Developments in Advanced Scenarios and Control Science on NSTX

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51st Annual meeting of the APS-DPP
Atlanta, GA
Nov. 2-6, 2009

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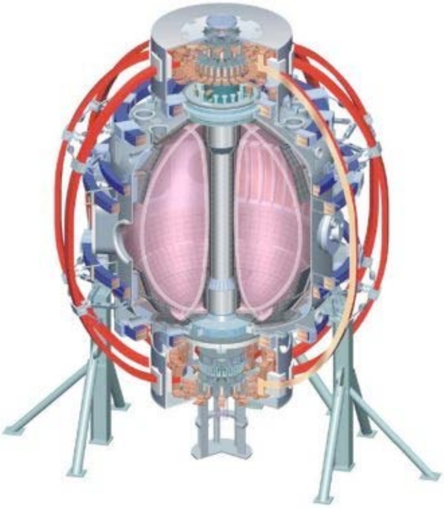
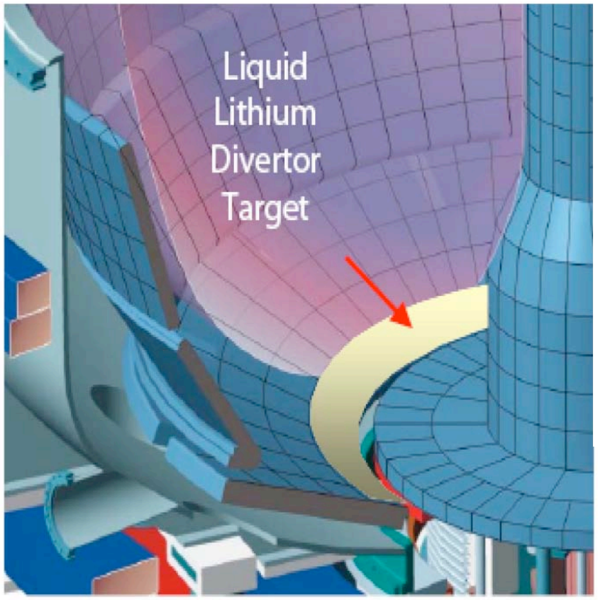
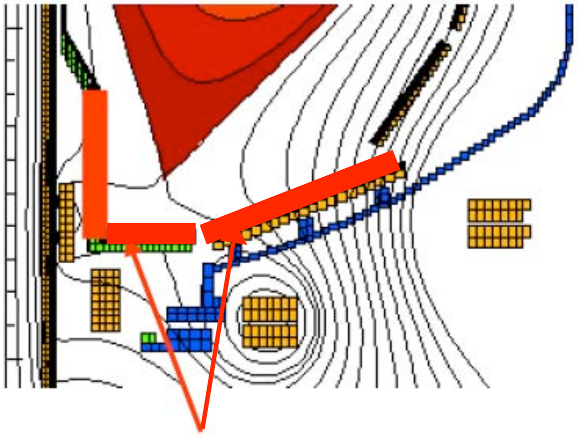


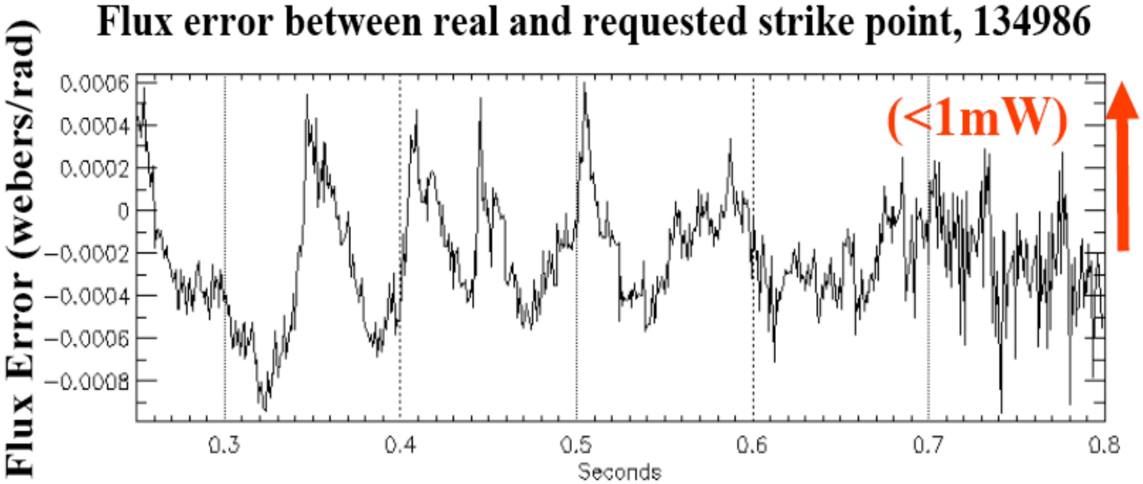
Strike point control enables research with the Liquid Lithium Divertor

- NSTX Plasma control has continued to enable access to advanced plasma regimes
- Scenarios with outer-only and outer+inner strike point control developed
  - Outer+inner strike point control is more stable - avoids bifurcation
- Second X-point complicates control
  - But adds new possibilities





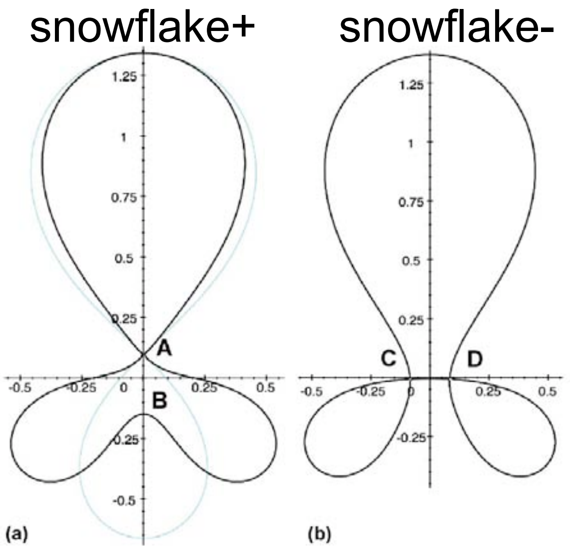
Segments to control strike points



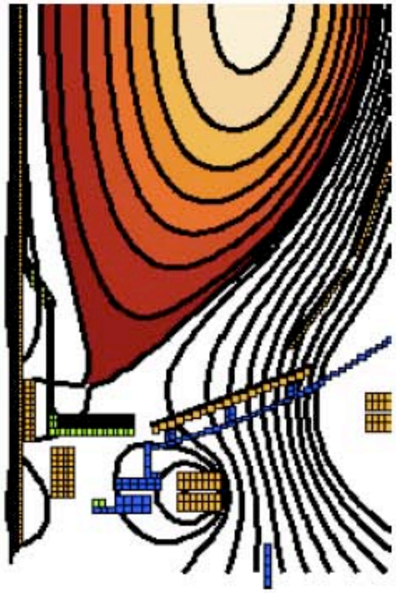
See E. Kolemen, Poster PP8.080

Snowflake divertor is a novel option for peak divertor heat load reduction in tokamaks

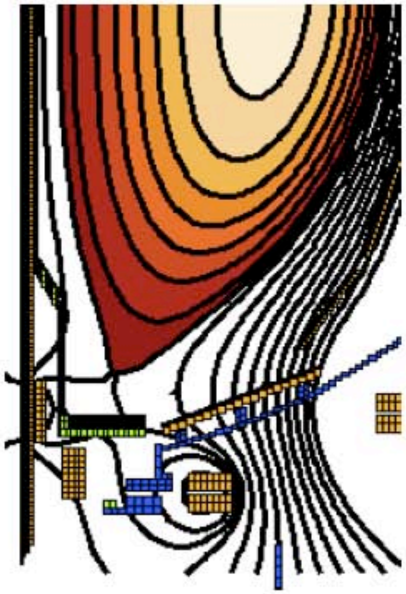
- Strike point control partially stabilizes snowflake configuration
- Scans across from snowflake+ to snowflake- configuration
- Will develop technique to control the separation between the two X-points


snowflake+ snowflake-

D. Ryutov, Phys. Plasmas 14, 064502 (2007)



Shot 135478, t=0.349s



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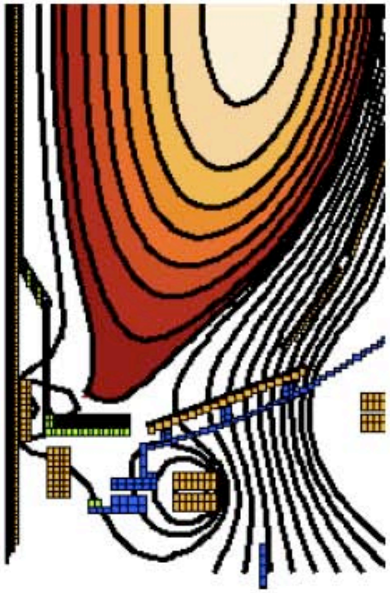

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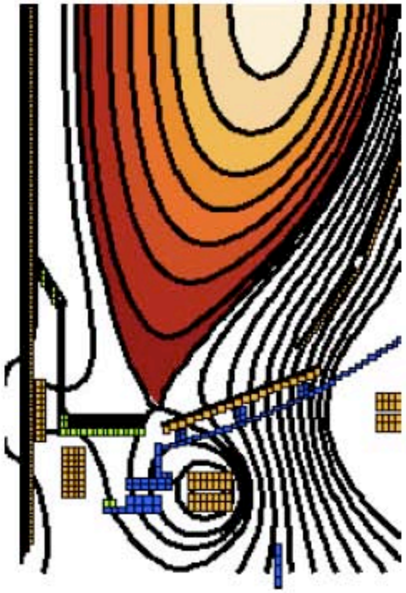
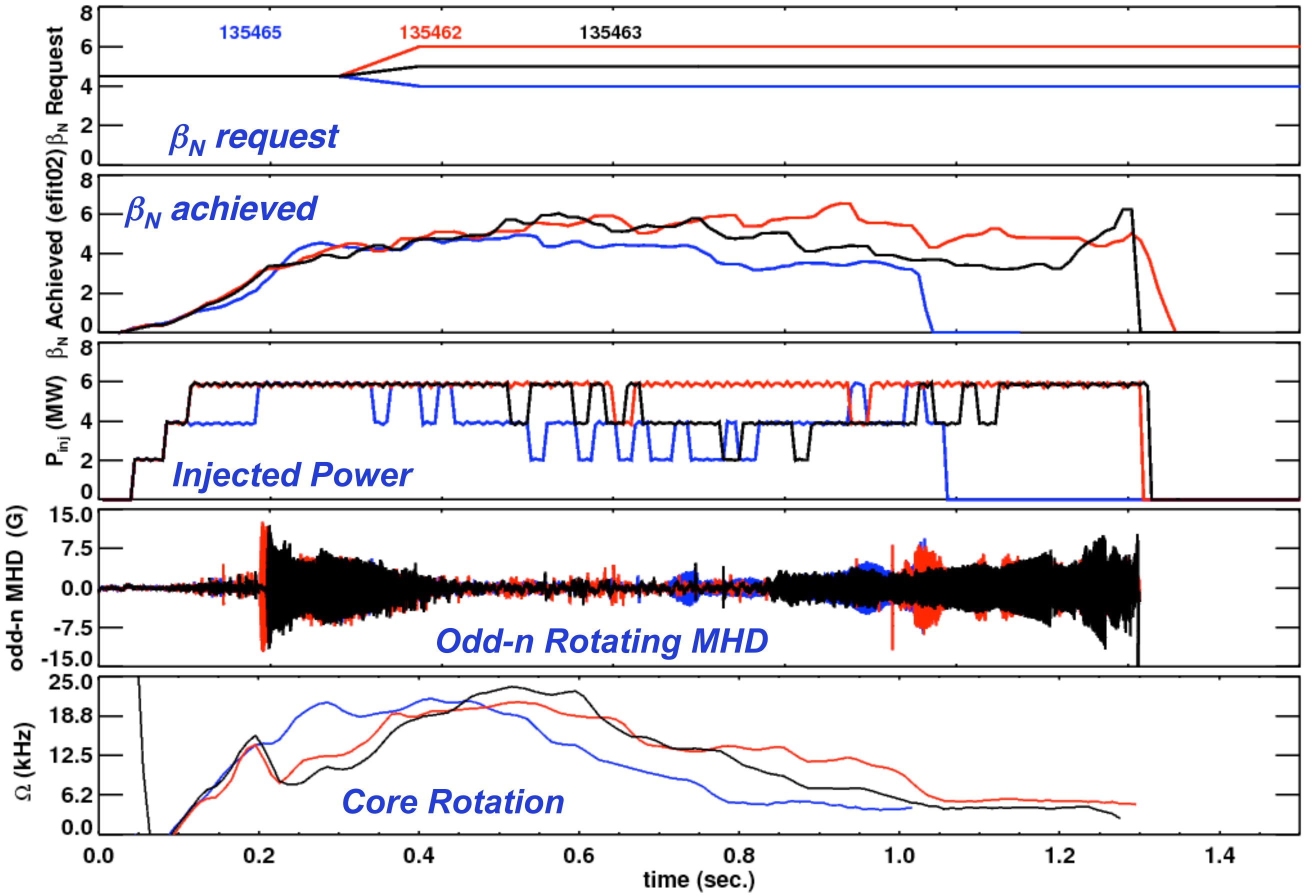


Shot 135486, t=0.199s

β_N control will enable reliable control of plasmas near with wall limit

- β_N control was commissioned using NBI feedback during the FY-09 run.
- Gains not yet optimized



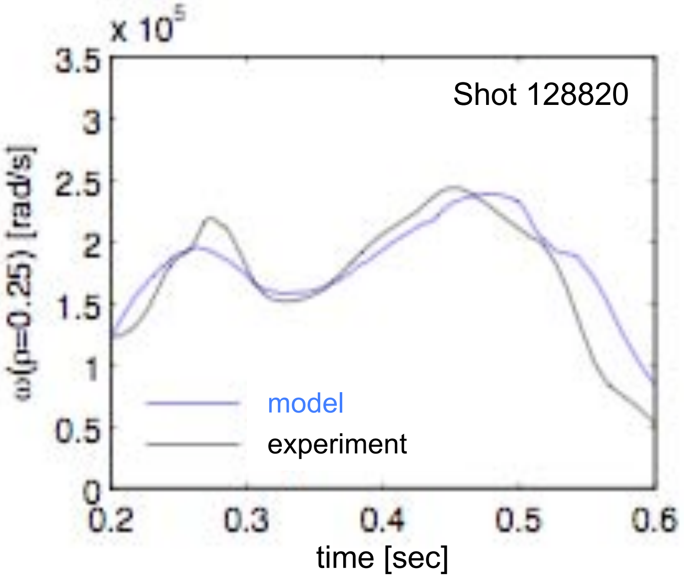
- Feedback gains adjusted between shots
- β_N requests of 4, 5, and 6
- Reconstructed β_N evolution varies with the trends correctly with the requested values
- Rotating MHD comes earlier when the beam power is reduced.
- Core MHD leads to a similar low rotation state in all cases

Rotation control will enable optimization of MHD stabilization physics and transport

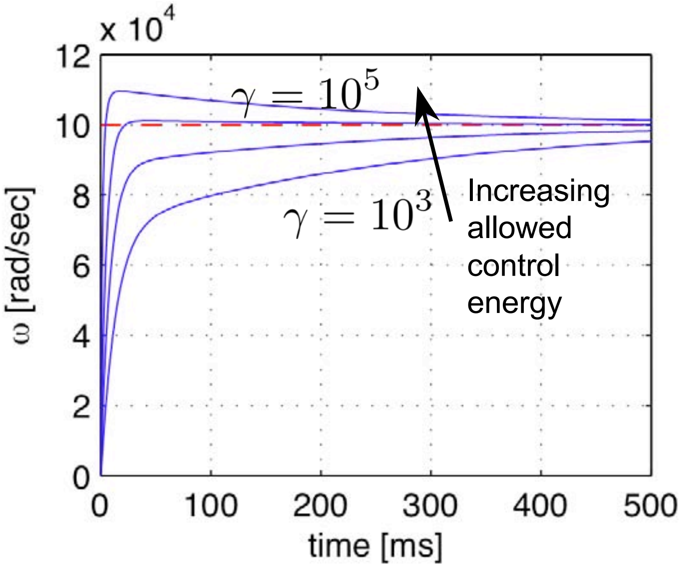
- Development of rotation model

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle R^2 (\nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho}\right] \boxed{+ \sum_j T_j + T_{\mathrm{NBI}} + T_{\mathrm{NTV}}}$$

  - One dimensional parabolic PDE model
  - Actuators: neutral beam injection, neoclassical toroidal viscosity (NTV).
  - Currently benchmarking models for neutral beam torque input and NTV



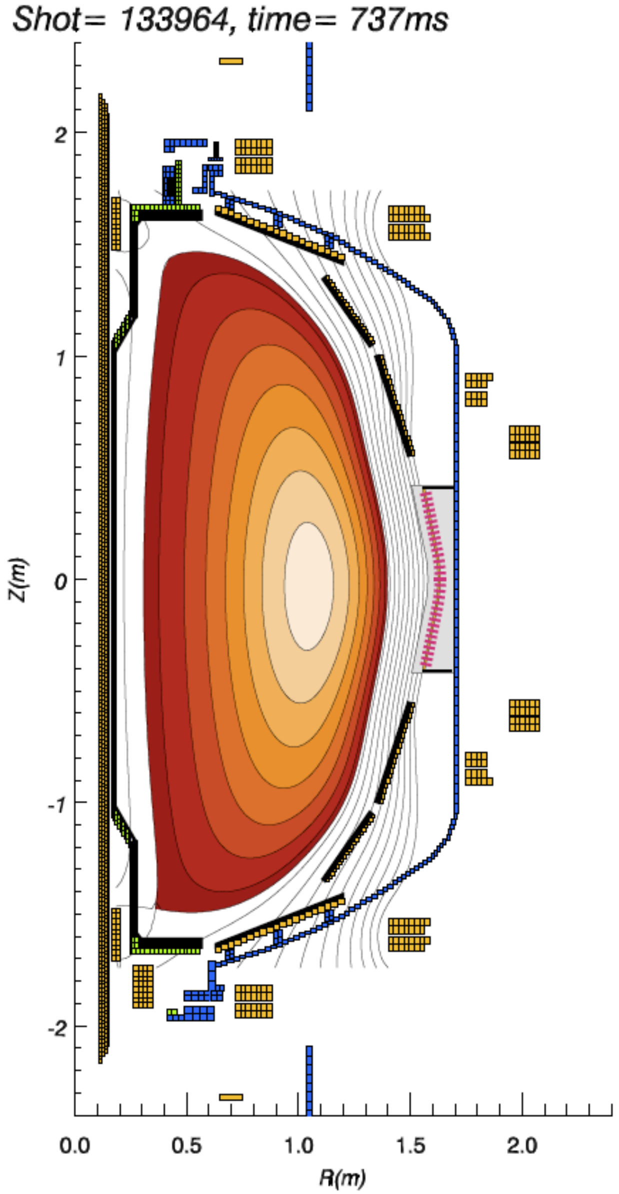
- Goal: Control of plasma rotation profile
  - Optimal control: linear quadratic regulator (LQR)
  - Real-time control with observer (LQE)
  - Reach desired rotational frequency within 50ms
  - Will determine range of possible profiles with NB+NTV
  - Will verify compatibility with simultaneous β control.



See K. Taira, Poster PP8.078

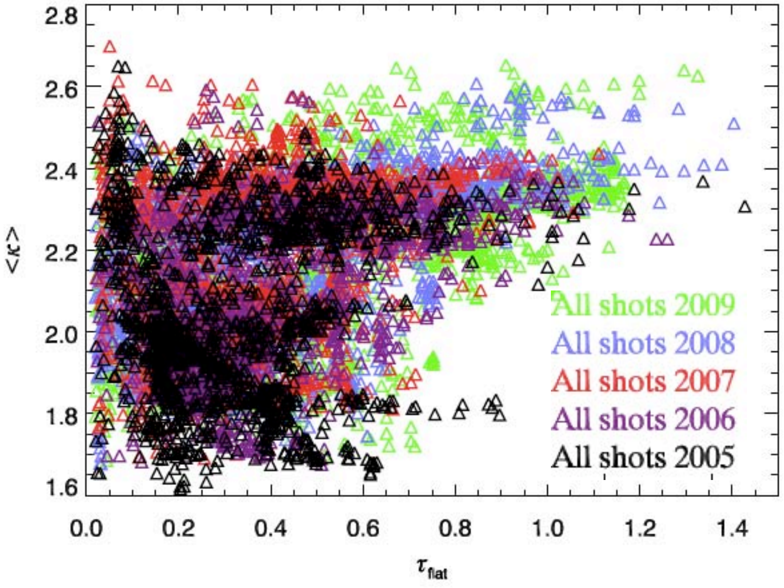
Scenario development has created reproducible plasma scenarios which are relevant for CTF and ST reactors

- Successfully developed high elongation scenarios, with lithiumization, and non-axisymmetric control
  - Benefits appear to add
- Have successfully attained high κ (~ 2.7) and high β_p simultaneously
- These values were sustained for long pulse ($\tau_{pulse} > \tau_{CR}$)
- Set record for sustained $\beta_p \sim 1.8$ during the I_p flattop

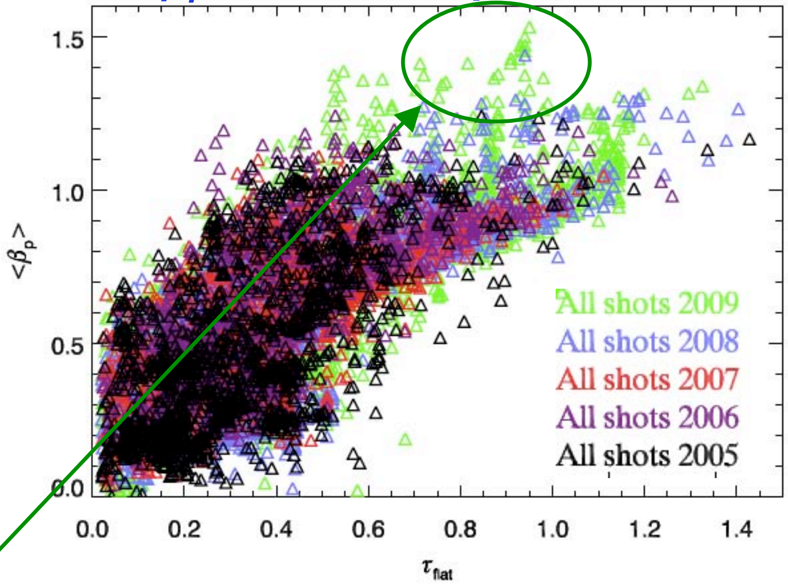


High κ scenario now routinely achieves higher β reproducible high non-inductive current fraction

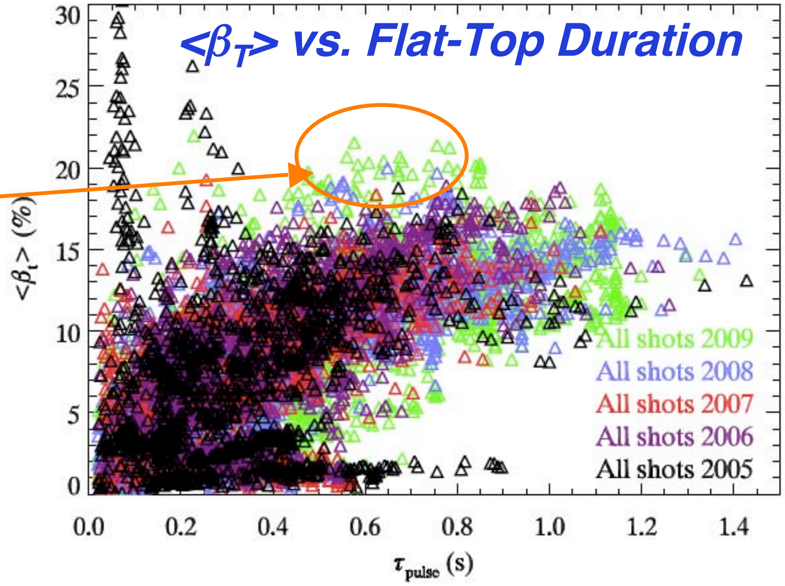
$<\kappa>$ vs. Flat-Top Duration



$<\beta_P>$ vs. Flat-Top Duration



- Two scenarios examined:
  - High-β_P scenario with maximum non-inductive fraction
  - High-β_T scenario at high I_N.
- Achieved β_p ~ 1.6% f_{NI} ~ 65% for ~$3\tau_{CR}$
  - Limited by TF flattop at peak field
- Achieved β_T ~ 20% for ~$2\tau_{CR}$

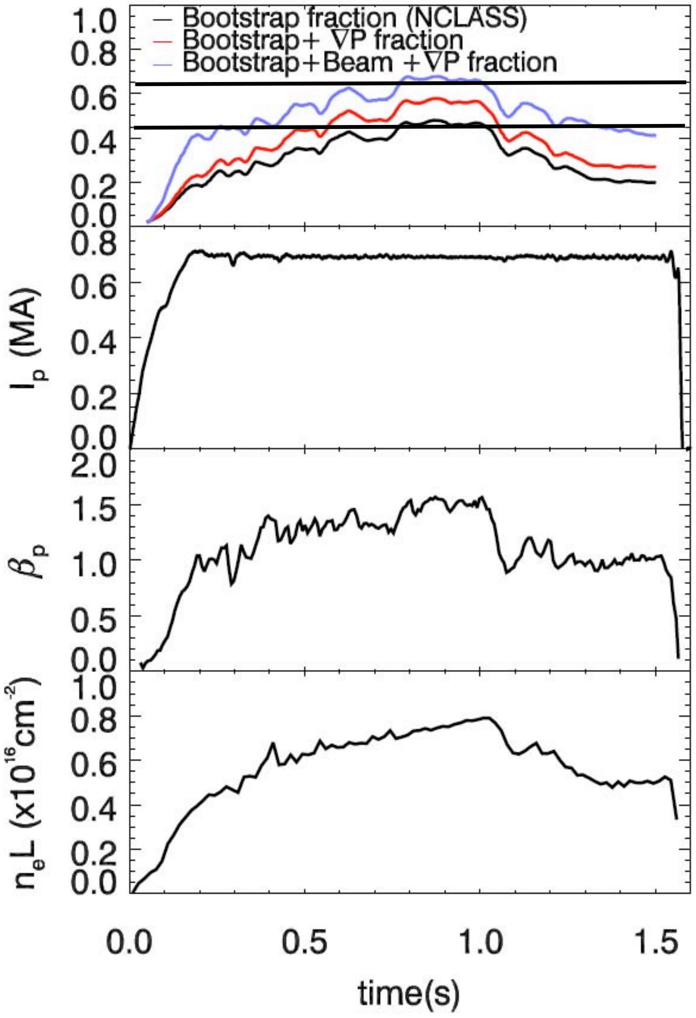


$<\beta_T>$ vs. Flat-Top Duration

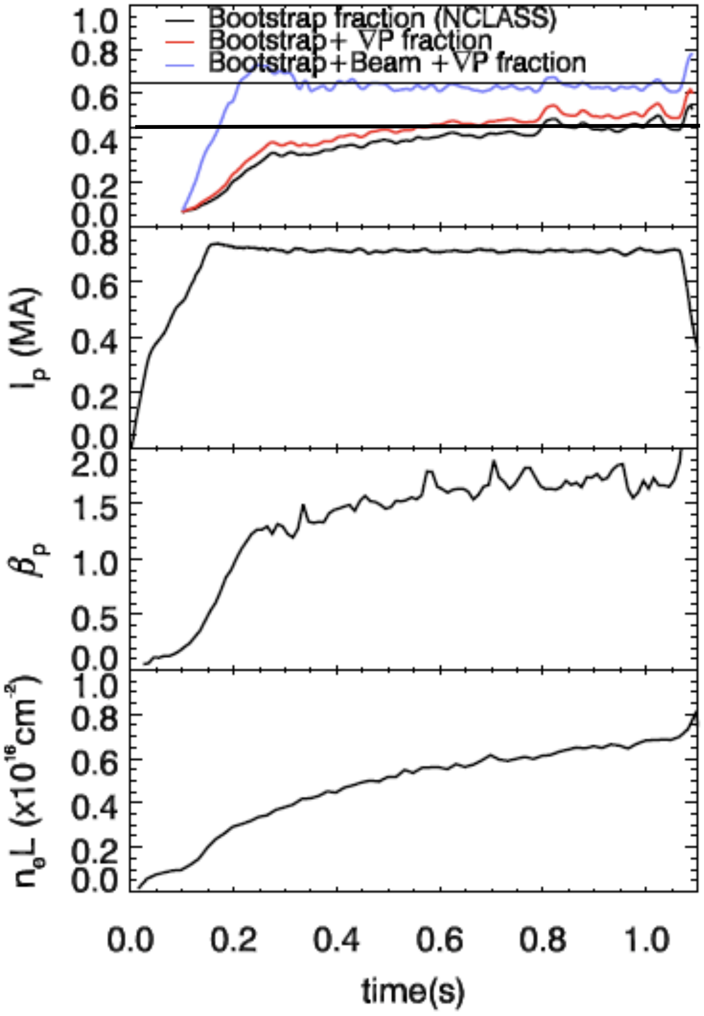
TRANSP indicates 65% f_{NI} maintained steady-state

- Same as f_{NI} achieved in previous "best discharges"
  - High non-inductive current fraction maintained longer - better control
- Analysis of current profile constituents shows ~20% deficit of current relative to total from MSE
  - Issues with Z_{eff}, reconstructions, edge bootstrap model?
- Early part of discharge has f_{NBI} ~ 40% - encouraging for NSTX-U and CTF

- ***Results of TRANSP analysis for shot 116318***



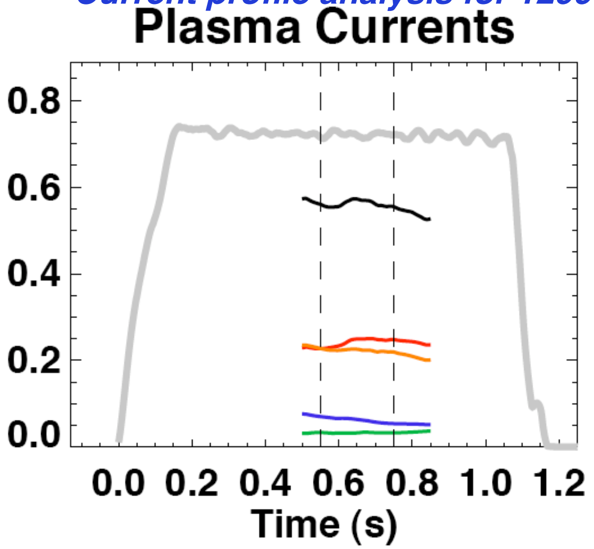
- ***Results of TRANSP analysis for shot 133964***

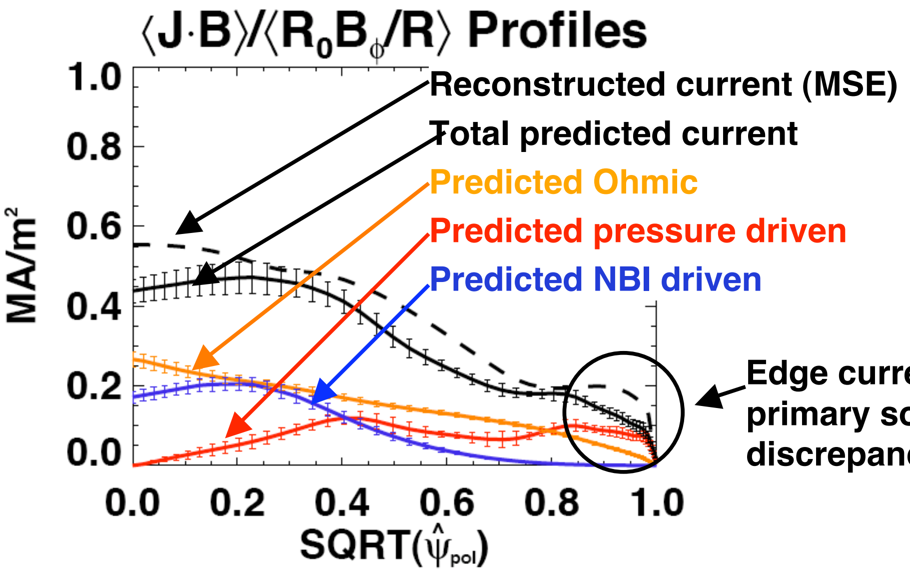


Current profile analysis shows ~20% discrepancy

- Previously, current profile analysis has given good agreement
- Most of total current discrepancy is at the boundary (area effect)
  - Edge bootstrap an important question
  - Correction of ~20% to n_e would raise non-inductive current fraction to record value
  - Z_{eff} high, also indicative of density anomaly

- *Current profile analysis for 129968*





Edge current primary source of discrepancy

Centrifugal Effects Important In These Cases

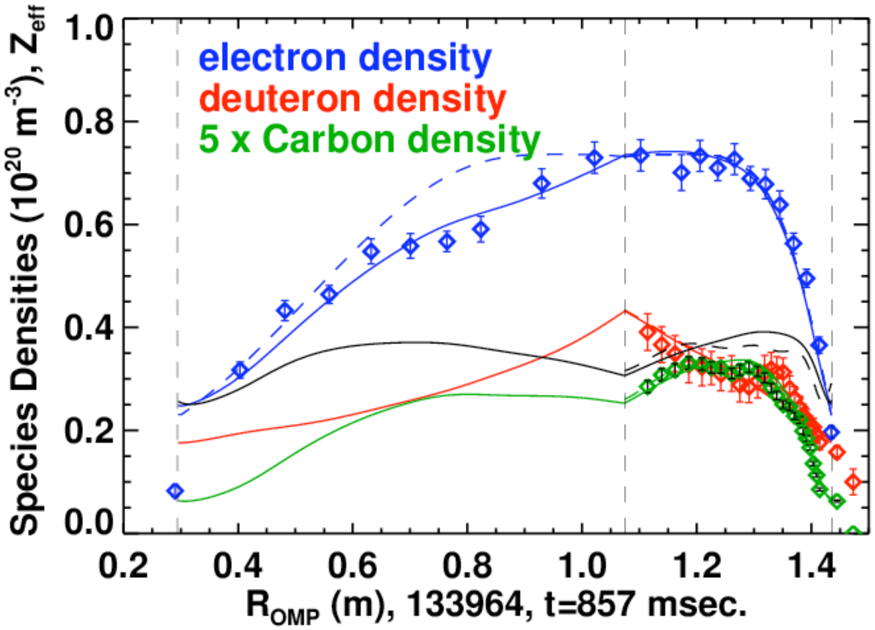
$$n_D(\psi,\theta) = n_{D,OMP}(\psi)\exp\left(\frac{\frac{1}{2}m_D\omega_D^2\left(R^2-R_{OMP}^2\right)-eZ_D\phi(\psi,\theta)}{T_D}\right)$$

$$n_e(\psi,\theta) = n_{e,OMP}(\psi)\exp\left(\frac{e\phi(\psi,\theta)}{T_e}\right)$$

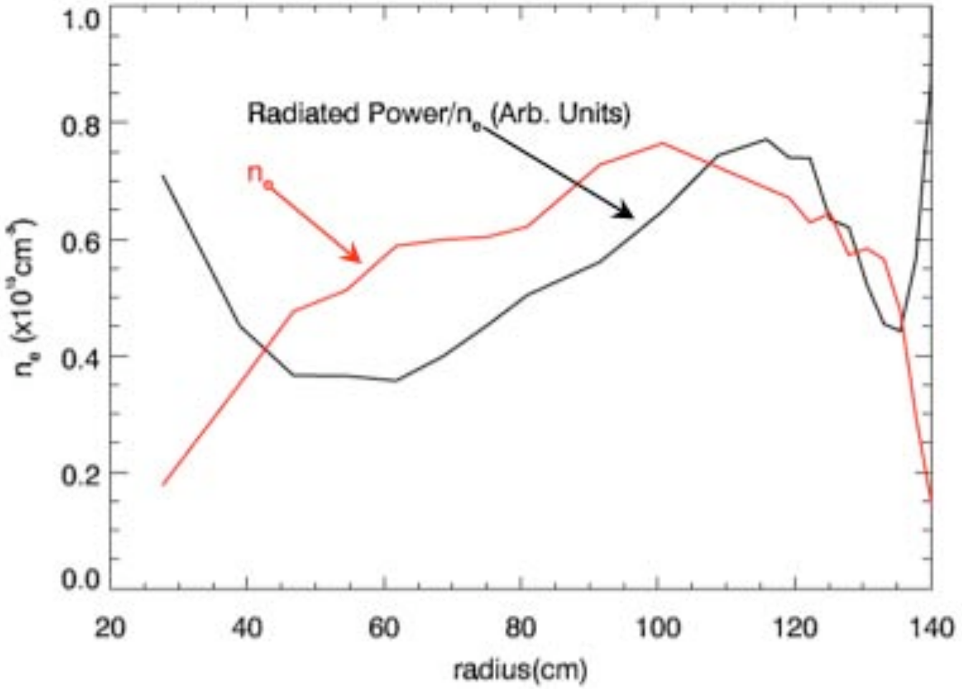
$$n_C(\psi,\theta) = n_{C,OMP}(\psi)\exp\left(\frac{\frac{1}{2}m_C\omega_C^2\left(R^2-R_{OMP}^2\right)-eZ_C\phi(\psi,\theta)}{T_C}\right)$$

$$0 = \sum_{j=e,D,C} n_j Z_j$$

- Solve for variation of potential $\phi(\psi,\theta)$ on a flux surface using iterative technique.
  - Include Carbon, Deuterium, and electrons.
  - See Wesson, Nuclear Fusion **37**, 579 (1997).
- Solutions yield $\langle Z_{eff}\rangle$, $\langle n_e\rangle$, $\langle n_D\rangle$, $\langle n_C\rangle$ for use in current component calculations,
- Significant asymmetry in radiated power profile as well.



Dave Gates, Stefan Gerhardt



Control science is the primary tool for Advanced Scenario development

- Improved control techniques have enabled access to new plasma regimes
  - Strike point control developed in support of LLD
  - Snowflake divertor achieved - will improve control in future
  - β control using NBI feedback commissioned
- Advanced Scenario development has realized plasmas which approach the requirements for a CTF and future ST reactors
  - High $\kappa \sim 2.7$ maintained simultaneous with record $\langle\beta_p\rangle \sim 1.6$
  - Record non-inductive current fraction maintained for ~ $3\tau_{CR}$ - limited by duration of the toroidal field (coil heating)
  - Discrepancy in measured and predicted total current point to even higher non-inductive current

Work supported by US DOE contract no. DE-AC02-09CH11466