U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Progress and Plans for NSTX Upgrade and Kinetic Resistive Wall Mode Stability

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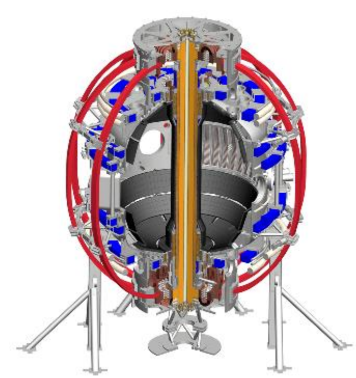
and the NSTX-U team

University of Washington,
Seattle, WA
October 26, 2015

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PPPL



Outline

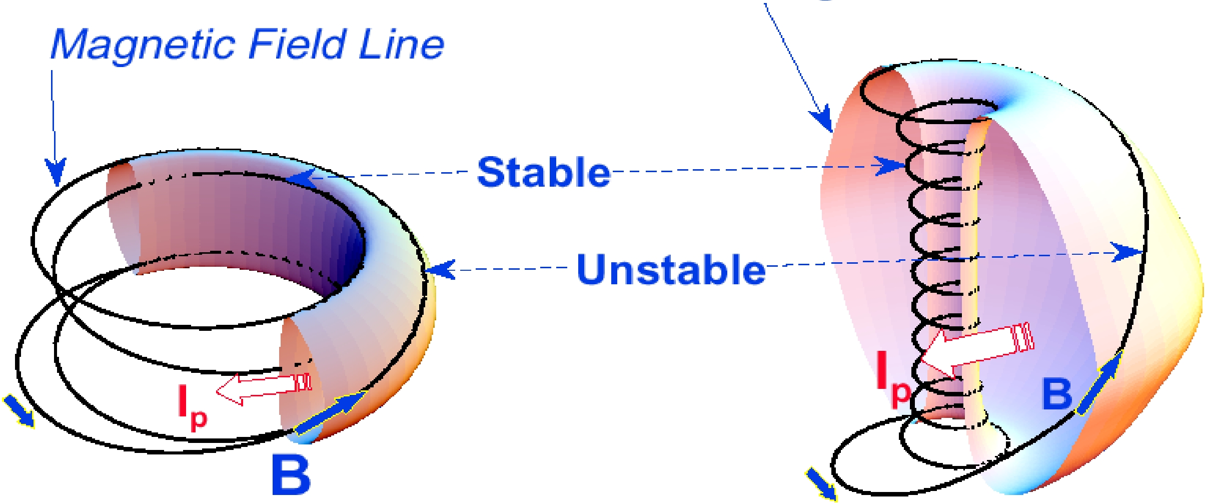
- **ST Overview and Motivation**
- **NSTX-U Mission and Status**
- **NSTX/NSTX-U Research Highlights**
  - **Transport and Turbulence**
  - **Power Exhaust**
  - **Plasma Start-up**
  - **Scenarios, Control, and Stability**
- **Modifications to Ideal Stability by Kinetic Effects**
- **Summary**

"Spherical" tokamak (ST) has aspect ratio A < 2

Aspect Ratio $A = R/a$	Elongation $\kappa = b/a$	Toroidal beta $\beta_T = \langle p \rangle / (B_{T0}^2/2\mu_0)$

Tokamak

$A \sim 3\text{-}4$,
$\kappa = 1.5\text{-}2$,
$q_{95} = 3\text{-}4$,
$\beta_T = 3\text{-}10\%$



ST

$A \sim 1.2\text{-}2$,
$\kappa = 2\text{-}3$,
$q_{95} = 6\text{-}20$,
$\beta_T = 10\text{-}40\%$

- ST has high I_P, economically, due to high κ and low A

  $$I_P \sim I_{TF} (1 + \kappa^2) / (2 A^2 q^*)$$

  Energy confinement time $\tau_E \propto I_P$

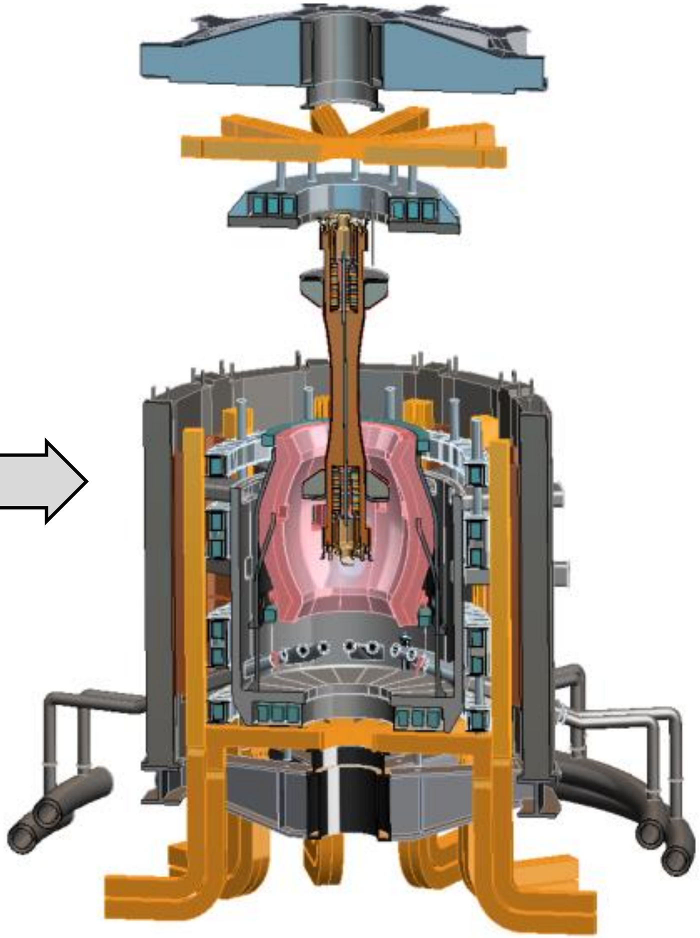
- Favorable average curvature improves stability at high beta

  Access high pressure, rapid rotation, low collisionality

Design studies show ST potentially attractive as FNSF

- **Projected to access high neutron wall loading at moderate R, P_{fusion}**
  - **W_n ~ 1-2 MW/m^2 , P_{fus} ~ 50-200MW, R ~ 0.8-1.8m**
- **Modular, simplified maintenance**
- **Tritium breeding ratio (TBR) near 1**
  - **Requires sufficiently large R, careful design**

PPPL ST-FNSF concept



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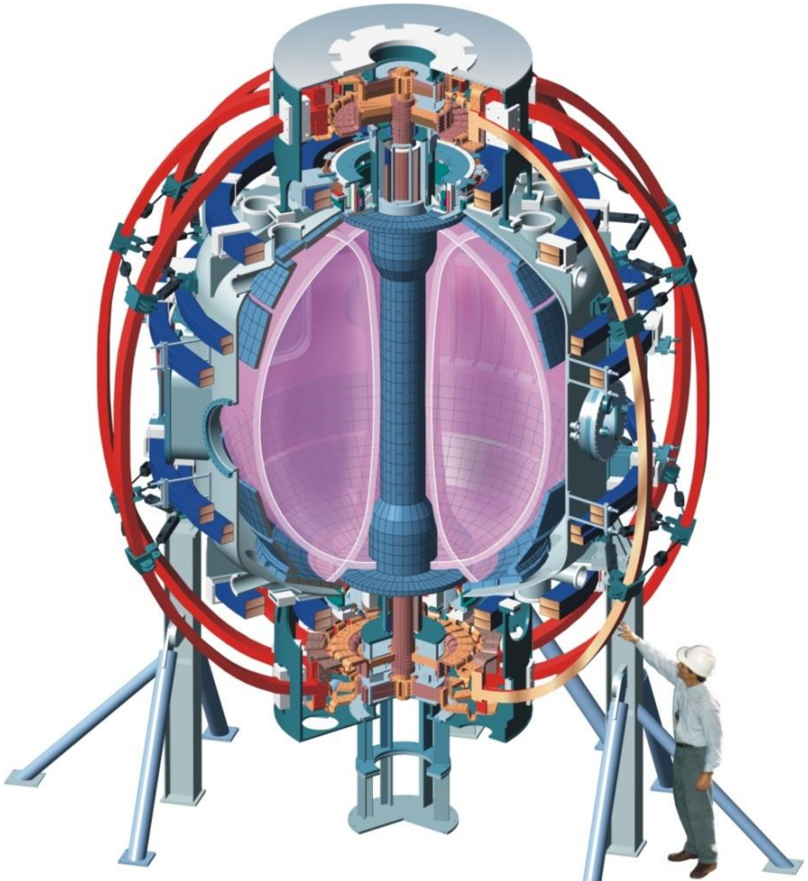
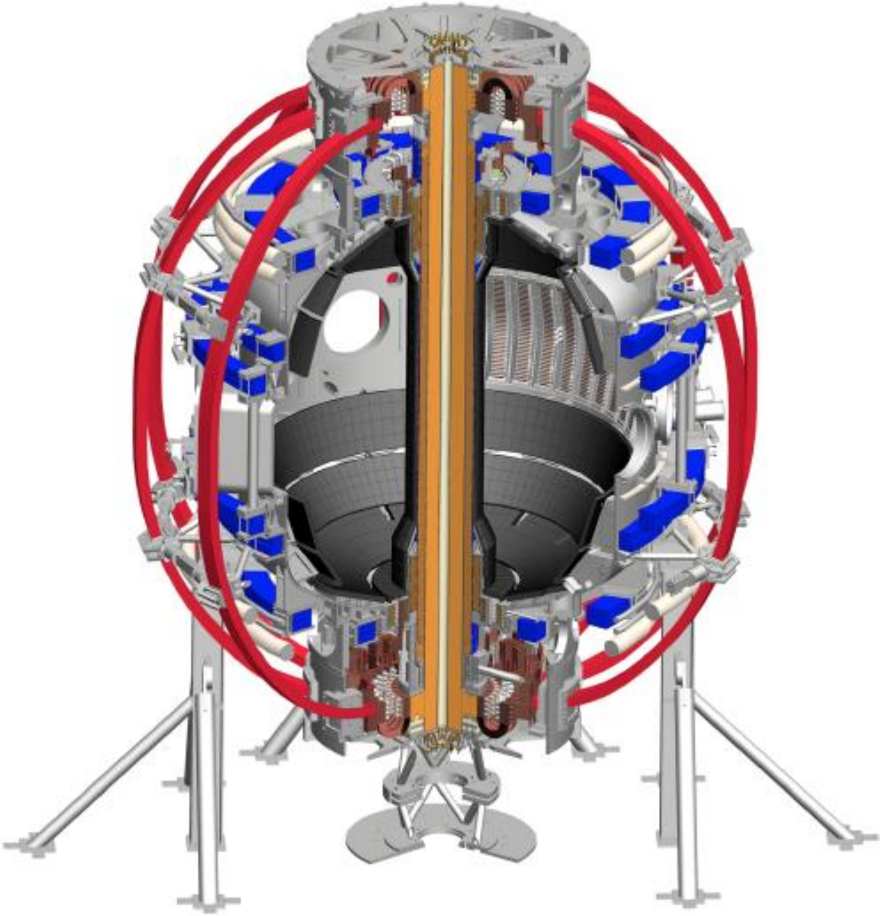
The National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physics Lab

NSTX
(1999-2011)



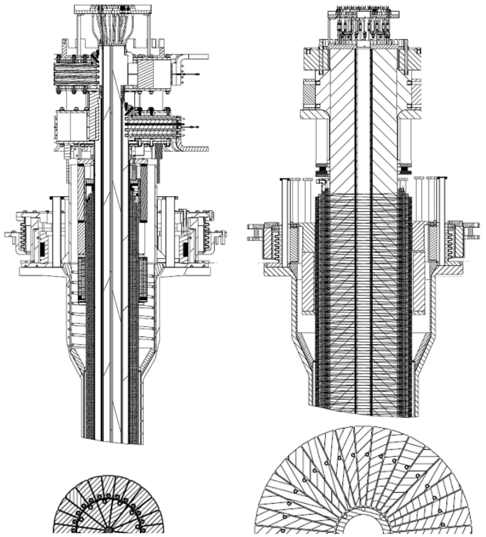
NSTX-U



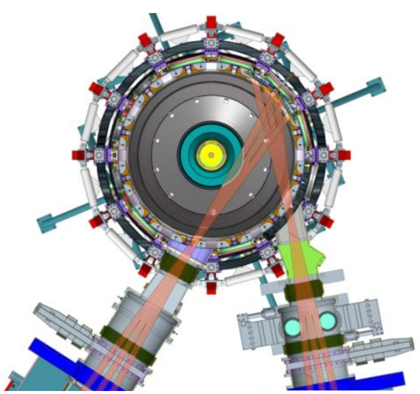
~2x higher B_T, I_p, P_{NBI} and ~5x pulse length vs. NSTX

The National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physics Lab

Previous center-stack | **New center-stack**



TF OD = 20cm | **TF OD = 40cm**

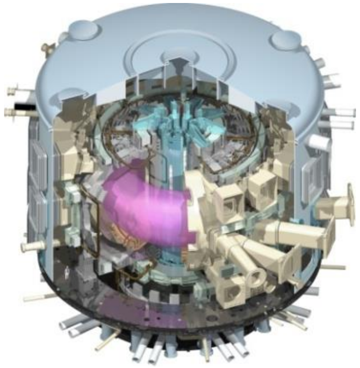


Present NBI | **New 2^{nd} NBI**

- New center column doubles toroidal magnetic field, plasma current
  - Access conditions closer to FNSF
  - Pulse lengths increase from 1 to 5 seconds
- Second neutral beam injection system
  - Doubles heating power, increases flexibility available for experiments
  - More tangential injection improves current drive, especially at small plasma current
- Increased flexibility in divertor configuration

NSTX Upgrade mission elements

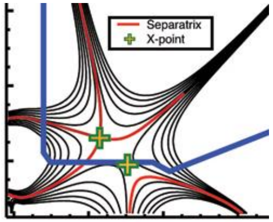
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond



ITER

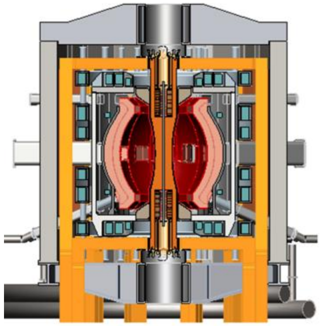
- Develop solutions for the plasma-material interface (PMI) challenge

Lithium

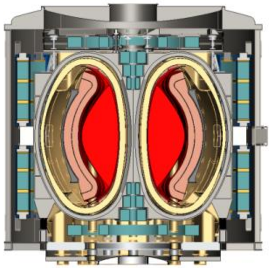


“Snowflake”

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



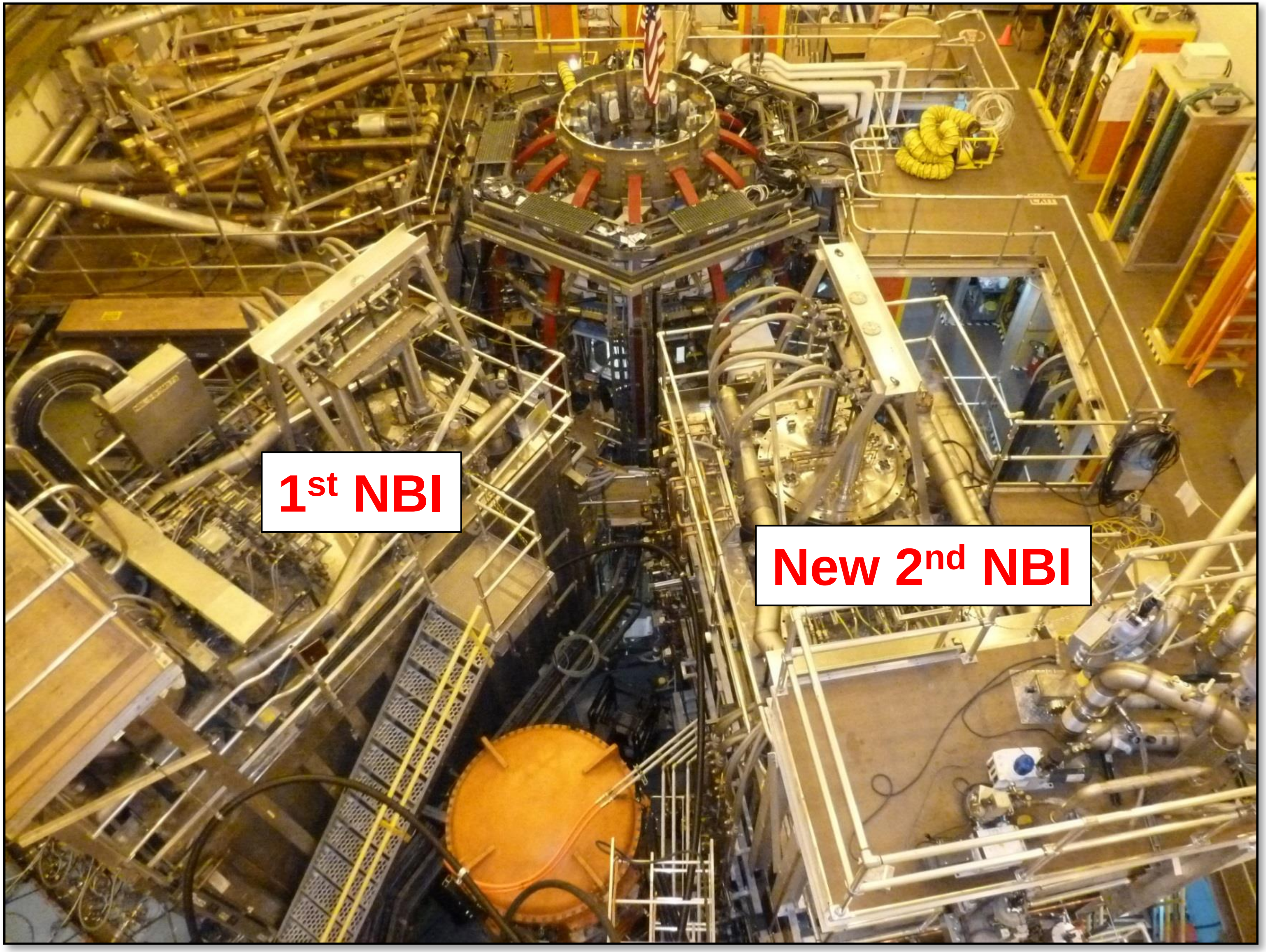
ST-FNSF / Pilot-Plant



- Develop ST as fusion energy system

NSTX Upgrade project recently completed

On cost and schedule, first test plasma ~100kA (Aug. 10, 2015)



NSTX Upgrade project recently completed

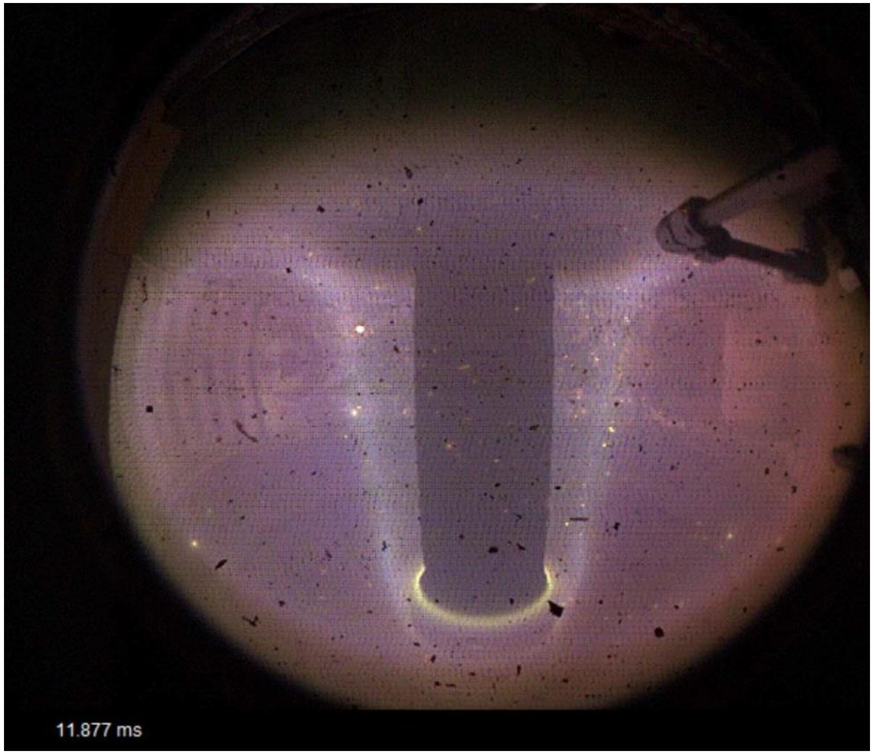
On cost and schedule, first test plasma ~100kA (Aug. 10, 2015)

Center stack installed

NSTX Upgrade project recently completed

On cost and schedule, first test plasma ~100kA (Aug. 10, 2015)

First test plasma
(Ohmic heating only)



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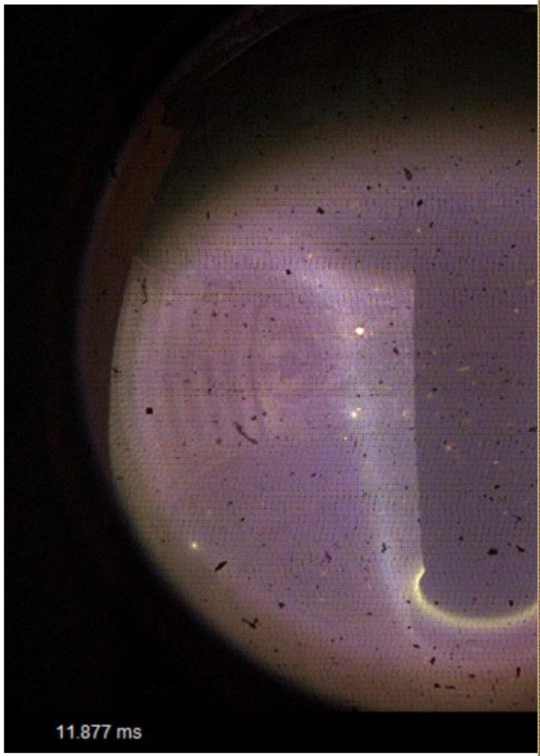

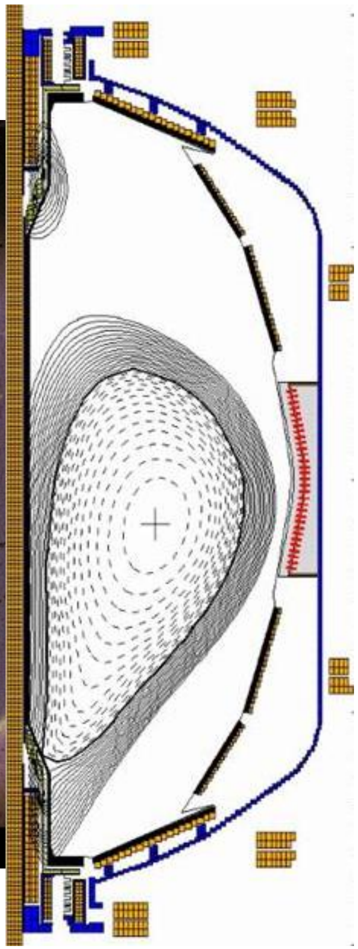

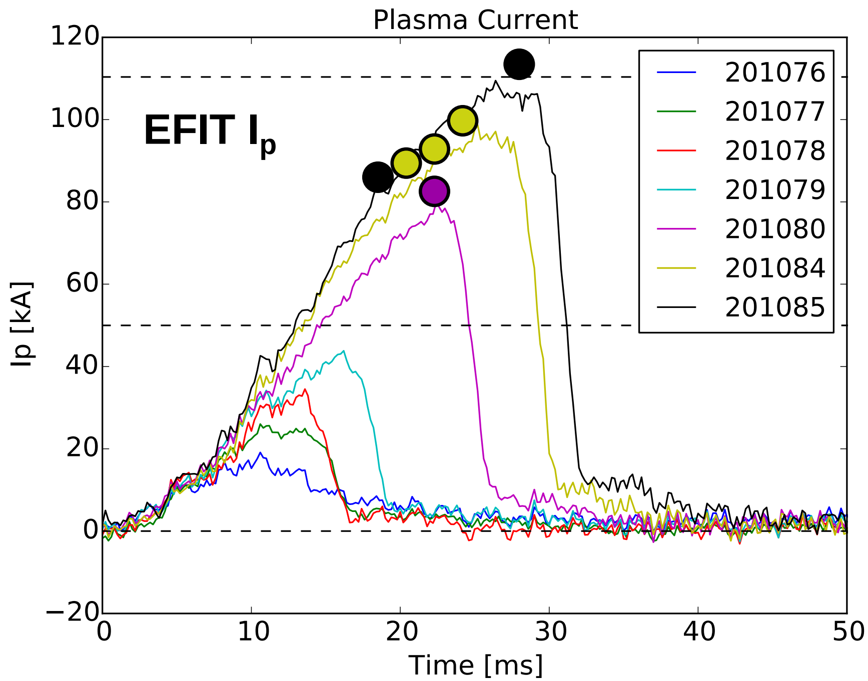

- NSTX-U EFIT Model created and used for first test shots
  - Challenging at I_p/I_{wall} ~ ¼, but successful (good magnetics)

Physics research operations to begin in December 2015

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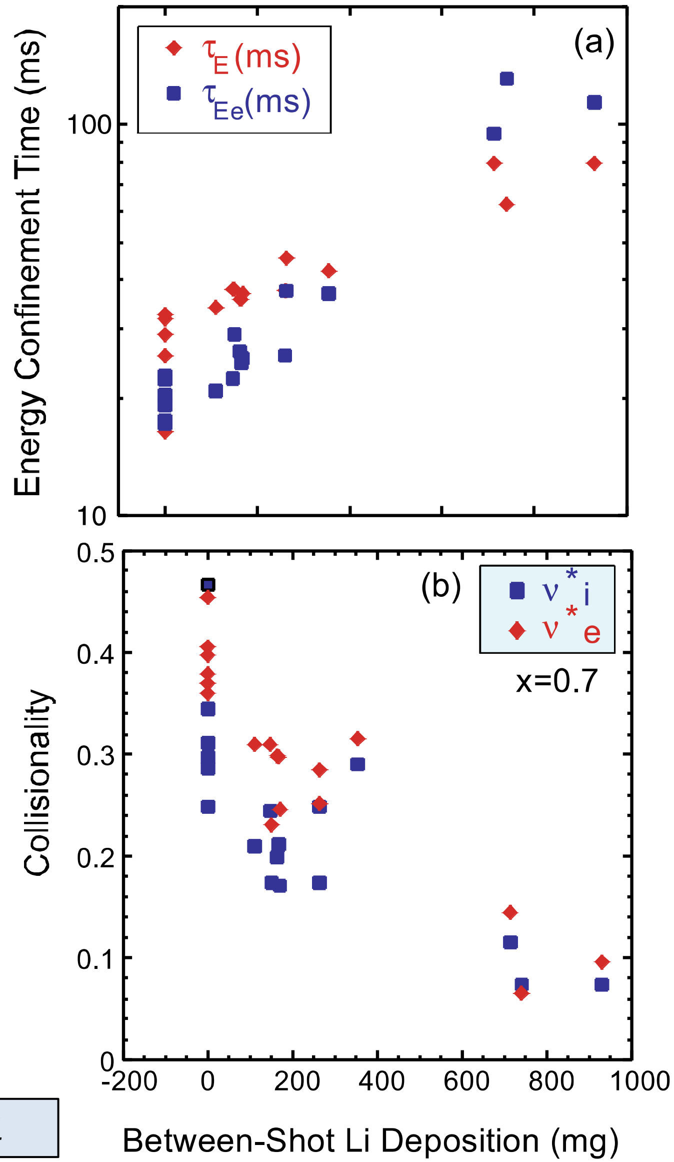
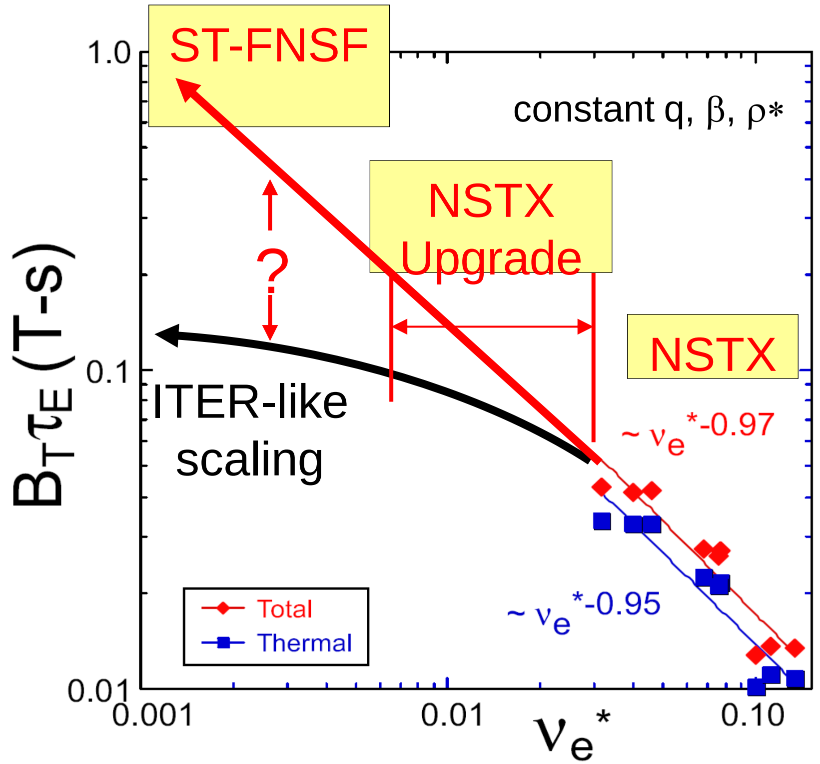
Low collisionality operation achieved on NSTX using lithium wall coatings

- Lithium coatings on carbon tiles reduced gas source from wall
  - Lead to a larger H-mode pedestal, larger core temperature
  - Confinement continued to improve with reduced collisionality
- Longer discharges will address first wall solutions
  - New diagnostics and campaigns with different wall materials will advance studies of plasma-wall interaction



R. Maingi, PRL 2011

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

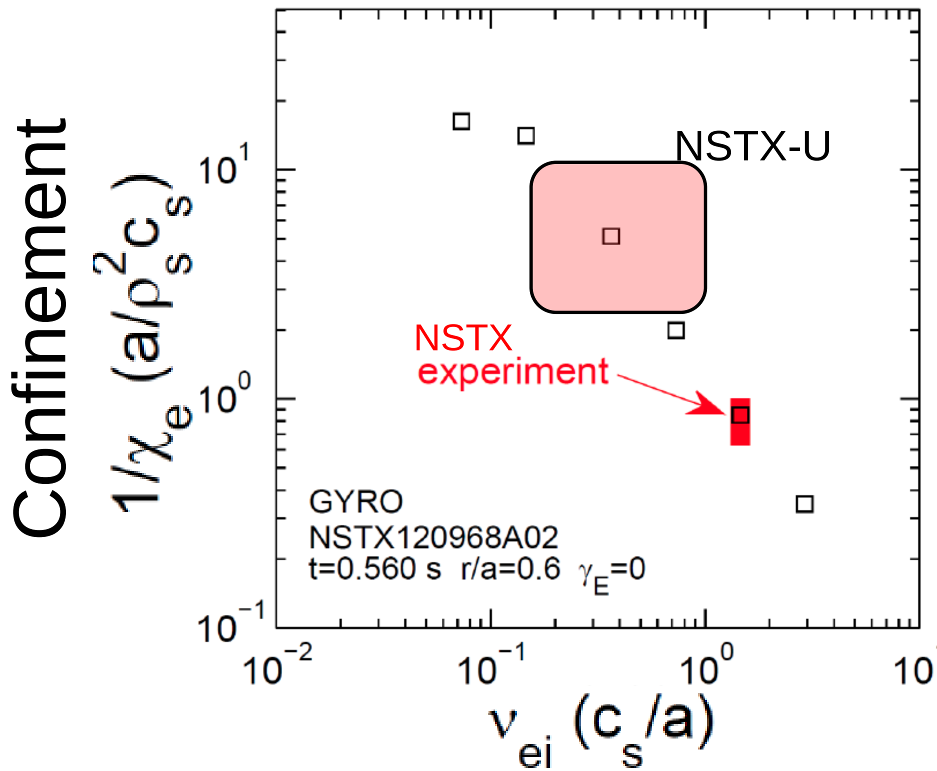


Normalized electron collisionality

$\nu_e^* \propto n_e / T_e^2$

S. Kaye, NF 2013

Micro-tearing-driven transport may explain ST τ_E collisionality scaling



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

Favorable confinement results could lead to more compact ST reactors

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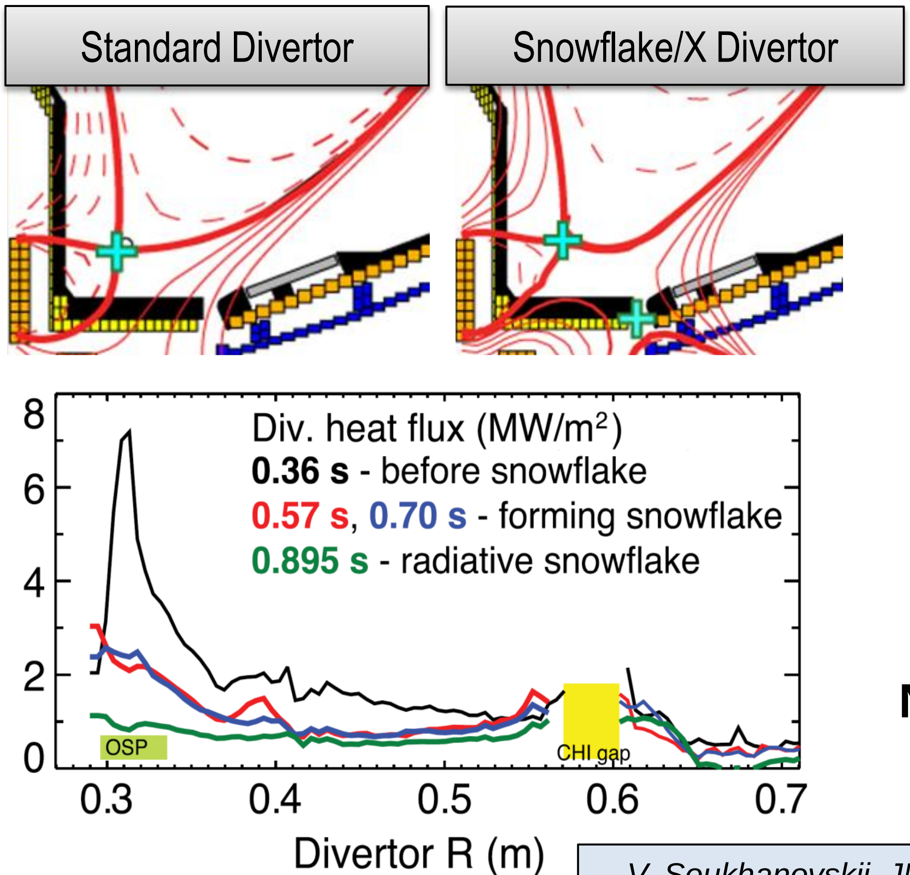
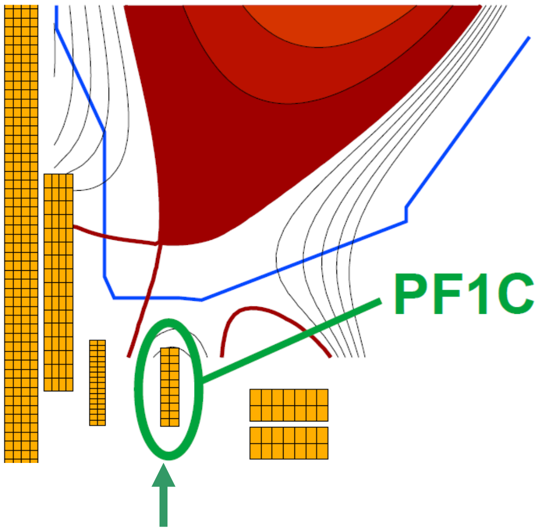
NSTX-U will test ability of radiation and advanced divertors to mitigate very high heat-fluxes

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



V. Soukhanovskii, JNM, 2013

NSTX-U peak heat fluxes will be up to 4-8 × higher than in NSTX



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

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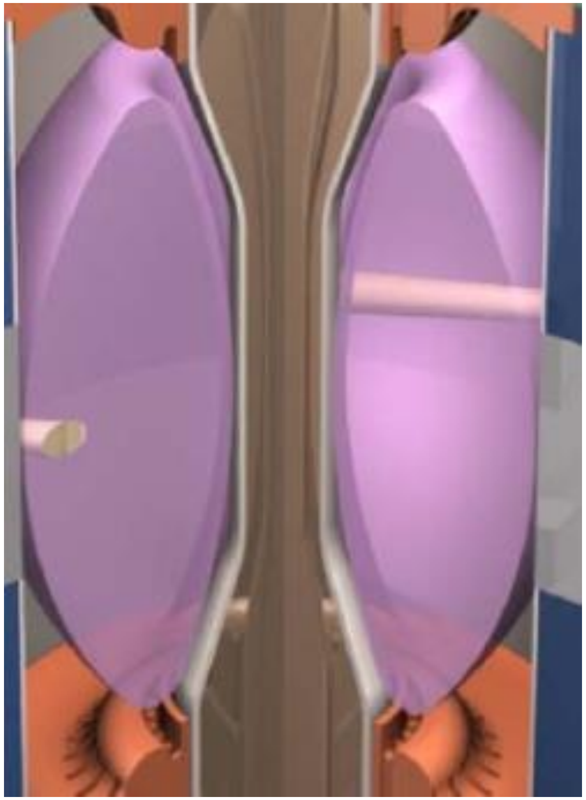
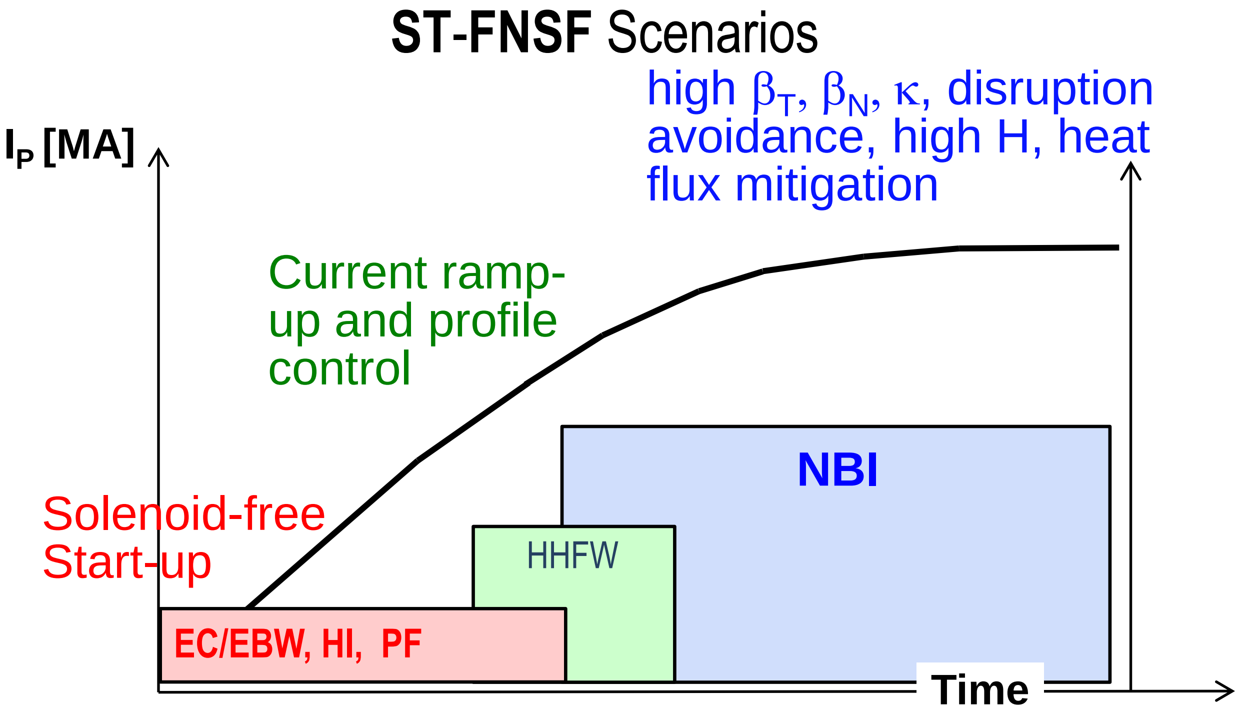
I_P Start-up/Ramp-up Critical Issue for ST-FNSF/Demo

Compact ST-FNSF has no/small central solenoid



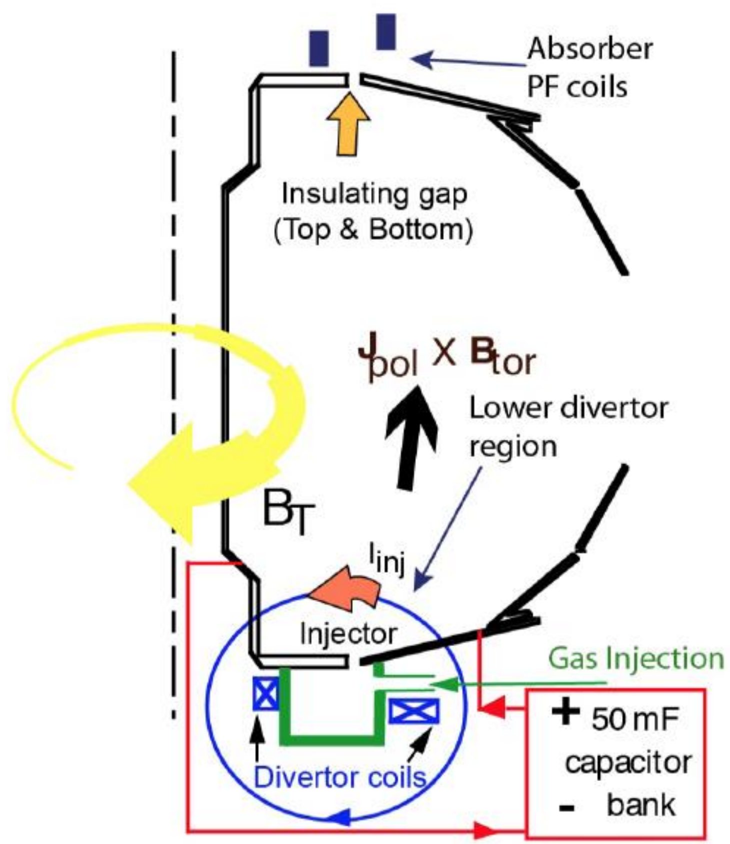
~ 1-2 MA of solenoid-free start-up current needed for FNSF



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

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

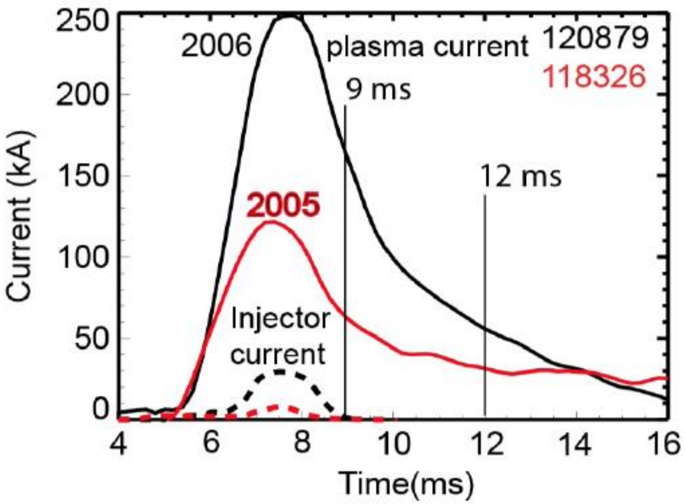


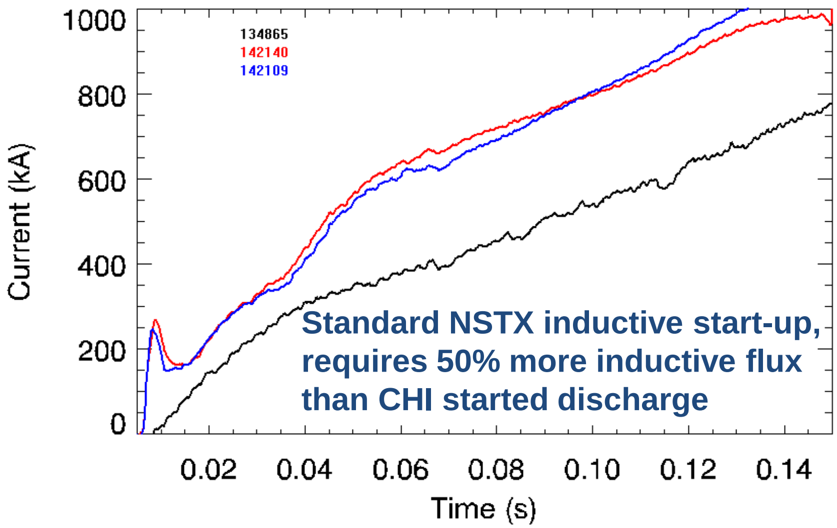
R. Raman et al., PRL 2006

R. Raman et al., POP 2011

UNIVERSITY of WASHINGTON

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





Standard NSTX inductive start-up, requires 50% more inductive flux than CHI started discharge

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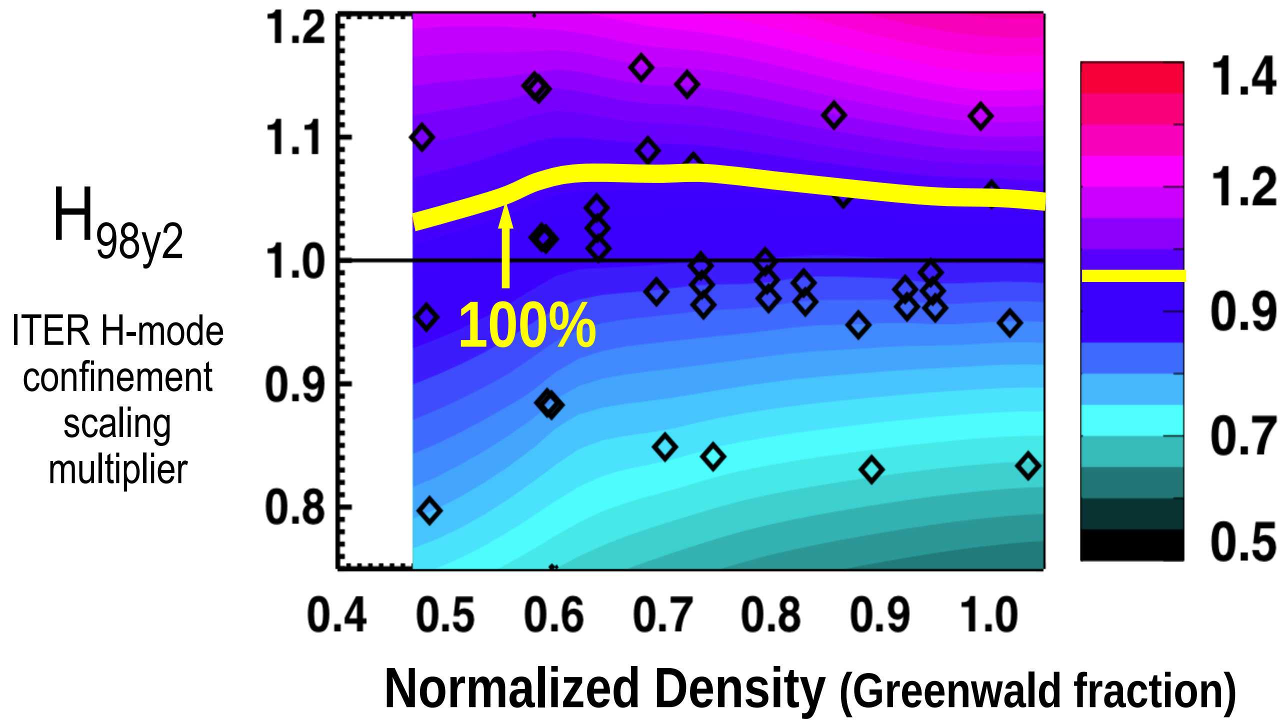
NSTX achieved 70% "transformer-less" current drive
Will NSTX-U achieve 100% as predicted by simulations?

TRANSP Contours of Non-Inductive Fraction



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

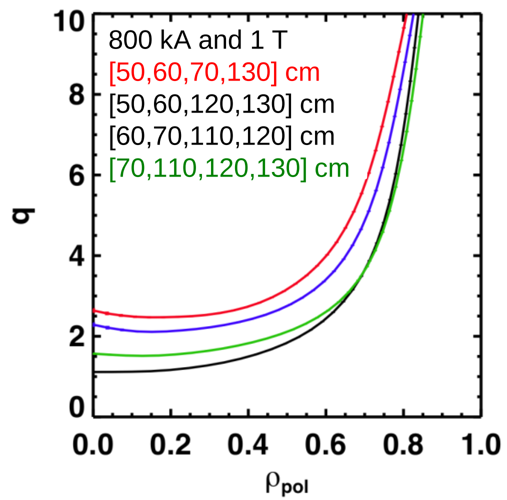
S. Gerhardt, NF 2012

Steady-state operation required for ST, tokamak, or stellarator FNSF

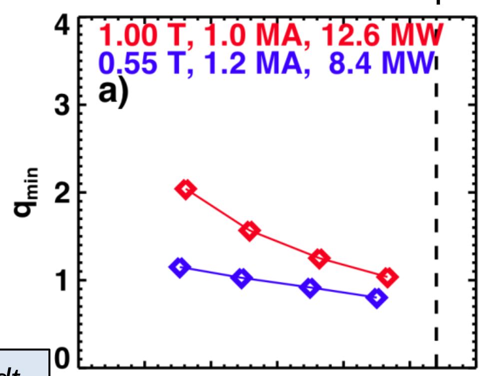
NSTX-U developing a range of profile control actuators for physics studies, scenario optimization

q-Profile Actuators

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

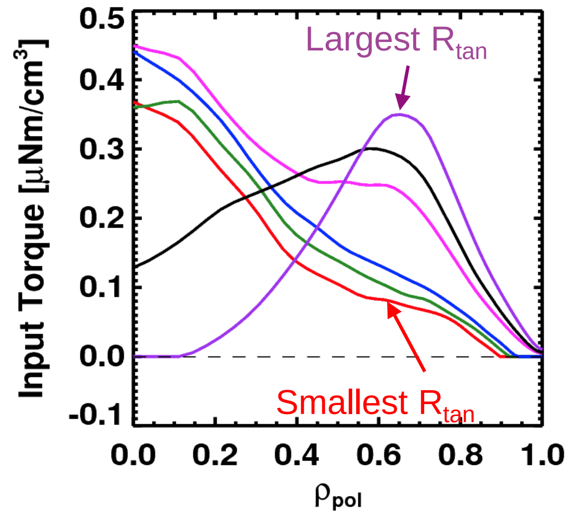


Variations in Outer Gap



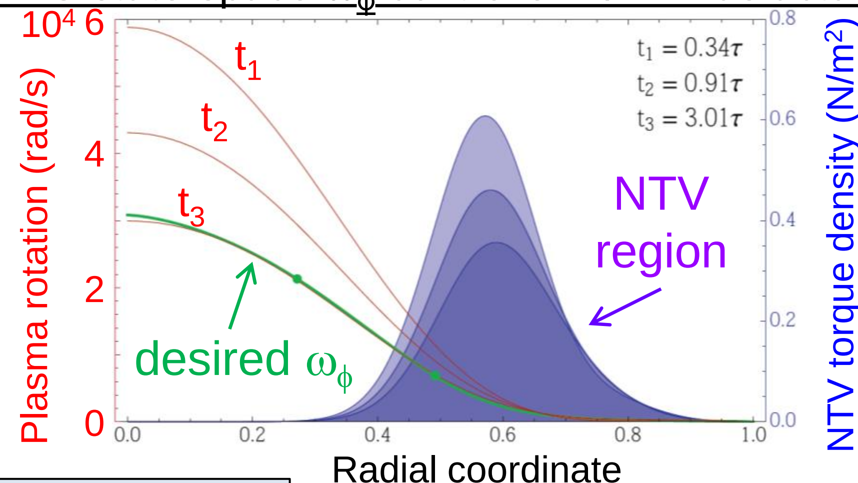
S. Gerhardt, NF 2012

Rotation Profile Actuators



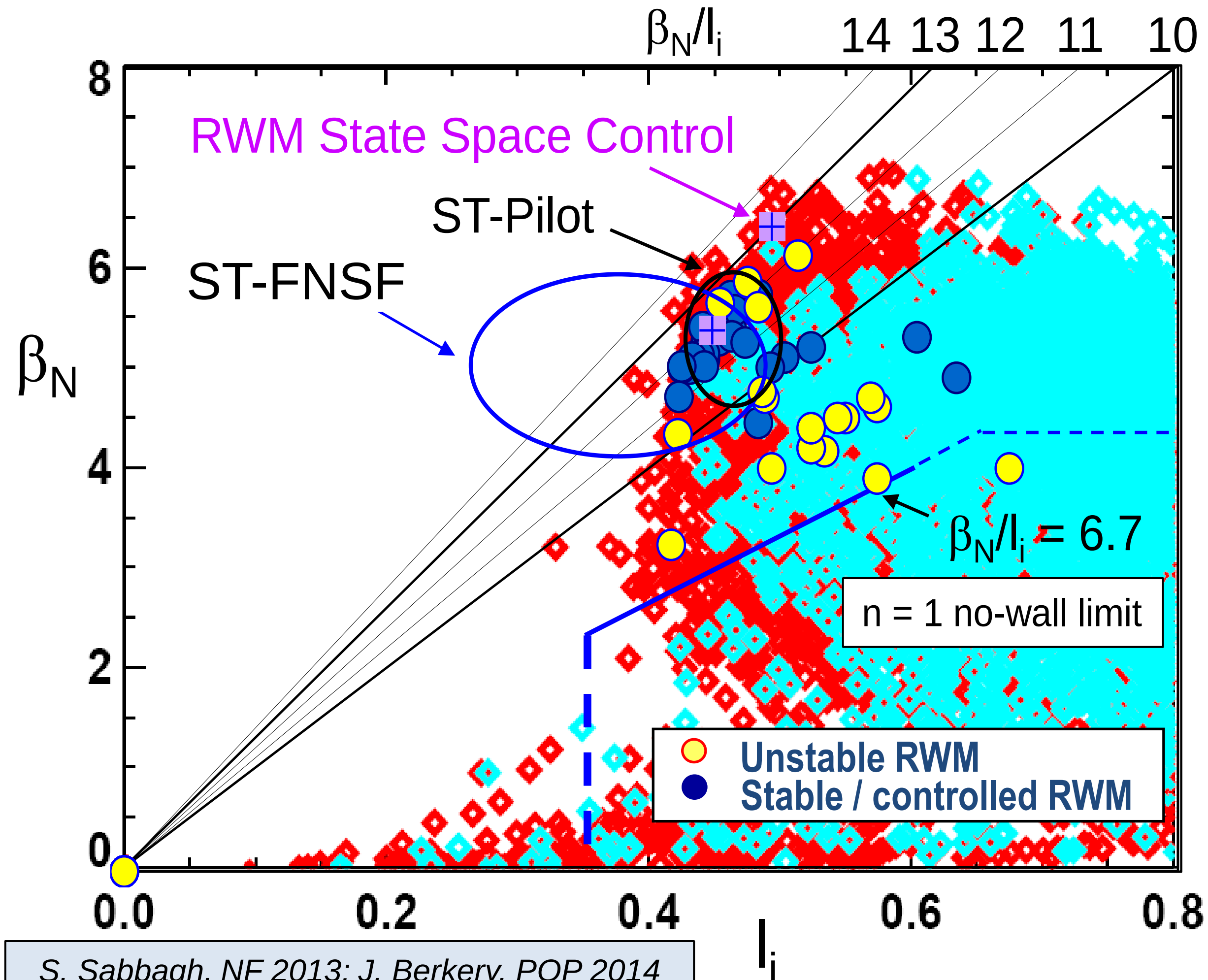
Torque Profiles From 6 Different NB Sources

NSTX-U state-space ω_φ controller w/NTV as actuator



S. Sabbagh, IAEA 2014

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



S. Sabbagh, NF 2013; J. Berkery, POP 2014

- High β_N for fusion performance, high non-inductive fraction for continuous operation
  - High bootstrap current fraction -> Broad current profile -> Low l_i = $\langle B_p^2 \rangle / \langle B_p \rangle_\psi^2$
- Unfavorable for ideal stability since low l_i reduces the ideal n = 1 no-wall beta limit

The highest β_N/l_i is <u>not</u> the least stable in NSTX

- Passive stability of the resistive wall mode (RWM) must be explained

Major NSTX-U mission is to achieve fully non-inductive operation at high β

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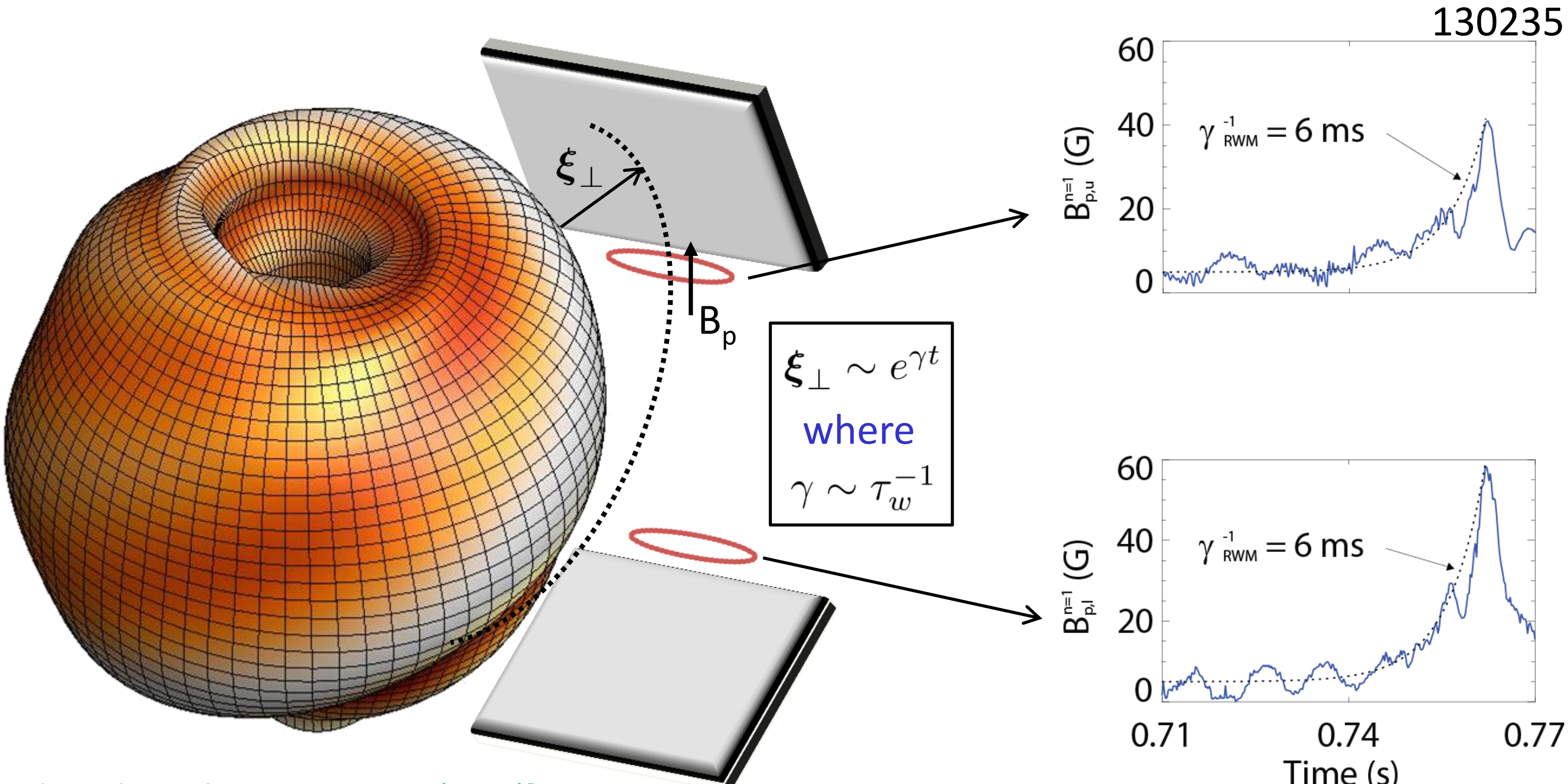
An unstable RWM is an exponential growth of magnetic field line kinking that can cause disruptions

- The resistive wall mode (RWM) is a kinking of magnetic field lines slowed by penetration through vessel structures



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

RWMs in NSTX cause a collapse in β, disruption, and termination of the plasma

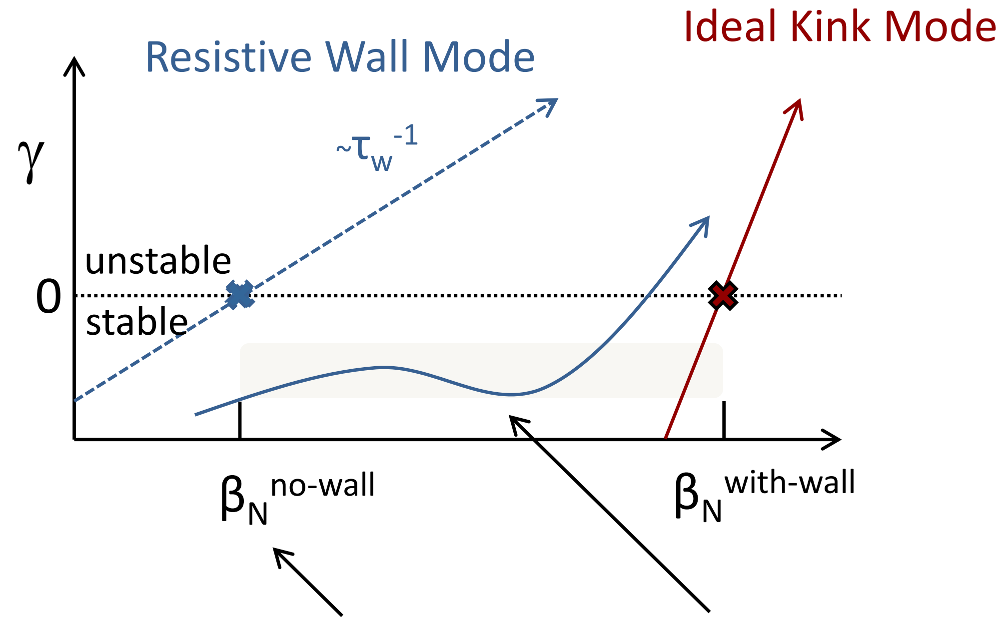
RWM dispersion relation evaluated with ideal and kinetic components allows for passive stabilization of the RWM

Resistive Wall Mode (RWM) fluid dispersion relation:

$$\gamma_f \tau_w = -\frac{\delta W_\infty}{\delta W_b}$$

τ_w^{-1} is slow enough for active stabilization (feedback)

However, experiments operate above the no-wall limit without active control!



Ideal Stability | Kinetic Effects

Passive stabilization

- Collisional dissipation
- Rotational stabilization

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

Models with scalar “critical rotation” for stability could not explain experiments

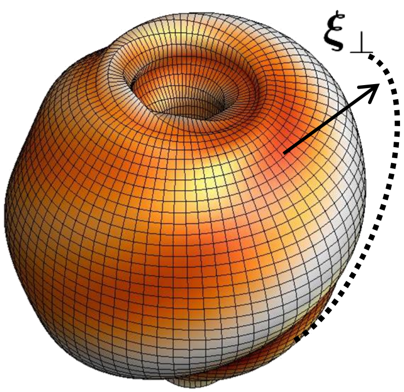
[B. Hu et al., Phys. Rev. Lett. 93, 105002 (2004)]

[S. Sabbagh et al., Nucl. Fusion 50, 025020 (2010)]

Kinetic effects arise from the perturbed pressure, are calculated in MISK from the perturbed distribution function

Force balance:

$$\rho \frac{d\mathbf{v}}{dt} = \mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbb{P}$$



leads to an energy balance:

$$-\frac{1}{2}\int \rho\omega^2 |\boldsymbol{\xi}_\perp|^2 d\mathbf{V} = \frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left[\tilde{\mathbf{j}} \times \mathbf{B_0} + \mathbf{j_0} \times \tilde{\mathbf{B}} - \nabla \tilde{p}_F - \nabla \cdot \tilde{\mathbb{P}}_K\right] d\mathbf{V}$$

Kinetic Energy — Fluid terms

Change in potential energy due to perturbed kinetic pressure is:

$$\delta W_K = -\frac{1}{2}\int \boldsymbol{\xi}_\perp^* \cdot \left(\nabla \cdot \tilde{\mathbb{P}}_K\right) d\mathbf{V}$$

δW_K is solved in MISK by using $\tilde{f}$ from the drift kinetic equation for $\tilde{\mathbb{P}}_K$

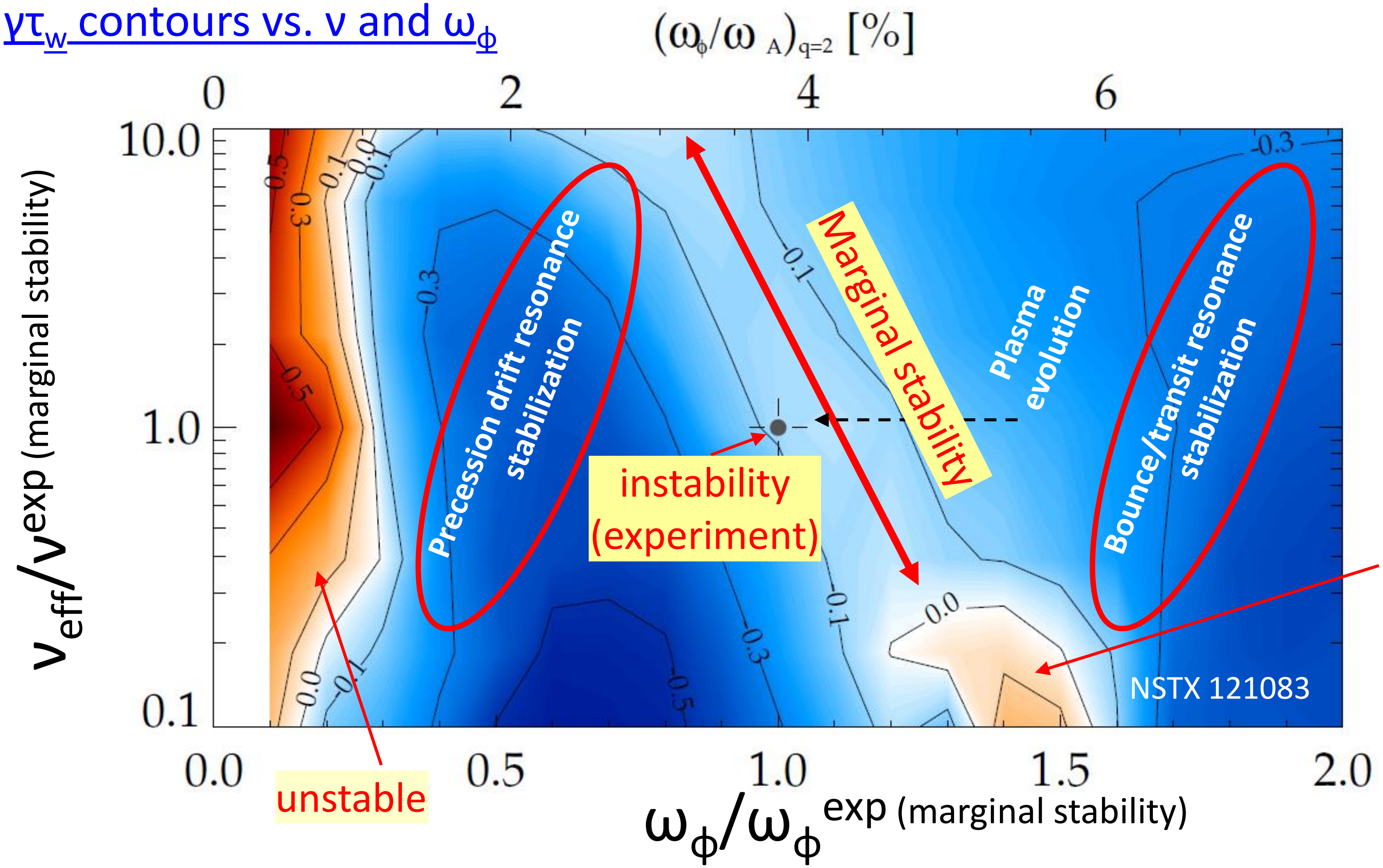
Precession Drift — Collisionality — ~ Plasma Rotation

$$\omega_E \approx \omega_\phi - \omega_{*i}$$

$$\delta W_K = \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2 \int\int\int \left[|\langle H/\hat{\varepsilon}\rangle|^2 \frac{(\omega - \omega_E)\frac{\partial f}{\partial \varepsilon} - \frac{n}{Ze}\frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega}\right] \frac{\hat{\tau}}{m_j^{\frac{3}{2}} B} \left|\frac{v_\parallel}{v}\right| \hat{\varepsilon}^{\frac{5}{2}} d\hat{\varepsilon}\, d(v_\parallel/v)\, d\Psi$$

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

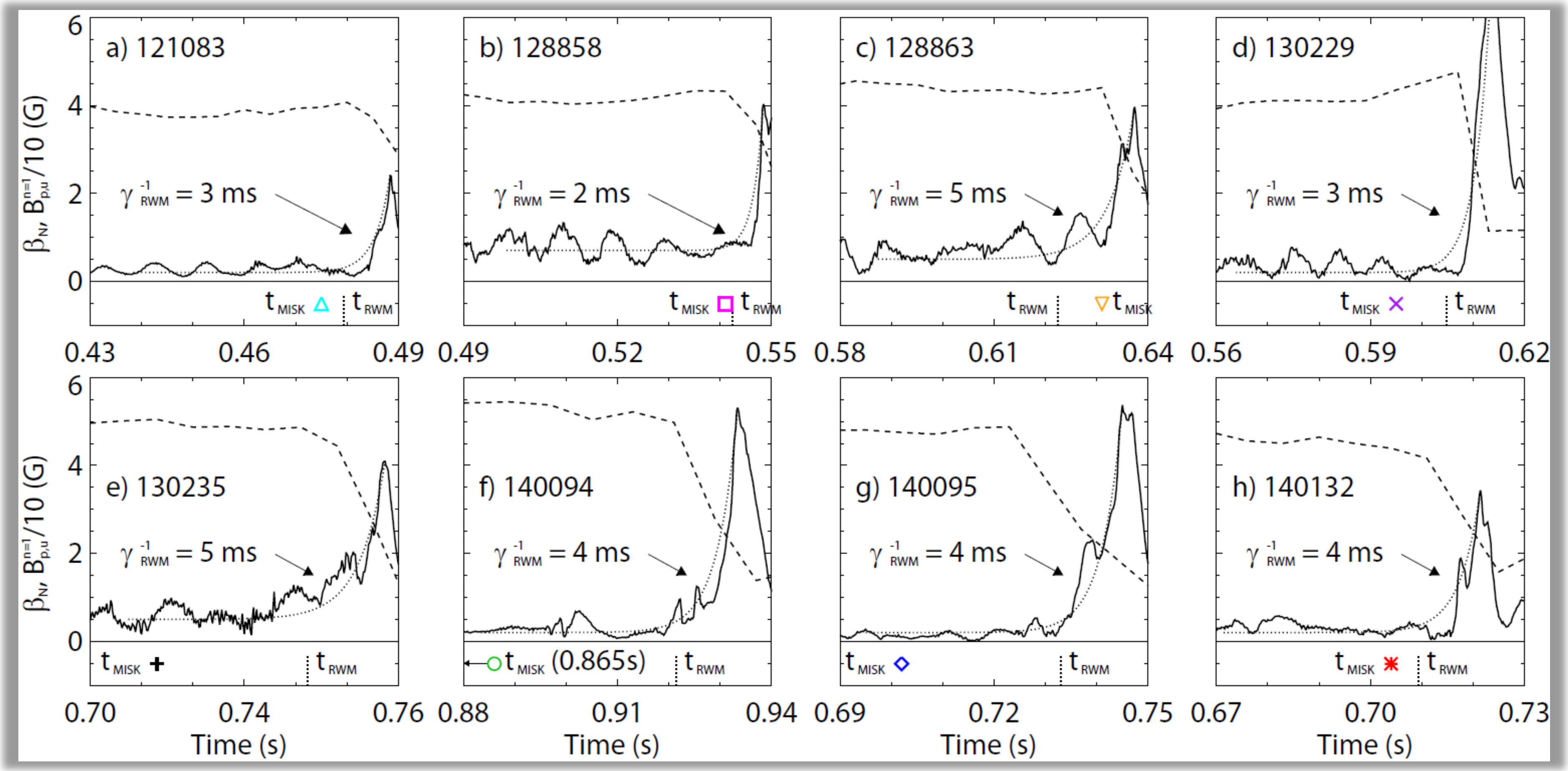
$\gamma\tau_w$ contours vs. ν and ω_ϕ



[J. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)]

- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Stability gradient with ω_ϕ stronger at low collisionality

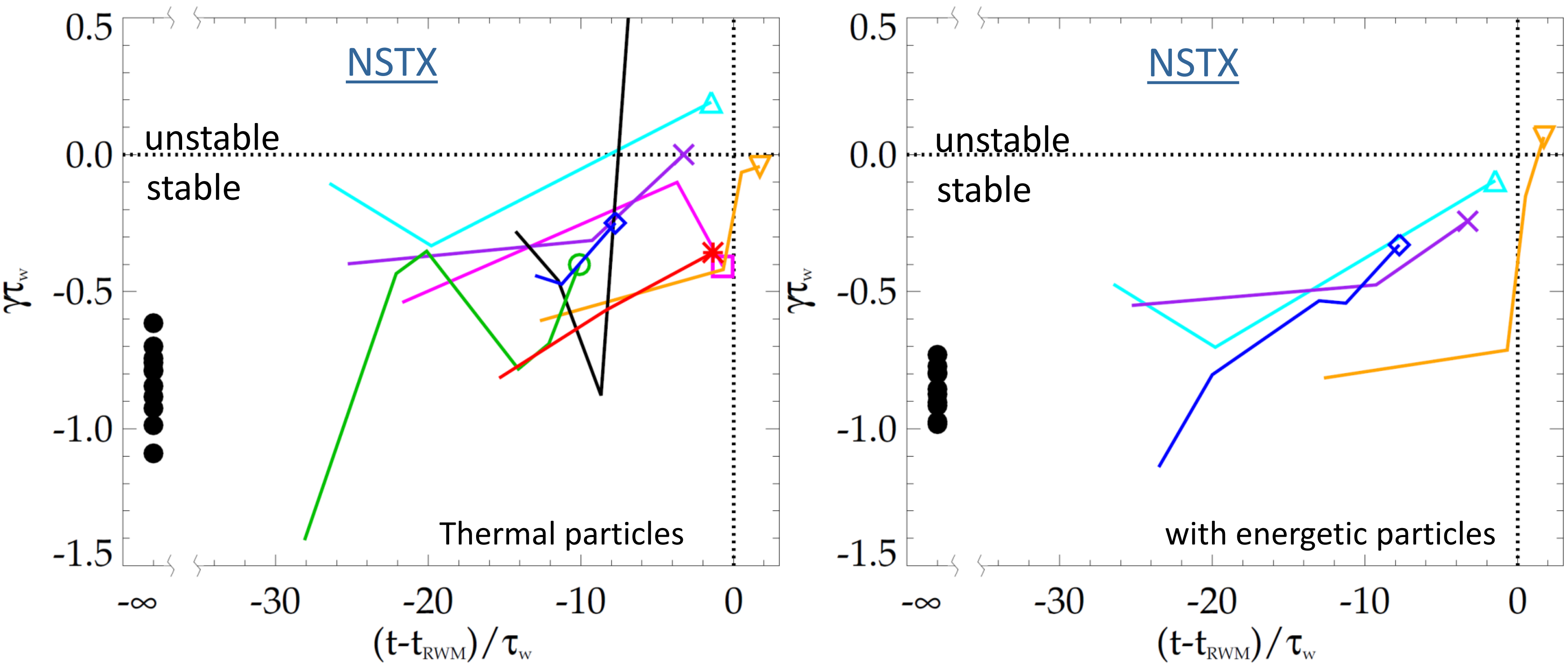
MISK calculations are grounded in validation against unstable experimental plasmas



- MISK calculations (at t_{MISK}) include kinetic effects, have been tested against many marginally stable NSTX experimental cases

[J. Berkery et al., accepted by Nuclear Fusion (2015)]

MISK calculations generally reproduce the approach towards marginal stability seen in experiments



- In each case, the calculations trend towards instability ($\gamma\tau_w$ = 0) as the time approaches the time of experimental RWM instability growth
  - Twelve equilibria from discharges with no RWM show no trend and are more stable in the calculations

[J. Berkery et al., accepted by Nuclear Fusion (2015)]

Summary

- NSTX-U project recently completed on cost and schedule with ~100kA test plasma in August
  - Physics research to begin in December 2015
- NSTX began, and NSTX-U will extend, opportunities to study toroidal confinement physics in novel regimes:
  - Low aspect ratio, strong shaping, high β, low collisionality
  - Advanced divertors, lithium walls, unique start-up solutions
  - Will inform optimal configuration for next-step FNSF device
- Modification of ideal stability by kinetic effects can explain resistive wall mode stability at high beta

More: Berkery APS poster Tues. morning, Sabbagh talk Weds. afternoon

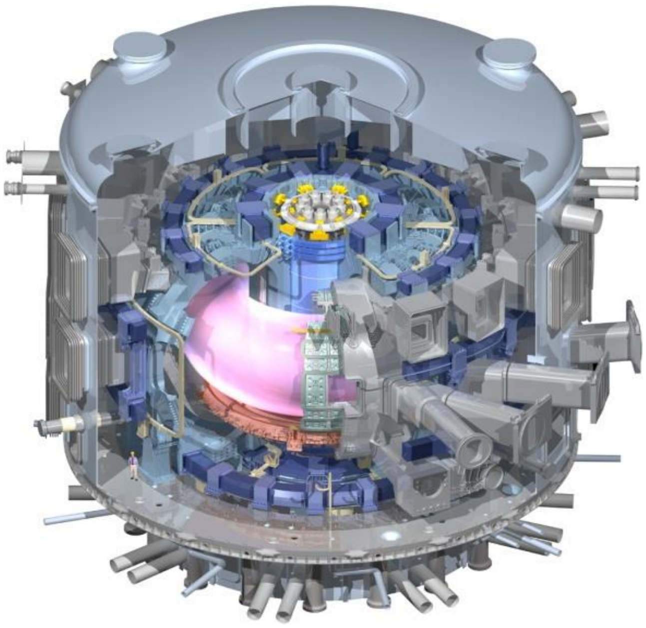
Backup

Unique ST properties also support ITER

ST Extends Predictive Capability for ITER and Toroidal Science

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

Burning Plasma Physics - ITER



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 2nd 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

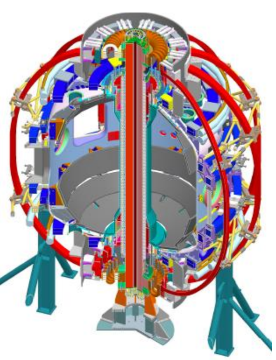
Five Year Facility Enhancement Plan (green = ongoing)

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

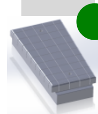
Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack

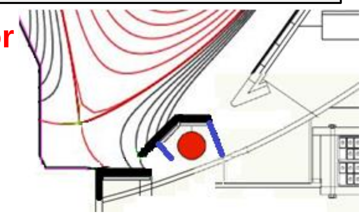


Boundary Science + Particle Control

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

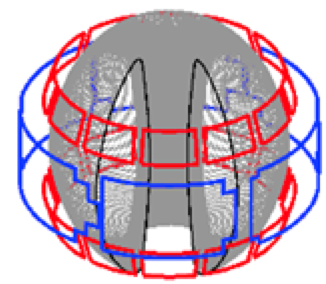


- Lower divertor cryo-pump
- High-Z PFC diagnostics
- LLD using bakeable cryo-baffle

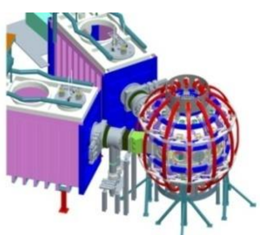


Core Science

- 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



2nd NBI



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