NSTX

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Advanced Scenarios and Control Overview for 2009-13

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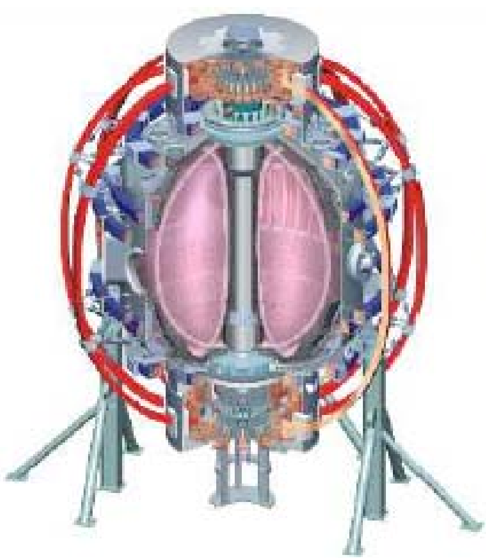
For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-B318, PPPL
July 28-30, 2008



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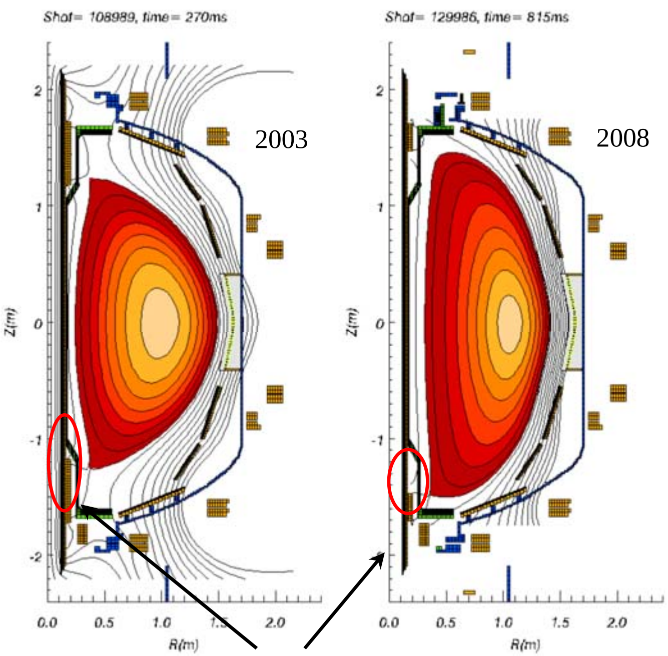
Advanced Scenarios and Control (ASC) Outline

- Experimental results from 2003-8
- ASC plan 2009-2011
  - Scenario integration goals
  - Review of integrated modeling results
  - Approaches to achieving these goals
- ASC Plan from 2012-2013 and beyond
  - Role of CS upgrade in integration goals
  - Role of 2nd NBI in long-term integration goals
  - Control system upgrade plans
- Summary and timeline

Optimized shape control has enabled access to advanced regimes on NSTX

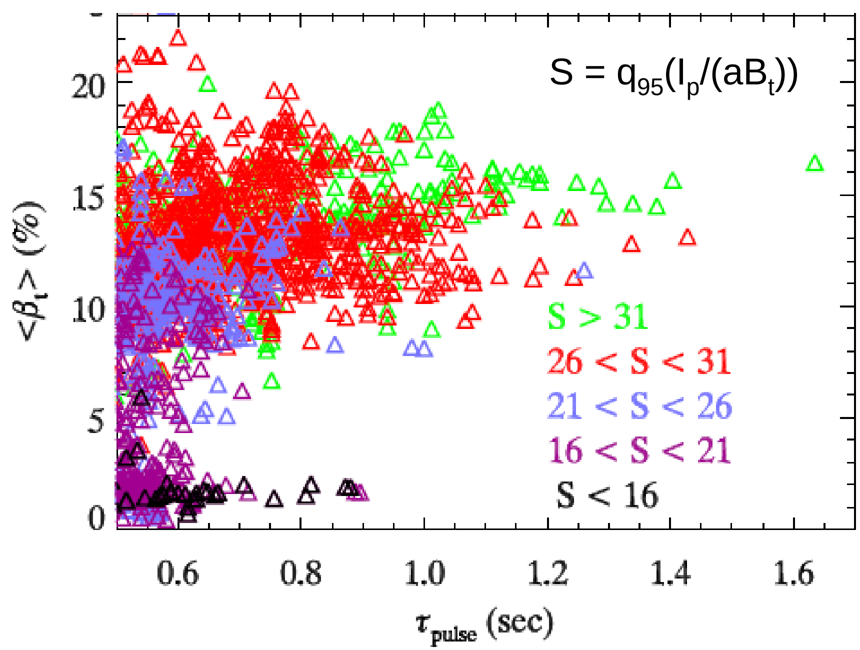
- NSTX has achieved record values of plasma shaping - S doubled over 5 yr plan time frame
- Continuous technology improvements have allowed control of plasmas with high elongation
- PF coil enhancements have enabled achievement of high triangularity
- rtEFIT developed in collaboration with GA has helped enable achievement of reliable plasma shape control
- Improvements in plasma performance are directly associated with improvements in plasma shaping
- 2008 NSTX combined highest shaping and highest β_N giving longest pulse to date
  - Non-axisymmetric control also important
- Shape control development approaching completion (vessel limitations)

$\kappa = 2.0$, $\delta = 0.8$, S ~ 23 $\kappa = 3$, $\delta = 0.8$, S ~ 41



- ***PF1A coil upgraded***

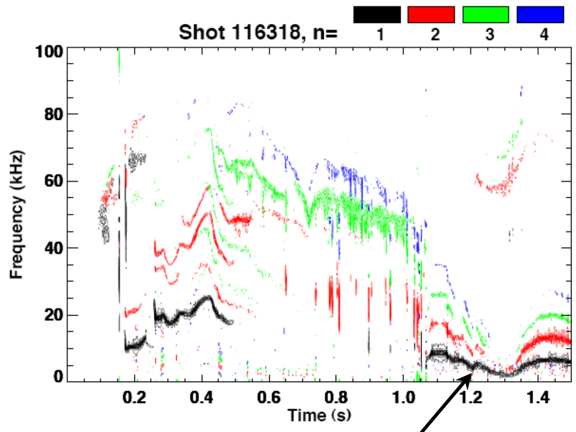
Plot of pulse averaged toroidal β vs. pulse length



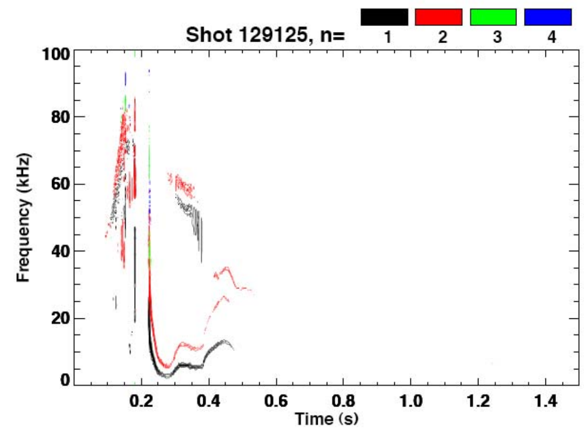
n=1 RFA feedback combined with n=3 correction now routinely used to maintain plasma rotation

- Non-axisymmetric feedback has been developed in collaboration with Columbia University
- Has enabled delay in the onset of deleterious MHD
- Plasma rotation is maintained throughout discharge
- Was in use during most long pulse discharge development in 2008 run

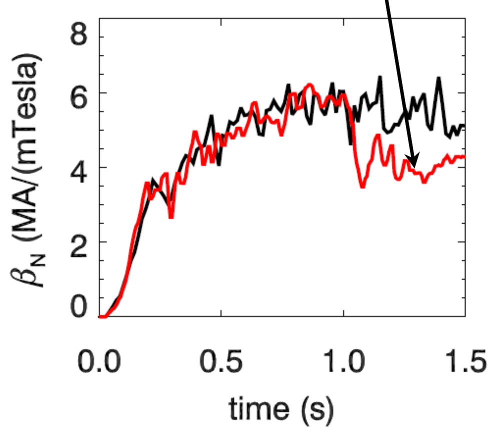
- ***2005 Long pulse discharge w/o n=1 feedback and n=3 correction***



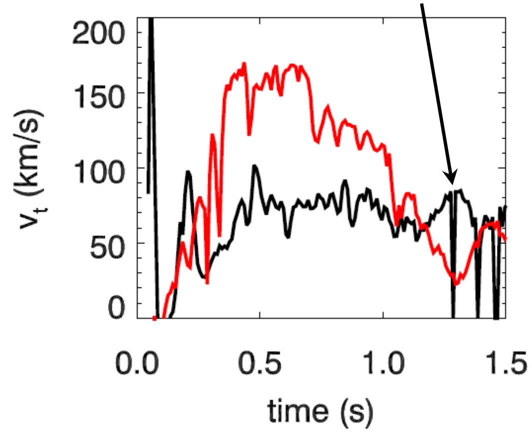
- ***2008 Long pulse discharge with n=1 feedback and n=3 correction***



n=1 mode drops β



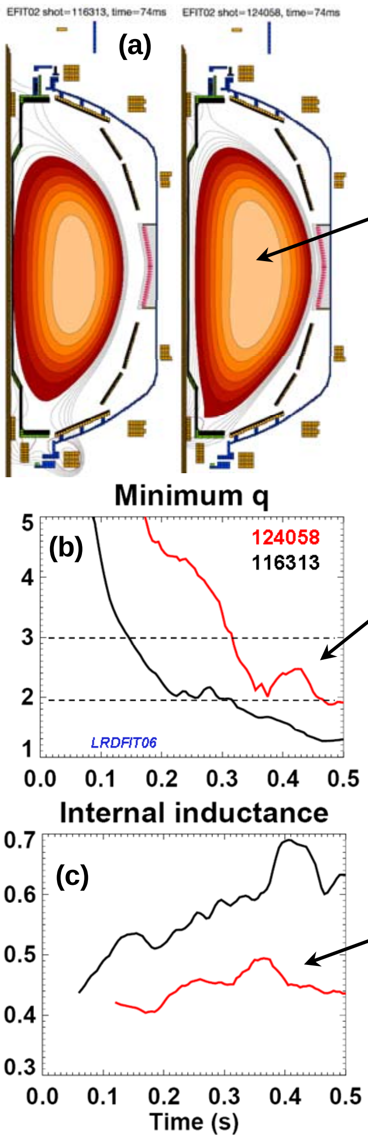
- ***n=1 feedback + n=3 correction maintains rotation***



CHERS v_t at R = 128cm

Early H-mode access with early shaping limits flux consumption during current ramp, raises q_{min}

- Reduced flux consumption during I_p ramp-up important for minimizing size of ohmic solenoid in future ST's
- Elevated q_{min} required for high non-inductive current drive cases
- Diverting the plasma early in the current ramp achieves both goals
  - Reduces plasma flux by lowering li
  - Leads to earlier H-mode transition raises β, increases bootstrap current
  - Higher Te slows ohmic current penetration raises q(0)

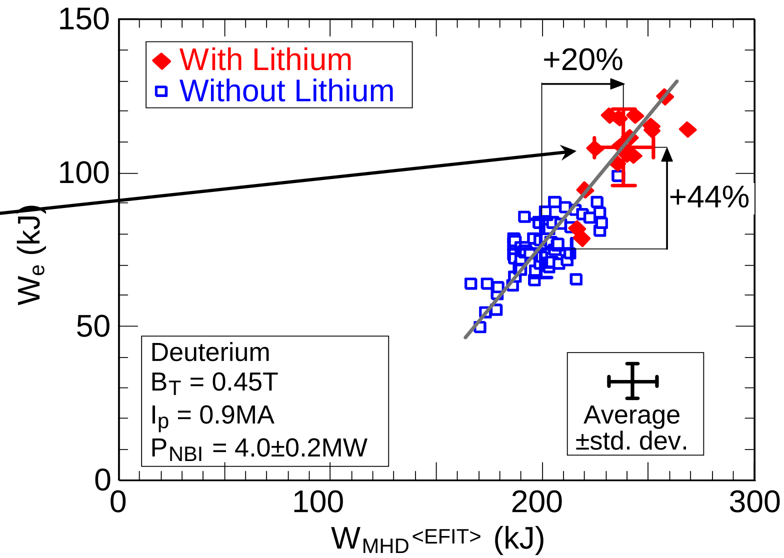


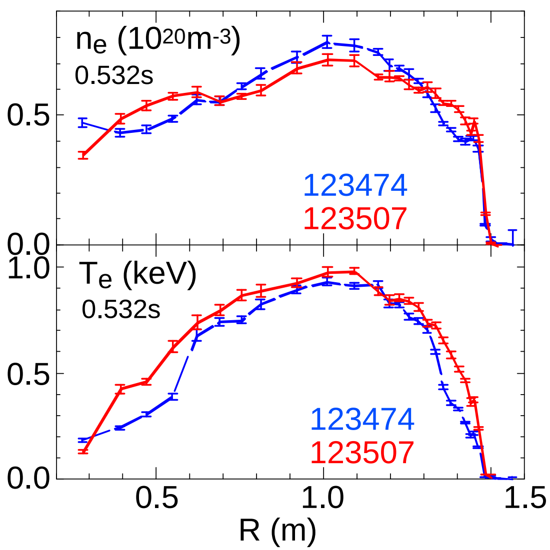
- ***Plasma diverts at t= 70ms***
- ***Raising q_{min}***
- ***And Lowering l_i***

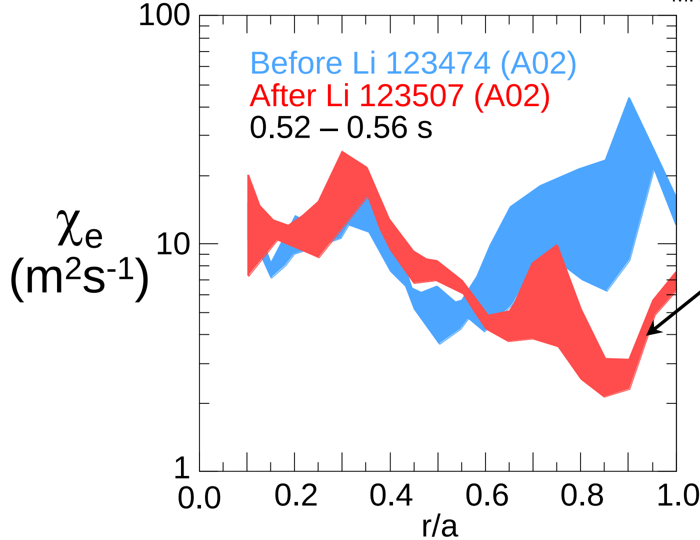
Lithium evaporation increases energy confinement

- Confinement improvement primarily in electron channel
- Improvement primarily due to broadening of electron temperature profile
- Two evaporators more effective than one

- ***Electron confinement improves with lithium evaporation***



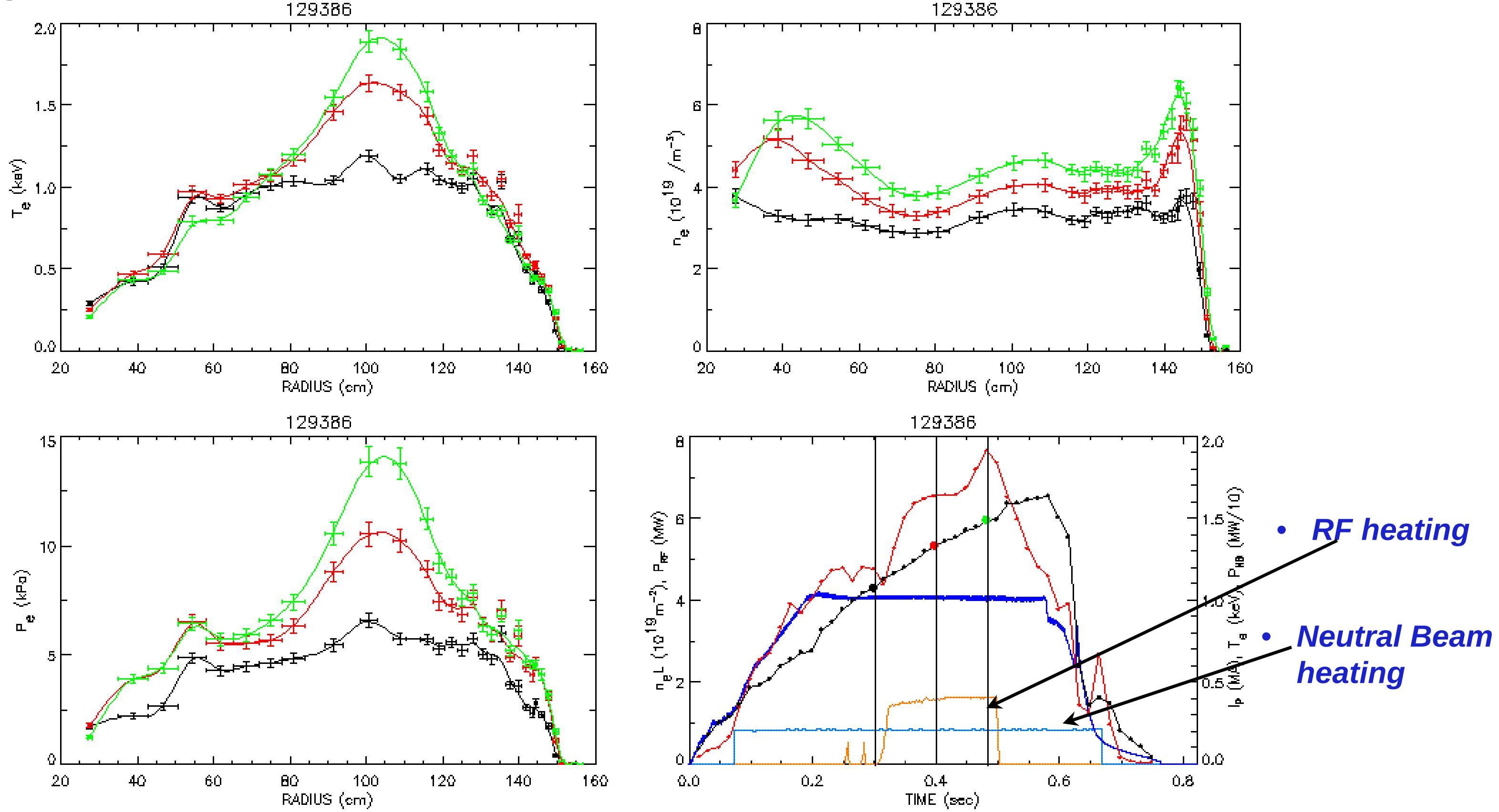




- ***Edge electron thermal diffusivity decreases***

High toroidal field (0.55T) improves RF coupling in beam heated H-mode plasmas

- Able to double central electron temperature during high density H-mode with 2MW of RF heating power
- High TF crucial to RF coupling
- Opens possibilities for manipulating q profile during high performance discharges



Goal of NSTX integrated scenario research is to narrow the gap between present performance and next-step STs

- Next-step ST's operate at lower f_{GW}, higher $f_{NBI\text{-}CD}$, higher confinement

GOALS: reduce n_e, increase NBI-CD, increase thermal confinement

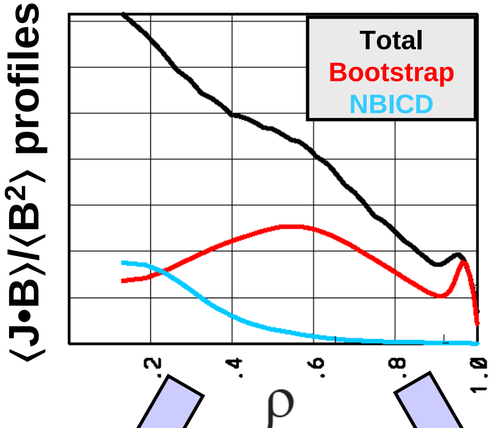
Present high β_N & f_{NICD}	NSTX	NHTX	ST-CTF
A	1.53	1.8	1.5
κ	2.6-2.7	2.8	3.1
β_T [%]	14	12-16	18-28
β_N [%-mT/MA]	5.7	4.5-5	4-6
f_{NICD}	0.65	1.0	1.0
$f_{BS+PS+Diam}$	0.54	0.65-0.75	0.45-0.5
$f_{NBI\text{-}CD}$	0.11	0.25-0.35	0.5-0.55
$f_{Greenwald}$	0.8-1.0	0.4-0.5	0.25-0.3
H_{98y2}	1.1	1.3	1.5
Dimensional/Device Parameters:			
Solenoid Capability	Ramp+flat-top	Ramp to full I_P	No/partial
I_P [MA]	0.72	3-3.5	8-10
B_T [T]	0.52	2.0	2.5
R_0 [m]	0.86	1.0	1.2
a [m]	0.56	0.55	0.8
I_P / aB_{T0} [MA/mT]	2.5	2.7-3.2	4-5

- Optimal operational regime will be determined by electron confinement!

Integrated modeling indicates potential path from best NSTX plasmas towards increased f_{NICD} scenarios

TSC modeling
(C. Kessel)

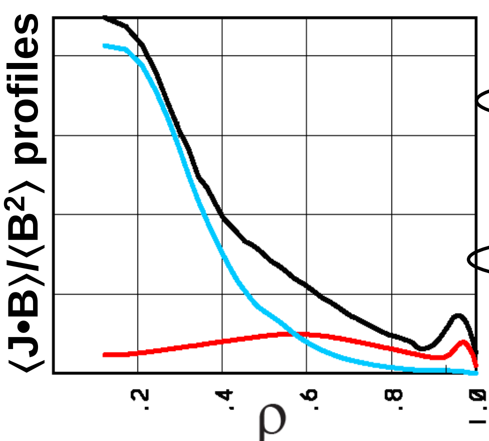
Scenarios have:
I_P=0.68-0.7MA
B_T=5.2-5.5kG



NSTX highest f_{NICD}

$n_{20}(0)$ = 0.85
κ = 2.2
H_{98} = 1.1
β_N = 5.7
$q(0) \approx 1.2$
f_{BS} = 55-60%
f_{NBICD} = 10%
f_{NICD} = 65-70%

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

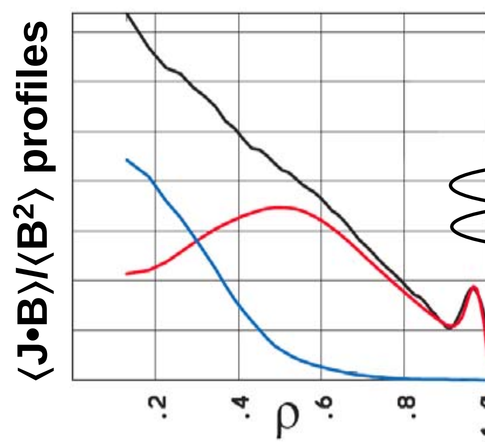


Low-n_e, high-f_{NBICD}

$n_{20}(0)$ = 0.36
κ = 2.2
H_{98} = 1.1
β_N = 5.6
q(0) → 1
f_{BS} = 35%
f_{NBICD} = 55%
f_{NICD} = 90%

f_{BS} and f_{NBICD} similar to ST-CTF

- **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?



High β_N, high-f_{BS}

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

f_{BS} and f_{NBICD} similar to NHTX

2009-2011 research plan (pre CS 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
  - Characterize pumping with LLD (FY09 gas balance milestone)
  - Study pedestal and ELM stability vs. pedestal ν^* and Li (FY10 milestone)
  - Test and understand ELM suppression observed with Li
  - Characterize NBI J(r) redistribution from fast-ion and low-frequency MHD (FY09 milestone)

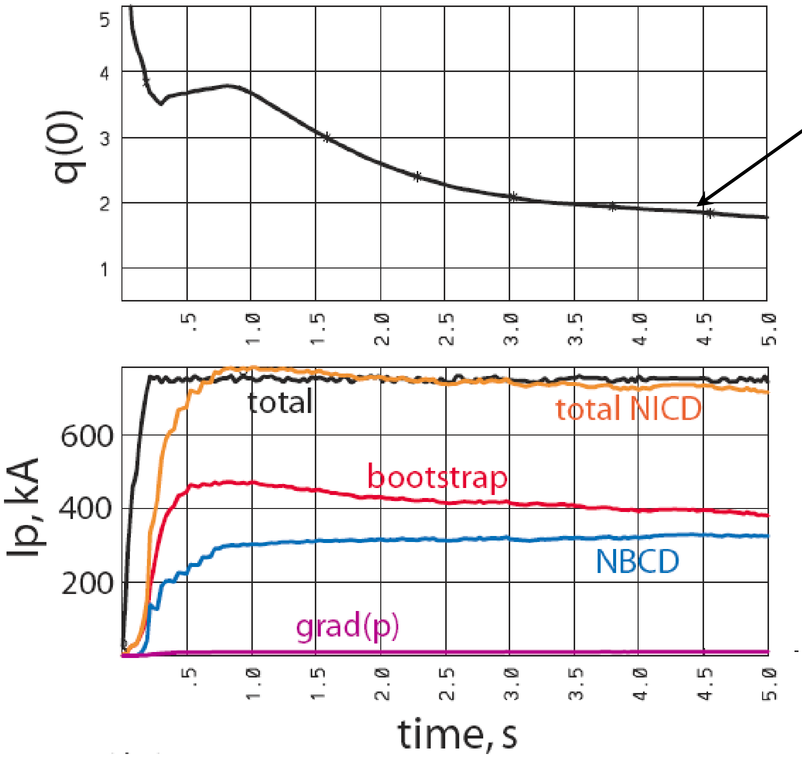
- Plan for developing high normalized beta, high bootstrap fraction scenario
  - Assess confinement, ELM, thermal profile modifications from LLD
  - Increase NBI-CD using profile modifications from LLD
  - Use HHFW with ELM resilience to increase W_e, f_{BS}, and f_{NICD} in discharges with high q_{min}
  - Perform high-elongation high β operation – (FY09 milestone)
    - $\kappa \sim 2.8$, $\tau \geq \tau_{CR}$
    - Integrated ELM control
    - β feedback
- Implement real-time CHERS and v_ϕ control
  - Test as means of pressure profile control

Center Stack upgrade enables advanced operation in low collisionality regime

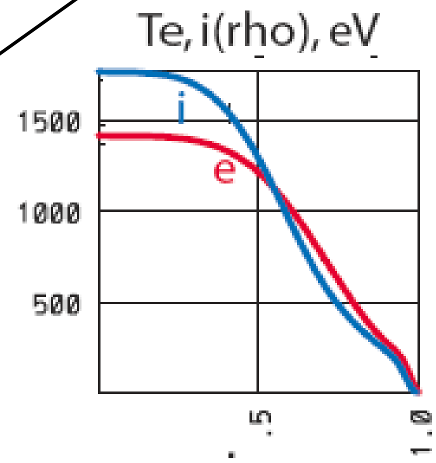
- Achieve lower ν^* through the B_t dependence of electron confinement
  - Need 100% NICD, both bootstrap and NBICD increase at lower ν^*
  - Up to a factor of four reduction in ν^* possible with density control
- Extend pulse so that NSTX can operate for multiple τ_{CR} at lower ν^*
  - Higher T_e gives larger τ_{CR}, need longer pulse ~3-4 τ_{CR} for equilibration
  - NSTX now has τ_{CR} ~ 0.35s, if we double T_e then need ~4s pulse
- Operate at high β_p with a plasma current high enough (I_p > 700kA) to confine full energy fast ions from the neutral beams
  - Larger range of q available with confined NBI
- Enable HHFW coupling in long pulse discharges
  - HHFW coupling improved at higher TF (higher critical density)
- Operate at an aspect ratio and collisionality closer to future STs
  - NHTX, ST-CTF, and ARIES-ST all plan higher A and lower ν^* than NSTX

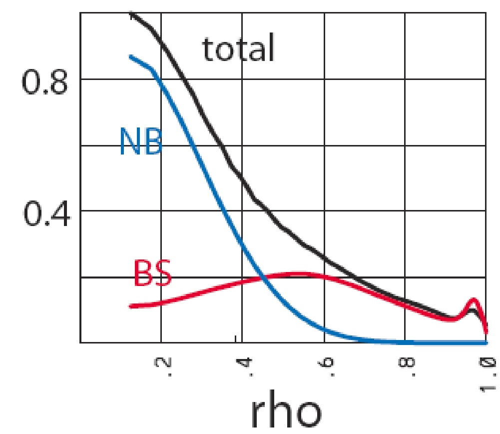
Integrated scenario modeling indicates 100% non-inductive operation possible with B_t = 1T

- Assumes 6.15 MW absorbed beam power for 5s
  - 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



Long pulse required to reach equilibration





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

Research for 2012-2013 (post center stack upgrade)

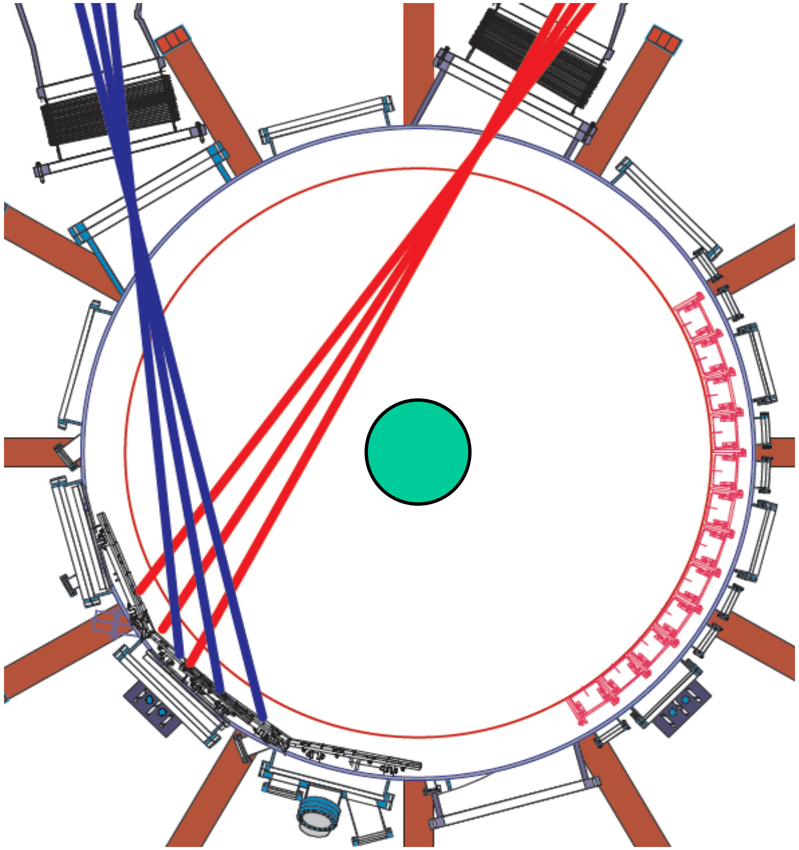
- FY2012 research plans
  - Assess impact of higher A on vertical stability and n > 0 no-wall and ideal-wall stability limits. Determine if sufficient power available to reach n > 0 stability limits at higher B_t.
  - Study effect of higher B_t on energy confinement
  - Assess impact of higher B_t on non-inductive current drive sources, e.g.:
    - bootstrap fraction via increased q and confinement
    - NBI-CD efficiency as a function of Te
    - fast-ion-driven instabilities and possible redistribution of fast-ions and NBI-CD.
  - Study effect of higher B_t and I_P on SOL and divertor heat-flux widths
  - Assess impact of longer pulse-length on divertor temperature evolution, and develop operating scenarios that minimize peak heat flux as required.
  - *Study effect of NCC coils on pedestal stability in long-pulse discharges (incremental)*
  - Implement real-time MSE diagnostic for future current profile control
- FY2013 research plan
  - Assess HHFW coupling, heating, and CD at higher B_t
  - Vary central HHFW-CD to vary q(0), assess impact on confinement and MHD stability
  - Assess impact of NCC coils *(incremental)* on rotation damping and SOL heat flux widths in sustained conditions.
  - Implement real-time equilibrium reconstruction using real-time MSE
  - *2nd NBI (incremental)*

NBI upgrade provides a flexible tool for providing additional NBI-CD and heating power

- Increased current drive profile flexibility
  - Varying NBICD profiles from the three new sources
- Off axis NBI current drive capability
  - Current profile control will be required to maintain profiles with optimal stability
- Higher current drive efficiency from outboard tangential sources
  - More current drive capability may be required to reach $f_{NI} \sim 1$
- Additional power to reach β-limit
- Larger tangency radius $\rightarrow$ more torque $\rightarrow$ higher rotation drive and more flexible rotation control

New 2nd NBI R_{TAN}=110,120,130cm

Present NBI R_{TAN}=50,60,70cm

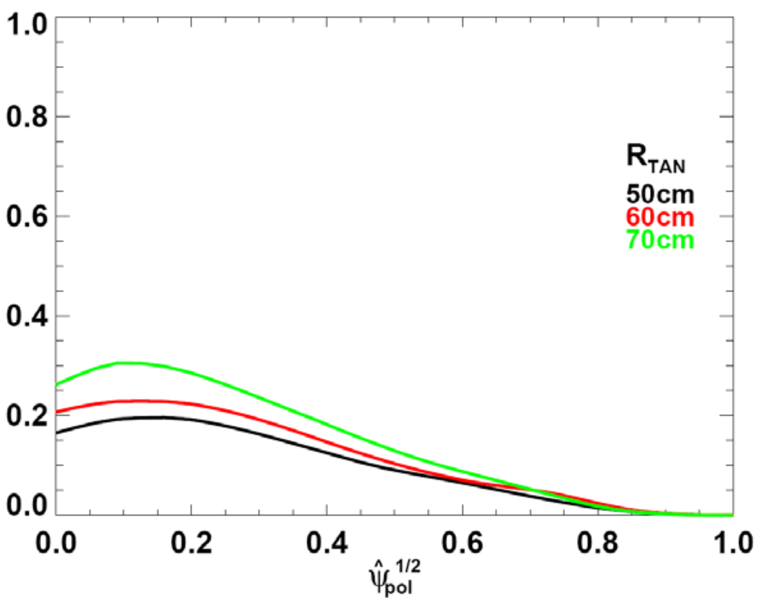


Current drive flexibility greatly enhanced with 2nd NBI

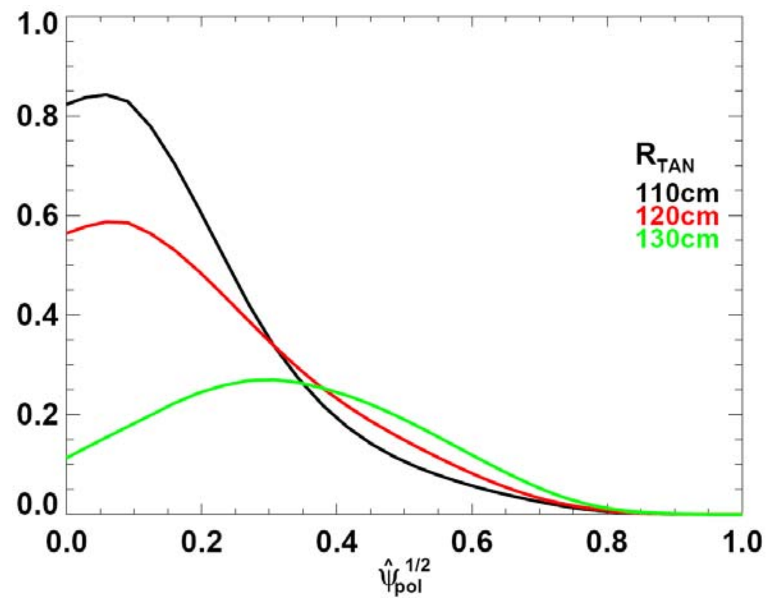
- Can drive current from strongly peaked on axis, to peaked off axis depending on source chosen
- Overall higher efficiency increases utility of NBICD during plasma current ramp phase
- Effective current profile control tool when coupled with real-time MSE

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

- ***Existing three sources***



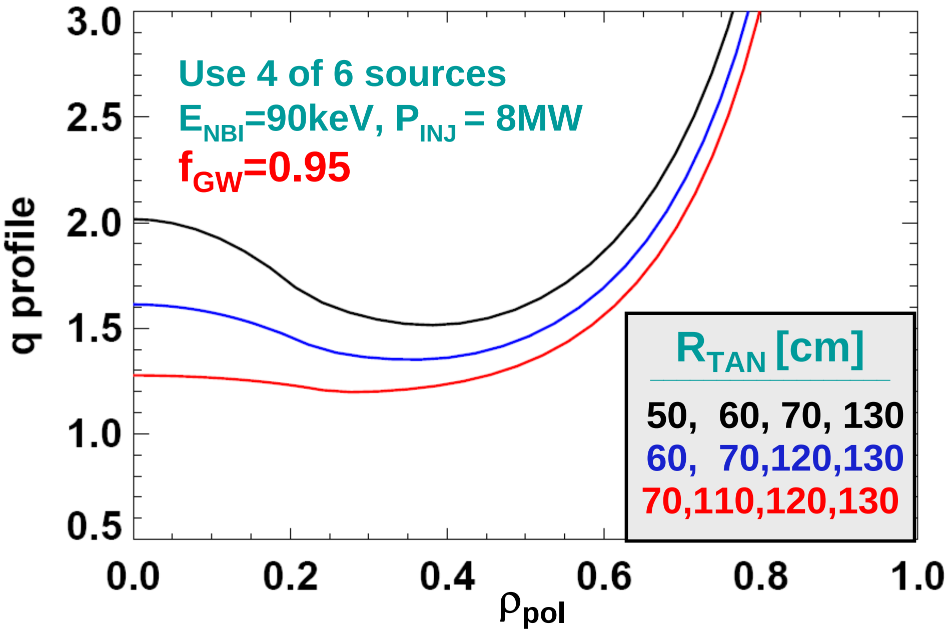
- ***New NBI sources***



P_{NBI}=2MW E_{NBI}=90keV, I_p=0.82MA, f_{GW}=0.58 $\overline{n_e} = 4.4\times10^{19}\text{m}^{-3}$, $\overline{T_e}$ = 1.2keV

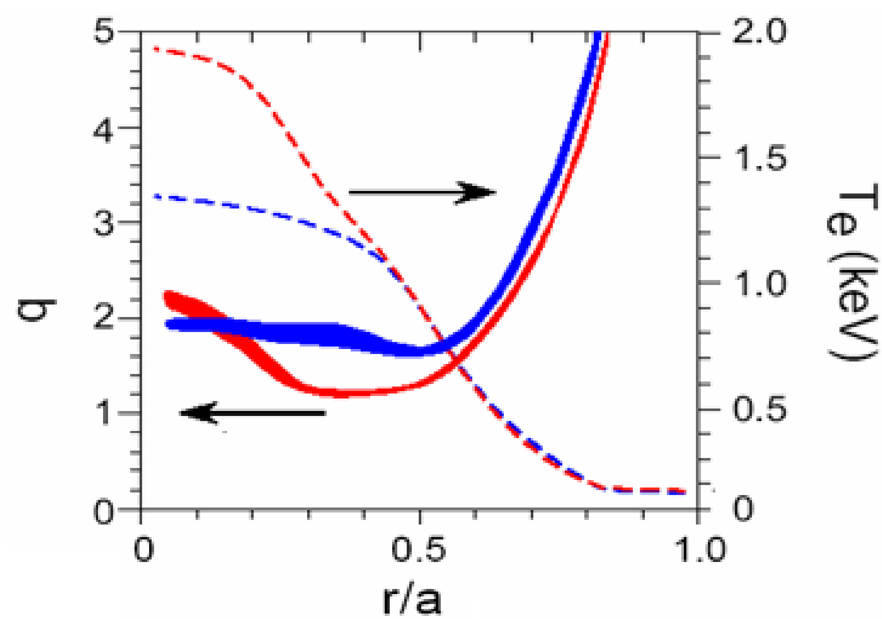
2^{nd} NBI would enable control of core q and χ profiles in fully non-inductively-driven scenarios using only NBI + bootstrap

- Combination of available sources can control q_{MIN} and core q-shear
  - At H_{98y2}=1.2, J control with q_{MIN} > 1.2 requires operation with f_{GW} > 0.9



I_P = 725kA, B_T=0.55T, β_N = 6.2, β_T = 14%
H_{98y2} = 1.2, f_{NICD} = 100%, $f_{\nabla p}$ = 73%

- Magnetic shear control could be important tool for controlling core confinement and MHD stability
  - Core transport reduced in RS L-mode



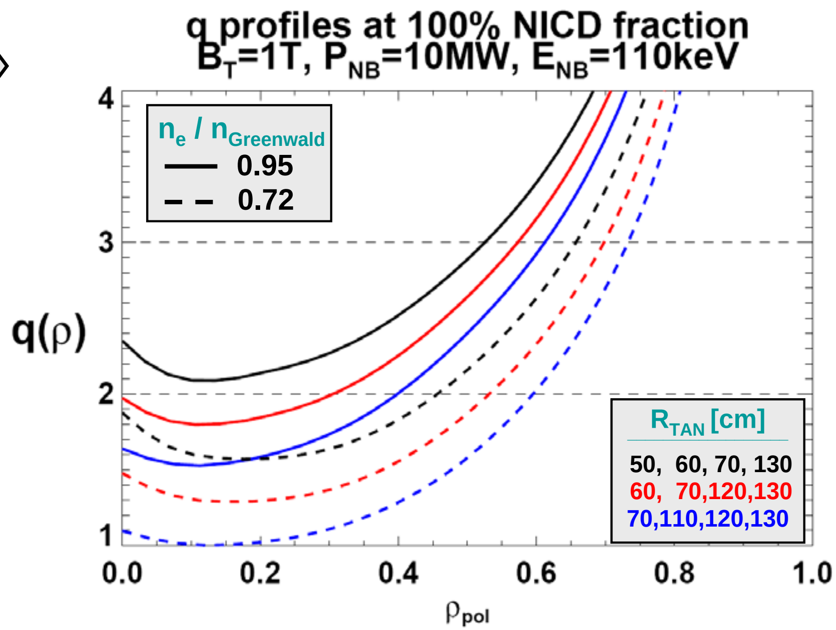
Real-time MSE, CHERS available by FY11

Combination of 2^{nd} NBI + B_T=1T operation predicted to enable access to fully non-inductive operation at high q_{min} = 1.5 - 2

Study transport, stability (especially NTM) of high q_{min} plasmas assumed for NHTX, ST-CTF

- TRANSP calculations indicate a wide range of q_{min} achievable
  - Combines RF electron heating with variable NBI current drive
  - Does not require major extrapolation in normalized parameters
- Higher β_T case also identified:
  - B_{T0} = 0.75T
  - I_P=1MA,
  - β_T = 16%,
  - β_N = 6.1,
  - n_e / $n_{Greenwald}$ = 0.7,
  - $q_{min} \geq 1.3$
  - $H_{IPB98(y,2)}$ =1.25

TRANSP calculations of fully non-inductive current profiles with variable q_{min}



Scenario parameters:

B_T=1T	β_N=5
I_P=0.95MA	β_T=10%
n_e / n_{Gr} = 0.72, 0.95	P_{NB}=10MW
$H_{IPB98(y,2)}$= 1.2	P_{RF}=4MW

Research plans with 2nd NBI (incremental or beyond 2013)

- Investigate:
  - Impact of more tangential injection on fast-ion distribution function and on Alfven eigenmode stability.
  - Predicted vs. measured power deposition and current drive profiles from new NBI sources.
  - Impact of higher power and lower collisionality on SOL and divertor heat-flux widths
  - Impact of higher power and/or more tangential injection and/or possible fast-ion losses on divertor temperature evolution
  - Operating scenarios that minimize peak heat flux as required.

- Vary mix of NBI sources to vary NBI-CD profile:
  - Modify q profile, and assess impact of global stability and confinement properties
  - Using real-time MSE, implement and assess algorithms for NBI-based J profile control

Summary of Advanced Scenarios & Control Research Plans

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

Advanced Scenarios and Control Timeline

08	09	10	11	12	13

NSTX-U fully non-inductive target scenario:

- $I_P \leq 1MA$, $B_T \leq 1T$
- $f_{NICD} \leq 100\%$
- $f_{NBICD} = 0.2\text{-}0.4$
- $f_{BS} = 0.6\text{-}0.8$
- $f_{GW} = 0.6\text{-}0.8$
- $H_{98y2} = 1.2\text{-}1.4$
- $\beta_N = 5\text{-}6$
- $\beta_T = 10\text{-}16\%$
- $\tau_{flat} \leq 3\text{-}4\tau_{CR}$
- No/small ELM

Physics

- Assess J_{NBICD} & redistribution vs. n_e and fast-ion MHD
- Understand, increase, control Li pumping
- Assess H_{98}, ELMs, β_N vs. n_e & Lithium
- Increase β_N, f_{BS}, f_{NICD} with HHFW
- ELM control w/ mid-plane RMP, Lithium
- Long-pulse n_e control (pumping & fueling)
- Assess long-pulse H_{98}, ELMs, β_N vs. B_T and υ^*
- Reconstruct J, q-profile in real-time
- Improved control of ELM/RWM/EF/rotation

Tools

- Dual LITER
- Liquid Li Divertor (LLD)
- Upgraded control computer
- HHFW V_{ANT}, P_{RF} upgrade
- HHFW ELM resilience
- β control
- n_e control
- real-time v_ϕ
- v_ϕ control
- Real-time MSE
- Long-pulse divertor and core fuelling
- CS upgrade
- Real-time MSE rt-EFIT
- 2nd NBI
- HHFW J(0) control, NBI J(r) control