Development of Advanced Spherical Torus Operating Scenarios in NSTX

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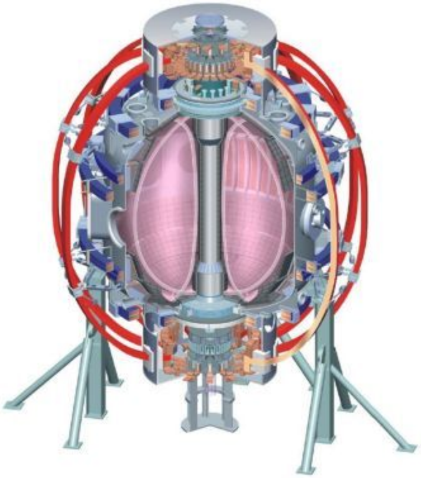
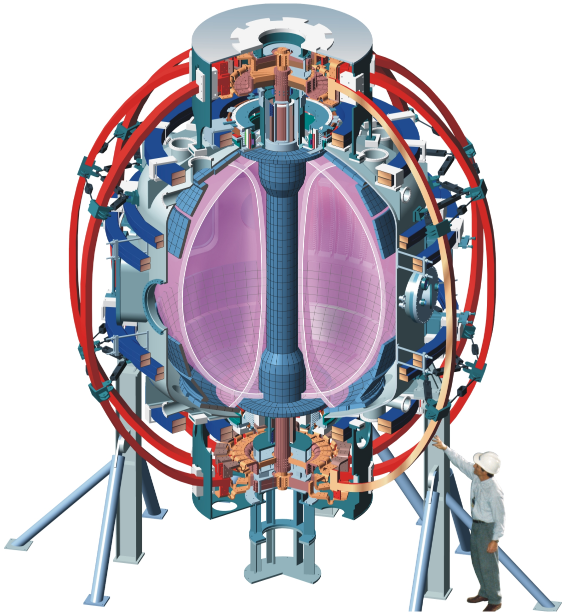
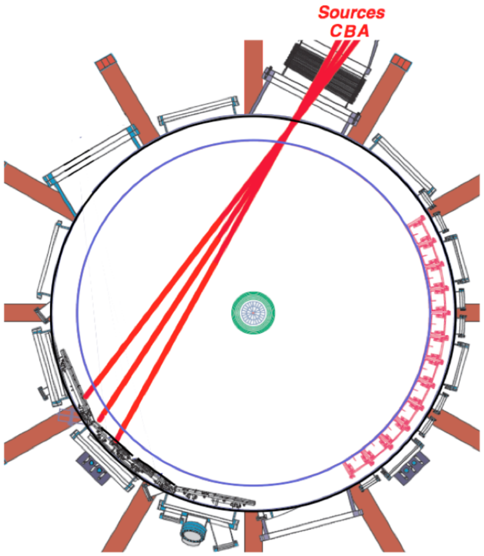


Overview and Global Performance Studies

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



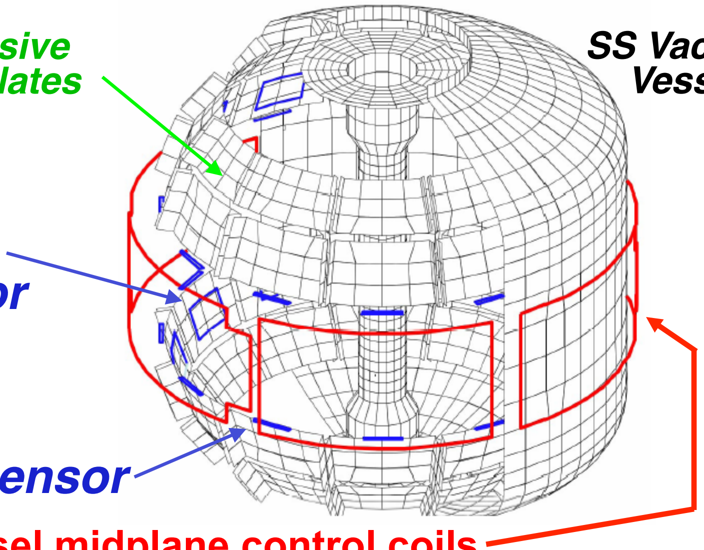


3-D Field Coils Important For Scenario Development

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

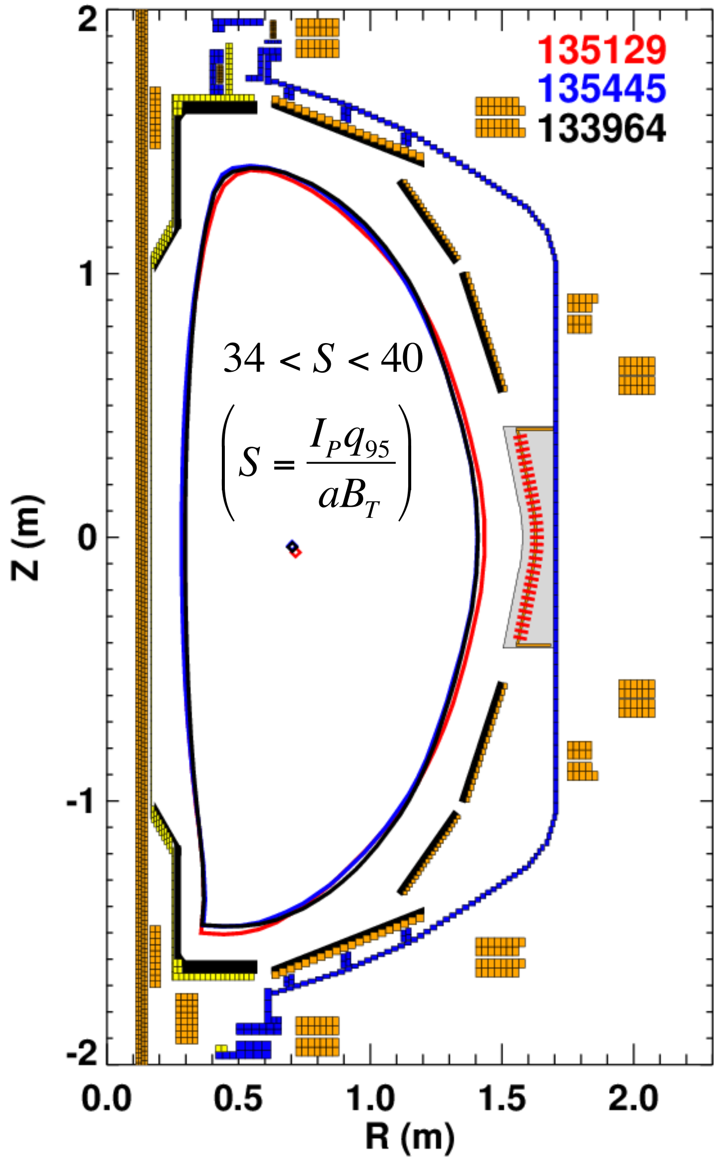
SS Vacuum Vessel

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



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

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

$q^*=4.7$

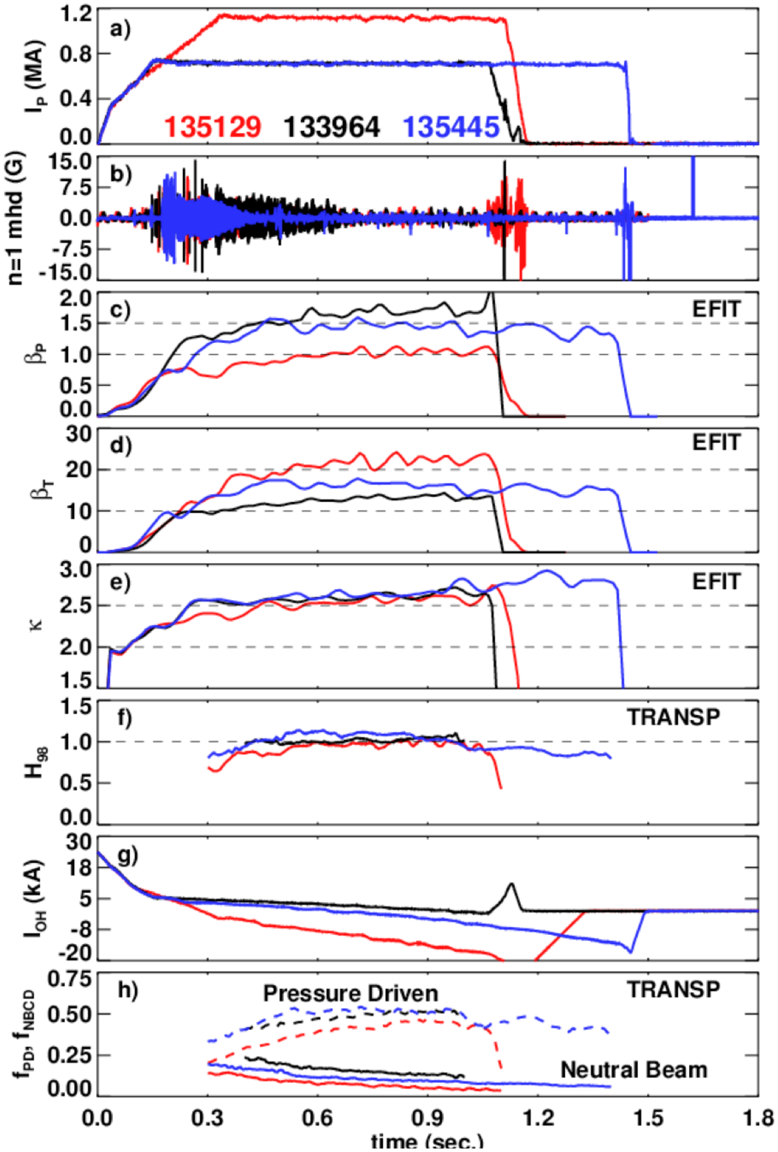
$B_T=0.48$ T

$I_P=700$ kA

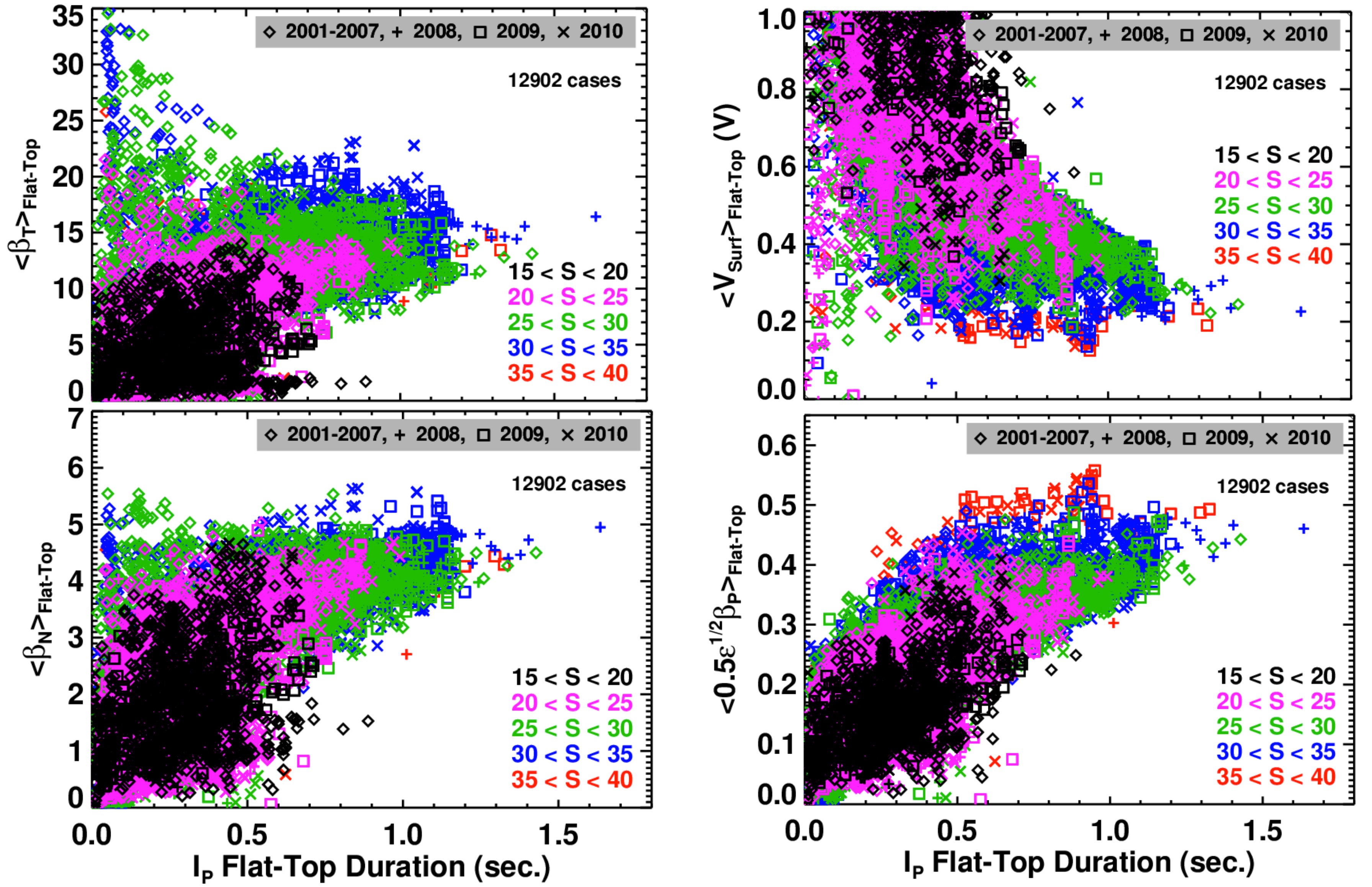
All

$H_{98}>=1$

$\kappa=2.6-2.7$



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



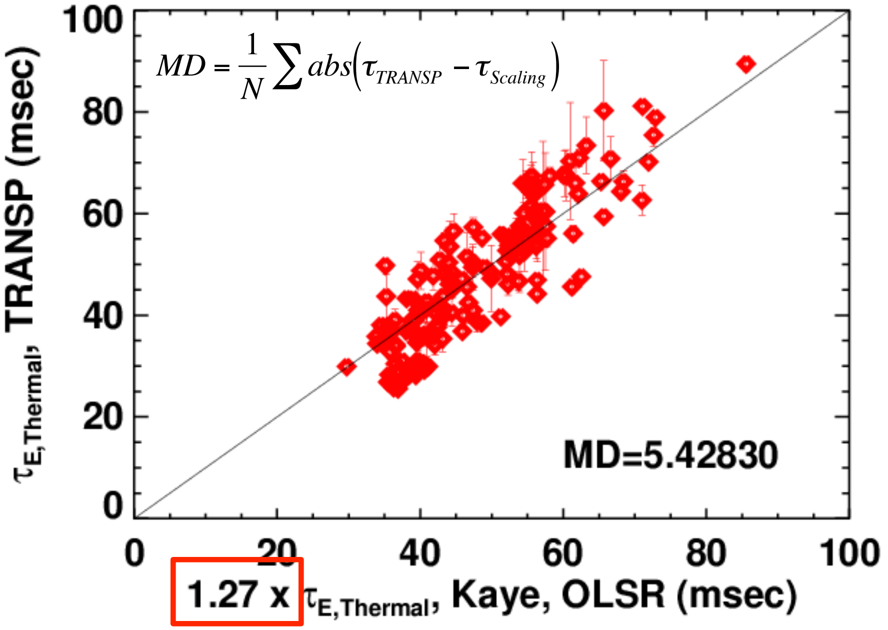
Lithiumized Discharges Shows Confinement Scaling Similar to Higher Aspect Ratio

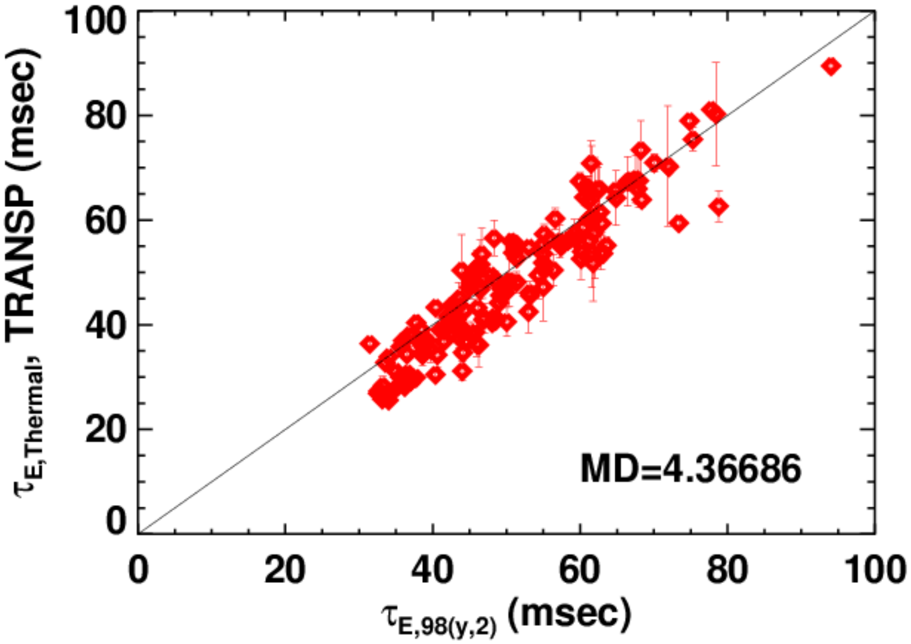
Consider > 75 msec averaging windows, at least one current diffusion time into the I_P flat-top, at high-κ and δ, in lithium conditioned discharges

Criterion excludes many high-confinement discharges

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

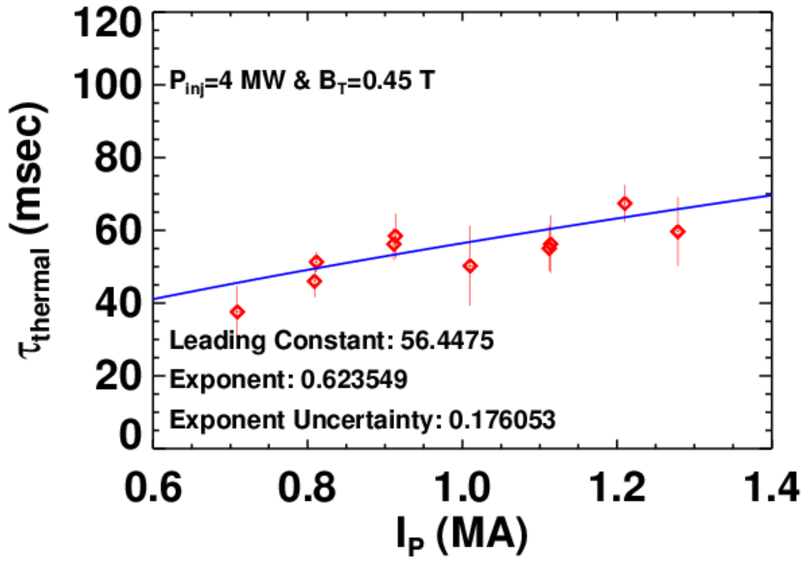
$$\tau_{E,th,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_{abs}^{-0.69} \kappa^{0.8}$$

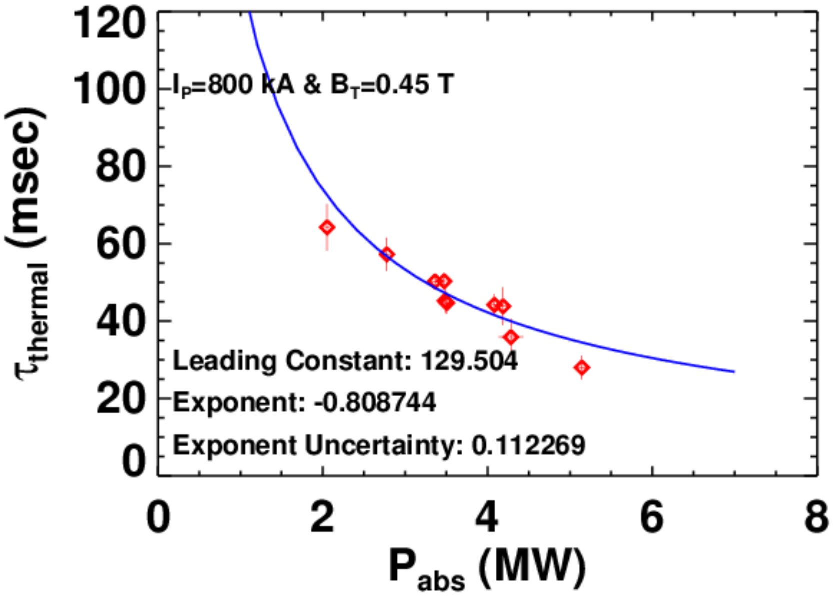


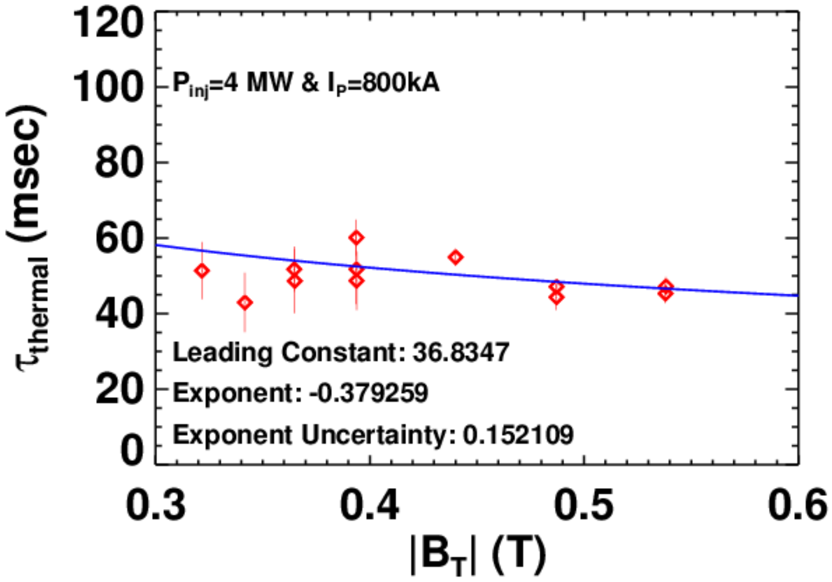


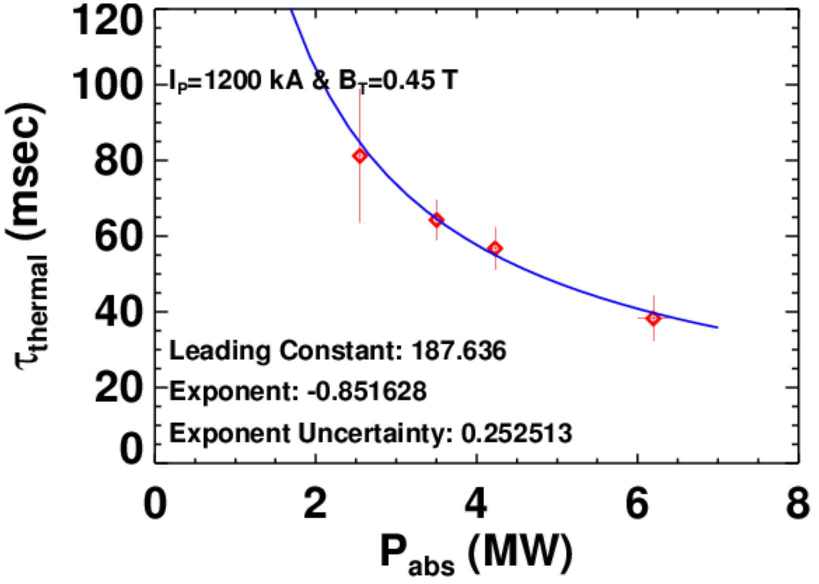
- Confinement exceeds previous low-A scaling by ~30%.
  - – Lithium conditioning, strong shaping, higher β_N and longer-pulse duration.
- Working to revise ST-scalings for τ_E in this class of discharge.

Dedicated Scans Show Confinement Trends in Lithiumized High-Performance Plasmas









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:

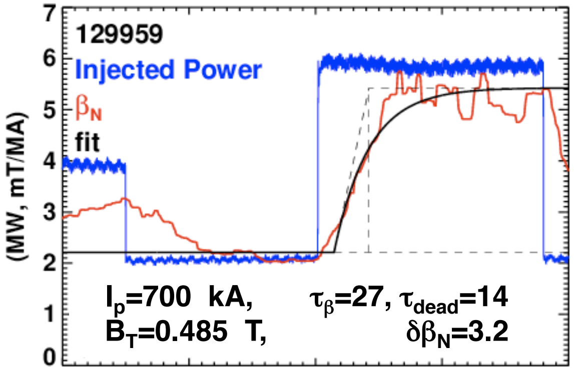
$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

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

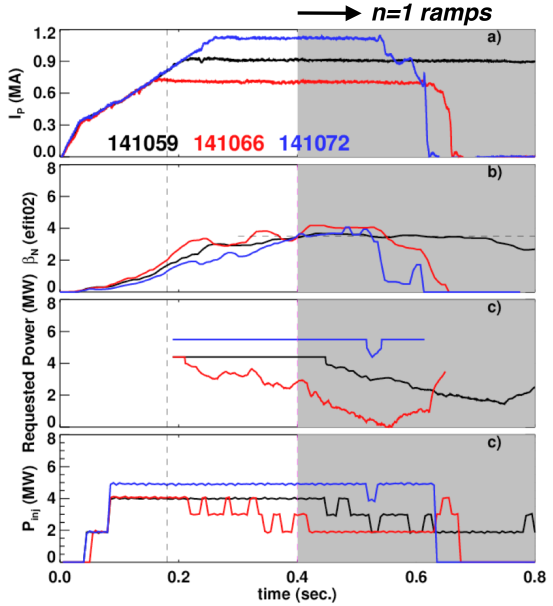
$$\overline{C}_{\beta_N} = \frac{I_P V B_T}{200\mu_0 a\tau}$$

- 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

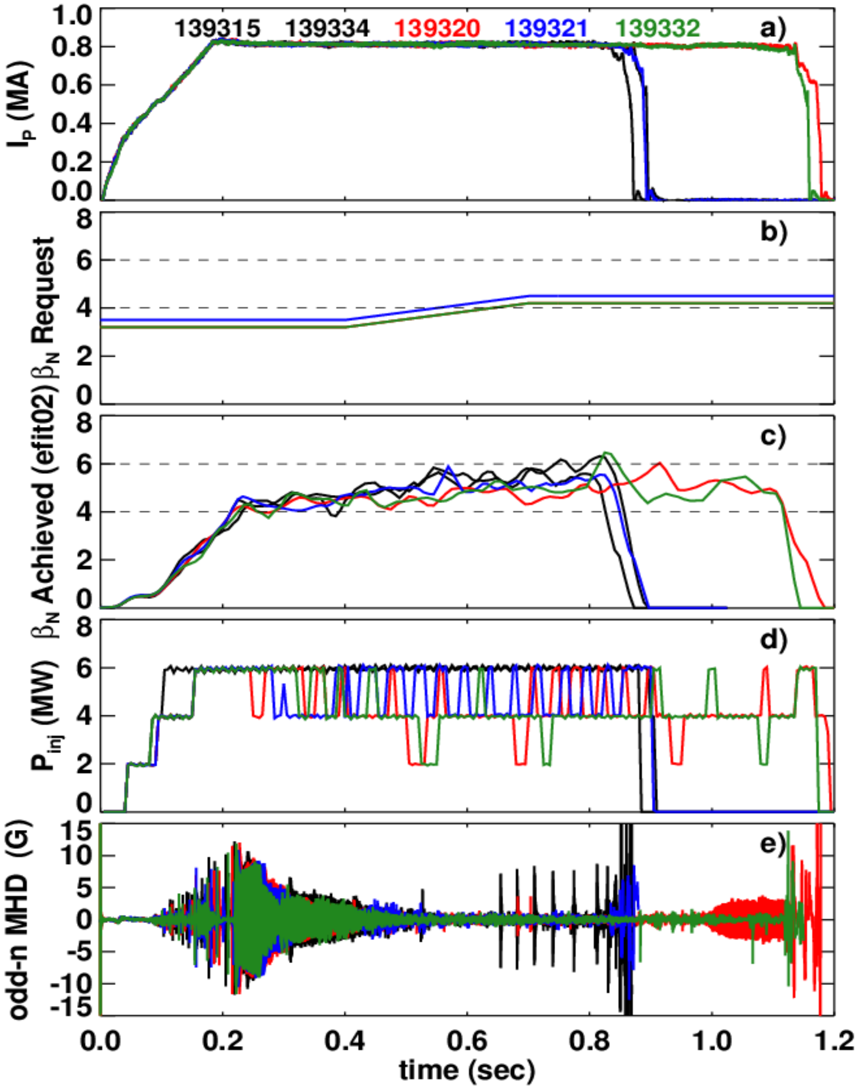


Constant-β_N During I_P and B_T Scans



Controller Can be Used to Maintain β_N Near Stability Limits

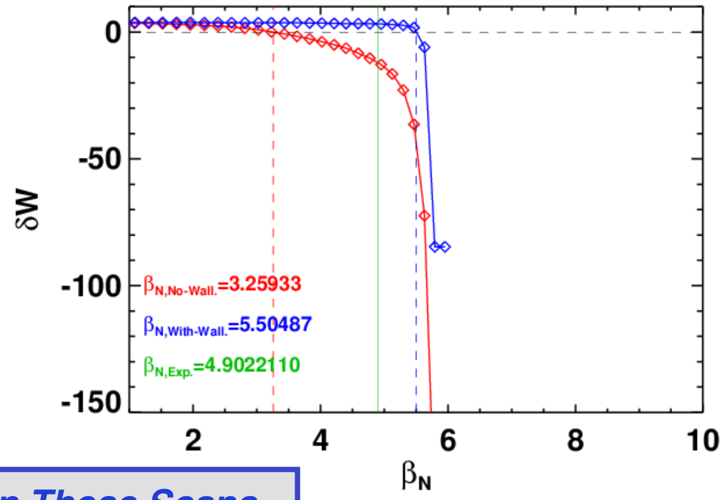
- Black discharges have full 6 MW injected power.
  - Disrupt at ~0.85 sec.
- Green and red discharges have β_N control.
  - Shots run through.
- Blue case has slightly higher β_N request.
  - Disrupts at similar time.
- Necessary to program proper time-dependent β_N request.
  - Must not request β_N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



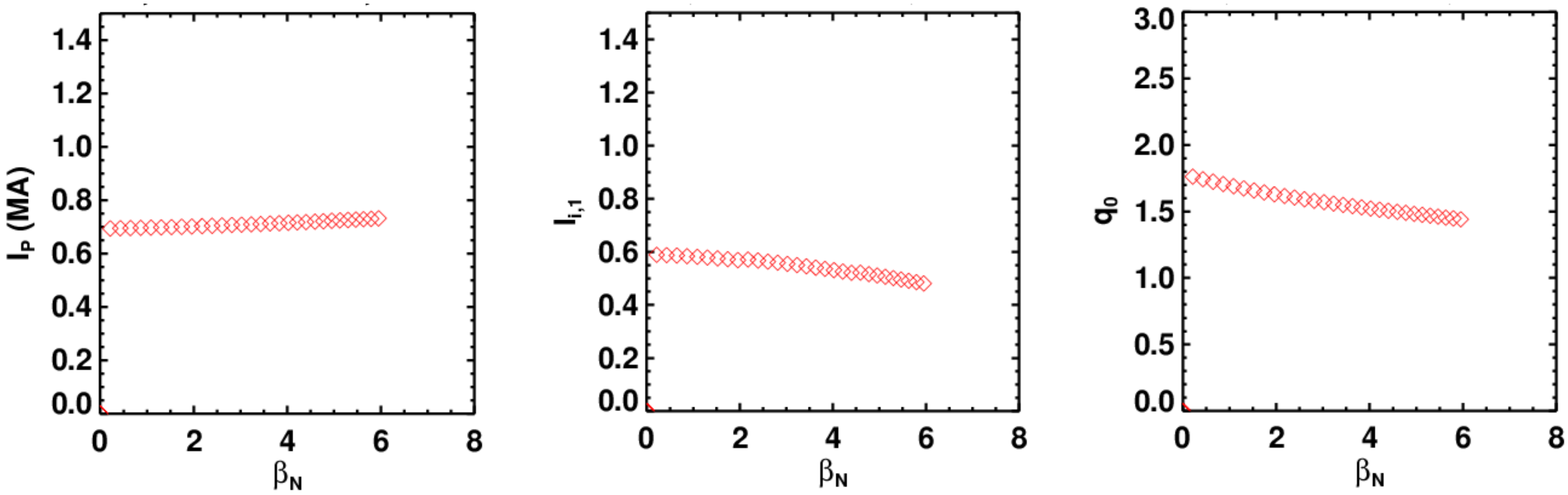
Compute Time Dependent Ideal Stability Limits with CHEASE and DCON

- Scale pressure profile with CHEASE.
  - Simple scalar multiplier.
  - Typically scan $1<\beta_N<9$, in 0.2 increments.
  - Small changes occur in I_P, q_0, l_i
- Compute n=1 δW with DCON.
  - Both no-wall and with-wall limits.
- Repeat calculations for many times during a single shot.

δW vs. $\beta_{N,}$ n=1

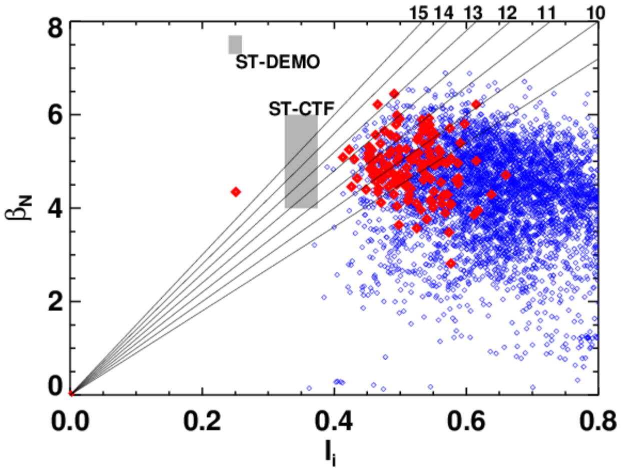


Typical Variation of Equilibrium Parameters with β_N In These Scans

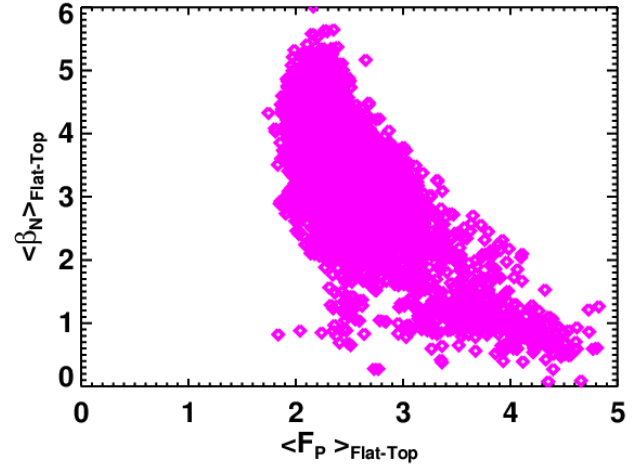


No-Wall β_N Limit Can Vary Widely Depending on Profiles; Best Shots Near With-Wall Limit

β_N vs l_i

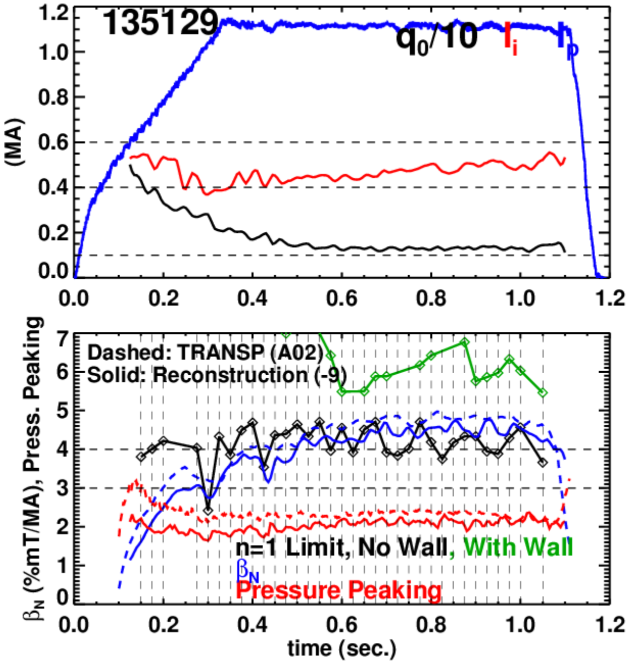


β_N vs F_P

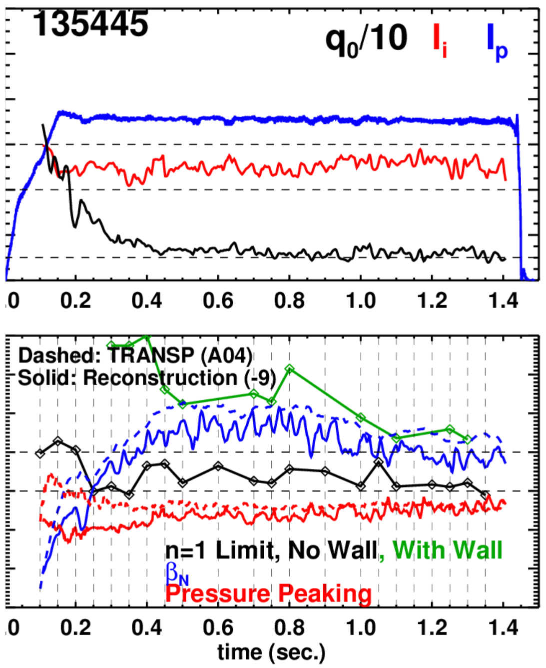


- MSE constrained equilibria using EFIT code.
- Use CHEASE to scale the pressure profile.
- DCON to evaluate n=1 no- & with-wall limits.
- Repeat calculation for many times during discharge.

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

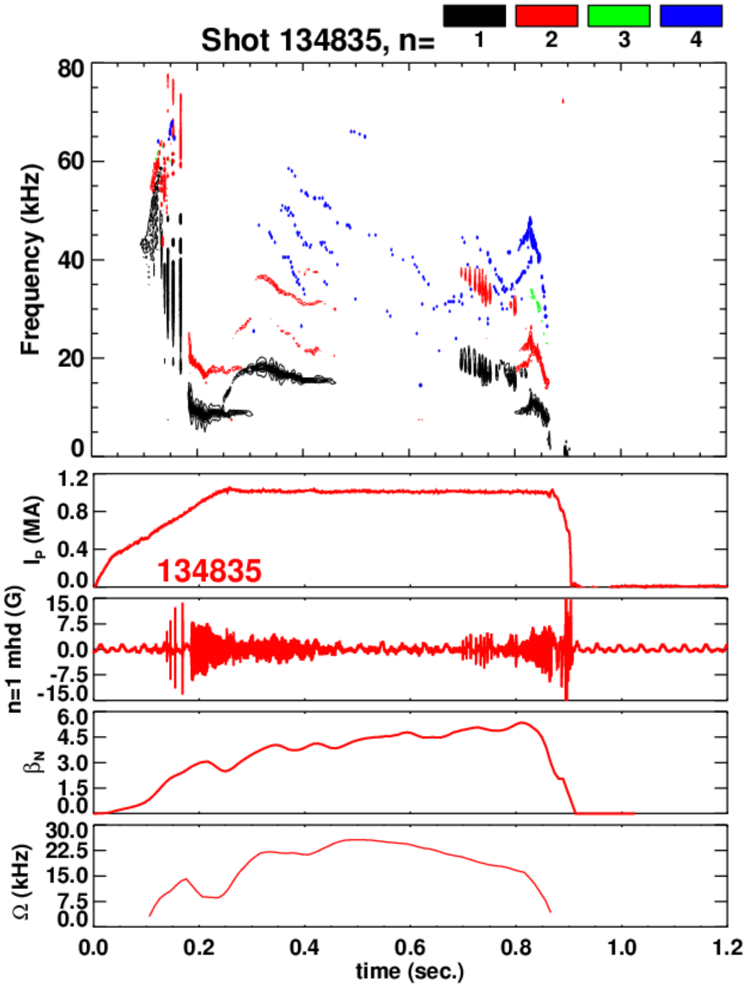


135129
Long Pulse Target
I_P=700 kA, B_T=0.38 T



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

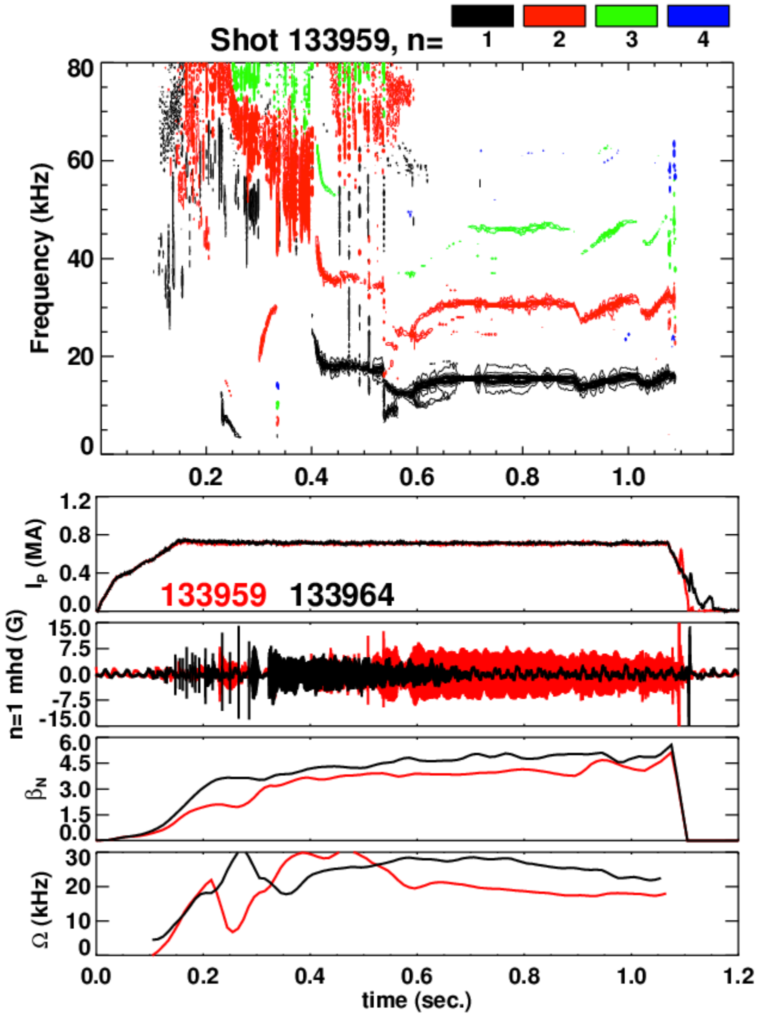
Plasma Current

Odd-n MHD

β_N

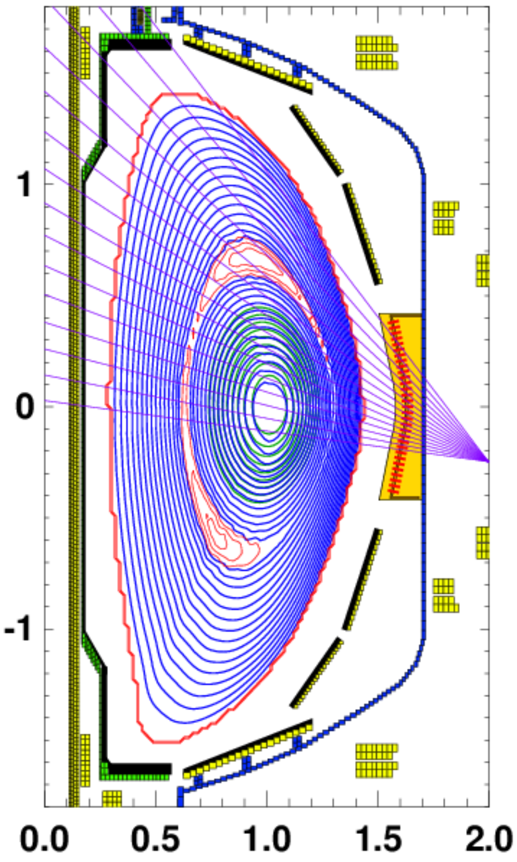
Core Rotation Frequency

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.*

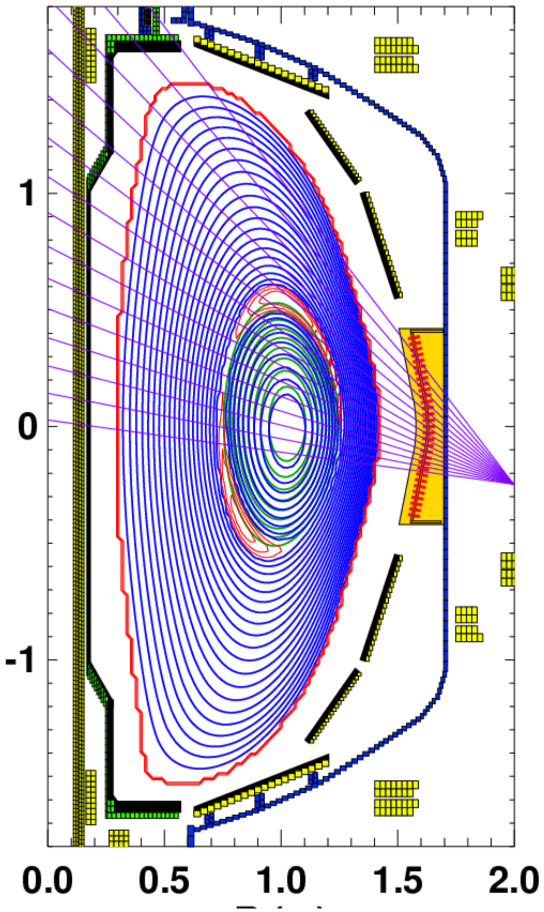
$$\delta\psi_h = A(\psi)\cos(n\phi - m\theta)$$

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

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

- *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)

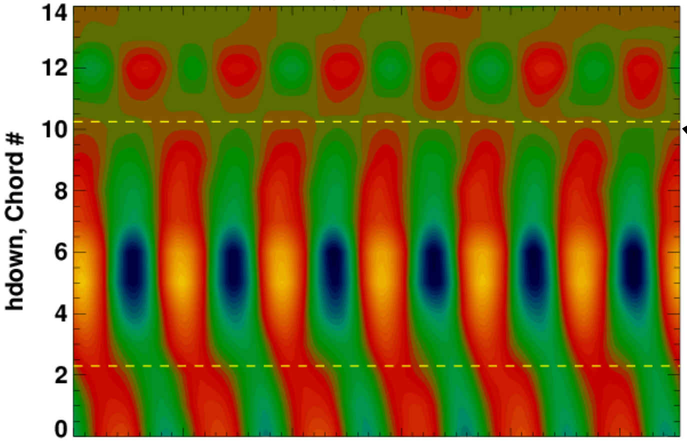


Model Eigenfunctions Can Match USXR Emission For Both Cases

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



Edge

Core

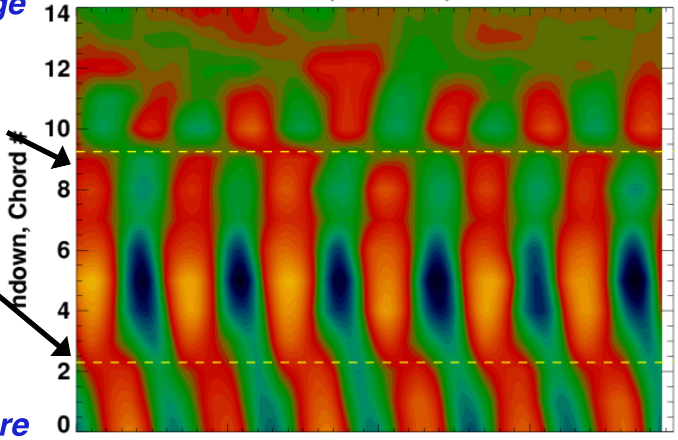
Chord tangent to q=2.
Inversion across 2/1 island.

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

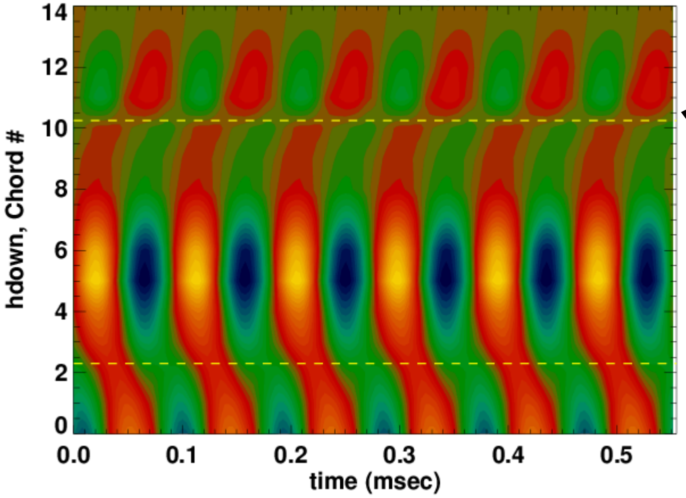
Edge

Core

Measurement, 133959, t=0.882000



Simulation, 134835, t=0.835000



Edge

Core

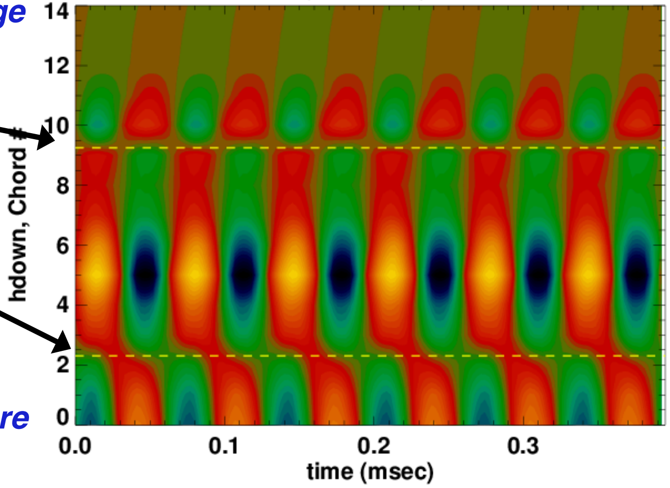
Chord tangent to q=2.
Inversion across 2/1 island.

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

Edge

Core

Simulation, 133959, t=0.882000

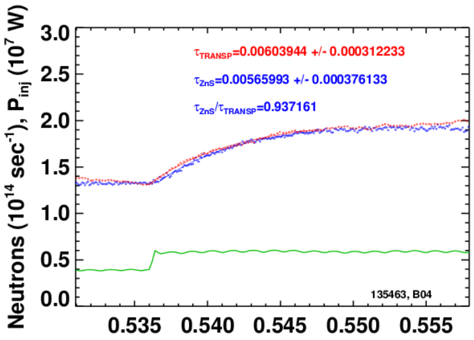


How to Eliminate Core n=1 Modes?

- 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

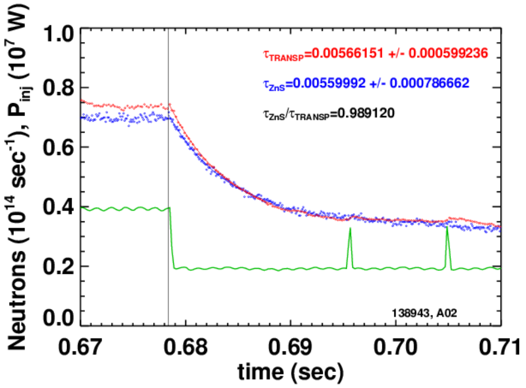


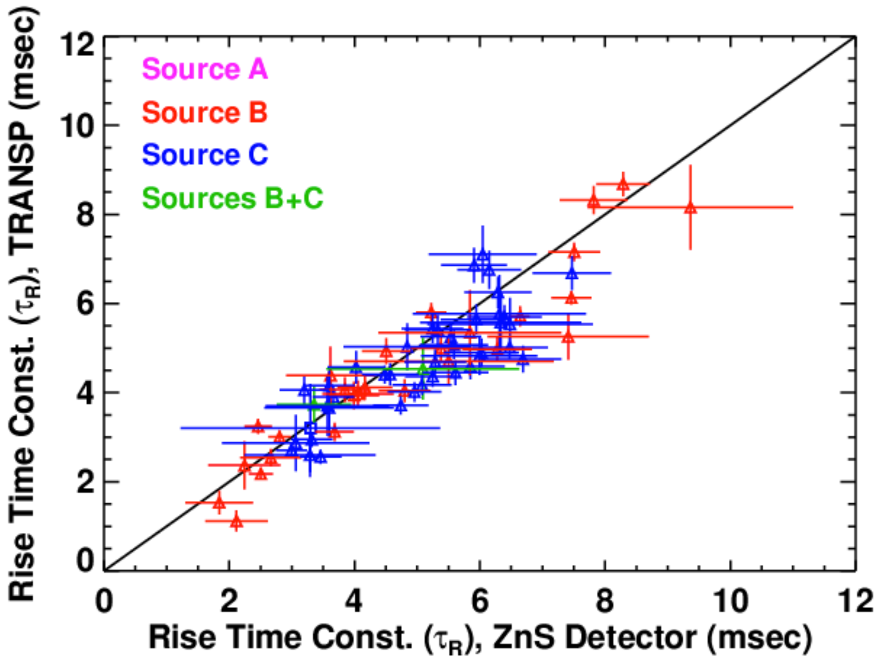
Exponential Fits For Rise and Decay

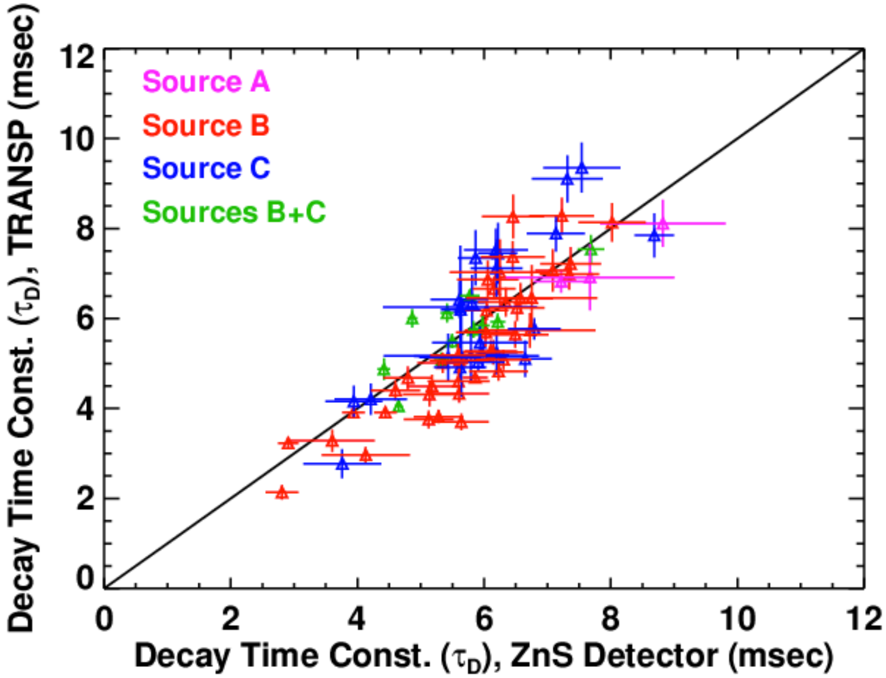
$$\frac{dR_N}{dt} = c - \frac{R_N}{\tau_R}$$

$$\frac{dR_N}{dt} = -\frac{R_N}{\tau_D}$$

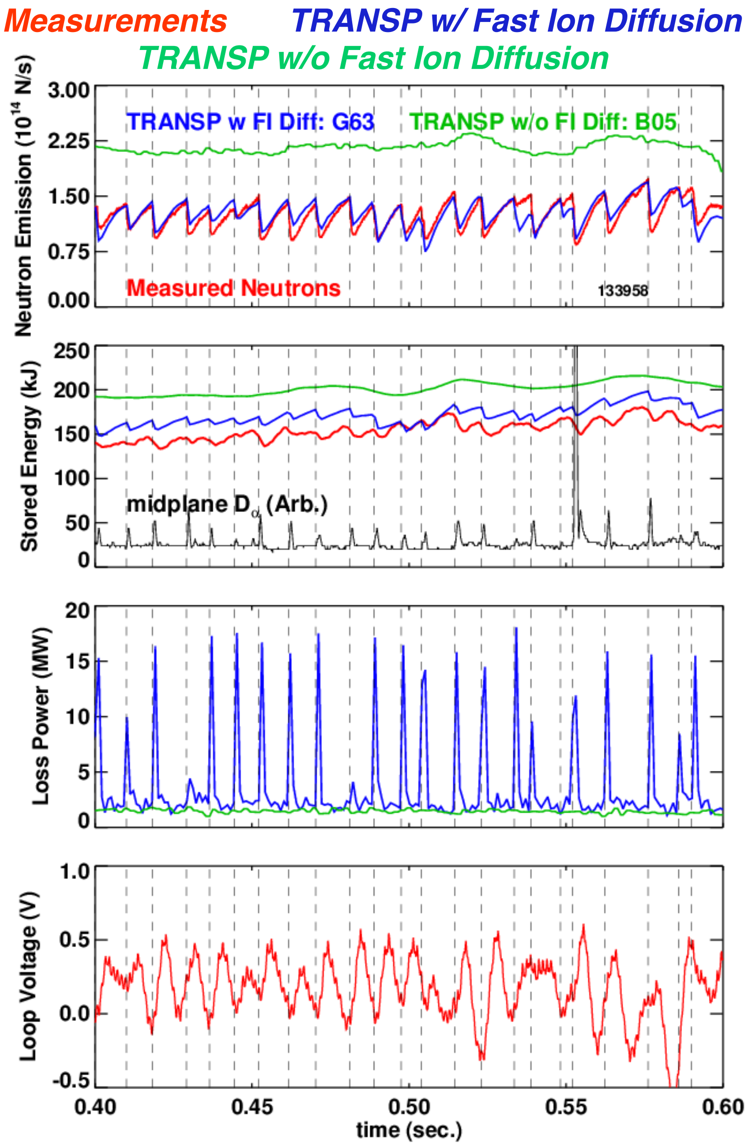
Apply the Same Fit to Measurements and TRANSP Simulations
(MHD-free Periods of Discharges)





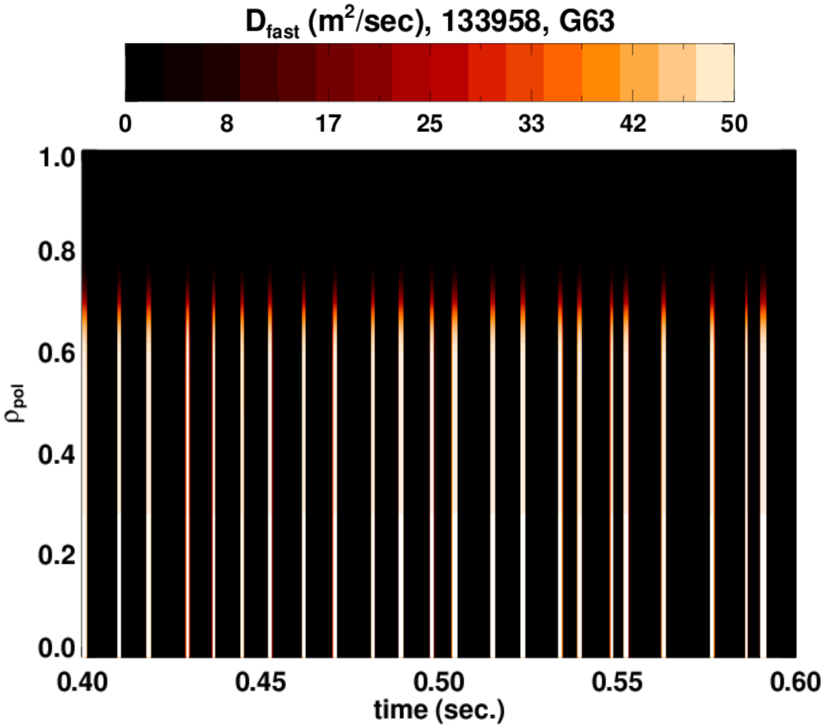


TAE Avalanches Simulated in TRANSP Using Impulsive Anomalous Fast Ion Diffusion



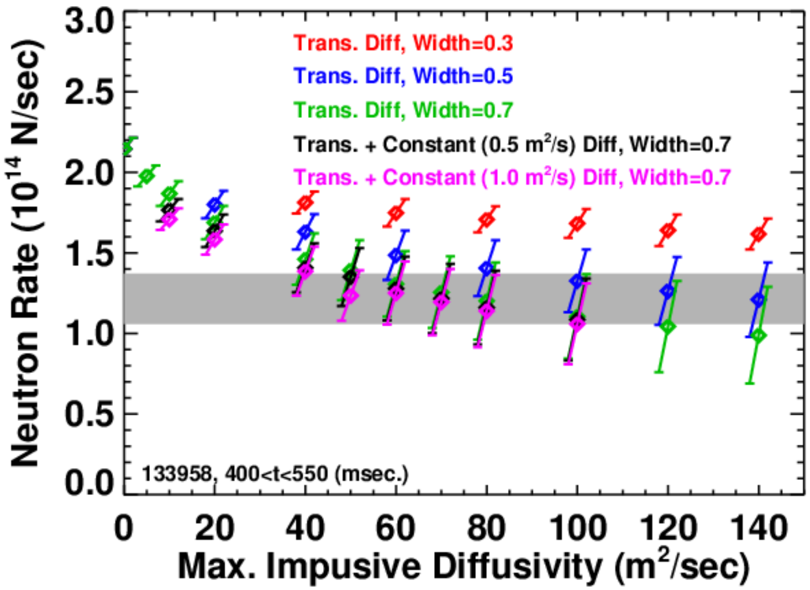
- ***Adjust start time and duration of the pulses to match measured neutron rate drops.***
- ***Fix amplitudes, widths for a given TRANSP run.***

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



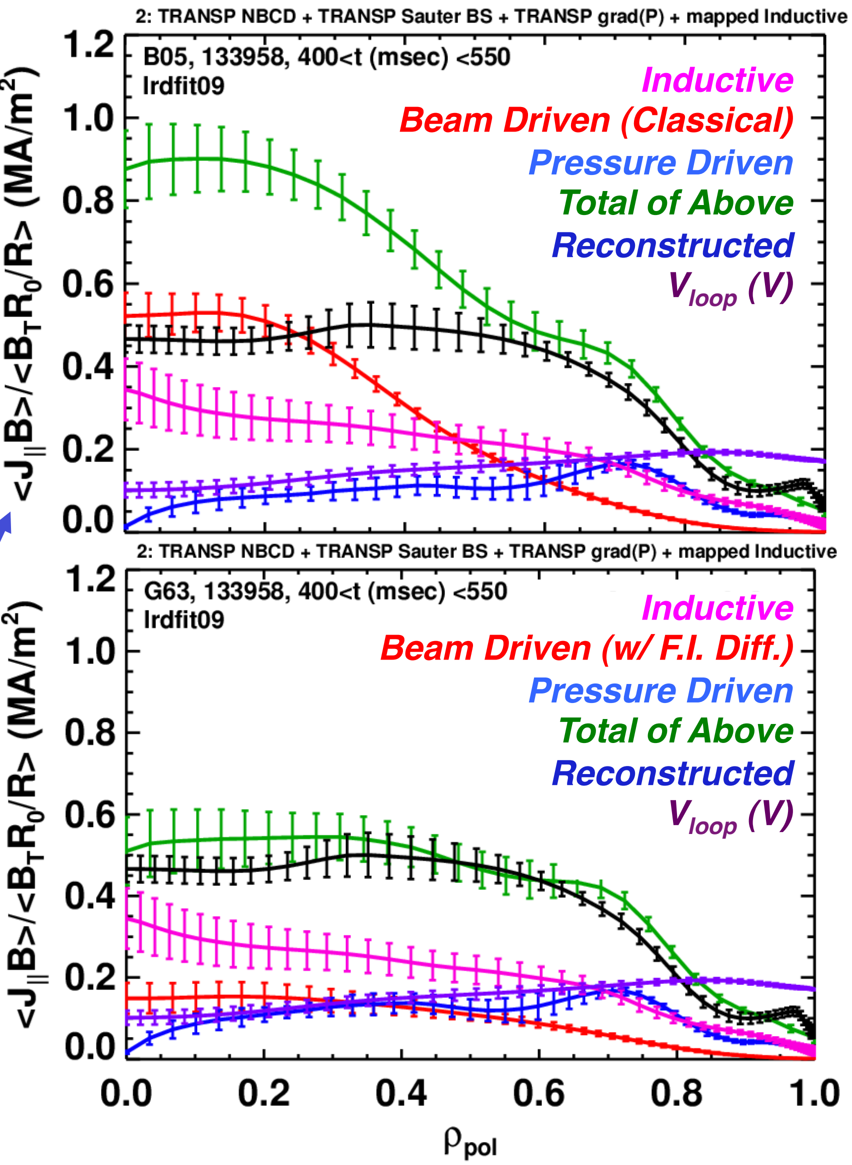
“Optimized” Fast Ion Diffusion Profile Leads to Agreement on the Current Profile

Optimal Fast Ion Diffusivity Determined From Neutron Rate Drops



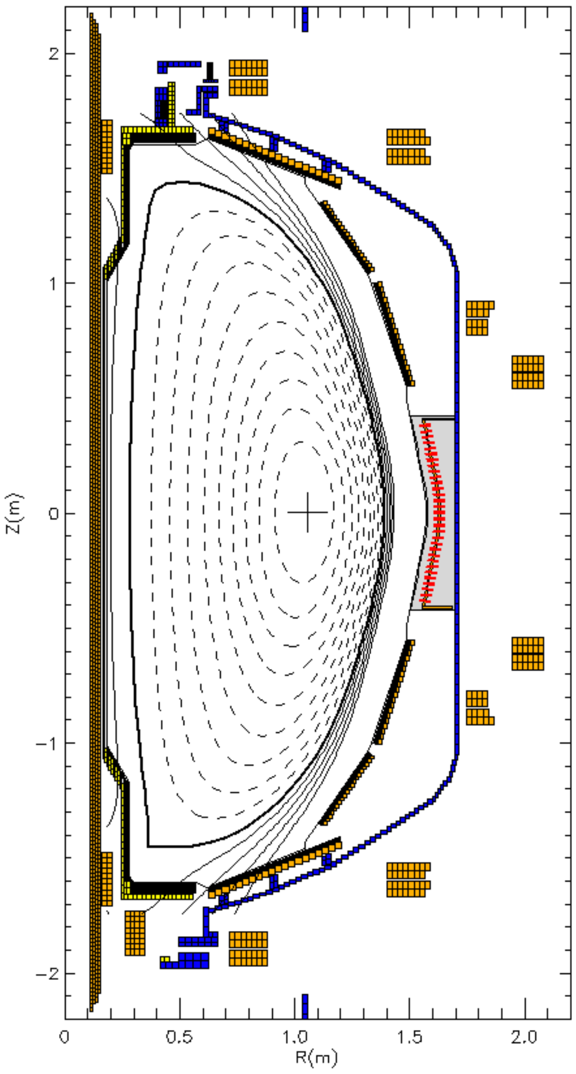
Current profile comparison without fast ion diffusion.

Current profile comparison with impulsive fast ion diffusion.

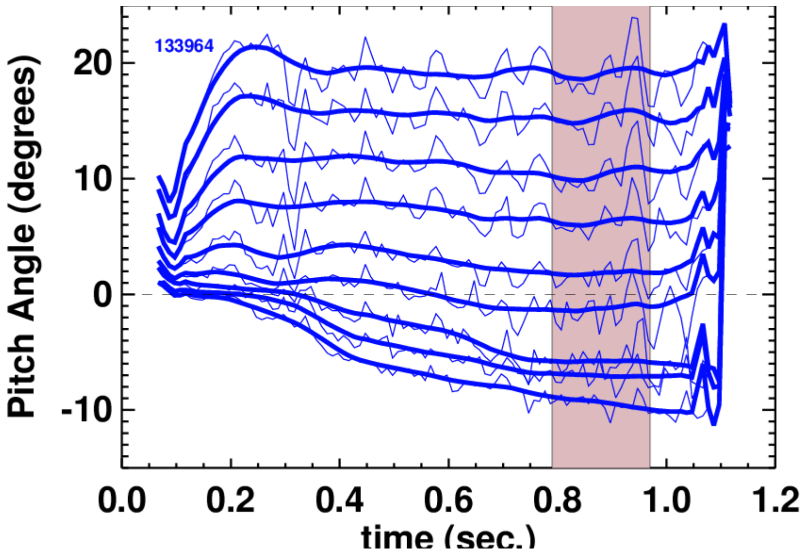


J(ρ) Profile Record of Low V_{loop} Shot Can Be Understood Without Anomalous Fast Ion Diffusion

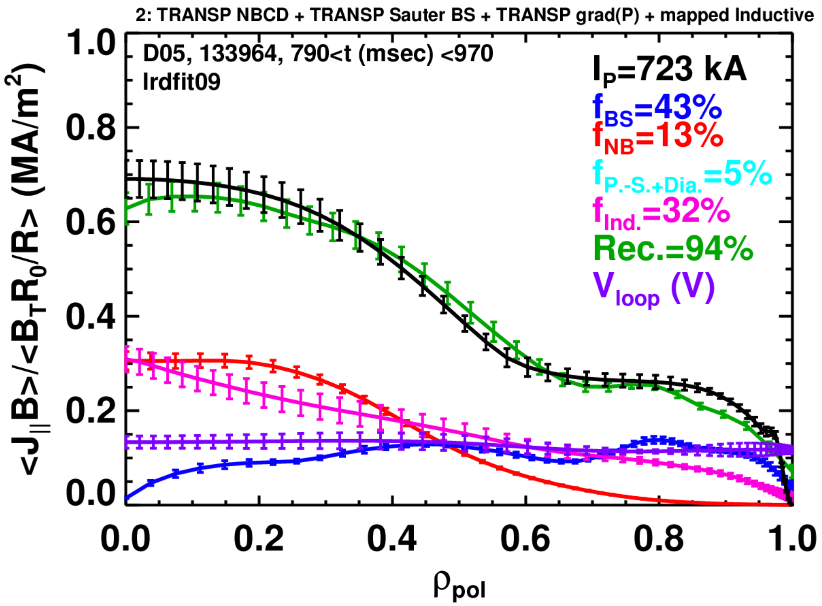
κ=2.6, I_P=700 kA, B_T=0.48 T



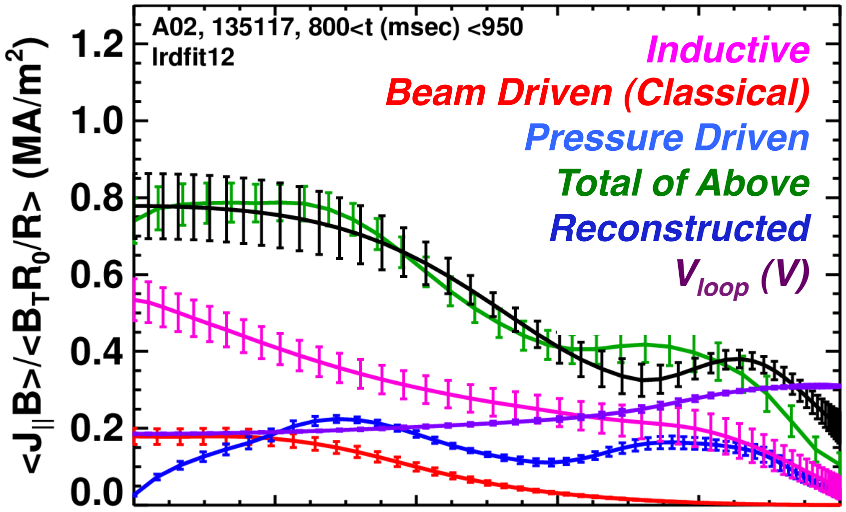
Near Fully Evolved Pitch Angles



Good Agreement Between Reconstructed Current Profile and the Constituent Sum



Current Profile Reconstructions Have Been Done For a Wide Range of Plasmas

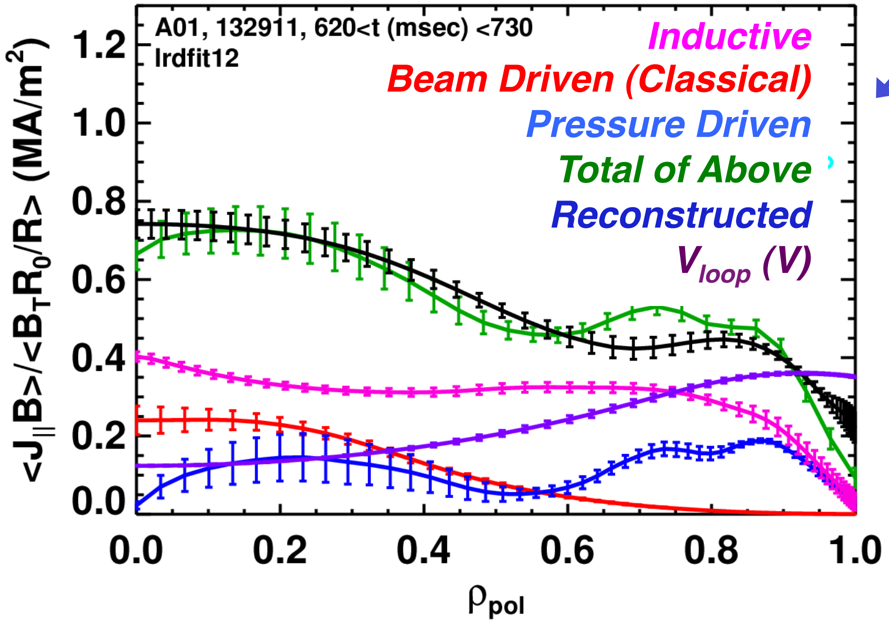


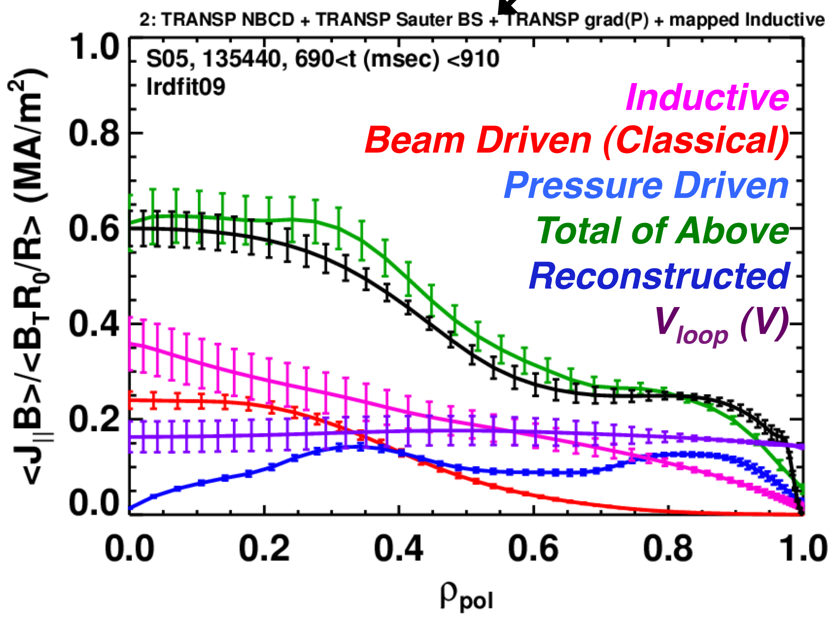
1100 kA, Optimized For Sustained High β_T

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

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

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

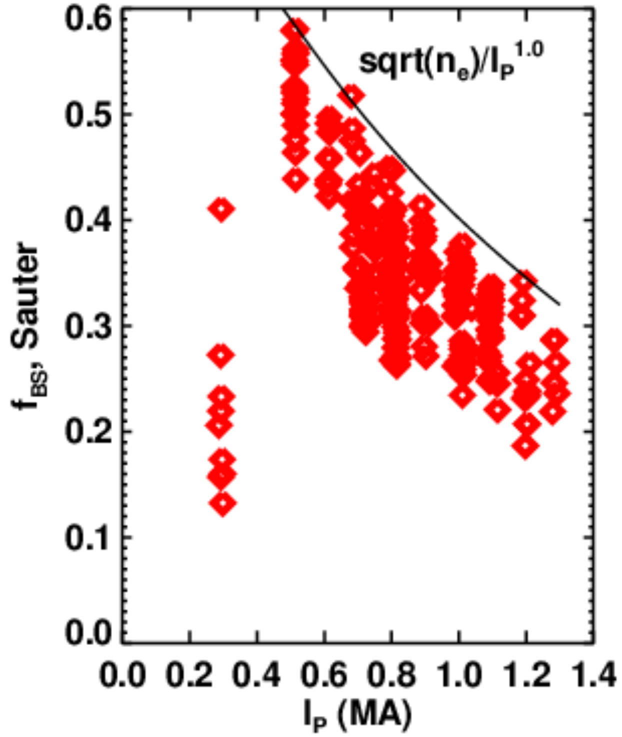
$$f_{BS} \propto \frac{\sqrt{n_e}}{I_P^{1.35}}$$

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

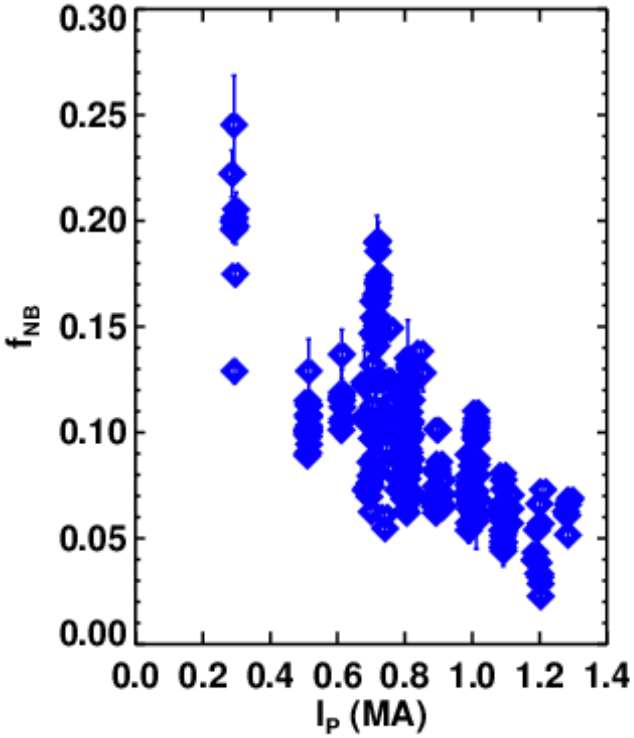
$$f_{NB} \propto \frac{S_{FI}\,\mathrm{v}_{FI}\,\tau_{SD}}{I_p}$$

Total non-inductive fraction reaches 65-70%
Reduced I_P experiments are planned.

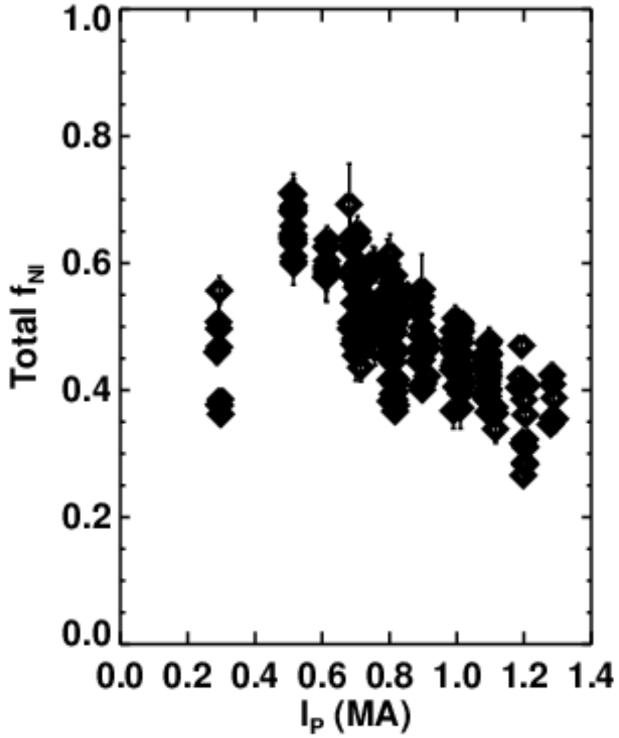
Bootstrap Fraction



Beam Current Drive Fraction

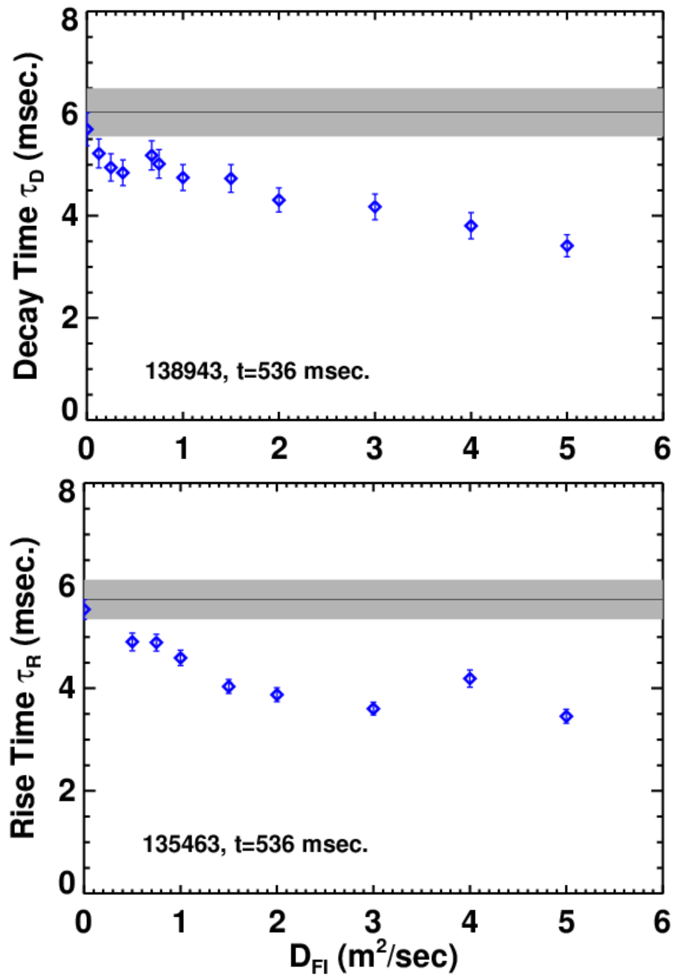


Non-Inductive Fraction

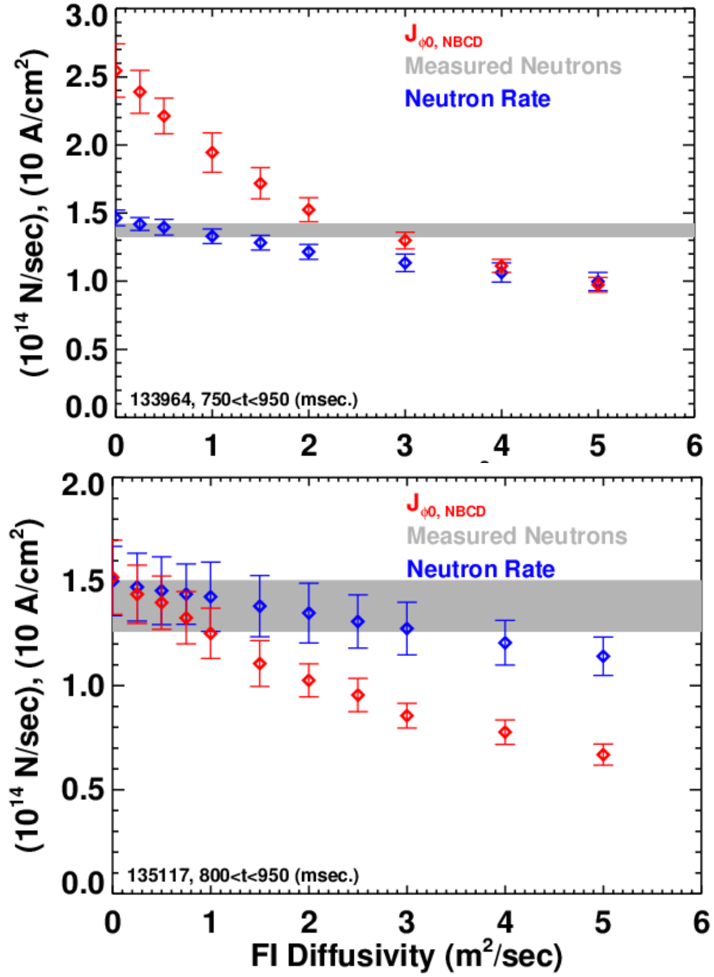


We Can Place an Upper Bound on the Fast Ion Diffusivity In MHD-Quiescent Discharges

Use the Decay/Rise Times after Beam Steps



Using the Neutron Emission Rate and Central Current Density.



Both methods indicate that the D_{FI}<~1-2 m^2/sec in MHD free periods.

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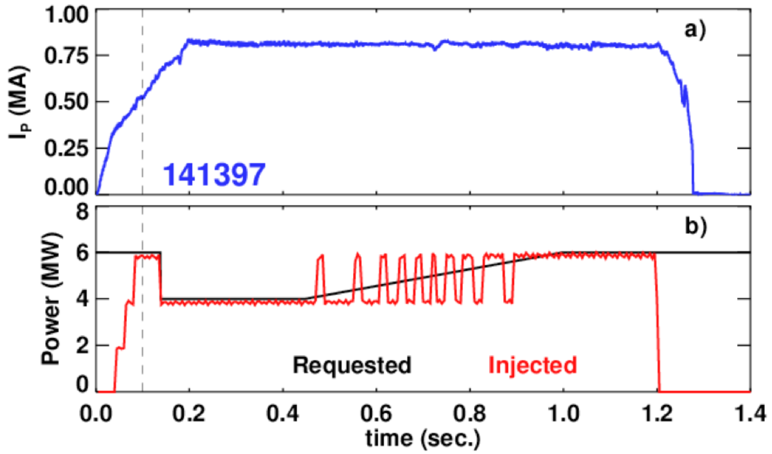
Er…backup

β_N Controller Has Proven Useful For Many XPs.

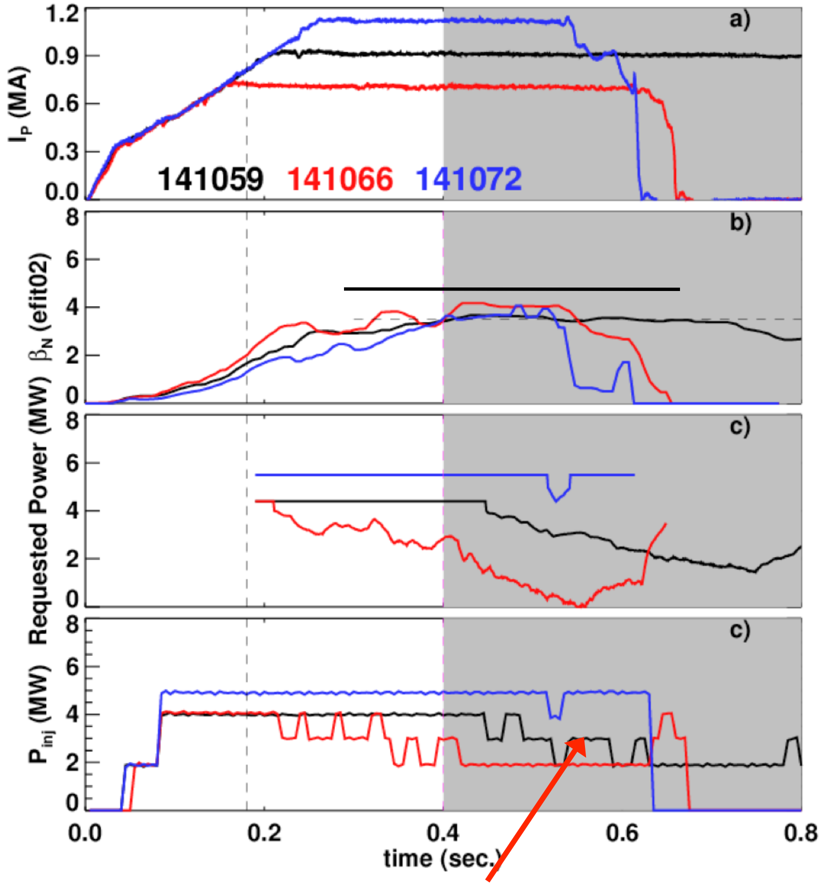
Controller Used to Provide a Slow Ramp in the Injected Power



Controller Allows Experiments to be Executed With Many Fewer Shots, Less Detailed Pre-Programming

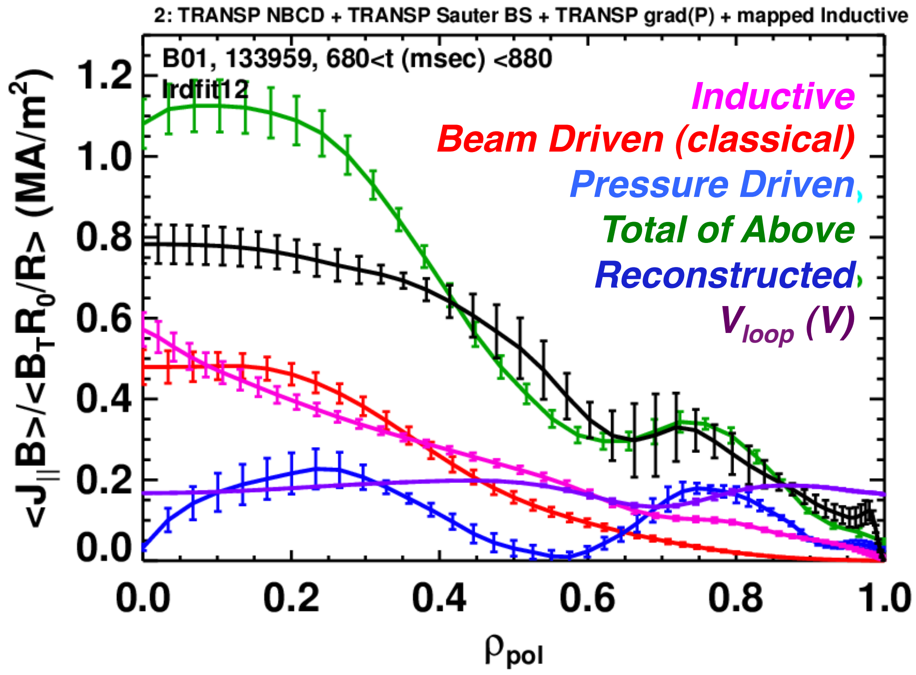
Controller Used to Keep β_N Fixed During I_P Scans

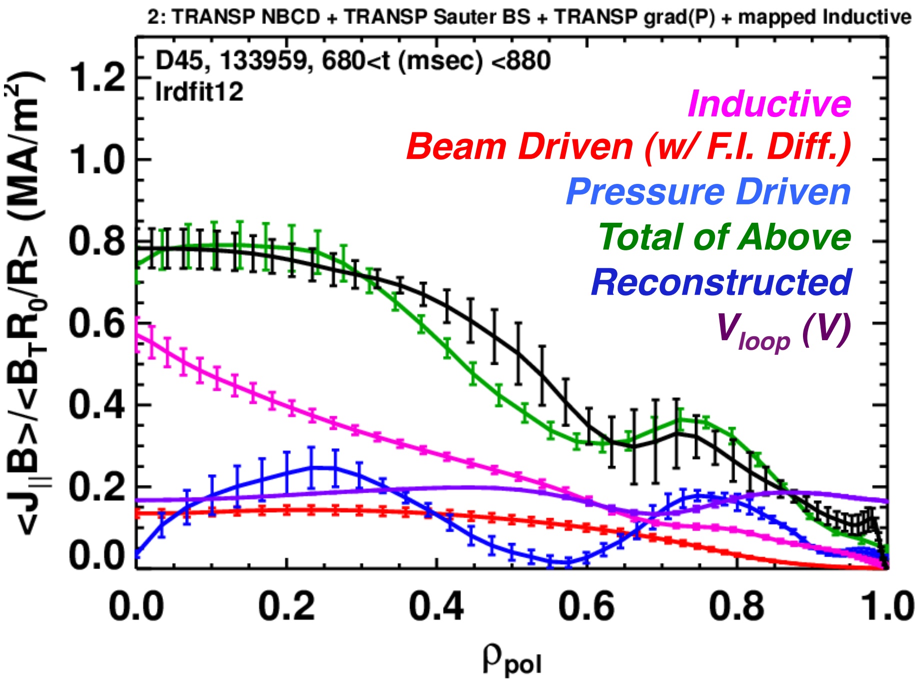
n=1 fields applied



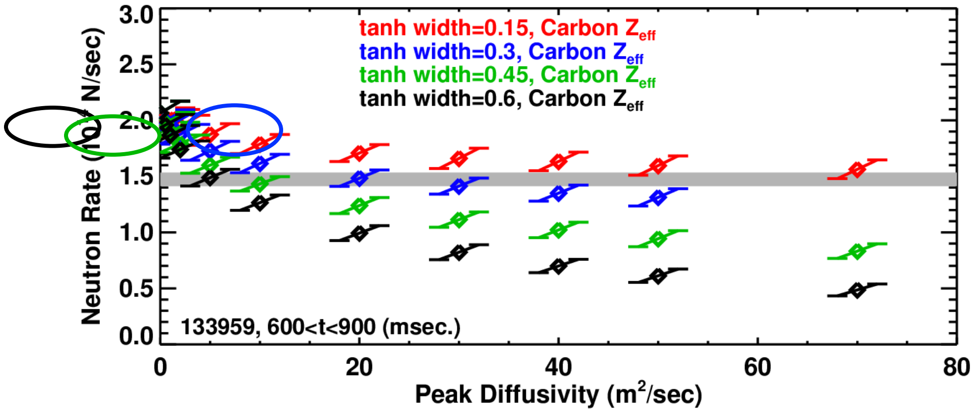
Diagnostic source A not allowed to modulate

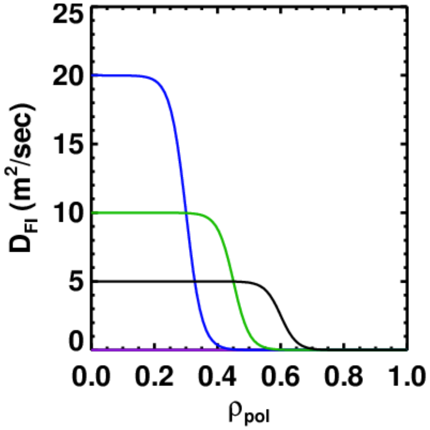
Current Profile Matches Better When Fast Ion Diffusion is Included

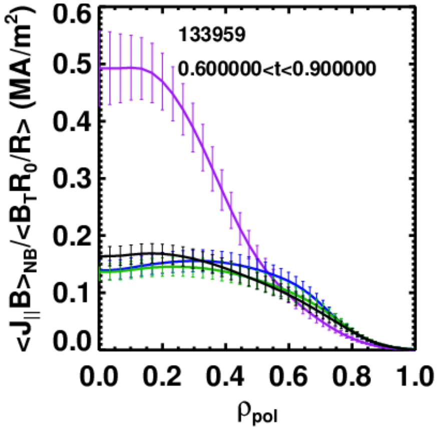




Simulate Effect of Tearing Mode with Temporally Constant Fast Ion Diffusion.







Progress In Scenario Development Since 2008 IAEA FEC

- Developed κ~2.6-2.7 scenarios over a wide range of normalized currents.
- Implemented a β_N controller.
- Developed new confinement scalings for high-κ lithiumized discharges.
- Developed improved strike-point regulation and shape control….poster by E. Kolemen.
- Developed improved RWM control…poster by S. Sabbagh.