NSTX-U

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Overview of NSTX-U Research Program Plans

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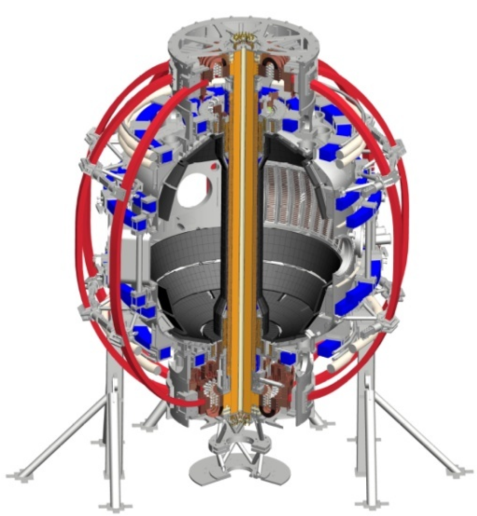
X Science LLC

J. Menard (PPPL)

NSTX-U Program Director

For the NSTX-U Research Team

NSTX-U PAC-35 Meeting
PPPL – B318
June 11-13, 2013



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Outline

- PAC Charges
- NSTX-U mission, priorities, assessments
- FY14-16 overview and milestones
- FY14-16 research plan highlights
- ITPA and ITER contributions
- ST-FNSF mission and configuration study
- Ideas to enhance NSTX-U attractiveness
- Summary

PAC-35 Charge Questions

1. Assess the operational preparation and research priorities and preliminary plans for the first two run-years of NSTX-U with emphasis on the first run year
2. Please comment on and/or expand the preliminary set of ideas to make NSTX-U more attractive/available to university scientists – including early career researchers and students
   - Background: NSTX has been asked by Fusion Energy Sciences to develop/implement ideas to “Expand engagement with university scientists to enhance the NSTX-U program”.
3. Comment on progress and plans for establishing and expanding the partnership between the NSTX-U program and the PPPL Theory department

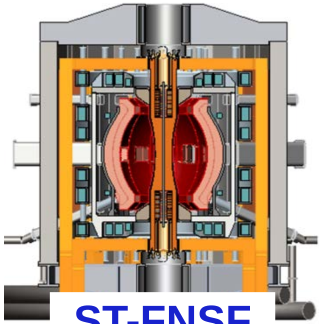
- Responses to PAC-33 comments are listed in the XL file on PAC-35 website
- Many PAC recommendations were incorporated into the 5 year plan - thank you!

In response to PAC-33 specific requests for presentations / information:

- ➢ Stan Kaye will present report on status of improved NSTX-U / PPPL Theory partnership
- ➢ Francesca Poli will present modelling of non-inductive start-up, ramp-up, sustainment

NSTX Upgrade mission elements

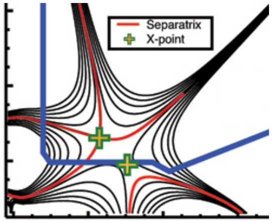
- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**



ST-FNSF

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

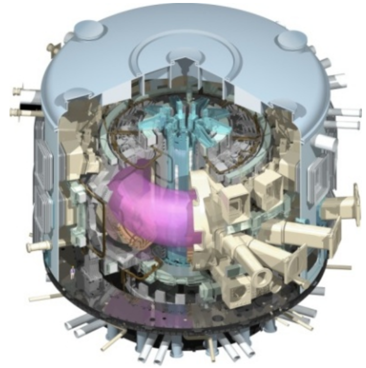
Liquid metals/Li



"Snowflake"

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

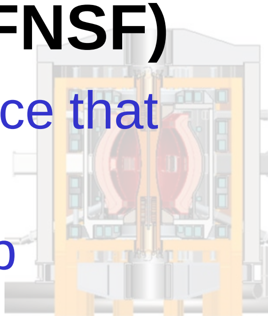
ITER



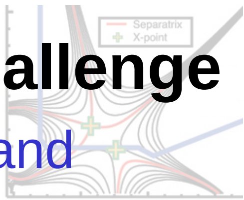
- **Develop ST as fusion energy system**

5 highest priority goals of NSTX-U 5 year plan:

- **Advance ST for Fusion Nuclear Science Facility (FNSF)**
  1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
  2. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid



- **Develop solutions for plasma-material interface challenge**
  3. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
  4. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps



- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  5. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

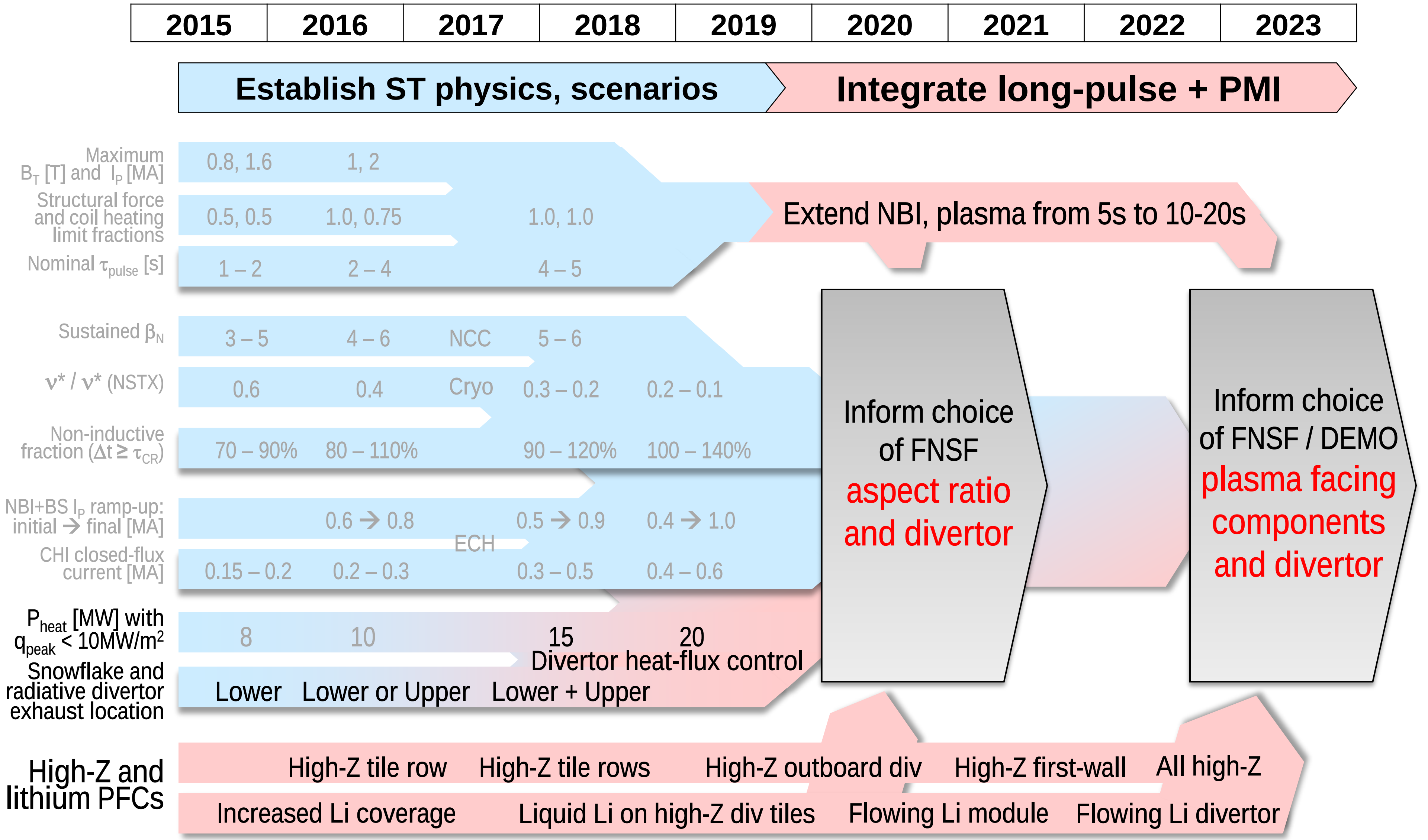
5 year goal is to develop ST understanding and integrated scenarios necessary for assessing ST viability as FNSF

	2015	2016	2017	2018	2019	2020
Max B_T [T], I_P [MA]	0.8, 1.6	1, 2				
Structural force and coil heating limit fractions	0.5, 0.5	1.0, 0.75		1.0, 1.0		
Nominal τ_{pulse} [s]	1 – 2	2 – 4		4 – 5		
Sustained β_N	3 – 5	4 – 6	NCC	5 – 6		Inform choice of FNSF aspect ratio and divertor
ν^* / ν^* (NSTX)	0.6	0.4	Cryo	0.3 – 0.2	0.2 – 0.1	
Non-inductive fraction ($\Delta t \geq \tau_{CR}$)	70 – 90%	80 – 110%		90 – 120%	100 – 140%	
NBI+BS I_P ramp-up: initial → final [MA]		0.6 → 0.8	ECH / EBW	0.5 → 0.9	0.4 → 1.0	
CHI closed-flux current [MA]	0.15 – 0.2	0.2 – 0.3		0.3 – 0.5	0.4 – 0.6	
P_{heat} [MW] with q_{peak} < 10MW/m^2	8	10		15	20	
Snowflake and radiative divertor exhaust location	Lower	Lower or Upper		Lower + Upper Divertor heat-flux control		

Cryo: access lowest ν^*, compare to Li **ECH / EBW:** bridge T_e gap from start-up to ramp-up

Off-midplane non-axisymmetric control coils **(NCC):** rotation profile control (NTV), sustain high β_N

10 year goal: integrate 100% non-inductive + high β & τ_E with advanced divertor solution + high-Z solid / liquid metal walls



2013: External review of NSTX-U was favorable

- **5 year plan programmatic comments (debrief report):**
  - "quality of proposed research is excellent, employing state-of-the-art diagnostics to obtain data that will be compared to theory using wide variety of numerical models."
  - "Proposed research is essential for advancing ST to a nuclear science mission."

- **5 year plan facility enhancement comments (written report):**
  - "…addition of cryo-pump will be an excellent addition to their program."
  - "NCC will greatly enhance physics studies and control"
  - "Given the essential need for non-inductive startup for FNSF-ST, acquisition of a 28 GHz gyrotron to provide capability for heating CHI plasmas to allow better absorption of HHFW, is important to the long-term program"
  - "The proposed additions of the flowing liquid Lithium divertor and divertor Thomson scattering diagnostic are desirable."

- **FESAC Prioritization of Proposed Scientific User Facilities:**
  - Grade: A - "absolutely central" for enabling world leading science: energetic particle physics for ITER, high power density & flux expansion + liquid metals, FNSF viability

NSTX-U Team Remaining Scientifically Productive

Active in Scientific Conferences, Publications, and Collaborations

- Strong APS meeting (7 invited talks, 52 additional presentations) participation in the fall 2013. Three NSTX APS-DPP press releases available on the web.
- All of the FY2013 milestones were completed on schedule
- Significant collaboration research contributions are being made in diverse science areas by the NSTX-U research team *(for more details see: next slide, this talk, all other PAC presentations)*
- 7 IAEA orals by NSTX-U researchers (~50/50 NSTX/collaboration)
- 61 refereed publications for CY 2013 with 4 PRLs
- Two NSTX researchers received APS Fellowship (Gates, Skinner)
- NSTX-U (S. Gerhardt) led 3 facility joint research target (JRT)

Overview of FY2014 NSTX-U research activities

- Collaborations supporting NSTX-U, ITER, FNSF
  - DIII-D: Snowflake/detachment, pedestal/Li, QH, RWM, operations
  - C-Mod: Pedestal structure, high-Z PFC studies, RF
  - KSTAR: NTV physics, MHD stability and control
  - MAST: Momentum and particle transport, EBW plasma start-up
  - York: Synthetic aperture μ-wave imaging (DBS, BXO)
  - EAST: Joint analysis of NSTX/EAST Li/boundary physics data
  - MAGNUM-PSI: study and develop high-Z + Li PFCs

- Prepare for NSTX-U operation
  - Finish data analysis, publications from NSTX, collaborations
  - Transition off-site collaboration/researchers back to NSTX-U
  - Finalize physics design of long-term facility enhancements
    - Row of high-Z tiles on outboard divertor, divertor cryo-pump
    - ECH/EBW for start-up/ramp-up, off-midplane 3D coils
  - Prepare diagnostics, control system, analysis for NSTX-U ops

Overview of FY2015-16 NSTX-U research activities

- Resume operation, explore new regimes:
  - High β + lower ν^*, higher non-inductive w/ higher B_T, I_P, 2nd NBI
- FY2015
  - Complete CD-4 for NSTX Upgrade Project near end of CY14
  - Obtain first data at 60% higher field/current, 2-3× longer pulse:
    - Re-establish sustained low l_i / high-κ operation above no-wall limit
    - Study thermal confinement, pedestal structure, SOL widths
    - Assess current-drive, fast-ion instabilities from new 2nd NBI
- FY2016
  - Extend NSTX-U performance to full field, current (1T, 2MA)
    - Assess divertor heat flux mitigation, confinement at full parameters
  - Access full non-inductive, test small current over-drive

Near-term upcoming NSTX-U Program events

- Input to FESAC sub-panel on 10 year strategic plan for FES
  - Articulate coordinated strategy for U.S. spherical tokamak facilities
  - Address critical issues in support of FNSF and ITER
    - Start-up / ramp-up / sustainment, disruptions, energetic particles, …
  - Plans for long-term increased emphasis on PMI / PFC / liquid metals

- Research Forum to solicit experimental proposals for FY2015 run campaign tentatively planned for December 2014
  - Waiting for successful VPI of OH coil before finalizing Forum dates
  - Each topical science group (TSG) will nominally follow year-by-year priorities/detailed plans developed for recent 5 year plan
  - The research forum specifically requests abbreviated eXperimental Proposals (XPs) be presented at the forum
    - Motivation, goal, shot plan, # of run days, diagnostics, analysis…
  - XP prioritization will be strongly driven by annual research milestones

NSTX-U research milestones target exploitation of new Upgrade capabilities, exploration of new regimes in FY15-16

	FY2014	FY2015	FY2016
Expt. Run Weeks:	0	18 20	16 20
Macroscopic Stability	R14-1 Assess access to reduced density and ν^* in high-performance scenarios (with ASC, BP TSGs)		
Transport and Turbulence		R15-1 Assess H-mode τ_E, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI} (with BP, M&P, ASC, WEP TSGs)	IR16-1 Assess τ_E and local transport and turbulence at low ν^* with full range of B_T, I_P, and NBI power
Boundary Physics		IR15-1 Develop snowflake configuration, study edge and divertor properties (with ASC, TT, MP)	R16-1 Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density
Materials & PFCs			R16-2 Assess high-Z divertor PFC performance and impact on operating scenarios
Waves+Energetic Particles	R14-2 Assess reduced models for *AE mode-induced fast-ion transport	R15-2 Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile (with SFSU, MS, ASC TSGs)	R16-3 Assess fast-wave SOL losses and core thermal and fast ion interactions at increased B_T, I_P
Solenoid-free Start-up/ramp-up			R16-4 Develop high-non-inductive fraction NBI H-modes for ramp-up & sustainment (Joint ASC+SFSU)
Adv. Scenarios and Control	R14-3 Assess advanced control techniques for sustained high performance (with MS, BP TSGs)	R15-3 Develop physics+operational tools for high-performance discharges (with CC, ASC, MS, BP, M&P TSGs)	
ITER Needs + Cross-cutting			
Joint Research Target	Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks	Quantify impact of broadened current and pressure profiles on tokamak confinement and stability	Assess disruption mitigation and warning / prediction techniques (+ additional theory contribution)

NSTX-U Topical Science Groups (TSGs) play lead role in carrying out research program

Topical Science Groups

Macroscopic Stability
J. Berkery**, J.-K. Park
Theory: A. Boozer**

Transport and Turbulence
Y. Ren, W. Guttenfelder
Theory: G. Hammett

Boundary Physics
V. Soukhanovskii##, A. Diallo
Theory: C.-S. Chang

Materials and PFC Research
M. Jaworski, C. Skinner
Theory: D. Stotler

Waves and Energetic Particles
M. Podestá, R. Perkins
Theory: N. Gorelenkov, N. Bertelli

Solenoid-free start-up & ramp-up
R. Raman#, D. Mueller
Theory: S. Jardin

Advanced Scenarios & Control
S. Gerhardt, E. Kolemen
Scenario modelling: F. Poli

Cross-Cutting / ITER needs
J. Menard, S. Kaye, R. Maingi
Theory/Modeling: J. Canik*

***Columbia University, ## LLNL*
*#University of Washington, *ORNL*

TSG Responsibilities:

- Determine and address highest priority scientific issues through discussion and consensus at open meetings
- Draft scientific milestones with Program/Project directors
- Define facility/theory resources needed to achieve goals
- Organize NSTX-U Research Forum sessions
- Propose and execute experiments to achieve milestones and address research priorities
- Present TSG results and plans at annual PAC meetings
- Lead brainstorming, organization, writing of 5 year plan
- Aid results dissemination with Physics Analysis Division
  - Publications, talks, seminars, colloquia, conferences, ITPA, BPO
- Provide summaries of scientific progress at NSTX-U team meetings and other venues to promote discussion
- Assist and report to NSTX-U Program/Project directors

Planned FY2014-16 research supports 5 highest priority goals of NSTX-U 5 year plan:

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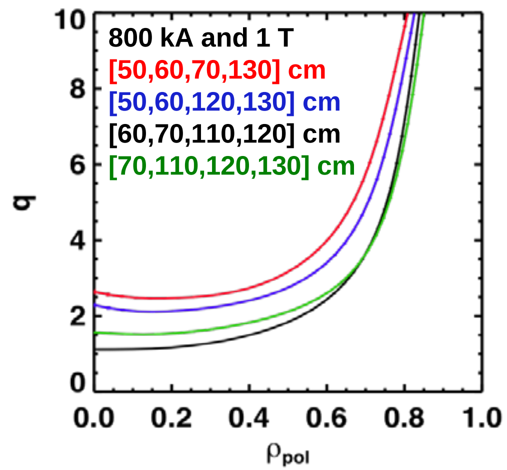
  5. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

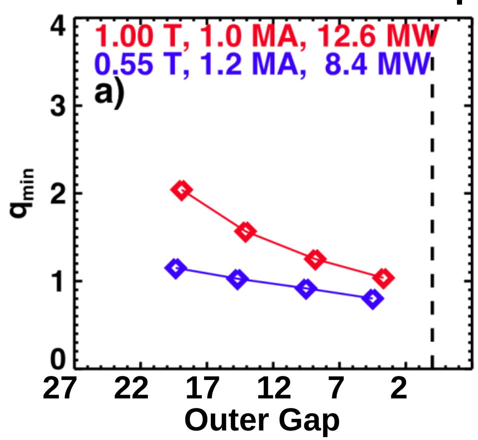
q-Profile Actuators

Variations in Beam Sources

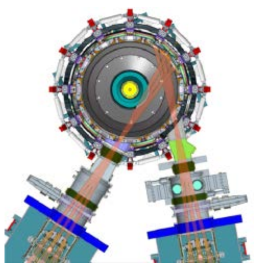
800 kA Partial Inductive, 87% < f_{NI} < 100%



Variations in Outer Gap

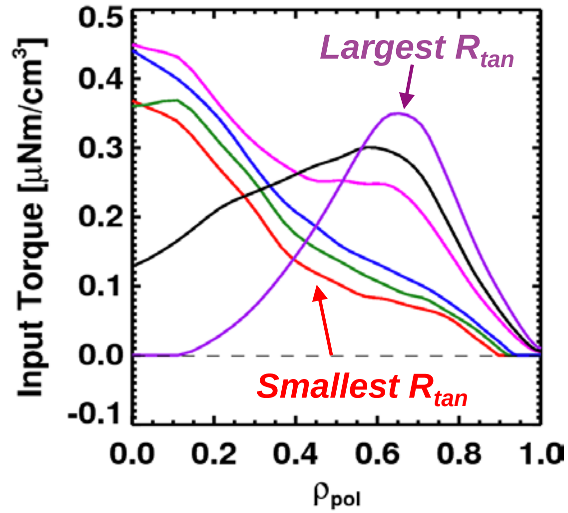


For more info see presentations by Gerhardt and Poli

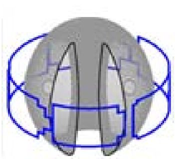


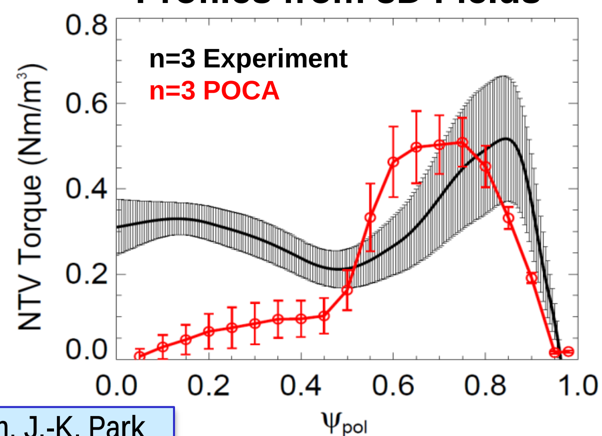
Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



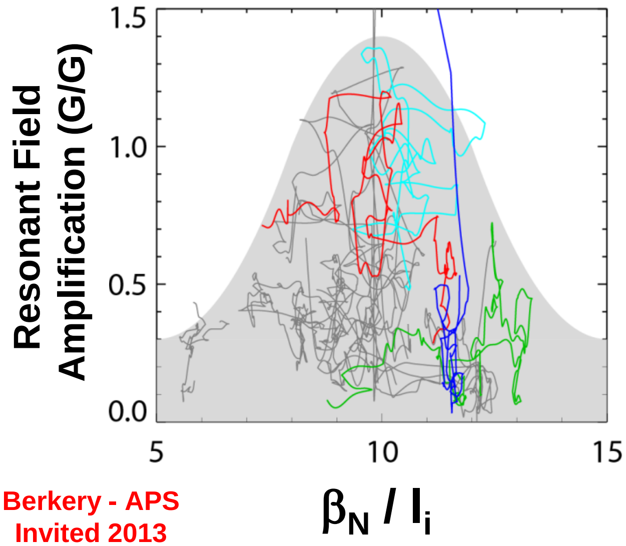
Measured and Calculated Torque Profiles from 3D Fields



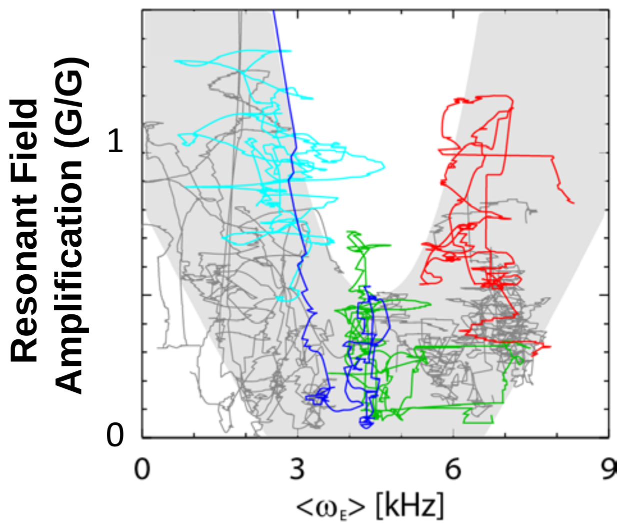


K. Kim, J.-K. Park

Rotation profile control will be an important tool for accessing and sustaining high β

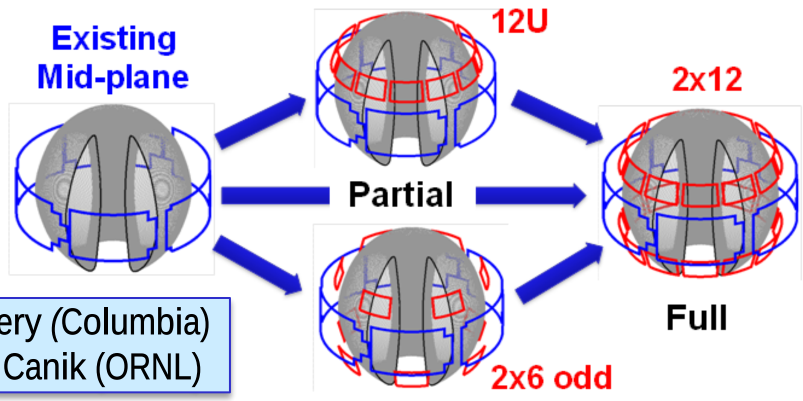


Berkery - APS Invited 2013



E×B rotation frequency

- n=1 MHD spectroscopy: high β_N can be more stable → important for advanced scenarios
- For these plasmas, high β_N was correlated with rotation that maximizes RWM damping
  - *Stabilization from ion precession drift resonance*
  - *Strong motivation for rotation profile control*
- 5YP: Off-midplane 3D coils enable control of resonant vs. non-resonant torques, v_ϕ profile



S. Sabbagh, J. Berkery (Columbia)
J-K Park (PPPL), J. Canik (ORNL)

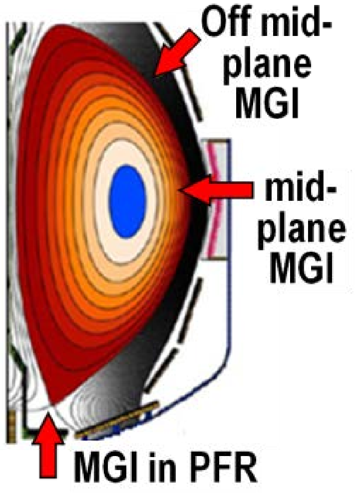
Advanced Scenarios and Control Research Plans for FY2014-16:
Implement advanced controls, explore high non-inductive & I_P scenarios

- FY14: Develop and implement advanced control algorithms in preparation for NSTX-U operation
  - Snowflake control on DIII-D (PPPL+LLNL+GA)
  - J profile control using on/off-axis 2nd NBI
    - ORISE post-doc: J profile control algorithms w/ TRANSP as plasma simulator
    - Implement rt-MSE (Nova Photonics) in rt-EFIT for q-profile reconstruction
  - Rotation control: 2nd NBI deposition flexibility + 3D fields/NTV
- FY14: DIII-D/National Campaign: test 100% NI at lower B_T
- FY14-15: Re-establish NSTX-U control and plasma scenarios
- FY15: Assess new 2nd NBI current-drive vs. R_{TAN}, n_e, outer gap
  - Push toward 100% non-inductive at higher B_T, P_{NBI}
- FY15: Explore scenarios (τ_E, l_i, MHD) at up to 60% higher I_P, B_T
- FY16: Explore scenarios at full I_P and B_T capability of NSTX-U
  - Goal: Access 100% non-inductive, test small I_P overdrive

Macroscopic Stability Research Plans for FY2014-16:

Complete 3D coil physics design, re-establish high-β ops, test MGI

- FY14: JRT - analysis for plasma response to 3D fields (J-K Park)
  - Also, complete physics design of new Non-axisymmetric Control Coils (NCC) for mode, error field, and v_ϕ control
- FY14: Understand/model low-density/ramp-up disruptions in NSTX in prep for low ν^* operation in NSTX-U scenarios
  - Hybrid fast-ion + $\nabla\Omega_\phi$ + ∇p-driven kink is a leading candidate early mode
- FY15: Re-establish n=1-3 error-field correction, RWM control, minimize EF rotation damping, sustain operation above no-wall limit
- FY15: Test poloidal dependence of Massive Gas Injection (outboard vs. private flux region)
- FY16: Contribute unique MGI data (low-A, injector location) for mitigation + warning, prediction
  - Assess mitigation triggering via real-time warning in NSTX-U



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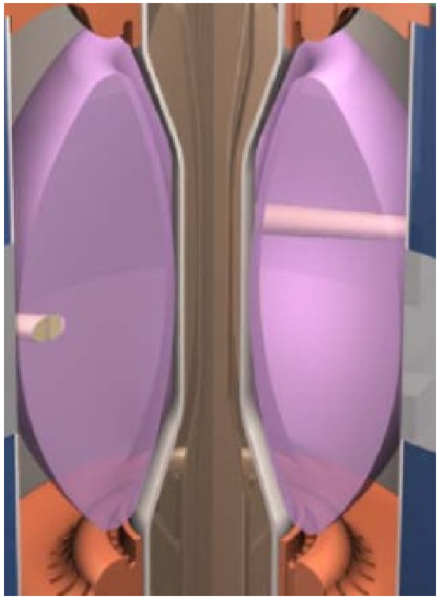
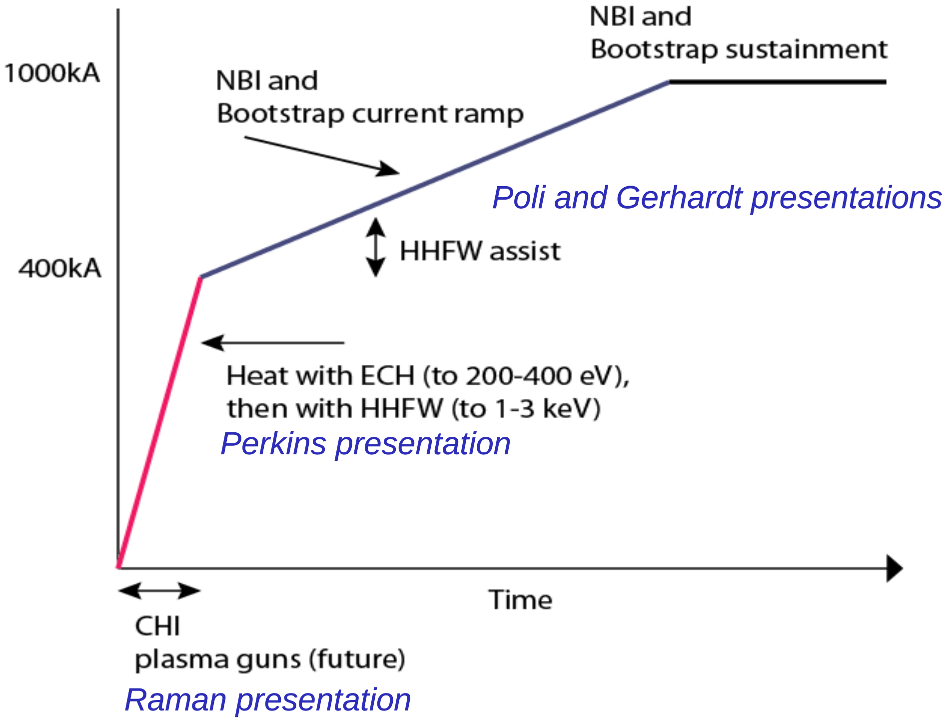
Plasma initiation with small or no transformer is unique challenge for ST-based Fusion Nuclear Science Facility

ST-FNSF has no/small central solenoid



NSTX-U Non-Inductive Strategy:

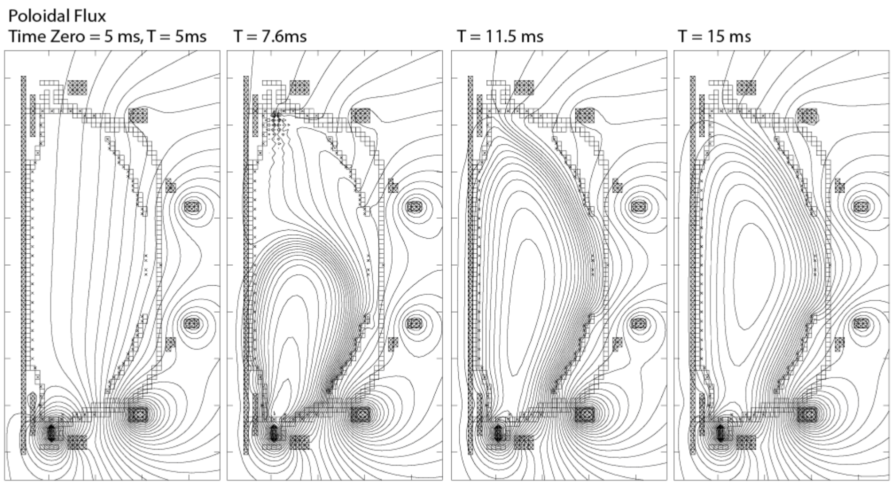


- **NSTX-U 5 year plan goal:**
  - Generate ~0.4MA closed-flux start-up current with helicity injection
  - Heat CHI with ECH and/or fast wave, ramp 0.4MA to 0.8-1MA with NBI

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

- TSC code successfully simulates CHI I_P ~200kA achieved in NSTX

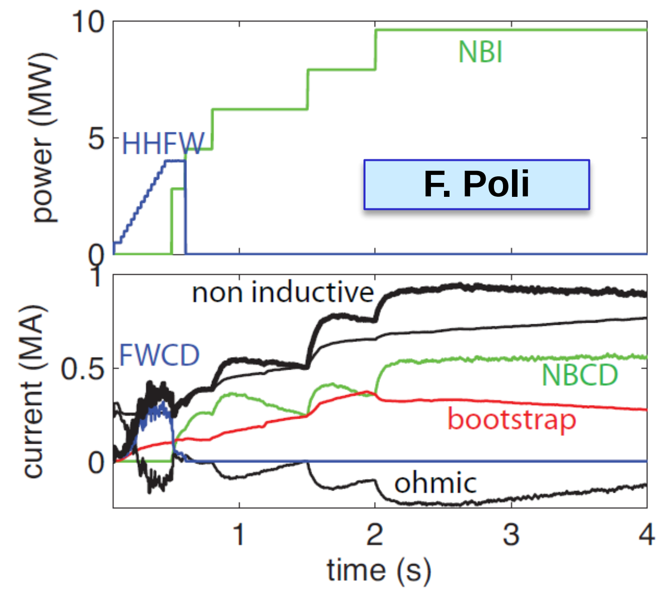
FY14: Implemented NSTX-U geometry in TSC



- TSC + tools included in 5 year plan support CHI I_P → 400kA in NSTX-U
  - 2.5 x higher injector flux (scales with I_P)
  - Higher B_T = 1T (increases current multiplication)
  - > 2kV CHI voltage (increases flux injection)
  - 1MW 28GHz ECH (increases T_e)

R. Raman (U-Wash)

- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
  - 1.5-2x higher CD efficiency, 3x lower prompt loss
- New TRANSP simulations of ramp-up: 0.3MA→0.9MA with FW+BS→NBI+BS
  - 1st self-consistent NBI-CD calcs during NI ramp-up

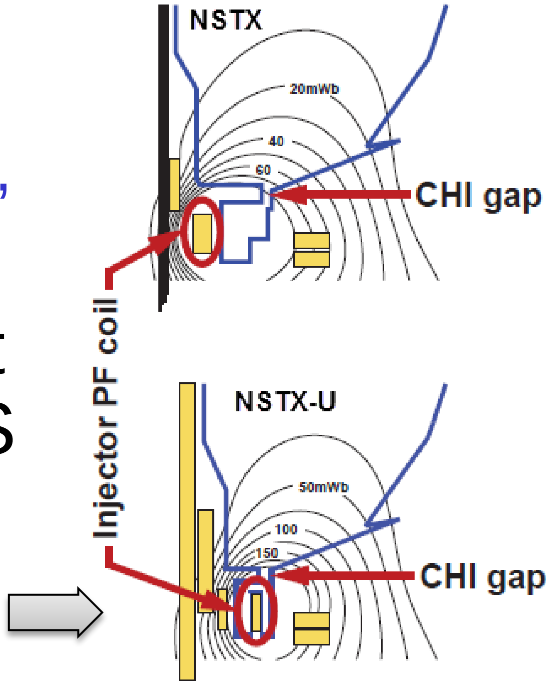


- $V_{surface}$ = 0 constraint → need to add induction from PF coil swing (future)

Solenoid-Free Start-up and Ramp-up Research Plans for FY2014-16:

Prepare CHI for NSTX-U, assess CHI/NBI start-up/ramp-up

- FY14: Complete design of upgraded capacitor bank and diagnostics for NSTX-U, implement CHI gap tiles
  - Also finish CHI design study for QUEST, possibly implement CHI
- FY14: DIII-D/National Campaign: test small current overdrive using NBI+BS
- FY15: Establish NSTX-U CHI, assess impact of new injector, gap, higher B_T



- FY15-16: Initial tests of small NBI+BS overdrive ramp-up using new 2nd NBI and higher B_T

Finalize ECH/EBW design, simulate & develop reliable FW H-mode

- FY14-15: Guide 1MW/28GHz ECH/EBW engineering design
  - ECH to heat CHI, form target for HHFW/NBI
  - EBW H&CD for start-up, sustainment

- FY16: Assess fast-wave SOL losses and core thermal and fast ion interactions at increased B_T, I_P

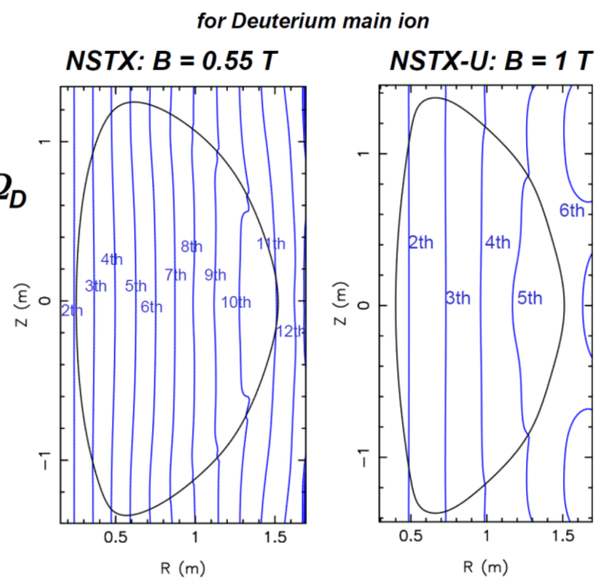
B_T → $2 \times B_T$

ω/Ω_D → $0.5 \times \omega/\Omega_D$

High harmonic regime in NSTX

↓

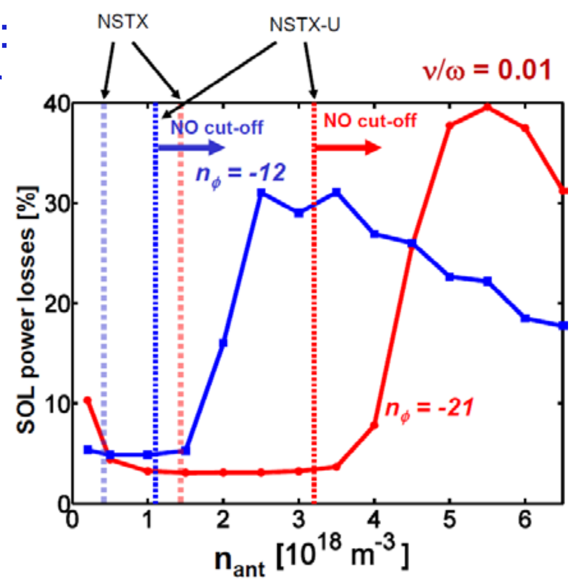
Mid harmonic regime in NSTX-U



AORSA modeling: higher B → lower SOL losses

$$n_{e,\mathrm{FW cut-off}} \propto \frac{k_\parallel^2 B}{\omega}$$

N. Bertelli



Planned FY2014-16 research supports 5 highest priority goals of NSTX-U 5 year plan:

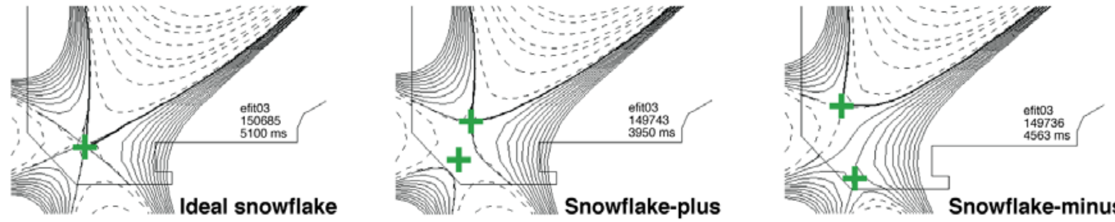
- Advance ST for Fusion Nuclear Science Facility (FNSF)
  1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF
  2. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid

- **Develop solutions for plasma-material interface challenge**
  3. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
  4. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

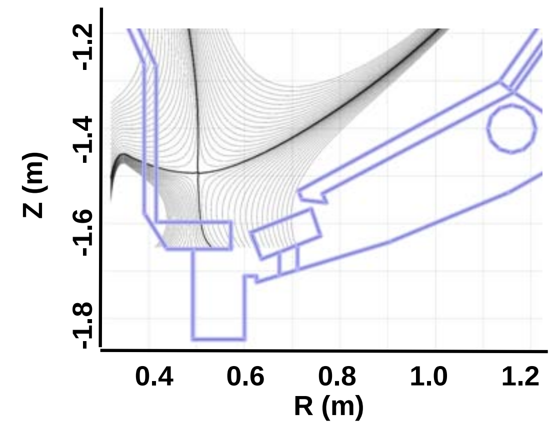
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  5. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

Snowflake divertor results + simulations project to favorable particle and power exhaust control in NSTX-U, next-steps

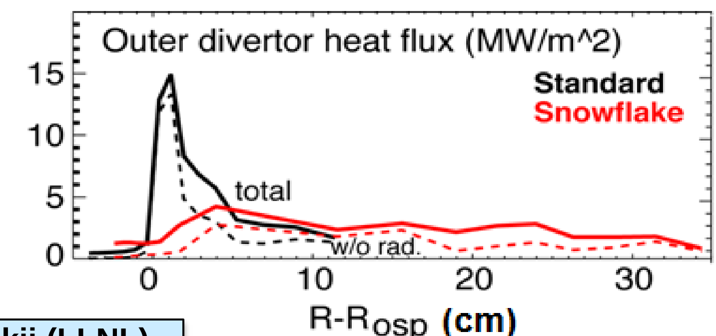
- Snowflake on DIII-D (GA+LLNL+PPPL collaboration) extended 2-3x reduction in q_{peak} to 3s duration
  - Compatible with cryo-pumping (n_e/n_G= 0.4-0.75)



- NSTX-U divertor cryo projections: $f_G \leq 0.5$ for wide range of I_P (λ_{SOL})
  - Standard/snowflake/X: 0.6/0.7 to 1.5/2MA
  - Maintain $q_{peak} \leq$ 10MW/m^2



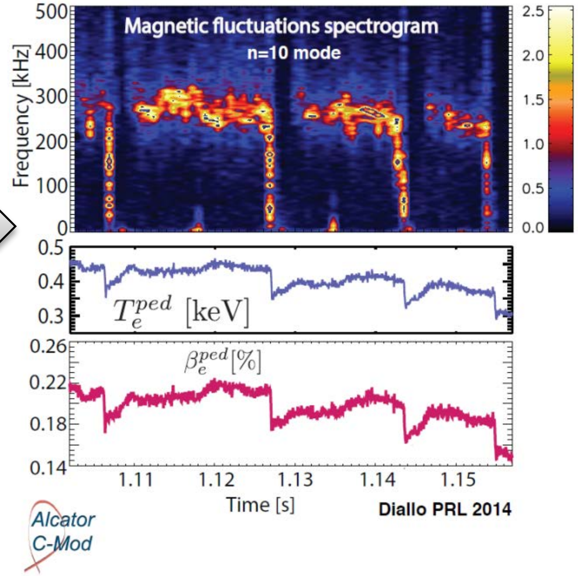
- Multi-fluid edge transport model (UEDGE) predicts factor of ~5 reduction in NSTX-U peak heat flux
  - Geometry + impurity radiation (4% C)
  - UEDGE also being applied to ST-FNSF advanced divertor options



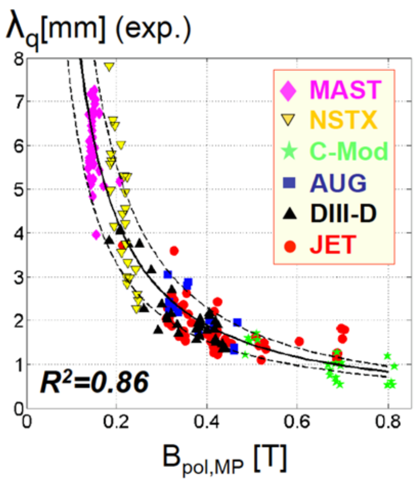
E. Meier, V. Soukhanovskii (LLNL)

Boundary Physics Research Plans for FY2014-16:
Advance heat flux, cryo, pedestal, SOL studies, extend to higher B_T, I_P

- FY14: Complete divertor-cryo physics design
- FY14: Pedestal/SOL collaborations
  - C-Mod: Measured field-aligned EM mode that clamps pedestal ∇T_e – consistent with kinetic ballooning mode (KBM) and EPED/ELITE
  - NSTX-U/DIII-D: Analysis of enhanced pedestal (EPH) / very-high confinement (VH) H-modes
    - Both obtain $H_{98y,2}$ >> 1, likely from increased E×B shear
    - New: Li dropper in DIII-D: 2-3× higher p_{ped}, 1.5× higher H_{98}

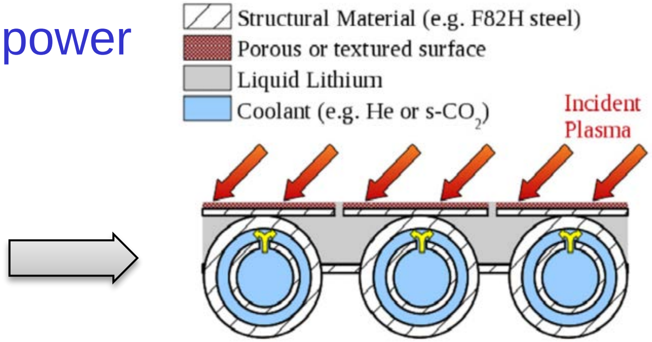


- FY15: Measure pedestal structure, SOL width, ELM types, snowflake/X performance at up to 60% higher I_P, B_T, 2× higher P_{NBI}
- FY16: I_P → 2MA → test snowflake/X, detachment, PFCs with $q_{||}$ up to 4-5× higher than NSTX



Materials and Plasma Facing Components Plans for FY2014-16:
Advance Li understanding/technology, support NSTX-U wall conditioning

- FY14: Develop Li-coating tools for upper PFCs of NSTX-U to increase Li coverage of C, D pumping, thermal confinement
- FY14-15: Lab-based R&D for advanced Li PFCs
  - Study Li on metal substrates, response to plasma power and particle fluxes (MAGNUM-PSI)
  - High-heat-flux high-Z PFC design (TZM or W lamellae)
  - Flowing Li loop tests
  - Develop capillary-restrained gas-cooled Li PFC



- FY14: EAST: assess particle/impurity control w/ triggered ELMs, cryo-pumping, lithiumization, high-Z PFCs
- FY15: Test lithium granule injector (LGI) for ELM triggering and impurity control, Li coating performance in NSTX-U
- FY16: Begin to assess high-Z (+Li coated) PFC performance with 1 row of W or TZM tiles on outboard divertor (at large R)

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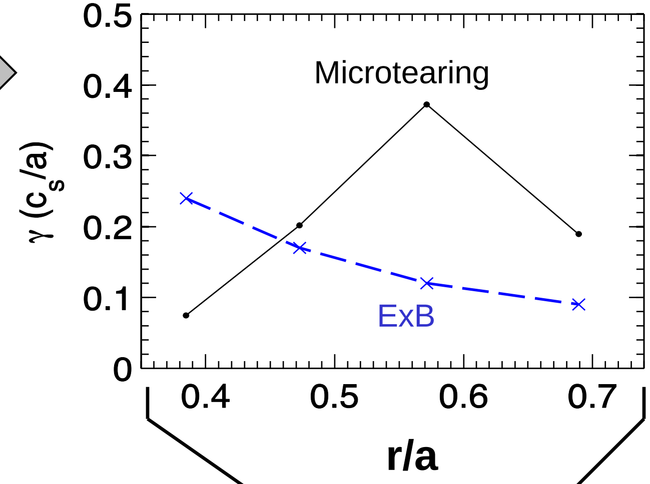
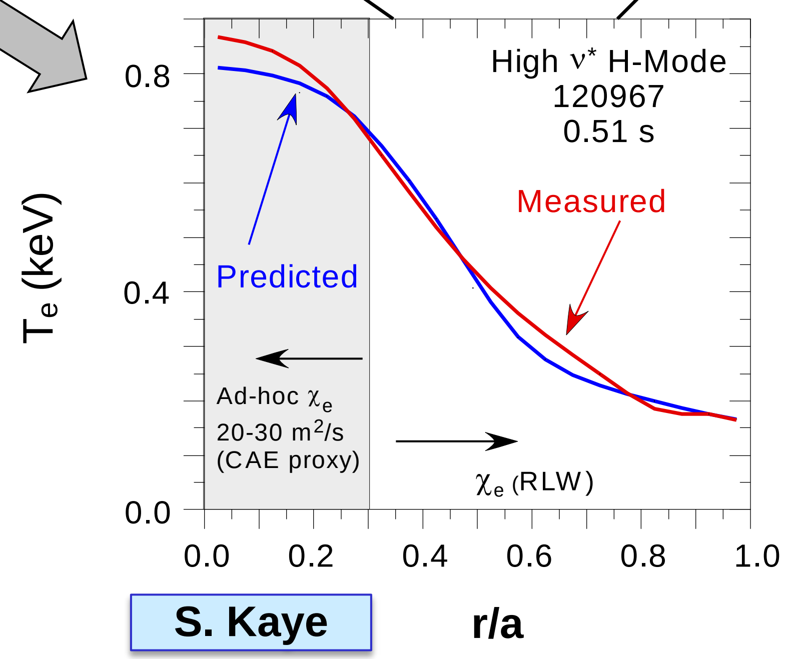
Testing predictability of T_e profiles using reduced χ_e models in regimes where single micro-instability is dominant

- Linear gyrokinetic simulations find microtearing unstable in mid-radius region of high-collisionality H-modes
  - Other micro-instabilities subdominant at this location for this class of discharge



- Reduced model for microtearing χ_e (Rebut-Lallia-Watkins (RLW) - 1988) shows reasonable agreement between predicted & measured T_e for r/a > 0.3
  - χ_e much larger than RLW must be used in core to match central T_e
  - Enhanced core electron thermal transport may be due energy transfer from core GAE/CAE → mid-radius KAW → electrons
    - See presentations by Kaye, Podestá, Guttenfelder

E. Belova – HYM code (Theory/NSTX-U partnership)

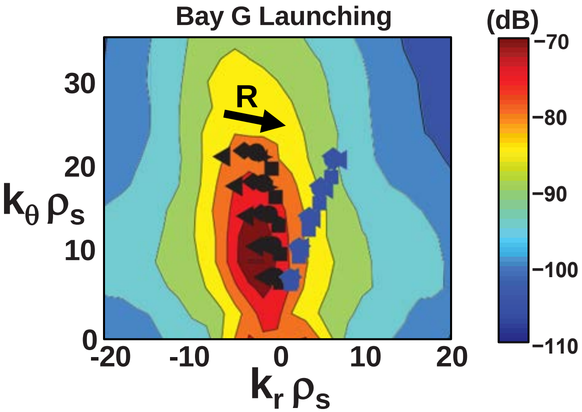


S. Kaye

Transport and Turbulence Research Plans for FY2014-16:

First τ_E data at higher B_T, I_P + turbulence, develop reduced χ_e models

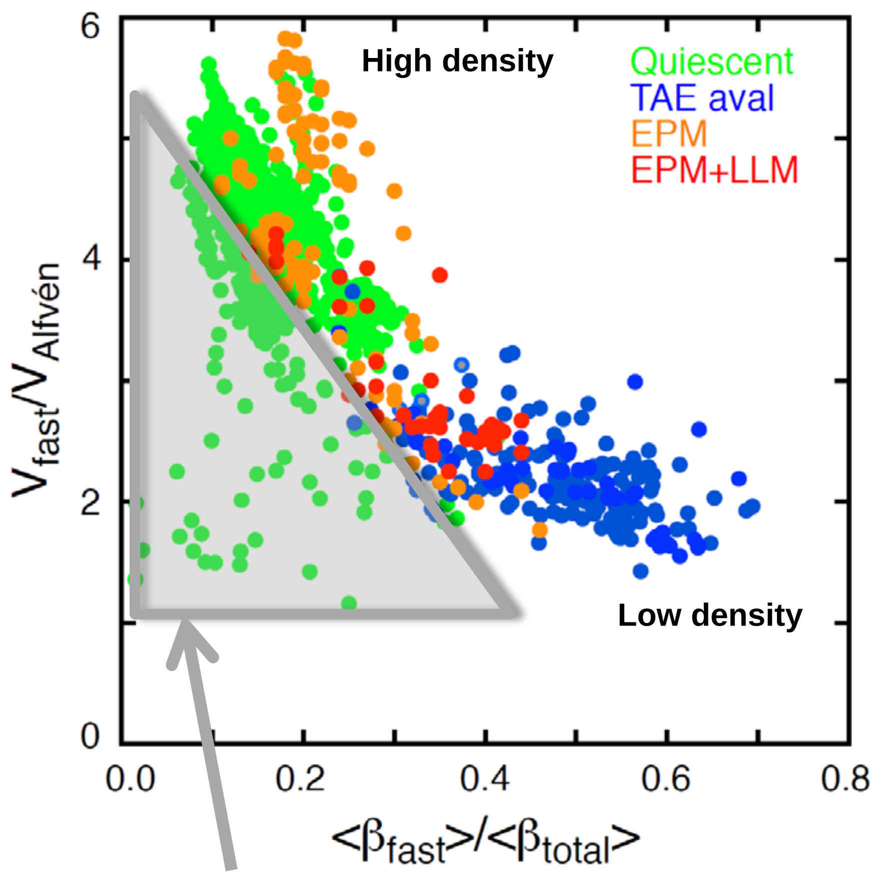
- FY14-16: Develop model $\chi_{e,\,AE}$ using measured CAE/GAE mode structures and HYM/ORBIT simulations (w/ EP group)
- FY14-16: Develop and validate reduced transport models using ST data + linear and non-linear gyro-kinetic simulations
- FY15: Extend ST confinement scalings and understanding with up to 60% increase in B_T and I_P
  - Measure low-k δn (BES w/ increased edge channel count), 1st polarimetry data
- FY16: Extend confinement studies to full B_T, I_P → 2-3× lower ν^*
- FY16: Initial utilization of new high-k FIR scattering system for ETG turbulence ⇨
  - Measure k_r & k_θ to study turbulence anisotropy
- FY16 (incremental): Study turbulence vs. ν^*, rotation, q with high-k + BES + polarimetry



FY13-14: Assessed parametric dependence of TAE avalanches and energetic particle modes (EPMs) in NSTX

Identified regimes w/ small fast-ion loss: important for NSTX-U, FNSF, ITER

- Modes lead to neutron rate decrements up to 30%
- TAE avalanches only occur for $\beta_{fast} > 0.3\ \beta_{total}$
- Conversely, quiescent plasmas were only seen where $\beta_{fast} < 0.3\ \beta_{total}$
- Two types of EPM:
  - **Higher q_{min}~2-3 (earlier in shot), more continuous → long-lasting mode (LLM)**
  - **Lower q_{min} → 1 (later in shot), more bursty and fishbone-like, n=1-3**

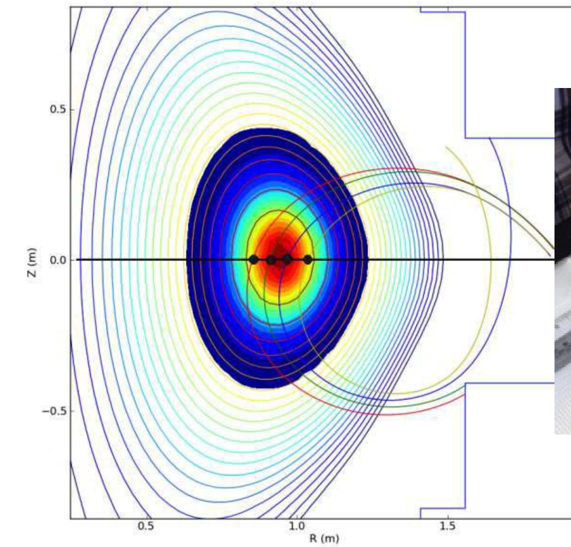


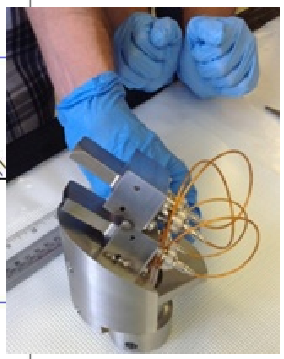
NSTX quiescent operating range
(NSTX-U will access up to 2× lower v_f/v_A)

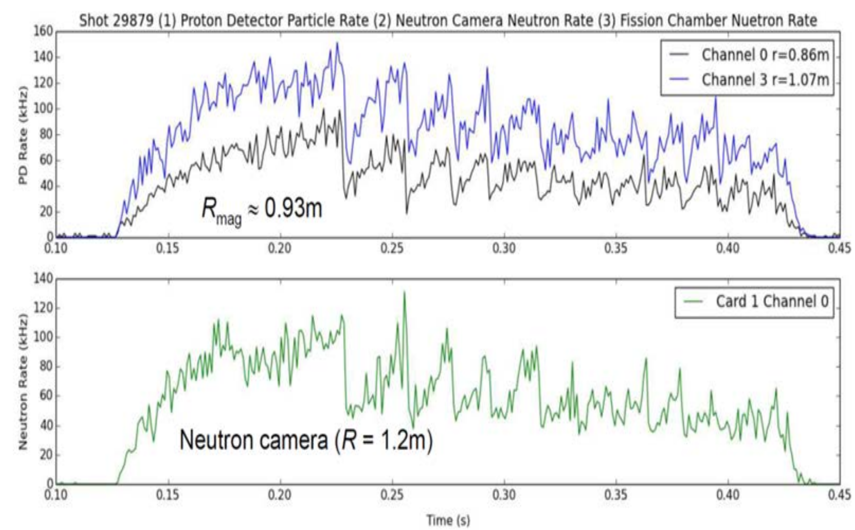
E. Fredrickson

Developed new DD fusion product detector through collaboration with MAST

- Detector measures radial profile of DD fusion reactivity
  - 3 MeV protons and 1 MeV tritons
- Profiles obtained for range of plasma conditions:
  - Quiescent, sawtoothing, fishbones
- DD detector and neutron camera show similar time-dependence – profile comparisons ongoing
- Results encouraging for development of higher channel count system for NSTX-U
  - Smaller, cheaper than neutron-camera





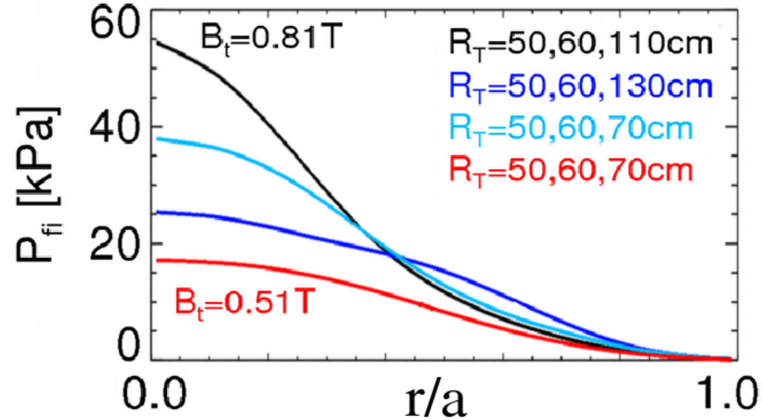


D. Darrow (PPPL), W. Boeglin and R. Perez (Florida International University)

Energetic Particle Physics Research Plans for FY2013-15:

Develop full + reduced fast-ion transport models, characterize new 2nd NBI

- FY14: Collaborate with DIII-D/National Campaign studying AE thresholds & fast-ion transport vs. q_{min} and on/off-axis NBI
- FY14: Finalize design/implementation of prototype AE antenna and of upgraded ssNPA diagnostic
- FY14-15: Develop reduced model for AE-induced fast ion losses – needed for NBICD in STs/ATs/ITER
- FY14-15: Contribute to development of reduced model of electron thermal transport from CAE/GAE
- FY15-16: Measure fast-ion (FI) density profiles, confinement, current drive, AE stability
  - Exploit new 2nd NBI and higher B_T, access to reduced v_{fast} / v_A



Outline

- PAC Charges
- NSTX-U mission, priorities, assessments
- FY14-16 overview and milestones
- FY14-16 research plan highlights
- ITPA and ITER contributions
- ST-FNSF mission and configuration study
- Ideas to enhance NSTX-U attractiveness
- Summary

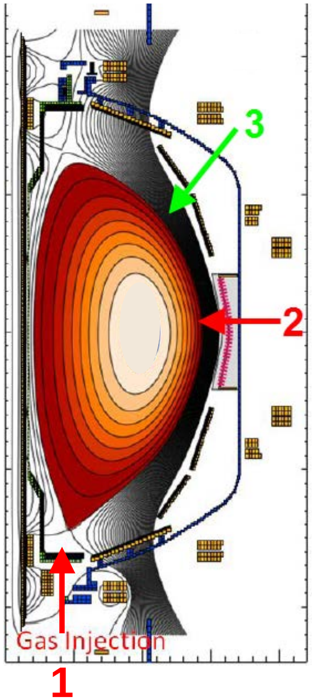
Supporting ITER through ITPA participation

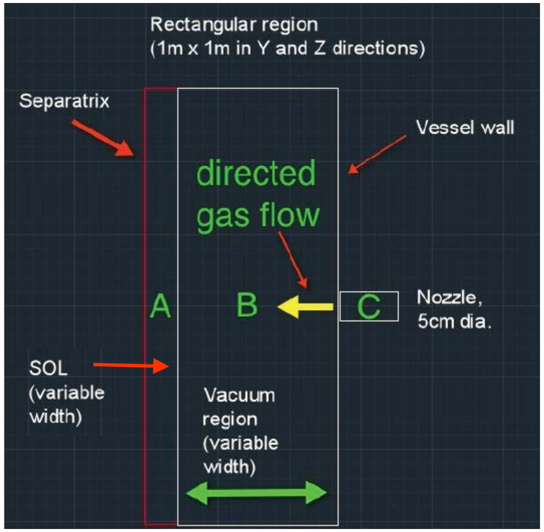
- Representatives in every Task Group, leadership in several:
  - R. Maingi: chair of Pedestal and Edge Physics TG
  - S. Sabbagh: Leads WG on RWM code benchmarking, RWM stability & control
- Active in 25 JEX/JACs with many contributors from NSTX-U

Pedestal, Scrape-Off Layer, Divertor				
PEP-26	Critical edge parameters for achieving L-H transitions	PEP-36	ELM energy losses and their dimensionless scaling in the context of operational parameters	*Maingi (chair), Ahn, Canik, Chang, Diallo, Goldston, Jaworski*
PEP-27	Pedestal profile evolution following L-H/H-L transitions	DSOL-24	Disruption heat loads	
PEP-29	Vertical jolts/kicks for ELM triggering and control	DSOL-28	Narrow heat flux widths and divertor power dissipation	
Energetic Particles				
EP-2	**Fast ion losses and redistribution from localized AEs**	EP-6	Fast ion losses and associated heat loads from edge perturbations (ELMs and RMPs)	*Fredrickson, Fu, Gorelenkov, Heidbrink, Kramer, Podestá*
EP-4	Effect of dynamical friction (drag) at resonance on non-linear AE evolution			
Integrated Operating Scenarios				
IOS-3.2	Define access conditions to get to a steady-state scenario	IOS-4.3	Collisionality of confinement in advanced inductive plasmas	*Gerhardt, Kessel, Poli, Gates*
IOS-4.1	Access conditions for advanced inductive scenarios with ITER-relevant conditions	IOS-5.2	Maintaining ICRH coupling in expected ITER regime	
Macroscopic Stability and Control				
MDC-2	Joint experiments on resistive wall mode physics	**MDC-17**	**Active disruption avoidance**	*Sabbagh, Berkery, Jardin, Park, Zakharov, Gerhardt, Menard*
MDC-14	Rotation effects on neoclassical tearing modes	MDC-18	Evaluation of axisymmetric control aspects	
MDC-15	**Disruption database development**	**MDC-21**	**Global mode stabilization physics and control**	
Transport and Turbulence				
TC-9	Scaling of intrinsic plasma rotation with no external momentum input	**TC-17**	**ρ^* scaling of intrinsic torque**	*Kaye (previous chair), Ren, Guttenfelder, McKee/Smith*
TC-10	**Experimental identification of ITG, TEM and ETG turbulence and comparison with codes**	**TC-24**	**Impact of resonant magnetic perturbations on transport and confinement**	
TC-15	**Dependence of momentum and particle pinch on collisionality**			

Supporting ITER through massive gas injection (MGI) research for disruption mitigation

MGI research will assess gas penetration efficiency at different poloidal locations





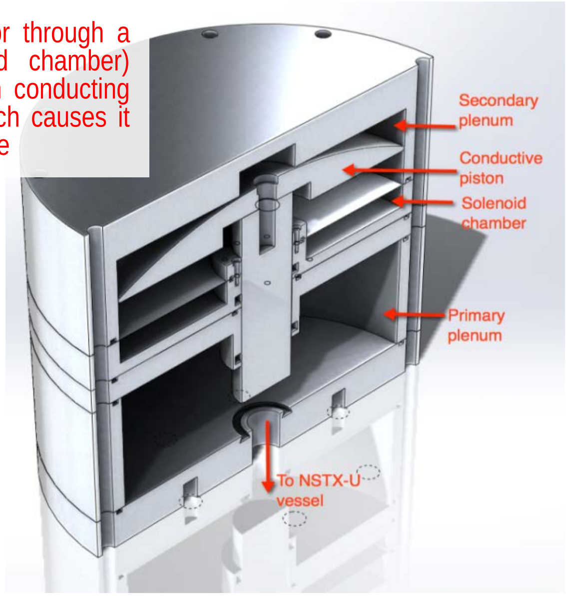
Predictive capability: Modeling using DEGAS-2 is quantifying the gas penetration past the SOL for NSTX-U

- NSTX-U can offer new insight by:
  - Reducing the amount of gas
  - Injecting gas into the private flux and lower x-point regions of divertor to determine if these are more desirable locations for MGI

NSTX-U researchers successfully tested, will utilize pulsed-induction MGI valves

- Same design as is being developed for ITER
- Builds on designs used on JET and TEXTOR
- Eliminates magnetic material in valve that can saturate in external magnetic field
- Sub-ms opening time → well suited for MGI
- Can operate at very high pressure (5-10kTorr)

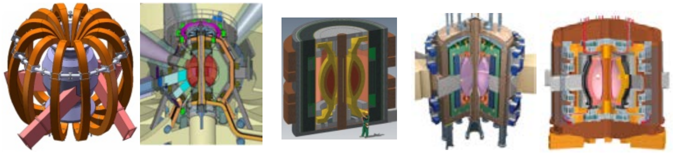
Discharging small capacitor through a pancake coil (in solenoid chamber) induces image currents on conducting (non-magnetic) piston, which causes it open on a sub ms time scale



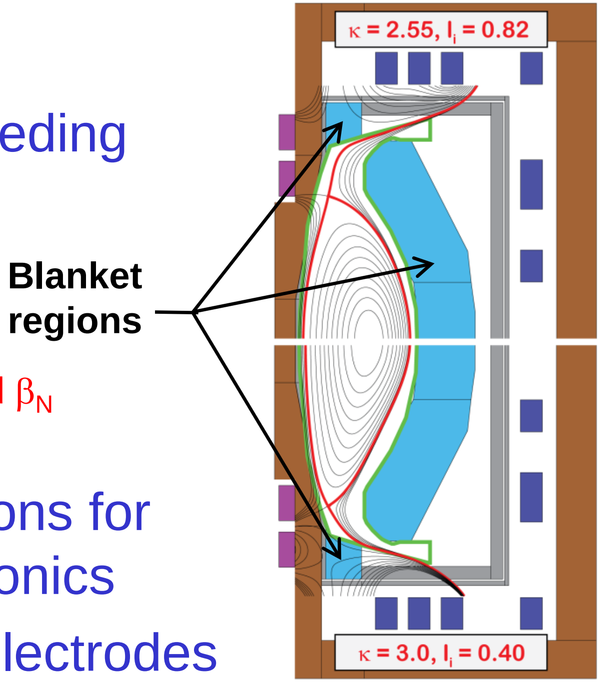
R. Raman (University of Washington)

NSTX/ST researchers contributing to LDRD-funded study of Mission and Configuration of an ST-FNSF

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



- Goals of study:
  - Review existing designs, ID advantageous features, improve configuration
  - Develop self-consistent assessment + configuration for use by community
  - Assess T self-sufficiency, maintainability, flexibility
- FY2013-14 results/progress:
  - Tritium breeding ratio (TBR) ~ 1 likely requires breeding blanket near top+bottom of centerstack (CS)
  - Identified coil configuration compatible with:
    - Breeding in CS end region + vertical maintenance
    - Ex-vessel PF coils on outboard, can be S/C, support range of l_i and β_N
    - Divertor power exhaust: q_{peak} ~ 3-5MW/m^2, partially detached
  - Now carrying out free-boundary TRANSP simulations for NNBI+BS current drive, fusion performance, neutronics
  - Exploring methods / locations to incorporate CHI electrodes



NSTX-U collaborators offered many good ideas on how to enhance research program attractiveness

- NSTX-U Program has 2014 FES “Notable Outcome”:
  - “Expand engagement with university scientists to enhance NSTX-U program”
  - Note to FES: expect collaborators to request / need ~2-3 run-days / year on-average (based on 2010 run statistics)
- NSTX-U Program coordinated 3 meetings with 22 FES-funded NSTX-U collaboration grantees
  - Asked for brainstorming on “Ideas to enhance participation in NSTX-U research and/or program by U.S. Universities, early-career researchers, students”
  - Two main categories of ideas: (1) FES, (2) NSTX-U / PPPL
- NSTX-U/PPPL is in preliminary stages of deciding what ideas to implement - we welcome your input

Suggestions / ideas for FES (1)

1. Stabilize funding to prevent loss of personnel and to enable engaging graduate students in research
   - Fluctuations in funding harmful – especially for smaller groups with little funding margin

2. FES-related DOE solicitations should explicitly encourage student research
   - 2013 NSTX-U Collaboration Solicitation does not explicitly encourage student research
     - In contrast, NSF-DOE Basic Plasma Science solicitations do explicitly encourage support for education – important criterion in proposal review
   - Suggest/encourage additional funding for students

Suggestions / ideas for FES (2)

3. Expand Early Career Research (ECR) awards to University Scientists and/or Research Professors
   - Early Career Awards have proven very effective for initiating long term collaboration with major facilities
   - Current DoE solicitations for early career researchers only cover tenure track faculty (up to $150k/yr)
     - Many university researchers are encouraged to be PIs on collaboration proposals, but cannot apply for these awards
   - Extending ECR to research faculty positions could:
     - Foster new strong collaborations with universities
     - Perhaps lead to formation of new tenure-track positions

Note: FES has previously inquired about such expansion within the Office of Science, but there is/was reluctance to expand to non-tenure-track

Suggestions / Ideas for NSTX-U/PPPL (1)

1. Identify graduate and undergraduate ‘independent research’ projects to be done for academic credit
   - Coordinate / ID topics across major research facilities
   - Solicit interested students from range of Universities
   - Scope: senior thesis / similar – 6 – 12 month project
     - Would be more in-depth / extensive than SULI/NUF summer project
2. Host student visits to national facilities during operations
   - Advertise the NSTX-U research environment
   - Provide a context for students with their peers
3. Set aside run-time explicitly for exploratory ideas
   - Target students, early career, groups outside main-line fusion
4. Have a “fellow/scholar” program for mid-career research collaborators to aid in promotions at home institution
   - Small seed funding for travel can help support students in projects affiliated with NSTX-U from their home institutions

Suggestions / Ideas for NSTX-U/PPPL (2)

5. Actively encourage proposals from University Researchers to DoE, NSF, etc. that **directly benefit NSTX-U** – such encouragement could also target other activities at PPPL

6. Direct PPPL funding of small, targeted 1-year NSTX-U subcontracts with University Researchers
   - Benefits researchers by raising their stature, both within and outside of the University, while also providing exposure to increased opportunities
     - Such contracts could act as a stepping stone to full DoE Grants

7. Develop/utilize remote experimental collaboration IT/software capabilities to enhance participation of off-site researchers

8. Allocate space for a “diagnostic test laboratory” (this will be included as part of PPPL “campus plan”)

Leading candidate ideas to promote NSTX-U program attractiveness

- Support consideration of all 3 ideas for FES
  - Stabilize funding (in progress), encourage student participation in collaboration solicitations, non-tenure-track ECR (difficult)
- Several NSTX-U/PPPL ideas could be high impact
  - Students: senior projects, visits/travel, targeted run-time
  - Universities: joint proposals, short-term direct grants, enhanced collaboration tools (remote control room)

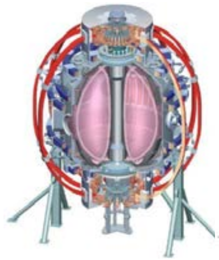
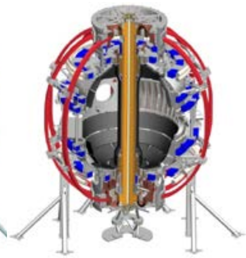
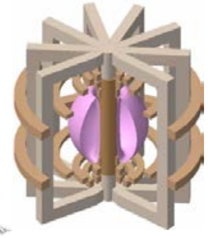
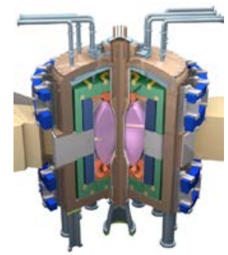
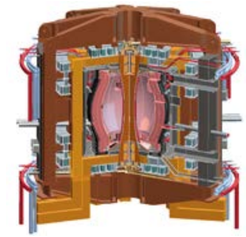
➢ Idea: NSTX-U Innovative Research Award (NIRA)
  - Target innovative / breakthrough R&D – fund primarily universities
    - High-impact science and/or address critical NSTX-U / ITER / FNSF needs
  - Encourage early-career and student participation / leadership
  - Fund from (supplemented) NSTX-U science budget: $0.5-1M / year
  - Typical award level: up to ~100-200k / year for up to 3 years
    - Awards granted twice per year, annual progress review and funding renewal
  - Review: NSTX-U management + small committee + FES concurrence

Summary

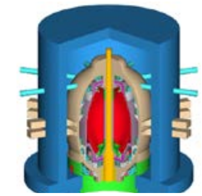
- Research team productive during Upgrade outage
  - Publications, conferences, JRT and ITPA leadership
- 5 year plan and near-term research goals in place for research campaign starting spring 2015
  - Research forum / CD-4 to be held near end of this CY
  - Goals/milestones emphasize high-priority research for FNSF and ITER
- Developed ideas to enhance NSTX-U attractiveness
  - Will finalize ideas with FES, implement as resources permit

Backup Slides

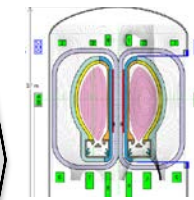
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs

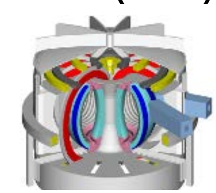
Low-A Power Plants



ARIES-ST (A=1.6)



JUST (A=1.8)



VECTOR (A=2.3)

Parameter	NSTX	NSTX Upgrade	Plasma Material Interface Facility	Fusion Nuclear Science Facility	Pilot Plant
Major Radius R_0 [m]	0.86	**0.94**	1.0	1.3	1.6 – 2.2
Aspect Ratio R_0 / a	≥ 1.3	**≥ 1.5**	≥ 1.8	≥ 1.5	≥ 1.7
Plasma Current [MA]	1	**2**	3 – 4	4 – 10	11 – 18
Toroidal Field [T]	0.5	**1**	2	2 – 3	2.4 – 3
Auxiliary Power [MW]	≤ 8	**≤ 19***	30 – 50	22 – 45	50 – 85
P/R [MW/m]	10	**20**	30 – 50	30 – 60	70 – 90
P/S [MW/m^2]	0.2	**0.4-0.6**	0.7 – 1.2	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

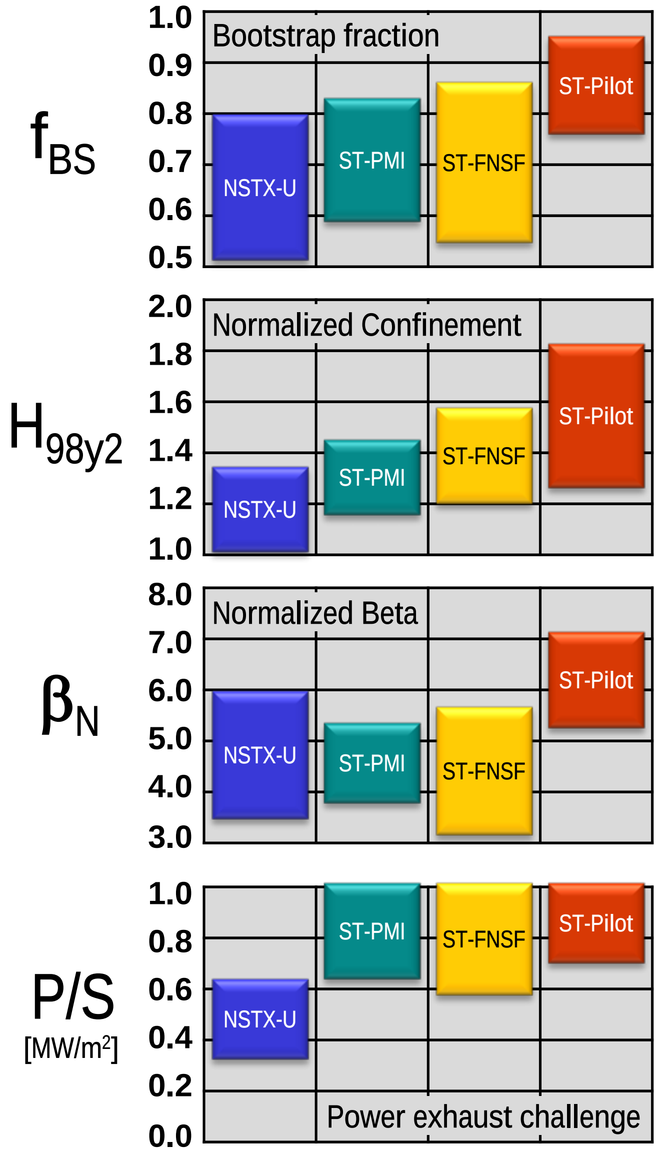
Key issues to resolve for next-step STs

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

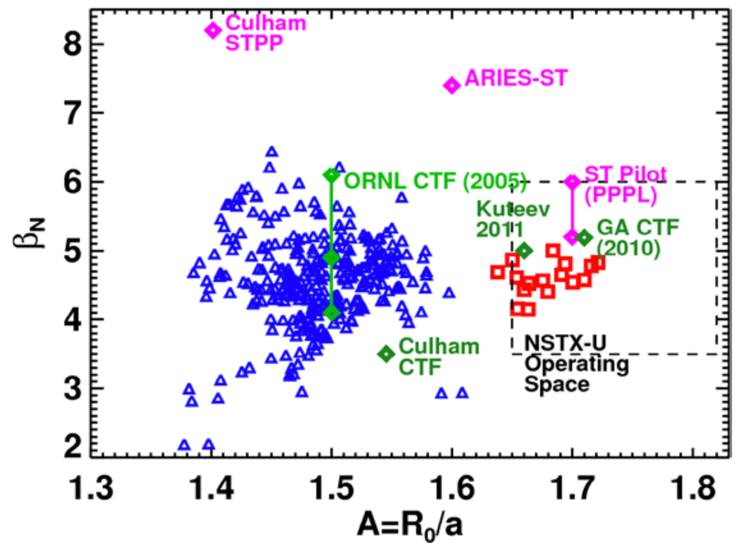
5 year plan goal: access performance levels of next-steps, approach Pilot-Plant regimes

Requirements for tokamak / ST next-steps:

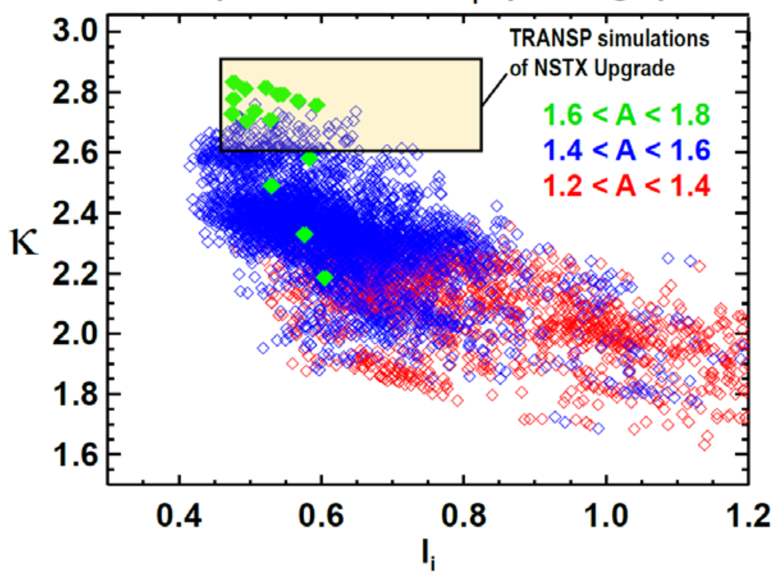
- **Full non-inductive (NI) current drive for steady-state operation**
  - ST requires NI start-up/ramp-up
- **High confinement to minimize auxiliary heating, device size**
- **Sustained high β to minimize magnet size, forces, power**
- **Divertor/first-wall survival with intense power/particle fluxes**



NSTX has already accessed A, β_N, κ needed for ST-based FNSF – next step is to access & control 100% non-inductive

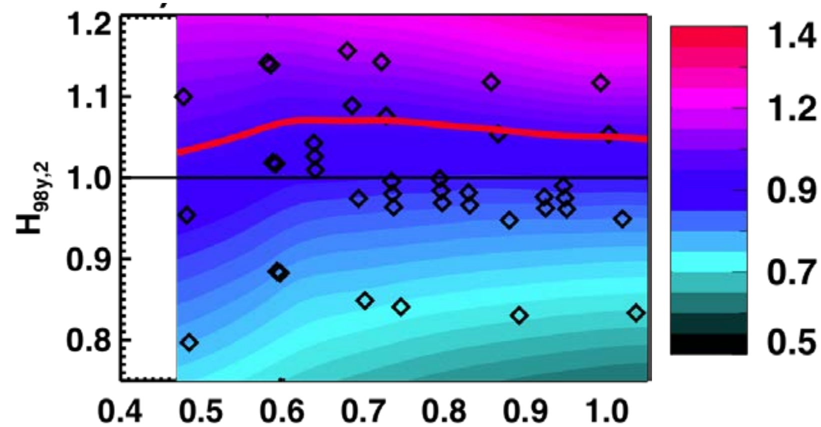


NSTX experimental κ vs. l_i operating space

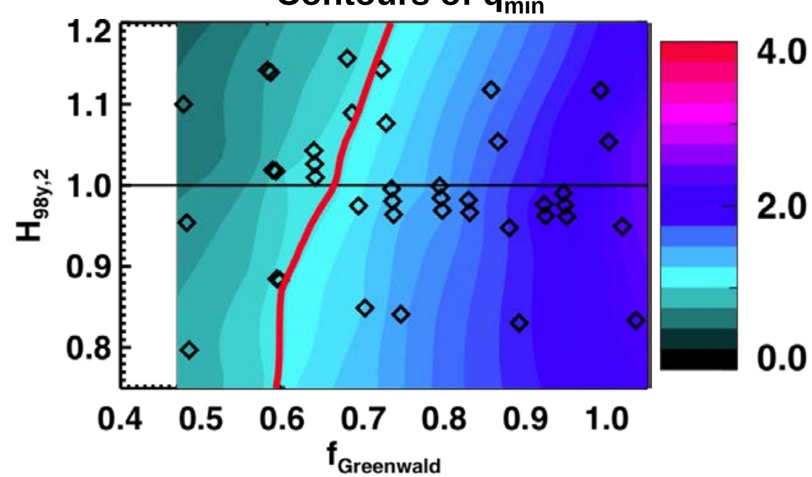


NSTX-U TRANSP predictions:
B_T=1.0 T, I_P=1 MA, P_{inj}=12.6 MW

Contours of Non-Inductive Fraction



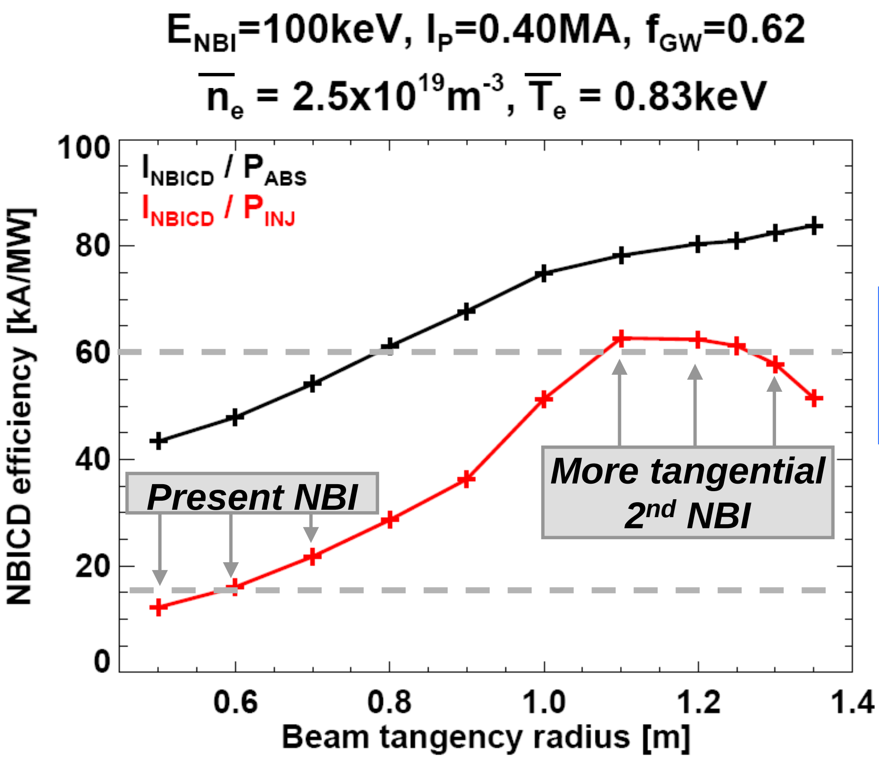
Contours of q_{min}

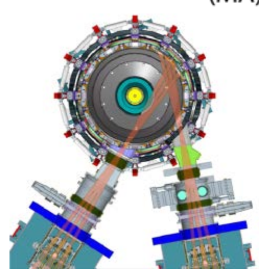


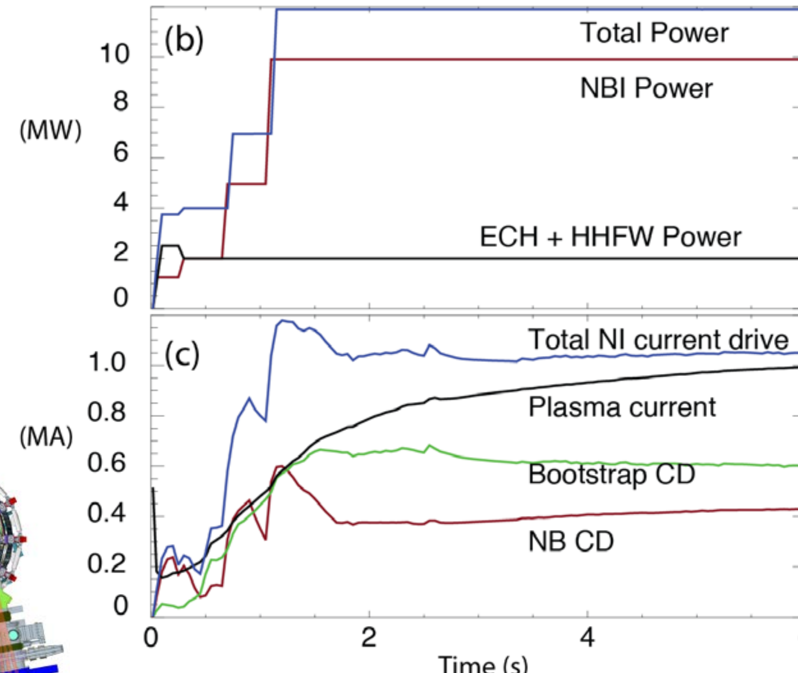
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new CS + more tangential 2nd NBI

- More tangential NBI provides 3-4x higher CD at low I_P:
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
    - Now modeling coupling to 0.2-0.3MA (TRANSP)
  - 1.5-2x higher current drive efficiency

- TSC simulation of non-inductive ramp-up from initial CHI target
  - Simulations now being improved to use TRANSP/NUBEAM loop within TSC
  - Experimental challenges:
    - Maximum NBI power in low l_i CHI plasma



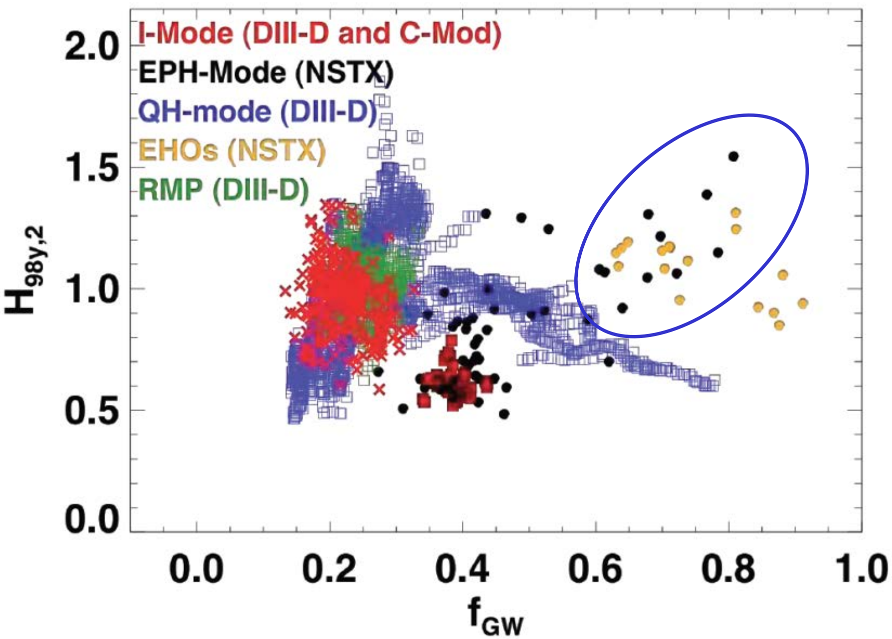


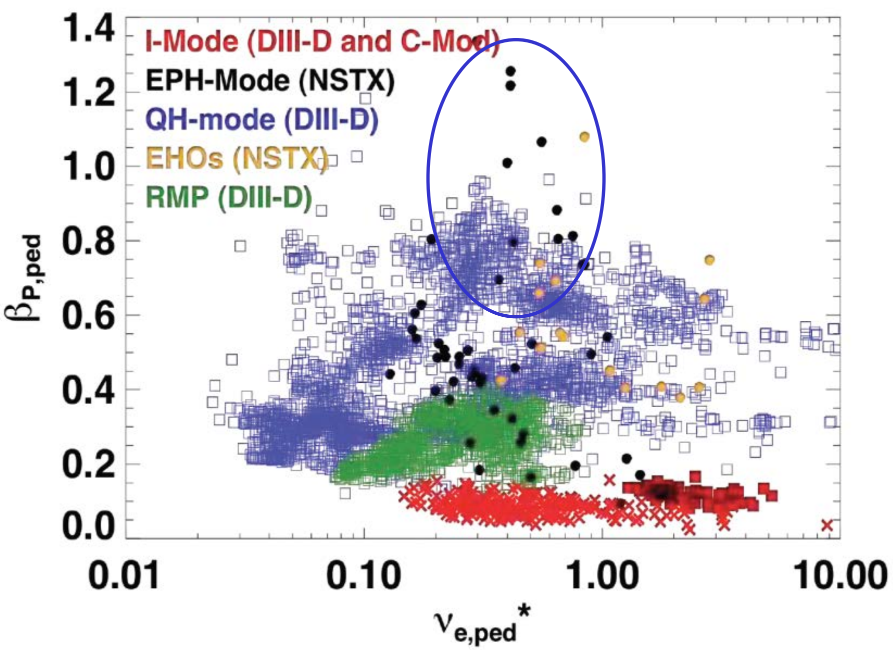


R. Raman, F. Poli, C.E. Kessel, S.C. Jardin

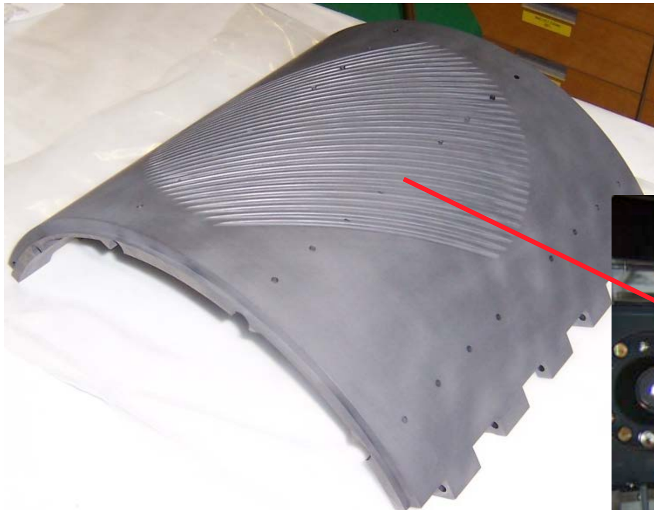
NSTX-U (S. Gerhardt) led 3 facility joint research target (JRT)

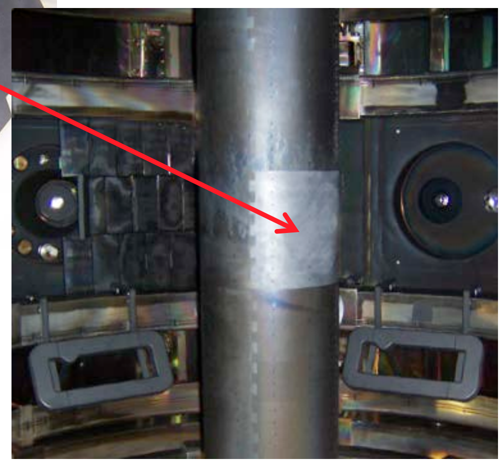
- 2013 JRT: "Explore enhanced confinement regimes without large edge instabilities, but with acceptable edge particle transport and a strong thermal transport barrier, and extrapolate … to ITER."
- NSTX contributed data from Enhanced Pedestal H-mode (EPH)
- **EPH is attractive regime of nearly stationary high confinement, β:**
  - **$H_{98} \leq 1.6$ with $\beta_N = 6\text{-}6.5$ and high non-inductive fraction = 60-70%**



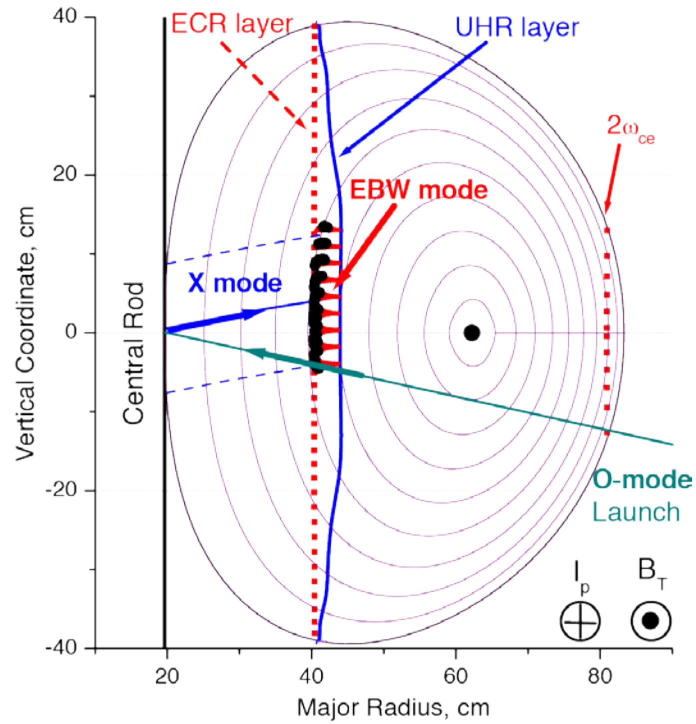


Participated in MAST 28 GHz EBW start-up campaign that achieved record plasma current





Grooved reflecting polarizer machined into center column in MAST



- 28 GHz O-mode weakly absorbed (< 2%) below $n_e \sim 1 \times 10^{19}\ m^{-3}$ cut off
- Polarizer on center column converts to X-Mode that then 100% converts to EBWs
- Previously achieved I_p~33 kA but arcs in waveguide limited RF power [Sept 2009]
- **During EBW start-up campaigns in 2013 coupled 70-100 kW for 300-400 ms achieving I_p = 50-75 kA → η_{eff} ~ 0.5-1 A/W**

ORNL-led + G. Taylor (PPPL)