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

NSTX Research Progress towards NSTX Upgrade and Next-Step STs*

J. Menard, PPPL

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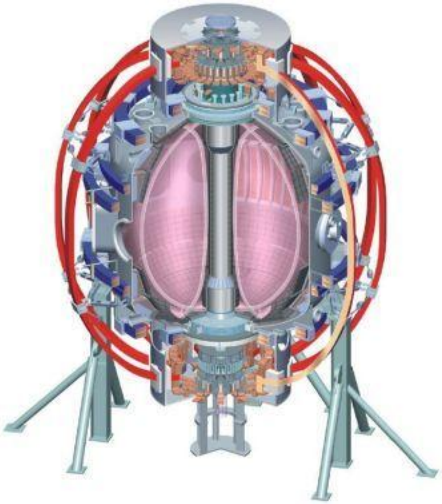
16th International Workshop on Spherical Torus (ISTW2011)

September 27-30, 2011
National Institute for Fusion Science
Toki, Japan



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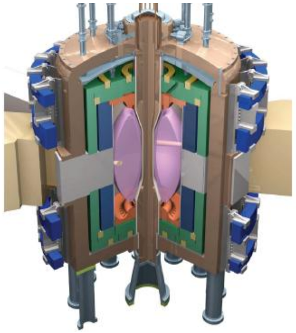
Outline

- NSTX and FNSF missions
- NSTX transport and stability results
- NSTX Upgrade performance capabilities
- ST Pilot Plant studies
- Summary

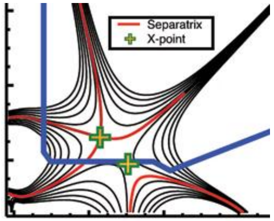
NSTX Mission Elements

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



ST-FNSF

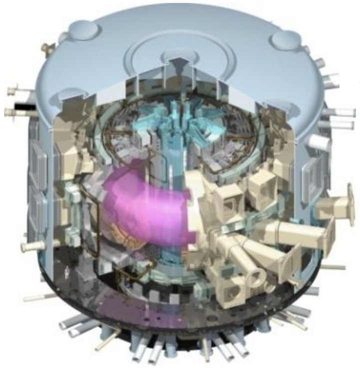
- Develop solutions for plasma-material interface



“Snowflake”

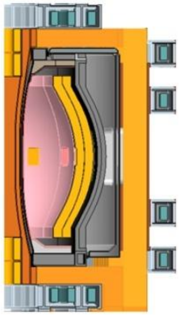
Lithium

- Advance toroidal confinement physics for ITER and beyond



ITER

- Develop ST as fusion energy system

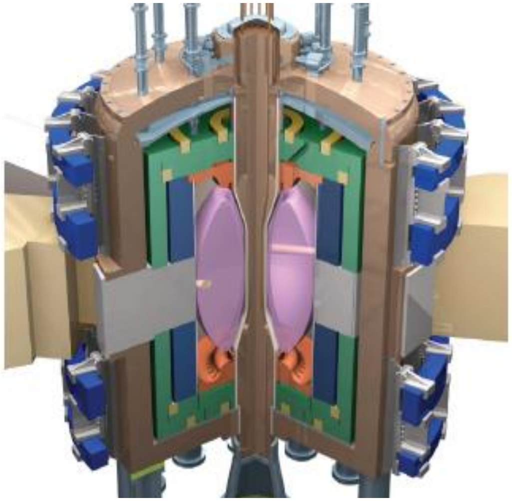


ST Pilot Plant

Mission of ST-FNSF

(See presentation by M. Peng)

- **Provide a continuous fusion nuclear environment of copious neutrons to develop an experimental database on:**
  - Nuclear-nonnuclear coupling phenomena in materials in components for plasma-material interactions
  - Tritium fuel cycle
  - Power extraction



ST-FNSF

- **Complement ITER, prepare for component test facility (CTF):**
  - Low Q (≤ 3): 0.3 x ITER
  - Neutron flux ≤ 2 MW/m^2: 3 x
  - Fluence = 1 MW-yr/m^2: 5 x
  - t_{pulse} ≤ 2 wks: 1000 x
  - Duty factor = 10%: 3 x

Low-aspect-ratio "spherical" tokamak (ST) is most compact embodiment of FNSF

High-Priority Research Areas for ST-FNSF

ReNeW Thrust 16 (2009): "Develop the ST to advance fusion nuclear science"

1. Develop **MA-level plasma current formation and ramp-up**

2. Advance **innovative magnetic geometries, first wall solutions**

3. Understand **ST confinement and stability** at fusion-relevant parameters

4. Develop **stability control techniques** for long-pulse, disruption-free ops

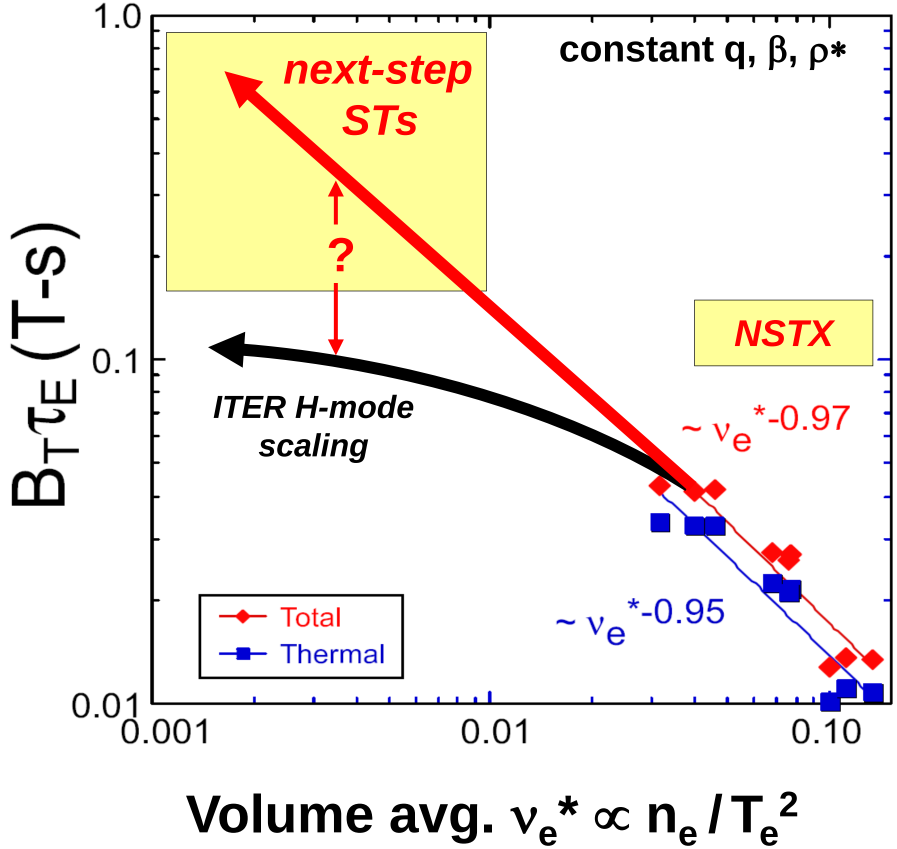
5. **Sustain current, control profiles** with beams, waves, pumping, fueling

6. Develop normally-conducting radiation-tolerant **magnets** for ST applications

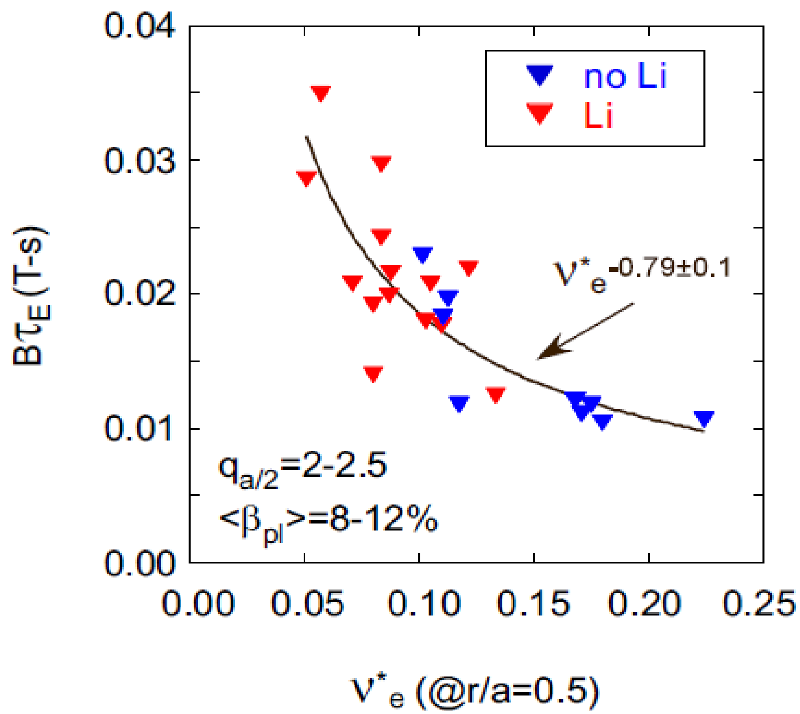
7. **Extend ST performance** to near-burning-plasma conditions

This talk will focus on how NSTX and NSTX Upgrade address the ST-FNSF physics research areas 3, 4, 7 above

NSTX is continuing to explore the favorable collisionality scaling ($\propto 1/\nu_{e*}$) of ST energy confinement



- Increased τ_E with lithium may be result of reduction in ν_e^*



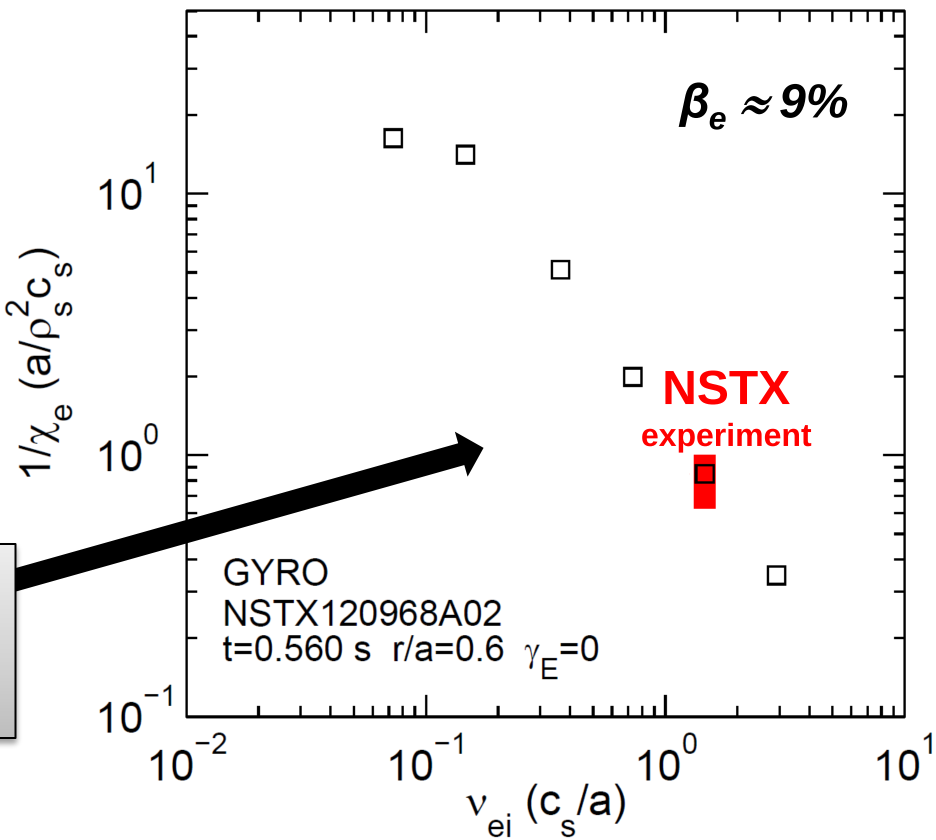
- Expts also show weak β scaling: $\tau_{E\text{-th}} \sim \beta^{-0.12,\,-0.25}$ (no Li, with Li)
  - Important for high-β ST and AT scenarios
  - Beta scaling strong function of ELM character – Type III ELMs → strong degradation

New NSTX turbulence simulations are advancing the understanding of ST energy confinement

- Non-linear gyrokinetic turbulence simulations of micro-tearing instabilities predict $\tau_E \propto 1/\chi_e \propto 1/\nu_e^*$

- Predominantly electromagnetic turbulence – result of high β
- Candidate explanation for ST confinement scaling observed on NSTX and MAST

W. Guttenfelder, PRL 106, 155004 (2011)

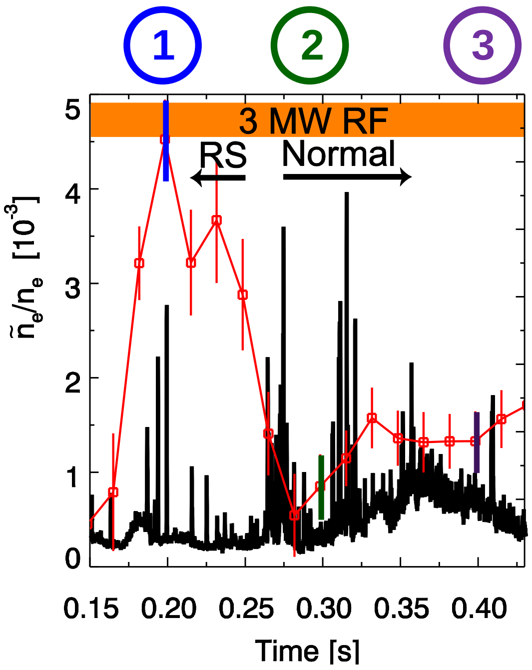


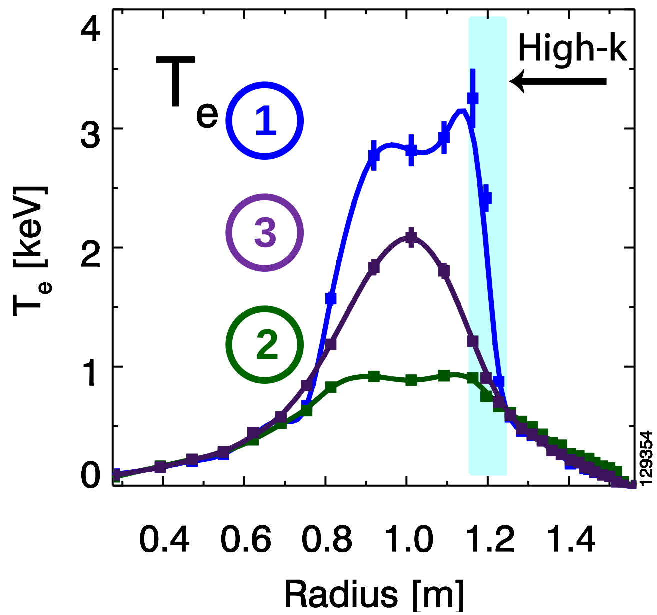
Lower ν* accessible in Upgrade will clarify roles of micro-tearing vs. ETG, TEM in ST e-transport

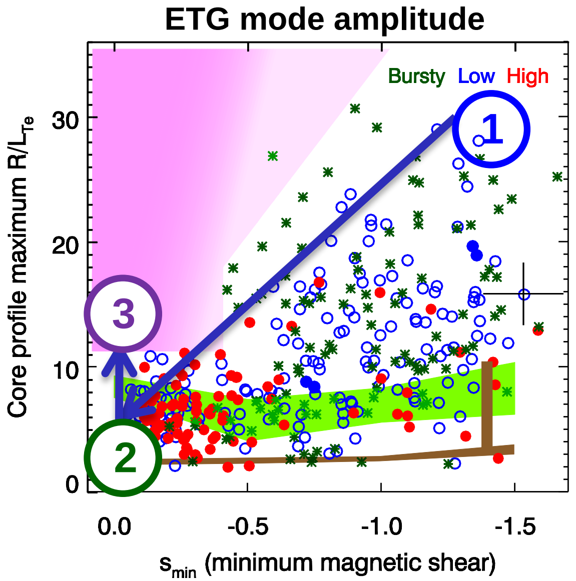
Reversed shear suppresses mode growth even at supercritical ETG gradients during e-ITBs

1. Intermittent, short duration bursts of ETG observed during RS phase
   - Average ETG mode amplitude low, T_e gradient well above ETG critical
   - GYRO simulations indicate non-linear up-shift of critical ETG gradient
2. A series of large amplitude, closely spaced in time ETG bursts collapse Te profile
   - Magnetic shear becomes zero/positive due to anomalous current redistribution
3. T_e profile can only be reheated to ETG critical gradient at zero shear
   - ETG mode amplitude grows to a moderate continuous level

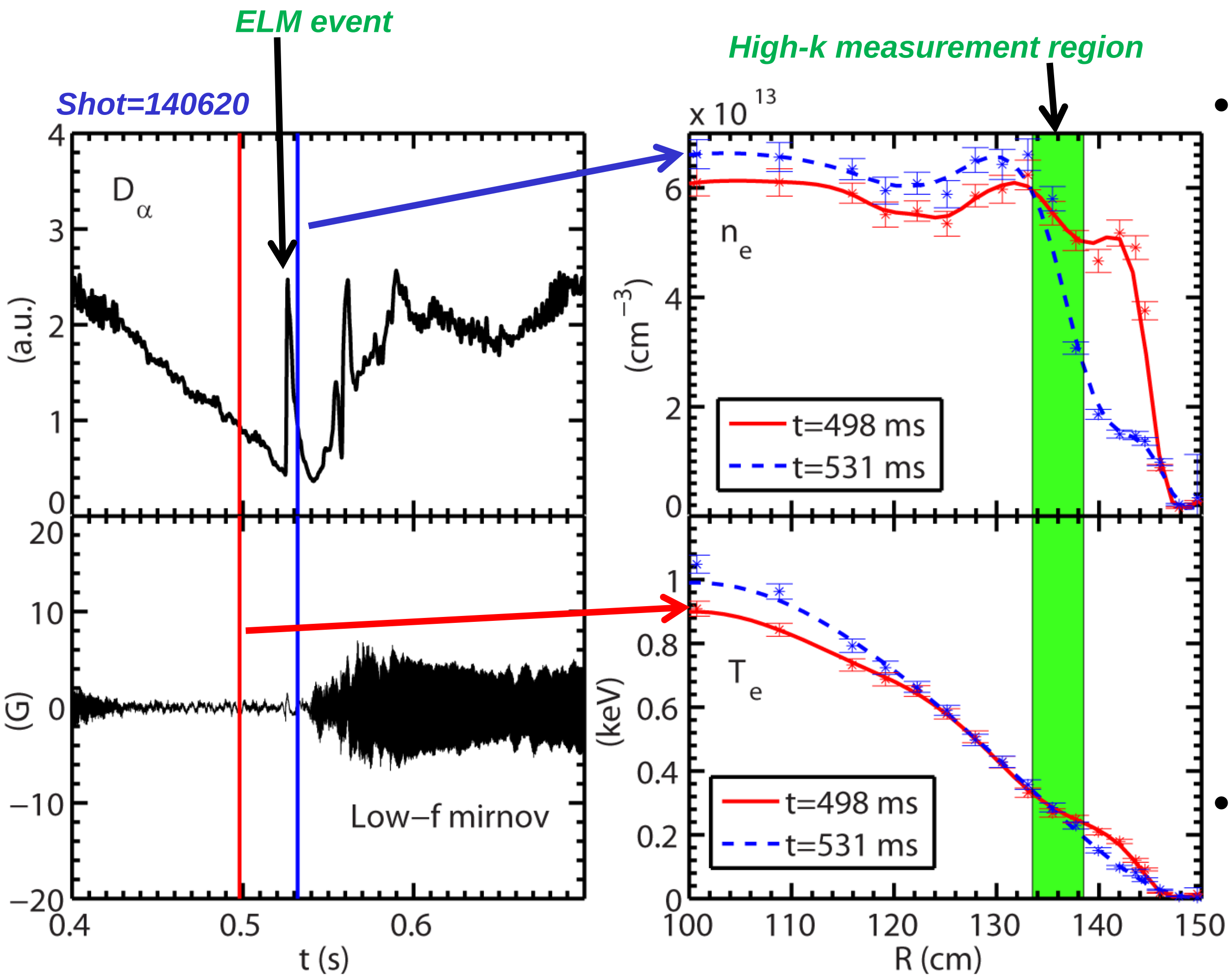
H.Y. Yuh, PRL 106, 055003 (2011)







Large density gradient induced by an ELM event used to probe high-k turbulence and electron transport



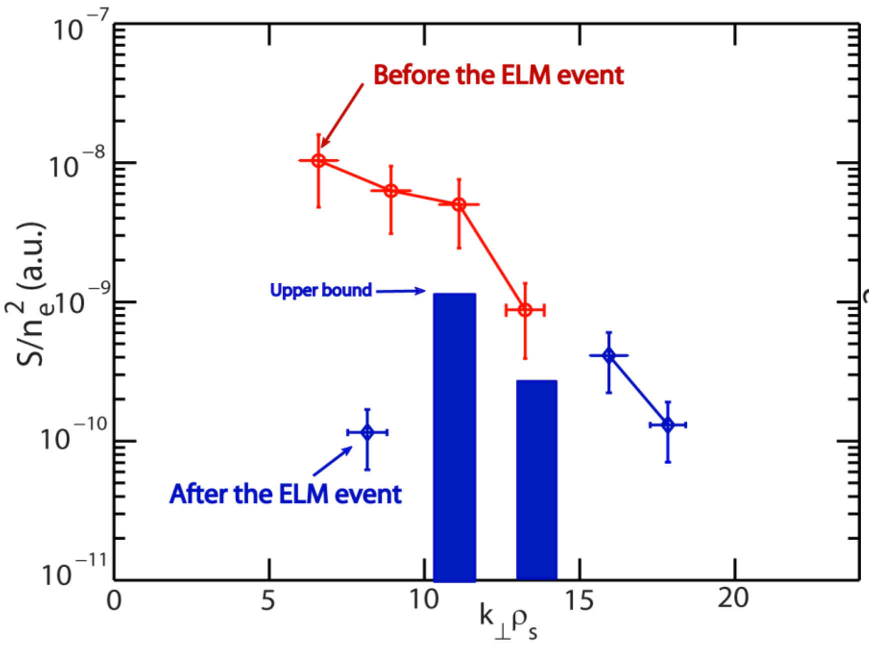
- After the ELM event:
  - A factor of 4 increase in density gradient
  - 60% increase in electron temperature gradient
  - 60 % decrease in ion temperature gradient
  - 40% increase in T_i
  - Less than 25% variation in all other equilibrium quantities
- No large global MHD mode appears before and right after the ELM event

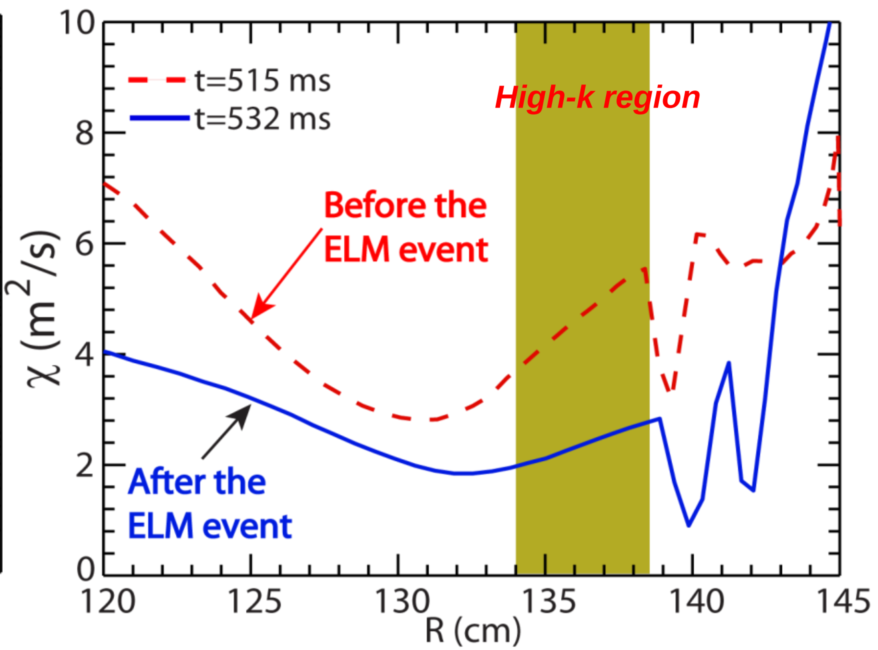
Y. Ren, PRL 106, 165005 (2011)

Correlation Found between Reduction of Turbulence Spectral Density and Improvement of Plasma Thermal Confinement

- Significant decrease in wavenumber spectral power is observed for modes with longer wavelength, $k_\perp \rho_s \lesssim 10$
- The spectral power of the large wavenumbers, $k_\perp \rho_s \gtrsim 15$, is unaffected

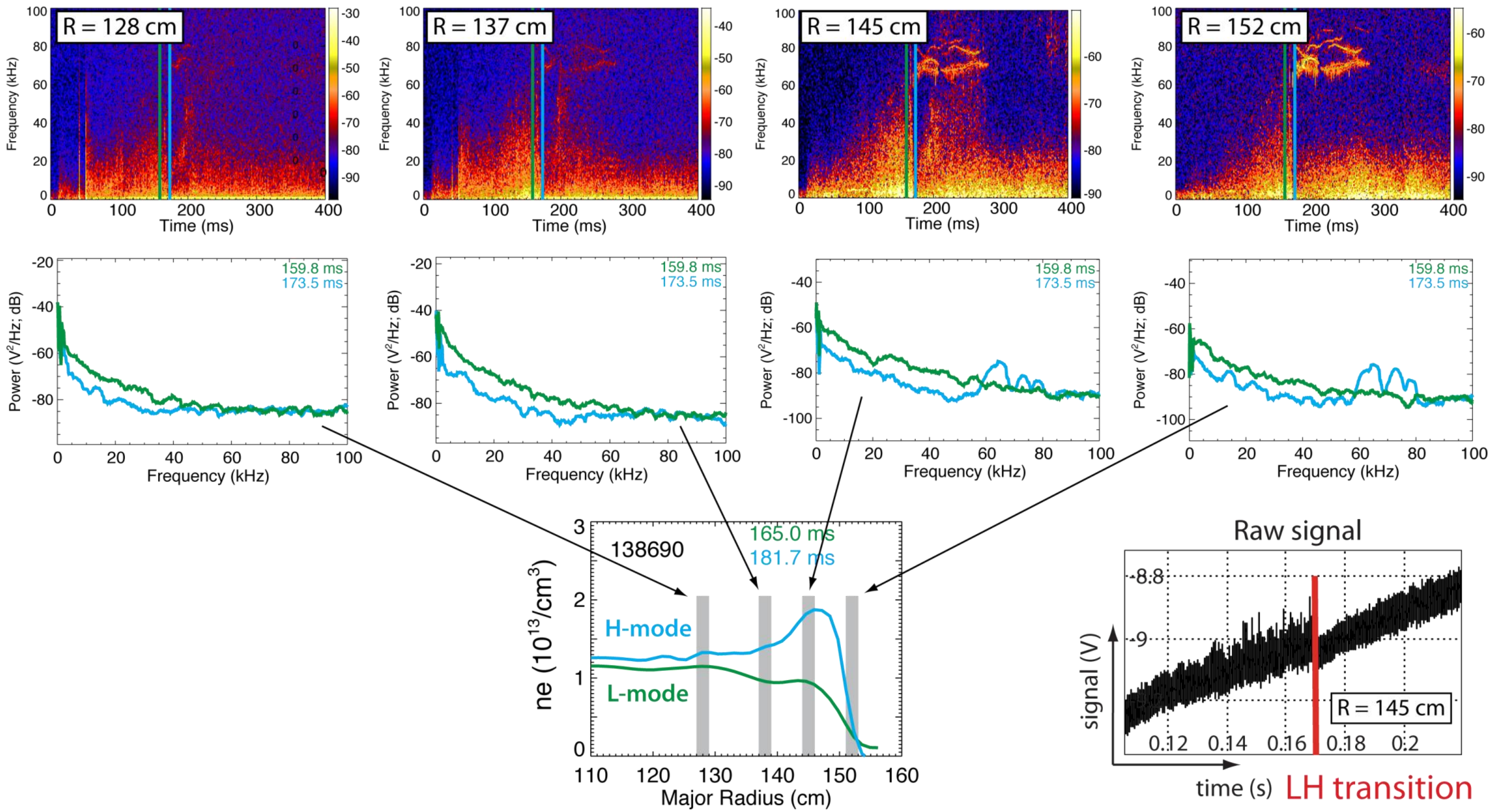
- Plasma thermal diffusivity is decreased by about a factor of 2 after the ELM event
- This increase correlates well with the decrease of the spectral power of the longer wavelength mode





Y. Ren, PRL 106, 165005 (2011)

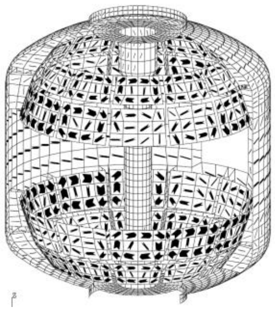
New BES commissioned in 2010: observed decrease in fluctuations at L-H transition from edge to core regions



D. Smith, Univ. Wisconsin

NSTX is 1st tokamak to implement advanced resistive wall mode state-space controller, utilized it to sustain high $\beta_N \sim 6$

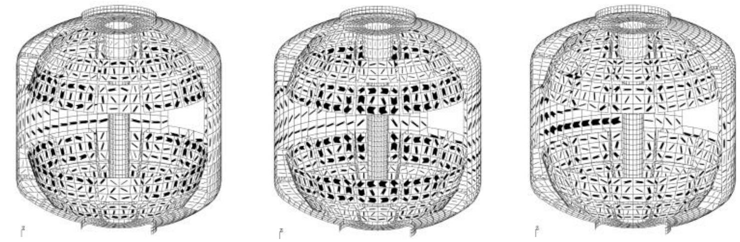
Full 3-D model



~3000+ states

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)



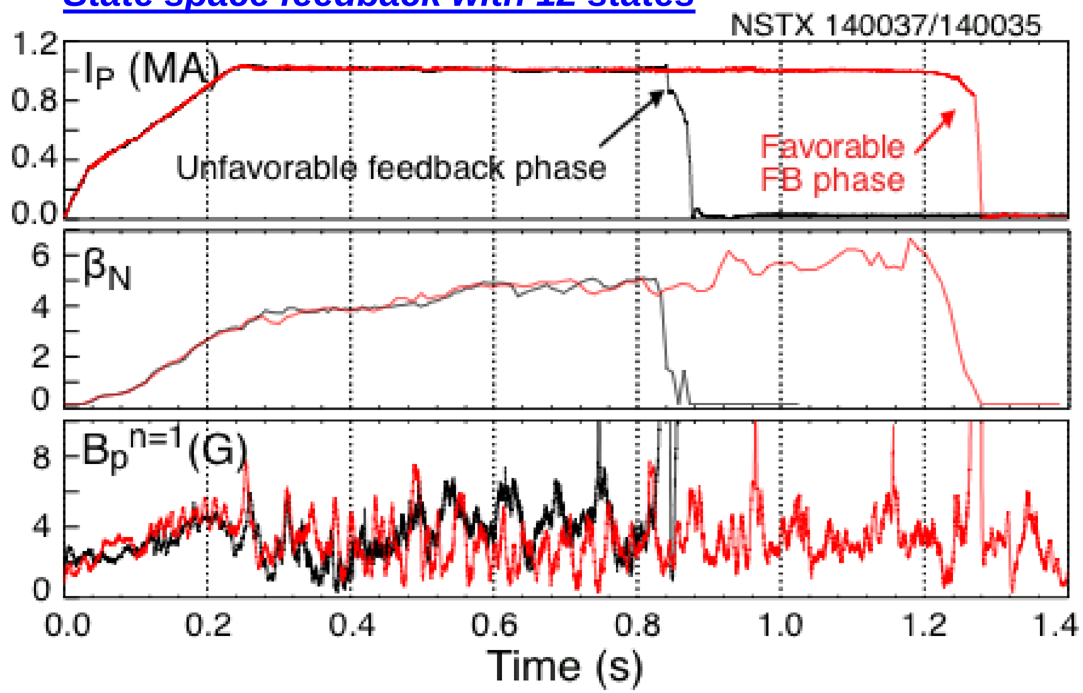
$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$ $\hat{x}_N$

truncate

- *Device R, L, mutual inductances*
- *Instability B field / plasma response*
- *Modeled sensor response*

- **Controller can compensate for wall currents**
  - Including mode-induced current
  - Examined for ITER
- **Successful initial experiments**
  - Suppressed disruption due to n = 1 applied error field
  - Best feedback phase produced long pulse, $\beta_N = 6.4$, $\beta_N / l_i = 13$

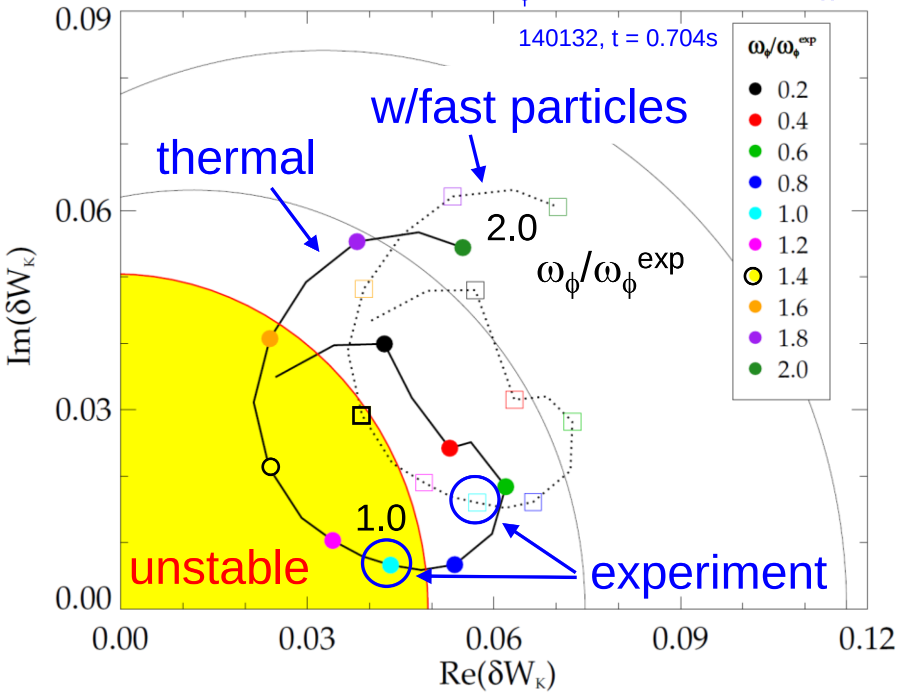
State space feedback with 12 states

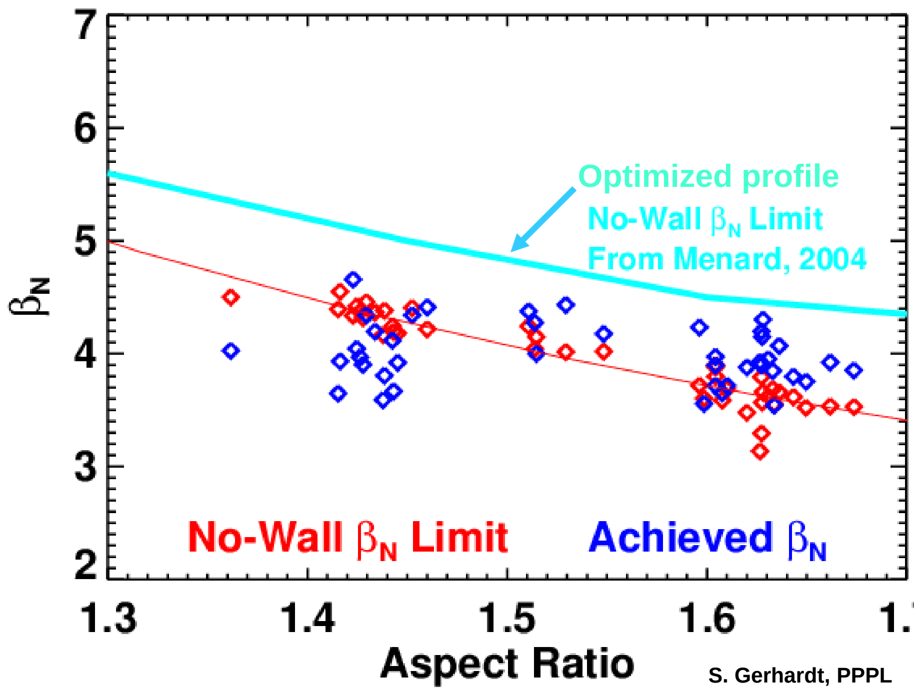


S. Sabbagh, Columbia Univ.

Reduced stability in low l_i target plasma as ω_ϕ reduced, RWM instability is approached; stability also reduced at higher A

RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)





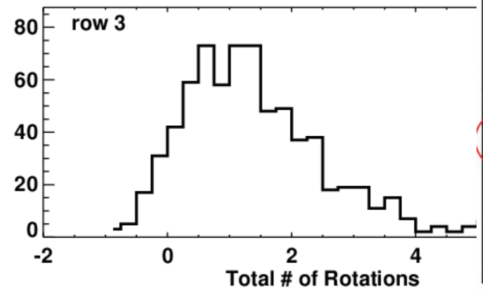
MISK shows plasma stable at time of minimum l_i, and marginally stable at RWM onset (l_i = 0.49)

J. Berkery, Columbia Univ.

Reduction of calculated n = 1 no-wall β_N limit in increased aspect ratio plasmas

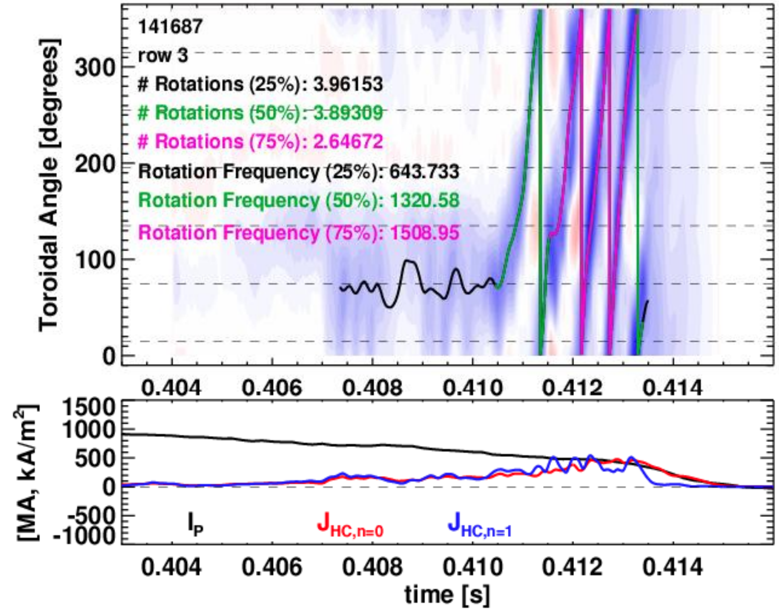
NSTX is addressing disruption physics for FNSF and ITER

- **Example: halo current (HC) dynamics**
  - HC rotation is a key issue for ITER: mechanical resonances could cause significant damage
  - NSTX studying parametric dependencies of the n=1 HC magnitude and rotation dynamics



S. Gerhardt, PPPL

Contours of halo current flowing into the lower divertor of NSTX

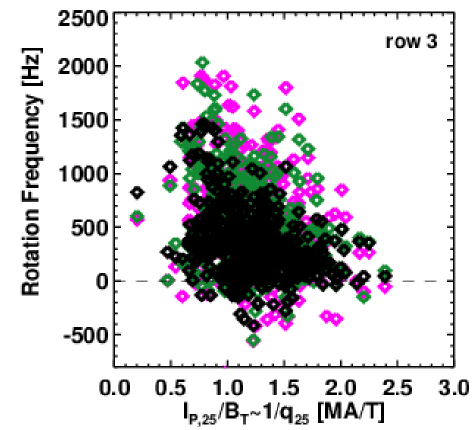


- **Other key contributions:**
  - Current quench database physics
  - Divertor heat loading with fast dual-band IR
  - Fast and slow n=1 control, and rotation profile optimization, for avoidance of disruptive MHD
  - Future – New disruption mitigation studies: Optimization of poloidal location of MGI

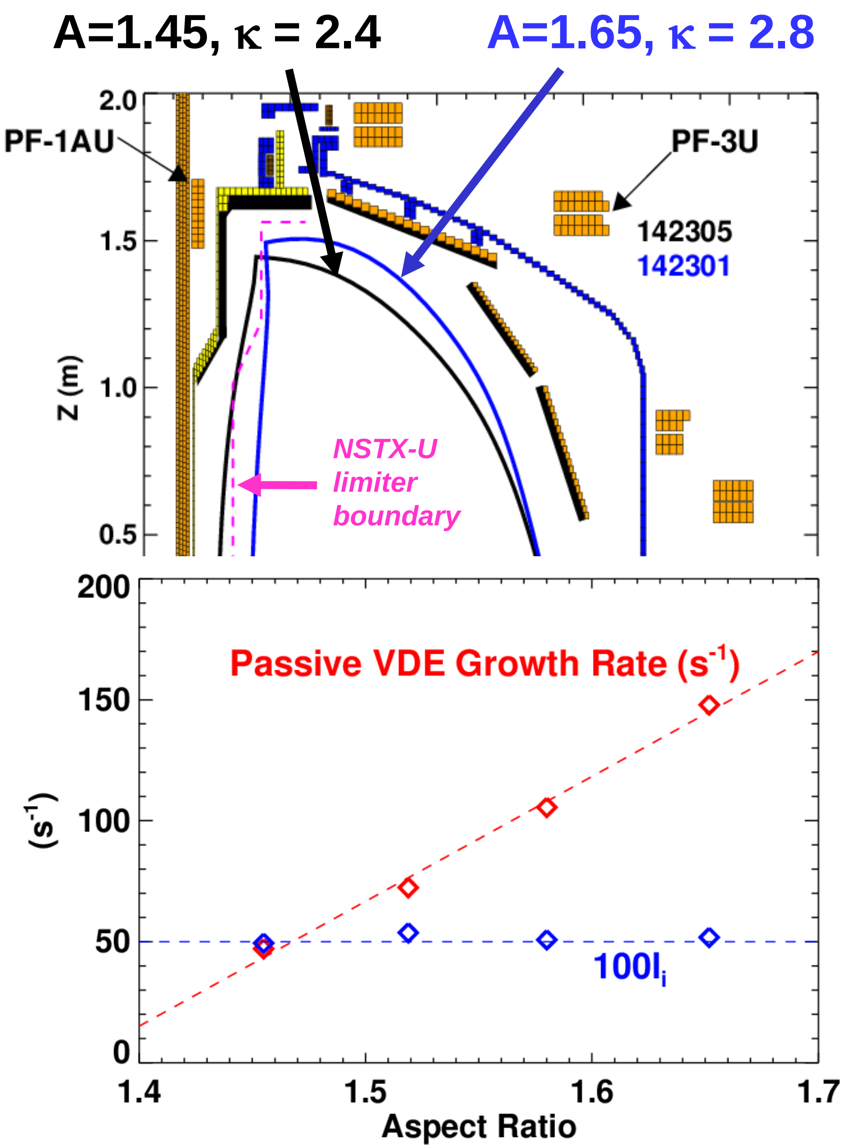
ORNL

Columbia University

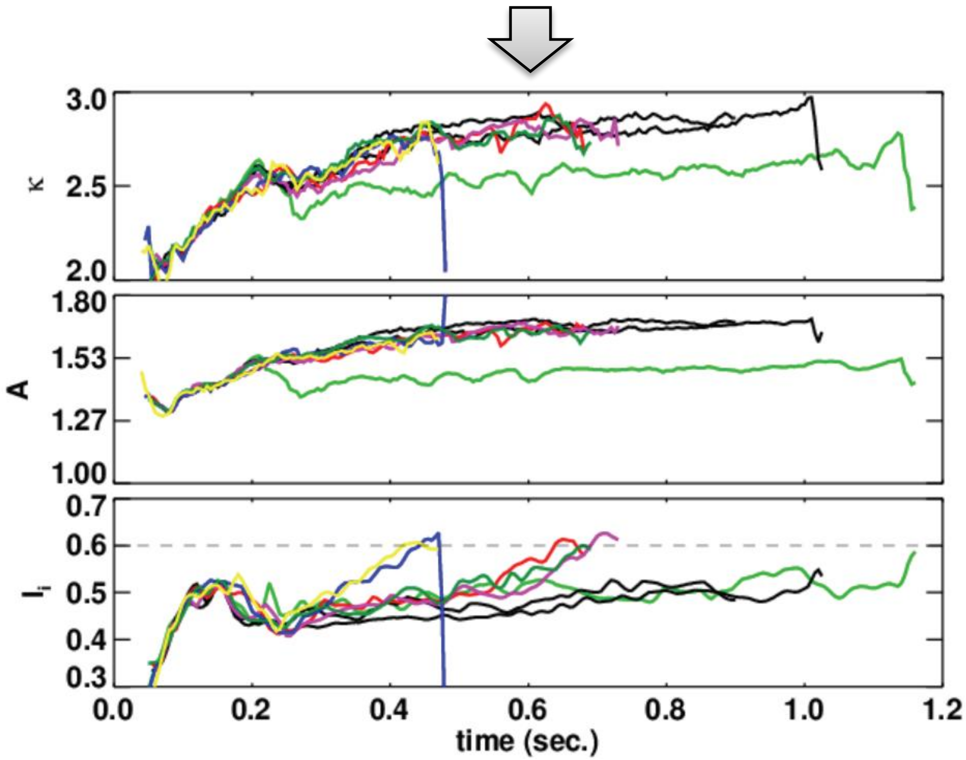
Univ. Washington



NSTX has begun to explore stability impact of higher aspect ratio and elongation in preparation for Upgrade, next-steps



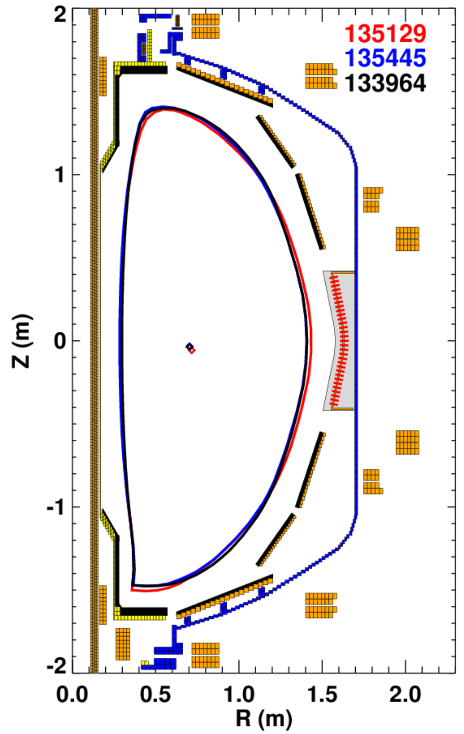
- Successfully operated at $\beta_N > 4$ for several τ_{CR} at Upgrade A and κ
- Found $l_i \leq 0.6$ required to avoid VDE at higher A with present n=0 control



S.P. Gerhardt , Nucl. Fusion 51 (2011) 073031

In 2009-10, NSTX demonstrated sustained high-elongation configurations over a range of currents and fields

High-β_T	***Long Pulse***	***High-β_P***
q*=2.8	***q*=3.9***	***q*=4.7***
B_T=0.44 T	*B_T=0.38 T*	*B_T=0.48 T*
I_P=1100 kA	*I_P=700 kA*	*I_P=700 kA*

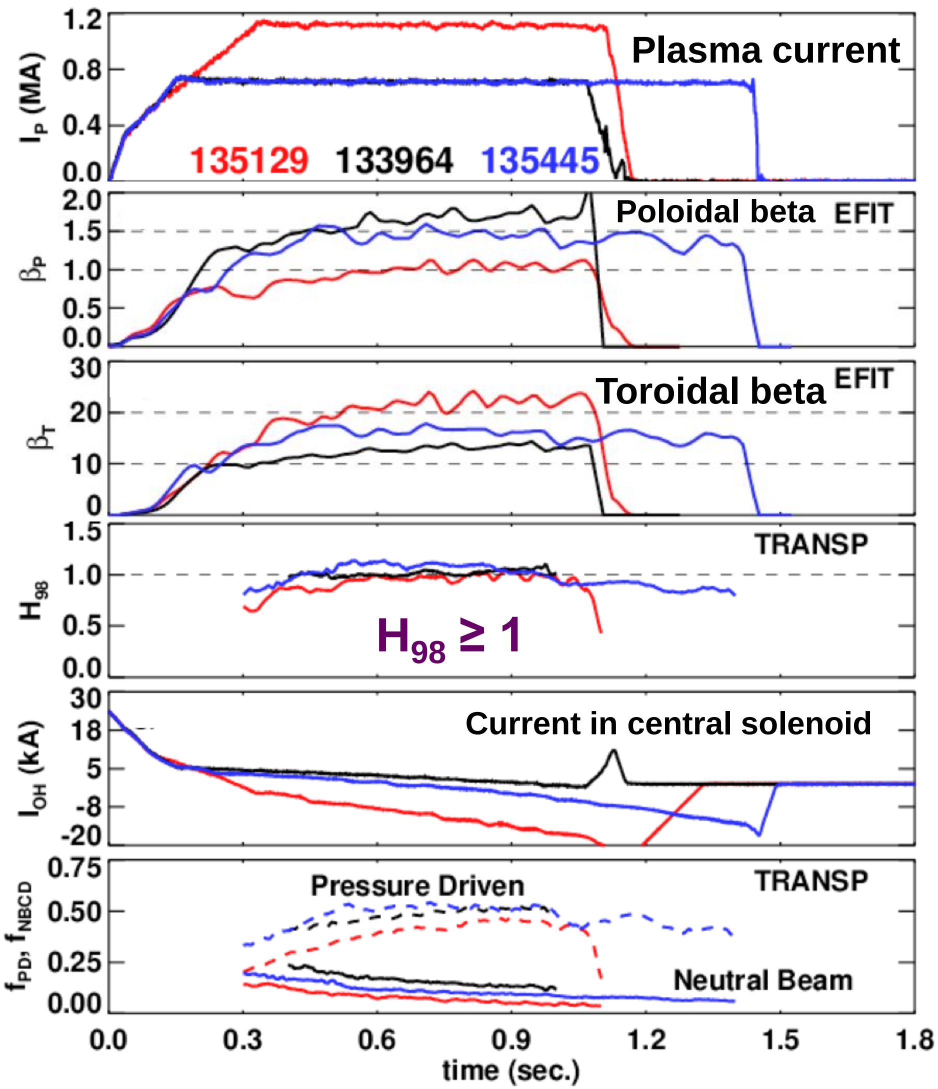


$$q^* = \frac{\varepsilon\left(1+\kappa^2\right)\pi a B_{T0}}{\mu_0 I_P}$$

κ ~ 2.6-2.7

δ ~ 0.8

Double Null



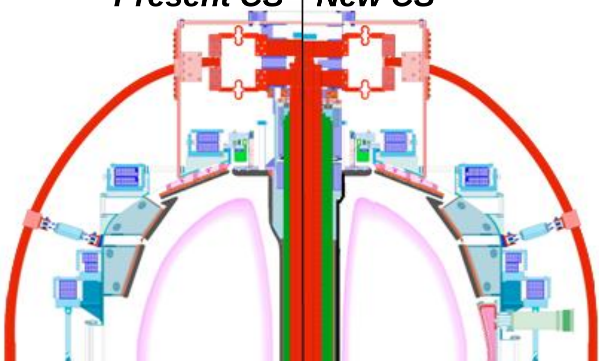
Pulse-lengths limited by OH, TF coil heating limits

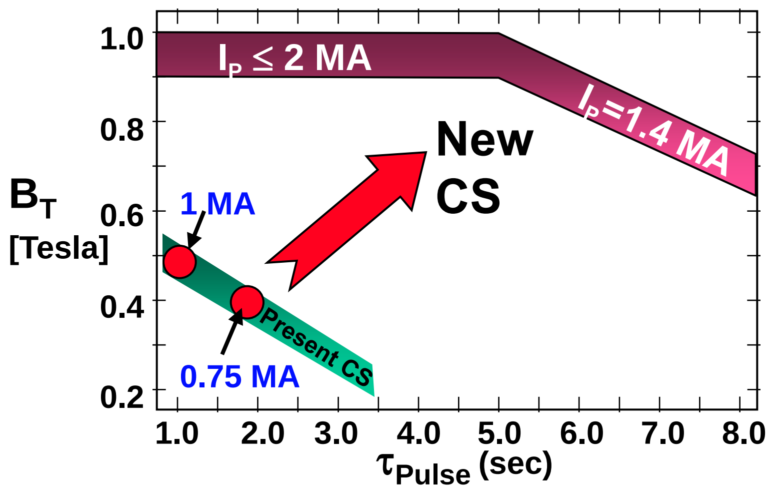
NSTX Upgrade designed to extend NSTX results: 5x longer pulses, 100% non-inductive, ultimately with q profile control

New center stack for 1T, 2MA, 5s

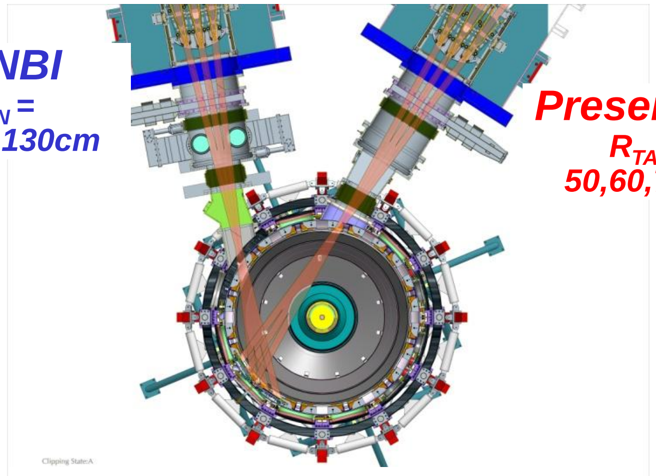
R_0/a = 1.25-1.3 ➡ 1.5-1.6

Present CS | *New CS*

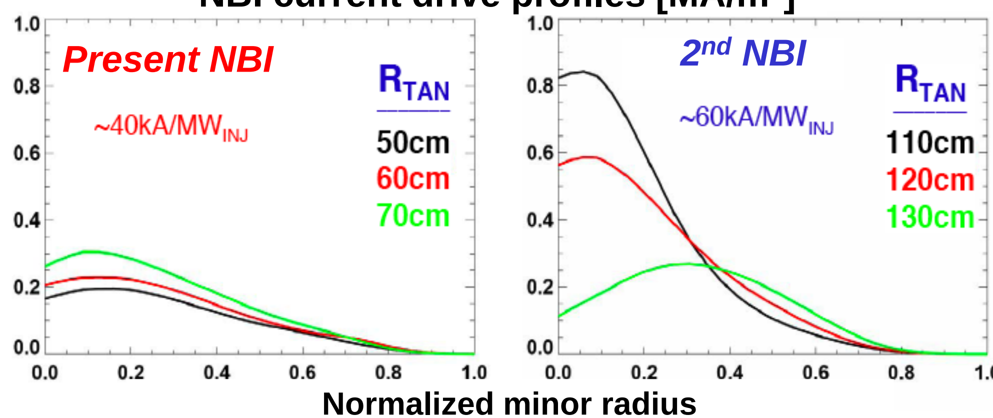




2nd NBI with 5 MW, 5s at larger $R_{Tangency}$



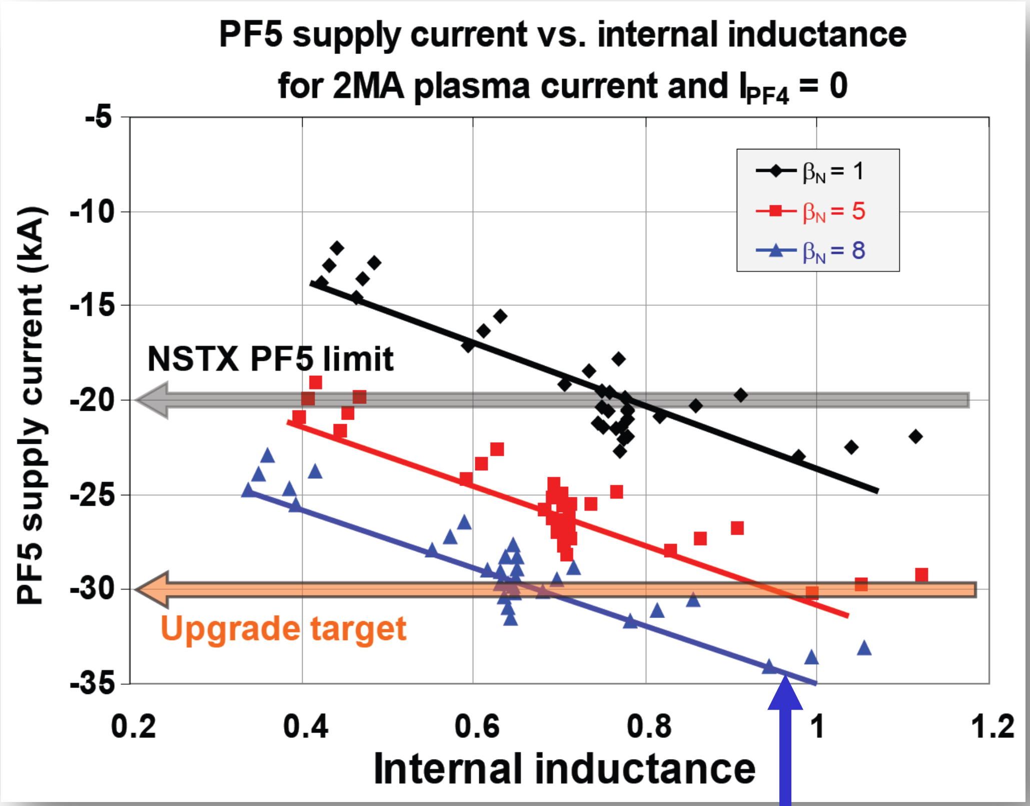
NBI current drive profiles [MA/m²]



Magnet operation at ~1T (vs. 0.55T):
ν^* reduced 3-6x, $nT\tau$ up to 10x higher

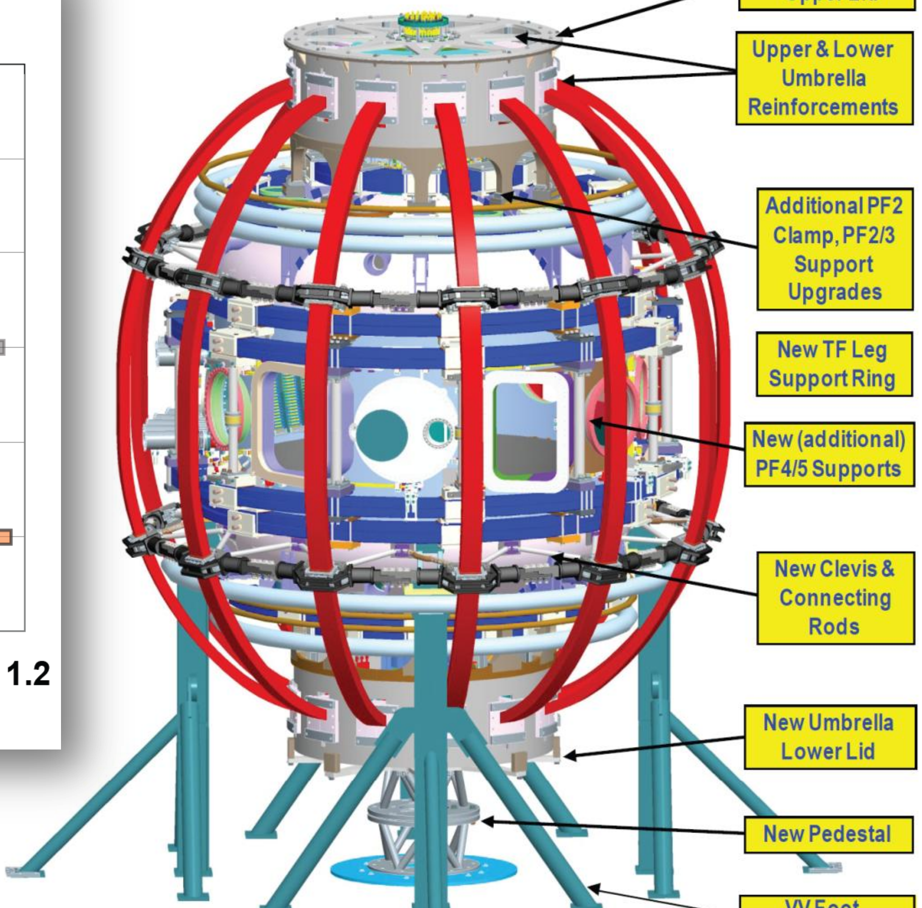
Up to 2x higher NBI current drive efficiency:
Non-inductive ramp-up, sustainment, J(r) control

Upgrade structural enhancements designed to support high β at full I_P = 2MA, B_T=1T: $\beta_N = 5, l_i \leq 1$ and $\beta_N = 8, l_i \leq 0.6$



High l_i, high-β_N scenarios determine the maximum vertical field (PF5) current required

NSTX Upgrade

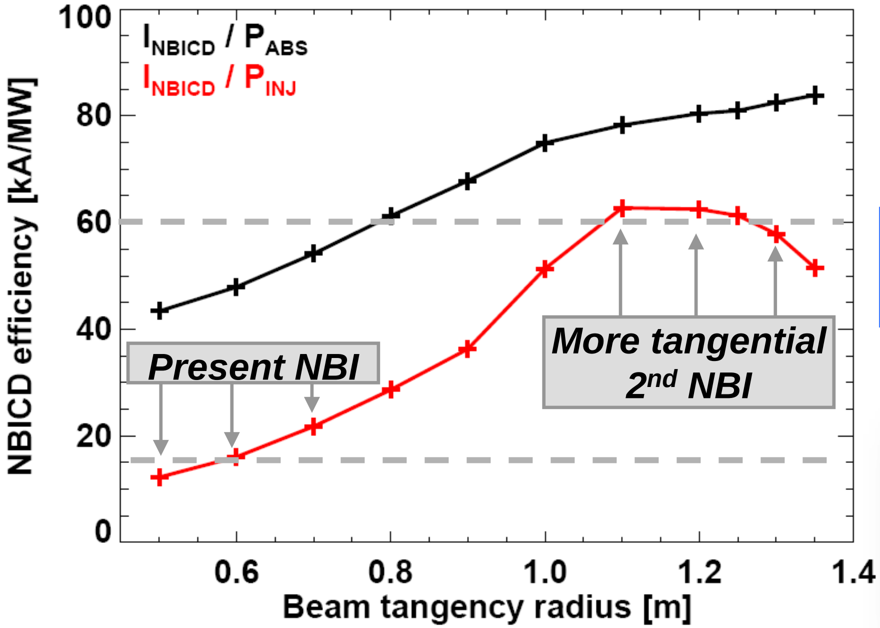


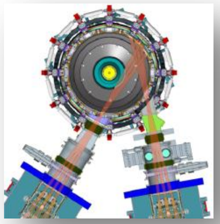
Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new CS + more tangential 2^{nd} NBI

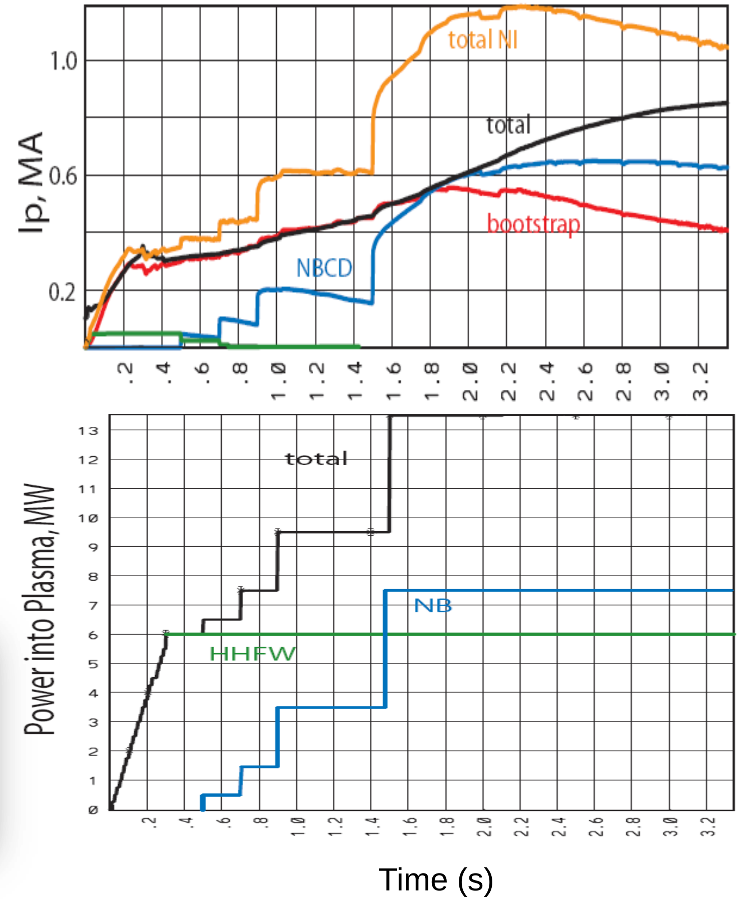
- **New CS provides higher TF (improves stability), 3-5s needed for J(r) equilibration**
- **More tangential injection provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
  - 1.5-2x higher current drive efficiency

E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5 \times 10^{19} m^{-3}$, $\overline{T}_e$ = 0.83keV



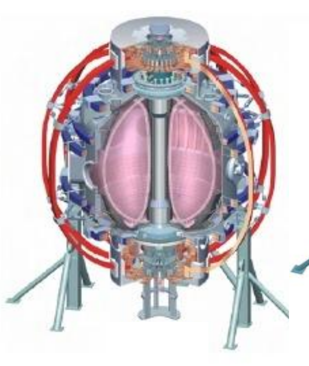


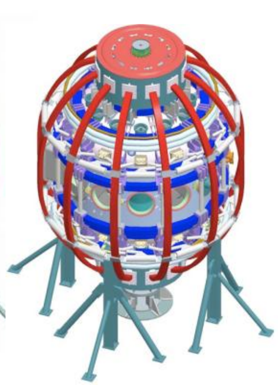


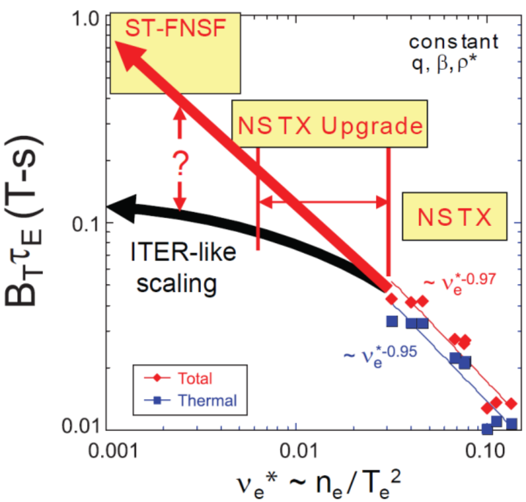
NSTX Upgrade will bridge the device and performance gaps toward next-step STs

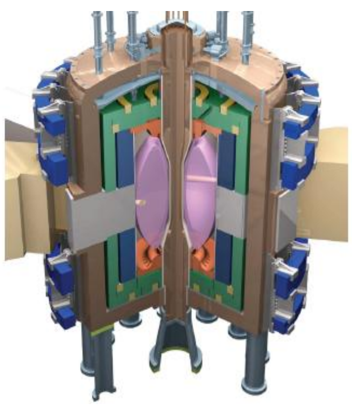
	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	ST Pilot Plant
Major Radius R_0 [m]	0.86	0.94	1.3	2.2
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.6	≥ 1.7
Plasma Current [MA]	1	2	4 → 10	10 → 20
Toroidal Field [T]	0.5	1	2-3	2-3
P/R, P/S [MW/m,m^2]	10, 0.2*	20, 0.4*	30 → 60, 0.6 → 1.2	40 → 100, 0.3 → 1
Fusion gain Q_{DT}			0 → 1-3	0 → 10-20

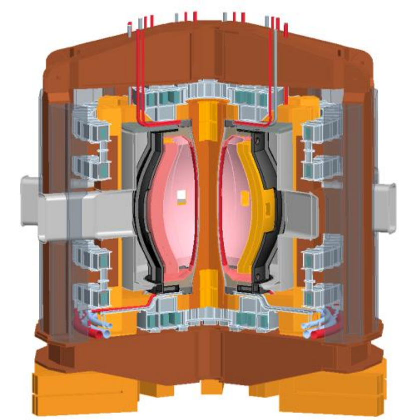
*** Includes 4MW of high-harmonic fast-wave (HHFW) heating power**











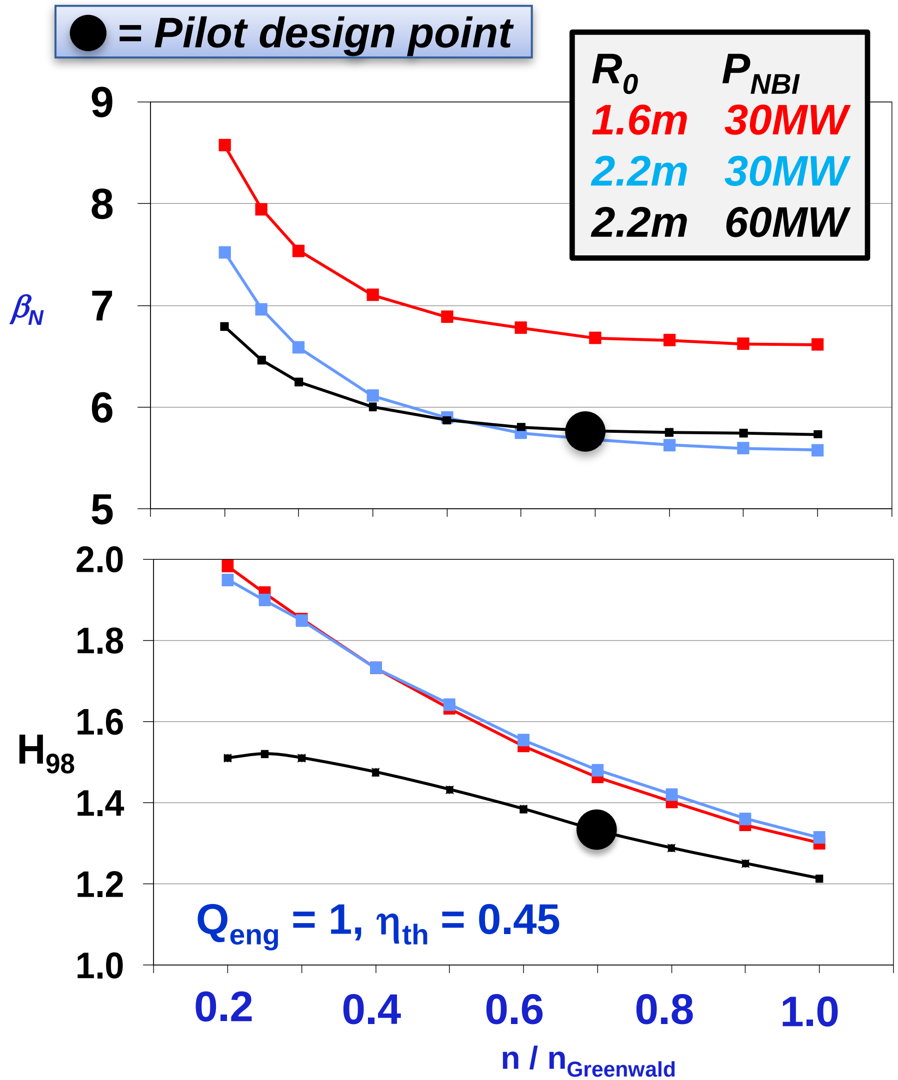
Pilot plant goals, capabilities

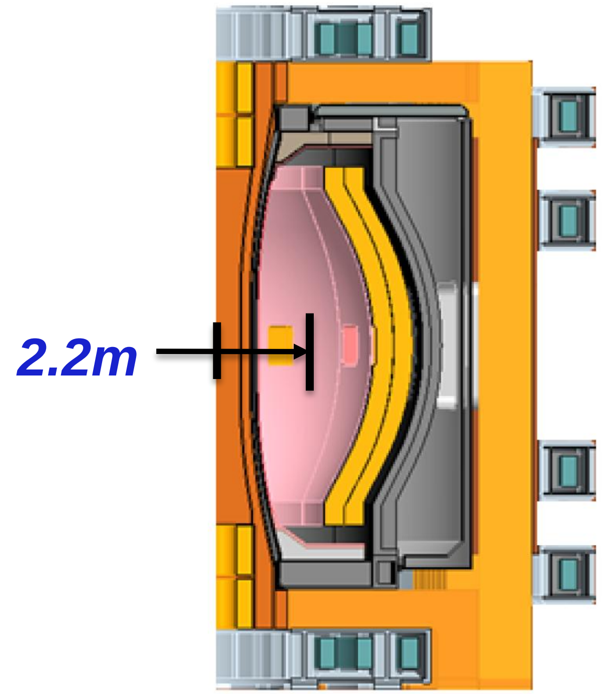
- Pilot Plant goal:

  Integrate key science and technology capabilities of a fusion power plant in a next-step R&D facility

- Targeted ultimate capabilities:
  - Fusion nuclear S&T development, component testing
    - Steady-state operating scenarios
    - Neutron wall loading ≥ $1MW/m^2$
    - Tritium self-sufficiency
  - Maintenance scheme applicable to power plant
    - Demonstrate methods for fast replacement of in-vessel components
  - Net electricity production
    - Bridge gap between ITER/CTF and power plant (~1-1.5 GWe)

Size of ST pilot depends primarily on achievable β_N



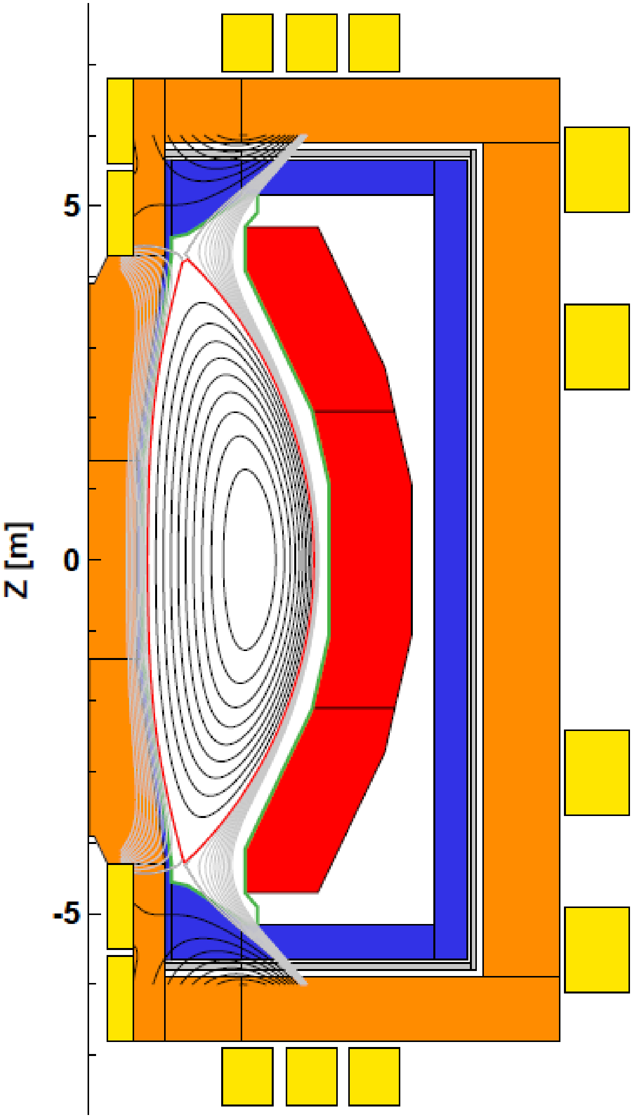


- A = 1.7 = 2.2m / 1.3m
- B_T = 2.4T, I_P = 18-20MA
- Avg. W_n = 1.9-2.9 MW/m^2
- Peak W_n = 3-4.5 MW/m^2

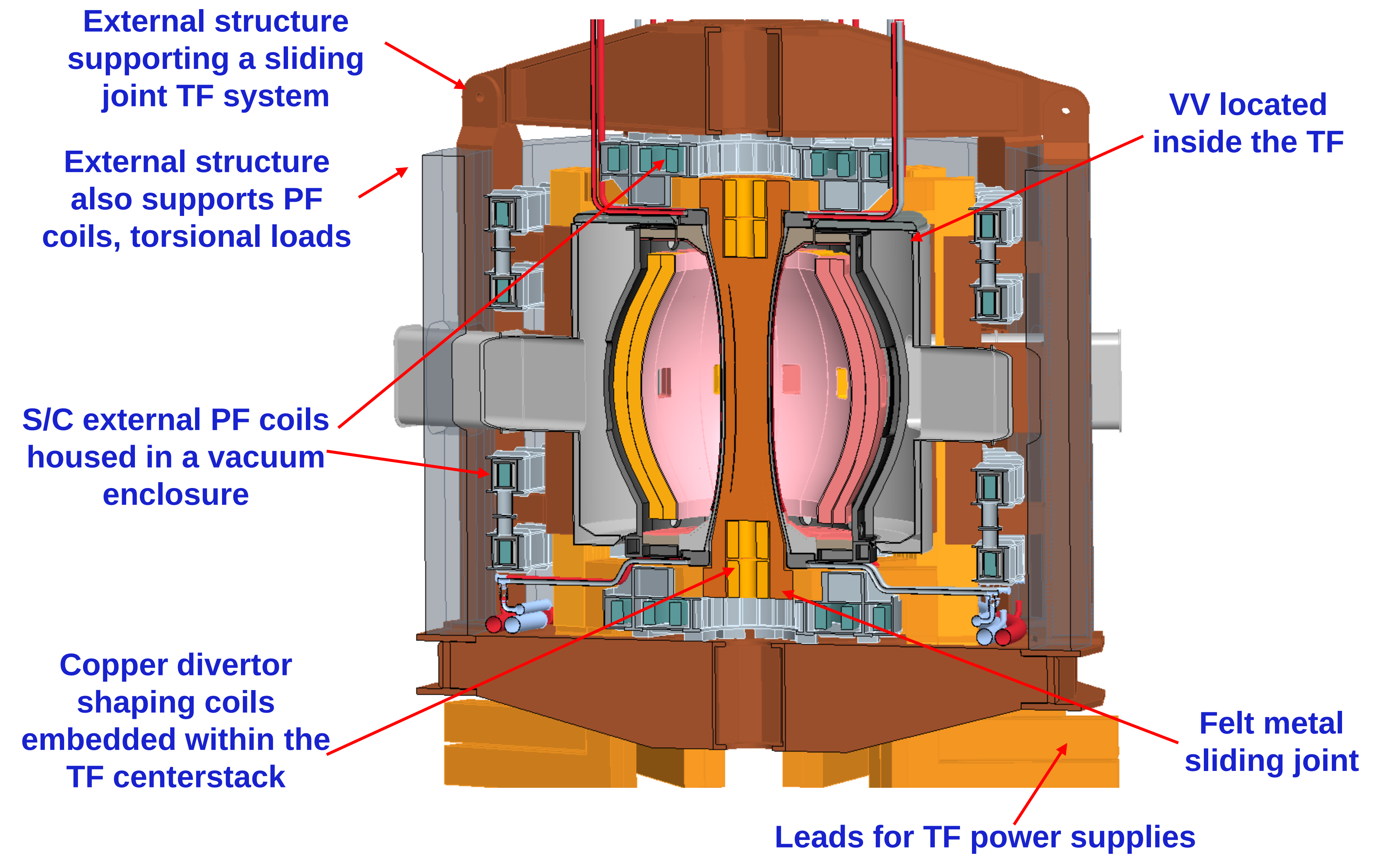
Higher density favorable for reducing β_N and H_{98} (also fast ion fraction)

ST pilot plant design features

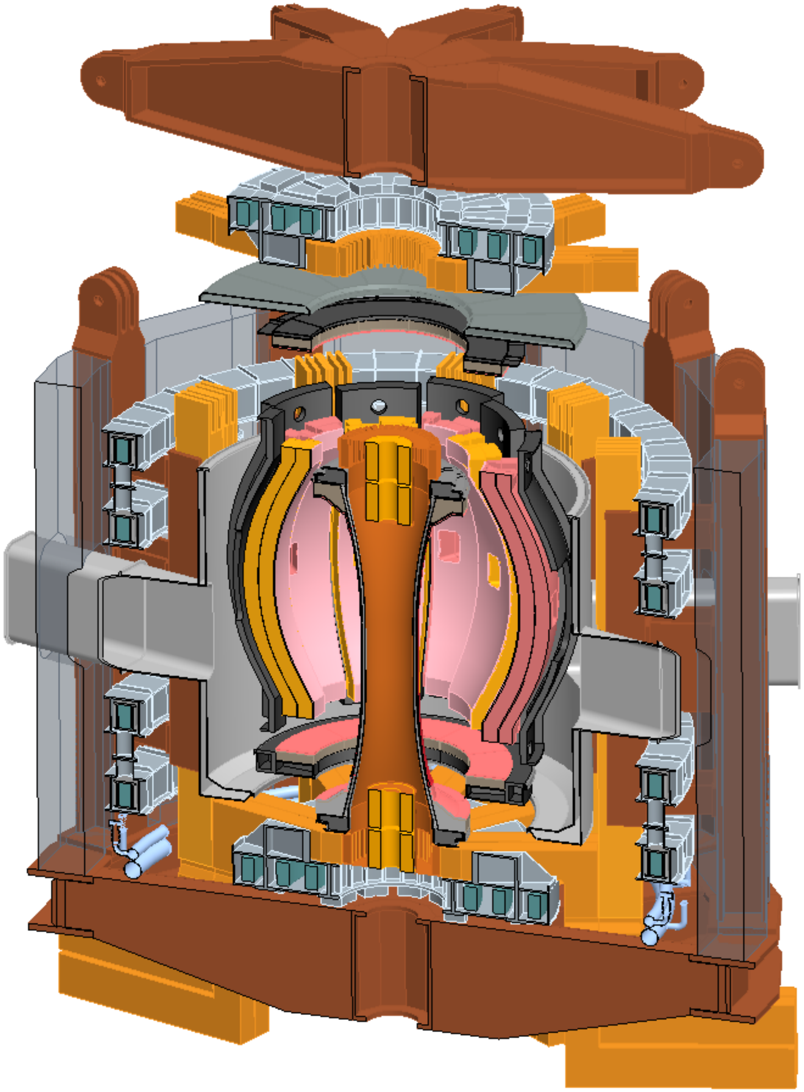
- Flared TF rod to reduce power: 150-200MW
- Strong shaping for stability, bootstrap current
  - Elongation ~3 and triangularity ~ 0.6
- DN divertor for power handling
  - Avg. heat flux over wetted area = 7MW/m^2
  - Peak heat flux could be much higher
  - May need snowflake, flowing Li, Super-X, radiation…
- PF coils in ends of TF rod to produce diverted high δ plasma, protect PF coils
  - All other PF coils superconducting
- Vacuum vessel independent of TF legs
  - 10 TF outer legs, ripple < 0.25% at plasma
- Conformal blankets to maximize TBR
  - Entire blanket structure removable vertically
- Shielding for vessel, TF outer legs, PF coils outside center-stack → lifetime components
- Center-stack shielded for 1-2 FPY



Engineering design details of ST pilot plant



ST pilot plant employs vertical maintenance with removable center-stack and blanket components



Blanket modules can be lifted as unit or as sub-assemblies

Summary

- NSTX has achieved significant advancements in the understanding of confinement, stability, MHD control
- NSTX Upgrade is designed to access:
  - Reduced collisionality - relevant to all ST physics areas
  - Full non-inductive operation with equilibrated profiles
  - Non-inductive ramp-up with NBI current drive
  - High beta at full field and current
- Investigating ST pilot-plant configuration as high-performance next-step for:
  - High neutron wall loading
  - Demonstrating tritium self-sufficiency
  - Electricity break-even