NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Research plans for Advanced Scenarios and Control

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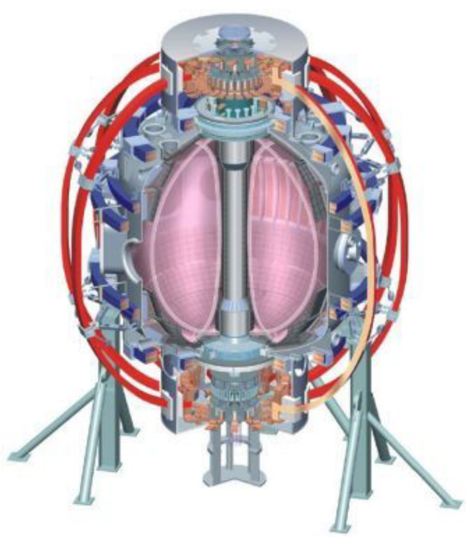
D. A. Gates, J. E. Menard (Deputy)
PPPL
For the ASC-TSG

NSTX PAC-25
B318, LSB
February 18-20, 2009



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NSTX has made substantial progress towards viable ST scenarios for steady state operation

- Scenario development is central to the NSTX Mission:
  - Establish attractive ST operating scenarios & configurations
  - Complement tokamak physics and support ITER
  - Understand unique physics properties of the ST $\Rightarrow$ basis of all the elements of the NSTX mission
- Control science is the primary tool for scenario development

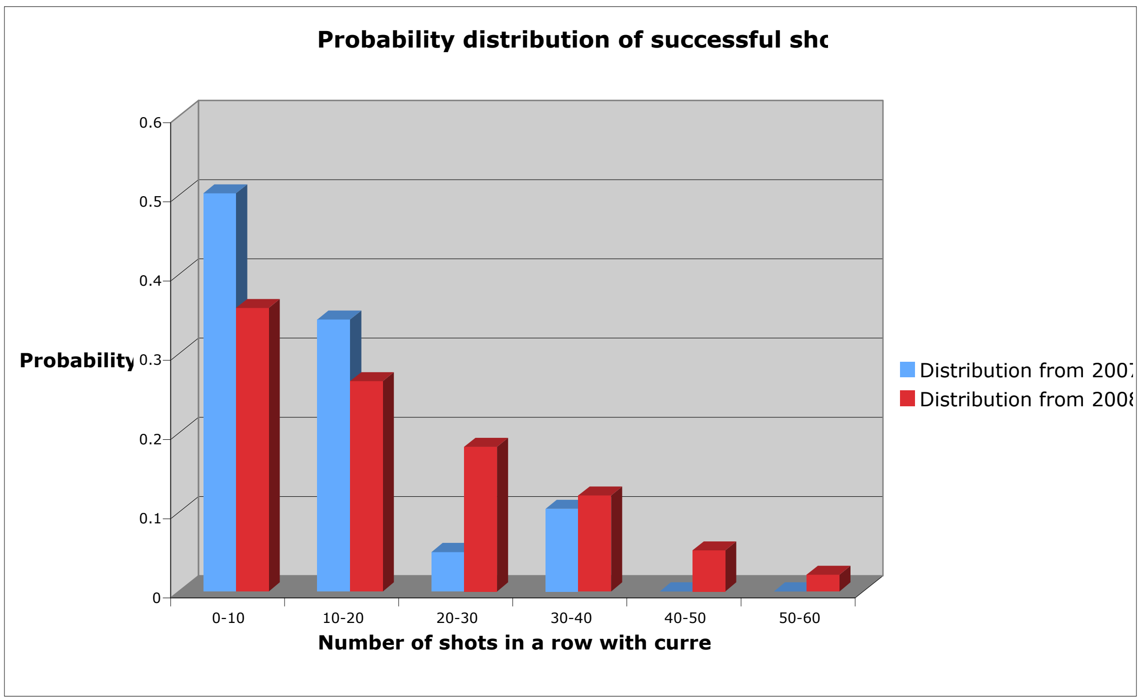
Outline

(Note: Response to PAC-23 recommendations are interspersed)

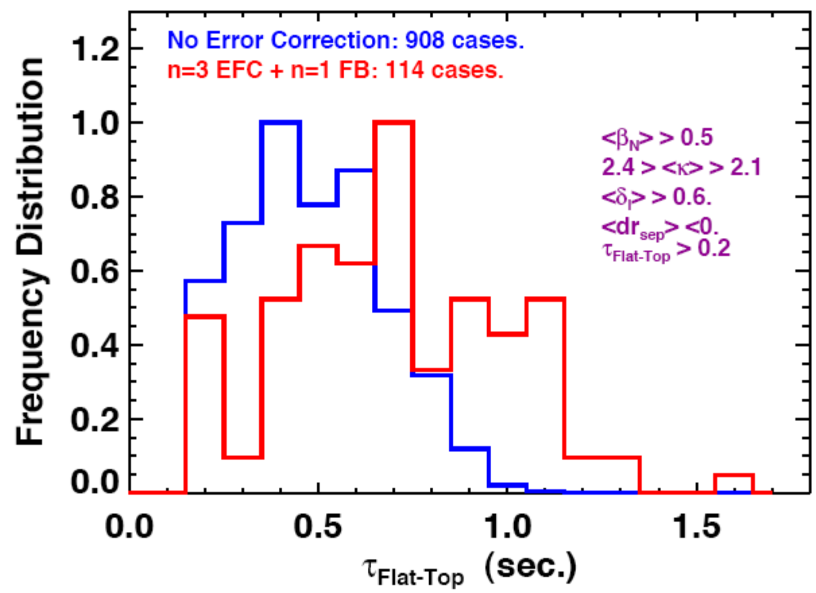
- Highlights from the 2008 run
- ASC research plans for 2009-11
- Integrated scenario and control modeling
- Summary

Control science is the primary tool for scenario improvement

- Real-time control computer upgrade restored reliable operation
  - Addition of RWM/RFA feedback caused overload of the real-time data acquisition on the previous computer system
  - Upgraded to modern multi-processor architecture (4 dual core AMD)
- Reliability substantially improved and latency reduced
  - Paves the way for further improvements



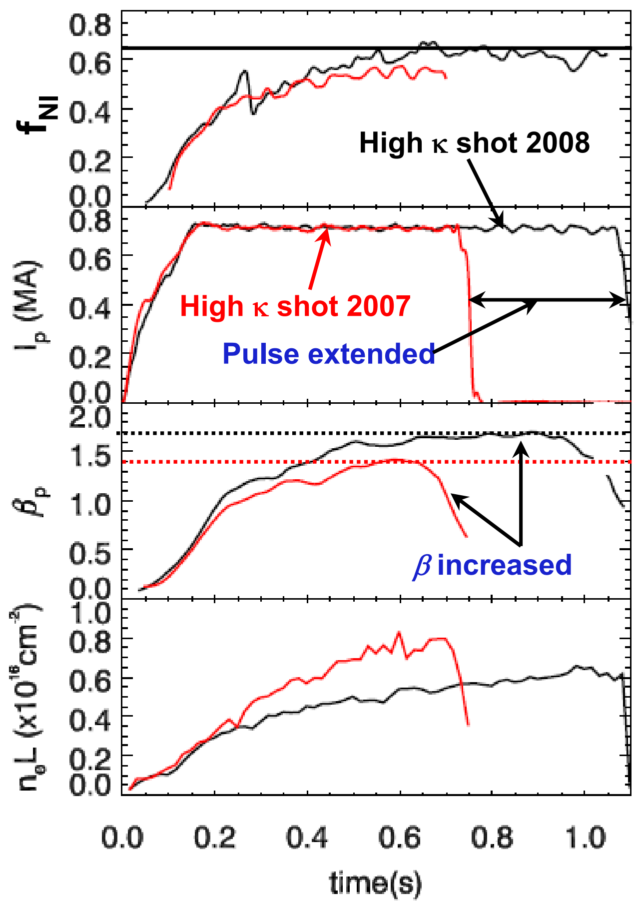
- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Feedback gain increased from 2007
  - Reduced latency
  - Filtering capability added
- Control statistically raises β and increase pulse length



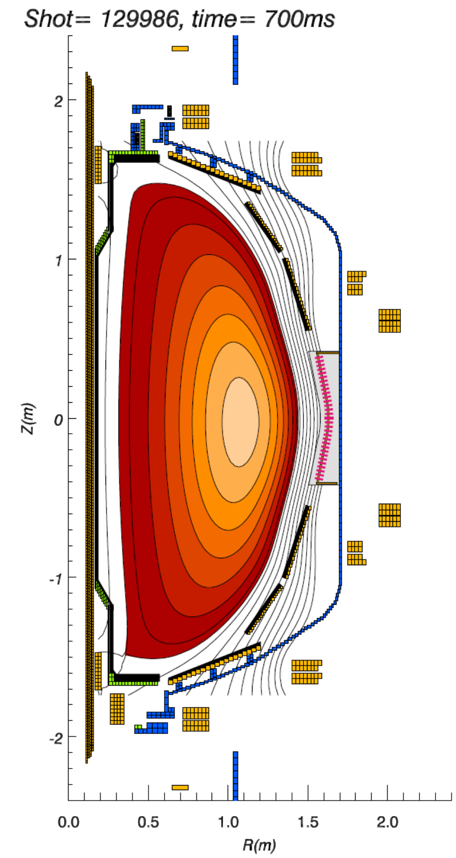
NSTX has now accessed long pulse at high β simultaneous with extreme plasma shaping

- Because of improved vertical stability at low aspect ratio, NSTX can access very high elongation $\kappa \sim 3$
  - $f_{bs} \sim (1+\kappa^2)/2$
- β maintained well above the no-wall limit, $\beta_N \sim 5$
- Pulse extended - maintained non-inductive current fraction $f_{NI} \sim$ 65% for 1-2 τ_{CR} - limited by TF coil heating limit
  - Uses n=3/n=1 control
  - Also uses lithium coating to improve confinement
  - reconstructed I_p ~25% below measured value - indicates f_{NI} could be higher
  - Very low surface voltage <100mV for ~ 2 τ_{CR}

Time history of global parameters and non-inductive current fraction as determined by TRANSP, constrained by MSE

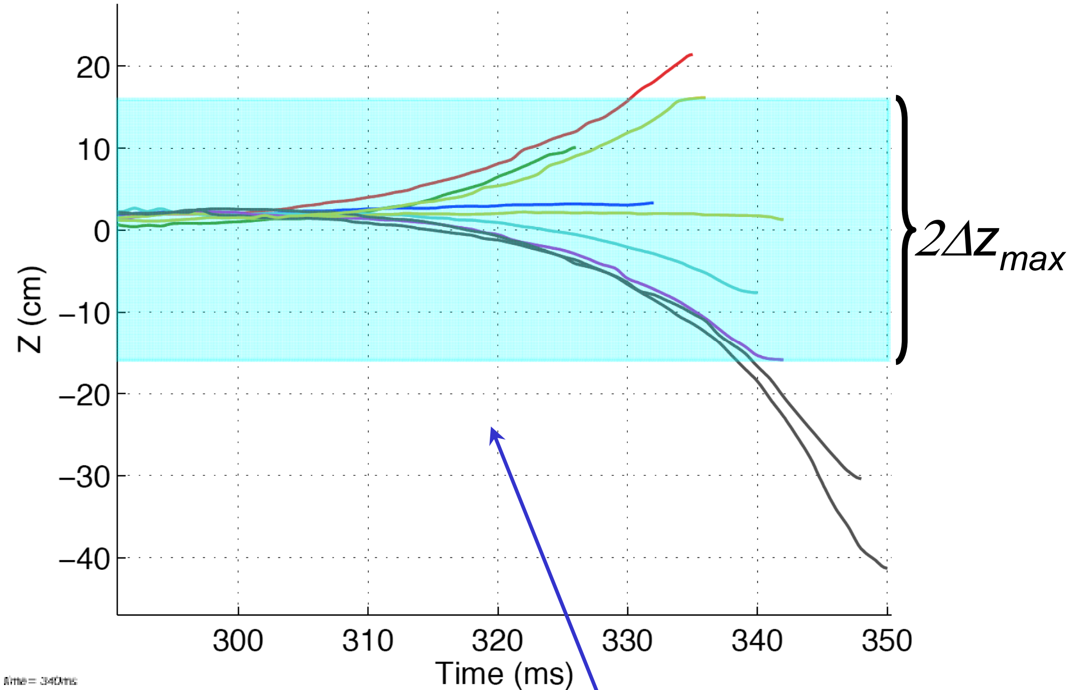


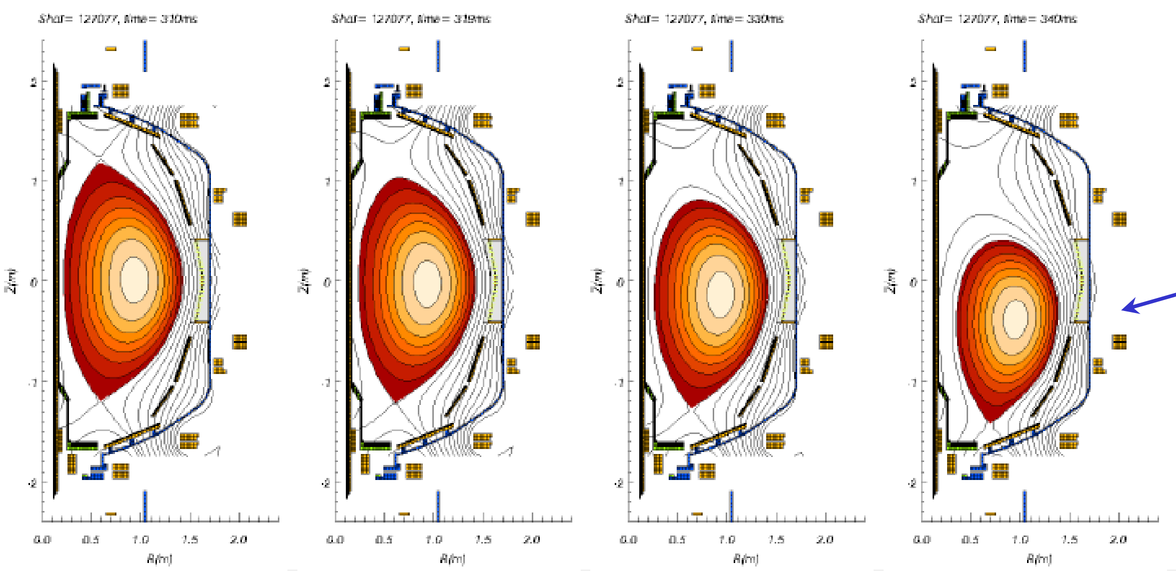
Cross-section of $\kappa \sim 2.7$ equilibrium



NSTX has improved understanding of n=0 stability for ITER

- **Response to PAC recommendation 21:** Place a high priority on providing vertical stability information to ITER
- Experiments using induced VDEs have measured Δz_{max}
- Results consistent with $\Delta z_{max}/a > 0.1$ for robust control
- Crucial that ITER has robust vertical control - internal control coil added





- *Typical induced VDE Evolution on NSTX*

Broad progress towards increased f_{NICD} scenarios as determined by integrated scenario modeling (1)

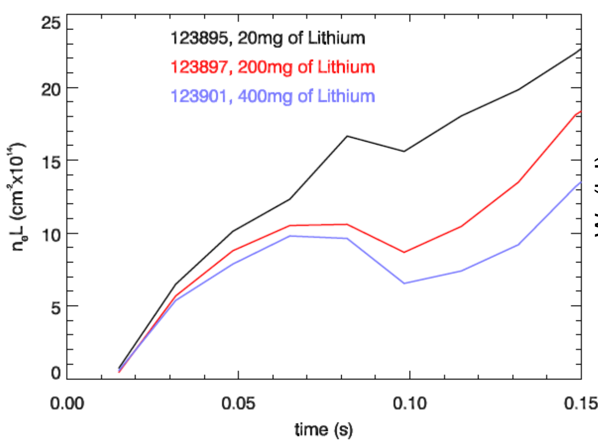
Scenario 1: ***f_{BS} and f_{NBICD} similar to ST-CTF***

- **Transient, low n_e, high f_{NBICD}**
  - **Reduce n_e, broaden T_e with LLD**
  - **Maintain q(0) > 1 w/ J_{NBI} redistribution?**

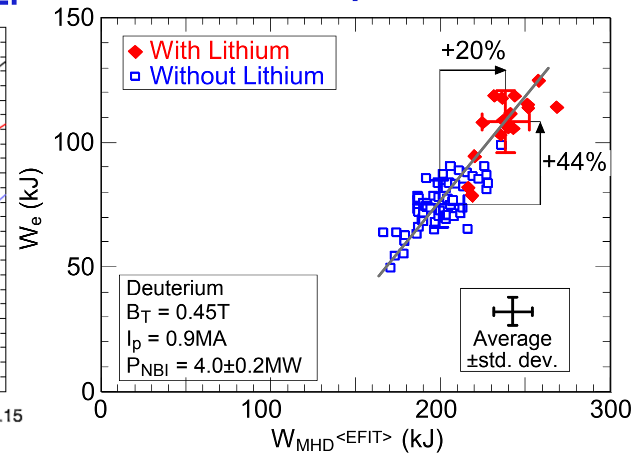
Low-n_e, high-f_{NBICD}

$n_{20}(0) = 0.36$
$\kappa = 2.2$
$H_{98} = 1.1$
$\beta_N = 5.6$
$q(0) \rightarrow 1$
$f_{BS} = 35\%$
$f_{NBICD} = 55\%$
$f_{NICD} = 90\%$

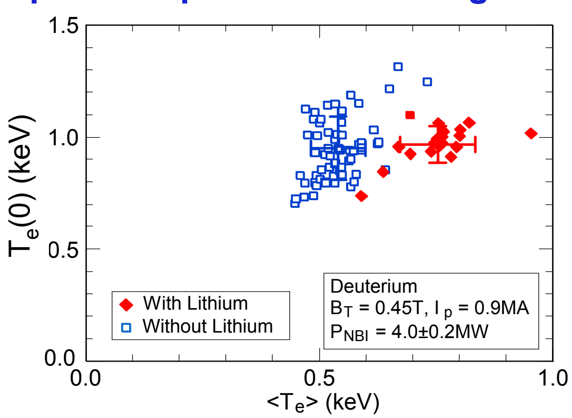
Transient density reduction w/ Li



Confinement improvement w/ Li



Temperature profile broadening w/ Li



- Evaporated Li has demonstrated:
  - Transient pumping
  - Broadened T_e profiles, increased e-confinement
- In FY2010-11, will test if LLD:
  - Provides more continuous pumping
  - Enhances effects of Li/pumping on edge profiles

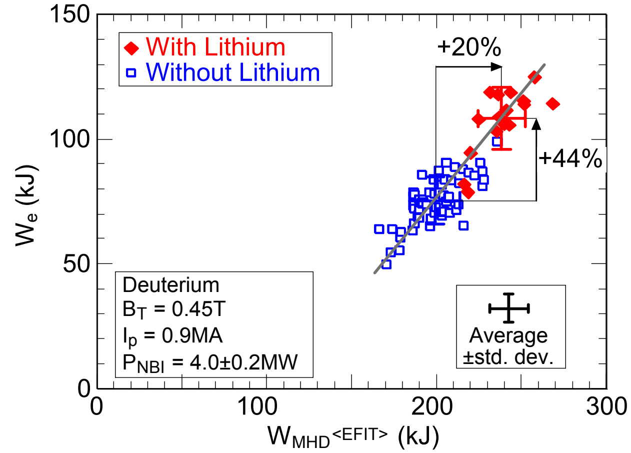
Broad progress towards increased f_{NICD} scenarios as determined by integrated scenario modeling (2)

***Scenario 2:* f_{BS} and f_{NBICD} similar to NHTX**

- **High density, high-β_N, high-f_{BS}**
  - Control n_e, broaden T_e, increase H_{98} with LLD
  - Increase $W_{electron}$, β_N, f_{BS} with HHFW

- HHFW has demonstrated:
  - Core e-heating in D NBI-heated H-mode
  - Acceptable/improved core impurity levels
- In FY09-11, will test if upgraded HHFW:
  - Provides stronger e-heating in D H-mode
  - Provides ELM-resilient heating

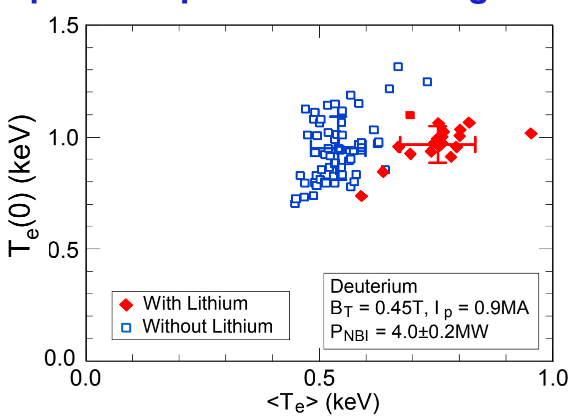
Confinement improvement w/ Li



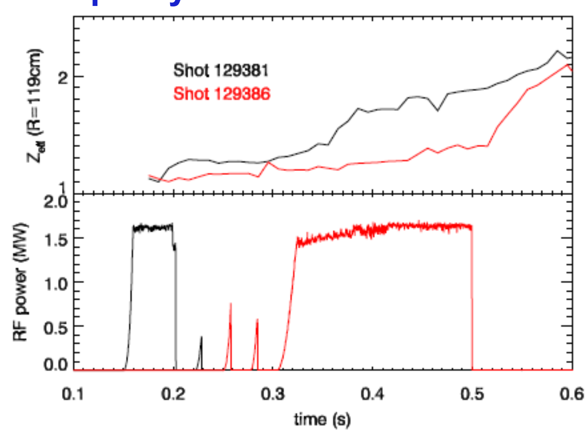
High β_N, high-f_{BS}

- $n_{20}(0) = 0.75$
- $\kappa = 2.6$
- $H_{98} = 1.4$
- $\beta_N = 6.6$
- $q(0) = 1.4$ to 2.4
- $f_{BS} = 75\%$
- $f_{NBICD} = 25\%$
- $f_{NICD} = 100\%$

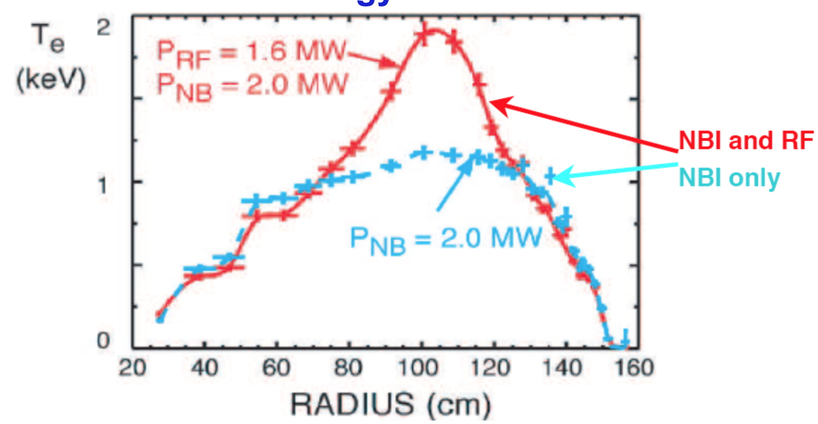
Temperature profile broadening w/ Li



Impurity reduction with HHFW



Electron stored energy increase with HHFW



LLD + upgraded HHFW will provide powerful new capabilities for advanced scenario development in FY2009-11

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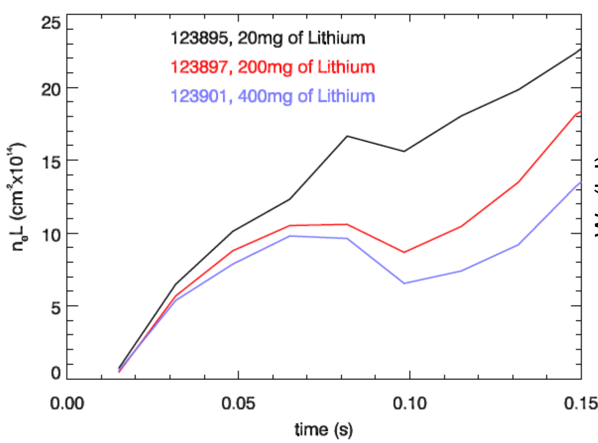
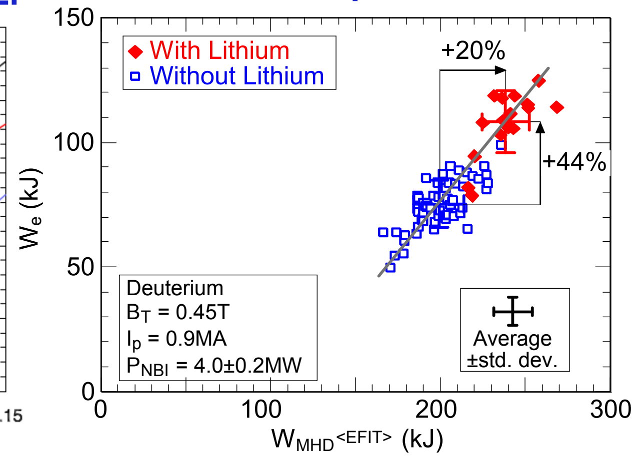
Transient density reduction w/ Li



Confinement improvement w/ Li



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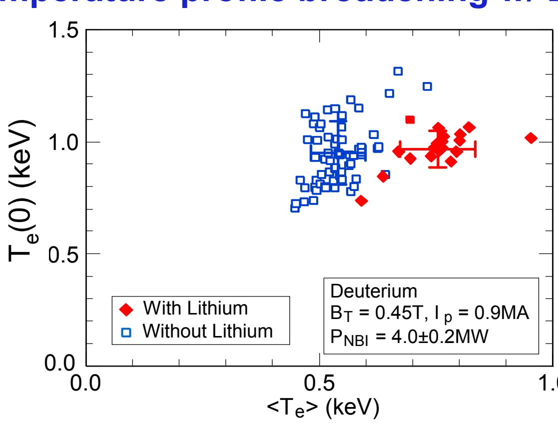
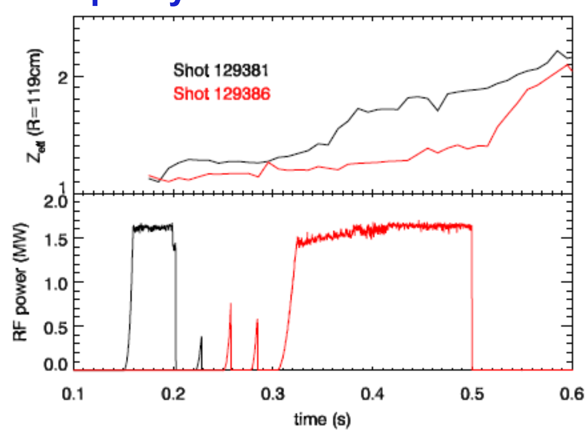
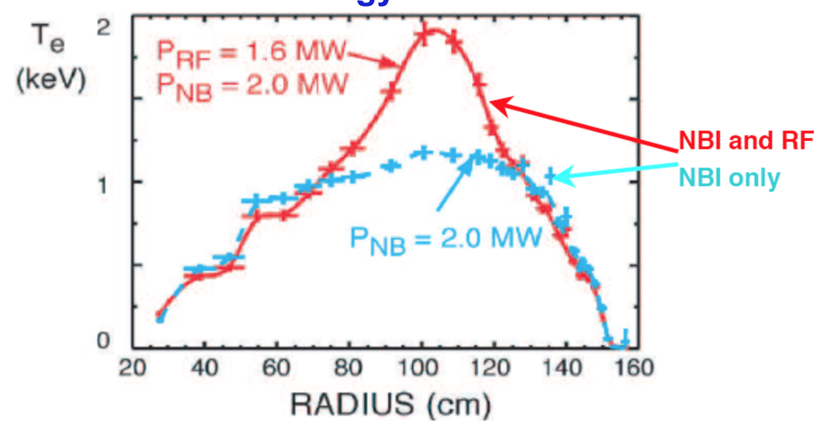
Temperature profile broadening w/ Li



Impurity reduction with HHFW



Electron stored energy increase with HHFW



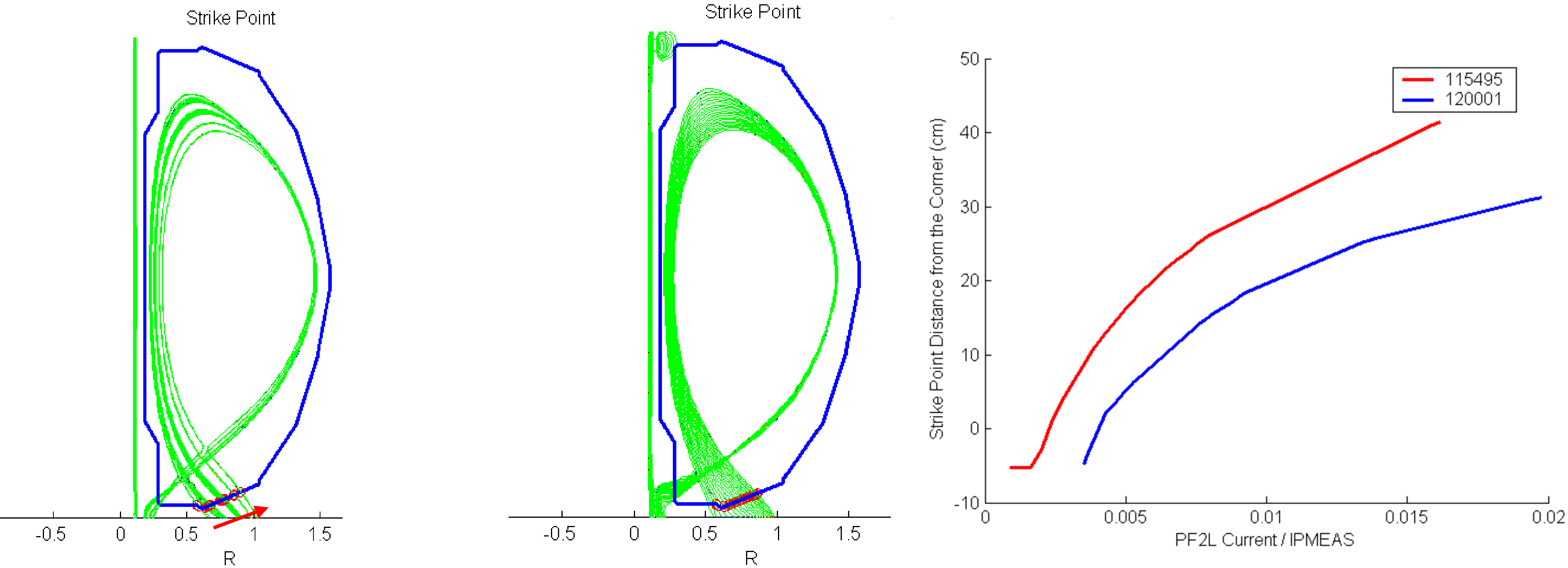
2009-2011 research plan (pre-CS/NBI upgrade)

(GOAL: f_{NICD} = 80-90% for $\tau \sim \tau_{CR}$ - TF pulse too short for equilibration)

- Plan for developing low density, high NBI-CD fraction scenario
  - Assess H-mode characteristics vs. collisionality and lithium conditioning (FY10 BP milestone)
  - Characterize NBI J(r) redistribution from fast-ion MHD (FY09 incremental ASC milestone, ITPA/IOS - 4.1,5.1)
  - Dependence of integrated plasma performance on collisionality (FY11 ASC milestone)
  - Implement strike point control for LLD (FY09)
- Plan for developing high normalized beta, high bootstrap fraction scenario
  - Perform high-elongation high β operation – (FY09 ASC milestone)
    - $\kappa \sim 2.8$, $\tau \geq \tau_{CR}$
    - β feedback (FY09)
    - Understand discrepancy between measured and reconstructed current
  - Characterize HHFW heating, CD, and ramp-up in H-mode plasmas (FY10 WPI milestone, ITPA IOS-5.2)
  - Improved MHD control (β-control, Robust control, RFA feedback, improved gain)
- Real-time CHERS and v_ϕ control (Incremental FY11)
  - Test as means of pressure profile control

Strike point control being developed for the ST (no inboard coils)

- **PAC recommendation 22:** Make plans for LLD - may required increased effort/manpower (PPPL student, Princeton University MAE post-doc)
- Study quantifies how equilibrium strike point responds to PF2L
- Lump all system dynamics into single time constant, τ.
  - Determine τ experimentally by applying step impulse and measuring response

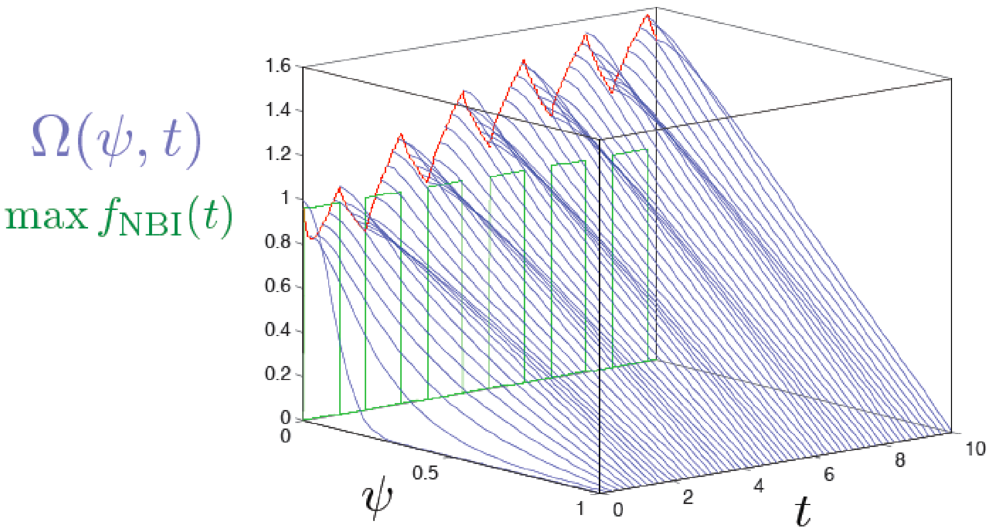


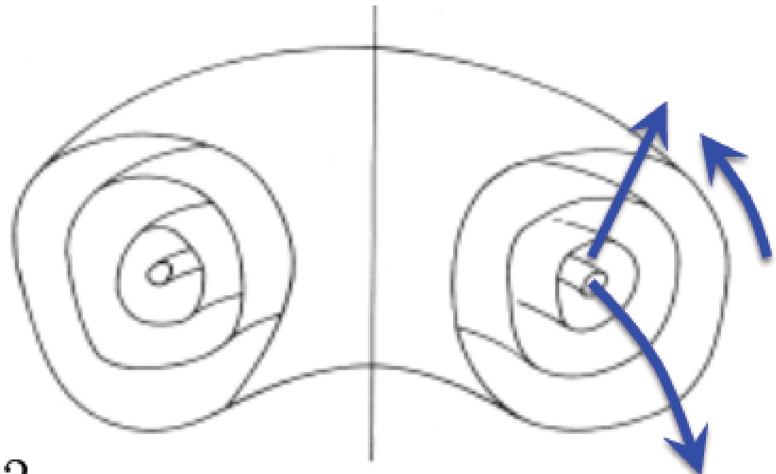
The change in the strike point with varying PF2L current

(Other PF currents fixed)

Predictive rotation model being developed

(K. Taira, E. Kolemen, Prof. C. Rowley, MAE Dept., Princeton University,)





$$\frac{\partial v_T}{\partial t} - \nabla \cdot \xi_\zeta \nabla v_T + \mu_{iT} \frac{\tilde{B}^2_{\mathrm{eff}}}{B_0^2}(v_T - v^*) = f_{\mathrm{NBI}}$$

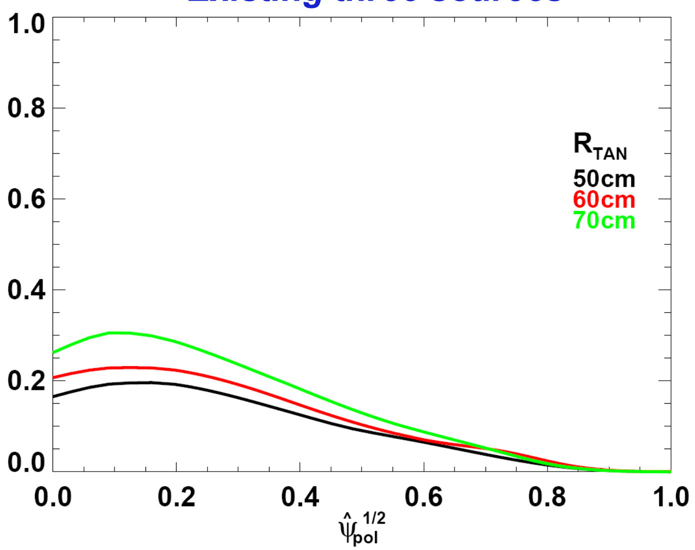
inertial	diffusion	neoclassical toroidal viscosity	neutral beam injection

Ref: J. D. Callen et al, Toroidal Rotation in Tokamak Plasmas, 2008

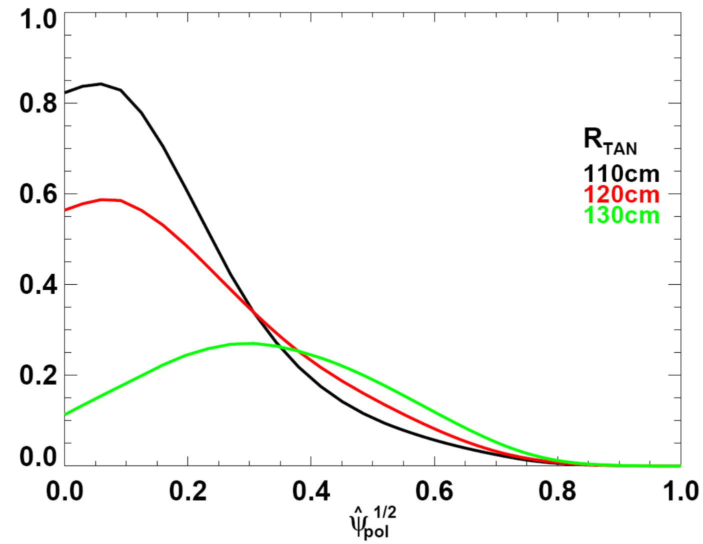
Center Stack and NBI upgrades enable advanced operation in low collisionality regime

- Center stack upgrade
  - Achieve lower ν^* through the B_t dependence of electron confinement
  - Extend pulse so that NSTX can operate for multiple τ_{CR} at lower ν^*
  - Operate at high β_p with a plasma current high enough (I_p > 700kA) to confine full energy fast ions from the neutral beams
  - Enable HHFW coupling in long pulse discharges
- NBI upgrade
  - Operate at an aspect ratio and collisionality more like future STs
  - Can drive current from strongly peaked on axis, to peaked off axis
  - Overall higher efficiency increases utility of NBICD during plasma current ramp

- ***Existing three sources***



- ***New NBI sources***



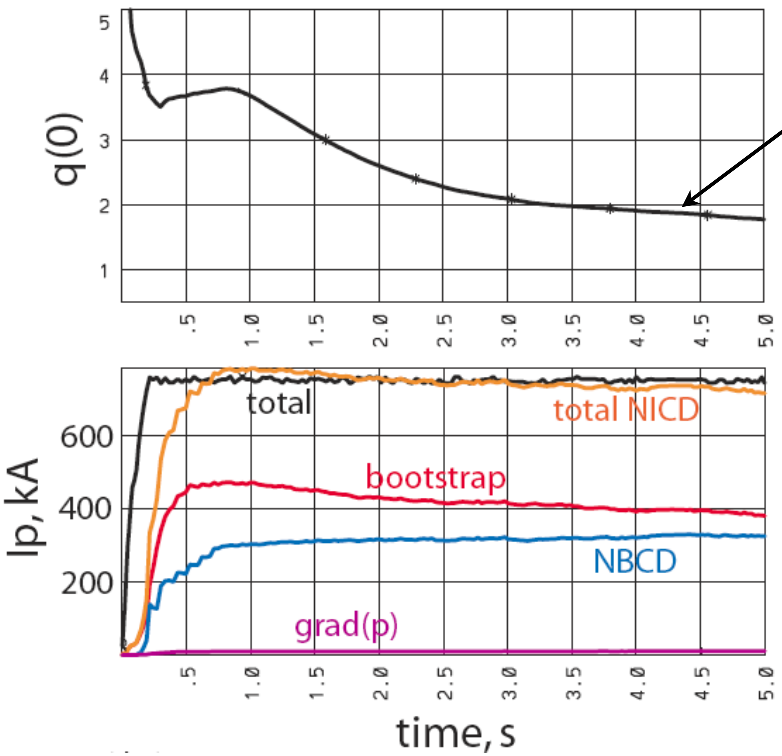
$\langle J \cdot B \rangle / \langle R_0 B_\phi / R \rangle$ [MA/m^2]

P_{NBI}=2MW

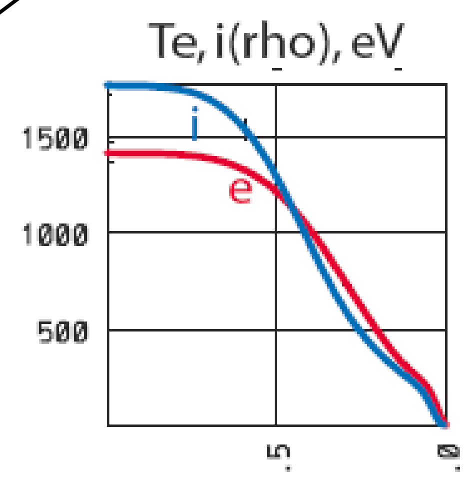
E_{NBI}=90keV, I_P=0.82MA, f_{GW}=0.58 $\overline{n_e} = 4.4 \times 10^{19} m^{-3}$, $\overline{T_e}$ = 1.2keV

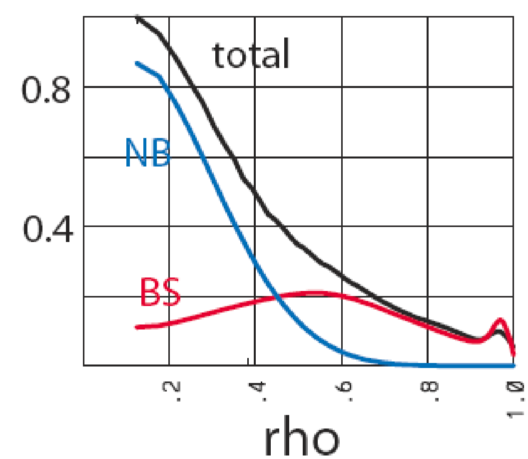
Integrated scenario modeling indicates 100% non-inductive operation possible with B_t = 1T

- Assumes 6.15 MW absorbed beam power for 5s
  - Single beam NBI power limited to ~5MW for long pulse - will require additional beam power
- Can achieve q_{min}>1 with fully non-inductive current drive
- Scenario achievable without major extrapolations in density, achieved β_N, or confinement time
  - Requires T_e increases with B_t and density control to moderate levels
- **Response to PAC recommendation 23**: Do more scenario modeling for experimental plans
  - Due to resource limitations, integrated modeling effort focused on upgrades for 5 year plan
  - Kessel no longer available to NSTX (ITPA/ITER) - need new personnel
  - Modeling of strike point control and rotation control done using simpler models



Long pulse required to reach equilibration





- ***Scenario parameters***
- ***H_{98} = 1.15***
- ***I_p = 750kA***
- ***n/n_{Gr} = 0.6***
- ***Bt = 1.0T***

Summary of Advanced Scenarios and Control research plans

- Plasma control tools will continue to be improved providing research opportunities for advanced scenario development
  - β control (FY09)
  - Strike point control (FY09)
  - Improved MHD control
  - Real-time rotation control (incremental)
- Focus on reduced collisionality for increased non-inductive current drive efficiency and to narrow the gap between NSTX and future STs
  - By increasing T_e, reducing density w/ Lithium (2009-2011)
  - By increasing TF through improved electron confinement (2012-2013)
- LLD provides important opportunity for controlling density in 2010-2011 time frame
- Center stack upgrade will provide expanded operational space consistent with high NICD fraction
- NBI upgrade will provide an extremely flexible tool for current profile control and to assist current ramp-up