NSTX-U

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

NSTX-U Research Plans for FY2013-15

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U Tulsa
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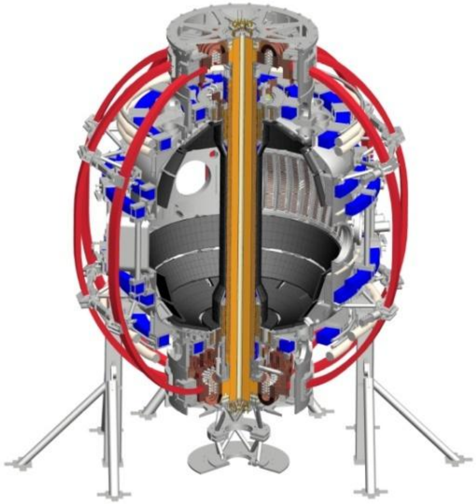
X Science LLC

J. Menard, M. Ono - PPPL

For the NSTX-U Research Team

FY2015 FES Budget Planning Meeting
Germantown, MD
April 10, 2013



Culham Sci Ctr
York U
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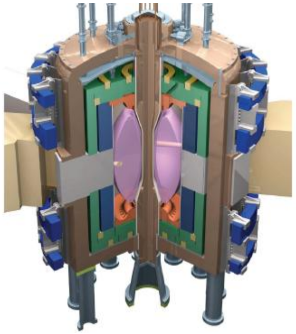
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

- NSTX-U mission, priorities, FY13-15 overview
- FY13-15 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF mission and configuration study
- Summary

NSTX Upgrade mission elements

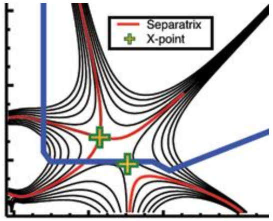
- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**



ST-FNSF

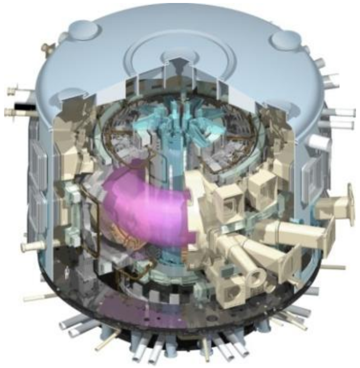
- **Develop solutions for the plasma-material interface challenge**

Lithium



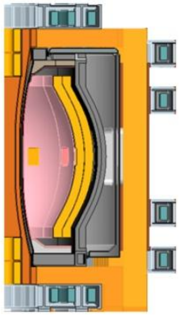
"Snowflake"

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



ITER

- **Develop ST as fusion energy system**



ST Pilot Plant

FY13-15 planned research supports 5 highest priority goals for NSTX-U 5 year plan:

1. Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
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5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solution for SS-PMI, FNSF, beyond

Overview of FY2013 NSTX-U research activities

- Finalizing NSTX-U 5 year plan for FY2014-2018
  - Plan to be submitted this month, reviewed next month
  - First 2-3 years: prepare for operation, explore new regimes
    - High β + lower ν^*, higher non-inductive w/ higher B_T, I_P, 2nd NBI
  - Proposed long-term upgrades under consideration:
    - Base: divertor cryo, ECH/EBW for start-up, off-midplane 3D coils
    - Incremental: convert PFCs to high-Z, implement divertor Thomson

- Collaborations supporting NSTX-U, ITER, FNSF
  - DIII-D: Snowflake & NTM control, pedestal transport, operations
  - MAST: AE* physics, micro-tearing/turbulence, EBW start-up
  - EAST: Lithium and high-Z PFCs, long-pulse control, ICRF
  - C-Mod: Pedestal structure/turbulence, high-Z PFC studies
  - KSTAR: NTV physics, MHD equil/stability, plasma control
  - LHD: 3D equilibrium, transport (J-K Park visiting professor)

Overview of FY2014-15 NSTX-U research activities

- FY2014
  - Transition off-site collaboration/researchers back to NSTX-U
  - Finish data analysis, publications from NSTX, collaborations
  - Prepare diagnostics, control system, analysis for NSTX-U ops
  - Complete CD-4 for NSTX Upgrade Project
- FY2015
  - Initiate operation, carry out research program for NSTX-U
  - Obtain first data at higher field, current, 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 and fast-ion instabilities from new 2^{nd} NBI
    - Push toward full non-inductive operation, high current operation

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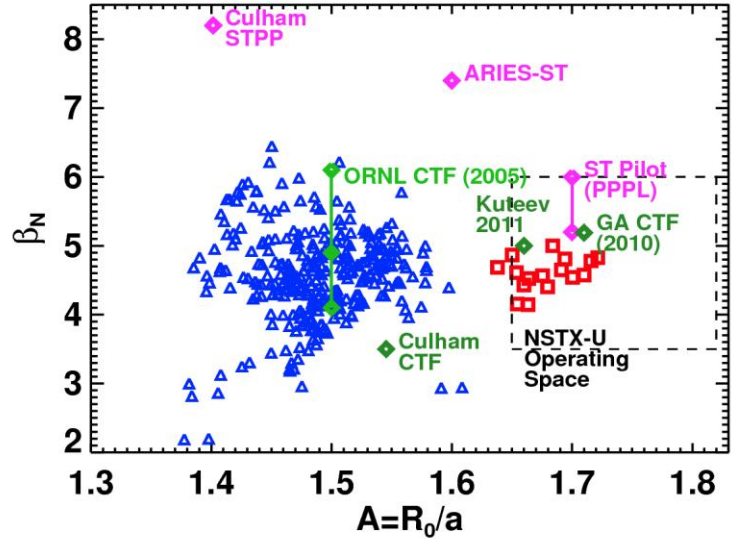
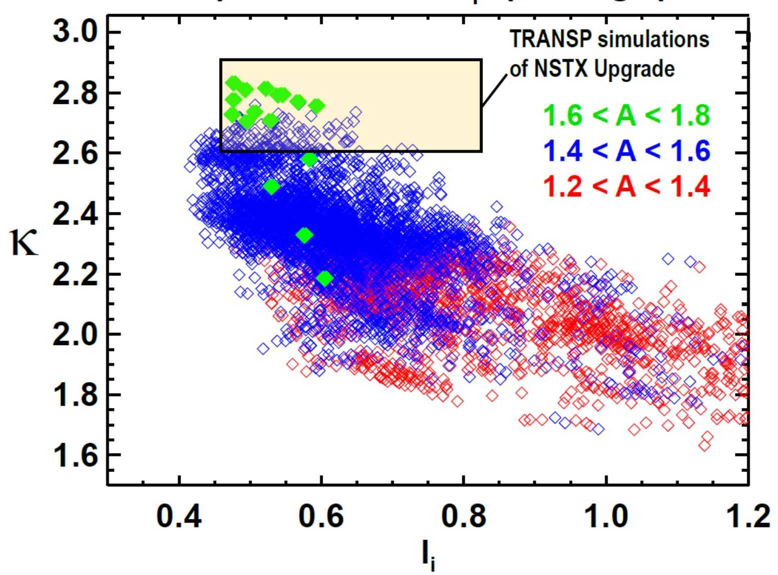
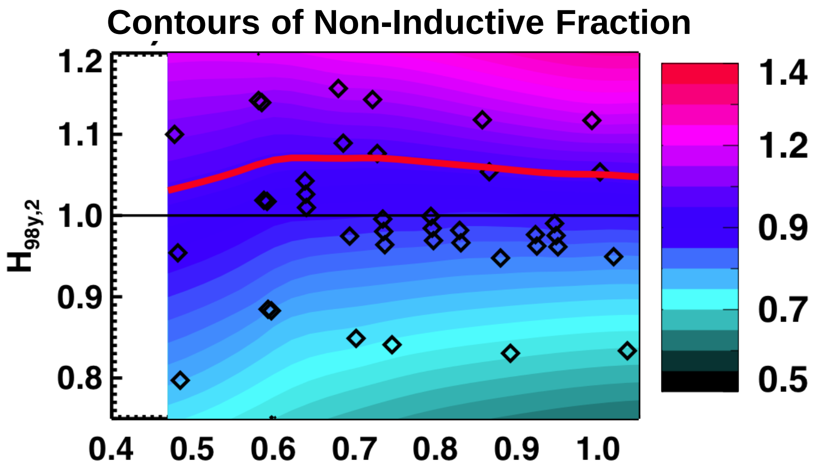
NSTX has already accessed A, β_N, κ needed for ST-based FNSF – next step is to access & control 100% non-inductive

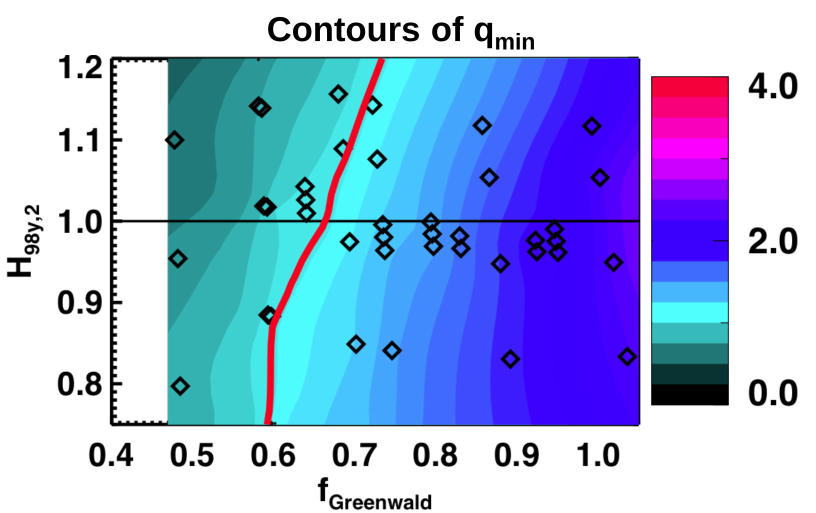


NSTX experimental κ vs. l_i operating space



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

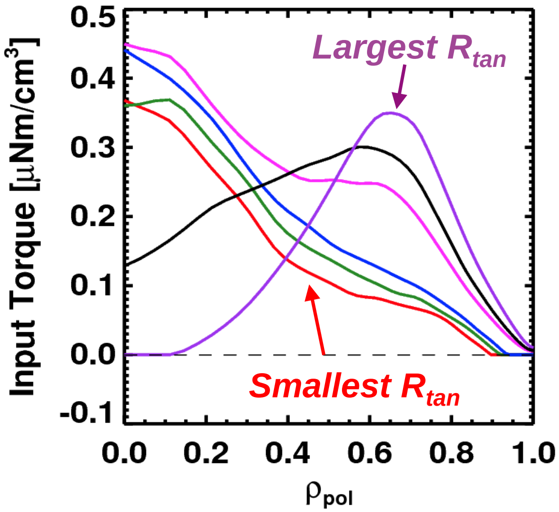




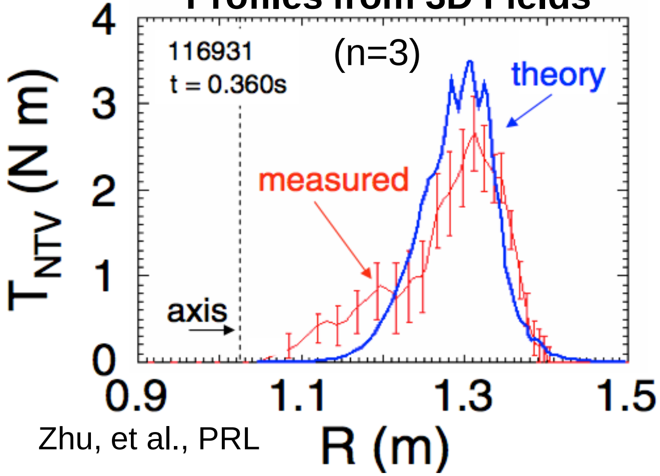
NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



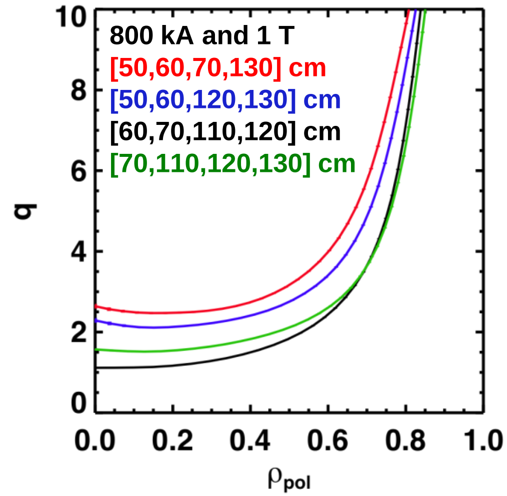
Measured and Calculated Torque Profiles from 3D Fields



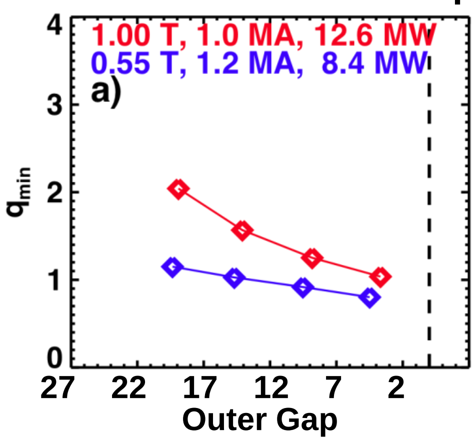
Zhu, et al., PRL

q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive, 87% < f_{NI} < 100%



Variations in Outer Gap



R14-3

Advanced Scenarios and Control Research Plans for FY2013-15:

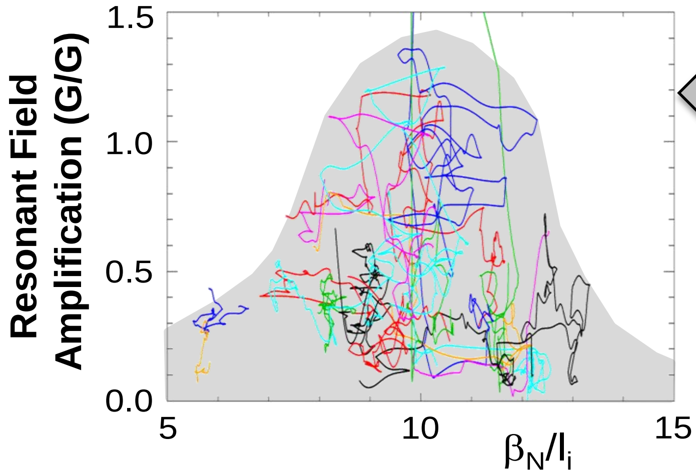
Develop advanced control algorithms, explore new NSTX-U scenarios

- JRT-2013: "Evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs), and to improve understanding of the underlying physical mechanisms that allow increased edge particle transport while maintaining a strong thermal transport barrier" *(Led by S. Gerhardt)*

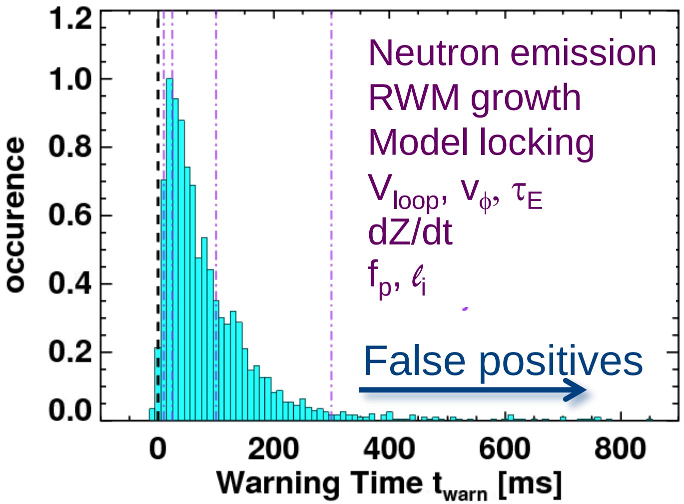
- FY13-14: Develop and implement advanced control algorithms in preparation for NSTX-U operation **R14-3**
  - Snowflake control on DIII-D (PPPL+LLNL+GA)
  - J profile control using on/off-axis 2nd NBI (PPPL + Lehigh)
    - Implement rt-MSE (Nova Photonics) in rt-EFIT for q-profile reconstruction
  - Rotation control: 2nd NBI deposition flexibility + 3D fields/NTV

- 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 operation at higher B_T, P_{NBI}** **R15-3**
- FY15: Explore scenarios (τ_E, l_i, MHD) at up to 60% higher I_P, B_T

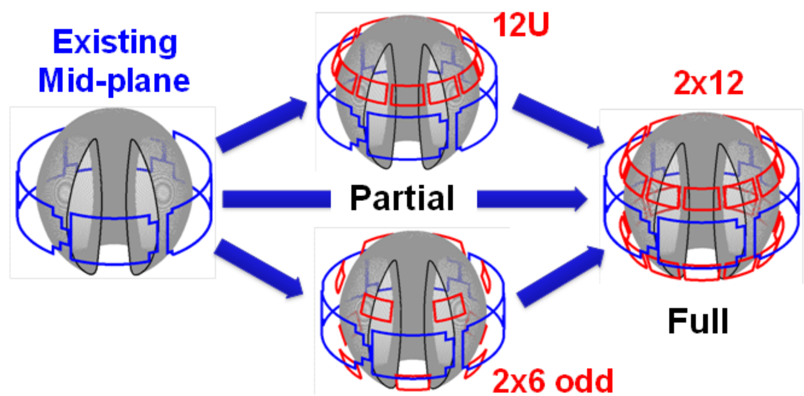
NSTX is making leading contributions to high-β_N & disruption warning research, assessing possible 3D coil upgrades



- n=1 MHD spectroscopy: high β_N can be more stable → important for advanced scenarios
- Developing disruption warning algorithms
  - Based on sensors + physics-based variables
  - < 4% missed, 3% false positives
  - ITER requires 95-98% prediction success
  - Will assess applicability/extension to ITER through ITPA Joint Activity, and for ST-FNSF



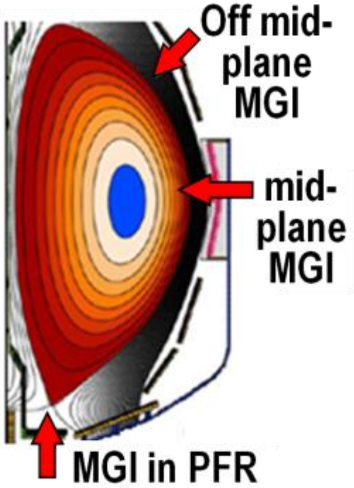
- Identified several off-midplane 3D coil sets favorable for profile, mode control



Macroscopic Stability Research Plans for FY2013-15:

Advance disruption warning and 3D coil design, re-establish high-β ops

- FY13-14: Complete compilation of NSTX disruption database and precursor ID for disruption characterization and prediction
  - Prepare real-time disruption warning algorithms for NSTX-U **R13-4**
- FY13-14: Complete physics design of new Non-axisymmetric Control Coils (NCC) for RWM, TM, RMP, EFC, NTV/v_ϕ control
- FY14: Understand/model low-density/ramp-up disruptions in NSTX in preparation for low ν* operation in NSTX-U scenarios
  - Leverage DIII-D, KSTAR, MAST collaborations **R14-1**
- FY15: Re-establish n=1-3 error-field correction, RWM control, minimize rotation damping, sustain operation above no-wall stability limit
- FY15: Test poloidal dependence of Massive Gas Injection (outboard vs. private flux region)
  - Longer-term goal: trigger mitigation via real-time warning



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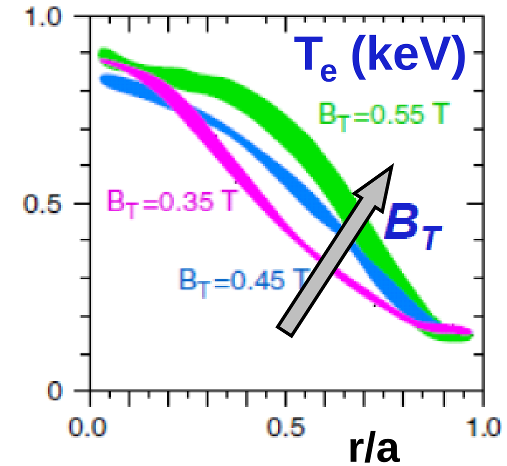
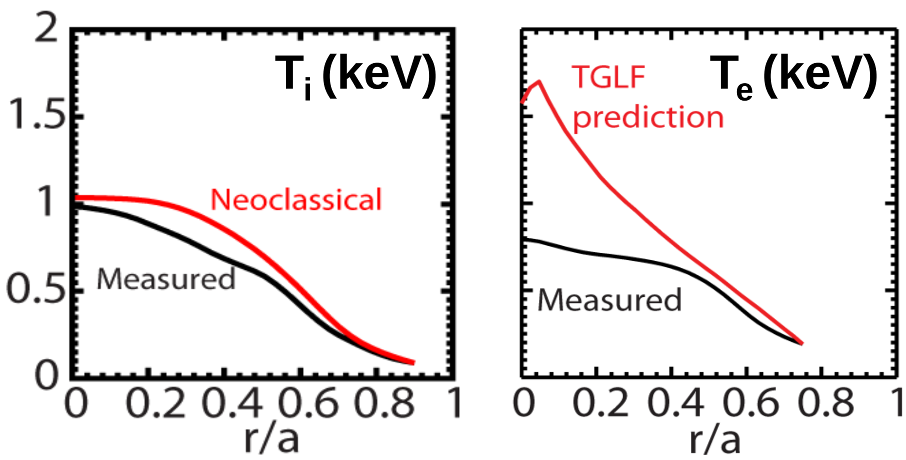
Beginning to test/utilize transport models to predict NSTX temperature profiles, identify possible missing physics

- 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/ν* in both datasets**



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

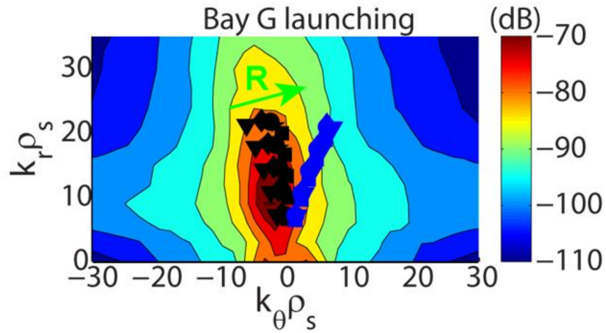


- Over-prediction of core T_e in NSTX may be due to transport from GAE/CAE modes not included in gyro-Landau-fluid model

Transport and Turbulence Research Plans for FY2013-15:

Complete turbulence diagnostic design, obtain first τ_E data at higher B_T, I_P

- FY13: Complete integrated physics and optical design of the new high-k FIR scattering system for ETG turbulence **R13-1**
  - Measure k_r & k_θ to study turbulence anisotropy



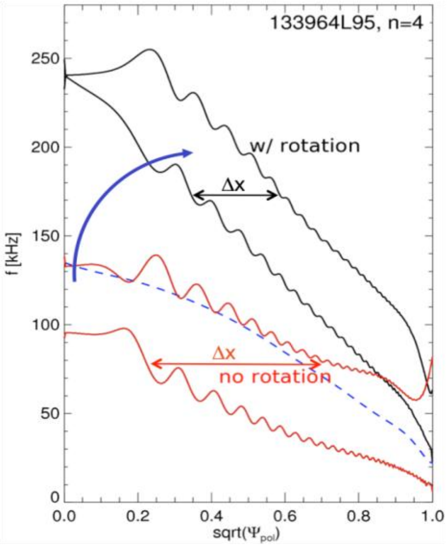
- FY13-14: Investigate micro-tearing on MAST by varying relevant parameters (β, ν, Z_{eff}) and using BES diagnostics
- FY13-15: Develop model $\chi_{e,\,AE}$ using measured CAE/GAE mode structures and ORBIT simulations (w/ EP group)
- FY14-15: Develop and validate reduced transport models using ST data + 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 (higher in later years) **R15-1**
  - Measure low-k δn (BES w/ increased edge channel count), 1^{st} polarimetry data

Developing improved energetic particle simulation tools and understanding utilizing NSTX data for NSTX-U, ITER, FNSF

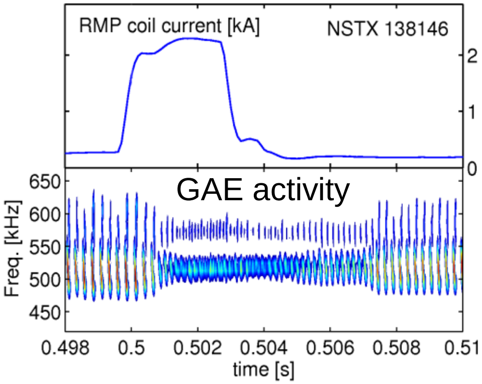
- Expect mode-number up-shift at higher B
  - B will be up to 2x higher in NSTX-U vs. NSTX
  - Broad spectrum possible from large $v_{fast} / v_{Alfvén}$

$$k_\perp \rho_f \sim 1 \Rightarrow \frac{nq}{a} \frac{v_f}{\omega_{cf}} \sim 1$$
$$\Rightarrow n \sim B \Rightarrow n = 2 - 10$$

- Plasma rotation & associated Doppler shift can significantly alter radial gap width
  - NSTX-U rotation expected to be 2-4x higher
  - Consistent treatment of rotation crucial for correct computation of both drive and damping
    - Implementing rotation effects in NOVA-K



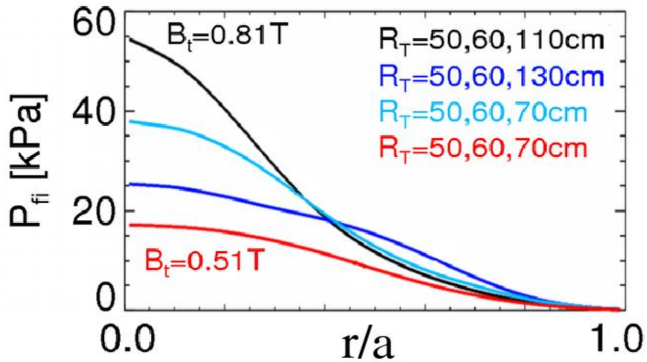
- Many competing influences on AE stability:
  - Destabilizing effects: higher β_{fast}, more tangential injection and resonance with passing ions
  - Stabilizing: Large R_{TAN} → broader fast-ion density
  - 3D fields: direct transport, also thru rotation profile



Energetic Particle Physics Research Plans for FY2013-15:

Develop full + reduced models of fast-ion x-port, characterize new 2^{nd} NBI

- FY13: Collaborate with MAST and DIII-D on AE experiments to provide data for reduced fast-ion transport models
- FY13-14: Develop reduced model for AE-induced fast ion losses – needed for NBICD in STs/ATs/ITER R14-2
- FY13-14: Contribute to development of reduced model of electron thermal transport from CAE/GAE
- FY14: Finalize design/implementation of prototype AE antenna and of upgraded ssNPA diagnostic
- FY15: Measure fast-ion (FI) density profiles, confinement, current drive, AE stability with new 2^{nd} NBI R15-2



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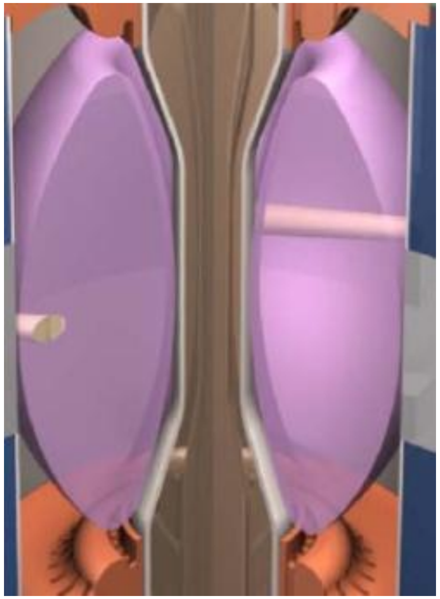
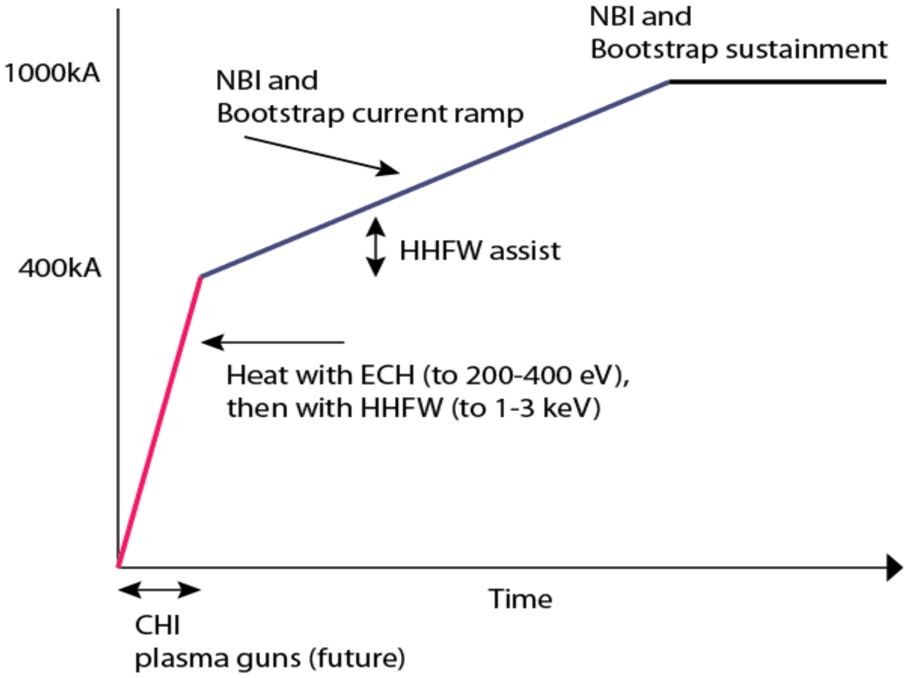
Plasma initiation with small or no transformer is unique challenge for ST-based Fusion Nuclear Science Facility

ST-FNSF has no/small central solenoid



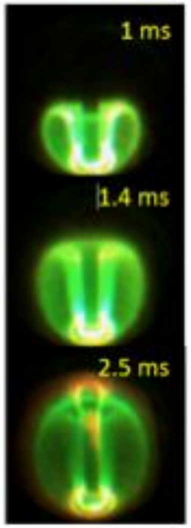
NSTX-U Non-Inductive Strategy:

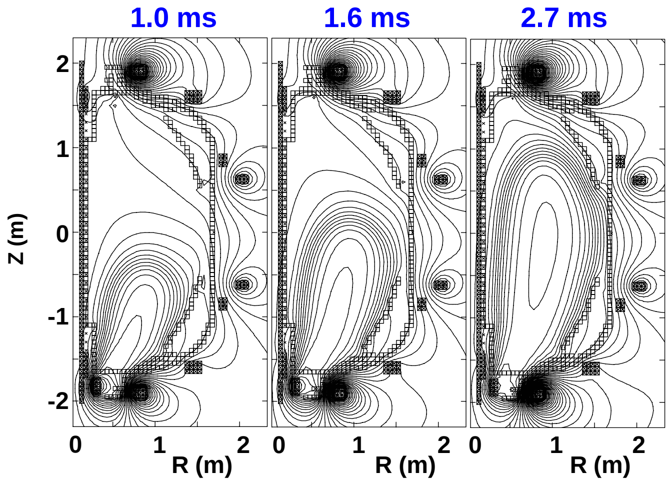


- **NSTX-U 5 year plan goal:**
  - Generate ~0.4MA closed-flux start-up current with helicity injection
  - Heat CHI with ECH and/or fast wave, ramp 0.4MA to 0.8-1MA with NBI

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

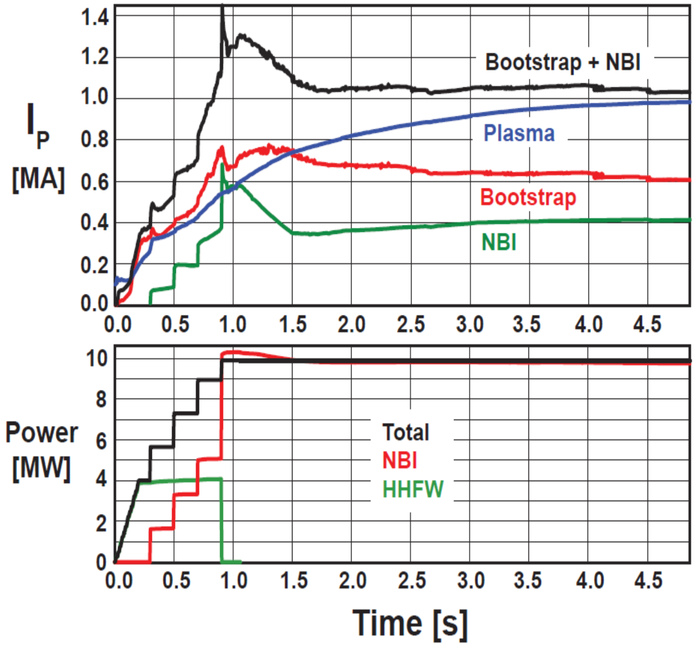
- TSC code successfully simulates CHI I_P ~200kA achieved in NSTX





- 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)

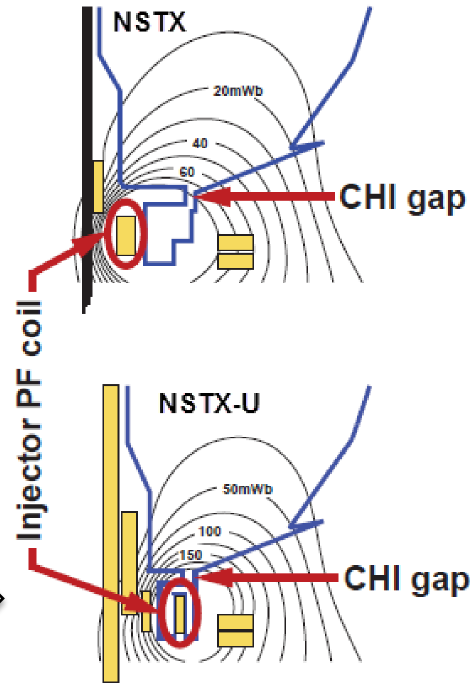
- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
  - 1.5-2x higher CD efficiency, 2x higher absorption
- TSC: non-inductive ramp-up from 0.4MA to 1MA possible w/ BS + NBI



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

Simulate CHI start-up/ramp-up, prepare CHI for NSTX-U

- FY13: Model CHI start-up → ECH+HHFW+NBI ramp-up scenarios using the NSTX-U vessel + coil geometry
  - Extend TSC simulations to include time-evolving TRANSP NBI current-drive and coupling/ramp-up of low-I_P plasmas
- FY13-14: Complete design of upgraded capacitor bank and diagnostics for NSTX-U, implement CHI gap tiles
- FY13-14: Finish CHI design study for QUEST, possibly implement CHI
- FY15: Establish NSTX-U CHI, assess impact of new injector, gap, higher B_T

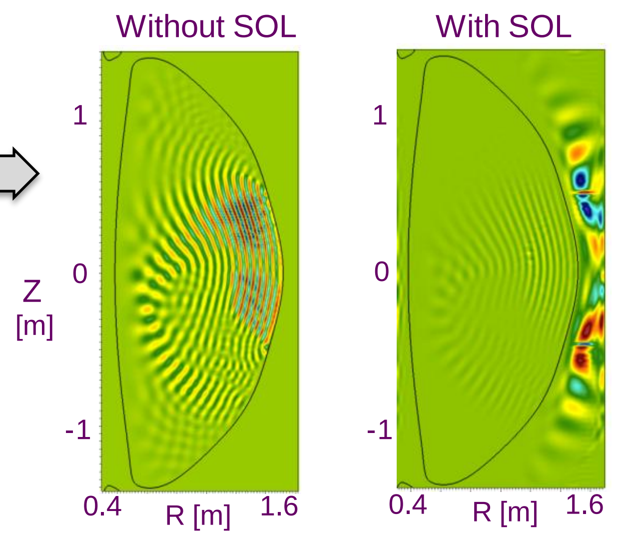


- FY15: First tests of NBI ramp-up using new 2nd NBI

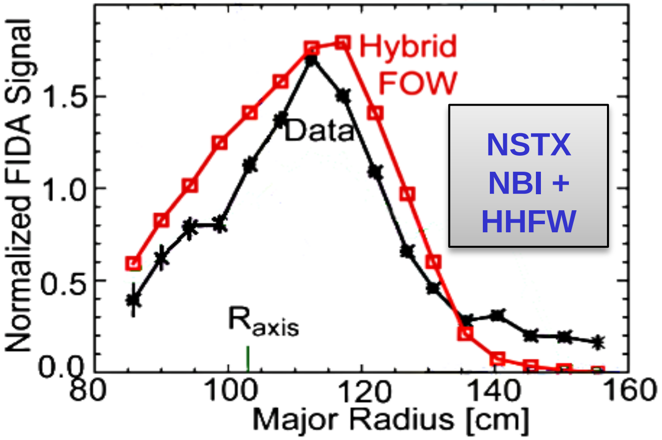
IR15-2

Developing and validating advanced fast-wave simulations supporting NSTX-U non-inductive start-up and ITER ICRF

- AORSA simulations for NSTX-U:
  - Edge power losses often observed in NSTX
  - SOL profiles and antenna model can strongly influence edge wave-fields & power deposition
  - 40-50% of FW power predicted to be absorbed by thermal & fast ions for antenna using heating phasing (k_ϕ = 13 m^{-1})
- CQL3D Fokker-Planck simulations:
  - Full-orbit "Hybrid" finite orbit width version of code now shows good agreement with NSTX fast ion diagnostic (FIDA) data
  - Future: simulate and interpret NSTX-U data
- At full field, NSTX-U will operate in an ion-cyclotron-harmonic regime similar to ITER ½-field pre-activation phase

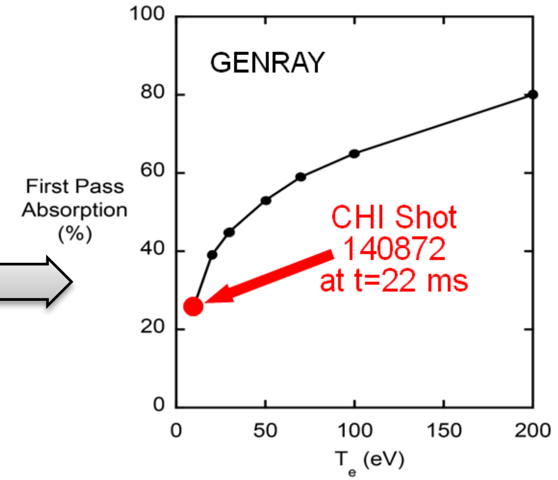


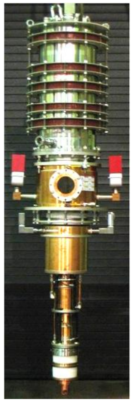
AORSA Re($E_{||}$) simulations for 30 MHz FW
n_ϕ = 12 heating in **NSTX-U** w/ $B_T(0)$ = 1T



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

- FY13: Extend HHFW coupling / heating calculations to higher I_P, B_T NSTX-U equilibria – emphasis on fast-ion interactions
- FY13: Collaborate with MAST on EBW start-up
- FY13-14: Complete physics design of 1MW/28GHz ECH/EBW system for NSTX-U. Design goals: R13-3
  - ECH to heat CHI plasma to form target for HHFW/NBI+BS I_P ramp-up
  - EBW H&CD for start-up, sustainment





- FY14: Collaborate on EAST to develop/guide reliable ICRF-heated H-mode scenarios for NSTX-U, ITER

IR15-2

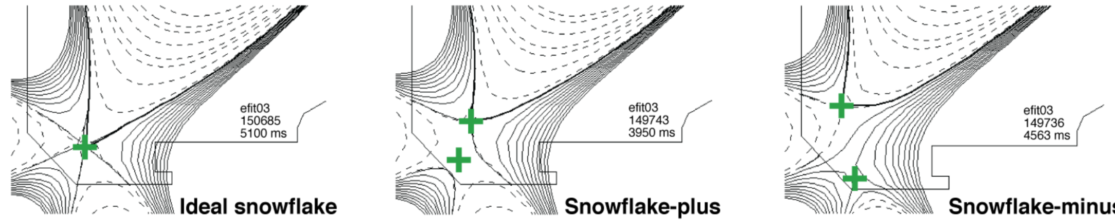
- FY15: Assess, optimize HHFW coupling and heating at higher B_T and I_P and support low-I_P heating for non-inductive ramp-up

FY2013-15 planned research supports 5 highest priority goals for NSTX-U 5 year plan:

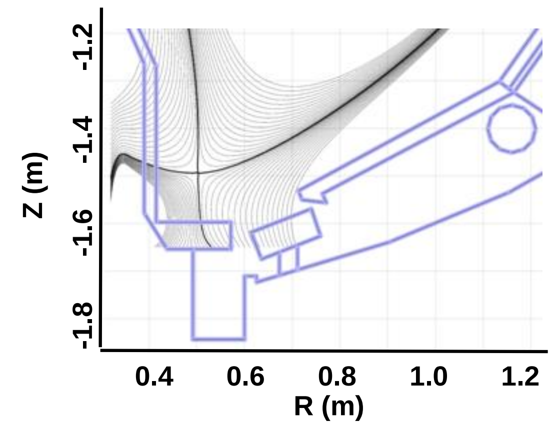
1. Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q & rotation to dramatically extend ST plasma understanding
3. Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid
4. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solution for SS-PMI, FNSF, beyond

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

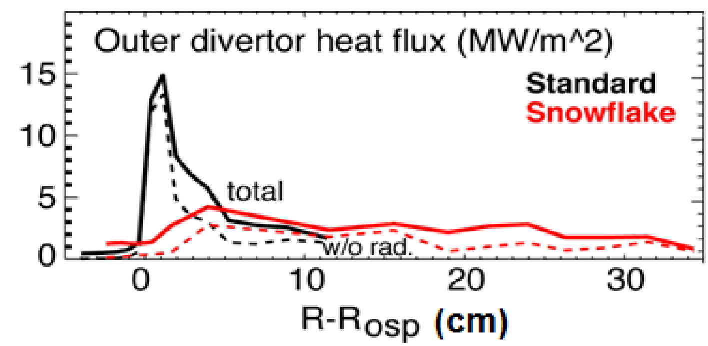
- Snowflake on DIII-D (GA+LLNL+PPPL collaboration) extended 2-3x reduction in q_{peak} to 3s duration



- NSTX-U divertor cryo projections: $f_G \leq 0.5$ for wide range of I_P (λ_{SOL})
  - Standard/snowflake: 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)

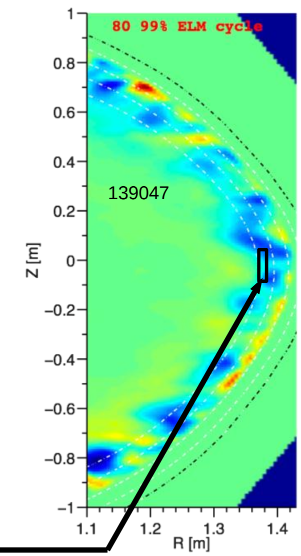


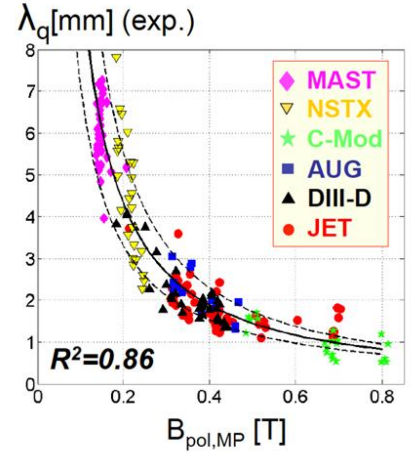
Boundary Physics Research Plans for FY2013-15:

Advance snowflake, cryo, pedestal, SOL studies, extend to higher B_T, I_P

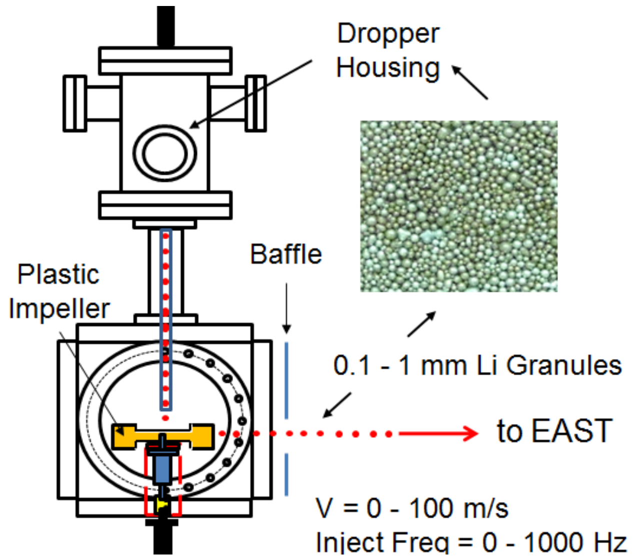
- FY13: Complete modeling of synergy of snowflake with detachment in NSTX and NSTX-U, extend to FNSF
- FY13-14: Complete NSTX-U cryo-pump physics design, integrate w/ detached snowflake
- FY13-14: Continue/complete collaborations on pedestal and SOL transport (DIII-D, C-Mod) to improve edge predictive capability
  - NSTX: Measured ion-scale correlation lengths at pedestal top consistent with XGC1 predictions
    - Low-k turbulence consistent with ITG and/or KBM
  - XGC0 and 1 also being utilized to understand L→H threshold, QH-mode edge transport in DIII-D
- FY15: Measure pedestal structure, SOL width, ELM types, snowflake performance at up to 60% higher current, field, 2× higher P_{NBI}

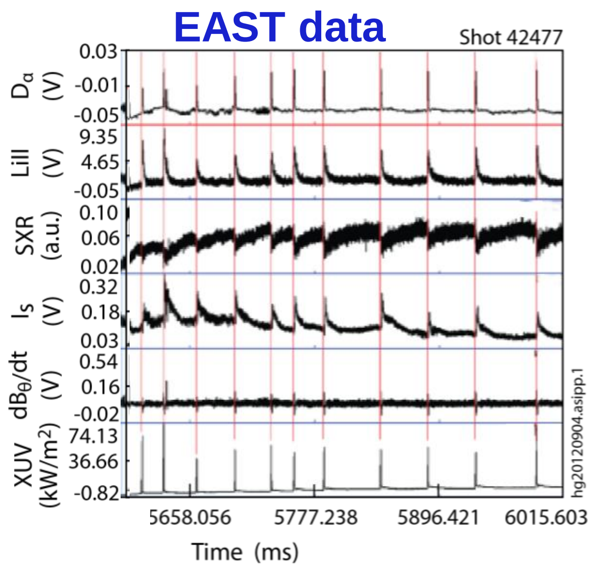
R15-1
IR15-1





Lithium Granule Injector (LGI) is promising tool for pedestal/ELM control and scenario optimization



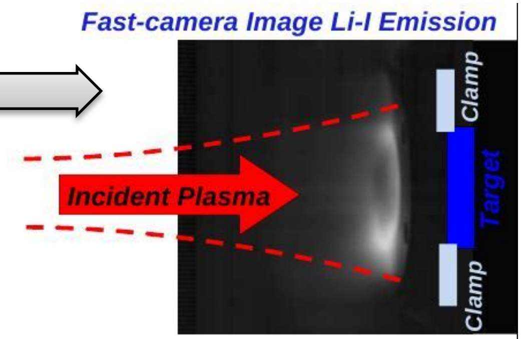


- Successful EAST collaboration
  - Demonstrated LGI ELM-pacing at 25 Hz with nearly 100% triggering reliability
  - Capable of up to 1 kHz injection
- LGI will be tested on NSTX-U for high-frequency ELM pacing
  - Possible density control technique:
    - Combine Li coatings for D pumping with LGI for ELM-expulsion of carbon
  - Goal: reduce Z_{eff} to ~2-2.5
  - Injection of Li granules could also potentially replenish PFC Li coatings
- JET/ITER: potentially interested in testing Be granules for ELM pacing

Materials and Plasma Facing Components Plans for FY2013-15:

Advance Li understanding/technology, support NSTX-U wall conditioning

- FY13: Study Li-conditioned surface composition and plasma behavior using Materials Analysis and Particle Probe (MAPP – Purdue collaboration) on LTX in-prep for NSTX-U R13-2
- FY13-14: Develop Li-coating tools for upper PFCs of NSTX-U to increase Li coverage of C, D pumping, thermal confinement
- FY13-15: 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 collaboration: assess particle/impurity control w/ triggered ELMs, cryo-pumping, lithiumization, high-Z PFCs
- FY15: Test LGI, Li coating dependence/evolution in NSTX-U

Outline

- NSTX-U mission
- FY13-15 research overview and plans
- Milestone summary
- ITPA contributions
- ST-FNSF mission and configuration study
- Summary

Administration FY13 request-level funding would greatly limit run-time in FY15, and limit field and current near NSTX levels

	FY2013	FY2014	FY2015
Expt. Run Weeks:	0	0	0-6
Macroscopic Stability		R14-1 **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	R13-1 **Perform integrated physics+optical design of new high-k_θ FIR system**		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)~~ **MG weld repair likely required to access B_T and I_P significantly above NSTX levels**
Boundary Physics			
Materials & PFCs	R13-2 **Assess relationship between lithium-conditioned surface composition and plasma behavior**		
Waves+Energetic Particles	**Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios**	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)
Solenoid-free Start-up/ramp-up	R13-3		
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	R13-4 **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks**	**TBD**

+15% above Administration FY13 request-level provides run-time and field + current to exploit new Upgrade capabilities

	FY2013	FY2014	FY2015
Expt. Run Weeks:	**0**	**0**	**16**
Macroscopic Stability		R14-1 **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	R13-1 **Perform integrated physics+optical design of new high-k_θ FIR system**		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)
Boundary Physics			
Materials & PFCs	R13-2 **Assess relationship between lithium-conditioned surface composition and plasma behavior**		
Waves+Energetic Particles	**Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios** R13-3	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)
Solenoid-free Start-up/ramp-up			
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	R13-4 **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks**	**TBD**

Full operation case accelerates snowflake + start-up/ramp-up research for FNSF, fully utilizes facility during 1st year of ops

	FY2013	FY2014	FY2015
Expt. Run Weeks:	0	0	20
Macroscopic Stability		R14-1 **Assess access to reduced density and ν* in high-performance scenarios** (with ASC, BP TSGs)	
Transport and Turbulence	R13-1 **Perform integrated physics+optical design of new high-k_θ FIR system**		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)
Boundary Physics			**Develop snowflake configuration, study edge and divertor properties** (with ASC, TT, MP) IR15-1
Materials & PFCs	R13-2 **Assess relationship between lithium-conditioned surface composition and plasma behavior**		
Waves+Energetic Particles	**Perform physics design of ECH & EBW system for plasma start-up & current drive in advanced scenarios** R13-3	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)
Solenoid-free Start-up/ramp-up			**Assess CHI & low-I_P FW heating at higher B_T, test NBI+BS I_P ramp-up** (with WEP, ASC TSGs) IR15-2
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	R13-4 **Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**		
Joint Research Target	**Stationary regimes w/o large ELMs, improve understanding of increased edge particle transport**	**Quantify plasma response to non-axisymmetric (3D) magnetic fields in tokamaks**	**TBD**

Outline

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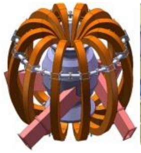
NSTX-U team continuing to strongly support ITER through participation in ITPA joint experiments and activities

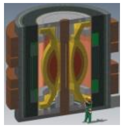
Pedestal/Edge Physics and DIVSOL			
DSOL-24	Disruption heat loads	PEP-27	Pedestal profile evolution following L-H/H-L transition
PEP-6	Pedestal structure and ELM stability in DN	PEP-29	Vertical jolts/kicks for ELM triggering and control
PEP-19	Basic mechanisms of edge transport with RMP	PEP-34	ELM energy losses and their dimensionless scaling
Energetic Particles			
EP-2	Fast ion losses and redistribution from localized Aes	EP-6	Fast ion losses and associated heat loads from edge perturbations
Integrated Operating Scenarios			
IOS-3.2	Define access conditions to get to SS sceanrio	IOS-4.3	Collisionality scaling of confinement in advanced inductive regime
IOS-4.1	Access conditions for advanced inductive scenario	IOS-5.2	Maintaining ICRH coupling in expected ITER regime
MHD			
MDC-2	Joint experiments on resistive wall mode physics	MDC-17	Active disruption avoidance
MDC-8	Current drive prevention/stabilization of NTMs	MDC-18	Evaluation of axisymmetric control aspects
MDC-15	Disruption database development		
Transport and Confinement			
TC-9	Scaling of intrinsic rotation with no external momentum input	TC-15	Dependence of momentum and particle pinch on collisionality
TC-10	Exptl id of ITG, TEM and ETG turbulence and comparison with codes	TC-17	ρ^* scaling of the edge intrinsic torque
TC-11	He and impurity profiles and transport coefficients	TC-24	Impact of RMP on transport and confinement
TC-12	H-mode transport and confinement at low aspect ratio		

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

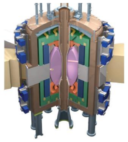


Russia

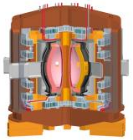
Culham



UT Austin



ORNL



PPPL

- Overarching goal of study:
  - Determine optimal mission, performance, size
- Goals of study:
  - Review existing designs, ID advantageous features, improve configuration
  - Key considerations for configuration:
    - T self-sufficiency
    - Maintainability, upgradeability, overall flexibility
    - Key components: coils, divertors, shields, blankets, ports
  - Develop self-consistent assessment + configuration for use by community
- FY2013 progress:
  - Developing/comparing configurations with range of sizes: R=2.2, 1.6, 1.0m
  - Assessing impact of different divertors: conventional, snowflake, super-X
  - May be minimum device size required (R~1.5-1.6m) for TBR > 1 with DCLL
    - Preliminary: breeding in divertor and/or centerstack first-wall/shield may be required

Summary: NSTX-U FY2013-15 research plan strongly supports FES 10-year vision elements

- **ITER research**
  - Leading contributions to non-linear AE* dynamics, fast-ion transport, disruption warning, response to 3D δB, RWM control
- **Control science, plasma-wall interactions, FNSF**
  - Prepare NSTX-U to extend high-β + high-non-inductive scenarios to full non-inductive operation with advanced control
  - Provide critical data on SOL-widths and turbulence, novel snowflake divertors, Li-based PFCs – all for high power density
  - NSTX + Upgrade will provide critical confinement, stability, and sustainment data for assessing ST as potential FNSF
- **Validated predictive capability**
  - Will access new & unique high-β + low-ν* regime, exploit wide variation of rotation, q, fast-ion drive to test leading models

Incremental funding needed to fully utilize NSTX-U capabilities during FY15

Backup Slides

FES 10 year vision elements for U.S. fusion research

U.S. DEPARTMENT OF ENERGY | Office of Science

Where we need to be in 10 years, in MFE

- **Elements of a vision for 2021**:
  - **ITER Research** - The U.S. has a strong research team hitting the ground on a completed ITER project in Cadarache. This team is capable of asserting world leadership in burning plasma science
  - **Fusion materials science** - The U.S. has made strides in fusion materials science and passed critical metrics in tokamak and ST operations with national research teams. It is prepared to move beyond conceptual design of a fusion nuclear science facility
  - **Extend the reach of plasma control science and plasma-wall interactions**- U.S. fusion research has successfully levered international research opportunities in long pulse plasma control science, plasma-wall interactions, and 3-D physics.
  - **Validated predictive capability**- The U.S. is a world leader in integrated computation, validated by experiments at universities and labs. Such computation should be transformational, as it must reduce the risks associated with fusion development steps

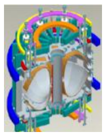
Update and Outlook for the Fusion Energy Sciences

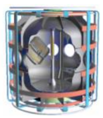
E.J. Synakowski
Associate Director, Office of Science
Fusion Energy Sciences

For the University Fusion Associates Town Hall Meeting
APS-DPP, Providence, RI
October 29, 2012

STs and planned NSTX-U program support and accelerate wide range of development paths toward fusion energy

- **Extend Predictive Capability**
  - Non-linear Alfvén modes, fast-ion dynamics
  - Electron gyro-scale turbulence at low ν^*
  - High β, rotation, shaping, for MHD, transport


LTX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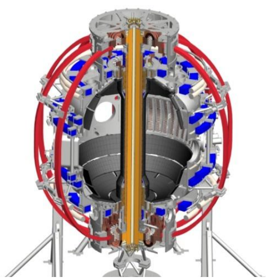
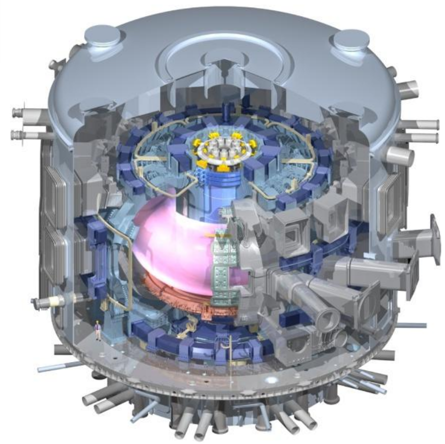

NSTX-U

<u>STs Narrow Gaps to Pilot/DEMO</u>:

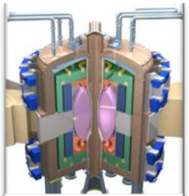
- **Goal: 100% non-inductive + high β**
- **Plasma-Material Interface Research**
  - Strong heating + smaller R → high P/R, P/S
  - Novel solutions: snowflake, liquid metals, Super-X (MAST-U), hot high-Z walls (QUEST)

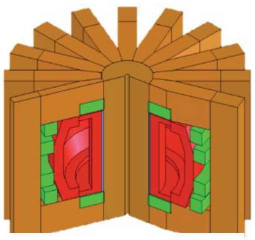
- **Fusion Nuclear Science Facility**
  - High neutron wall loading
  - Potentially smaller size, cost
  - Smaller T consumption
  - Accessible / maintainable

Burning Plasma Physics - ITER

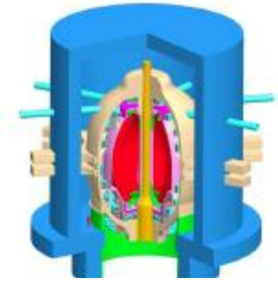


Fusion Nuclear Science Facility

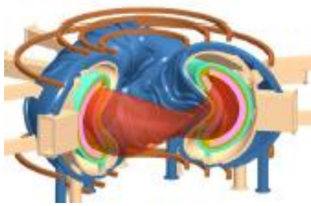

FNSF-ST


FNSF-AT

Pilot Plant or DEMO

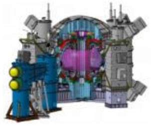

ARIES-ST


ARIES-AT

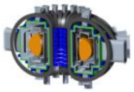

ARIES-CS

Steady-State, Plasma-Material Interface R&D


EAST


JT-60SA


NHTX


VULCAN

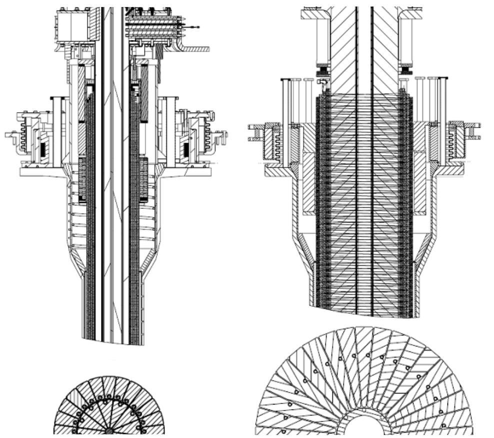

KSTAR


W7-X, LHD


QUASAR

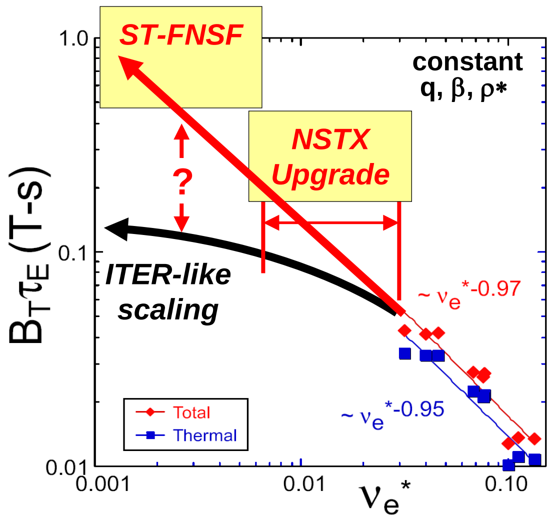
NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities

Previous center-stack | New center-stack

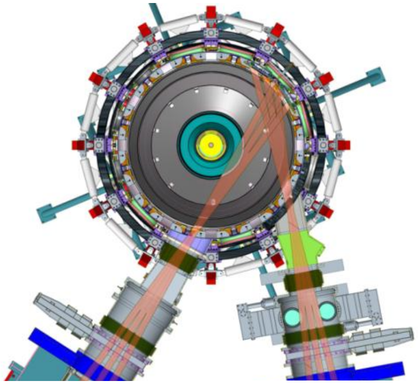


TF OD = 20cm | TF OD = 40cm

- 2x higher B_T and I_P increases T, reduces ν^* toward ST-FNSF to better understand confinement
- Provides 5x longer pulses for profile equilibration, NBI ramp-up



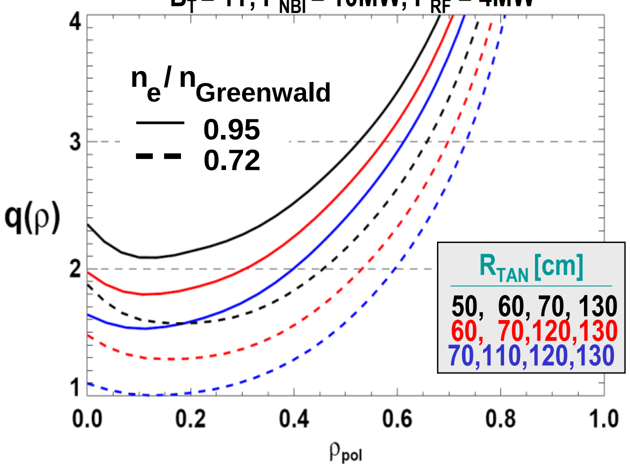
Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI | New 2nd NBI

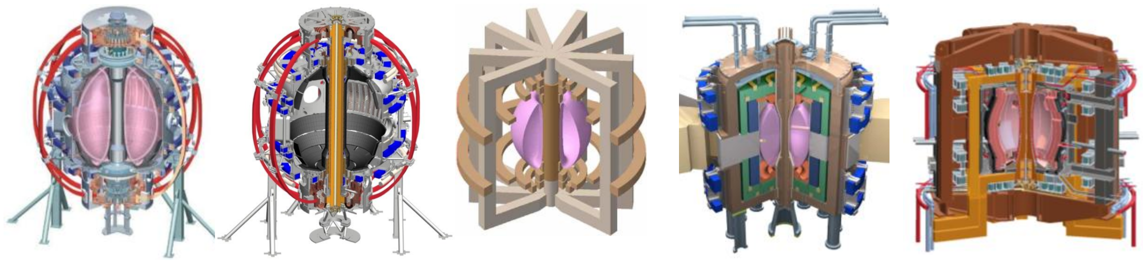
- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with q(r) profile controllable by: tangency radius, density, position

I_P=0.95MA, H_{98y2}=1.2, β_N=5, β_T = 10%
B_T = 1T, P_{NBI} = 10MW, P_{RF} = 4MW

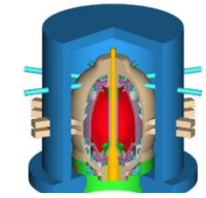


J. Menard, et al., Nucl. Fusion 52 (2012) 083015

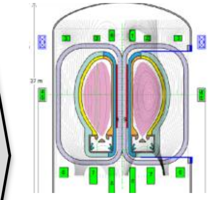
NSTX Upgrade will access next factor of two increase in performance to bridge gaps to next-step STs



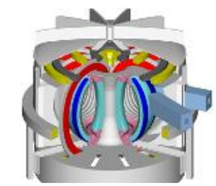
Low-A Power Plants



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

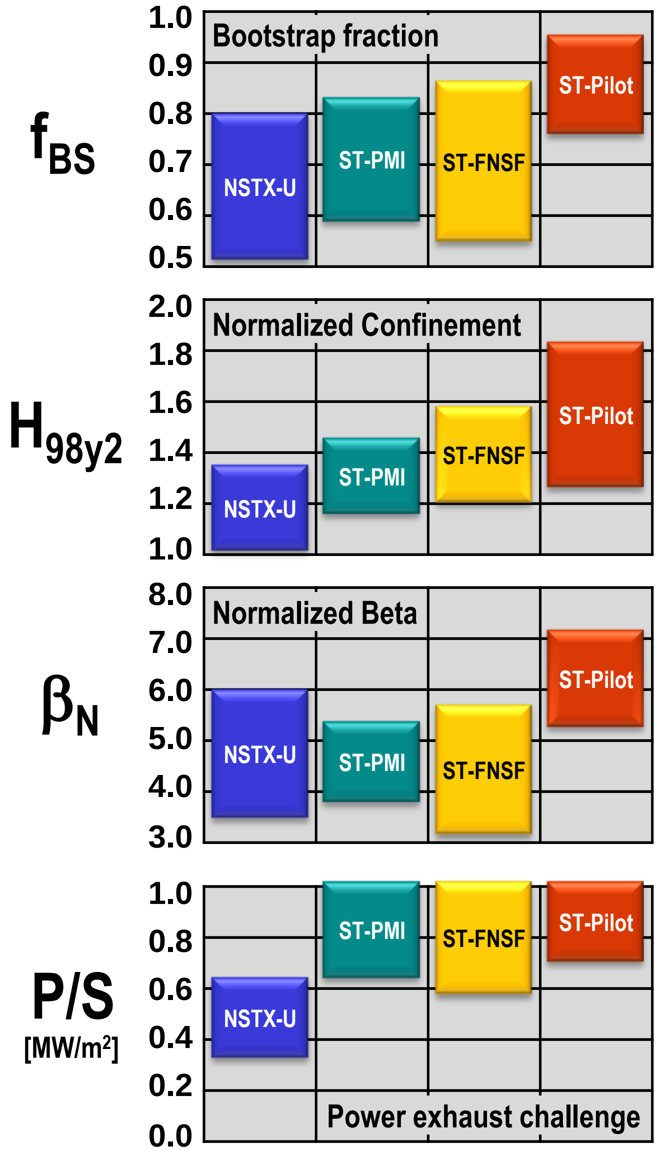
Key issues to resolve for next-step STs

- **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:

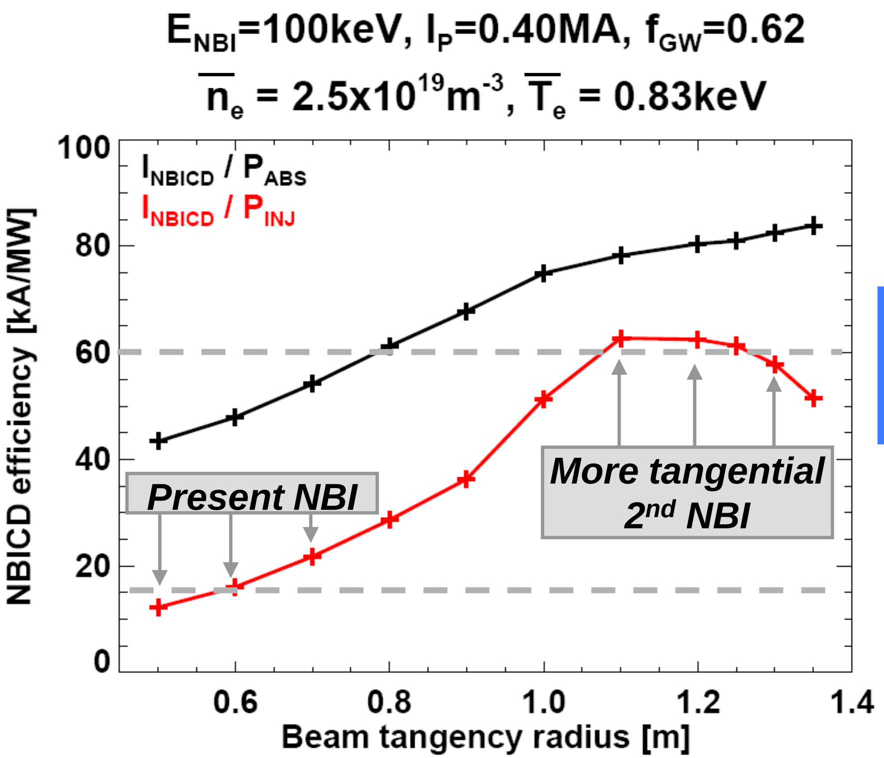
- **Full non-inductive (NI) current drive for steady-state operation**
  - ST requires NI start-up/ramp-up
- **High confinement to minimize auxiliary heating, device size**
- **Sustained high β to minimize magnet size, forces, power**
- **Divertor/first-wall survival with intense power/particle fluxes**

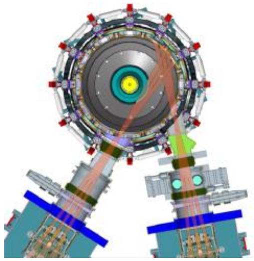


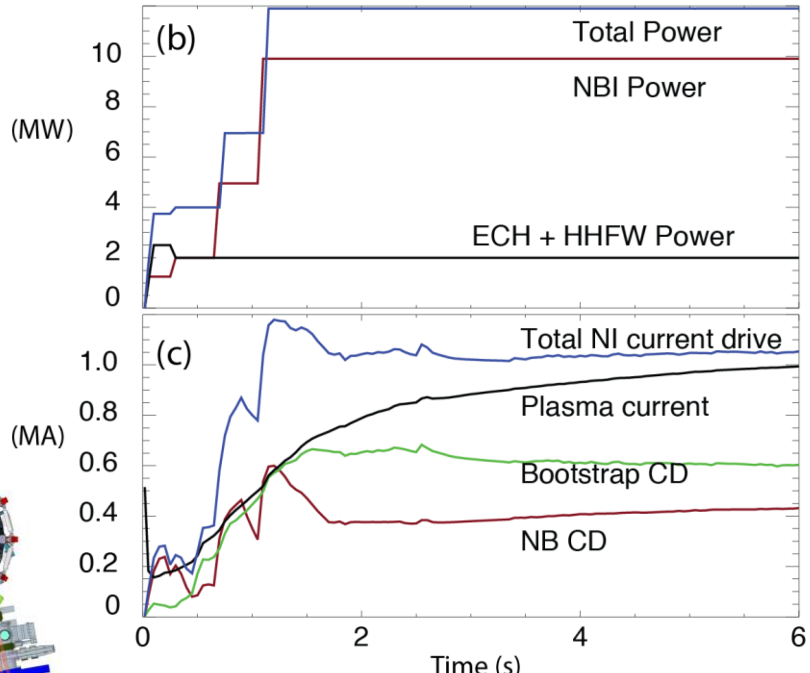
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new CS + more tangential 2nd NBI

- **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







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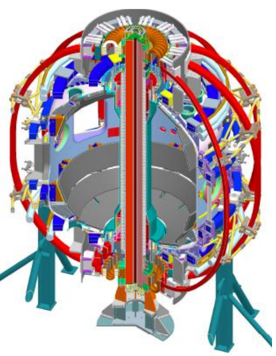
5 year plan tools with 5YP base funding

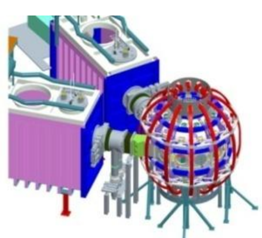
(FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018
Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:	16	14	14	16

New center-stack



2nd NBI



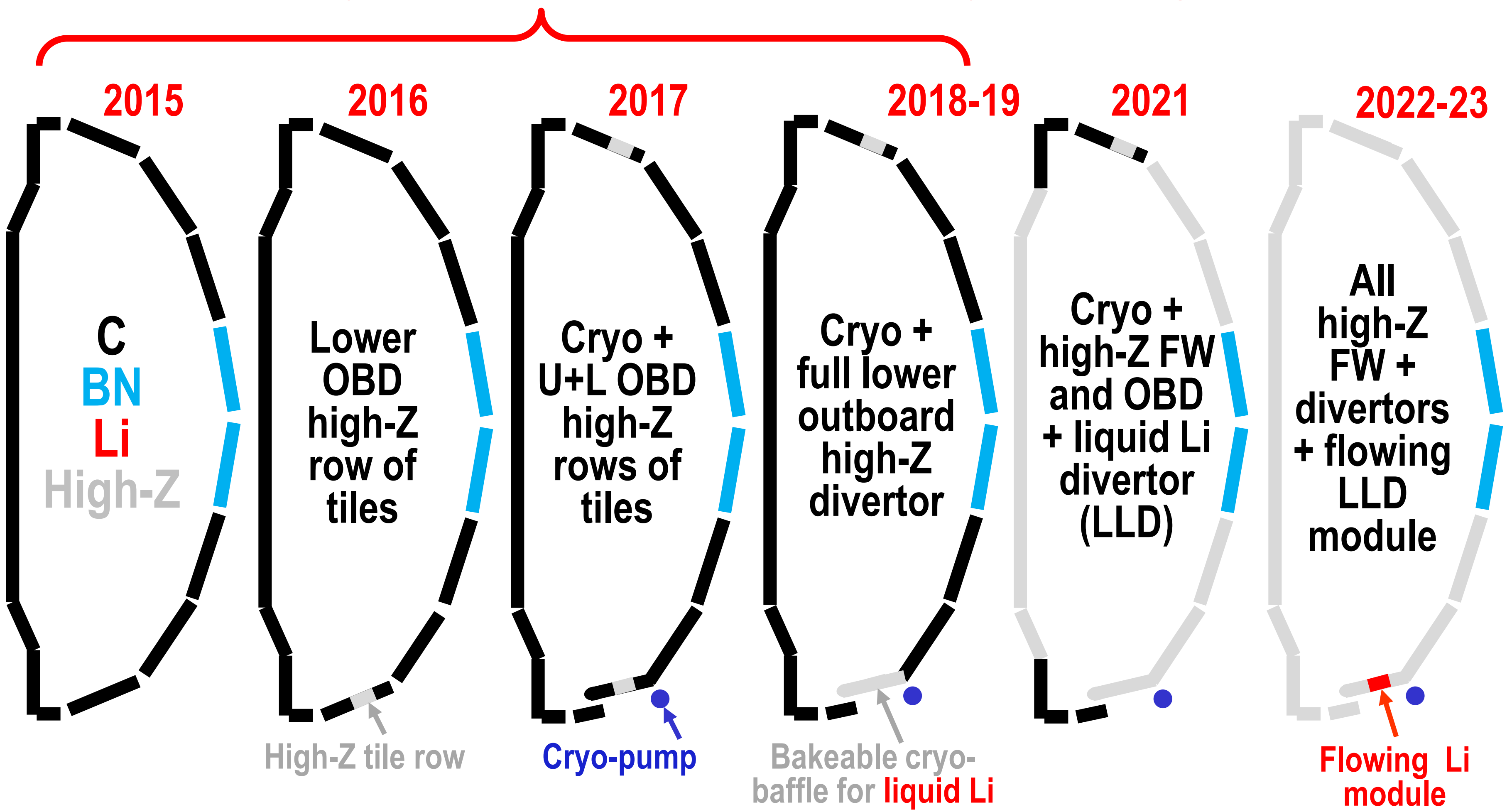
Topic	Tools
Start-up and Ramp-up	Upgraded CHI for ~0.5MA; 1 MW ECH/EBW; up to 0.5 MA plasma gun
Boundary Physics	Lower divertor cryo-pump; High-Z PFC diagnostics
Materials and PFCs	High-Z tile row on lower OBD; High-Z tile row on cryo-baffle; Full high-Z lower OBD
Liquid metals / lithium	Li granule injector; Upward LiTER; LLD using bakeable cryo-baffle
MHD	MGI disruption mitigation; Partial NCC; Enhanced MHD sensors
Transport & Turbulence	δB polarimetry; High k_θ
Waves and Energetic Particles	1 coil AE antenna; 4 coil AE antenna; Charged fusion product
Scenarios and Control	Establish control of: Snowflake; $\bar{n}_e$; Rotation; q_{min}; Divertor P_{rad}

- Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017
  - NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

NSTX-U internal component staging supports goal to assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Base budget case

Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD



NSTX-U internal component staging supports goal to assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Incremental budget case

Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD