Advanced Scenarios and Control Research in NSTX: Progress in FY-09 and Future Plans

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NSTX PAC-27
B318, PPPL
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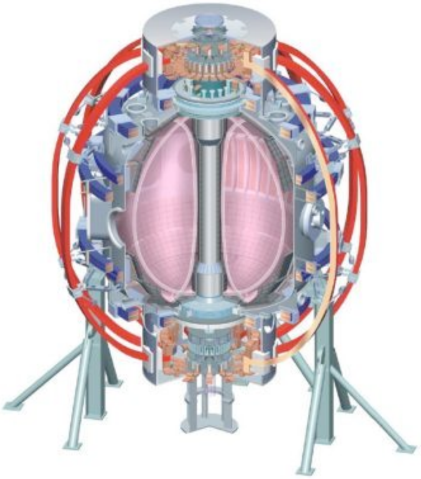

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Steady-State STs Will Rely on Strong Shaping & High-β

Common Features of Present & Future STs

- ***High-κ and strong shaping.***
- ***β_N values at or above the no-wall limit.***
- ***Bootstrap fractions ≥50%.***
- ***Confinement ≥ H-mode scaling.***
- ***Comprehensive shape, profile and stability control.***

Configuration Specific Features

- ***Range of normalized currents.***
- ***Wide range of NBCD fractions.***
- ***Wide range of normalized densities.***

[1]: Peng, et al, PPCF 2005, Phase #3, 2 MW/m^2 NWL
[2]: ARIES-ST

	NSTX	NSTX-U	NHTX	ST-CTF[1]	ST-Demo[2]
κ	2.6	2.7	3	3.1	3.5
β_N	5.7	5.7	5	4-6	7.5
$l_i(1)$	0.55	0.65	0.6	0.35	0.25
I_N	2.5	2.1	3	4.5	6.7
f_{GW}	0.8	0.7	0.45	0.28	0.8
f_{BS}	0.54	0.7	0.7	0.5	0.96
f_{NBCD}	15	30	0.3	0.5	0
H_{98}	1.	1.2	1.3	1.5	1.3

Scenario and control needs of these future devices, coupled to NSTX capability, are used in forming ASC research plans.

Goals for the Advanced Scenarios and Control TSG

- ***Achieve long-pulse density control for increased NBCD using improved fueling and lithium conditioning.***
- ***Develop high non-inductive current fraction plasmas with high-β and high bootstrap fraction.***
- ***Develop scenarios utilizing High-Harmonic Fast Waves for core electron heating, impurity reduction, and current drive.***
- ***Develop and implement improved plasma control techniques to achieve advanced operating scenarios.***

Research Milestone R(11-2):

Assess the dependence of integrated plasma performance on collisionality.

- **Use LLD to reduce the density.**
- **Use HHFW to heat the electrons.**
- **Assess non-inductive current fraction, confinement, core and pedestal stability, pulse-duration, impurity content.**
- **Compare with time-dependent simulation codes (TRANSP & TSC).**

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Outline: FY-09 Results and Future Plans

- High-κ neutral beam heated scenario development
  - Incorporation of LLD into ASC research
- Shape and divertor control research
- Density and impurity control research
- Incorporation of HHFW heating in advanced scenarios
- Non-inductive current ramp-up
- Rotation Control Development
- Summary

Plans Are Indicated in Grey Boxes

Studied a Range of High-κ Discharge Scenarios in 2009

High-β_P, q_{95}≈15:

Maximize non-inductive fraction

Limited by I^2t on TF coil

Long pulse, q_{95}≈11:

Fully equilibrated profiles

Match TF I^2t and solenoid current limit

High-β_T, q_{95}≈8:

Toward reactor I_N, β_T and q^*

Limited by solenoid current or MHD.

<u>All configurations:</u>

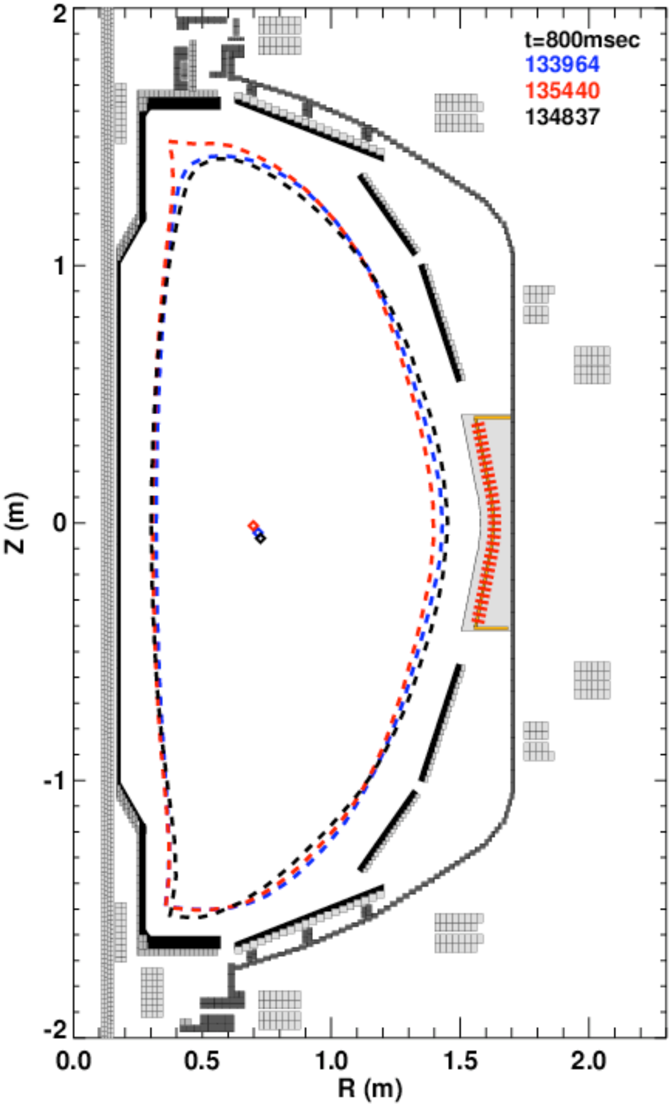
High-κ and δ (κ~2.7 & δ~0.8)

Near double-null ($|dr_{sep}|$<3mm)

(Shaping and improved power handling)

Lithium Conditioning

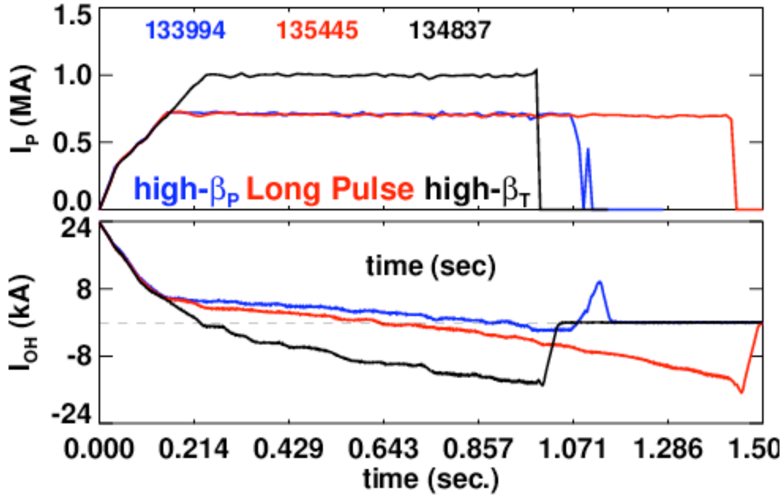
Dynamic Error Field Correction+RWM Control

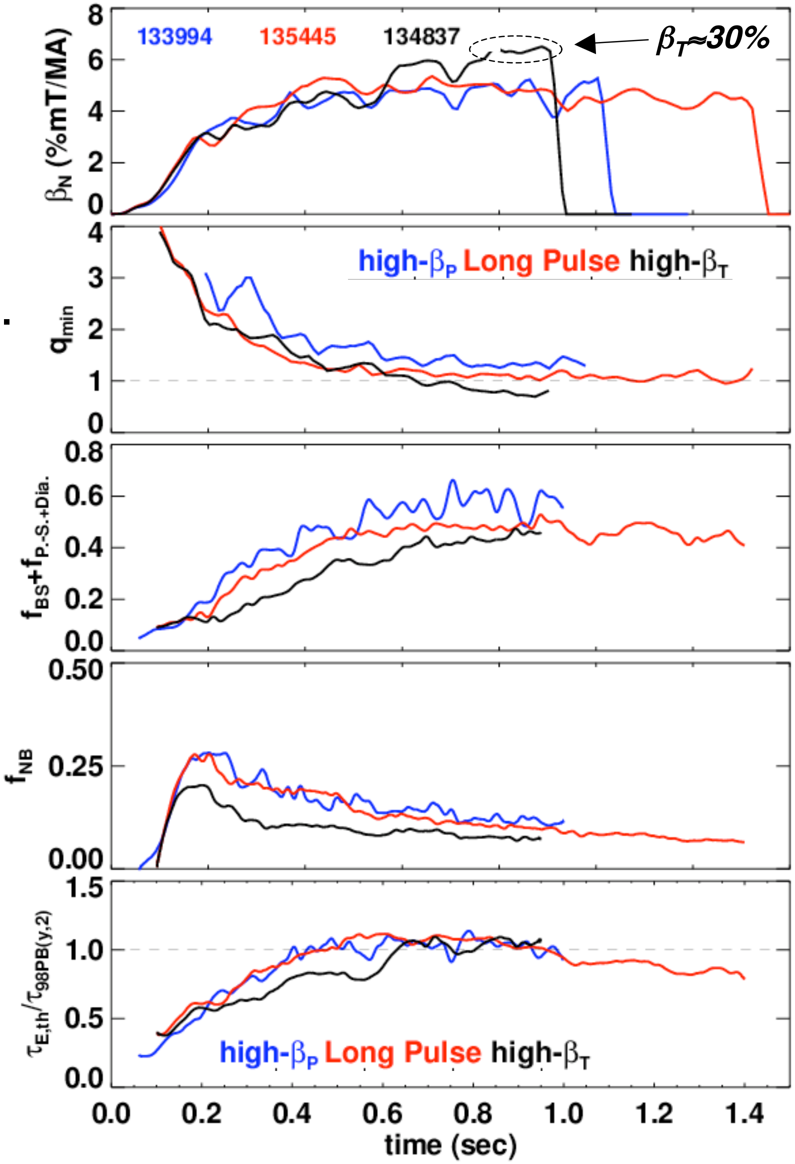


PAC25-30

Large Non-Inductive Fraction and Good Confinement Achieved Over a Range of q at High-κ

- $\beta_N \geq 4.5$ for all scenarios.
  - Matches ST-CTF design point.
- f_{BS} approaching 55-60%.
  - Matches ST-CTF design point.
- Early $f_{NB}>25\%$, decreases as density rises.
  - Loss in f_{NBCD} partially made up for with f_{BS}.
- $H_{98}\sim 1$ in all cases.
  - Further confinement improvements are desirable.



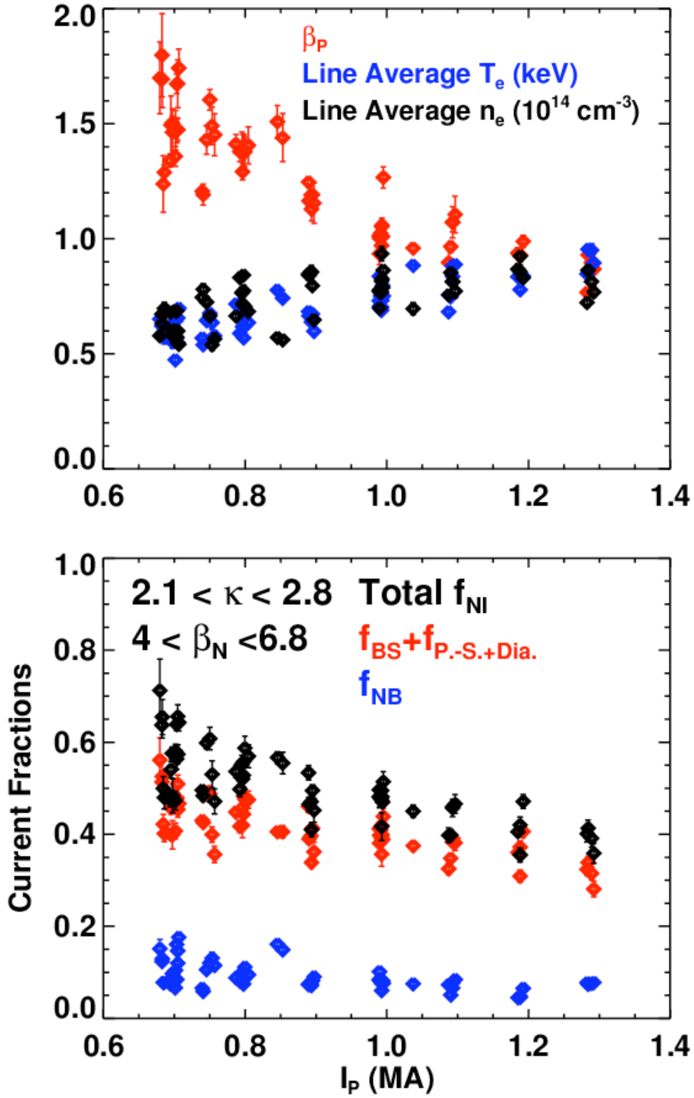


Present Configurations Are Limited to f_{NI}<70%

Loss of NB heating efficiency prevents operating at lower plasma current.

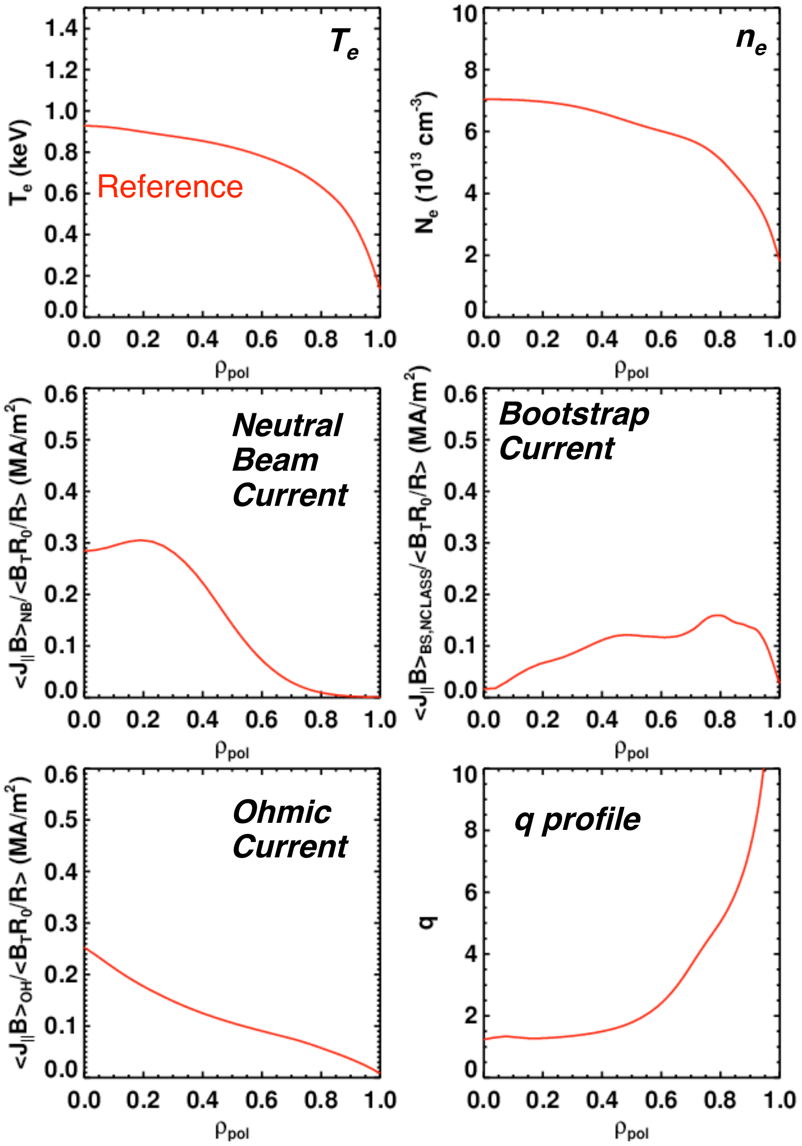
Near-term options for increasing f_{NI} in high-power NBI scenarios:

- Reduce density for increased NBCD.
  - –Pumping with LLD.
- Increase the temperature for higher NBCD and bootstrap current.
  - –Confinement improvements with LLD and/or HHFW heating.



LLD Expected to Have Major Impact on Non-Inductive Currents

- Utilize profiles from high-κ, high-β_P shot.
  - Fix plasma boundary and Z_{eff}=2.
- Scales profiles to examine effect of f_{NI}.
  - Reference
    - **f_{NBCD}=15% , f_{NI}=75%, H_{98}=1.1**



PAC25-32

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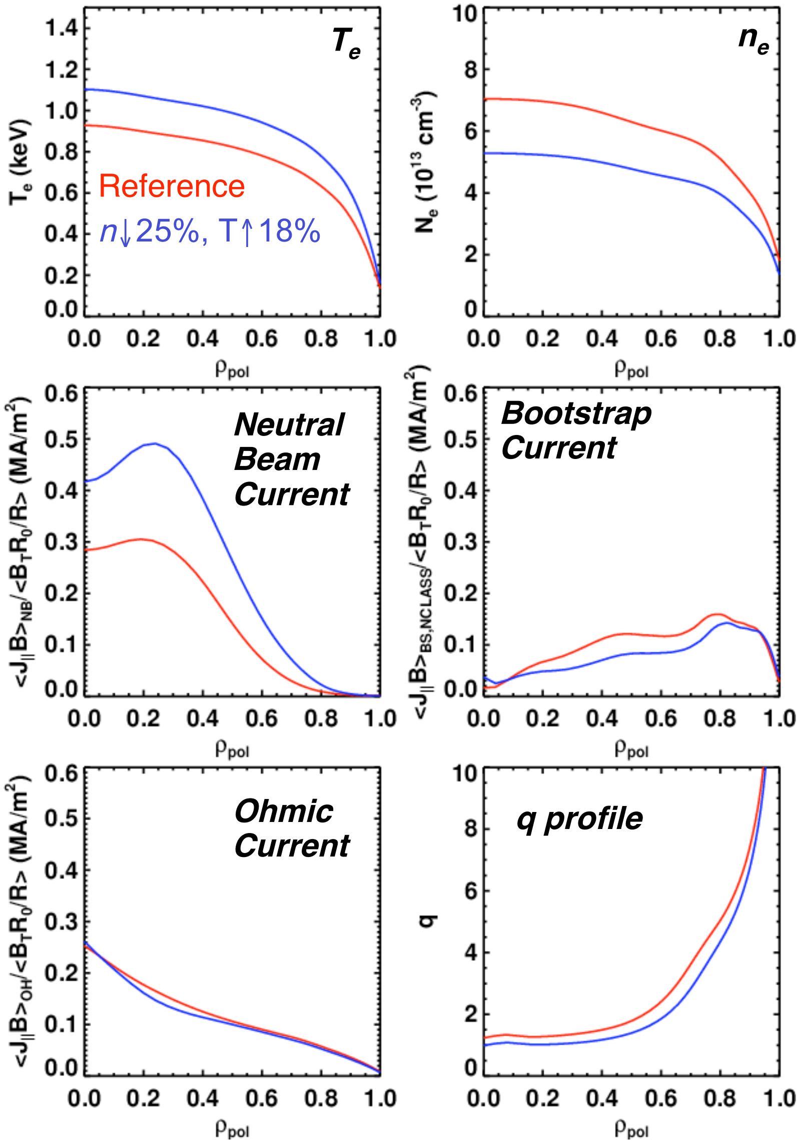
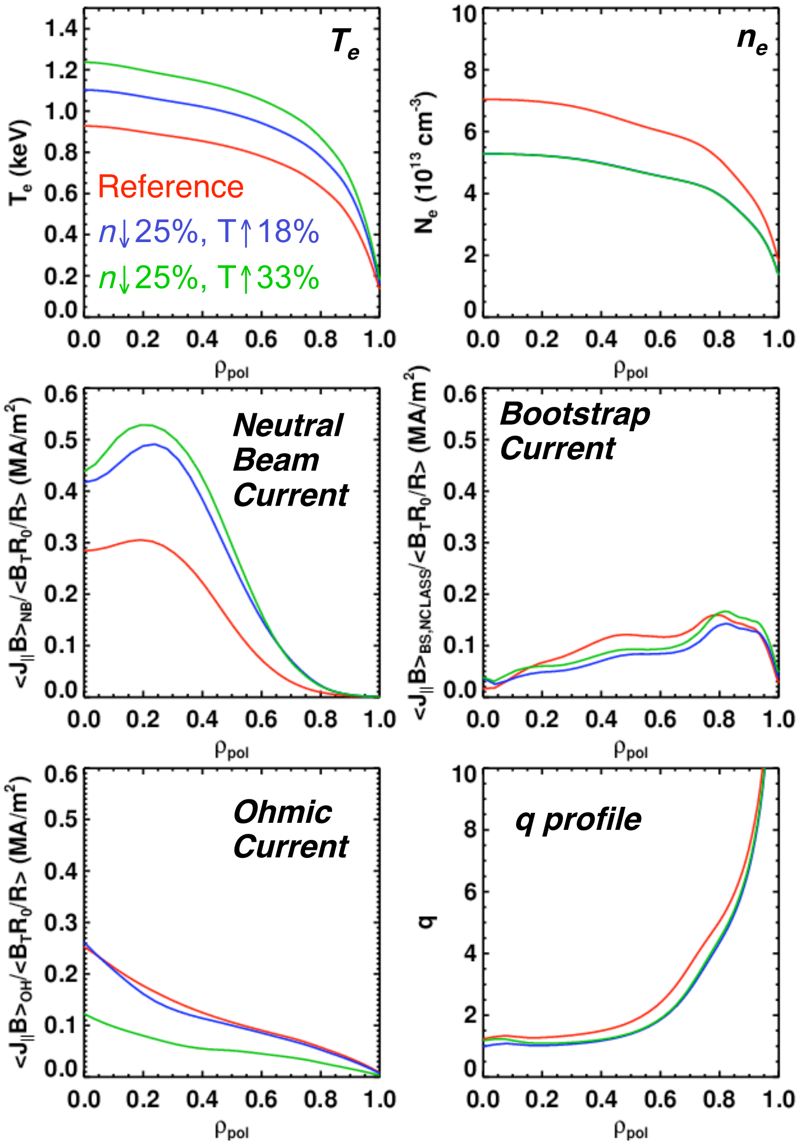
  - Reference
    - **f_{NBCD}=15% , f_{NI}=75%, H_{98}=1.1**
  - Density ↓ 25%, Temperature ↑ 18%
    - **f_{NBCD}=26% , f_{NI}=80%, H_{98}=1.1**



PAC25-32

LLD Expected to Have Major Impact on Non-Inductive Currents

- Utilize profiles from high-κ, high-β_P shot.
  - Fix plasma boundary and $\boldsymbol{Z_{eff}}$**=2**.
- Scales profiles to examine effect of f_{NI}.
  - Reference
    - $\mathbf{f_{NBCD}}$**=15% ,** $\mathbf{f_{NI}}$**=75%,** $\mathbf{H_{98}}$**=1.1**
  - Density ↓ 25%, Temperature ↑ 18%
    - $\mathbf{f_{NBCD}}$**=26% ,** $\mathbf{f_{NI}}$**=80%,** $\mathbf{H_{98}}$**=1.1**
  - Density ↓ 25%, Temperature ↑ 33%
    - $\mathbf{f_{NBCD}}$**=27% ,** $\mathbf{f_{NI}}$**=90%,** $\mathbf{H_{98}}$**=1.3**
- Increasing T_e and T_i by 25% in Z_{eff}=2 reference case yields fully non-inductive operation.
  - Z_{eff}=3 requires 40% increases in the temperatures.



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- Simulations demonstrate the importance of the thermal transport response to LLD.
  - New post-doc for transport modeling starting in March.
- Recently revisiting TSC models for NSTX:
  - Realistic vessel model for time dependent simulations (R. Sayer, ORNL)
  - Calibrated against flux loop data for single coil vacuum shots.
- Beginning to model discharge evolution with TSC+NUBEAM.
  - Make discharge evolution modeling more routine.

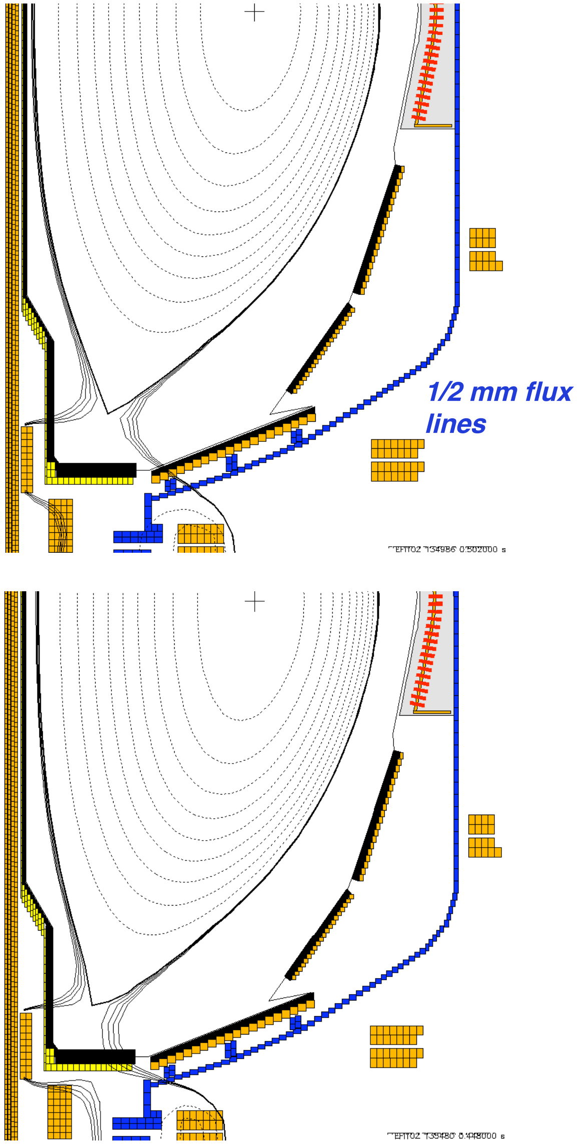
Plans for increased f_{NI} operation

- Study the effect of LLD on NBI high-κ scenarios.
  - Reduced density for increased NBCD.
  - Confinement improvements at fixed density?
- Develop scenarios with HHFW+NBI for core electron heating.
- Assist with HHFW-only experiments at reduced-I_p.

PAC25-32

Divertor Control Improvements in FY-09 Supported Multiple NSTX Programmatic Needs

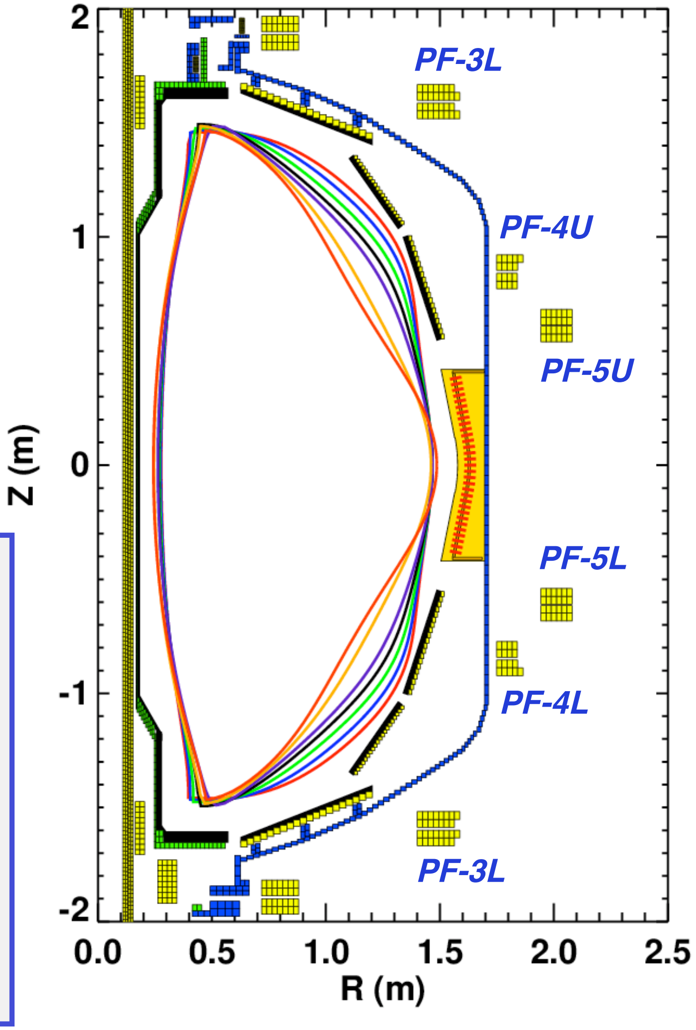
- High-κ, $-\beta$, low-l_i discharges test limits of control.
- Developed outboard strike-point (OSP) radius control on the outboard divertor at moderate δ.
  - Open-loop system-ID experiment as first XP of 2009 run.
  - Closed loop testing and validation.
  - Direct support of LLD operational scenarios.
- Used that experience to develop additional control schemes:
  - OSP radius control on the horizontal inner divertor.
  - Inner strike point control on the vertical inboard divertor.
- This capability used for snowflake divertor experiments (Soukhanovskii, et al.)
  - Adjust the outer squareness, OSP radius, and ISP height to achieve desired dual X-point configuration.



Control Development Will Extend the Range of Achievable Plasma Shapes by Using all PF Coils in Feedback Control

- Address ST specific issues.
  - Without inboard coils, control of the inner gap requires sacrifice of some other shape parameter.
- Need to develop control of high flux-expansion divertors.
  - Contributes to NSTX-Upgrade development.
- Control develop is the primary responsibility of our new post-doc Egemen Kolemen.

Boundary shapes possible when PF4 & PF-5 provide vertical field

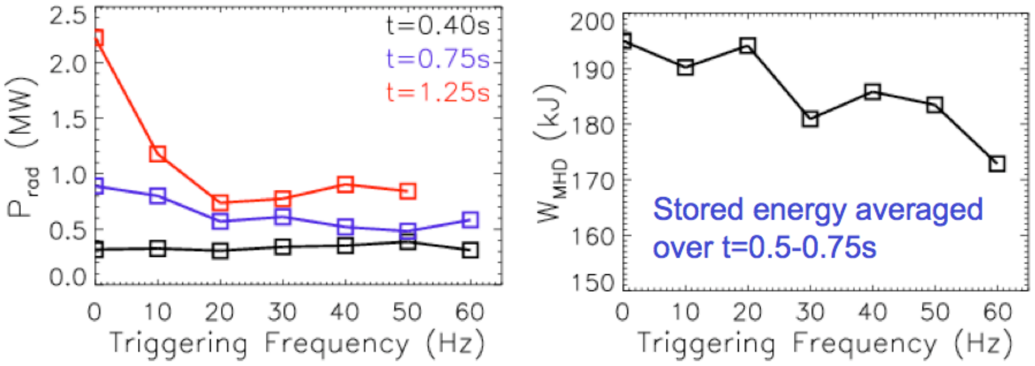


Boundary Control Plans in 2010

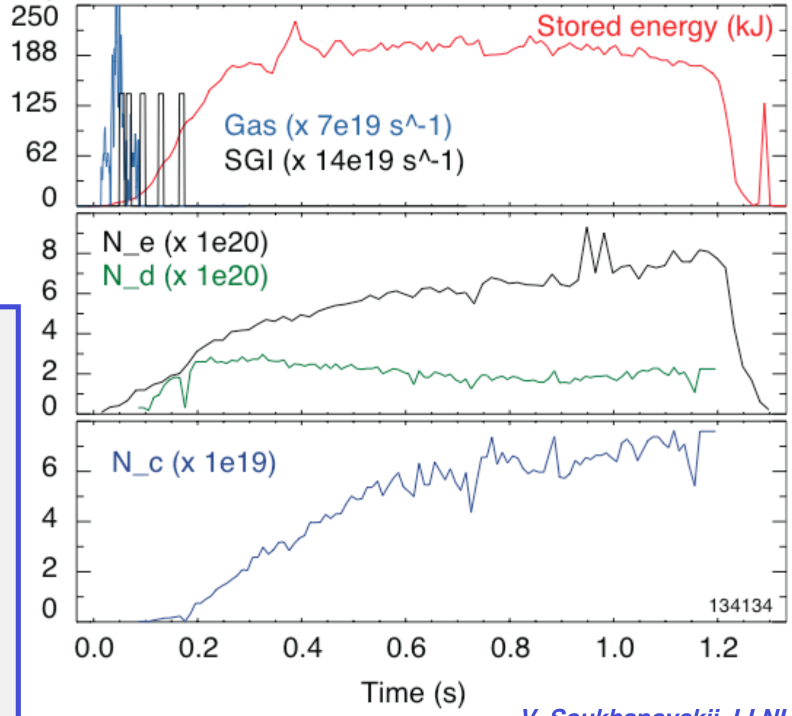
- Implement routine upper and lower outer strike-point control.
- Develop OSP radius and X-point height control.
- First test of squareness control.
- Develop realtime detection of multiple X-points for future snowflake divertor control (LLNL, GA, PPPL collaboration).

Impurity Control and Fuelling Methods Important For Future Scenario Development with Lithium

- Substantial radiated power reduction with low-frequency 3-D field ELM triggering.
    - Little time-average braking.
    - Little confinement degradation.
- Deuterium inventory control with Supersonic Gas Injection
    - Lithium conditioned discharge.
    - No high field side gas injection.
    - Deuterium density reduced through the shot.
    - Increased electron density from carbon source.
- Combined rapid pacing + SGI:
    - Maintain flat ne-bar for ~350 msec.



John Canik, Rajesh Maingi, Aaron Sontag, ORNL



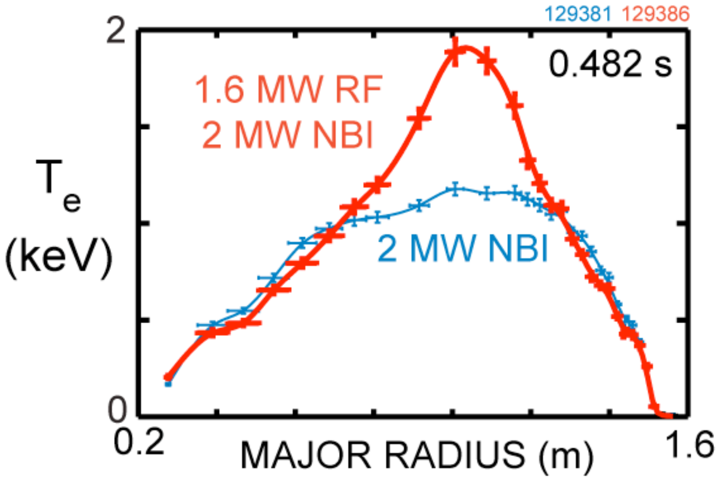
V. Soukhanovskii, LLNL

Impurity & Fuelling Related Plans in ASC in 2010

- Synergy between vertical jogs & 3-D fields for ELM pacing with minimal performance impact.
    - Support for ITER needs.
- Improved early discharge evolution with error field correction & reduced impurity content.
- Glean operational knowledge on LLD pumping and fuelling from BP and Li TSG XPs.

Exciting Plans to Incorporate HHFW into Advanced Scenarios

- H-mode electron heating shown in 2008 & 2009.
  - See HHFW talk by G. Taylor for more details.
- Antenna upgrades in 2009 resulted in limited HHFW availability for ASC experiments.



PAC25-18,25,29

ASC Experiments with HHFW Planned in 2010

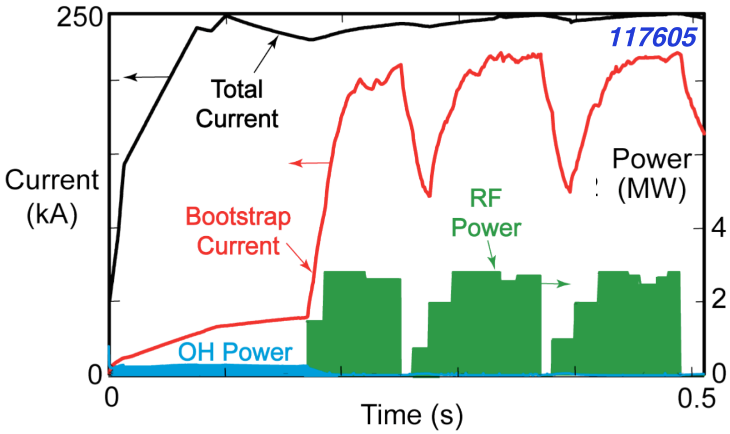
- HHFW heating during the I_P flat-top in H-mode.
  - Develop lower-collisionality targets for increased NBCD.
  - Additional goal to reduce impurity accumulation with core heating.
- Use of early HHFW for modifications to the current ramp.
  - Develop an efficient pre-heating method.
  - Develop an actuator for a q_{min} controller for NSTX-U (with rt-MSE).
- Development of reversed-shear H-mode.
  - Dramatic reduction in core electron transport in reversed-shear L-mode discharges…potential for major reduction in core transport.

Beginning a multi-year effort to incorporate HHFW in advanced plasma scenarios.

Non-Inductive Ramp-Up and 100% Bootstrapped Scenario Developed in Conjunction with WPI & SFSU TSGs

- Previous experiments demonstrated periods of f_{BS} up to 0.85 at low current.
- Experiments in 2010 lead by WPI & SFSU.
- Unique scenario and control needs:
  - rtEFIT convergence at low plasma current.
  - Outer-gap maintenance for HHFW coupling.
    - Rendered difficult by low I_P, rapid profile evolution around RF trips.
  - Determination of the optimal shape for sustainment experiments.

HHFW Heating at Low I_P



Experiments in 2010 with HHFW at low T_e and I_P

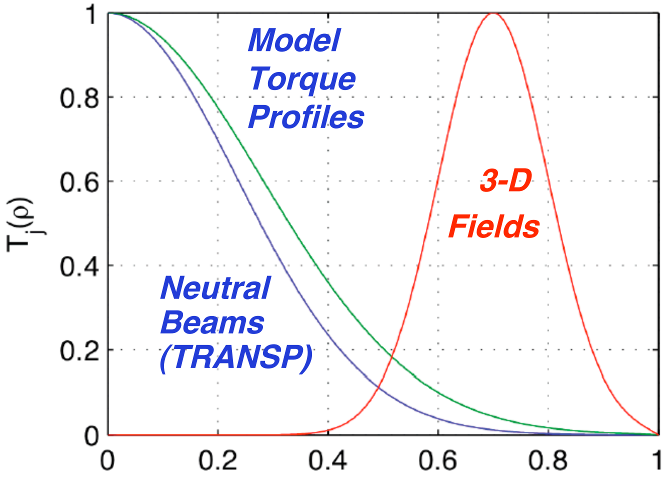
- Form low-current Ohmic target, then add RF.
- HHFW Heating of low-I_P Plasmas
  - Begin with a 500 kA discharge, at 3MW of RF.
  - Reduce I_P in steps to achieve heating at low current.
- Sustainment of HHFW-Driven 100% Non-Inductive H-Mode
  - Fix I_P at ~400 kA, test ability of different RF power and antenna phasings to sustain I_P.

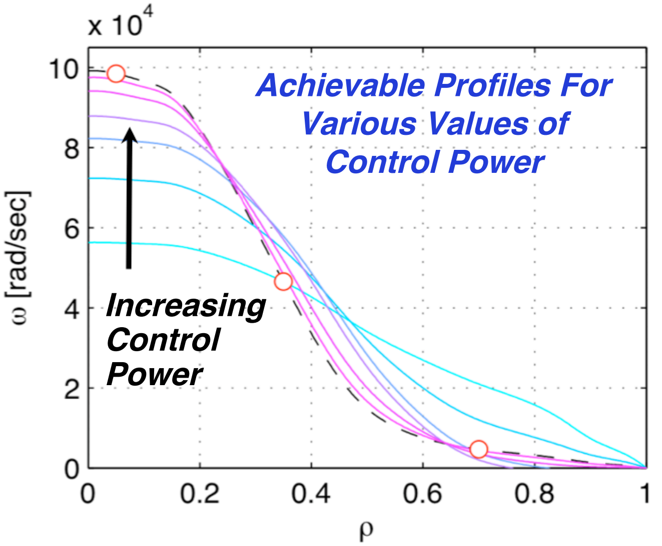
First step to integrating non-inductive ramp-up into advanced scenarios

PAC25-28

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

- β_N control demonstrated in 2009.
- 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.
- FY-12 milestone on the *physics*, *measurement*, and *control* aspects of rotation control.
  - Progress in off-line algorithm development.
  - Developing rt-V_ϕ diagnostic for FY-11.





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

Summary

- ASC research supports near term NSTX goals.
  - Strikepoint control development for LLD experiments.
  - ELM-triggering techniques for impurity reduction.
  - Scenario development with HHFW heating.

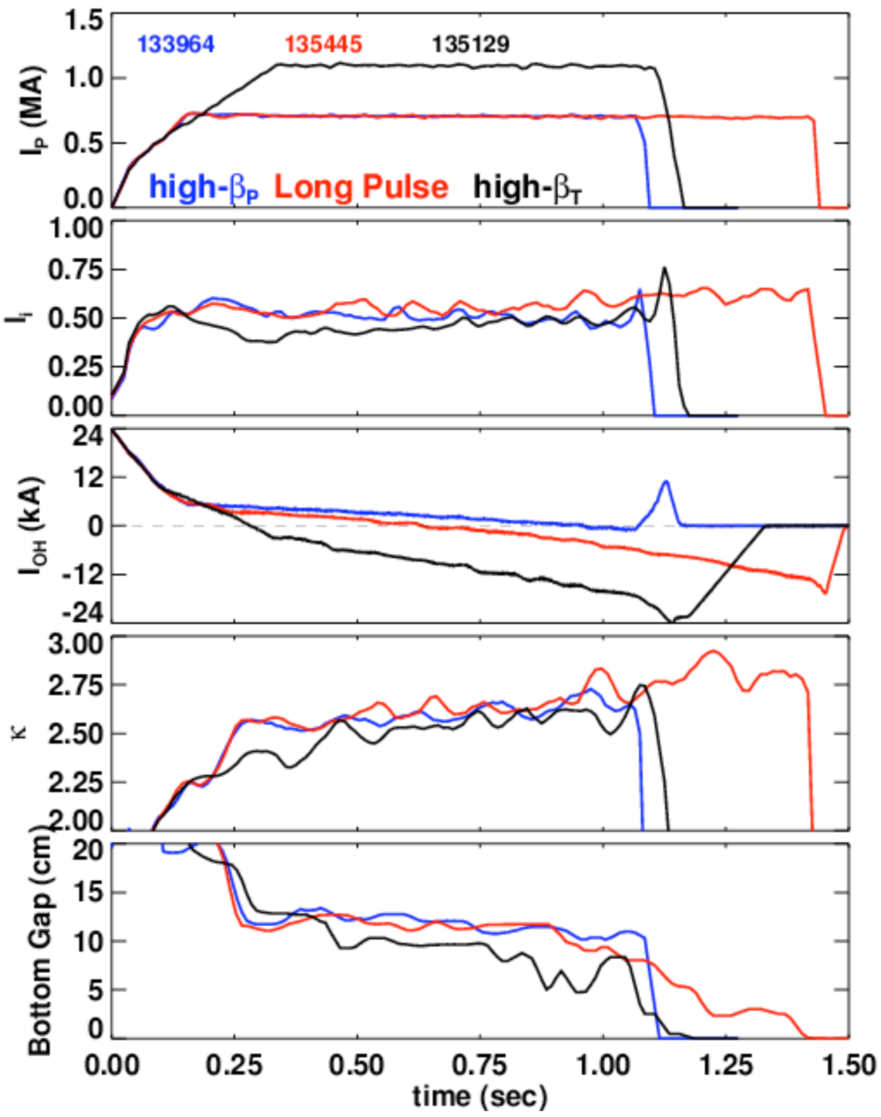
- ASC research supports NSTX-Upgrade development.
  - Advanced divertor control for handling high heat-flux.
  - Beginning profile control development.

- ASC research supports the needs of next-step STs.
  - Neutral beam current drive studies.
  - Stability and confinement at high-β_P and β_T.
  - Integrated performance at reduced collisionality and large non-inductive fraction.
  - Control techniques for the ST, and for tokamaks in general.

The Rest is Backup

High-κ, –β, low-l_i Discharges Test Limits of Control

- Shape control more difficult at high-κ and low-l_i:
  - Bottom-gap goes to zero when the OH leakage flux becomes too large.
  - Control of elongation through the outer-squareness is insufficient.
- Strike-point control will be important for optimizing pumping with LLD.
- High-β_T discharges require precise tuning of input power.
  - Too much power → RWM
  - Too little power → core rotating MHD



Control Plans For High-κ Scenarios

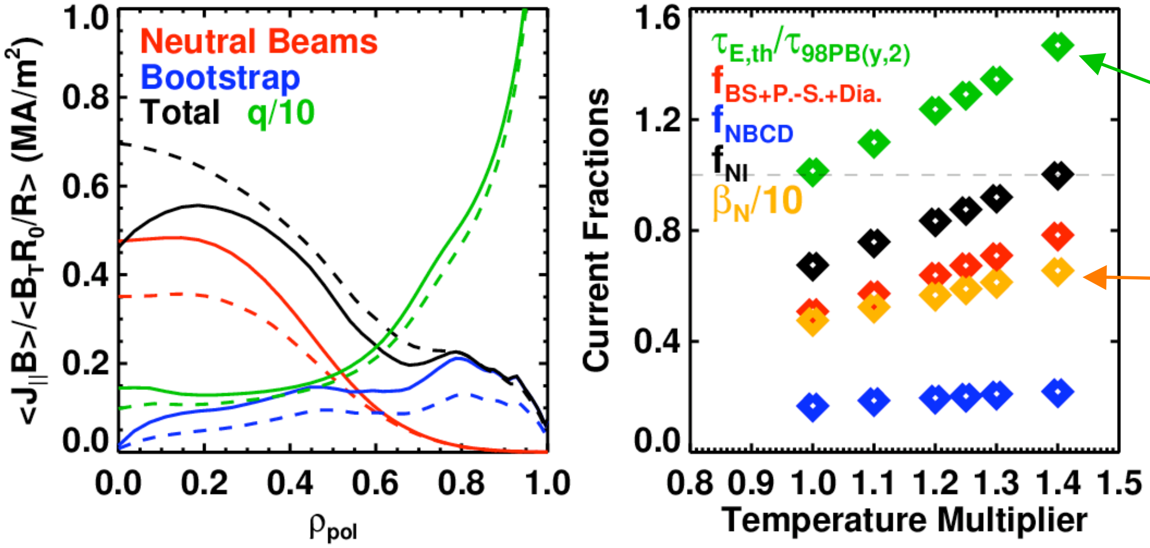
- Incorporate X-point height and OSP radius control.
- Incorporate β_N control.

Fully Non-Inductive Operations Possible with Higher Temperature, Same Density

- TRANSP simulations with boundary and profile shapes from high-κ, high-β_P discharge 133964, $Z_{eff}=3$
- Scale T_e and T_i by the same factor, leaving densities unchanged.

Solid: Scaled Profiles for $f_{NI}=1$

Dashed: Reference Profiles



H=1.5

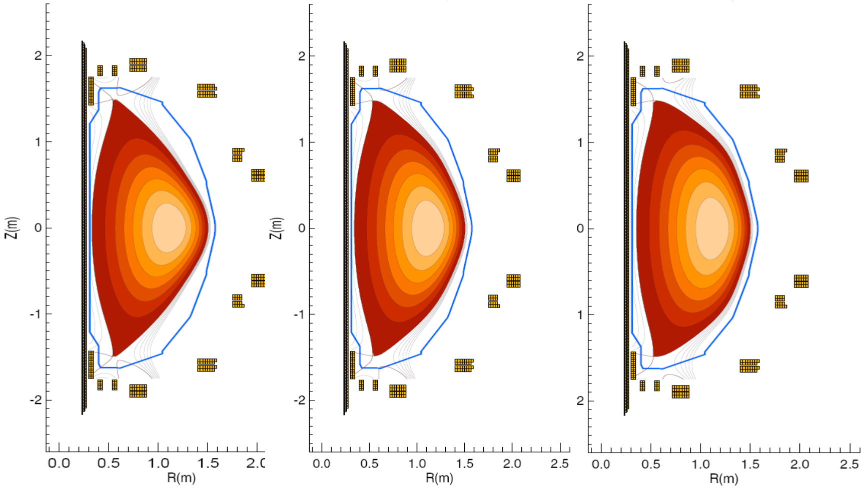
(assuming 6 MW injected)

β_N=6.5

- With $Z_{eff}=2$, required temperature increase is only 25%.

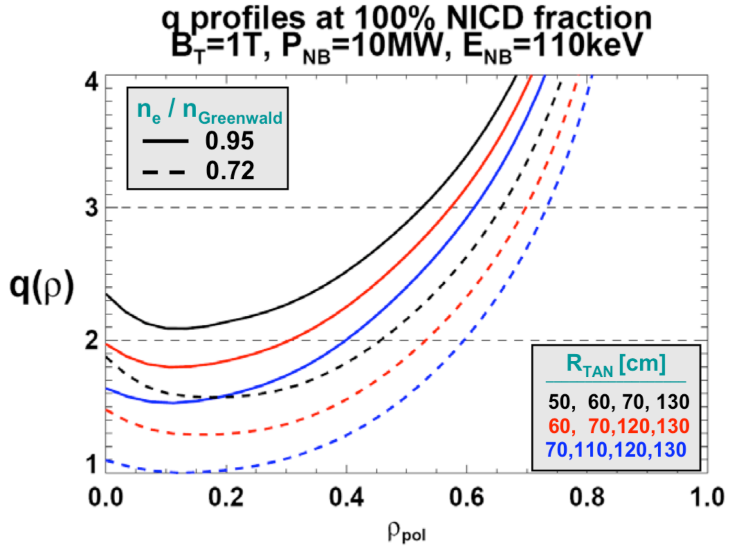
Research Described in This Talk Supports NSTX-Upgrade Needs

Plasma Control



- Developing integrated shape control utilizing all available coils.
  - Upgrade is designed for a range of κ,δ,ζ …develop control of these quantities.
- Advanced divertor may be part of the power handing strategy for the upgrade.
  - Snowflake divertor control will prepare for this contingency.
- Control of the current profile will be important in the upgrade.
  - State-space control of the rotation will be an important step for this profile control.

Scenario Development

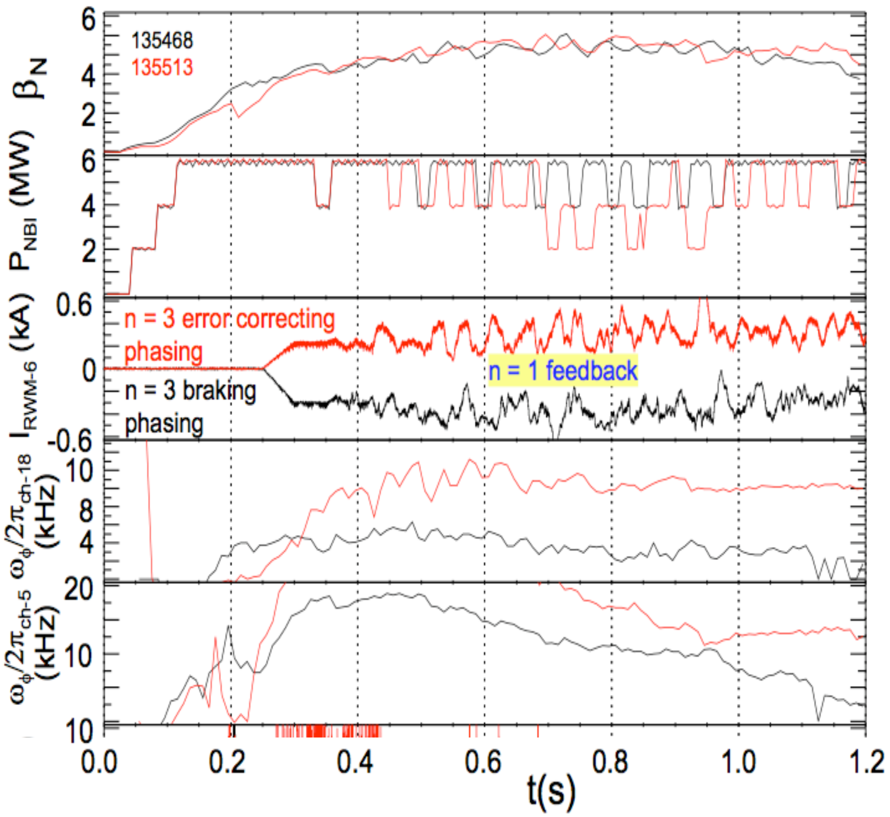


- Neutral beam current drive important in 100% NICD scenarios.
  - Experiments at reduced collisionality expands NBCD into upgrade-relevant regime.
- Improved predictions of transport will enable netter scenario modeling for the upgrade.
  - New post-doc providing support with transport simulations.
- Reversed shear H-modes with HHFW, if possible, may lead to improved scenarios for the upgrade.

Development of Real-Time Neutral Beam Control Allowed β_N

- β_N control demonstrated in 2009.
- Modulate NBs so that $\beta_{N,rtEFIT}$ follows a request waveform.
- Further optimization and capability exploitation is planned in 2010.
  - XMP to optimize gains.
  - Incorporation into long-pulse high-β scenarios (ASC)
  - Test of disruptivity reduction (MS)

Demonstration of β_N control at various levels of magnetic braking and plasma rotation



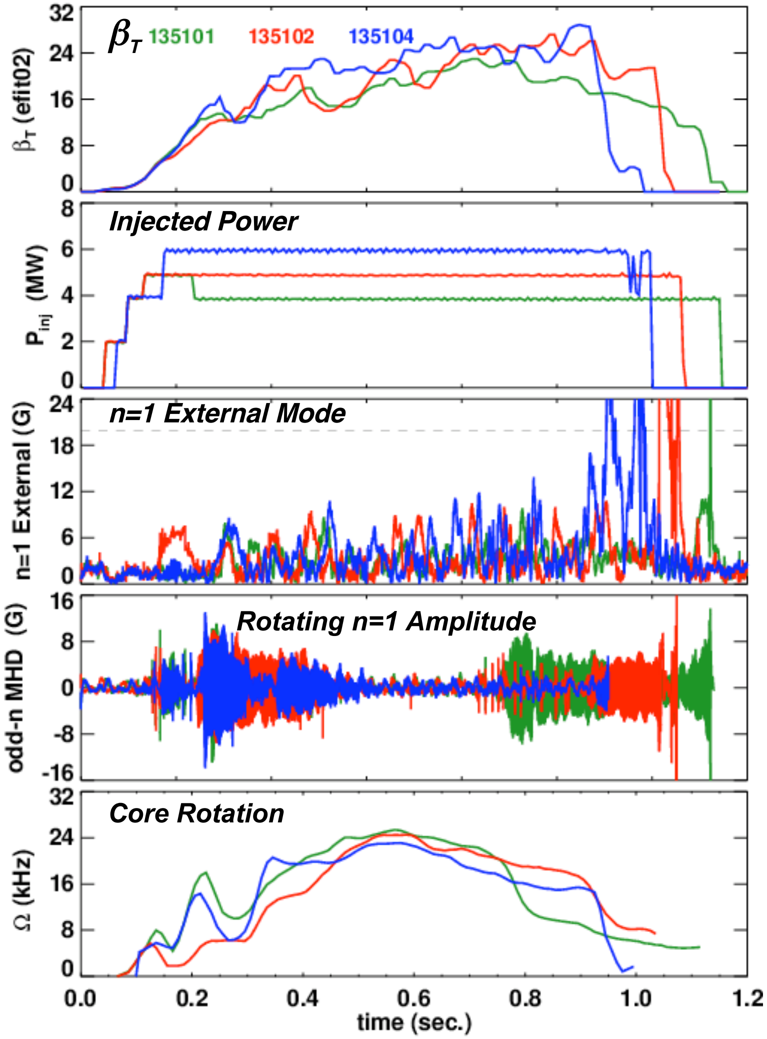
Brief Response to PAC-25 Comments

- **PAC25-18**: …the PAC recommends that scenario development be initiated for the use of HHFW heating to provide access to high beta.
  - We agree, and have planned two experiments in ASC to attempt this. Additional experiments are schedule through the WEP group, though with somewhat different goals.
- **PAC25-25**:…a focus of these studies could be establishing the ability to couple HHFW power to ramping plasmas…
  - We agree, and have an experiment planned to develop this technique.
- **PAC25-28**:…develop scenarios with controlled density rise…
  - We agree that this is quite important. It will play a role in the ASC experiments, as well as the overall LLD program.
- **PAC25-29**:…work towards integration of of HHFW heating and potentially current drive into standard scenarios.
  - We agree. See response to PAC25-18.
- **PAC25-30**:…In addition to the impressive integrated SN scenario, the PAC recommends to apply similar techniques in DN.
  - Many of our high-κ scenarios this past year had very small values of dr_{sep}, and this will continue going forward.
- **PAC25-31**: Non-solenoidal I_P ramp-up techniques…should be integrated into standard scenarios.
  - Experiments in concert with the WEP and SFSU TSGs will begin this long-term effort.
- **PAC25-32**:The TSC modeling is seen as important for the development of integrated scenarios and optimizing the current ramp-up….. It is important to maintain staff/expertise in this area and to work aggressively towards the implementation of a realistic transport model in TSC.
  - NSTX has hired a new post-doc to work on transport modeling and simulations. However, we have been unable to fill an advertised position for devoted TSC modeling.

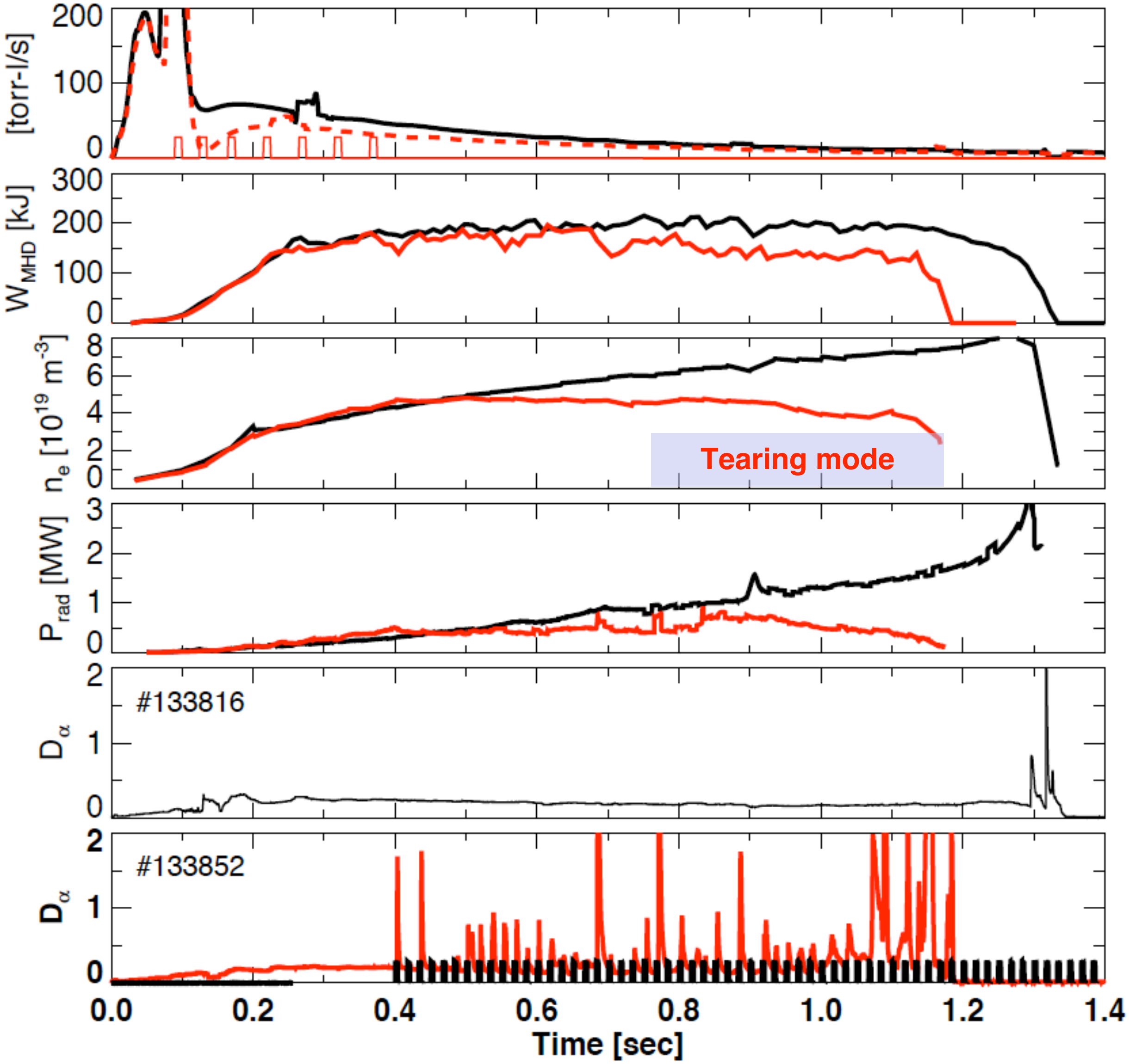
Stability of High-β_T Scenarios is Sensitive to Variations in the Input Power

- Higher power level leads to RWMs and rapid disruption.
- Lower input powers lead to rapid q-evolution and onset of core MHD.
  - Higher temperature at increased power slows current penetration.
  - Higher pressure provides bootstrap current, which helps maintain elevated q_0.
- Critical to maintain β at the highest values consistent with ideal stability.
- *Utilize β_N control* to maintain high-β state against transient increases in confinement and other β oscillations.

Variations in Input Power Lead to Different MHD at high-β_T



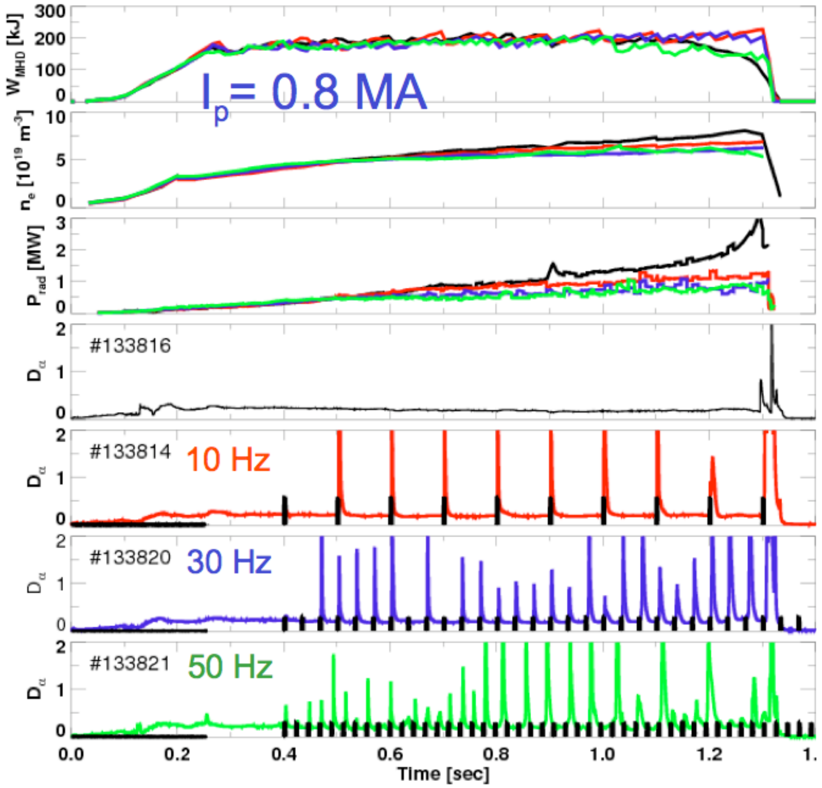
ELM pacing + optimized fueling allows quasi-stationary global parameters for ~ 0.35 sec



- Fueling from slow valve on center stack reduced, replaced with SGI on LFS
- Stored energy comparable until tearing mode
- Density rise arrested
- Radiated power controlled
- Reference discharge ELM-free
- ELMs triggered with 3D fields

Impurity Accumulation in Lithiated ELM-Free H-mode was Arrested Using Magnetic ELM Pacing

- Driven ELM frequencies up to 62.5 Hz achieved with 100% triggering efficiency.
  - ELM size reduced at higher frequency.
- Time-average magnetic braking is strong at high frequencies.
  - Deleterious to performance.
- Sweet spot: Strong reduction in radiated power with pacing frequency of ~10-20 Hz



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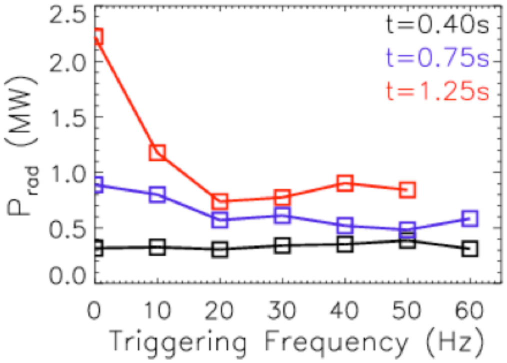
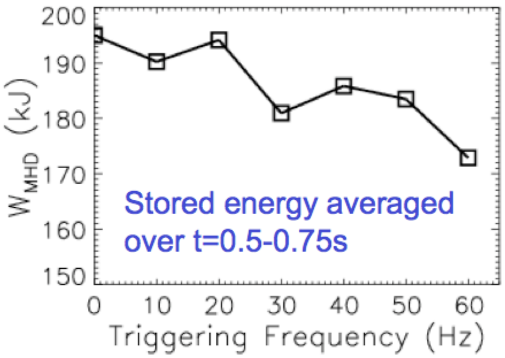
- Possible to arrest average density and P_{rad} rise when combined with SGI.
  - Drop in edge density and P_{rad}, but continued increase in the core.
- Demonstrated ELM pacing by vertical position jogs.

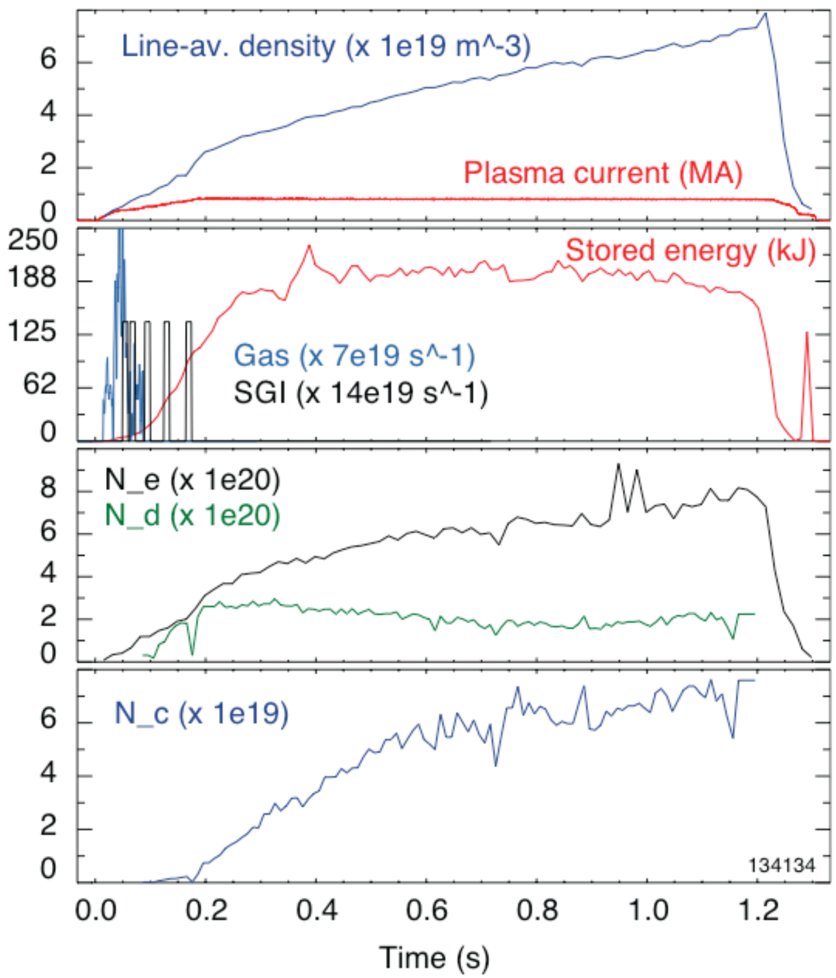




Control of the Deuterium Density In High Performance Plasmas Was Demonstrated With Supersonic Gas Injection

- No center-stack gas fuelling.
- Moderate evaporation rate of 6-9 mg/min.
  - Sufficient to go ELM free.
- Deuterium ion density control.
  - Rise in electron density due to carbon accumulation.
- Provides valuable experience with SGI fuelling+Li pumping.

Controlled Deuterium Inventory with SGI Fuelling



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