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Comments on Control & High-κ Scenario Development in 2010

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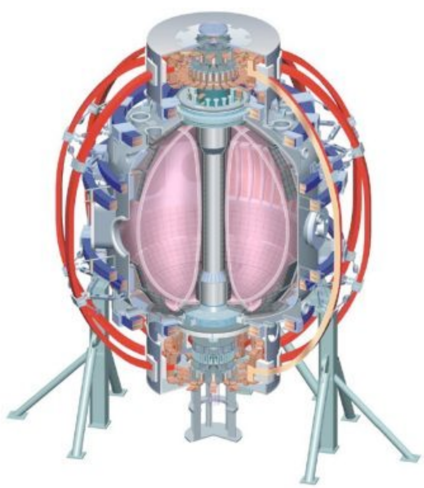

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Can (Simplistically) Divide the High-κ Scenarios into Three Groups

High-β_P, $q_{95}\approx15$:

Maximize non-inductive fraction

Limited by I^2t on TF coil

Long pulse, $q_{95}\approx11$:

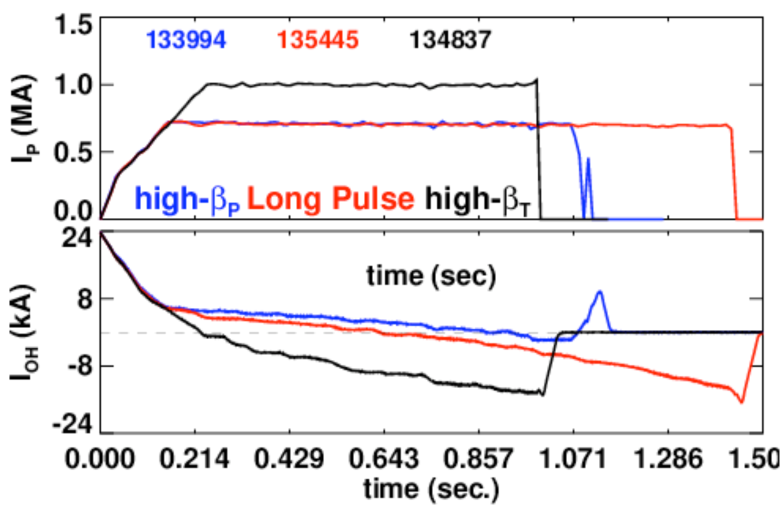
Fully equilibrated profiles

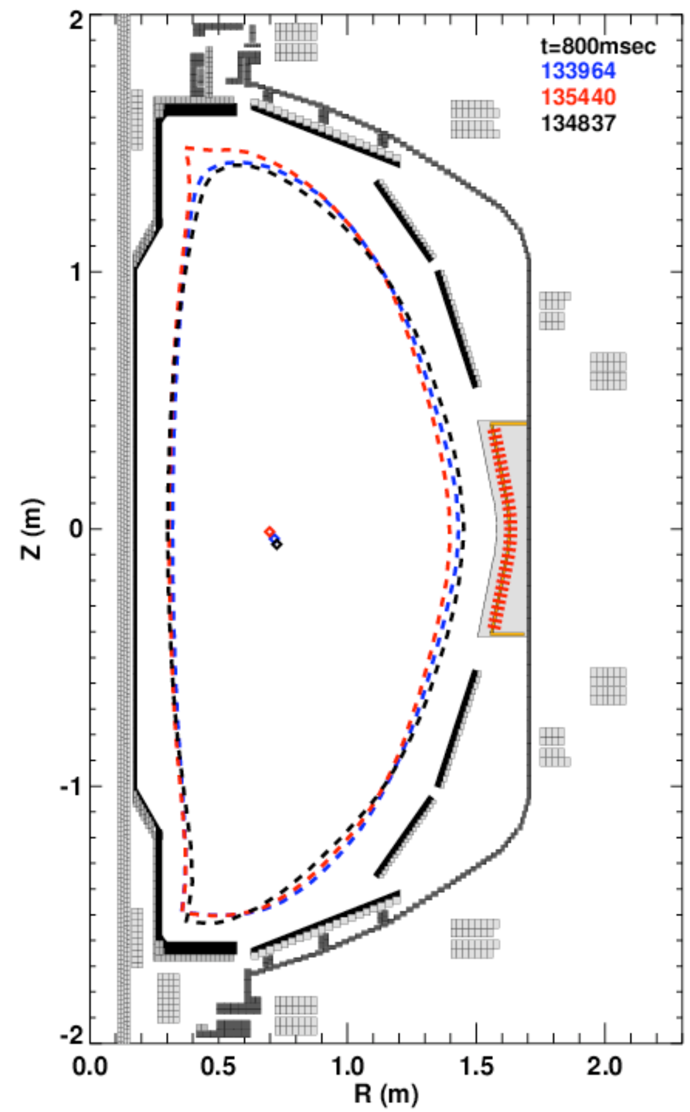
Match TF I^2t and solenoid current limit

High-β_T, $q_{95}\approx8$:

*Toward reactor I_N, β_T and q**

Limited by solenoid current or MHD.





Scenario Development

- High-β_P Scenario
  - Highly reproducible with 6 MW input, with minimal MHD trouble.
    - Occasional non-disruptive tearing made confinemtn degradation.
  - Plasma boundary was reasonably well controlled.
    - May be even better this year with new rtEFIT basis vectors.
  - Biggest limitation was the VERY large impurity accumulation.
- High-β_T & Long Pulse Scenarios
  - Reduced toroidal field causes all kinds of mhd.
  - Both operated at reduced power, and were disruptive if power was exceeded.
    - Could use β_N control.
  - Both had bottom gap ->0 as the OH current became large.
    - Consequence of the large elongation.
    - Could use better shape control.
  - Also had impurity problems…

Related Control Development

- ASC XP for combined X-point height and OSP radius control (1 day, Kolemen).
  - Should be final doing review in a few weeks.
  - Most useful for high-β_T and long pulse scenarios.
- ASC XP on first test of squareness variations (1/2 day, Kolemen).
  - Looks like the hardware interlocks will be completed for this run.
  - If the engineers get it ready, then we need to use it.
  - Could (potentially) improve any of the scenarios.
- MS XP & XMP on β_N-control (1/2 + 1/2 Gerhardt).
  - Would most benefit the high-β_T and long pulse scenarios.

Scenario Development XPs

- 2 days at forum for high-κ beam shot development, + 1/2 for squareness studies.
- Allocate 1 day to:
  - XP-1006: Development of High-Elongation Beam Heated Scenarios with Reduced Impurity Content and Increased Non-Inductive Fraction (Gerhardt, et al.).
- Allocate 1+1/2 day to:
  - Optimized control for very long pulse discharges (Kolemen, et al.)
  - Impact of squareness variation on high-κ discharges (Kolemen, et al.)
  - *Exact breakdown between these TBD.*

Old & Backup

Suggested Goals in 2010

- **Exploit LLD pumping**
  - Best done in the ***high-β_P scenario***, where q_{min} is somewhat elevated.
    - Increases tolerance for NBCD driving q_{min} down.
  - Big deal if we need to change the shape to increase the pumping…high-B_T is again most forgiving if we need to sacrifice some triangularity.
- **Test available means for impurity reduction**
  - Suggest to develop these in the ***high-β_P scenario***, as they are most stable and closest to fully non-inductive.
  - Suggestions include:
    - Low-frequency ELM pacing.
    - Modification to early discharge evolution (dr_{sep}, H-mode timing).
- **Incorporate improved control techniques**
  - β, OSP Radius, and X-point height control will likely show the greatest benefit in the ***long pulse or high-β_T scenarios***.
- **Study the effects of squareness variation**
  - Best done in ***long pulse or high-β_T scenarios***, where the impact on beta-limits can be addressed (for instance, use β-control to determine the beta-limit at different values of squareness).

Notes:

- Time allocation at time of forum: 2 days allocated to high-κ development + 1/2 days for squareness study…can these fit in the 2.5 day box?
- Assume that the following XPs are done, and use their output:
  - Early discharge optimization to reduce impurities (Menard)
  - β_N control XMP, maybe XP as well (Gerhardt)
  - Combined X-point height and OSP radius control development (Kolemen)
- If LLD cannot be run hot, need contingencies.
  - Can study impurity accumulation with LITER alone.
- May need to de-emphasize one of high-β_T or long pulse.
  - Similar issues with respect to MHD stability and boundary control.
  - If no hot LLD, then may permit additional time for these.
- Impurity control will be helpful for all scenarios.
  - Propose to develop it in high-β_P scenario, but can hopefully use it in other cases with minimal development.

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:

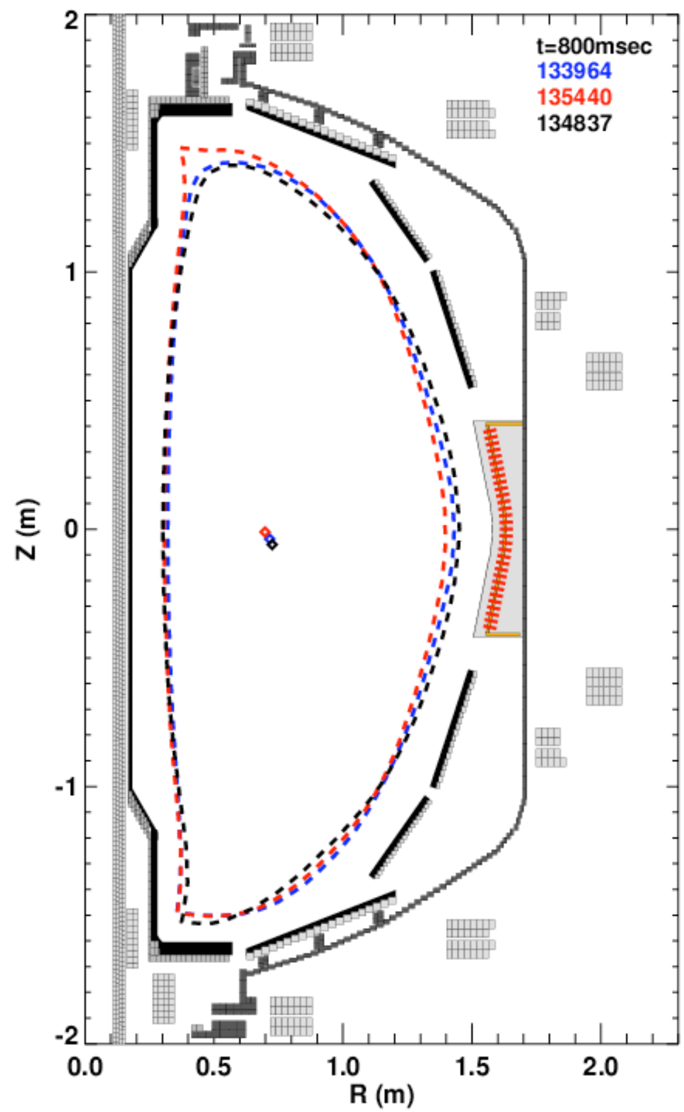
Fully equilibrated profiles

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.



All configurations:

High-κ and δ (κ~2.7 & δ~0.8)

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

(Shaping and improved power handling)

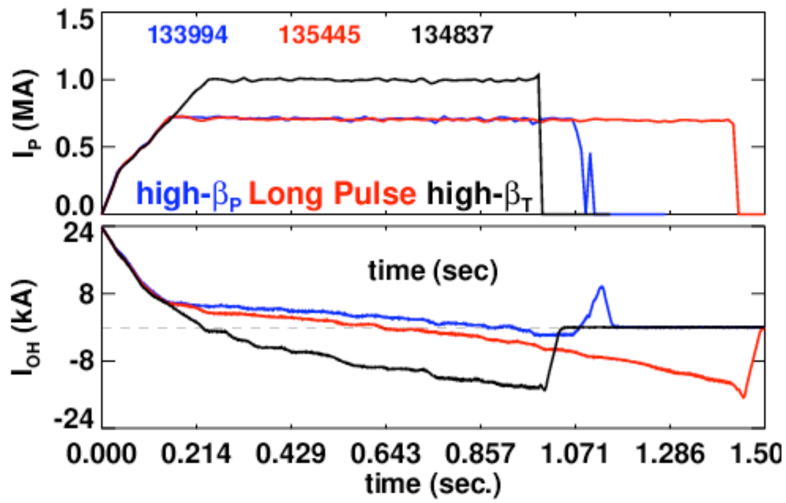
Lithium Conditioning

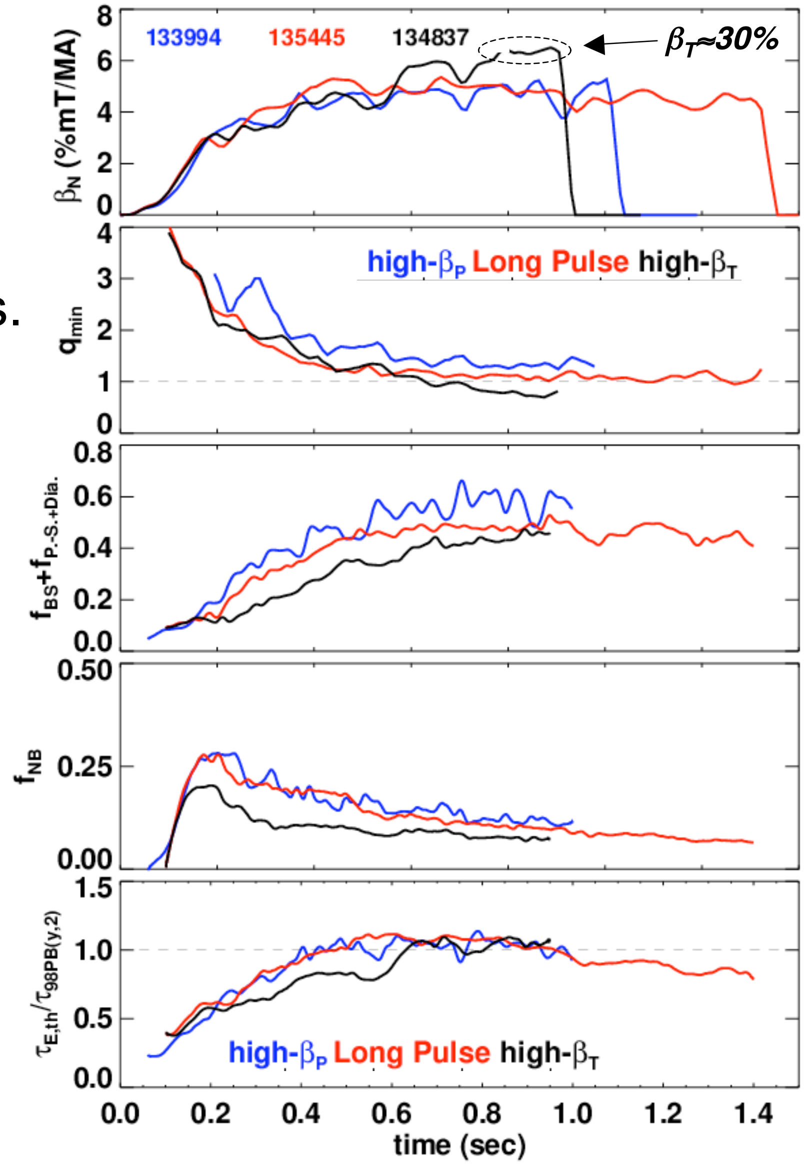
Dynamic Error Field Correction+RWM Control

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}~1 in all cases.
  - Further confinement improvements are desirable.



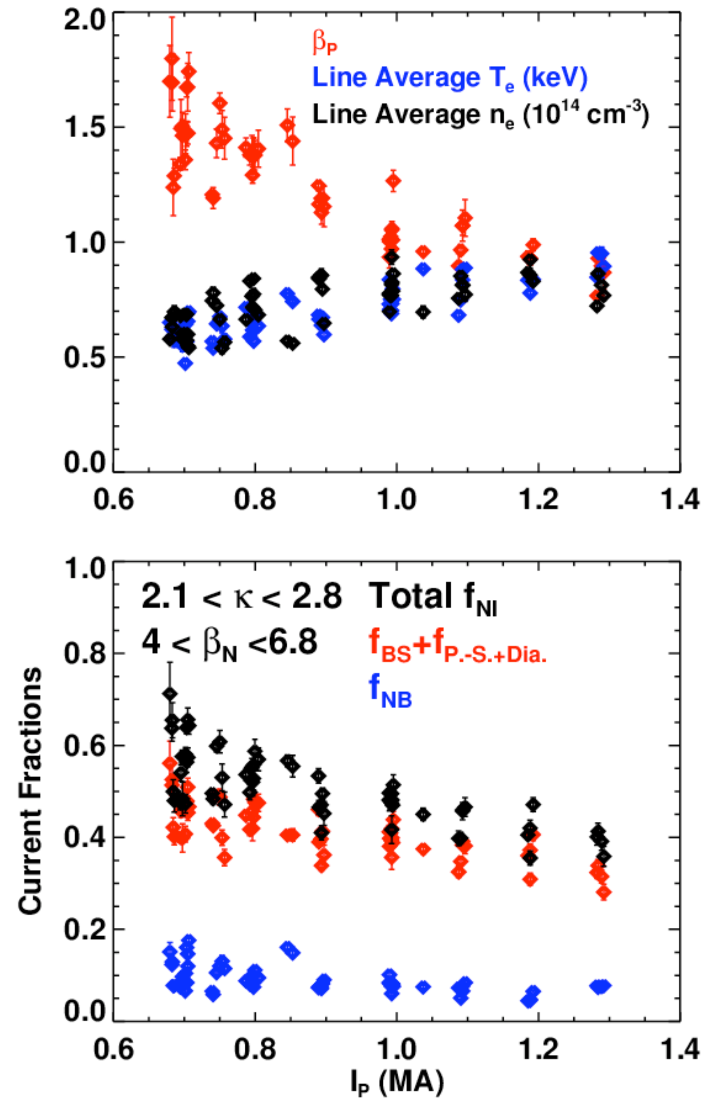


Present Configurations Are Limited to f_{NI}<70%

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

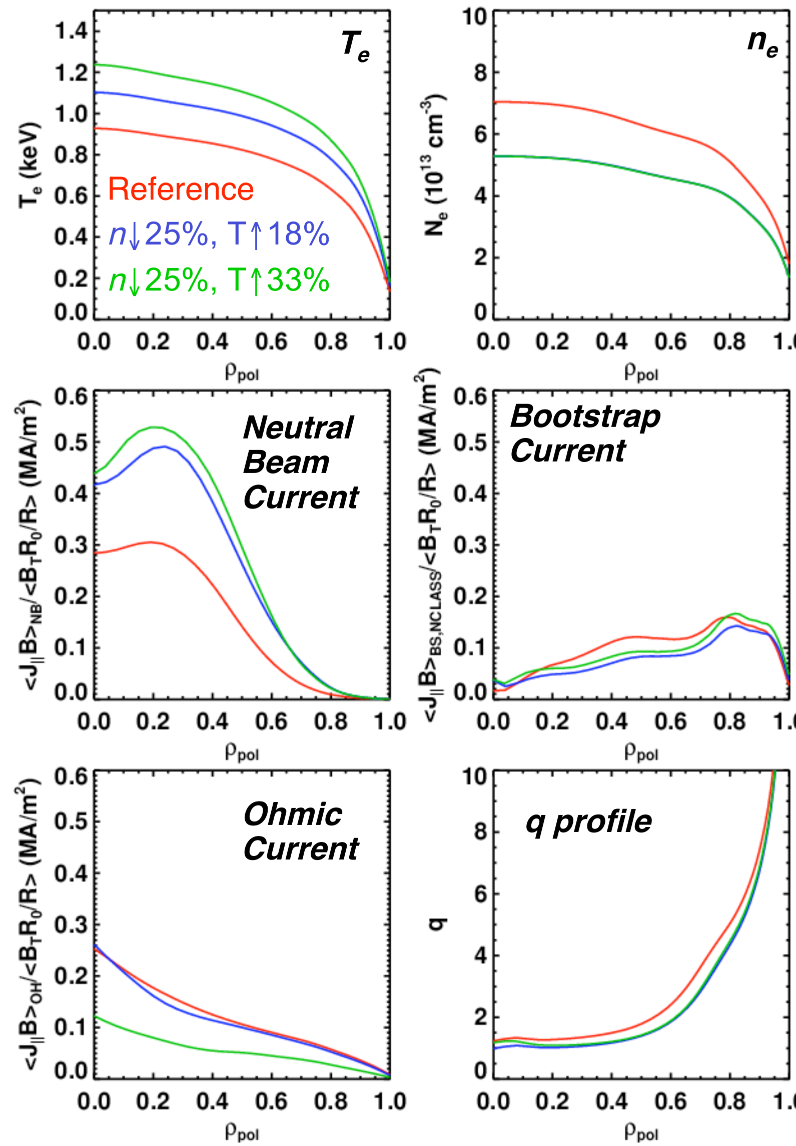
Near-term options for increasing f_{NI} in high-power NBI scenarios:

- 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**
  - Density ↓ 25%, Temperature ↑ 18%
    - **f_{NBCD}=26% , f_{NI}=80%, H_{98}=1.1**
  - Density ↓ 25%, Temperature ↑ 33%
    - **f_{NBCD}=27% , f_{NI}=90%, 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.

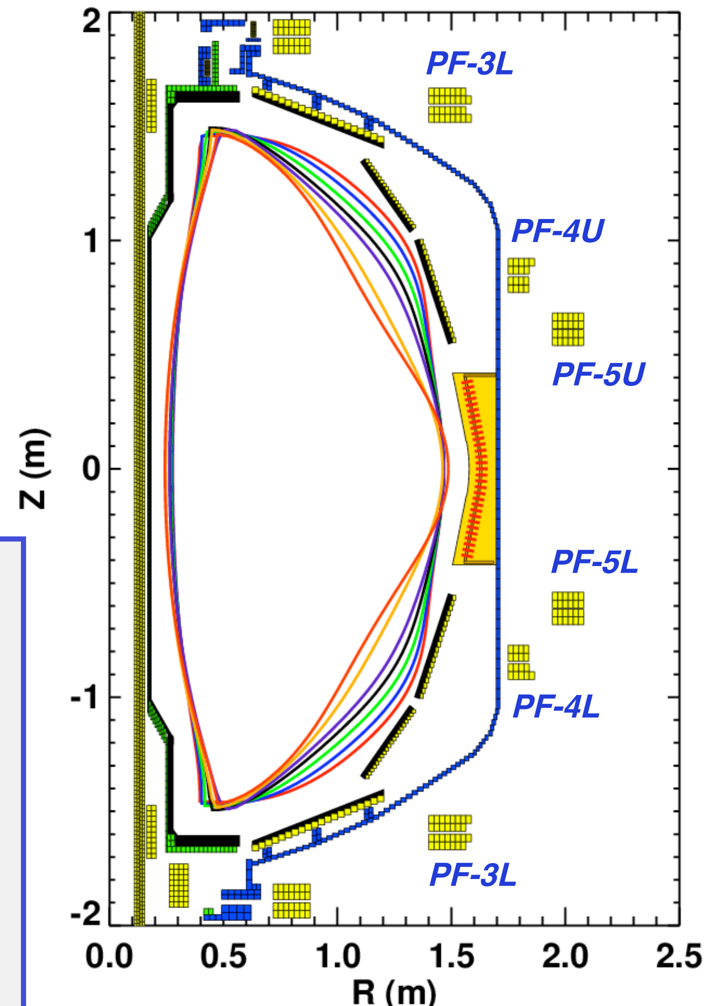


PAC25-32

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

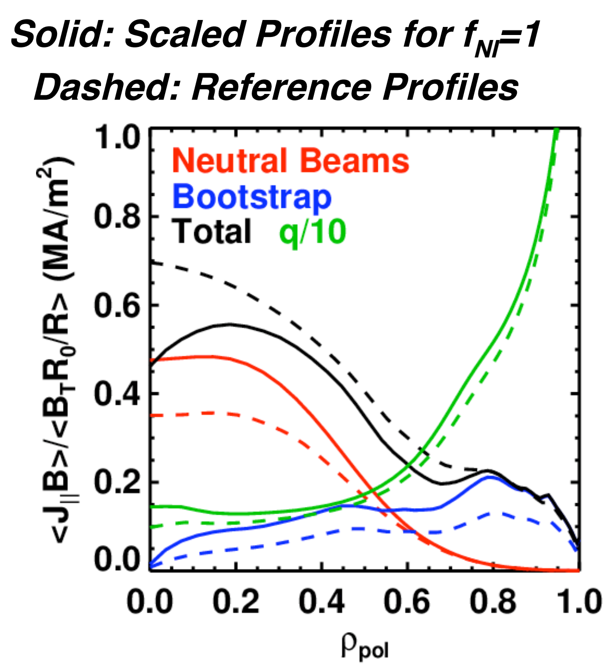


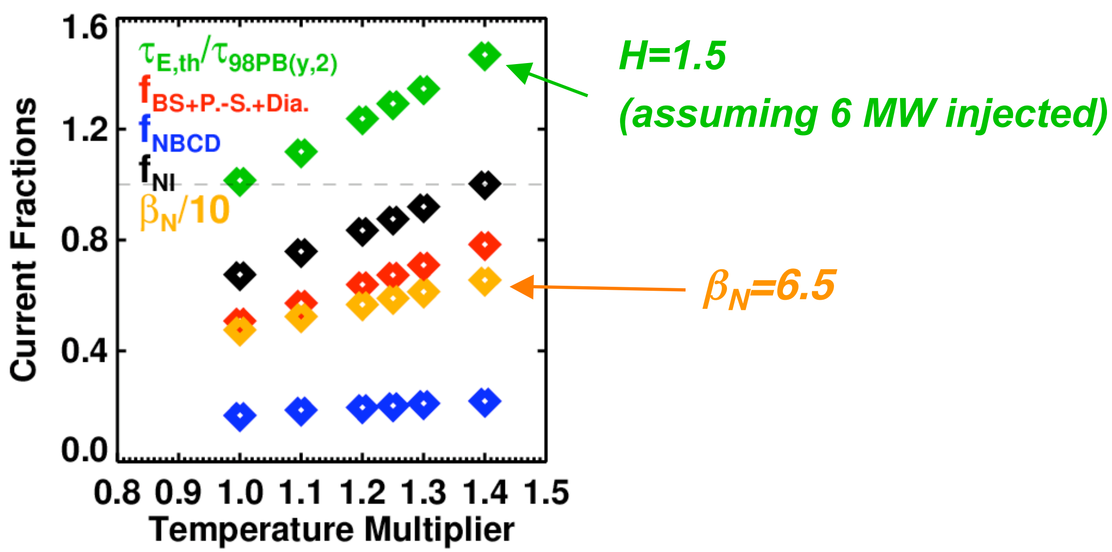
<u>Boundary Control Plans in 2010</u>

- 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).

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

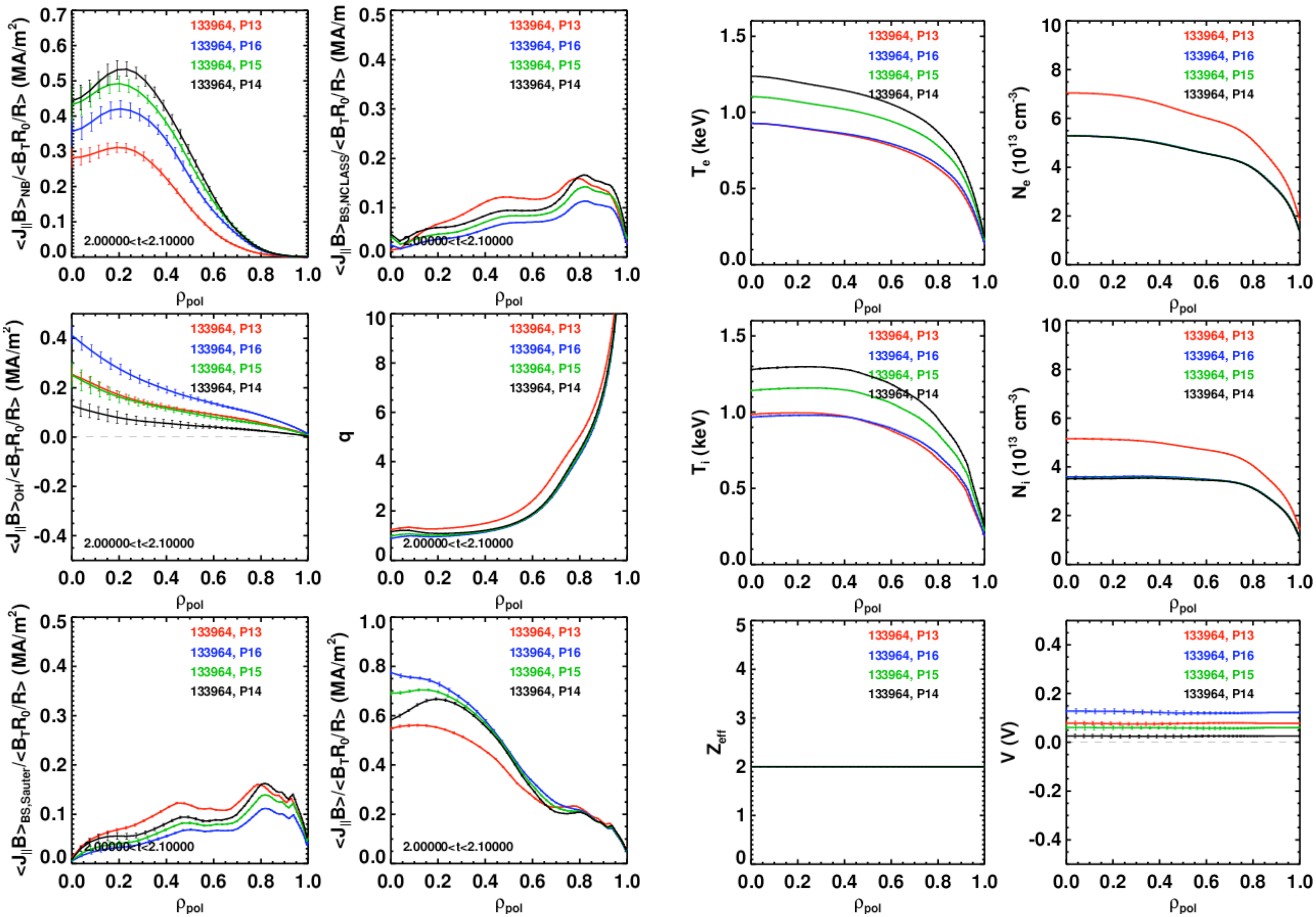
- TRANSP simulations with boundary and profile shapes from high-κ, high-β_P discharge 133964, Z_{eff}=3
- Scale T_e and T_i by the same factor, leaving densities unchanged.



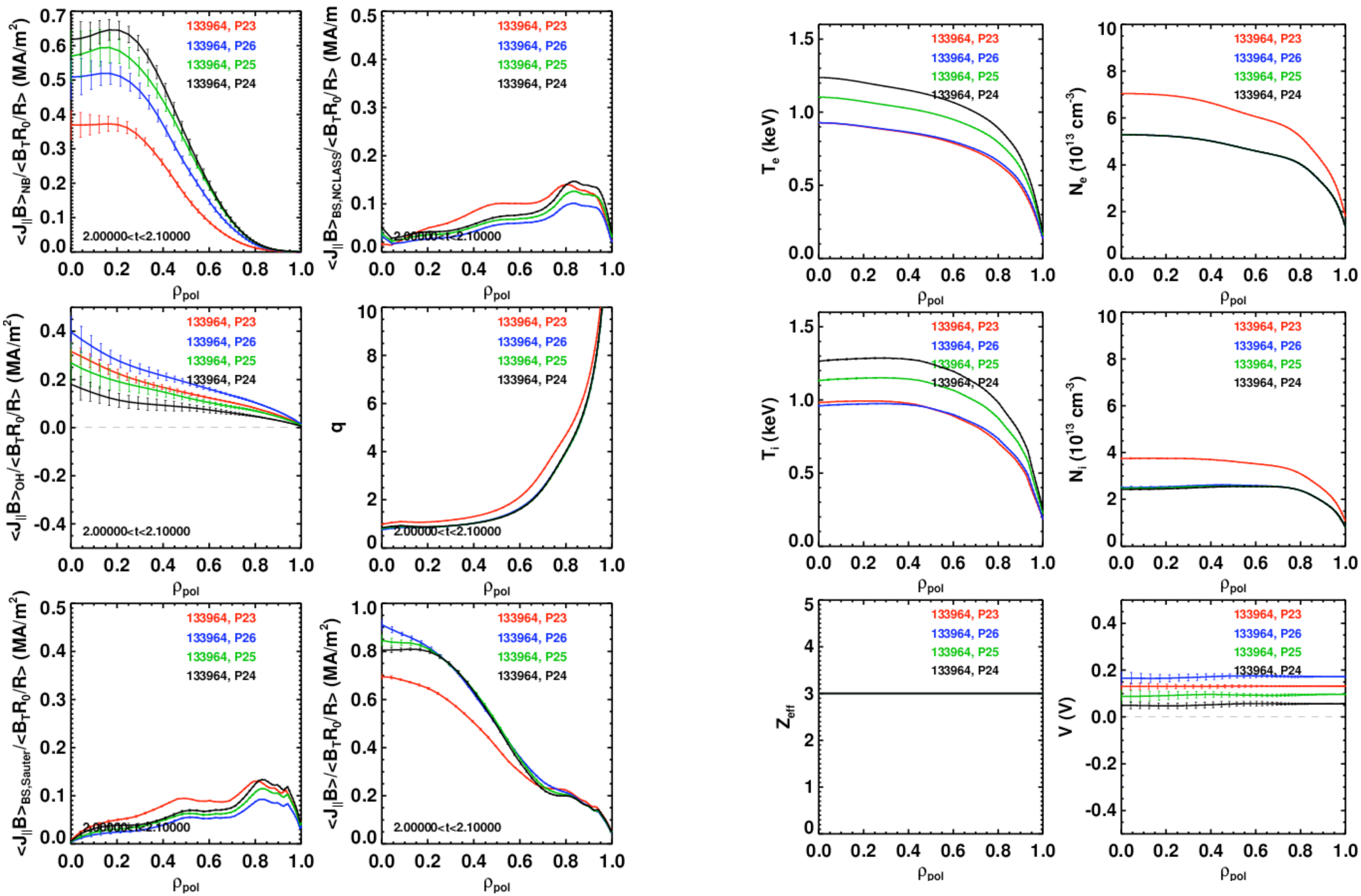


- With Z_{eff}=2, required temperature increase is only 25%.

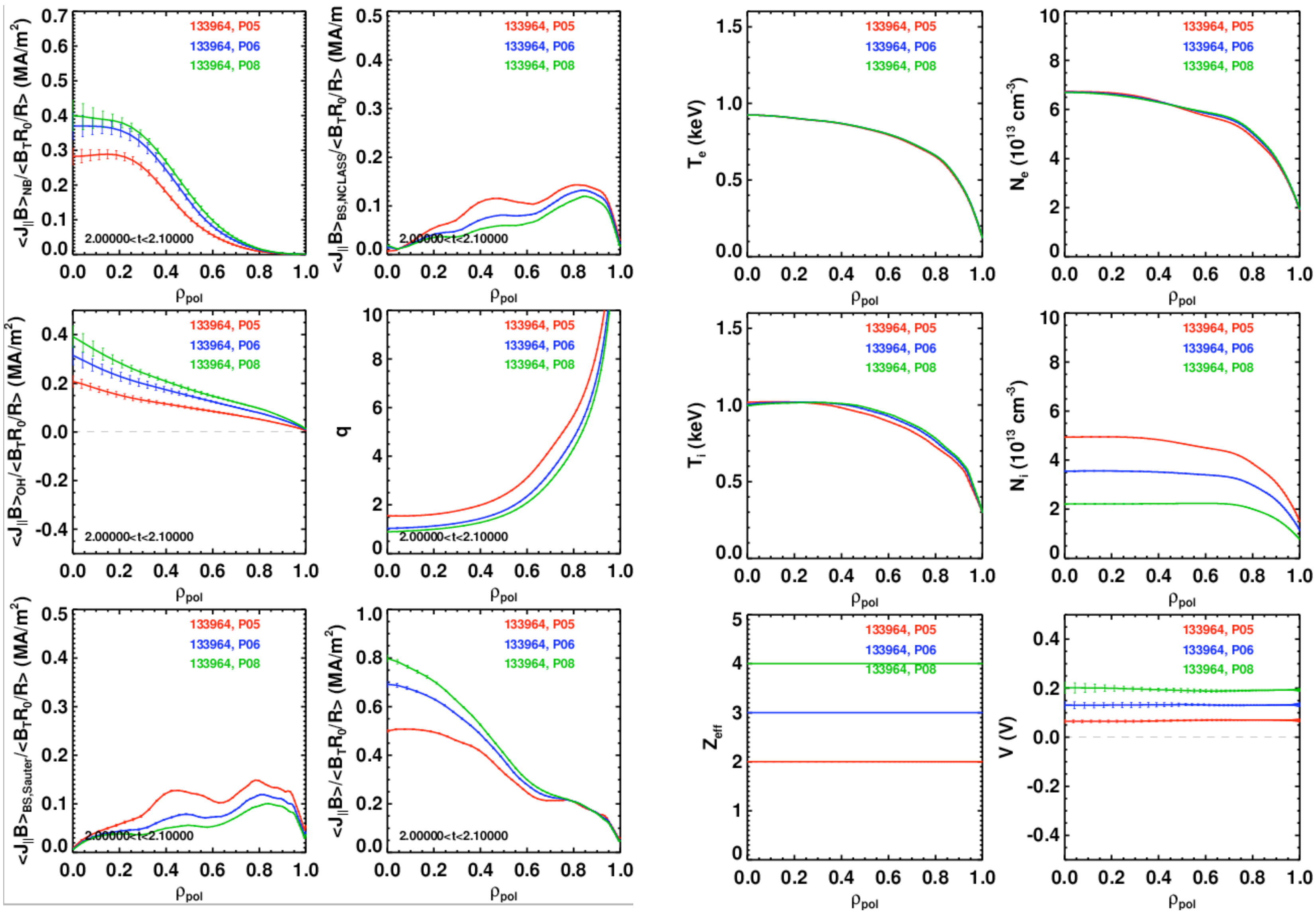
Reference Case Compared to Reduced Density & Various Temperatures, Z_{eff}=2, LEVGEO=8



Reference Case Compared to Reduced Density & Various Temperatures, Z_{eff}=3, LEVGEO=8



Z_{eff} Scans (LEVGEO=11)



Issues To Be Considered For High-κ NB Heated Shots in 2010

- **The 2011 milestone calls for operation at reduced collisionality.**
  - Need to attempted to exploit LLD/Lithium pumping in 2010.
    - Will likely be tension between large shaping for stability and f_{NI}, and reduced shaping for pumping.
  - Reduced density, if achieved, will have unknown consequences
    - If the NBCD increases, it drives down q_{min} in a rather unfortunate way.
    - If RWM physics is more challenging, then high-β may be problematic.
- **Need to develop means to control the impurity content**
  - Z_{eff}=3 (or more) is common in high-elongation discharges.
    - Helps NBCD, but hurts bootstrap current and increases the loop voltage.
  - Radiated power is uncomfortably large.
  - Suspect that our 10-15% reconstructed current discrepancy is related to impurities.
  - Need to incorporate impurity control techniques.
    - Low-frequency ELM pacing.
    - Early discharge optimization (separate XP by JEM)
    - Other? Divertor gas puff?
- **Incorporation of improved control would benefit the scenarios:**
  - X-point height and OSP radius for long-pulse and high-β_T scenarios.
    - OH leakage flux hurt the most in these scenarios, driving bottom-gap to zero.
    - XP height and OSP radius control development allocated time is separate XP by Kolemen.
  - β_N-control for long-pulse and high-β_T scenarios.
    - These cases used less than 6MW, high-β_P case took all 6 MW.
    - Separate XMP/XPs for this development in MHD TSG.
- **Squareness is the final "unexploited" shape parameter.**
  - Could impact global stability and transport.
  - Could impact ELM behavior.
  - PF5/4 mutual force interlock hardware should be prepared for this run, so that we can try this.