Developing the Core Physics Scenarios For Next Step STs

Stefan Gerhardt

R. Andre, R. Bell, M. Bell, J. Breslau, E. Fredrickson, D.A. Gates, S. Jardin, S. Kaye, E. Kolemen, H. Kugel, B.P. LeBlanc, J.E. Menard, D. Mueller (PPPL)
R. Maingi (ORNL)
S.A. Sabbagh (Columbia University)
H. Yuh (Nova Photonics)
and the NSTX team

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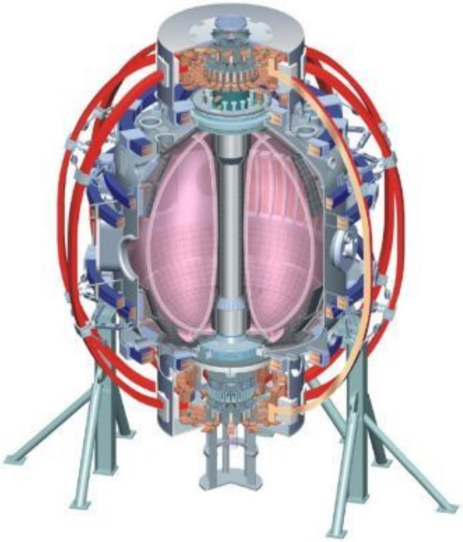


The Spherical Torus Is a Candidate For Future Fusion Devices

- Potential advantages of the ST:
  - Compact size & high neutron wall loading
  - High-β
  - Simplified maintenance scheme
- Basic considerations indicate how to achieve the scenarios:
  - Troyon Scaling: $\beta_T = \beta_N \frac{I_P}{aB_T}$
  - High bootstrap current:

$$f_{BS} \propto q\beta_N$$

  - Increase the safety factor

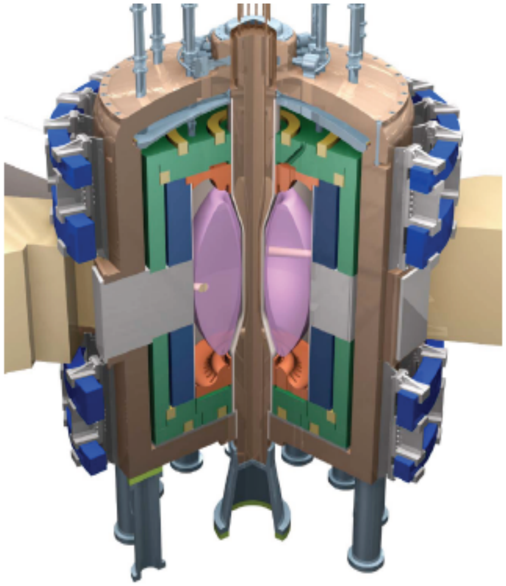
$$q^* \propto \left(1+\kappa^2\right)$$

  - Utilize high confinement

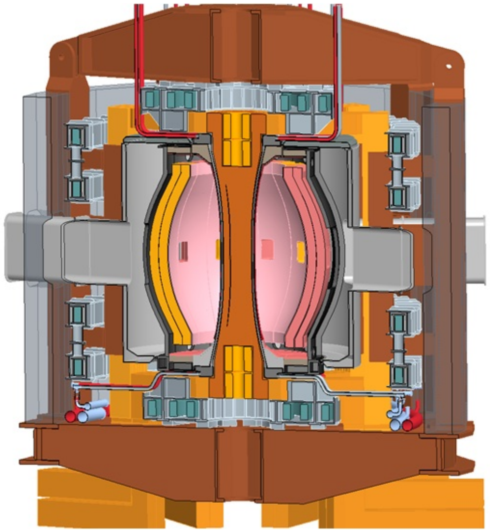
$$\beta_N \propto W_{tot} \propto P_{heat}\tau_{confinement}$$

  - MHD stable at the required β_N.

Fusion Nuclear Science



Pilot Power Plants



	β_N	κ	$H_{98y,2}$
Component Testing	**3-5**	**2.5-3.2**	**1.2-1.6**
Power Plant	**6-8**	**3-3.5**	**1.3-1.6**

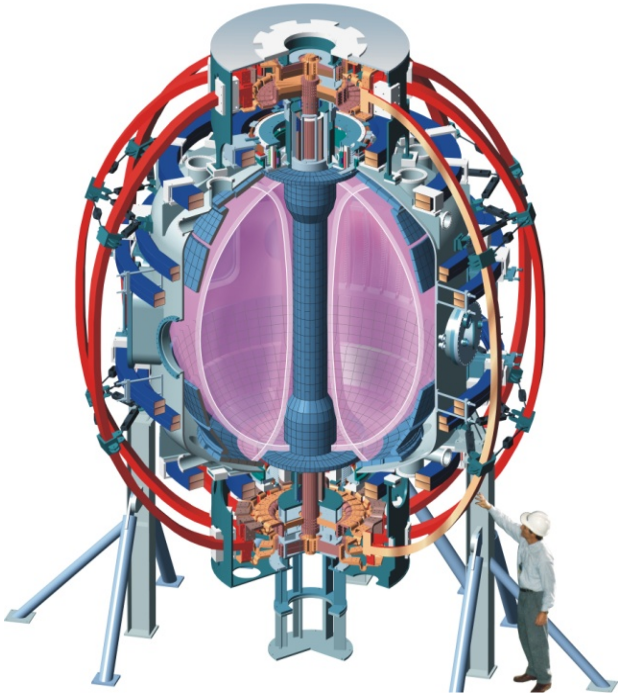
Outline

- Motivation
- NSTX Device
  - Facility improvements facilitating high-performance ST plasmas.
- NSTX results
  - Global transport in high-performance plasmas
  - Maintenance of the high-β_N state
  - Non-inductive current sustainment
- Projections to NSTX-Upgrade.
  - Comparison to existing NSTX operating space

Conclusions in the form of implications for NSTX-Upgrade scenario projections

Critical issues of plasma startup & rampup, divertor physics, fast-ion physics, RF Heating not discussed in this talk.

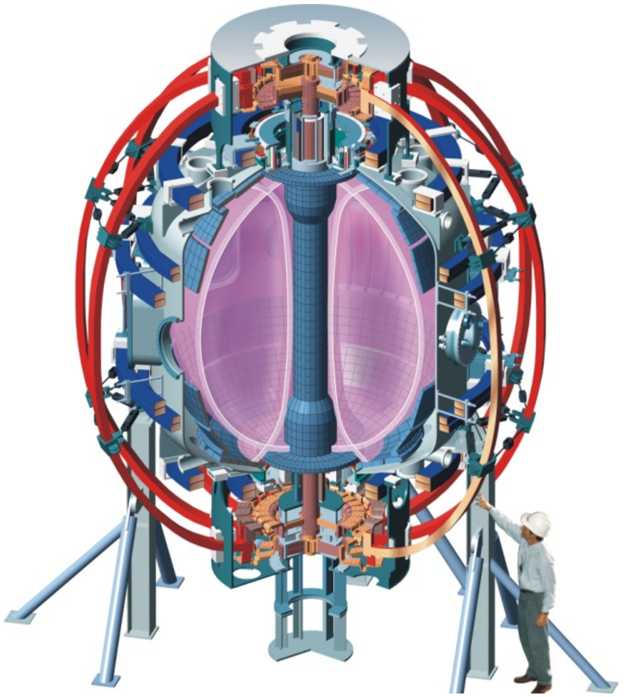
Progress Towards High Performance ST Scenarios Has Benefited from Facility Improvements



Aspect ratio (typical)	**< 1.6**
Toroidal Field B_{T0}	**< 0.55 T**
Plasma Current I_p	**≤1.3 MA**
NBI (<100kV)	**< 7 MW**
Pulse Length	**< 2 s**
Elongation	**< 2.9**
β_N	**< 7**
H	**<1.2 in H-mode**

- Improved plasma control
  - Reduced latency facilitates operation at high elongation.
  - Routine n=1 dynamic error field correction & RWM control.
- Lithium conditioning of the plasma facing components.
  - Increased confinement and reduced internal inductance
  - Shortened shot cycle

Best NSTX Discharges Exhibit Many Characteristics Necessary for Next-Step Devices



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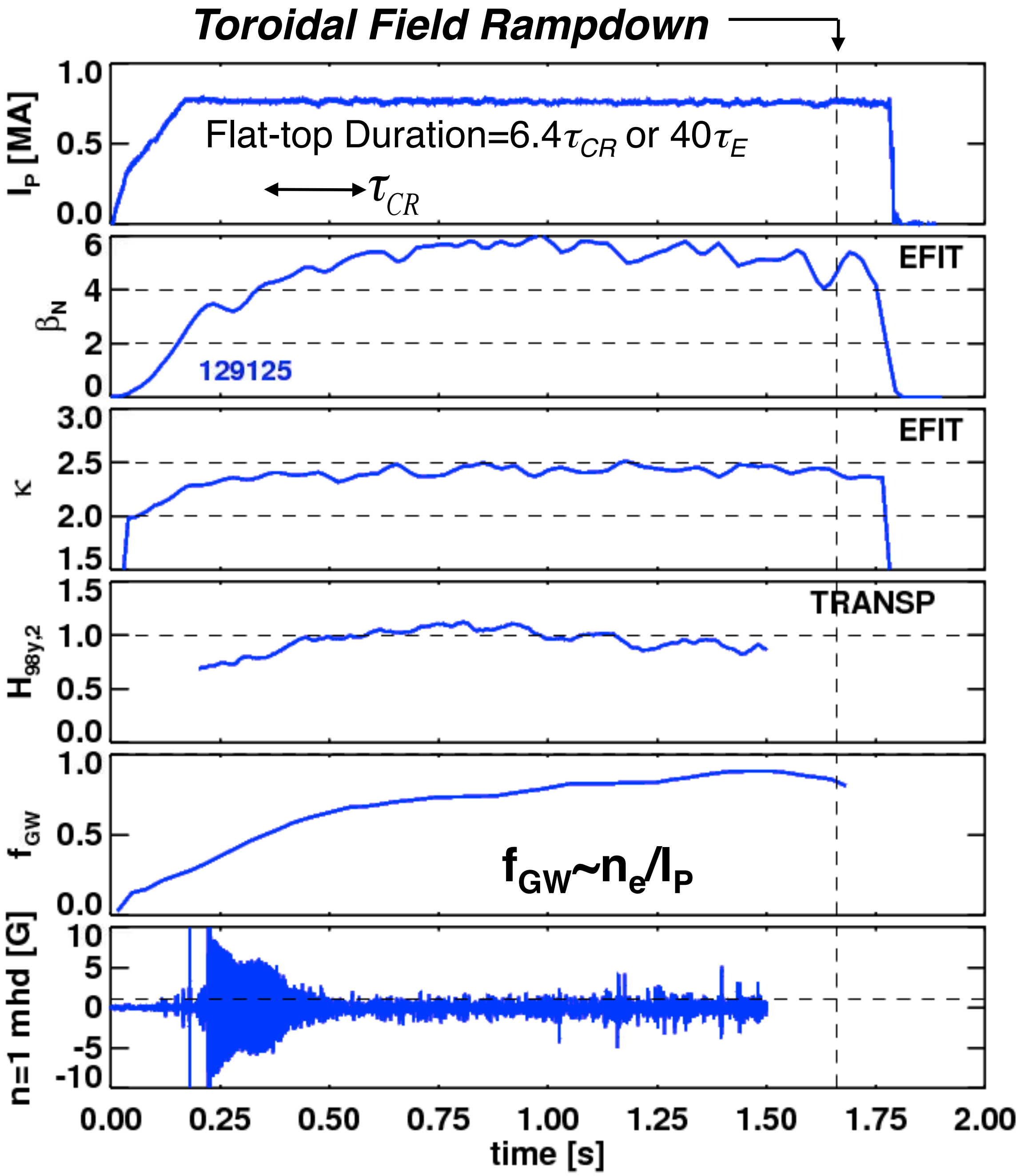

Outline

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- NSTX Device.
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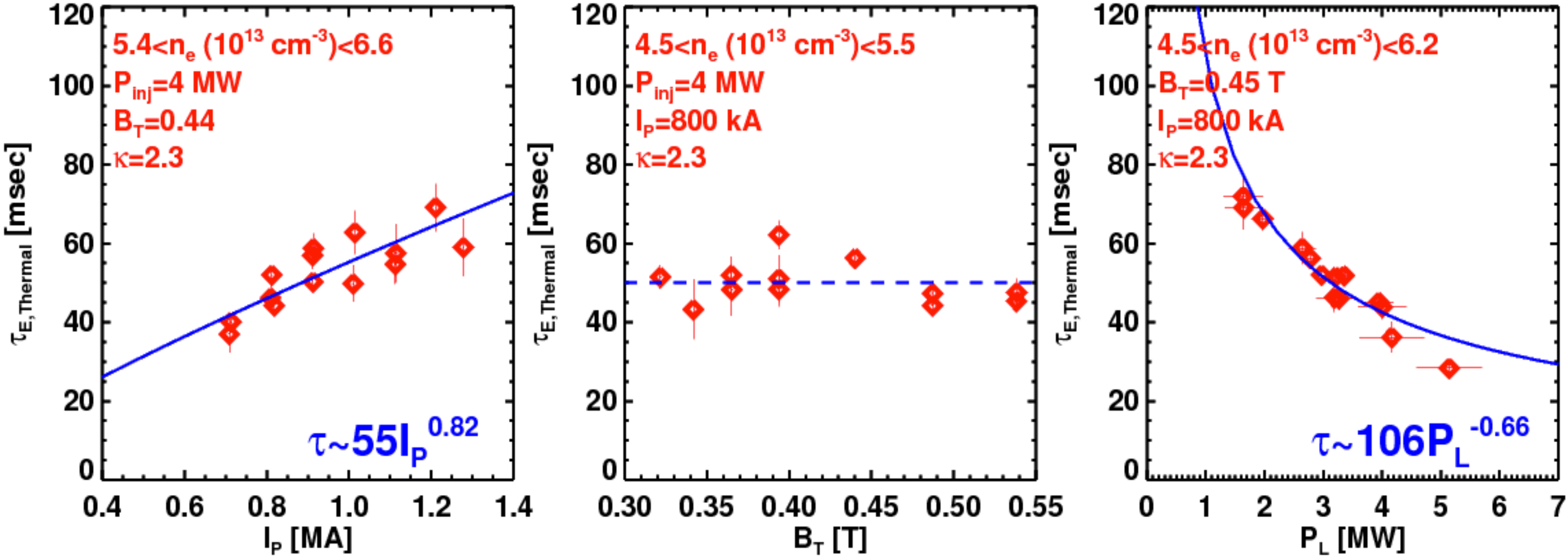
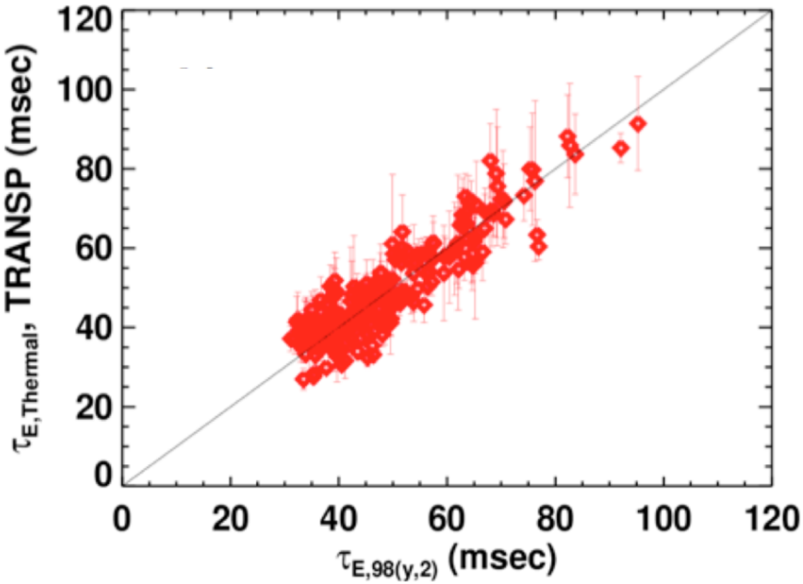
- NSTX results
  - Transport in high-performance plasmas
  - Global stability limits
  - Non-inductive current sustainment
- Projections to NSTX-Upgrade.

Dedicated Scans with Lithiumized PFCs Show Global Confinement Trends Similar to Conventional Aspect Ratio



- Results are similar to ITER-98 scaling expression

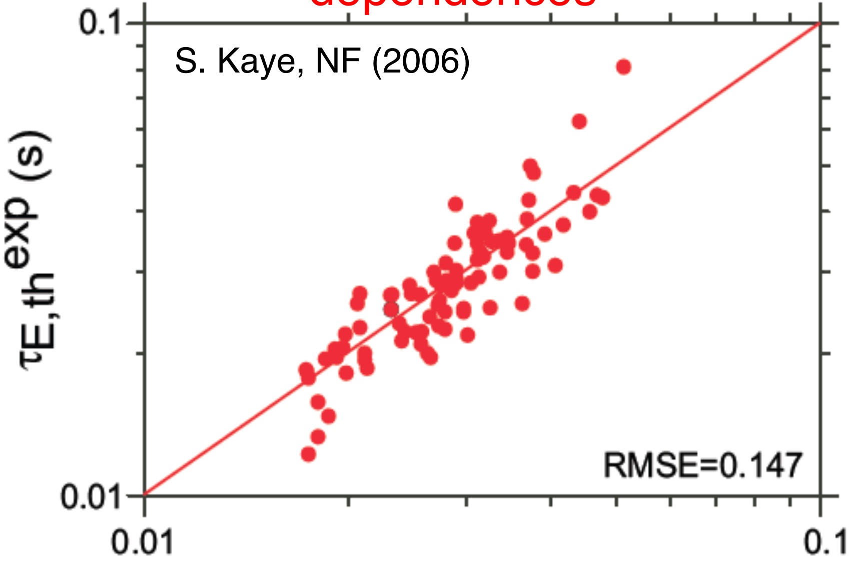
$$\tau_{98} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69} R_0^{1.97} \varepsilon^{0.58} \kappa^{0.78}$$



S. Kaye, R. Maingi

It Remains Unclear What I_P and B_T Scalings To Assume When Projecting ST Global Confinement

Confinement with boronized graphite showed Weaker I_P, stronger B_T dependences



$$\tau_{ST} = 4.7\times10^{-9} I_P^{0.57} B_T^{1.08} \overline{n}_e^{-0.44} P_{Loss}^{-0.73}$$

Similar B_T scaling reported by MAST

- These two scaling expressions appear to imply different collisionality dependencies.

$$B\tau_{98y,2}^{th} \sim \nu_{*e}^{-0.2} \qquad B\tau_{ST}^{th} \sim \nu_{*e}^{-0.95}$$

  - ST scaling generally more favorable for 100% non-inductive operation
- Different dynamics with and without lithium
  - Electron temperature broadening
  - Impurity content
  - See poster PP9.00030 by S. Kaye.
- Underscores the need to extend confinement scalings
  - to higher field and current
  - to lower collisionality

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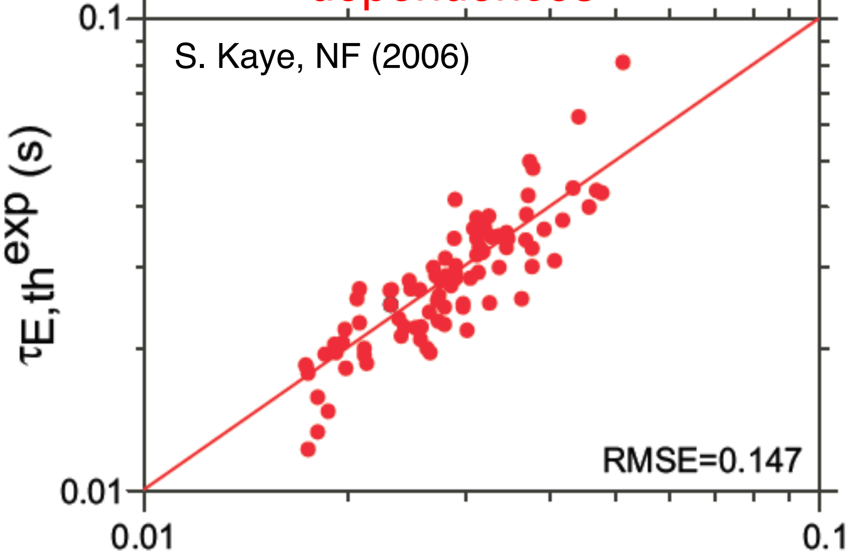

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For NSTX-Upgrade projections: Global Confinement

•Test two thermal confinement scalings

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

$$\tau_{ST} \propto I_P^{0.57} B_T^{1.08} \overline{n}_e^{0.44} P_{Loss}^{-0.73}$$

•Test a range of thermal profile shapes

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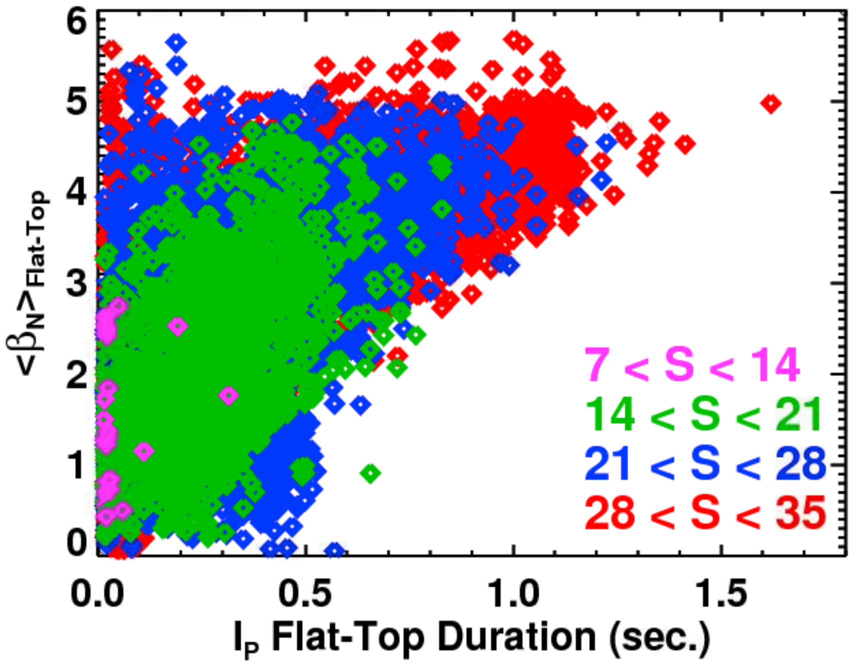
Both Boundary Shaping and Profile Variations Impact Reliability of High-β_N Operation

Boundary Shaping Effects

- Define a shape parameter* *S*
  - "How much safety factor (q_{95}) does the shape have for the given I_P and B_T"

$$S = \frac{q_{95} I_P}{a B_T} \propto \frac{\left(1+\kappa^2\right)}{A} f\left(\kappa,\delta,\varepsilon,\ldots\right)$$

- Pulse-average β_N maximized for large values of *S*.



* Lazarus, et al, Phys. Fluids B 1991

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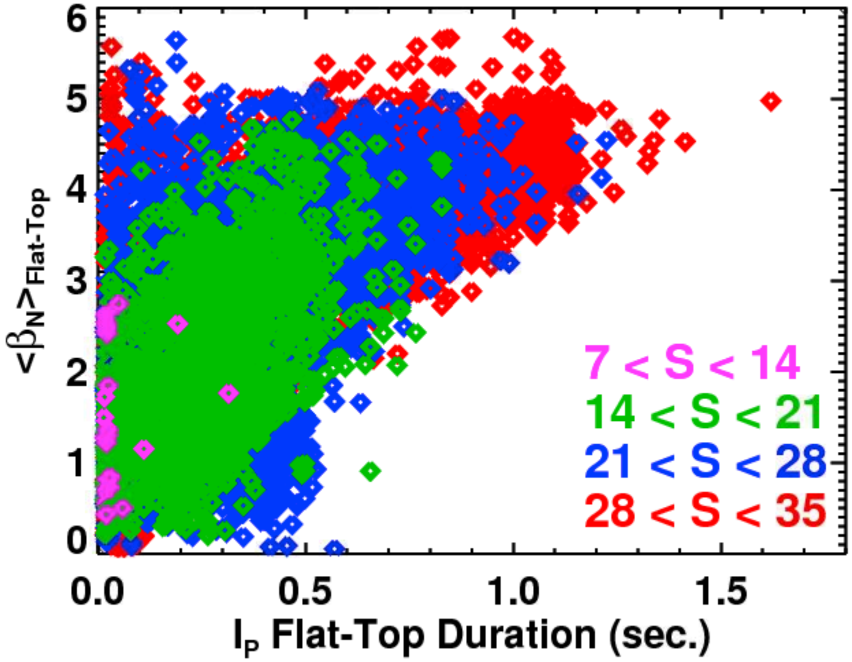

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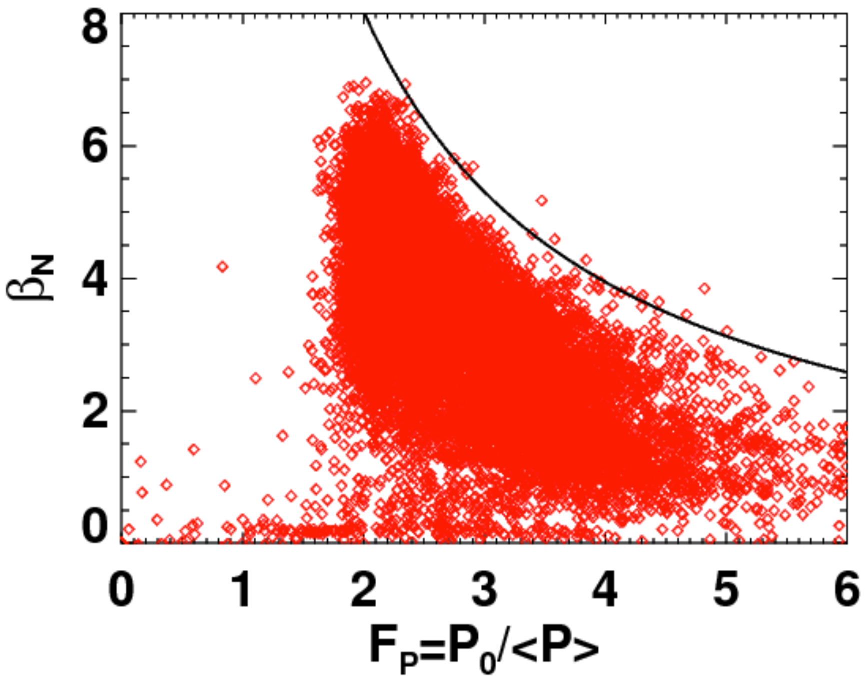
Pressure Profile Shape Effects

- β_N limit calculated to scale inversely with the pressure peaking.

$$F_P = \frac{P_0}{\langle P \rangle}$$

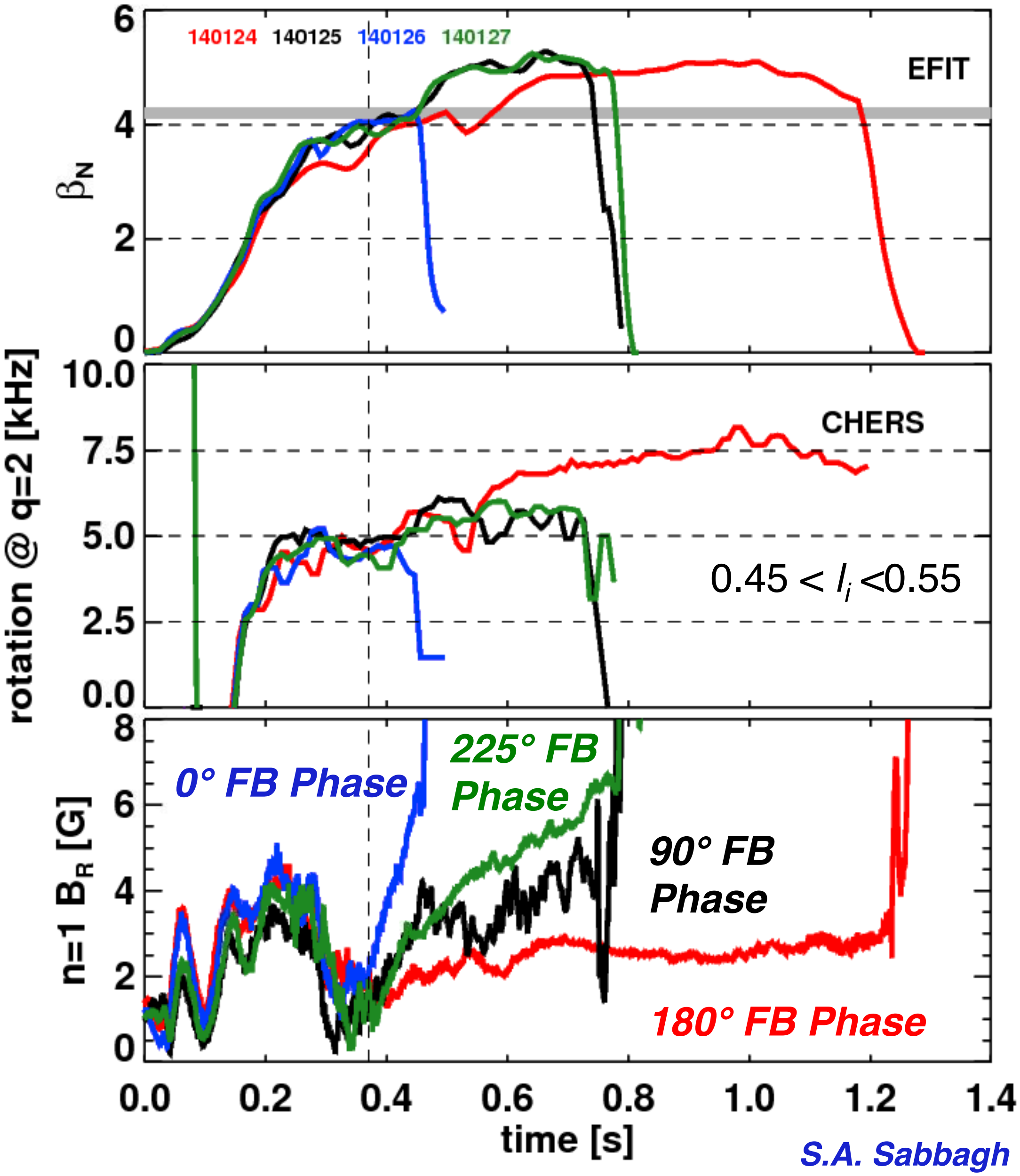
- Observations support this dependence.
- Rotation profile effects are important in determining RWM passive stability.



Control of n=1 Error Fields and RWMs Facilitates Operation Above the No-Wall β_N Limit

- Proportional feedback scheme
  - Detect n=1 magnetic perturbation amplitude and toroidal phase.
    - 2008-2009 mainly used B_P sensors.
  - Apply an n=1 field:
    - Phase shifted relative to detected field.
    - Amplitude proportional to the detected field.
- System does double duty:
  - Slow feedback on the plasma amplified n=1 fields for error field correction.
  - Fast feedback to stabilize RWMs.
- Recent research:
  - Optimize B_P + B_R detection
    - Uses 48 total, in vessel magnetic sensor
  - Developed state-feedback n=1 control

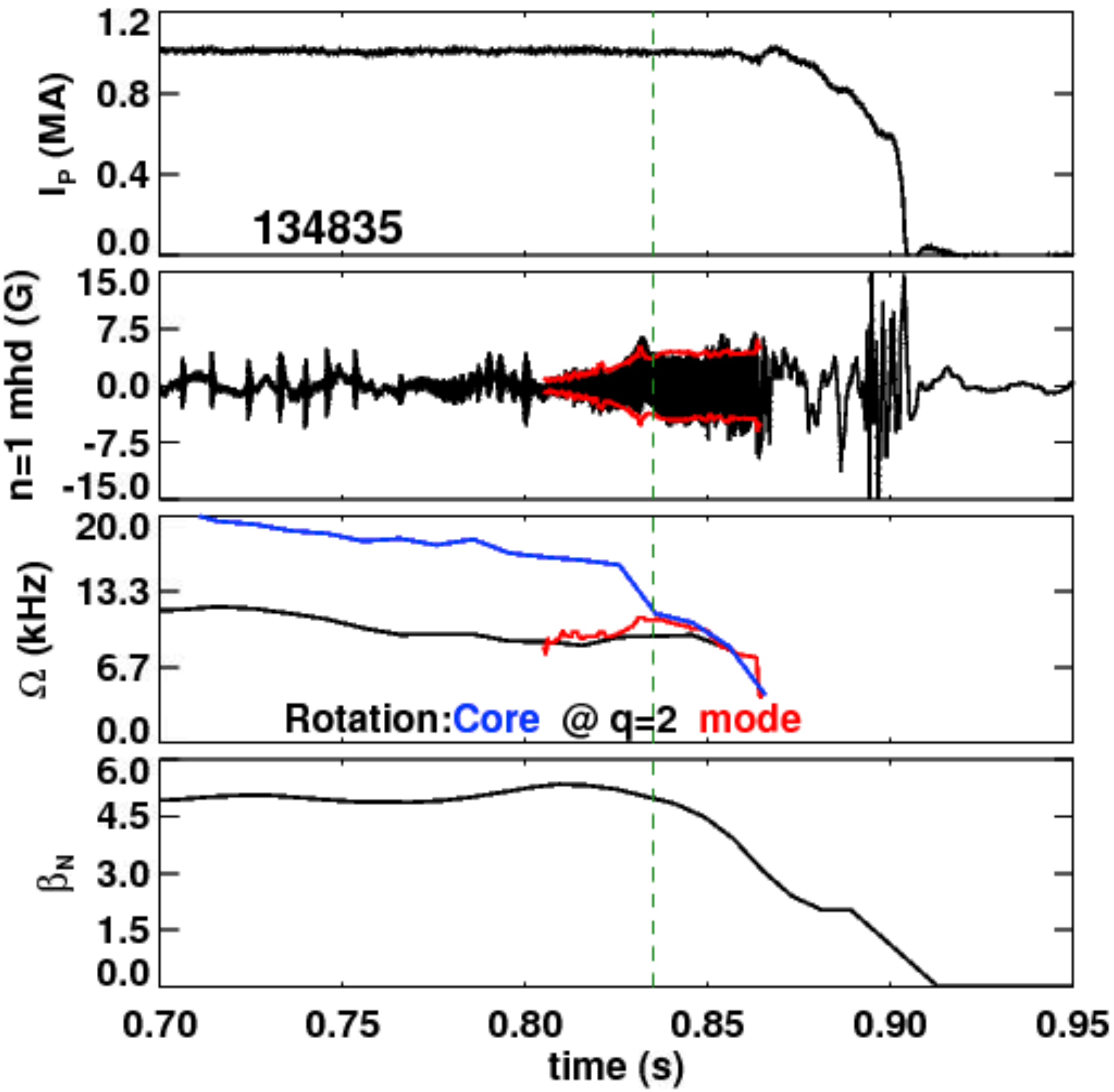
B_R Feedback Optimization



S.A. Sabbagh

When Global Stability Limits are Avoided, Rotating Core n=1 Modes Often Limit Performance

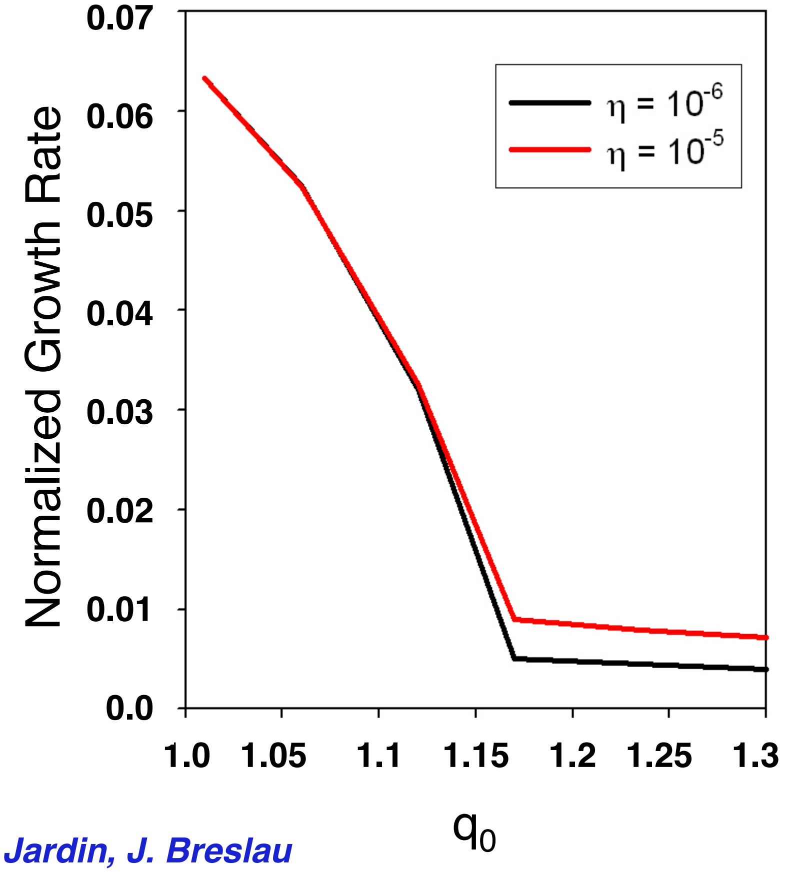
- Mode onset at t~800 msec.
  - Locks at t~860 msec, followed by disruption
- Initial rotation is with the q=2 surface.
  - First the core rotation is damped
  - Then the total rotation is reduced.
- β_N starts to decreases after mode onset.
- Analysis of soft X-ray data shows a coupled eigenfunction:
  - m/n=1/1 core kink
  - m/n=2/1 magnetic island



Elevated q_{min} Helps Avoid These m/n=2/1+1/1 Coupled Modes

- "Triggerless" modes in quiescent discharges as q_{min} approaches 1.
- From M3D-C1 simulations
  - Ideal modes become unstable as q_{min} ->1
  - Energetic particles are stabilizing.
- Non-linearly saturated states with core 1/1 and 2/1 islands have been found.
- Observed numerous additional triggering dynamics.
  - ELMs (and ELM stabilization w/ Lithium PFC conditioning helps avoid these).
  - EPMs
  - Spin-up of stationary "locked modes"
  - Have the characteristics of NTMs

Linear Growth Rate vs. q_0
(from M3D-C1, Breslau NF 2011)



S. Jardin, J. Breslau

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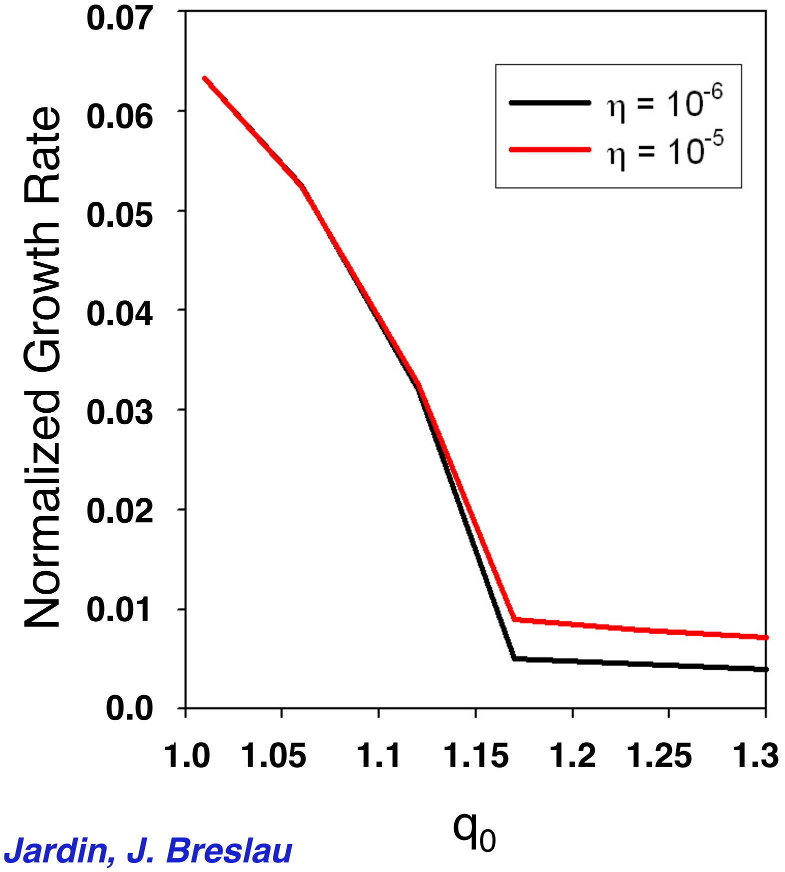

S. Jardin, J. Breslau

For NSTX-Upgrade projections: Global Stability

- Use high elongation and triangularity plasma boundaries
- Look for cases with broad pressure profiles and relaxed q_{min}>1.15
- Rely on n=1 control for stable operation above the no-wall β_N limit

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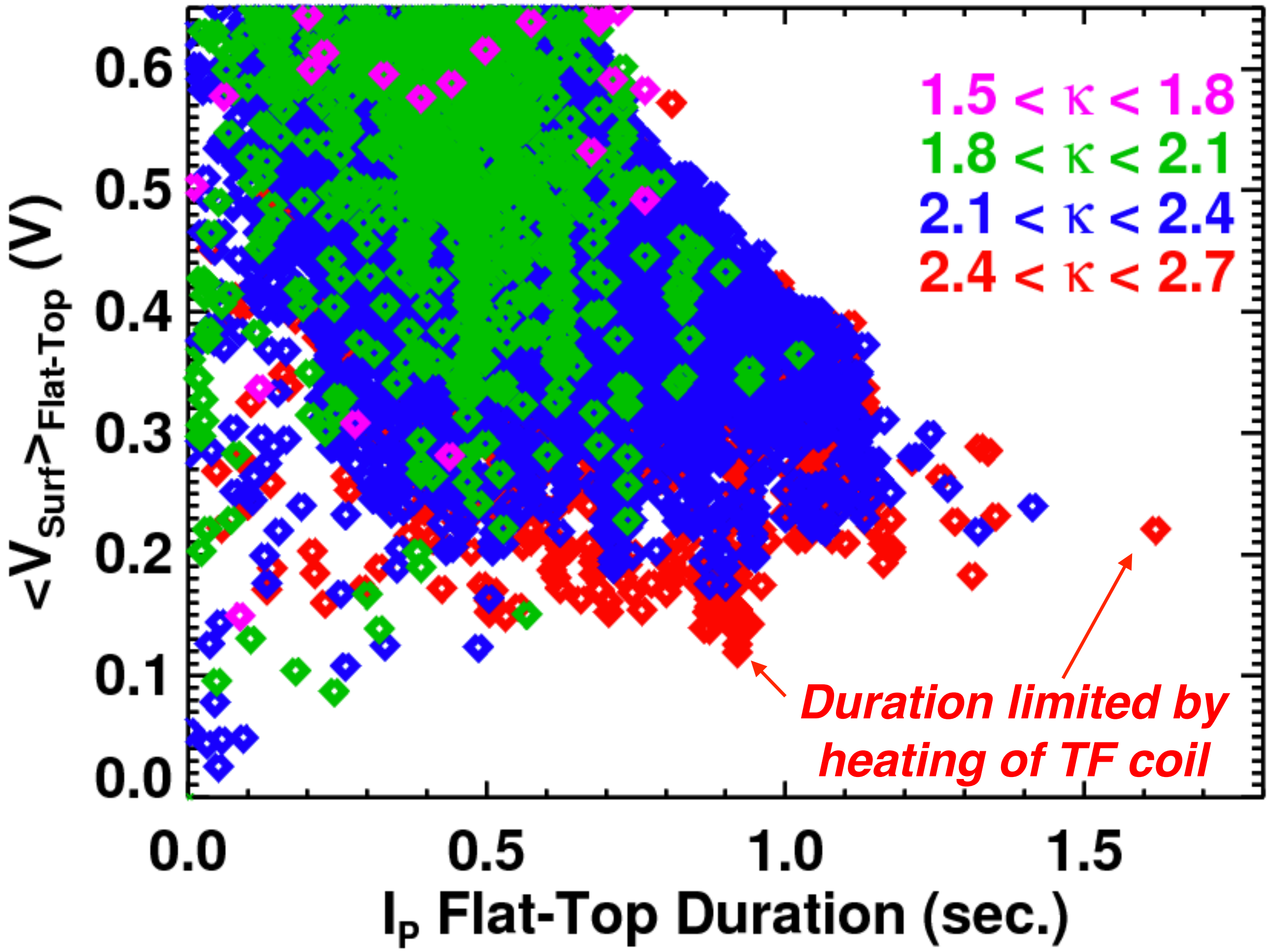
High Elongation Essential for Non-Inductive Sustainment

Average surface voltage, plotted against the flat-top duration.

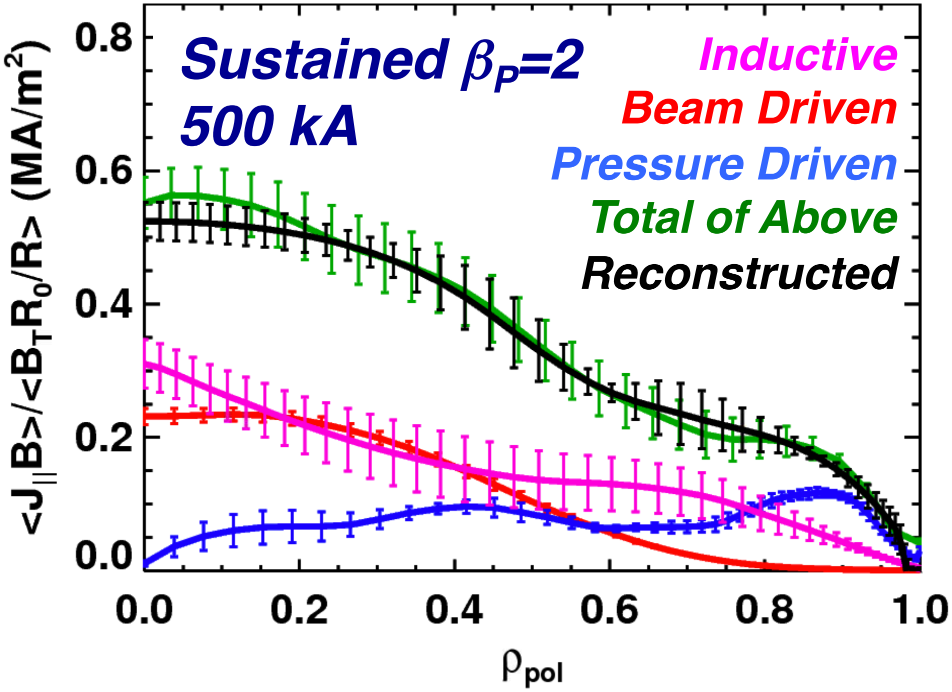


Duration limited by heating of TF coil

- Lowest surface voltages achieved at high elongation
- Longest pulses at high elongation

Neoclassical Current Profile Modeling Validated For a Wide Range of Scenarios

Inductive Currents: V_{loop} profile and neoclassical resistivity
Beam Driven: NUBEAM within TRANSP
Pressure Driven: Sauter Bootstrap + Diamagnetic and Pfirsch-Schlueter
Total of Above
Reconstructed From G.-S. Eqn.



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Total of Above
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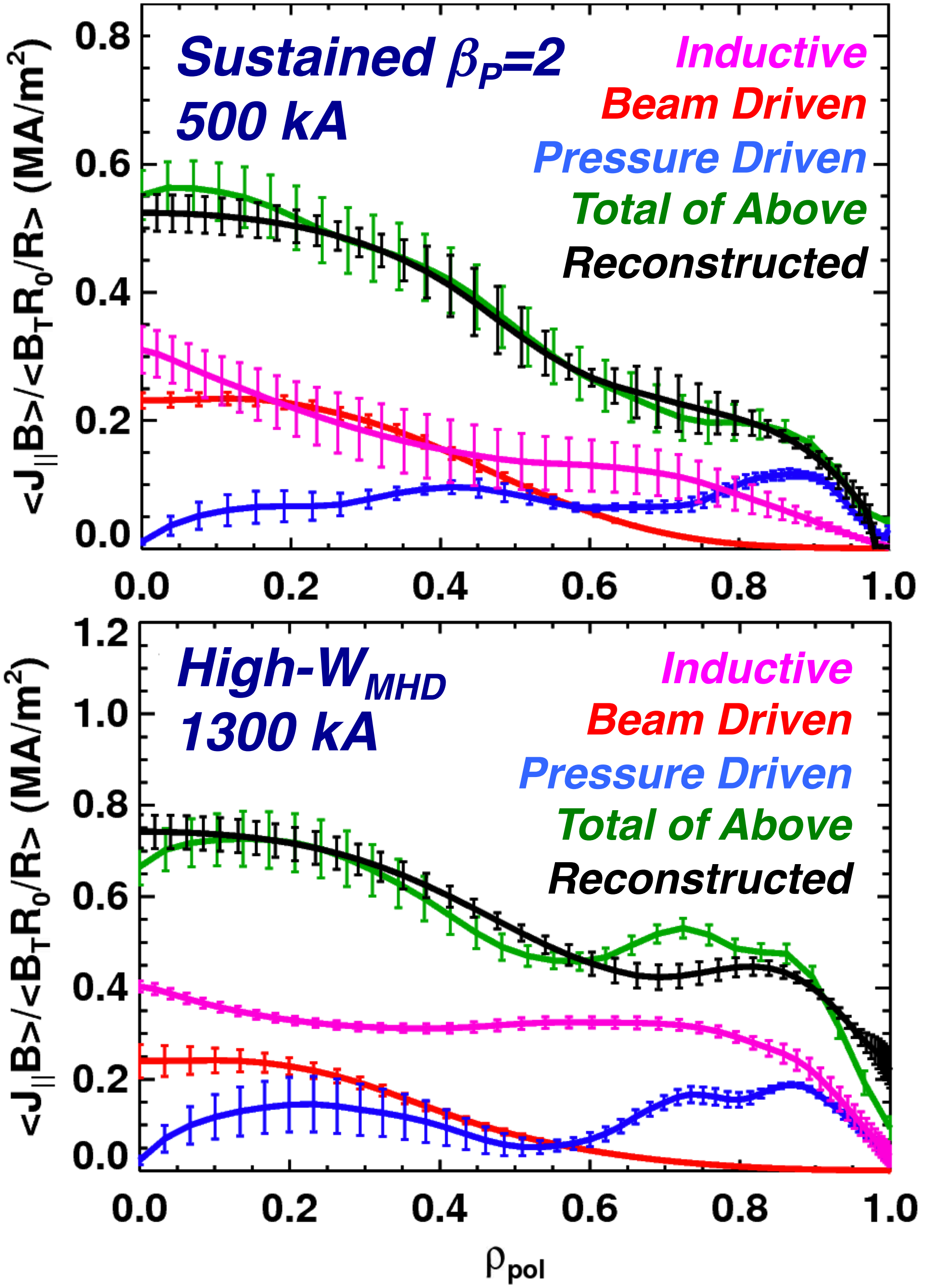
- Good agreement in current profile accounting when low-f MHD is absent.
  - Calculations assume classical beam ion physics
  - Data consistent with $D_{FI} < 1\text{-}1.5\ m^2/s$.
- Effects of TAE bursts have been modeled with transient fast ion diffusivity.
  - …or constant D_{FI}~4 m^2/s
  - Gerhardt, et al, Nuclear Fusion (2011)
- Maximum non-inductive fractions of 65-70%, with I_P=700-800 kA



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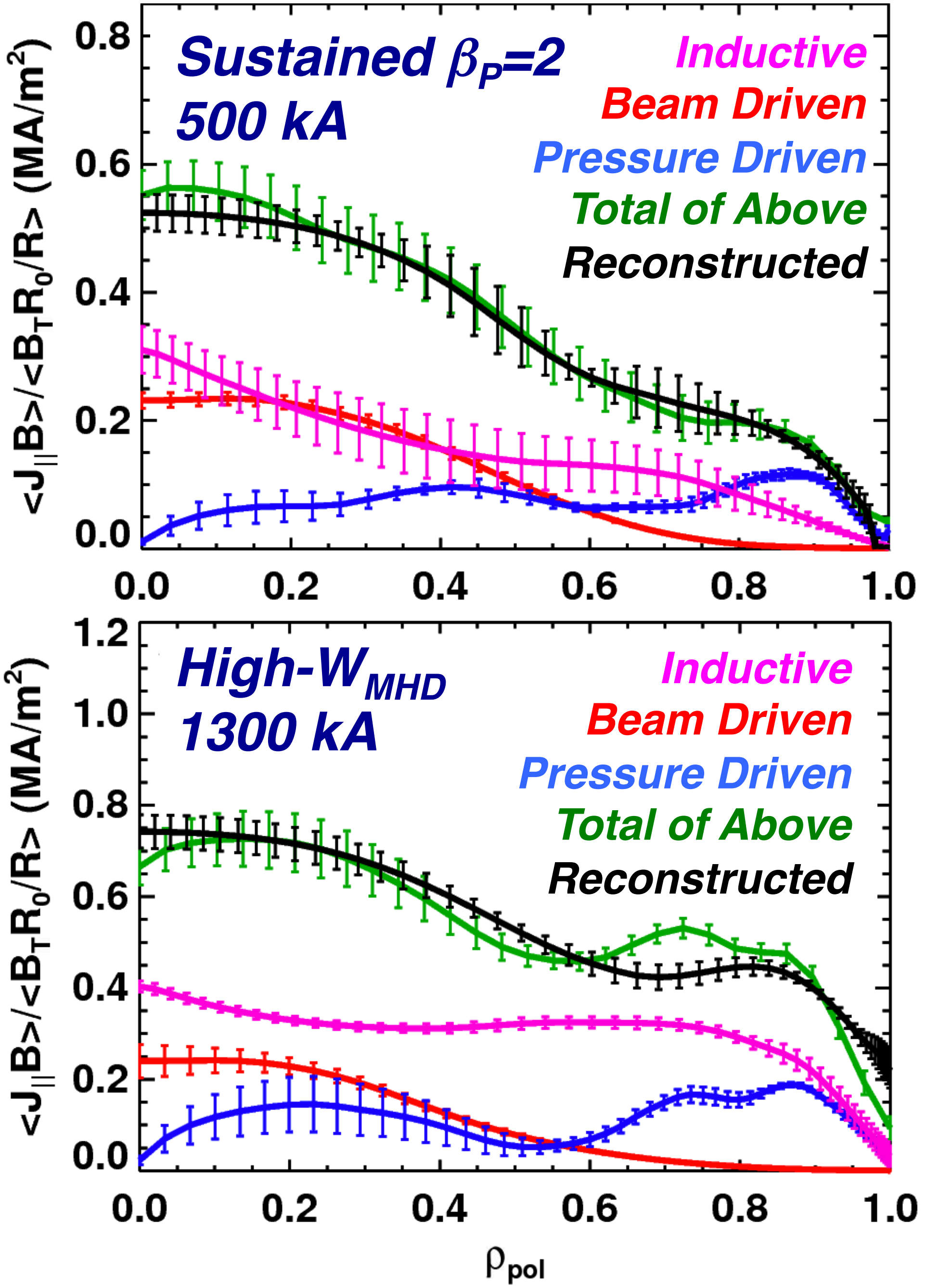
For NSTX-Upgrade Projections: Current Drive Modeling

- Use the Sauter model for the bootstrap current, NUBEAM for NBCD.
- Test effect of non-zero D_{FI}.
- Try to reduce β_{fast} to eliminate drive for fast ion modes.



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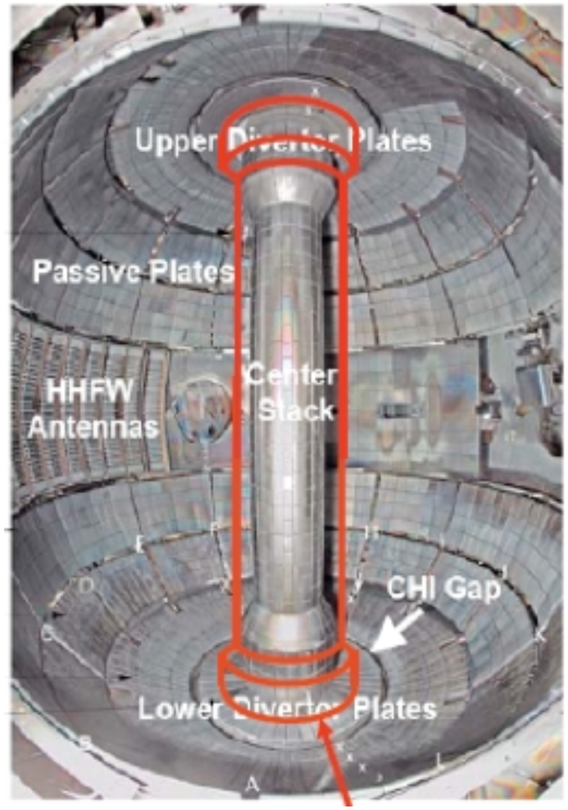
NSTX-Upgrade Designed to Study Fully Non-Inductive Sustainment and ST Physics at Higher Current and Reduced Collisionality

Center-Stack Upgrade



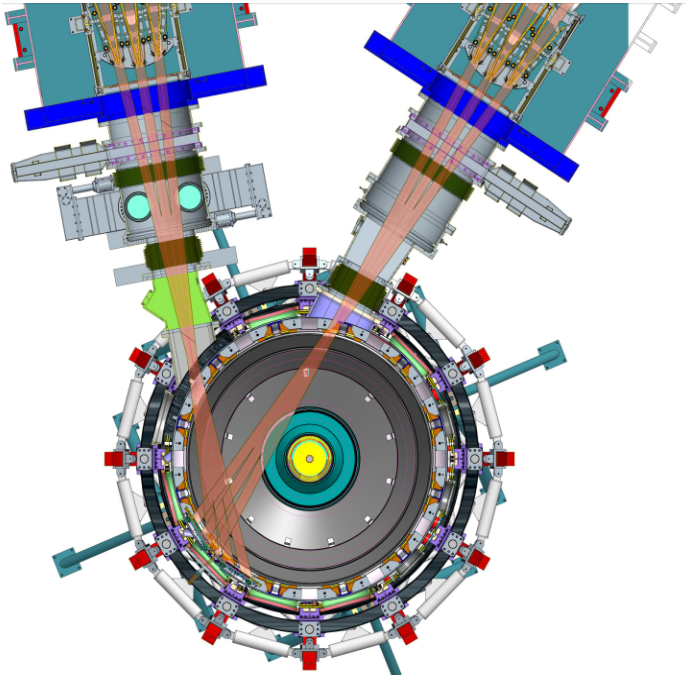
	NSTX	NSTX-U
B_T	0.55 T for ~1 s	1 T for ~5 s
I_P	1 MA for ~1s	2 MA for ~5 s
A	1.35-1.55	1.65-1.8

2ND Beamline Upgrade

(3 Sources per Beamline)

New 2nd NBI
(R_{TAN}=110, 120, 130cm)

Present NBI
(R_{TAN}= 50, 60, 70cm)



	Present NBI	2nd Beamline
Total Power at 90 kV	6.3 MW	6.3 MW
Typical Current Drive Efficiencies	30-40 kA/MW	70-80 kA/MW + off-axis

The Central Safety Factor Can Be Controlled by Appropriate Beam Selection

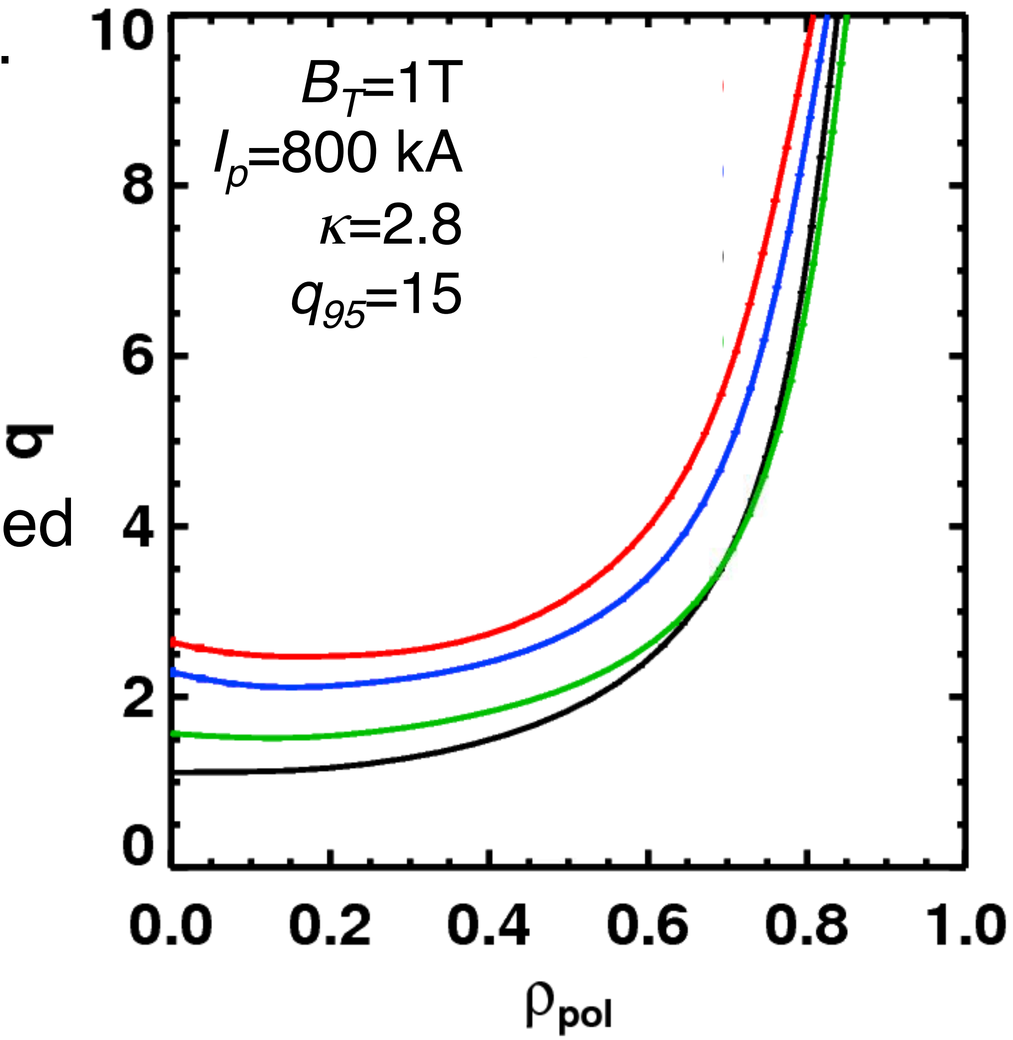
Each configuration uses a different combination of 4 NB sources.

R_{tan}=[50,60, 70, 130] cm, q_{min}=2.47,

R_{tan}=[50,60, 120,130] cm, q_{min}=2.14,

R_{tan}=[60,70, 110,120] cm, q_{min}=1.11,

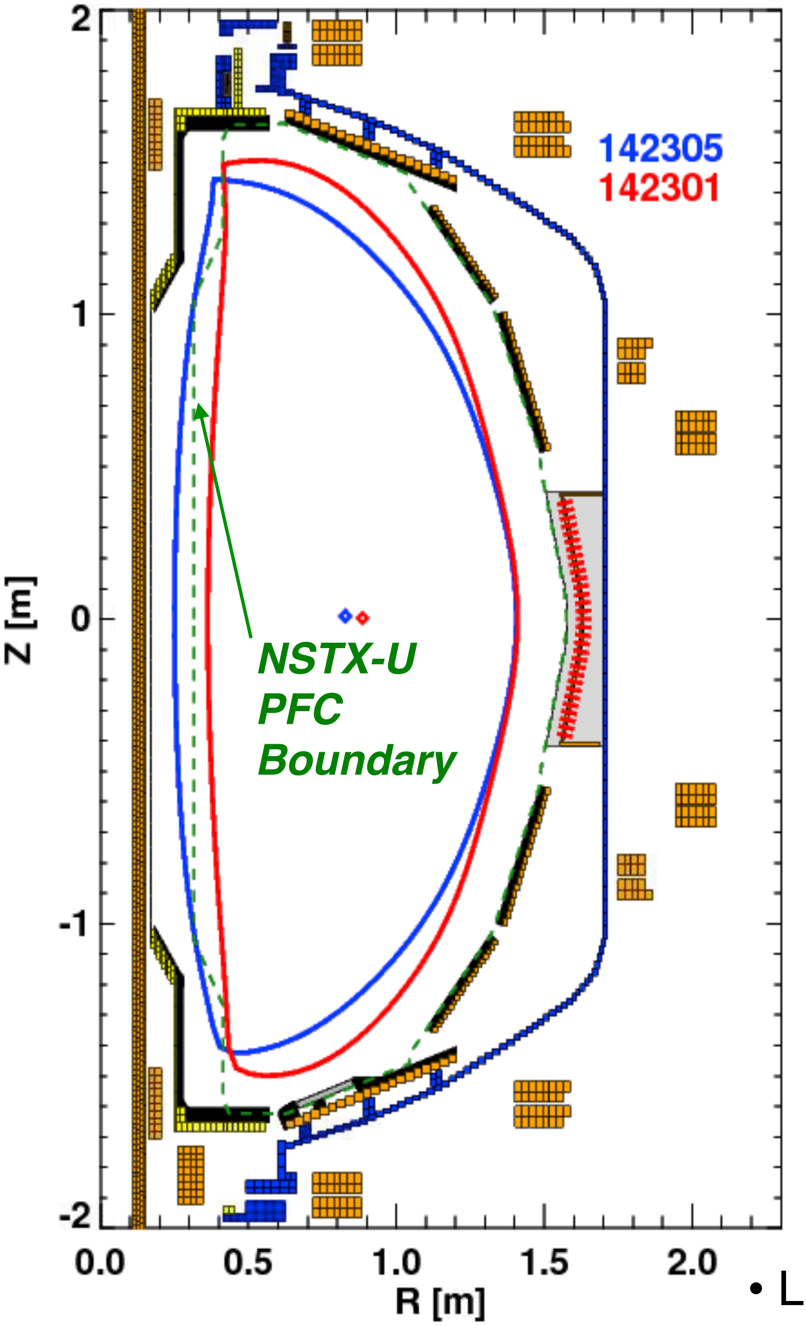
R_{tan}=[70,110,120,130] cm, q_{min}=1.51

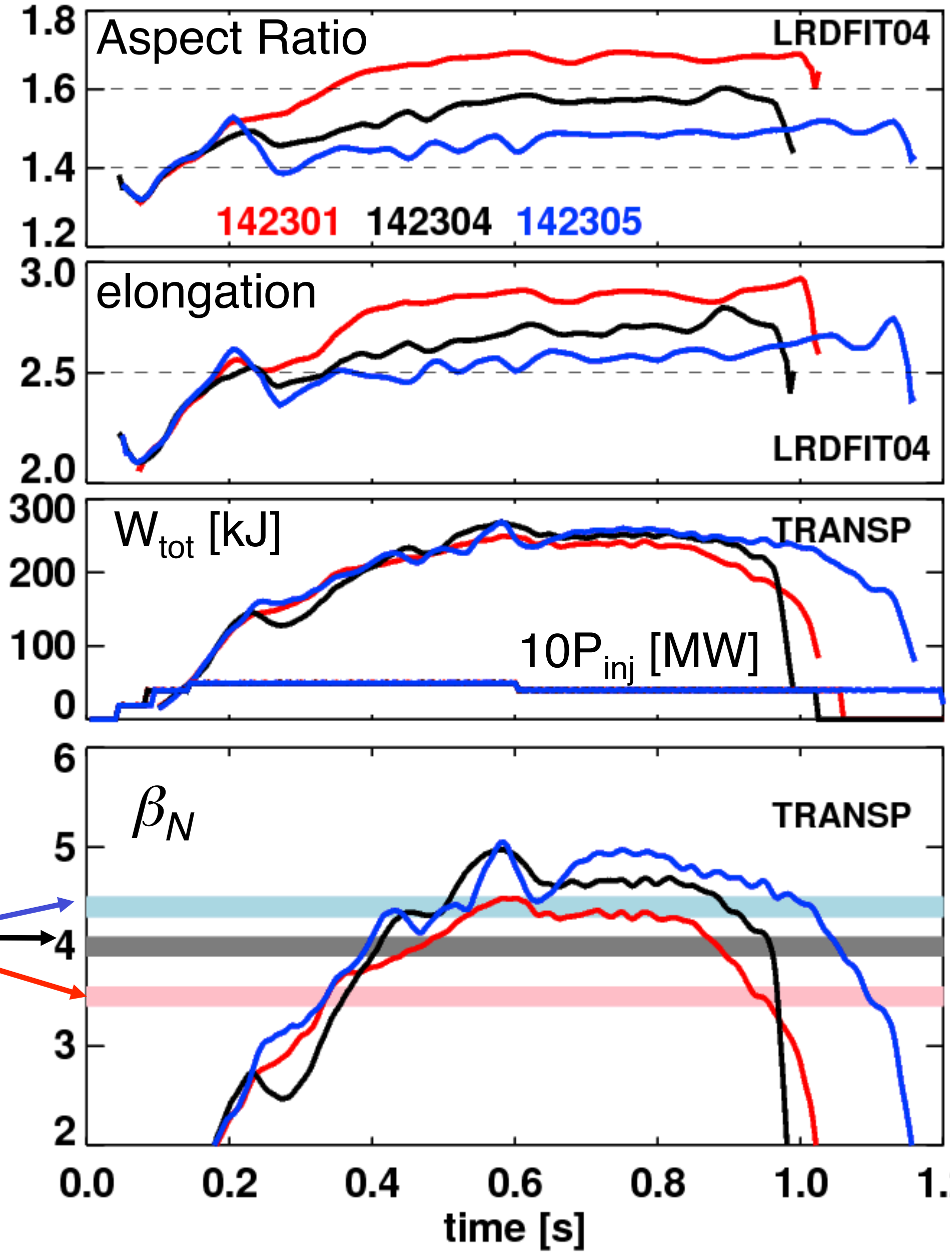


Allows range of q_{min} with relaxed profiles: $1.1<q_{min}<2.5$

Allows q_{min} control for the avoidance of m/n=1/1+2/1 kink/tearing modes

Prototype NSTX-Upgrade Scenarios Have Been Developed on NSTX

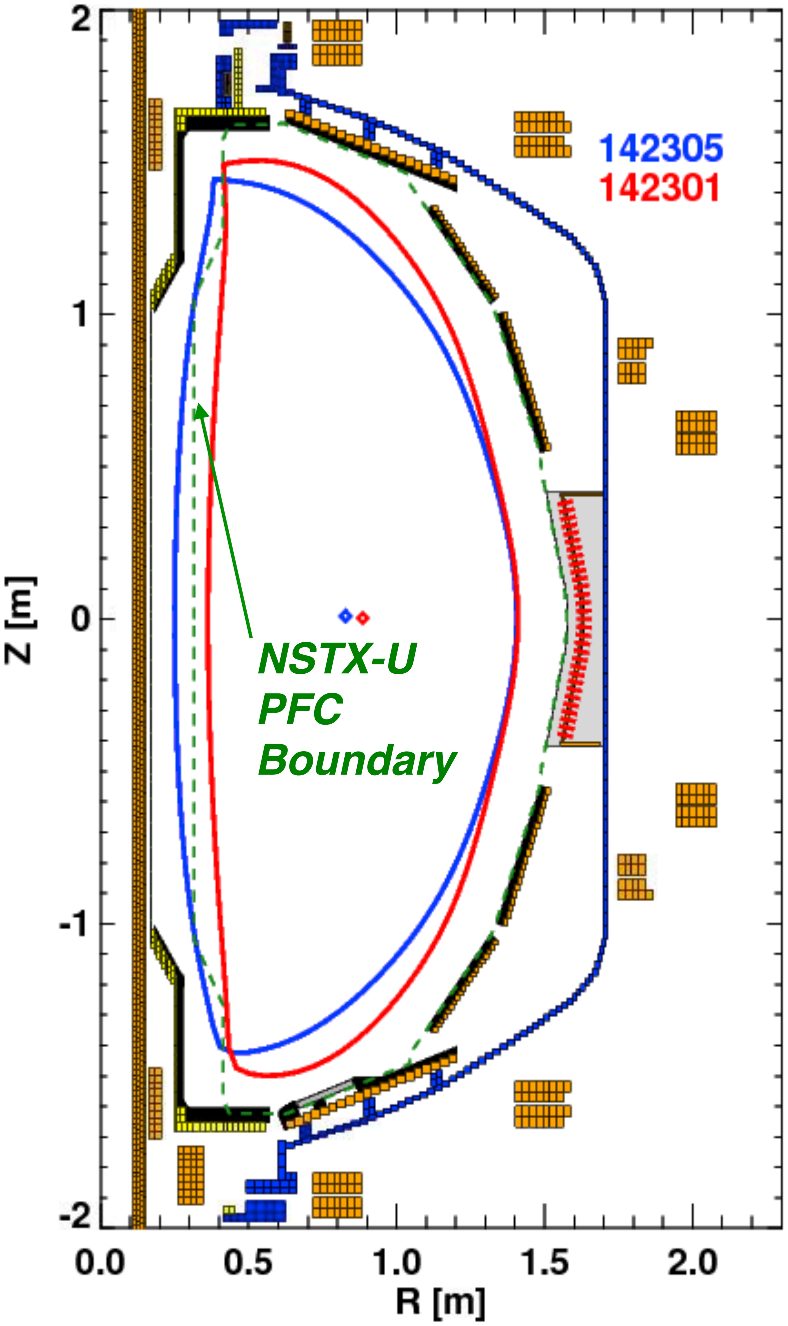




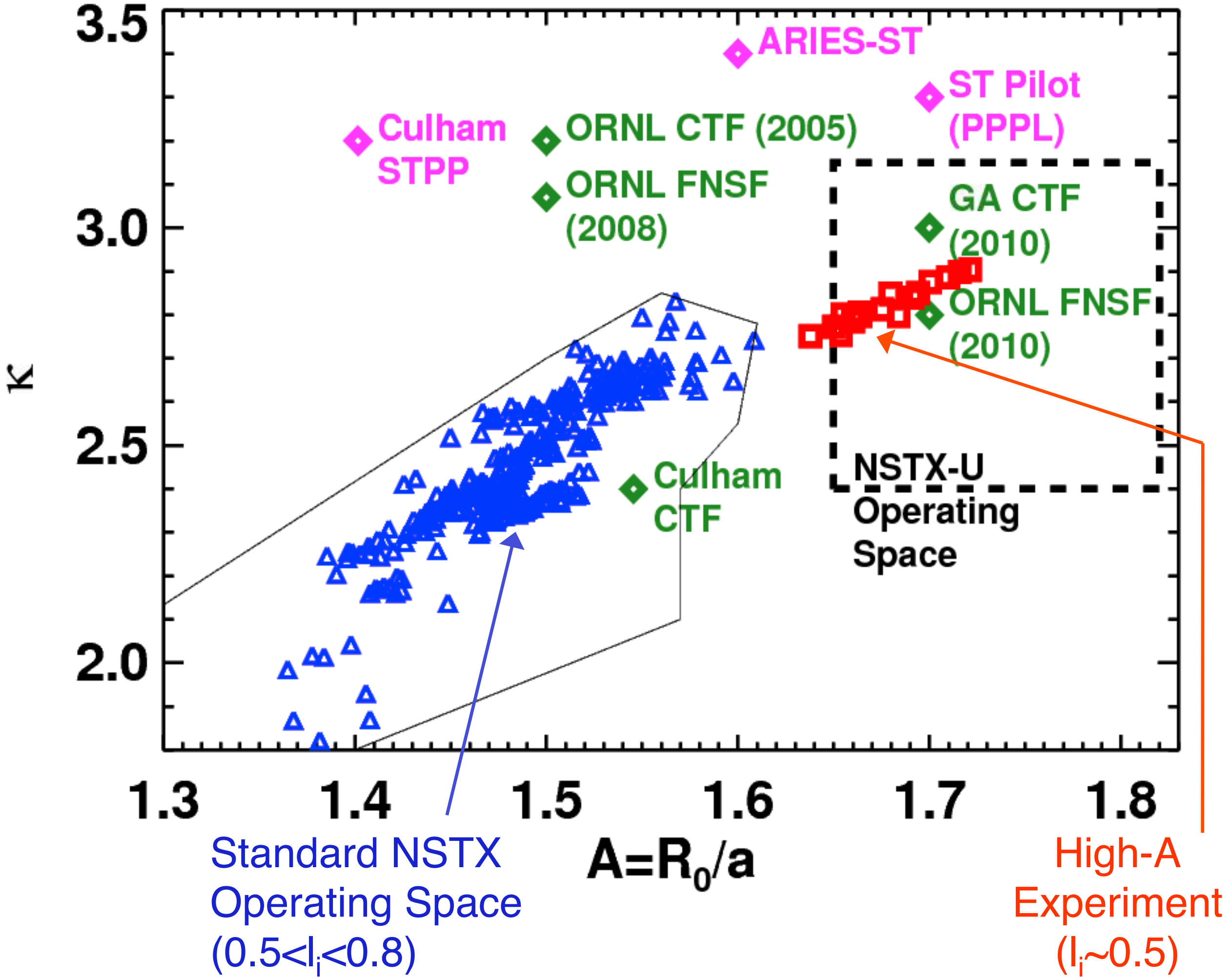
Computed no-wall β_N limit

- Late rollover in β_N and W_{MHD} due to onset of rotating n=1 MHD

Achieved Scenarios Encompass the Aspect Ratios of Proposed Next-Step STs



NSTX results
compared to
Pilot plants and power plants ($0.2 < l_i < 0.4$)
Nuclear component testing ($0.3 < l_i < 0.5$)

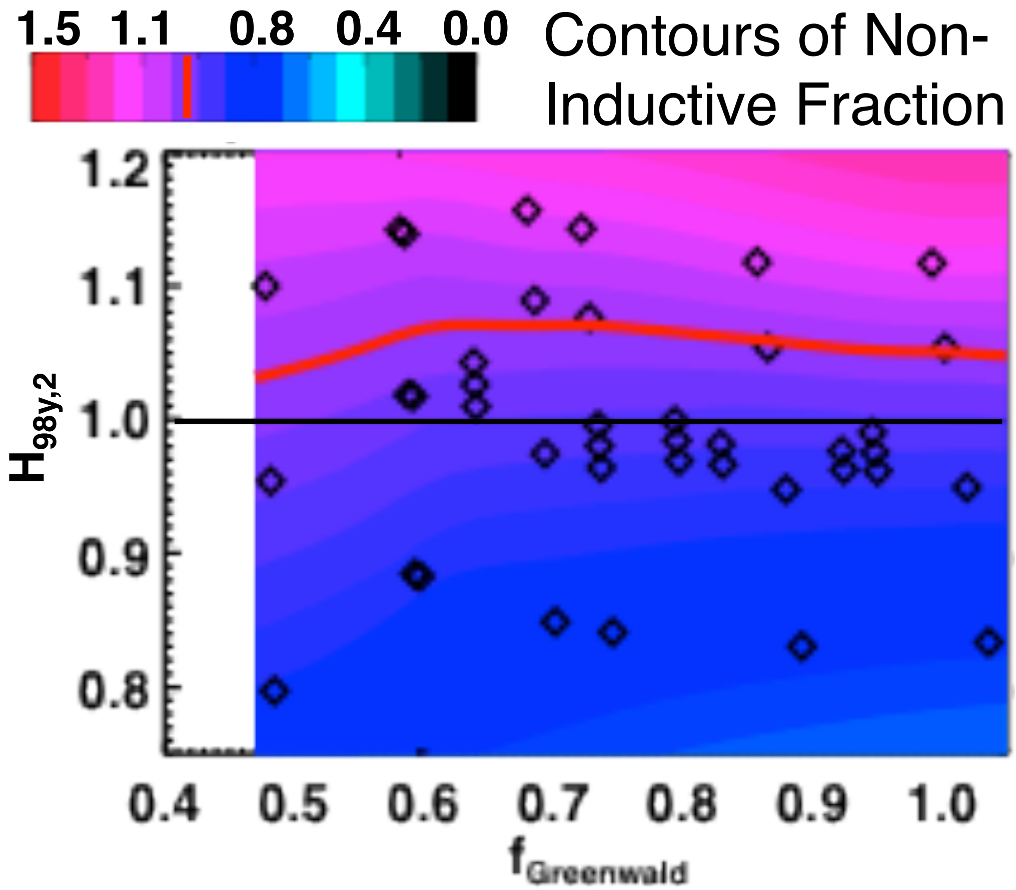


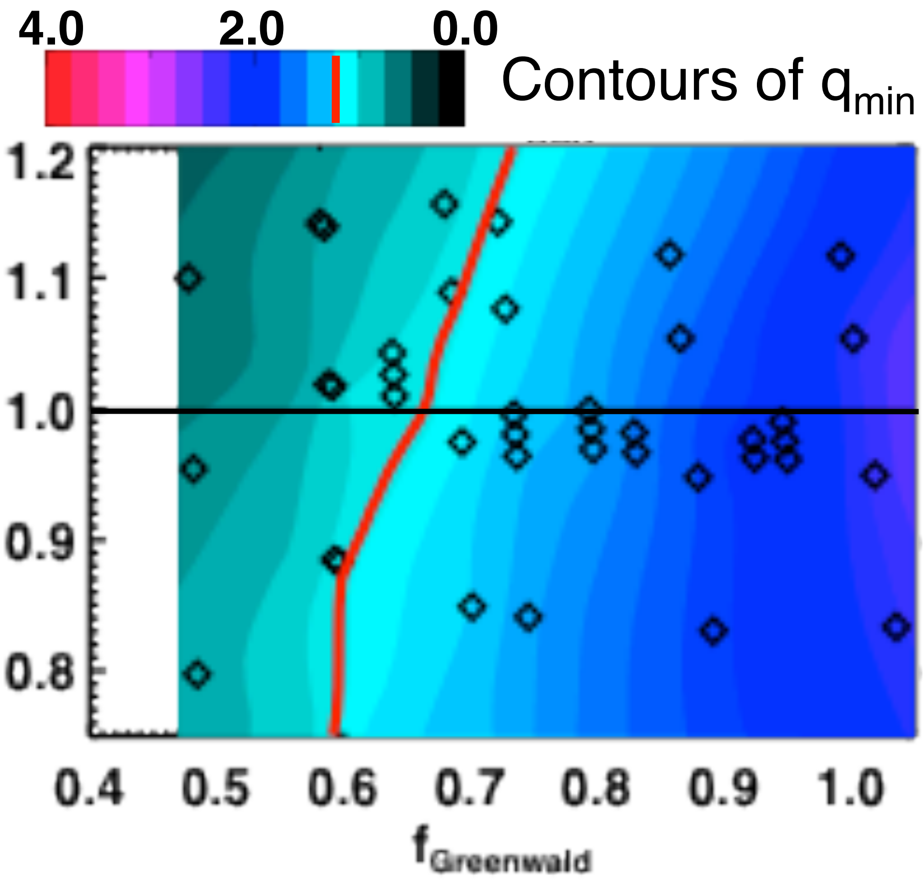
Projections to NSTX-Upgrade Made with Free-Boundary TRANSP

- Neoclassical theory to predict the ion temperature.
- Scale experimental electron profiles to achieve desired Greenwald density fraction and confinement level.
- Allow the current profile to fully relax

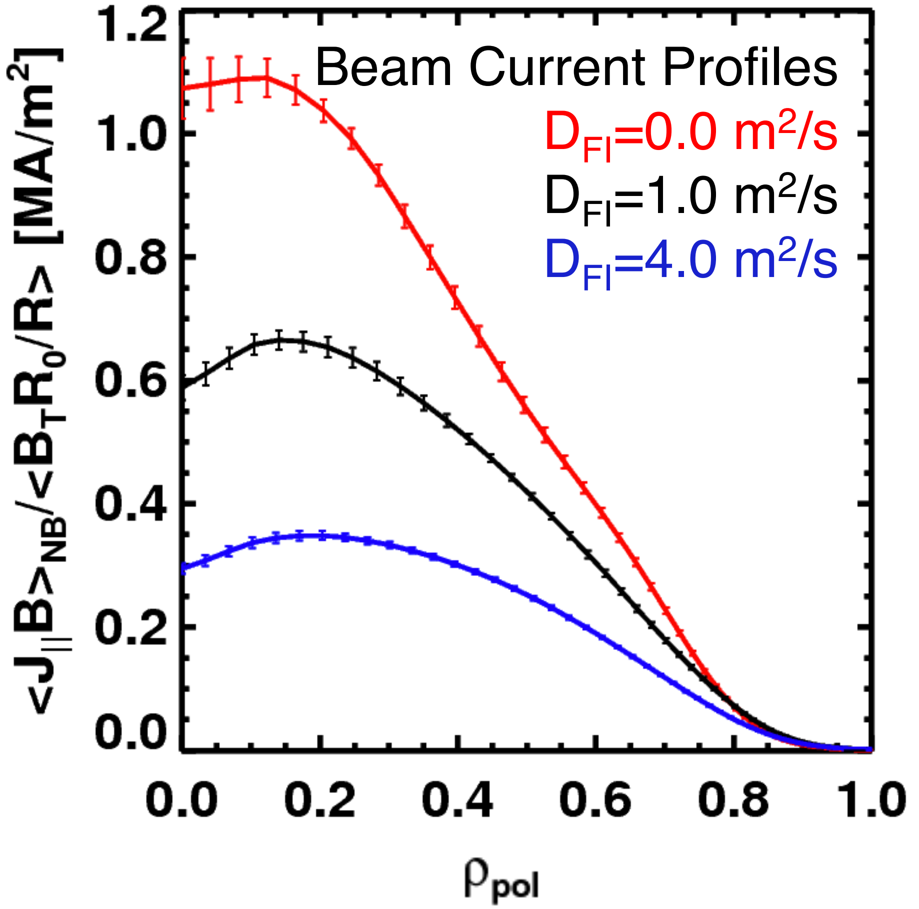
B_T=1.0 T, I_p=1.0 MA, κ= 2.75

Six sources with total P_{inj}=12.6 MW


Contours of Non-Inductive Fraction

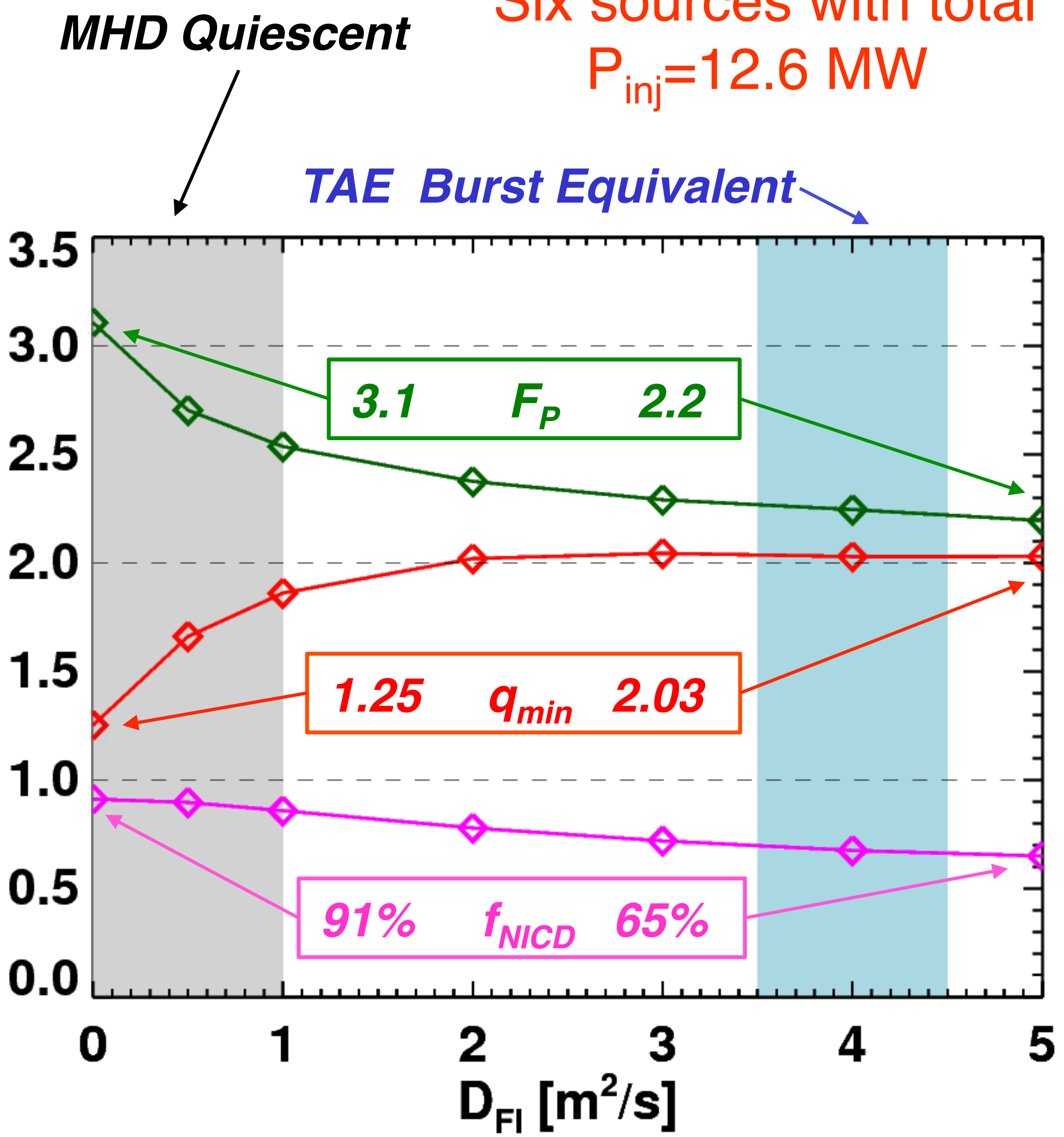

Contours of q_{min}

“Anomalous” Fast Ion Diffusivity Decrease Non-Inductive Fraction And Broaden Profiles



- The increase in q_{min} and reduction in F_P both improve the global stability.
- These scenarios will be an excellent laboratory for the study of fast ion transport.

B_T=1.0 T, I_p=1.0 MA,
$H_{98y,2}$=1.0, f_{GW}=0.7, κ= 2.75
Six sources with total
P_{inj}=12.6 MW



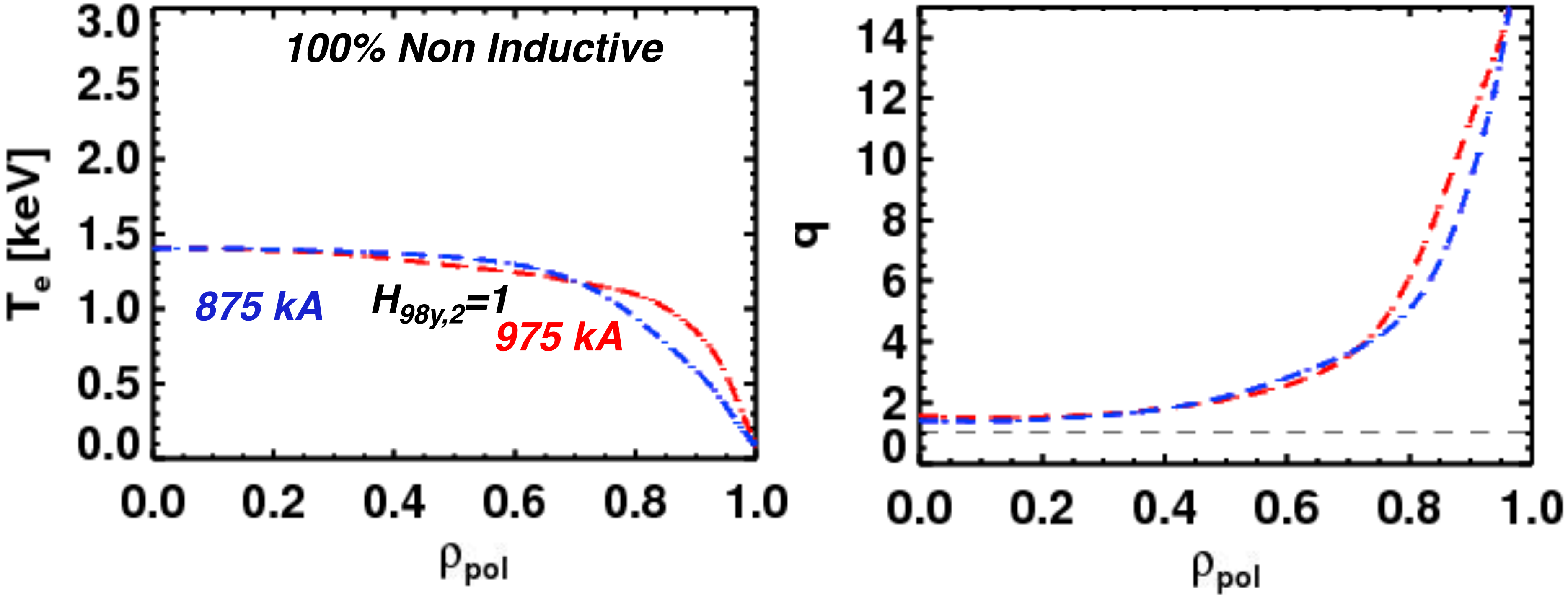
Facility Capabilities of NSTX-U Allow Confinement Scalings to be Tested with Full Non-Inductive Current Drive

- Configuration constants
  - B_T=1.0T
  - A=1.75, κ=2.8
  - f_{GW}=0.72
  - P_{inj}=12.6 MW from 6 total sources

Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

- Find the non-inductive current level for various confinement assumptions.



Facility Capabilities of NSTX-U Allow Confinement Scalings to be Tested with Full Non-Inductive Current Drive

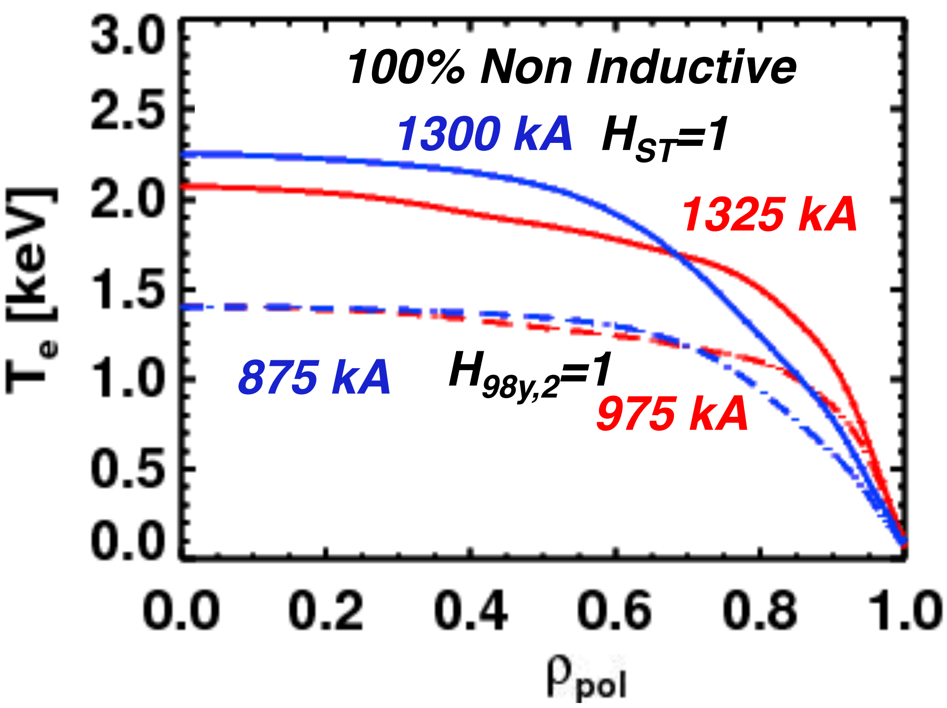
- Configuration constants
  - B_T=1.0T
  - A=1.75, κ=2.8
  - f_{GW}=0.72
  - P_{inj}=12.6 MW from 6 total sources
- Find the non-inductive current level for various confinement assumptions.

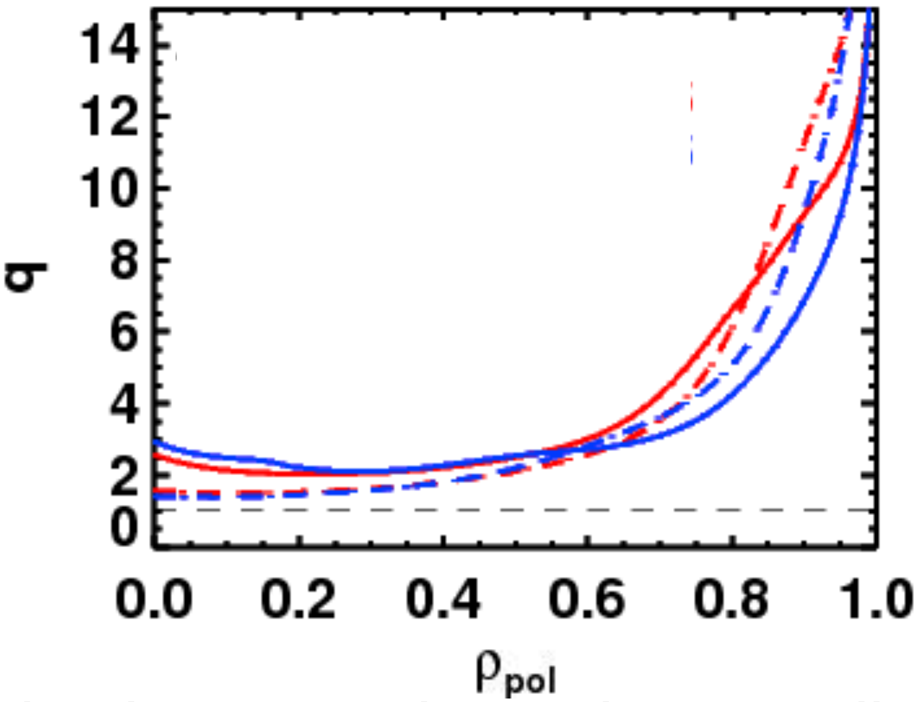
Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

Solid: ST confinement scaling

$$\tau_{ST} \propto I_P^{0.57} B_T^{1.08} \overline{n}_e^{0.44} P_{Loss}^{-0.73}$$





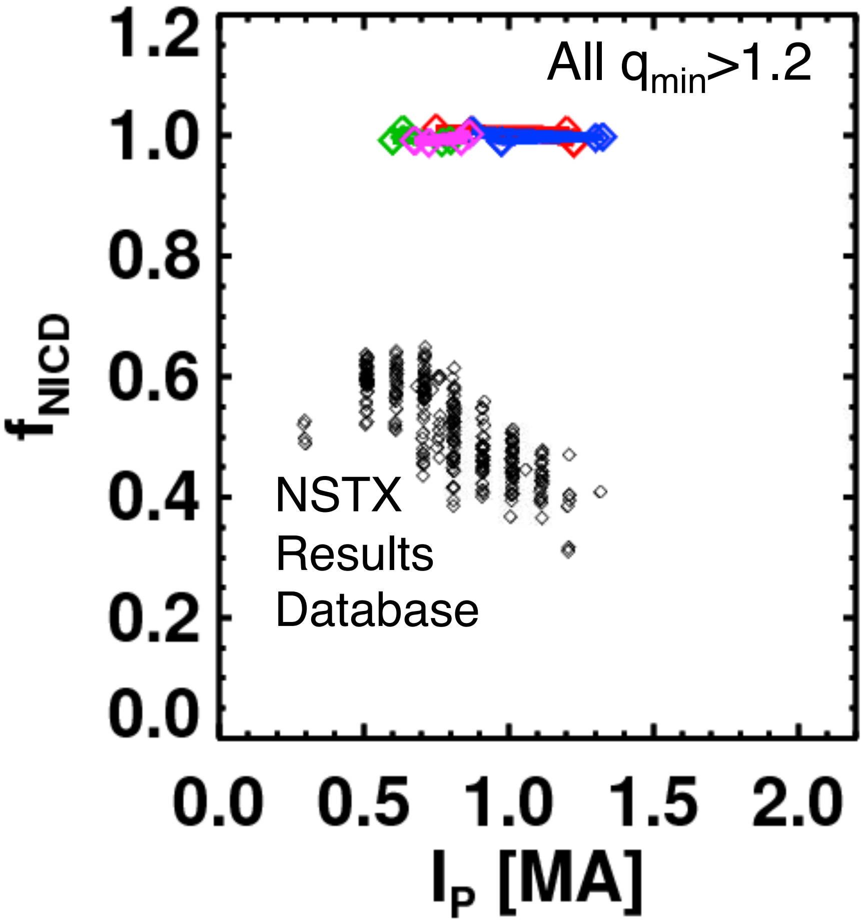
Four fully evolved 100% non-inductive operating points pending profile and confinement assumptions.

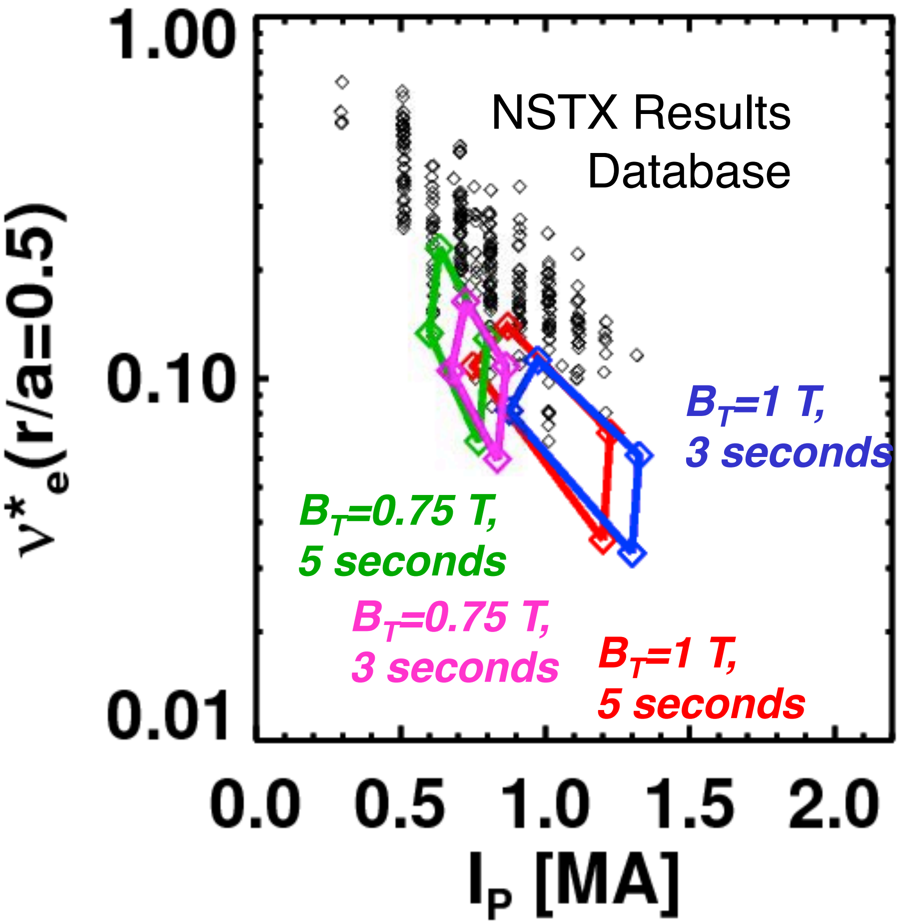
100% Non-Inductive Scenarios Identified For a Wide Range of Configurations & Confinement Assumptions

- Points are from existing NSTX database.
- Shapes bracket range of predictions.
  - Two profile assumptions.
  - Two confinement assumptions.
- Durations limited by NB pulse length limitations.

B_T=1.00 T, 6 beams, P_{inj}=12.6 MW
B_T=1.00 T, 6 beams, P_{inj}=10.2 MW
B_T=0.75 T, 4 beams, P_{inj}=8.4 MW
B_T=0.75 T, 4 beams, P_{inj}=6.8 MW

f_{GW}=0.72
D_{FI}=0

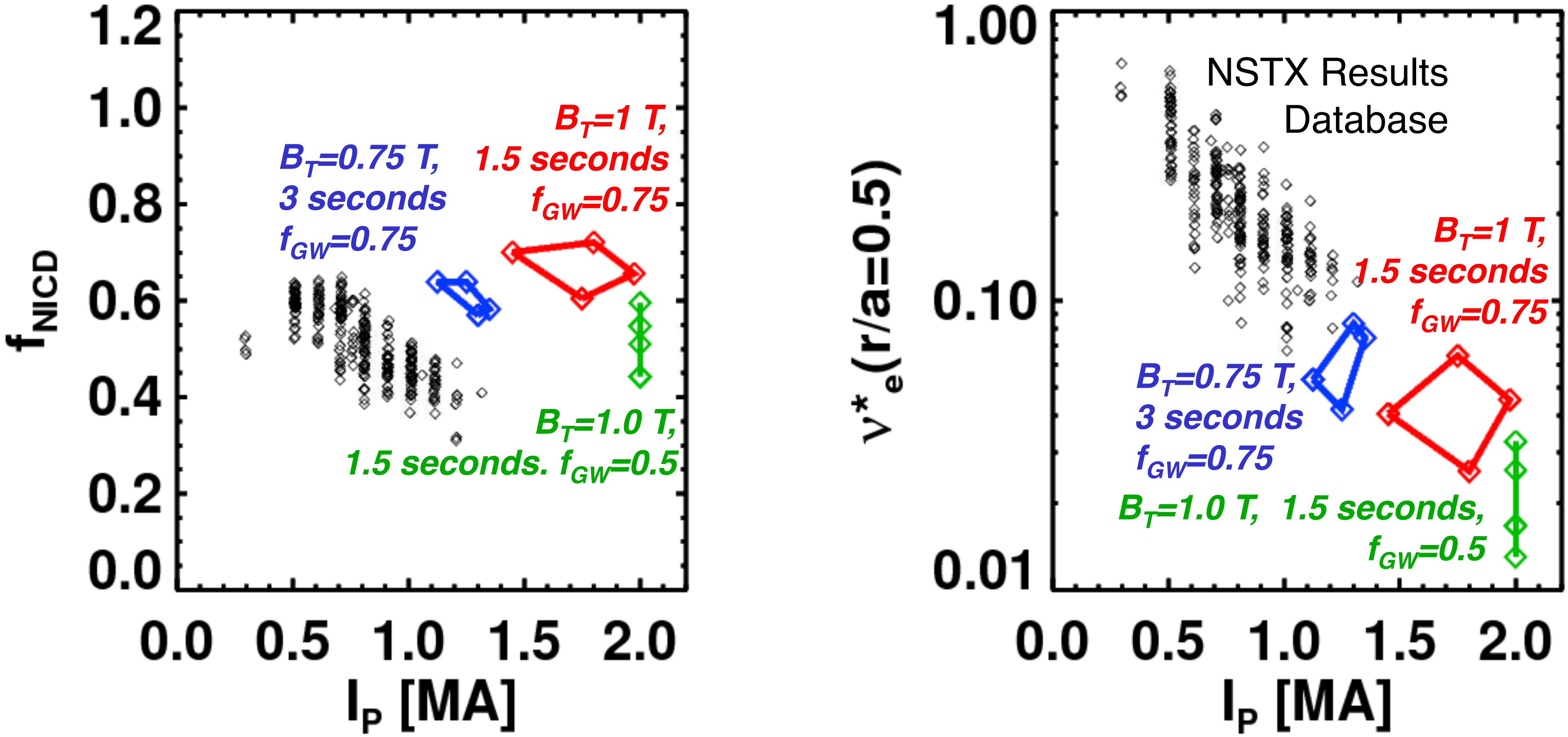




Partial-Inductive Scenarios Will Allow Confinement and Stability to be Studied at Higher-Current and Lower-ν^*

- Points are from existing NSTX database.
- Shapes bracket range of predictions.
  - Two profile assumptions.
  - Two confinement assumptions.
- Durations limited by NB pulse length limitations.

B_T=0.75 T, 4 beams, P_{inj}=8.40 MW, f_{GW}=0.75, q_{min}~1.15
B_T=1.00 T, 6 beams, P_{inj}=15.6 MW, f_{GW}=0.75, q_{min}~1.15
B_T=1.00 T, 6 beams, P_{inj}=15.6 MW, f_{GW}=0.50, q_{min}<1

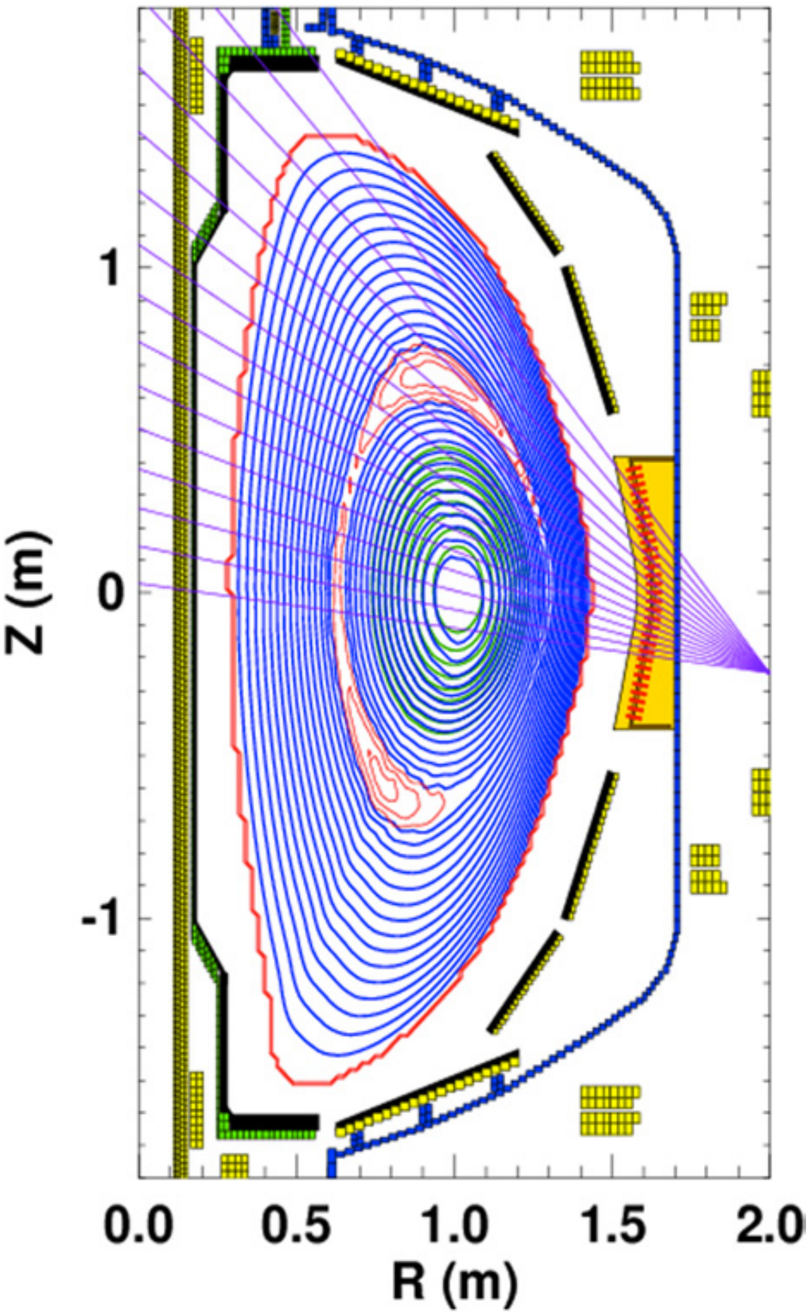


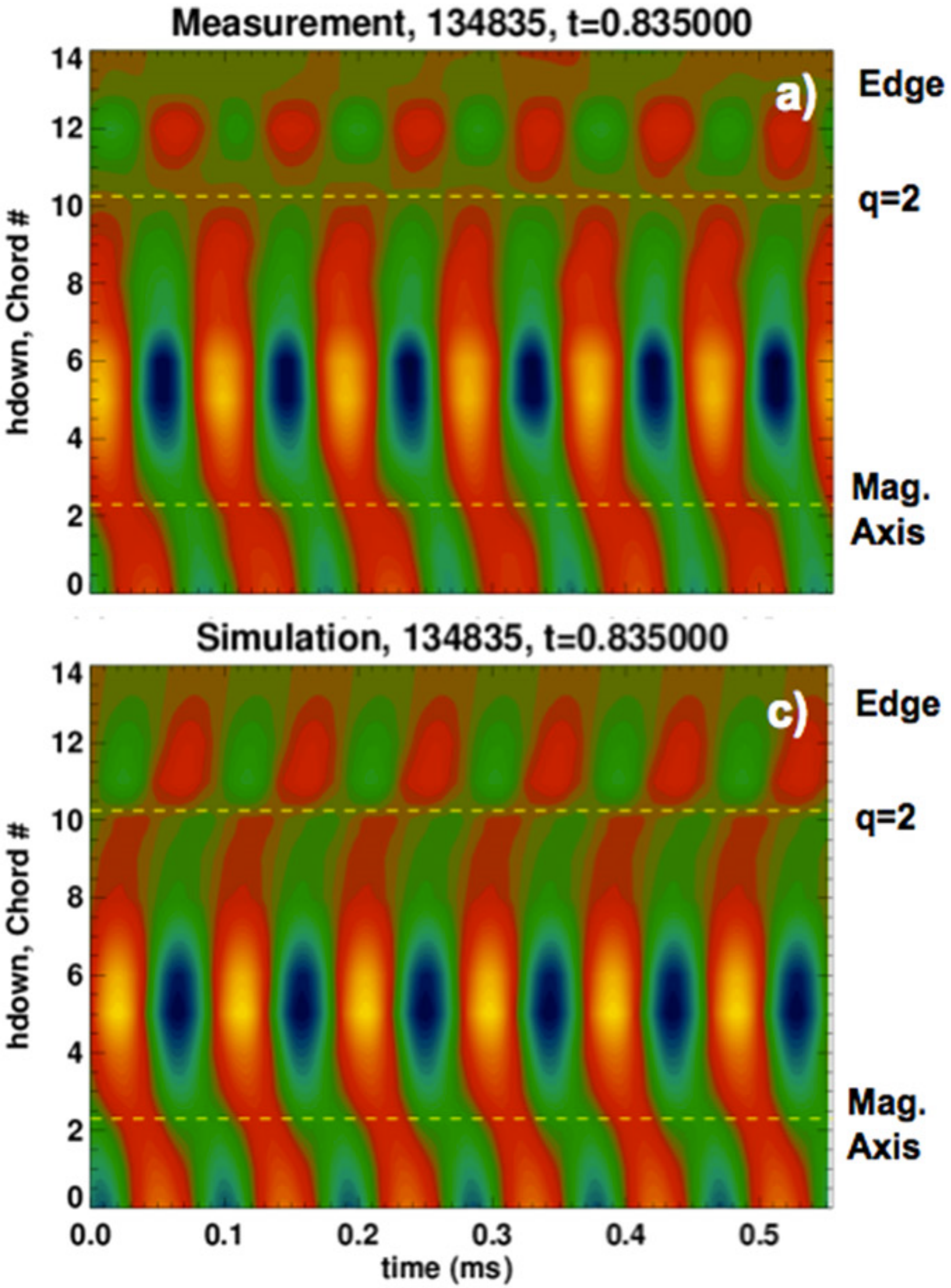
The NSTX Program is Developing Core Physics Knowledge for Next-Step Devices

- NSTX results provide a substantial basis for projecting to next-step STs.
  - Global confinement scaling with lithium PFC conditioning scales similarly to ITER-98y,2 scaling
    - With stronger I_P and weaker B_T dependencies than with boronized graphite.
  - High-β_N sustainment is facilitated by strong shaping, passive and active n=1 control, and maintaining elevated q_{min}.
  - The current profile in MHD-quiescent NB heated H-modes can be understood from neoclassical theory alone.
- NSTX-Upgrade will extend the physics basis for projections to next-step STs.
  - 0.8-1.3 MA scenarios will allow the demonstration of 100% non-inductive current drive with relaxed profiles.
  - 1.3-2.0 MA scenarios will allow transport and stability physics to be tested at higher current and field with significantly reduced collisionality.

Backup

Saturated Mode Has Strong 1/1 Kink Coupled to 2/1 Island

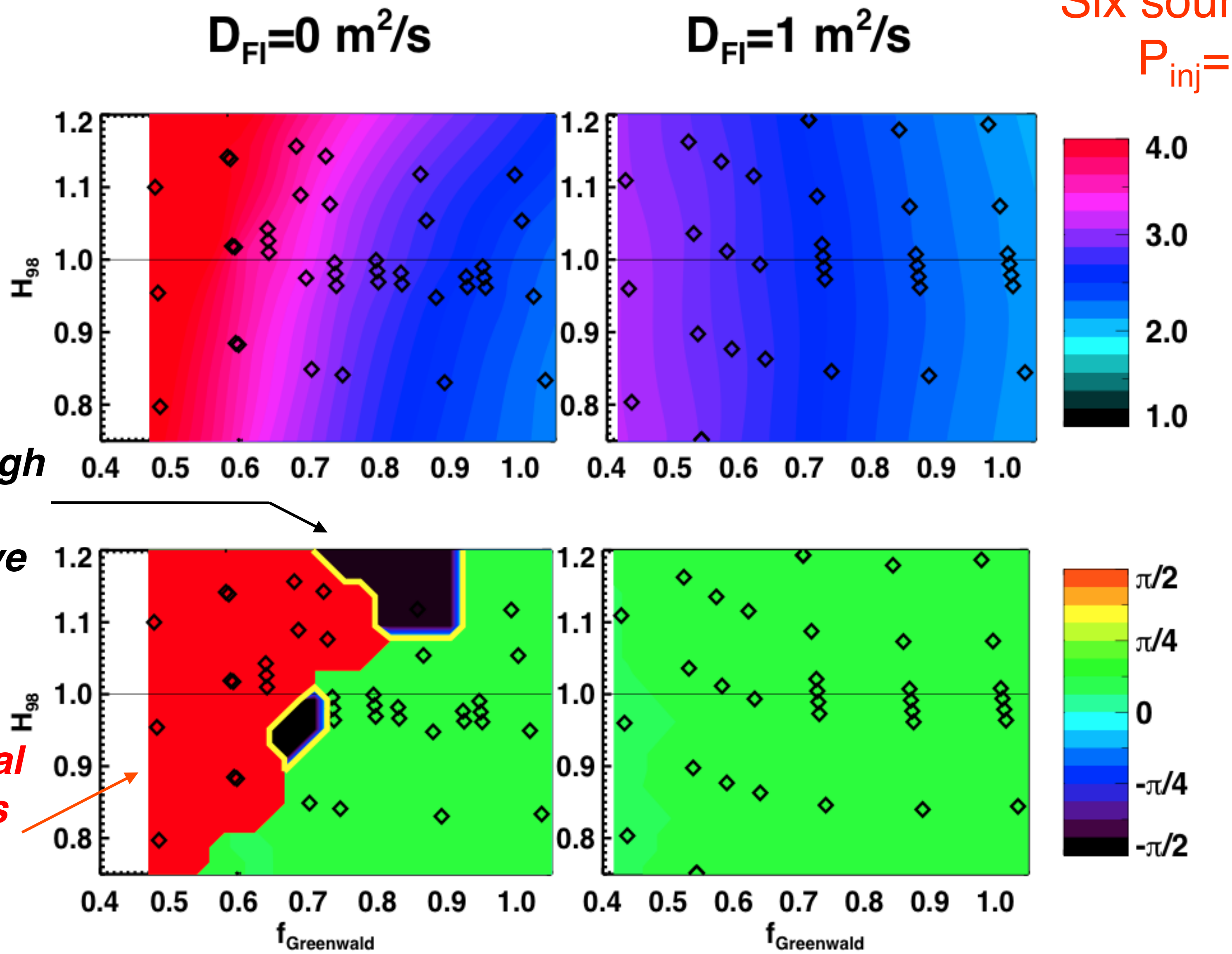




Profile Modifications with Non-Zero D_{FI} Can Improve Global n=1 Stability

B_T=1.0 T, I_p=1.0 MA, κ= 2.75

Six sources with total P_{inj}=12.6 MW



$F_P=P_0/<P>$

Too high F_P for achieved β_N

Internal modes from q_{min}<1

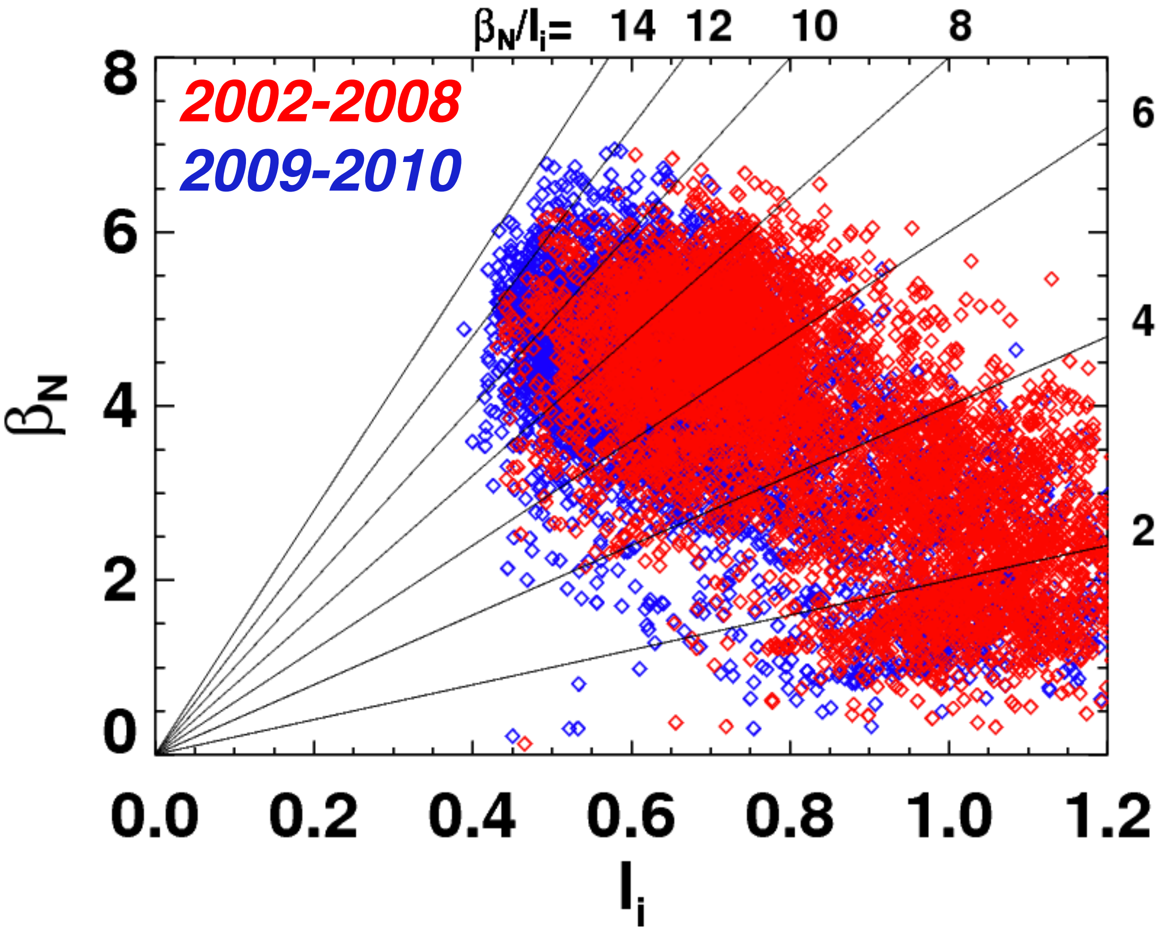
With-Wall n=1 Stability Parameter atan(δW/5)

Green is stable!

Computed by DCON

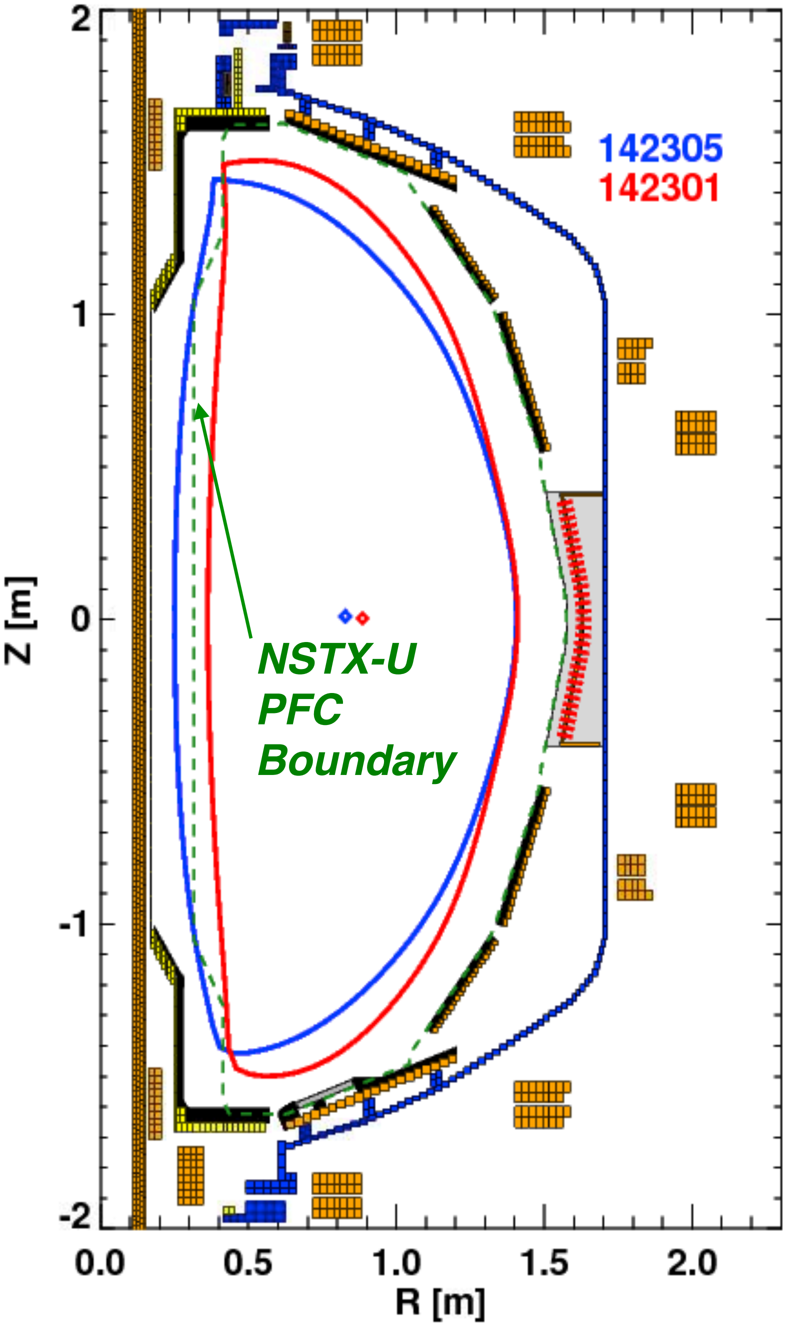
Very High Values of β_N / l_i Have Been Achieved with n=1 Control in NSTX

- No-wall β_N limit calculated to scale with l_i at conventional aspect ratio
  - l_i describes the “peakedness” of the current profile
- No strict stability limit associated with l_i.
  - Sustained β_N/l_i~12-13

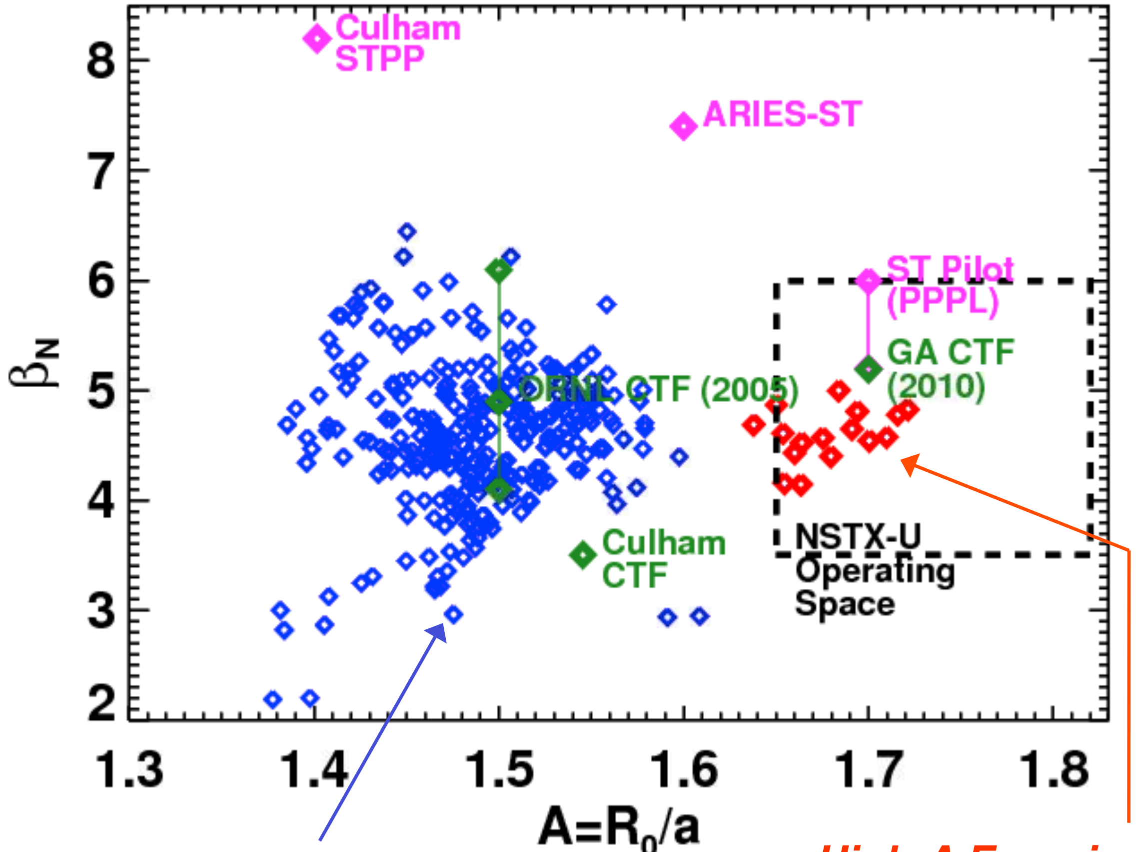


S.A. Sabbagh

Achieved Equilibria Scan the Aspect Ratios of Proposed Next-Step STs (II)



NSTX results (Low & High A)
compared to
Pilot plants and power plants
Nuclear component testing

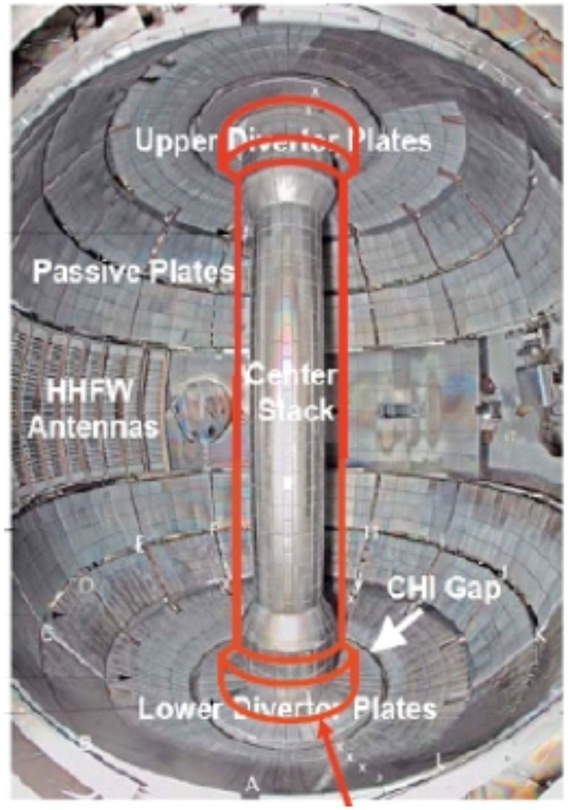


Standard NSTX Operating Space

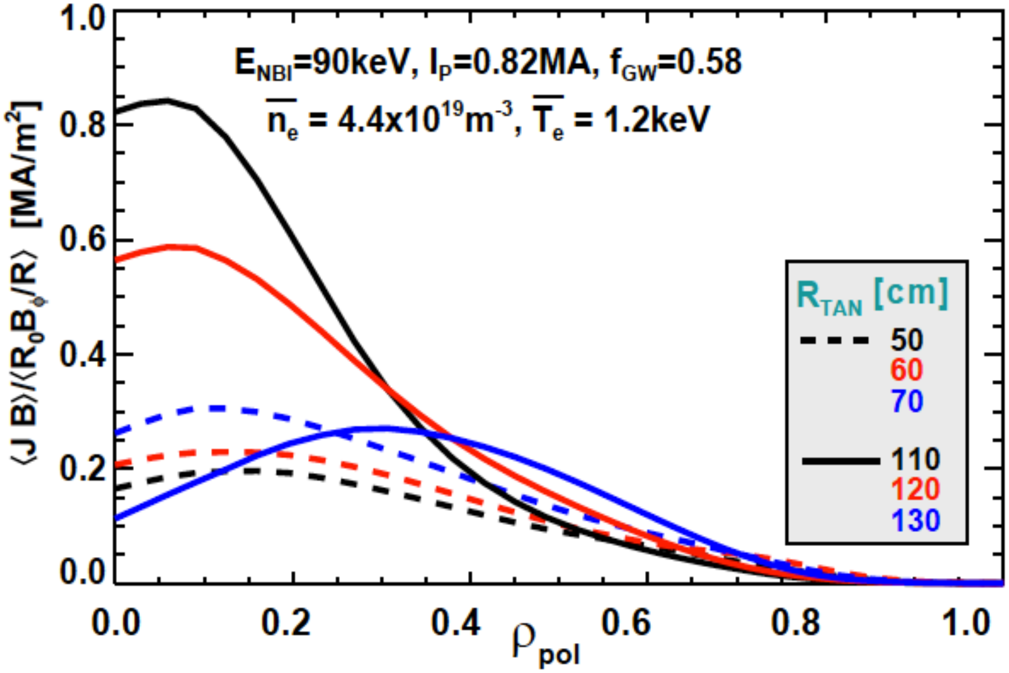
High-A Experiment
Did not systematically test the β_N limit!

NSTX-Upgrade Designed to Study Fully Non-Inductive Sustainment and ST Physics at Higher Current and Reduced Collisionality

Center-Stack Upgrade



2ND Beamline Upgrade

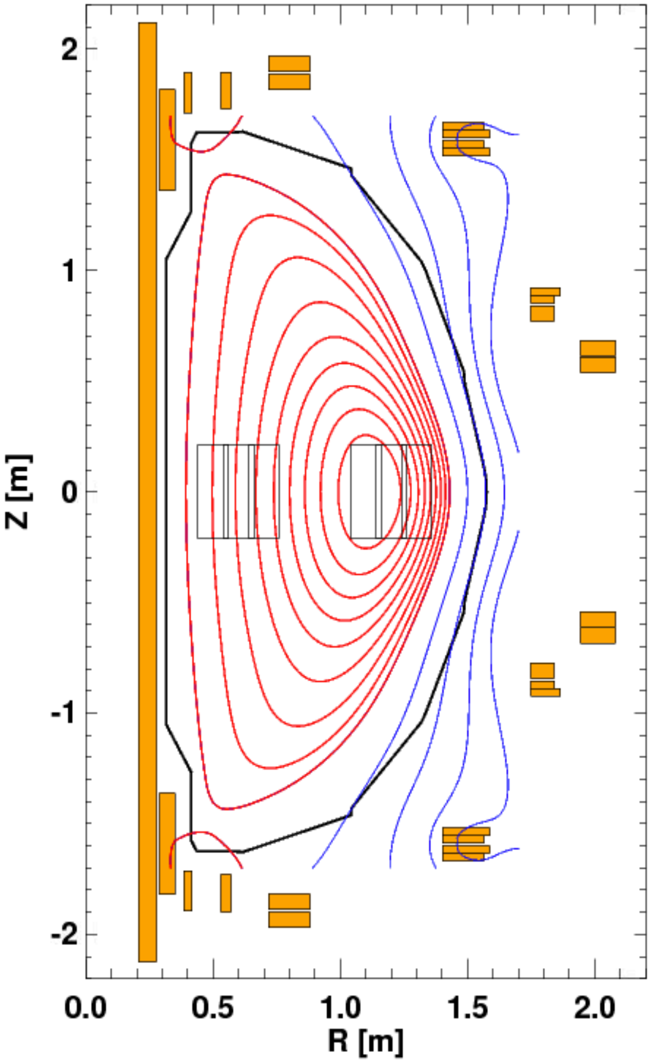


	NSTX	NSTX-U
B_T	0.55 T for ~1 s	1 T for ~5 s
I_P	1 MA for ~1s	2 MA for ~5 s
A	1.35-1.55	1.7-1.8

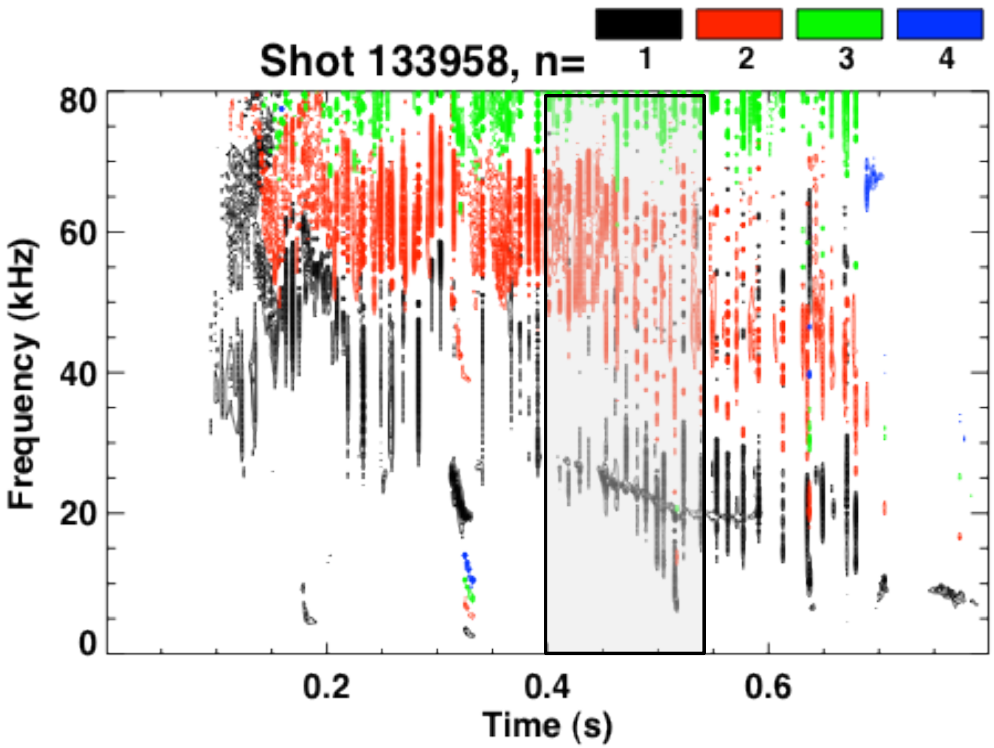
	Present NBI	2nd Beamline
Total Power at 90 kV	6.3 MW	6.3 MW
Typical Current Drive Efficiencies	30-40 kA/ MW	70-80 kA/ MW + off-axis

Projections to NSTX-Upgrade Made with Free-Boundary TRANSP and DCON

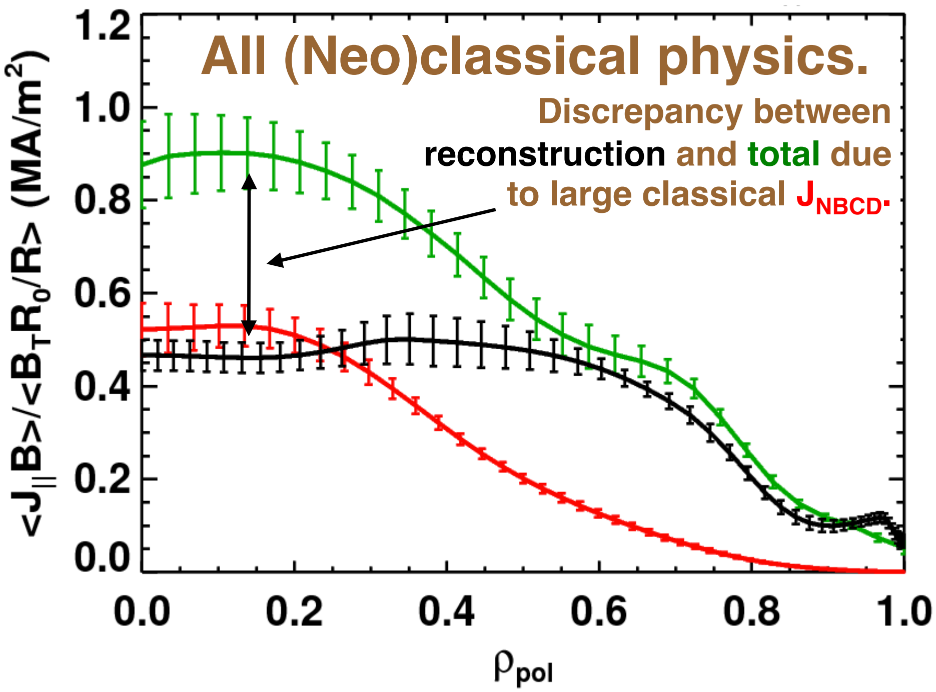
- Profile assumptions
  - Neoclassical theory to predict the ion temperature.
  - Scale experimental electron profiles.
    - $n_e(\psi)$ to achieve a desired $f_{GW}=n_e\pi a^2/I_P$
    - $T_e(\psi)$ to achieve a desired H_{98} or H_{ST}.
    - Test profiles from a number of discharges.
- Equilibria computed with new Free-Boundary TRANSP.
  - ISOLVER to generate self-consistent equilibria.
  - Sauter model for the bootstrap current, NUBEAM for NBCD.
  - Allow the current profile to fully relax.
- Ideal stability assessed with DCON.
  - Equilibria refined with fixed boundary equilibrium code CHEASE.
  - n=1 no- and ideal-wall limits tested.



TAE Avalanches Lead to Major Modifications of the Beam Driven Current Profile



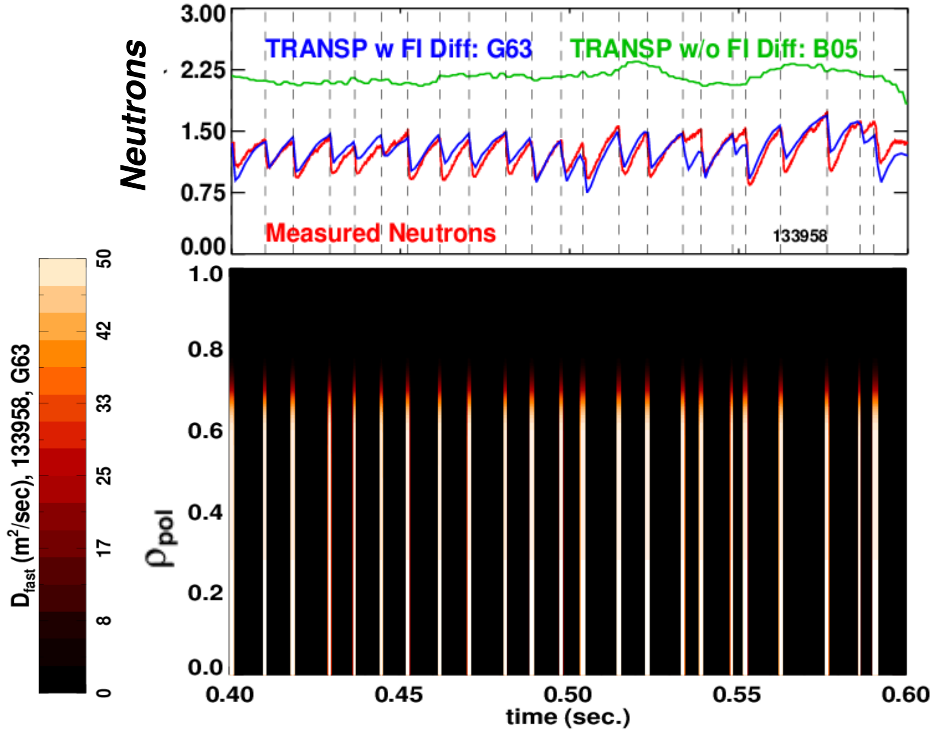
700 kA High-β_P with Rapid TAE Avalanches



All (Neo)classical physics.

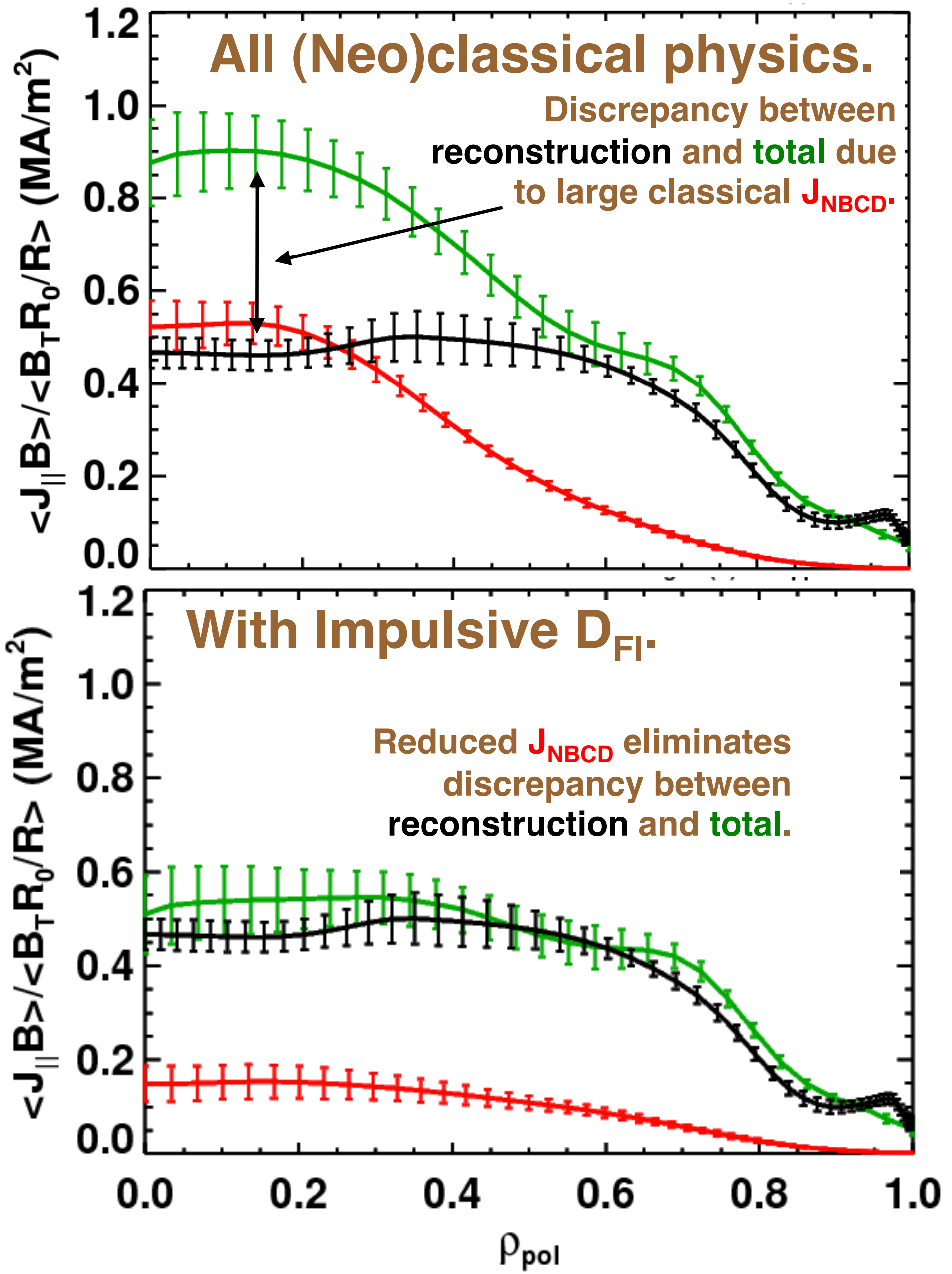
Discrepancy between **reconstruction** and **total** due to large classical J_{NBCD}.

TAE Avalanches Lead to Major Modifications of the Beam Driven Current Profile



- Modeled TAE avalanches using spatially and temporally localized fast-ion diffusivity $D_{FI}(\psi,t)$.
  - Use S_n dynamics to determine $D_{FI}(\psi,t)$ details.
- Time-average data can also be matched with a spatially & temporally constant D_{FI}~4 m^2/s.

700 kA High-β_P with Rapid TAE Avalanches


All (Neo)classical physics.

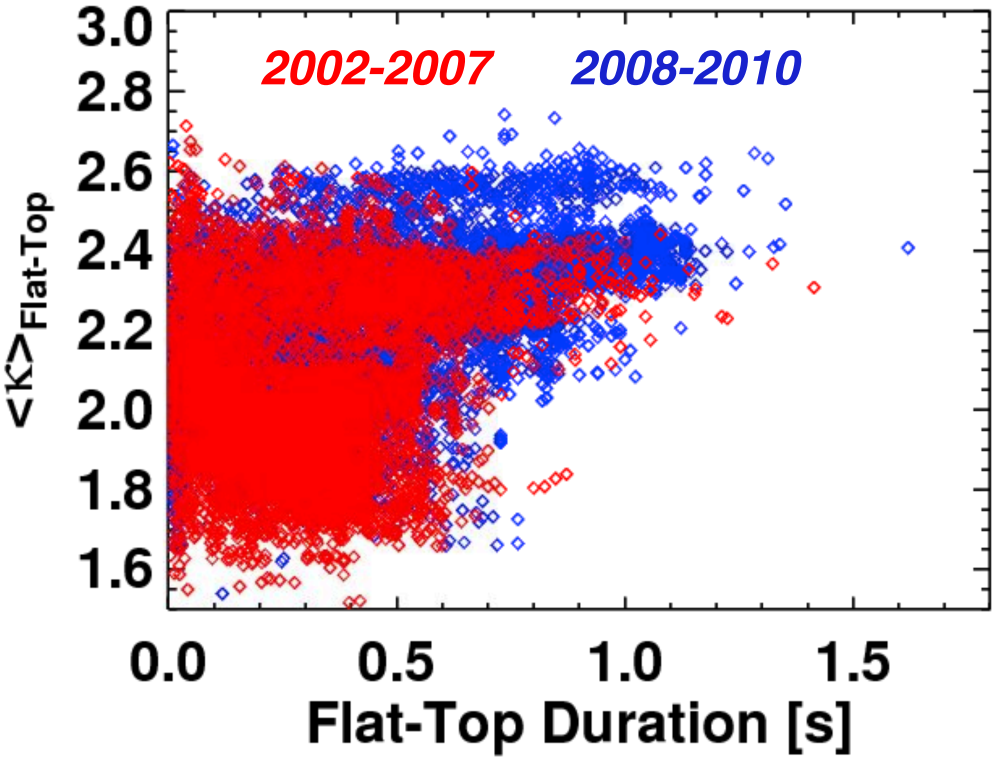
Discrepancy between **reconstruction** and **total** due to large classical J_{NBCD}.

With Impulsive D_{FI}.

Reduced J_{NBCD} eliminates discrepancy between **reconstruction** and **total**.

Recent Scenario Development in NSTX has Relied on Facility Improvements

Flat-top average elongation vs. I_P flat-top duration

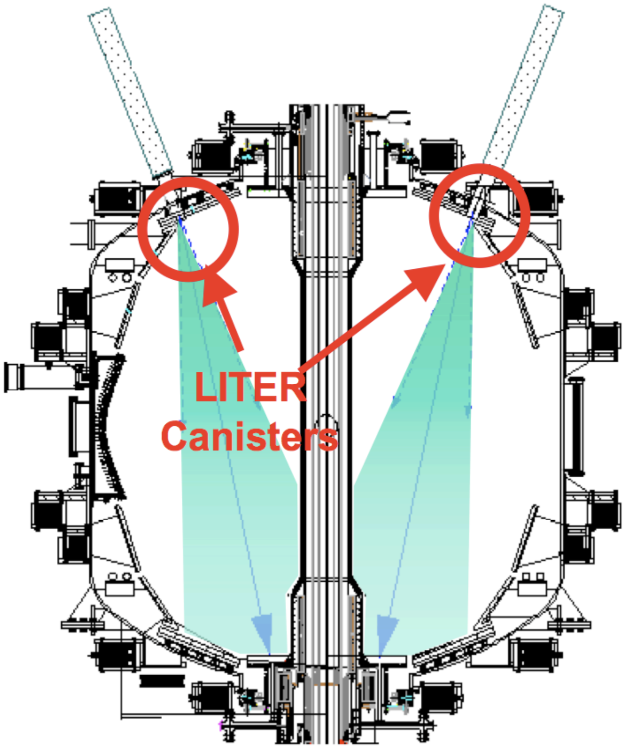


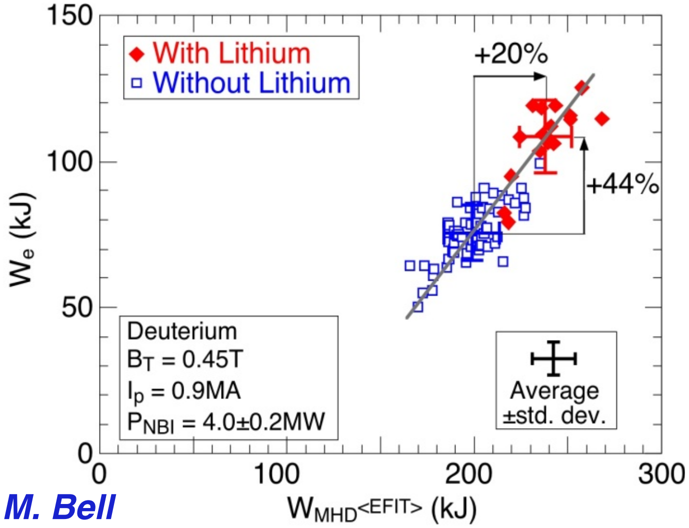
Important: $\beta_P\beta_T \sim\beta_N^2(1+\kappa^2)$

- Upgraded control system
  - Reduced latency facilitates operation at high elongation.
- Lithium conditioning of the plasma facing components.
  - Increased confinement and reduced internal inductance
  - Shortened shot cycle
- Routine n=1 dynamic error field correction & RWM control.
  - Improved discharge reliability at high-β_N.

D.A. Gates

Recent Scenario Development in NSTX has Relied on Facility Improvements





H. Kugel, M. Bell

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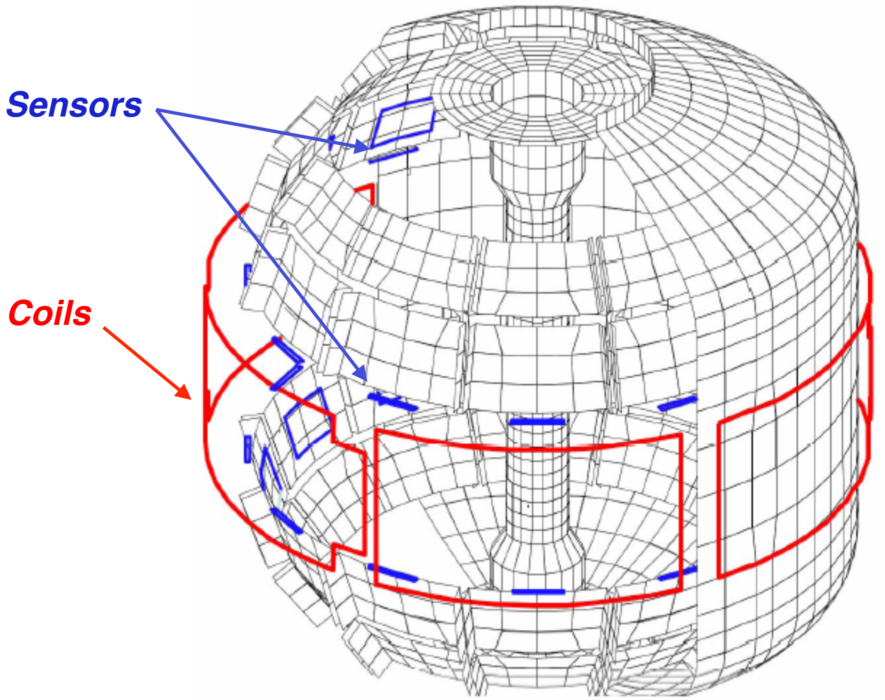
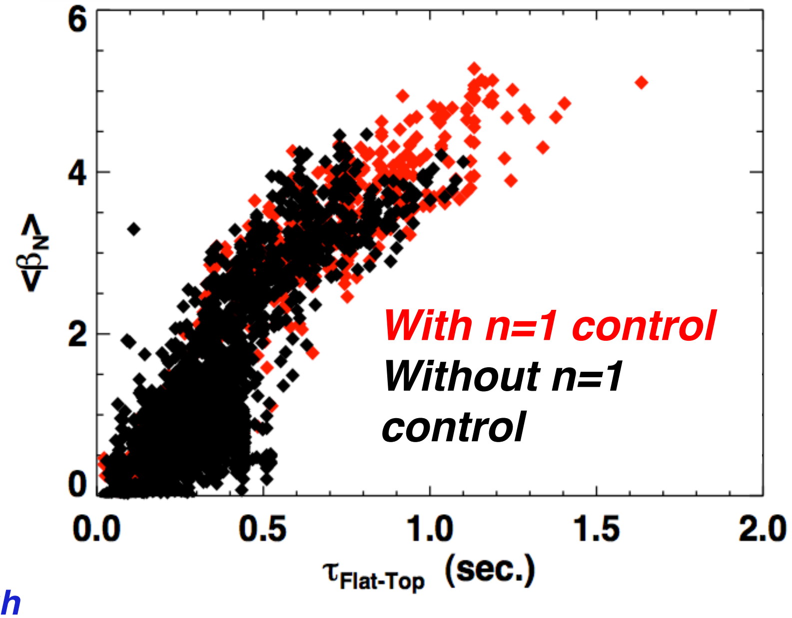
Recent Scenario Development in NSTX has Relied on Facility Improvements





S.A. Sabbagh

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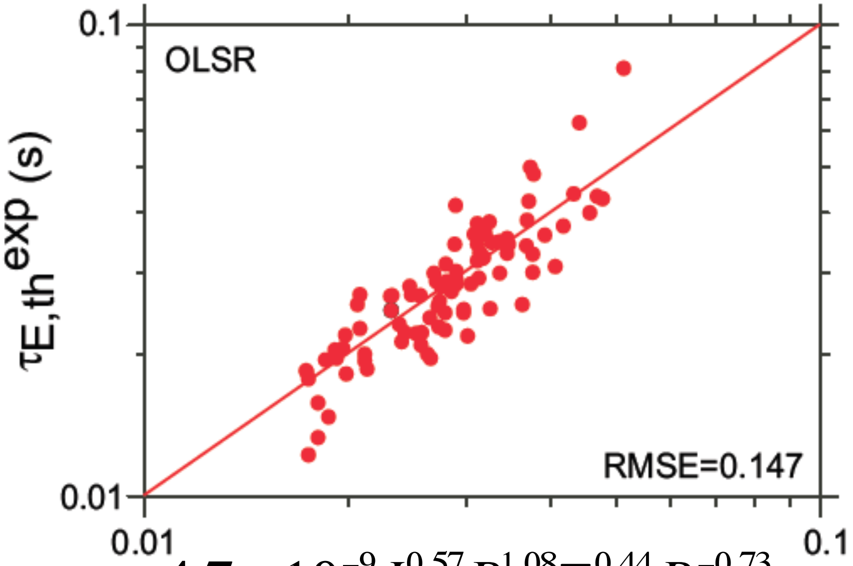
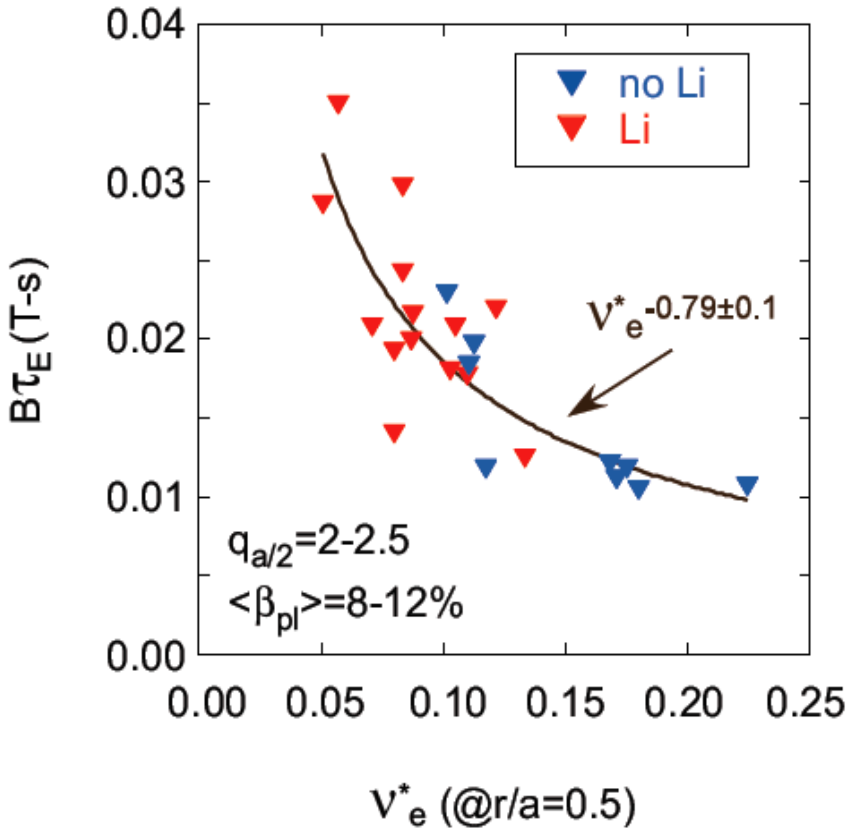
  - Improved discharge reliability at high-β_N.

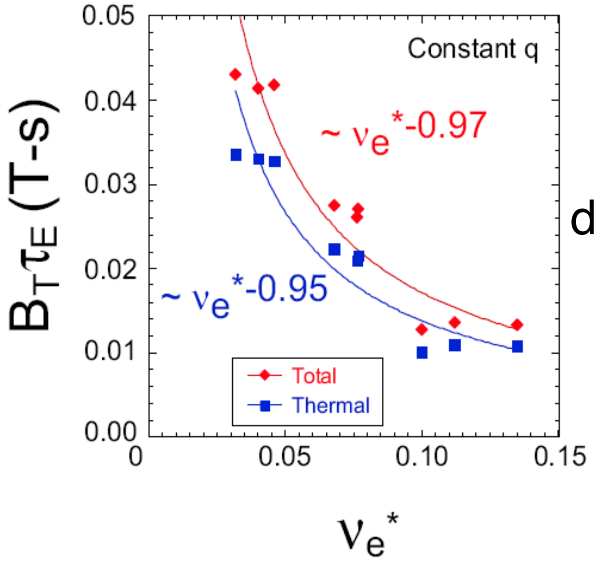
Collisionality Orders Transport in Discharges With and Without Lithium Conditioning.

Confinement with Boronized Graphite Showed Weaker I_P, stronger B_T dependences



$$4.7\times10^{-9}\,I_P^{0.57}B_T^{1.08}\overline{n}_e^{0.44}P_{Loss}^{-0.73}$$





Consistent with the collisionality dependence of micro-tearing transport (nonlinear GYRO)

W. Guttenfelder PRL 2011

For NSTX-Upgrade projections: Global Confinement

- Test two thermal confinement scalings

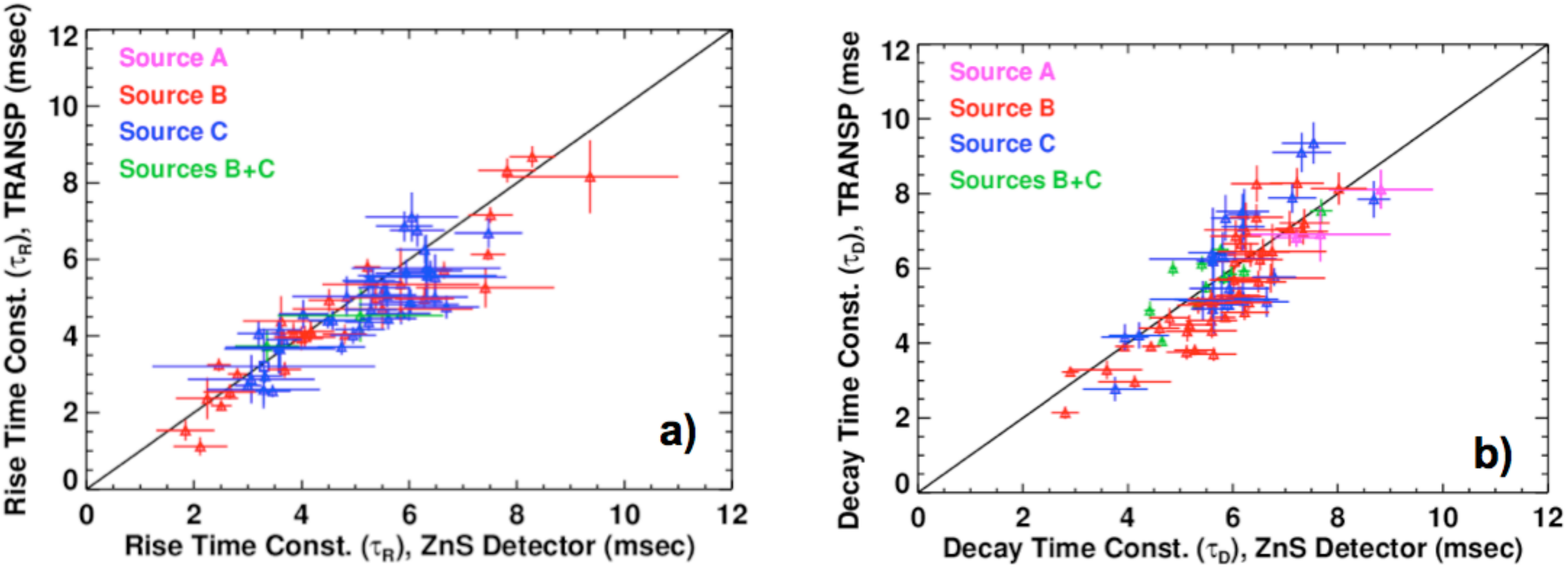
$$\tau_{98} \propto I_P^{0.93}B_T^{0.15}\overline{n}_e^{0.41}P_{Loss}^{-0.69}R_0^{1.97}\varepsilon^{0.58}\kappa^{0.78}$$

$$\tau_{ST} \propto I_P^{0.57}B_T^{1.08}\overline{n}_e^{0.44}P_{Loss}^{-0.73}$$

- Test a range of thermal profile shapes

Rise and Decay of Neutron Rate at NB Steps Generally Consistent with Classical Beam Physics

- H-mode discharges w/o low-f MHD.



S.P.. Gerhardt, el at., NF (2011)