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Advanced Scenarios and Control (ASC): Recent Results and Plans

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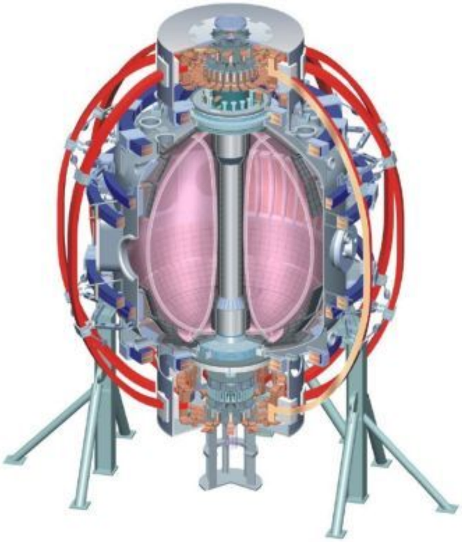
S.P. Gerhardt, TSG Leader
M. Bell, TSG Deputy
E. Kolemen, Theory & Modeling Support

NSTX PAC #29
Jan. 27th, 2011



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Motivation and Outline

- Goals of the ASC TSG:
  - 1: Develop control strategies for long-pulse high-β ST/AT scenarios.
    - Both control modeling and PCS development.
    - ASC personnel involved in developing control requirements for ITER.
    - Involved in ITPA IOS
  - 2: Combine control strategies with physics advances for improved scenarios….
    - …for NSTX & NSTX-Upgrade physics needs.
    - …for the long term ST development path.

In this talk

- Highlights of 2010 results:
  - $J_{||}(\psi)$ modeling, scenario development, shape control, NSTX-U prototyping.
    - **Indicate 2011-2012 plans in magenta.**
  - ASC impurity control efforts covered by R. Maingi's talk.
- Summary of implications for NSTX-Upgrade.
- Strategies and priorities for 2011 & 2012.

Example Scenario Goals For NSTX-Upgrade

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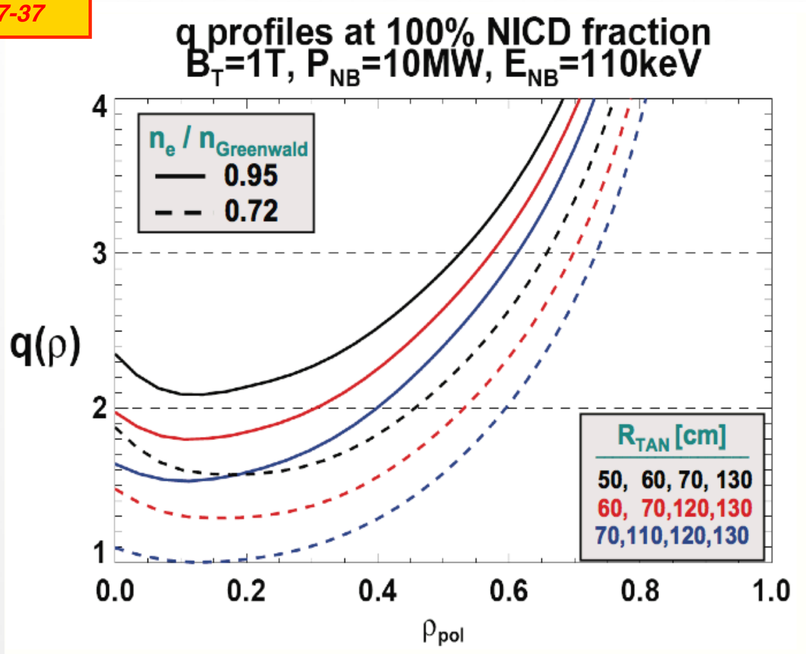
PAC 27-37

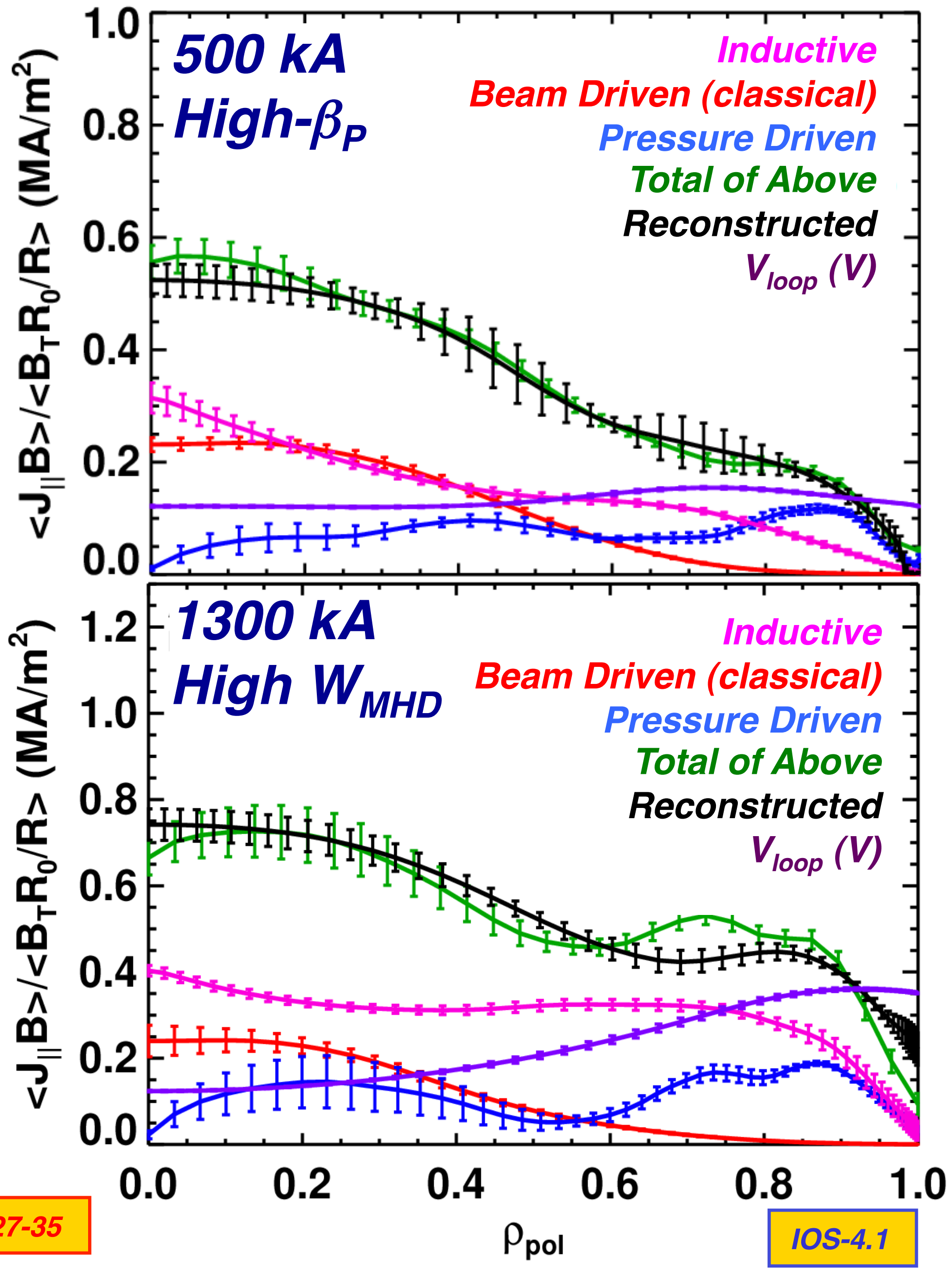


- 100% non-inductive scenarios with I_P=950 kA and elevated q_{min}
  - Avoid low-order NTMs and core kinks.
- N.I. fraction and shear reversal determined by:
  - Beam source and voltage
  - Plasma density.
  - Plasma shape.
- Must control these (and other) quantities for optimal performance in NSTX-U and future STs.

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.
V_{loop} (V)

- Good agreement in current profile accounting when low-f MHD is absent.
  - High-β_P, high-q_{95}
  - High-β_T, low-q_{95}
  - Maximum W_{MHD}, moderate q_{95}
  - longest-pulse, moderate q_{95}
- Data consistent with D_{FI}<~1m^2/s
- Validates the current profile modeling for NSTX-Upgrade.



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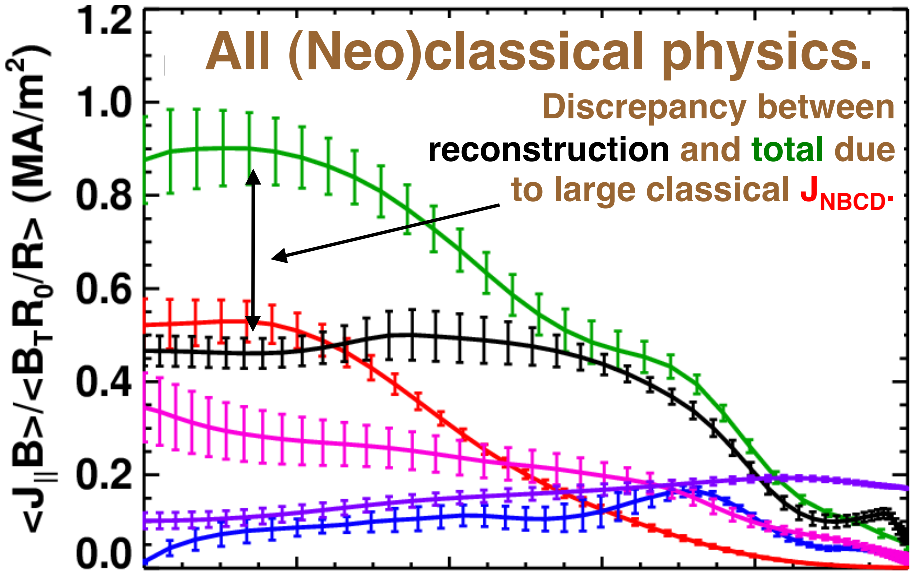
IOS-4.1

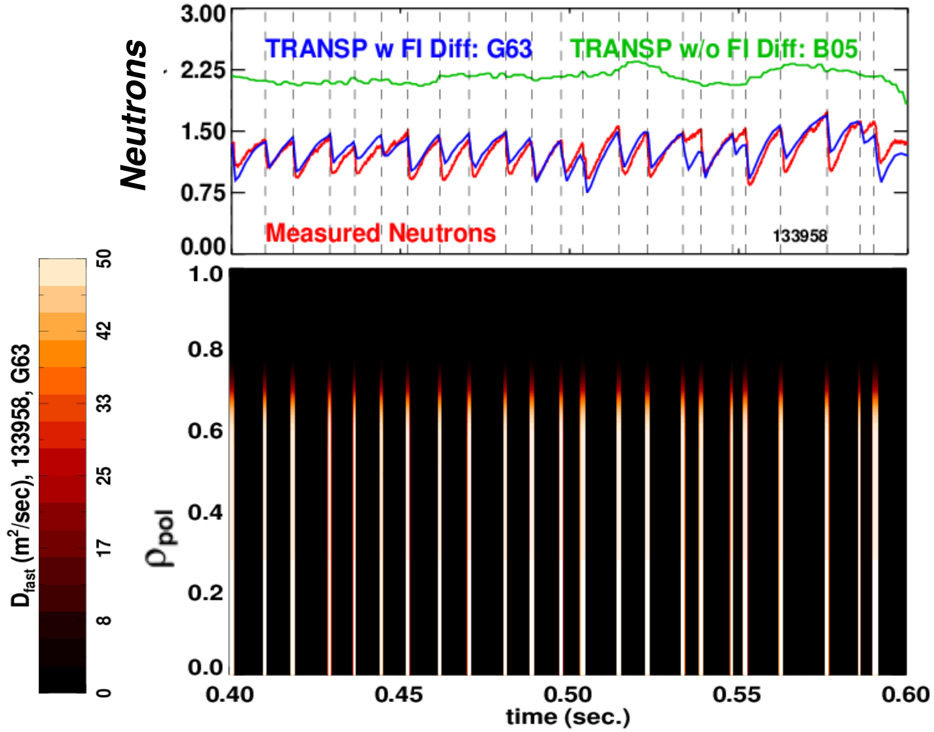
TAE Avalanches Lead to Major Modifications of the Beam Driven Current Profile

700 kA High-β_P with Rapid TAE Avalanches

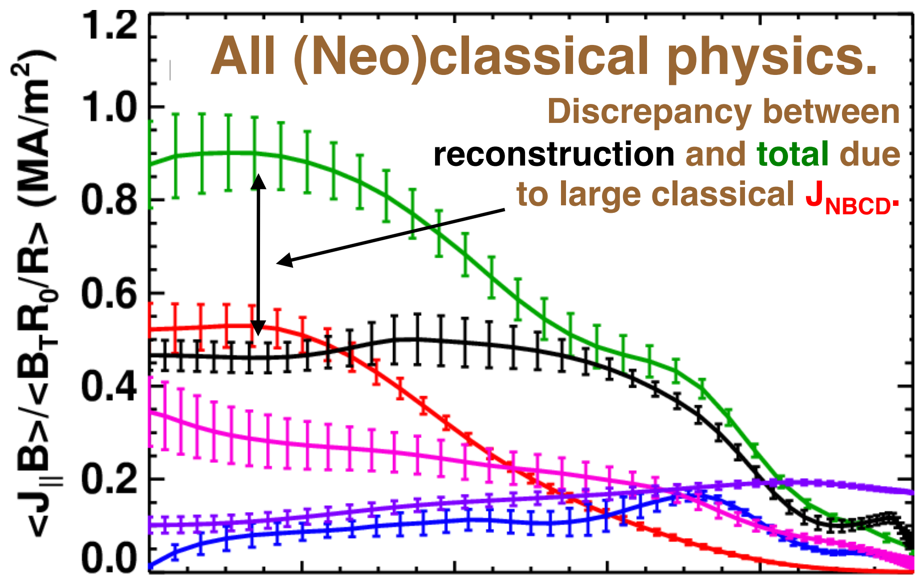


Discrepancy between reconstruction and total due to large classical J_{NBCD}.

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



700 kA High-β_P with Rapid TAE Avalanches

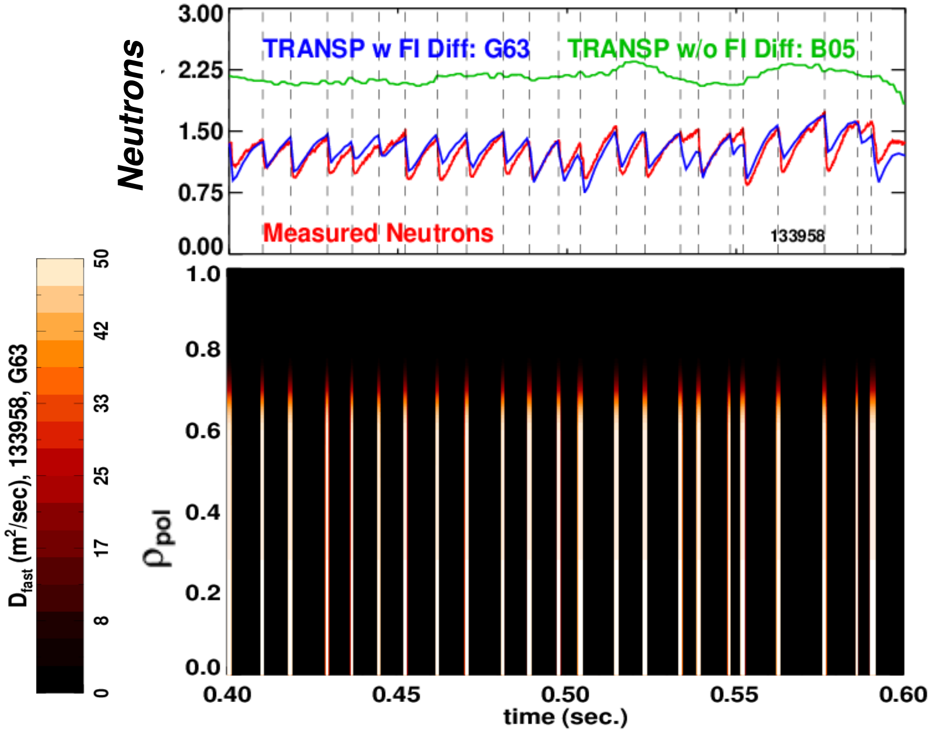


All (Neo)classical physics.

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

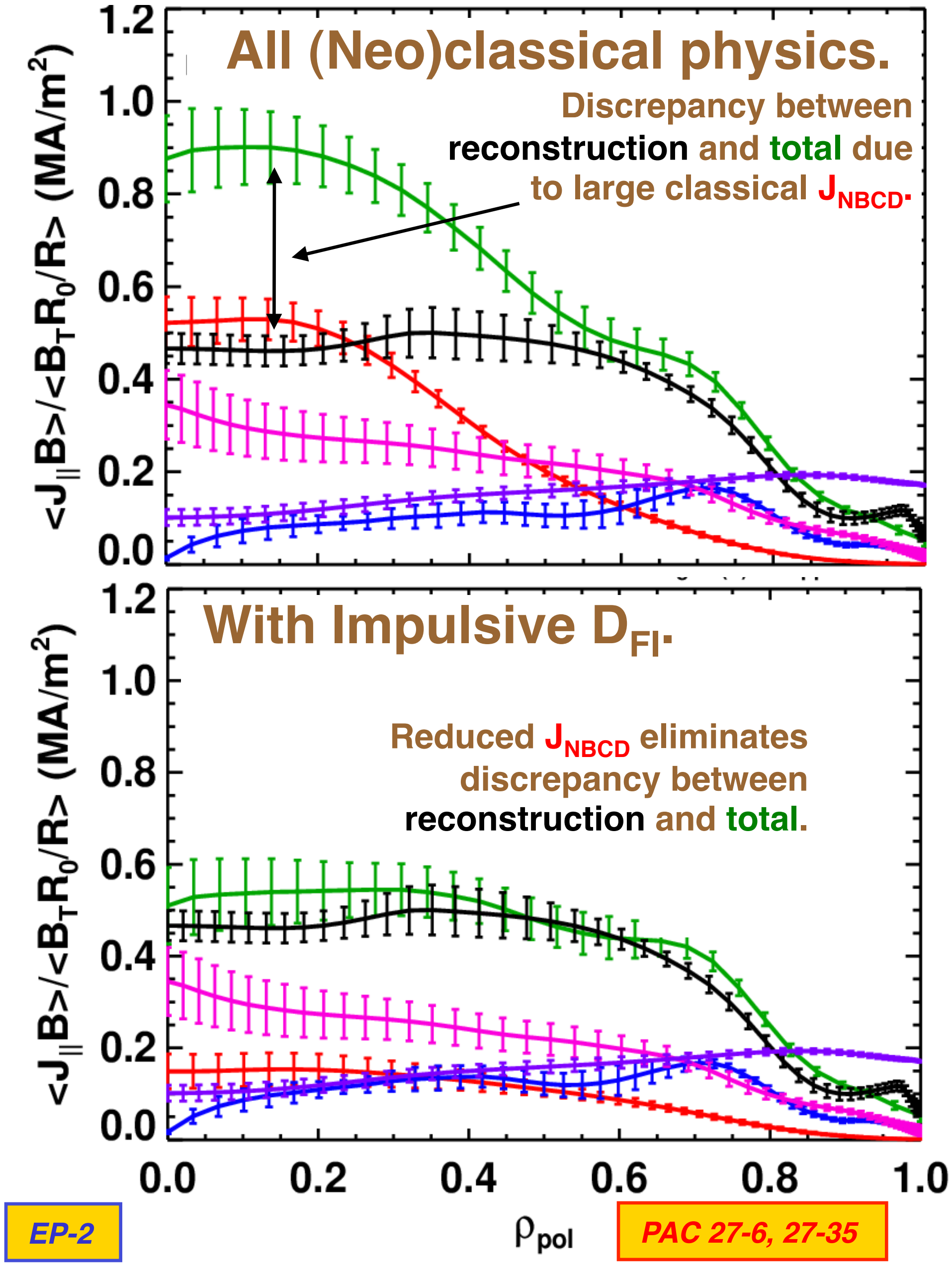
- Modeled TAE avalanches using spatially and temporally localized fast-ion diffusivity $D_{FI}(\psi,t)$.
  - Use S_n drops to determine $D_{FI}(\psi,t)$ details.
  - Reinforces need for predictive modeling of avalanche transport.

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 drops to determine $D_{FI}(\psi,t)$ details.
  - Reinforces need for predictive modeling of avalanche transport.
- FY-11 & 12 scenario modeling plans
  - Examine NSTX-U scenario results with various D_{FI} profiles, improved equilibrium solvers.
  - Interface with transport TSG to identify plausible transport models.

700 kA High-β_P with Rapid TAE Avalanches



All (Neo)classical physics.

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

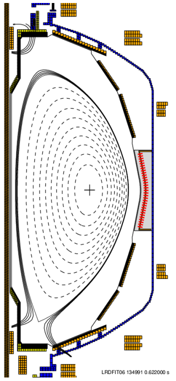
With Impulsive D_{FI}.

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

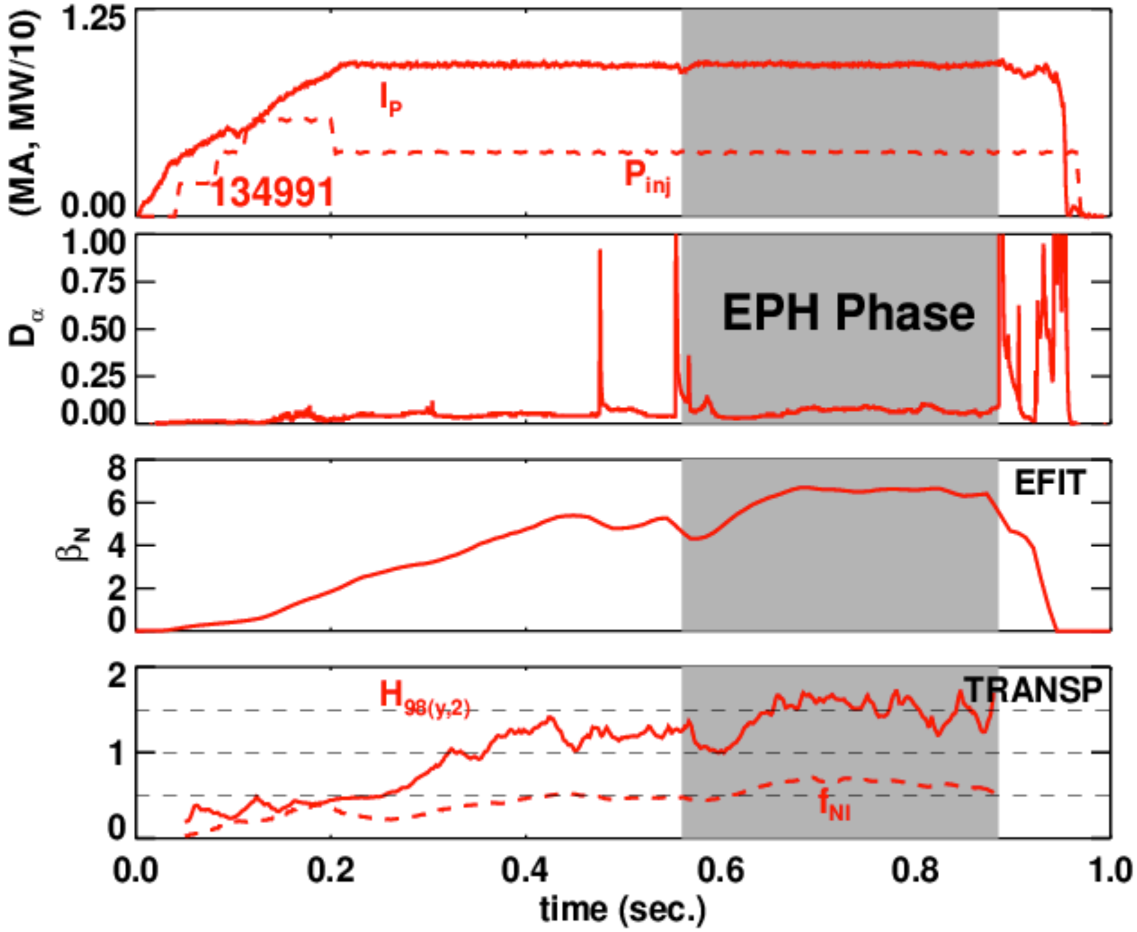
EP-2

PAC 27-6, 27-35

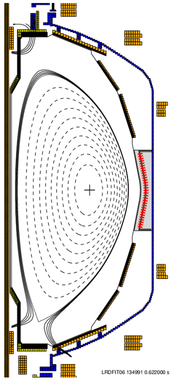
ASC Experiments Tested Triggering and Control of Enhanced Pedestal H-Modes (EP-H)



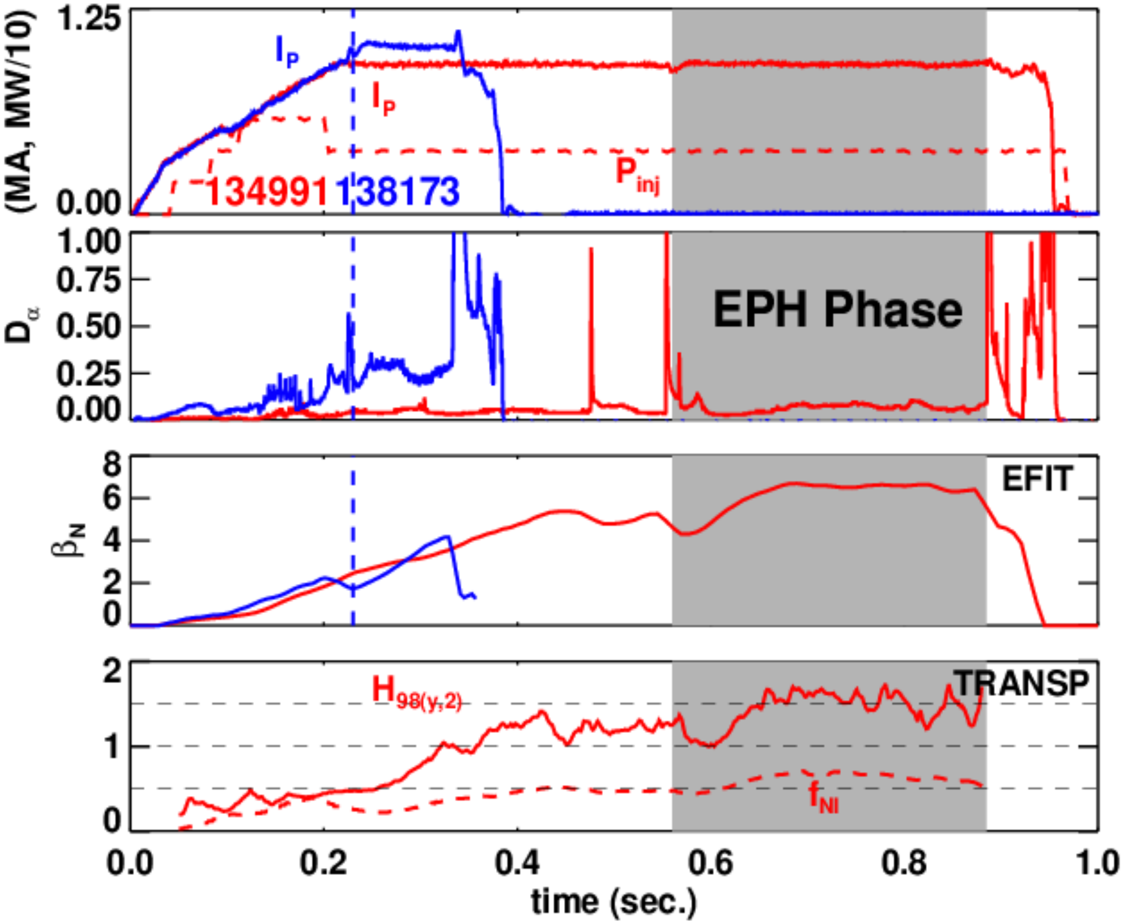
- EP-H typically triggered by an ELM
  - well after L->H transition.
- Confinement improves ~50%
  - f_{NI}~70% very high for this I_p/shape.



ASC Experiments Tested Triggering and Control of Enhanced Pedestal H-Modes (EP-H)



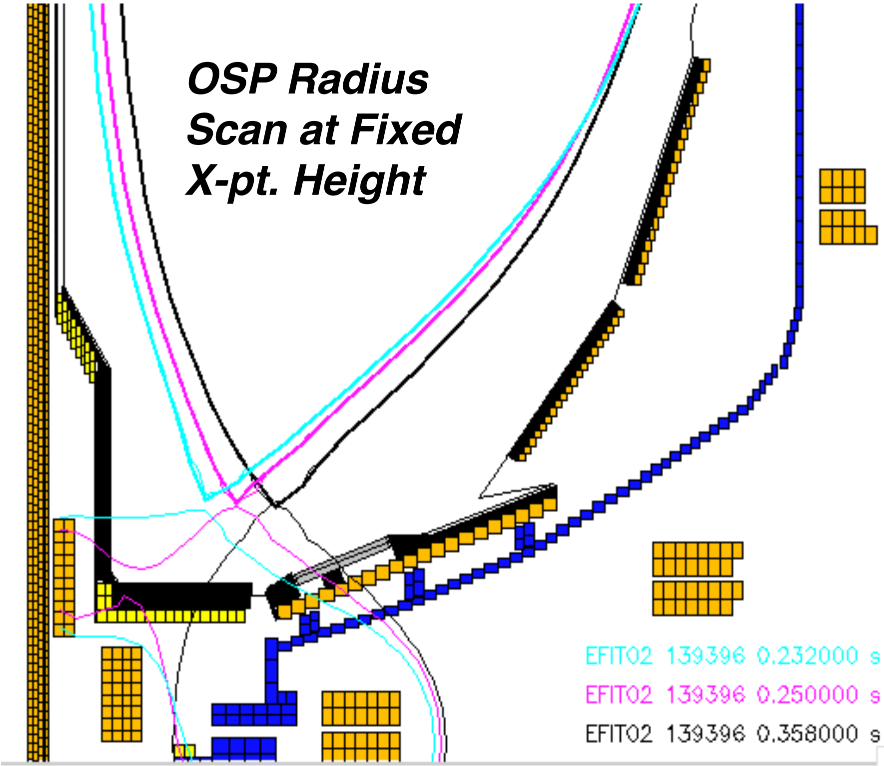
- EP-H typically triggered by an ELM
  - well after L->H transition.
- Confinement improves ~50%
  - f_{NI}~70% very high for this I_p/shape.
- Has typically resulted in β_N limit disruption.



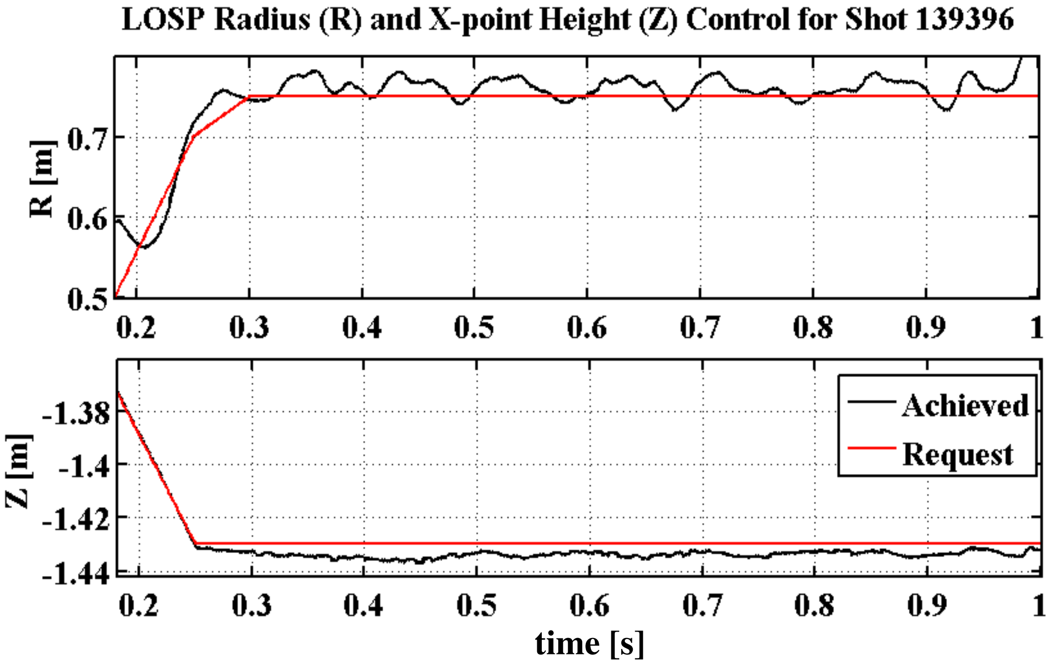
- 2010 run goal: reliably trigger and control EP-H modes.
  - n=3 pulses for triggering
  - β_N feedback for control
- n=3 pulses which triggered ELMs not reliable in triggering EP-H.
- Developed a low-q_{95} scenario with EP-H transitions at end of I_P ramp.
  - β_N controller reduced power after EP-H transition.
  - 2nd ELM terminated EP-H
    - (single LITER that day).
- Implications for FY-11 & 12:
  - Revisit when dual LITER system is operational.
  - Understand if q_{95}, I_P or something else governs access.
  - Assess prospect for high-f_{NI} operation at reduced I_P.

Developed Divertor/Boundary Control to Support Lithium Research and Boundary Physics Programs

- 2009: Developed a inner and outer lower strike-point (S.P.) controller.
- 2010: Dramatic improvements in control algorithms and tuning:
  - Refined 4 S.P. controller…used in initial LLD experiment.
  - Developed combined outer S.P. and X-point height controller



OSP Radius Scan at Fixed X-pt. Height



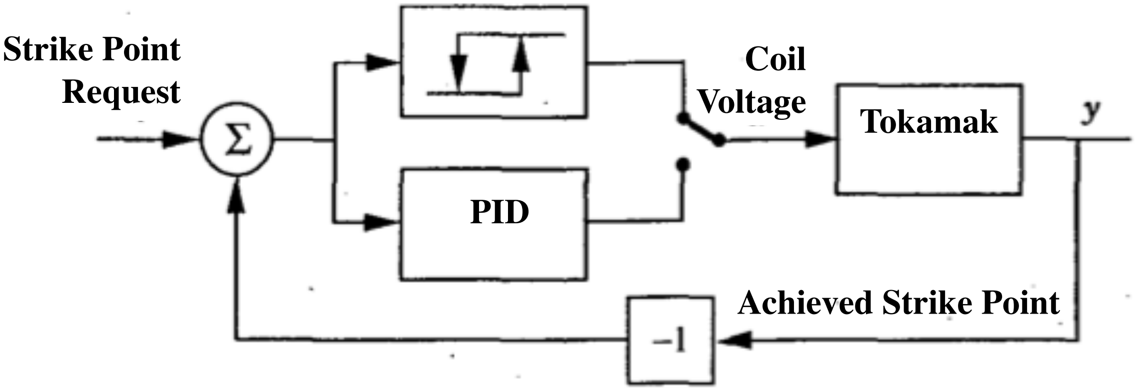
LOSP Radius (R) and X-point Height (Z) Control for Shot 139396

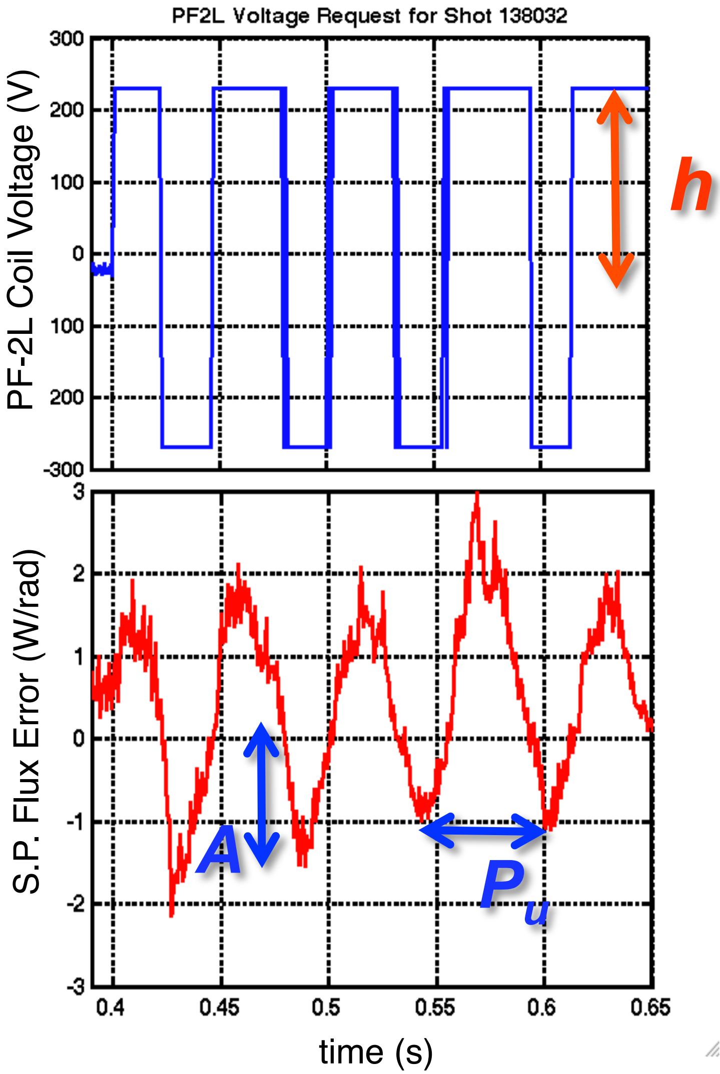
- Achieved RMS <1 cm X-point height error and <2 cm SP.
  - Use controller for later LLD experiments.

PAC 27-6

In-Line System-ID Facilitated Rapid Shape Control Development

- “Relay-Controller” replaces the PID operator with fixed positive or negative response.
  - New feature allows PID gains to be determined in a single shot.
- All gains derivable from the parameters h, A & P_U.



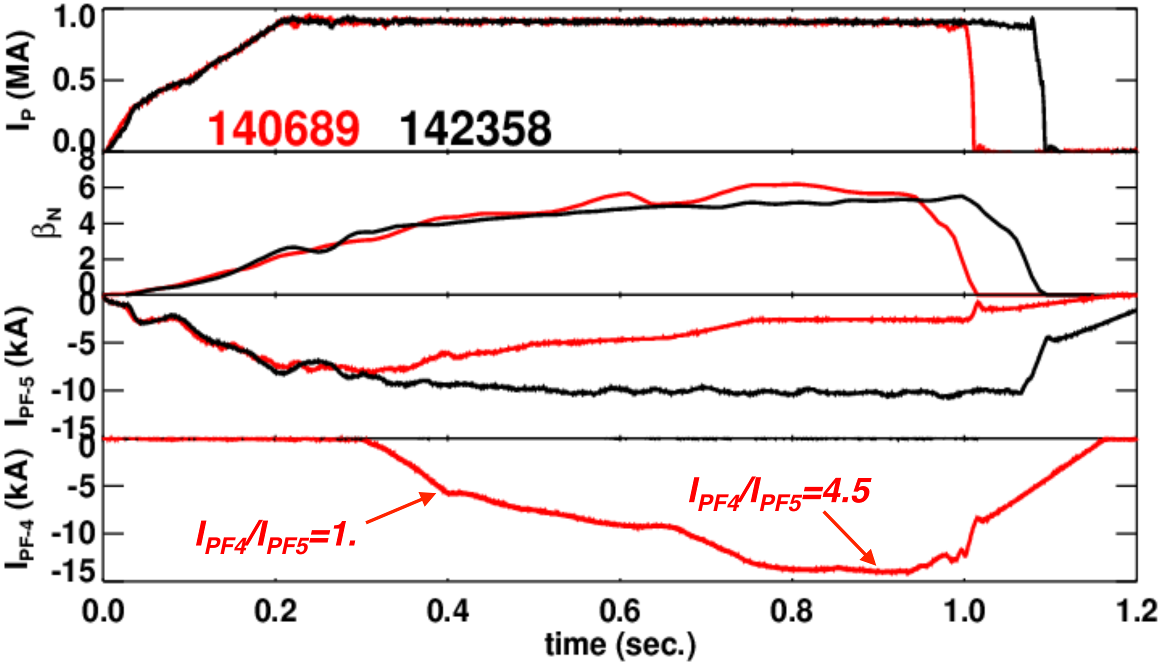


- Capability could be ported to other facilities using GA PCS and ISOFLUX.
- Plans for boundary control in FY-11 & 12
  - Add additional coils to boundary control schemes.
  - Improve transitions between control phases.
  - Support advanced divertor research.
    - Beginning to scope PCS requirement for snowflake control.

PAC 27-6

Use of PF-4 Coil in FY-10 Supports High-Current Upgrade Scenarios

- Required for high-current, high-l_i in NSTX-U ($I_{PF\text{-}4}/I_{PF\text{-}5}$~1/2).
  - Provides ability to vary and optimize the boundary squareness.
- Coil used with PF-4/PF-5 ratios far larger than required for NSTX-Upgrade.
- Plans for FY-11 & 12:
  - Revisit the effect of squareness on n=0 stability, integrated performance.
  - Incorporate PF-4 in more generic boundary control algorithms.



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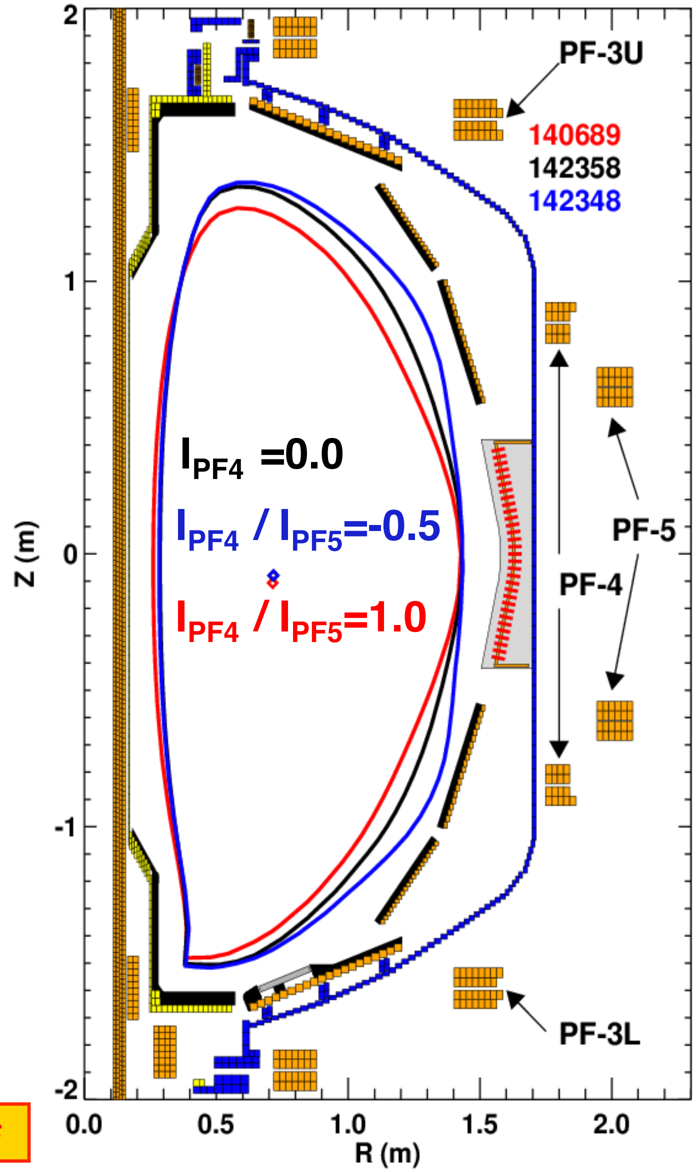
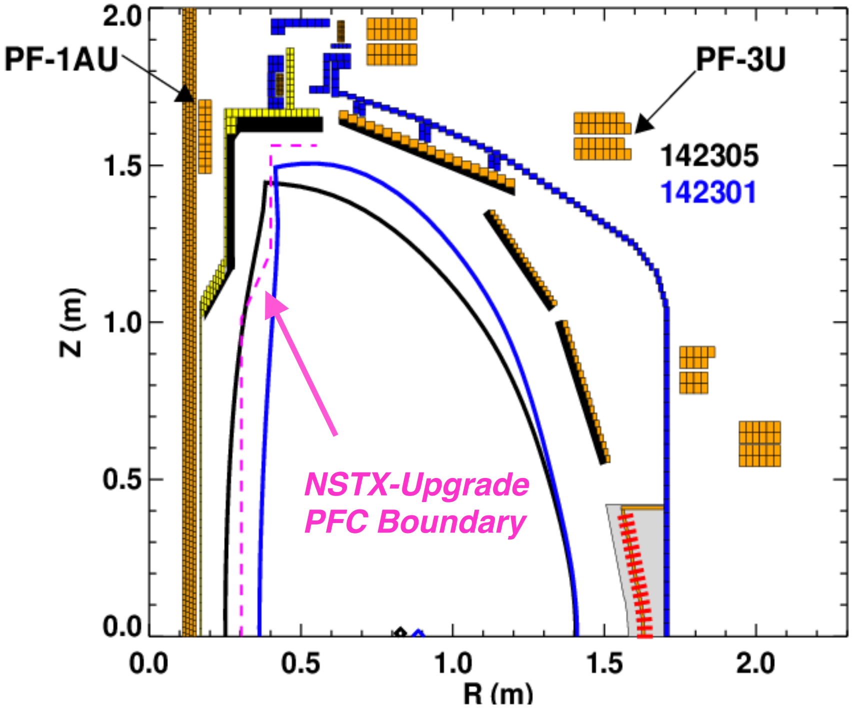
Example Shapes With Various PF-4 Currents



Discharges With NSTX-Upgrade Aspect Ratio and Elongation Produced for Long Pulse at High-β



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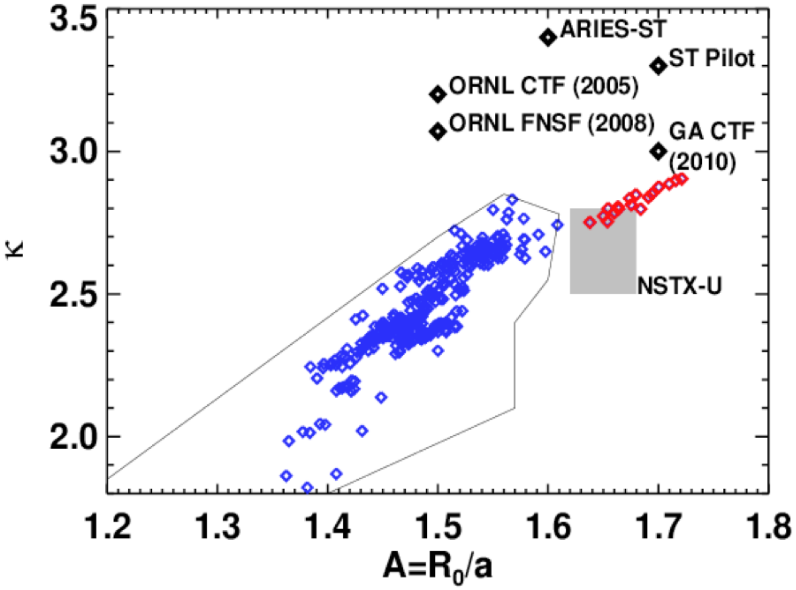
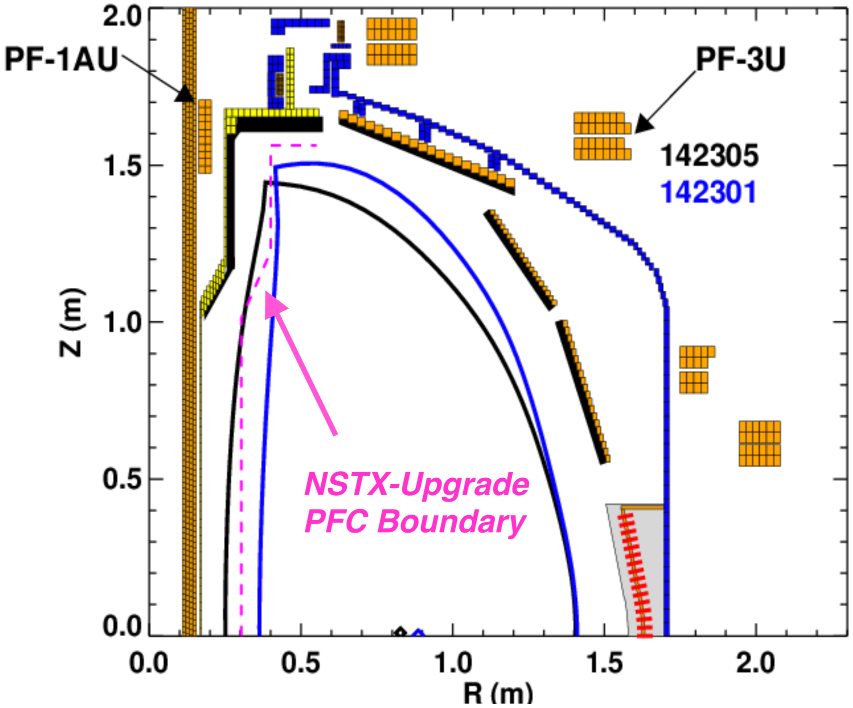
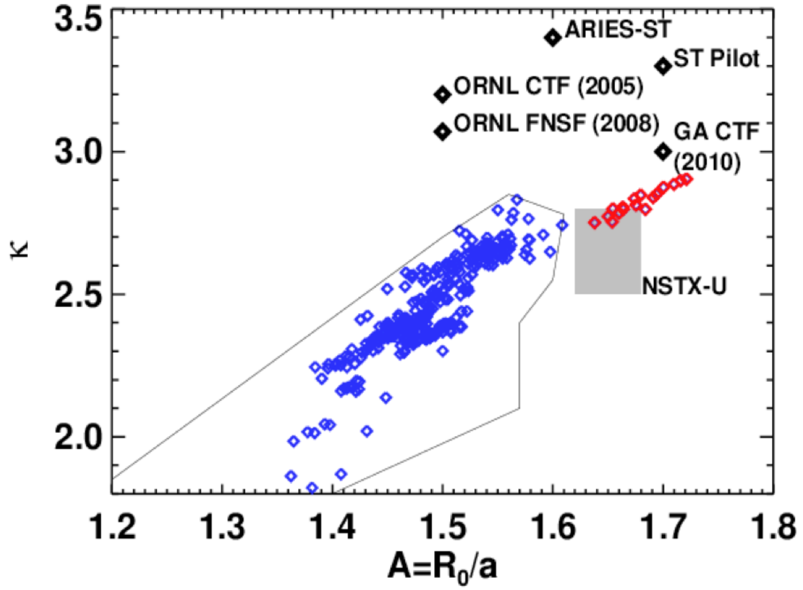


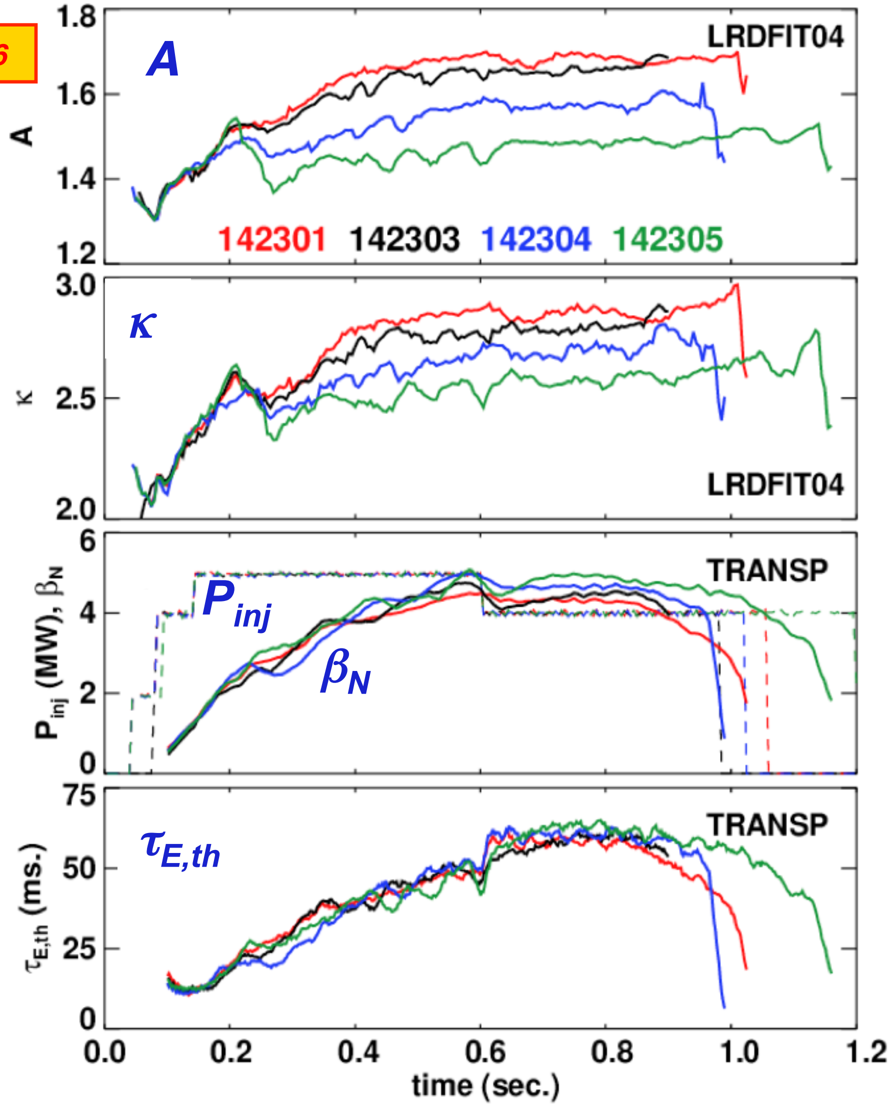
Discharges With NSTX-Upgrade Aspect Ratio and Elongation Produced for Long Pulse at High-β





PAC 27-6

Performance Characteristics vs. Aspect Ratio



Plans in 2011 & 12

- n=0 control at high-A (boundary and VDE)
- Integrated performance, including transport and divertors

Recent Results Are Quite Positive For NSTX-Upgrade and ST-Development, But Important Questions Remain

- Demonstrated long pulse, high-β_N operation at NSTX-Upgrade aspect ratio and elongation.
- Making substantial progress on divertor and boundary control, in support of many TSGs.
- Snowflake divertor & divertor gas injection shown to reduce heat flux & impurities (in BP TSG).
- Advanced RWM control proven successful (in MS TSG).
- Current drive modeling assumptions verified over a wide range of scenarios.
- Identified and studied a potentially important new operating regime (EP-H mode).

Outstanding ASC Issues for Focused Study in 2011 & 12

- Boundary control can be more challenging at high-κ.
- Vertical stability is degraded at higher aspect ratio.

} ***Motivates the n=0 control component of R(11-2)***

- Density reduction and impurity control remains challenging.
- Work with BP, LR, ITER TSGs to address these issues:
  - Improve reliability of scenarios with reduced n_e at start of flat-top.
    - ASC milestone R(12-3), supports lithium research program.
  - Reduce/control impurity accumulation.
    - Provide scenario and control support.

ASC Research in 2011 & 12 Will Directly Support Upgrade and Next-Step n=0 Control Needs

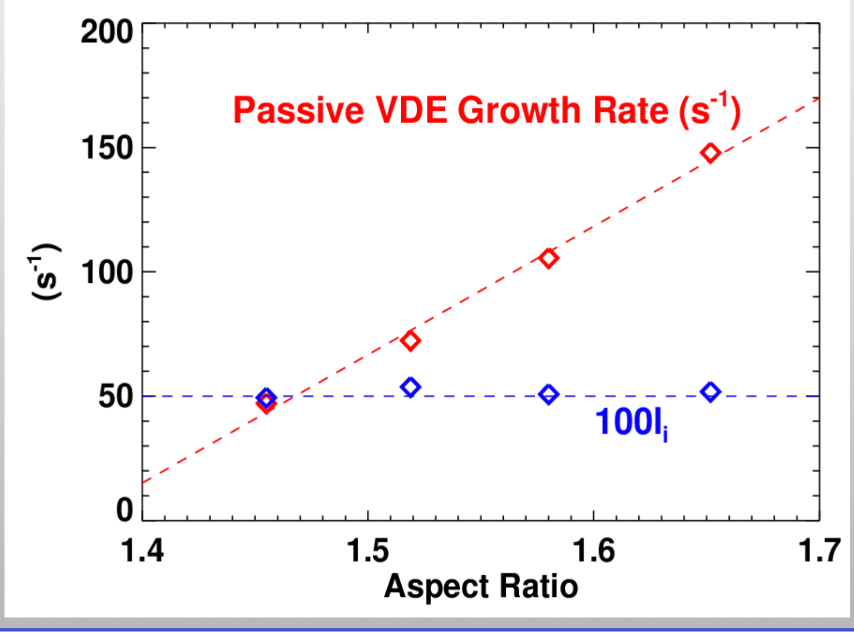
PAC 27-2, PAC 27-6

- Optimize boundary regulation and control.
  - Include more couplings between the boundary shape and different coils.
    - Use a more fully populated "M-matrix" in ISOFLUX.
    - Example problem: improved top/bottom gap control at high-κ & δ.
  - Modify PCS algorithms for reduced voltage transients at control transitions.

- Develop improved vertical control.
  - Improved realtime dZ_P/dt for derivative controller.
  - Optimize gains in scenarios of interest.
  - If insufficient, test RWM coils for n=0 control.
    - Less field than the PF-3 coils, but much faster.

- Continue to work towards rotation control.
  - State space control algorithm has been designed.
  - Installing fibers, spectrometer and camera.
    - Real-time curve fitting at 5kHz demonstrated.
  - Test realtime camera acquisition in 2011, assess if feasible for control in 2012.

- **Passive VDE growth rate increases by a factor of 3 at NSTX-U high-A and κ shape.**
- **Observe loss of Z_P control when l_i>~0.6 at A=1.65.**



ASC Research Will Support Low-n_e Startup and Impurity Control Goals For NSTX-Upgrade

- R(12-3) will optimize/understand low-density startup for Li research program and NSTX-U
  - Study the disruptive MHD that prevents lower fuelling (locked tearing modes, ideal MHD,…).
  - Implement density feedback for more reliable startup conditions.
  - Vary the ramp-rate, heating time history while reducing gas input.
  - Continue to explore error field correction, magnetic balance optimization, triggered ELMs.

- Will work with ITER, BP & LR TSGs to support divertor control needs and molybdenum tile optimization.
  - Balanced double null for heat flux mitigation.
  - High-performance scenarios w/ OSP on or off Moly. tiles (if installed).

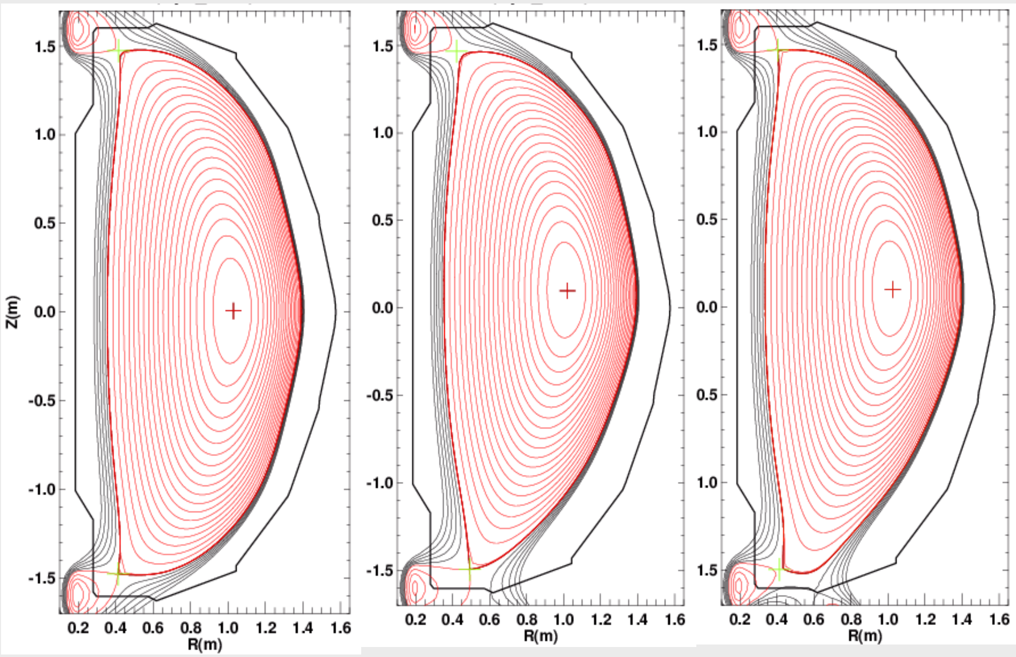
- Test HHFW to modify impurity transport (+ core heating) in H-mode.
  - Efforts deferred to 2011-12.

PAC 27-34

Simulated High Aspect Ratio and Elongation "Double Null" Divertor Solutions

PAC 27-2

Standard High-δ | **High-δ, LOSP on Molybdenum** | **High-δ, Lower Snowflake Minus**



FY-13 & 14 Outage Period Will Be Critical For Upgrade Operations and Physics Preparations

- Finish analysis & publication of experimental results from 2011/2012 run.
- Restoration of magnetic sensors for equilibrium reconstruction & control.
- Required upgrades to the plasma control system.
  - Additional coils and power supplies in PCS, downstream software.
  - rtEFIT updates for additional coils and new sensors.
  - Control of additional NB sources from PCS.
- Comprehensive scenario analysis in preparation for initial operations.
  - Test profiles against transport models, scenarios against stability constraints.
  - Model scenario implications of various particle and power handling concepts.
- Develop methodology for NSTX-U control needs.
  - Develop current profile control algorithms using rtEFIT and beam modulations.
  - Scope requirements and begin design of an rtMSE diagnostic.
  - Control requirements for particle & power handling concepts, including snowflake divertor.

ASC Research Supports the Needs of the NSTX Program, ITER, and the ST Development Path

- Boundary and divertor magnetic control:
  - Developed OSP radius and ISP height controller using inline system-ID.

- Scenario modeling:
  - Found good agreement with (neo)classical calculations when low-f MHD is absent.
  - Modeled modifications to NBCD from TAE avalanches and coupled m/n=1/1+2/1 modes.

- High performance scenario development:
  - Explored “Enhanced Pedestal H-mode”.

- Impurity reduction strategies (R. Maingi’s Talk):

- NSTX-Upgrade prototyping:
  - Development of squareness control/combined PF-4 & 5 operation.
  - Large aspect ratio studies.

Backup

FY-10 Run Information

ASC Experimental Highlights From the 2010 Run

- Improved magnetic control control:
  - Developed 4 SP controller to support LLD experiments.
  - Developed OSP radius and ISP height controller, using inline system-ID.
- Confirmed models of the current profile components over a range of q_{95}.
  - Found good agreement with (neo)classical calculations when low-f MHD is absent.
  - Modeled modifications to NBCD from TAE avalanches and coupled m/n=1/1+2/1 modes.
- High performance scenario development:
  - Explored “Enhanced Pedestal H-mode”.
  - Developed scenarios with sustained β_P>2.
- Scenario development with reduced density and impurities:
  - Tested RMP pulses for impurity screening.
  - Demonstrated modifications to the early magnetic balance for impurity reduction.
  - Studied lower-density startup with improved error field correction.
  - Tested impurity reduction techniques in the high-β_P low-V_{loop} scenarios.
- Prototyping of NSTX-Upgrade scenarios:
  - Development of squareness control/combined PF-4 & 5 operation.
  - Large aspect ratio studies.

ASC Experiments in 2010 and Early 2011 Runs

Receiving Run Time

XMP-64 (Kolemen et al.) Four S.P. controller (LLD support).

XP-1006 (Gerhardt, et al.) High-β_P scenarios with reduced impurities and higher f_{NI}. Includes low-I_P experiments.

XP-1003 (Kolemen, et al.) Combined X-point height and OSP radius control.

XP-1064 (Canik, et al.) Development of long-pulse enhanced pedestal H-mode.

XP-1027 (Canik et al.) RMPs below ELM triggering threshold for impurity screening.

XP-1025 (Canik et al.) Synergistic effects between 3D field and vertical jogs for ELM pacing.

XP-1004 (Menard, et al.) Application of early error field correction to advanced scenarios.

XP-1005 (Menard, et al.) Modifications to the early discharge evolution to reduce late impurities.

XP-1058 (Kolemen, et al.) Squareness control and optimization.

XP-1071 (Gerhardt, et al.) High aspect-ratio and elongation development

Planned But Not Run

XP-1007 (Bell, Canik, et al.) Use of HHFW for increasing f_{NI} and reducing impurities.

XP-1008 (Gerhardt, et al.) Early HHFW for modification of the current profile evolution.

ASC Related Publications in 2010

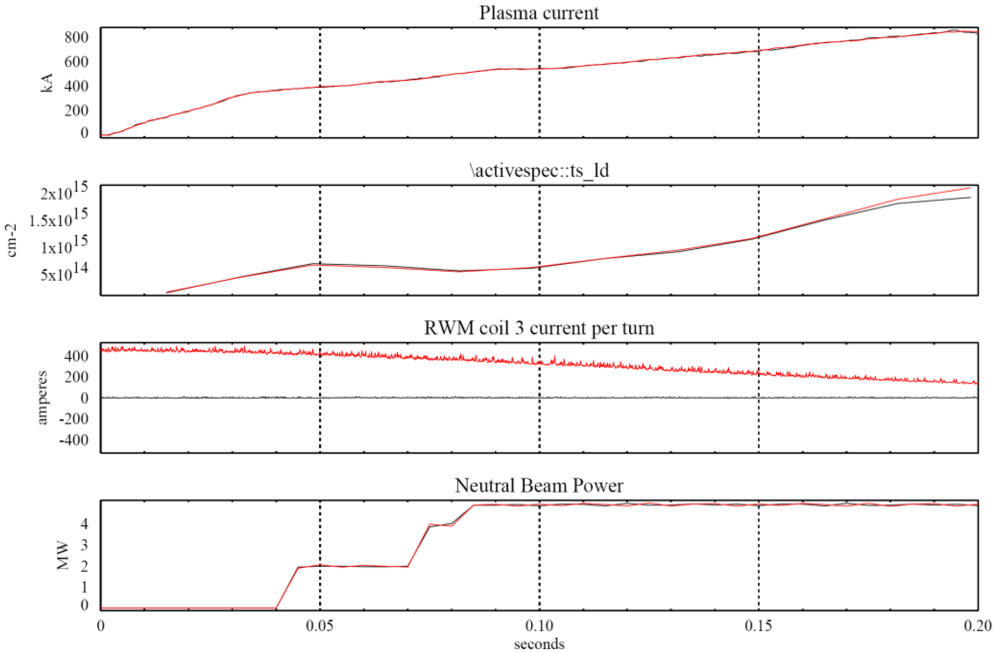
- R. Maingi, et al., Triggered Confinement Enhancement and Pedestal Expansion in High-Confinement-Mode Discharges in the National Spherical Torus Experiment, Phys. Rev. Lett. (2010).
- S.P. Gerhardt, et al., Calculation of the Non-Inductive Current Profile in High-Performance NSTX Plasmas, accepted at Nuclear Fusion.
- S.P. Gerhardt, et al., Implementation of β_N Control in the National Spherical Torus Experiment, accepted at Fusion Science and Technology.
- S.P. Gerhardt, et al., Recent Progress Toward an Advanced Spherical Torus Operating Point in NSTX, submitted to Nuclear Fusion.
- E. Kolemen, et al., Strike point control for the National Spherical Torus Experiment (NSTX), Nuclear Fusion (2010).
- E. Kolemen, et al., Plasma modeling results and shape control improvements for NSTX, submitted to Nuclear Fusion.
- IAEA, EPS, & APS contributed talks and posters.

Scenario Development With Reduced Density and/or Impurities

Low density plasmas with and without early EFC show early EFC increases rotation 10-20% for t=120-180ms

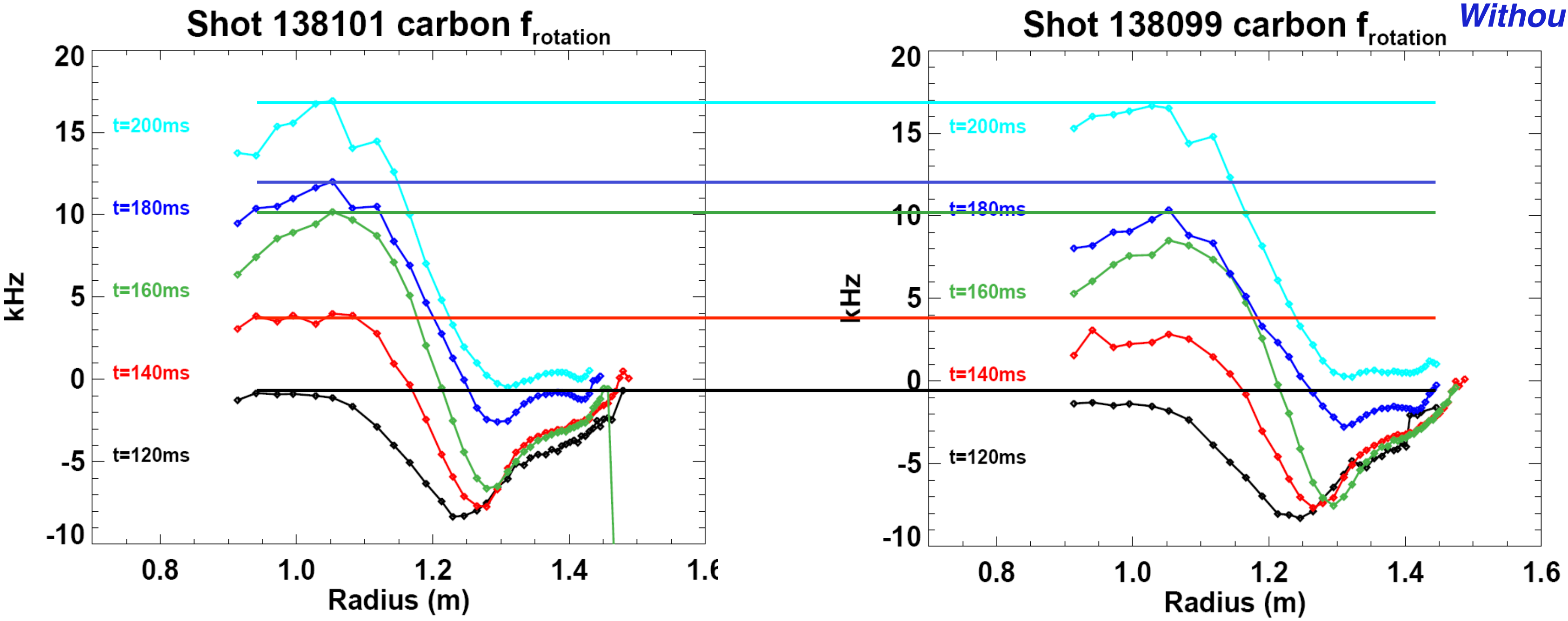
- Delay of early H-mode by reduced early fueling reduces density by 30-40% at t=0.2s (vs. reference)
  - Similar to what typically happens with increased LITER evaporation

- Additional EFC <u>phase</u>, amplitude scans (in 2011) might be able to further increase rotation at reduced density.



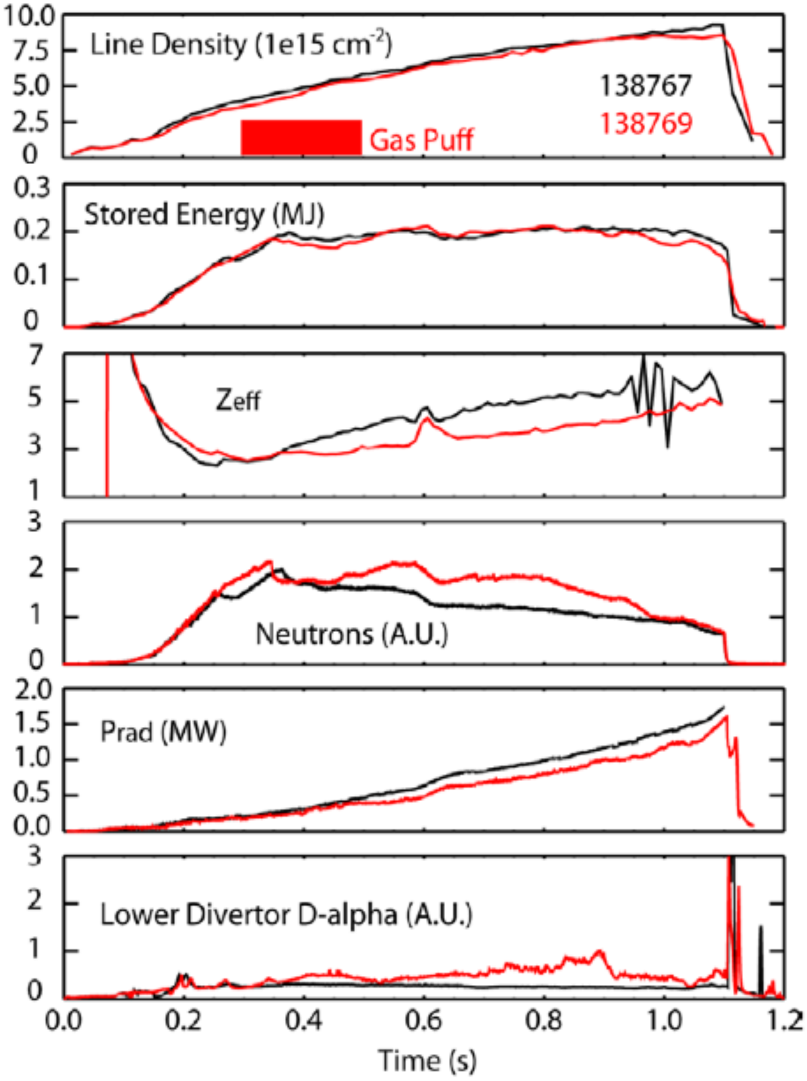
With Correction

Without Correction

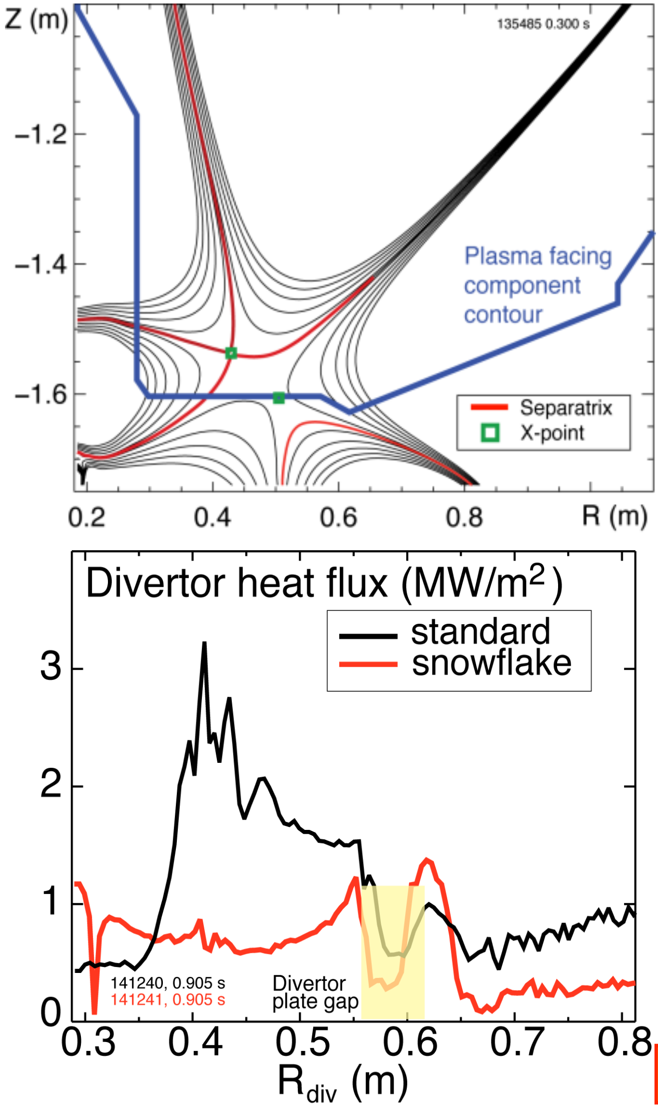


Divertor Modifications Can Reduce Heat Loading and Carbon Influx

Deuterium Gas Puff From CHI Gap



Snowflake Divertor



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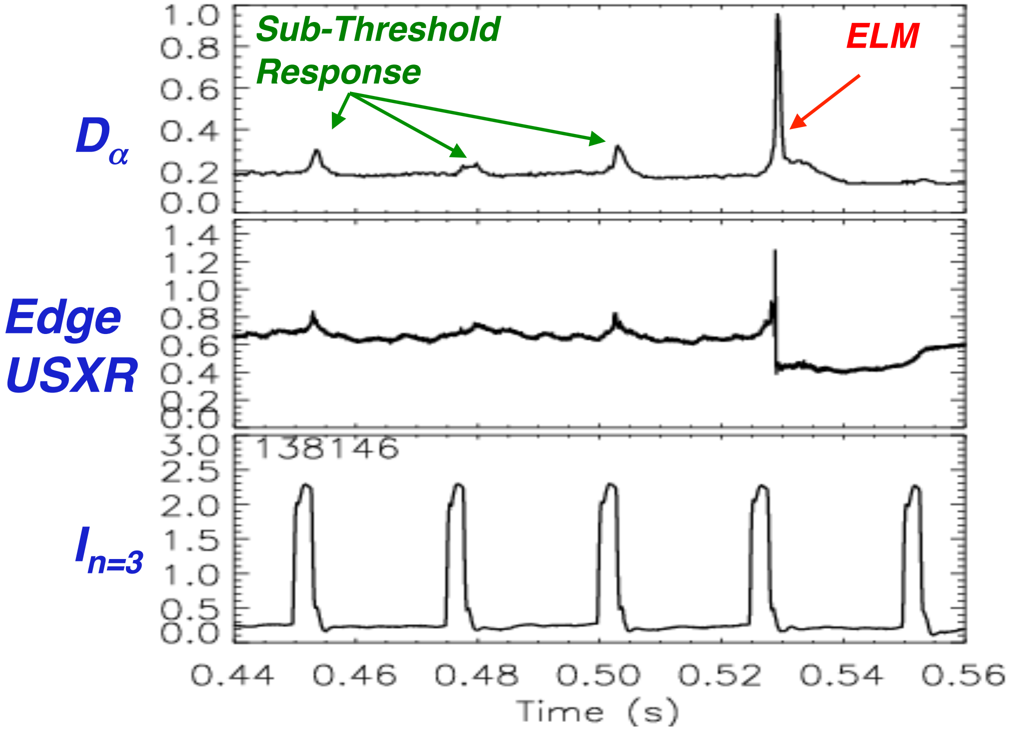
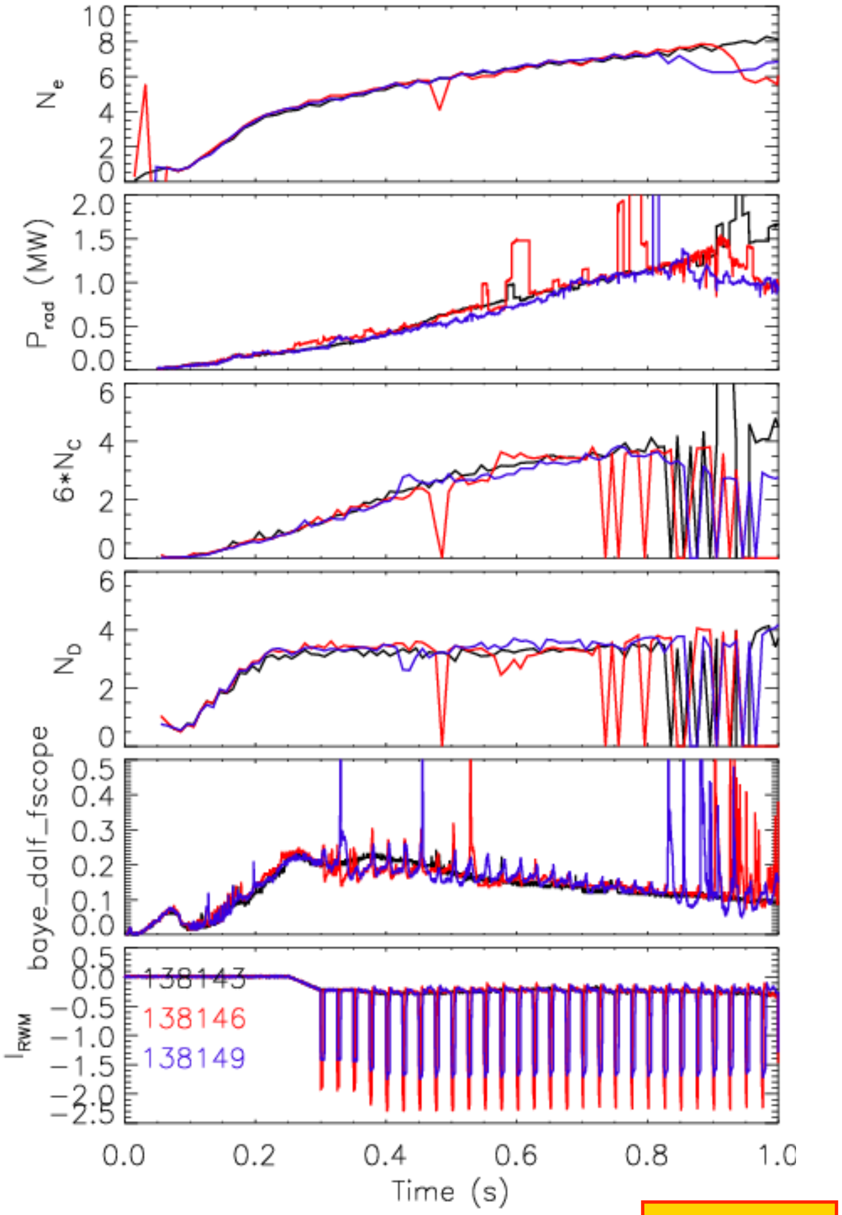
3D Field Pulses Below ELM Triggering Threshold Ineffective for Impurity Screening

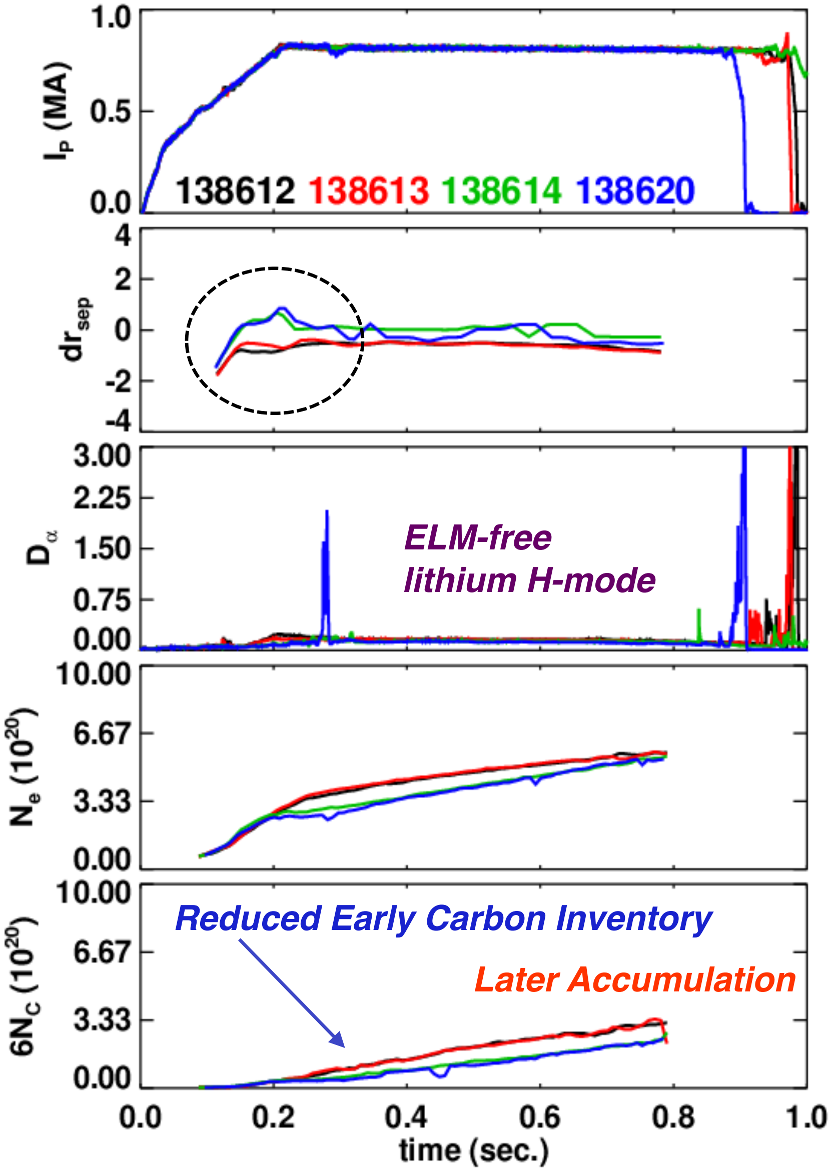
- Response to n=3 field observed in divertor D_α even when pulse is too brief or low amplitude to trigger ELM
- 3D field optimized for sub-threshold pulses
    - Maximize n=3 amplitude, duration while avoiding large ELMs
- Without ELMs, particle expulsion insufficient for impurity control
    - No dramatic impact on P_{rad} or carbon inventory evolution





PAC 27-33

Early δr_{sep} Change from -7mm to 0 Reduces Impurity Confinement and/or Generation and Reduces C Z_{eff} by ~1

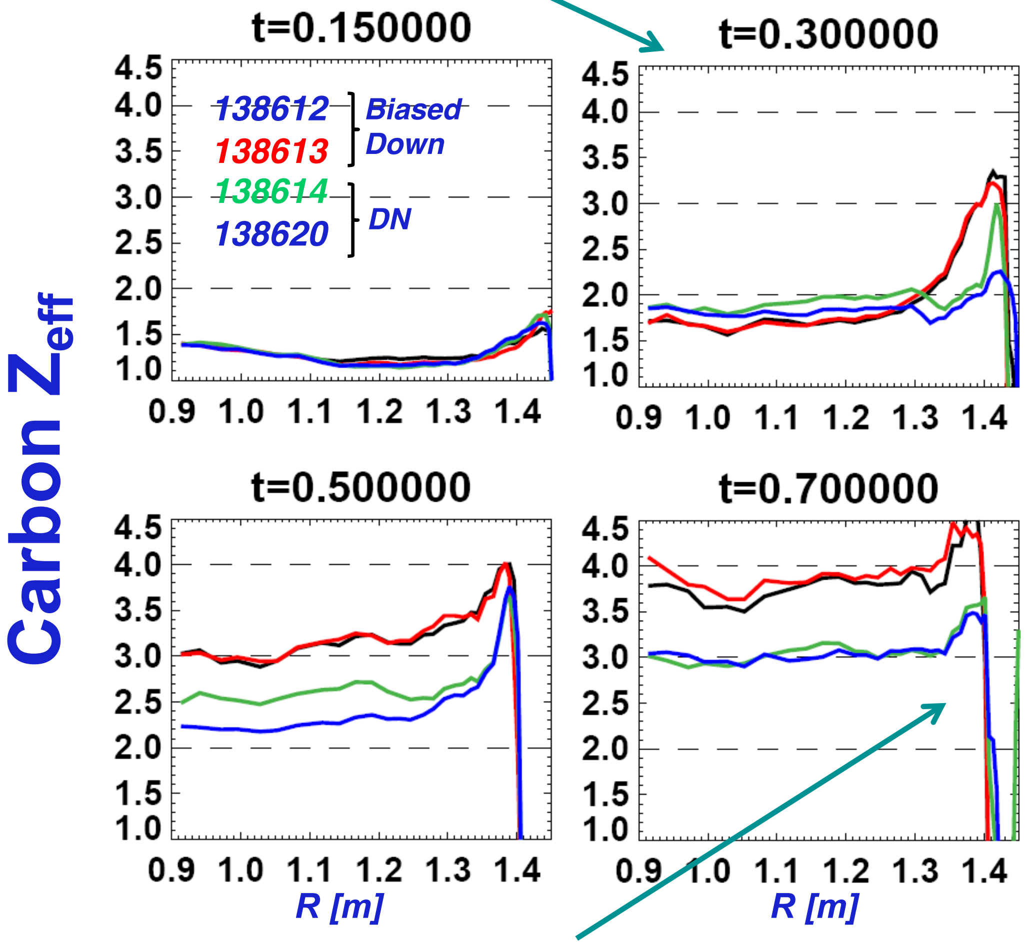


ELM-free lithium H-mode

Reduced Early Carbon Inventory

Later Accumulation

Size of H-mode C impurity "ear" near t=0.3s influences late Z_{eff}



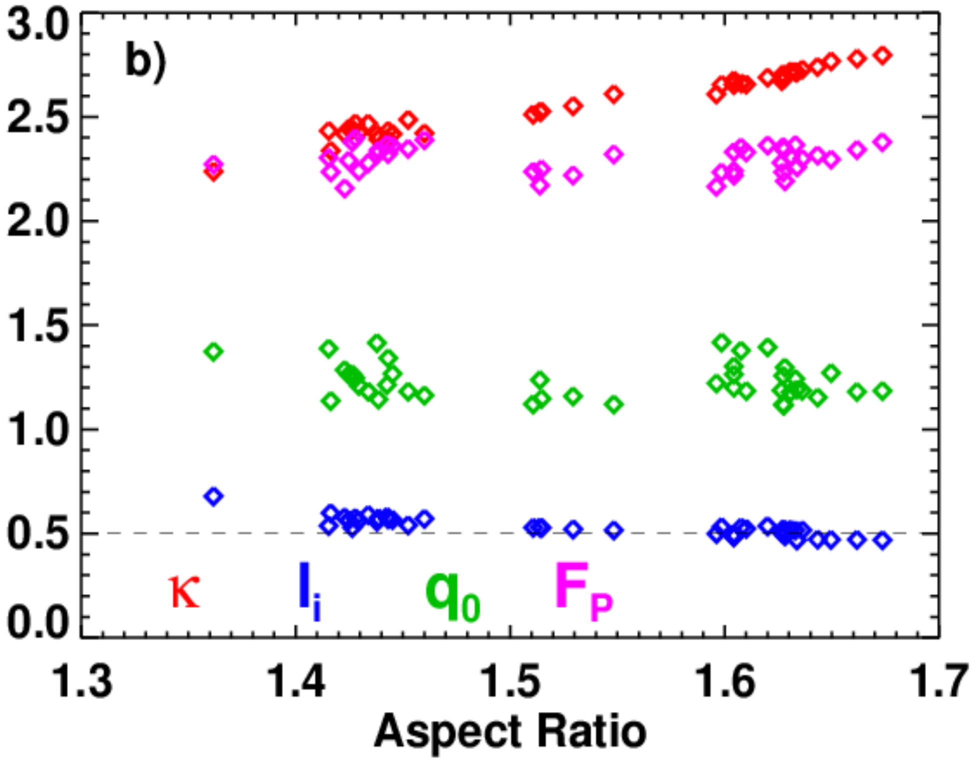
Carbon Z_{eff} reduced by ~1 unit late in shot

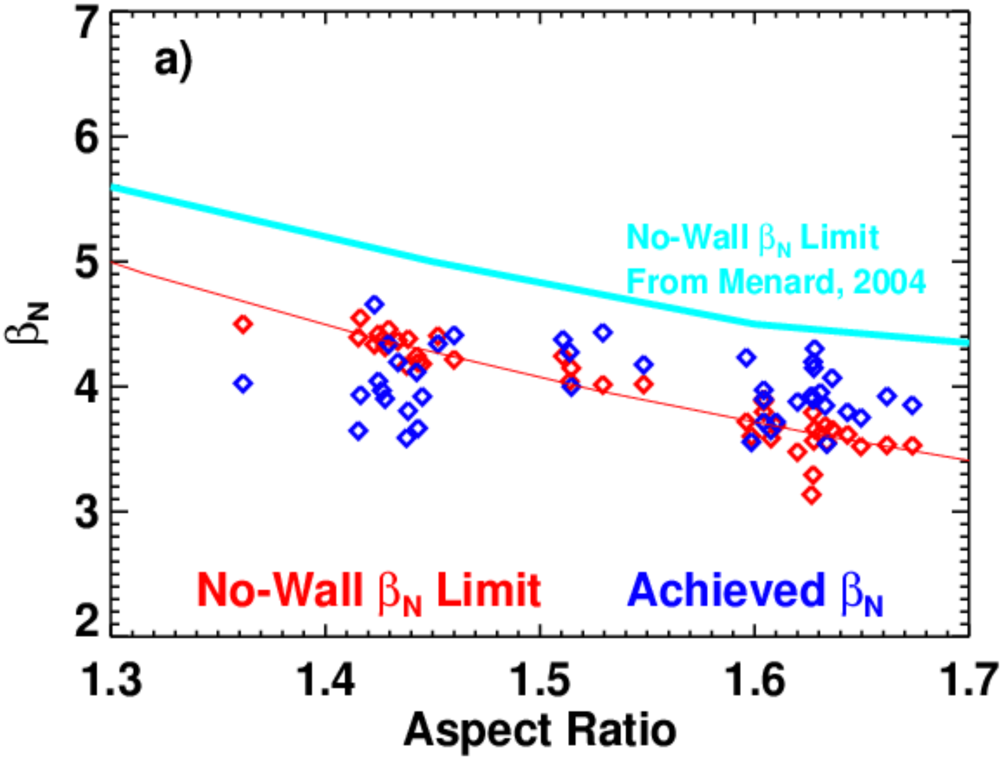
PAC 27-33

Scenario Development For NSTX Upgrade

Significant Reduction of the Calculated No-Wall β_N Limit in Large-Aspect Ratio Scenarios

- Use actual equilibria, reconstructed with MSE, Te-Isotherm, magnetics.
- For each reconstructed equilibria
  - Scale pressure profile up and down many times, and compute fixed boundary equilibria (CHEASE)
  - Compute δW for each one, find β_N where $\delta W=0$ (DCON).
- Repeat for many many time slices and then sort those with similar q_0.
- l_i tended to decrease with A, but no clear trend in F_P.
- Experiment did not actively push the β_N limit…high-priority task in FY-11/12

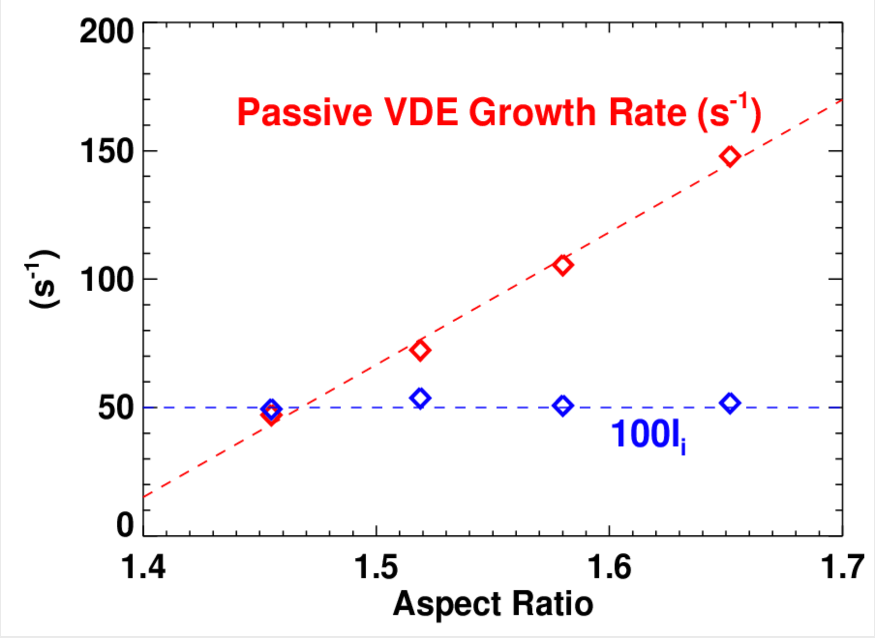


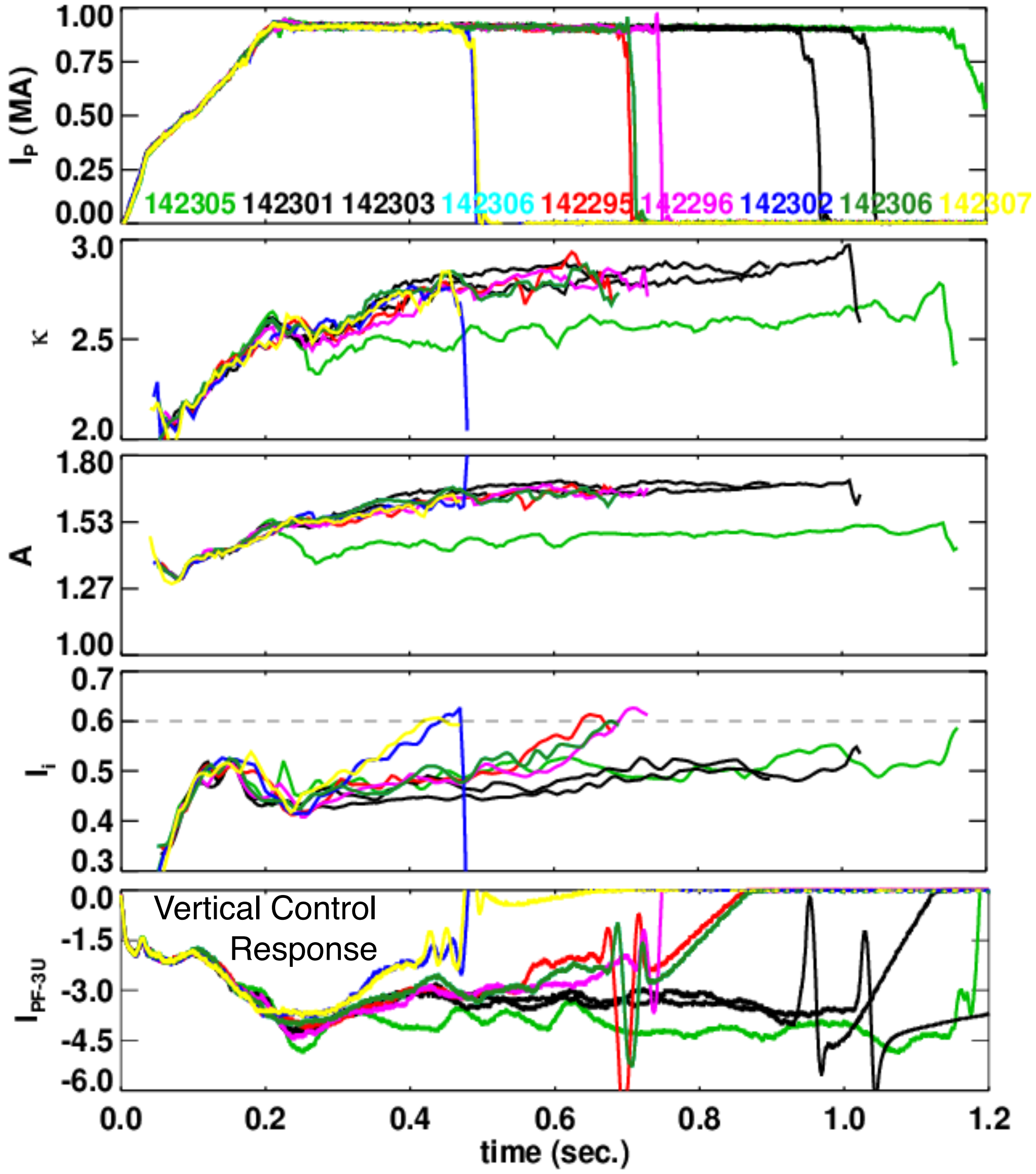


Vertical Stability Will Be More Challenging in NSTX-Upgrade

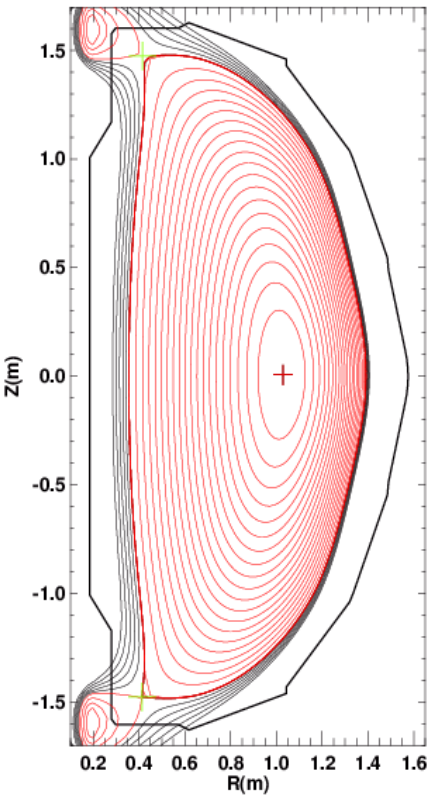
- High-A & κ plasma tend to loose n=0 control when l_i>0.62.
- Provides motivation for improvements to the vertical controller.

- Freeze vertical control, allow the plasma to drift vertically.
- Factor of 3 increase in growth rate for fixed l_i.

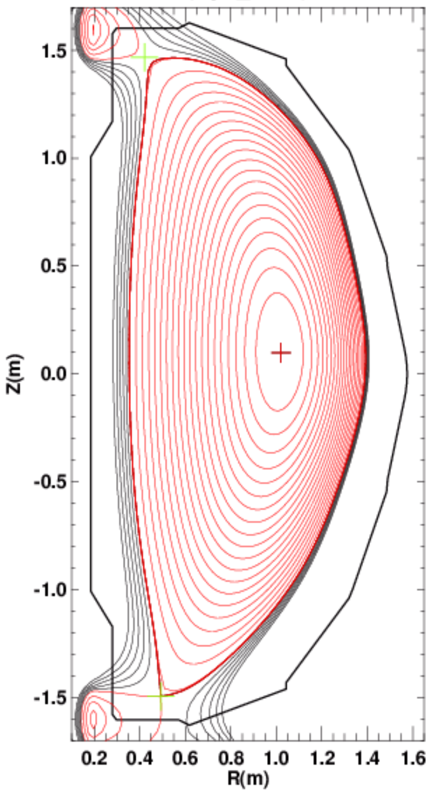




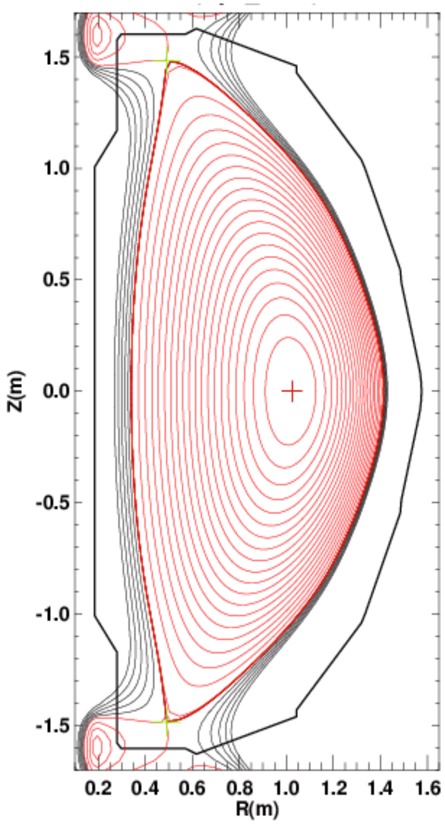
Wide Variety of “Double Null” Divertors, with High-A and κ, are Possible with NSTX Coil Set



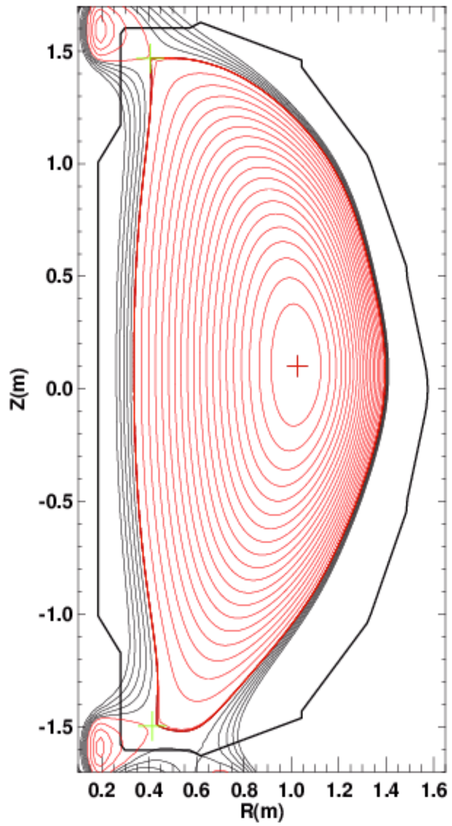
Standard High-δ
PF-1A Only



High-δ
LOSP on Moly.
UOSP On Graphite
w/ PF-1B



High-δ
LOSP on Moly.
Up-Down Symmetric
w/o PF-1B



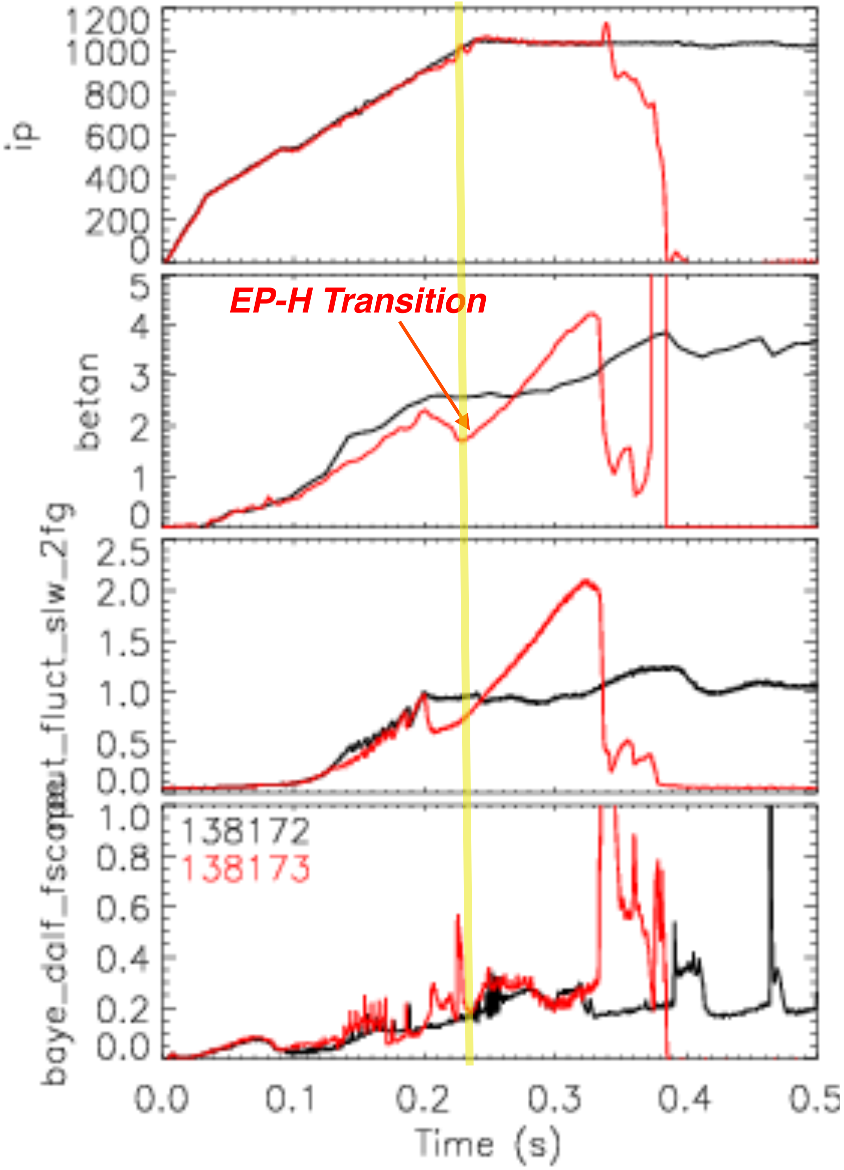
High-δ, Lower
Snowflake Minus
w/ PF-1B

EPH Mode Development

EP-H Development in 2010 Attempted to use SGI, 3-D Fields, and β_N Control to Develop a Reliable Scenario (I)

Day #1: Test triggering of EP-H with 3-D Field Pulses

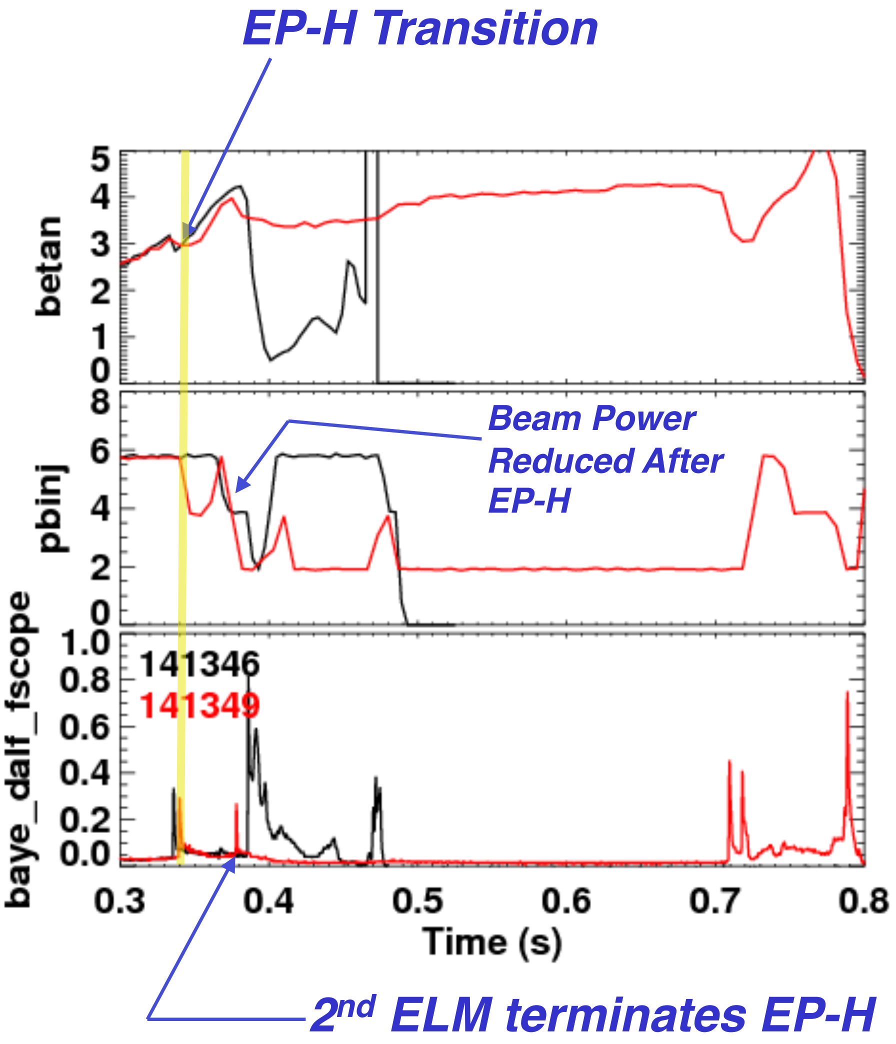
- Goals
  - Use Lithium and SGI to facilitate transition.
  - Trigger EP-H (with e.g. 3D fields, SGI)
  - Sustain using feedback (β_N + RWM)
- Results
  - Able to produce EP-H late in current ramp using SGI
    - Not successful in extending these into flat-top
  - Failed to get EP-H in flat-top using 3D field pulses (*too early in run?*)
- Status
  - Mid-run database of observed EP-H's suggested low-q_{95} would help with access.
  - Idea for next attempt: try low-q discharge
    - Begin with I_p/B_t=1.2/.45



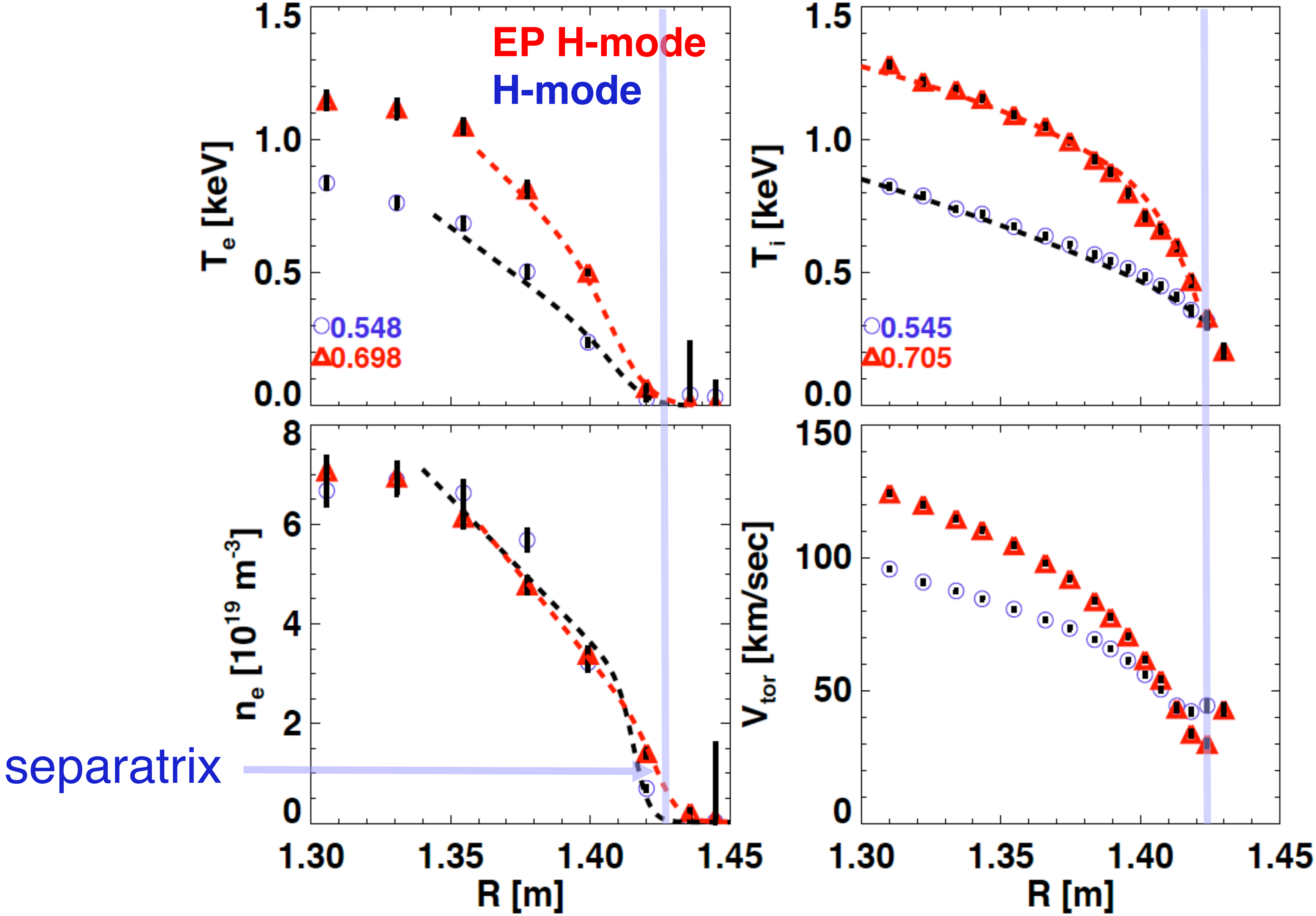
EP-H Development in 2010 Attempted to use SGI, 3-D Fields, and β_N Controls to Develop a Reliable Scenario (II)

Day #2 (1/2 day): Attempt to optimize the pre-SoFT transition scenario

- Natural EP-H phases commonly attained at reduced q_{95}~6 (I_p=1.2 MA)
  - No SGI or n=3 triggers used
  - Occurred (early) in flat-top
- β-feedback control attempted to extend EP-H
  - Aggressive feedback parameters (gain and target beta) successful in rapidly dropping power following transition
  - Early disruption avoided, but second ELM ended EP-H (*more Li needed?*)

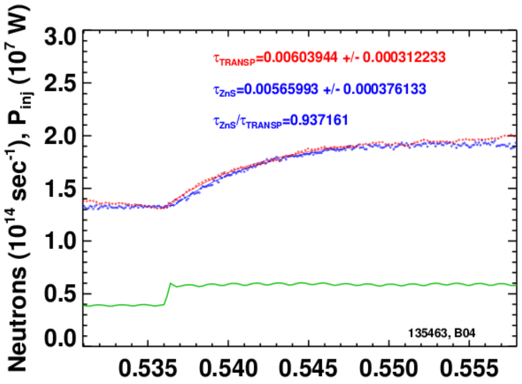


Thermal barrier: Edge T_e, T_i double, with a reduction in the edge n_e gradient, and an increase in v_ϕ shear



Modeling of High Performance H-Mode Plasmas

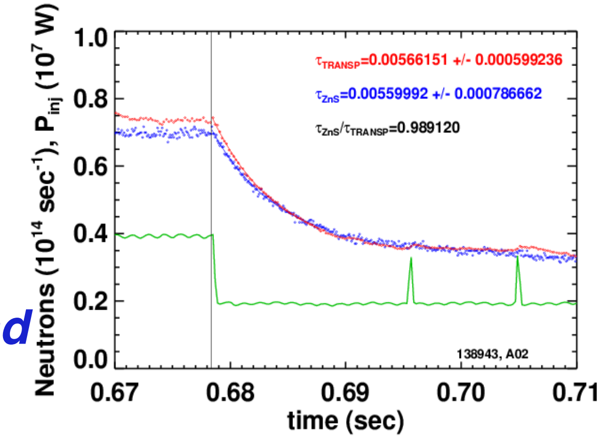
Successful Bench-Mark of TRANSP Neutron Dynamics Against Measurements

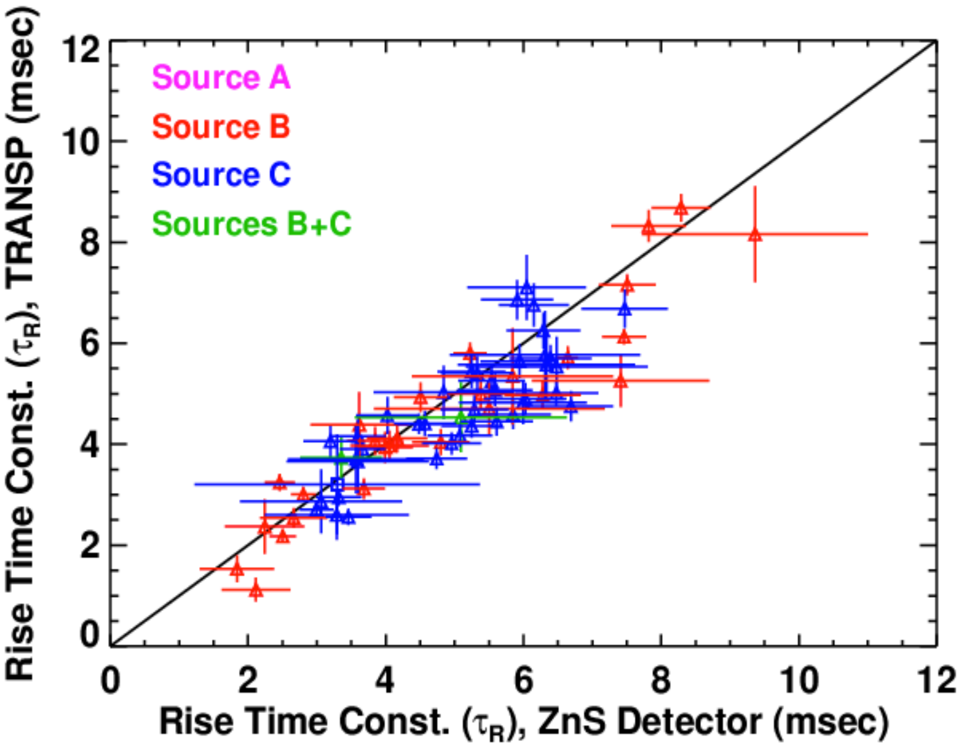


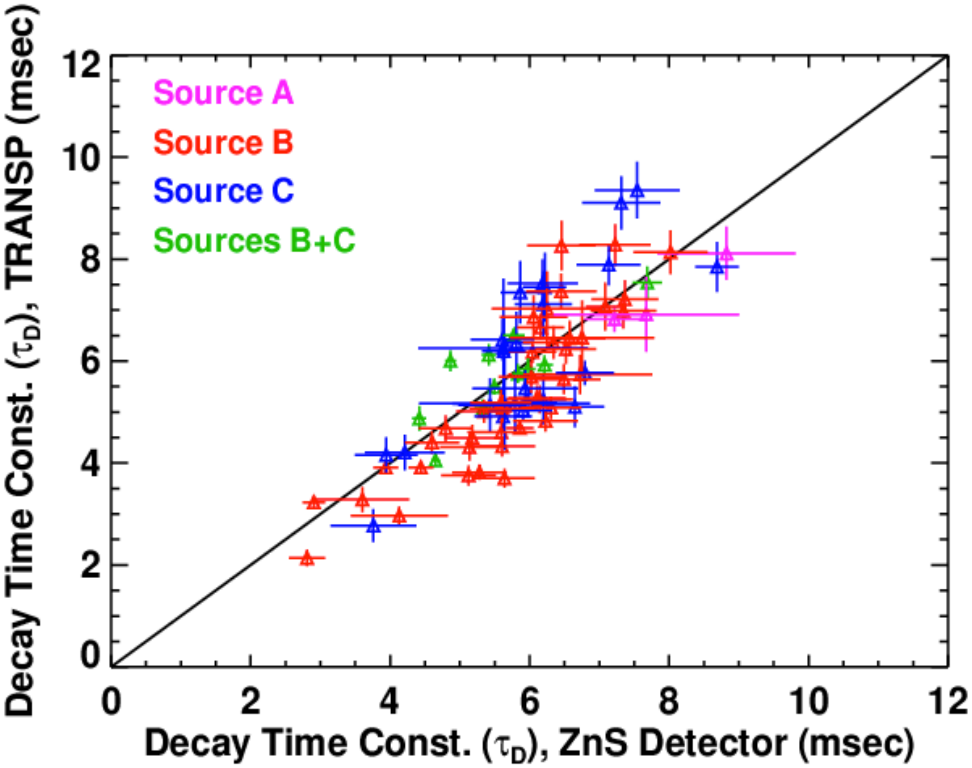
Exponential Fits For Rise and Decay

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

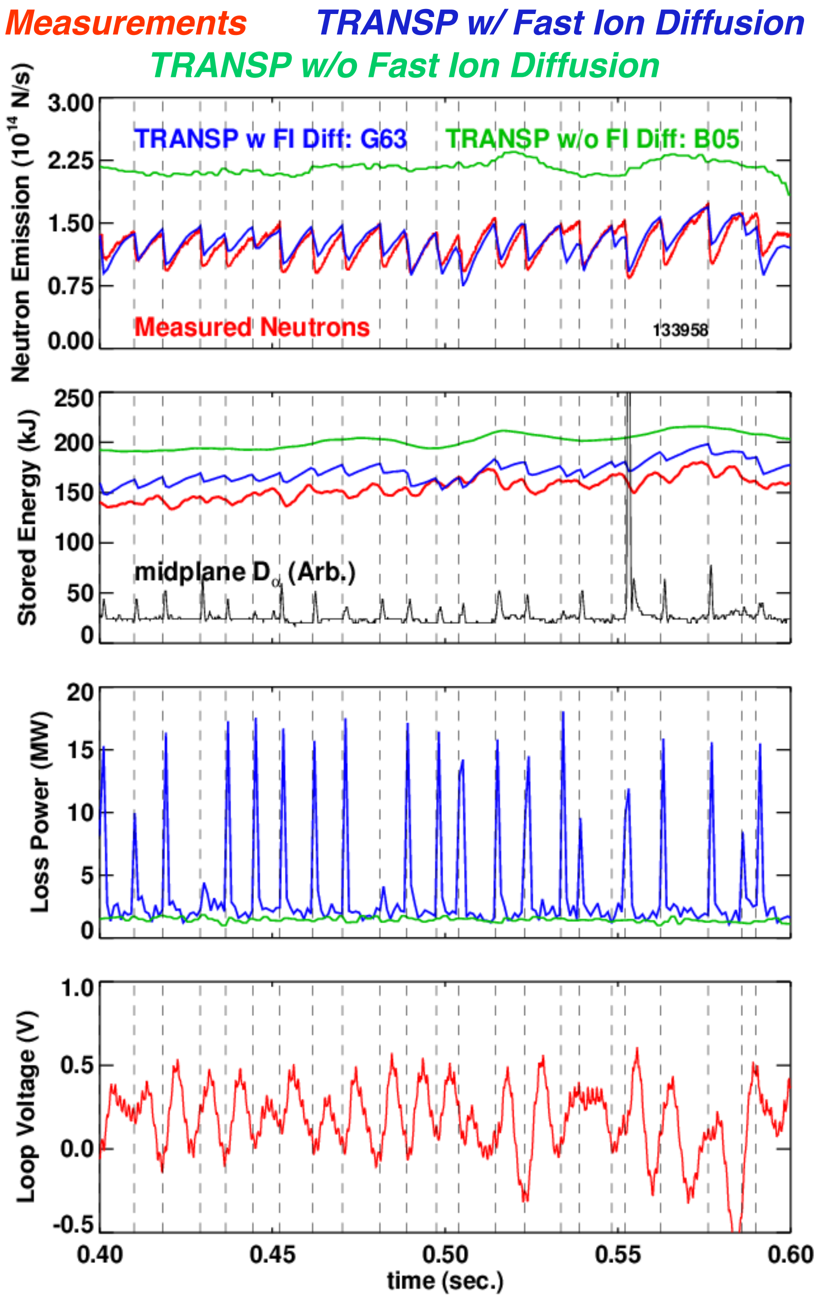
Apply the Same Fit to Measurements and TRANSP Simulations (MHD-free Periods of Discharges)





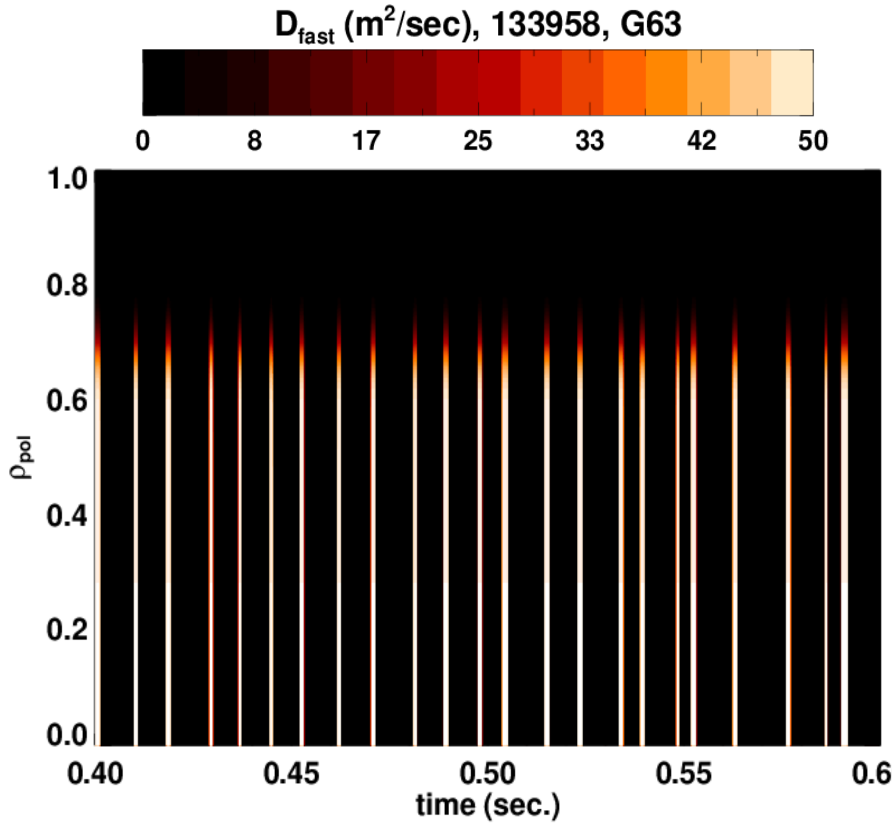


TAE Avalanches Simulated in TRANSP Using Impulsive Anomalous Fast Ion Diffusion



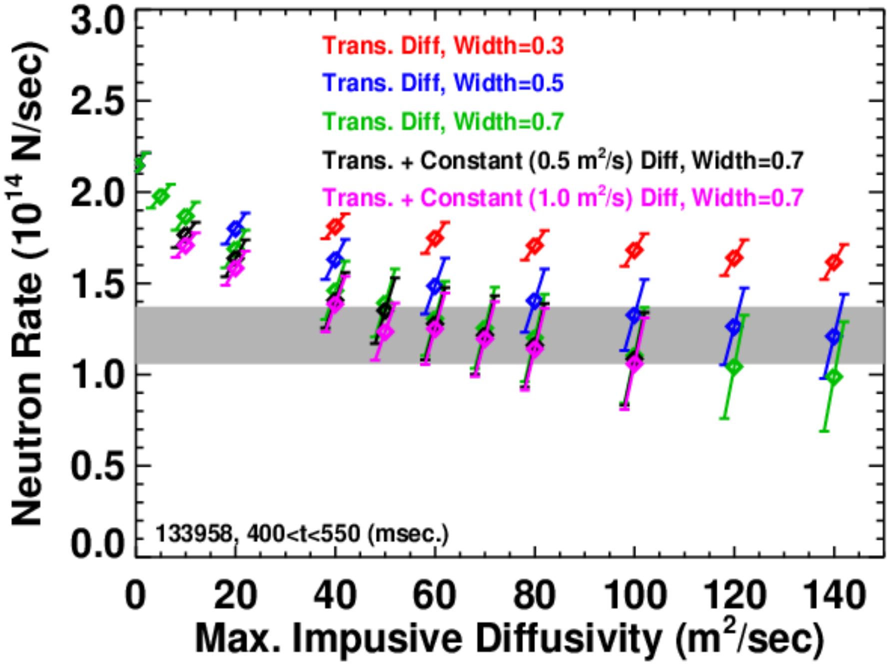
- ***Adjust start time and duration of the pulses to match measured neutron rate drops.***
- ***Fix amplitudes, widths for a given TRANSP run.***

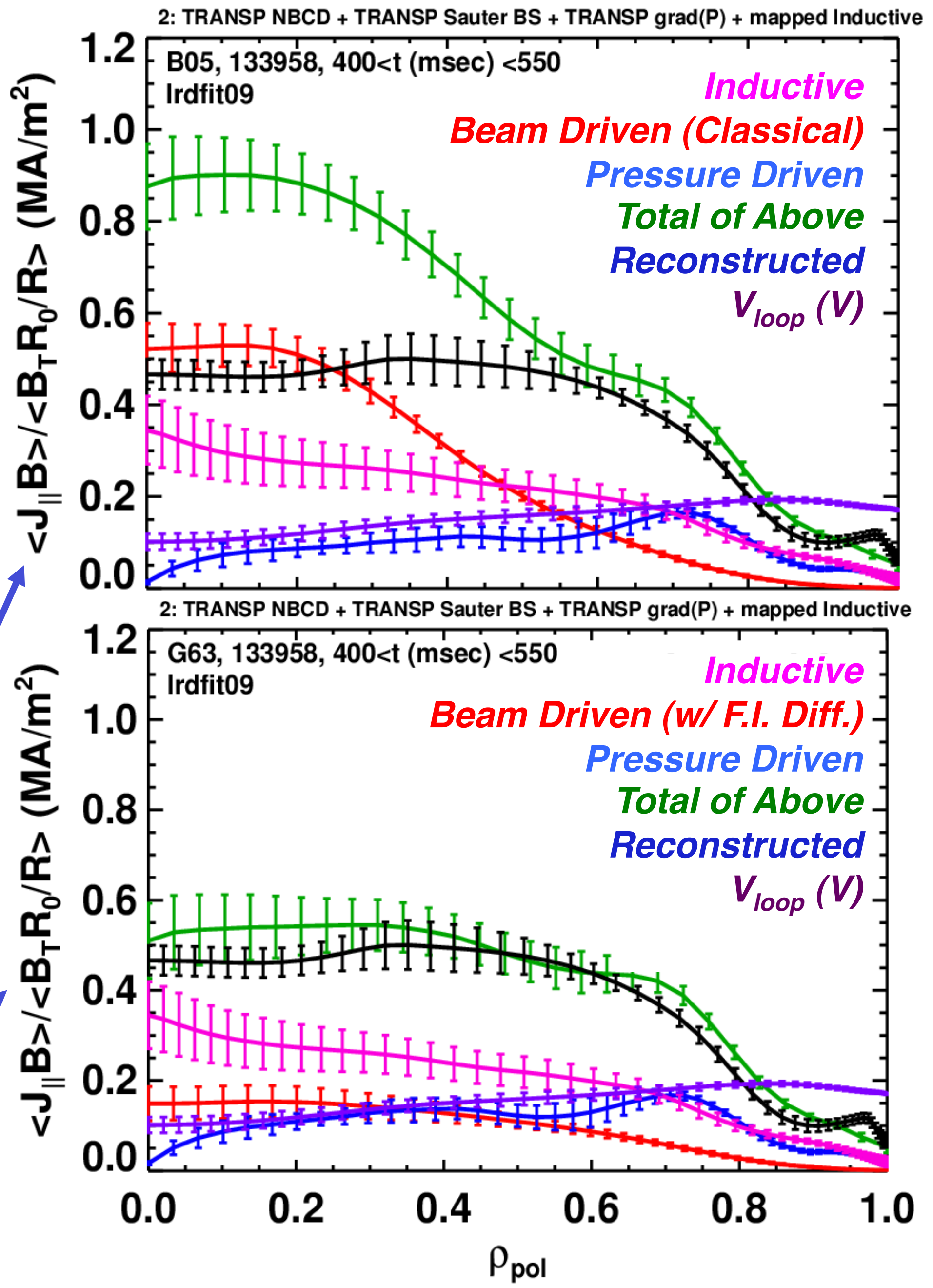
$$D_{FI}\left(\rho_{pol},t\right)=\frac{A_{FI}(t)}{2}\left[1-\tanh\left(\frac{\rho_{pol}-w}{0.05}\right)\right]+D_{FI,DC}$$



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

Optimal Fast Ion Diffusivity Determined From Neutron Rate Drops

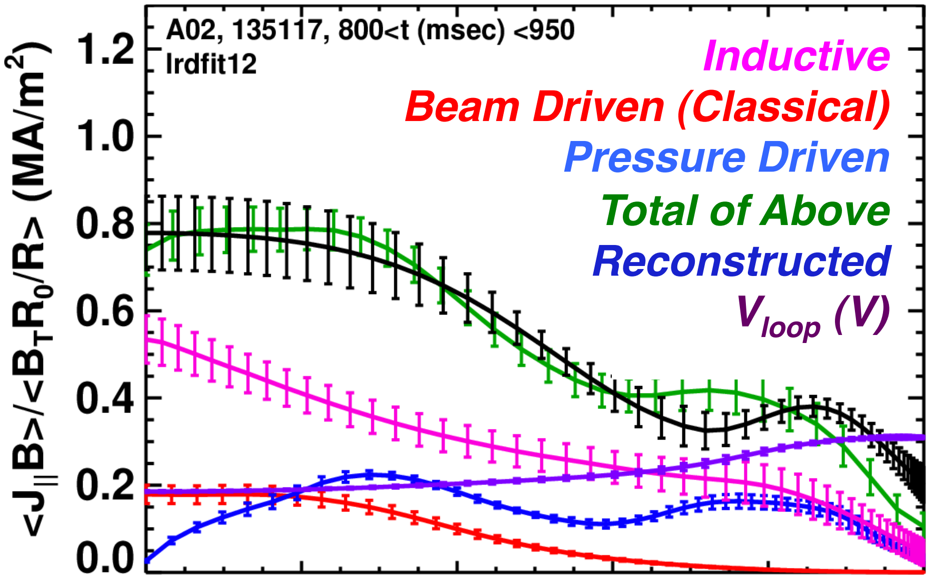




Current profile comparison without fast ion diffusion.

Current profile comparison with impulsive fast ion diffusion.

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

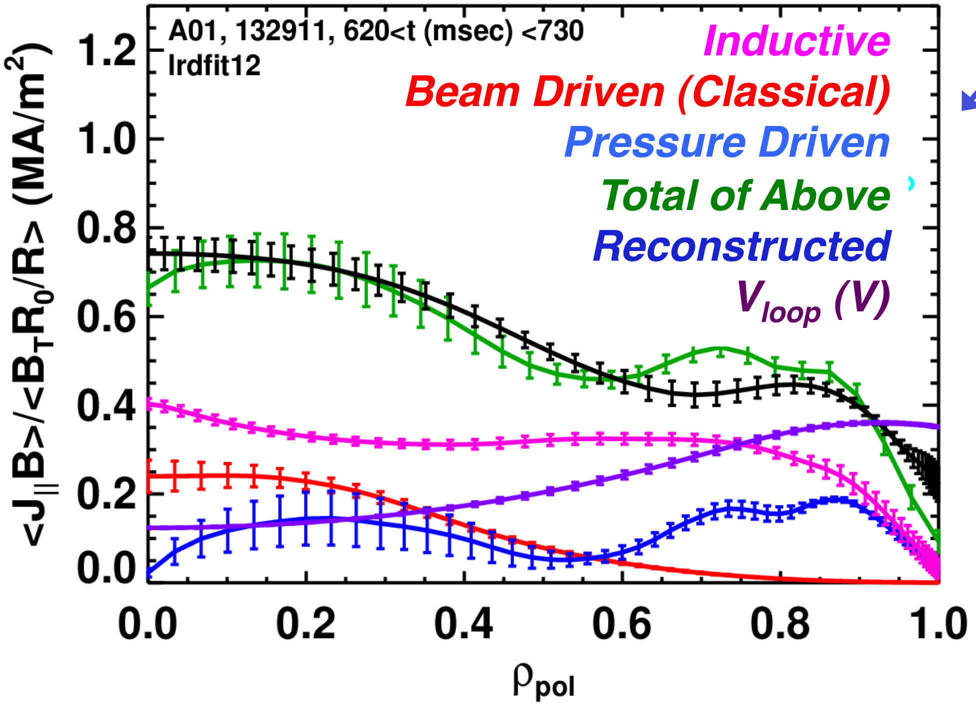


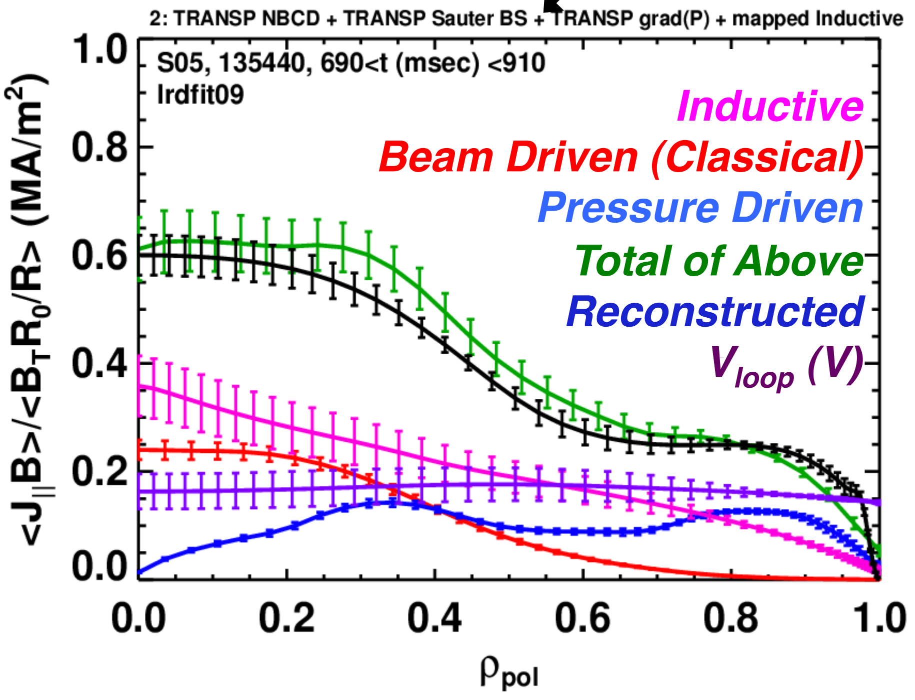
1100 kA, Optimized For Sustained High β_T

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

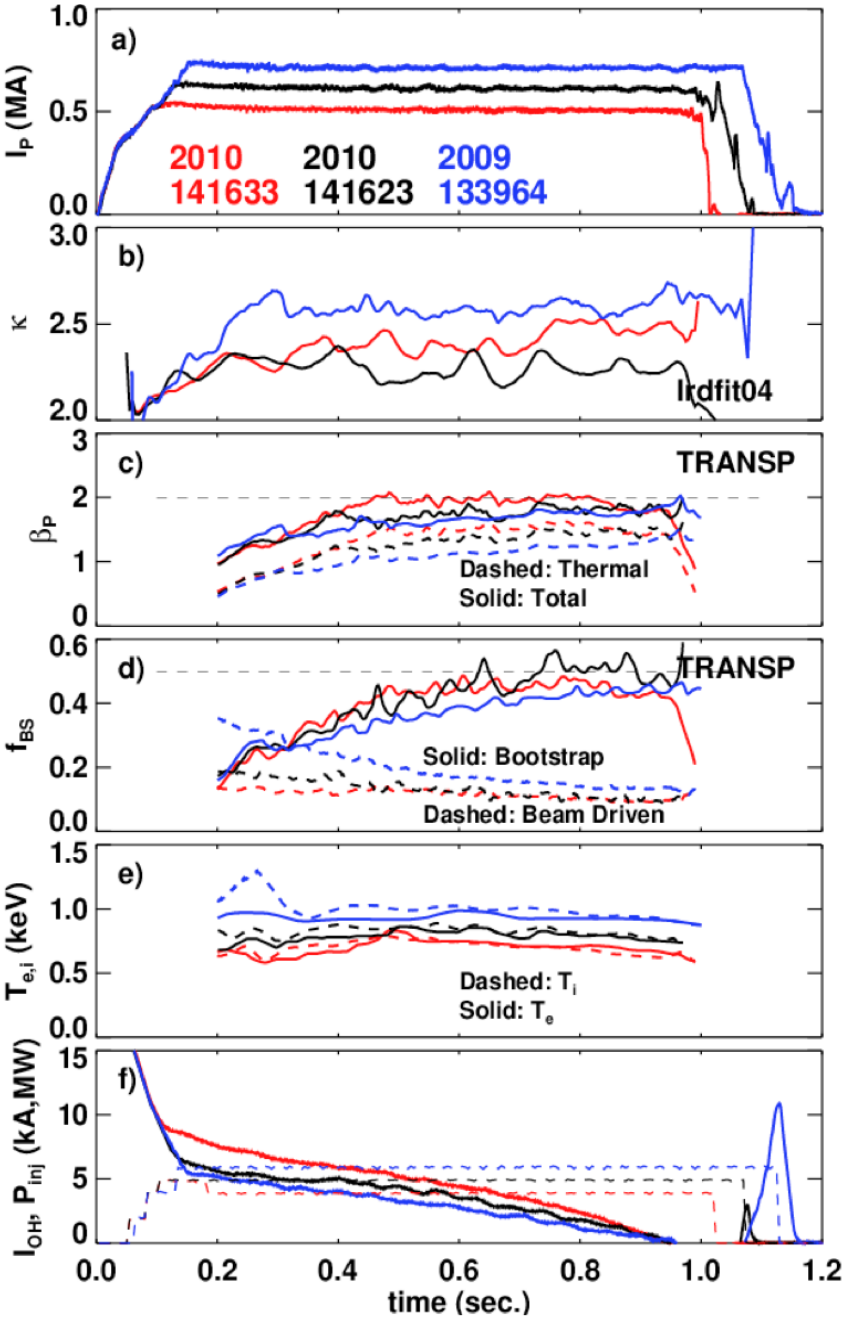




Other Scenario Development

Developed Scenarios With Sustained β_p=2

- Show 500, 600 & 700 kA discharges from 2009 and 2010.
- 500 kA case sustains a total β_P of 2.
- NBCD fraction is much lower for the high β_P cases.
  - Injected power is lowest
  - Electron temperature is lowest.
- Average loop voltage is minimized at the higher current.



Other Control Development

Plasma Control System (PCS) Development Focused on Milestone and NSTX-Upgrade Research Needs

- 2 new PCS programmers hired in October and November of 2010.
  - Previous PCS programmer gone to gradschool.
  - Hires are an important investment in future capabilities.
  - Their learning curve likely a pace setting item for near-term control development.
- Important PCS physics development tasks (in approximate priority order).
  - 2nd SPA installation and code upgrades.
    - Restoration of previous capabilities, RWM coils for n=0 control, n=1&2 LQG RWM.
  - Improved n=0 equilibrium and stability control.
    - Improved dZ/dt estimator, reduced voltage transients during control transitions.
  - Density feedback.
    - Realtime processing of the FIRETIP interferometer signal.
- Realtime V_ϕ diagnostic being developed for rotation control.
  - Presently installing fibers, spectrometer, and camera.
  - Various strategies for transferring data to PCS being evaluated.
  - State space rotation controller has been designed, awaits realtime diagnostic data.

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:

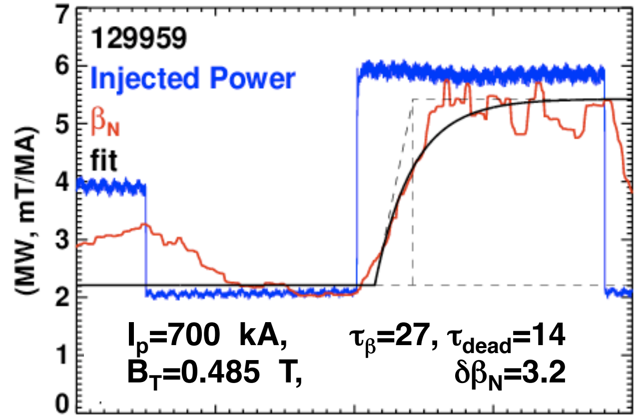
$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

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

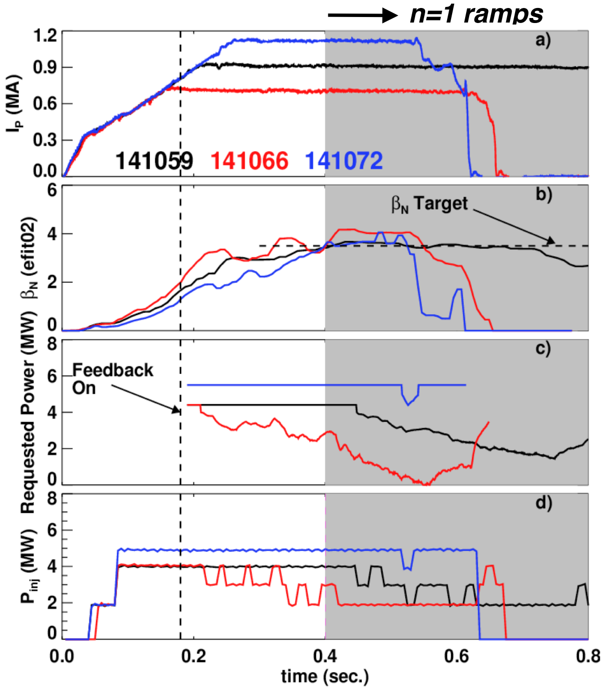
$$\overline{C}_{\beta_N} = \frac{I_P V B_T}{200\mu_0 a\tau}$$

- 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

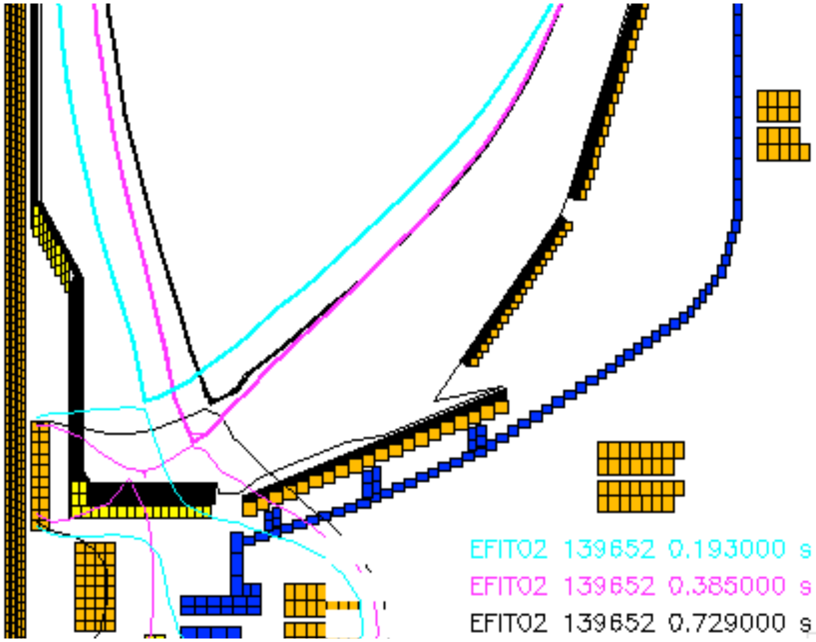


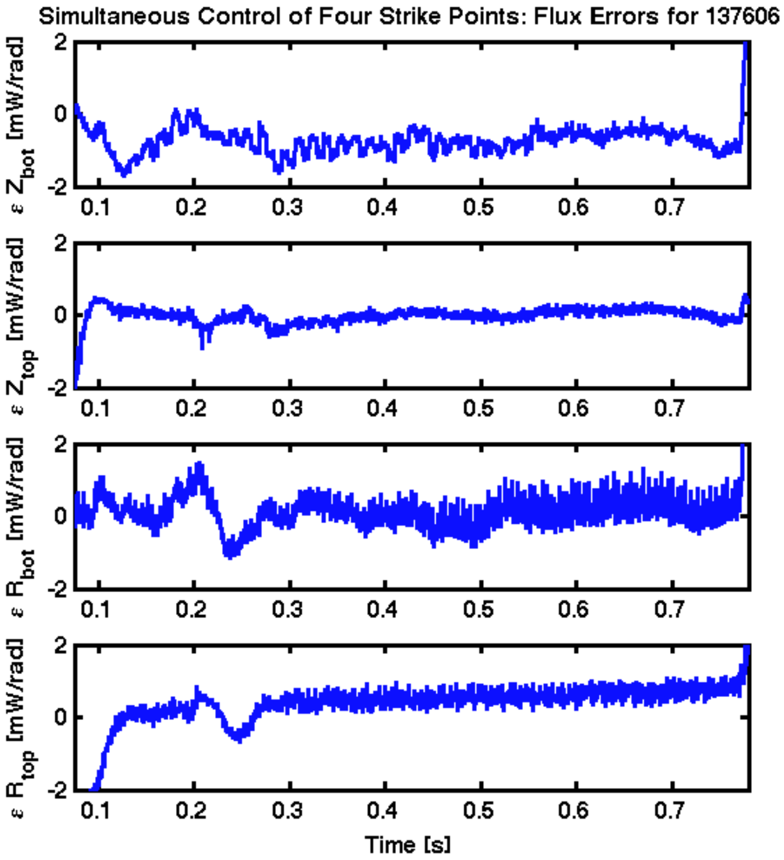
Constant-β_N During I_P and B_T Scans

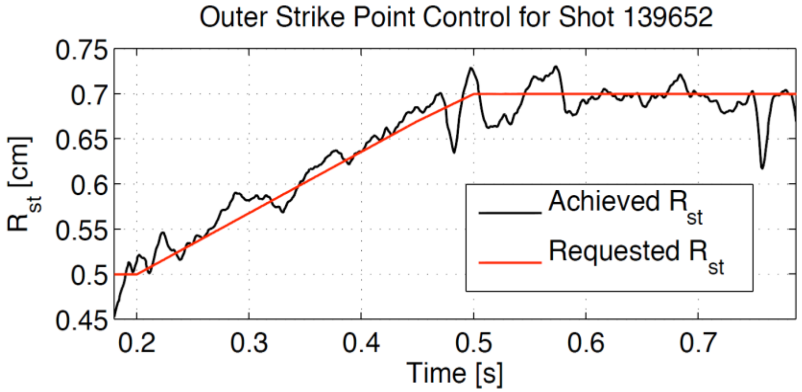


Control of 4 Strike Points Developed To Support LLD Experiments

- FY-09 S.P. Control
  - Had uncontrolled dr_{sep} ramps when only lower S.P. under control.
- FY-10: Optimized 4 S.P. Controller
  - Eliminated dr_{sep} ramps.
  - Used for initial LLD experiments.

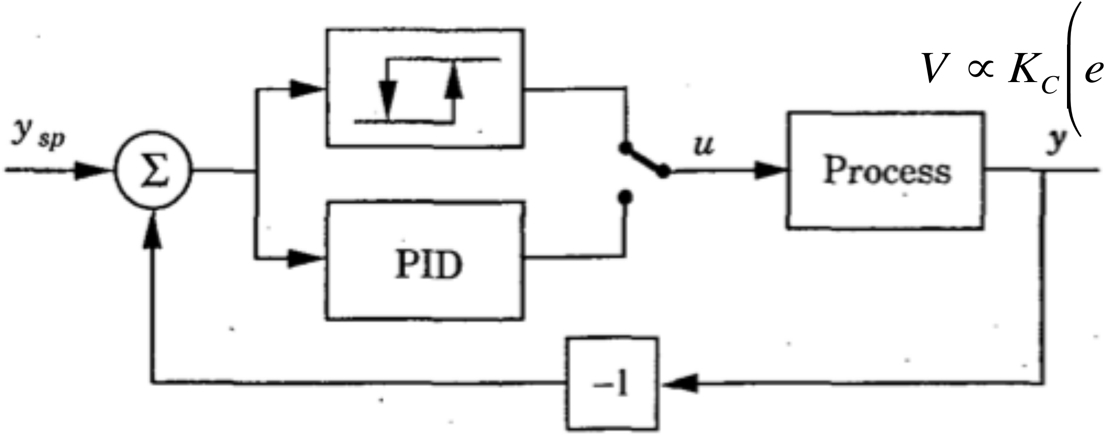




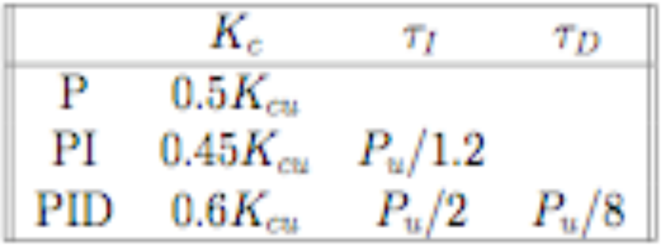


New Capability for Experimental System ID: Closed Loop Auto-tune with Relay Feedback

$$V \propto K_C\left(e + \frac{1}{\tau_I}\int edt + \tau_D \frac{de}{dt}\right)$$



- The closed-loop plant response period (P_u) & amplitude (A) are used for PID controller tuning.

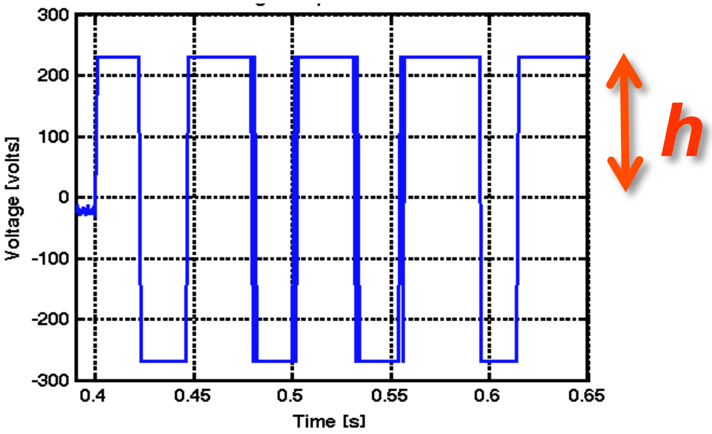


	K_c	τ_I	τ_D
P	$0.5K_{cu}$		
PI	$0.45K_{cu}$	$P_u/1.2$	
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$

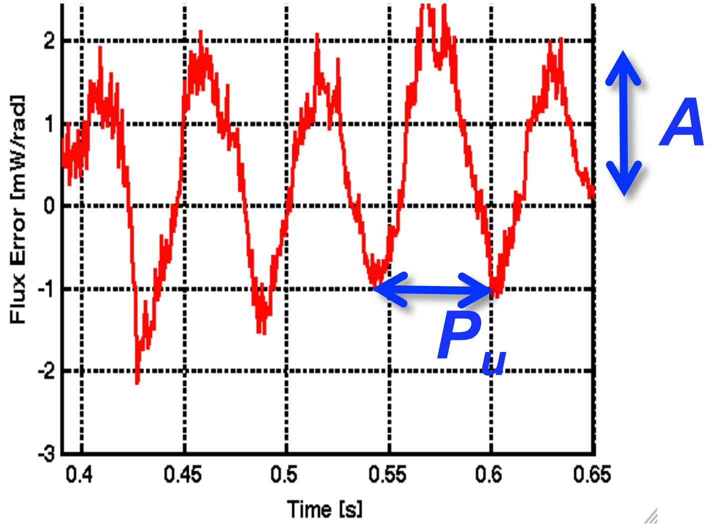
$$K_{cu} = \frac{4h}{\pi A}$$

- Multiple advantages to closed loop tuning:
  - Single-shot system-ID
    - Save experimental time.
  - Enable system ID for actuators that can’t be open loop
    - e.g. vertical control.

Control Output (PF-2L Coil Voltage)

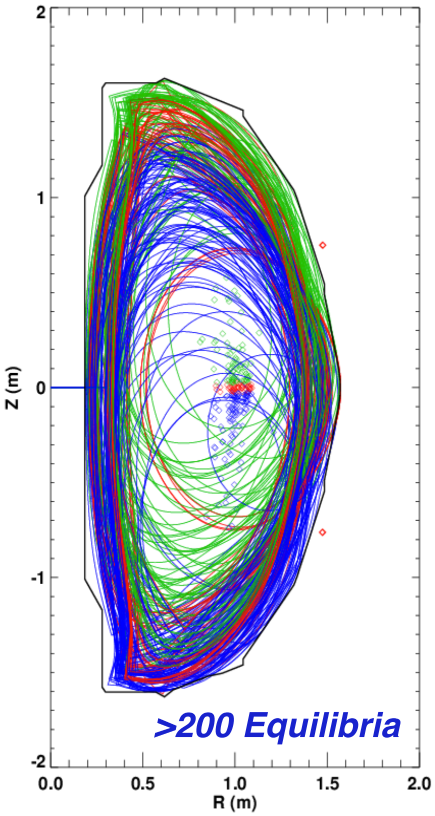


Process Output (Flux Error at Outer S.P.)



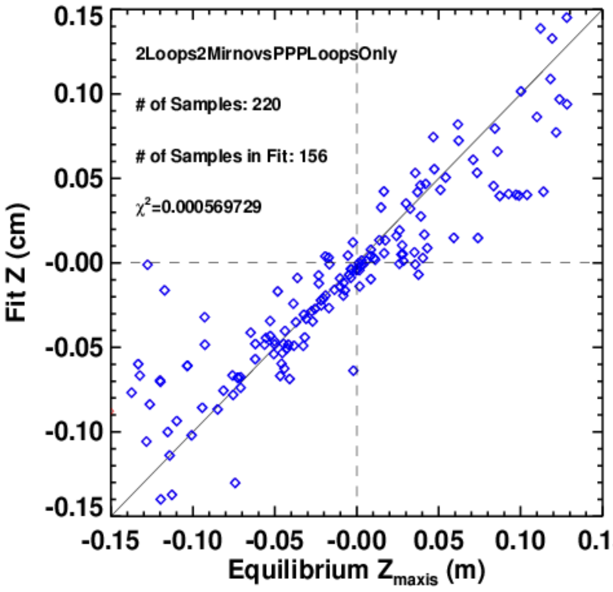
Developing a Better Reatime dZ/dt Estimator For Improved Vertical Control in 2011 & 12

- NSTX has historically used the voltage difference between two loops for derivative control on the vertical position.
  - Assume that $Z_P = \alpha(\psi_U - \psi_L)$, so that $\frac{dZ_P}{dt} = \alpha(V_U - V_L)$.
  - Proportional part of PD controller provided by ISOFLUX.
- Use of additional loops can significantly improve the fidelity of the position, and thus velocity, estimate.
- Bringing additional loop voltages into PCS for improved dZ/dt measurement

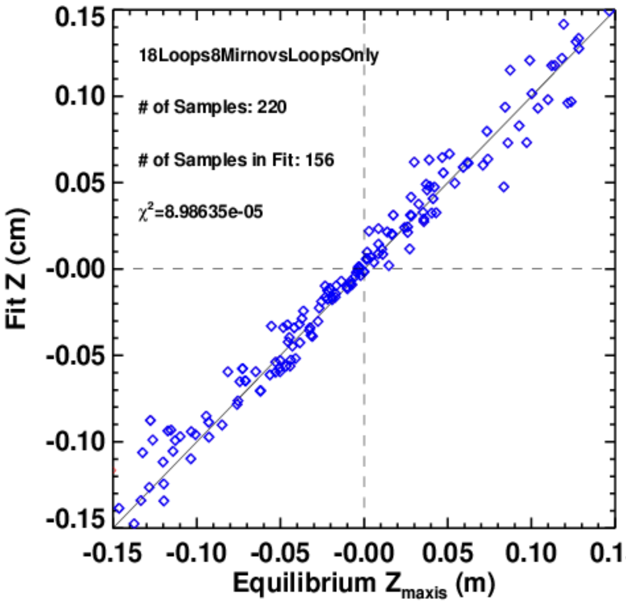


Fit Axis Location to Weighted Sum of Flux Loops $Z_P = \sum_{j=1}^{N_{loops}} \alpha_j \psi_j$

Best fit of Z_P with 2 Loops

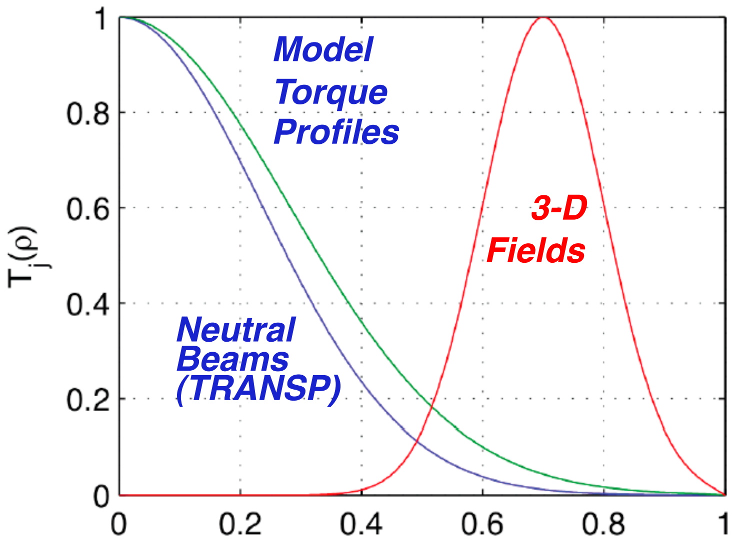


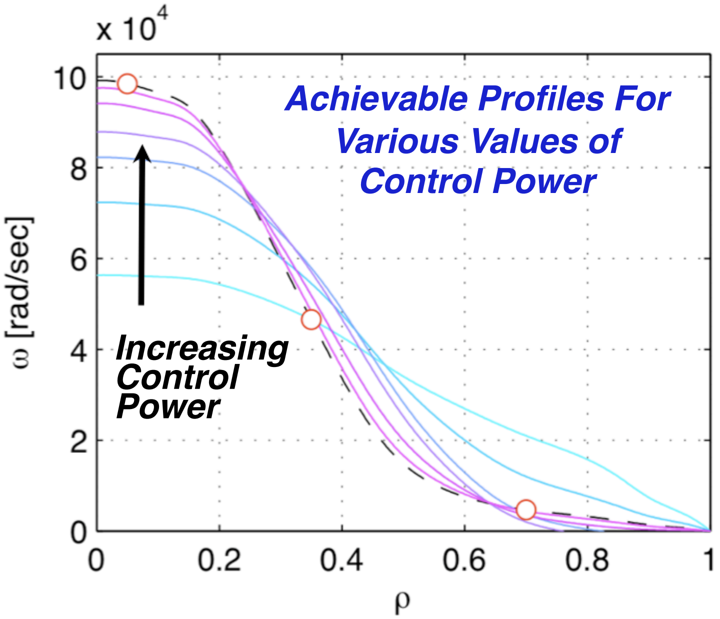
Best fit of Z_P with 18 Loops



Development of Real-Time NB Control Enables β_N and Rotation Control

- β_N control demonstrated in 2009, optimized in 2010.
- Long-term plan to control the rotation profile.
  - RWM & EF physics as a function of β and rotation.
  - Transport dynamics vs. rotation shear.
  - Pedestal stability vs. edge rotation.
  - ***What is the optimal rotation profile for integrated plasma performance?***
- Use a state-space controller based on a momentum balance model.
  - Neutral beams provide torque.
  - 3-D fields provide braking.
  - Different toroidal mode numbers provide different magnetic braking profiles.
    - Use 2nd Switching Power Amplifier (SPA) for simultaneous n=1,2 &3 fields.
- Developing rt-V_ϕ diagnostic for FY-11.
  - Camera has been purchased.
  - Is being tested for real-time acquisition.
- PCS control algorithm implementation driven by the measurement.





K. Taira, E., Kolemen, C.W. Rowley, and N.J. Kasdin, Princeton University.

Improvements to the Shape Controller Will Allow Higher Performance Scenarios and Reduce Development Time.

- Key issue: individual controllers are "selfish"
  - Good control of individual quantities like outer gap or S.P. radius…
  - …but bottom or inner gaps go to zero.
- ISOFLUX controller produces voltage requests via the "M-Matrix" of weights.

$$\overset{\textbf{Coil Voltages}}{\begin{bmatrix} V_1 \\ V_2 \\ V_n \end{bmatrix}} = \overbrace{\begin{bmatrix} M_{11} & M_{1n} \\ & \\ M_{n1} & M_{nn} \end{bmatrix}}^{\textbf{M-Matrix}} \overset{\textbf{Segment Errors}}{\begin{bmatrix} (PID)_1 \\ (PID)_2 \\ (PID)_n \end{bmatrix}}$$

  - M is essentially a diagonal matrix for present scenarios.
    - Implies that the controllers are ignorant of each other.
- More accurate boundary control can be achieved with more complex M-matrix.
  - Accounting for controller interactions.
    - Important at the number of coils increases.
  - Proper weighting of the most important parameters.
    - Can be scenario dependent.
- Desired physics and operations benefits:
  - Better regulation of inner and bottom gaps in high-performance plasmas.
  - More rapid development of complex scenarios.
- Highly desirable for NSTX-Upgrade, where manual programming of 16 coils, including interactions, will likely be impossible.

Example high-κ shape and control segments

OH leakage flux drives the bottom gap to zero