NSTX

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NSTX FY2011 Year-End Report

Facility and Diagnostic Upgrades, Research Highlights

Masayuki Ono and Jon Menard

for the NSTX Research Team

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
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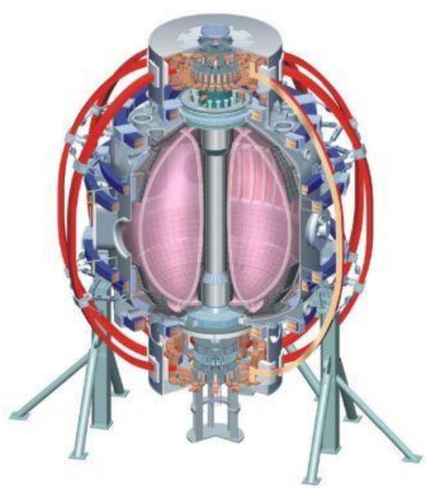
Videoconference with FES
PPPL - B205
October 27, 2011



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ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
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ASCR, Czech Rep

Outline

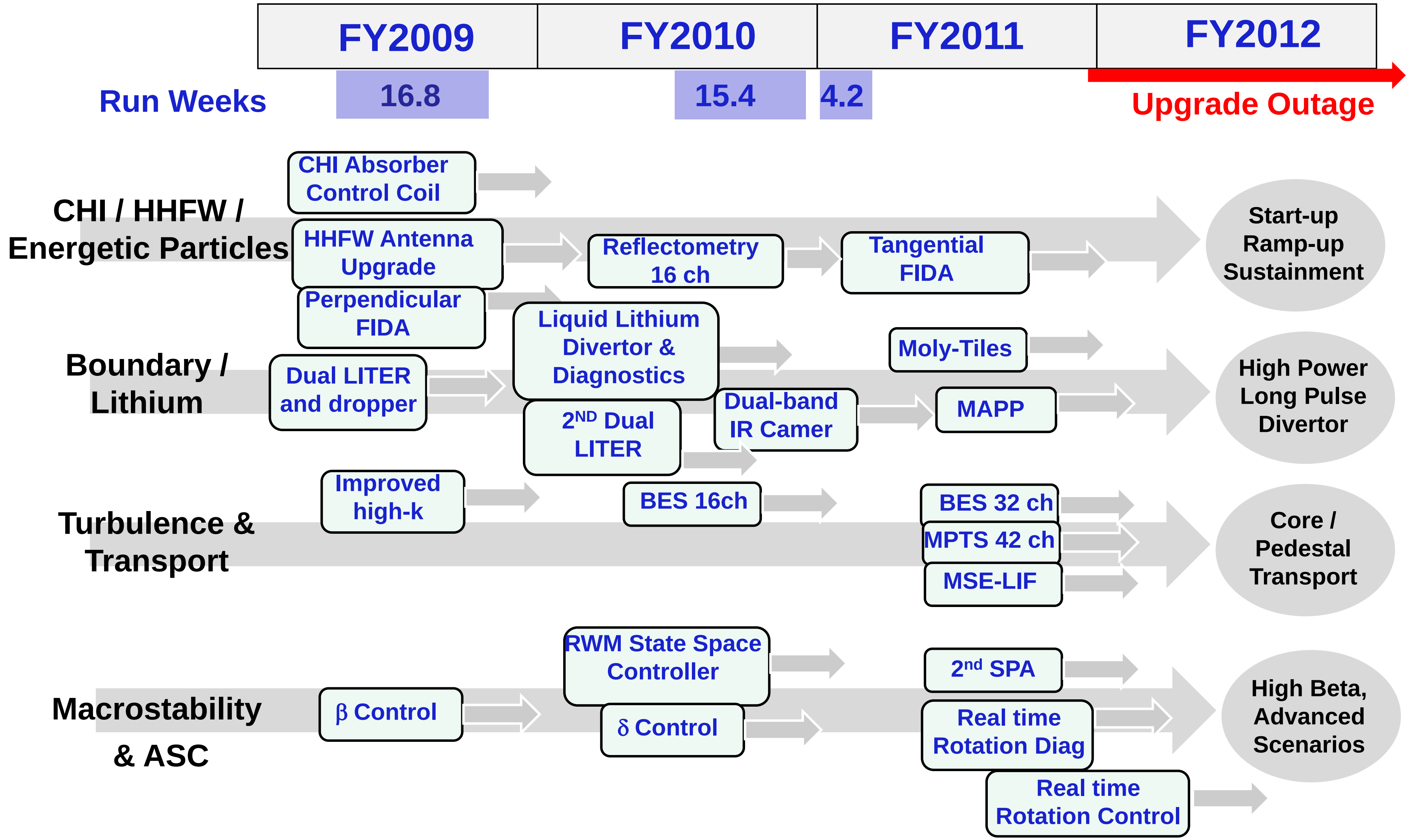
- Milestones
- Facility and Diagnostic Overview
- Research Results
- Summary

NSTX FY2011 Milestones

- **DOE Joint Research Target:** *"Improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone."* (Completed)
- **R(11-1):** Measure fluctuations responsible for turbulent electron, ion and impurity transport. (Completed)
- **(R11-2)**: Assess ST stability dependence on plasma aspect ratio and boundary shaping. (Completed)
- **R(11-3)**: Assess very high flux expansion divertor operation. (Completed)
- **R(11-4)**: H-mode pedestal transport, turbulence, and stability response to 3D fields. (Partially completed)
- **F(11-1):** Operate NSTX Facility for 14 Experimental Run Weeks. (Not completed)
- **D(11-1):** Complete the commissioning of a real-time plasma velocity (RTV) diagnostic system. (Completed)
- **AF(11-1):** Complete commissioning of facility upgrades. (Completed)
- **AD(11-1):** Complete commissioning of diagnostic upgrades. (Completed)

The final year-end reports submitted to DOE. Also reported at ISTW-2011

NSTX Facility Overview
To Support NSTX Mission Elements and Upgrades



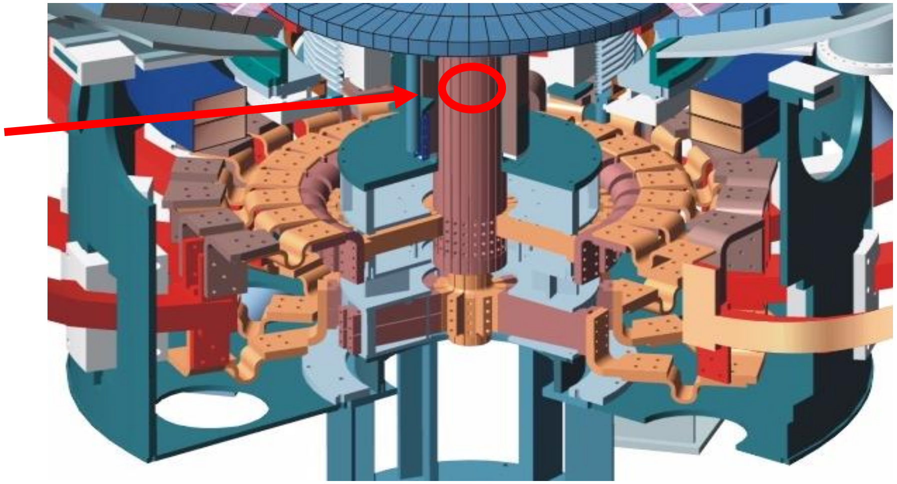
Facility Milestone F(11-1): Operate NSTX Facility for 14 Experimental Run Weeks (Target – Sept. 2011, 4.21 run weeks completed – Oct. 2010)

- **Achieved 4.2 run weeks with 839 plasma shots on October 25, 2010 which represents a record ~ 200 plasma shots per run week.**
- **Completed the 2011 outage including diagnostic installations and calibrations in June 2011 and prepared to resume operation.**
- **During the recommissioning ISTP, an electrical failure in the toroidal field (TF) coil inner bundle occurred on July 20, 2011**
- **Dissection of the bundle revealed that the fault was caused by a gradual deterioration of the insulation by residues of a flux containing zinc-chloride used during fabrication of the TF bundle in 2003.**
- **A panel of external experts in magnet construction conducted an independent review of the TF failure on September 7, 2011 endorsing the findings.**
- **After carefully assessing options, it was decided to proceed directly to the planned NSTX Upgrade Project outage as this would result in an acceleration of its upgrade schedule by about six months.**
- **A number of improvements will be implemented in manufacturing the new TF bundle for the upgrade.**

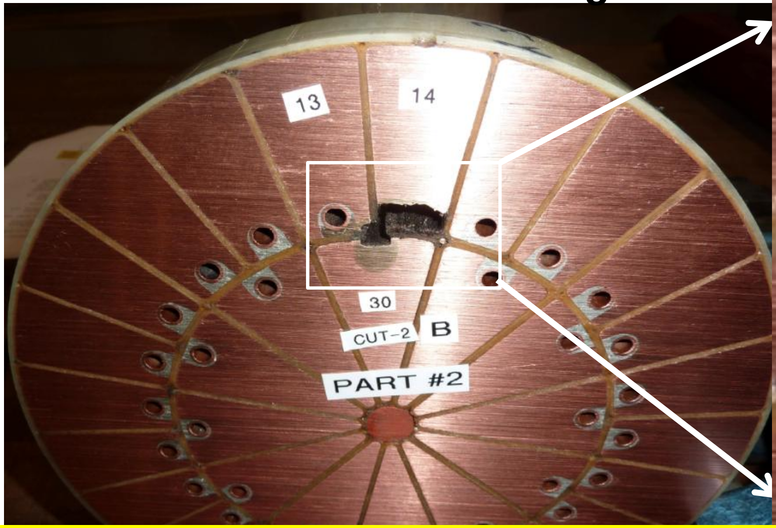
NSTX TF Fault Occurred on July 20, 2011

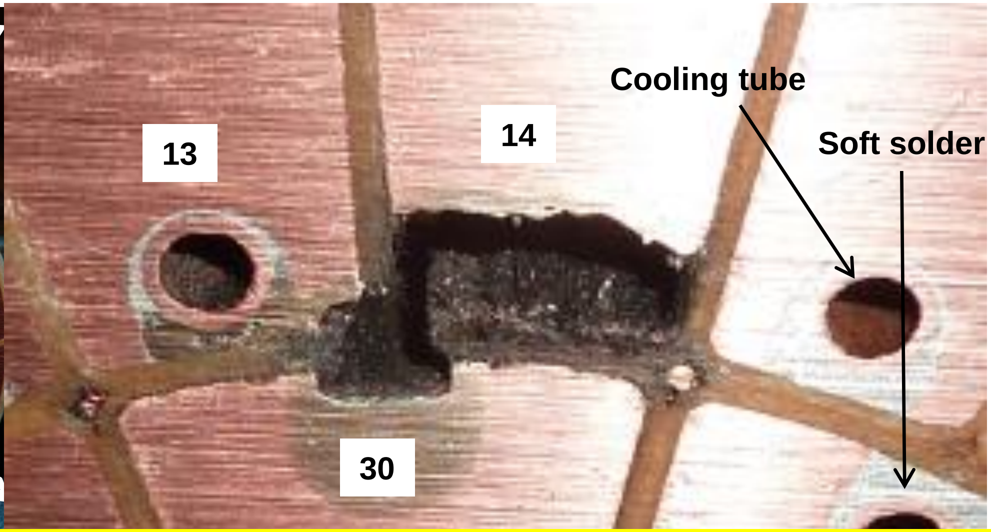
TF Bundle Operated for 7+ years for 20,000 shots

- TF bundle short occurred ~ 2 feet from the bottom in a relatively low mechanical stress area.
- TF bundle dissection and analyses showed no sign of fatigue.
- Zinc chloride based flux used for cooling water tube soldering was the cause of insulation failure.



Dissection of shorted region

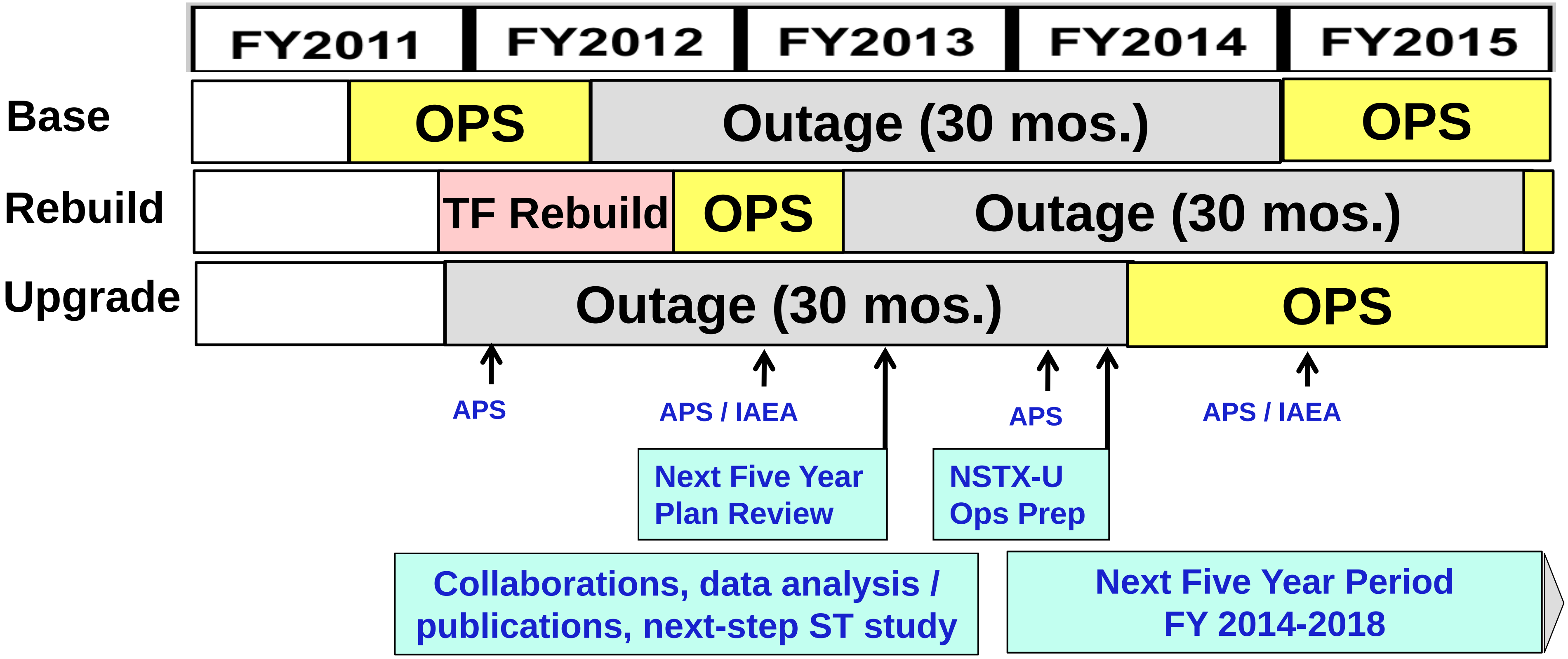




TF Upgrade will use rosin flux and change the procedures for removing the flux residues

Upgrade acceleration maximizes NSTX run time and scientific productivity over next 5 yr period (2011-15)

Option:	Pre-Upgrade Ops	Post-U pgrade Ops	Total Ops
Base plan	8 months	12 months	20 months
Rebuild TF	7 months	2 months	9 months
Upgrade	0	19 months	19 months



ARRA Funding Greatly Enhanced Research Capability

Planned ARRA Upgrades Completed on Schedule

Enhanced operation of Major Fusion Facilities in FY09 and FY10

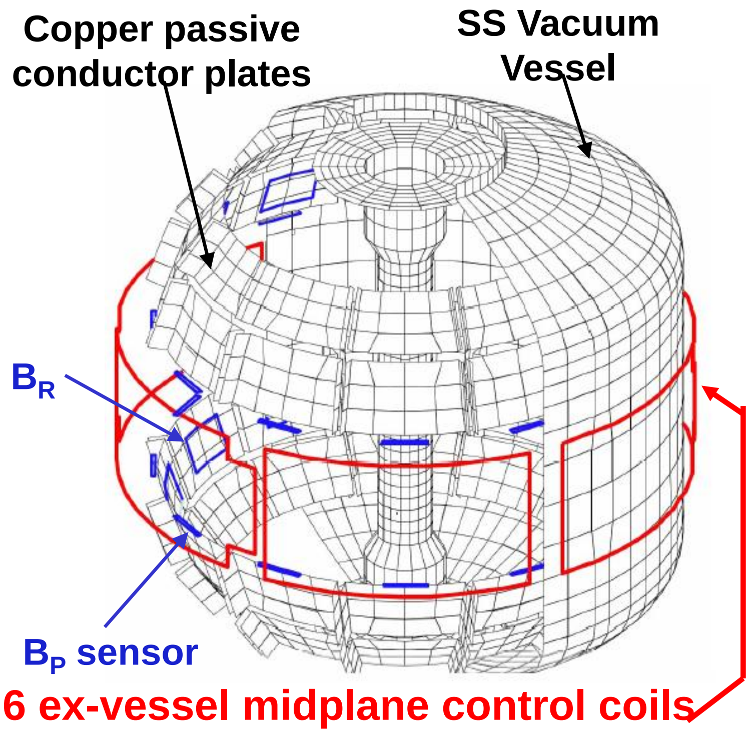
- 5 extra run weeks in FY 09 and one extra in FY 10 enabled the NSTX researchers to conduct high priority fusion plasma experiments.

Diagnostics and Facility Upgrades in FY 09 - 11:

- Extra 12 channels for the multi-pulse Thomson scattering system for improved H-mode pedestal and plasma edge spatial resolution to support the FY 11 joint research milestone.
- Motional Stark Effect Laser Fluorescence advanced diagnostic system for internal magnetic and electric field measurements was installed.
- Enhancement to the liquid lithium divertor target capability for modifying edge collisionality, including two lithium evaporators, LLD diagnostics and molybdenum tiles on the inboard divertor.
- Post Doctoral Fellows to support the enhanced research capabilities.
- 2nd switching power amplifier system for improved error field/resistive wall mode/resonant magnetic perturbation spectra to control the edge error field.

2nd SPA Successfully Installed and Commissioned

Sustain β_N and Understand MHD Behavior Near Ideal Limit

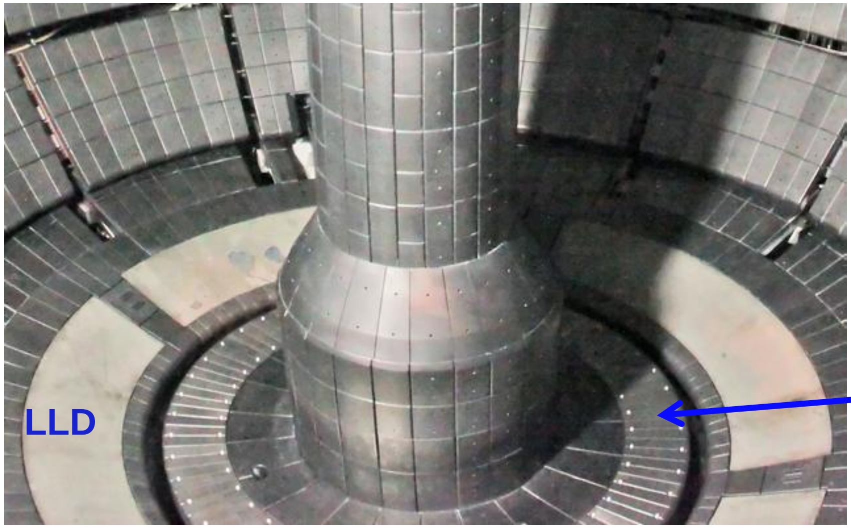


2nd 3-channel Switching Power Amplifier (SPA) comissioned in July 2011 powers independent currents in six EFC/RWM coils for simultaneous control of n = 1, 2, 3 field harmonics

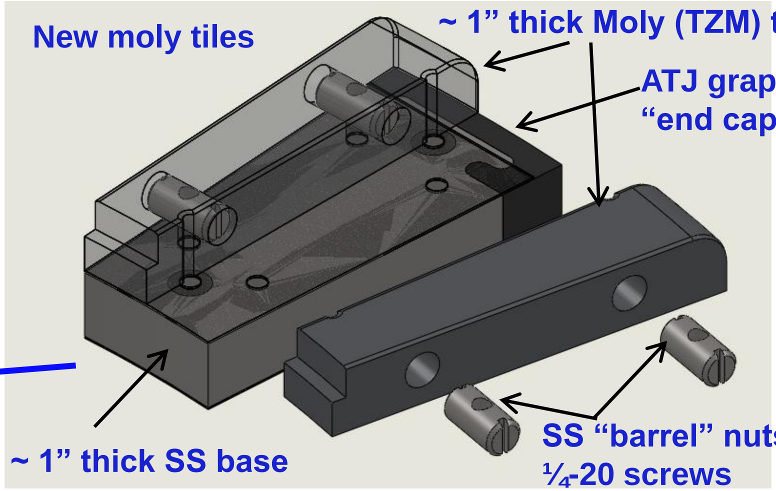
- RWM spectrum dependence
- Rotation and beta effects on NTMs
- Response to 3D fields for EFC, ELM and Neoclassical Toroidal Viscosity physics
- Disruption physics

Molybdenum Tiles Installed for In-Board Divertor

Liquid Lithium Covered Molybdenum Surfaces Reduced Carbon Influx



Split-top Moly on SS tile satisfies design requirements



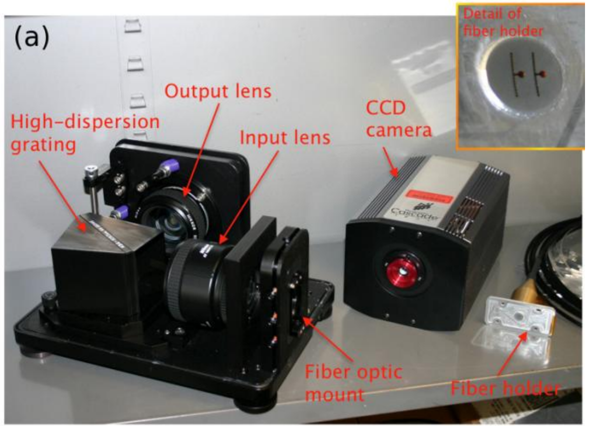
Molybdenum tiles manufactured and installed on inboard divertor in April 2011

- Supported by ARRA funding
- Replace 48 second row tiles with 1" thick molybdenum tiles
- Three tiles contain diagnostics
- Lithium coating with LITER ~ 2 x outer LLD rate
- Plasma heating can liquefy lithium on surface

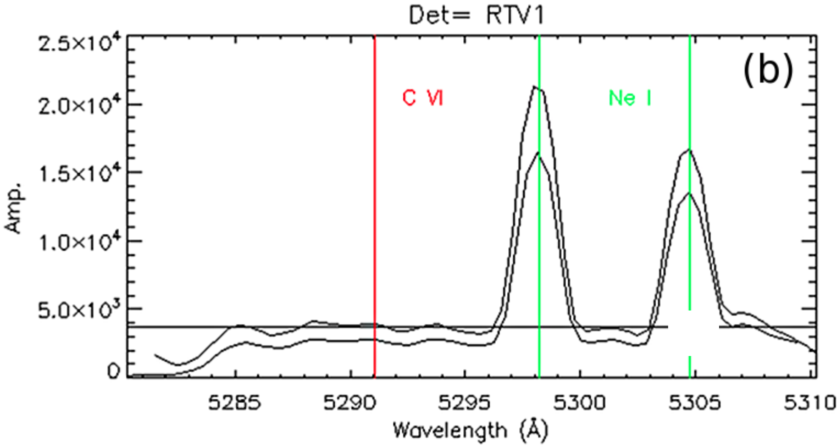
Real Time Velocity Diagnostics Developed
Important Tool for Advanced Plasma Control

A Real-Time Velocity (RTV) diagnostic will be incorporated into the plasma control system for feedback control of the plasma rotation profile using the NBI and non-resonant magnetic braking as the actuators

- **Based on active charge-exchange recombination spectroscopy (CHERS)**
- **Measures at six radial locations and a sampling rate of 5 kHz.**
- **Uses two toroidally separated views to distinguish the heating NB view from the background (intrinsic) contribution.**
- **Installed and commissioned on NSTX in July 2011**

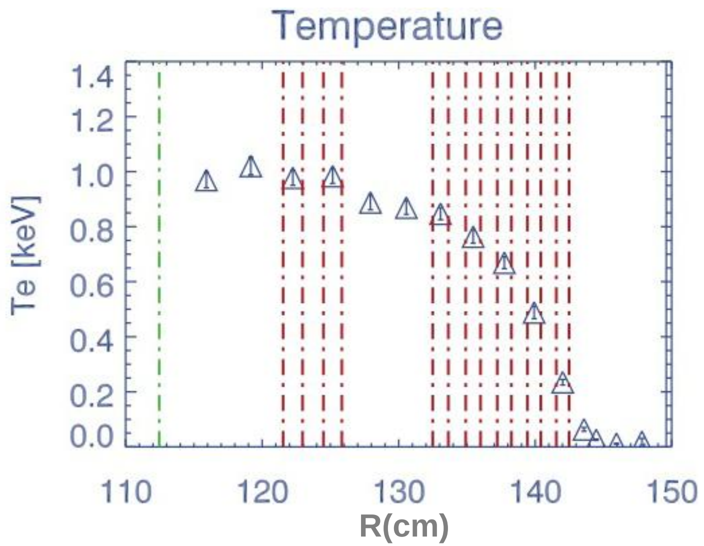


RTV hardware including CCD camera & spectrometer

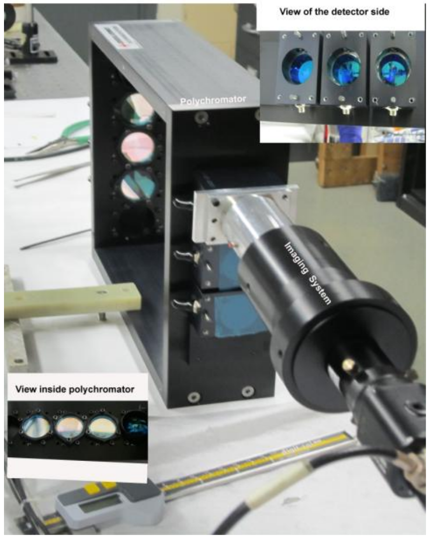


Example of spectra measured on two channels during a Ne glow.

Enhanced Pedestal / Profile Diagnostics
for Pedestal and Core Transport Joint Research Targets



Additional 12 channels enhance resolution in pedestal to ~1 cm and improve diagnosis of ITB in plasma core

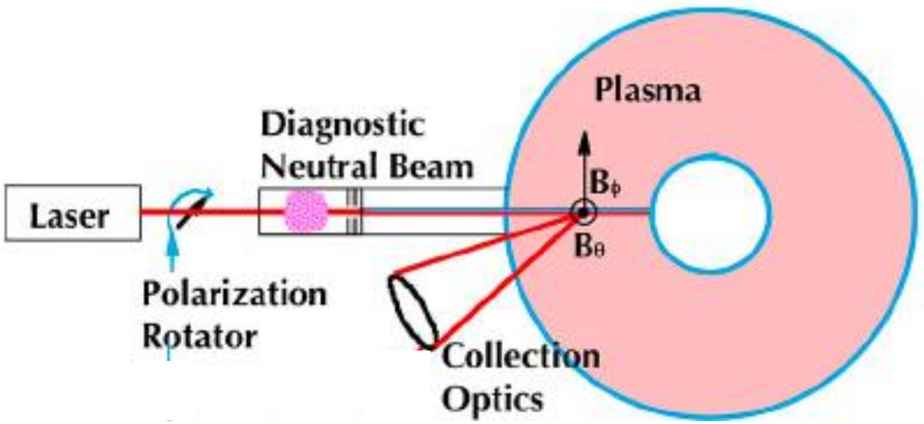


Polychromator assembly

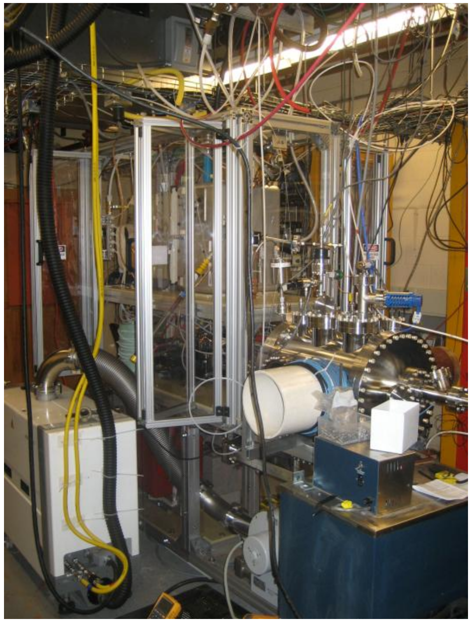
- **Twelve additional channels for the multi-pulse Thomson scattering (MPTS) system were installed and commissioned in July, 2011.**
- **Calibration was performed in situ by employing Rayleigh and Raman scattering of the light from the MPTS laser system by nitrogen and argon introduced into the vacuum vessel**

MSE-LIF Installed for Enhanced Pedestal / Profile Diagnostics
Installed and Commissioned on NSTX in August 2011

The Motional Stark Effect measurement based on Laser Induced Fluorescence (MSE-LIF) diagnostic will provide measurements of the field line pitch angle profile without requiring injection of the heating neutral beam.



Schematic of the MSE-LIF system



Nova Photonics

MSE-LIF system installed on NSTX

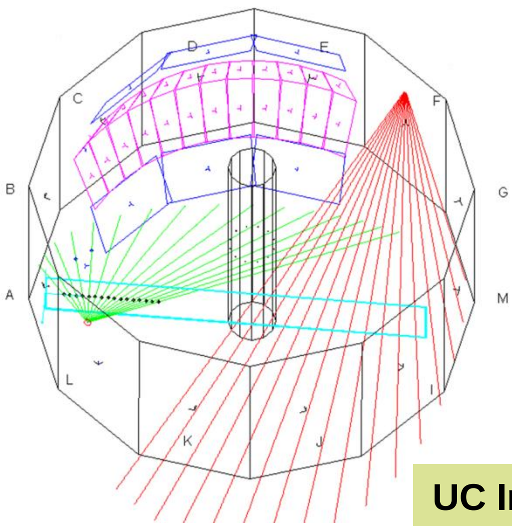
MSE-LIF provides unique capabilities

- **Measure RF-driven current without the heating neutral beam.**
- **Measure total magnetic field in plasma to reconstruct total plasma pressure.**
- **Together with MSE-CIF, yield radial electric field profile**

t-FIDA upgrade was implemented in 2011

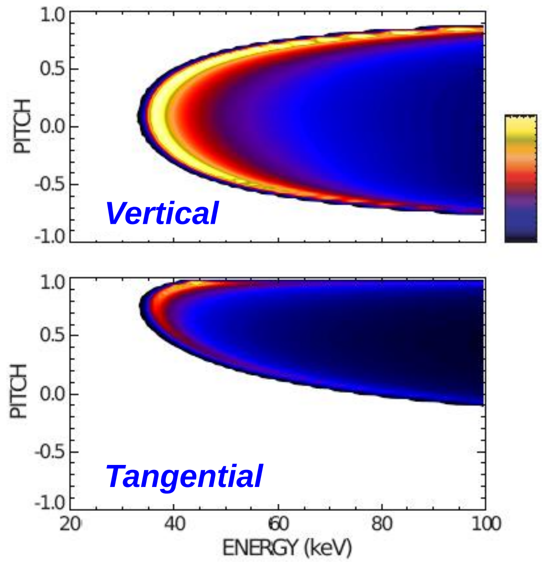
Energetic Particle Capability for α-Physics and NBI CD

Fast Ion D-Alpha Diagnostic Providing Crucial Energetic Particle Data



UC Irvine

Tangential FIDA Views



- A new tangential Fast-Ion Deuterium-Alpha (t-FIDA) diagnostic, with a view mostly tangential to the B field, has been built, installed and commissioned in FY 2011.
- Complements the vertical FIDA, as it measured fast ions parallel to B, particularly valuable for non-inductive current drive research in the NSTX Upgrade.
- The observation geometry with both active and background views has been aligned to an accuracy < 5 mm at the measurement location.

Additional Facility and Diagnostic Capabilities Led by Collaborators Became Available in FY 2011

- **Upgraded 32 channel Beam Emission Spectroscopy diagnostic system (U. Wisc.) for low-k turbulence and transport research.**
- **A high resolution tangential Multi-Energy SXR (ME-SXR) array (JHU) for an improved diagnostic of the edge / H-mode pedestal plasma.**
- **Real time density measurement by the FIReTIP system (UCD) to be utilized for density feedback control.**
- **A wide angle, 30 Hz infrared camera system, two tile-mounted eroding thermocouples (response time ~ 1 ms) near the PFC surface, and a set of 16 new filterscope chords (ORNL) were implemented.**
- **A new vacuum-ultraviolet divertor spectrometer (SPRED), a new near-infrared spectrometer, and a new optical Penning gauge (LLNL) for divertor-boundary research.**
- **Massive gas injector (MGI) at two different poloidal locations (U. Wash.) for disruption control optimization. NSTX can offer new insights by injecting gas into the private flux and lower x-point regions.**
- **A single-channel 288 GHz radial polarimeter/interferometer (UCLA) on a Bay G midplane port on NSTX for MHD driven magnetic fluctuations.**

Strong Publications and Conference Participations

Growing Number of Highly Capable Young Researchers

Half of the publications and invited talks were led by collaborators

Publications:

- 58 papers published in 2011 with 15 additional manuscripts being reviewed.
- Six PRLs published in 2011 four of which were led by junior researchers

IAEA and invited talks:

- 25 papers presented at 2010 IAEA meeting, the most for NSTX.
- 10 invited papers presented at 2010 APS meeting, the most for NSTX.
- 12 invited talks given at other conferences.

Honors and Recognitions:

- S. Sabbagh (Columbia) was honored at IAEA for his Nuclear Fusion Paper Award.
- J. Menard (PPPL) and S. Sabbagh (Columbia) were elected APS-DPP Fellows.
- J-K Park (PPPL) received the Rosenbluth Outstanding Doctoral Thesis Award.
- J-K Park received the 2011 Outstanding Young Researcher Award (OYRA) from Association of Korean Physicists in America (AKPA)
- NSTX received the State of New Jersey Commissioner of Labor and Workforce Development’s 2010 Continued Excellence Award for working 10 consecutive years (2,011,666 hours) without an away from work lost time injury/illness case.

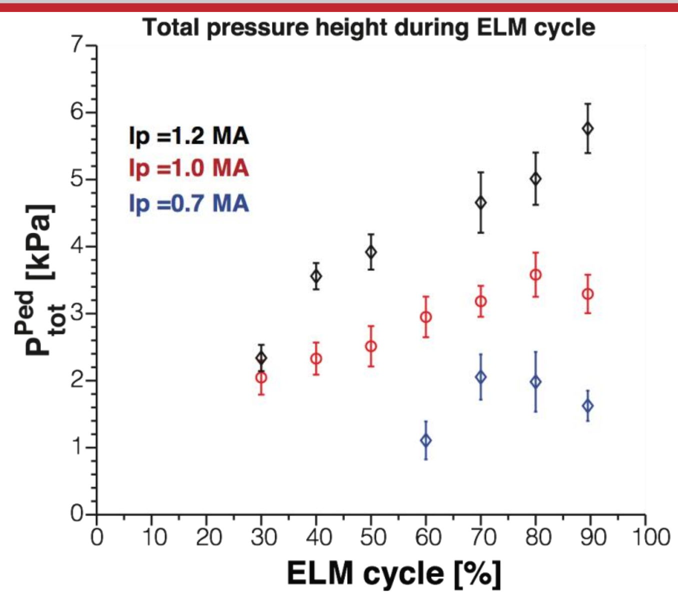
Research Results Outline

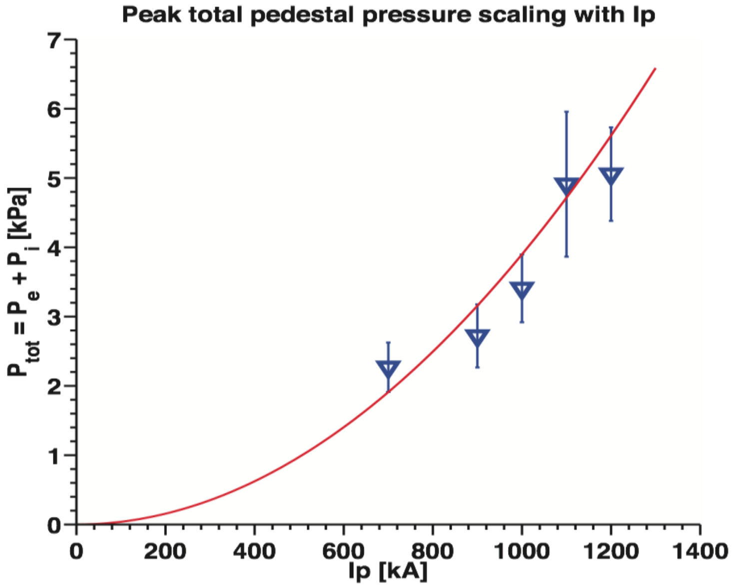
- Joint Research Target contributions from NSTX
- NSTX research milestone highlights
- Additional research highlights
- Summary

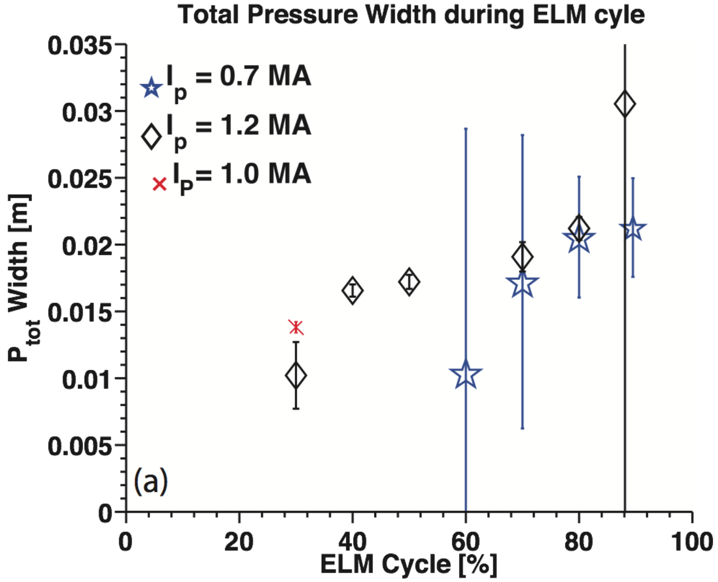
NSTX FY2011 Research Milestone Overview

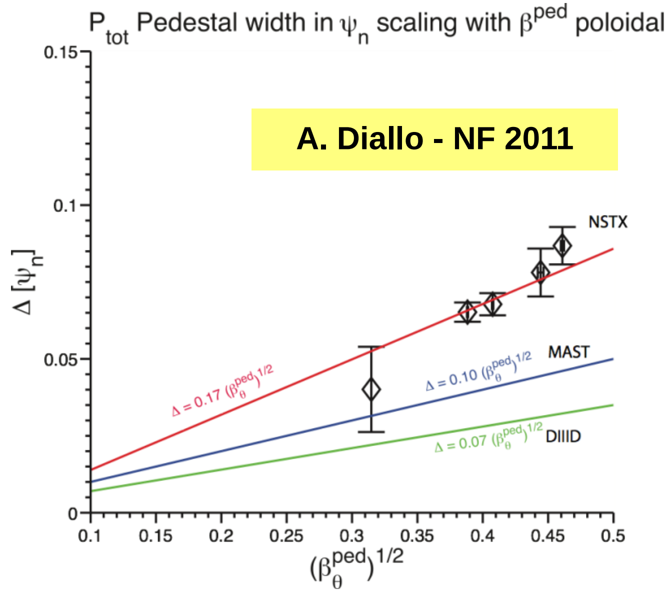
- **Joint Research Target:** *"Improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone."*
- **R(11-1):** Measure fluctuations responsible for turbulent electron, ion, impurity transport
  - Utilize new diagnostic capabilities, characterize turbulent fluctuations
- **R(11-2):** Assess ST stability dependence on plasma aspect ratio, boundary shaping
  - Prepare for Upgrade operating scenarios, explore ideal and RWM stability
- **R(11-3):** Assess very high flux expansion divertor operation
  - Combine with other heat flux mitigation techniques, optimize control
- **R(11-4):** H-mode pedestal transport, turbulence, and stability response to 3D fields
  - Utilize perturbative impurity transport experiments

JRT-11: Inter-ELM pedestal structure and dynamics in NSTX depend strongly on I_P



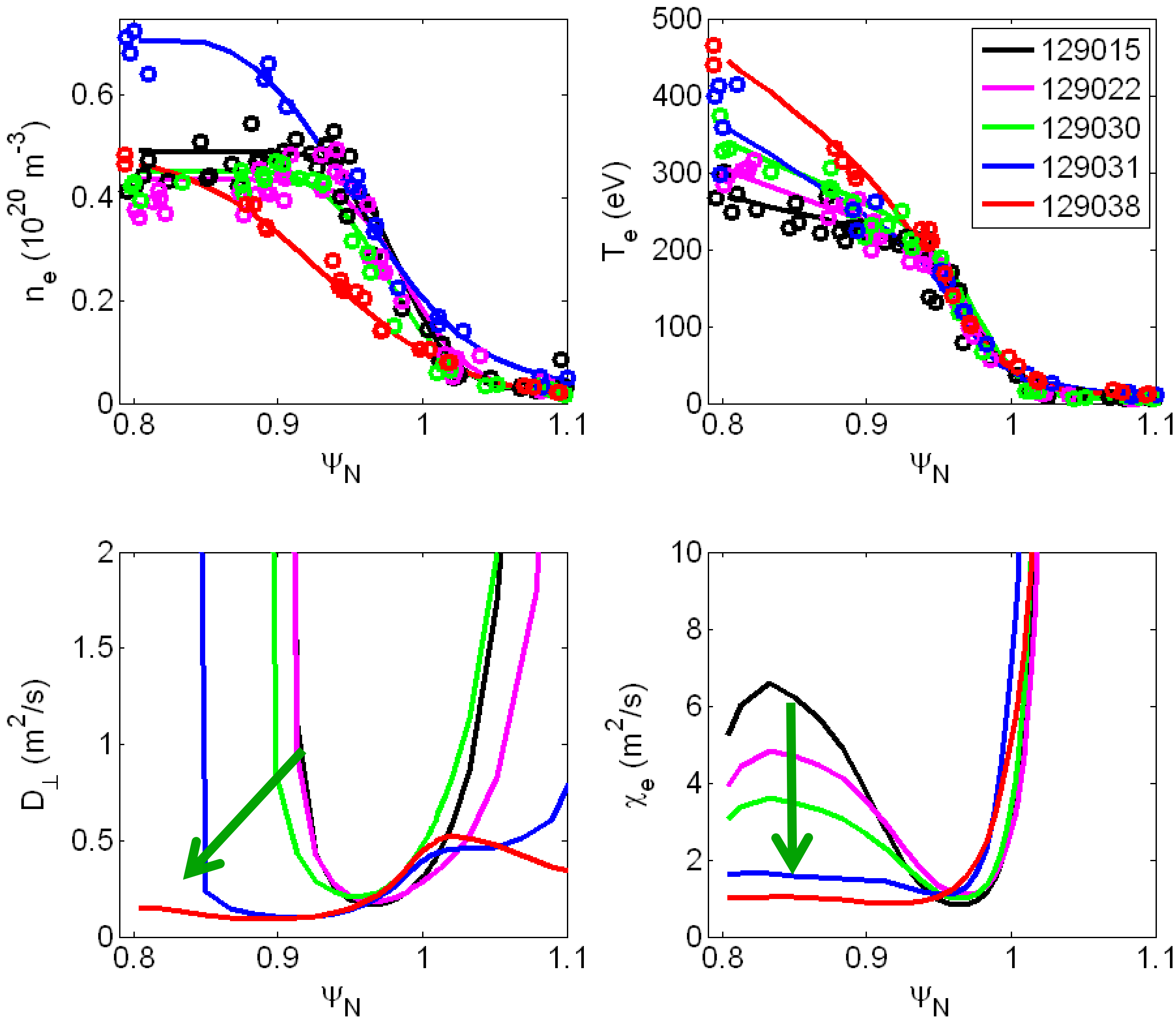






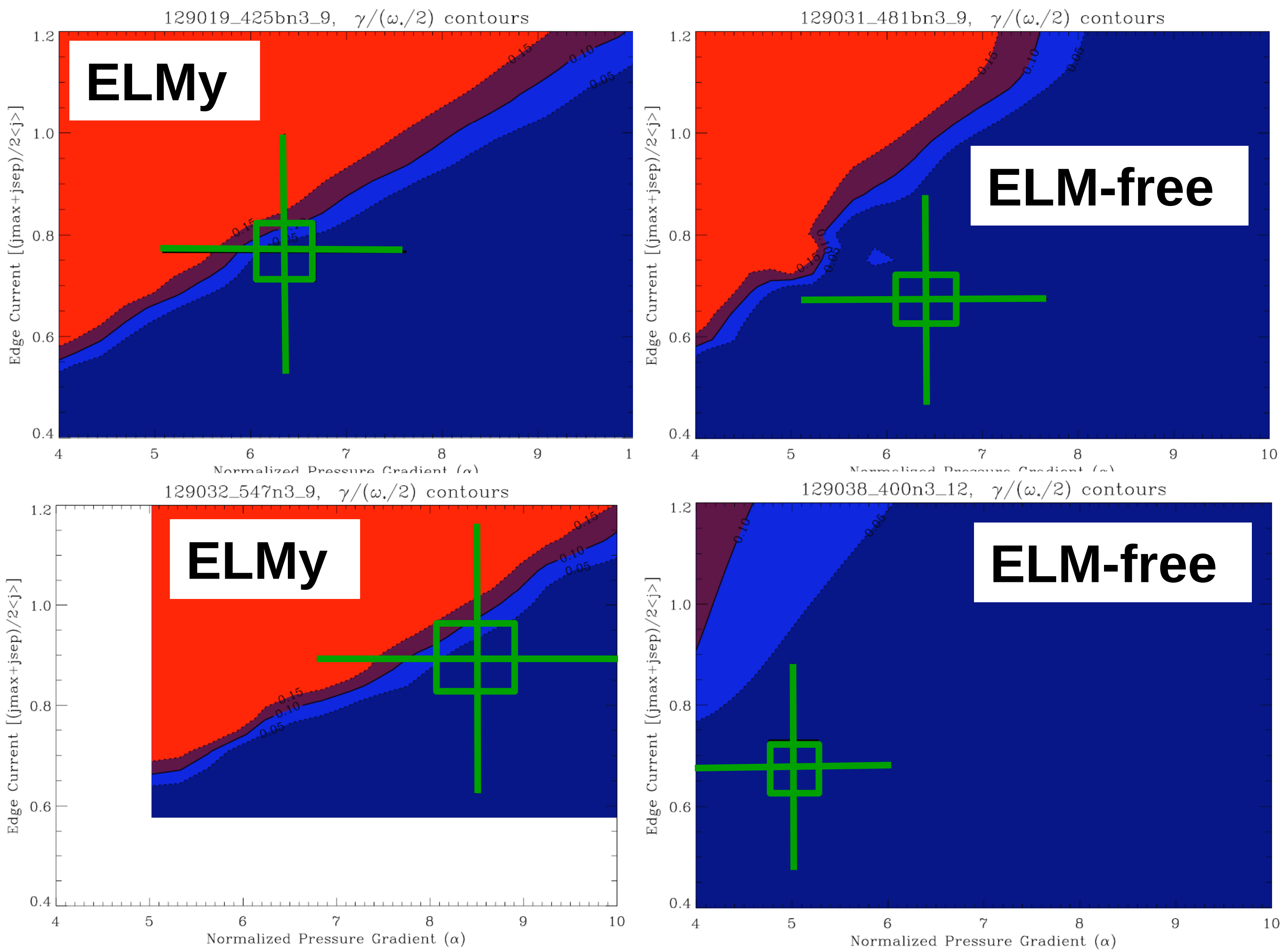
JRT-11: As lithium evaporation increases (direction of green arrow), edge barrier widens, pedestal-top χ_e reduced

- Several shots analyzed with increasing lithium thickness (direction of arrow) →
- ELMy to reduced frequency to ELM-free
- T_e gradient clamped



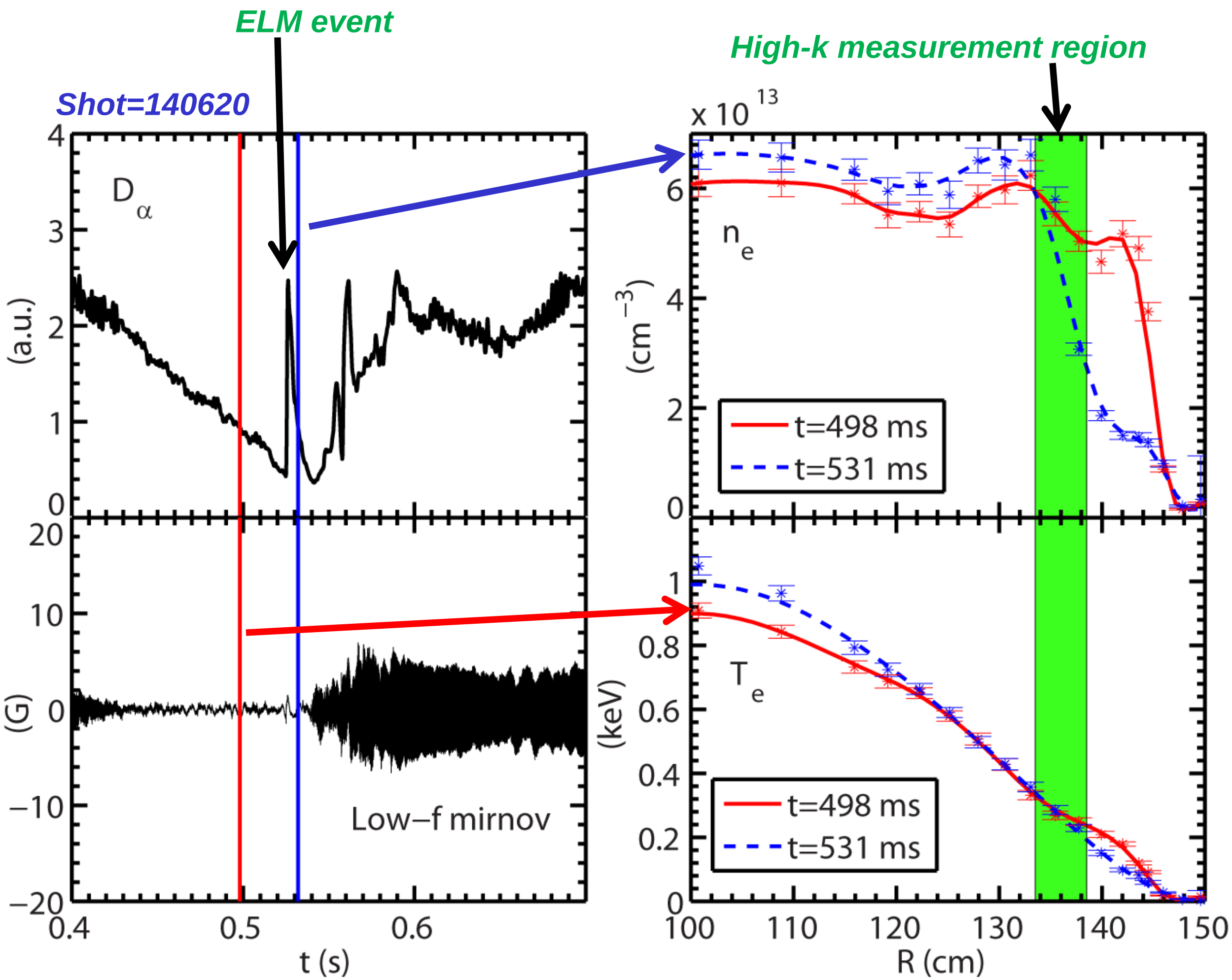
J. Canik PoP 2011

JRT-11: ELMy discharges close to the kink/peeling stability boundary, ELM-free discharges are farther away



D. Boyle
PPCF 2011

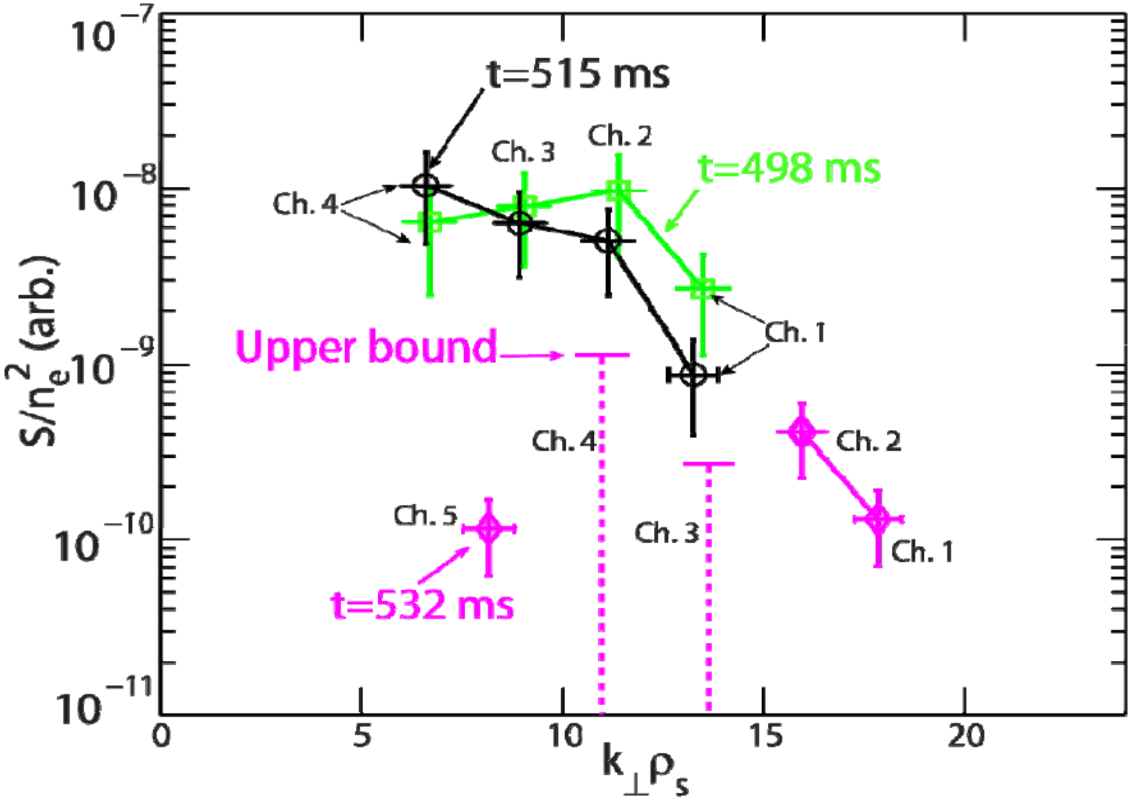
R11-1: Large density gradient induced by ELM events used to probe high-k turbulence and electron transport



- After the ELM event:
  - A factor of 4 increase in density gradient
  - 60% increase in electron temperature gradient
  - 60 % decrease in ion temperature gradient
  - 40% increase in T_i
  - Less than 25% variation in all other equilibrium quantities
- No large global MHD mode appears before and right after ELM

Y. Ren, PRL 106, 165005 (2011)

R11-1: High-k turbulence in H-mode pedestal decreases post ELM crash

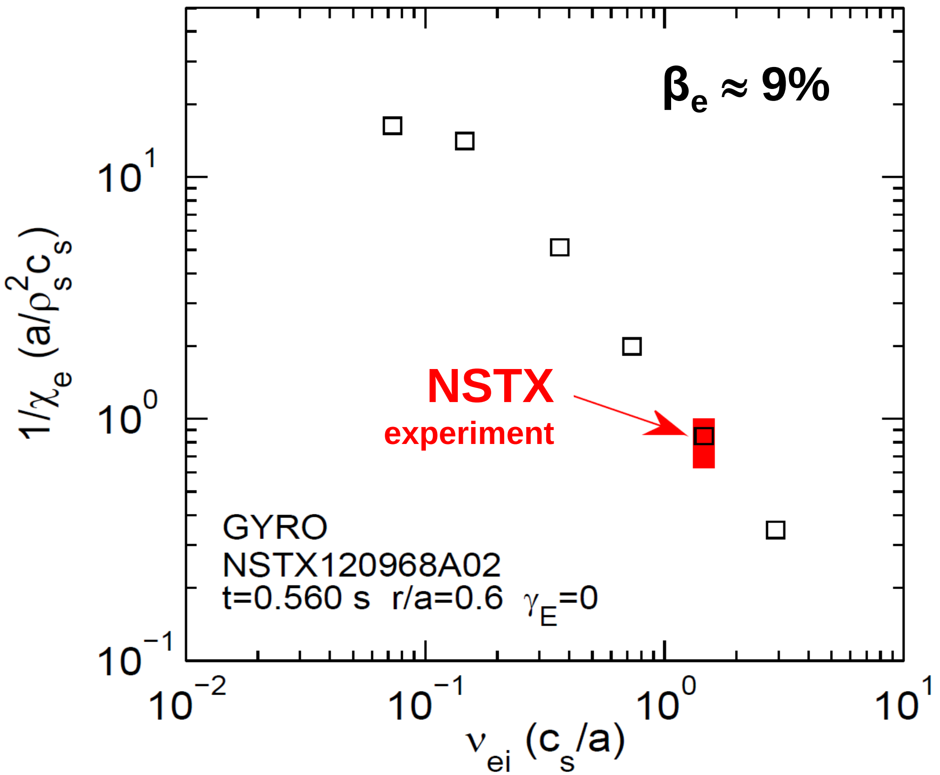


Y. Ren

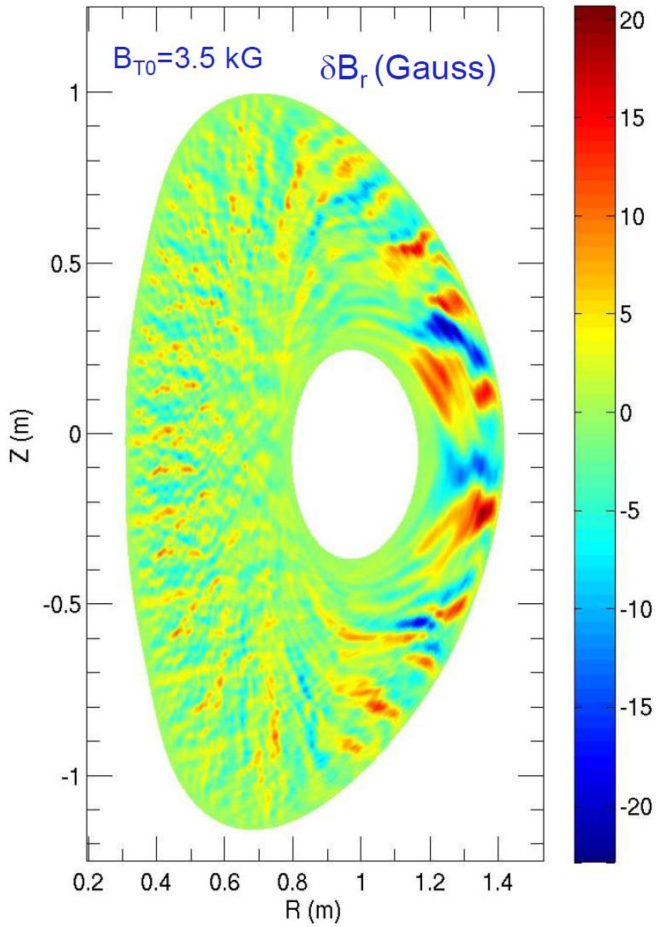
Pre-ELM: black/green post-ELM: purple

- Largest decrease in turbulence observed for lower k
- Post-crash measured χ_e is reduced, ETG modes stabilized (GS2)

R11-1: Extended non-linear GYRO calculations of micro-tearing turbulent electron transport



W. Guttenfelder, PRL 106, 155004 (2011)

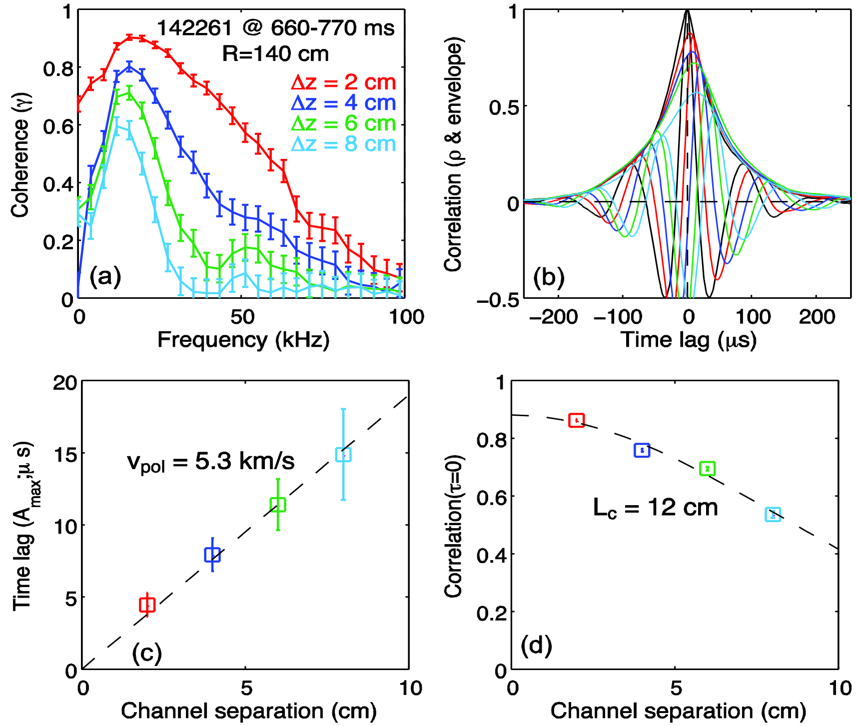


- μ-tearing produces experimentally relevant e-transport: $\tau_{E\text{-}e} \propto 1/\chi_e \propto 1/\nu_e^*$
- E×B shear predicted to reduce transport from micro-tearing (ongoing research)

- Simulations → 98% of transport caused by δB_r, projected to be detectable w/ polarimetry (UCLA)

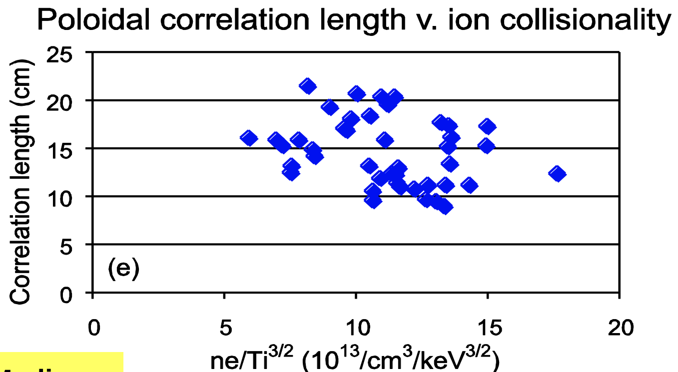
R11-1: Correlation analysis of BES data beginning to provide insight into ST ion-gyro-scale turbulence

- Database of correlation lengths assembled in FY2011
  - Broadband spectra extend to ~100 kHz
  - R=140 cm (r/a~0.85) → poloidal correlation lengths y ~10-20 cm



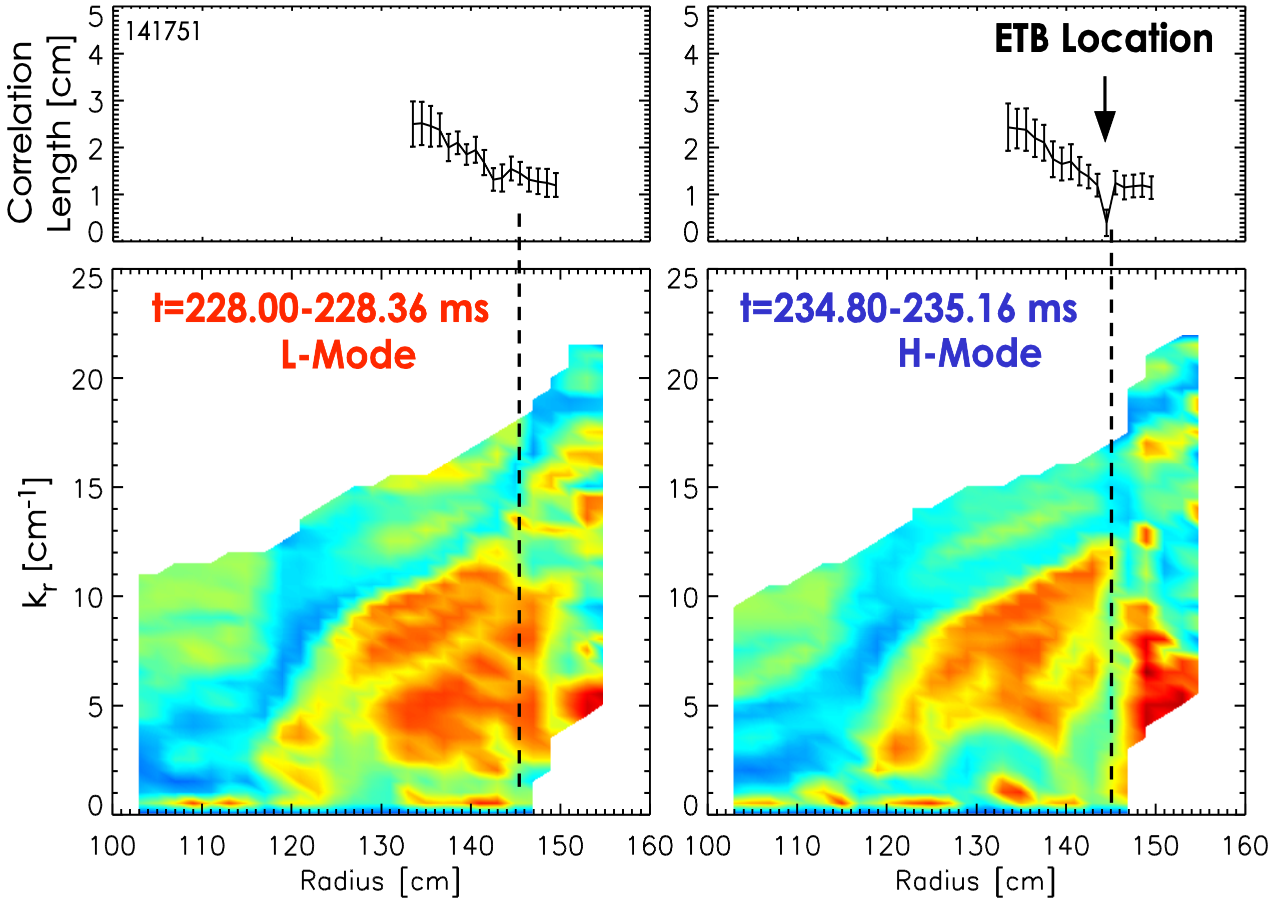
- Poloidal correlation length trends in stationary H-modes:
  - Increase at higher n_e, ∇n_e, ∇T_e, $q/\hat{s}$
    - ($\hat{s}$ is normalized magnetic shear)
  - Decrease at higher T_i and ∇T_i
  - Scalings change from early to late H-mode phase → may indicate different turbulent modes active at different times

- Preliminary: correlation lengths decrease at higher ion collisionality
  - B_T=4.4kG, I_P=900kA, P_{NBI}=4 MW



D.R. Smith – UW Madison

R11-1: New Doppler Backscattering diagnostic used to study turbulence dynamics of L→ H transition

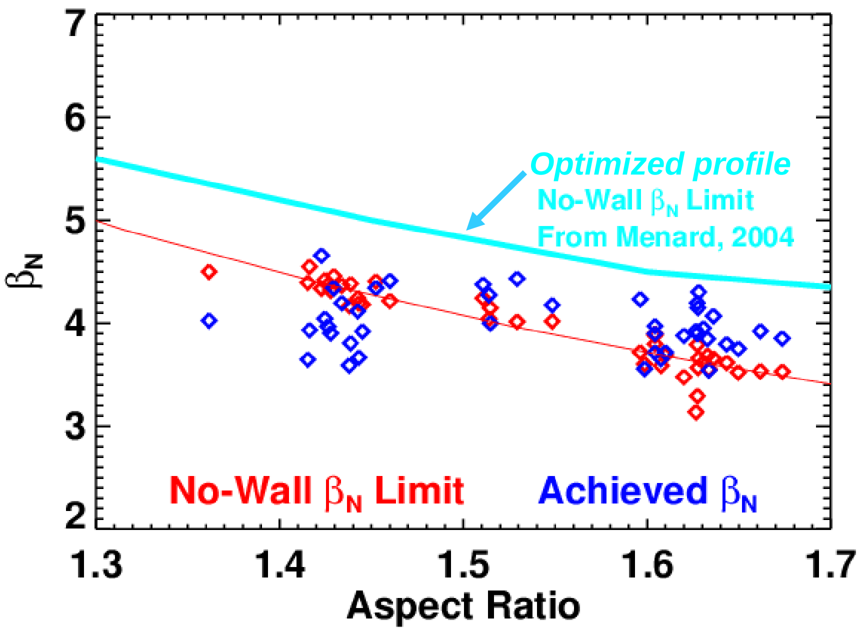


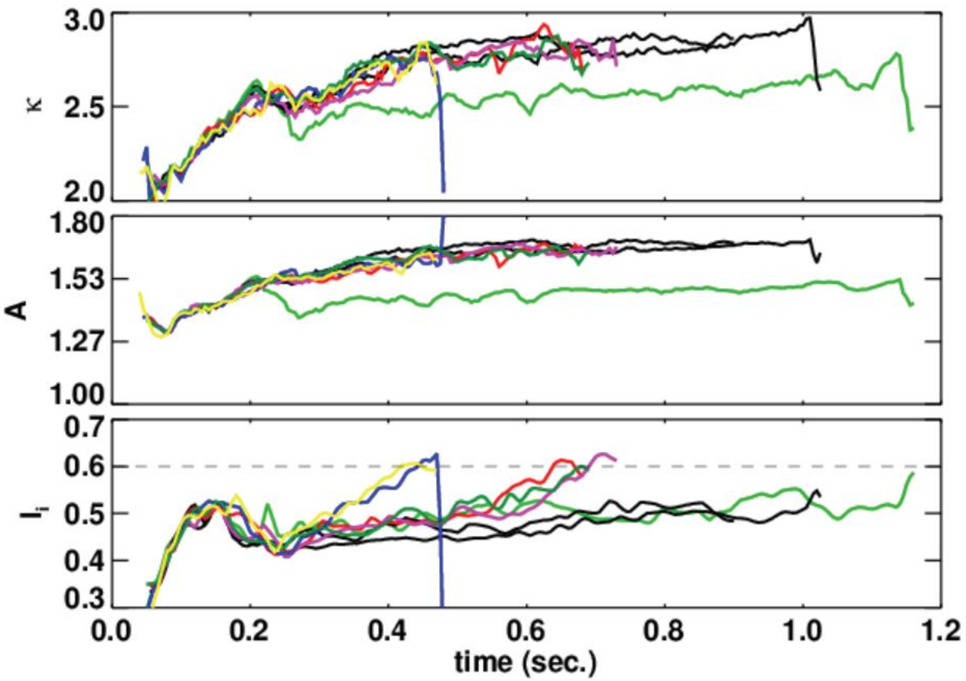
S. Kubota - UCLA

- Observe reduction in radial correlation length (top) over narrow radial region immediately after L→H transition, combined with suppression of turbulence over wide range of k_r (bottom) in same narrow radial region

R11-2: NSTX explored effects of aspect ratio, shaping, current profile on MHD stability

- Successfully operated at $\beta_N > 4$ for several τ_{CR} at Upgrade A and κ





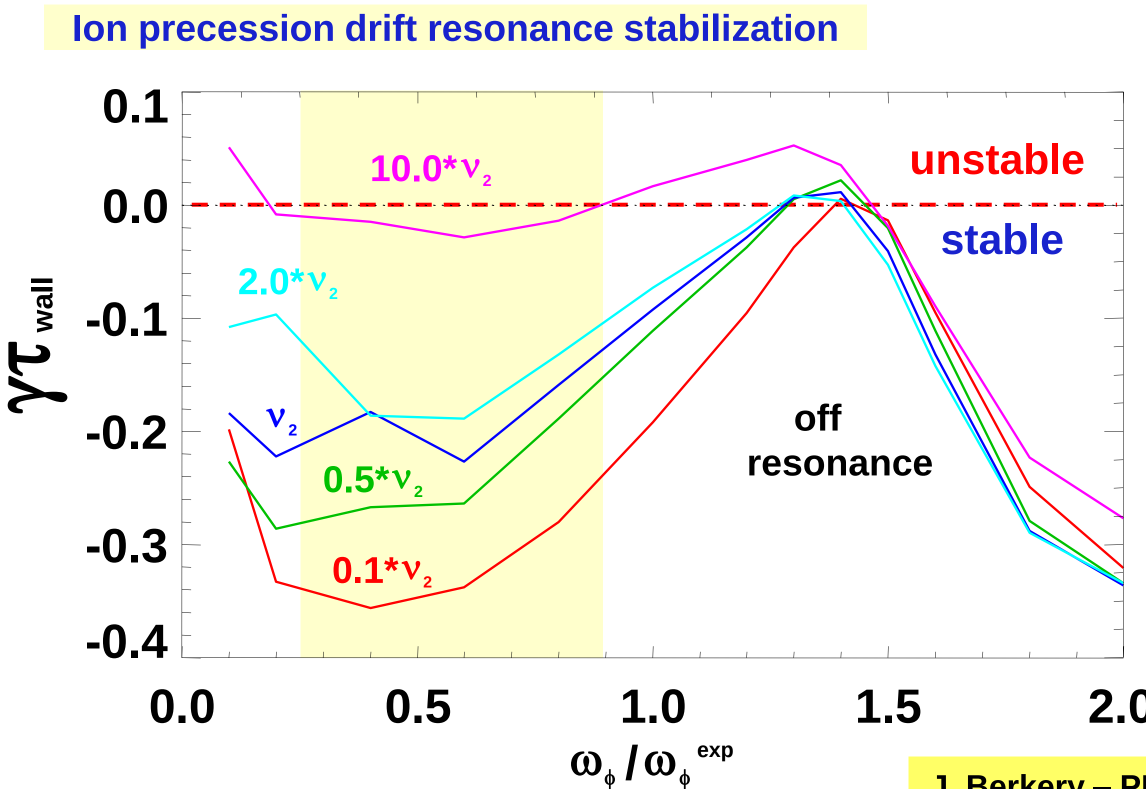
- Reduction of calculated n = 1 no-wall β_N limit observed in plasmas with increased A

S. Gerhardt – Nucl. Fusion 51 (2011) 073031

- Found $l_i \leq 0.6$ required to avoid VDE at higher A with present n=0 control

R11-2: NSTX calculations explored effects of collisionality on RWM stability

Expect NSTX-U to have higher T_i, reduced ion collisionality

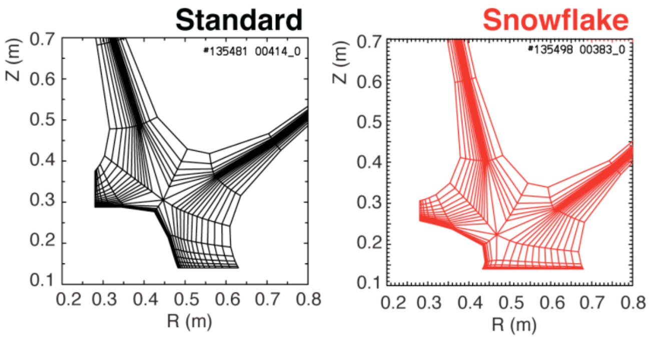


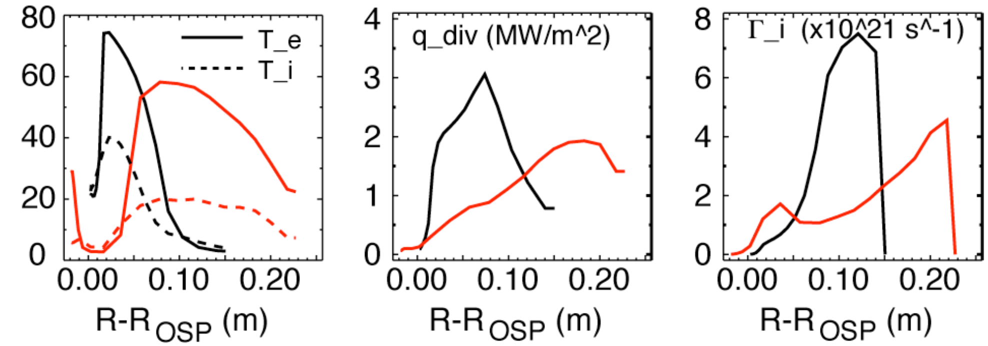
J. Berkery – PRL 106, 075004 (2011)

MISK analysis indicates reduced collisionality could improve RWM stability

R11-3: NSTX tested very high flux expansion + detachment for large heat-flux reduction

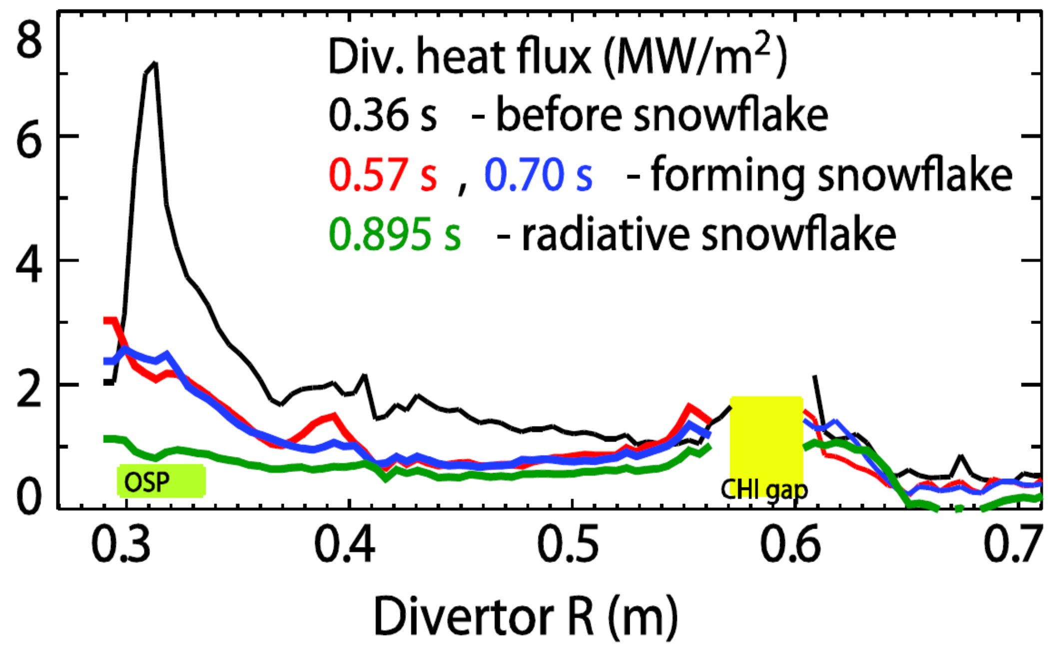
- UEDGE modeling performed comparing conventional divertor to snowflake





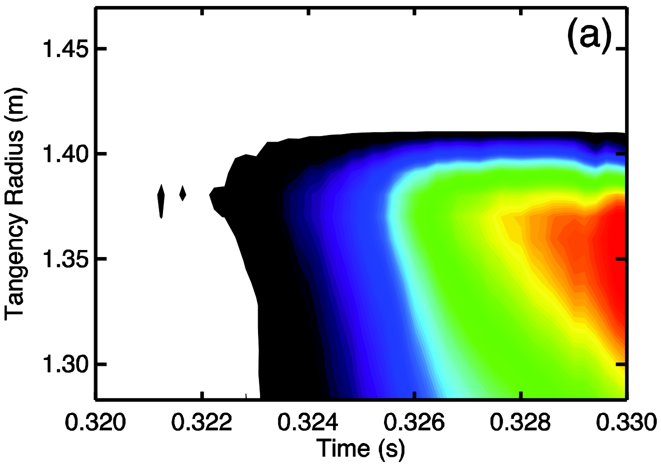
V. Soukhanovskii (LLNL) – EPS 2011

- Snowflake divertor synergistic with detachment/radiative divertor → large heat flux redution

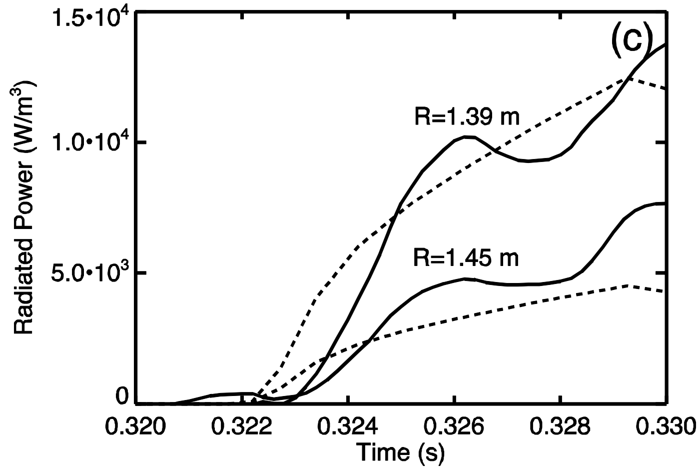


R11-4: Multi-energy SXR array used to measure neon impurity transport in edge region

Measured X-ray brightness

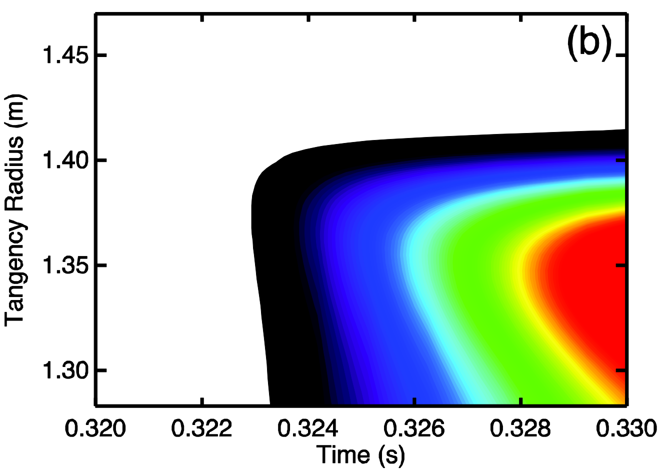


Radiated power density

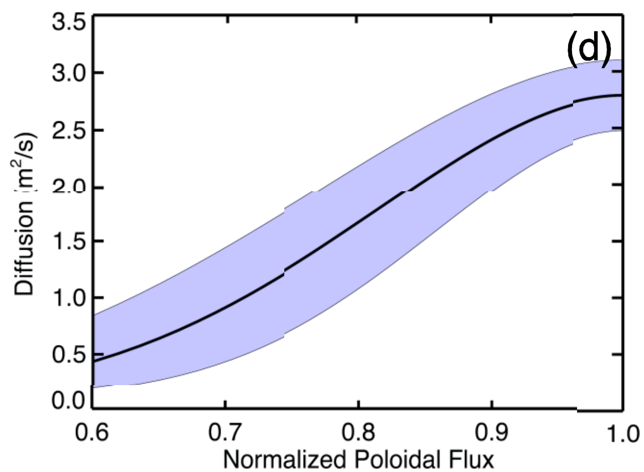


Bolometry (solid)

STRAHL code (dashed)



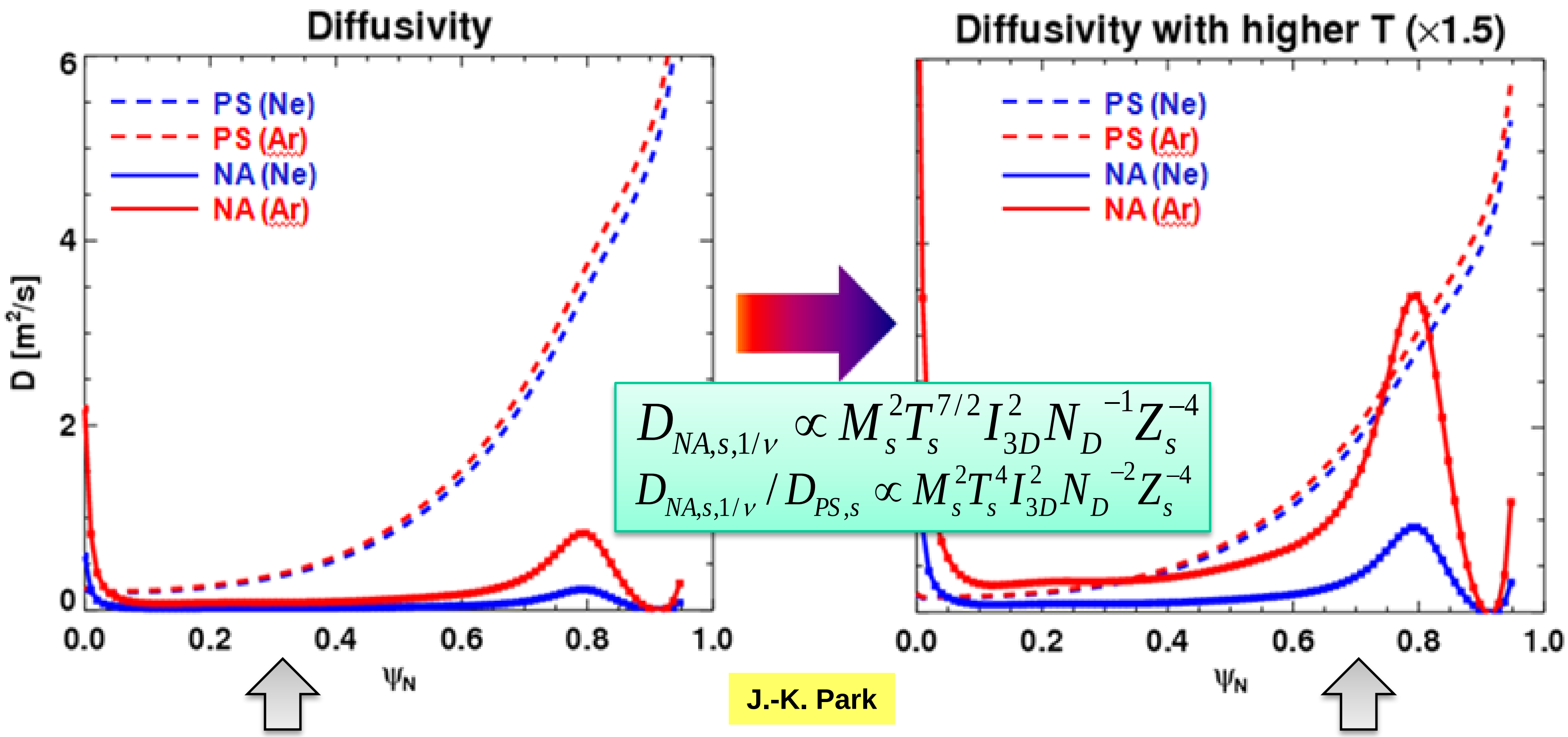
Modeled X-ray brightness



Modeled neon diffusivity

D. Clayton - JHU

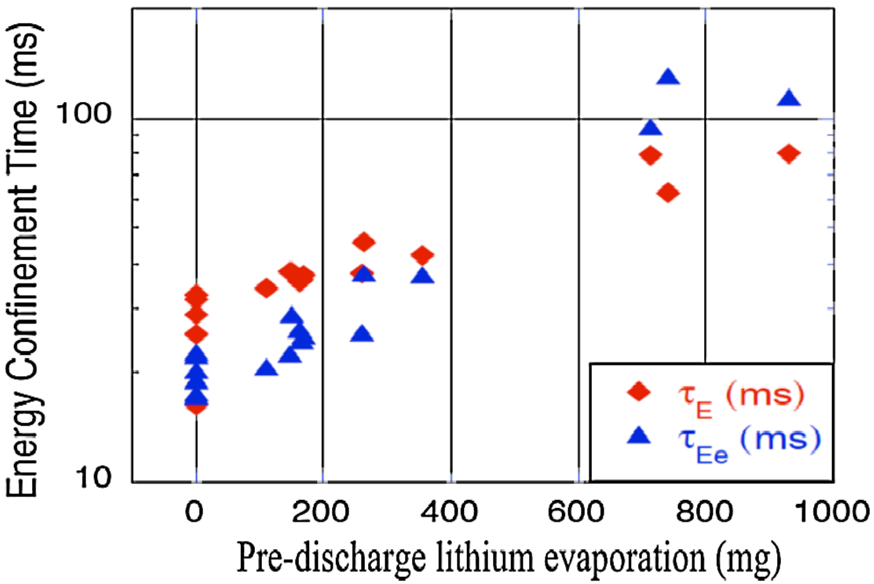
R11-4: FY2011-12 plan was to test 3D field structure using measured and predicted impurity transport



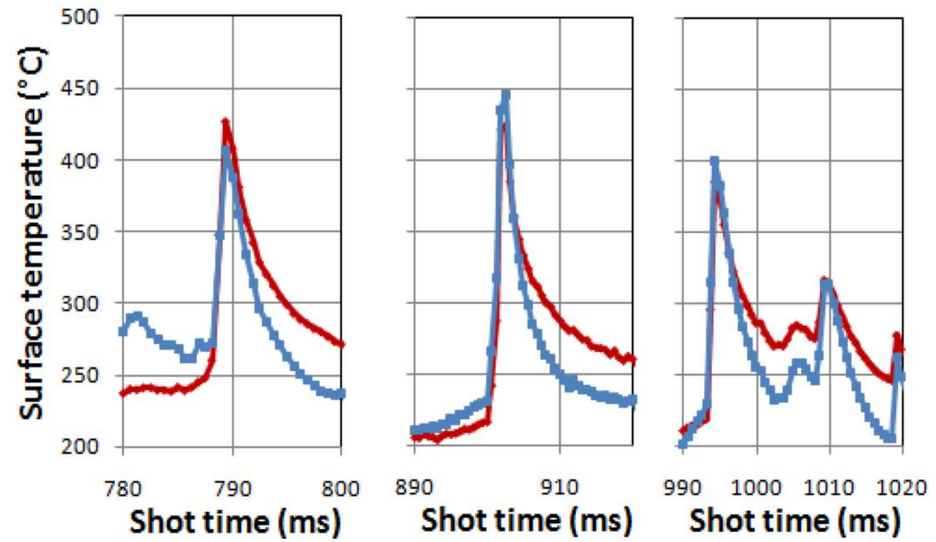
$$D_{NA,s,1/\nu} \propto M_s^2 T_s^{7/2} I_{3D}^2 N_D^{-1} Z_s^{-4}$$
$$D_{NA,s,1/\nu} / D_{PS,s} \propto M_s^2 T_s^4 I_{3D}^2 N_D^{-2} Z_s^{-4}$$

- Comparison of predicted particle diffusivity profiles by 3D (NA) and 2D (PS) neoclassical theory for: Ne and Ar ions, n=3 I_{EFC}=2kA, $T_e(0)$ ~ 0.8keV
- 1.5 higher Ar ion temperature predicted increase 3D particle transport to 2D levels → plan: use higher current, enhanced-pedestal H-mode to test

NSTX investigated effects of Li PFCs on plasma confinement and divertor thermal evolution



R. Maingi – PRL 107, 145004 (2011)

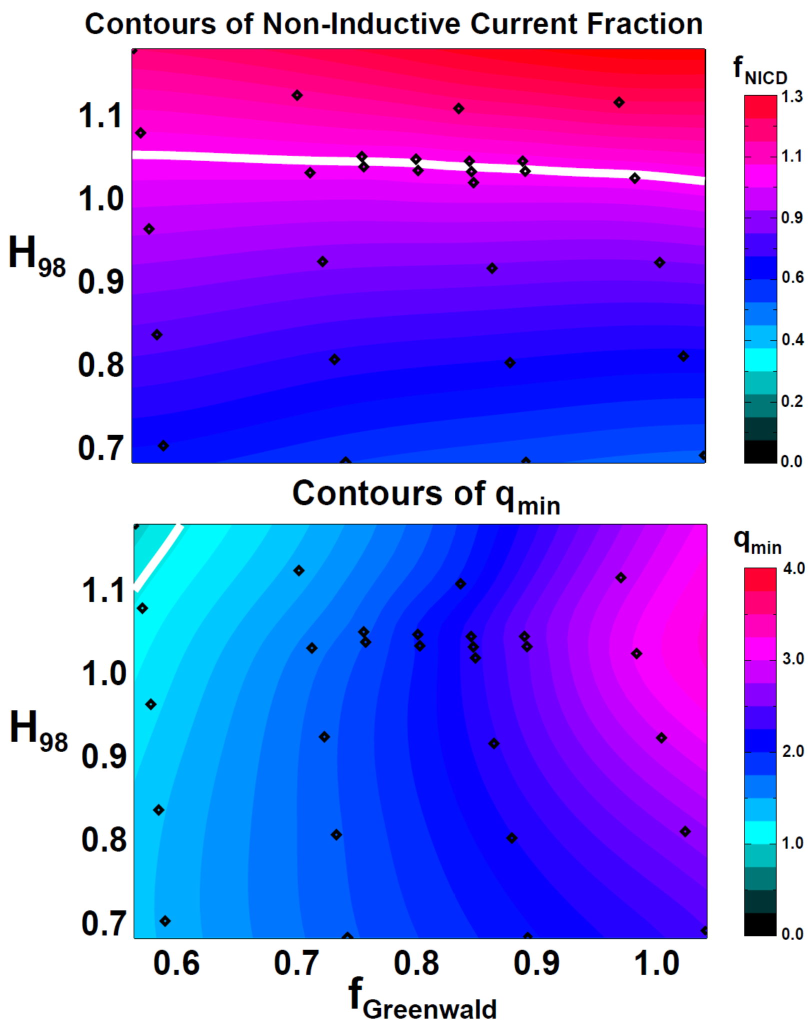


A. McClean – preliminary analysis

- Energy confinement increases continuously with increased Li evaporation in NSTX.
- High confinement very important for FNSF and other next-steps - what is upper bound?

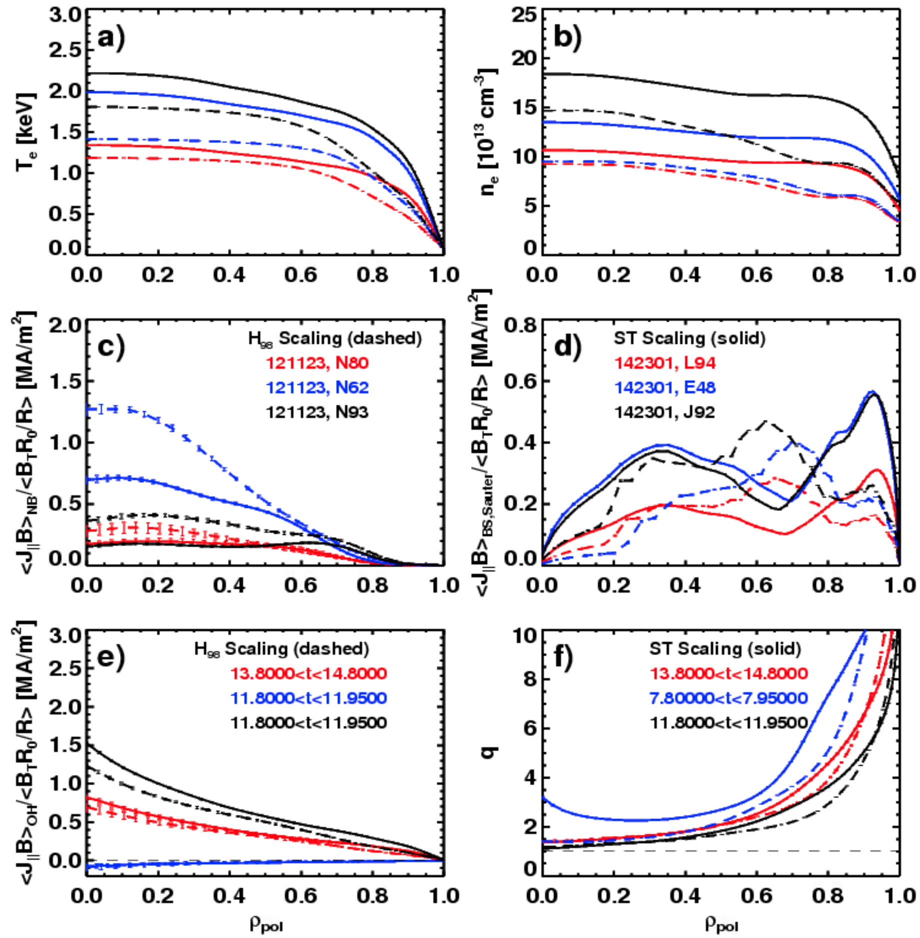
- Peak surface temperature of LLD coated with Li apparently limited to < 450-500C during repeated ELM events.
- Possible Li evaporative cooling as means to protect substrate?

Free-boundary TRANSP modeling of range of NSTX Upgrade scenarios extended in FY2011



A=1.75, κ =2.8, B_T =1.0T, I_P =1.0MA

90 kV Beams R_{tan} = [50, 60, 70, 110, 120, 130] cm



10 sec pulse, 3x80 kV, 0.75 T, 850 < I_P [kA] < 1000

f_{NI}=100%, 6x90 kV, 1.00 T, 850 < I_P [kA] < 1300

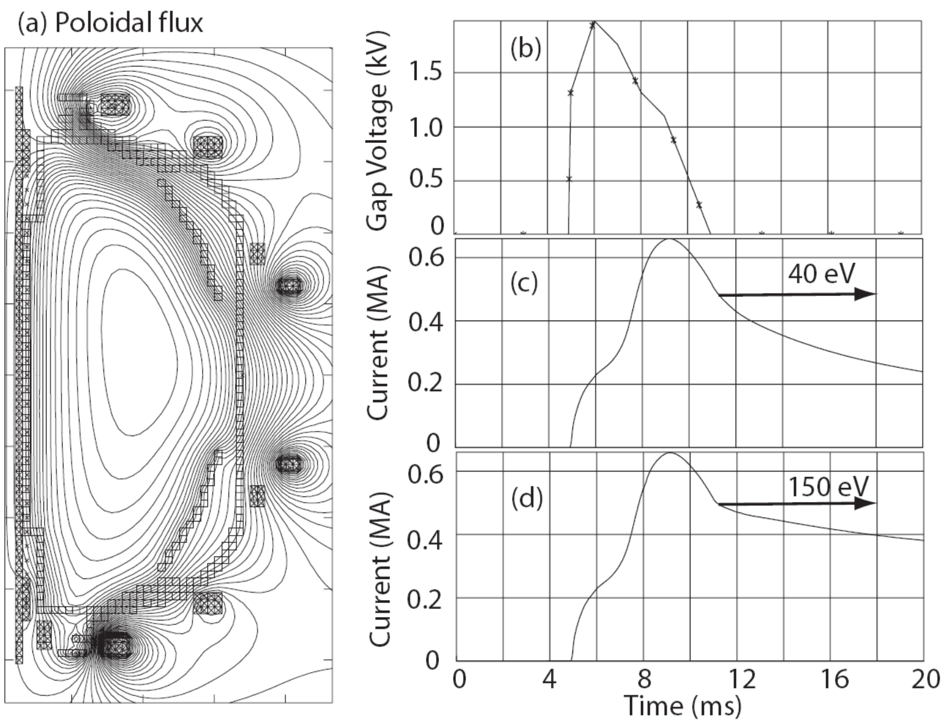
higher current q_{min}>1, 6x90 kV, 1.00 T, 1350 < I_P [kA] < 1900

S. Gerhardt – NF in prep

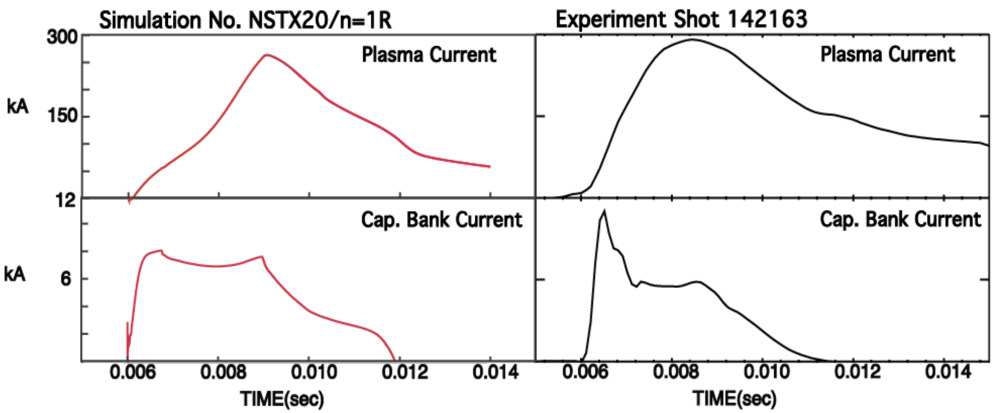
J. Menard - NSTX-U overview – submitted to NF

Simulations of CHI project to increased start-up current in NSTX Upgrade

- TSC simulations of transient CHI start-up in NSTX-U have been performed **R. Raman – U. Wash**
- TF increased to 1 T and injector flux increased to about 80% of max allowed → **can generate up to ~600kA of toroidal current**
  - **Figs (a-c): T_e = 40 eV, Z_{eff} = 2.5**
  - **Fig (d): T_e = 150 eV for t > 12 ms**



- NIMROD simulations of CHI have been initiated **B. Hooper**
- Initial comparisons of simulated (left) with experimental (right) injector current and plasma current are favorable



Research Results Summary

- Joint Research Target:
  - NSTX pedestal structure systematically assessed for first time
  - Effects of lithium on edge transport and pedestal stability quantified

- Milestone research highlights
  - Investigated modes (ETG, μ-TM) responsible for anomalous transport
  - Quantified vertical and kink stability vs A, RWM versus collisionality
  - Snowflake-divertor: heat flux mitigation with detachment, control
  - Calculate impurity ion transport from 3D fields measurable at higher T_i
    - Consider testing impurity 3D transport physics in another device during outage

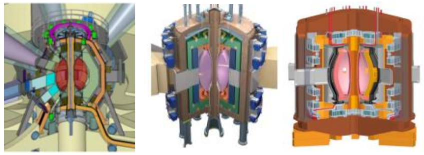
- Additional research highlights
  - Continuous increase in τ_E with Li, assessing Li PFC temperature clamping
  - Extended scenario modeling for NSTX-U, CHI projects favorably to NSTX-U

Staff plans for FY2012-13 analysis and research

- Complete analysis and publication of FY2011-12 data
- Develop, write NSTX Upgrade 5 year plan for 2014-18
  - Draft outline of research plan is provided in subsequent slides
- Planning and design studies supporting post-Upgrade ops:
  - Start-up: CHI upgrades, point helicity injection (plasma guns)
  - Boundary: Divertor cryo-pumps, divertor diagnostics
  - Lithium: Additional Mo tiles, upward Li evaporators, next-gen LLD
  - Transport, EP: New high-k scattering, polarimetry, assess solid-state NPA
  - MHD: 3D-coil physics design for RWM/RMP/TM/EFC/NTV/TAE + disruption force diagnostics, disruption precursor ID
  - Control: Real-time-MSE for NBI J-profile control, rt-control of heat flux
- Collaborate on domestic and international facilities
  - Initial collaboration planning process described in subsequent viewgraph
- Update/extend physics design of ST-FNSF
  - LDRD to further develop design concepts, utilize NSTX team expertise
  - Predictive modeling of start-up, sustainment, transport, stability, divertor

FY2012 LDRD proposal: NSTX/ST researchers will contribute to study of Mission and Configuration of an ST-FNSF

- Overarching goal of studies:
  - Determine optimal mission, performance, size



- Review proposed ST devices: UK-CTF, FNSF, Pilot Plant, others
- The goals of this study are:
  - Put physics and engineering design basis on more uniform footing
  - Review existing designs, identify advantageous features, utilize these features in an updated and potentially improved configuration
  - Assess potential of designs to achieve T self-sufficiency
  - Assess maintainability and upgradeability of internal components (divertors, shields, blankets), identify maintenance strategies
  - Perform at least one self-consistent and detailed physics and engineering assessment for use by community
  - Strong ST community input for definition, mission, design (STCC)
- Partially fund 6 PPPL/non PPPL engineers, input from 13+ NSTX physicists, also encourage non-US collaboration

Held team-wide discussions on FY12-13 collaboration opportunities and expectations

- Collaboration should aim to support NSTX-Upgrade mission
- For all researchers, use Upgrade outage as opportunity to:
  - Extend and improve your ongoing and future research on NSTX
  - Learn about other facilities – bring back knowledge, best practices
  - Try or learn something new – new physics, diagnostics, analysis, …
- Aim to form small teams from NSTX (PPPL + non-PPPL)
  - Coordinating research plans, analysis, travel, and participation
- Expectations for researchers:
  - Select 1 primary and 1 secondary/backup collaboration project
  - Aim for first author paper (Nature, PRL, NF…), invited presentation
  - At very least, be a co-author, extend/improve your NSTX research
  - Present results periodically to NSTX, PPPL research seminars
- Facilities: MAST, DIII-D, C-Mod, LHD, EAST, KSTAR, JET, small expts, PPPL, ITER diagn.
- Funding: PPPL covers salaries of PPPL NSTX researchers by default
- Challenge: no additional NSTX funding dedicated to collaboration

NSTX Made Excellent Progress in FY 2011

The NSTX team will remain productive throughout Upgrade outage

- All of the facility and diagnostic milestones including those for the ARRA funded upgrades were completed on schedule except for the run week milestone due to the TF fault
- All the research milestones were completed except for the 3D field milestone (R-4) which was partially completed
- NSTX research team was highly productive in terms of honors, publications and invited talks at major conferences
- NSTX team responded rapidly to the TF fault event:
  - Identified the cause of the TF fault and incorporated necessary changes to the Upgrade TF bundle manufacturing process
  - Decision was made to go into the upgrade outage immediately to accelerate the upgrade completion by ~ 6 months
- A detailed planning process has been initiated to utilize the researchers most productively through data analyses, publication / conference presentations, national and international collaborations, and planning for the post upgrade operation

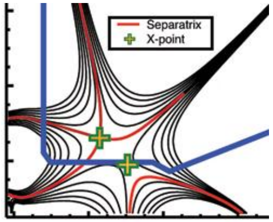
Backup

NSTX Upgrade + follow-on upgrades will enable access to broad range of new ST regimes

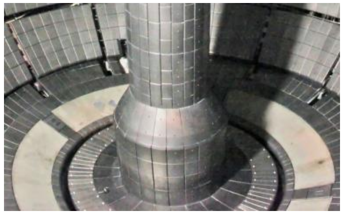
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

1 MA Plasma | **Upgrade Outage** | **1.5 → 2 MA Plasma**

- HHFW Upgrade
- LLD
- Moly-tile
- CHI Control Coils



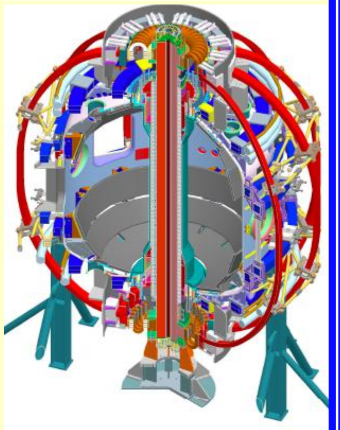
"Snowflake"

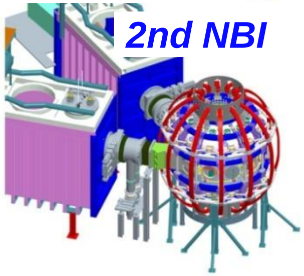


Lithium

- 2nd NBI

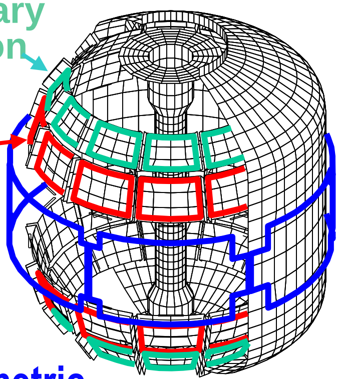
New Center-stack





2nd NBI

- 1 MW ECH/EBW
- Long–pulse Divertor
- 0.5 MA CHI
- 0.5 MA Plasma Gun
- 1 MA CHI / Plasma Gun
- NCC Upgrade



Non-axisymmetric Control Coils (NCC)

NSTX Upgrade Research Goals

- Low collisionality plasma regimes
- 100% non-inductive operation
- Long-pulse, high power divertor
- Advanced high-β scenarios