Development of Advanced Spherical Torus Operating Scenarios in NSTX

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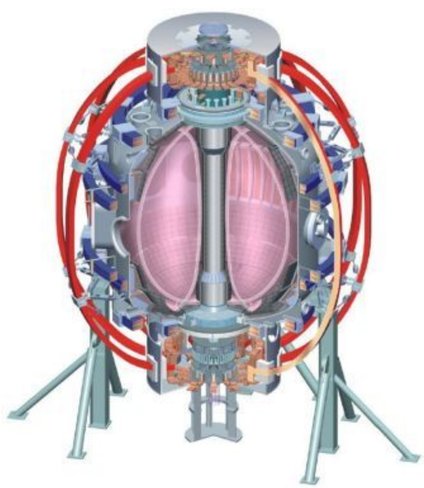

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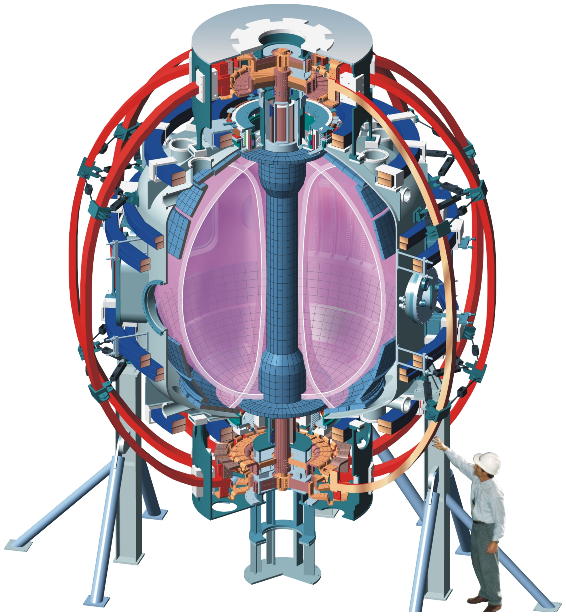
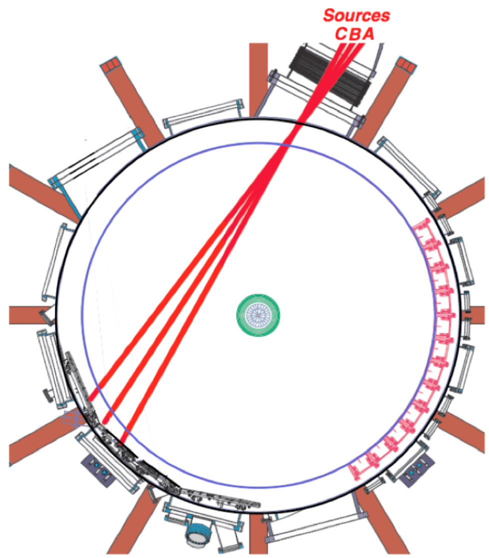
The mission of NSTX is to demonstrate high β scenarios consistent with steady state operation

- Overview of steady state operation requirements
- Global performance studies
- Confinement scaling studies
- Current profile analysis
- Global Stability and non-axisymmetric control
- New plasma control capabilities
- Summary

NSTX and Steady State Operation Research

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



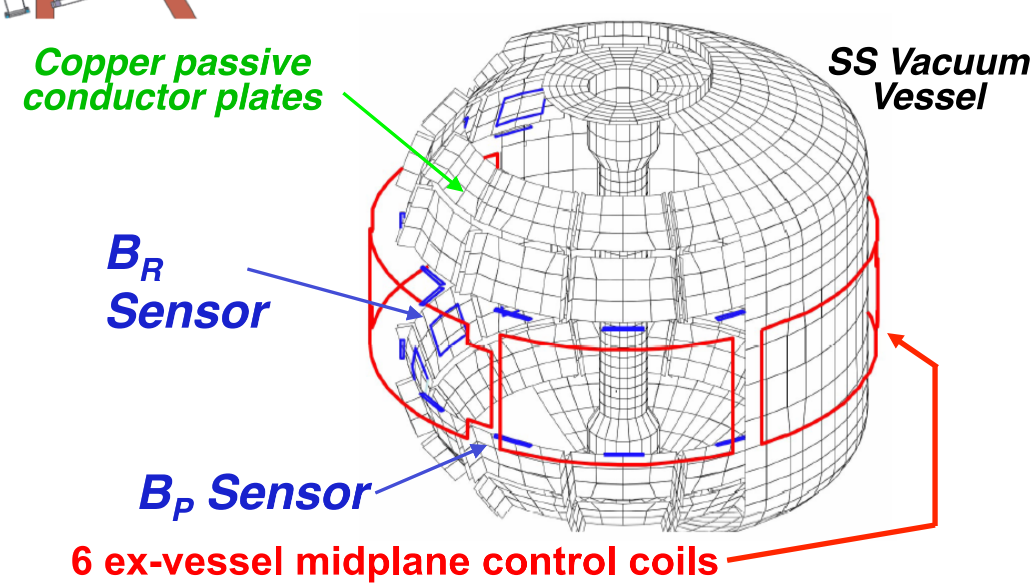


3-D Field Coils Important For Scenario Development

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.



Plasma shaping and β_N are determining factors for performance of steady-state burning plasmas

- Reactor designs aim at the highest shaping that technology can support
- High shaping (S) requirement for AT-like scenarios comes from self-sustainment at high β_t
  - Define sustained β figure of merit:

$$\beta_{sus} \equiv f_{bs}\beta_t \sim S\beta_N^2$$

  - (high β_t is required to compete with TF losses)

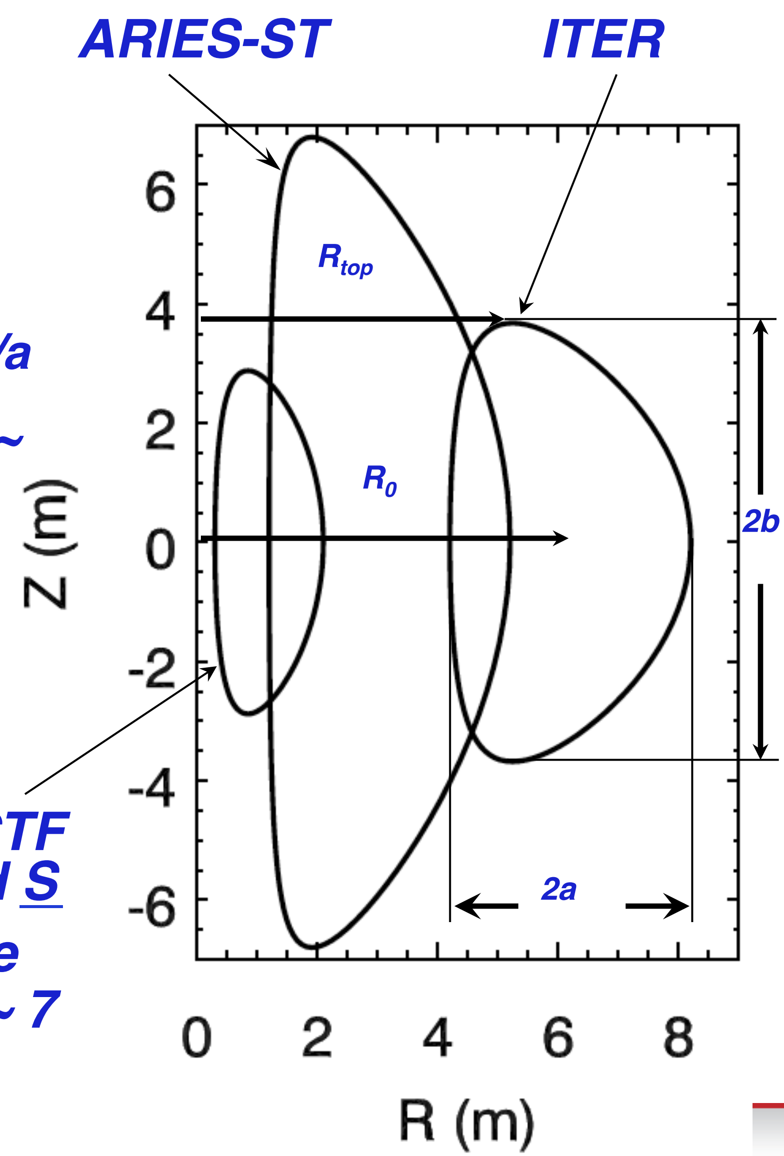
Shape factor definitions:

$\varepsilon = a/R_0$

$\kappa = b/a$

$\delta_{top} = (R_{top}-R_0)/a$

$S = q_{95}(I_p/aB_t) \sim (1+\kappa^2)f(\varepsilon,\delta)$

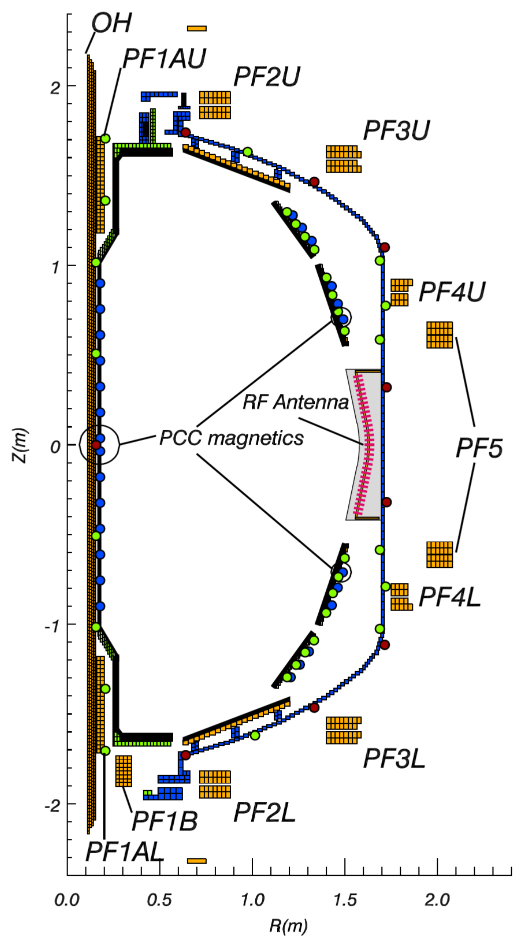


- ***Indicates need to optimize both β_N, and S***
- ***For NSTX simulations indicate possible 100% non-inductive operation with $\beta_N \sim 7$ only with strong shaping***

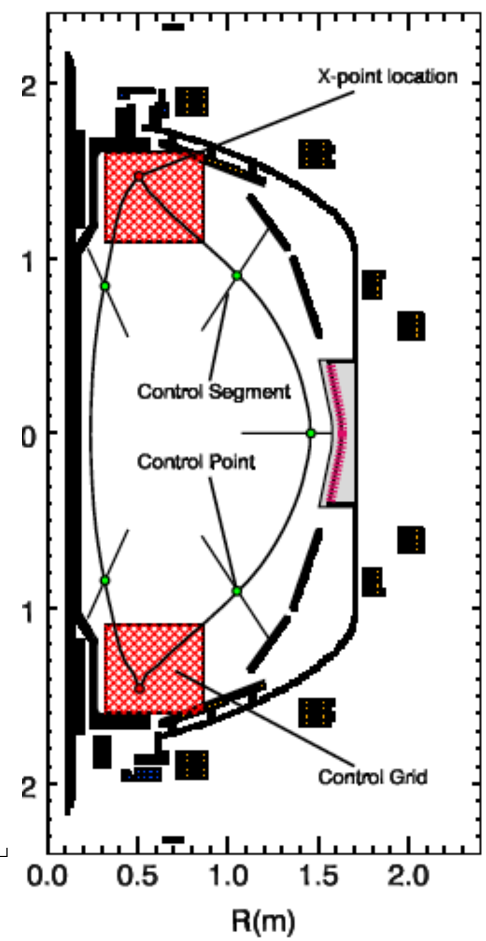
rtEFIT+isoflux controls shape

- Measure magnetic fluxes, fields, coil and vessel currents
- Solve GS equation
  - Assume a polynomial for the current and pressure profiles
- User defines plasma boundary
- Control segments chosen to intersect boundary
- Control point is intersection of segment and boundary
- Control difference between x-point and control point flux

Location of measurements used in real time reconstruction

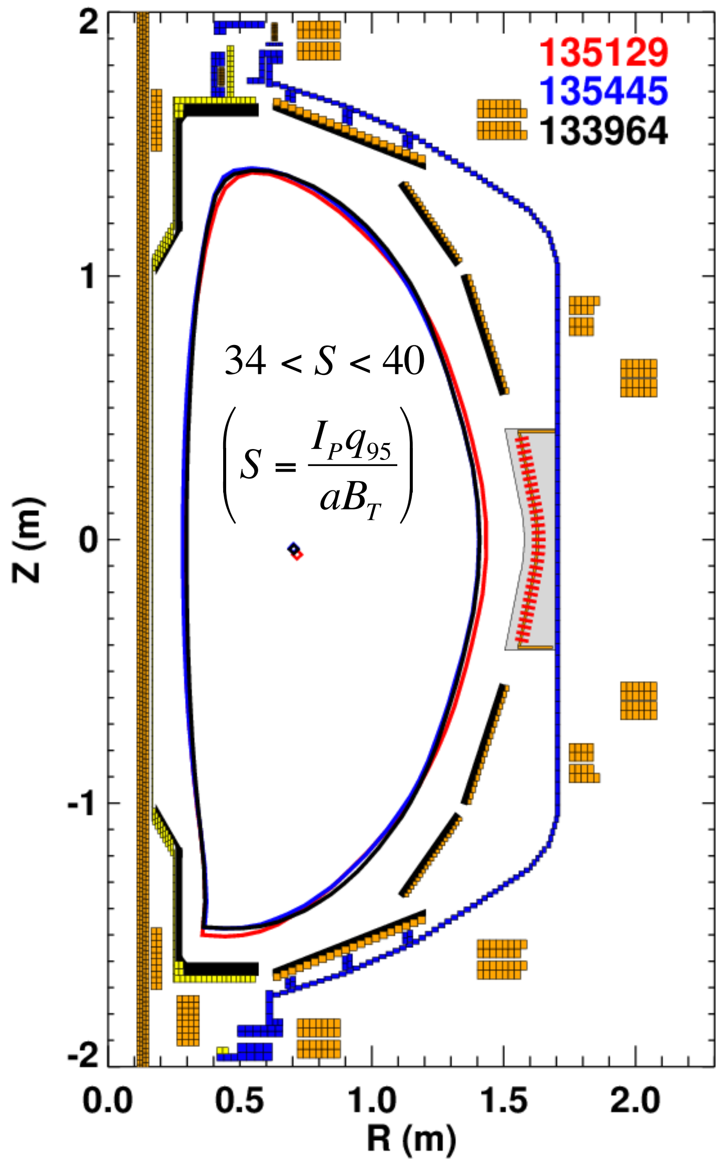


Geometry of control grids and segments



Global Performance Studies

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



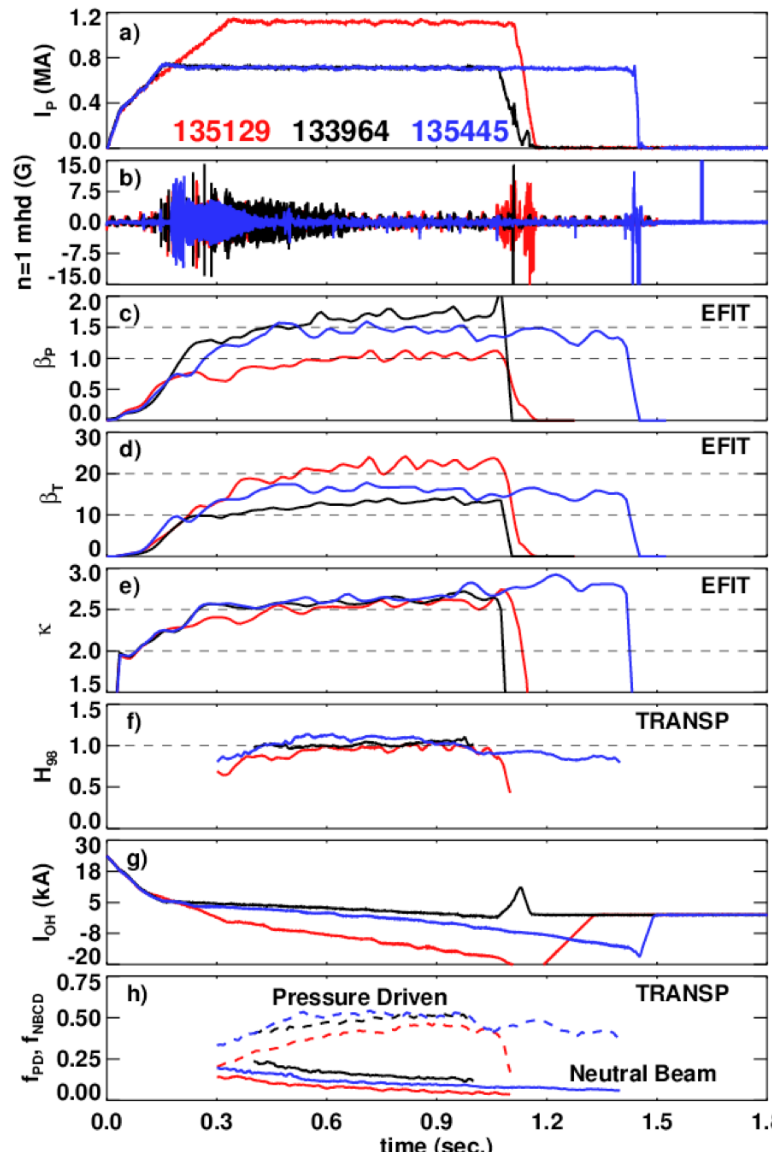
$$q^* = \frac{\varepsilon\left(1+\kappa^2\right)\pi a B_{T0}}{\mu_0 I_P}$$

High-β_T
$q^*=2.8$
$B_T=0.44$ T
$I_P=1100$ kA

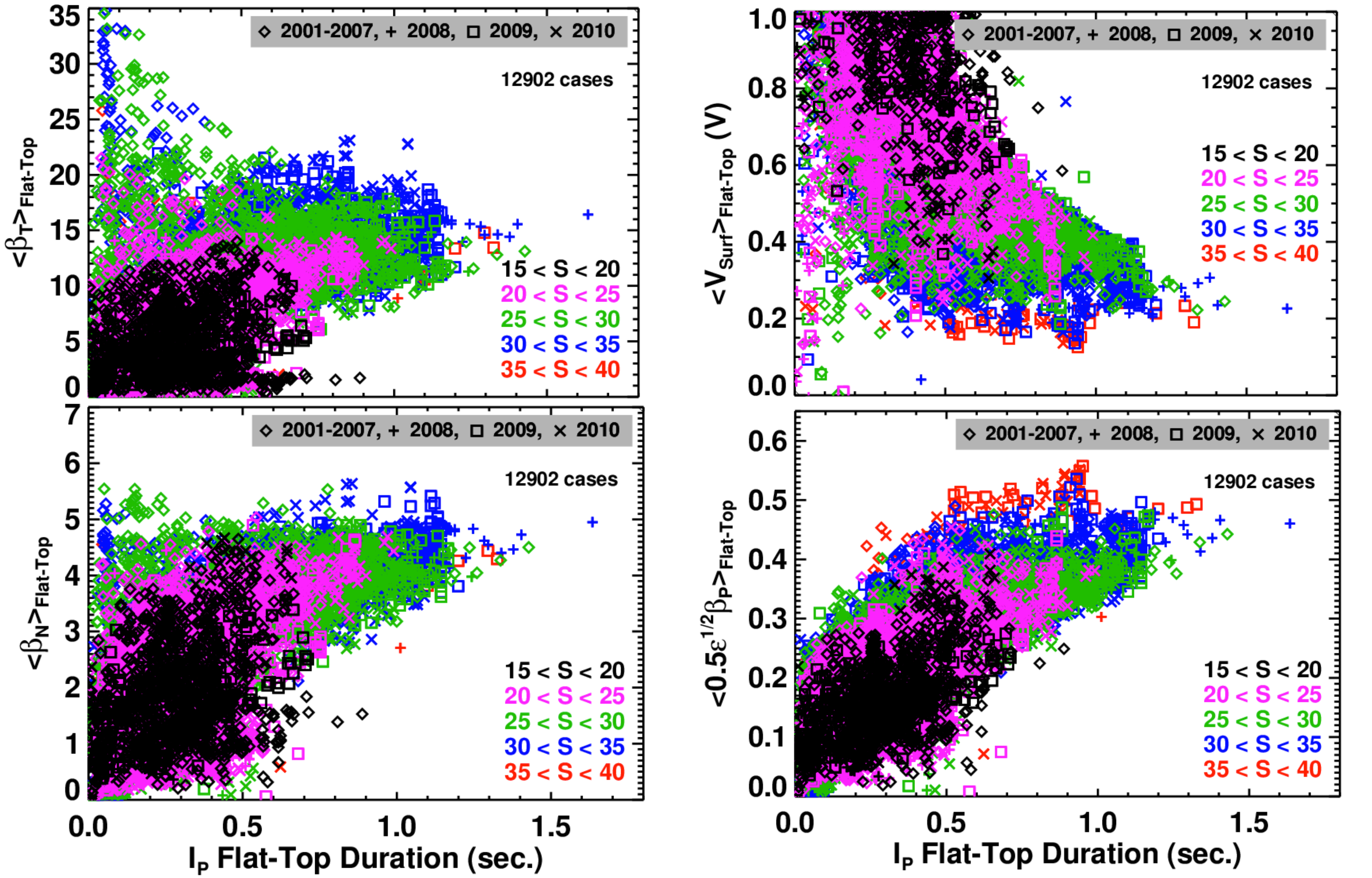
Long Pulse
$q^*=3.9$
$B_T=0.38$ T
$I_P=700$ kA

High-β_P
$q^*=4.7$
$B_T=0.48$ T
$I_P=700$ kA

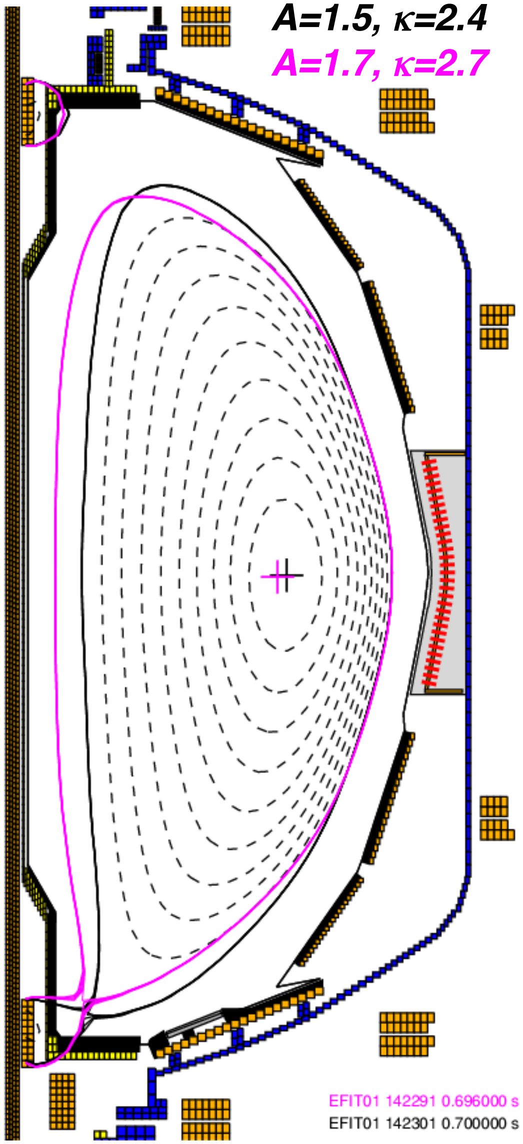
All
$H_{98}>=1$
$\kappa=2.6\text{-}2.7$



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

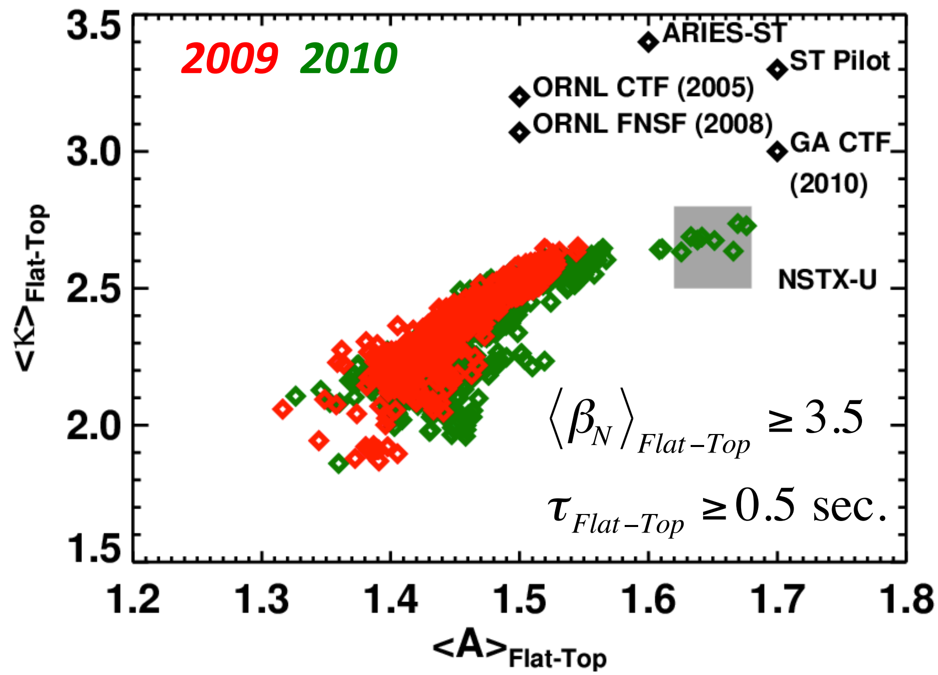


Next-Step STs Motivate Study of Larger Aspect Ratio Plasmas



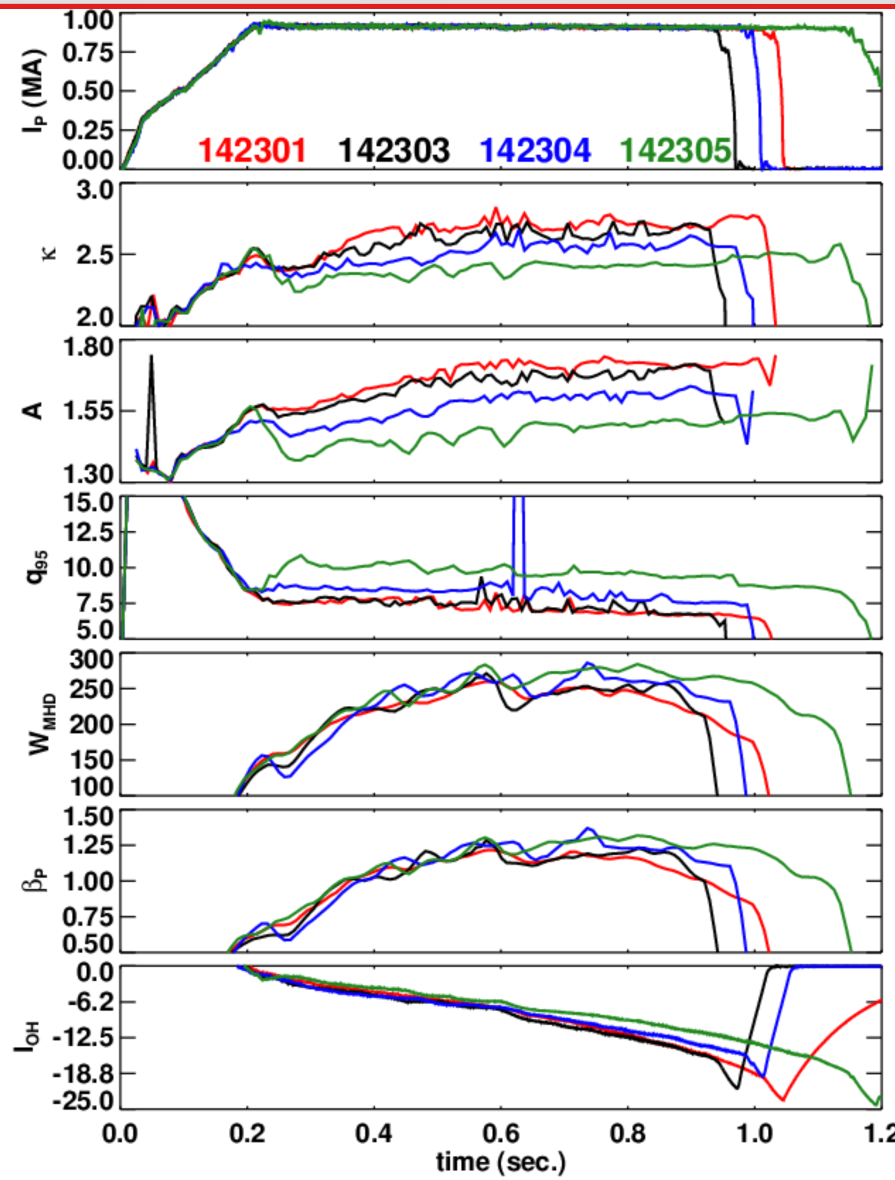
- *Recent ST studies looking at higher aspect ratio.*
  - *NSTX-Upgrade*
  - *NHTX*
  - *GA versions of ST-FNST*
  - *PPPL ST Pilot Plant*
- *Likely deleterious to both n=0 and n=1 stability.*
- *Achieved in NSTX by two steps:*
  - *Increase the inner divertor coils current to max. level*
  - *Increase the elongation.*

Typical high-performance plasma boundary.
Higher aspect-ratio boundary.



Initial Studies of Increasing the Aspect Ratio Show No Strong Degradation

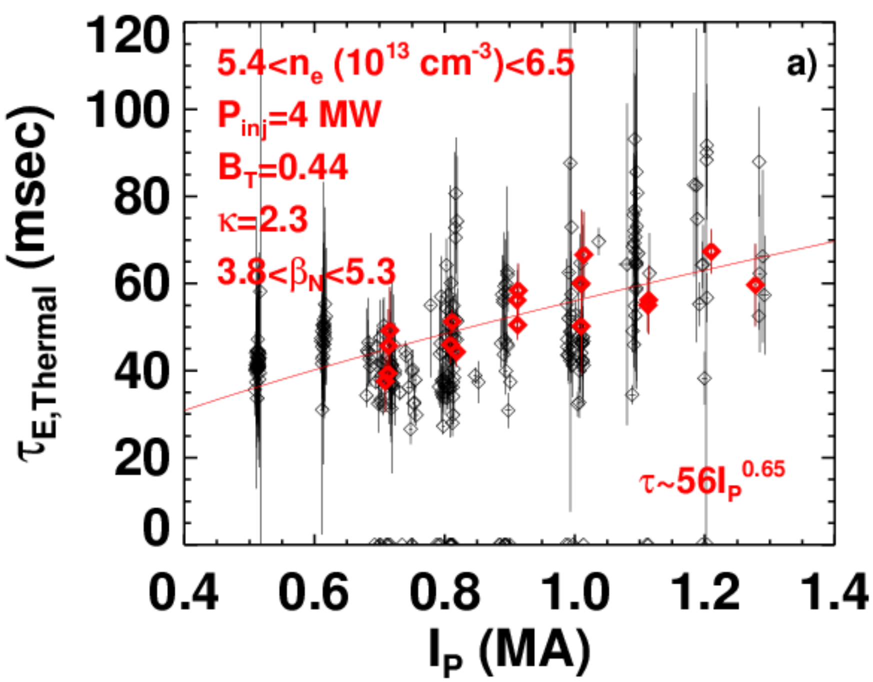
- Increased elongation does not compensate increased aspect ratio in edge q.
- May be some degradation of confinement
- Demonstrates the existence of a viable NSTX-U operational scenario

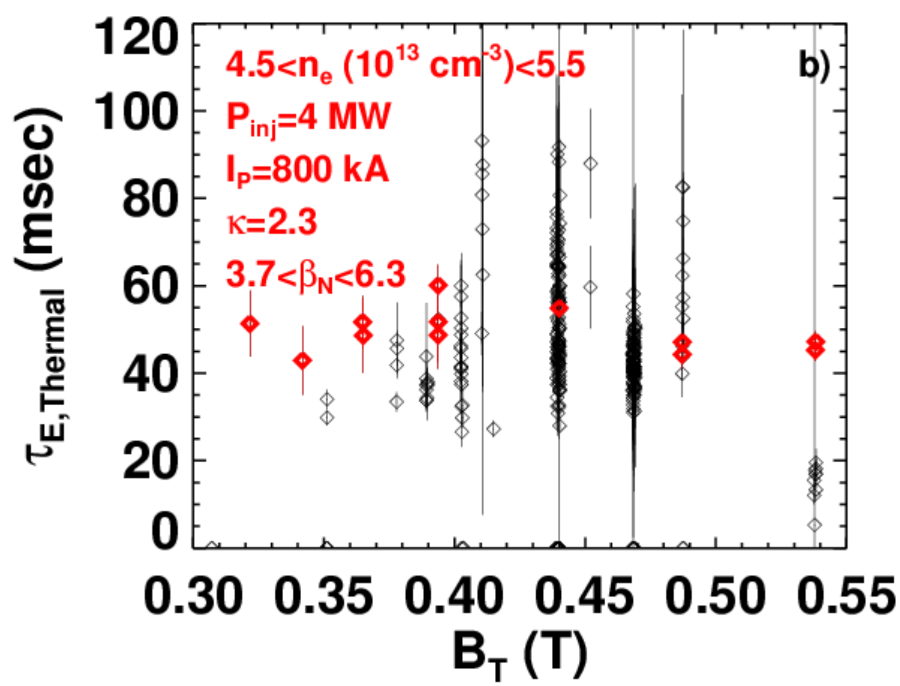


Confinement scaling

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?



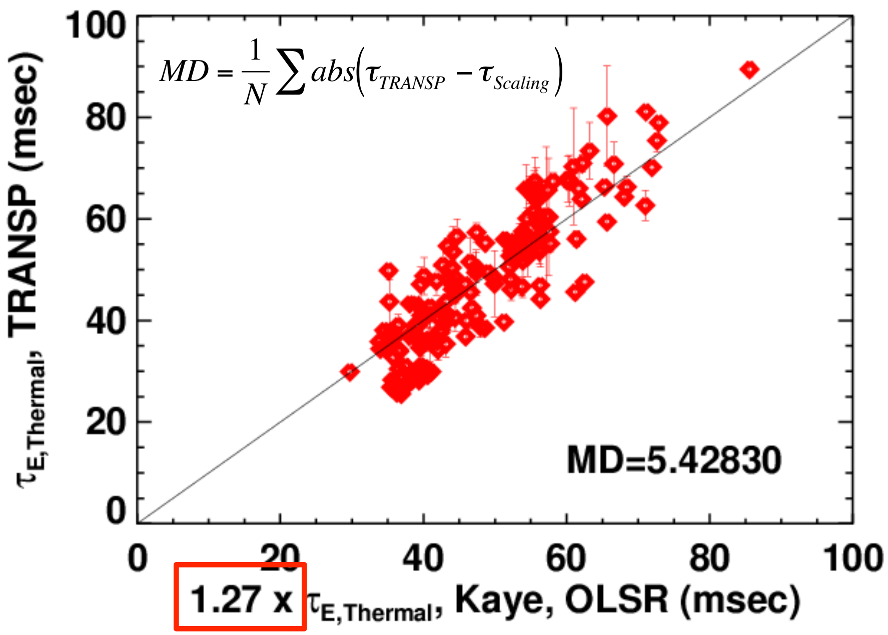


Lithiumized Discharges Shows Confinement Scaling Similar to Higher Aspect Ratio

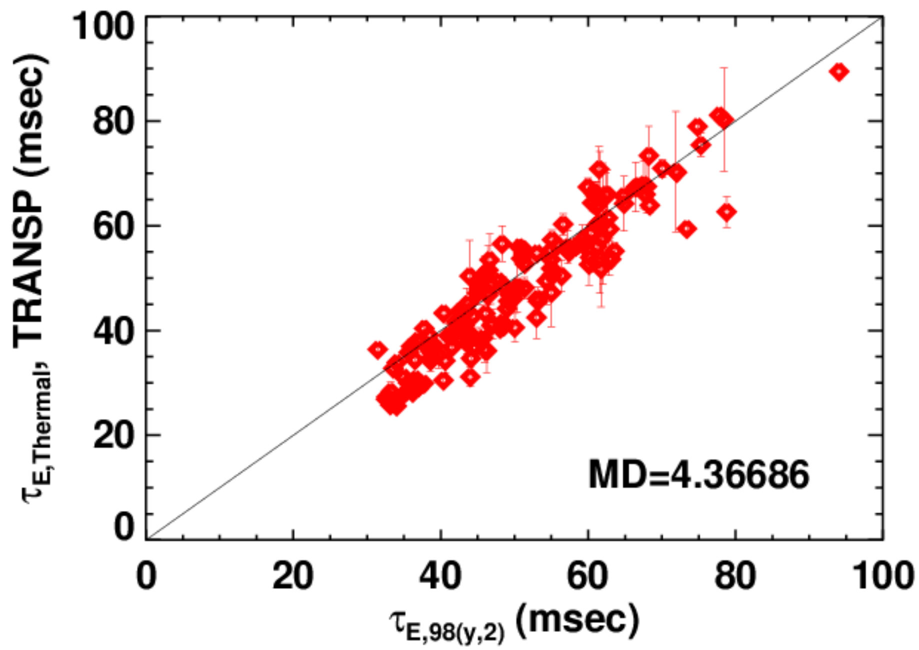
Consider > 75 msec averaging windows, at least one current diffusion time into the I_P flat-top, at high-κ and δ, in lithium conditioned discharges

Criterion excludes many high-confinement discharges

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



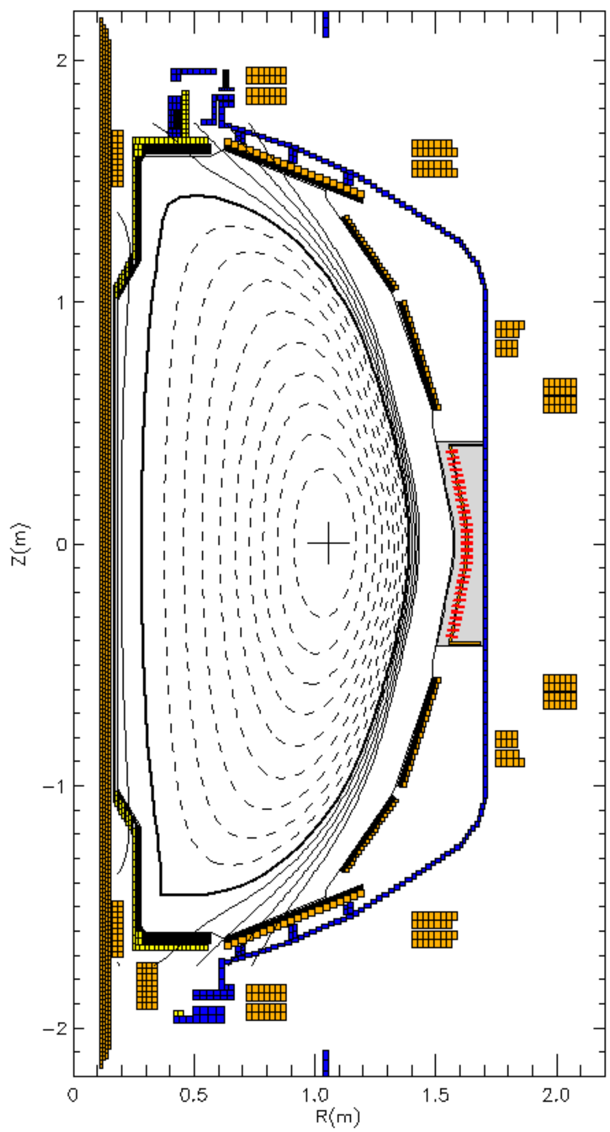
$$\tau_{E,th,ITER-98} \propto I_P^{0.93} B_T^{0.15} n_e^{0.41} P_{abs}^{-0.69} \kappa^{0.8}$$



- 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.

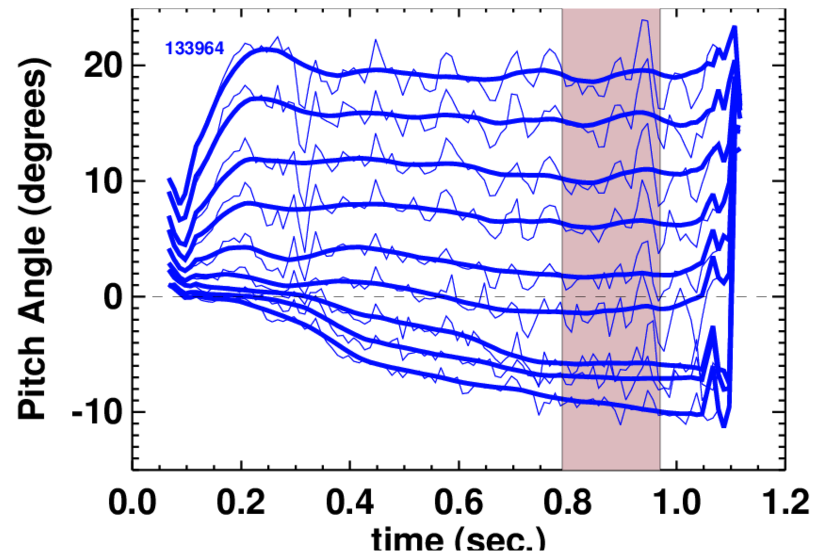
Current Profiles and the Non-Inductive Fraction

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

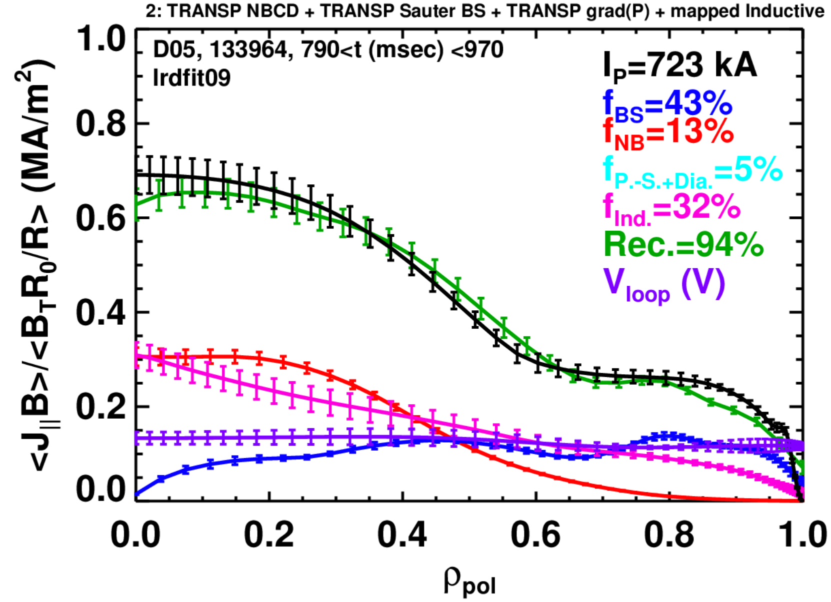


κ=2.6
I_P=700 kA
B_T=0.48 T

Near Fully Evolved Pitch Angles



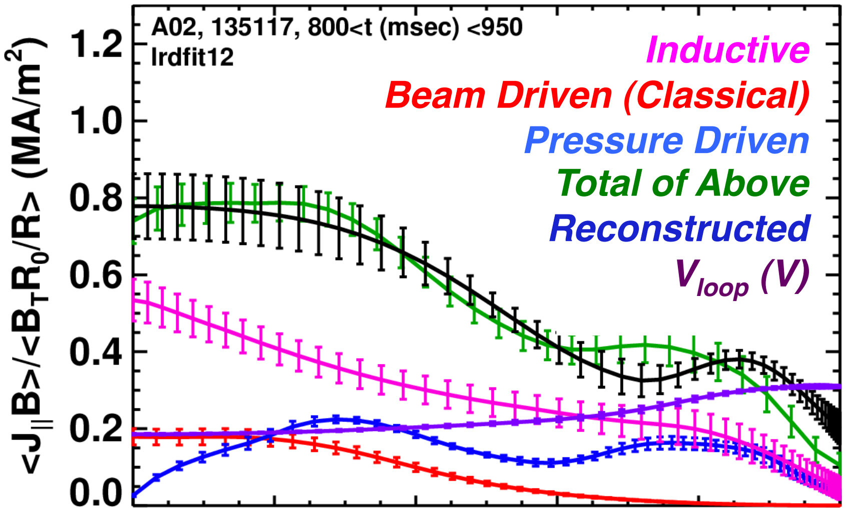
Good Agreement Between Reconstructed Current Profile and the Constituent Sum



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

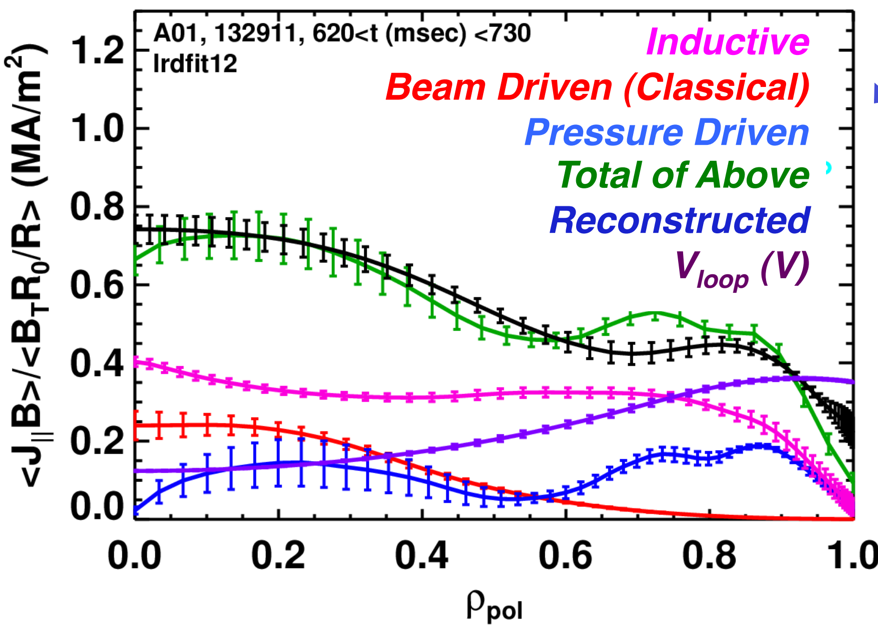
1100 kA, Optimized For Sustained High β_T

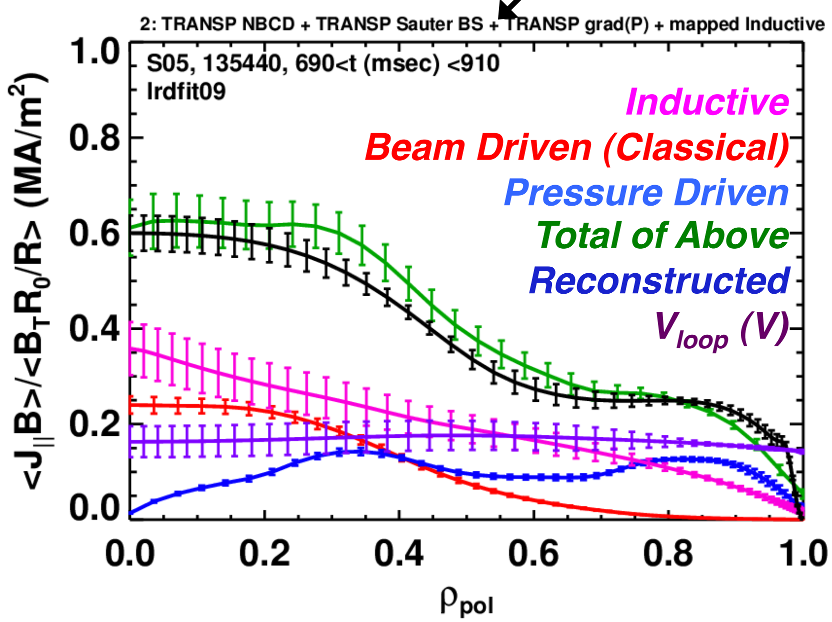
All analysis during MHD free periods, with no anomalous fast ion diffusion.



1300 kA, Optimized For Sustained For Large Stored Energy

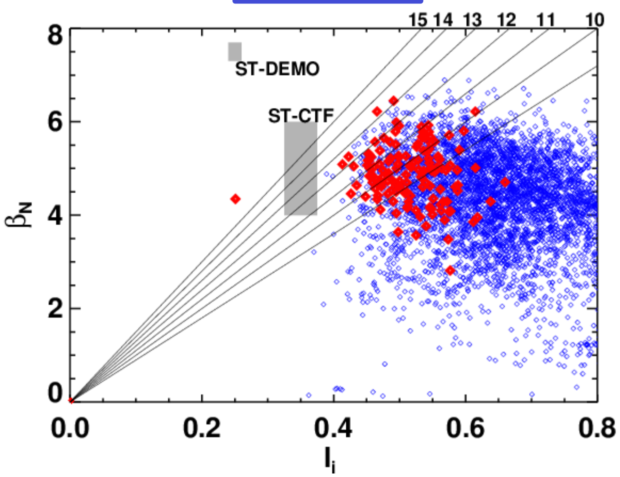
700 kA, Optimized For Long Pulse



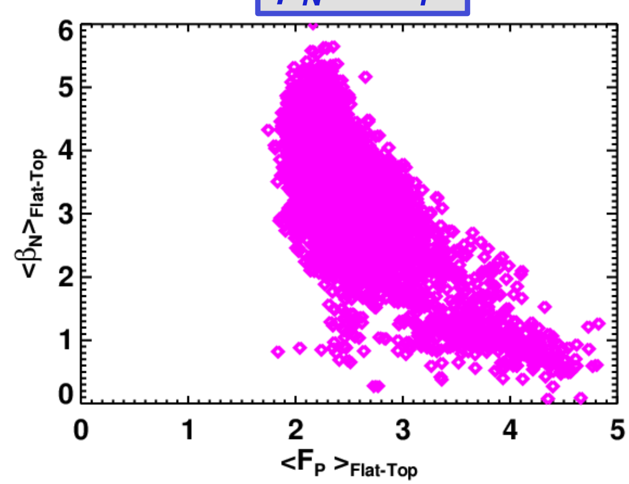


No-Wall β_N Limit Can Vary Widely Depending on Profiles; Best Shots Near With-Wall Limit

β_N vs l_i



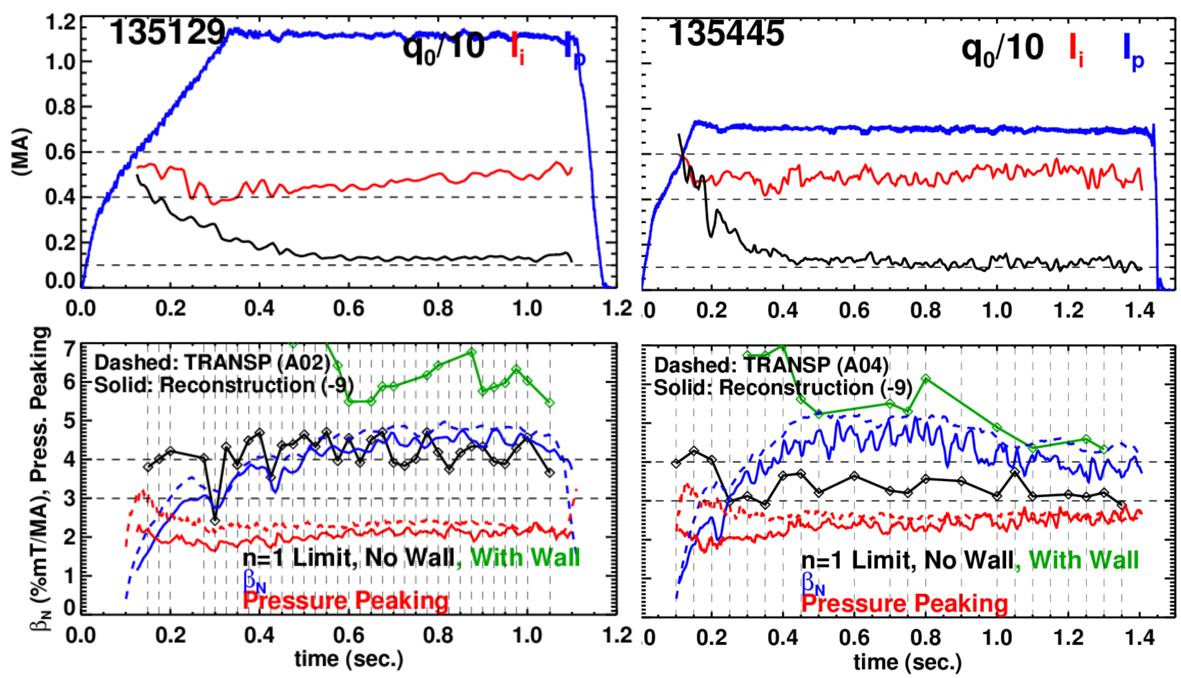
β_N vs F_P



- 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

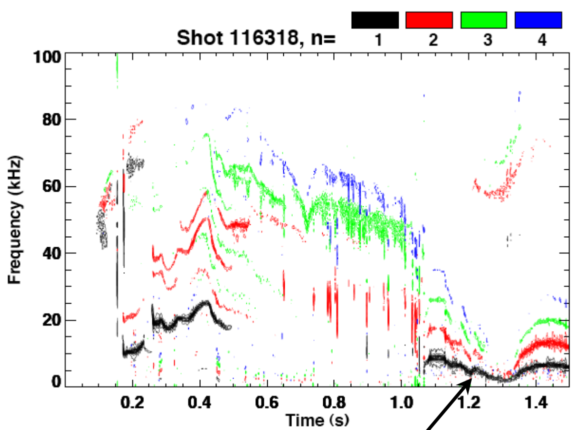
135129
Long Pulse Target
I_P=700 kA, B_T=0.38 T



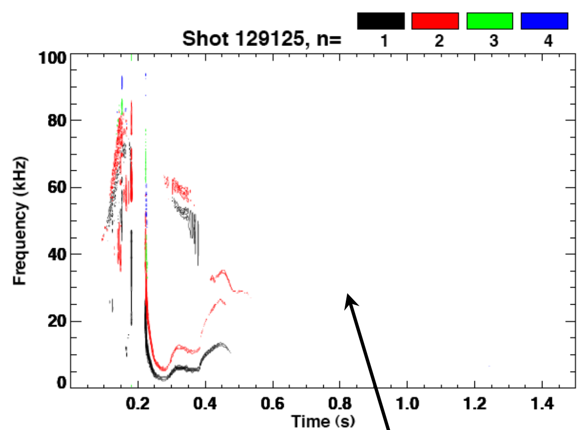
Global Stability and non-axisymmetric control

n=1 RFA/RWM control combined with n=3 error correction increases β and extends pulse

MHD spectrogram w/o n=1 feedback and n=3 correction

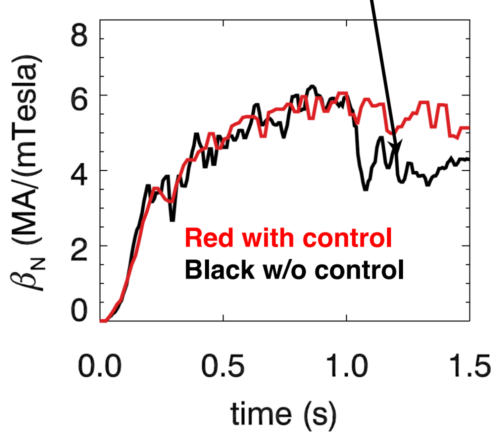


MHD spectrogram with n=1 feedback and n=3 correction

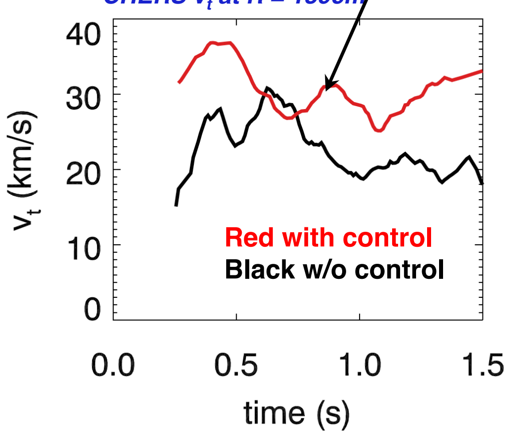


n=1 mode drops β

No MHD, β and rotation maintained

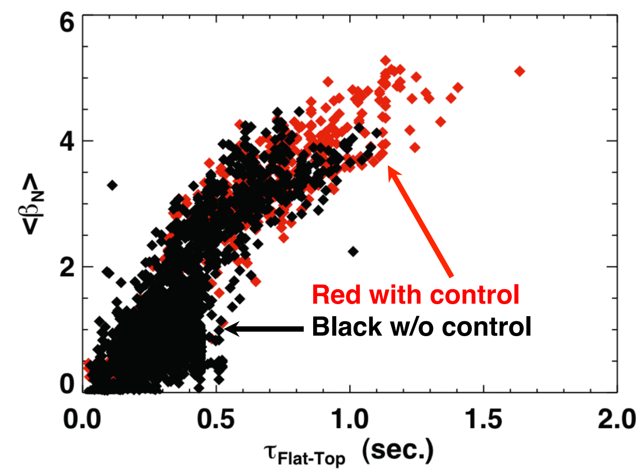


CHERS v_t at R = 139cm

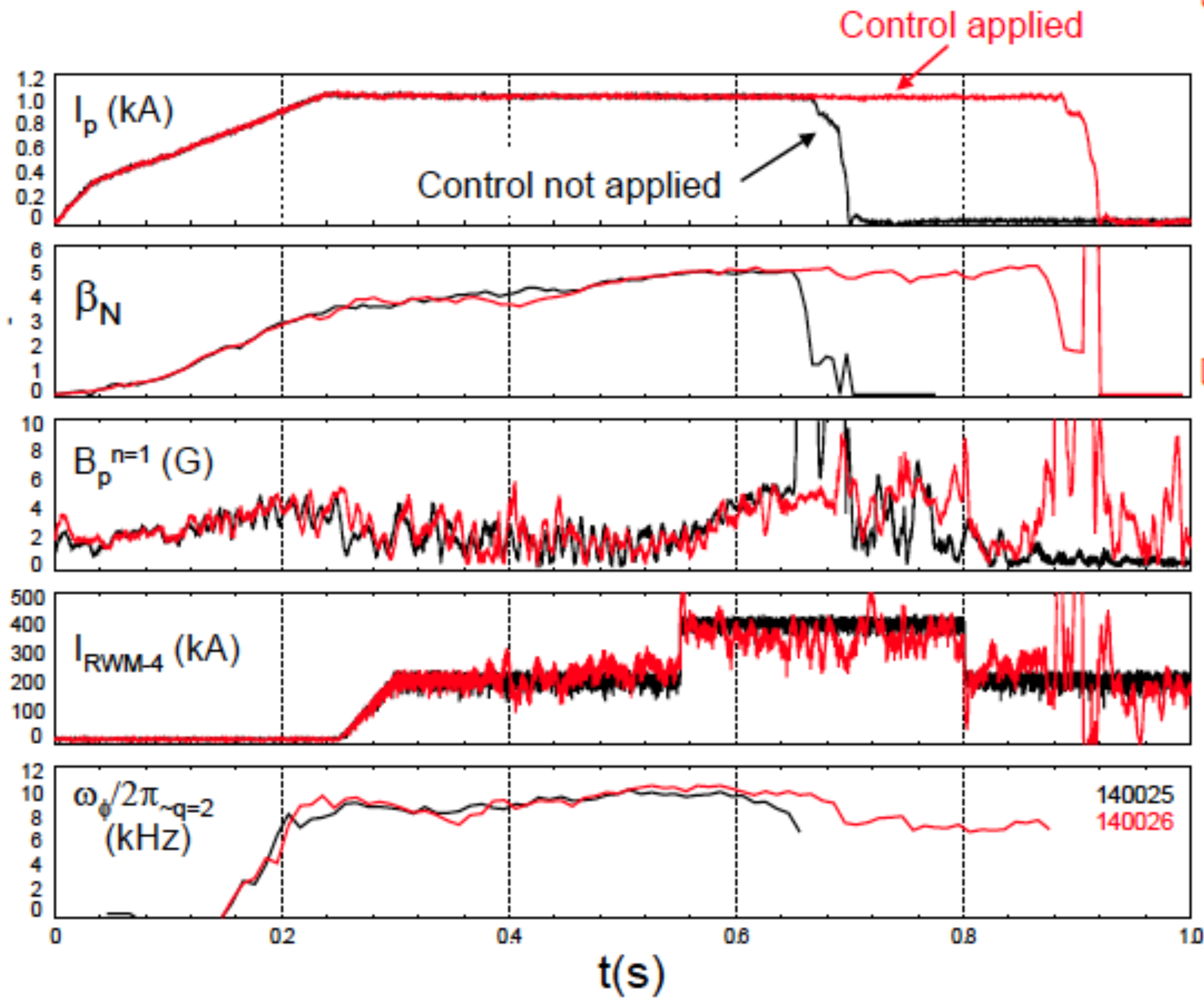


- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Control statistically raises β and increase pulse length

Pulse averaged β_N vs. current flat-top



RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field



- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

New control system capabilities

Substantial investment in NSTX control capability is continuing

- Improved control capability is the engine that drives advanced scenario development
- β_N control developed and used successfully to improve reproducibility of experimental performance
- Simultaneous strike point control and X-point control developed in support of LLD and NSTX-U
- Real-time rotation diagnostic has been developed – will now be tested first on NSTX-U
- Snowflake divertor control being developed for upgrade
- Working towards current profile control using radial array of beam sources early in the NSTX-U project
- Evaluating control system upgrade for the outage period

NSTX has developed the physics basis for NSTX-U and has answered many questions about the viability of an ST-FNSF

- Highly shaped, high β_N, *high* f_{NI} plasmas with good confinement have been reproducibly controlled
  - Demonstrated NSTX-U shape
  - Measured confinement scaling
  - Understood current drive sources
  - Measured and controlled β-limiting modes
- Investments in advanced control capability have been key to this success
- NSTX-U will benefit directly from this effort and will continue the advancement of the ST physics basis