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

Development of Advanced Spherical Torus Operating Scenarios in NSTX

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- *Colorado Sch Mines*
- *Columbia U*
- *CompX*
- *General Atomics*
- *INL*
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and the NSTX Research Team

2010 APS DPP

- *Culham Sci Ctr*
- *U St. Andrews*
- *York U*
- *Chubu U*
- *Fukui U*
- *Hiroshima U*
- *Hyogo U*
- *Kyoto U*
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- *ASIPP*
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- *IPP, Jülich*
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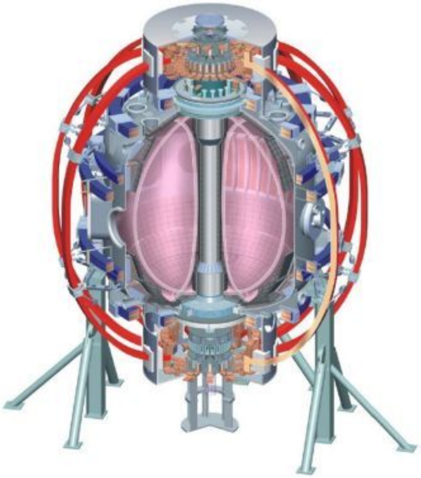
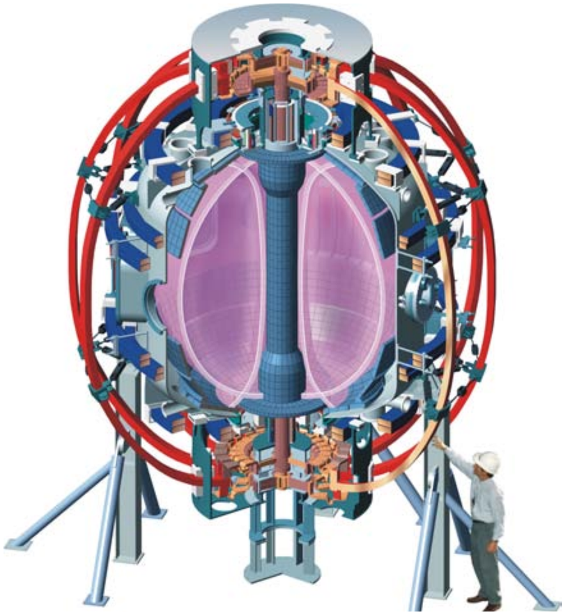
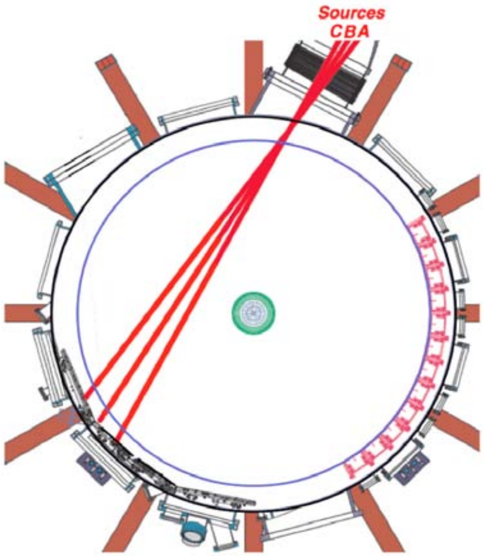
- *ASCR, Czech Rep*
- *U Quebec*



Overview

NSTX is a Medium Sized Spherical Torus With Significant Capabilities for High-β Scenario Research





3-D Field Coils Important For Scenario Development

Pre-programmed n=3 correction

Main VF coil is not a perfect circle

n=1 feedback system

Internal B_R and B_P sensors

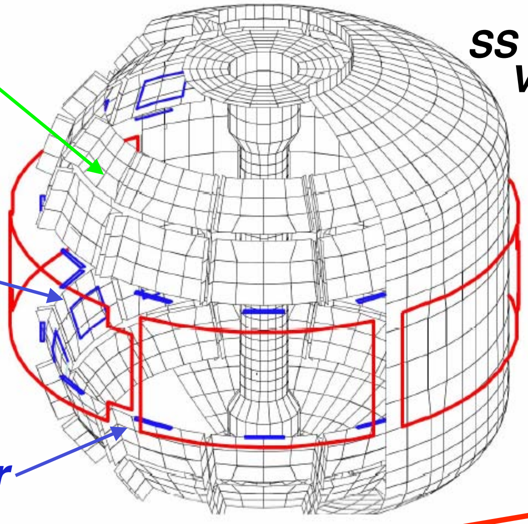
Slow response: error field correction

Fast response: RWM control

Now testing state-space RWM controller.

Aspect ratio A	1.27 – 1.7
Toroidal Field B_{T0}	0.35 – 0.55 T
Plasma Current I_p	≤1.4 MA
NBI (<100kV)	7 MW

Lithium conditioning of PFCs via a dual evaporator system.



Copper passive conductor plates

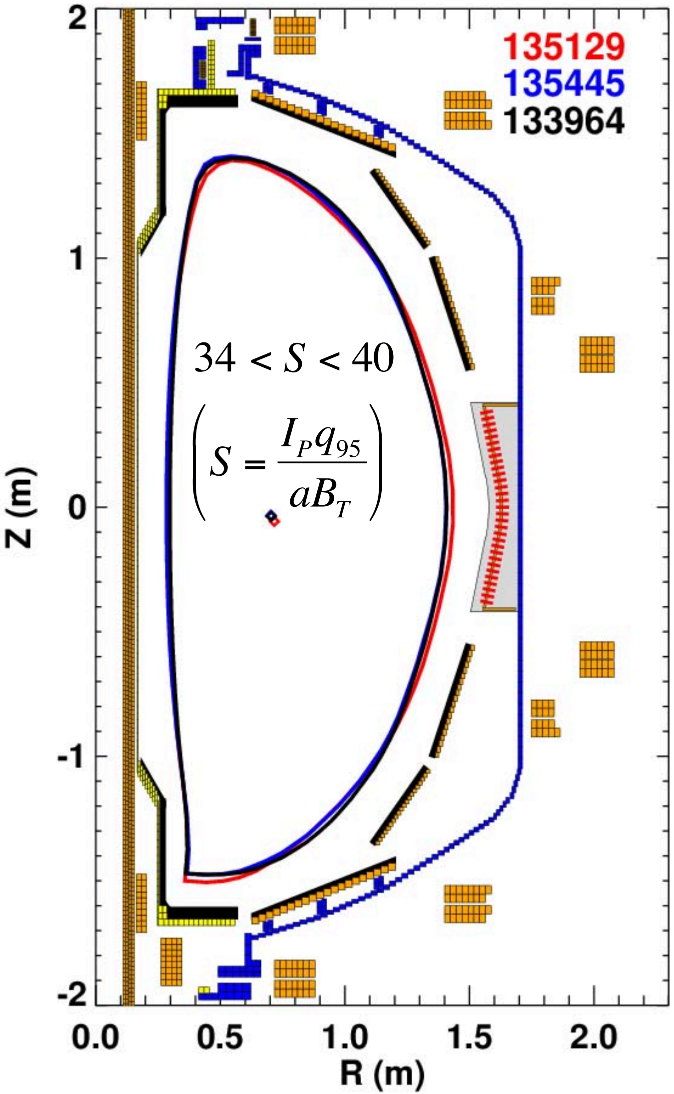
SS Vacuum Vessel

B_R Sensor

B_P Sensor

6 ex-vessel midplane control coils

High-Elongation Configurations Developed to Challenge Limits in β_T, Non-inductive Current Fraction and Sustainment



$34 < S < 40$

$$\left(S = \frac{I_P q_{95}}{a B_T} \right)$$

Aspect Ratios 1.45-1.55

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

High-β_T

$q^*=2.8$

$B_T=0.44$ T

$I_P=1100$ kA

Long Pulse

$q^*=3.9$

$B_T=0.38$ T

$I_P=700$ kA

High-β_P

$q^*=4.7$

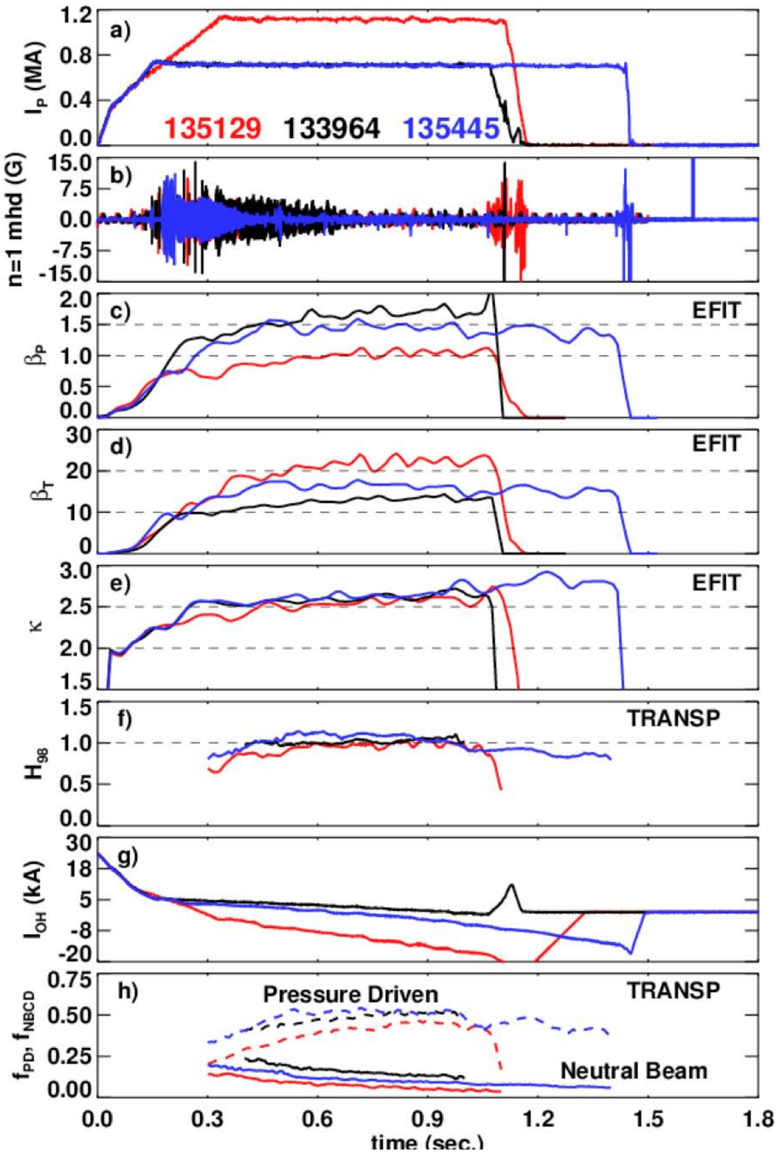
$B_T=0.48$ T

$I_P=700$ kA

All

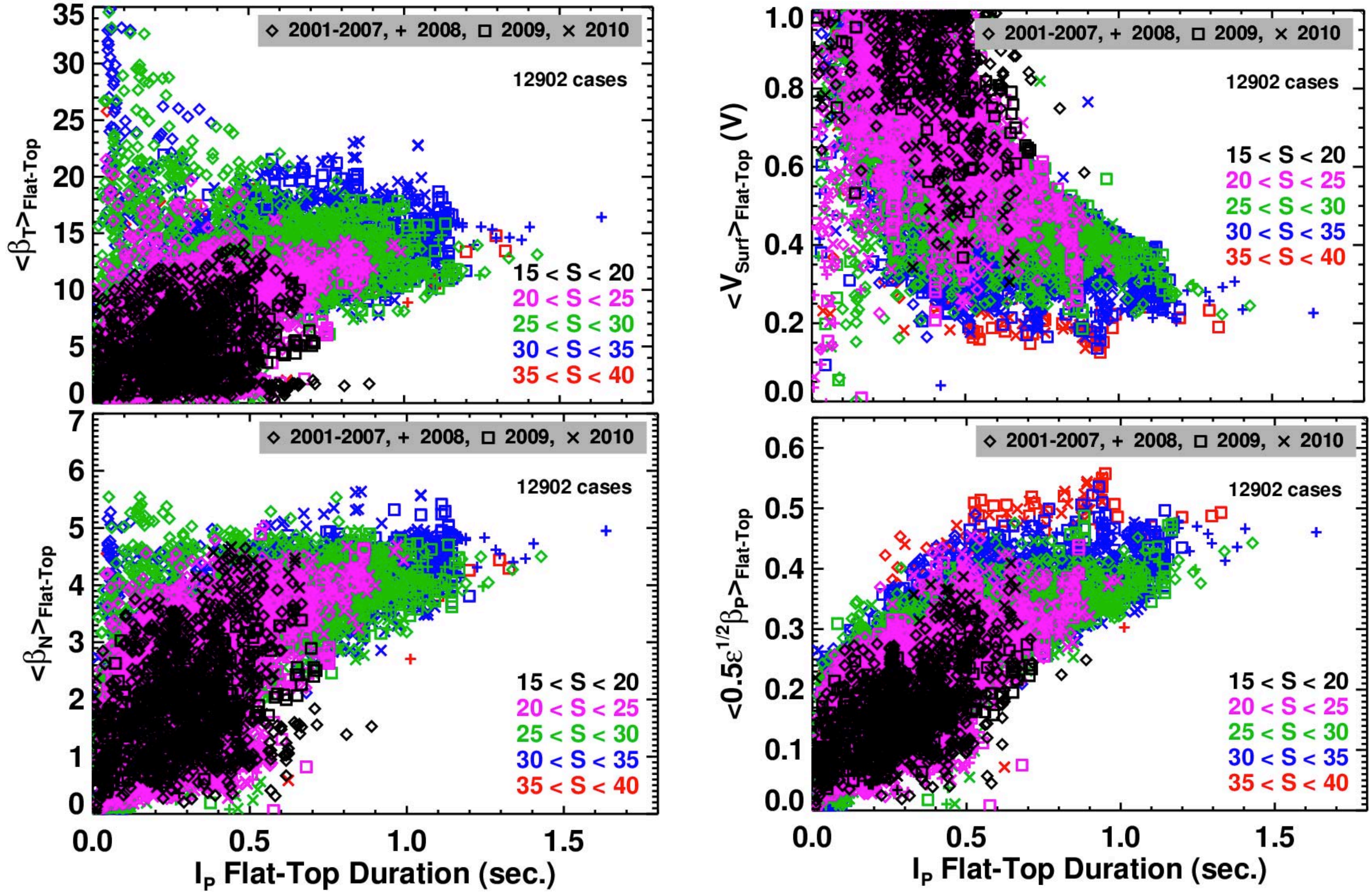
$H_{98}>=1$

$\kappa=2.6$-2.7



Global Performance and Confinement

Strong Shaping has Helped NSTX Make Continued Progress on a Range of Optimization Targets

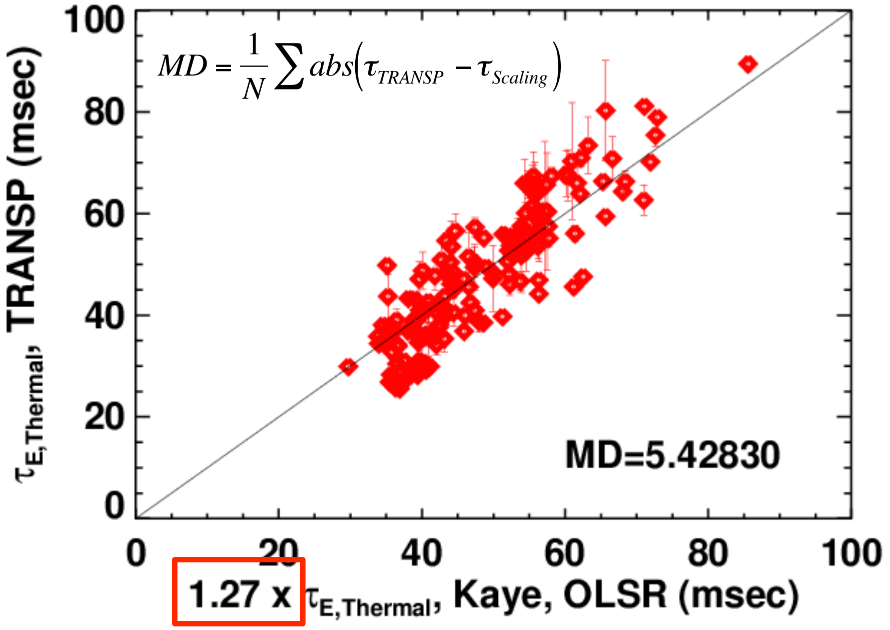


Lithiumized Discharges Shows Confinement Scaling Similar to Higher Aspect Ratio

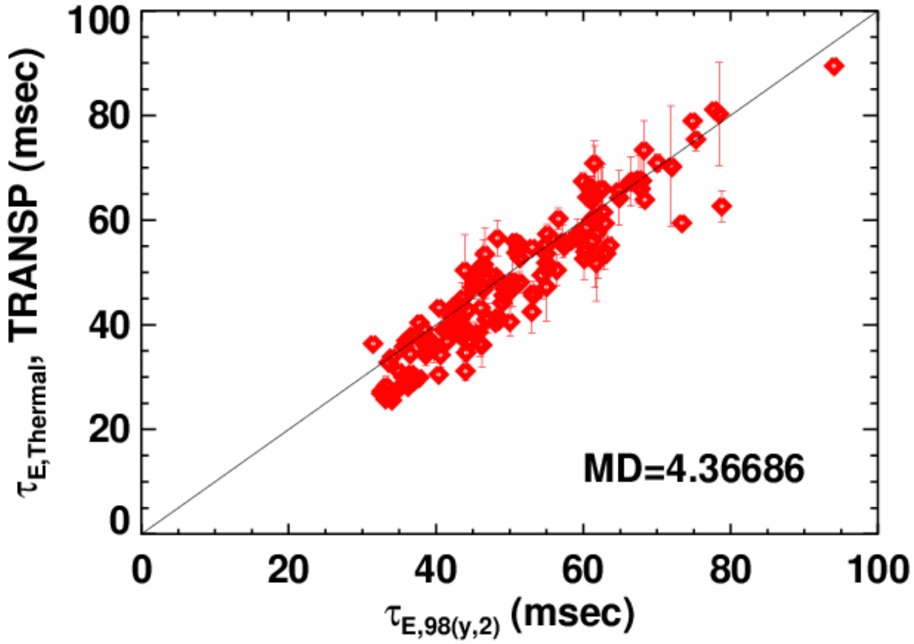
Consider > 75 msec averaging windows, at least one current diffusion time into the I_P flat-top, at high-κ and δ, in lithium conditioned discharges

Criterion excludes many high-confinement discharges

$$\tau_{E,th,Kaye,OLSR} \propto I_P^{0.57} B_T^{1.} n_e^{0.44} P_{abs}^{-0.73}$$



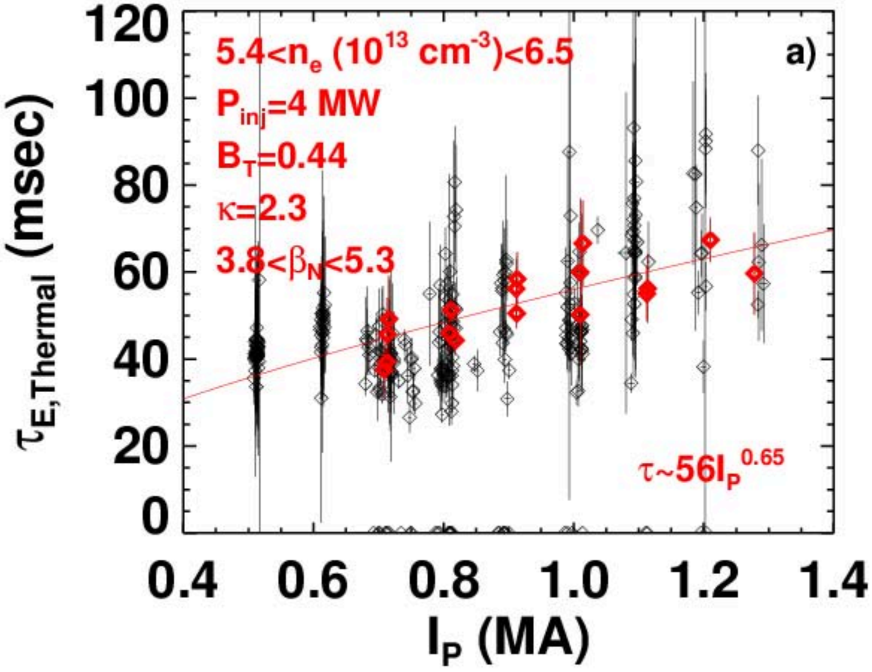
$$\tau_{E,th,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_{abs}^{-0.69} \kappa^{0.8}$$

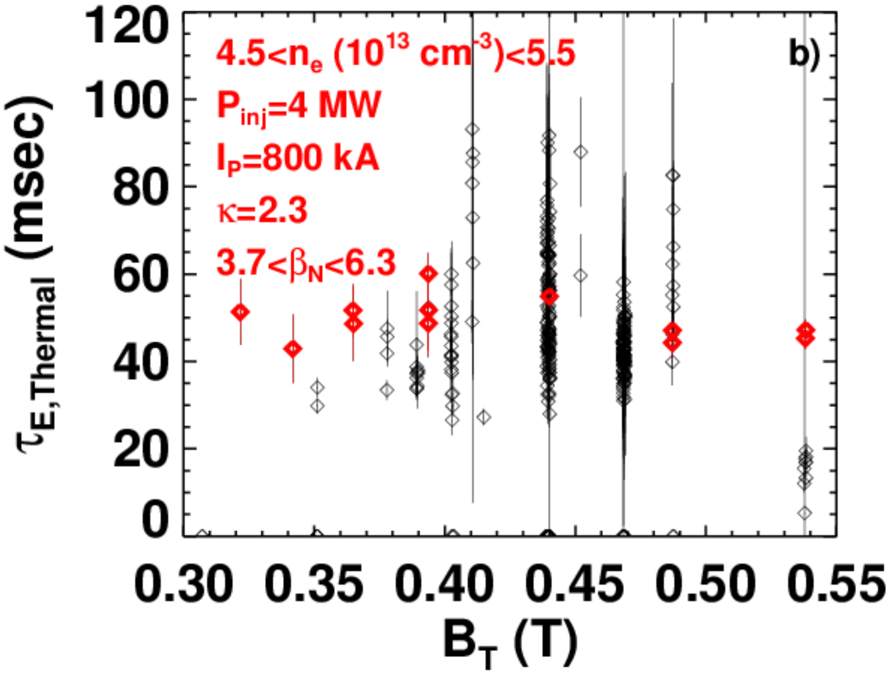


- Confinement exceeds previous low-A scaling by ~30%.
  - Lithium conditioning, strong shaping, higher β_N and longer-pulse duration.
- Working to revise ST-scalings for τ_E in this class of discharge.

Dedicated Scans Show Confinement Trends in Lithiumized High-Performance Plasmas

- Dedicated scans as part of the 2010 JRT on SOL physics.
  - Red below, black is full database.
- I_P scaling intermediate between ITER-98 and previous NSTX.
- B_T scaling is very weak.
- Difference due to Lithium, collisionality?



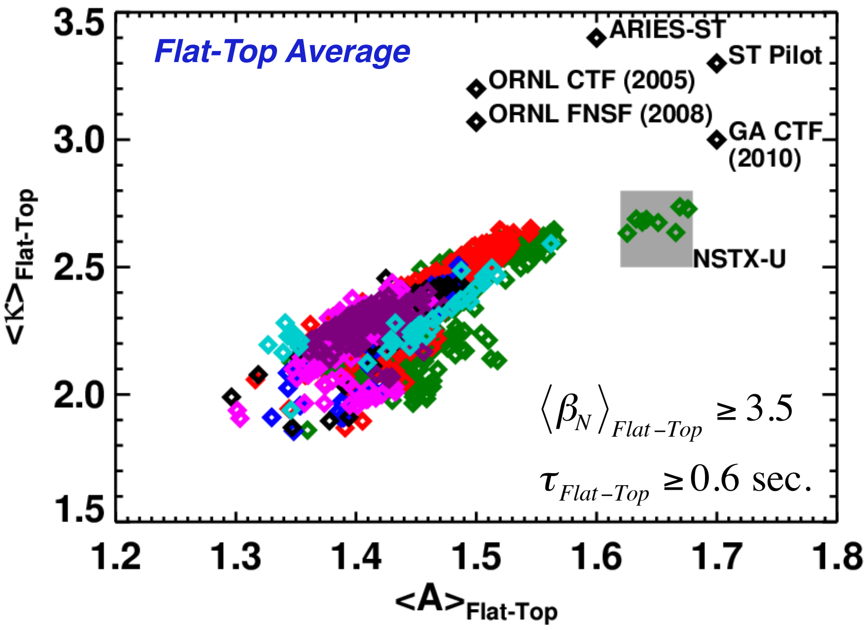


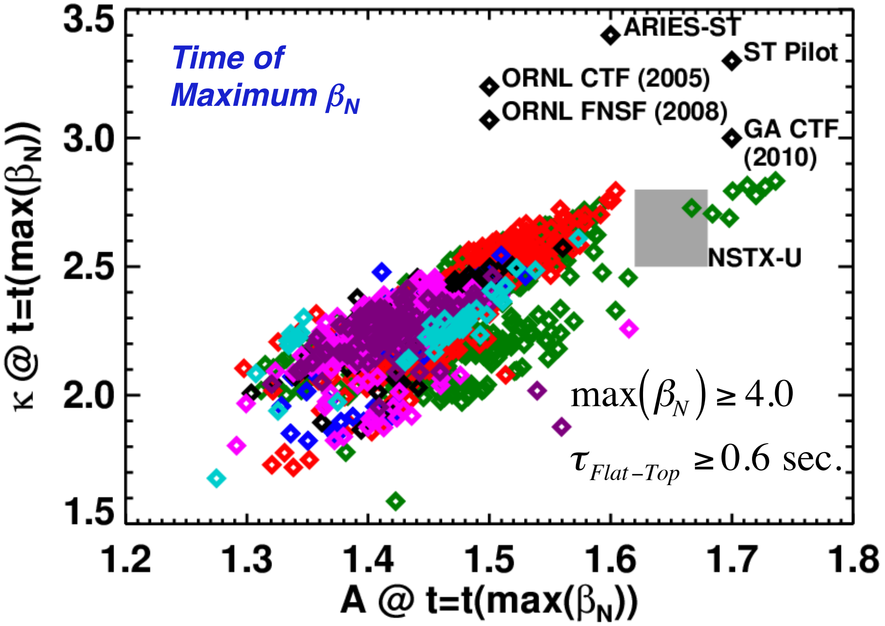
Larger Aspect-Ratios For NSTX-Upgrade

Higher-Aspect Ratio Plasmas are a Significant Extension of the NSTX Operating Space

- ***Recent ST studies looking at higher aspect ratio.***
  - ***NSTX-Upgrade, NHTX***
  - ***GA versions of ST-FNSF***
  - ***PPPL ST Pilot Plant***
- ***Likely deleterious to both n=0 and n=1 stability***
- ***Beginning to assess these scenarios in NSTX***

2004 ***2005***
2006 **2007**
2008 ***2009***
2010

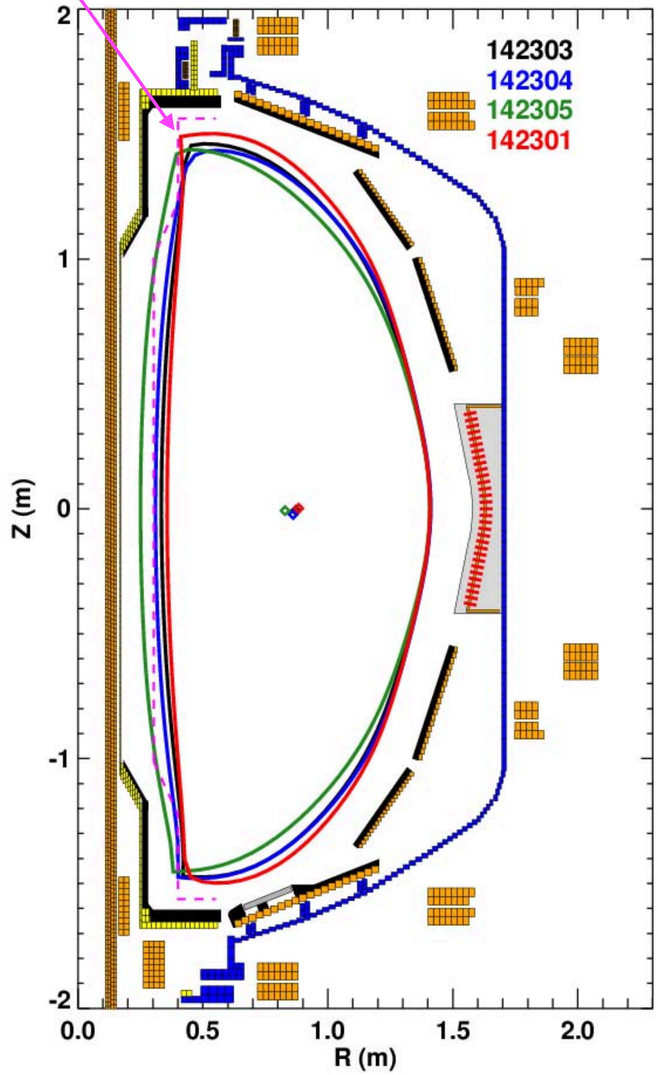




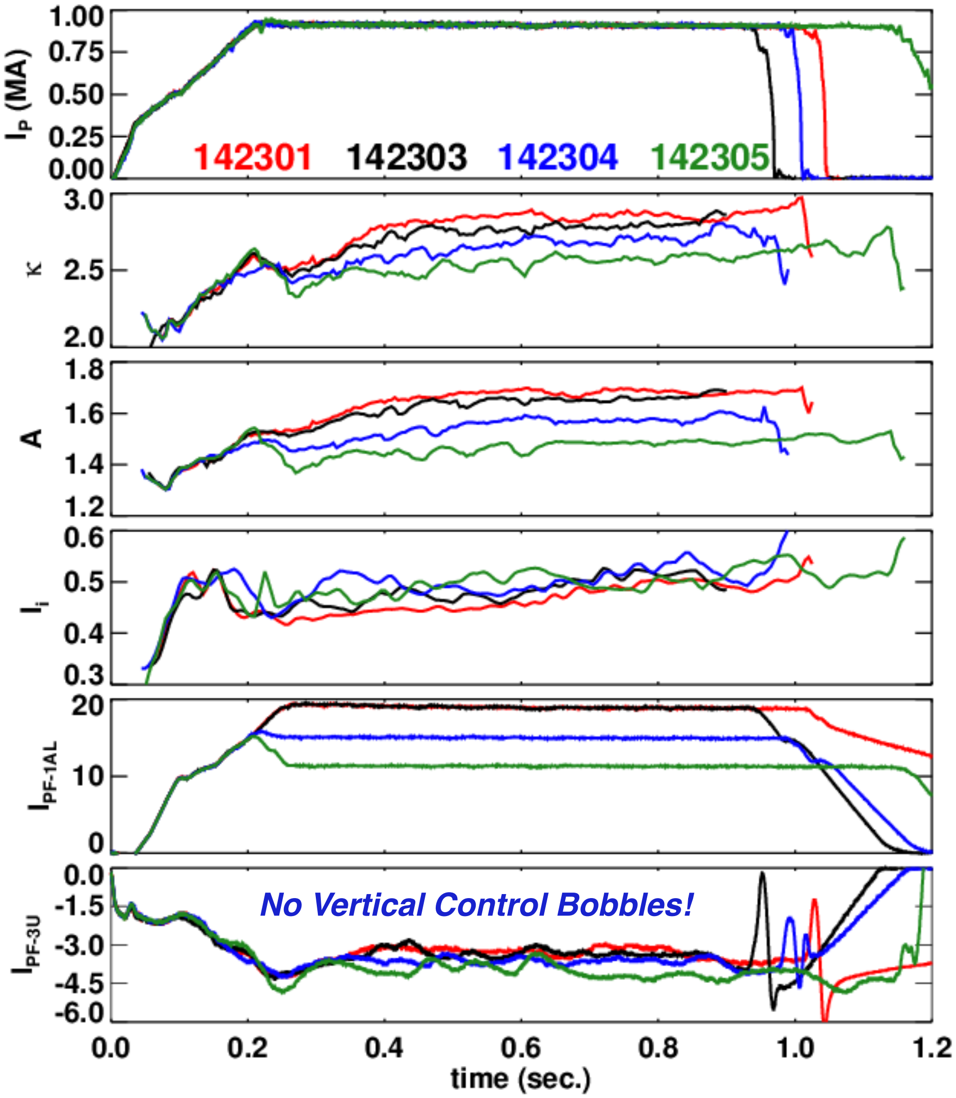
Recent Experiments Are a Significant Extension in the κ vs A (=R_0/a) operating space.

High-A Shape Compatible with NSTX-Upgrade Center Column, with No Control Problems

NSTX-Upgrade Center Column Outline



142305: Standard "Fiducial" *Others: Increasing A and κ*



No Vertical Control Bobbles!

High-Performance Sustained For All Aspect Ratios

- β_N is somewhat reduced at fixed power with larger aspect ratio:
  - Confinement is a bit worse at higher A… not expected from standard ITER scaling.

$$\tau_{ITER-98(y,2)} \sim \frac{R_0^2\kappa}{\sqrt{A}}$$

$$\frac{\tau_{HAR}}{\tau_{LAR}} \sim \left(\frac{88}{85}\right)^2 \frac{2.85}{2.5}\sqrt{\frac{1.45}{1.68}} \approx 1.1$$

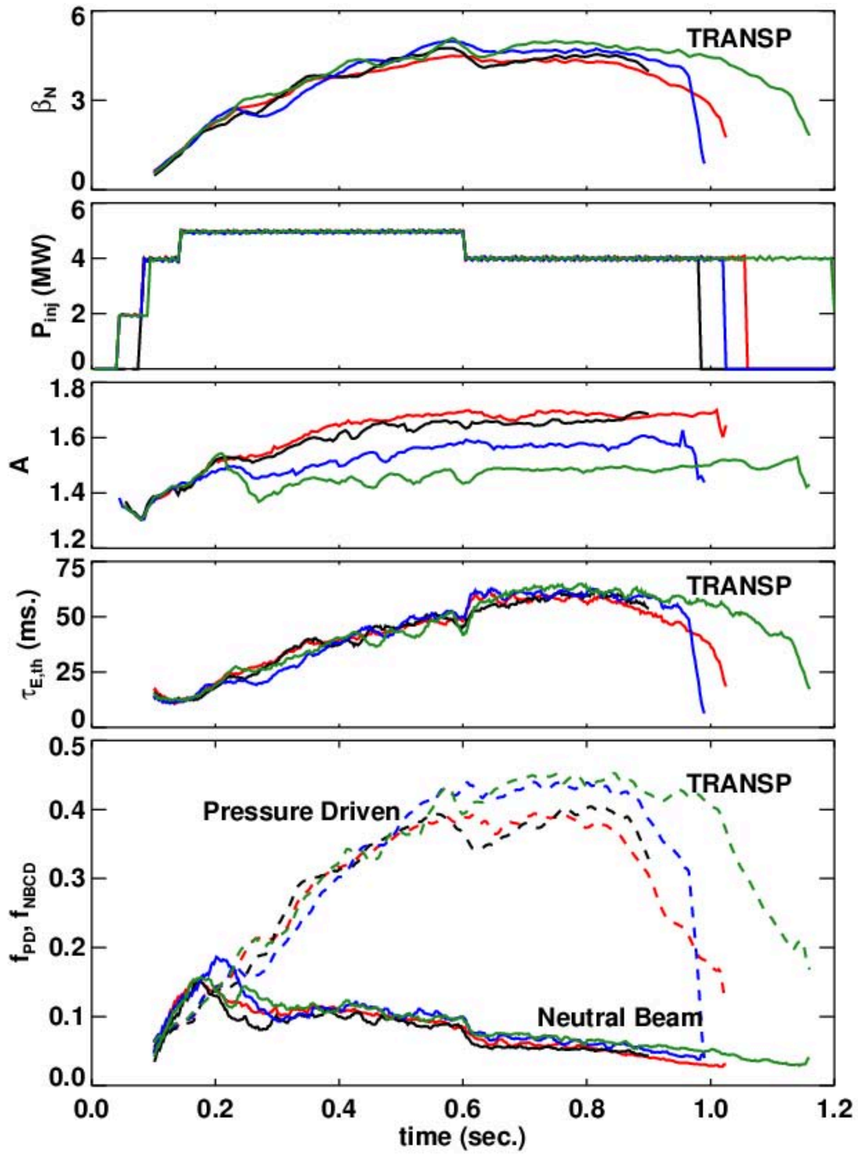
  - Plasma are a bit taller.

$$\beta_N = \frac{aB_T\beta_T}{I_P} = \frac{2\mu_0 Wa}{VB_T I_P}$$

$$V \propto R_0 a^2 \kappa$$

$$\beta_N = \frac{2\mu_0 Wa}{R_0 a^2 \kappa B_T I_P} \propto \frac{W}{a\kappa I_P} \propto \frac{\tau_E}{(height)}$$

- Bootstrap current drops as $q\beta_N$.
  - Both q and β_N are lower.
  - Core n=1 modes and RWMs were the common performance limiting instabilities.



Global Stability

β_N Controller Implemented Using NB Modulations and rtEFIT β_N

- Controller implemented in the General Atomics plasma control system (PCS), implemented at NSTX.
- Measure β_N in realtime with rtEFIT.
- Use PID scheme to determine requested power:

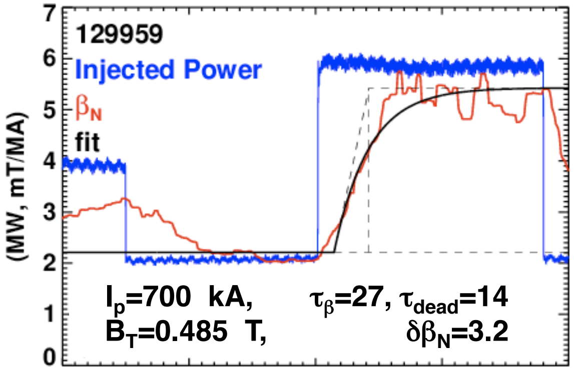
$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

$$P_{inj} = P_{\beta_N}\overline{C}_{\beta_N} e + I_{\beta_N}\overline{C}_{\beta_N}\int e dt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

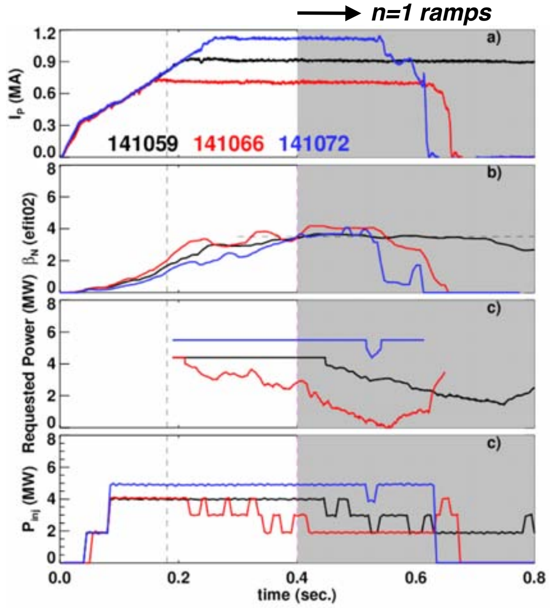
$$\overline{C}_{\beta_N} = \frac{I_P V B_T}{200\mu_0 a\tau}$$

- Use Ziegler-Nichols method to determine P & I.
  - Based on magnitude, delay, and time-scale of the β_N response to beam steps.
- Convert "analog" requested power to NB modulations.
  - Minimum modulation time of 15 msec.

Determination of Gains Using Ziegler-Nichols Method

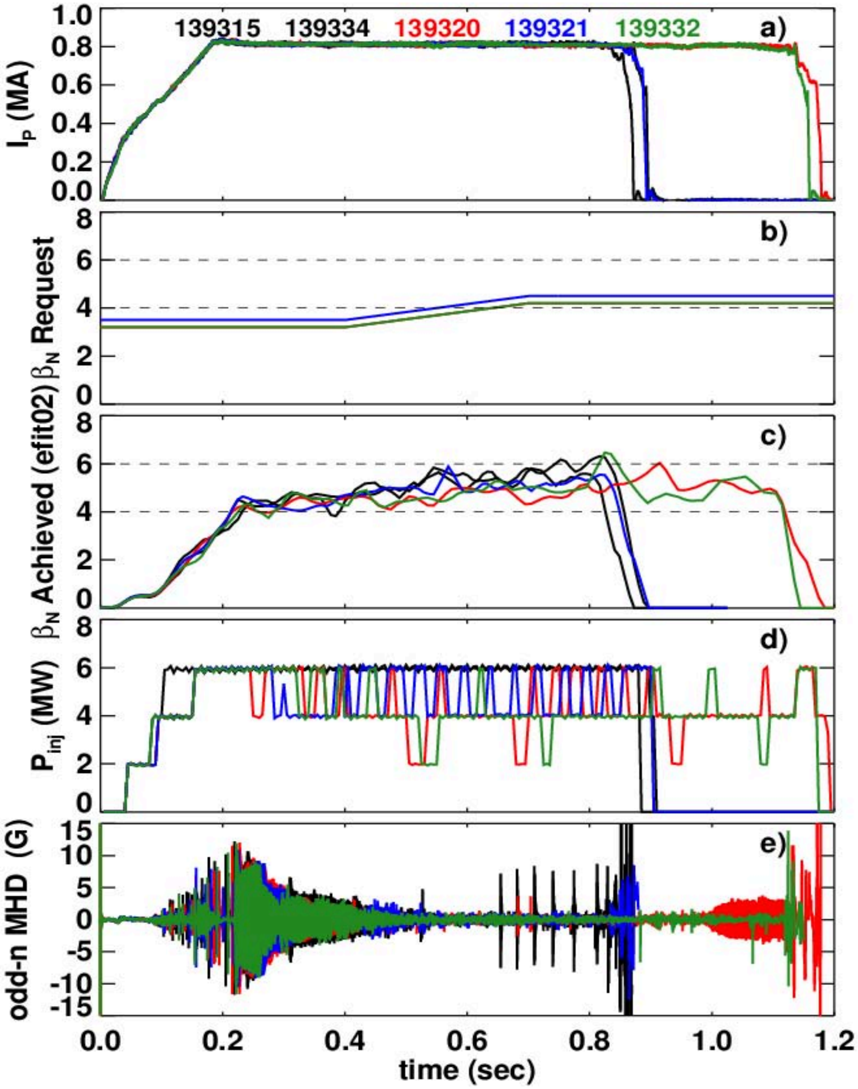


Constant-β_N During I_P and B_T Scans



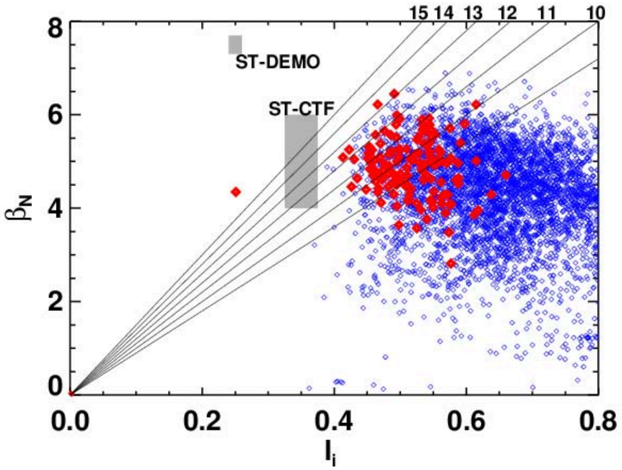
Controller Can be Used to Maintain β_N Near Stability Limits

- Black discharges have full 6 MW injected power.
  - Disrupt at ~0.85 sec.
- Green and red discharges have β_N control.
  - Shots run through.
- Blue case has slightly higher β_N request.
  - Disrupts at similar time.
- Necessary to program proper time-dependent β_N request.
  - Must not request β_N values that exceed the instantaneous limit in a time evolving plasma.
  - Feedback on a variable like RFA might eliminate this issue?

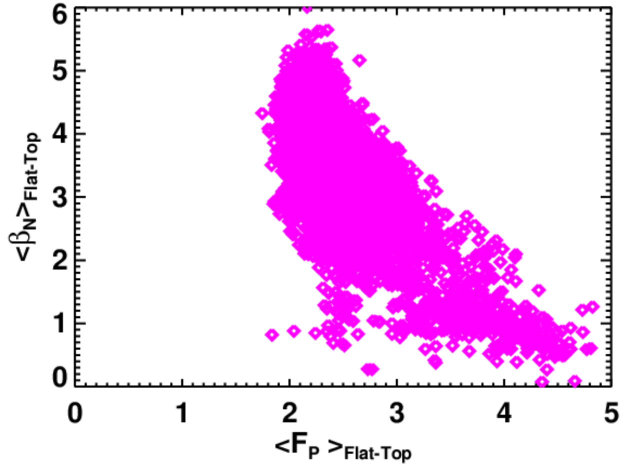


No-Wall β_N Limit Can Vary Widely Depending on Profiles; Best Shots Near With-Wall Limit

β_N vs l_i

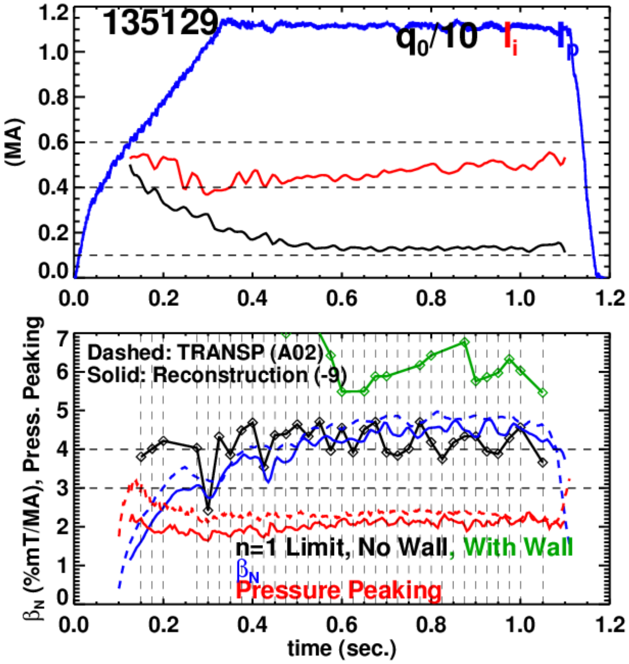


β_N vs F_P

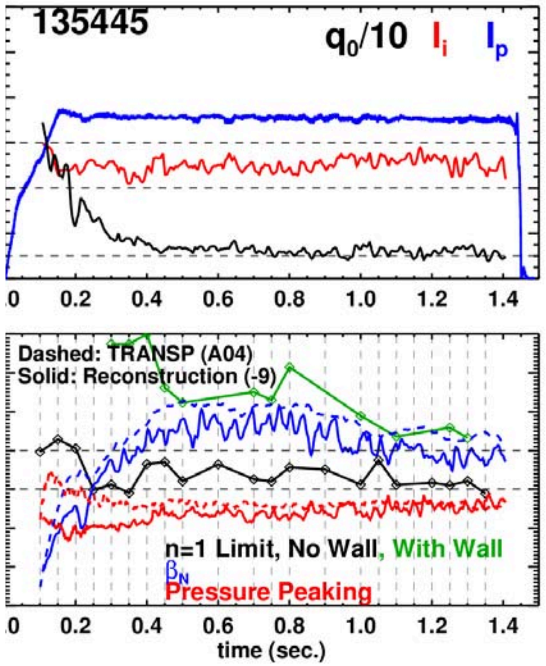


- MSE constrained equilibria using EFIT code.
- Use CHEASE to scale the pressure profile.
- DCON to evaluate n=1 no- & with-wall limits.
- Repeat calculation for many times during discharge.

135129
High-β_T target
I_P=1100 kA, B_T=0.45 T

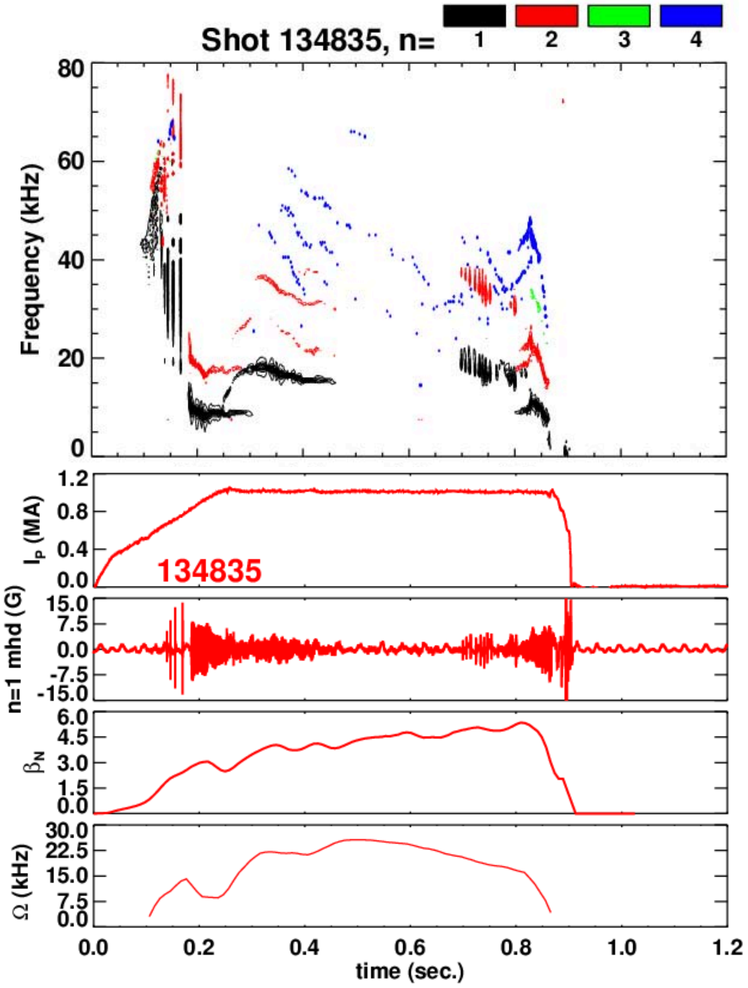


135129
Long Pulse Target
I_P=700 kA, B_T=0.38 T



Core n=1 Modes Limit Performance Over a Range of q_{95}

Optimized for high β_T
(κ=2.6, I_P=1.0 MA, q_{95}=7)



Mirnov Coil Spectrogram

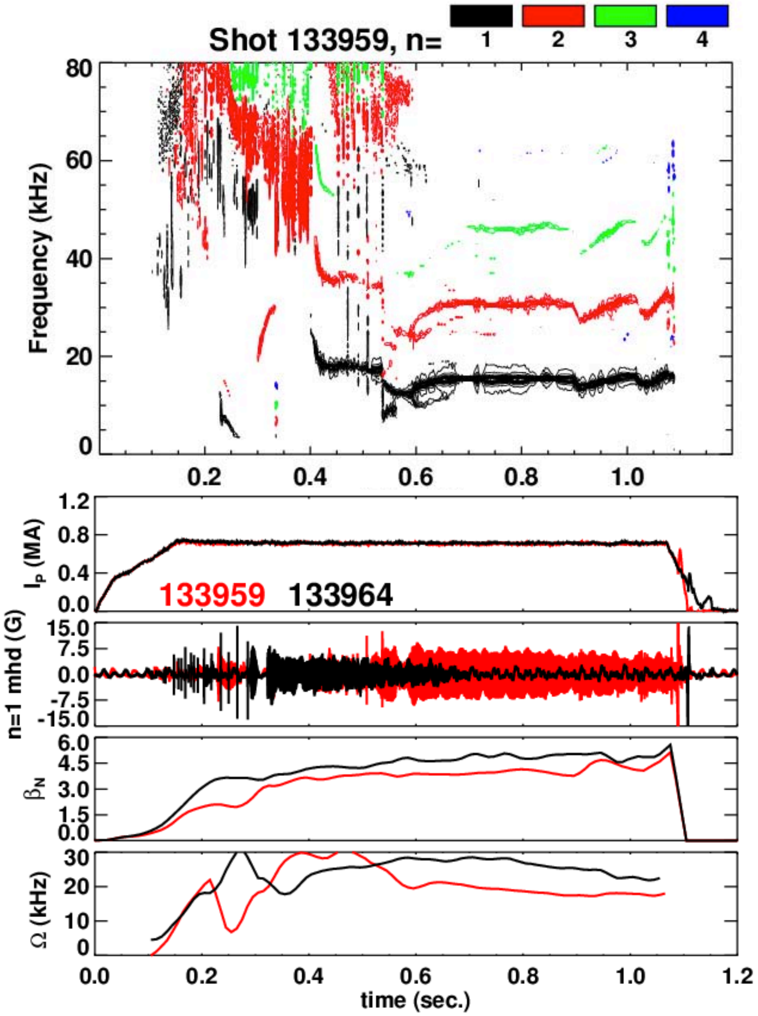
Plasma Current

Odd-n MHD

β_N

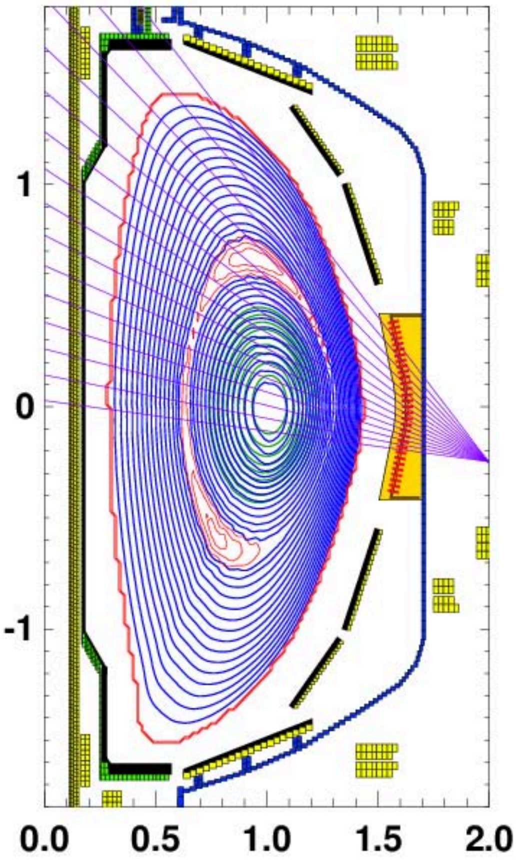
Core Rotation Frequency

Optimized for high β_P
(κ=2.6, I_P=0.7 MA, q_{95}=13)



Use a Coupled 2/1 Island + 1/1 Kink Eigenfunction to Understand Mode Structure

Optimized for high β_T
(κ=2.6, I_P=1.0 MA, q_{95}=7)



Method:

- ***Compute an MSE constrained equilibrium reconstruction.***
- ***Invert the USXR emission as a function of helical flux using a regularized inversion method.***
- ***Apply resonant helical flux perturbation to open an island on the q=m/n surface.***

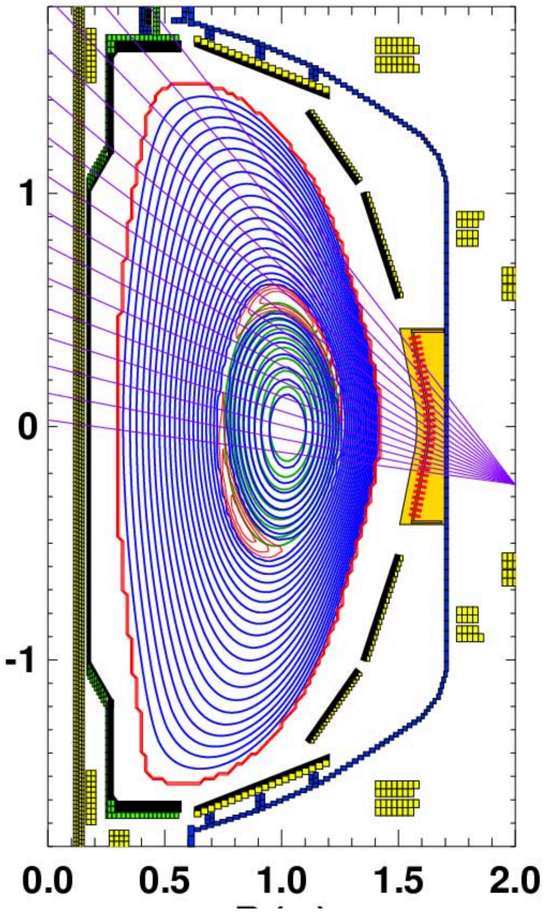
$$\delta\psi_h = A(\psi)\cos(n\phi - m\theta)$$

- ***Apply a simple shift to the core surfaces.***

$$\xi_{1,1} = \begin{cases} \xi_0 & r < r_c \\ \xi_0 e^{-\left[(r-r_c)/r_f\right]^2} & r > r_c \end{cases}$$

- ***Compute the expected chordal emission through the USXR chords.***
- ***Compare to measured emission contours.***
- ***Adjust the island and shift parameters, and repeat integration and comparison.***

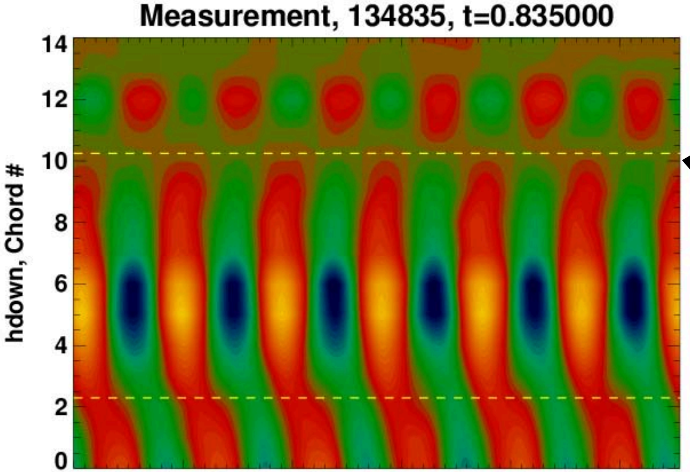
Optimized for high β_P
(κ=2.6, I_P=0.7 MA, q_{95}=13)

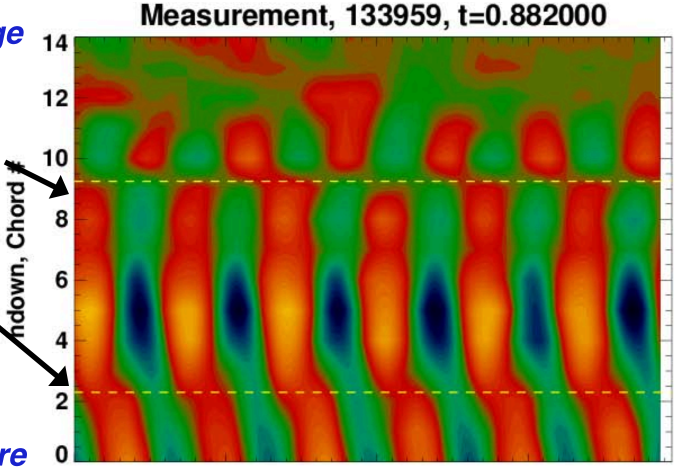


Model Eigenfunctions Can Match USXR Emission For Both Cases

Optimized for high β_T
(κ=2.6, I_P=1.0 MA, q_{95}=7)

Optimized for high β_P
(κ=2.6, I_P=0.7 MA, q_{95}=13)


Measurement, 134835, t=0.835000

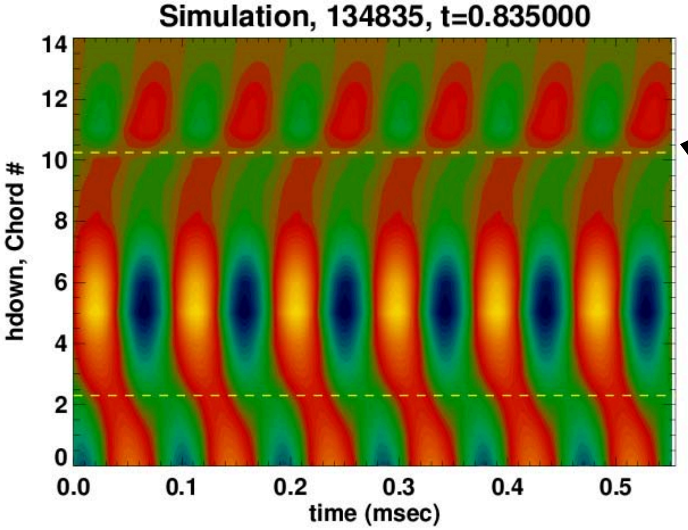

Measurement, 133959, t=0.882000

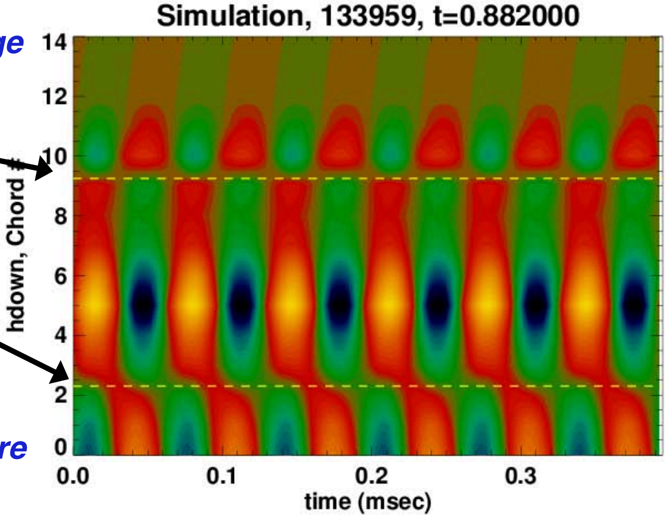
Edge

Core

Chord tangent to q=2. Inversion across 2/1 island.

Chord passing through magnetic axis. Inversion across 1/1 mode.


Simulation, 134835, t=0.835000


Simulation, 133959, t=0.882000

Edge

Core

Chord tangent to q=2. Inversion across 2/1 island.

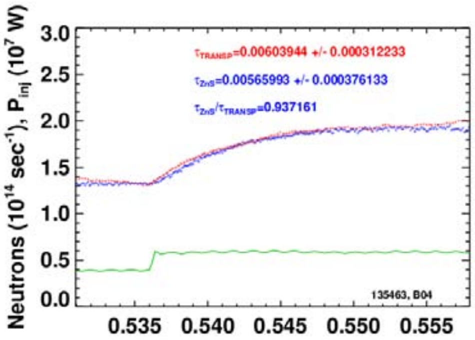
Chord passing through magnetic axis. Inversion across 1/1 mode.

How to Eliminate Core n=1 Modes?

- Modes can often be triggered by ELMs or EPMs.
  - Direct triggering or profile modifications?
  - Lithium helps to avoid ELMs.
- Triggering modes is easier when the flow shear at q=2 is reduced.
- “Triggerless” modes are also often observed.
  - These are non-resonant 1/1 modes.
  - Strong sensitivity to details of q-profiles.
  - Modes can by eliminated by increasing the injected power, slowing the q-profile evolution.
- Maintaining elevated q_{min} would help eliminate these instabilities.
  - Would 3/1 modes limit performance…how high does q_{min} need to be?
- Open question:
  - Why do some discharges maintain q_0 near 1 without core MHD, while other discharges develop these modes?

Current Profiles and the Non-Inductive Fraction

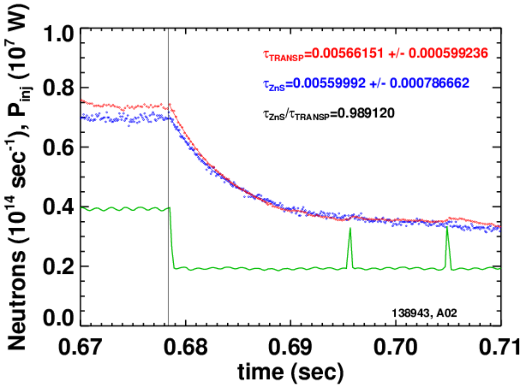
Successful Bench-Mark of TRANSP Neutron Dynamics Against Measurements

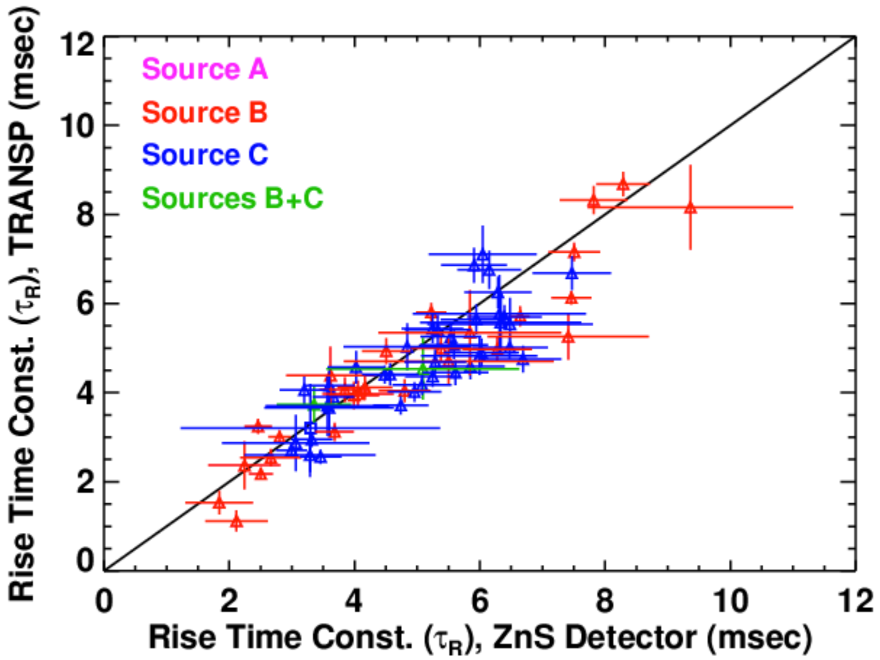


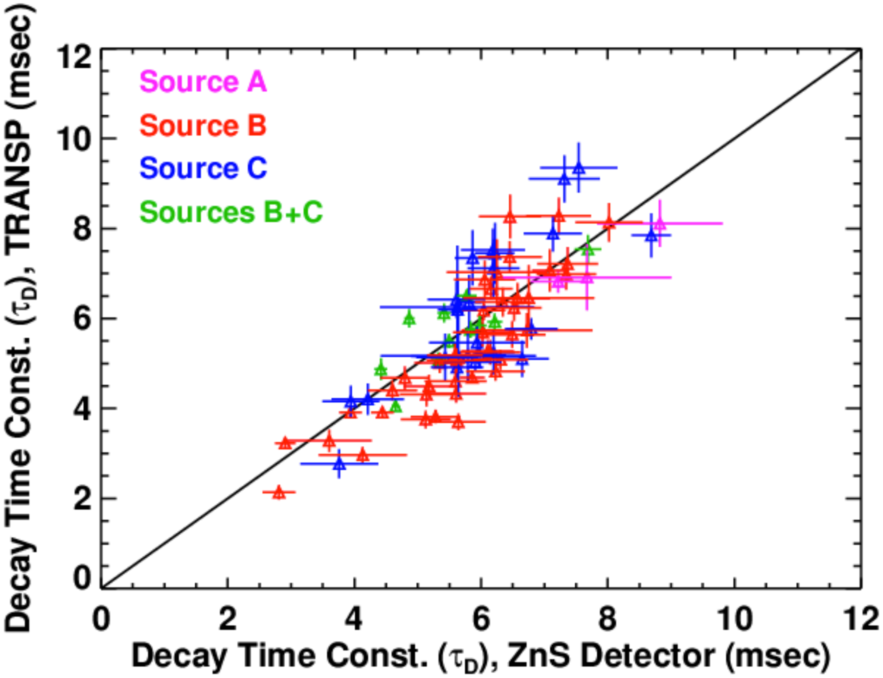
Exponential Fits For Rise and Decay

$$\frac{dR_N}{dt} = c - \frac{R_N}{\tau_R} \qquad \frac{dR_N}{dt} = -\frac{R_N}{\tau_D}$$

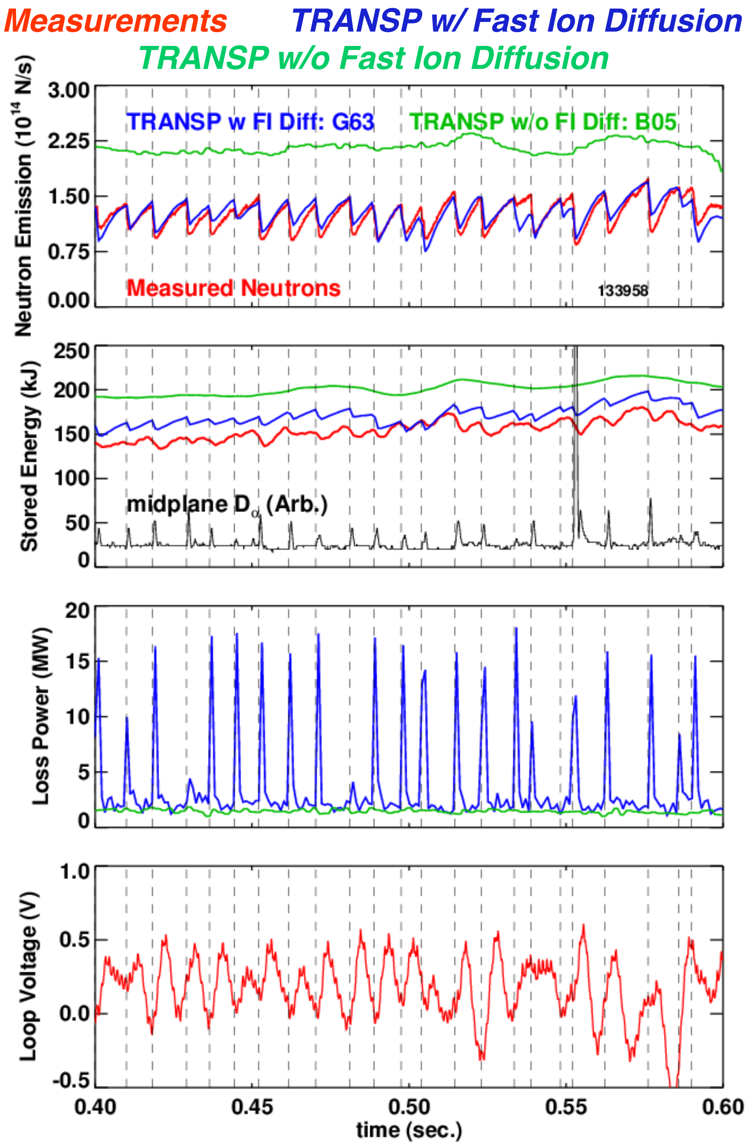
Apply the Same Fit to Measurements and TRANSP Simulations (MHD-free Periods of Discharges)





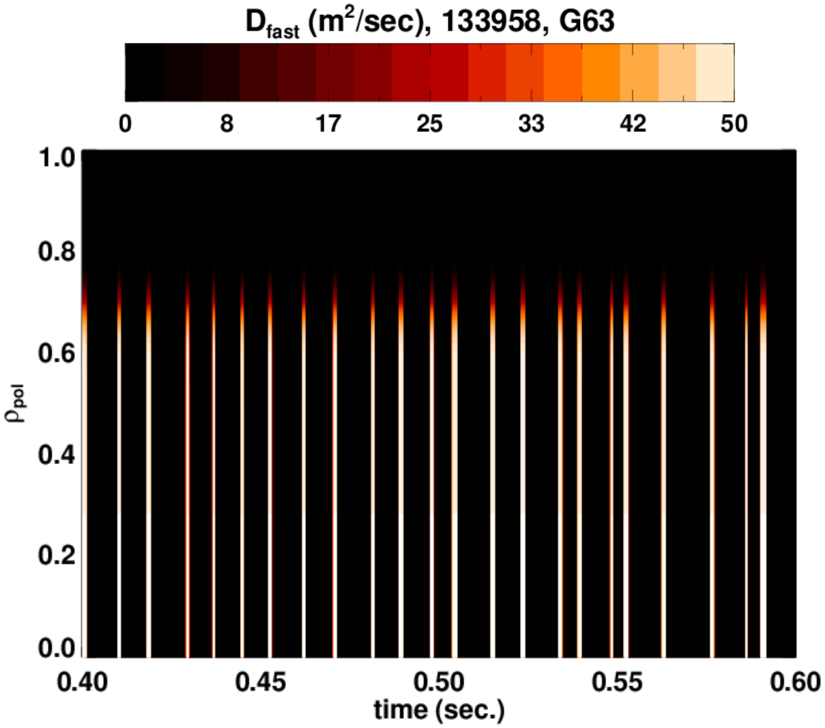


TAE Avalanches Simulated in TRANSP Using Impulsive Anomalous Fast Ion Diffusion



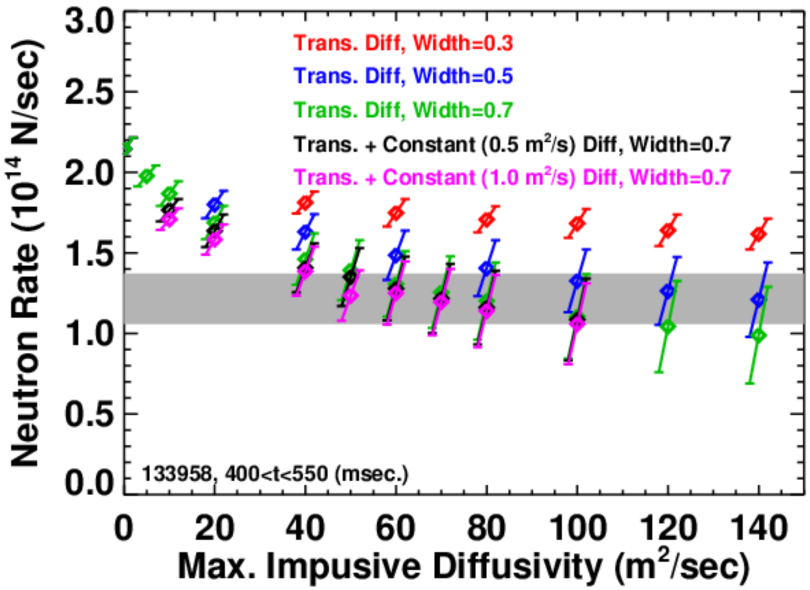
- *Adjust start time and duration of the pulses to match measured neutron rate drops.*
- *Fix amplitudes, widths for a given TRANSP run.*

$$D_{FI}\left(\rho_{pol},t\right) = \frac{A_{FI}\left(t\right)}{2}\left[1-\tanh\left(\frac{\rho_{pol}-0.05}{w}\right)\right] + D_{FI,DC}$$



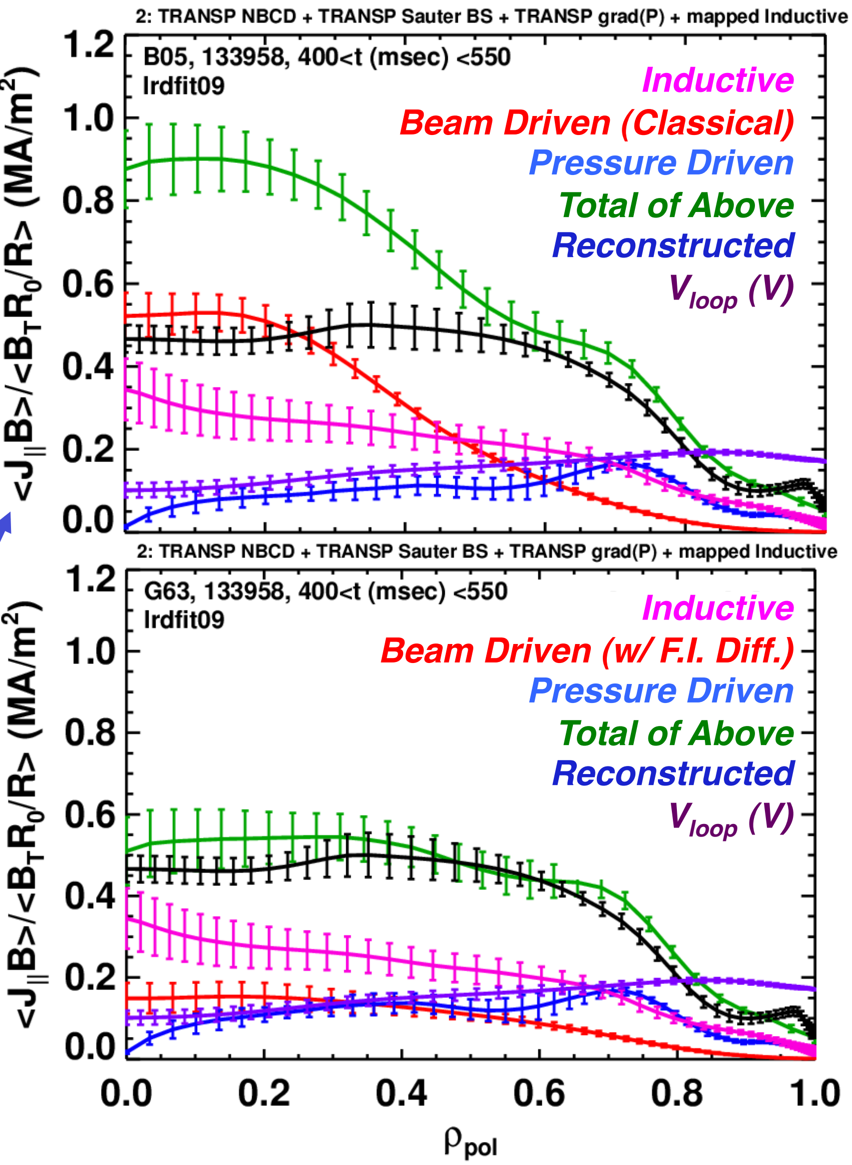
“Optimized” Fast Ion Diffusion Profile Leads to Agreement on the Current Profile

Optimal Fast Ion Diffusivity Determined From Neutron Rate Drops

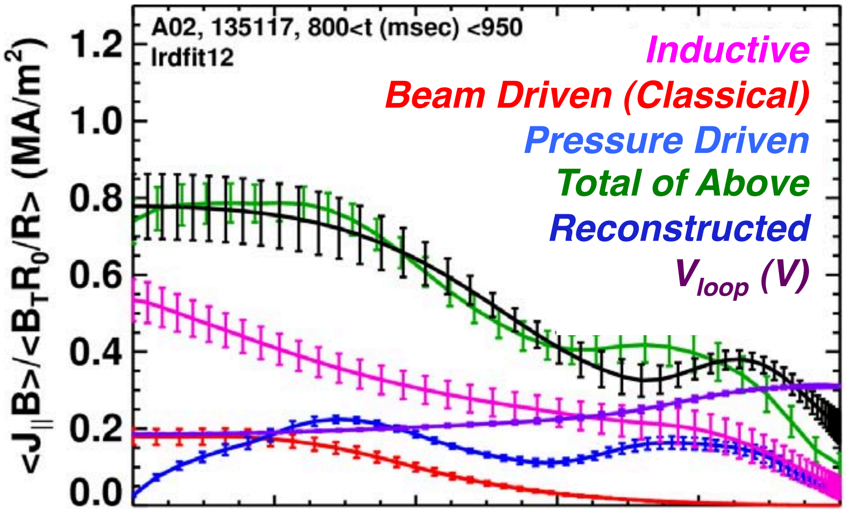


Current profile comparison without fast ion diffusion.

Current profile comparison with impulsive fast ion diffusion.



Current Profile Reconstructions Have Been Done For a Wide Range of *MHD-Free* Plasmas

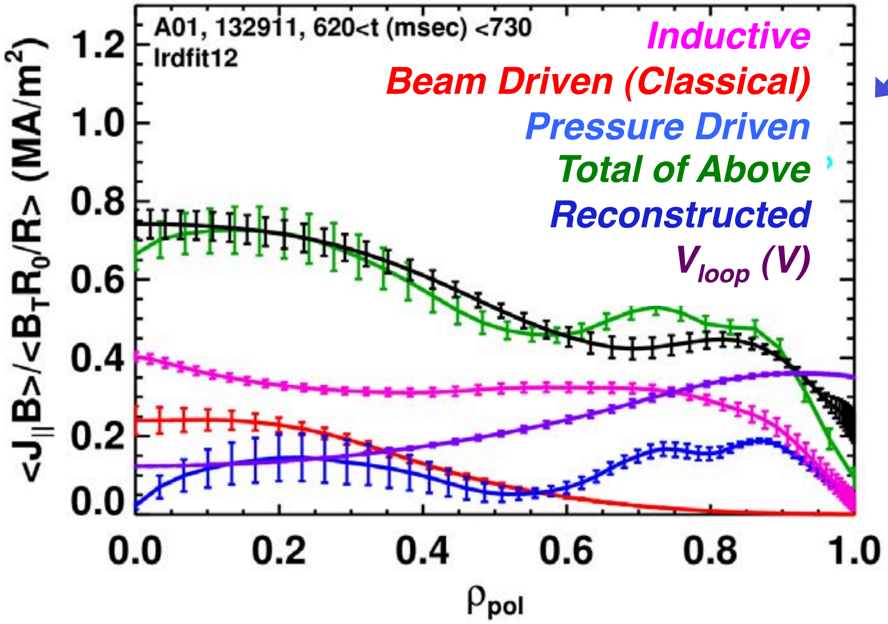


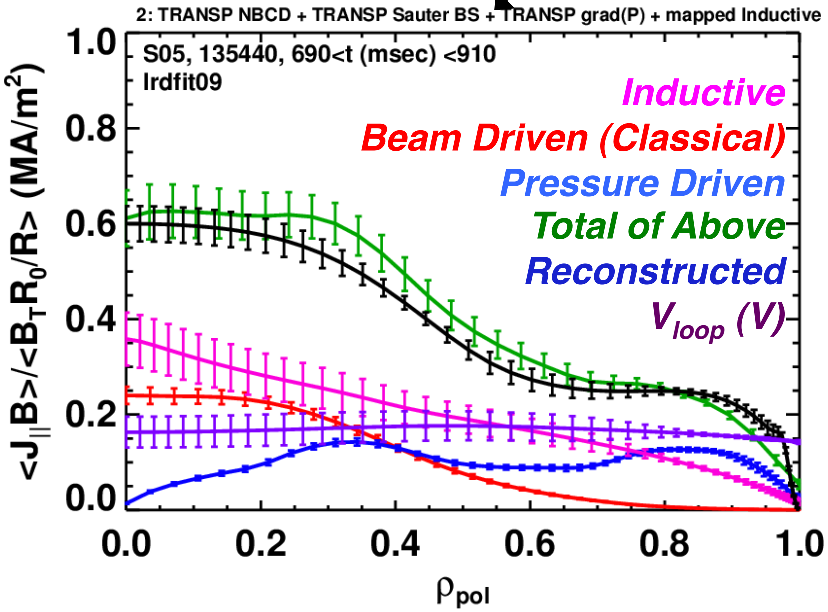
1100 kA, Optimized For Sustained High β_T

All analysis during MHD free periods, with no anomalous fast ion diffusion.

1300 kA, Optimized For Sustained For Large Stored Energy

700 kA, Optimized For Long Pulse





Non-Inductive Fractions are Maximized at Low Plasma Current

$$f_{BS} \propto \beta_P \propto \frac{P_{inj}\tau_{E,Thermal}}{I_P^2}$$

$$\tau_{E,Thermal} \propto I_P^{0.65}\sqrt{n_e}P_{abs}^{-0.7}$$

$$f_{BS} \propto \frac{\sqrt{n_e}}{I_P^{1.35}}$$

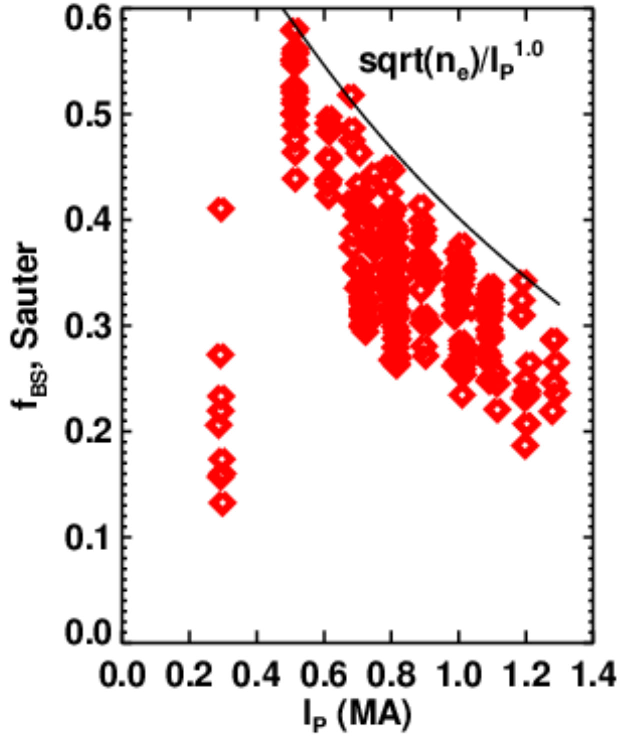
Ignores P_{inj}, B_T, & shaping.

Slowing-down time and beam parameters determine the neutral beam current drive

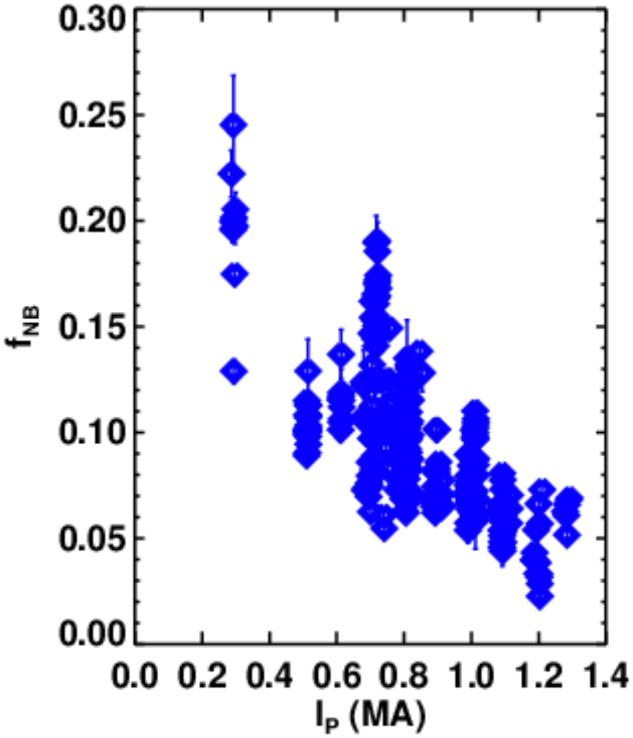
$$f_{NB} \propto \frac{S_{FI}\mathrm{v}_{FI}\tau_{SD}}{I_p}$$

Total non-inductive fraction reaches 65-70%

Bootstrap Fraction



Beam Current Drive Fraction



Non-Inductive Fraction