# Confinement and stability discoveries from high-beta spherical tori

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*With contributions from the NSTX, MAST Pegasus, and other ST research teams*

**Norman Rostoker Memorial Symposium**

**The Fairmont Newport Beach Hotel**

**August 24-25, 2015**

U.S. DEPARTMENT OF ENERGY

PRINCETON UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

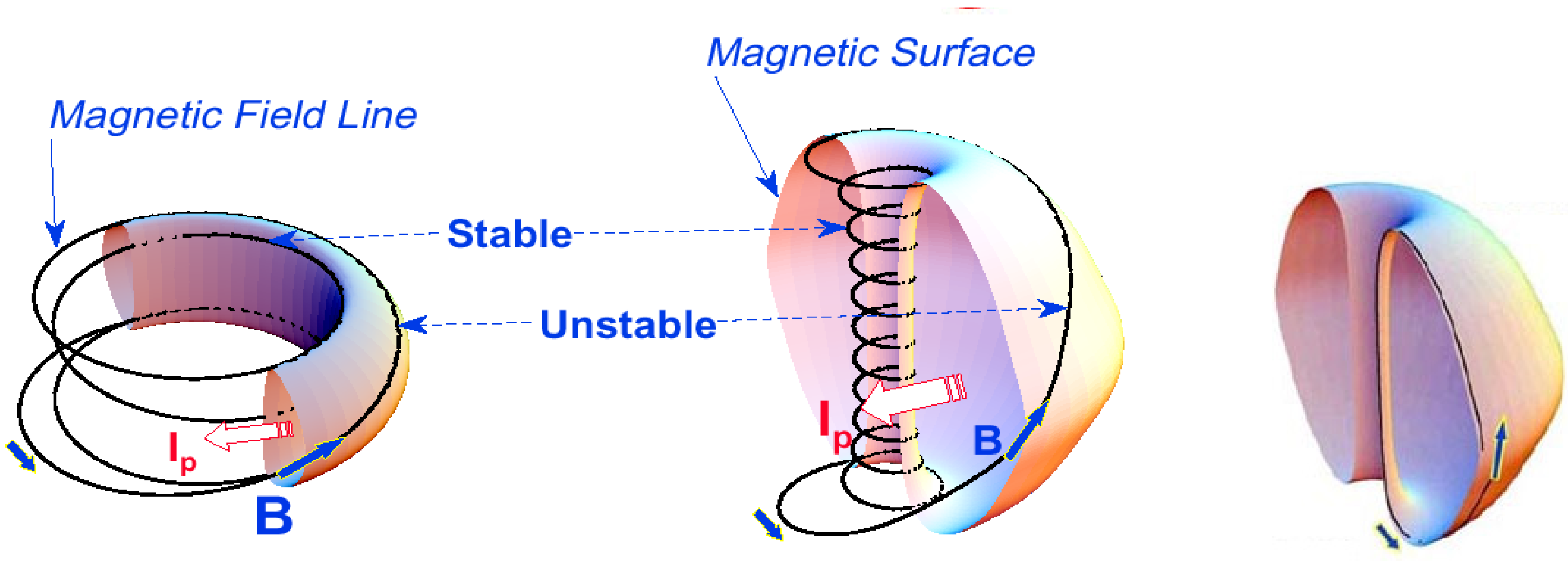
# Outline

- **ST overview**
- **Global MHD Stability**
- **Energy Confinement**
- **Energetic Particles**
- **ST Upgrade Status**
- **Summary**

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

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

- Natural elongation makes its spherical appearance
- Favorable average curvature improves stability at high beta




**Tokamak**

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

**ST**

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

**FRC**

$A \sim 1$,
$\kappa = 0.5\text{-}10$,
$q \sim 0$,
$\beta \sim 100\%$

# High $\beta_T$ enables compact Fusion Nuclear Science Facility (FNSF) with high neutron wall loading

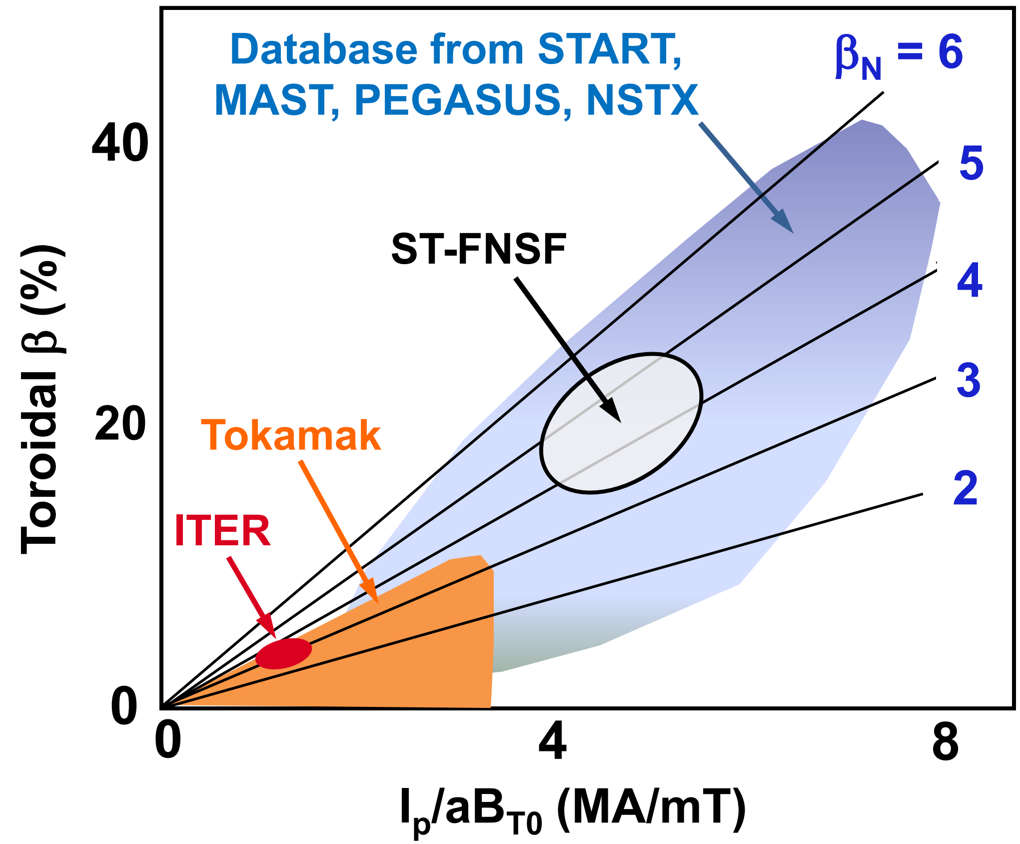
$P_{fusion} \propto \langle p \rangle^2 \times Vol$

$P_{fusion} \propto \beta_T^2 \; B_{T0}^4 \times Vol$

Physics limited

$

Investment & engineering limited




$W_n \propto P_{fusion} / Area$

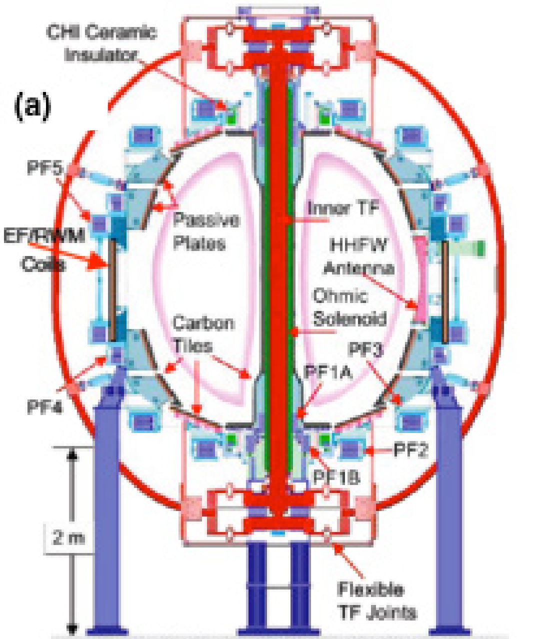
$W_n \propto \beta_T^2 \, B_{T0}^4 \, a$ (not strongly size dependent)

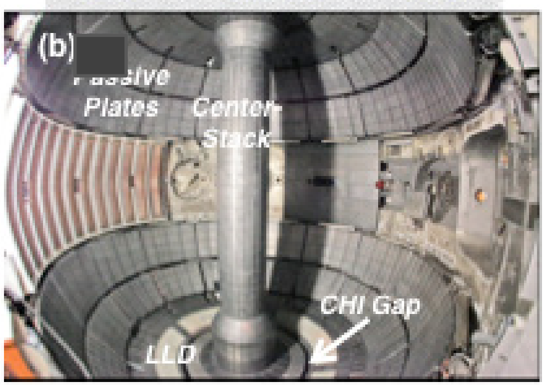
**$W_n$ ~ 1-2 MW/m² with R ~ 1-2m FNSF feasible!**

# MA-Class ST Research Started ~2000

## Complementary Physics Capabilities of NSTX and MAST

NSTX




M. Ono, IAEA 2000, NF 2001

### Complementary Capabilities

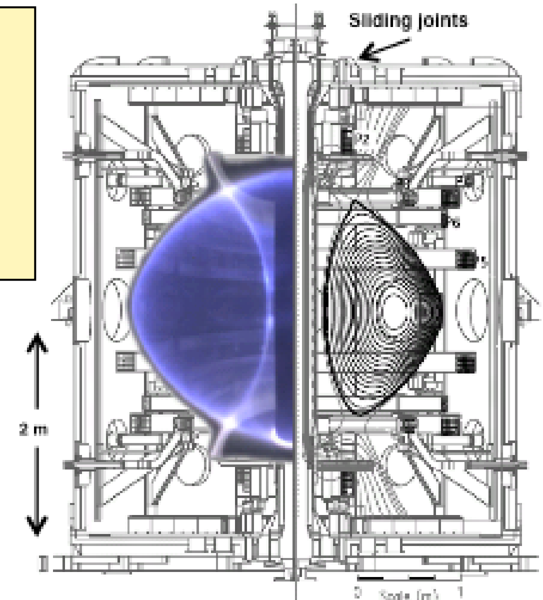
| | |
|---|---|
| Passive Plates | Large divertor volume |
| Helicity Injection | Merging/Compression |
| Fast wave heating | Electron Cyclotron |
| 1 x 6 RWM Coils | 2 x 12 ELM coils |

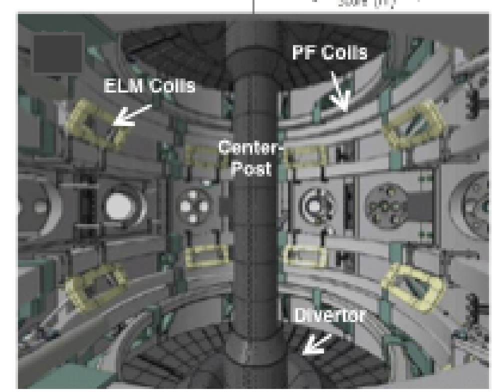
### Similar Capabilities

| NSTX | MAST |
|---|---|
| R = 85 cm | R = 80 cm |
| A ≥ 1.3 | A ≥ 1.3 |
| $\kappa$ = 1.7 - 3.0 | $\kappa$ = 1.7 – 2.5 |
| $B_T$ = 5.5 kG | $B_T$ ~ 5.0 kG |
| $I_p \leq$ 1.5 MA | $I_p \leq$ 1.5 MA |
| $V_p \leq 14\ m^3$ | $V_p \leq 10\ m^3$ |
| $P_{NBI}$ = 7.4 MW | $P_{NBI}$ = 4.0 MW |

- Comprehensive diagnostics
- Physics integration
- Scenario development

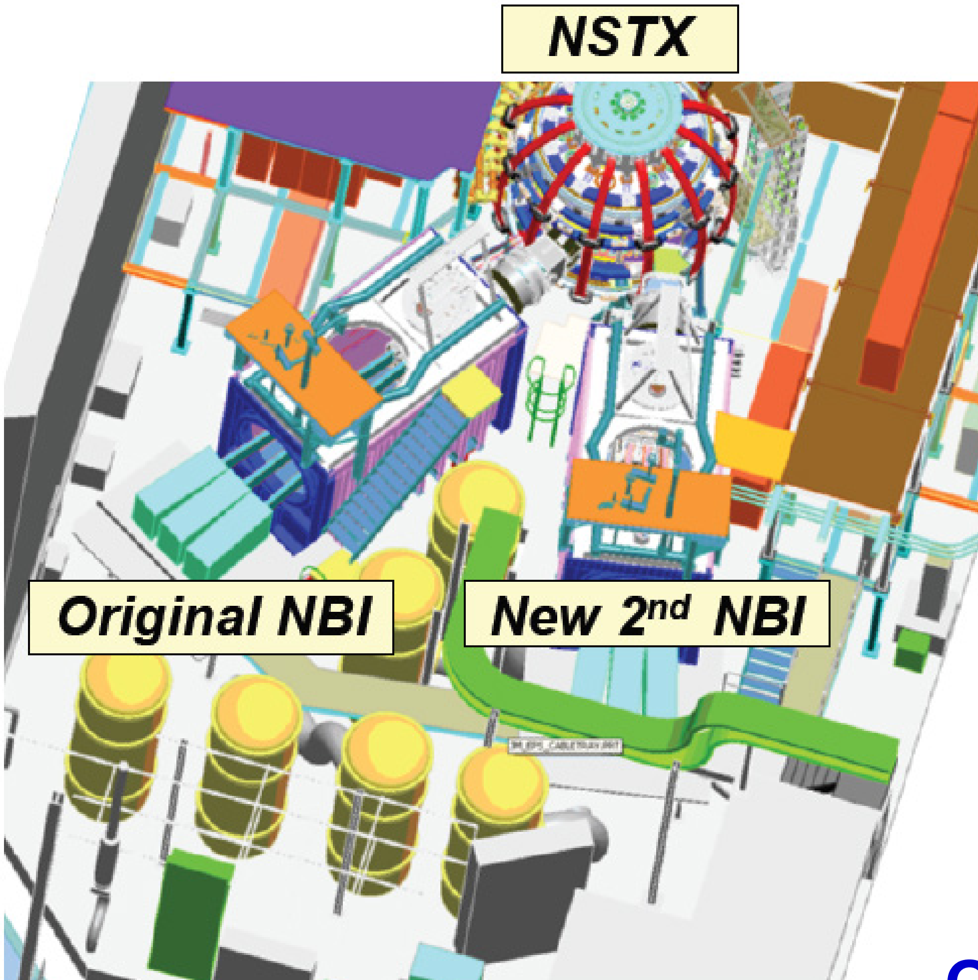
MAST

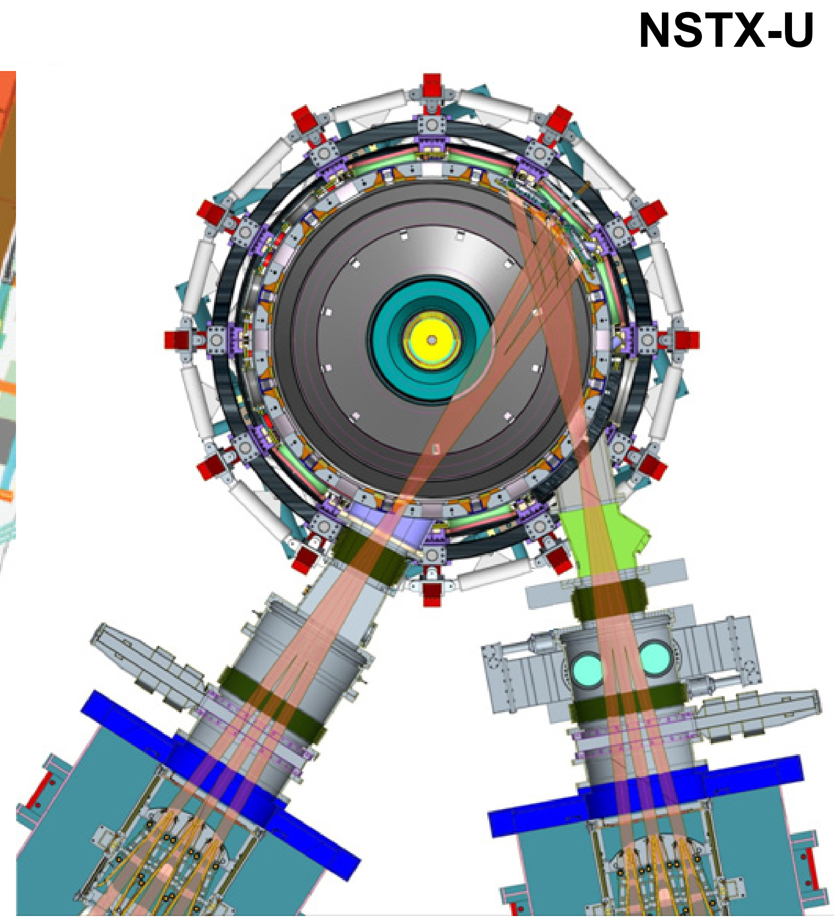



A. Sykes, IAEA 2000, NF 2001

# Mega-ampere-class STs rely heavily on co-injected neutral beams for heating, current drive




**Original NBI**
($R_{TAN}$ = 50, 60, 70cm)
5MW, 5s, 80keV

**New 2nd NBI**
($R_{TAN}$=110, 120, 130cm)
5MW, 5s, 80keV

# New physics accessed in ST → enhanced understanding of toroidal confinement physics

- Lower A → higher $\beta$, strong shaping
- Higher $\beta$ →
  - Electromagnetic effects in turbulence
  - More potential drive for fast-ion-driven instabilities
    - Simulate fast-ion transport of ITER / burning plasmas
  - Over-dense plasmas: RF heating, current drive
- Low-A / high-$\beta$ broadly impact transport, stability:
  - Higher fraction of trapped particles (low A)
  - Increased normalized orbit size (high $\beta$)
  - Increase flow shear (due to low B, low A)
- Compact geometry (small R) → higher power and particle fluxes relevant to ITER, reactors

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# Simulations find $\langle\beta_N\rangle$ is more aspect ratio invariant than $\beta_N$ – both with & without wall stabilization

Para / diamagnetic effects and $B_P$ / B ratio important at low-A

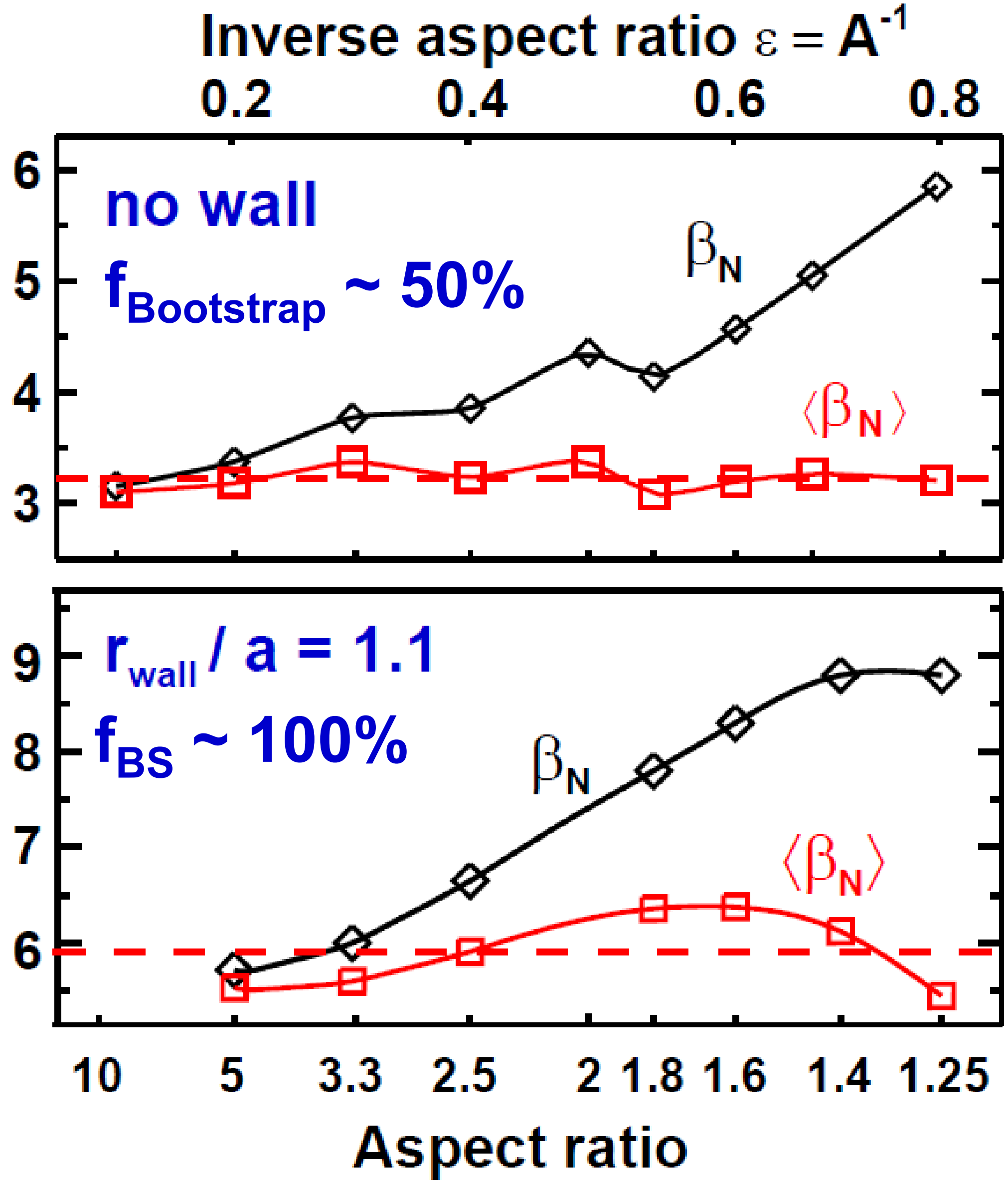
$$\beta_T \equiv 2\mu_0\langle p\rangle / B_{T0}^2$$

$$\langle\beta\rangle \equiv 2\mu_0\langle p\rangle / \langle B^2\rangle$$

$$I_N \equiv I_P / aB_{T0} \text{ [MA/mT]}$$

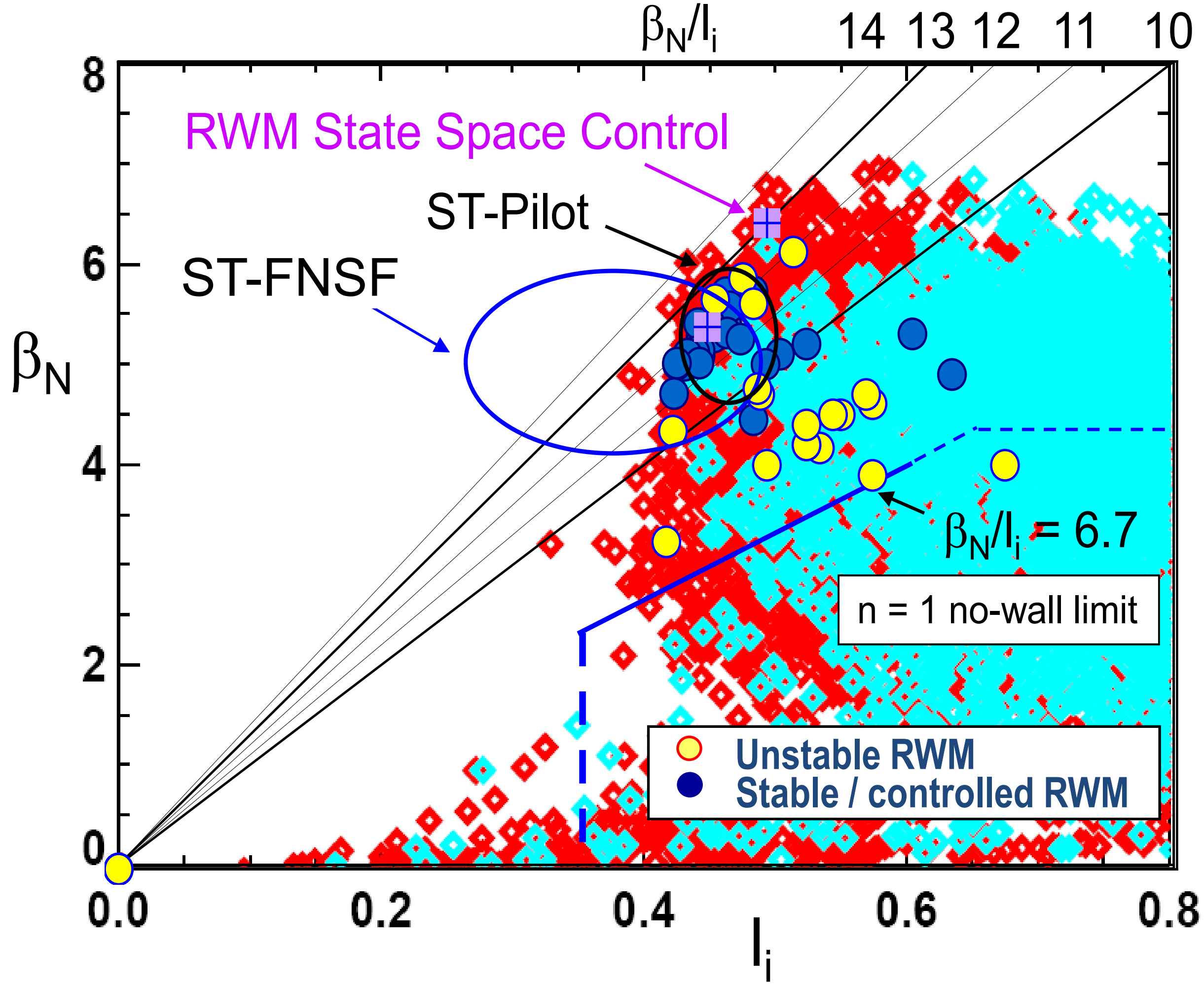
$$\beta_N \equiv \beta_T(\%) / I_N$$

$$\langle\beta_N\rangle \equiv \langle\beta\rangle(\%) / I_N$$




J. Menard, PoP 2004, PPPL-3779

# Record $\beta_N$ and $\beta_N$ / $l_i$ accessed in NSTX using passive + active resistive wall mode stabilization

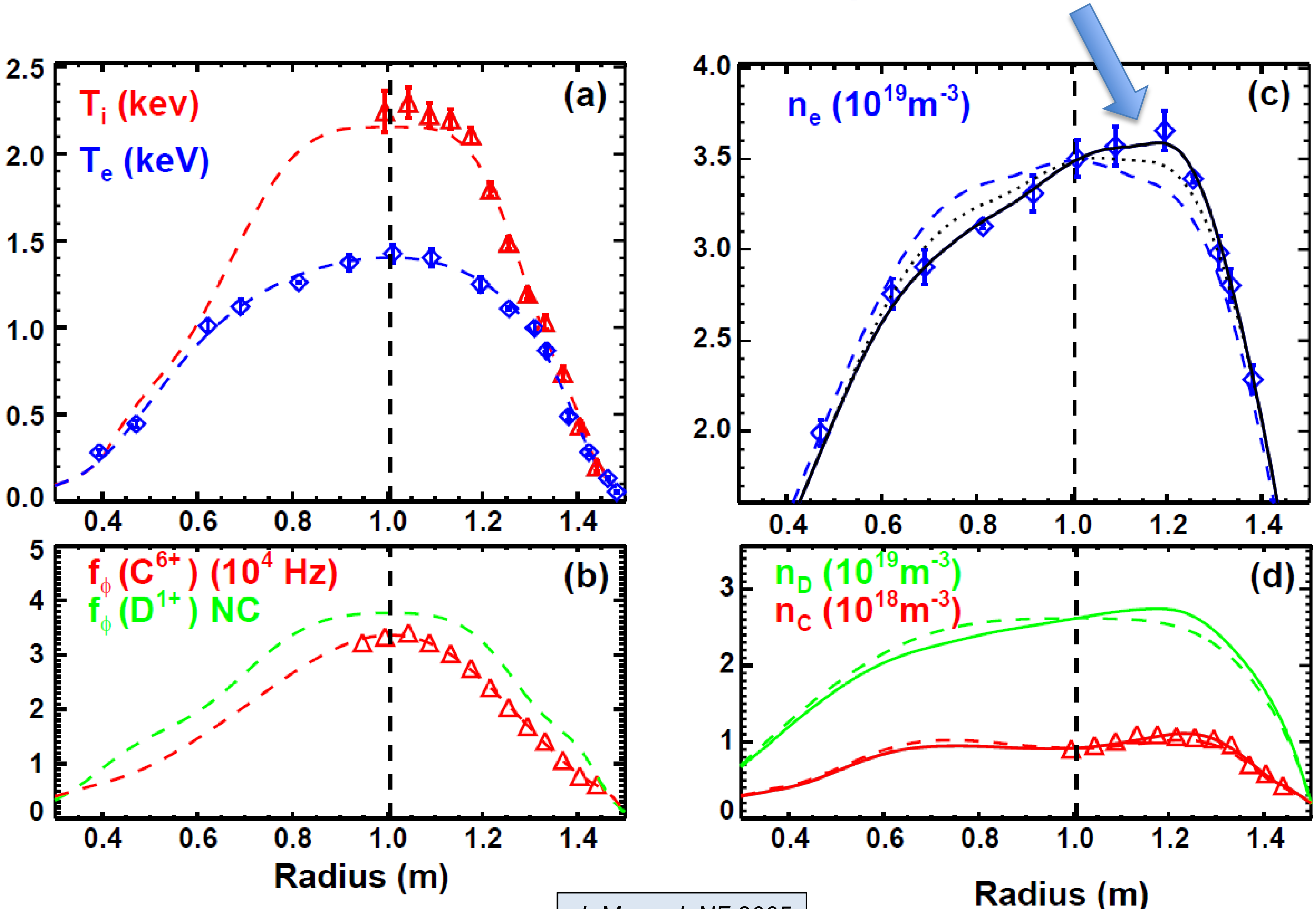



- High $\beta_N$ regime is important for bootstrap current generation.
- High $\beta_N$ / $l_i$ regime important since high $f_{BS}$ regime has low $l_i$.

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

**Major NSTX-U mission is to achieve fully non-inductive operation at high $\beta$**

# Rotation / centrifugal effects important and measureable in equilibrium




J. Menard, NF 2005

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

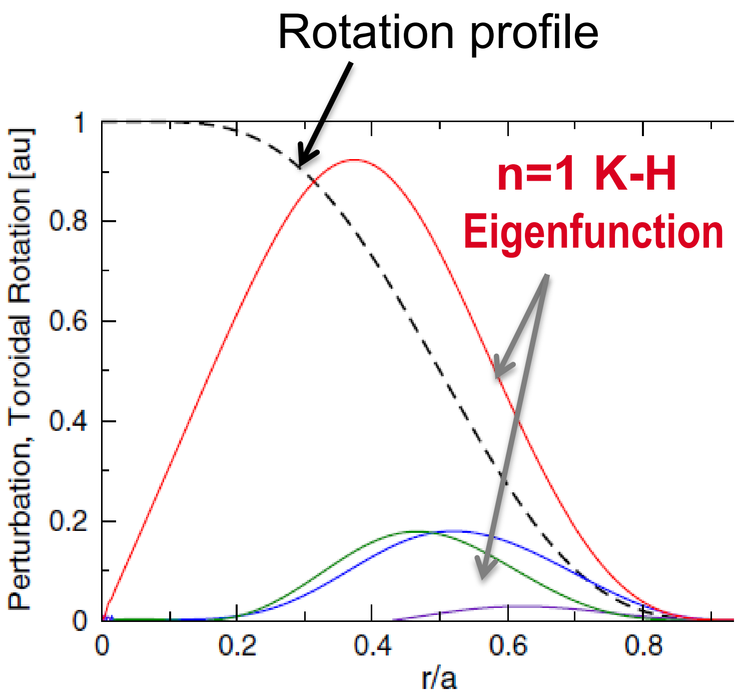



**Figure 4.** The $n = 1$ $KH_{\parallel}$ eigenfunction when the flow profile (dashed line) is centred at $r/a = 0.5$.

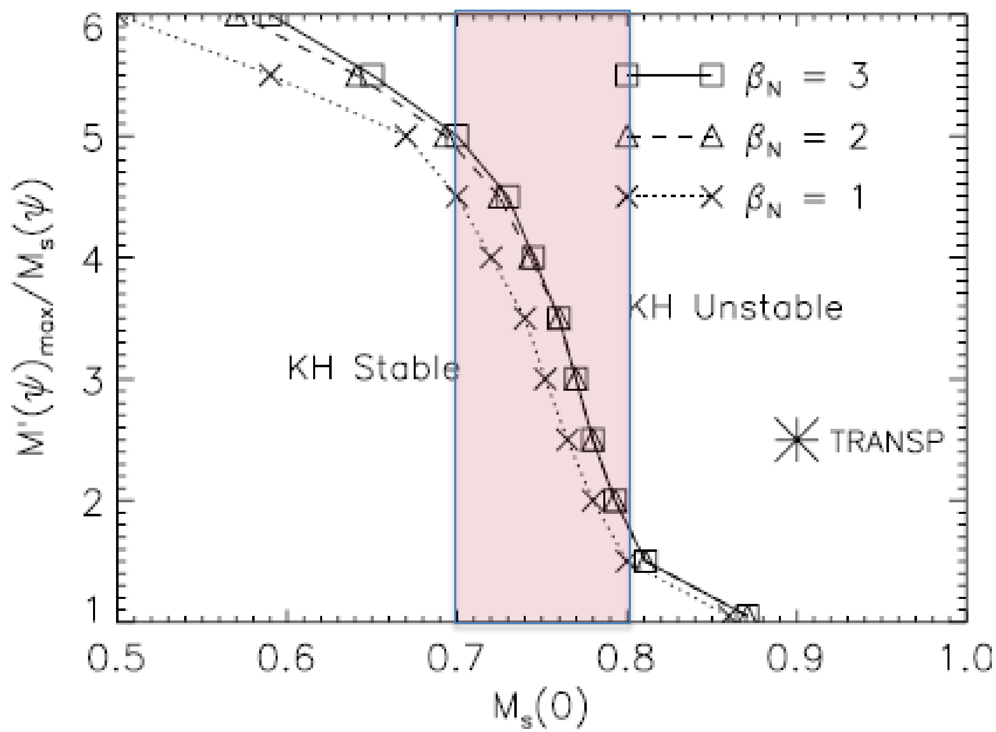
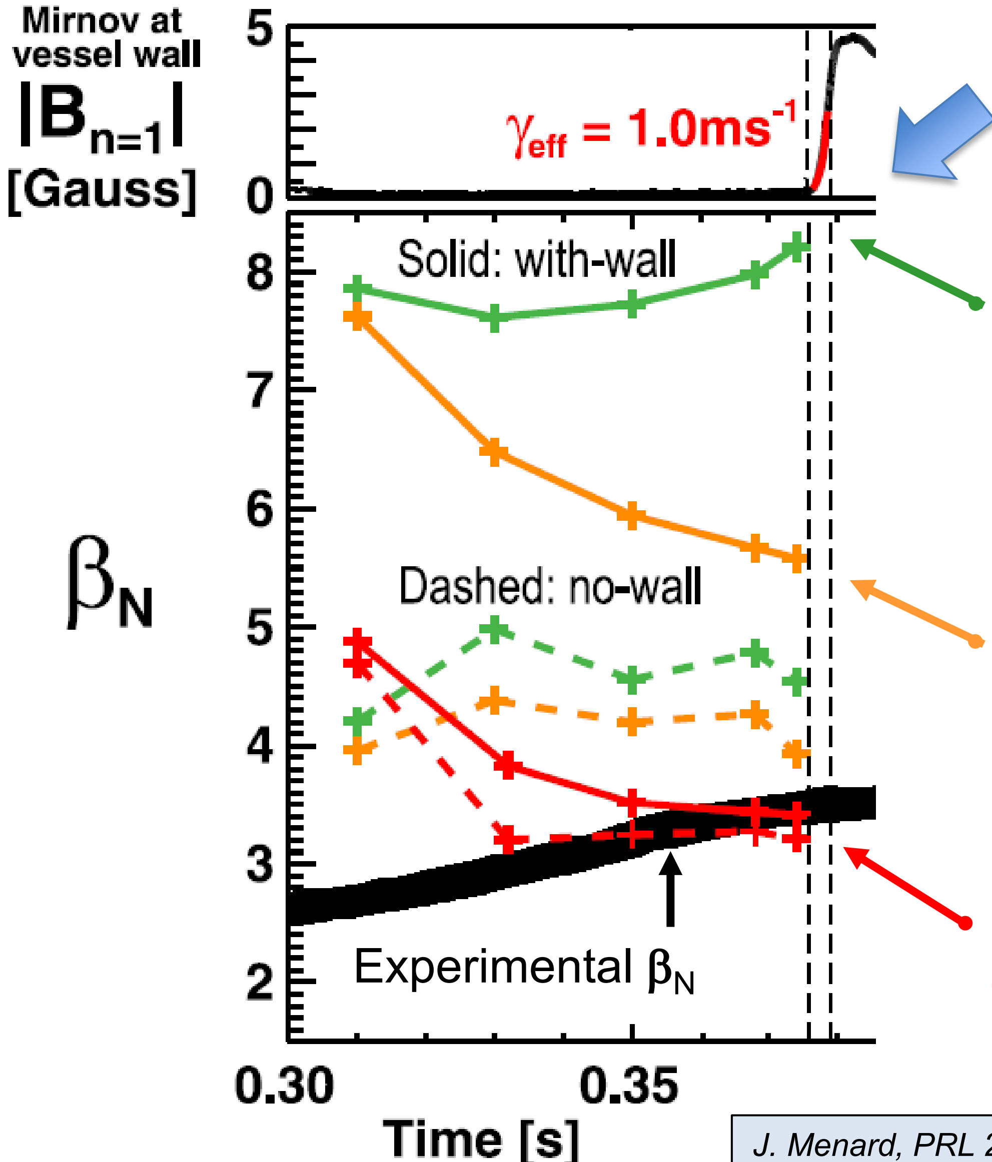



**Figure 5.** The $KH_{\parallel}$ stability boundary in terms of flow speed and gradient for three different plasma pressures when the safety factor is fixed at $q_{min} \simeq 1.3$. A typical rotation profile from TRANSP predictions is shown for reference, indicating that CTF with fully uni-directional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

*I. Chapman, NF 2012*

# Hybrid MHD-drift-kinetic stability calculations find rotation + fast-ions can weaken wall-stabilization of ∇p-driven kink




- MARS-K code needed / used to explain NSTX instability onset at highest rotation, $\beta_{fast}$ fractions

Low-rotation fluid with-wall limit is very high → marginal $\beta_N$ ~ 7-8

Increasing rotation lowers max $\beta_N$ to ~5.5 at mode onset time

Full kinetic treatment including fast-ions → marginal $\beta_N$ ~3.5 → most consistent with experiment

J. Menard, PRL 2014

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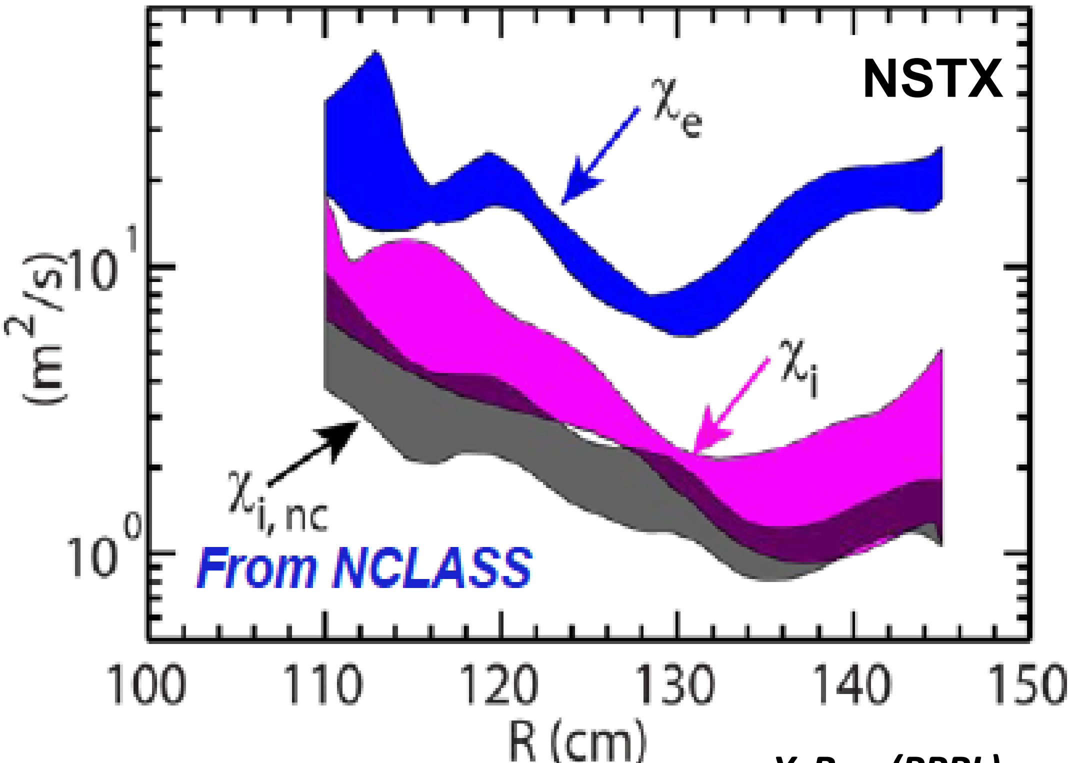
# High confinement multiplier H needed for compact ST

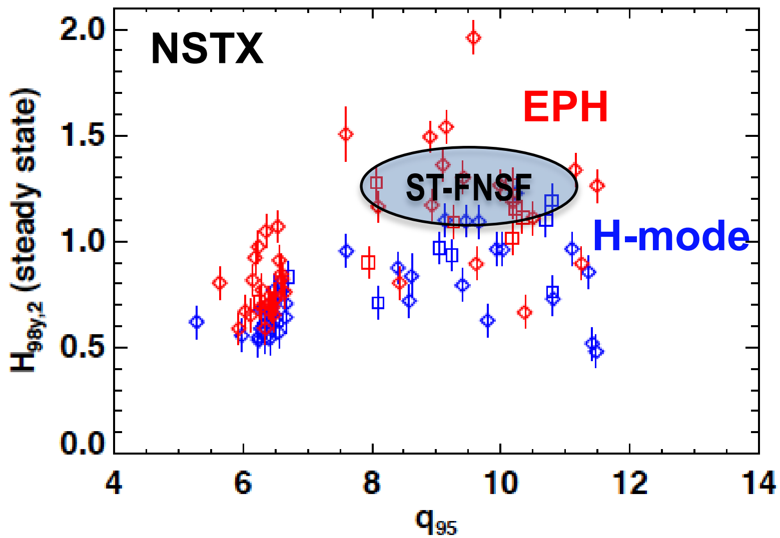
Fusion gain Q depends strongly on "H", $Q \propto H^{5\text{-}7}$
H = 1.2 – 1.3 enables compact FNSF, design flexibility/margin

- 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)*

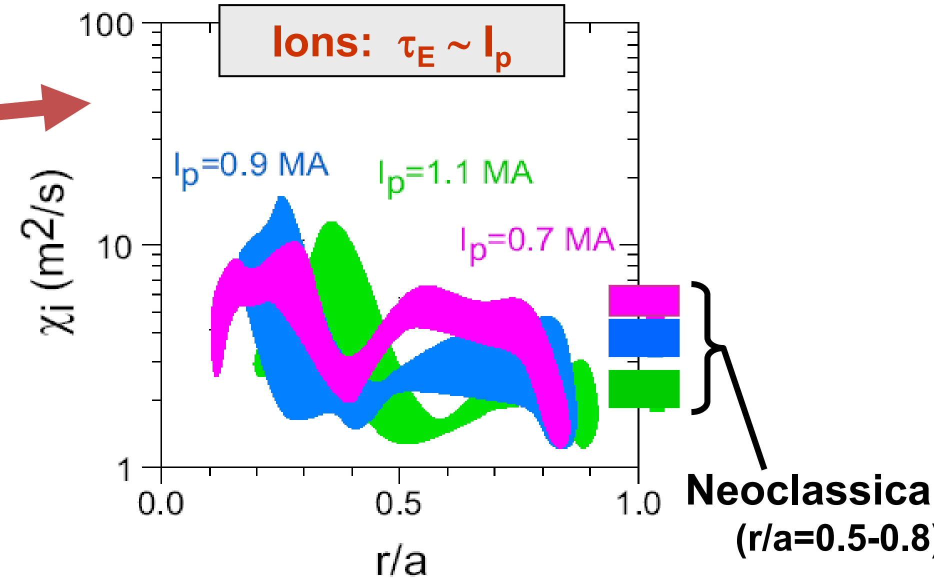
**Enhanced pedestal H-mode (EPH) has H up to 1.5-2 → attractive for ST-FNSF**



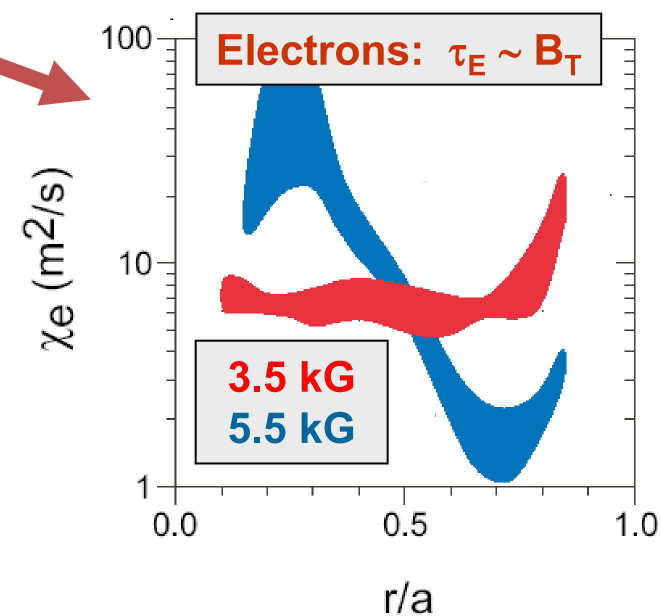

*R. Maingi, PRL 2010*
*S. Gerhardt NF 2014*

# Electron and ion $\tau_E$ 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



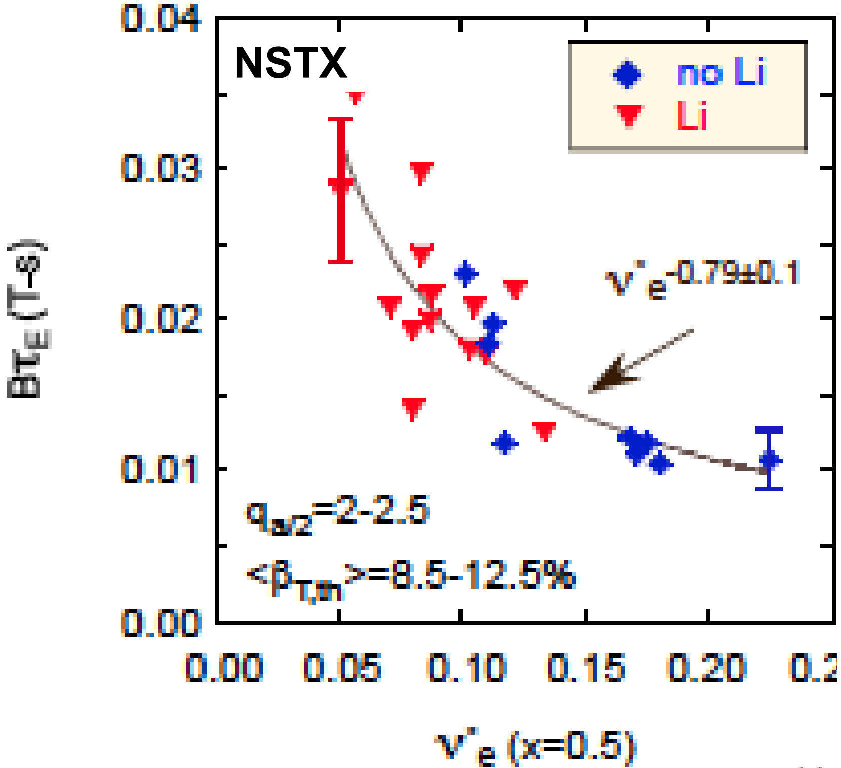

*S.M. Kaye, PRL 2007*

# Favorable confinement trend with collisionality, β found

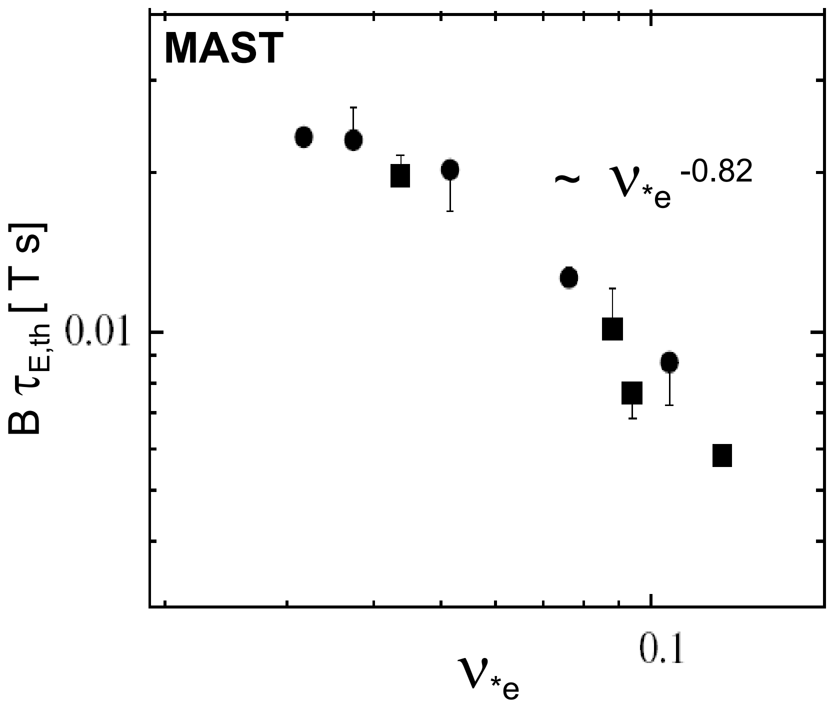
## Important implications for future ST FNSF, Demo with lower $\nu_*$

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

**$\tau_{E,\,th} \propto \nu_{*e}^{-0.8}\ \beta^{-0.0}$ ST scaling**




S.M. Kaye, NF 2007, 2013



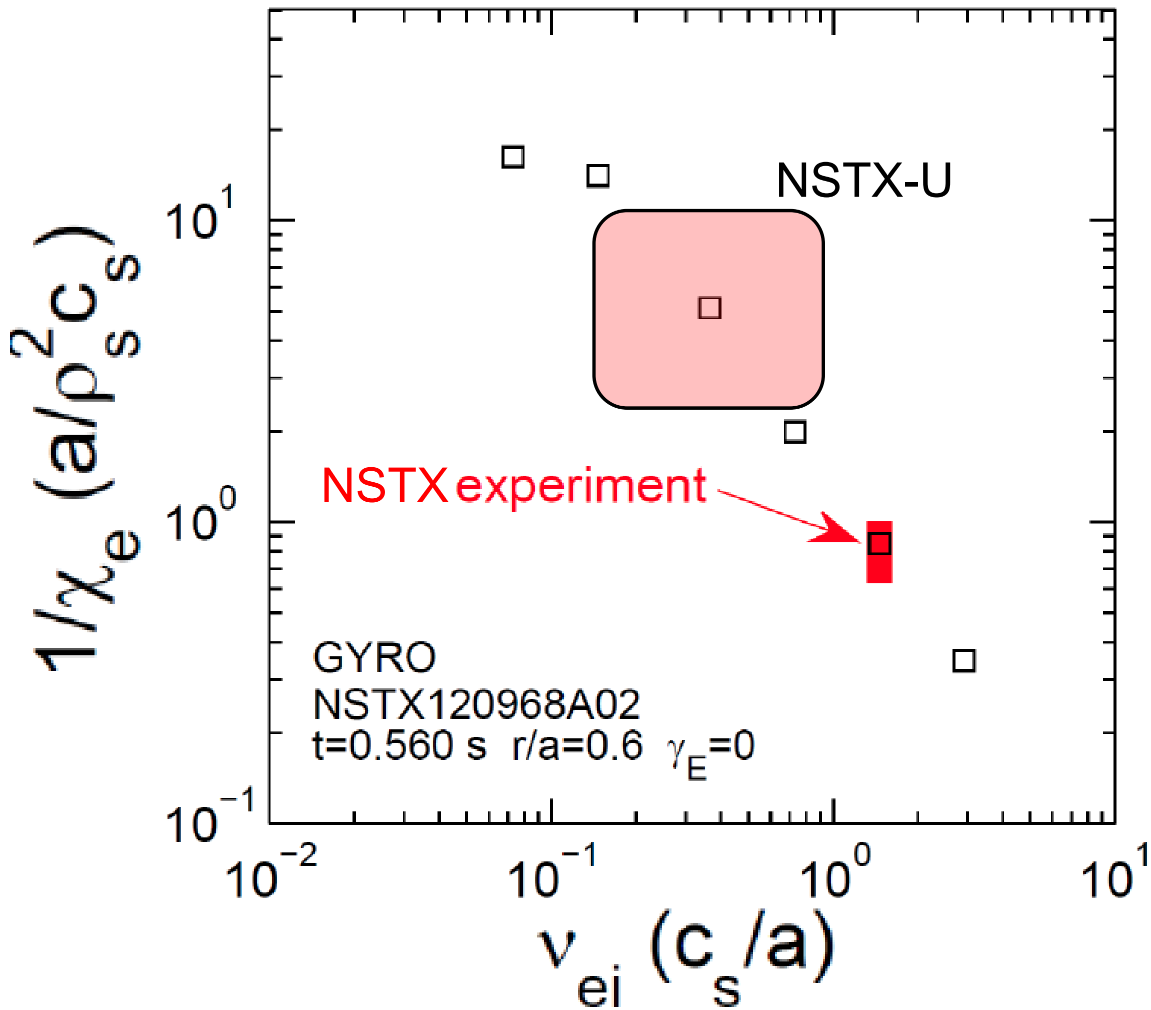

$$\nu_* \propto \bar{n}_e / T^2$$

M. Valovic, NF (2011)

**Very promising ST scaling to reactor condition, if continues on NSTX-U/MAST-U**

# Micro-tearing-driven (MT) transport may explain ST $\tau_E$ collisionality scaling

**MT-driven $\chi_e$ vs. $\nu_{ei}$ using the GYRO code**




- MT growth rate decreases with reduced collisionality in qualitative agreement with the NSTX experiment.
- Further electron confinement improvement expected due to reduced collisionality.

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

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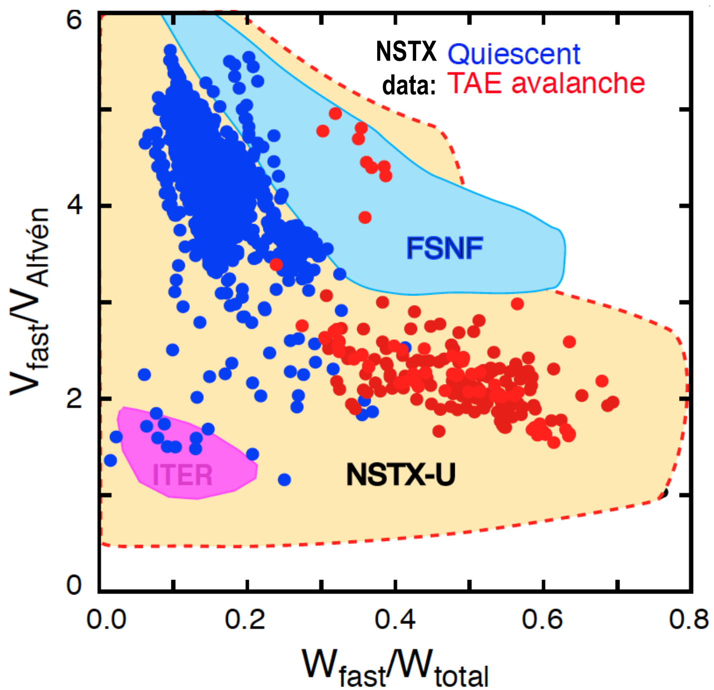
# NBI-heated STs excellent testbed for α-particle physics

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

- α-particles couple to Alfvénic modes strongly when $V_\alpha > V_A \sim \beta^{-0.5} C_s$
- $V_\alpha > V_A$ in ITER and reactors: condition easily satisfied in ST due to high β
- Fast-particle-driven Alfvén Eigenmodes: Toroidal, Global, Compressional
- NSTX-U will also explore $V_{fast} < V_A$ regime giving more flexibility

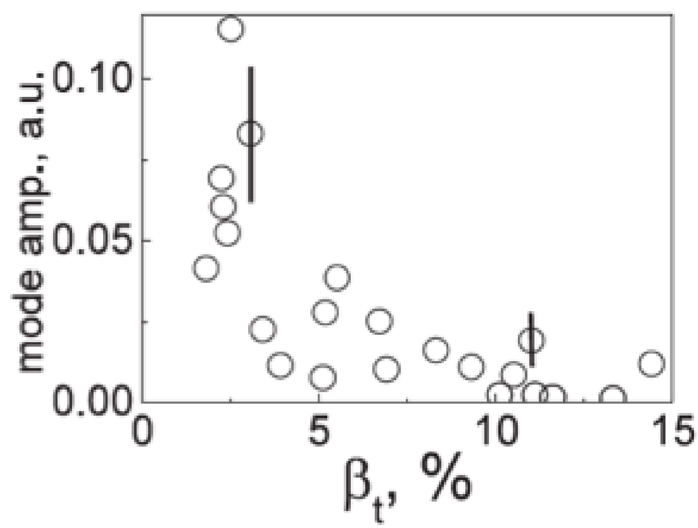
EP parameter space




E. Fredrickson, NF 2013

TAEs significantly modified at high β as $V_A \rightarrow C_s$

Stabilization of TAEs at high β in MAST

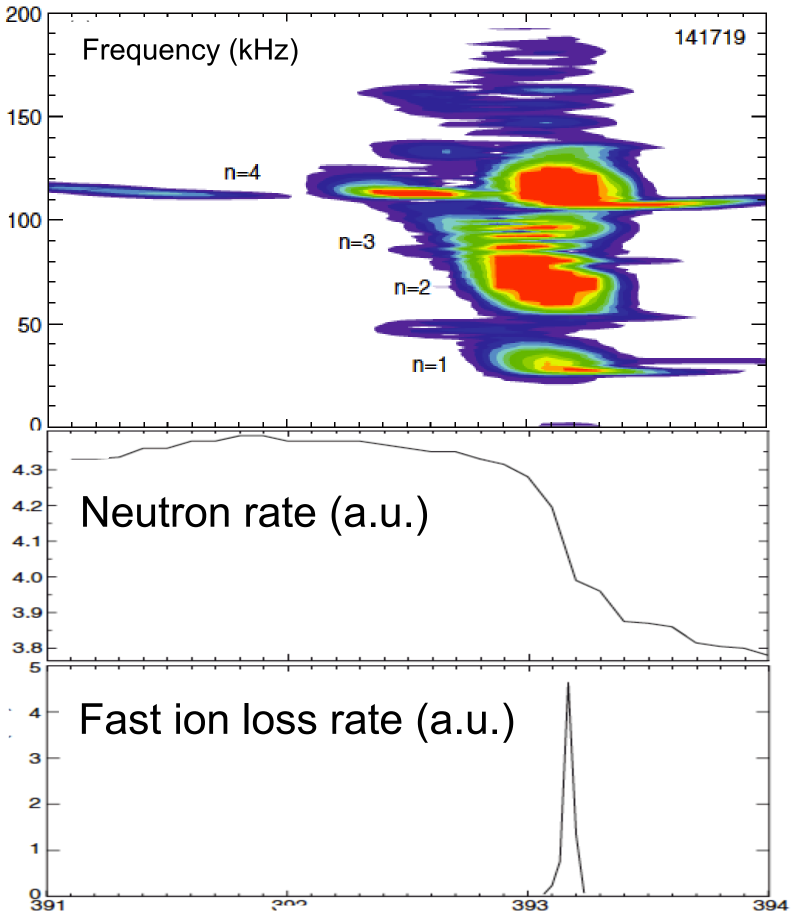



M.P. Gryaznevich, PPCF 2004

# "TAE avalanche" shown to cause energetic particle loss

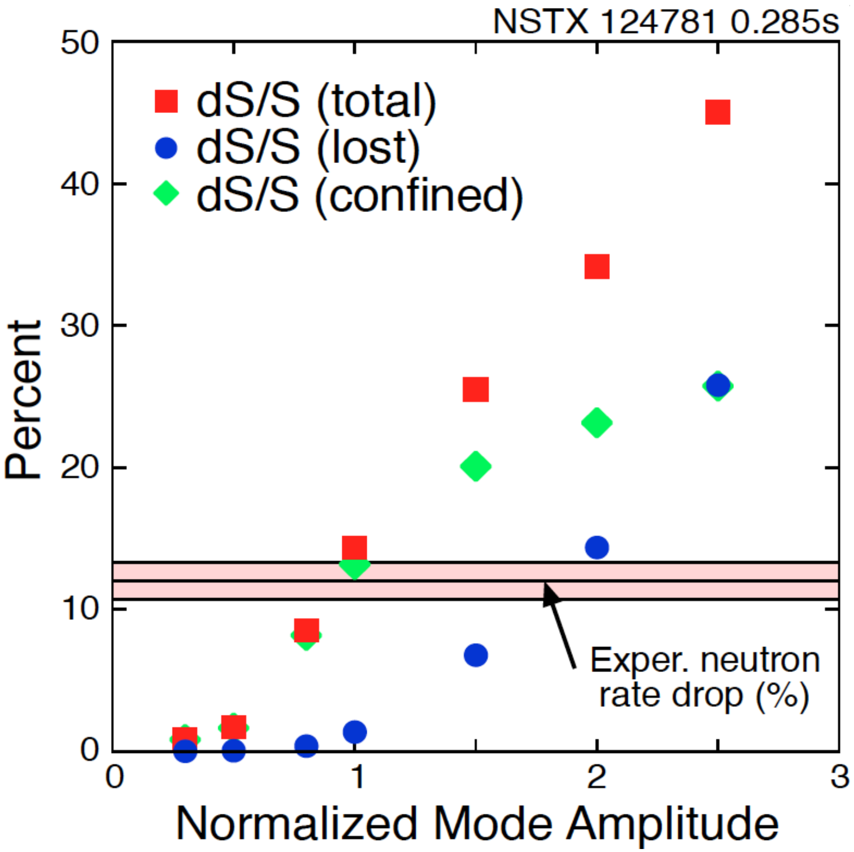
## Uncontrolled α-particle loss could cause reactor first wall damage

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




D.S. Darrow, NF (2013)

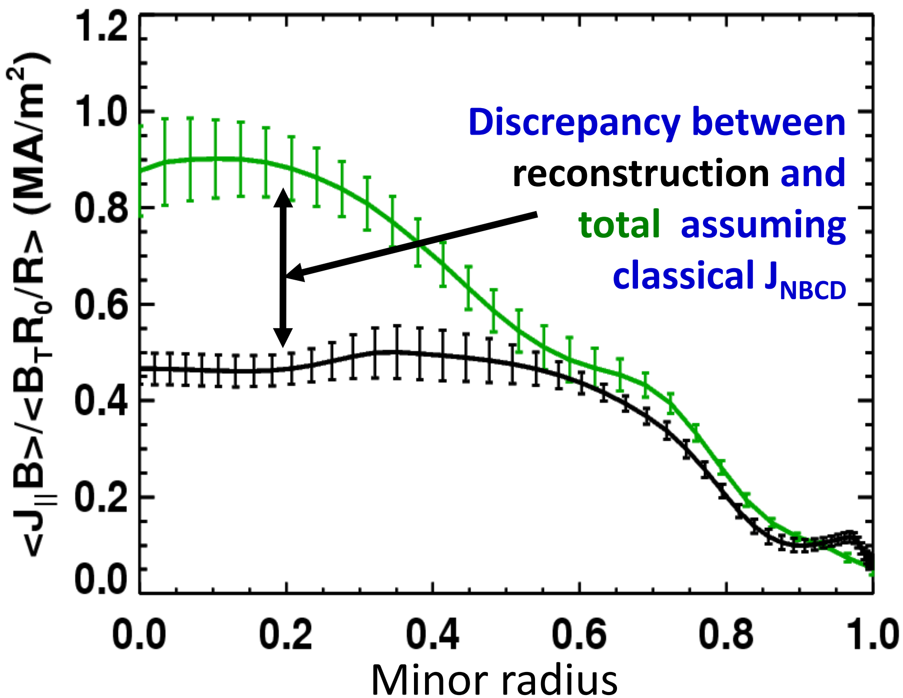
Progress in simulation of neutron rate drop due to TAE avalanche




E. Fredrickson, NF 2013

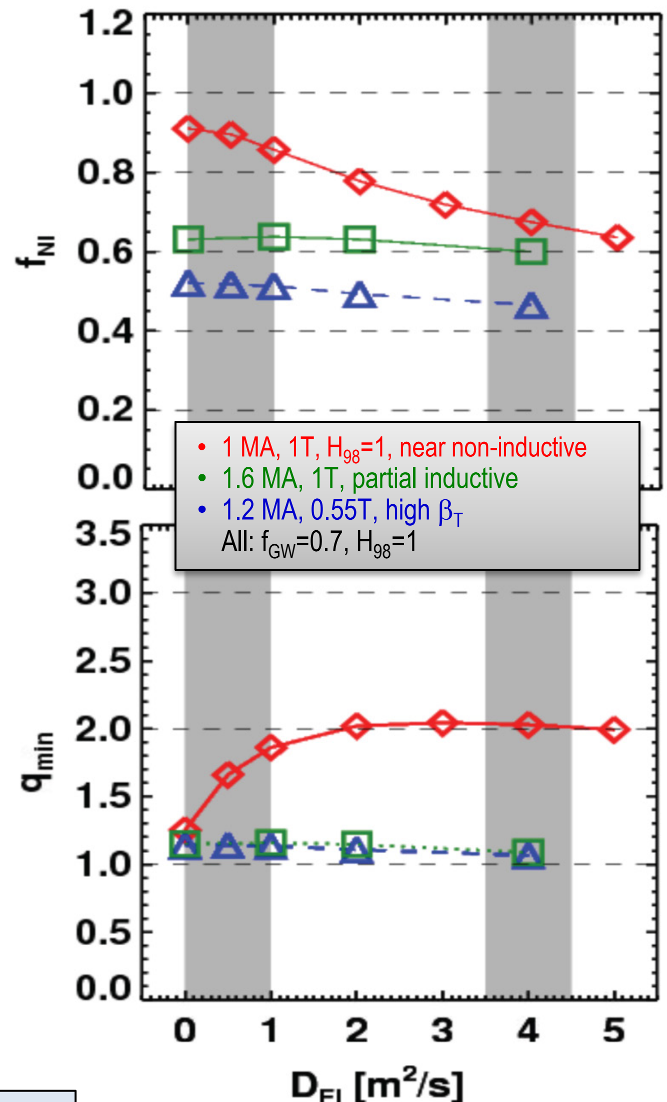
# Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

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




700kA high-$\beta_P$ plasma with rapid TAE avalanches has time-average $D_{FI}$ = 2-4m²/s

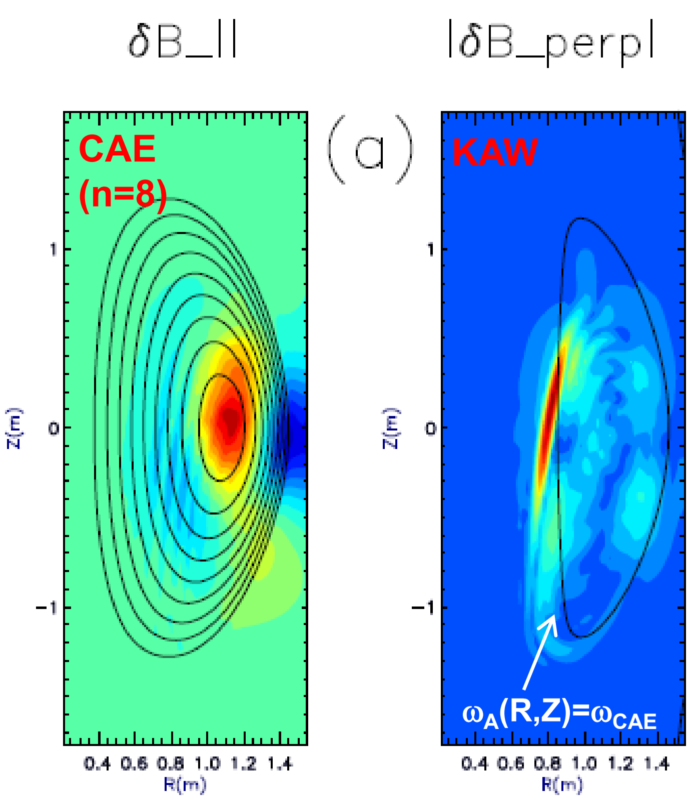
NSTX-U TRANSP simulations




*S. Gerhardt NF 2011, NF 2012*

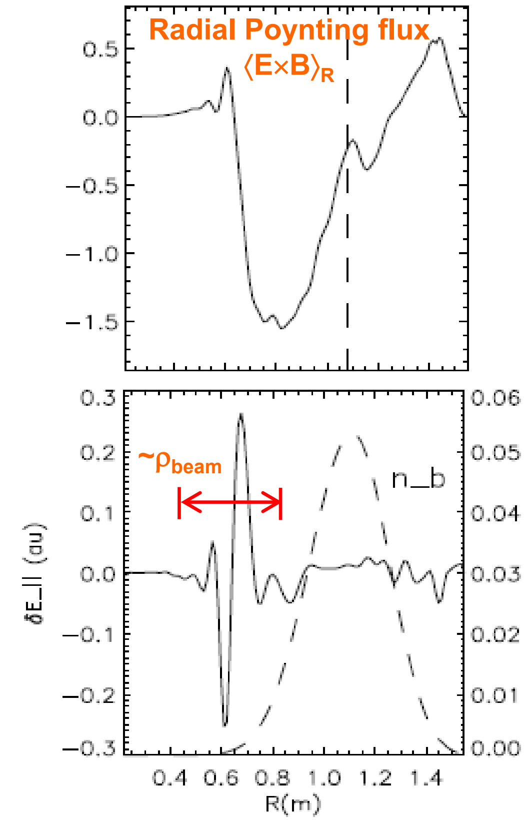
# CAE mode-conversion to kinetic Alfvén waves (KAW) predicted to transfer core NBI power to mid-$\rho$ electrons

1) GAE/CAEs cause large $\chi_e$ 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 $\rho$ <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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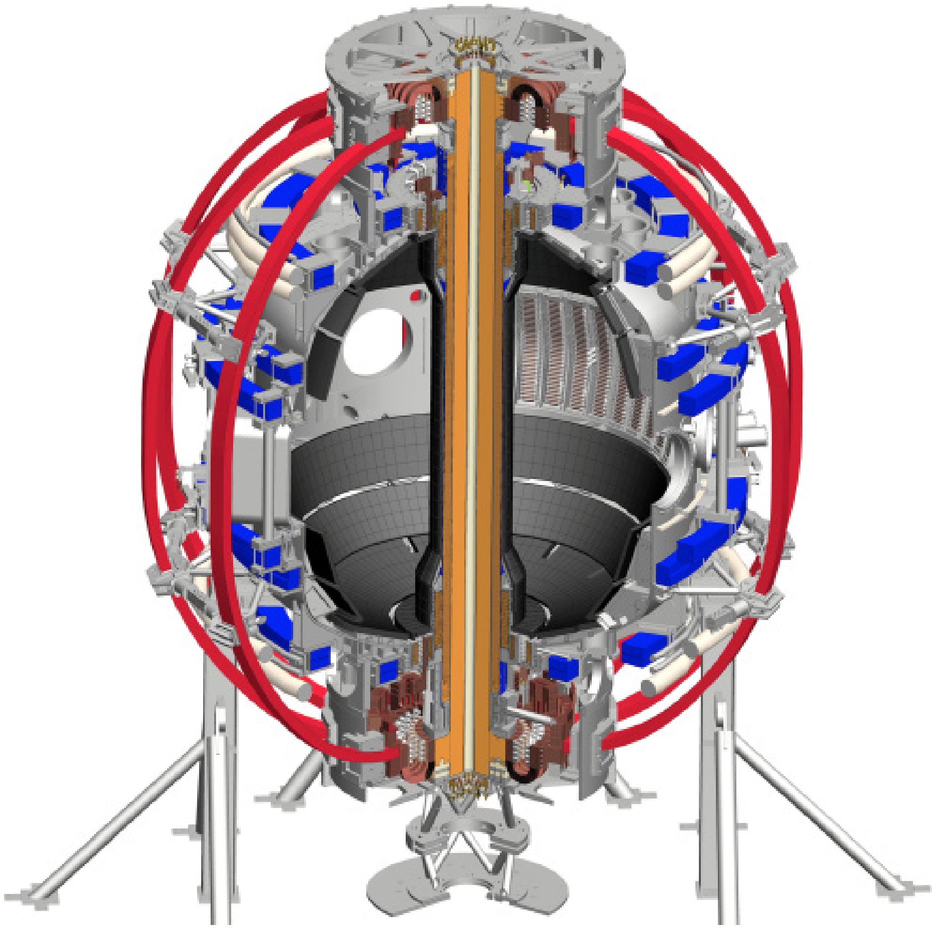
# NSTX and MAST are undergoing major upgrades

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

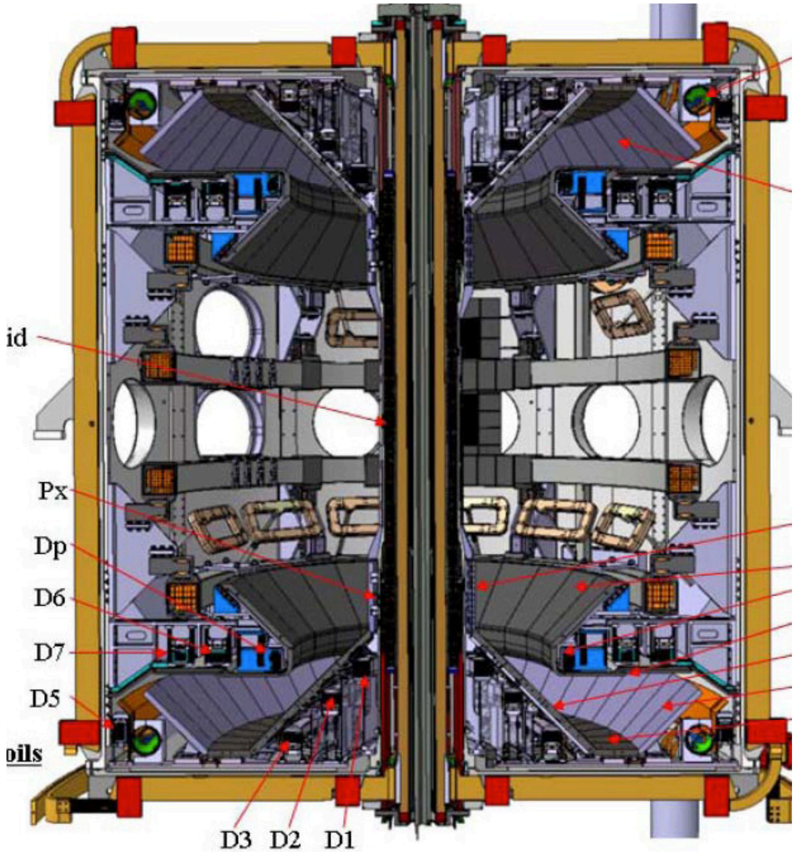
**NSTX-U**



Highly tangential 2nd NBI for non-inductive sustainment, profile control

*First test plasma few weeks ago*

**MAST-U**

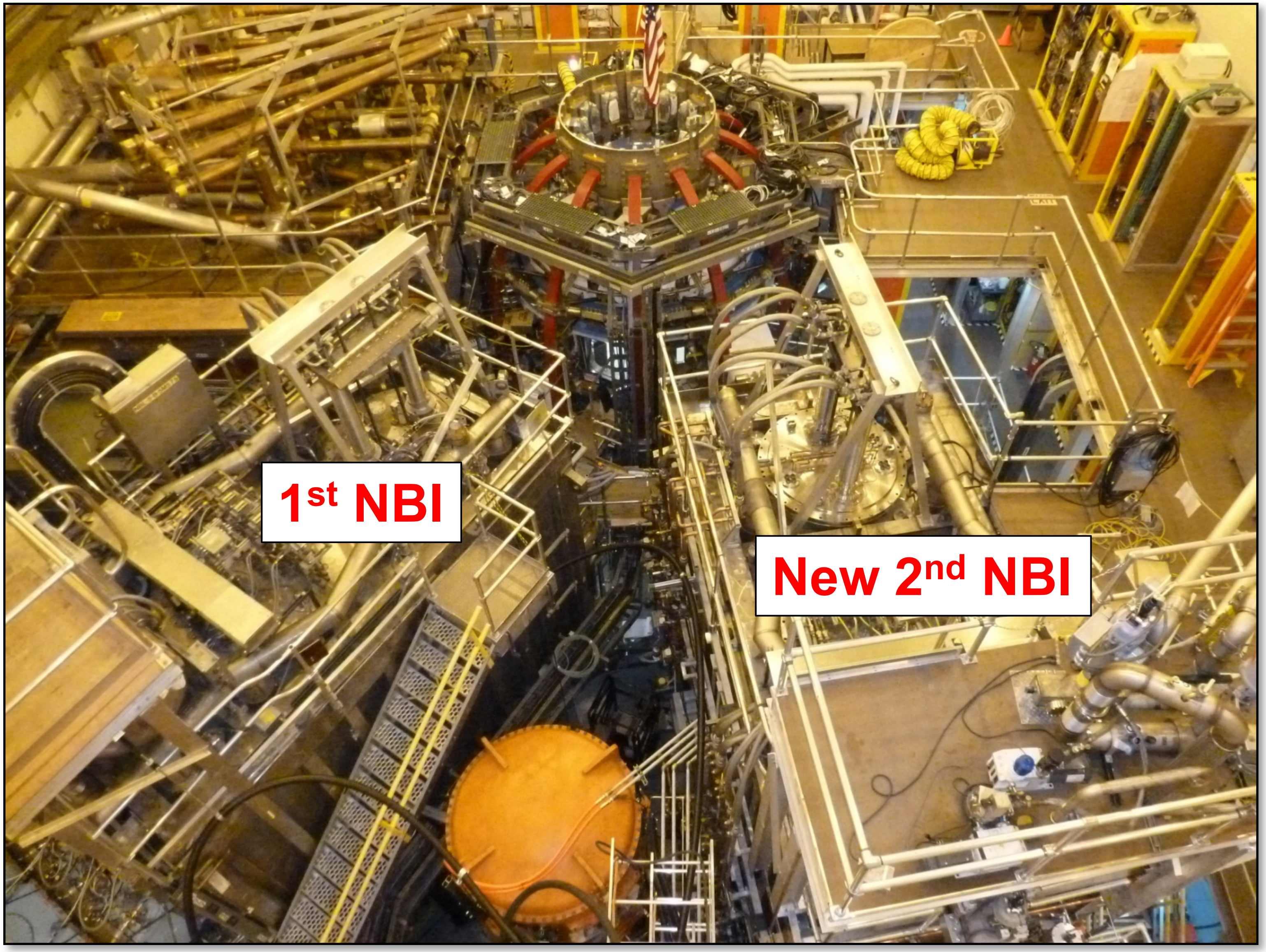



Super-X divertor configuration for FNSF/DEMO divertor solution

*First test plasma 2017*

# NSTX Upgrade project recently completed

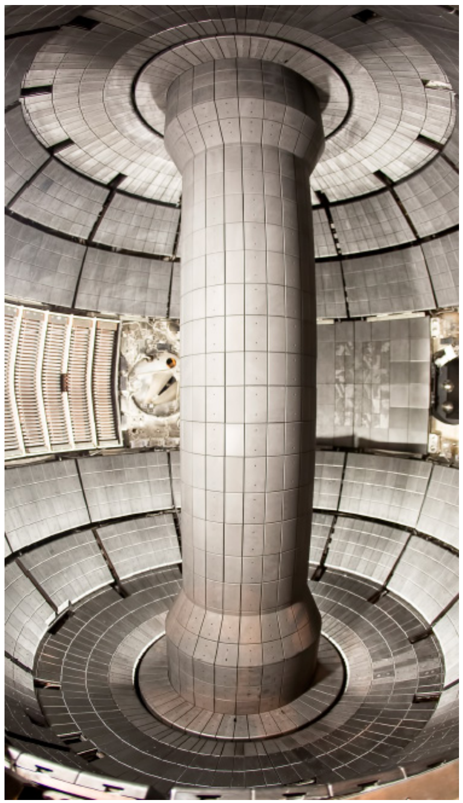
On cost and schedule, first test plasma ~100kA (Aug. 10, 2015)



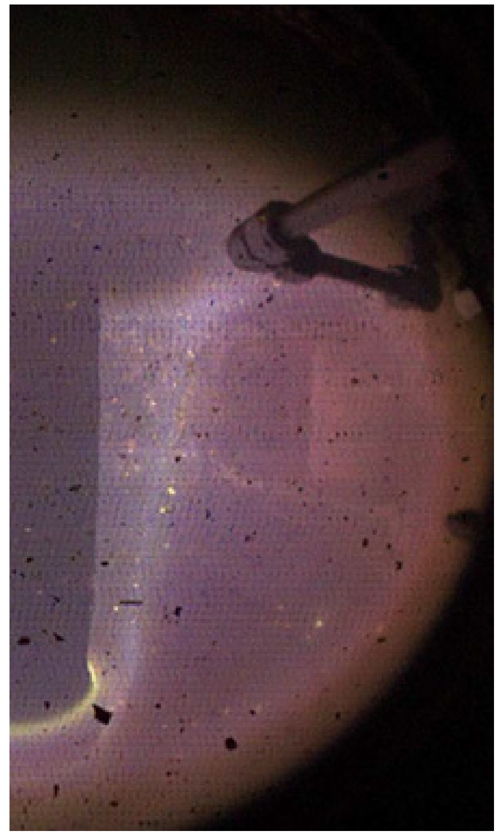
# New centerstack (CS) highlights: Jan – Aug 2015

**CS crane lift**

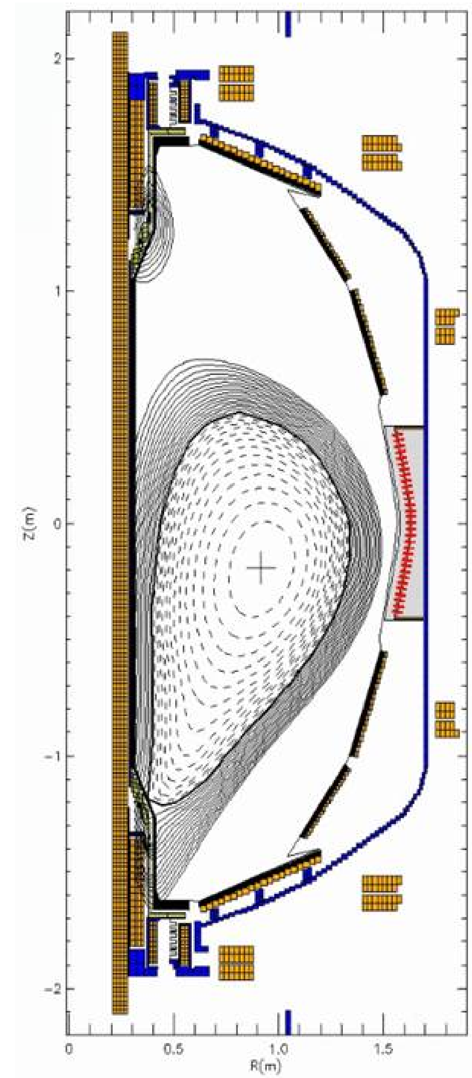
**CS installed**



**First test plasma**
**(Ohmic heating only)**



**Magnetics functional → EFIT reconstructions**



# Summary

- Upgraded STs will provide many opportunities to study toroidal confinement physics in new regimes:
  - Low aspect ratio, strong shaping, high $\beta$, low collisionality
  - Access to strong fast-ion instability drive, high rotation
  - Advanced divertors, lithium walls, high-Z PFCs
- There are potentially interesting linkages between ST and CT / FRC physics that could be explored further:
  - Role of rapid rotation, strong beams, kinetic effects, …
- Thank you!