Overview of Research Plans for NSTX Upgrade*

Jonathan Menard, PPPL

For the NSTX-U Research Team

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Princeton University
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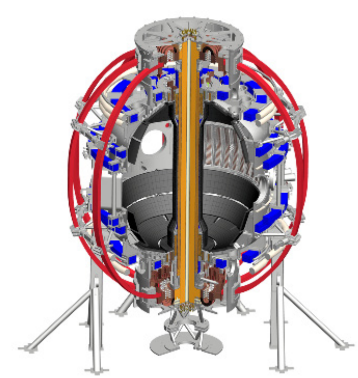
**This work supported by the US DOE Contract No. DE-AC02-09CH11466*

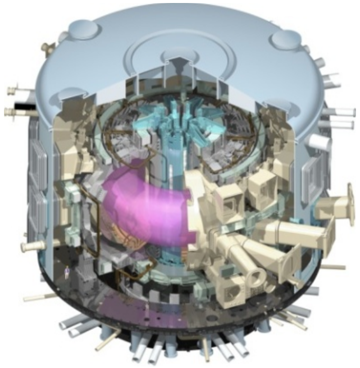


Outline

- **NSTX-U Mission and Motivation**
- **NSTX/NSTX-U Research Highlights and Goals**
  - **Global MHD Stability**
  - **Transport and Turbulence**
  - **Energetic Particles**
  - **Power Exhaust**
  - **Plasma Start-up**
- **Brief Summaries of NSTX-U Research Plans**
- **Summary**

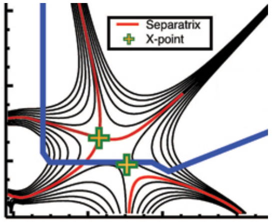
NSTX-U Mission Elements:

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



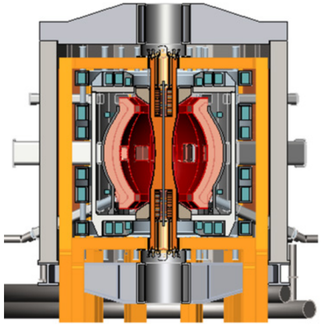
- Develop solutions for the plasma-material interface (PMI) challenge

Liquid metals / Lithium

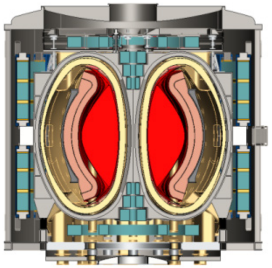


"Snowflake"

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



ST-FNSF / Pilot-Plant



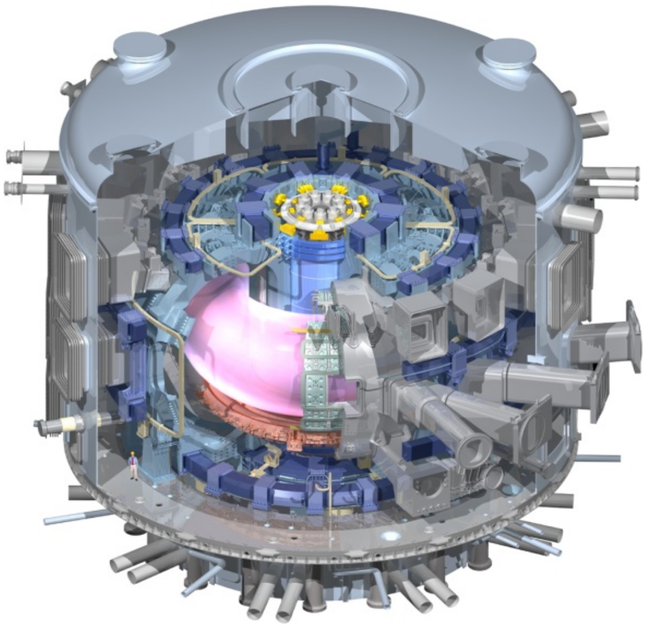
- Develop ST as fusion energy system

Unique ST properties support ITER

ST Extends Predictive Capability for ITER and Toroidal Science

- High β physics, rotation, shaping extend stability, transport knowledge
- STs can more easily study electron scale turbulence at low collisionality → important for all magnetic fusion
- NBI fast-ions in present STs mimic DT fusion product parameters in ITER → study burning plasma science
- Access ITER-level divertor heat fluxes → study SOL / detachment physics

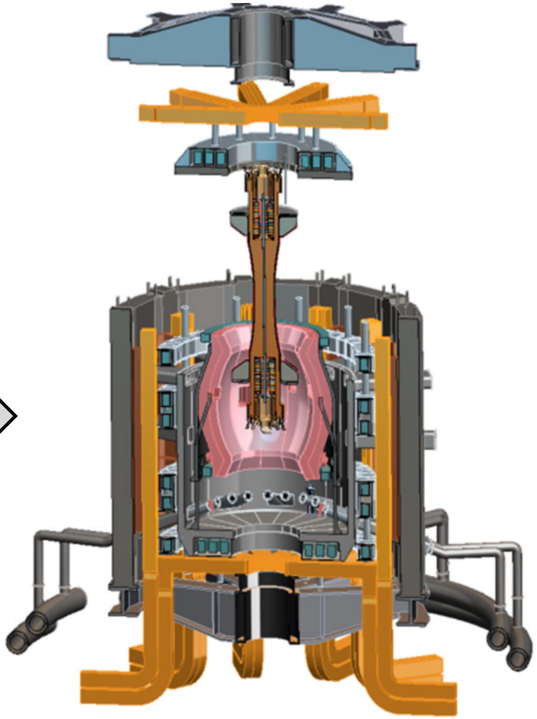
Burning Plasma Physics - ITER



Design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF)

- FNSF can help develop reliable fusion nuclear components
  - Substantial integrated R&D, testing needed to develop components
  - An FNSF facility should be: modest cost, low T, and reliable

- ST-FNSF projected to access high neutron wall loading at moderate size and fusion power
  - W_n ~ 1-2 MW/m^2 , R ~ 0.8-1.8m, P_{fusion} ~ 50-200MW
- Modular, simplified maintenance
- Tritium breeding ratio (TBR) ≈ 1
  - Using only/primarily outboard breeding requires sufficiently large R, careful design



PPPL ST-FNSF concept

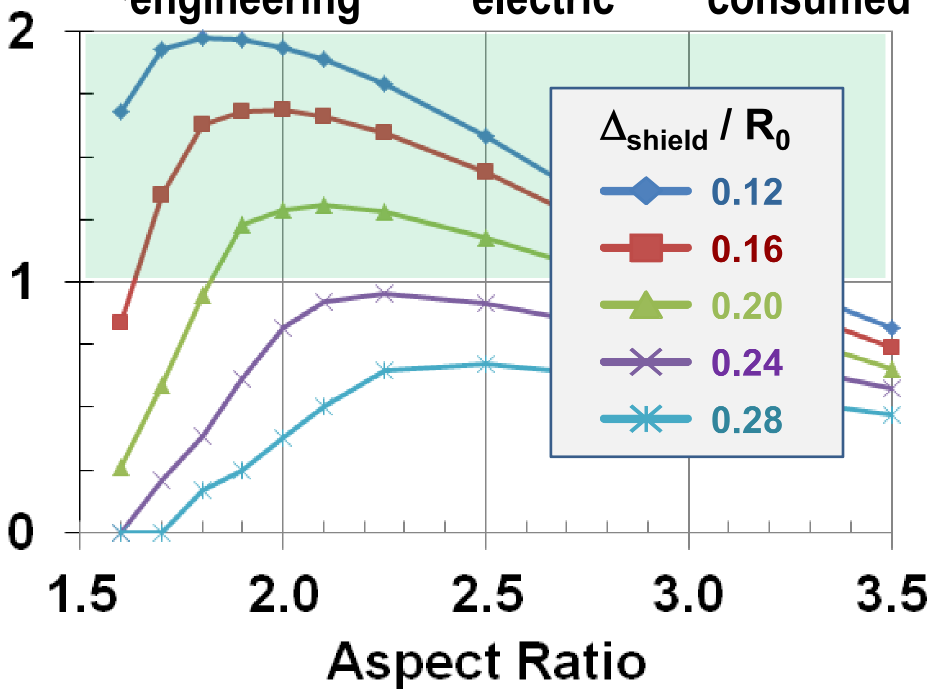
High Temperature Superconductors (HTS) attractive for ST*

(~10× lower magnet cooling power vs. Cu, less thermal shielding required)

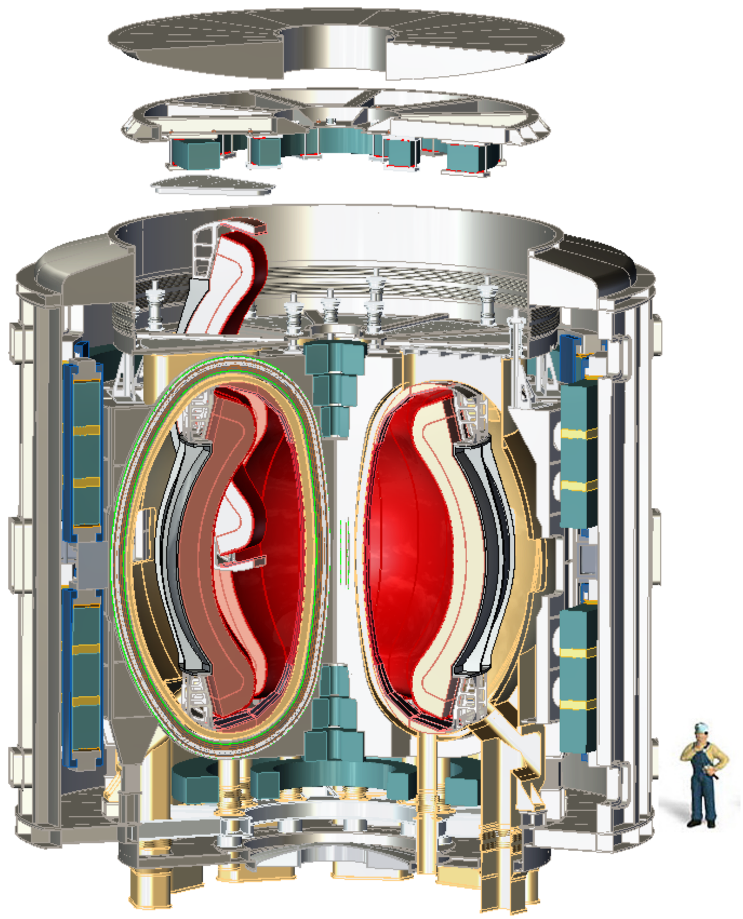
Net electricity easiest near A=2 if:

- Inboard T breeding minimized / eliminated
- Central solenoid minimized / eliminated

$Q_{engineering} = P_{electric} / P_{consumed}$



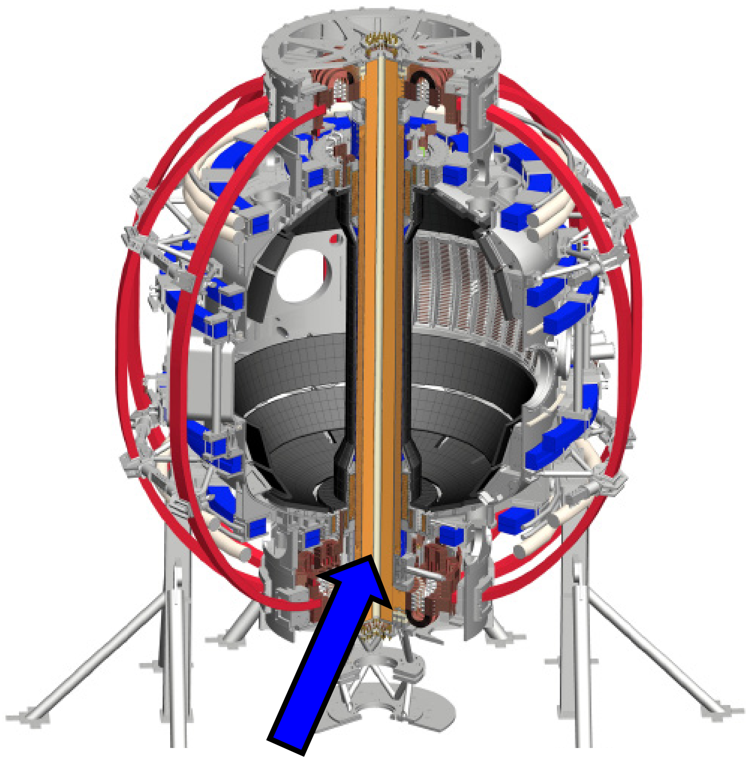
Magnet lifetime increases exponentially with Δ_{shield}



Work supported by Tokamak Energy (UK) - 2014

R_0 = 1.4m, B_T = 3.2-4T, I_P = 7-8MA, $P_{fusion\text{-}DT}$ = 100MW
H_{98y2} = 1.7-2, H_{ST} ~ 1, A = 1.8-2, κ ~ 2.5-2.7, δ ~ 0.5

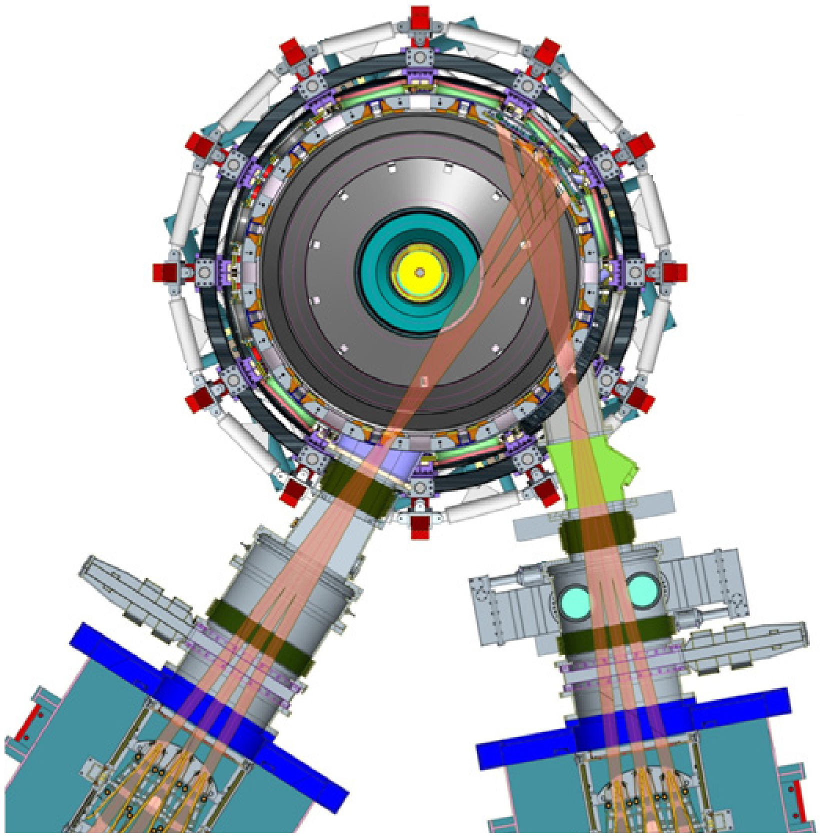
Upgrade of NSTX has 2 major elements



New Centerstack Magnet

Access high β, high T, low collisionality

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



Original NBI **New 2nd NBI**

Tangential 2nd NBI increases current drive for non-inductive sustainment

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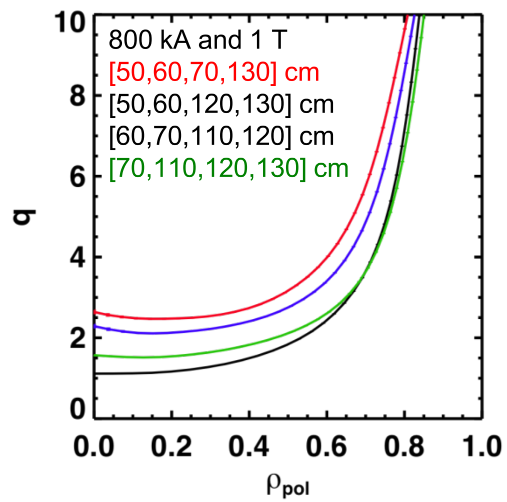
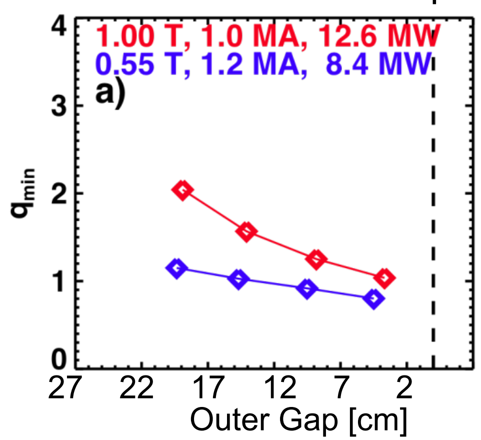
NSTX-U developing a range of profile control actuators for physics studies, scenario optimization for FNSF/Pilot

q-Profile Actuators

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

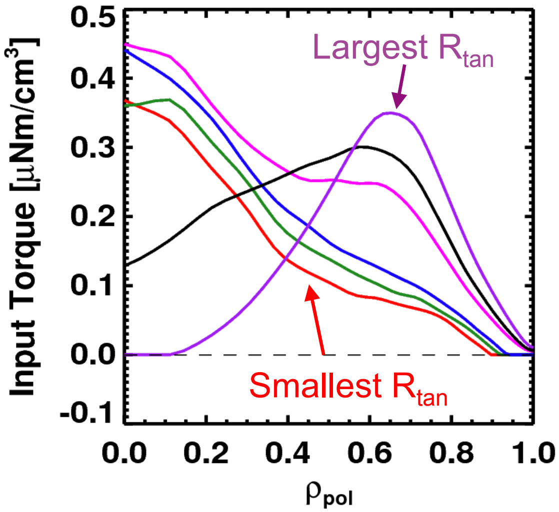


Variations in Outer Gap

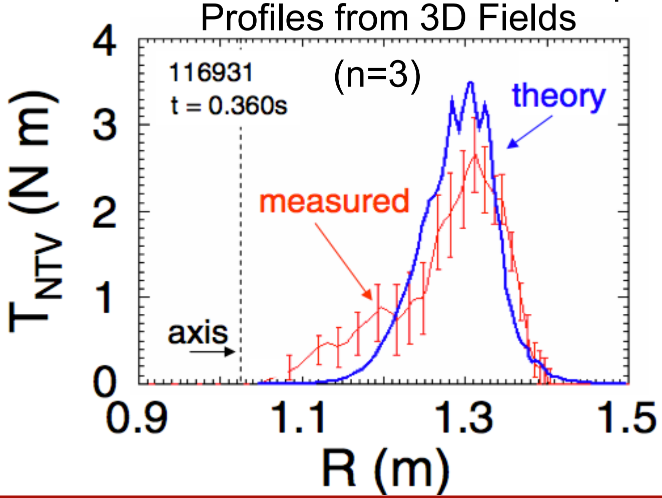


Rotation Profile Actuators

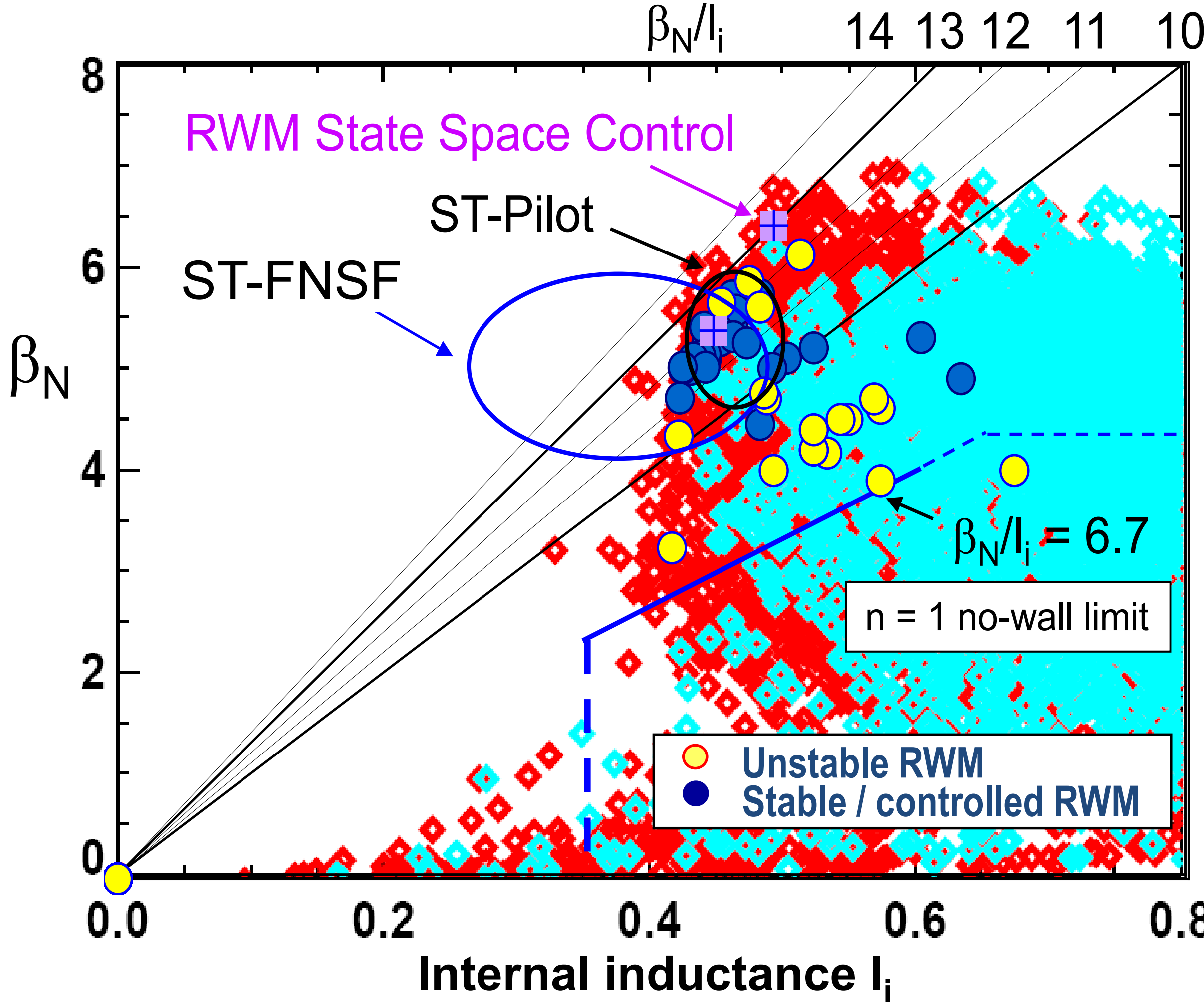
Torque Profiles From 6 Different NB Sources



Measured and Calculated Torque Profiles from 3D Fields



Record β_N and β_N / l_i accessed in NSTX using passive + active resistive wall mode stabilization



- High β_N regime important for self-generated bootstrap current generation
- High β_N / l_i regime important since high $f_{bootstrap}$ has low internal inductance l_i

S. Sabbagh, PRL 2006
J. Berkery, PRL 2011
W. Zhu, PRL 2006

Goal: Achieve fully non-inductive operation at high β_N and high β_T

Kelvin-Helmholtz (KH) instabilities predicted when central sound-speed Mach number $M_s \approx 0.7$-0.8

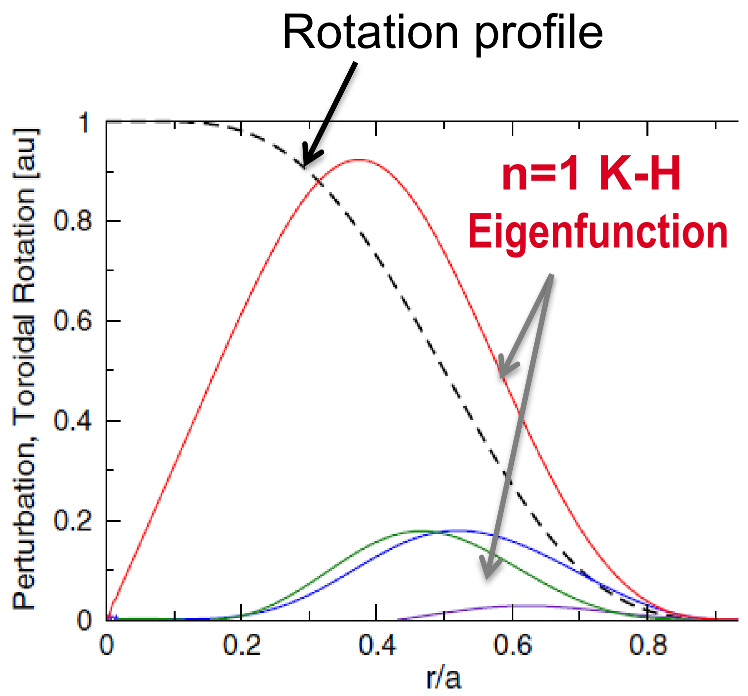


Figure 4. The $n = 1$ $KH_{\parallel}$ eigenfunction when the flow profile (dashed line) is centred at $r/a = 0.5$.

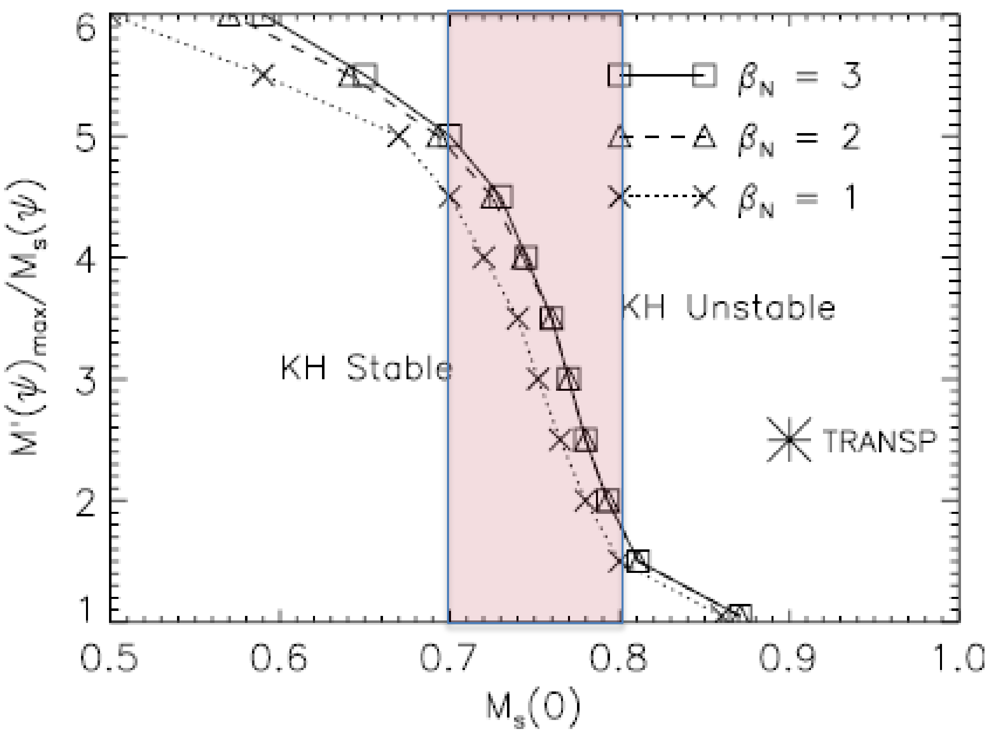
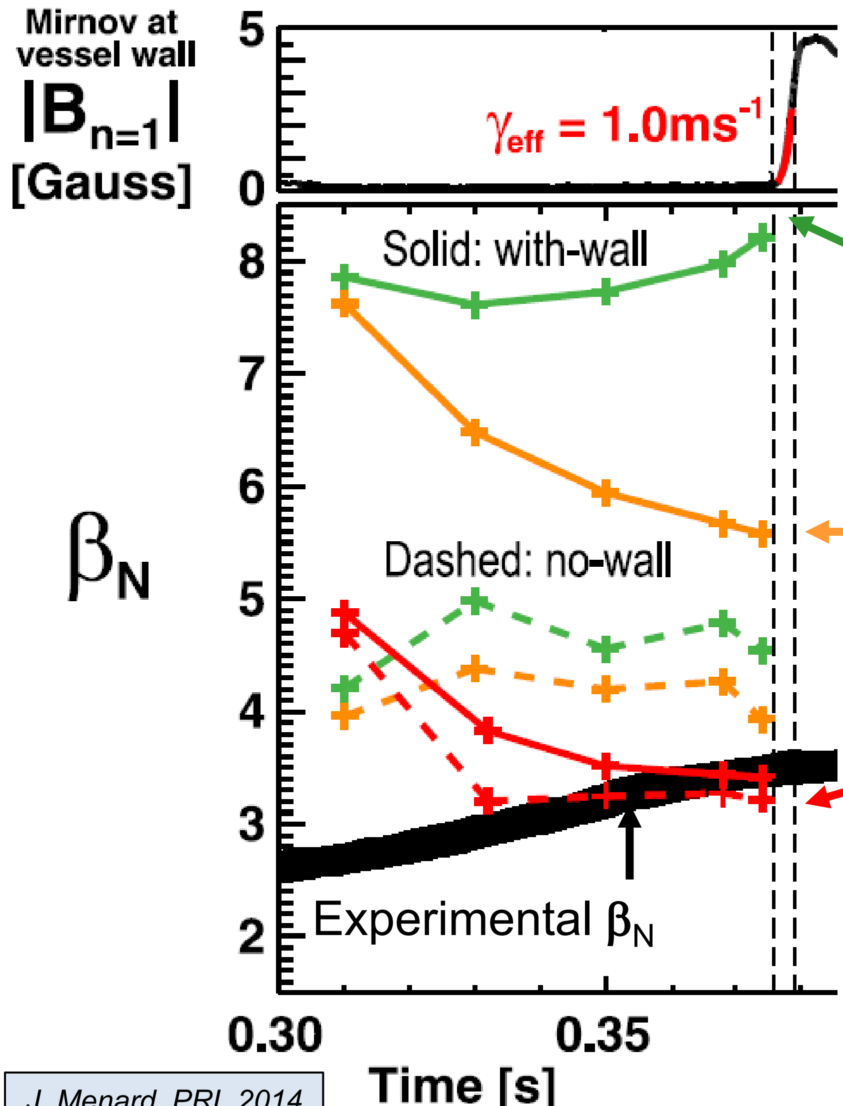


Figure 5. The $KH_{\parallel}$ stability boundary in terms of flow speed and gradient for three different plasma pressures when the safety factor is fixed at $q_{min} \simeq 1.3$. A typical rotation profile from TRANSP predictions is shown for reference, indicating that CTF with fully uni-directional beams is likely to be $KH_{\parallel}$ unstable.

I. Chapman, NF 2012

Rotation shear and fast-ion population both reduce stability of global pressure-driven kink mode



J. Menard, PRL 2014

- Hybrid MHD-drift-kinetic MARS-K consistent with NSTX Ideal Wall Mode onset at high rotation, β_{fast}

Low-rotation fluid with-wall limit is very high → marginal β_N ~ 7-8

Increasing rotation lowers max β_N to ~5.5 at mode onset time

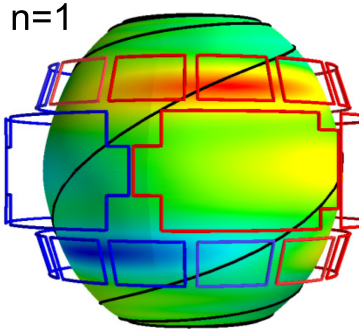
Full kinetic treatment including fast-ions → marginal β_N ~3.5 → most consistent with experiment

Goal: Use 2nd NBI + 3D fields to optimize rotation shear, fast-ion profiles for RWM, IWM

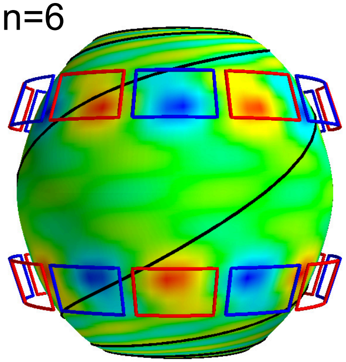
Non-axisymmetric Control Coil (NCC) physics design completed: Optimized for NTV braking using IPECOPT

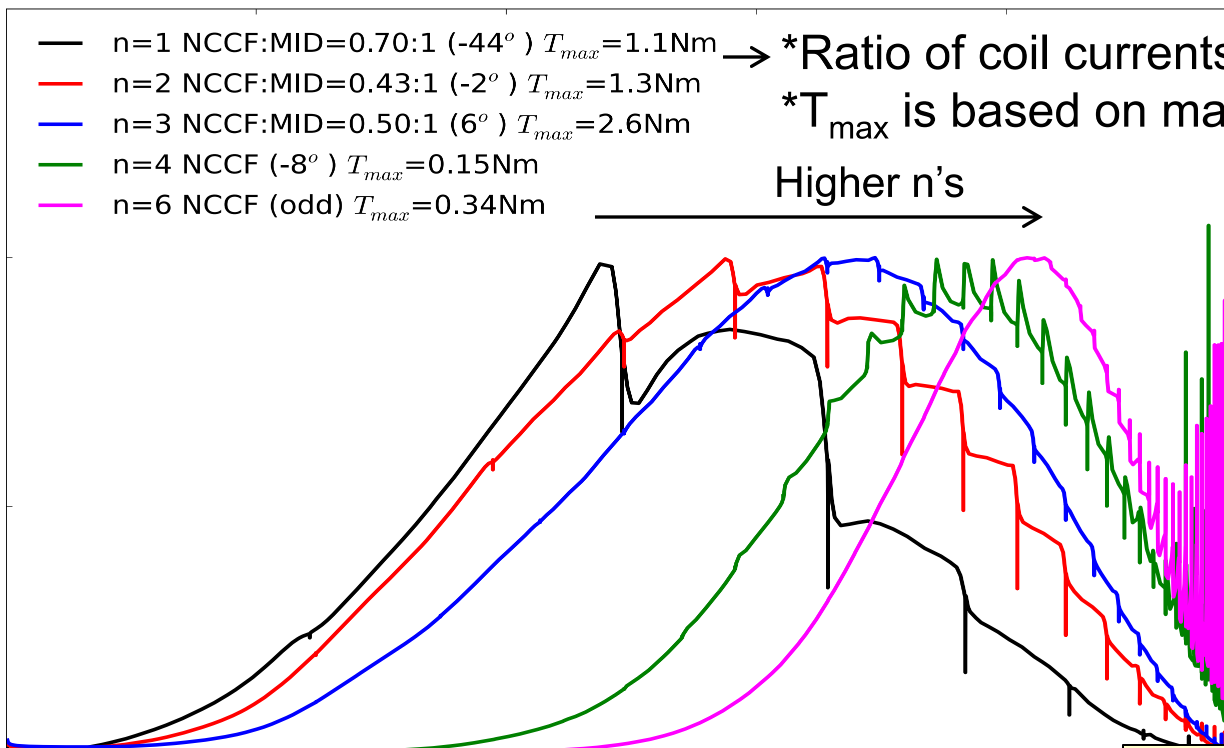
- NCC and midplane coils can be combined to remove the dominant resonant modes up to the second, giving the optimized NTV for core
  - NCC 2x12 provides n=1,2,3,4,6 optimized NTV, and 2x6 provides n=1,2,6
  - Optimized NTV can be used to control local torque with minimized resonance

n=1



n=6





NSTX-U / PPPL Theory Partnership

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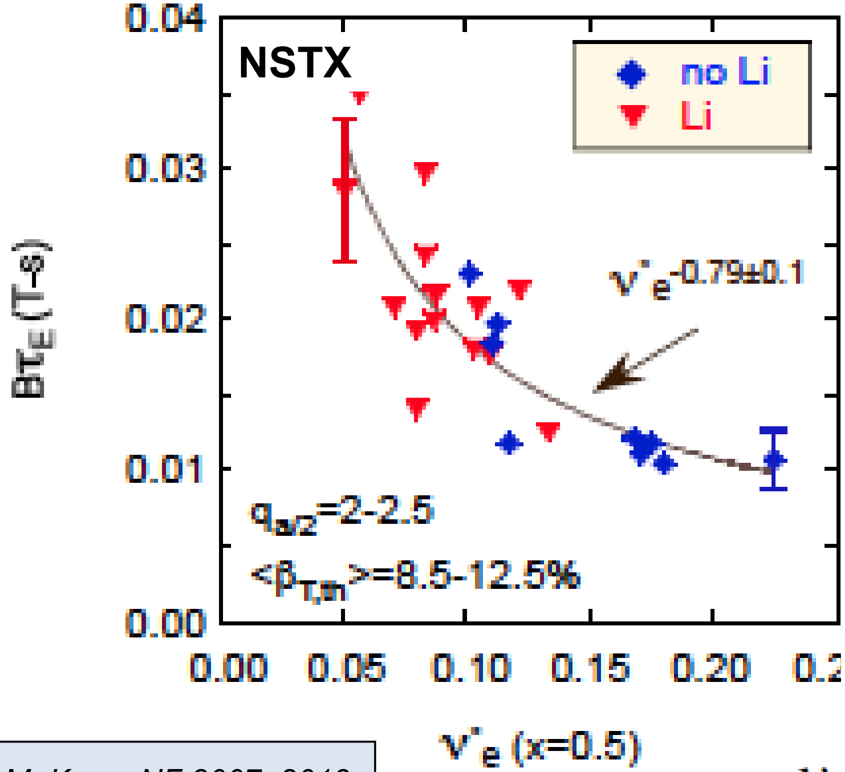
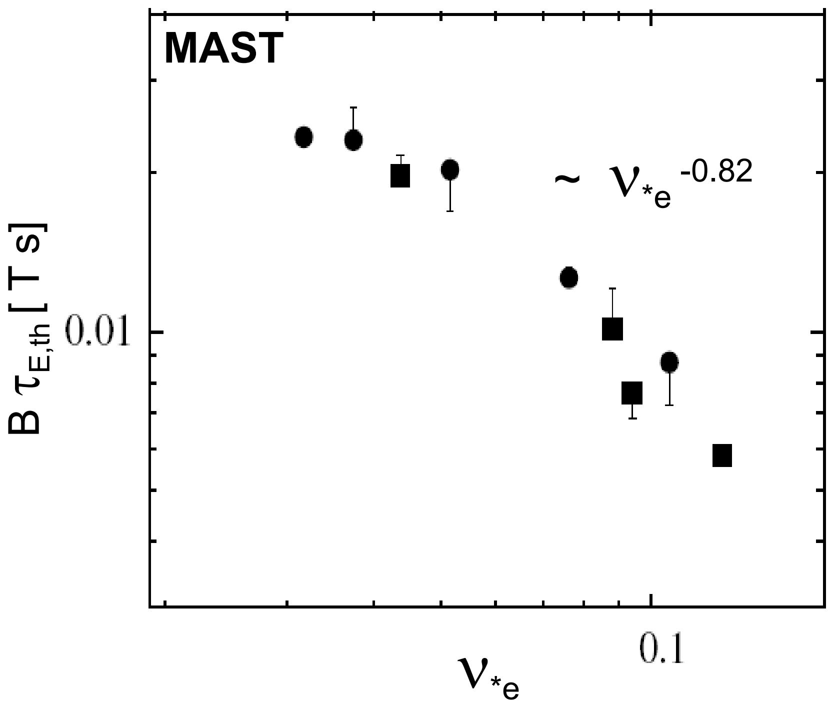
Favorable confinement trend with collisionality, β found

Important implications for future ST FNSF, Demo with lower ν_*

$\tau_{E,\,th} \propto \nu_{*e}^{-0.1}\ \beta^{-0.9}$ **tokamak empirical scaling (ITER 98$_{y,2}$)**

$\tau_{E,\,th} \propto \nu_{*e}^{-0.8}\ \beta^{-0.0}$ **ST scaling (NSTX and MAST)**





S.M. Kaye, NF 2007, 2013

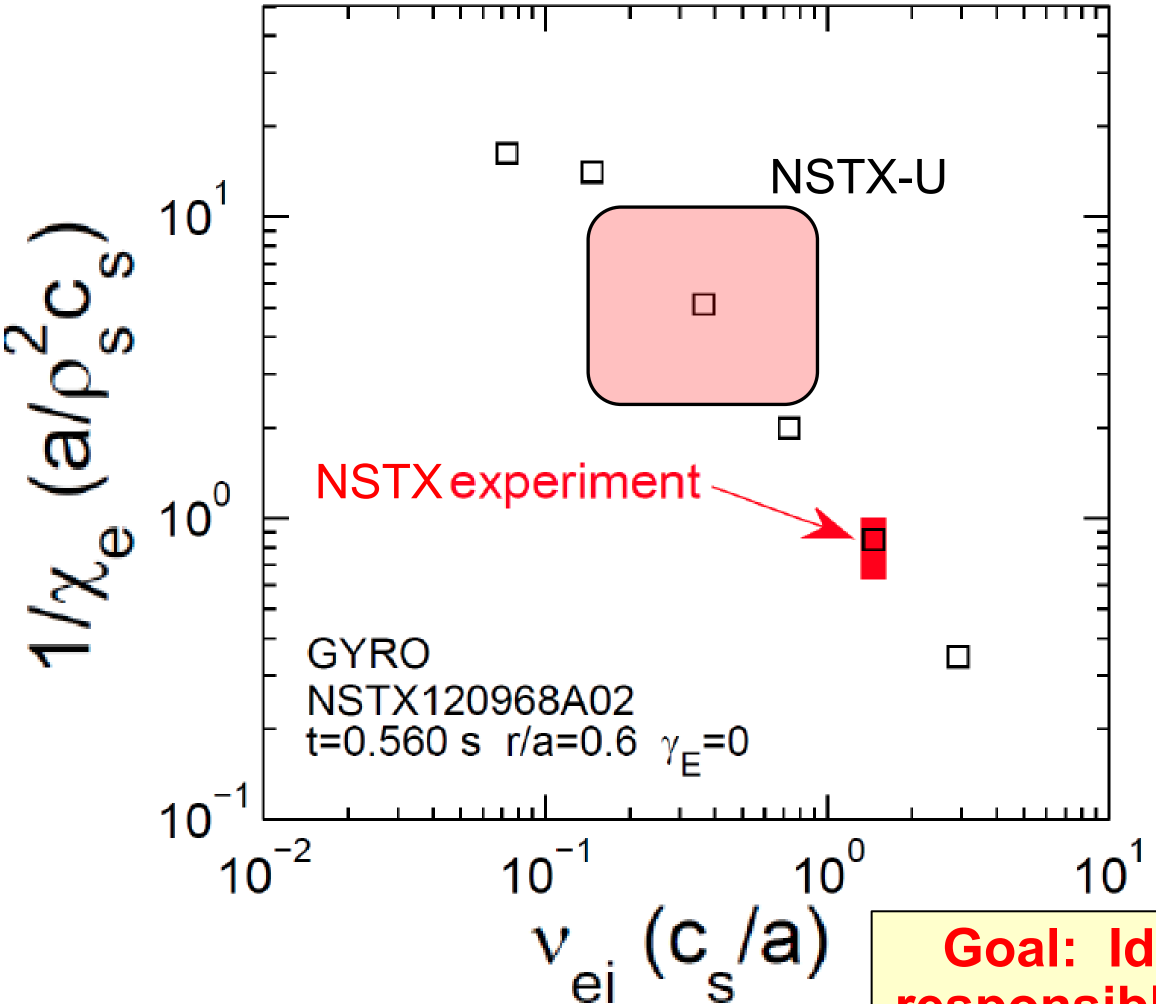
$$\nu_* \propto \bar{n}_e / T^2$$

M. Valovic, NF 2011

Goal: Assess if favorable collisionality scaling continues on NSTX-U/MAST-U

Micro-tearing-driven (MT) transport may explain ST τ_E collisionality scaling

MT-driven χ_e vs. ν_{ei} using the GYRO code



- Micro-tearing growth rate decreases with reduced collisionality in qualitative agreement with the NSTX experiment

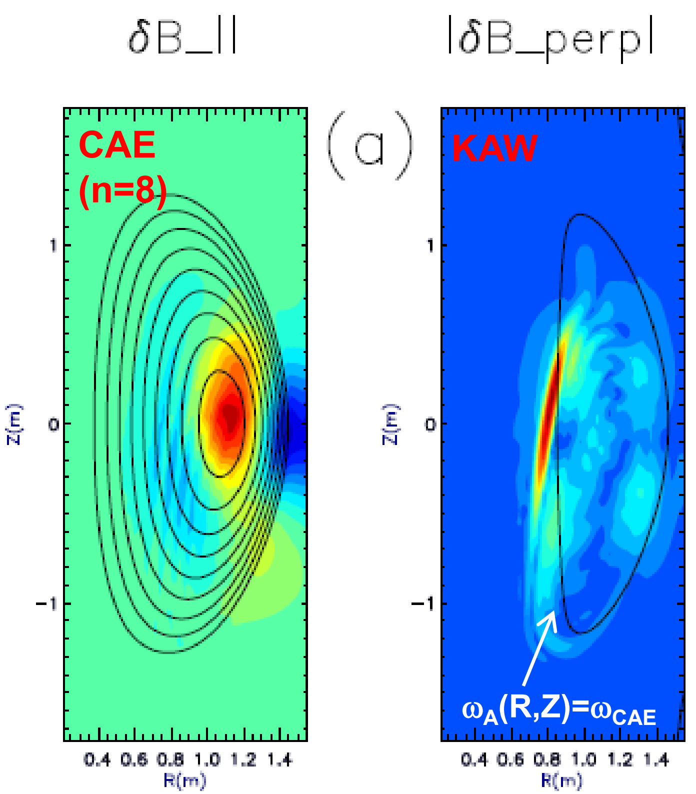
W. Guttenfelder, PoP 2013, PoP 2012, PRL 2011

- New: Dissipative Trapped Electron Mode (DTEM) has similar ν^* scaling (GTS - W. Wang)

Goal: Identify micro-instabilities responsible for collisionality scaling

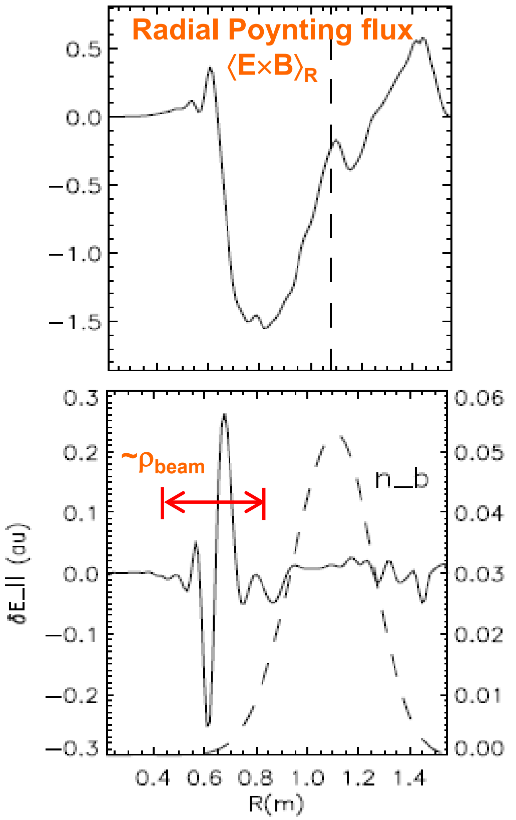
CAE mode-conversion to kinetic Alfvén waves (KAW) predicted to transfer core NBI power to mid-ρ electrons

1) GAE/CAEs cause large χ_e through stochastic orbits (N. Gorelenkov, NF 2010)
2) CAEs also couple to KAW - Poynting flux redistributes fast ion energy near mid-radius, $E_{||}$ resistively dissipates energy to thermal electrons
   – $P_{CAE \rightarrow KAW}$ ~ **0.4 MW** from QL estimate + experimental mode amplitudes
   – $P_{e,NBI}$ ~ **1.7 MW** for ρ <0.3, NBI power deposited on core electrons



Up to 25% of electron heating power transferred to KAW off-axis

HYM code
E. Belova, PRL 2015



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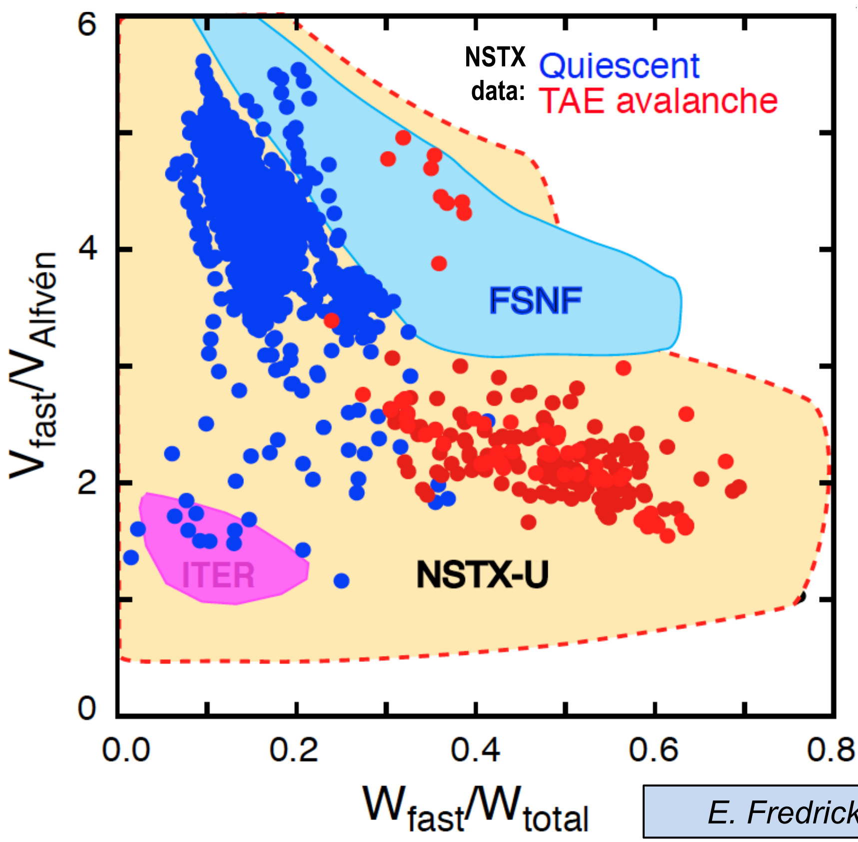
NBI-heated STs excellent testbed for α-particle physics

Alfvenic modes readily accessible due to high $V_{fast} > V_{Alfvén}$

- α-particles couple to Alfvénic modes strongly when $V_\alpha > V_{Alfven} \sim \beta^{-0.5} C_{sound}$
- $V_\alpha > V_A$ in ITER and reactors: condition easily satisfied in ST due to high β
- Fast-particle-driven Alfvén Eigenmodes: Toroidal, Global, Compressional

EP parameter space



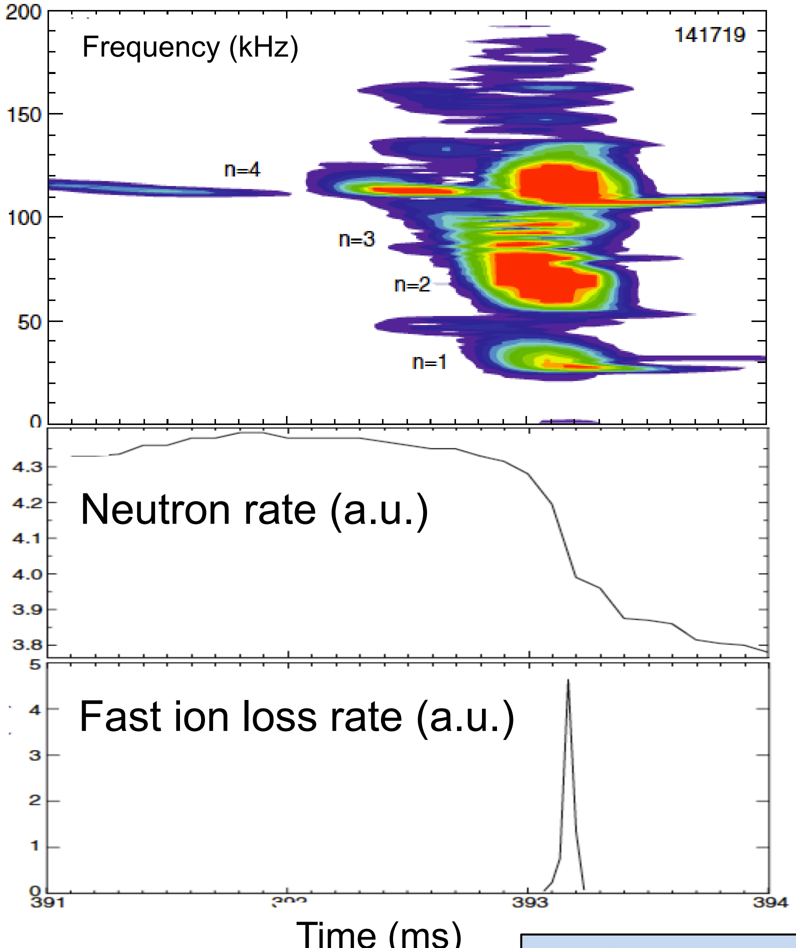
E. Fredrickson, NF 2013

- 2× higher toroidal field → NSTX-U will also explore $V_{fast} < V_A$ regime
- 2nd NBI → much more flexibility in fast-ion distribution function

"TAE avalanche" shown to cause energetic particle loss

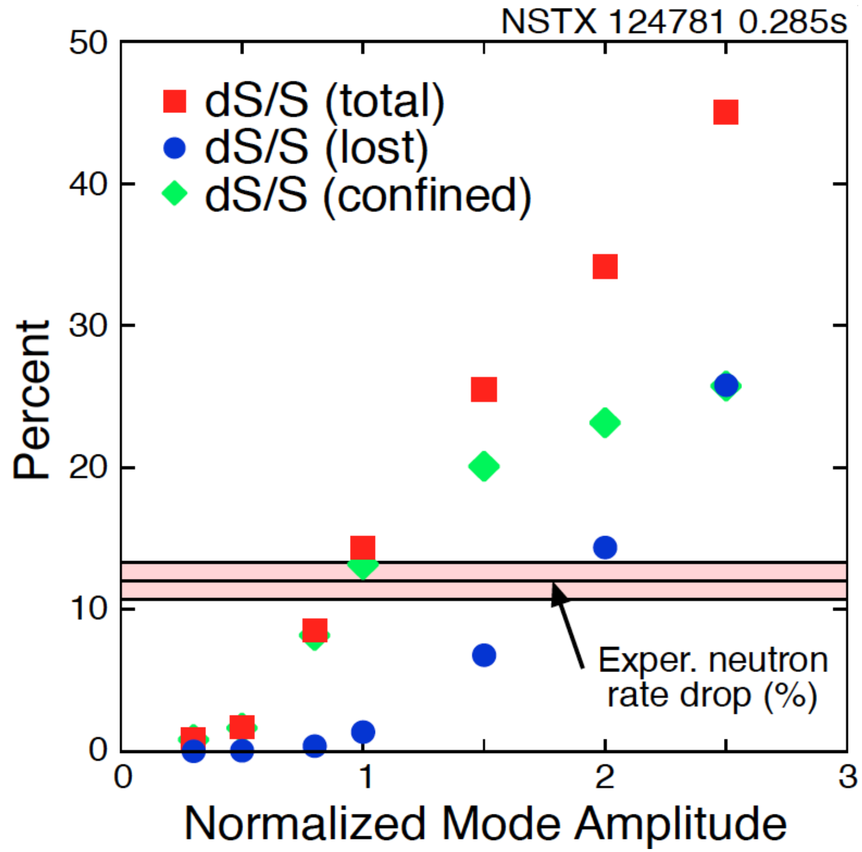
Uncontrolled α-particle loss could cause reactor first wall damage

Multi-mode TAE avalanche can cause significant EP losses as in "sea" of TAEs expected in ITER



D.S. Darrow, NF (2013)

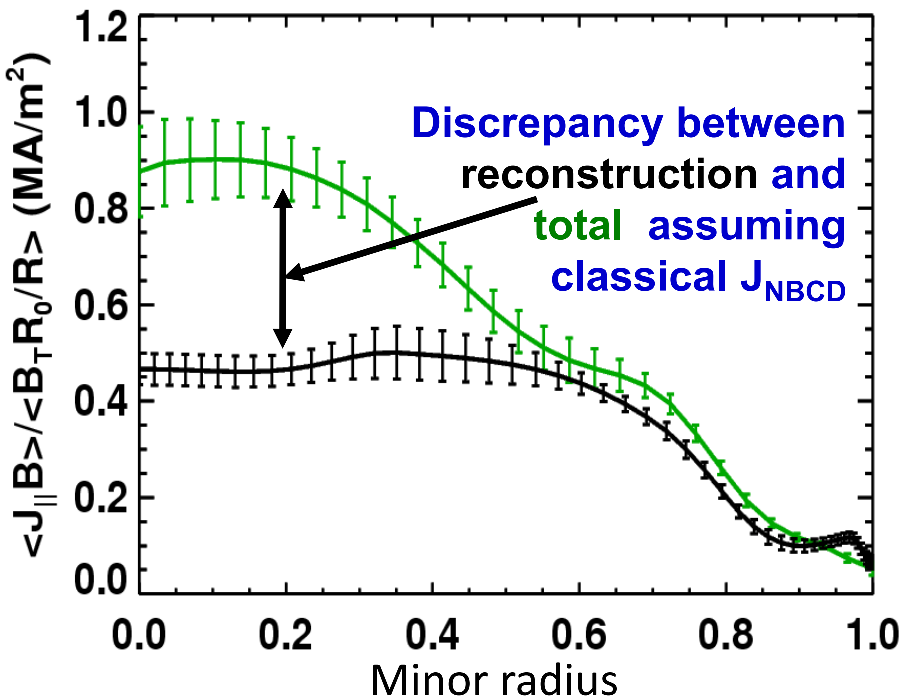
Progress in simulation of neutron rate drop due to TAE avalanche



E. Fredrickson, NF 2013

Goal: Assess if / how TAE “avalanches” impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT?

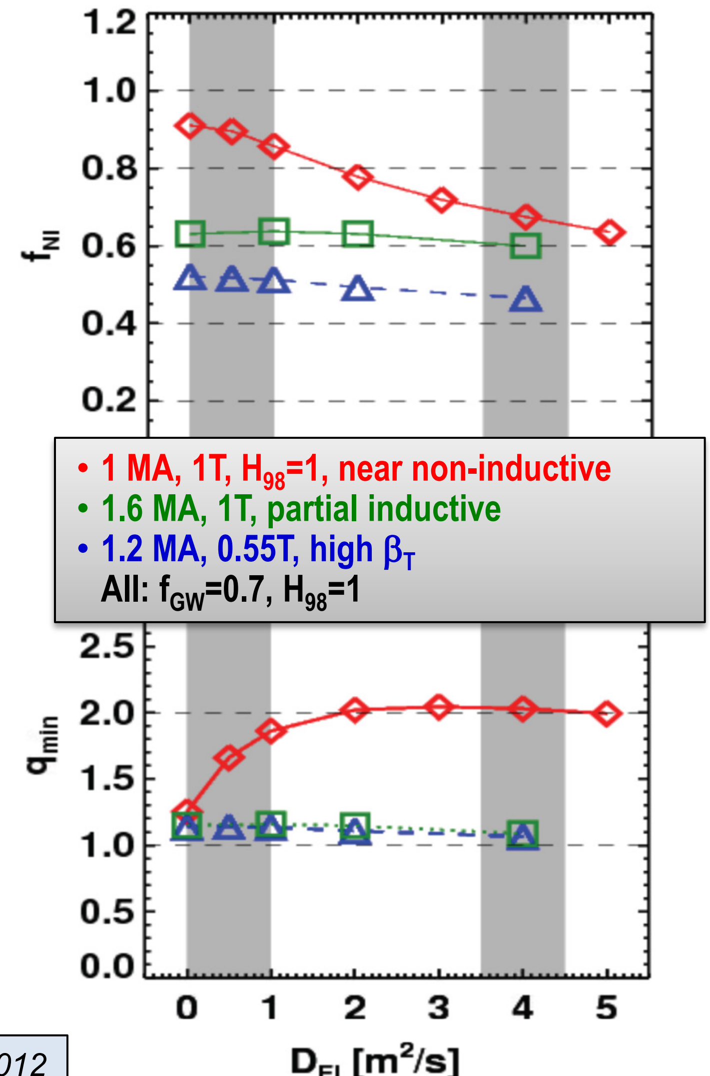
NSTX: rapid avalanches can lead to redistribution/loss of NBI current drive



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

S. Gerhardt NF 2011, NF 2012

NSTX-U TRANSP simulations



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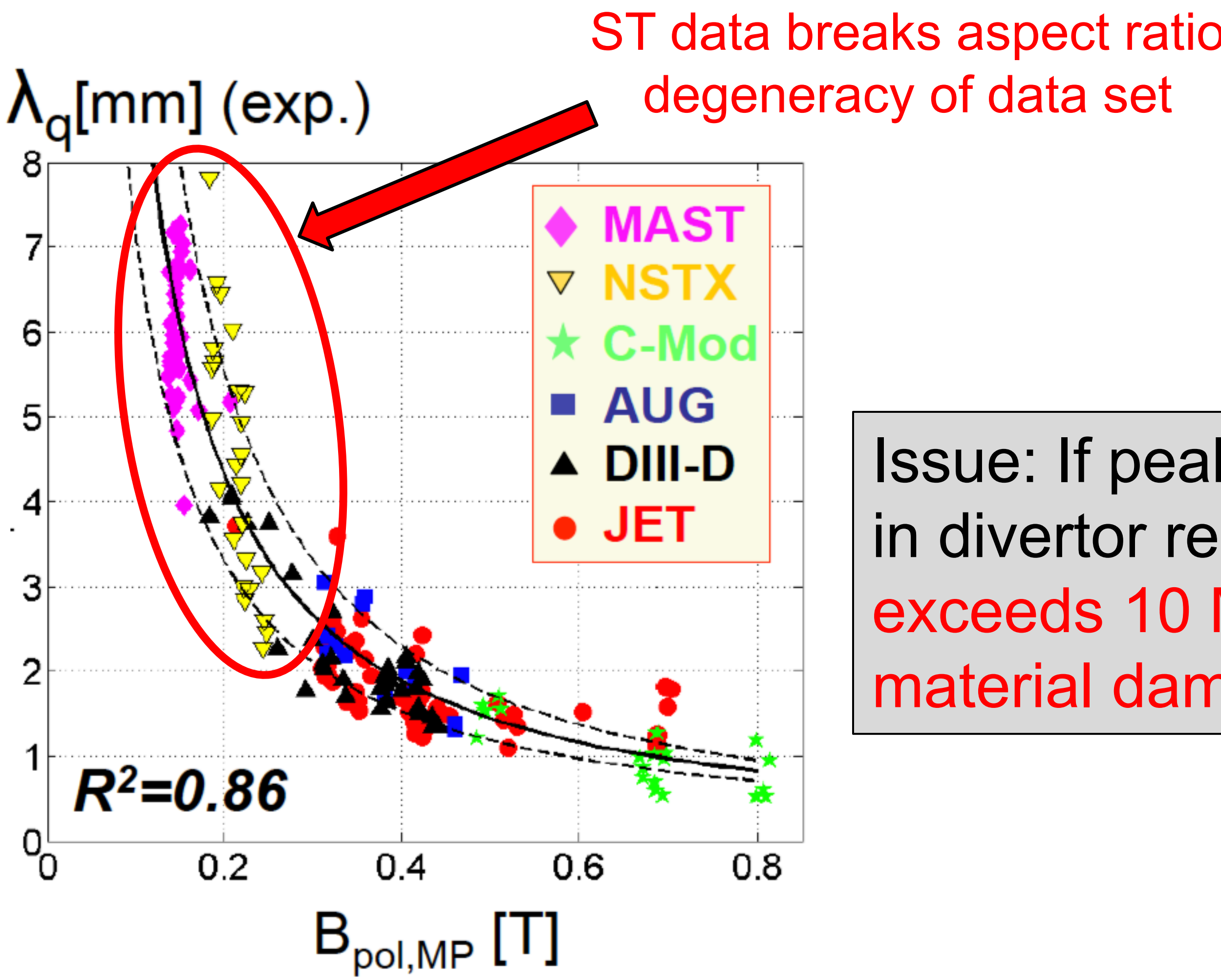
Tokamak + ST data: power exhaust width varies as 1 / $B_{poloidal}$

Will previous ST trend continue at 2× I_P , B_P , B_T, power?

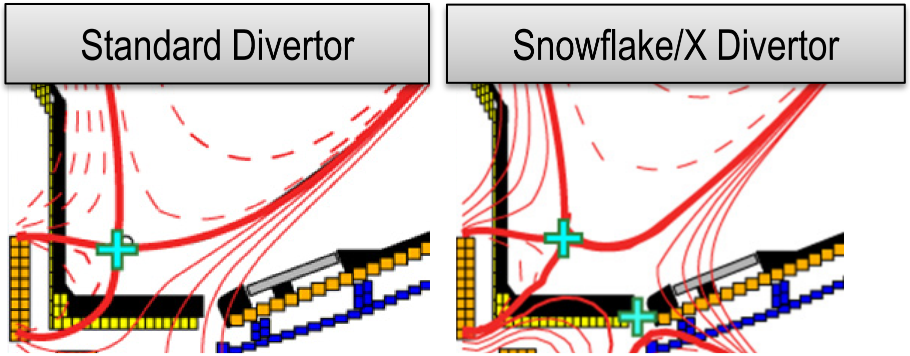


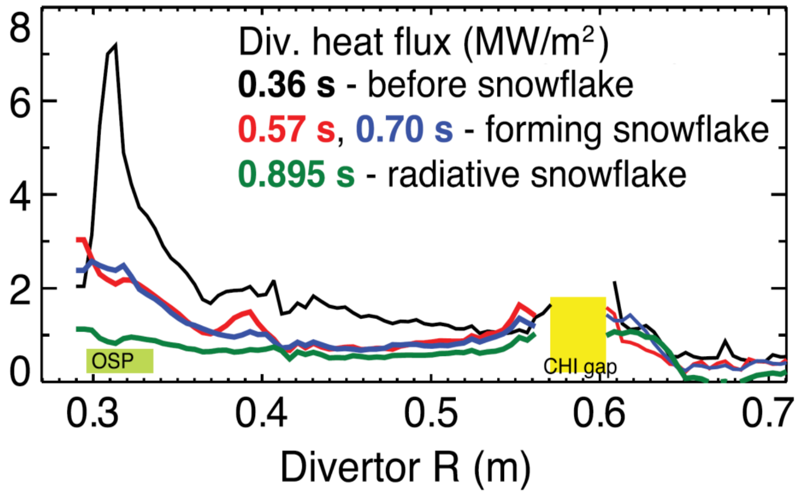
Issue: If peak heat flux in divertor region exceeds 10 MW/m^2 → material damage

Goal: Assess heat-flux width scaling at higher I_P, B_T – different than A=3?

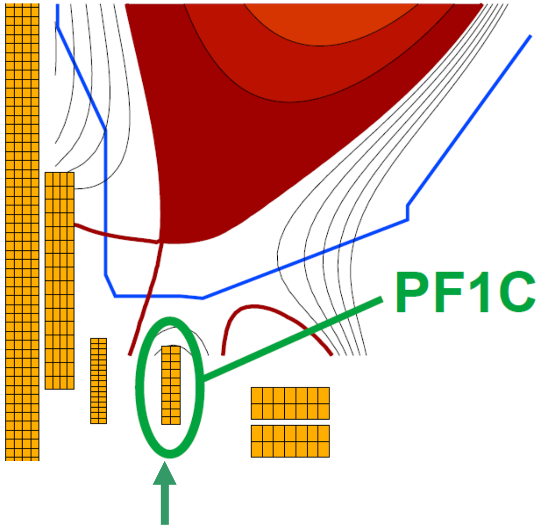
Goal: Test ability of radiation and advanced divertors to mitigate very high heat-fluxes

- NSTX: reduced heat flux 2-4 × via radiation (partial detachment)
- Additional null-point in divertor expands field, reduces heat flux





NSTX-U peak heat fluxes will be up to 4-8 × higher than in NSTX Up to 40-60MW/

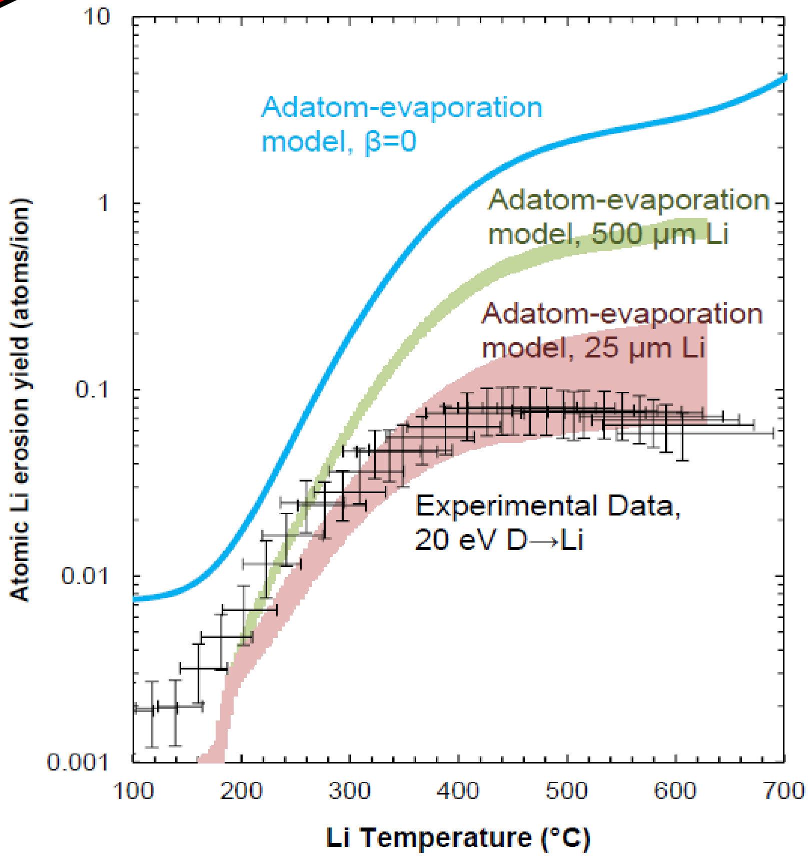


NSTX-U has additional coils for up-down symmetric snowflake/X, improved control

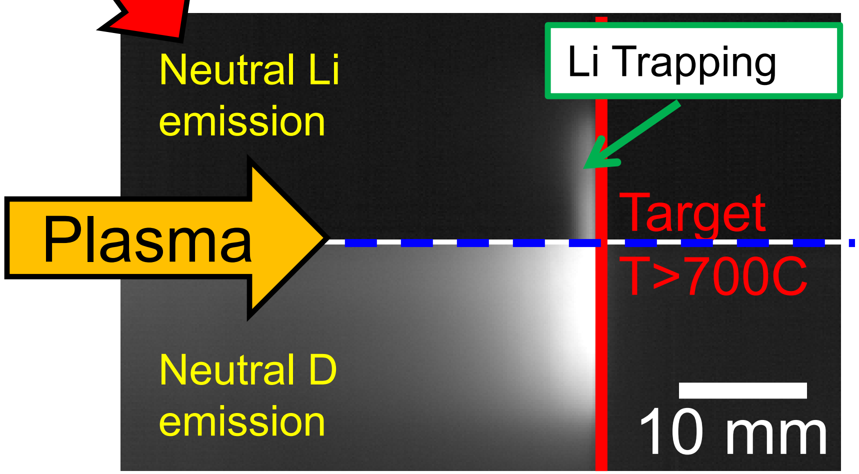
Discovery: Suppressed Li erosion and trapping at target observed in MAGNUM-PSI linear plasma device

- Mixed-material effect reduces erosion due to LiD formation
- Plasma pre-sheath potential well large enough to retain eroded Li
- Significant implications for evaporative cooling concepts

T. Abrams 2014 PhD Princeton U.,
T. Abrams 2015 Nucl. Fusion submitted,
M. Chen 2015 Nucl. Fusion submitted.



Li-I emission, t=2.5s

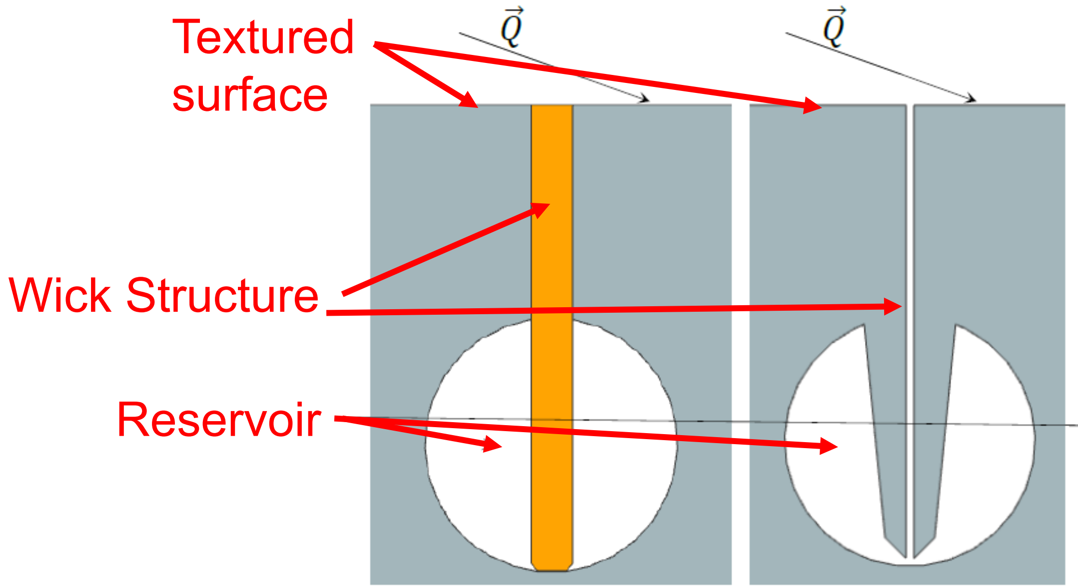


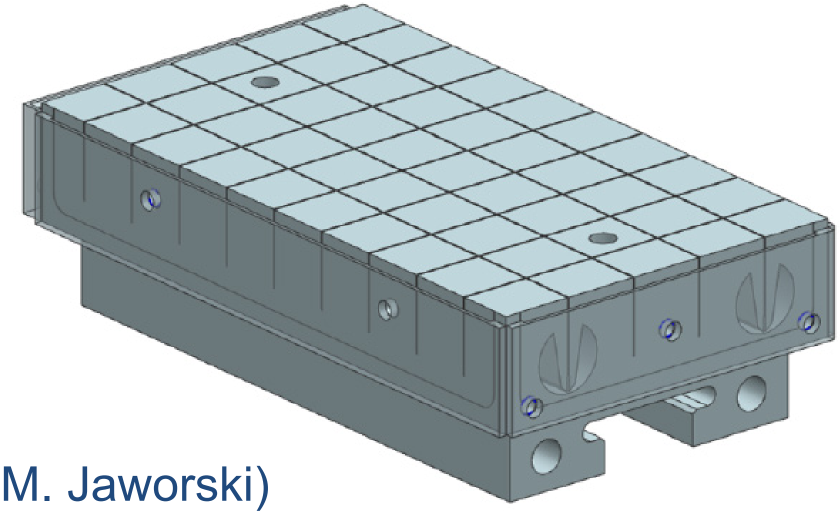
Jaworski, 3rd ISLA, 2013

Goal: Begin to assess high-Z and liquid metal PFCs

Developing pre-filled target integrating Li reservoir w/ high-Z tile

- Similar to Capillary Porous System (CPS) device but applicable as divertor PFC
- Utilizes wire-EDM fabrication to obtain complex geometry
- Emphasizes passive replenishment via capillary action





P. Rindt, TU/Eindhoven Thesis Project (advisor: M. Jaworski)

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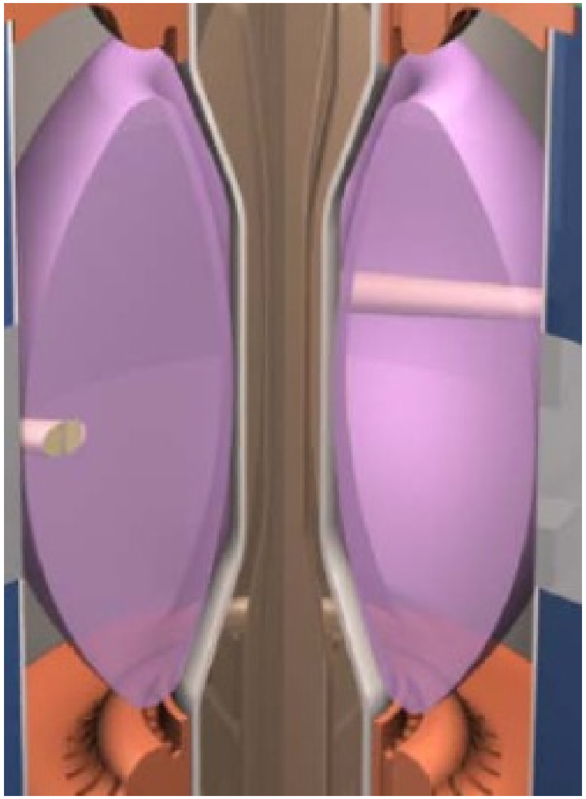
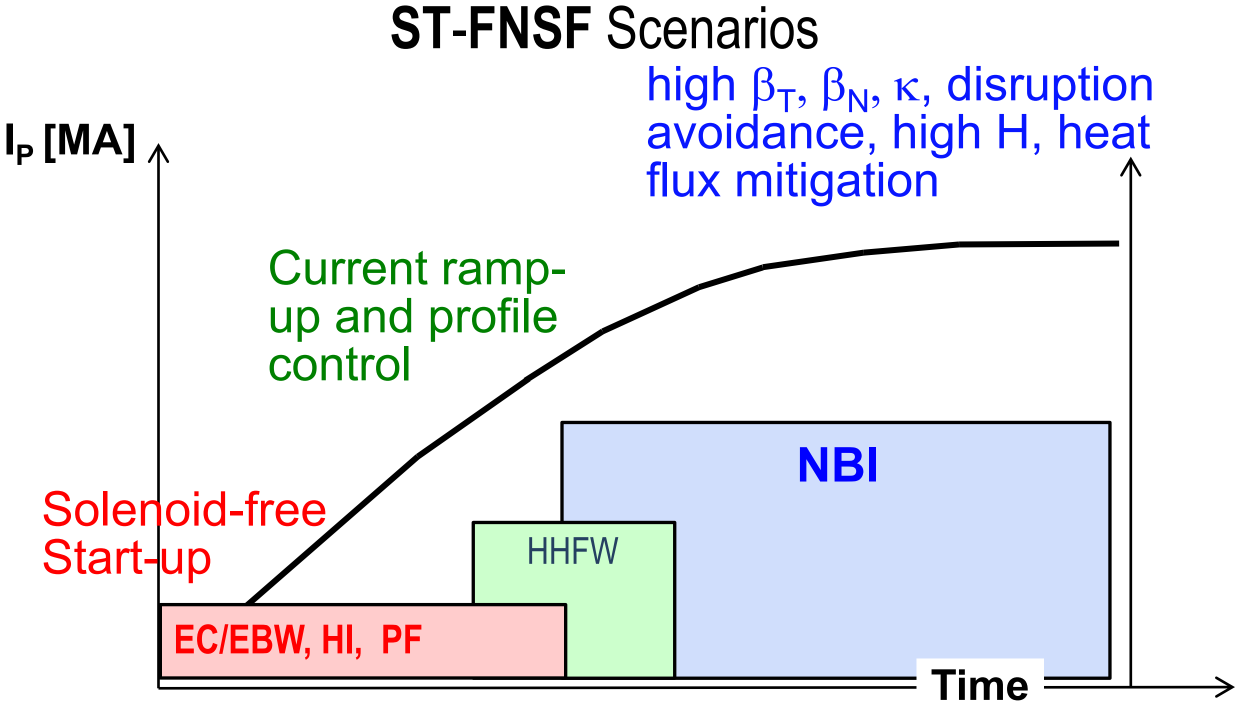
I_P Start-up/Ramp-up Critical Issue for ST-FNSF/Demo

Compact ST-FNSF has no/small central solenoid



~ 1-2 MA of solenoid-free start-up current needed for FNSF

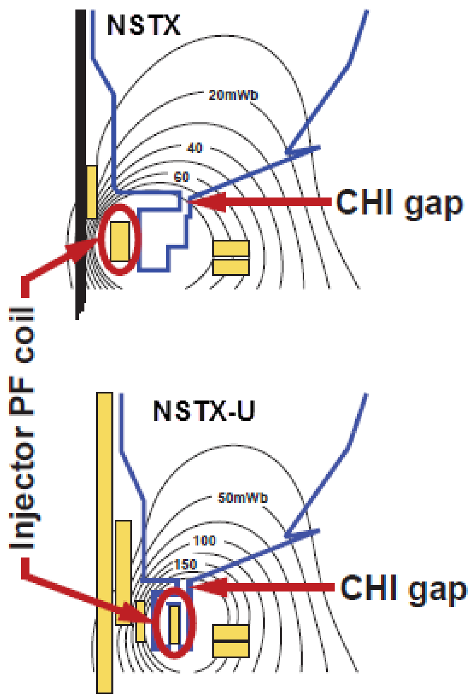


- Two novel techniques for solenoid-free start-up and ramp-up will be investigated
  - RF: ECH/EBW and HHFW
  - Helicity Injection

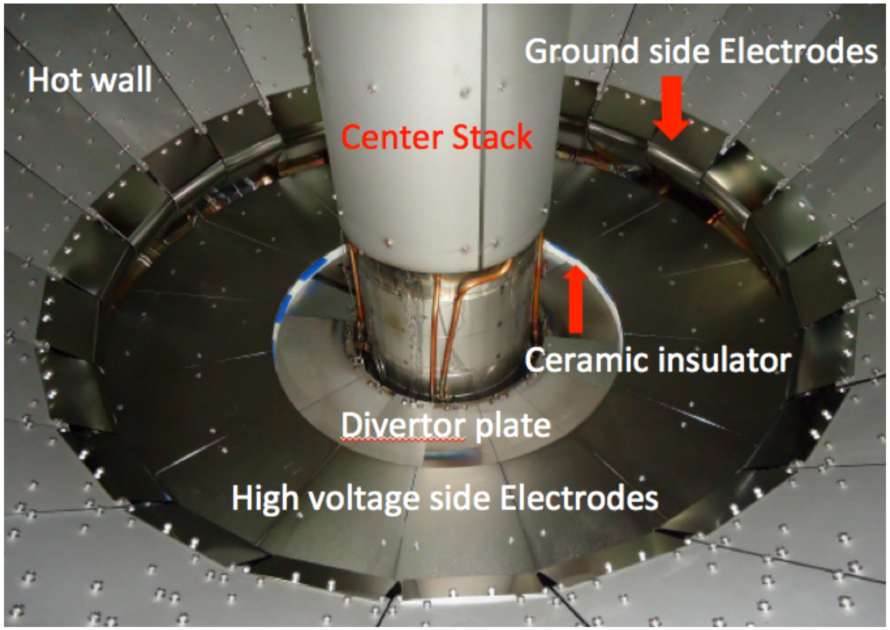
Collaborating with QUEST to explore CHI + ECH solenoid-free start-up in support of ST-FNSF

NSTX-U CHI Start-Up

- **Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX**
- **NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation**



QUEST CHI Implementation showing installed electrodes



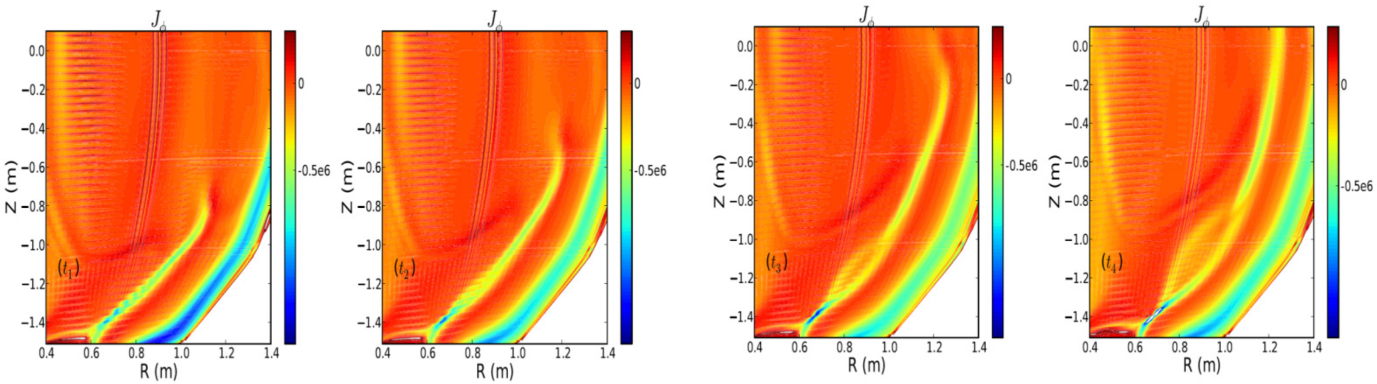
R. Raman, Univ. Washington

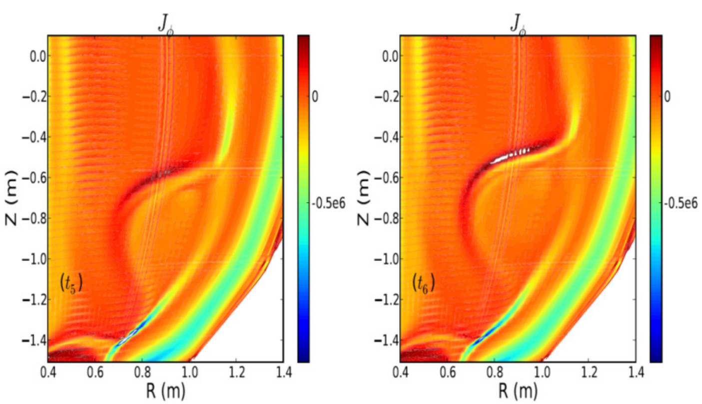
Preparing for CHI experiments on both NSTX-U and QUEST in 2016

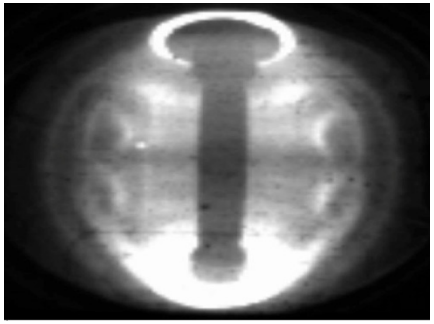
Discovery: Formation of “plasmoids” found in NIMROD simulations of Coaxial Helicity Injection (CHI) start-up

- Sweet-Parker reconnection basis for CHI flux closure
  - Break-up of S-P thin current layer leads to formation of plasmoids, which are inferred in expt
- NIMROD simulations (Ebrahimi et al., PoP 2013, PRL 2015) shown below:

Current sheet shown in the lower half of the device.





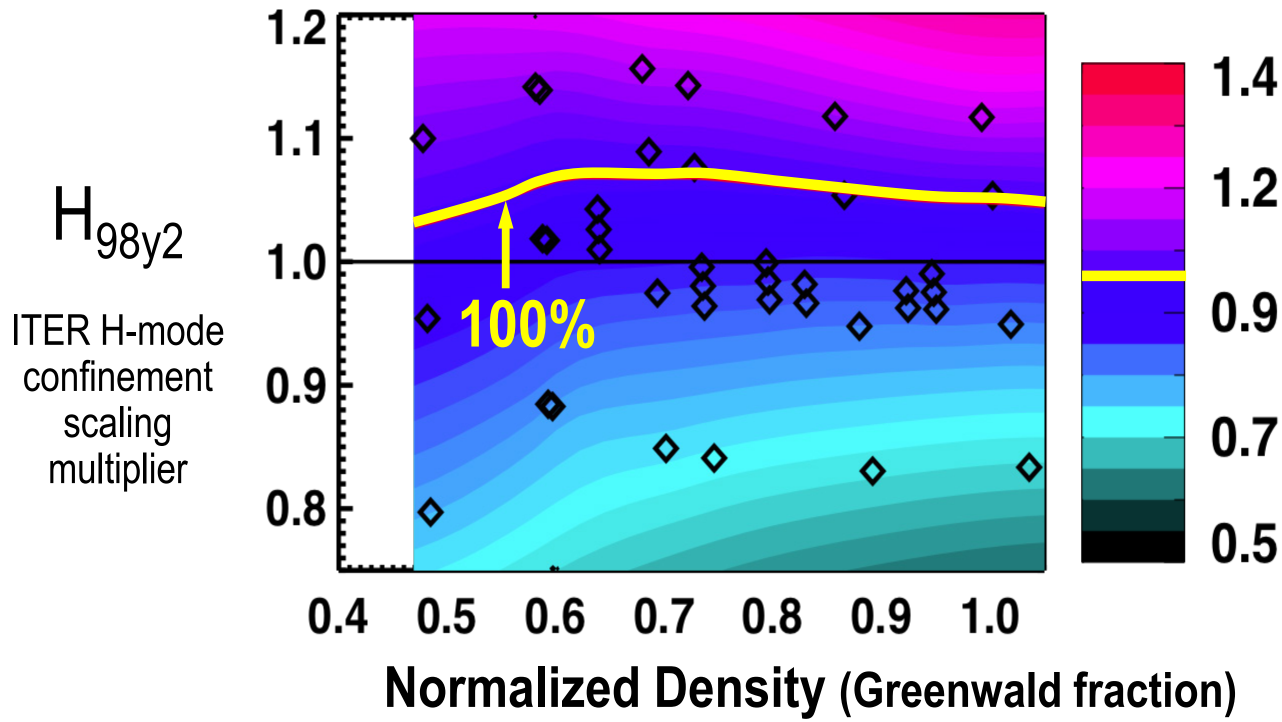


NSTX

Goal: Determine if plasmoids impact CHI start-up extrapolation to FNSF/Pilot

NSTX achieved 70% "transformer-less" current drive
Will NSTX-U achieve 100% as predicted by simulations?

TRANSP Contours of Non-Inductive Fraction



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

Goal: Assess viability and performance of 100% non-inductive ST

Outline

- NSTX-U Mission and Motivation
- NSTX/NSTX-U Research Highlights and Goals
  - Global MHD Stability
  - Transport and Turbulence
  - Energetic Particles
  - Power Exhaust
  - Plasma Start-up
- **Brief Summaries of NSTX-U Research Plans**
- **Summary**

Brief Overview of FY2016-18 NSTX-U Goals

- **FY2016**
  - 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 2^{nd} NBI
- **FY2017**
  - 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
  - First data with 2D high-k scattering, prototype high-Z tiles
- **FY2018**
  - Assess causes of core electron thermal transport
  - Test advanced q profile and rotation profile control
  - Assess CHI plasma current start-up performance
  - Study low-Z and high-Z impurity transport
    - Possibly test/compare pre-filled liquid-Li tiles/PFCs vs. high-Z solid

NSTX-U 5 year goal: Develop physics/scenario understanding needed to assess ST viability as FNSF/DEMO, support ITER

	2016	2017-18	2019	2020	2021
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	5 – 6		
ν^* / ν^* (NSTX)	0.6	0.4	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	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)		

NCC · **Cryo** · **ECH / EBW** (introduced in 2019)

→ Inform choice of FNSF/DEMO **aspect ratio and divertor**

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

NSTX-U 5 year goal: Establish ST-FNSF physics/scenarios
10 year goal: Integrate high-performance core + metal walls

2016-2020	2021-2025

Establish ST physics / scenarios:

- Non-inductive start-up, ramp-up
- Confinement vs. β , collisionality
- Sustain high β with advanced control
- Mitigate high heat fluxes
- Test high-Z divertor, Li vapor shielding

Inform choice of FNSF configuration:

- Lower A or higher A?
- Standard, snowflake, Super-X (MAST-U)?

High-performance + metal walls

- Convert all PFCs from C to high-Z
- Static → flowing Li divertor module(s), full toroidal flowing Li divertor, high T_{wall}
- 5s → 10-20s for PFC/LM equilibration
- Assess ST with high-Z, high-Z + Li

Inform choice of FNSF / DEMO plasma facing materials:

- High-Z acceptable? or need high-Z + Li?
- Assess for both divertor and first-wall

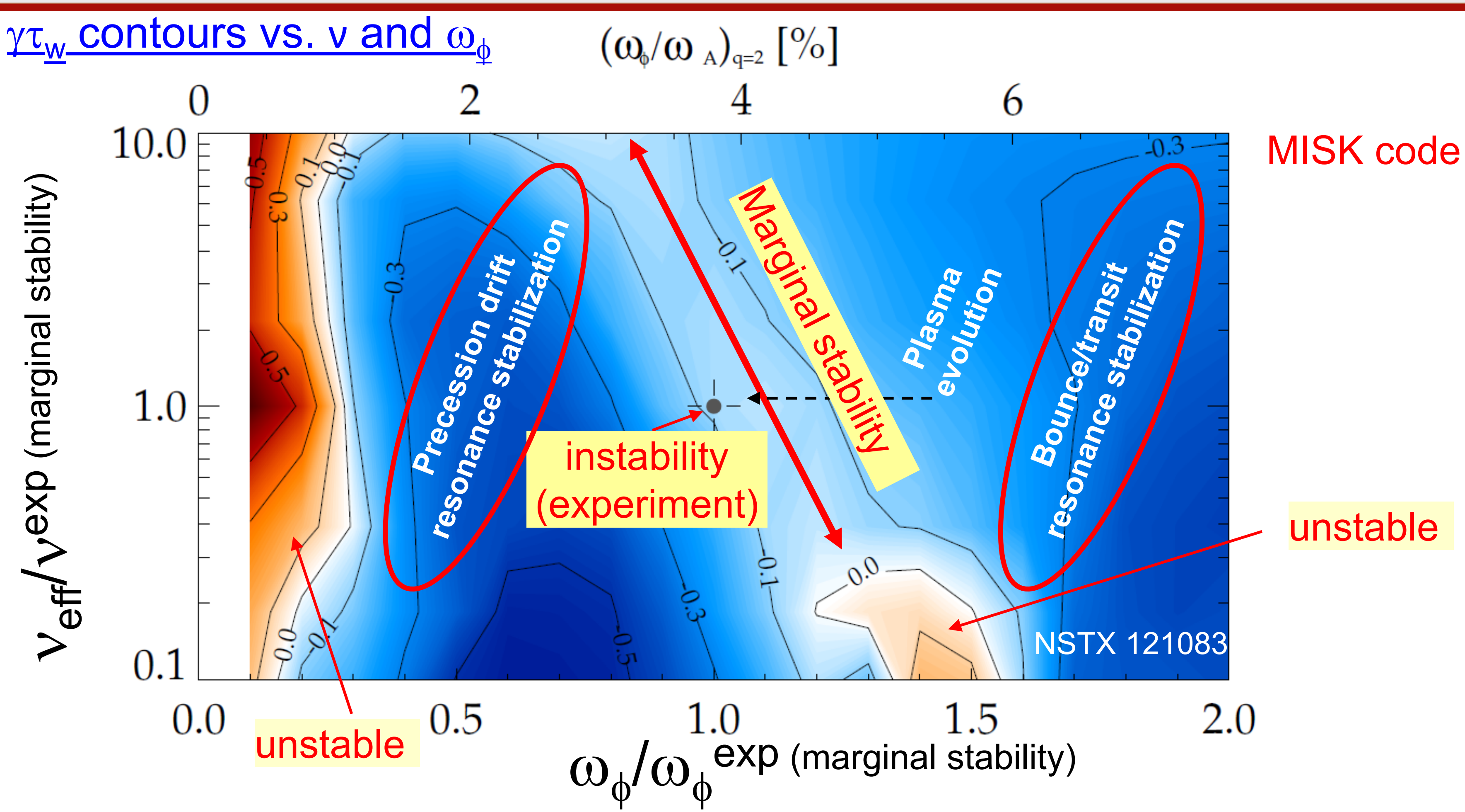
Summary

- NSTX-U will provide many opportunities to study toroidal confinement physics in novel regimes:
  - Low aspect ratio, strong shaping, high β, low collisionality
  - Access strong fast-ion instability drive, high rotation
  - Advanced divertors, high-Z walls, lithium walls
- NSTX-U/ST results will support ITER, develop PMI solutions, and inform optimal divertor configuration and aspect ratio for next-step devices
- Physics research to begin in December 2015

Thank you!   Any questions?

Backup

Kinetic RWM theory consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality

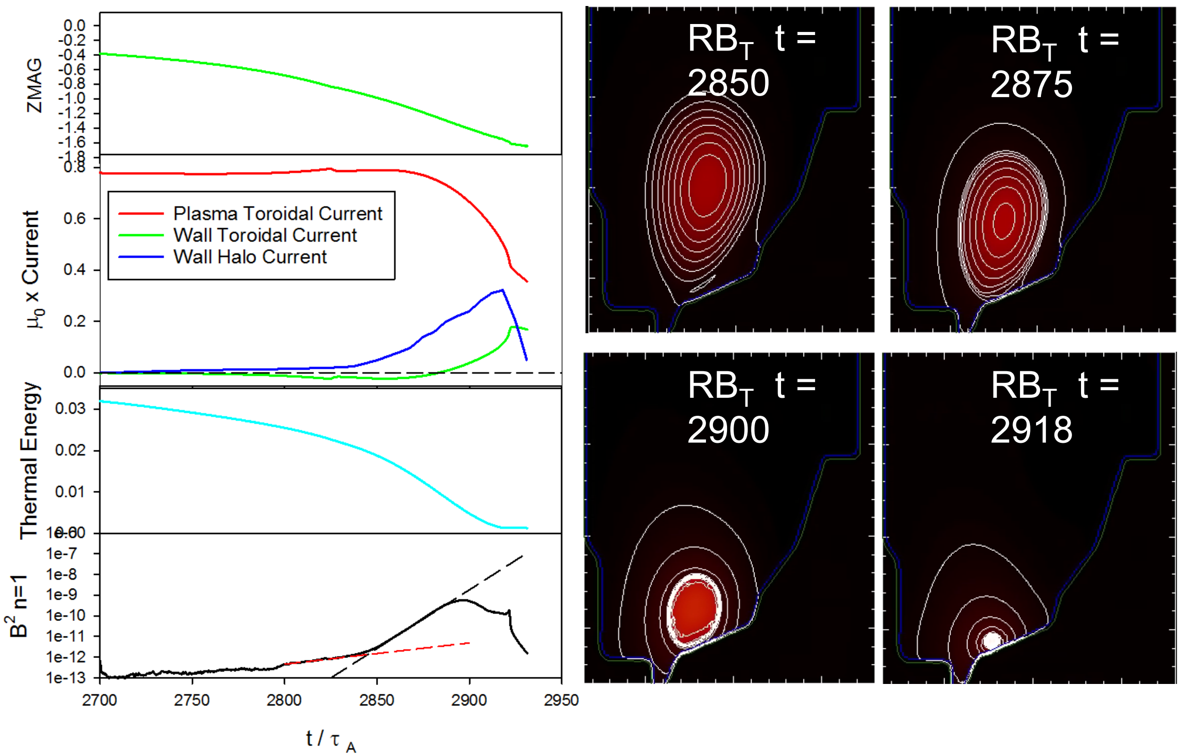


- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

S. Sabbagh, NF 2010
J. Berkery, PRL 2010

M3D-C1 modeling of Vertical Displacement Events (VDEs) has been extended to 3D

- Implemented arbitrary thickness resistive wall, giving 3 region computational space (vacuum, RW, plasma)
- 3D modeling of NSTX VDE with realistic wall resistivity (Jardin, Ferraro)
  - n=1 growth slow during drift (RWM?), growth then accelerates (external kink?)
  - Halo currents begin to form when plasma makes contact with vessel



NSTX Discharge 132859

- Disruption phase 2700 < t < 2950
- **Contours of RB$_T$ show halo currents**

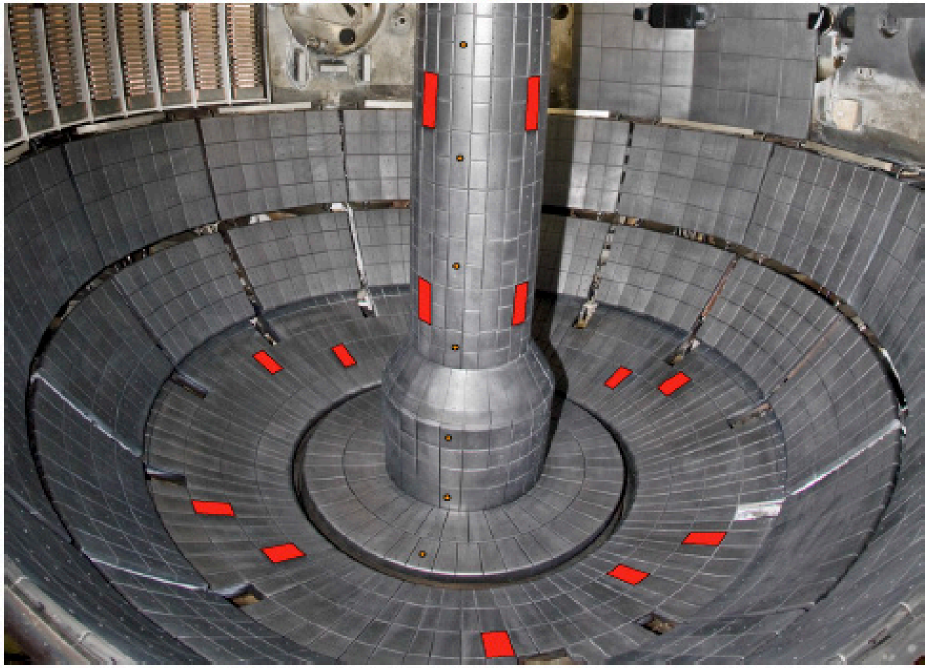
NSTX-U / PPPL Theory Partnership

M3D-C[1] with resistive wall capability will be used to determine optimal placement of new halo sensors

- Dynamics of halo currents and forces critical for ITER: particular concern are halo current asymmetries and rotation
- New sensors will measure halo currents, B-fields and JxB forces in NSTX-U
- Critical theoretical issues: (i) role of boundary conditions (ii) halo current distributions in 3D conducting structures (new post-doc D. Pfefferle)

Planned NSTX-U Base Configuration

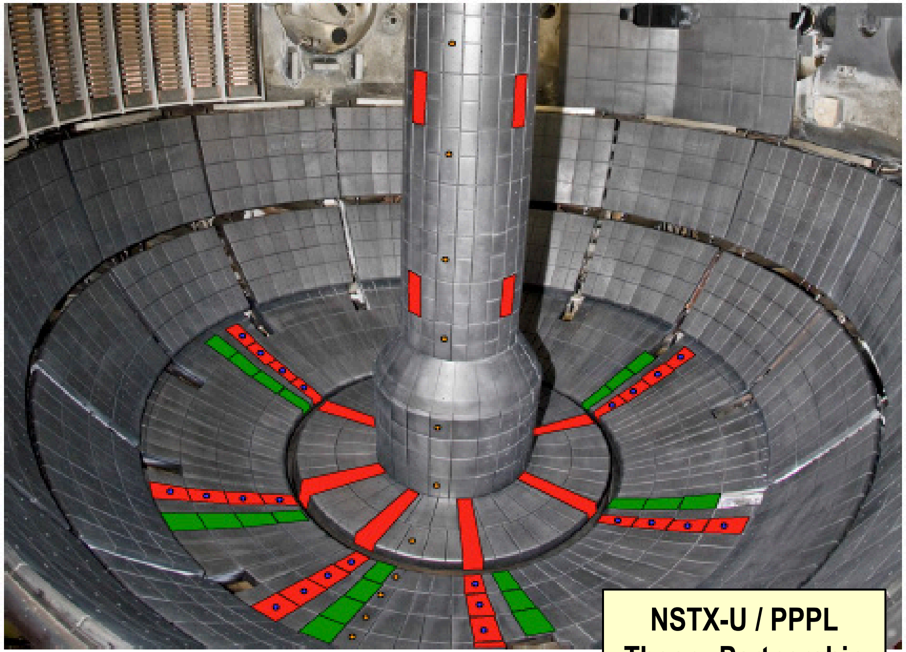
Normal Current Tiles   Single Axis B Sensors



R15/16-3, 17-2, 18-2, 2016 JRT

Potential NSTX-U Expanded Configuration   Tangent Current Tiles

Normal Current Tiles   Single Axis B Sensors   Multi-Axis B sensors



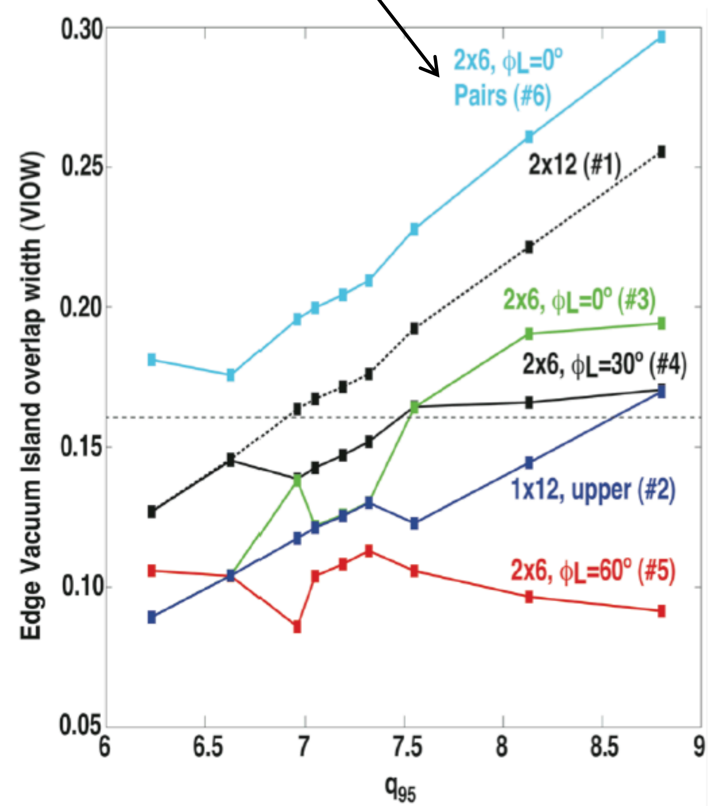
NSTX-U / PPPL Theory Partnership

Study of RMP characteristics with NCC extended with TRIP3D (T. Evans, GA) – 2x12 NCC (and 2x7) favorable for RMP

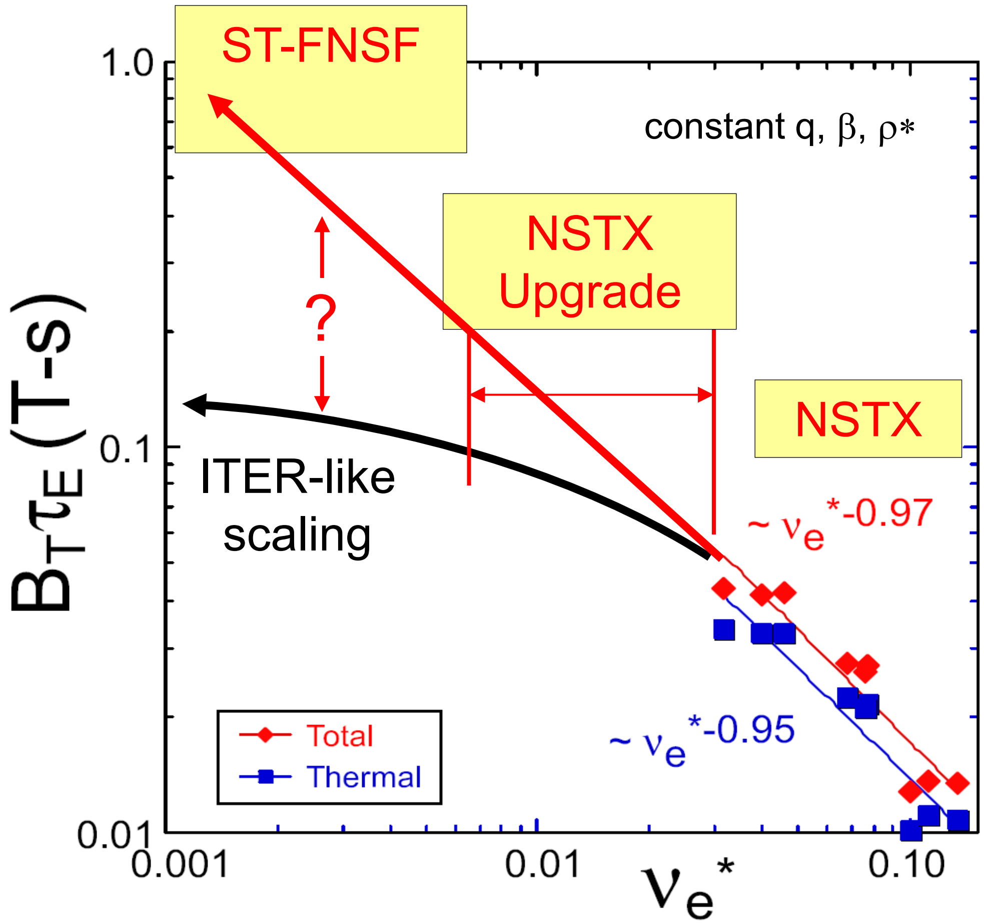
- Vacuum Island Overlap Width (VIOW) analysis shows full NCC 1kAt can produce sufficient VIOW in a wide range of q_{95}, but partial NCC needs more currents with low q_{95} targets
  - Also shows 2x7, with “one” more additional array upon partial NCC can provide the greater VIOW by toroidal coupling (n=2,4,9)

NCC Configurations Used for the plots Shown in Figures 1 and 2

#	Description, Color	NCC Configuration Layout
1	2x12 **dashed black line**	+ + - - + + - - + + - - + + - - + + - - + + - -
2	1x12, upper **solid blue line**	+ + - - + + - - + + - - □ □ □ □ □ □ □ □ □ □ □ □
3	2x6, ϕ_L=0° **solid green line**	+ □ - □ + □ - □ + □ - □ + □ - □ + □ - □ + □ - □
4	2x6, ϕ_L=30° **solid black line**	+ □ - □ + □ - □ + □ - □ □ + □ - □ + □ - □ + □ -
5	2x6, ϕ_L=60° **dashed red line**	+ □ - □ + □ - □ + □ - □ - □ + □ - □ + □ - □ + □
6	2x7, ϕ_L=0° Pairs **solid light blue line**	+ □ - □ + - □ + □ - □ □ - □ + □ - + □ - □ + □ □



Major motivation for NSTX/MAST Upgrades: Determine if confinement trend continues, or is like conventional A



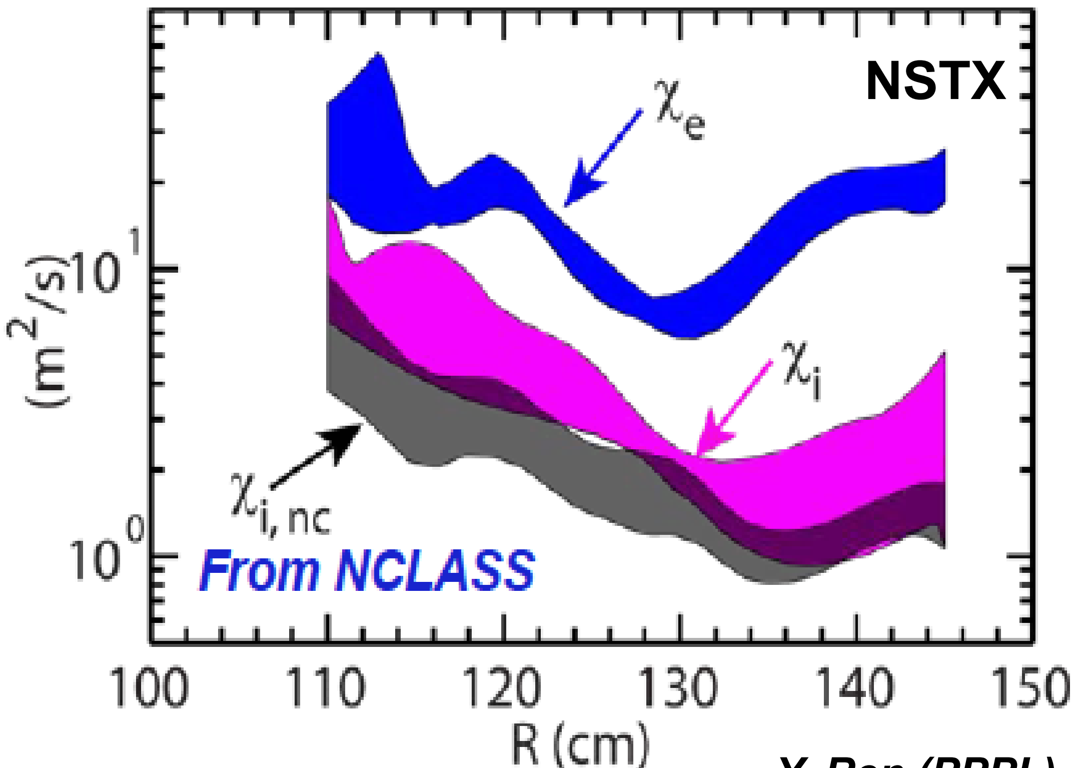
Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

Favorable confinement results could lead to more compact ST reactors

High confinement multiplier H needed for compact ST

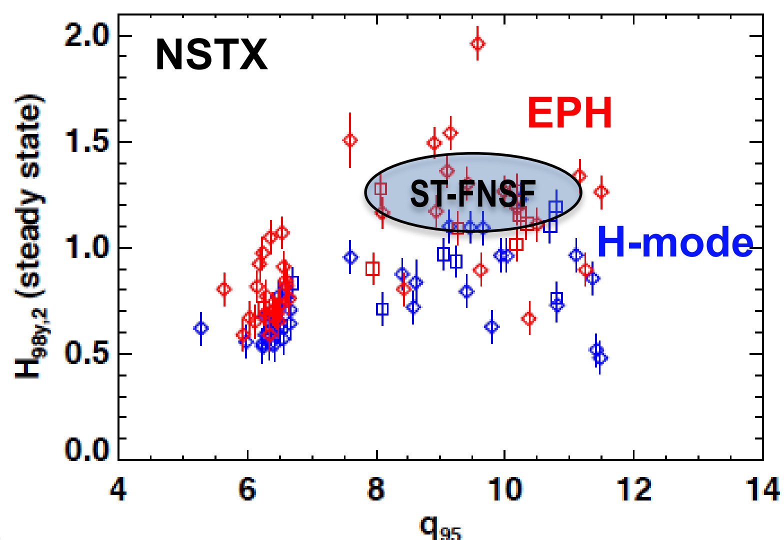
Fusion gain Q depends strongly on "H", $Q \propto H^{5\text{-}7}$

- Ion energy transport in H-mode ST plasmas near neoclassical level due to high shear flow and favorable curvature
- Electron energy transport anomalous (as for all tokamaks)



Y. Ren (PPPL)

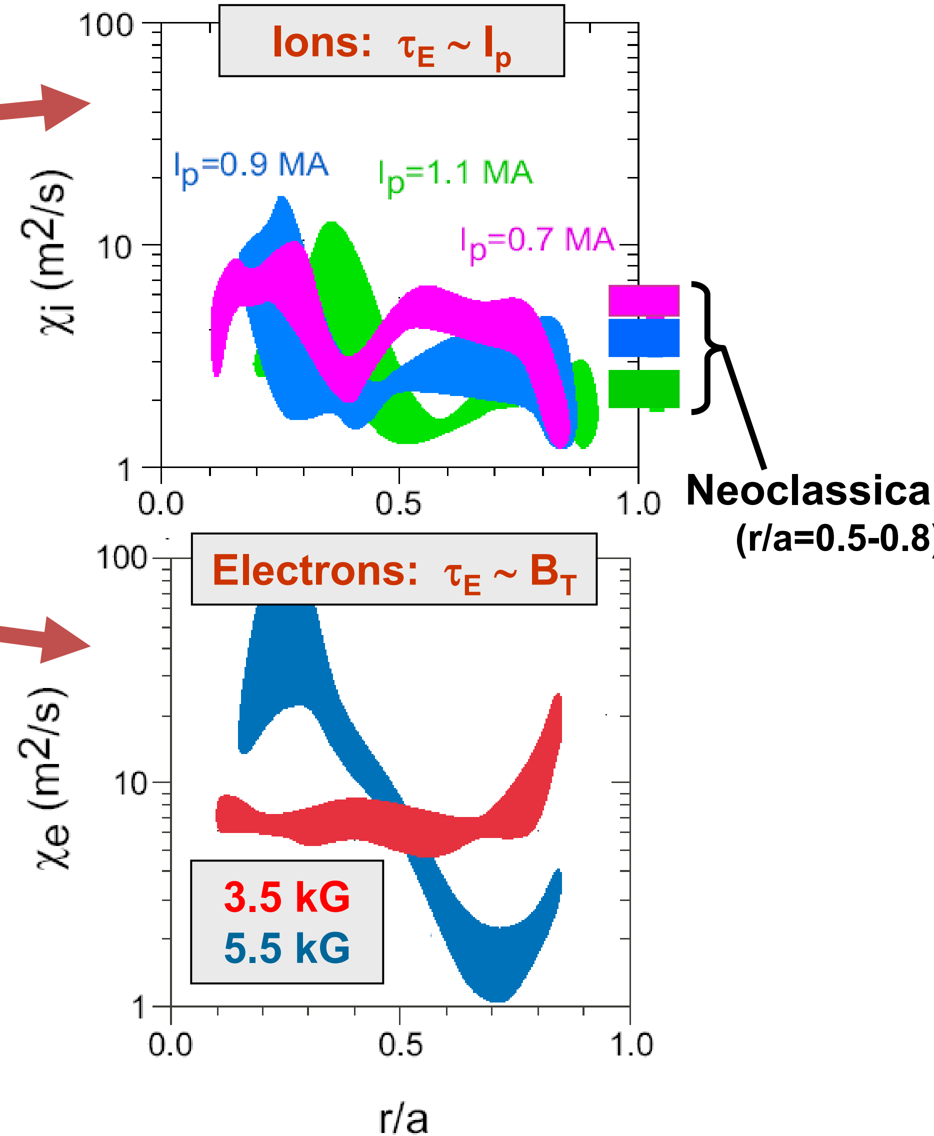
Enhanced pedestal H-mode (EPH) has H up to 1.5-2 → attractive for ST-FNSF



R. Maingi, PRL 2010
S. Gerhardt NF 2014

Electron and ion τ_E scale differently in ST, and different than at higher aspect ratio

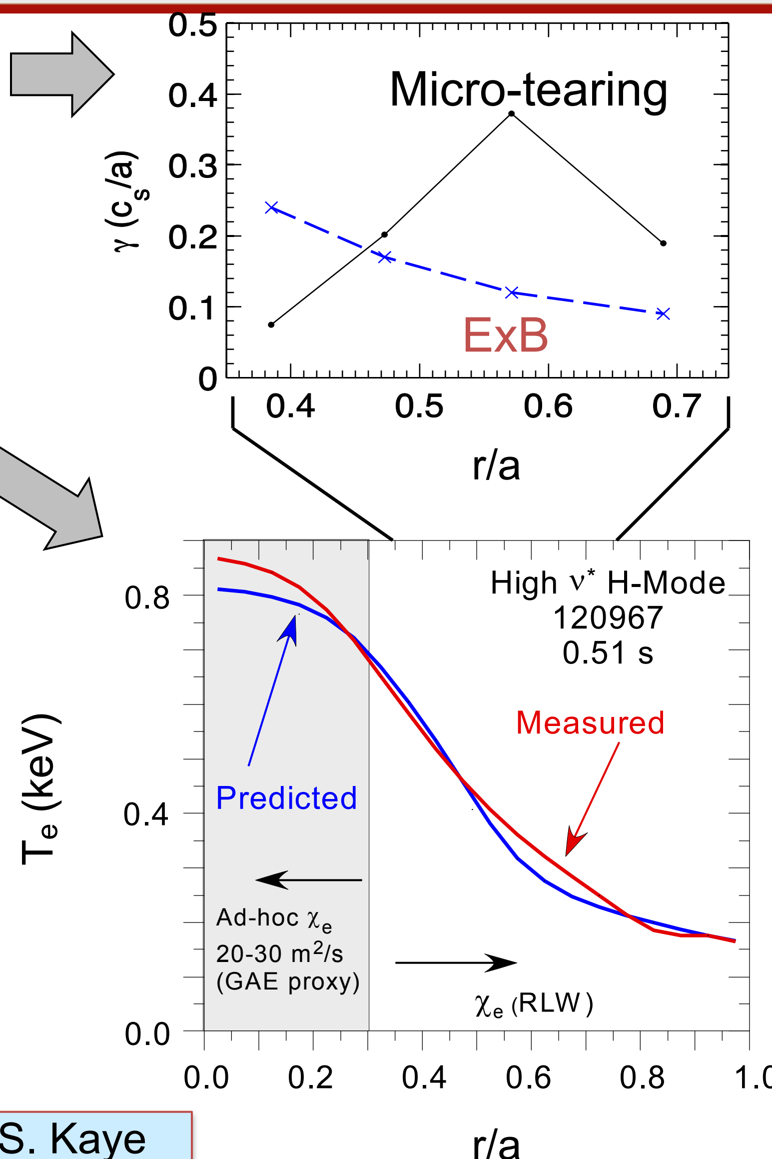
- **Ion $\tau_E \sim I_P$, consistent with neoclassical ion transport**
  - Implies ion turb. suppressed by high E × B shear → possibility of isolating causes of e-transport
- **Electron $\tau_E \sim B_T$**
  - Could imply Electron Temperature Gradient (ETG) modes, and/or electromagnetic turbulence



S.M. Kaye, PRL 2007

Progress in predicting T_e using reduced χ_e models in regimes where single micro-instability is dominant

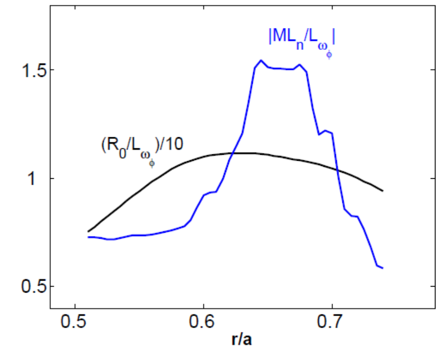
- Linear gyrokinetic simulations find microtearing unstable in mid-radius region of high-collisionality H-modes
  - Other micro-instabilities subdominant at this location for this class of discharge
- Reduced model for micro-tearing χ_e *(Rebut-Lallia-Watkins (RLW) - 1988)* shows reasonable agreement between predicted & measured T_e for r/a > 0.3
  - χ_e >> RLW must be used in core to match central T_e - may be due to GAE/CAE
- Reduced ETG models in low-β L-modes also show reasonable T_e agreement for r/a > 0.3 (not shown)



S. Kaye

Strong flow shear can destabilize Kelvin-Helmholtz (K-H) instability in NSTX (Wang, TTF 2014)

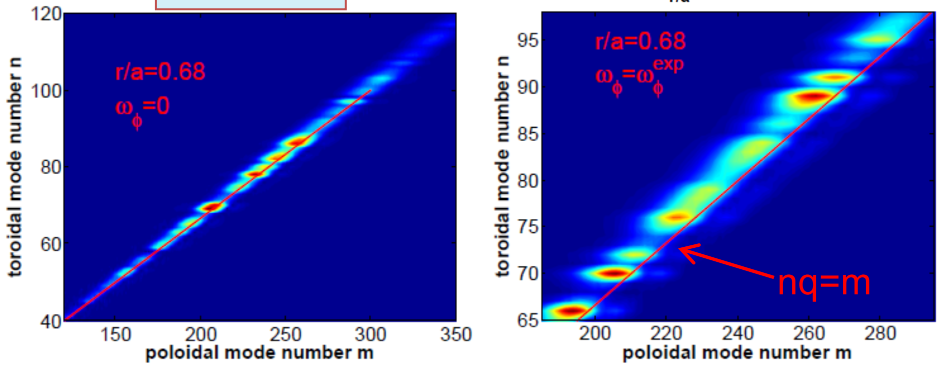
- K-H instability expected for $|ML_n/L_\omega|>1$ from linear analytic theory (Catto, 1973; Garbet, 1999)



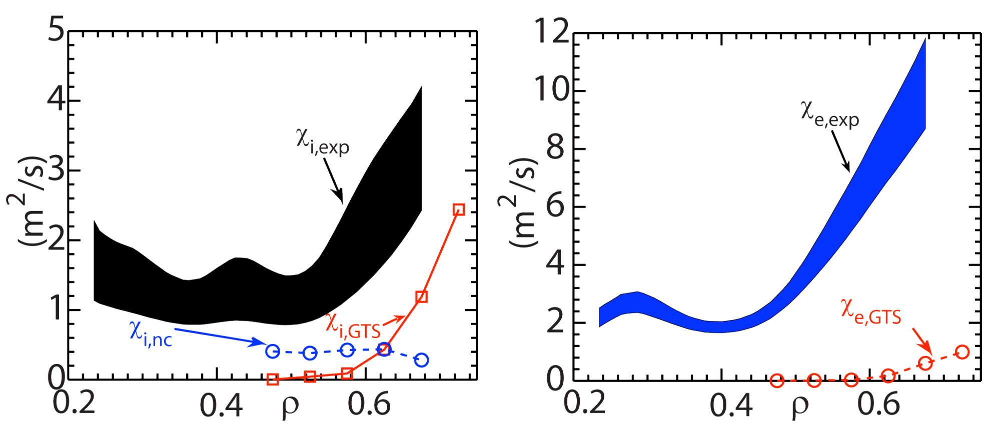
- K-H identified in global electrostatic ITG simulations for NSTX low β L-mode (Ren, 2013)
  - Mostly unstable K-H modes have finite $k_{||}$ (shifted away from nq=m)

$$k_{||} \sim \frac{k_\theta \rho_s}{2c_s}\frac{1}{n}\frac{d(nV_{||})}{dr} \sim \frac{d\omega_\phi}{dr}$$

GTS code



- K-H/ITG + neoclassical close to experiment χ_i
  - χ_e underpredicted
  - ETG possibly important



Nonlinear ETG simulations to be run in FY14-15 to investigate contribution in NSTX L-modes

New "kick" model for fast-ion transport predicts different J_{NB}, ion/electron power split, inferred thermal transport

Nucl. Fusion **55** (2015) 053018 M. Podestà *et al*

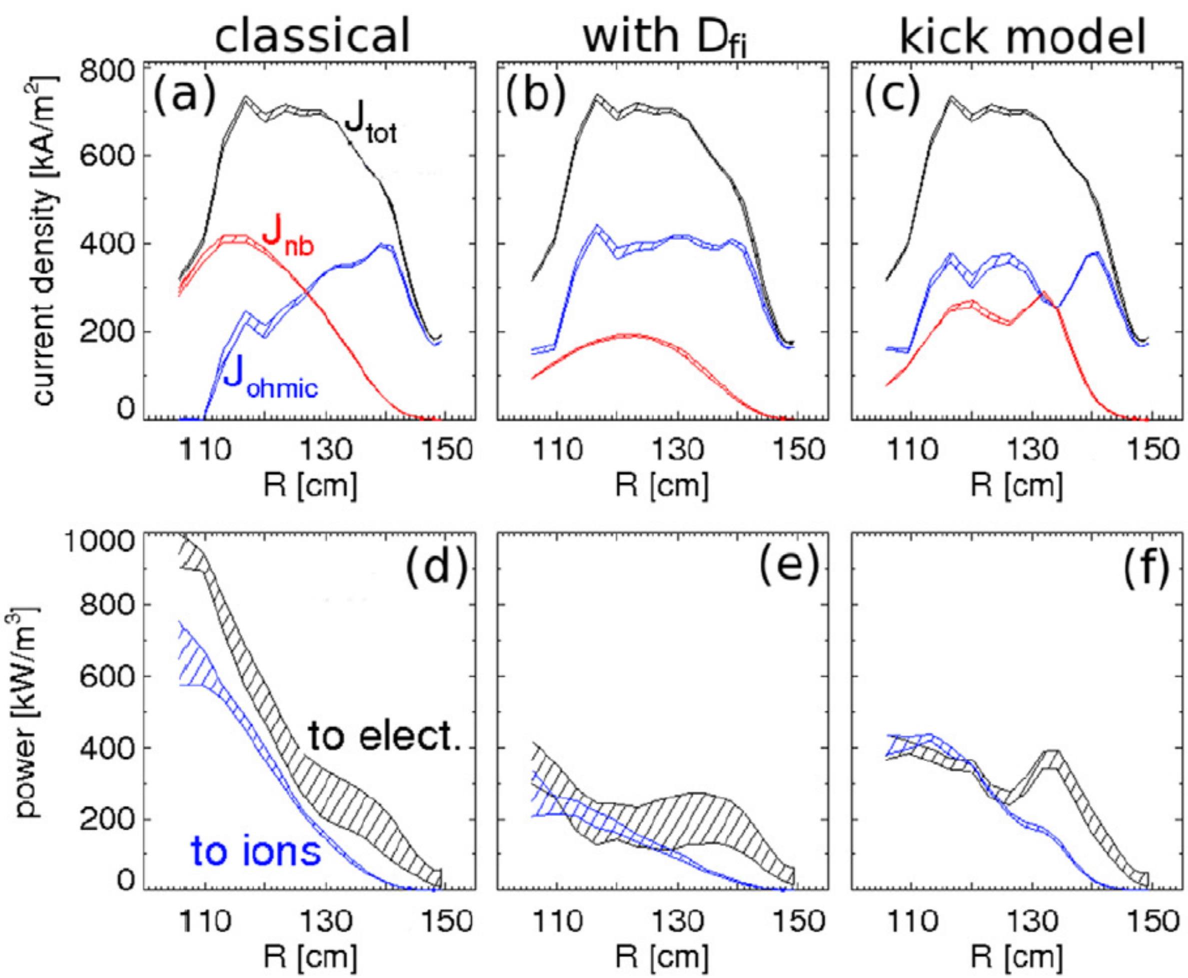
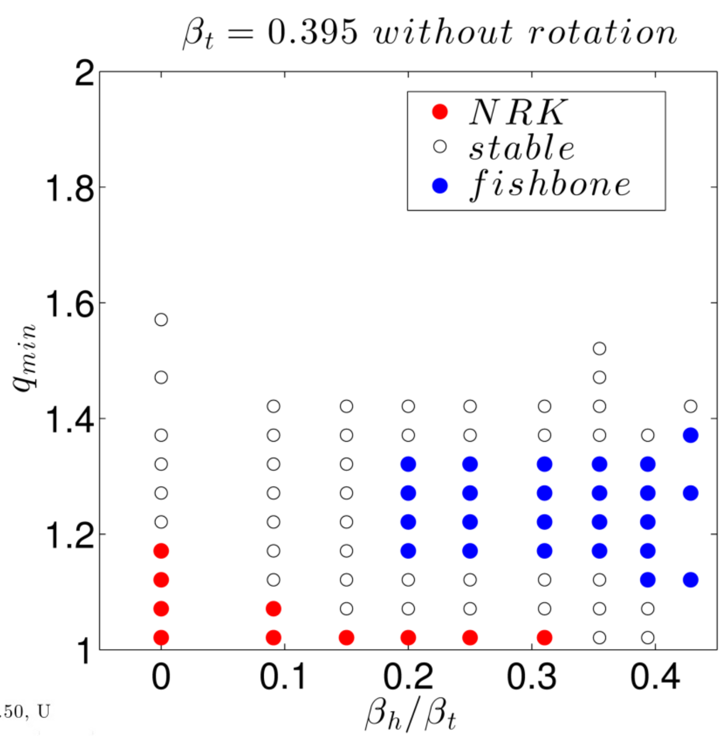
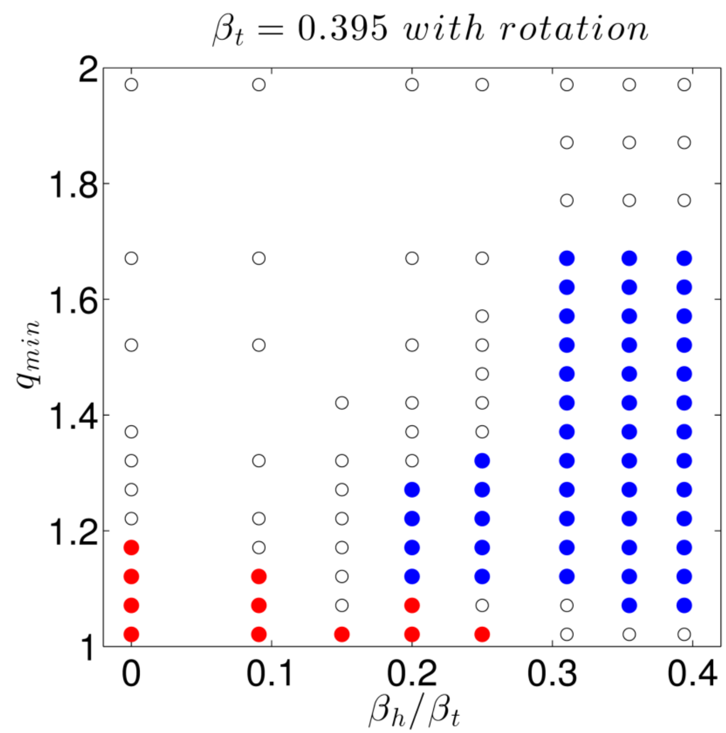


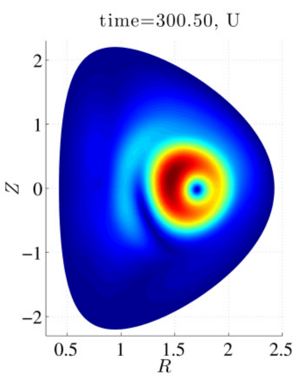
Figure 11. (*a*)–(*c*) Current density profiles calculated by TRANSP with different assumptions for fast ion transport (NSTX #139048). TRANSP results are averaged over t = 300–305 ms. (*d*)–(*f*) Total heating power transferred to electrons and ions for the three cases.

Linear stability analysis of fishbones with M3D-K finds rotation / rotation shear destabilizing at elevated q

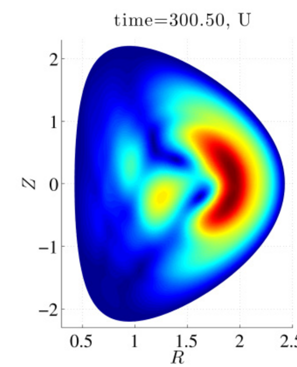




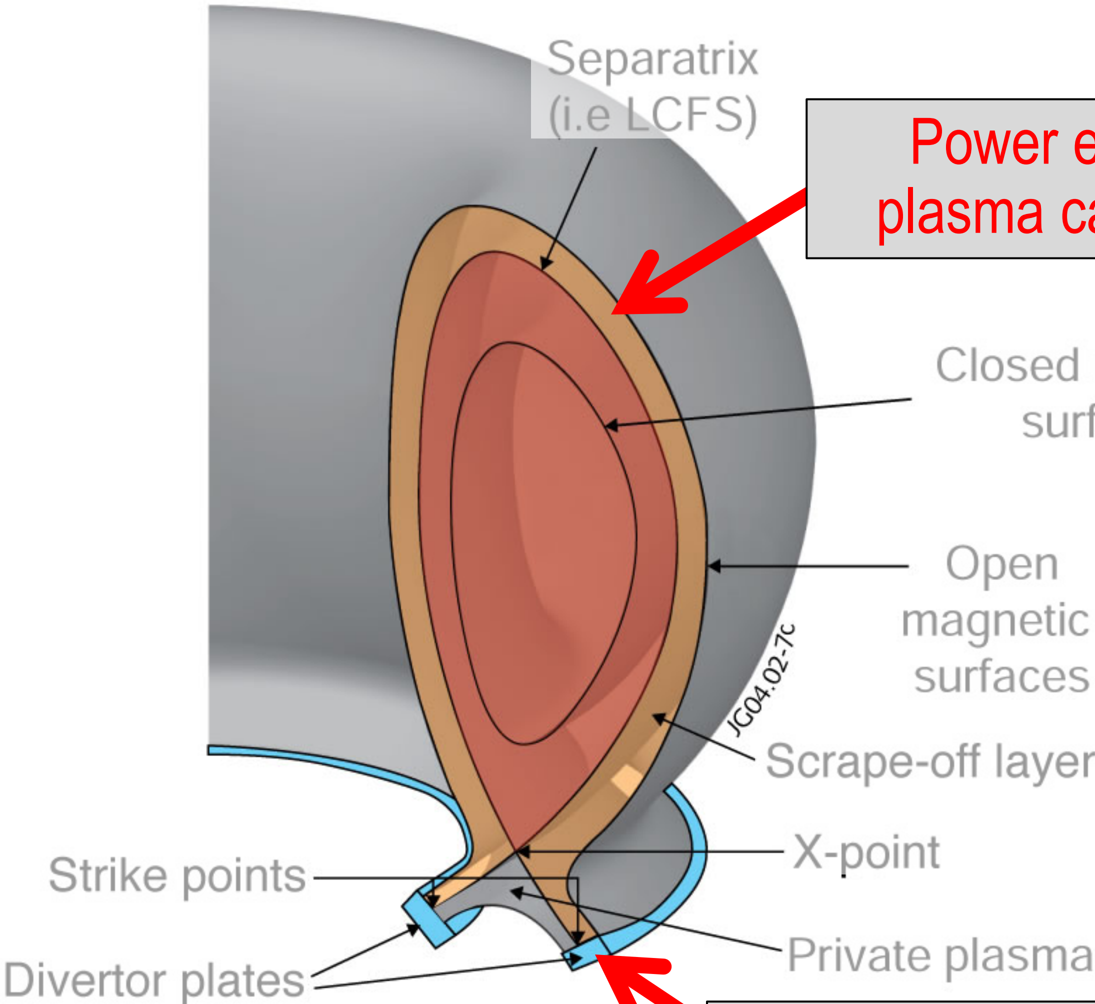
Guoyong Fu, Feng Wang
NSTX-U / theory partnership



- Eigenfunction broadens with rotation
  - Enhanced fast-ion transport or triggering / seeding of tearing modes?
  - Next step: investigate with non-linear runs.



All modern tokamaks / STs use a "divertor" to control where power and particles are exhausted



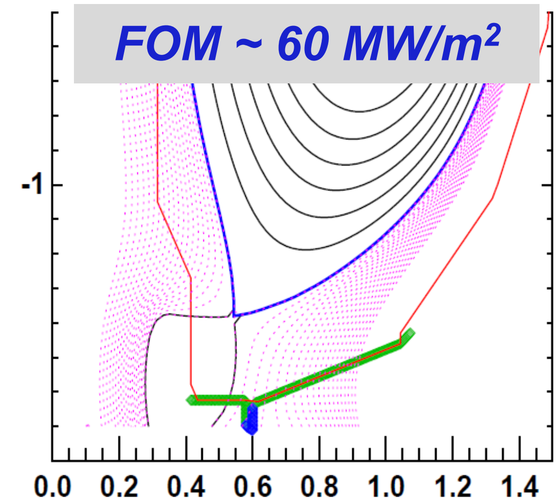
Power exhaust width outside main plasma can be very narrow (few mm)

Power / particles contact target plates here

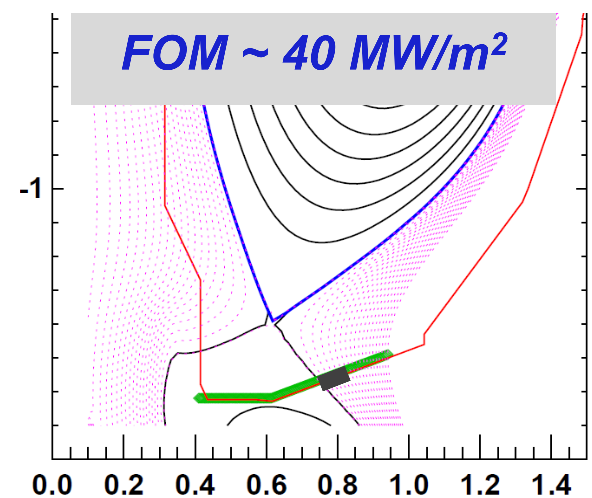
FY15 modelling → outboard row of high-Z tiles can access high heat-flux, maintain operational flexibility

- Shape developed to perform dedicated tests on outboard PFCs
  - ISOLVER free-boundary solver utilized with specified β_N
  - 0D-analysis obtains heating power for assumed confinement multiplier H_{98y2}
- Zero-radiation power exhaust provides heat flux figure-of-merit (FOM)
  - FOM calculates incident power accounting for magnetic shaping only
  - High-Z shape FOM is 66% of similar full-power, high-triangularity scenario

High-performance discharge

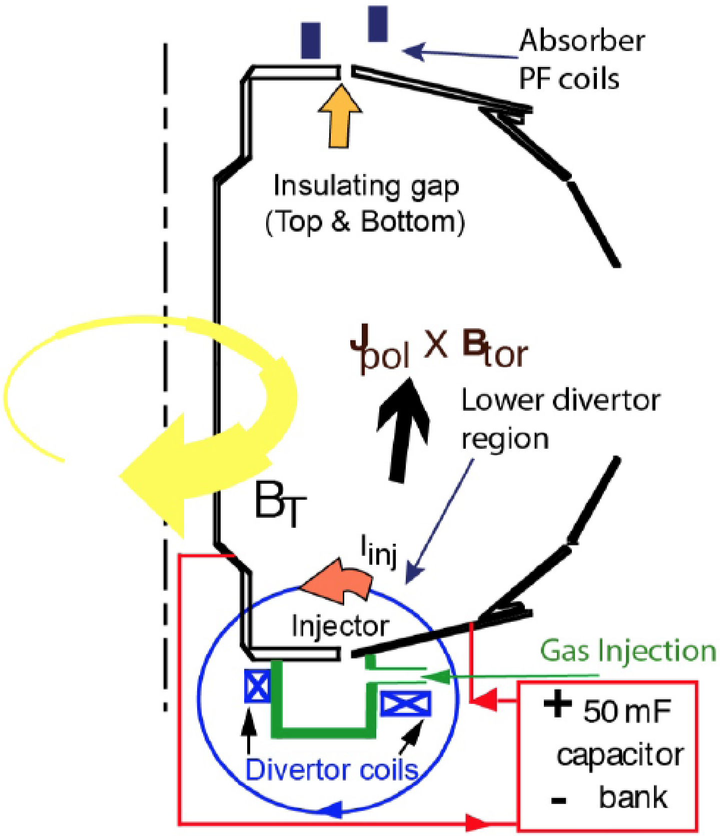


High-Z reference discharge



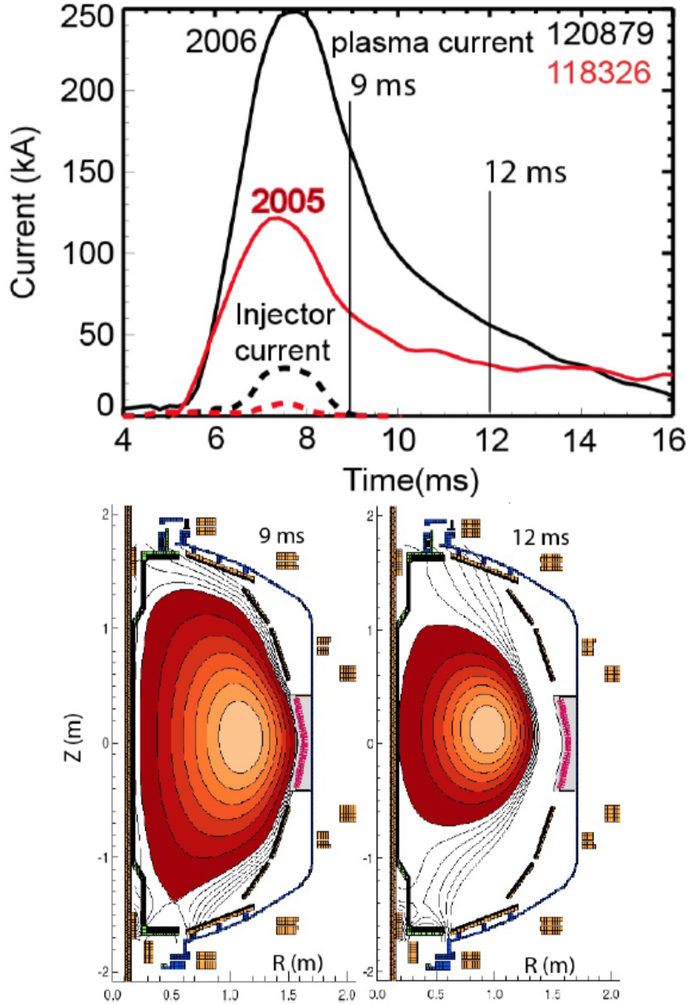
Helicity Injection is efficient method for current initiation
Coaxial Helicity Injection (CHI) concepts being developed

CHI developed on HIT, HIT-II
Transferred to NSTX / NSTX-U

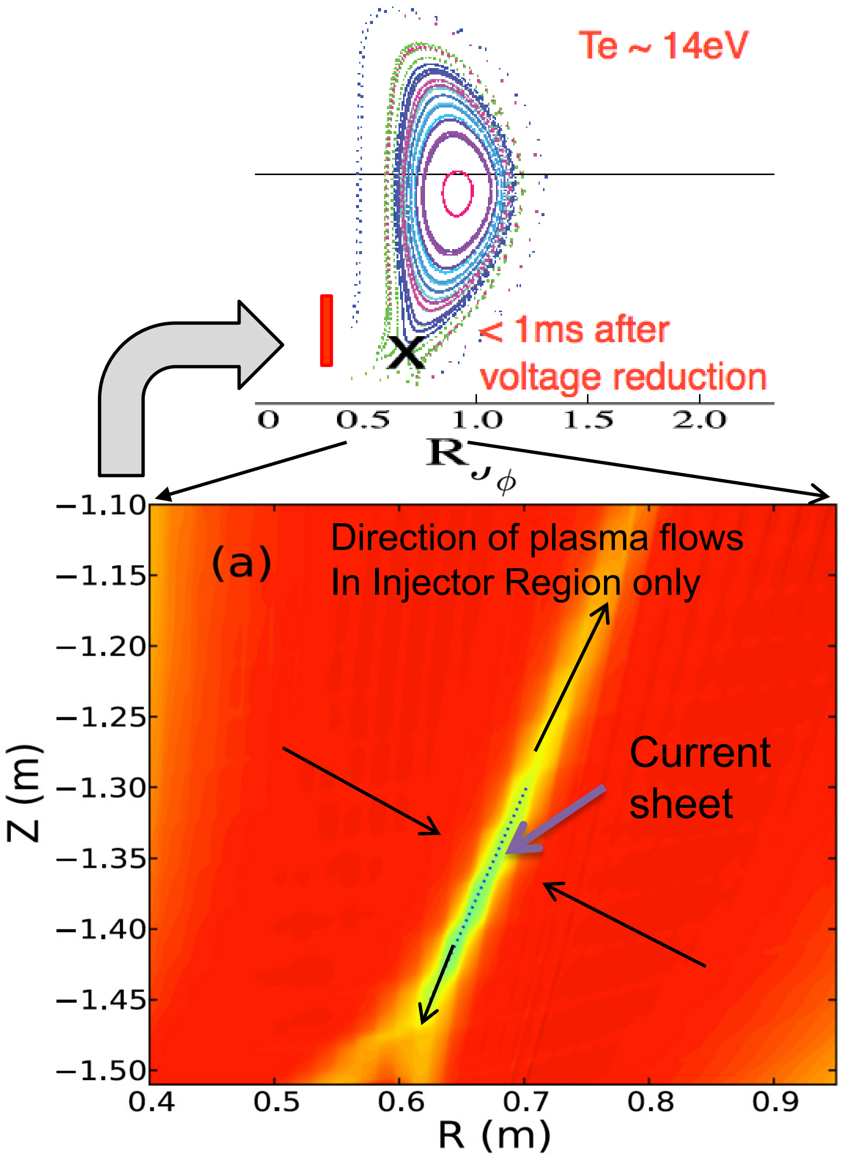


R. Raman et al., PRL 2006

Discharge evolution of 160 kA closed flux current produced by CHI alone in NSTX



CHI in NSTX has resemblance to 2D Sweet-Parker reconnection (NIMROD simulations)



- Toroidal electric field generated in injector region by reduction of injector voltage and current
  - $E_{toroidal} \times B_{poloidal}$ drift brings oppositely directed field lines closer and causes reconnection, generating closed flux

- Elongated Sweet-Parker-type current sheet
- n > 0 modes / MHD not strongly impacting 2D reconnection

F. Ebrahimi, PoP 2013, PoP 2014

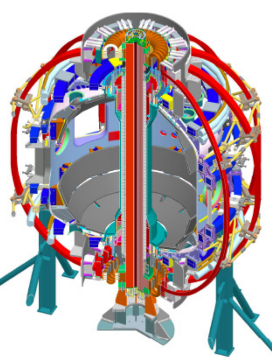
Five Year Facility Enhancement Plan (green = ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		14-16	16-18	12-16	10-12

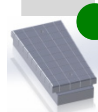
Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack

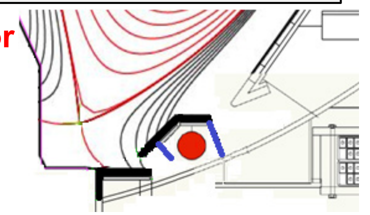


Boundary Science + Particle Control

- Pulse-burst MPTS
- Boronization
- Li granule injector
- MAPP
- Upward LiTER
- High-Z tile row on lower OBD



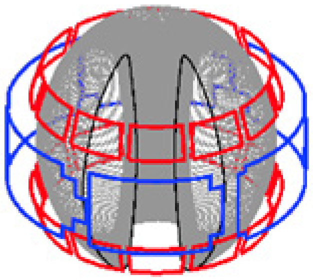
- Lower divertor cryo-pump



- High-Z PFC diagnostics
- LLD using bakeable cryo-baffle

Core Science

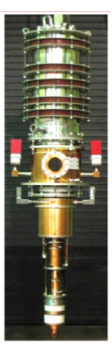
- MGI disruption mitigation
- Upgraded halo sensors
- Laser blow-off
- 42 ch MPTS
- 48 ch BES
- MSE/LIF
- High k_θ
- Charged fusion product
- 4 coil AE antenna
- δB diag. - incremental
- Off-midplane 3D coils (NCC)

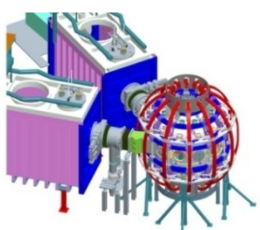


- Enhanced MHD sensors
- DBS, PCI, or other intermediate-k
- Neutron collimator

Integrated Scenarios

Establish control of:
- Snowflake
- FIReTIP
- Rotation
- $\bar{n}_e$
- q_{min}
- Divertor P_{rad}
- 1 MW ECH/EBW
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- HHFW limiter upgrade
- up to 1 MA plasma gun





2nd NBI

NSTX-U Milestone Schedule for FY2016-18

	FY2016	FY2017	FY2018
Run Weeks: Incremental	14 / 16	16 / 18	12 / 16
Boundary Science + Particle Control	R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2: Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1: Assess impurity sources and edge and core impurity transport IR18-1: Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3: Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	IR18-2: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for major facility enhancement(s) sometime during FY2018
Integrated Scenarios	R16-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1: Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4: Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2: Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3: Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT: Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT: TBD… possibly something on energetic particles	NSTX-U leads JRT: TBD