National Spherical Torus eXperiment Upgrade

NSTX-U: Recent Results and Plans

20th ISTW – Oct. 30 2019

S.M. Kaye
NSTX-U Interim Director of Research

Outline of Presentation

- What is NSTX-U?
  - NSTX-U short-term mission
  - Capabilities upgraded from NSTX
- NSTX-U mission in context of U.S. and world program
  - How does NSTX-U fit in?
  - 10 year mission and research goals (Maingi poster)
- NSTX-U status
  - Recovery project (Kaye poster)
- Selected research highlights from NSTX(-U) and collaborations

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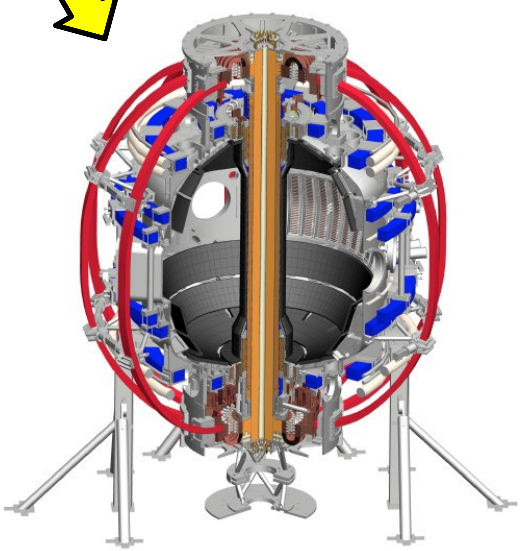
NSTX-U will provide unique regimes in the initial years of operations required to **optimize the geometry (R/a, κ, δ) of next-step devices**

- Elements of "near-term" program address core/boundary performance
  - Demonstrate **high-performance steady-state non-inductively sustained regimes** at large bootstrap fraction (f_{BS} > 0.7), large Greenwald density fraction (f_{GW} > 0.7) and β_N values surpassing typical conventional-A scenarios with sufficient stability margin for low disruptivity
  - Investigate if a **strong scaling of confinement and stability improvement with reduced collisionality** in regimes dominated by electron thermal transport at high-β and low-A persists at lower collisionality
  - Burning plasma (i.e., **ITER**)-related physics issues
  - **Unify predictive modeling of transport, stability and fast ion physics** at low-A, low-ν_e^* and high-β_N with conventional-A tokamaks to improve confidence in projections to next-step fusion devices, including ITER and a CPP

NSTX-U targeting major performance increase to explore new physics regimes

1. New Central Magnet

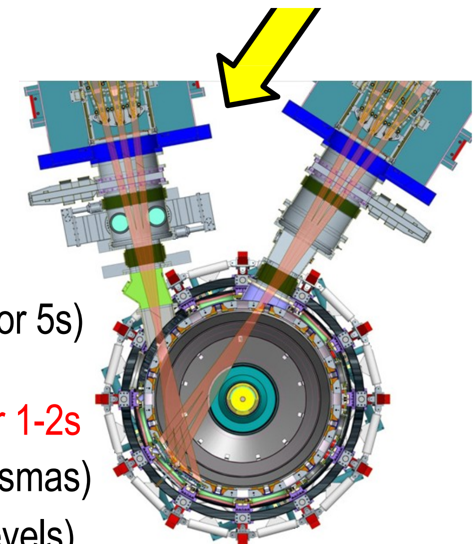
- ➢2× toroidal field (0.5 ➔ 1T)
- ➢2× plasma current (1 ➔ 2MA)
- ➢5× longer pulse (1 ➔ 5s)



➔ **Unique regime**

Study new transport and stability physics

2. Tangential 2nd Neutral Beam



- ➢2× heating power (5 ➔ 10MW for 5s)
  - Tangential NBI ➔ 2× η_{cd}
  - Up to 15MW NBI + 4MW RF for 1-2s
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)
- ➢4× divertor heat flux (➔ ITER levels)

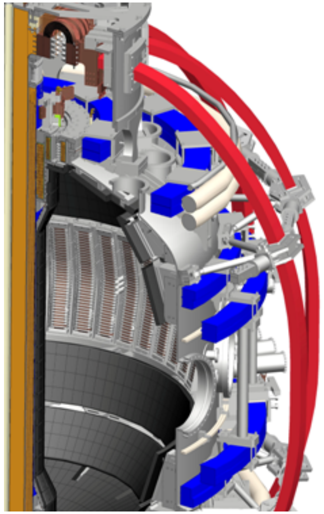
➔ **Sustain plasma without transformer**

Not yet achieved at high-β_T, low ν^*

Essential for any future steady-state ST

NSTX-U and MAST-U are the most capable devices in a world-wide ST research program

NSTX-U



Similar features:

- Major radius R = 0.8-1m
- Plasma current up to 2MA
- Pulse durations 1s → up to 5s
- Strong neutral beam heating

Having both NSTX-U and MAST-U important to confirm unique ST results

Complementary Research:

MAST-U (UK)

Core emphasis

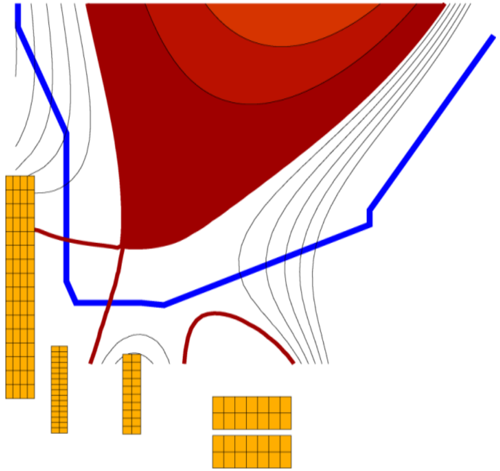
- Highest magnetic field, pressure
- Highest plasma beta in large ST
- 2× higher max power (NBI+RF) and edge heat fluxes
- 2× higher self-driven current
- Only large ST with RF heating

Boundary emphasis

- Highly-flexible "long-leg" divertor for power exhaust research
- Only large ST with off-midplane 3D magnetic field coils for edge instability control

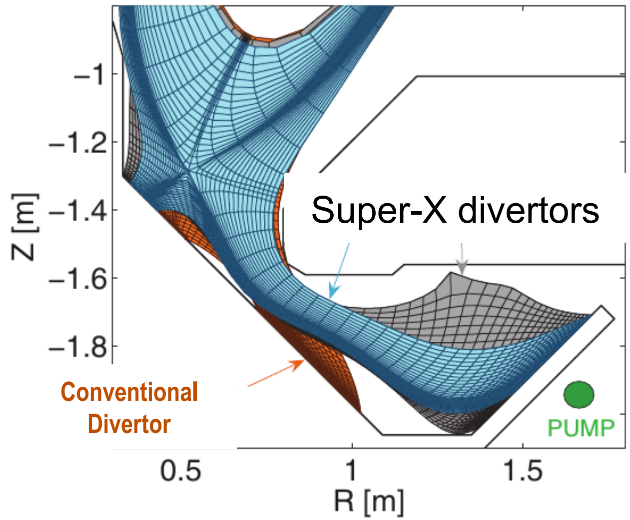
STs will provide leading contributions to development and understanding of advanced divertors

NSTX-U: Short-leg flared divertor + radiation to mitigate heat flux



New PF1 magnets for flaring control, highest shaping, highest ST edge parallel heat flux

MAST-U: World-leading pumped long-leg + flexible flaring, radiation



E. Havlickova, et al., Plasma Phys. Control. Fusion ***56*** *(2014) 075008*

Together provide science basis to integrate high performance ST core with advanced power exhaust

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NAS Strategic Plan Provides a Vision for the U.S. Fusion Program

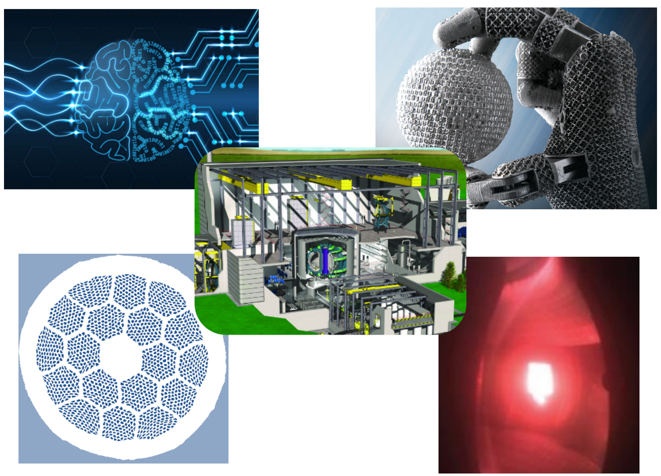
- Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research" (2019)
- Two main recommendations:
  - (1) The United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant
  - (2) The United States should start a national program of accompanying research and technology leading to the construction of a <u>compact pilot plant that produces electricity from fusion at the lowest possible capital cost</u>

FESAC TEC Report Identifies Liquid Metal PFCs as a Potential "Game-Changer"

FUSION ENERGY SCIENCES ADVISORY COMMITTEE REPORT

R. Maingi, co-chair

Transformative Enabling Capabilities for Efficient Advance Toward Fusion Energy



Feb. 2018

U.S. DEPARTMENT OF ENERGY | Office of Science *Fusion Energy Sciences*

- **Charge**: Identify promising Transformative Enabling Capabilities that could promote efficient advance toward fusion energy, building on burning plasma science and technology
- (Fast) **flowing liquid metal PFCs** may prove to be an attractive alternative to handle both high steady-state and transient plasma heat flux

The NAS and FESAC TEC recommendations point to the importance of the NSTX-U mission

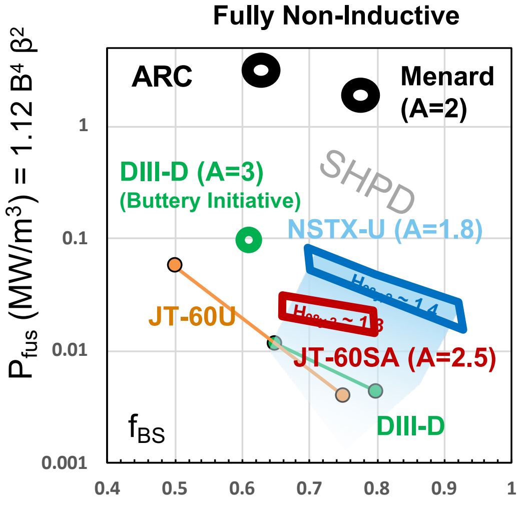
- NSTX-U will provide critical results required to optimize the geometry, including aspect ratio of next-step compact devices

- NSTX-U will provide unique regimes for studying burning plasma-related physics and improve predictive capabilities

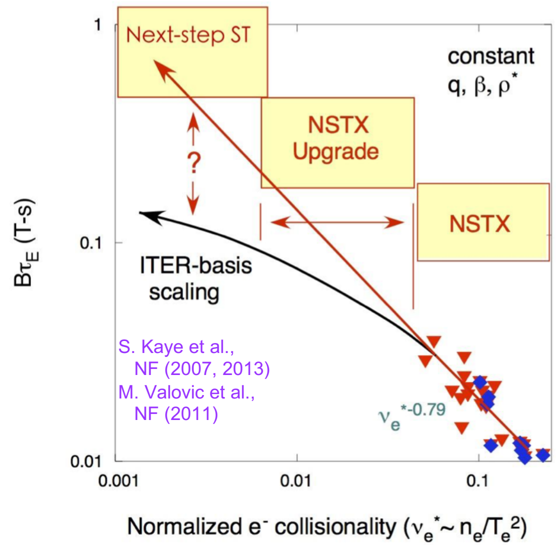
- NSTX-U will evaluate integrated operations with liquid metal PFCs that would enable compact systems

Research thrusts of NSTX-U address routes to optimizing design for compact Pilot Plant

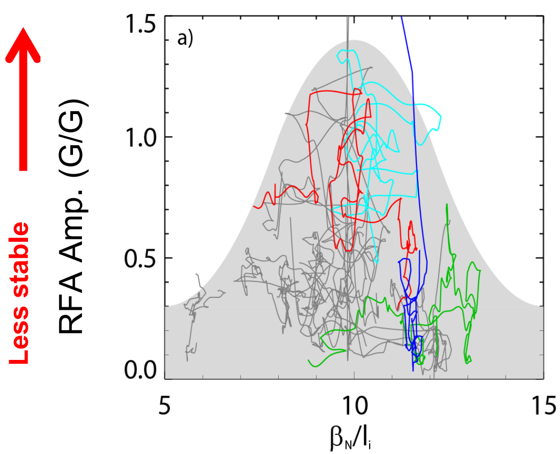
High-β_n (>5) and strong shaping (κ>2.5) route to non-inductive operation



Dimensionless confinement time scales inversely with collisionality at low-A



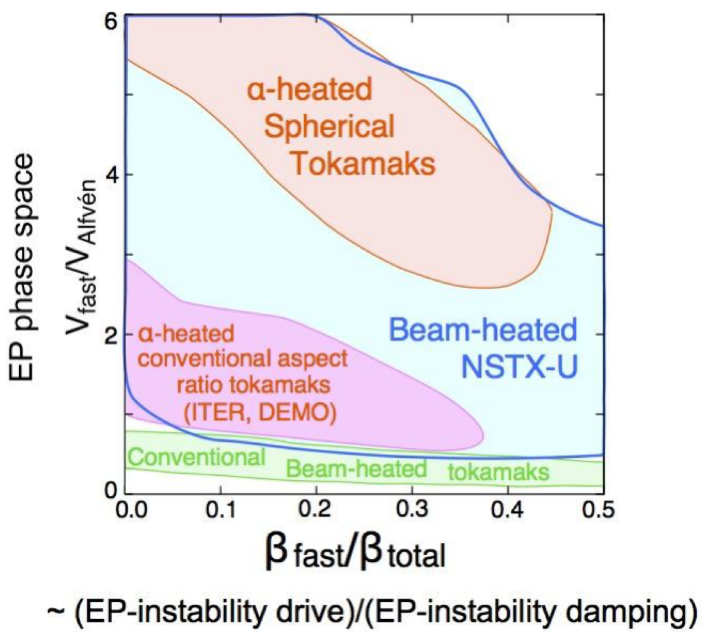
Kinetic stabilization of RWM provides increase of stability for β_N/l_i → 10 at critical rotation



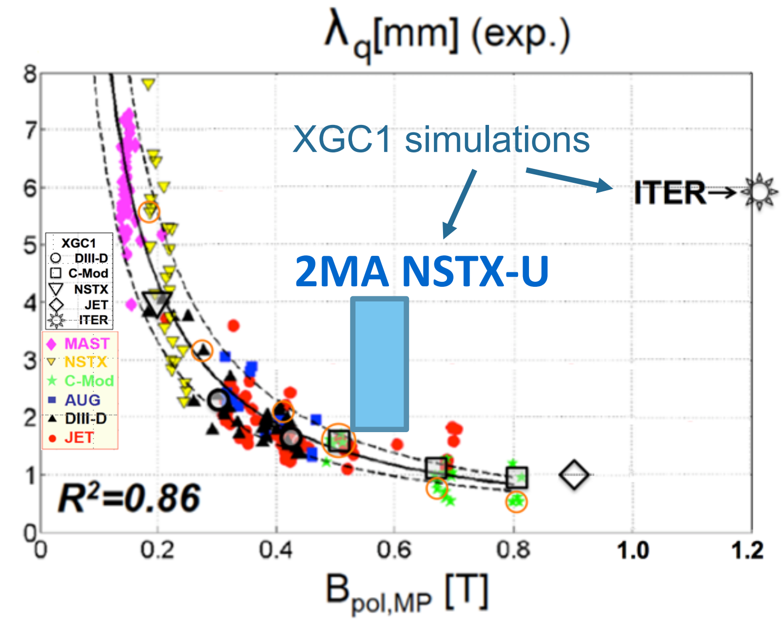
Provides possible transformative route to next-step, compact device

NSTX-U will access unique regimes critical for prediction and optimization in Burning Plasmas

NSTX-U will produce and study EP modes relevant to alpha driven instabilities expected at both high- and low- aspect ratio

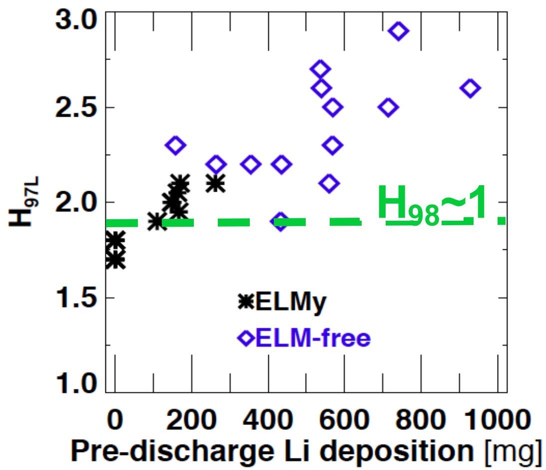


NSTX-U will play important role in understanding how power exhaust width extrapolates to future devices



The longer-term (5-10 yrs) mission has directed its focus on testing Liquid Metal PFCs (Maingi poster)

NSTX: Higher lithium deposition → higher confinement



<u>NSTX-U near-term</u>: Double Li deposition, effect on confinement (carbon tiles)

<u>Long-term</u>: Test liquid metals as transformative wall solution:

- Phase I: prefilled high-Z tiles/LM modules
- Phase II: complete toroidal coverage (LM/Vapor Box)

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

NSTX-U:	Construction	1st campaign Carbon	Phase I high-Z	Phase II - All metal/Liq. Lithium/VB
	Design & Fab. of Phase I, II	Li evap (top & bottom)	Pre-filled high-Z tiles /liquid Li modules	Fully toroidal/VB option

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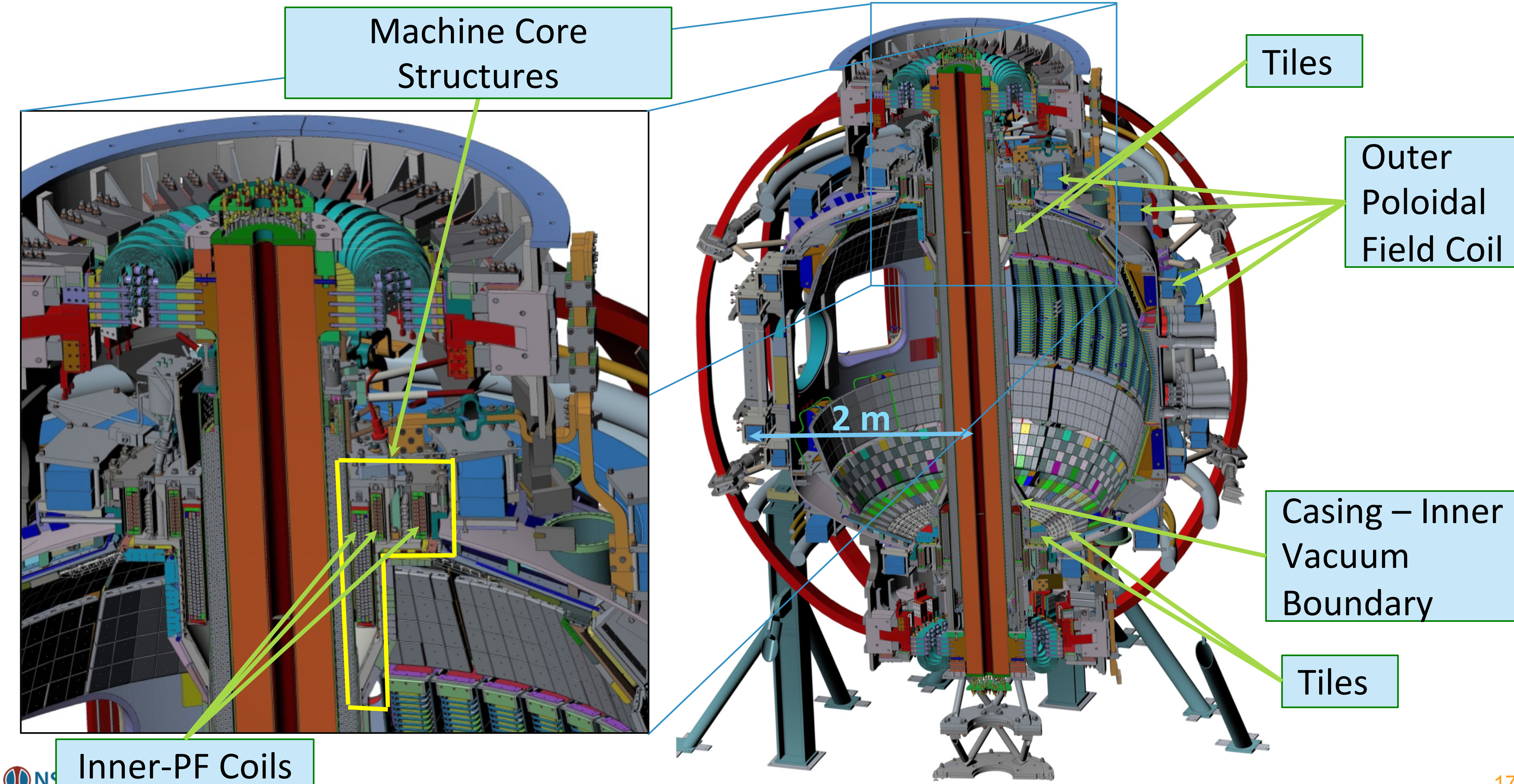
A Brief History of NSTX-U

- 1999 – 2010: NSTX operations
- 2011 – 2015: Upgrade (central solenoid, additional beam)
  - Operated for a 10 week run campaign in FY2016 before the upper PF-1a coil failed
- The goal of the NSTX-U Recovery Project is to address the technical deficiencies noted in 2016 and ensure reliable future operation
- NSTX-U Recovery Project has gone through an extensive and rigorous set of reviews
  - Requirements and interfaces are well documented, verification and validation process in place
  - Project has high design maturity
  - Project is actively working on the transition to an operating facility
    - Early finish date May ’21
- Project has transitioned from design to procurement and fabrication
  - Project will transition to installation early next year

Recovery scope extends beyond PF coils



Recovery components

- New inner PF coils designed to improve testability and ease of manufacture
  - Extensive prototyping program used to validate design and select vendors
- New centerstack casing being fabricated to accommodate full load spectrum
  - Accommodate all heating/cooling and coil support interfaces
- Passive plates modified to support full EM loads
- Plasma Facing Components are being designed to meet full performance thermal and EM loads with high reliability
- Machine instrumentation system will allow benchmarking and trending

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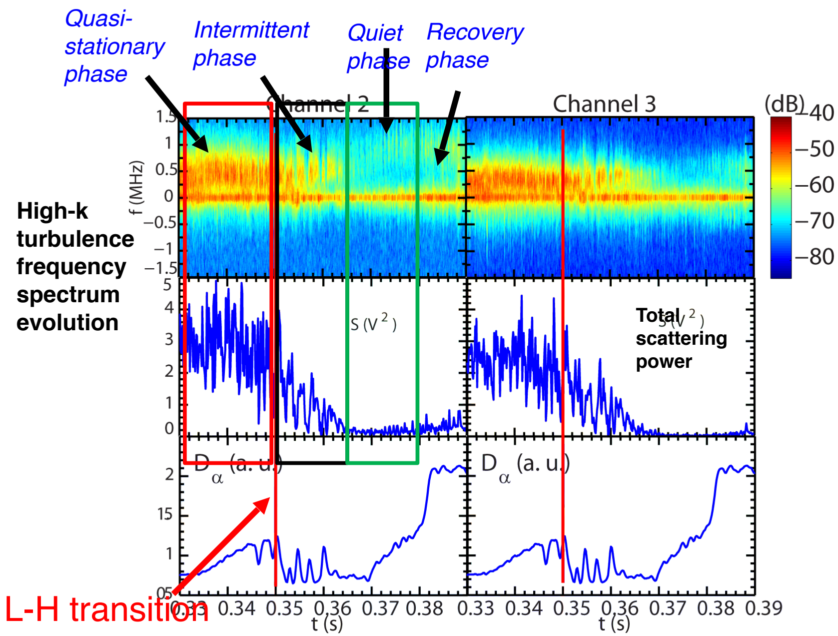
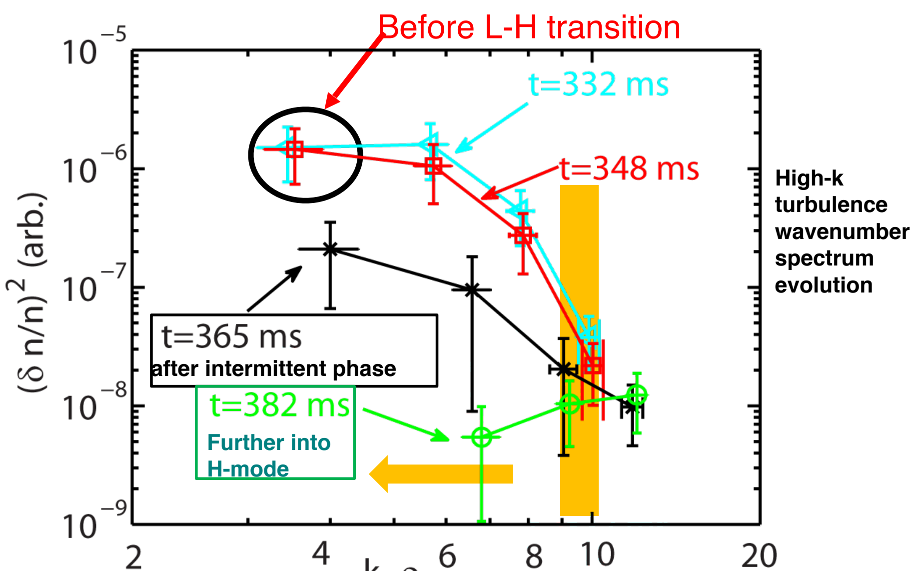
First detailed measurements of high-k (electron-scale) turbulence across L-H transition in NSTX reveal broad spectral changes

- Multiple turbulence phases identified across the L-H transition
- Suppression of high-k turbulence at lower wavenumbers, i.e., $k_{\perp}\rho_s \leq$ 9-10 (higher wavenumbers unaffected); similar to changes at ion scale (BES)

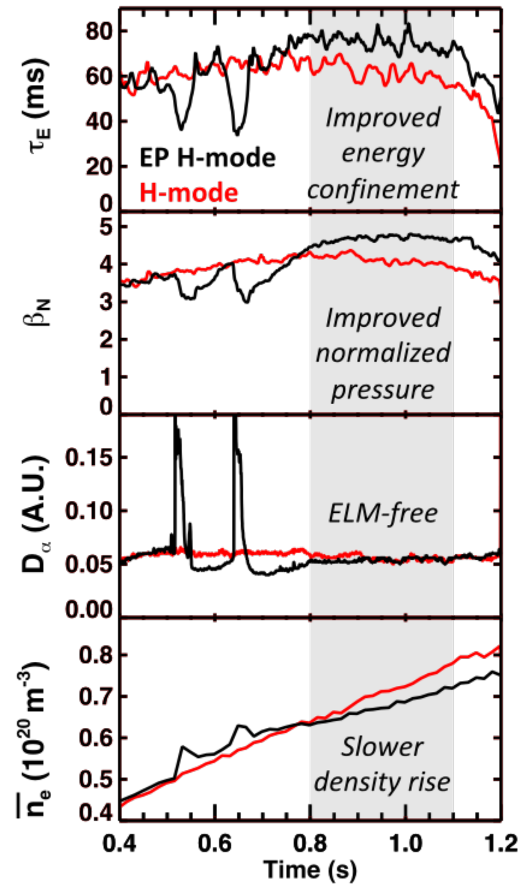




Ren et al., Nucl. Fusion (2019)

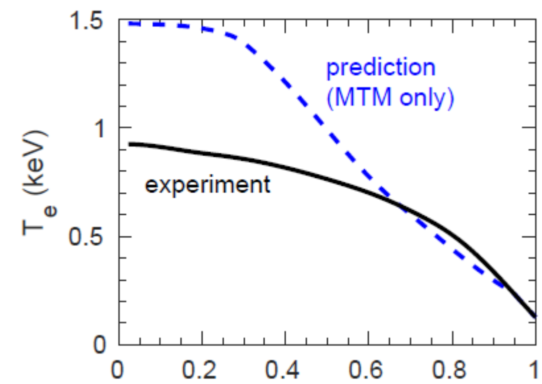
Mechanisms leading to Enhanced Pedestal (EP) H-mode are being better understood

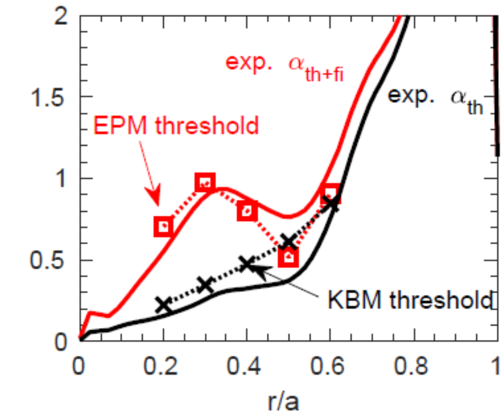
- EP H-mode is an attractive, potentially steady-state ELM-free regime
  - $H_{98y,2}$ typically ~1.5, reached 1.8
  - Reduced density and impurity accumulation
- Decrease in edge density following an ELM initiates a period of reduced edge collisionality
  - Reduced ν^* drives reduction in neoclassical transport
- Increased edge ∇p leads to higher anomalous transport (KBM/TEM)
  - Maintains lower edge density
- Balance between the two transport mechanisms results in maintenance of reduced ν^*, edge ∇p, higher τ_E



Gyrokinetic analyses shed light on source of core and edge transport

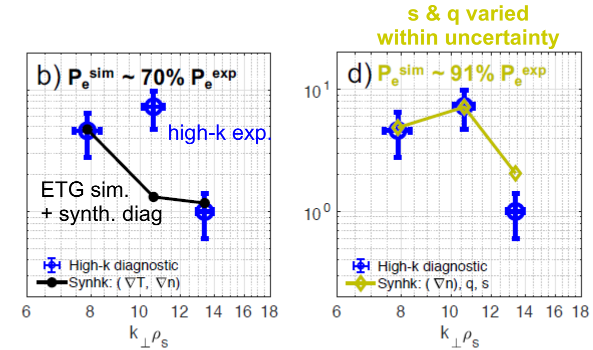
- Linear CGYRO analysis identifies unstable MTM & TEM outside r/a≥0.6 (top of pedestal)
  - Reduced Rafiq MTM model (part of Multi-mode transport model) predicts outer T_e profile
- Central profiles predicted to be very near or above threshold for energetic particle mode (EPM)
  - EPM threshold depends on total pressure (thermal + fast ion) gradient
  - Global, low-n ballooning modes also predicted unstable (M3D-C1)
- Developing hypothesis: **central T_e ultimately clamped by pressure limit**
  - GAE/CAE modes also postulated to influence core T_e



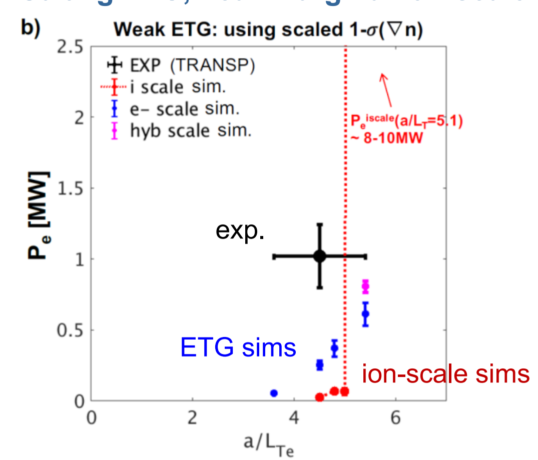


Electron-scale (ETG) turbulence can account for anomalous electron loss in lower-β NSTX H-mode

- Comprehensive validation effort suggests e-scale (ETG) accounts for anomalous e-transport
  - Utilized high-k turbulence measurements + novel synthetic diagnostic to constrain simulation results using numerous sensitivity scans
  - Small variation in geometry (s and q) improves match to high-k fluctuation spectra
- Single-scale simulations in an NSTX H-mode at intermediate β suggest multiscale simulations may be important
  - Similar to multiscale effect found in C-Mod
  - Strong ETG drive + near-marginal ion-scale stability (Howard, NF 2016)



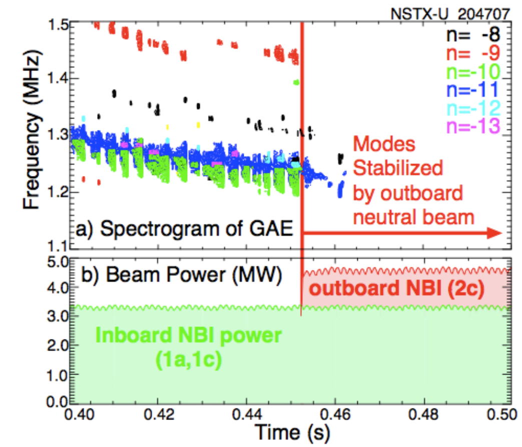
Strong ETG, near-marginal ion-scale



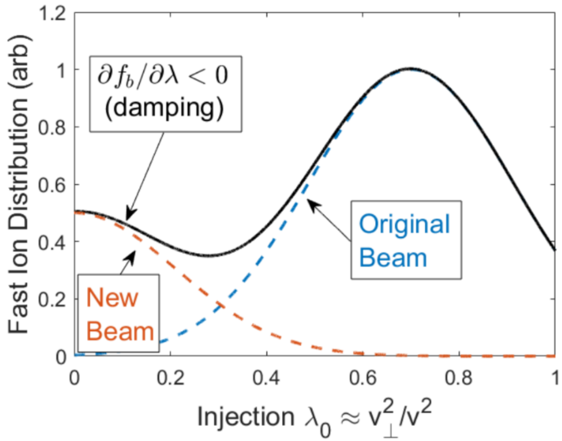
Ruiz Ruiz talk (next)

Modification of fast-ion distribution using tangential NBI can stabilize EP-drive modes

- Computational (HYM) and analytic models reproduce AE stabilization with tangential beam
  - Models identify regions of stability with regards to NBI parameters
  - Calculations indicate only a small fraction of tangential beam particles needed to stabilize mode



- Experiments and theoretical understanding allow for development of techniques to suppress EP (and potentially alpha)-driven modes through phase space techniques

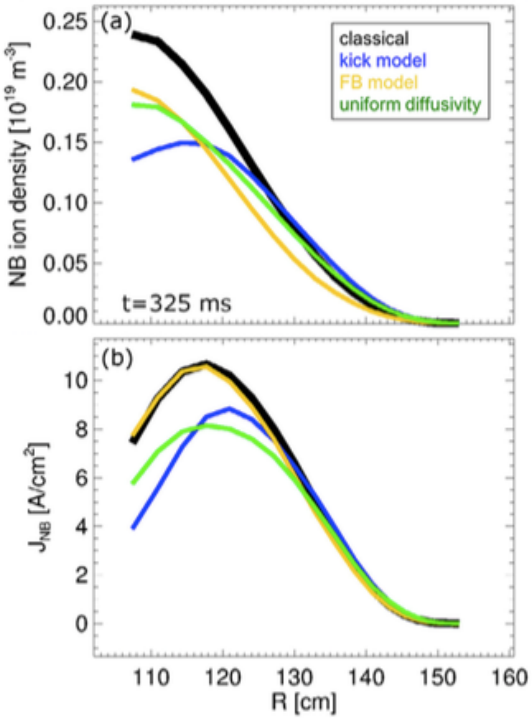


J. Lestz APS invited 2019
E.V. Belova et al., PoP submitted

Reduced models for EP transport due to sub-TAE instabilities being developed

- ‘Kick model’ in TRANSP extended from high-f (AE) version to include EP transport by low-f modes
  - Low-f NTMs, kinks, fishbones, and sawteeth coexist with AEs
  - Extended kick model validated with NSTX-U data
    - Improves upon ad-hoc models already implemented in TRANSP
    - Critical for understanding effect of modes on beam-driven current (and development of non-inductive scenarios)

- Kick model with NTMs applied to DIII-D and NSTX
  - Use Mirnovs and USXR to infer NTM parameters to study impact of NTM on EP transport
  - Presently investigating impact of EPs on NTM trigger and saturation toward comprehensive NTM module in TRANSP



J.-H. Yang, APS-DPP 2019

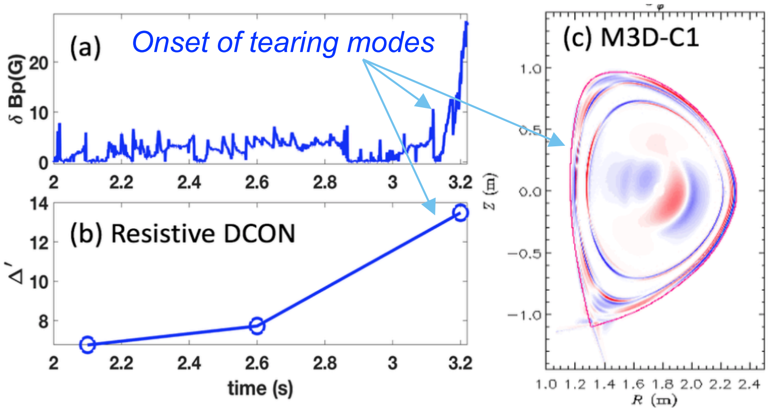
Reduced tearing mode models allow for mapping stable regimes in high-performance scenarios

- Full toroidal Δ′ required to predict TM stability in high-β, ST geometry with ‘extreme toroidicity’

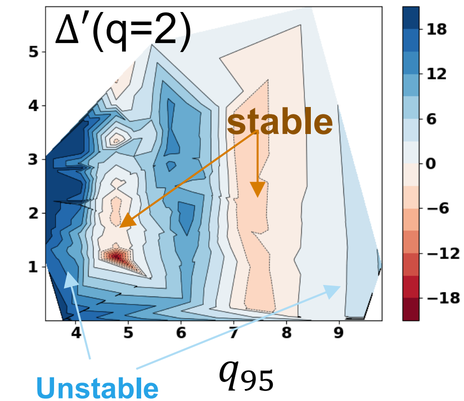
- RDCON is a reduced model that can calculate toroidal Δ′
  - Verified against full-MHD predictive simulations (M3D-C1) for DIII-D IBS cases

- RDCON used to map out stability space for NSTX-U
  - Being coupled to TRANSP through a reduced NTM model for scenario development
  - Also used for MTF stability calcs. (General Fusion)

Prediction of tearing modes in DIII-D IBS



n=1 Δ′ (q=2) *in NSTX-U 2MA, 1T, 12MW scenario*



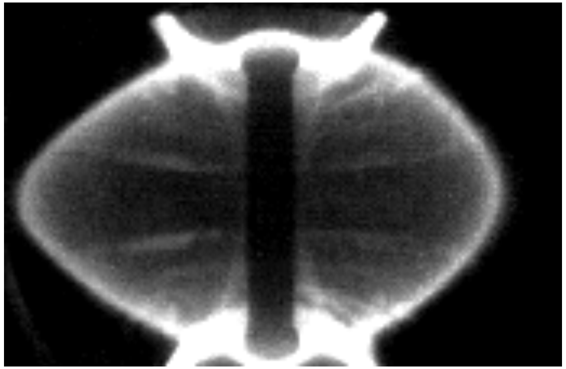
Z. Wang

Studies of observed global modes in MAST and NSTX allow for understanding the effect of wall proximity on mode structure

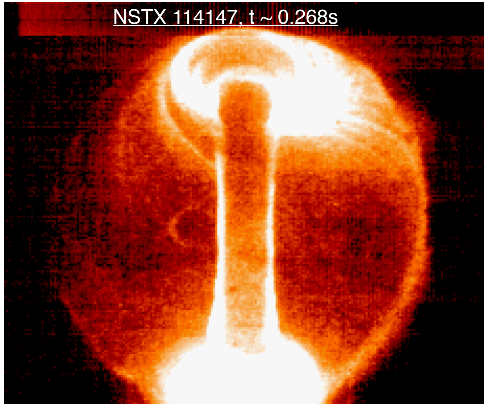
“egg shape event”

MAST

Fast camera image
(MAST 21436, t ~ 0.280s)

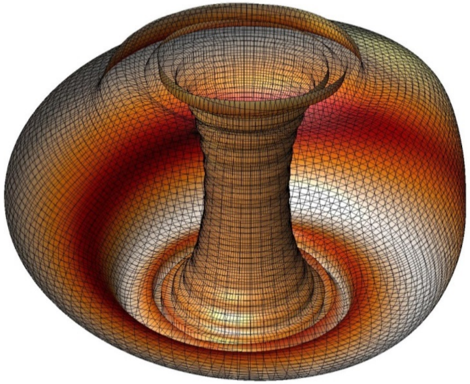


Images of plasma distortion due to global modes

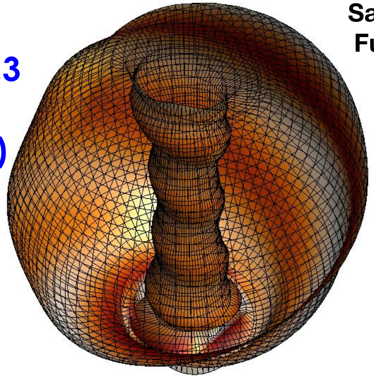


NSTX

**VALEN analysis (n = 1 RWM)
(using MAST 7090)**



**VALEN analysis (n = 1,2,3 RWM)
(reconstructed 114147)**

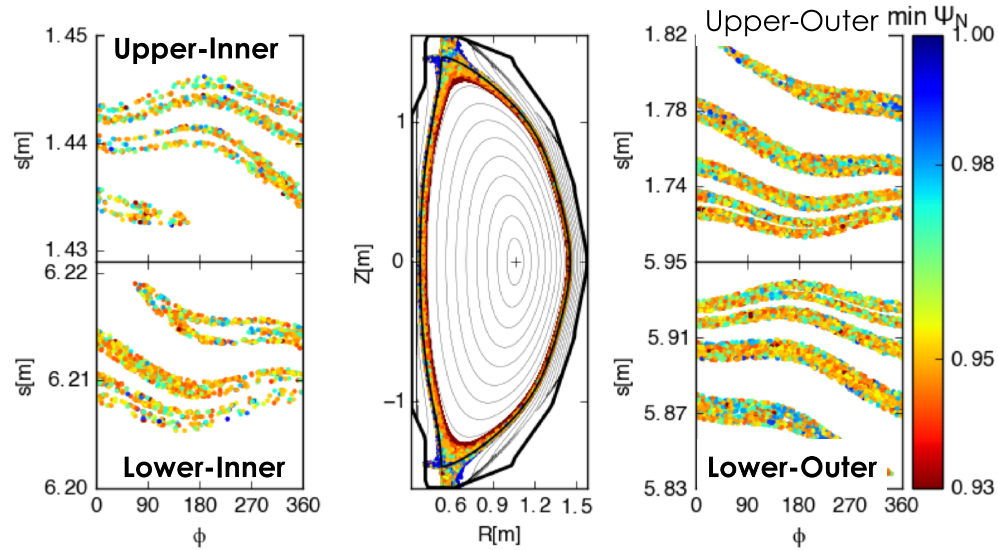


Sabbagh, et al., Nucl. Fusion 46 (2006) 635

VALEN code analysis reproduces similar distortions to respective NSTX and MAST observations

3D calculations indicate sensitivity of divertor footprints to error fields

- 5 mm shift of TF coil produces 10 cm wide footprint on outer divertor plates
- Footprint size linearly proportional to magnitude of TF, PF5 misalignment



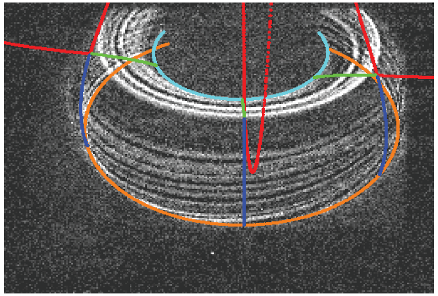
- Study predicts that error fields in NSTX-U will not expand footprints outside of divertor PFCs

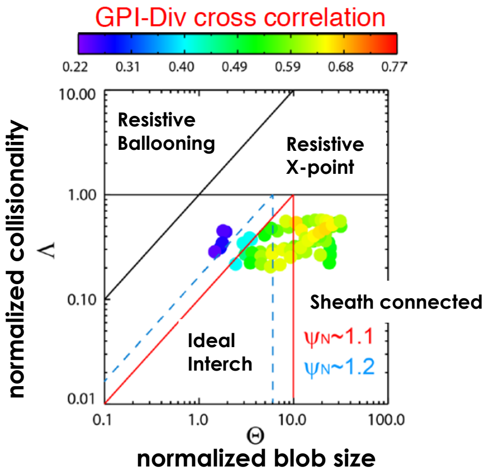
Munaretto (2019)

Fast camera imaging of divertor turbulence provides new insights into SOL turbulence

- Divertor leg fluctuations observed by fast imaging in NSTX-U
  - Intermittent; localized to bad curvature side
  - Simulations with ArbiTER code find unstable resistive ballooning modes [Baver (2016)]
- Disconnection of midplane turbulence from divertor plate due to X-point
  - Consistent with expectations from two-regime blob model [Myra (2005)]

Images in CIII emission



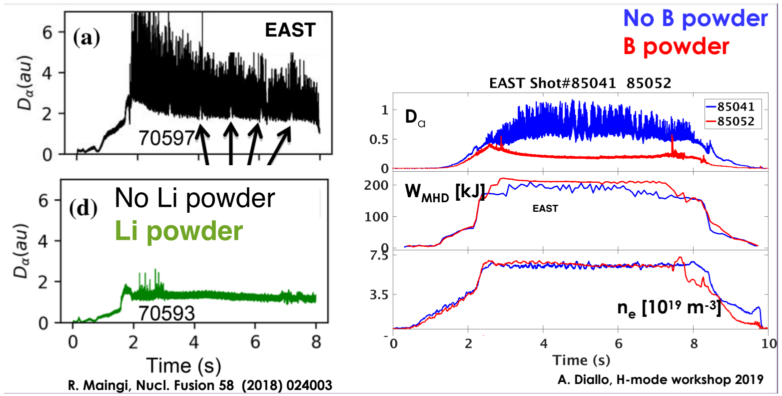


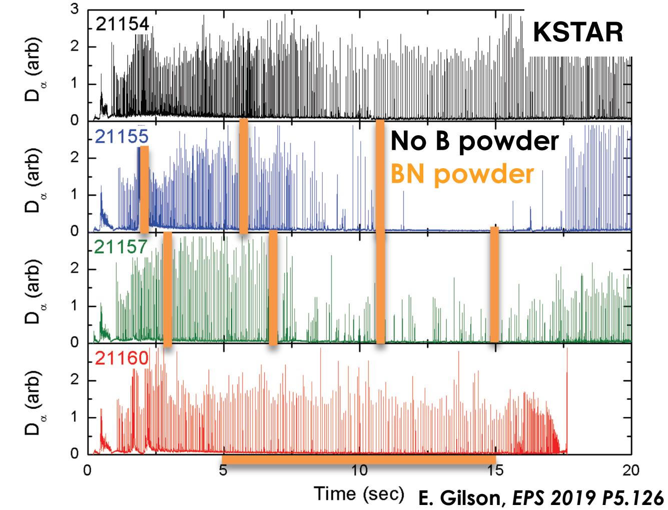
Scotti (2019)

Wall conditioning studies using low-Z impurity powder injection on EAST, DIII-D, KSTAR and ASDEX-U

- **EAST**: compared ELM suppression with Li powder injection (reduced recycling) with B powder (low frequency edge mode)
- **DIII-D**: B powder injection successfully used for wall conditioning to reduce recycling and density
- **KSTAR**: BN powder injection led to periods of ELM quiescence
  - Dependence on injection rate
- **AUG**: BN powder injection led to enhanced radiated power, reduced heat flux, improved stored energy
  - Similar to N_2 gas injection

- **Powder dropper is being considered for early deployment on NSTX-U**



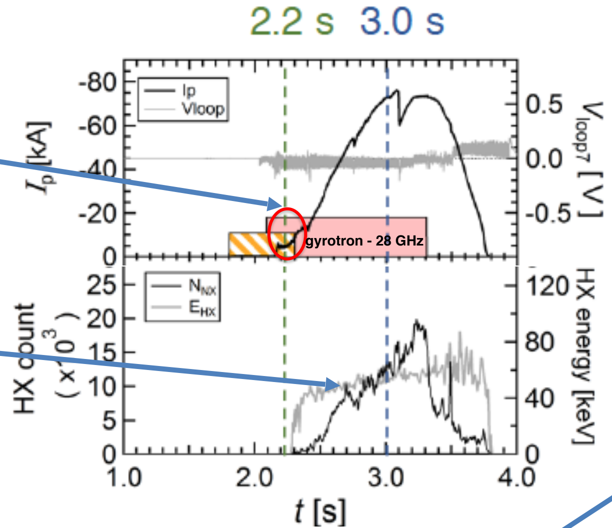


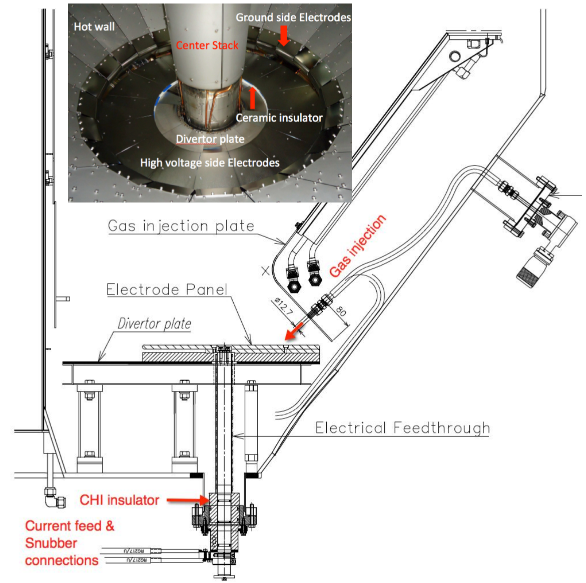
QUEST provides unique opportunity to understand and optimize non-inductive start-up/ramp-up

- **Experiment and modeling of 2nd harmonic electron cyclotron heating and current drive solenoid-free start-up in QUEST**

Initial pressure driven current phase
- **No X-ray**
- **No ECCD**

ECCD Phase
- **Increasing X-ray – energetic electrons**
- **$I_p \propto I_{X\text{-ray}} \propto n_{eh}$**
- **Minority energetic particle population**



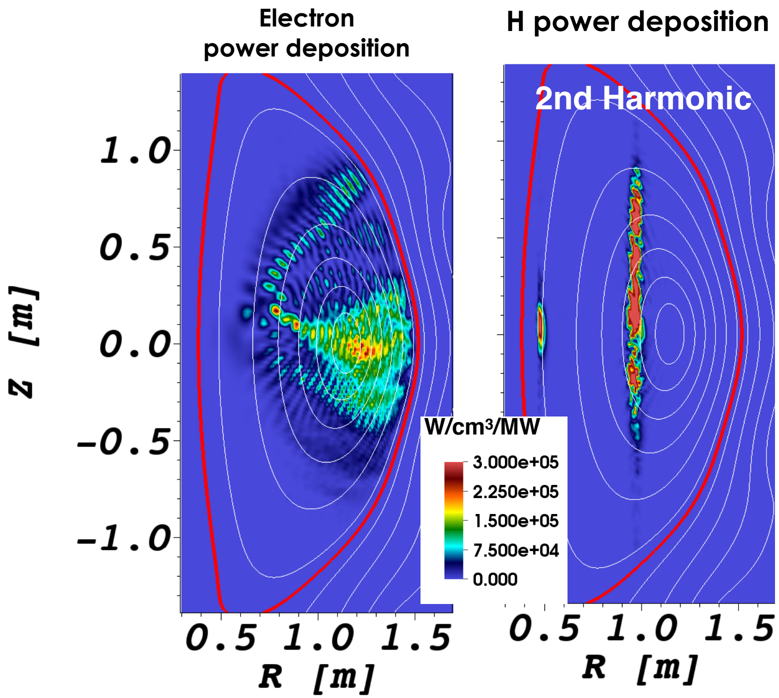


- **Transient CHI on QUEST has shown reliable discharge initiation, and plasma growth in biased electrode configuration**
  - **CHI to be tested also on URANIA**

N. Bertelli, invited talk at the 23rd Topical RF Conf. (China, 2019)

Numerical modeling is exploring optimization of HHFW using minority H species

- Performed through RF SciDAC collaboration
- 2D power deposition calculated by AORSA full wave code
- Looking at 0 to 10% H concentrations over range of wave numbers and TF
  - Find significant electron absorption of HHFW power
- Could provide attractive path for 2nd harmonic H minority heating in NSTX-U to assist in non-inductive ramp-up



N. Bertelli, invited talk at the 23rd Topical RF Conf. (China, 2019)

ST-specific collaborations established

- MAST Upgrade collaboration will afford opportunities for direct connection to NSTX-U research program (PPPL + collaborators)
  - Start-up, ramp-up, control (PPPL)
  - Equilibrium and stability, including EF and TM physics (PPPL, Columbia U)
  - Transport and turbulence, including gyrokinetic analysis (PPPL, UCLA)
  - Divertor physics (PPPL, ORNL, LLNL)
  - Energetic particle physics (PPPL, UC Irvine, Florida Int. U., UCLA)

- ST40 collaboration (public-private partnership with Tokamak Energy, Ltd., UK) funded and officially started
  - Three year collaboration including PPPL, ORNL, UC Irvine, U. Washington, Columbia Univ)
  - Areas of collaboration include:
    - Pedestal physics: PBLS (PPPL), divertor physics (ORNL)
    - Confinement, EP physics, EF/tearing physics (PPPL, UC Irvine)
    - Disruption prediction (Columbia U)
    - RF modeling for start-up/ramp-up (PPPL, ORNL)
    - Scoping of future capabilities: turbulence diagnostic (PPPL), CHI (U. Washington), Li injection (PPPL)

Summary

- NSTX-U high-level research goals well aligned with directions recommended in recent panel studies and anticipated in U.S. Community Planning Process
  - Critical for optimizing designs of next-step compact devices, aspects of burning plasma physics
  - Vital for developing predictive capability for fusion science through leverage provided by expanded operating regime

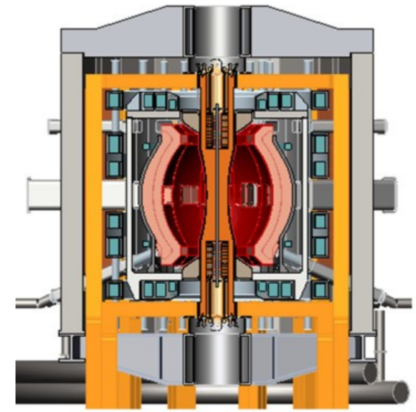
- NSTX-U Recovery project on track for completion in May ‘21 – July ‘22 time frame

- NSTX-U researchers (PPPL and collaborators) deeply involved in NSTX(-U) and domestic and international collaborations that can impact NSTX-U research

Backup

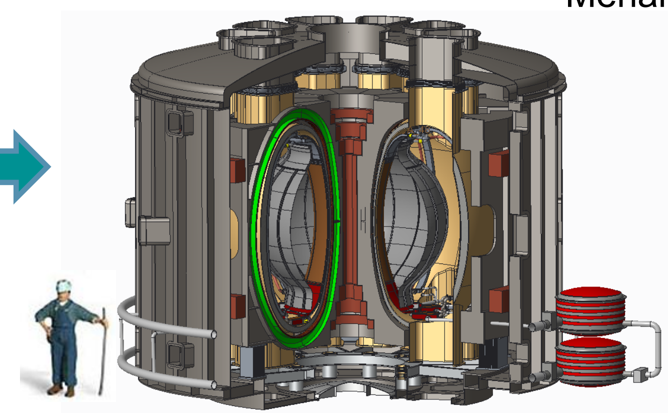
Has the NSTX-U mission changed over the past few years?

- Components of the short-term (1-3 yrs) research plan remain the same, and can benefit domestic strategy that is presently being developed by the U.S. fusion community
- NSTX-U Science mission can address critical issues for:
  - ST-based FNSF
  - Optimizing geometry (e.g., κ, δ, aspect ratio) of next step “compact” devices
  - ITER
- De-emphasize non-solenoidal startup; reassess if Pegasus/QUEST successful
- LM divertor primary long-term path; consider cryopump in addition



Menard (2016)

Menard, Brown



R=1.0m, A=2.4

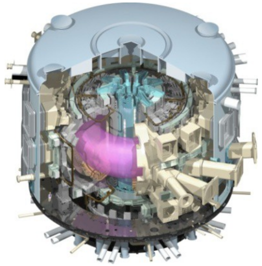
NSTX-U Mission Elements Support the NAS Vision

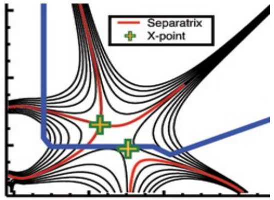
- Exploit unique Spherical Tokamak (ST) parameter regimes to advance predictive capability - for ITER and beyond

- Develop solutions for plasma-material interface (PMI) challenge

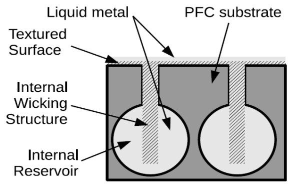
- Explore ST physics towards reactor relevant regimes (Fusion Nuclear Science Facility, low-A Pilot Plant)

ITER



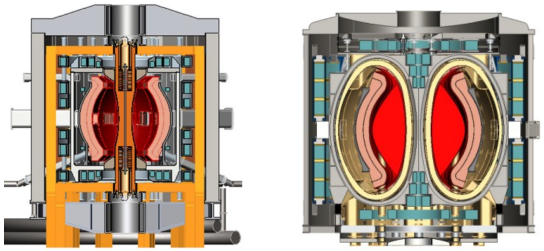


Advanced divertors



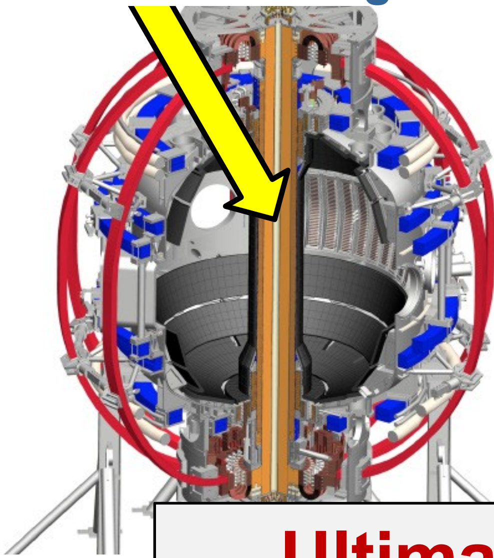
Liquid metals

ST-FNSF / Pilot-Plant



NSTX-U targeting major performance increase to explore new physics regimes

1. New Central Magnet



2. Tangential 2nd Neutral Beam

Ultimate Performance Goals:

- ➢2× toroidal field (0.5 ➔ 1T)
- ➢2× plasma current (1 ➔ 2MA)
- ➢5× longer pulse (1 ➔ 5s)
- ➢2× heating power (5 ➔ 10MW for 5s)
  - Tangential NBI ➔ 2× current drive efficiency
  - Up to 15MW NBI + 4MW RF for 1-2s
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)
- ➢4× divertor heat flux (➔ ITER levels)

NSTX-U vital for addressing key ST / fusion questions

Highest normalized pressure at high T

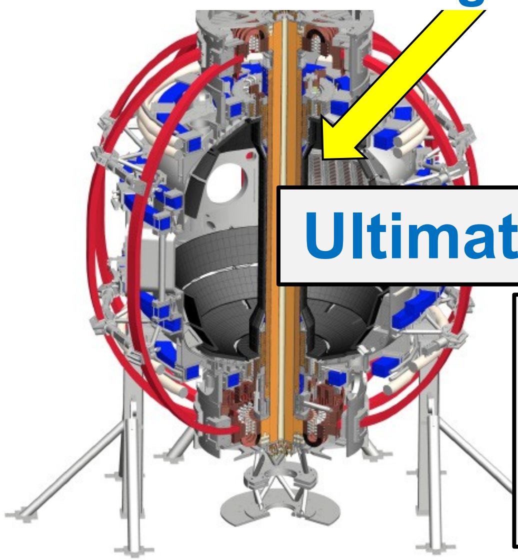
Unique regime, study new transport and stability physics

Sustain steady-state plasma

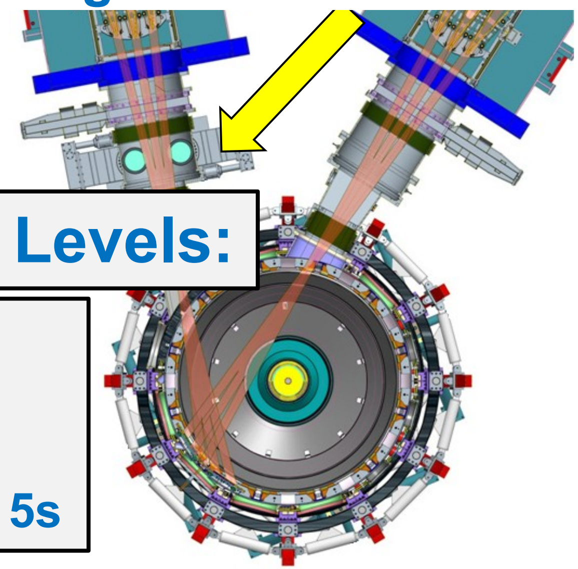
Not yet achieved at high-β_{T}, low ν^*

Two new tools:

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Ultimate Performance Levels:

B_t =1T
I_p = 2 MA
P_{NB} = 10 MW
Flat top duration = 5s

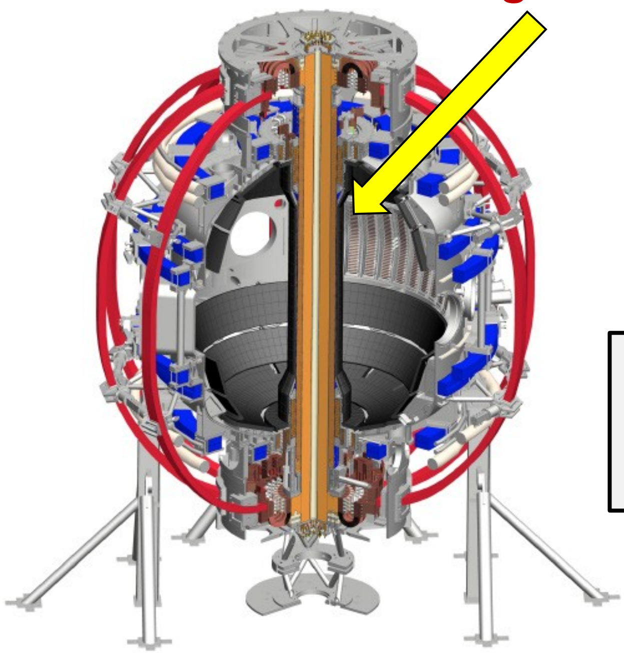
NSTX-U vital for addressing key ST / fusion questions

Will access new physics with 2 new tools:

Highest normalized pressure at high T

➔ Unique regime, study new transport and stability physics

1. New Central Magnet

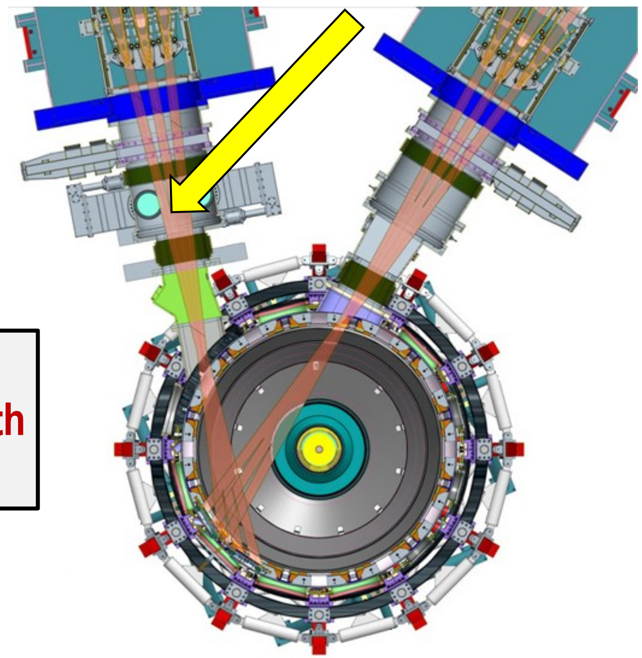


Sustain plasma without transformer

➔ Not yet achieved at high-β_T, low ν^*

Essential for any future steady-state ST

2. Tangential 2nd Neutral Beam



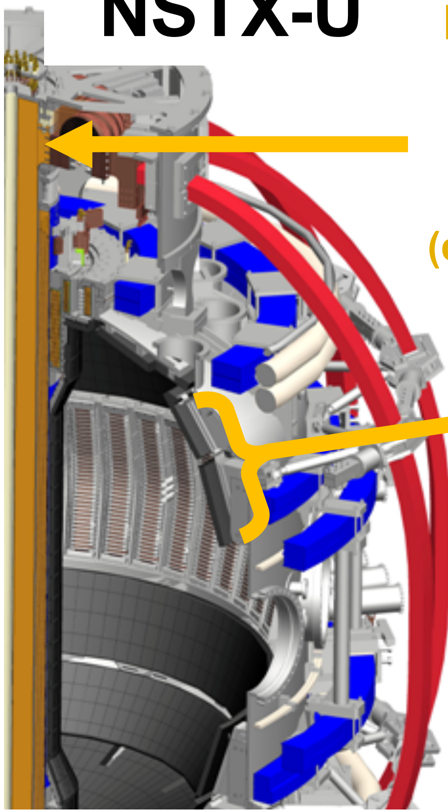
2× field, current, power
4× heat flux, 5× pulse length
Up to 10× higher $nT\tau_E$

NSTX-U has many unique aspects relative to MAST-U

- NSTX-U is unique when compared with MAST-U for addressing key goals:
- Higher pressure and field (enabling the key goal of assessing ST confinement)
- Longer pulse (enabling the key goal of developing sustained high beta scenarios)
- Close-fitting wall (enabling the key goal of developing sustained high beta scenarios)
- Higher density non-inductive scenario (enabling key goal of sustained high beta scenarios)
- HHFW (enabling the key goal of developing sustained high beta scenarios)
- Wall conditioning with lithium, wider pedestals and a path to lithium-wall.
- Wide shaping flexibility when applying full beam power (whereas MAST-U is limited by vertically-displaced beam geometry)
- Larger $q_{||}$ for short pulse to assess divertor scalings in STs
- More flexible beam injection tangency allowing studies of fast ion physics, momentum transport etc in wider range of scenarios as well as for current ramp-up development
- NSTX-U will benefit from strong collaboration with MAST-U to exploit complementary capabilities
- NSTX-U also has leading capabilities that contribute to mainline program

NSTX-U design enables access to 2-3× higher plasma pressure, temperature than MAST-U

NSTX-U



NSTX-U central magnet provides 1.5× higher toroidal field current

→ ~1.5 - 2× higher B_T^2

(depending on plasma shape)

Conducting plates can suppress global kink instabilities,

~1.5× higher β_T

$$p \propto \beta_T B_T^2$$

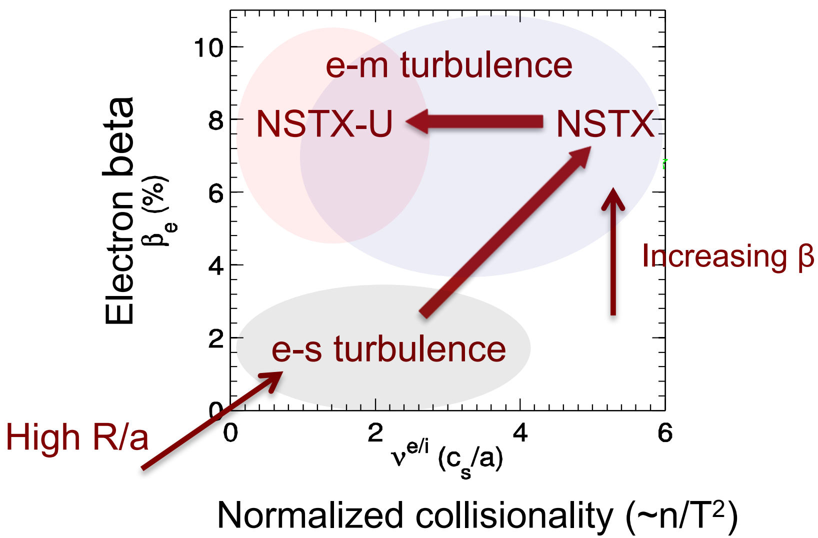
2-3× higher

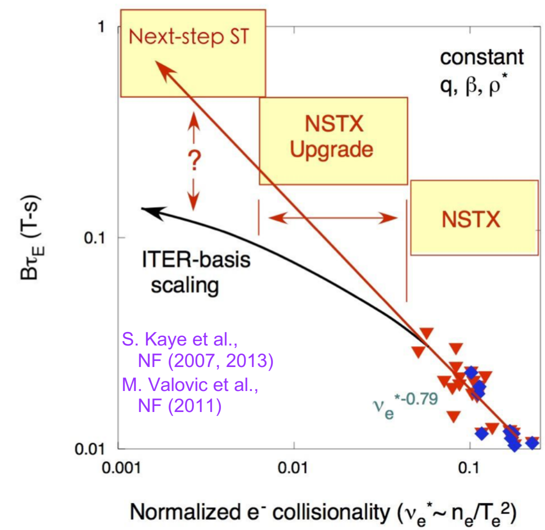
MAST-U

- Expect ~2× higher edge "pedestal" pressure due to higher B, shaping

Transport at low-A is fundamentally different than transport at conventional-A

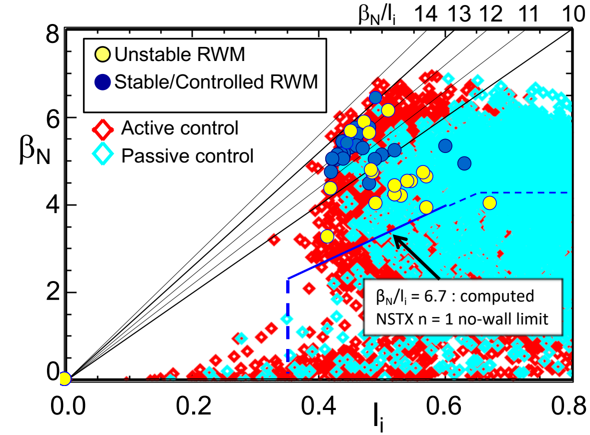
- Many features of low-A, high-β stabilize ES modes (ITG, TEM, ETG) in core
  - Neoclassical ion transport, MTM, KBM and EP modes drive electron transport
- Dimensionless confinement time scales inversely with collisionality at low-A ($\Omega_{ci}\tau_E \sim \nu_*^{-0.8}$)
  - Scaling extrapolates to an A=2 CPP with H_{ST} = 0.9 equivalent to $H_{98y,2}$ = 1.75
  - NSTX-U will operate at up to a factor of six lower ν_* than NSTX





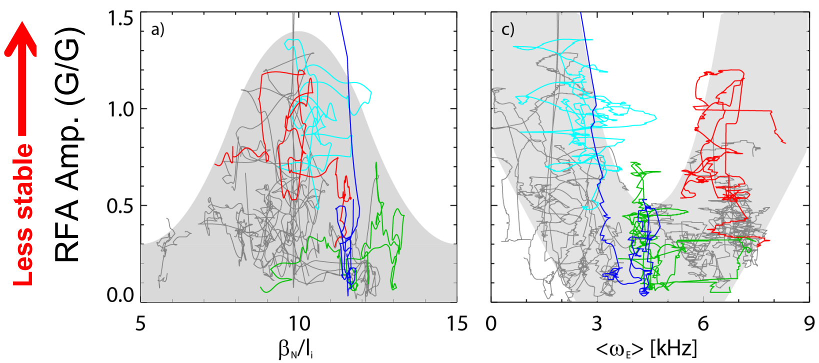
Stability at large β_N/l_i is a strong lever for a compact device

- $f_{BS} \sim \beta_N/l_i$ → Broad current and pressure profiles
  - NSTX achieved large β_N/l_i with $\beta_N / \beta_{no\text{-}wall} > 2$
- Stability increased as β_N/l_i → 10 at critical rotation
  - Kinetic stabilization of the RWM
  - Prediction that stabilization improves at lower collisionality will be tested on NSTX-U



S. Sabbagh et al., Nucl. Fusion **53**, 104007 (2013)

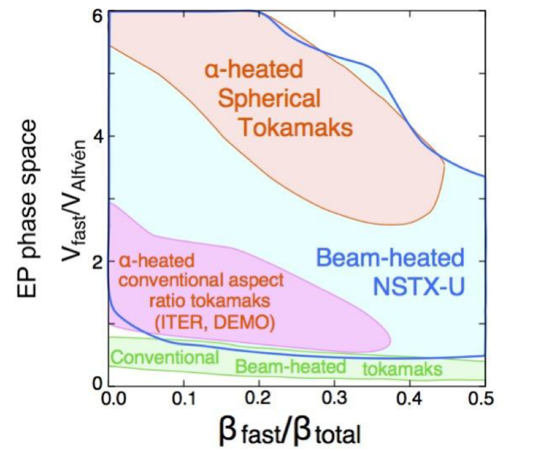
- NSTX-U has expanded suite of real-time control measurements and actuators
  - RT profile control using tangential NBI, density and shape actuators
  - Increased flexibility in the 3D field spectrum for EFC + rotation control



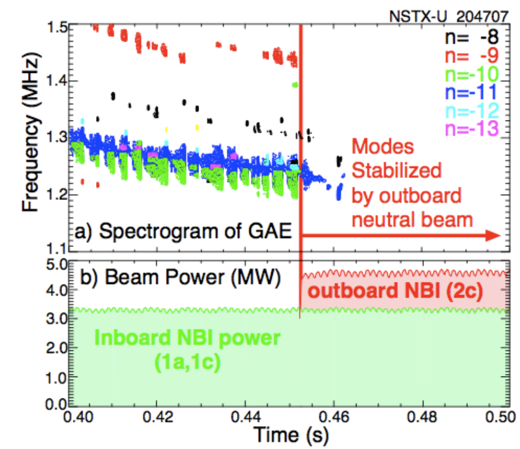
J.W. Berkery, et al., PoP **21** (2014) 156112,
J.W. Berkery, et al., Phys. Rev. Lett. **106** (2011) 075004

NSTX-U will access unique regimes in fast particle physics critical for prediction and optimization

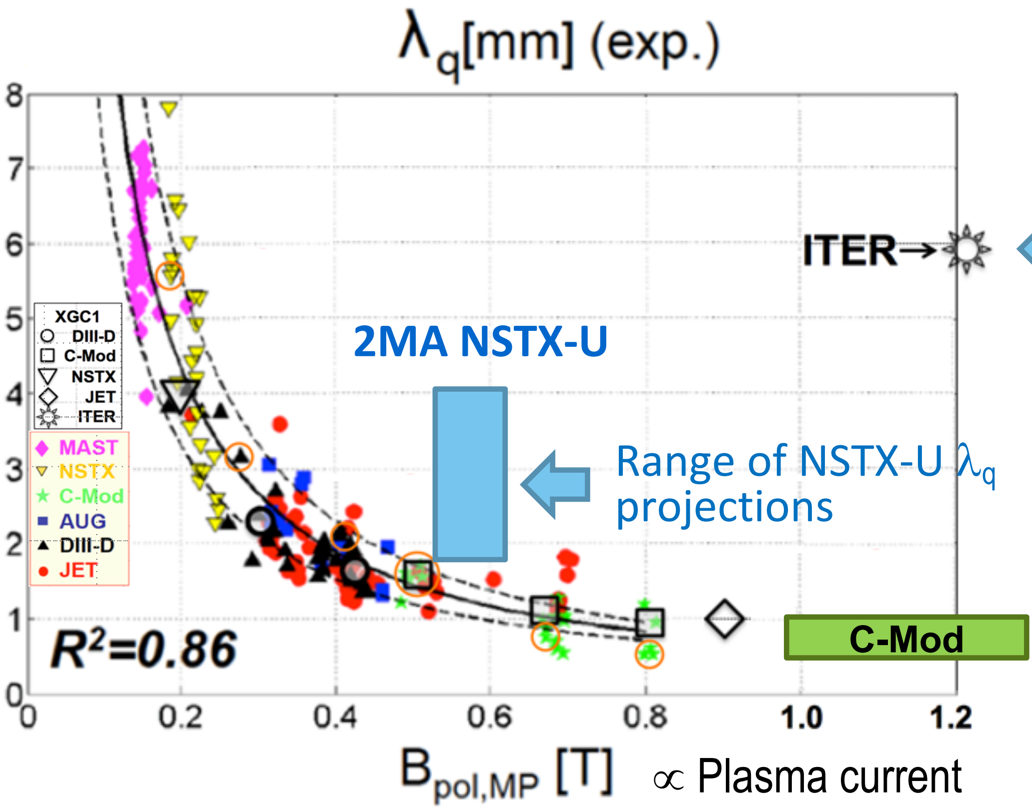
- NSTX-U will produce and study EP modes relevant to alpha driven instabilities expected at both high- and low- aspect ratio
  - Characterizing fast ion interaction with RF (see Diallo talk)
  - Important for ITER and CPP
- Modification of fast-ion distribution using tangential NBI can stabilize EP modes that enhance transport
  - Study and develop techniques to suppress alpha-driven modes through phase-space engineering



~ (EP-instability drive)/(EP-instability damping)



NSTX-U will play important role in understanding how power exhaust width extrapolates to future devices



XGC1 simulations predict turbulence will widen edge heat flux in ITER

C.S. Chang et al 2017 Nucl. Fusion **57** 116023

XGC1 studies of NSTX-U indicate enhanced TEM transport in the low ν^*, 2 MA NSTX-U pedestal, similar to mode expected for ITER

Recovery includes divertor tile improvements to access high current, power, shaping