NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

NSTX-U / KSTAR Collaboration Opportunities

Jonathan Menard (PPPL)

NSTX-U Program Director

NFRI – PPPL Collaboration Meeting
PPPL
October 21, 2013

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
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UC Irvine
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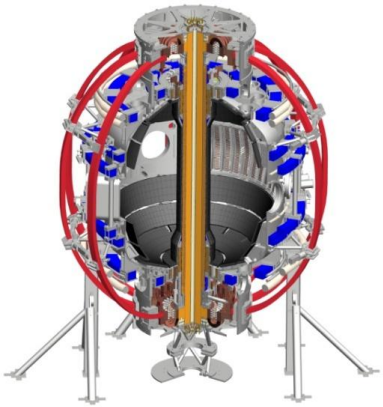
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Thanks to our KSTAR/NFRI visitors for coming to PPPL!

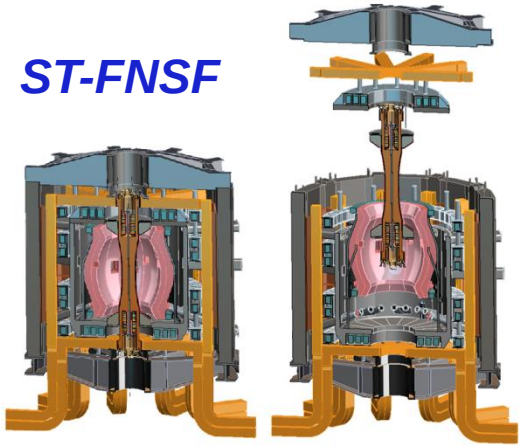
A few goals for this meeting:

- Identify research areas of common interest for possible collaboration w/ NSTX-U (this talk) and PPPL more broadly
- Identify research contacts to facilitate future collaboration
- Enhance KSTAR/NFRI researcher participation on NSTX-U, possibly through extended stays at Princeton/PPPL

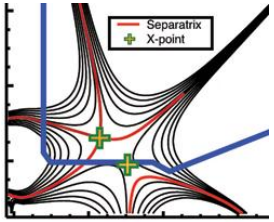
NSTX Upgrade mission elements

- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**

ST-FNSF



- **Develop solutions for the plasma-material interface challenge**

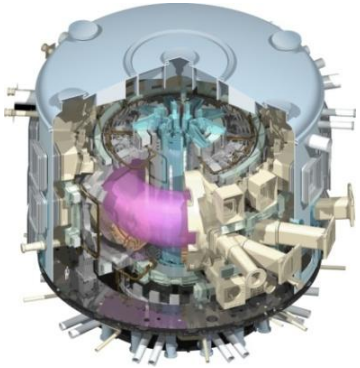


"Snowflake"

Lithium

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

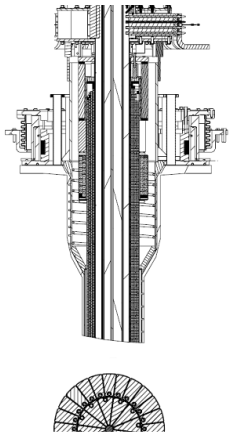
ITER



- **Develop ST as fusion energy system**

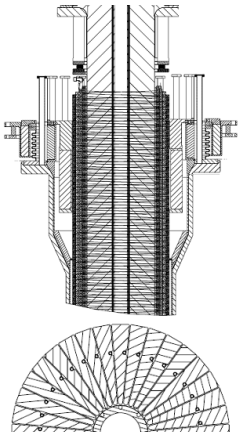
NSTX Upgrade incorporates 2 new capabilities:

Previous center-stack



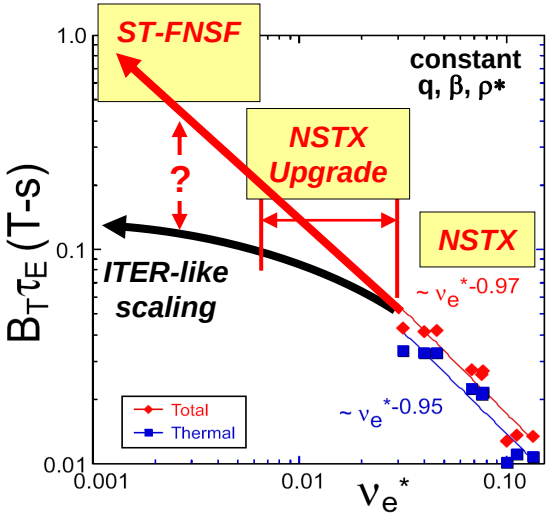
TF OD = 20cm

New center-stack

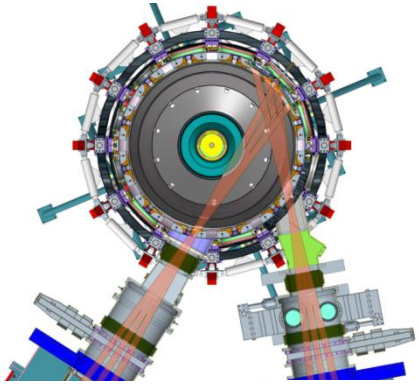


TF OD = 40cm

- Reduces ν^* → ST-FNSF values to understand ST confinement
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- 5x longer pulse-length
  - q(r,t) profile equilibration
  - Test non-inductive ramp-up



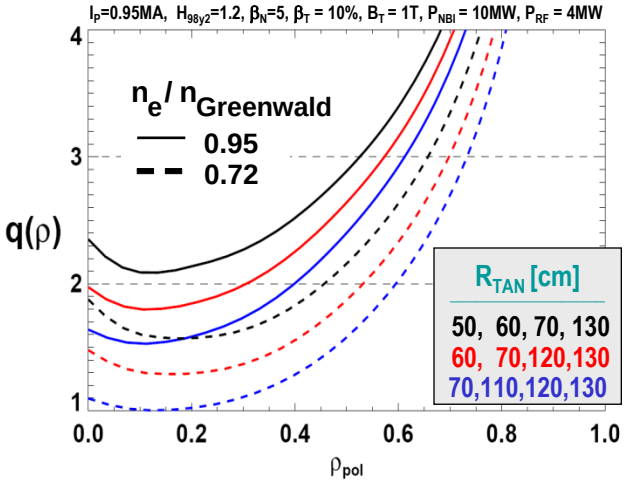
Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI

New 2nd NBI

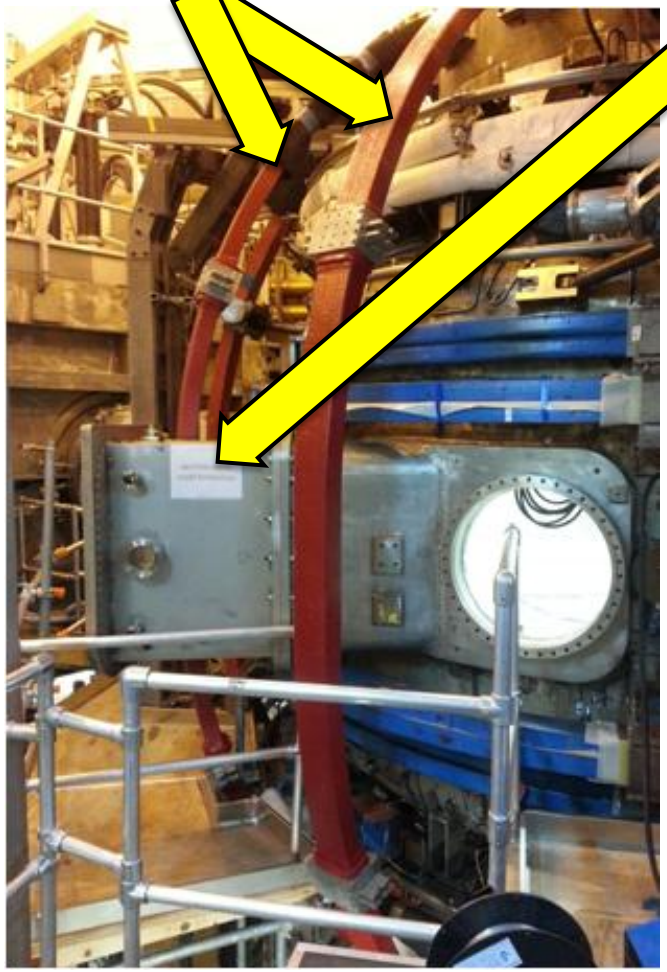
- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position (not shown)

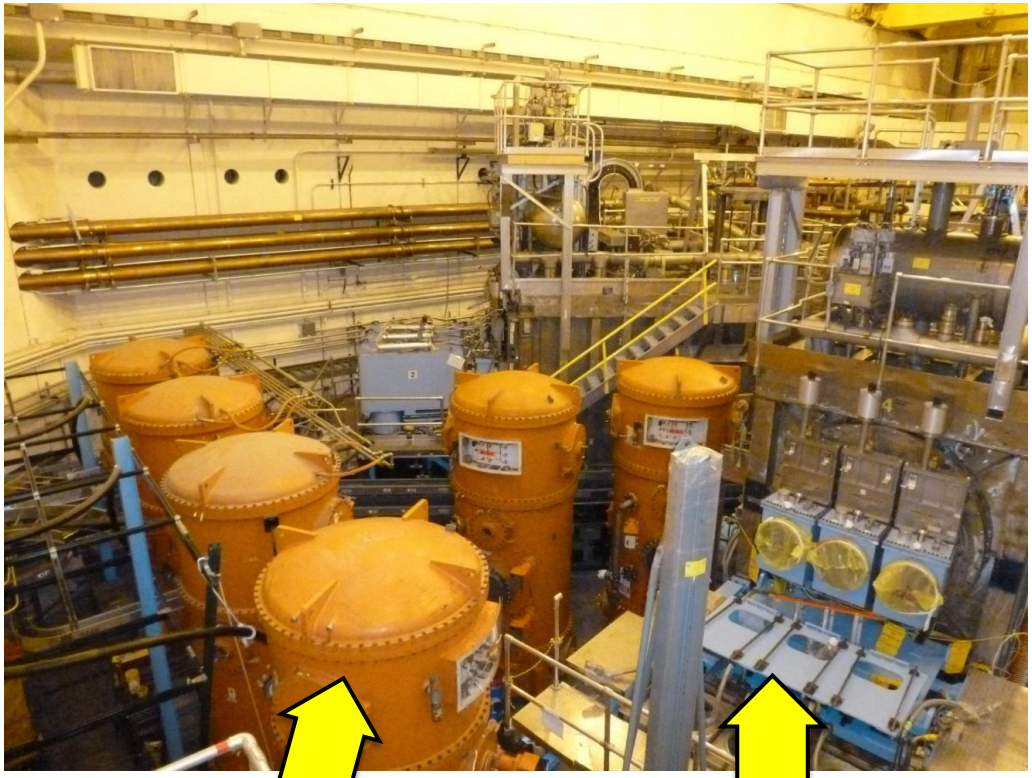


NSTX Upgrade project on schedule and cost

Good progress on 2nd NBI, device structural enhancements

- **New tangential NBI injection port installed**
- **2 new outer TF coils installed**

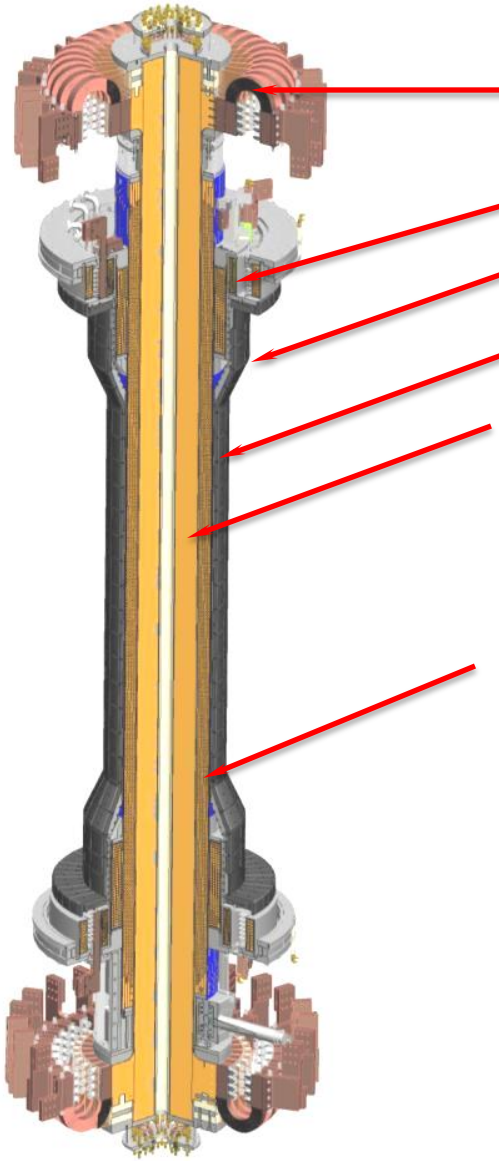




2nd NBI installed

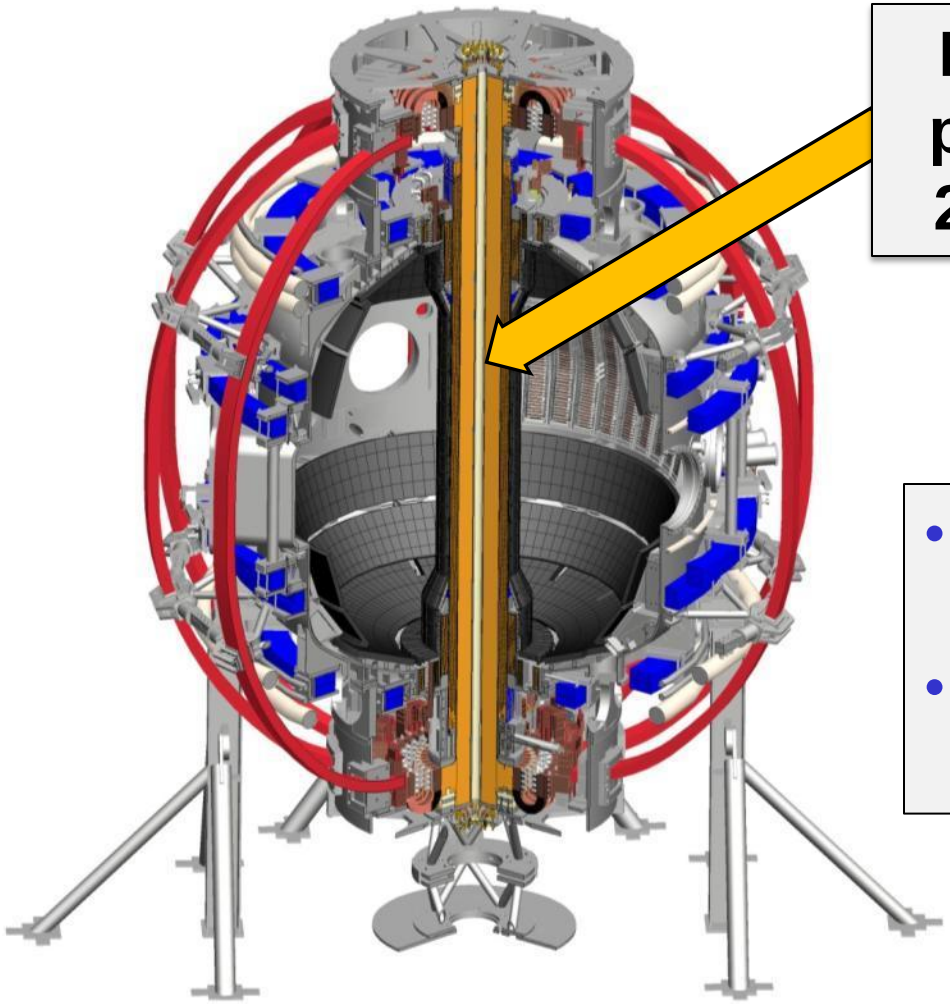
High Voltage Enclosures in-place

Centerstack is the critical path and highest risk



- **Components & Hardware**
  - Flex connectors – delivered
  - PF 1b,a,c coils - Awarded
  - PFC Tiles - delivered and being machined
  - Casing - delivered
- **Inner TF Bundle**
  - VPI 4 Quadrants - Completed
  - VPI Full Bundle - Completed
- **OH Solenoid**
  - OH Conductor delivered
  - Aqua-pour process - ***underway***
  - Begin winding OH solenoid – ***November***
  - VPI OH – ***Jan-Feb 2014***
- **Centerstack Assembly**
  - Delivery to NSTX Test Cell - ***May 2014***

NSTX-U operations schedule / plan



New centerstack installation planned for spring / summer 2014 - less than 1 year away

- **First plasma: late fall 2014**
- **Start research program: late 2014 - early 2015**

Highest priority research goals for NSTX-U:

1. Demonstrate 100% non-inductive sustainment
2. Access reduced ν^* and high-β combined with ability to vary q and rotation
3. Develop/understand non-inductive start-up, ramp-up (overdrive) for ST-FNSF with small/no solenoid
4. Develop high-flux-expansion "snowflake" divertor + radiative detachment to mitigate high heat fluxes
5. Assess high-Z + liquid Li plasma facing components

Longer-term (5-10 year) goal:

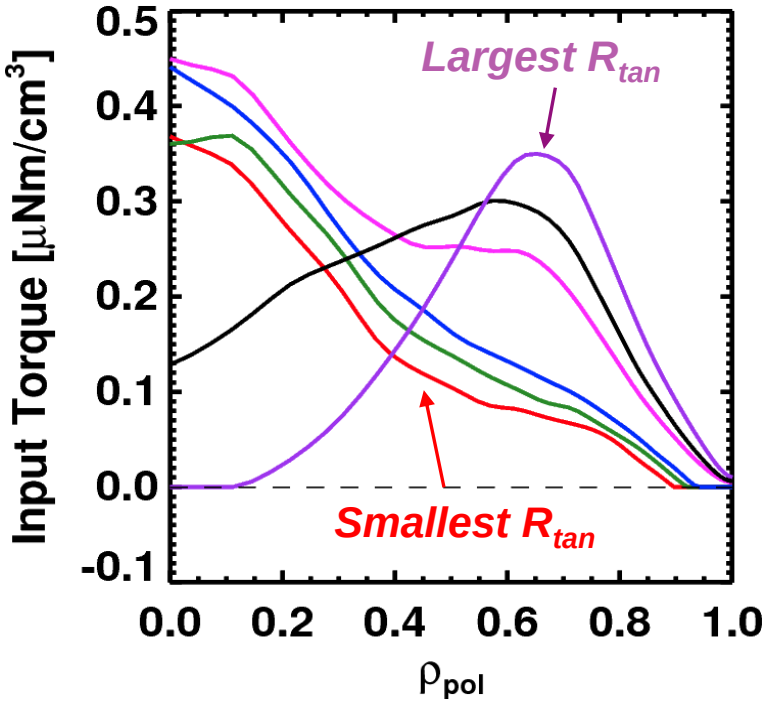
Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

Advanced Scenarios and Control 5 Year Goals:

- 100% non-inductive operation
- Lower ν^*: high-current, partial-inductive scenarios, extend to long-pulse
- Implement axisymmetric control algorithms and tools
  - Current and rotation profile control
  - Improved shape and vertical position control
  - Heat flux control for high-power scenarios
- Develop disruption avoidance by controlled plasma shutdown

Rotation Profile Actuators

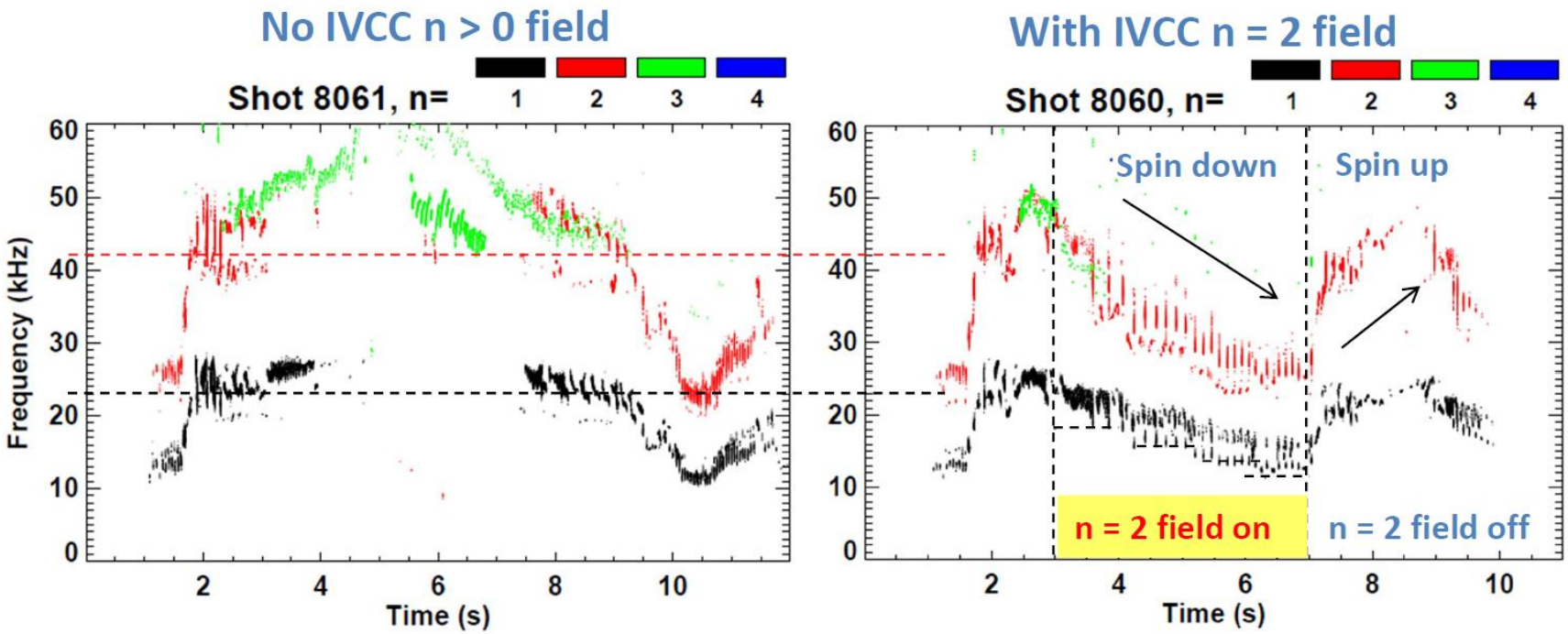
Torque Profiles From 6 Different NB Sources



- **Also torques from 3D fields**

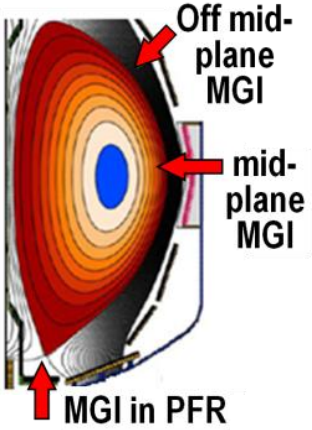
Collaboration opportunity:
KSTAR also using 3D fields for NTV/rotation control, ELM/EF control

KSTAR Data:



Macroscopic Stability 5 Year Goals:

- Study effects of reduced ν^*, q and rotation on LM, RWM, NTM
- Test state-space control for EF, RWM for ITER, next-steps
- Assess 3D field effects to provide basis for optimizing stability through rotation profile control by 3D fields
  - EF penetration, rotation damping, ELM triggering and suppression
- Understand disruption dynamics, develop prediction and detection, avoidance, mitigation
  - Enhance measurements of disruption heat loads, halos
  - Develop novel particle delivery techniques for mitigation:
    - MGI in private-flux-region (PFR), electromagnetic particle injector

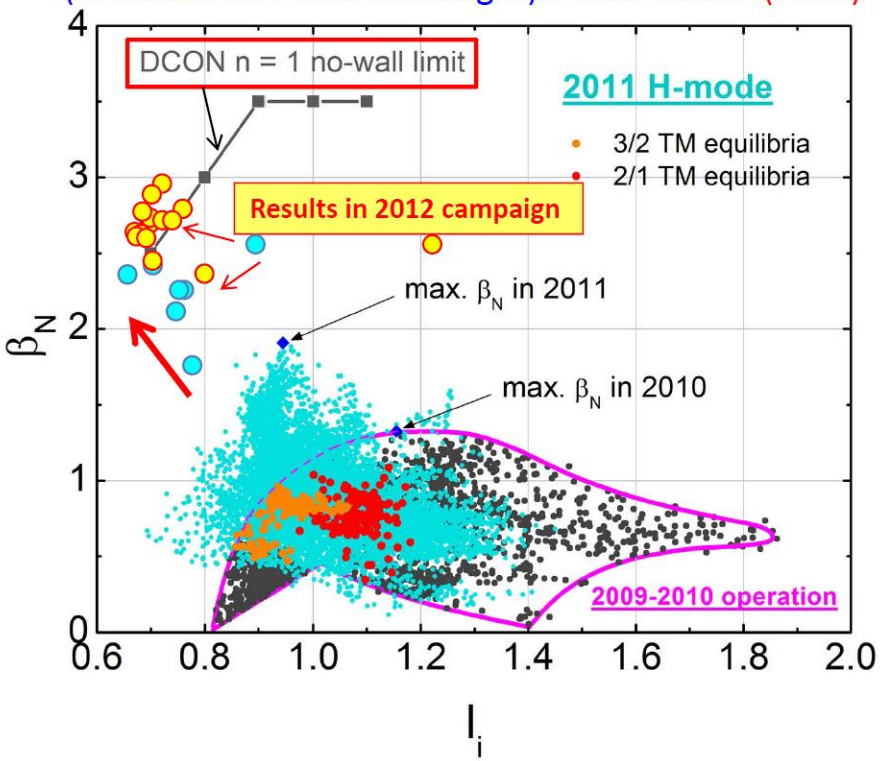


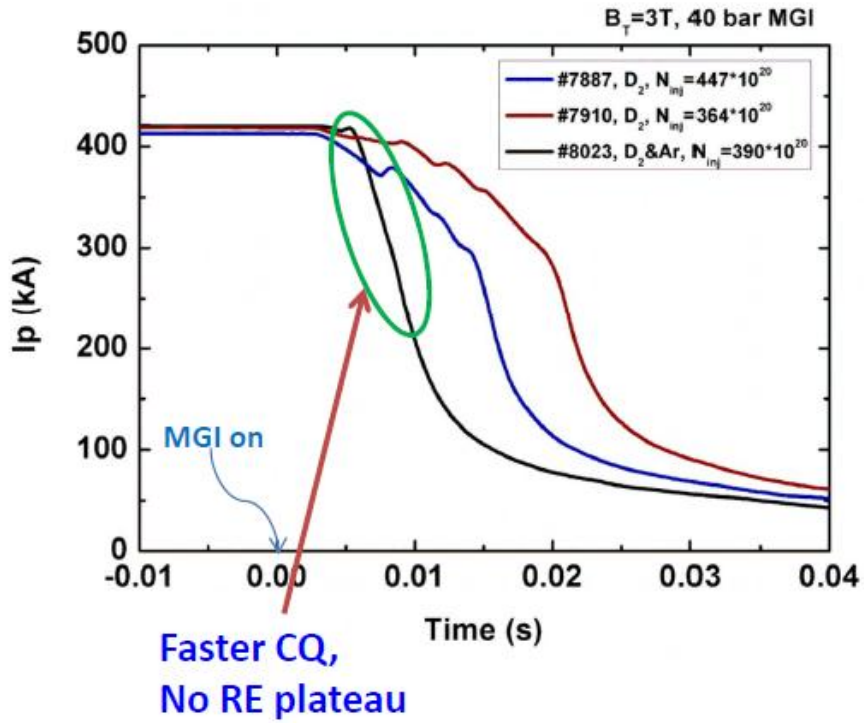
Collaboration opportunity:
KSTAR operating near no-wall stability limit, testing massive gas injection

KSTAR Data:

KSTAR equilibrium operating space 2009 – 2011

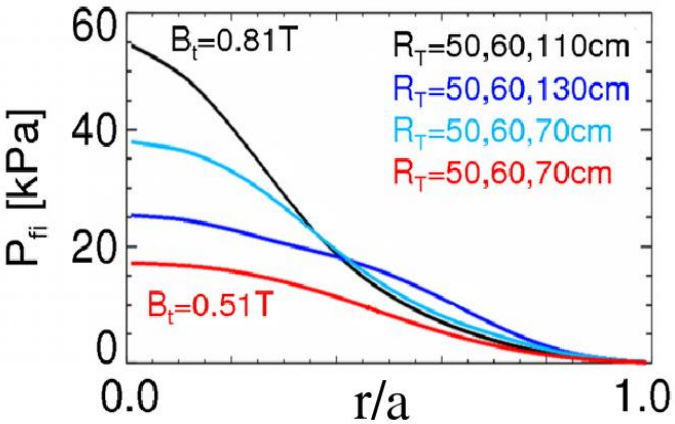
(evolution of > 130 discharges) + new results (2012)





Energetic Particle 5 Year Goals:

- Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER
  - Vary fast-ion instability drive using NBI, q, rotation, 3D fields
  - Measure *AE mode structure
    - Magnetics, BES, reflectometry
  - Characterize fast ion transport vs. *AE type
  - Compare data to simulation, develop reduced models
    - ORBIT, NOVA-K, M3D-K, HYM to understand mode-induced transport



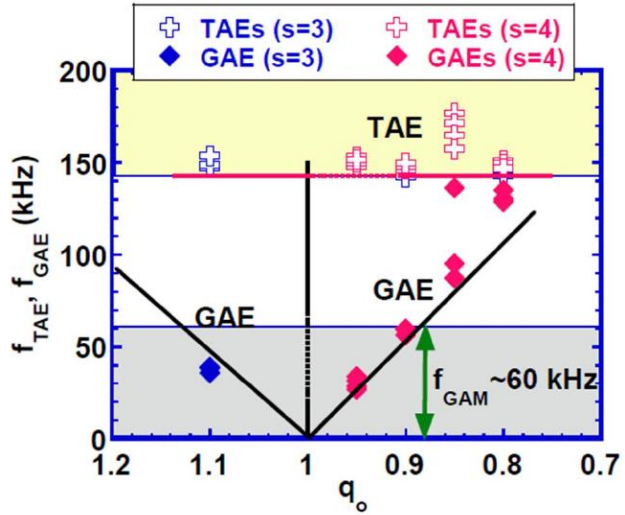
- Assess requirements for fast-ion phase-space engineering
  - AE spectroscopy, also stability control using NBI, q, rotation, 3D fields

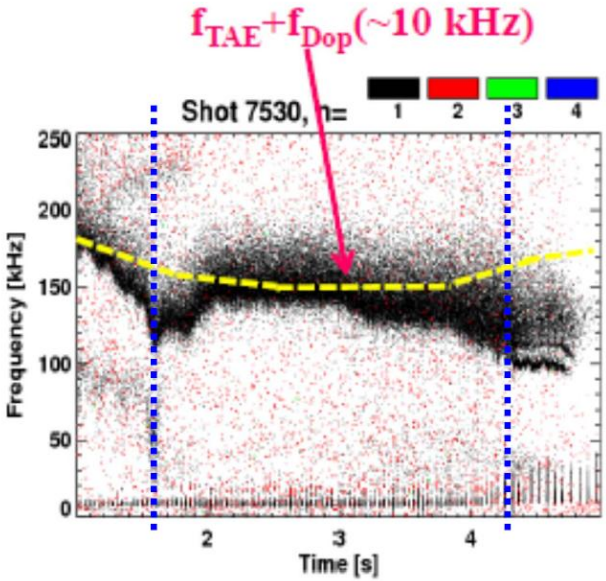
Collaboration opportunity:
KSTAR also observes Alfvén eigenmodes from NBI, fast-ion loss from MHD

KSTAR Data:

GAEs and TAEs in a D-shaped plasma
(AE3D calculation, κ~ 1.7, δ~ 0.2)
q profile with wide low-shear-region
➔ Core localized GAE with $n \neq 0$
q profile with narrow low-shear-region
➔ No GAE

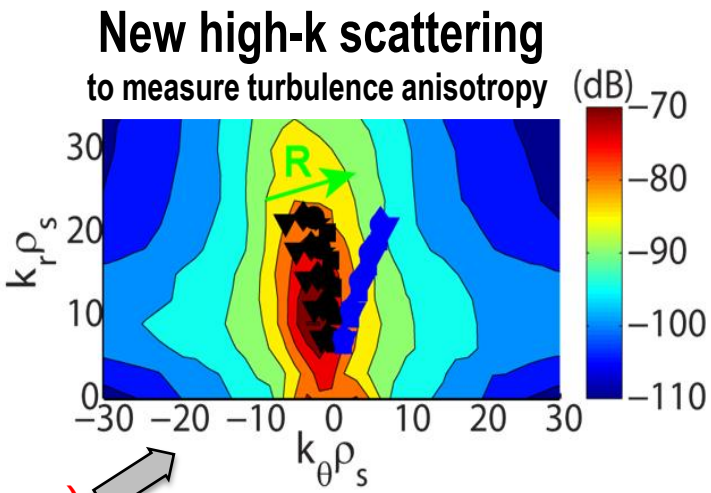
Estimation of q_0 from f_{GAE} (MHD spectroscopy)
q_0 ~ 1.0 ➔ 0.80 (t ~ 1 → 1.5s)
q_0 ~ 0.80 ➔ 0.82 (t ~ 1.5s → 1.8s)
q_0 ~ 0.82 ➔ 0.80 (t ~ 1.8s → 2.2 s)
q_0 ~ 0.80 ➔ 0.82 to 0.9 (t ~ 3.9s → 4.3s)





Transport and Turbulence 5 Year Goals:

- Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U
- Identify modes causing anomalous electron thermal, momentum, particle/impurity transport
  - Exploit scaling dependencies of modes
    - Example: μ-tearing $\chi_e \sim \nu^1$, ETG $\chi_e \sim \nu^0$
  - Relate predicted turbulence to data:
    - Low-k (BES), δB (polarimetry), high k_r & k_θ (μ-wave)
  - **Builds on identification of ETG w/ novel high-k_r scattering in NSTX**

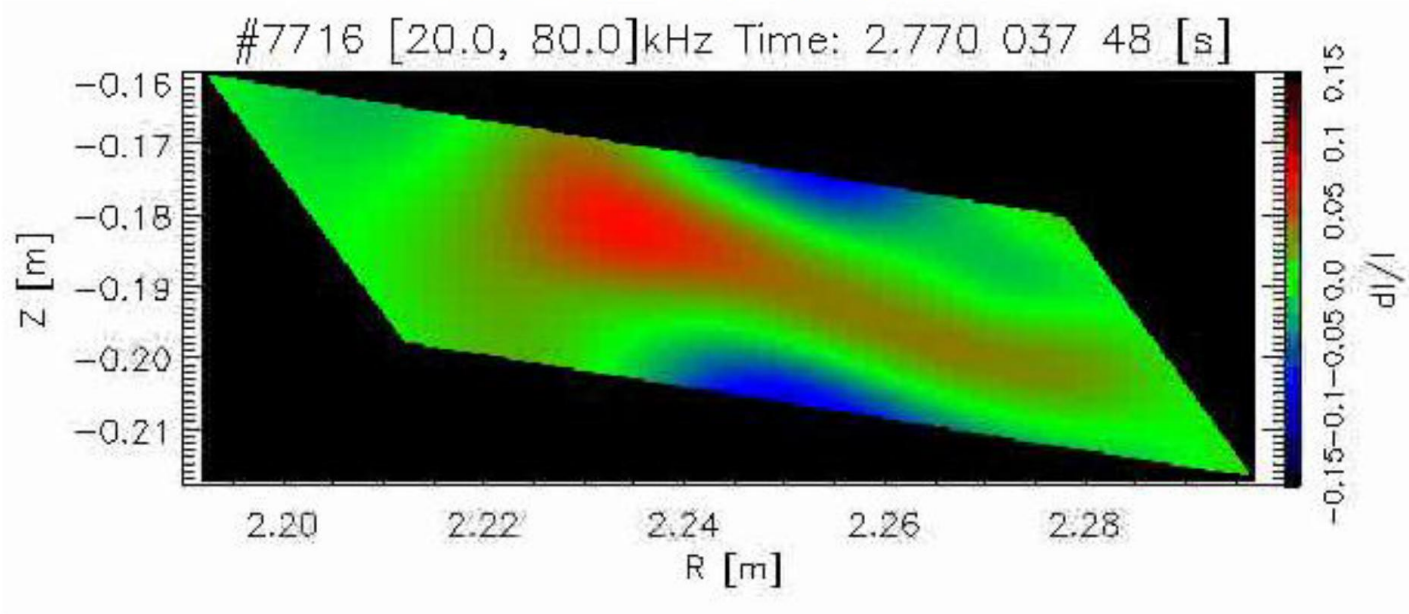


- Establish and validate reduced transport models

Collaboration opportunity:
KSTAR beginning to measure low-k turbulence with BES (also MIR, ECEI)

KSTAR Data:

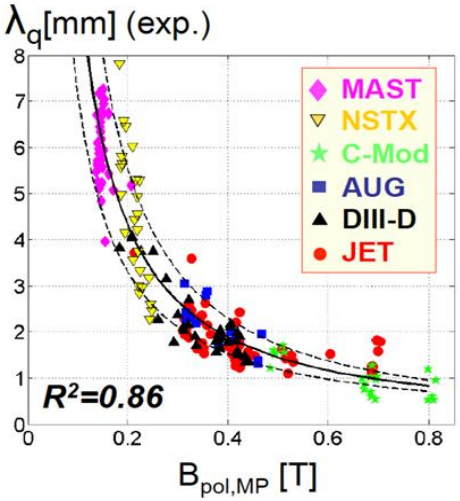
BES Movie for shot 7716



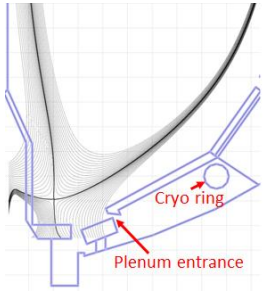
BES raw-data image which shows a poloidal flow velocity

Boundary Physics, SOL/Divertor, PMI 5 Year Goals:

- Assess, optimize, control pedestal structure, transport, stability
- Assess and control divertor heat fluxes
  - Measure SOL widths at lower ν, higher B_T, I_P, P_{SOL}
    - Compare data to fluid and gyro-kinetic models
  - Assess, control, optimize snowflake/X-divertor
  - Develop highly-radiating divertor w/ feedback control
  - Assess impact of high-Z tile row(s) on core impurities



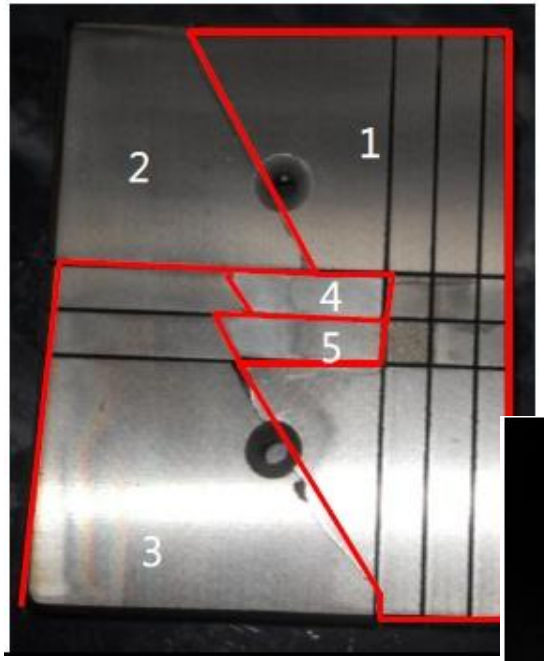
- Establish, compare particle control methods
  - Validate cryo-pump physics design, assess density control
  - Compare cryo to lithium coatings for n_e, impurity, ν^* control

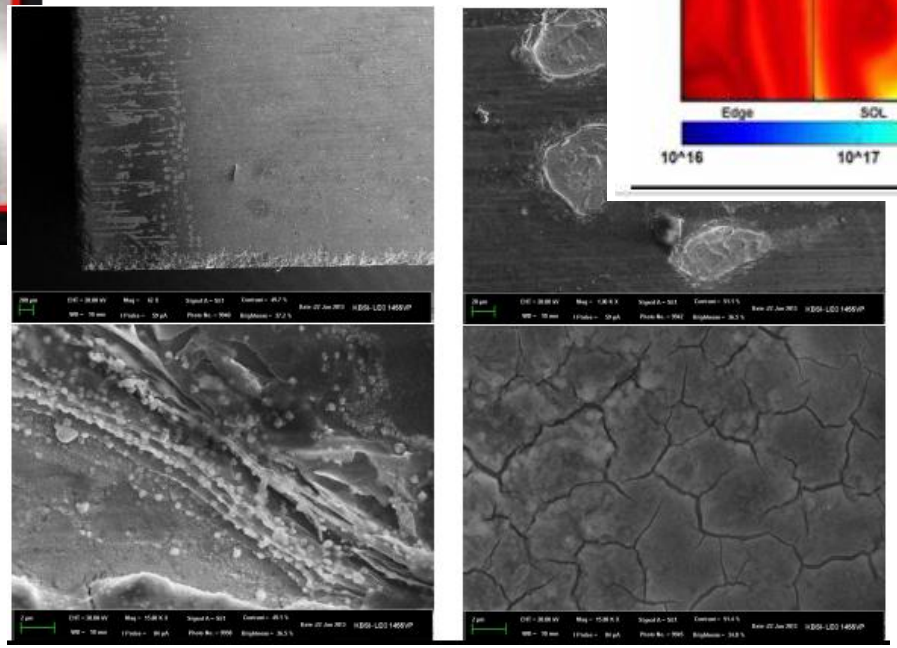


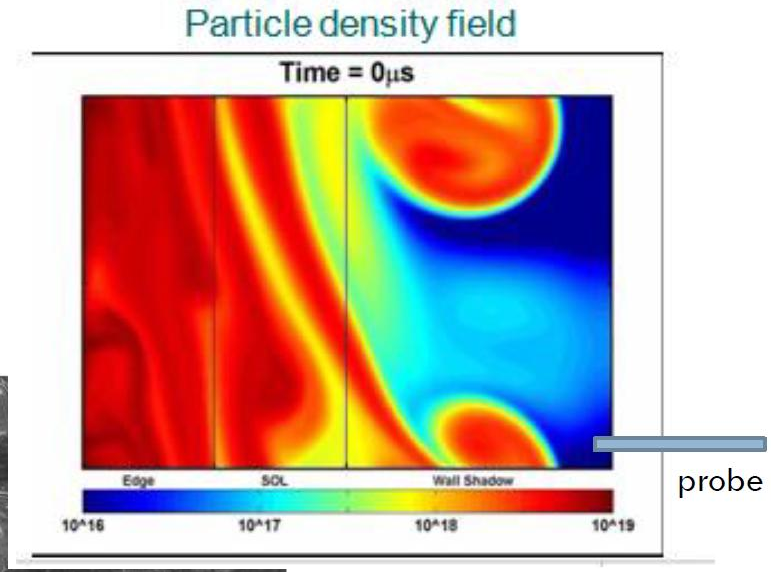
- Explore Li/liquid-metal plasma material interactions
  - Li surface-science, continuous vapor-shielding, material migration and evolution, lab R&D: flowing Li loops, capillary-restrained Li surfaces

Collaboration opportunity:
KSTAR studying castellated W, W surface effects & dust, far-SOL transport

KSTAR Data:







Summary

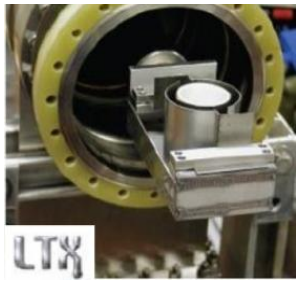
- **NSTX-U and KSTAR research programs have many common goals**
- **Many collaboration opportunities when NSTX-U begins operation in 2015**

Backup

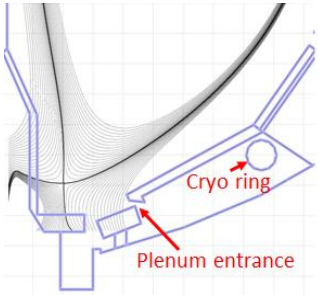
Proposed longer-term facility enhancements: (2014-2018)

- **Improved particle control tools**
  - Control deuterium inventory and trigger rapid ELMs to expel impurities
  - Access low ν^*, understand role of Li

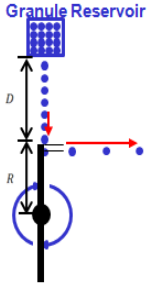
Upward Li evaporator



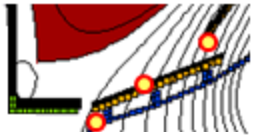
Divertor cryo-pump



Li granule injector (LGI)

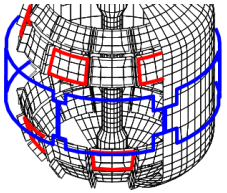


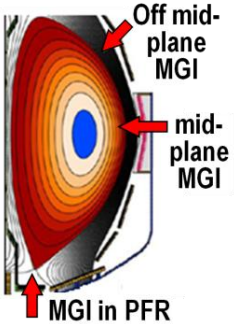
- **Disruption avoidance, mitigation**
  - 3D sensors & coils, massive gas injection



Extended low-f MHD sensor set

Midplane + off-midplane non-axisymmetric control coils (NCC)





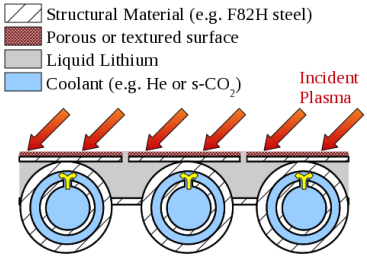
- **ECH to raise start-up plasma T_e to enable FW+NBI+BS I_P ramp-up**
  - Also EBW-CD start-up, sustainment

1-2MW 28 GHz gyrotron

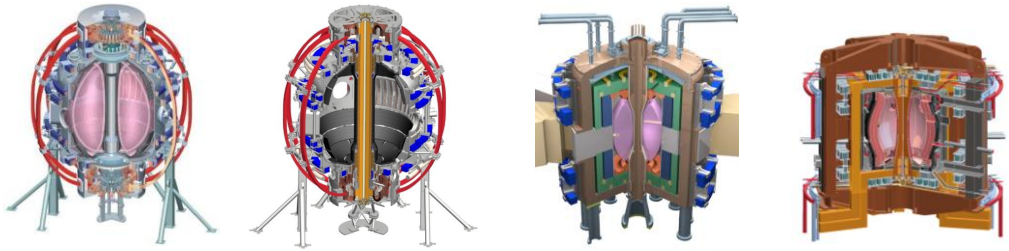
- **Begin transition to high-Z PFCs, assess flowing liquid metals**
  - Plus divertor Thomson, spectroscopy

High-Z tiles

Actively-supplied, capillary-restrained, gas-cooled LM-PFC



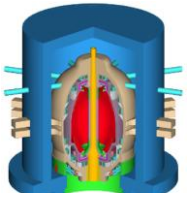
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs



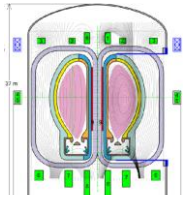
Parameter	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	22 – 45	50 – 85
P/R [MW/m]	10	**20**	30 – 60	70 – 90
P/S [MW/m^2]	0.2	**0.4-0.6**	0.6 – 1.2	0.7 – 0.9
Fusion Gain Q			1 – 2	2 – 10

**** Includes 4MW of high-harmonic fast-wave (HHFW) heating power***

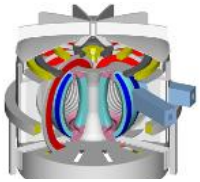
Low-A Power Plants



ARIES-ST (A=1.6)



JUST (A=1.8)



VECTOR (A=2.3)

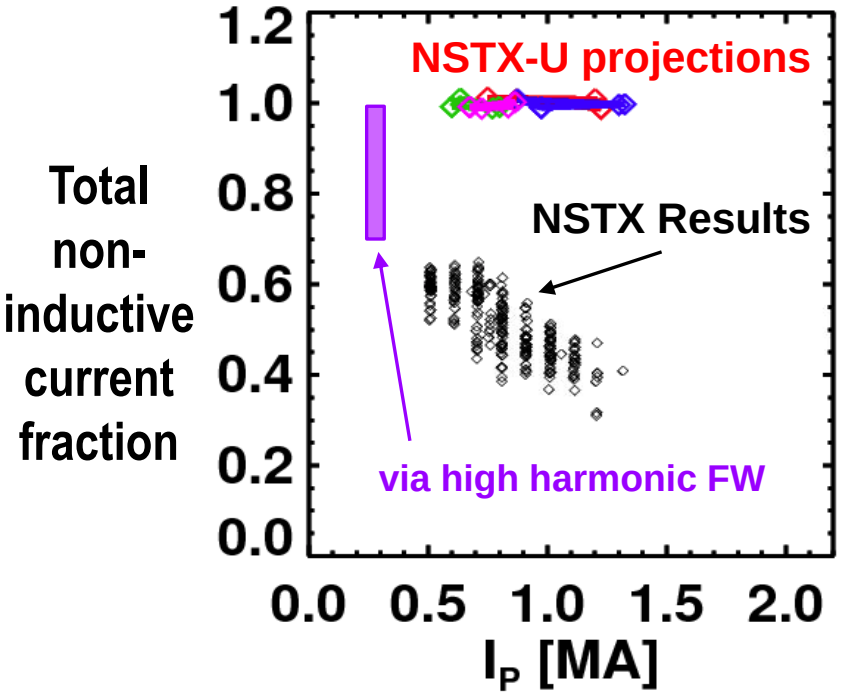
Key issues to resolve for next-step STs

- **Non-inductive start-up, ramp-up, sustainment**
- **Confinement scaling (esp. electron transport)**
- **Stability and steady-state control**
- **Divertor solutions for mitigating high heat flux**

TRANSP simulations support goal of accessing and controlling 100% non-inductive plasma operation

NSTX achieved:

- Maximum sustained non-inductive fractions of 65% w/NBI at I_P = 0.7 MA
- 70-100% non-inductive transiently with HHFW current-drive + bootstrap

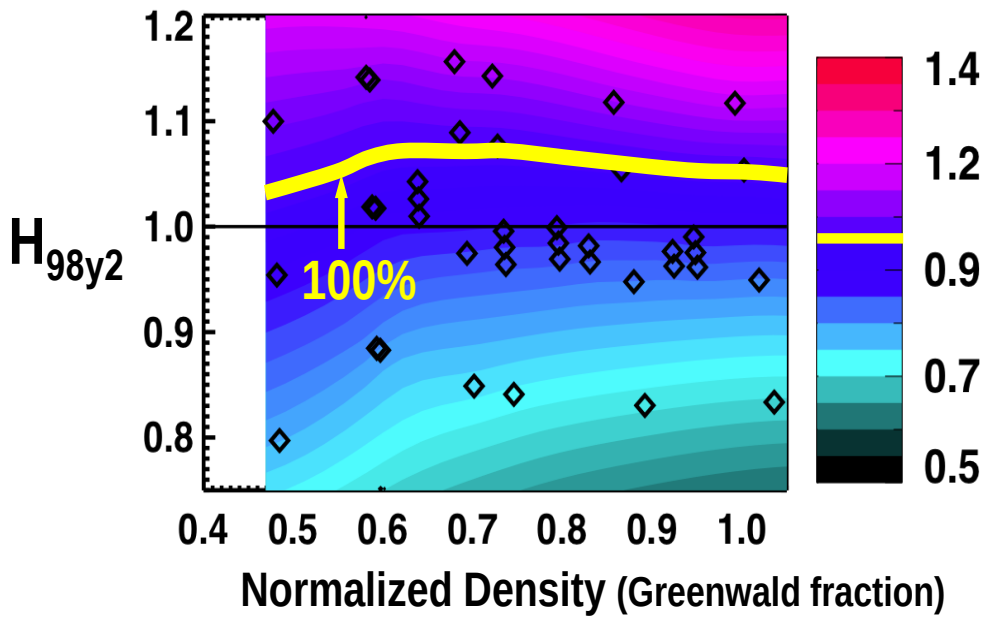


NSTX-U projections (TRANSP):

- 100% non-inductive at I_P = 0.6-1.3MA for range of power, density, confinement

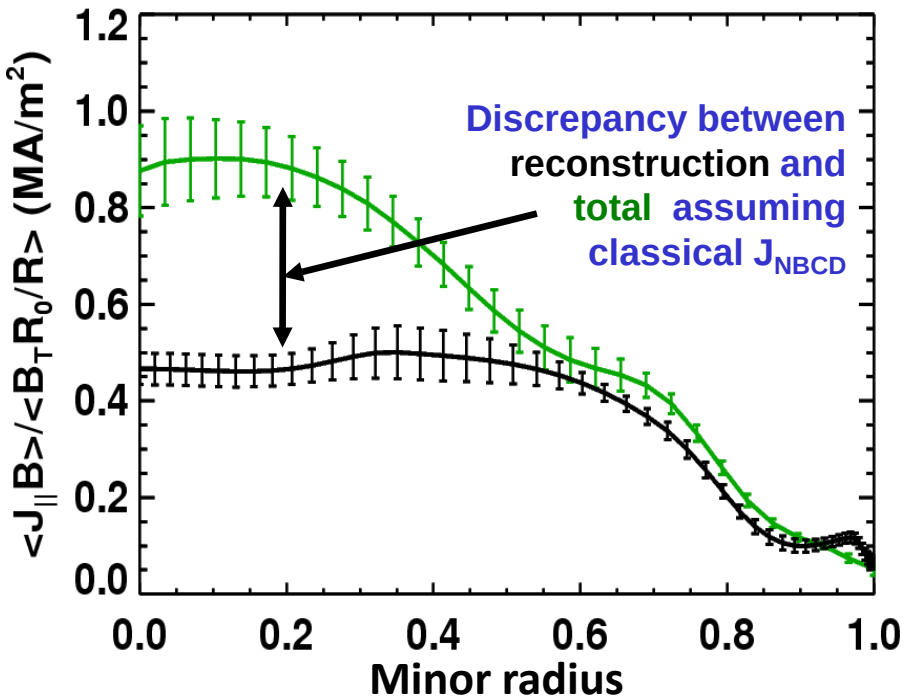
I_P=1 MA, B_T=1.0 T, P_{NBI}=12.6 MW

Contours of Non-Inductive Fraction



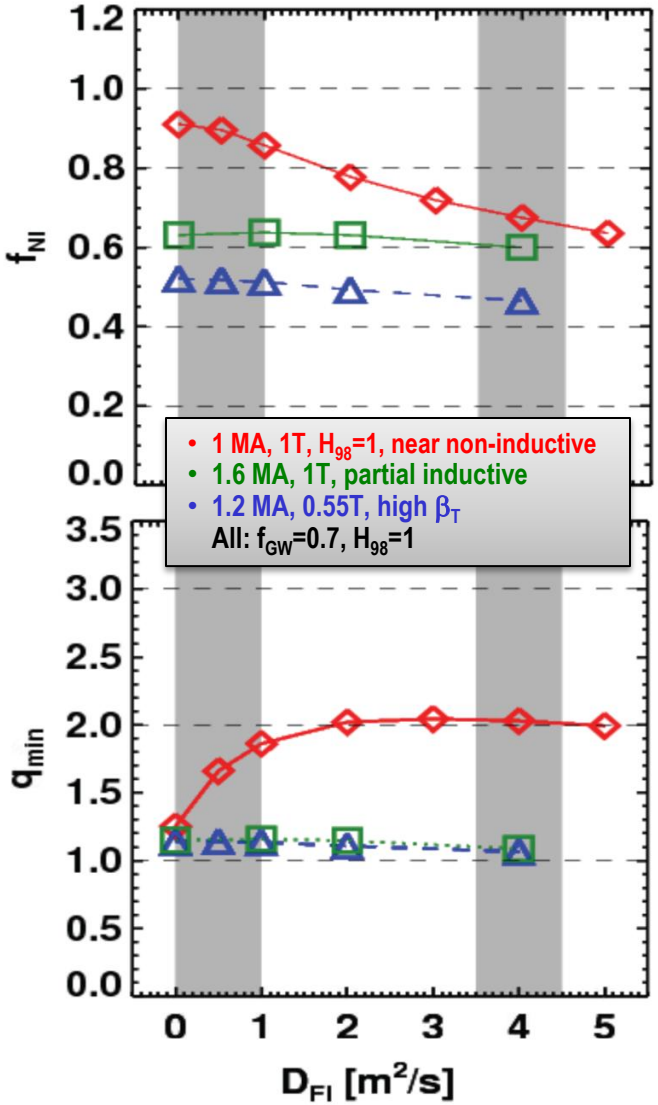
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

NSTX: rapid avalanches can lead to redistribution/loss of NBI current drive

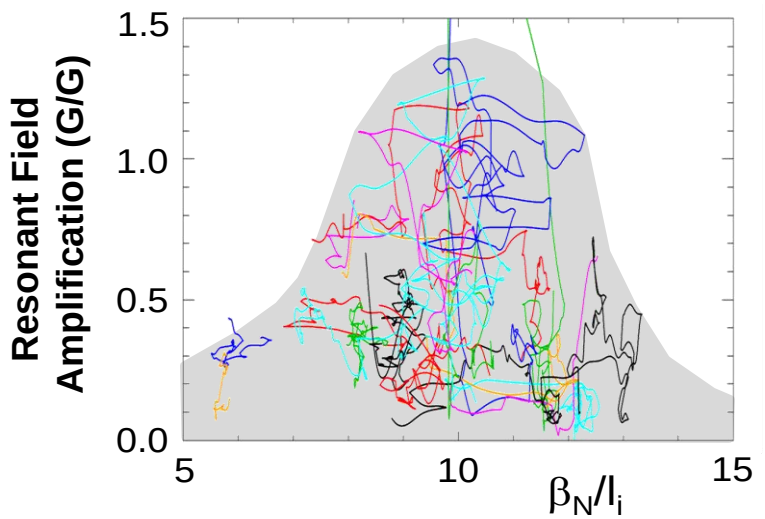


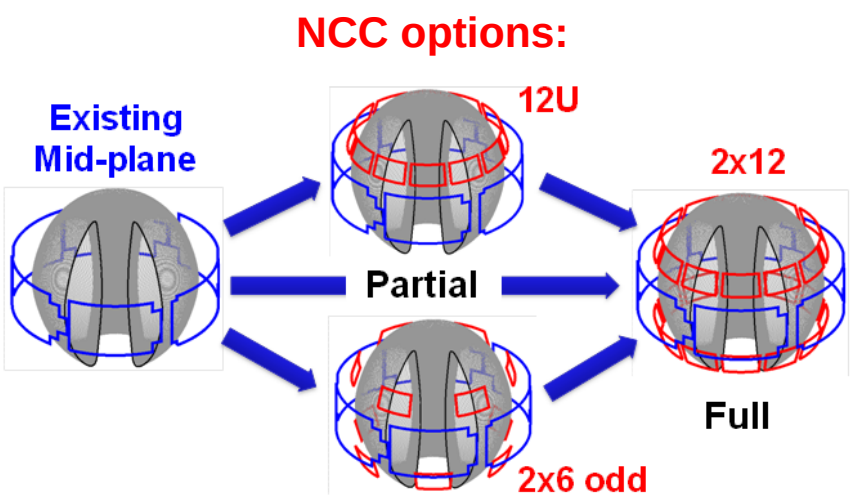
700kA high-β_P plasma with rapid TAE avalanches has time-average D_{FI} = 2-4m^2/s

NSTX-U TRANSP simulations



NSTX/NSTX-U is making leading contributions to high-β_N stability physics, and assessing possible 3D coil upgrades

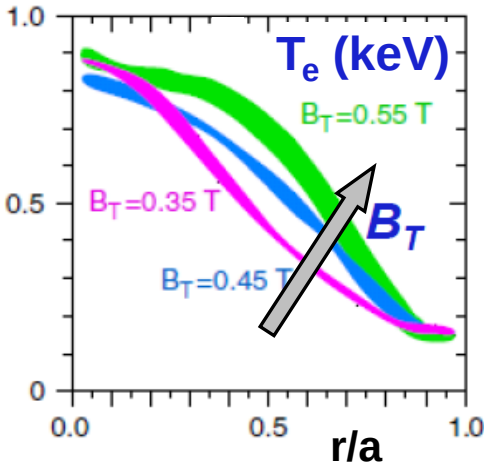




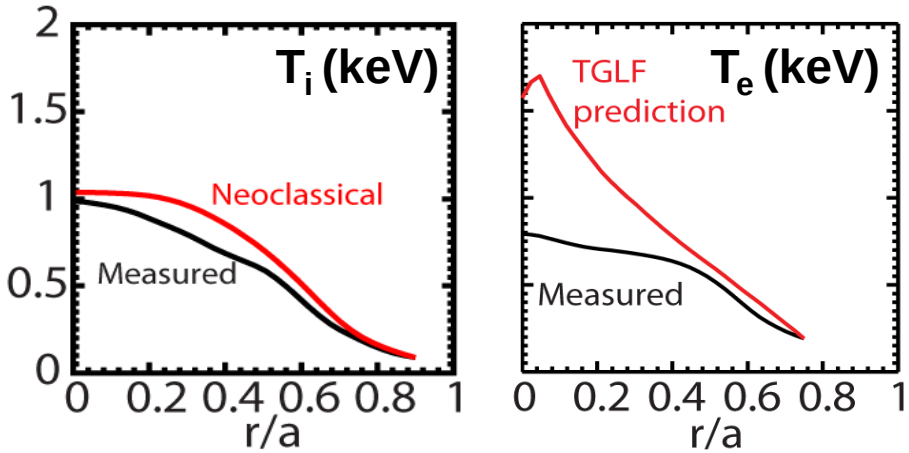
- n=1 MHD spectroscopy: high β_N can be more stable
  - Combination of rotation and current profile effects at high beta
  - Important for advanced scenarios
- Identified several off-midplane 3D coil sets favorable for profile and mode control
  - ~40% increase in n=1 RWM β_{active} / $\beta_{no\text{-}wall}$
  - ~5x reduction in n=1 EF resonant torque
  - ~10-100x variation in ratio of non-resonant to resonant n=3 torque in edge
    - Important for control, understanding of RMP ELM control, NTV rotation profile control

Beginning to test/utilize transport models to predict NSTX temperature profiles, identify possible missing physics

- NSTX H-modes showed broadening of T_e profile as B_T was increased
  - Similar broadening trend observed with increased lithium deposition
  - $B_T\tau_E$ scales as ~$1/\nu^*$ in both datasets



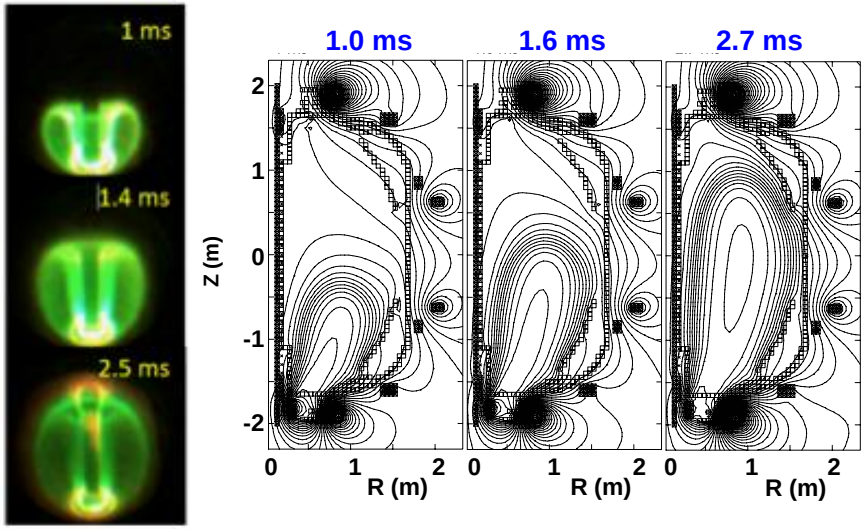
- Utilizing neoclassical + drift wave models to simulate NSTX T_i and T_e profiles (collaboration with GA)
  - Need model for χ in edge region
  - Discrepancy in core T_e prediction for beam-heated H-modes



- Over-prediction of core T_e in NSTX may be due to transport from GAE/CAE modes not included in gyro-Landau-fluid model

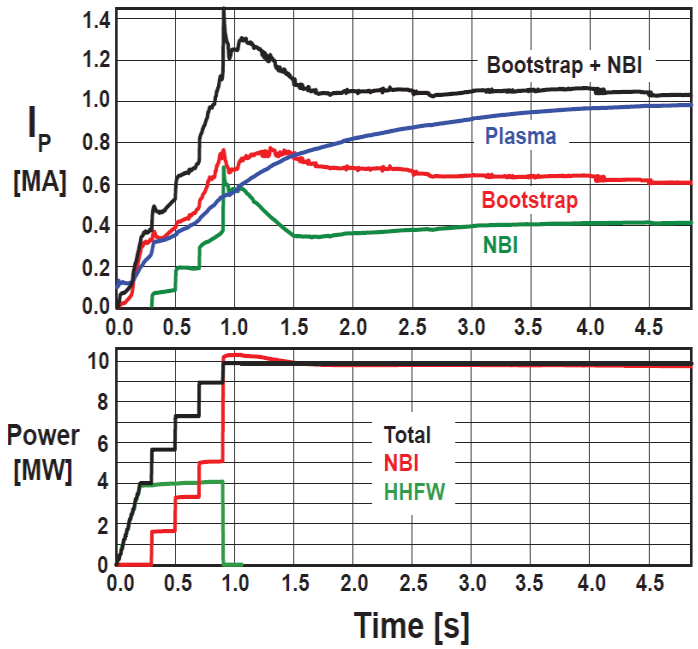
Simulations support non-inductive start-up/ramp-up strategy

- TSC code (2D) successfully simulates CHI I_P ~200kA achieved in NSTX



- TSC + tools included in 5 year plan support CHI I_P → 400kA in NSTX-U
  - Higher injector flux, toroidal field, CHI voltage
  - 1MW 28GHz ECH (increases T_e)

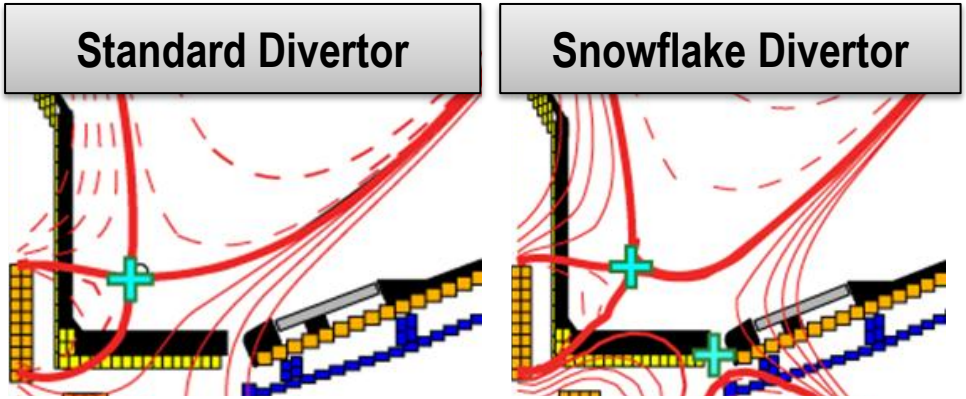
- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
- TSC: non-inductive ramp-up from 0.4MA to 1MA possible w/ BS + NBI

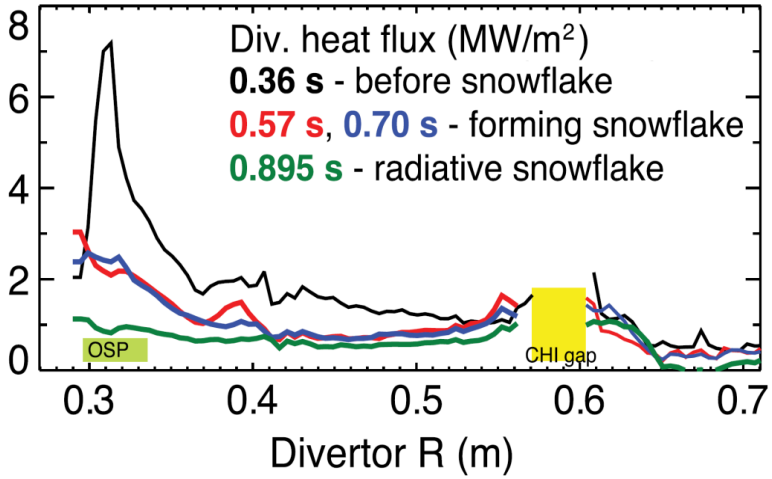


- But, RF heating (ECH and/or HHFW) of CHI likely required to couple to NBI

Snowflake divertor effective for heat flux mitigation

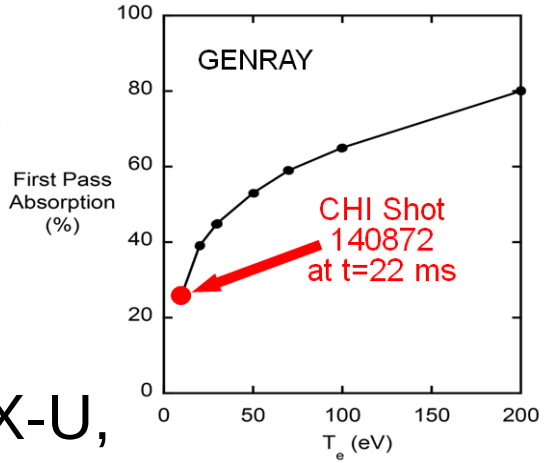
- NSTX: can reduce heat flux by 2-4× via partial detachment
- Snowflake → additional x-point near primary x-point
  - NSTX: High flux expansion = 40-60 lowers incident $q_{\perp}$
  - Longer field-line-length promotes temperature drop, detachment





Start-up/Ramp-up + RF Heating/Current Drive Goals:

- Test higher-current CHI start-up (~400kA)
- Test NBI + bootstrap current overdrive/ramp-up
- Develop HHFW and EC heating for fully non-inductive plasma current start-up and ramp-up
  - Extend HHFW to higher power (3-4MW), demonstrate HHFW-driven 100% non-inductive at 300-400kA
    - Goal: maintain I_P to confine 2nd NBI fast-ions
  - Use ECH (~1MW, 28GHz), then HHFW to increase T_e of CHI plasmas for NBI
  - Test high-power EBW to generate start-up current - builds on MAST results

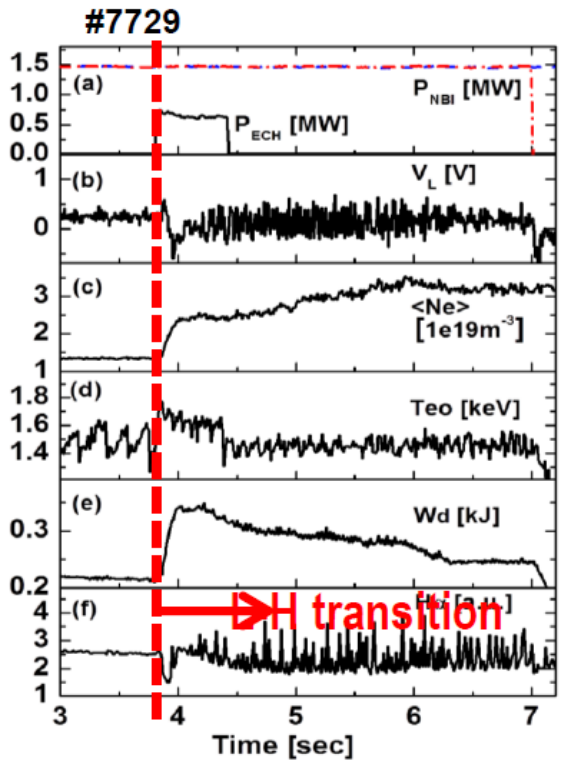
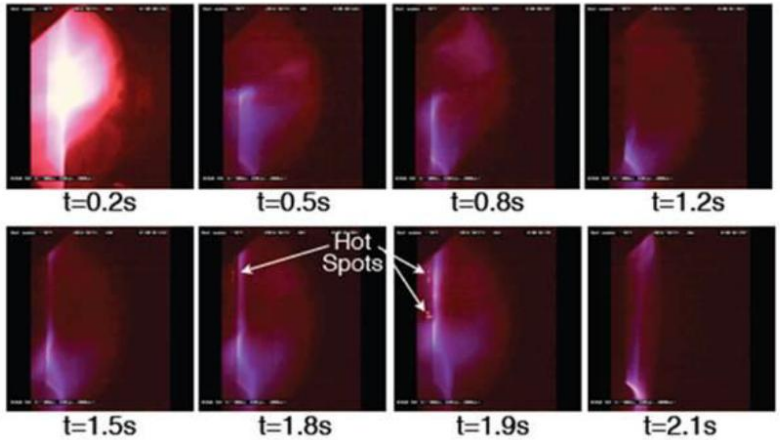


- Validate advanced RF codes for NSTX-U, predict RF performance in ITER and FNSF

Collaboration opportunity:
KSTAR using ECH, developing ICRF, testing non-solenoidal start-up (Kyoto)

KSTAR Data:

170 GHz ECH triggered L-H transition



- Ip ~ 12 kA achieved
- Bt = 3 T
- 84 GHz, 180 kW (2 s); 170 GHz, 450 kW (200 ms)