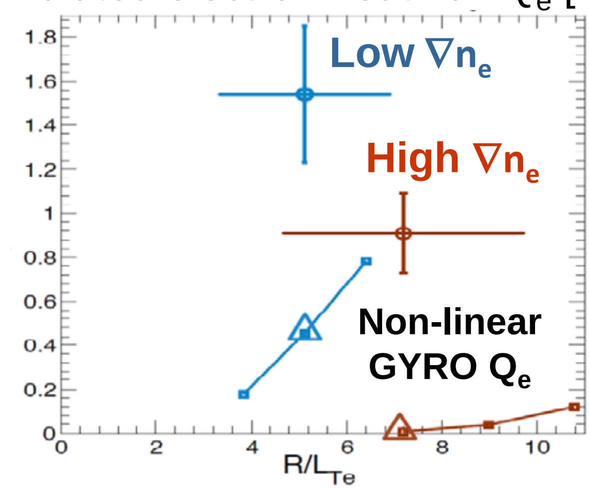




Experiment ~$(\delta n_e/n_e)^2$



Simulated electron heat flux Q_e [MW]



(Juan Ruiz Ruiz)

GYRO Q_e << experimental Q_e → Need EM, Alfvénic, low-k + high-k effects?

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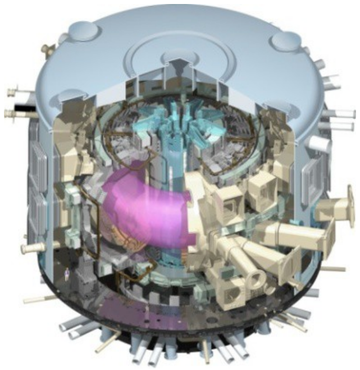

ITER

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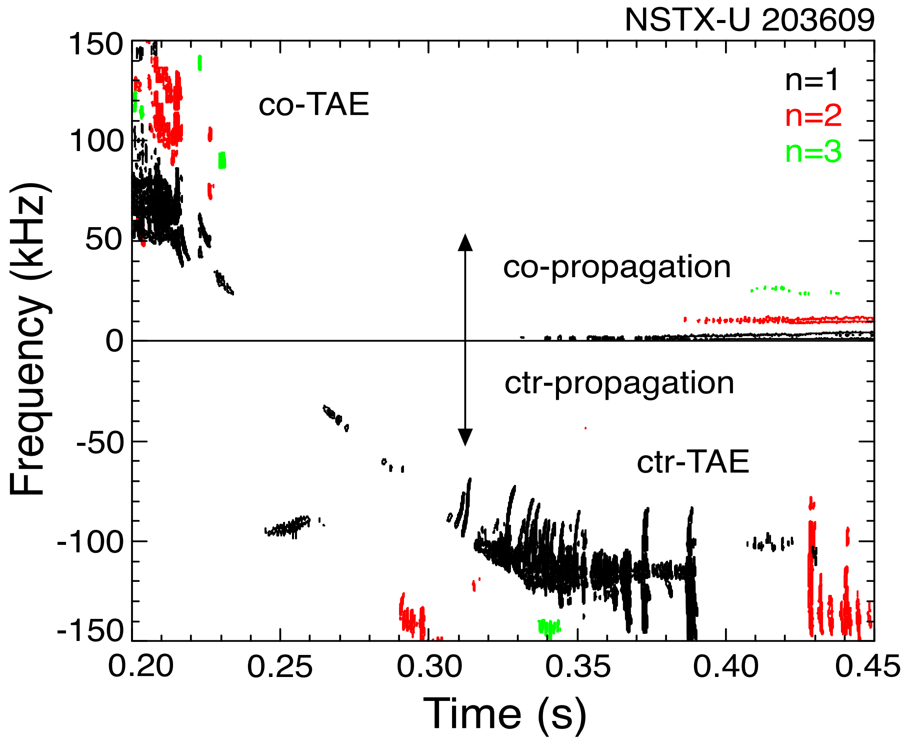
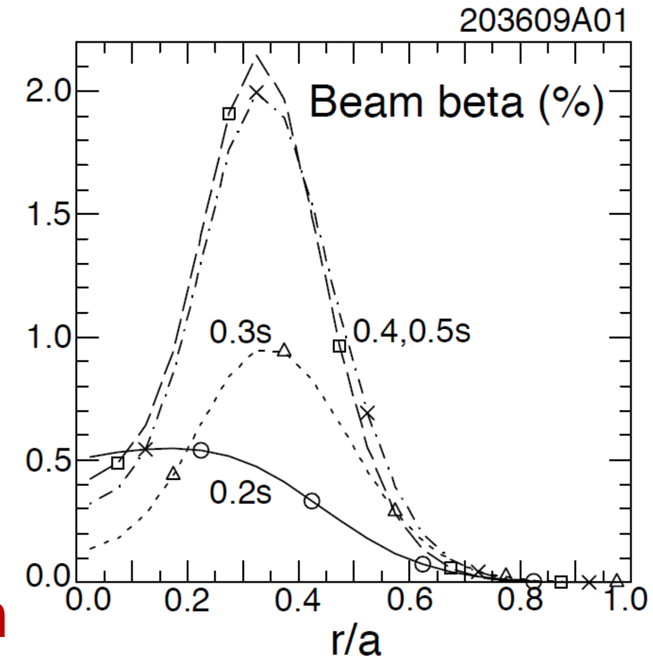
NSTX-U: Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)

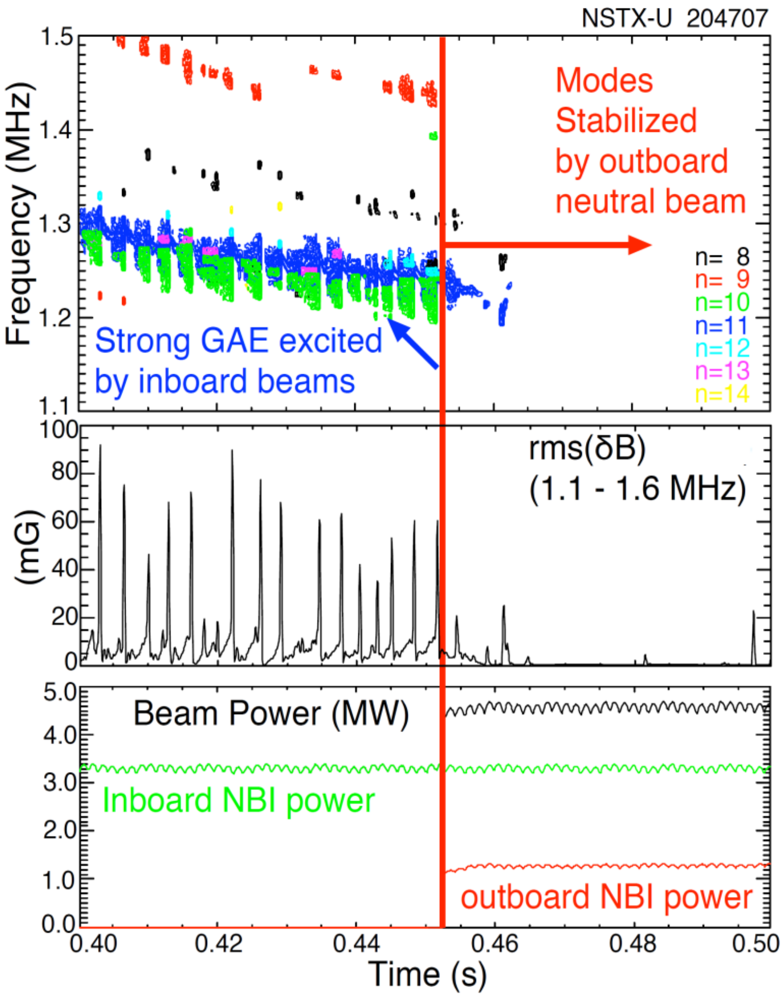


- Counter-propagating TAE predicted for **hollow** fast-ion profiles

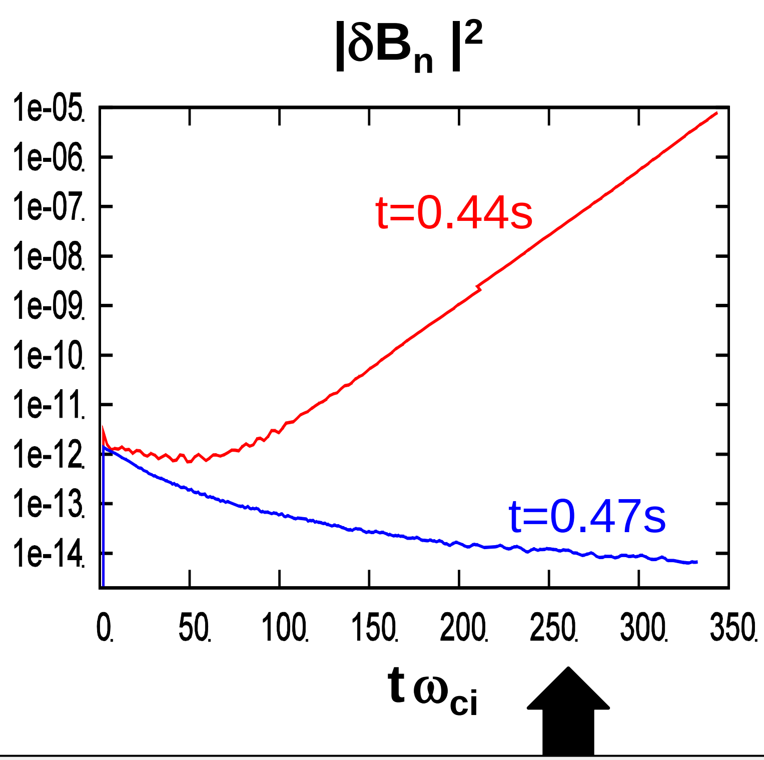


- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow
- **1st evidence of off-axis NBI deposition**

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



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

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

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ITER

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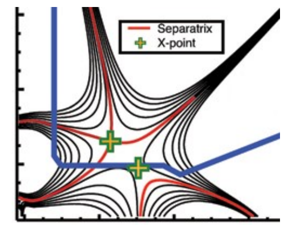


Snowflake/X

Liquid metals / Li

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant

ST-FNSF / Pilot-Plant

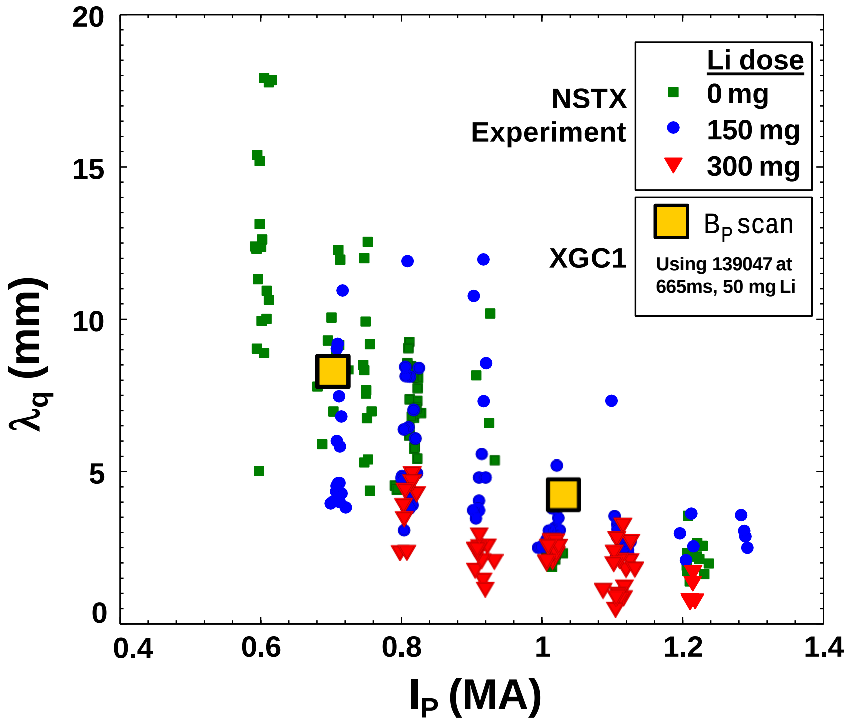
Improving understanding of SOL heat flux width trends in NSTX using XGC1 simulations

- 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

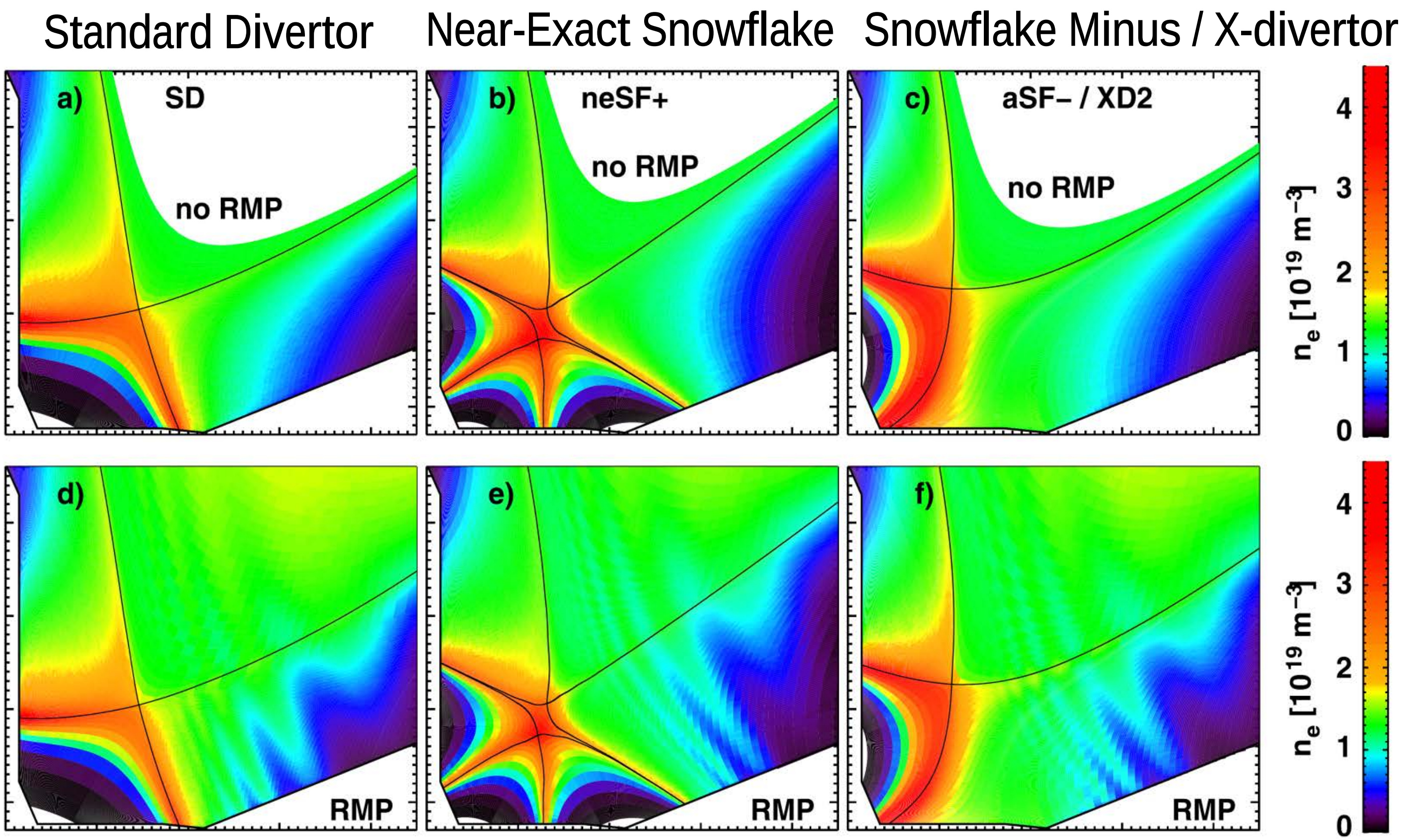


- **NSTX data and XGC-1: $\lambda_q \sim 1 / I_P^{1.5}$**
- **How will NSTX-U λ_q scale?**
- **Will SOL turbulence become important?**

C.S. Chang et al., Talk TH/2-1, Wednesday morning

Heat flux width determined primarily by neoclassical processes

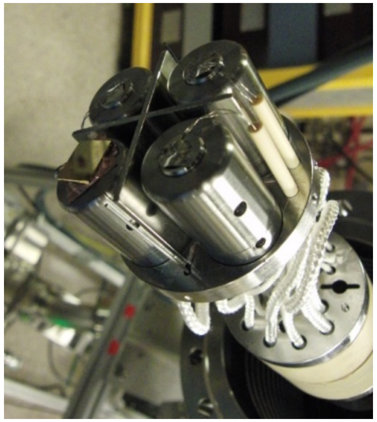
NSTX-U: First systematic simulations of advanced divertors combined with 3D fields with EMC3-EIRENE

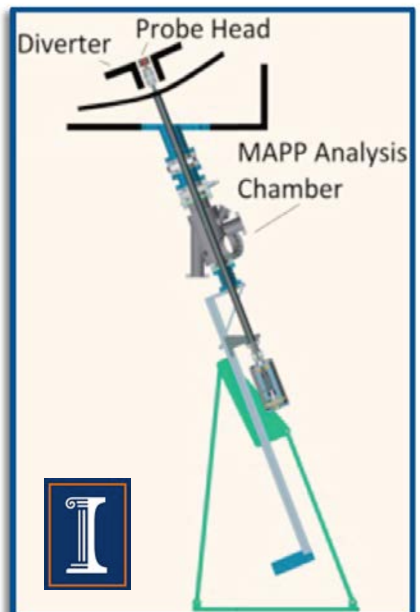


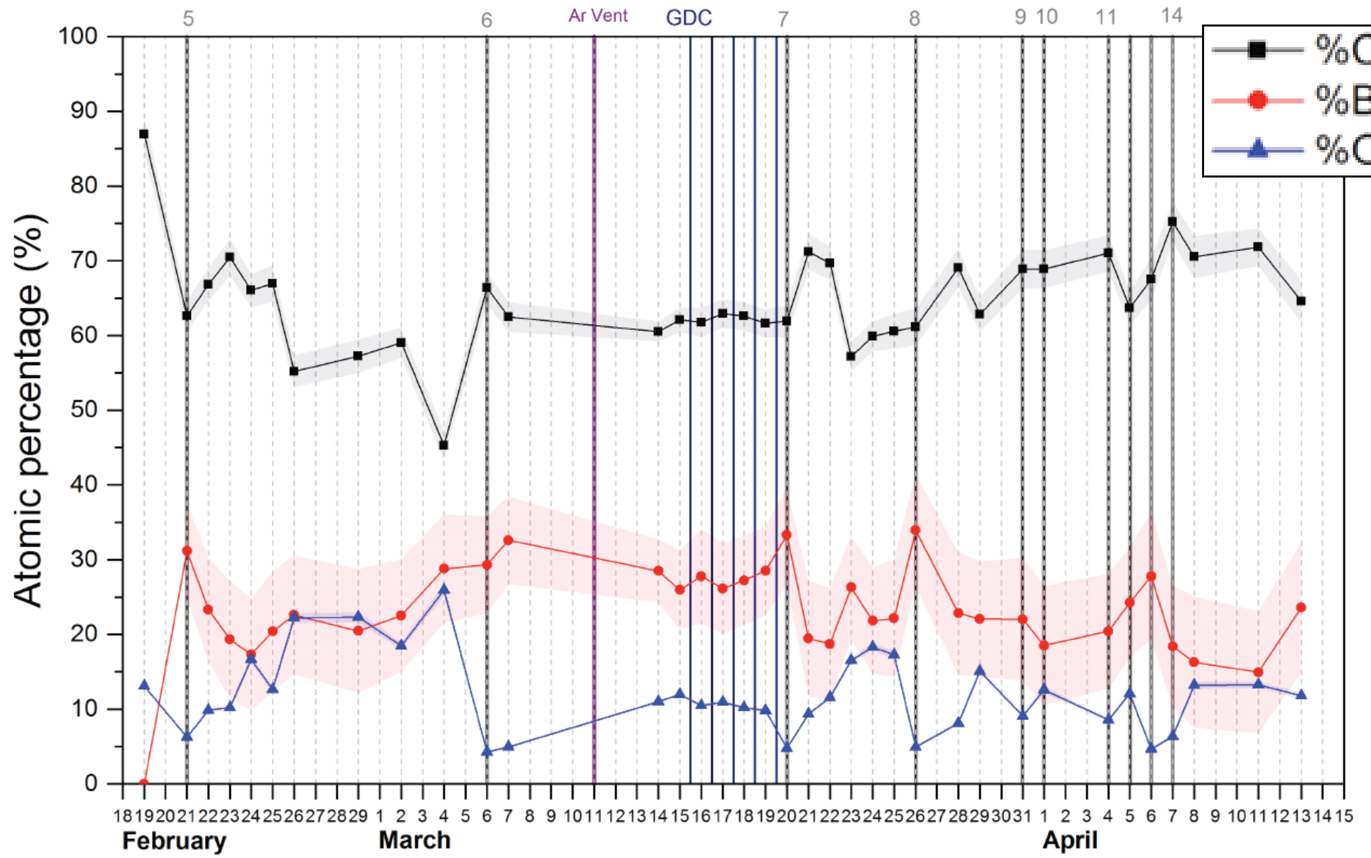
- **Divertor heat-flux trends:**
  - Peaked heat loads in Near Exact Snowflake
  - Lowest heat loads found for X-divertor-like configurations
  - RMP fields do not significantly impact toroidal average heat-flux

Related snowflake results from DIII-D and NSTX: Poster EX/P3-30 - V. Soukhanovskii, Wednesday

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 analysis
- Future: Use to understand complex Li chemistry and evolution

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ITER

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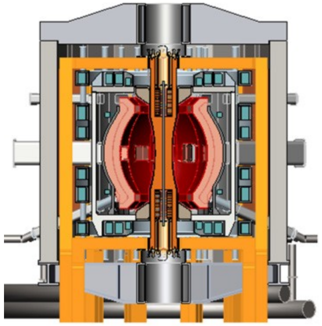
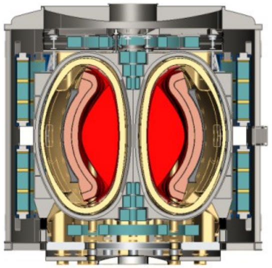
Liquid metals / Lithium

Snowflake/X

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant



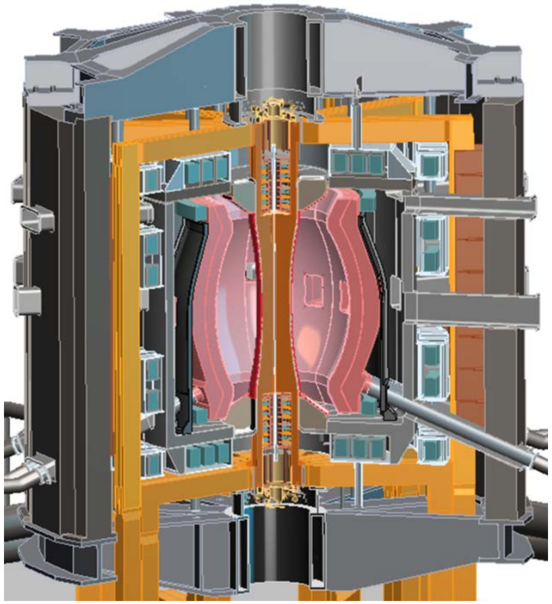
ST-FNSF / Pilot-Plant



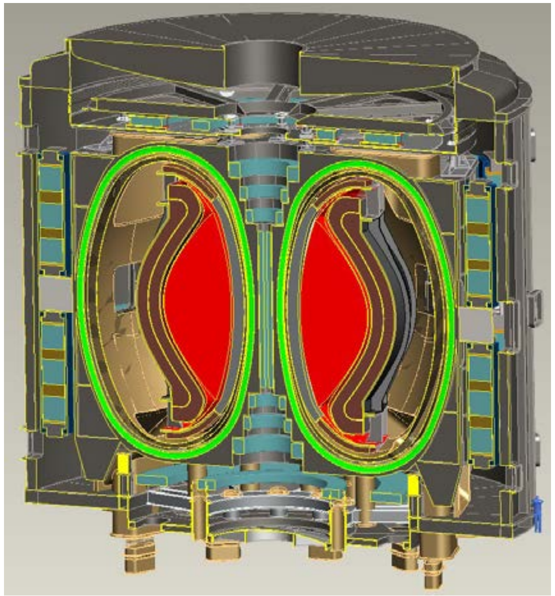
Recent design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) and Pilot Plant

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?)

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



FNSF with copper TF coils
$A=1.7$, $R_0 = 1.7m$, $\kappa_x = 2.7$, $B_T=3T$
Fluence = $6 MWy/m^2$, TBR ~ 1



FNSF / Pilot Plant with HTS TF coils
$A=2$, $R_0 = 3m$, $\kappa_x = 2.5$, $B_T = 4T$
$6 MWy/m^2$, TBR ~ 1, Q_{eng} ~ 1

FIP/P7-1 - T. Brown, Friday morning

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

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

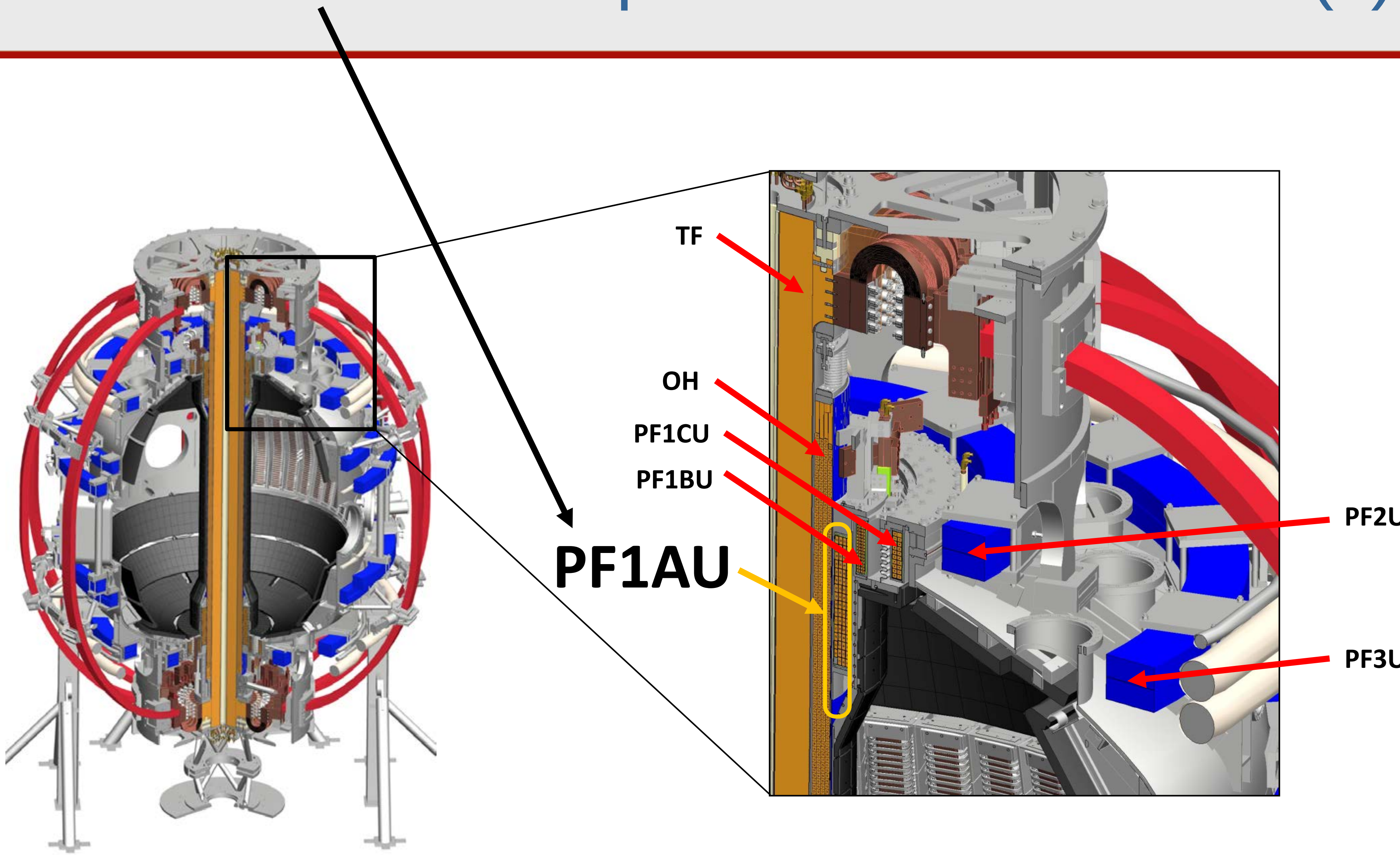
- Productive first year of operations on NSTX-U
  - *Rapid H-mode access, scenario development, error field correction*
  - *Surpassed NSTX maximum magnetic field and pulse-duration*
  - *New fast-ion physics with 2nd NBI – GAE stabilization, counter TAE*
  - *Commissioned new advanced PMI diagnostics – MAPP*
- Advancing predictive capability for core, edge, PMI
  - *Developing reduced models for RWM, understanding of halo rotation*
  - *Global ion-scale turbulence (GTS), ∇n ETG stabilization*
  - *GAE stabilization from 2nd NBI consistent with simulation (HYM)*
  - *Exploring SOL widths, advanced divertor interactions with 3D fields*
- Developed attractive ST-FNSF / Pilot Plant concepts
- Aim to resume NSTX-U physics operation in ~1+ years

IAEA-FEC presentations from NSTX-U

- Tuesday, October 18
  - OV/5-2 - J. Menard, “Overview of First Results from NSTX-U and Analysis Highlights from NSTX”
  - TH/P1-2 - F. Ebrahimi, “Physics of Flux Closure during Plasmoid-Mediated Reconnection in Coaxial Helicity Injection”
  - TH/P1-6 - J.-K. Park, “Self-Consistent Optimization of Neoclassical Toroidal Torque with Anisotropic Perturbed Equilibrium in Tokamaks”
  - TH/P1-7 - S. C. Jardin, “Nonlinear 3D M3D-C1 Simulations of Tokamak Plasmas Crossing a MHD Linear Stability Boundary”
  - TH/P1-10 - A. Fil, “Modelling and Simulation of Pedestal Control Techniques for NSTX-U”
  - TH/P1-21 - Z. R.Wang, “Nyquist Analysis of Kinetic Effects on the Plasma Response in NSTX and DIII-D Experiments”
- Wednesday, October 19
  - FIP/2-5 - M. Ono. “Liquid Lithium Loop System to Solve Challenging Technology Issues for Fusion Power Plant”
  - EX/P3-30 - V. Soukhanovskii, “Snowflake Divertor Configuration Effects on Pedestal Stability and Edge Localized Modes in NSTX and DIII-D”
  - TH/P3-14 - W. Guttenfelder, “Analysis and Prediction of Momentum Transport in Spherical Tokamaks”
  - EX/P4-30- J.-W. Ahn “Shielding and Amplification of Nonaxisymmetric Divertor Heat Flux by Plasma Response to Applied 3D Fields in NSTX and KSTAR”
  - EX/P4-33 - S. A. Sabbagh, “Isolation of Neoclassical Toroidal Viscosity Profile under Varied Plasma and 3D Field Conditions in Low and Medium Aspect Ratio Tokamaks”
  - EX/P4-34 - J.W. Berkery, “Characterization and Forecasting of Unstable Resistive Wall Modes in NSTX and NSTX-U”
  - EX/P4-35 - Y. Ren, “Exploring the Regime of Validity of Global Gyrokinetic Simulations with Spherical Tokamak Plasmas”
  - EX/P4-36 - F. Scotti, “Kinetic Profiles and Impurity Transport Response to 3D-Field Triggered ELMs in NSTX”
  - EX/P4-38 - R. Maingi. “Comparison of Helium Glow and Lithium Evaporation Wall Conditioning Techniques in Achieving High Performance H-Mode Discharges in NSTX”
  - EX/P4-40 - D. Smith, “Identification of Characteristic ELM Evolution Patterns with Alfvén-Scale Measurements and Unsupervised Machine Learning Analysis”
  - EX/P4-41 - E. Fredrickson, “Parametric Dependence of EPMs in NSTX”
  - EX/P4-42 - R. Perkins, “….A Proposed Mechanism for the Anomalous Loss of RF Power to the SOL of NSTX”
  - EX/P4-43 - M. D. Boyer, “Feedback Control Design for Noninductively Sustained Scenarios in NSTX-U Using TRANSP”
  - TH/P4-16 - G. Fu, “Hybrid Simulations of Beam-Driven Fishbone and TAEs in NSTX”
  - TH/P4-17 - E. Belova, “Coupling of Neutral-Beam-Driven Compressional Alfvén Eigenmodes to Kinetic Alfvén Waves in NSTX and Energy Channelling”
- Thursday, October 20
  - EX/5-3 - A. Diallo, “Energy Exchange Dynamics across L-H Transitions in NSTX”
  - MPT/P5-30 - M. A. Jaworski, “High-Temperature, Liquid Metal Plasma-Facing Component Research and Development for the NSTX-U”
  - EX/P6-46 - C. Myers, “A Multimachine Analysis of Non-axisymmetric and Rotating Halo Currents”
  - TH/P6-12 - J. Lore, “Pedestal-to-Wall 3D Fluid Transport Simulations on DIII-D and NSTX”
- Friday, October 21
  - FIP/P7-1 - T. Brown, “Development of a 3 m HTS FNSF Device and the Qualifying Design and Engineering R&D Needed to Meet the Low AR Design Point”
  - FIP/P7-36 - R. Lunsford, “ELM Pacing with High Frequency Multispecies Impurity Granule Injection in NSTX-U H-Mode Discharges”
  - FIP/P7-42 - R. Raman, “NSTX-U Contributions to Disruption Mitigation Studies in Support of ITER”

Backup

PF1AU coil developed turn-to-turn short(s)



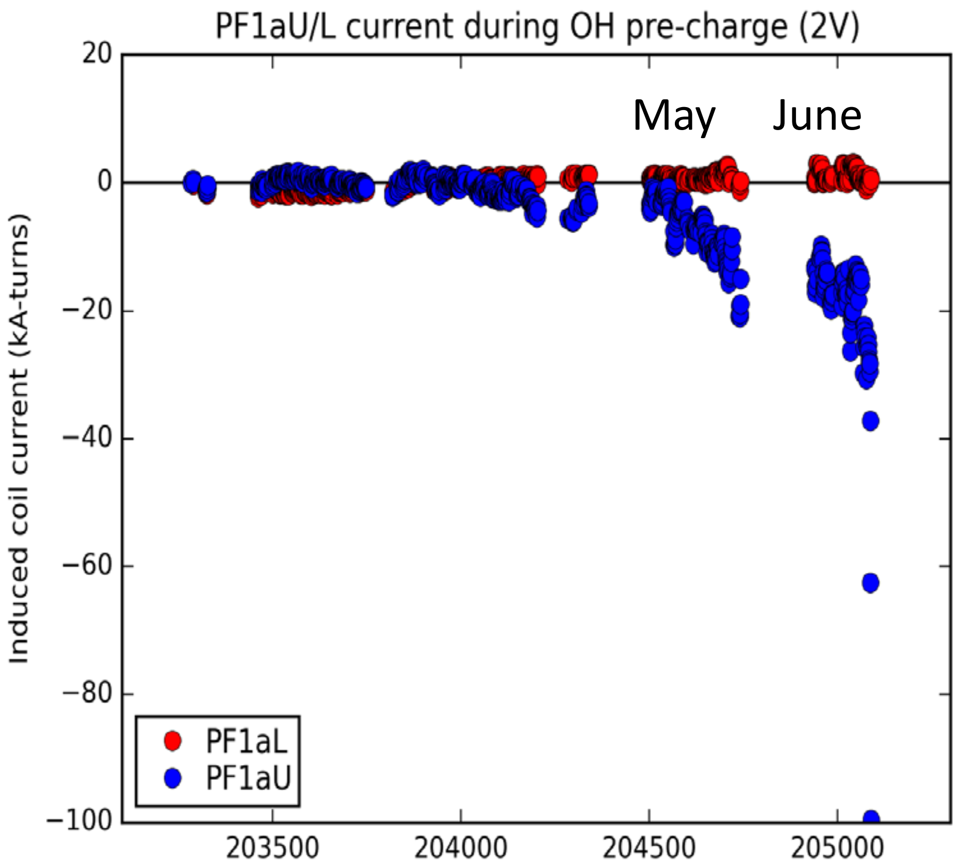
Evolution of induced current in PF1AU

- Coil carries current when open circuited (open circuited every shot before plasma is produced)

→ **turn-to-turn short**

- PF1AU first starts to conduct current at the end of the March / April run period

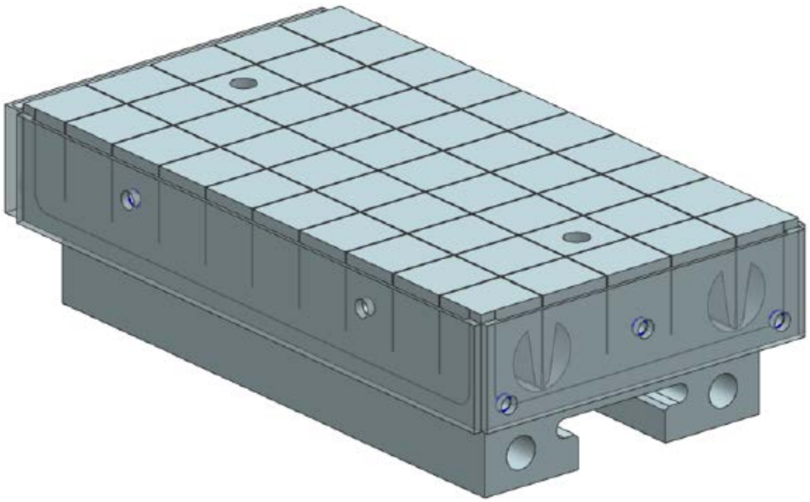
- Very fast degradation on the final run day in June



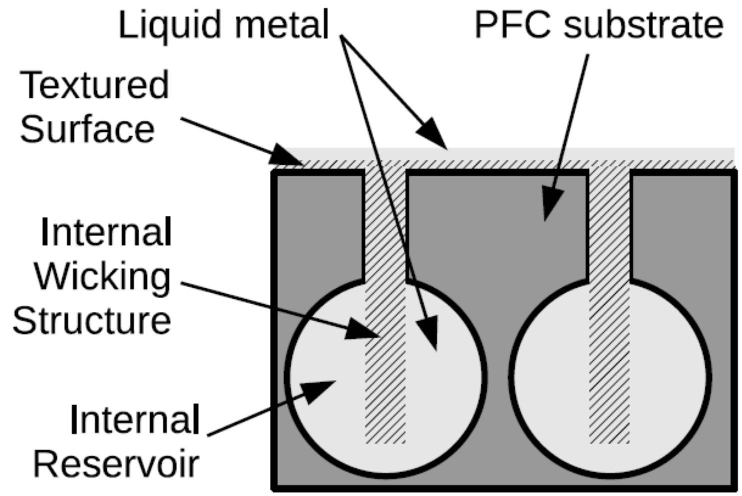
- PF1AL shows no anomalies, but will pre-emptively be replaced

NSTX-U plans for initiating conversion to high-Z PFCs and studying flowing liquid metal PFCs

1. Base high-Z tiles without Li reservoir will be tested first
   - Full toroidal row on OB divertor
   - Utilizes wire-EDM fabrication to obtain complex geometry



2. Later test pre-filled Li tiles:
   - Similar to capillary porous system (CPS) but applicable as divertor PFC
   - Passive surface replenishment
   - Bakeout → erodible high-Z layer/film
   - Test when technically ready



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