Research plans for Advanced Scenarios and Control

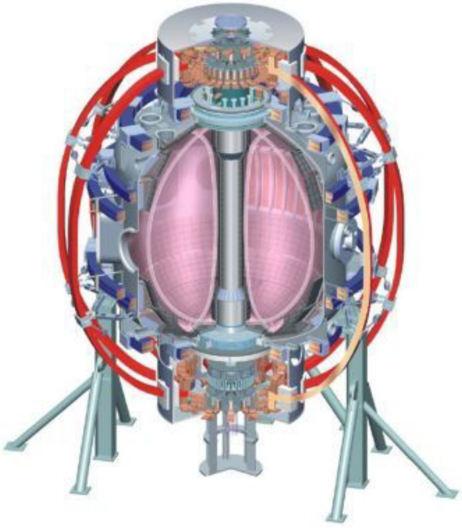
D. A. Gates, J. E. Menard (Deputy)

PPPL

For the ASC-TSG

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

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

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

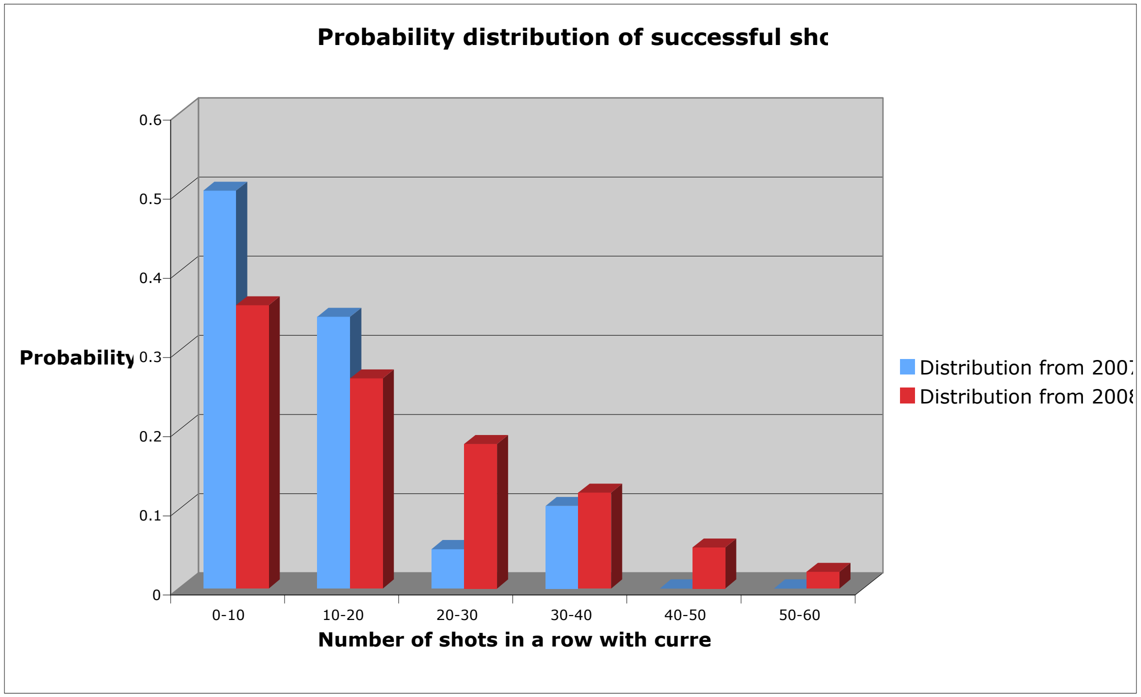
Outline

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

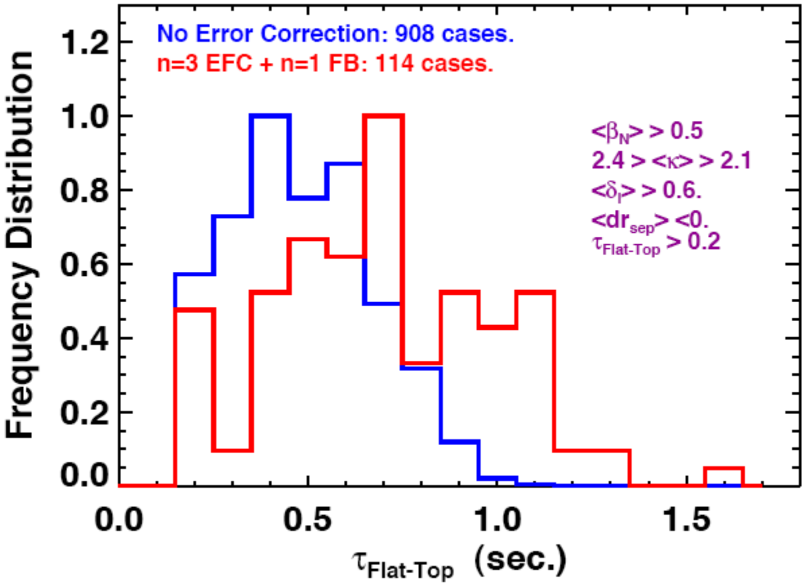
- Highlights from the 2008 run
- ASC research plans for 2009-11
- Integrated scenario and control modeling
- Summary

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



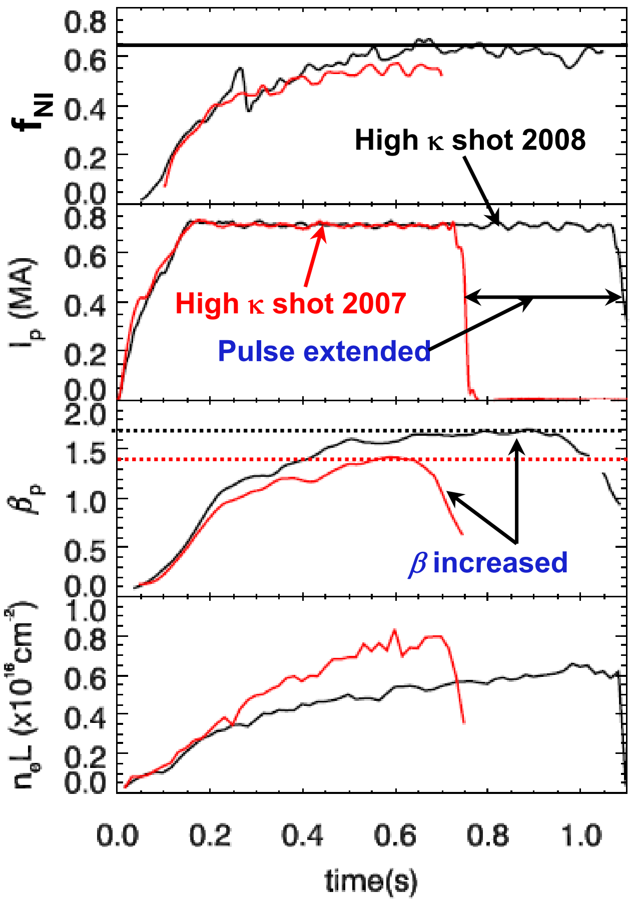
- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Feedback gain increased from 2007
  - Reduced latency
  - Filtering capability added
- Control statistically raises β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



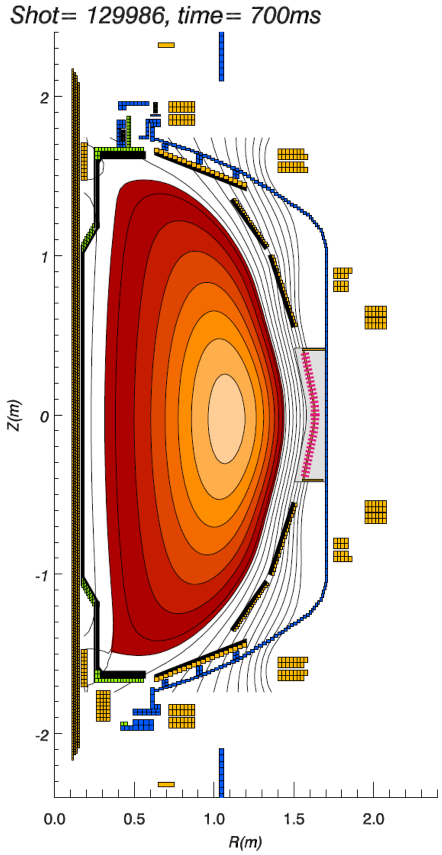
NSTX has now accessed long pulse at high β simultaneous with extreme plasma shaping

- 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 1-2τ_{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 ~ 2τ_{CR}

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

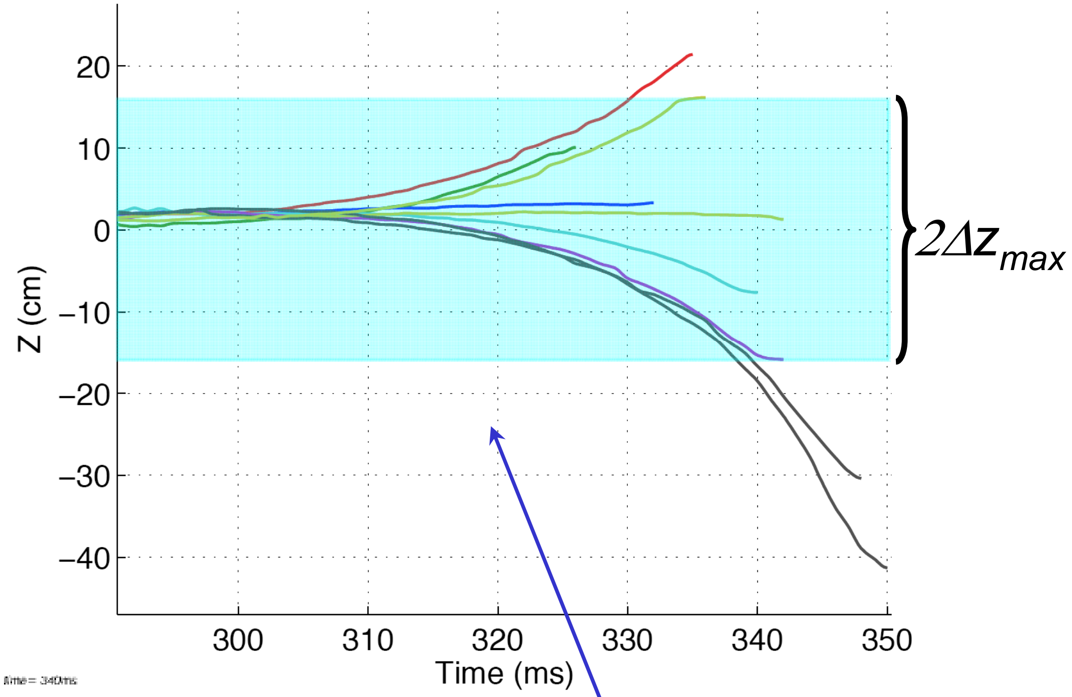


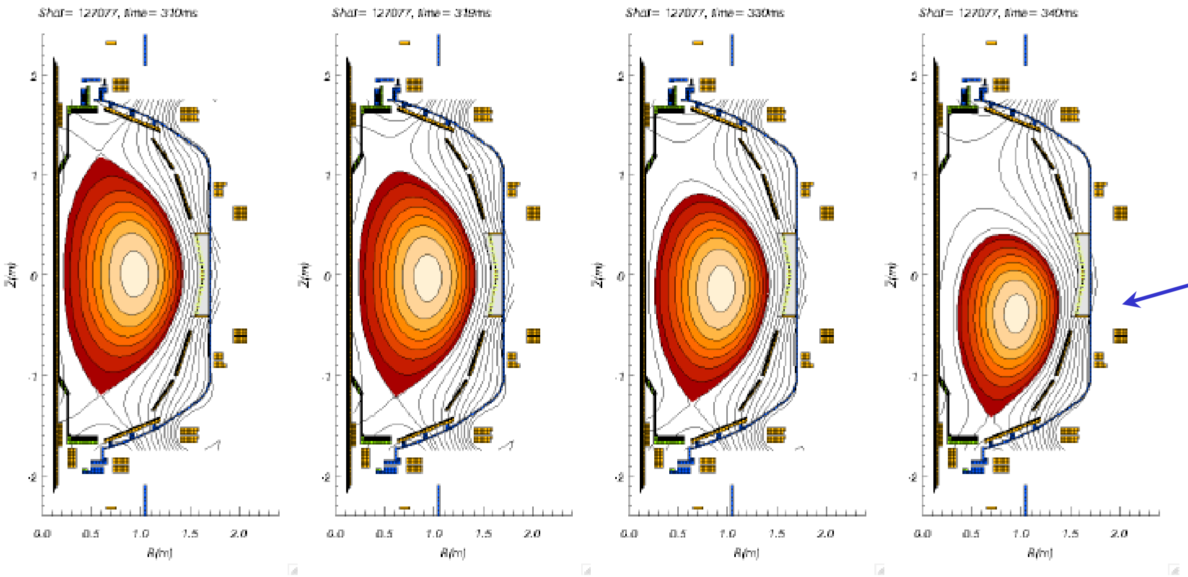
Cross-section of $\kappa \sim 2.7$ equilibrium



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}

$n_{20}(0) = 0.36$

$\kappa = 2.2$

$H_{98} = 1.1$

$\beta_N = 5.6$

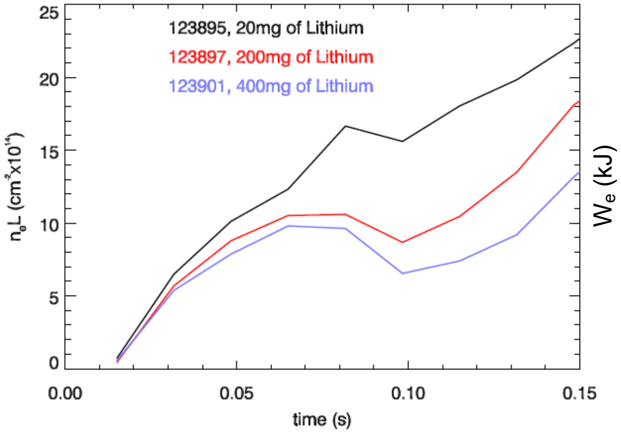
$q(0) \rightarrow 1$

$f_{BS} = 35\%$

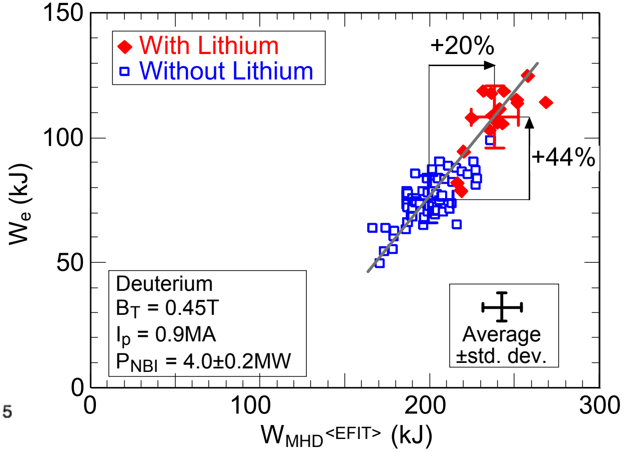
$f_{NBICD} = 55\%$

$f_{NICD} = 90\%$

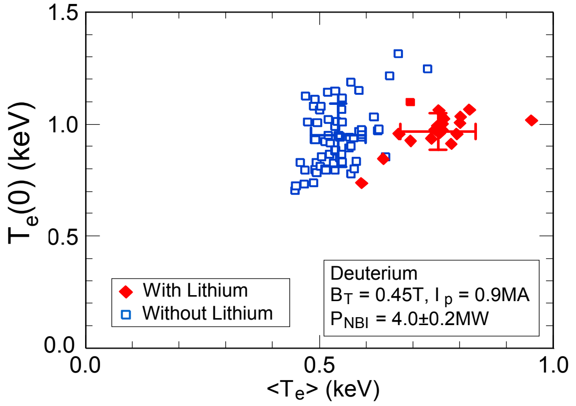
Transient density reduction w/ Li



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

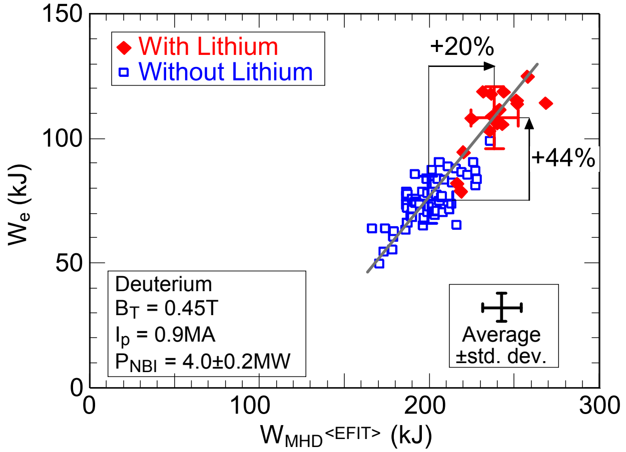
Broad progress towards increased f_{NICD} scenarios as determined by integrated scenario modeling (2)

<u>Scenario 2:</u> 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

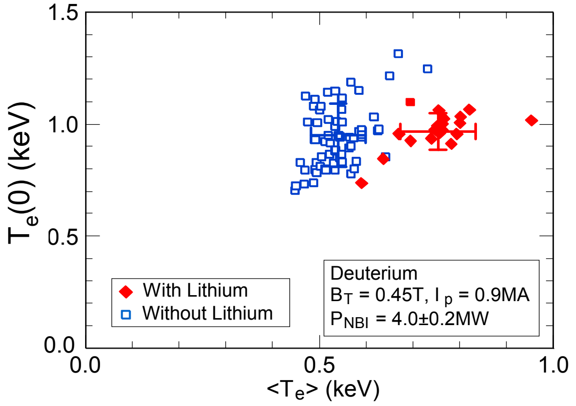
Confinement improvement w/ Li



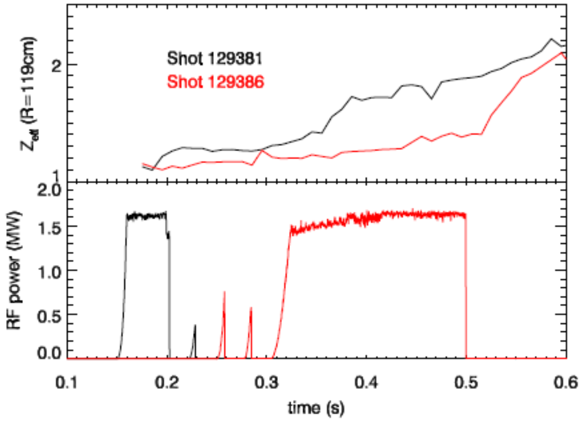
<u>High β_N, high-f_{BS}</u>

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

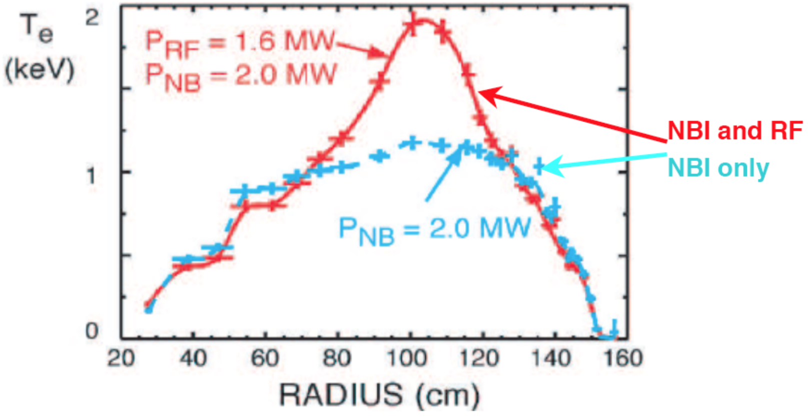
Temperature profile broadening w/ Li



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

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?

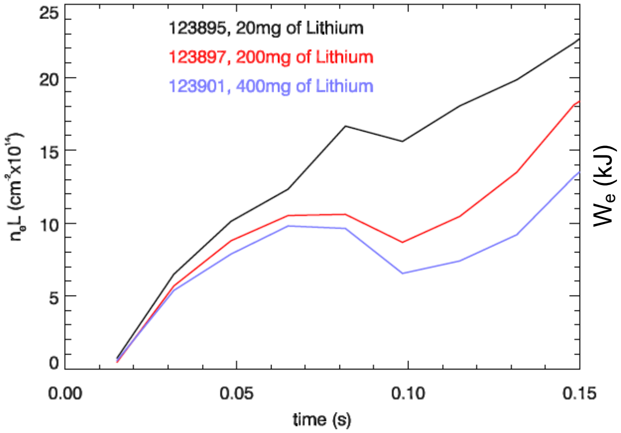
Scenario 2: f_{BS} and f_{NBICD} similar to NHTX

- **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

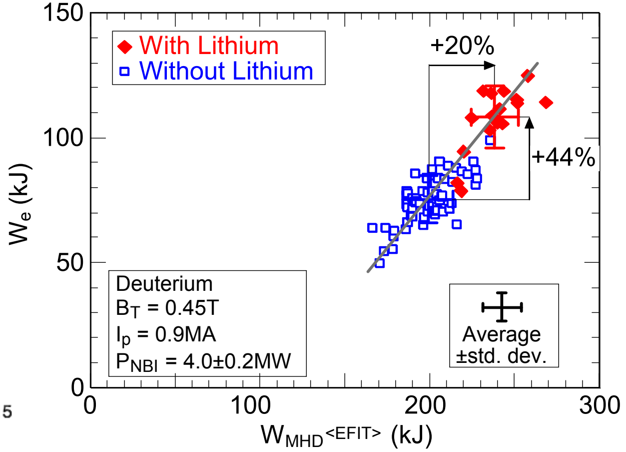
Low-n_e, high-f_{NBICD}

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

Transient density reduction w/ Li



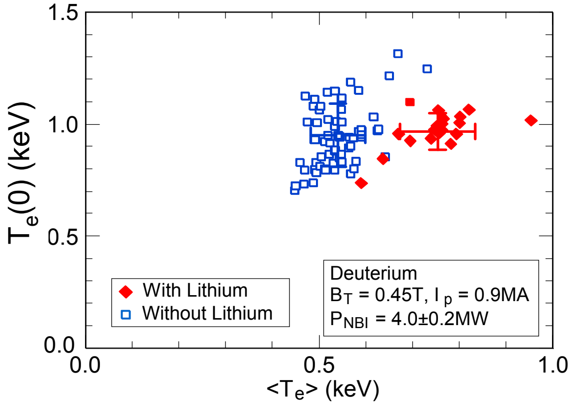
Confinement improvement w/ Li



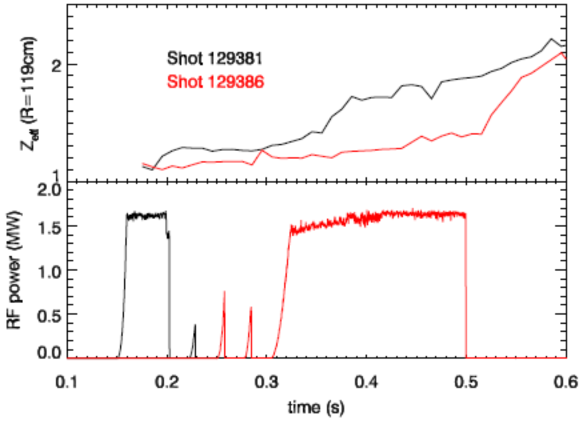
High β_N, high-f_{BS}

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

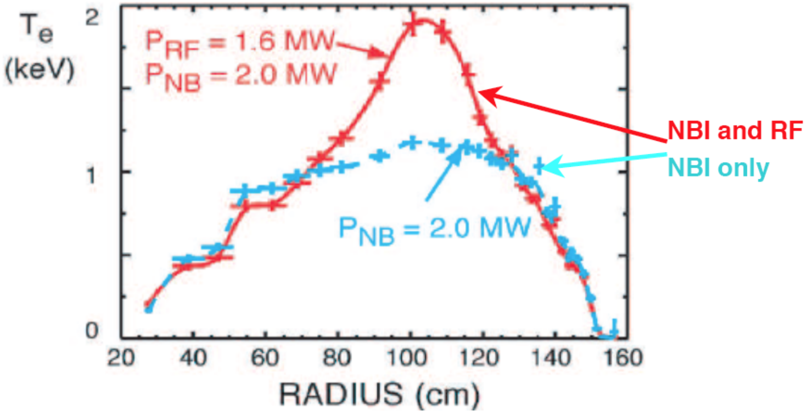
Temperature profile broadening w/ Li



Impurity reduction with HHFW



Electron stored energy increase with HHFW



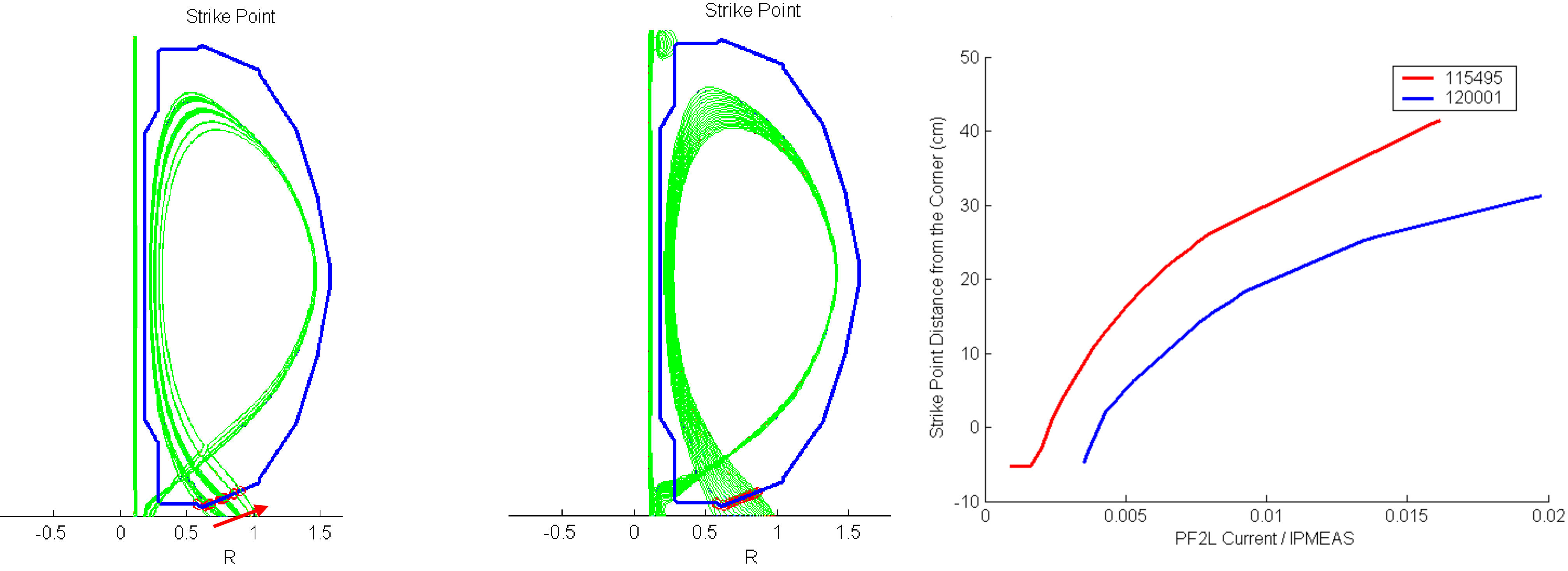
2009-2011 research plan (pre-CS/NBI upgrade)

(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

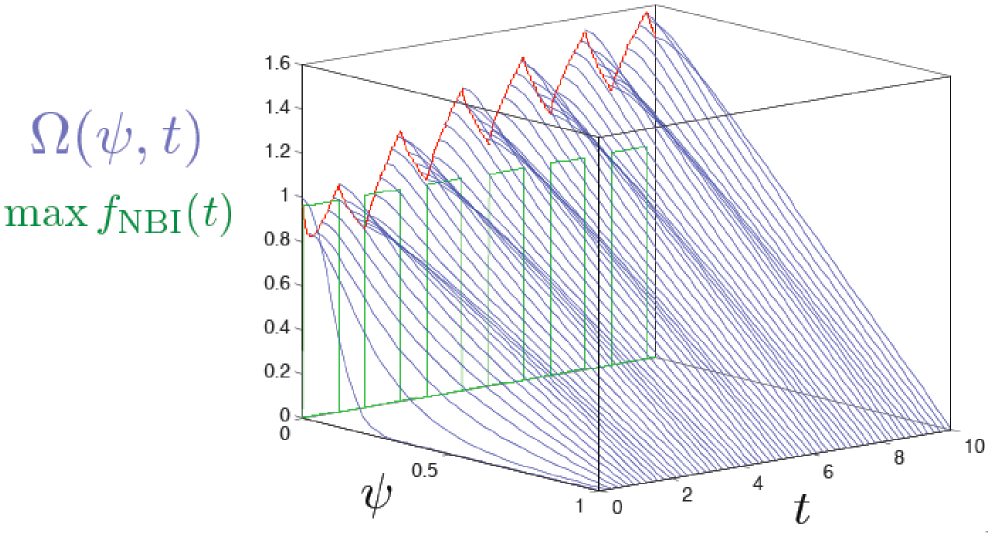


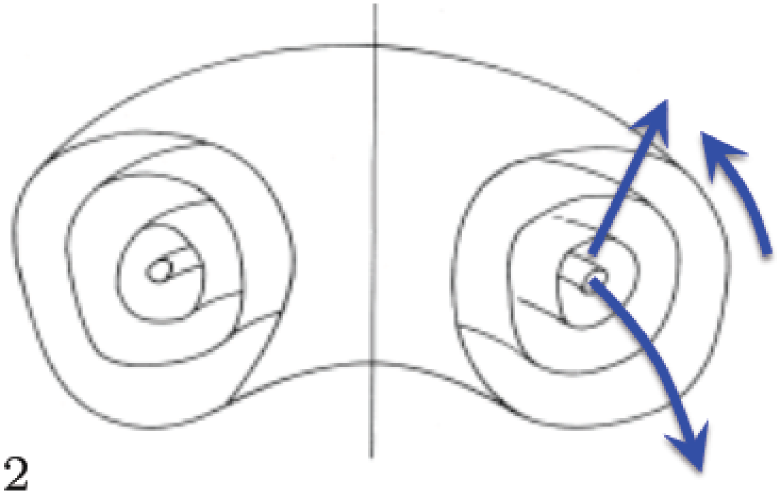
The change in the strike point with varying PF2L current

(Other PF currents fixed)

Predictive rotation model being developed

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





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

inertial

diffusion

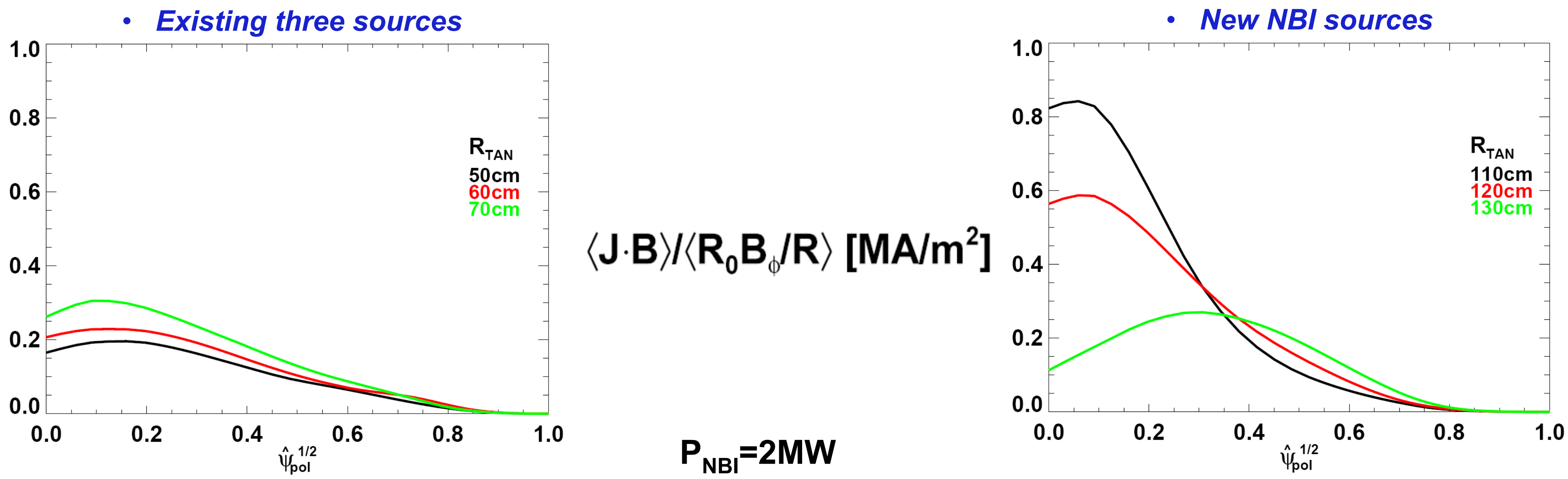
neoclassical toroidal viscosity

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



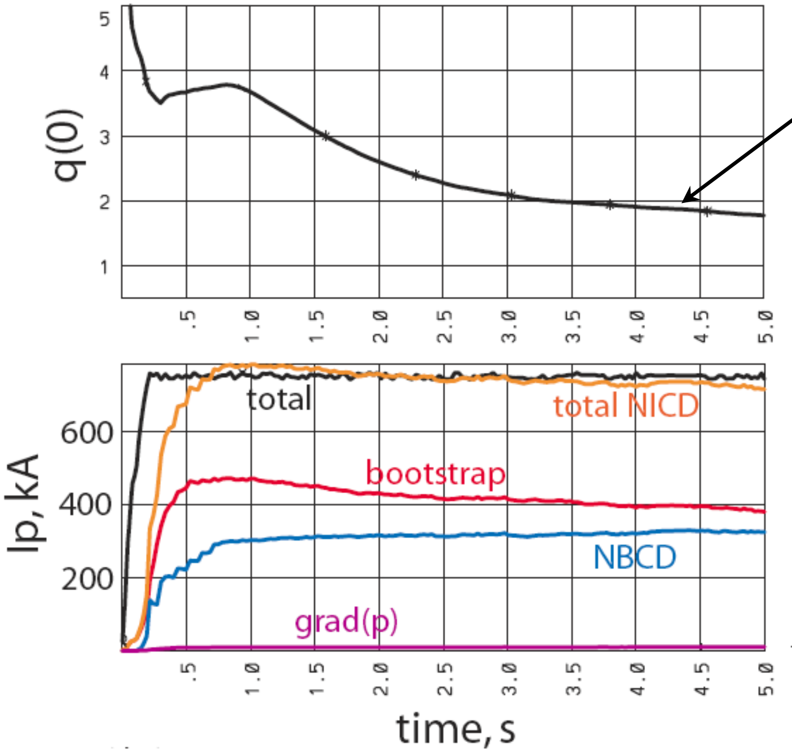
- ***Existing three sources***
- ***New NBI sources***

P_{NBI}=2MW

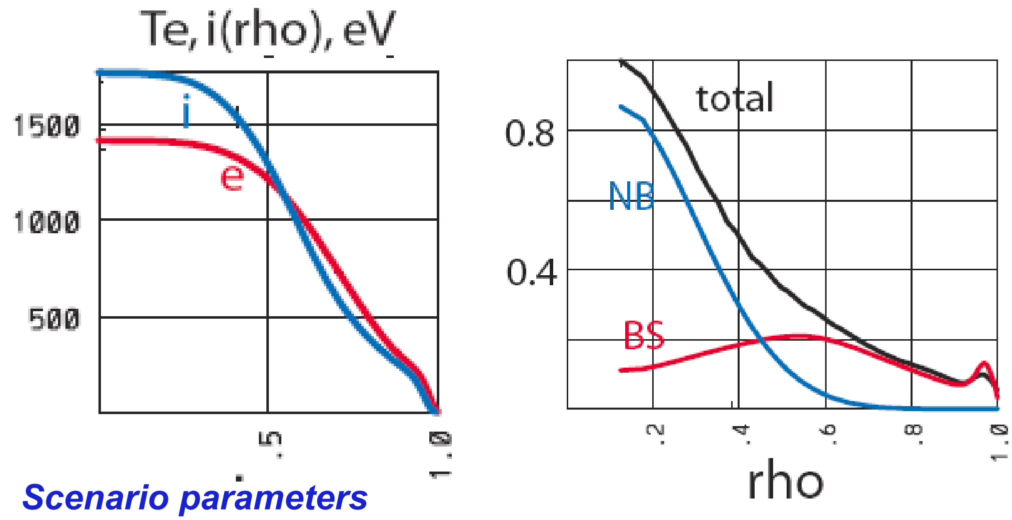
E_{NBI}=90keV, I_P=0.82MA, f_{GW}=0.58 $\overline{n}_e = 4.4\times10^{19}m^{-3}$, $\overline{T}_e$ = 1.2keV

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

Backup Slides

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 on rotation damping and SOL heat flux widths in sustained conditions.
  - Implement real-time equilibrium reconstruction using real-time MSE
  - *2nd NBI (incremental)*

Performance gaps between present and next-step STs motivate near-term research prioritization and upgrades

NHTX, **ST-CTF**: reduce: n_e & ν^*_e, increase: NBI-CD, confinement, start-up/ramp-up

ARIES-ST: increase: elongation, β_N, f_{BS}, confinement, start-up/ramp-up

Near-term highest priority is to assess NHTX → ST-CTF scenarios

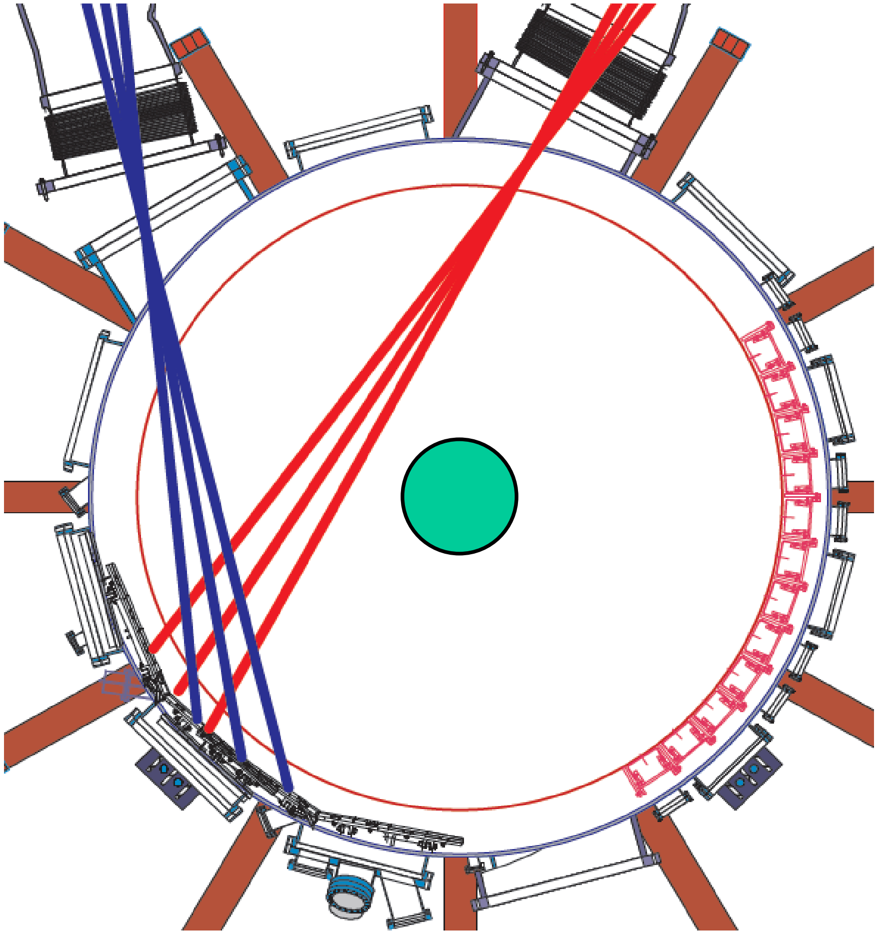
Present high β_N and f_{NICD}	NSTX	Upgraded NSTX	NHTX	ST-CTF	ARIES-ST
A	1.53	1.65	1.8	1.5	1.6
κ	2.6-2.7	2.6-2.8	2.8	3.1	3.7
β_T [%]	14	10-16	12-16	18-28	50
β_N [%-mT/MA]	5.7	5.1-6.2	4.5-5	4-6	7.5
$l_i(1)$	0.5-0.65	0.55-0.75	0.5-0.7	0.25-0.5	0.24
f_{NICD}	0.65	1.0	1.0	1.0	1.0
$f_{BS+PS+Diam}$	0.54	0.6-0.8	0.65-0.75	0.45-0.5	0.99
f_{NBI-CD}	0.11	0.2-0.4	0.25-0.35	0.5-0.55	0.01
$f_{Greenwald}$	0.8-1.0	0.6-0.8	0.4-0.5	0.25-0.3	0.8
ν^*_e	0.15	0.04	0.01	0.002	0.007
H_{98y2}	1.1	1.15-1.25	1.3	1.5	1.3

Dimensional/Device Parameters:

Solenoid Capability	Ramp+flat-top	Ramp+flat-top	Ramp to full I_P	No/partial	No
I_P [MA]	0.72	1.0	3-3.5	8-10	28
B_T [T]	0.52	0.75-1.0	2.0	2.5	2.1
R_0 [m]	0.86	0.92	1.0	1.2	3.2
a [m]	0.56	0.56	0.55	0.8	2.0
I_P / aB_{T0} [MA/mT]	2.5	1.8-2.4	2.7-3.2	4-5	6.7

NBI upgrade provides a flexible tool for studying NBICD as well as additional 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 → more torque → higher rotation drive and more flexible rotation control



New 2nd NBI

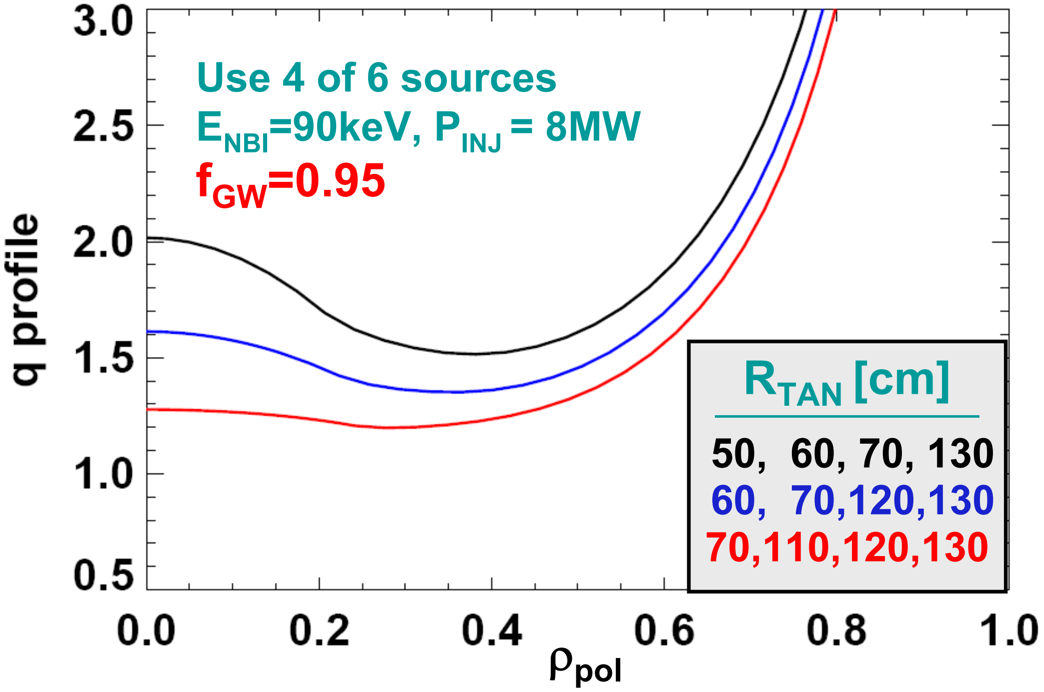
R_{TAN}=110,120,130cm

Present NBI

R_{TAN}=50,60,70cm

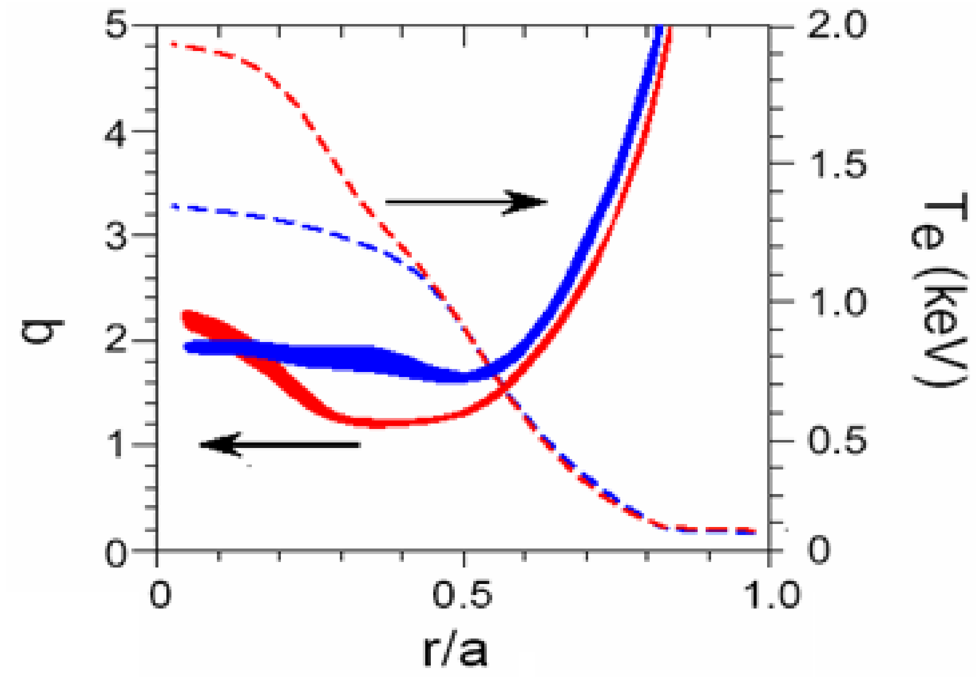
2^{nd} NBI would enable control of core *q* and χ profiles in fully non-inductively-driven scenarios using only NBI + bootstrap

- 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

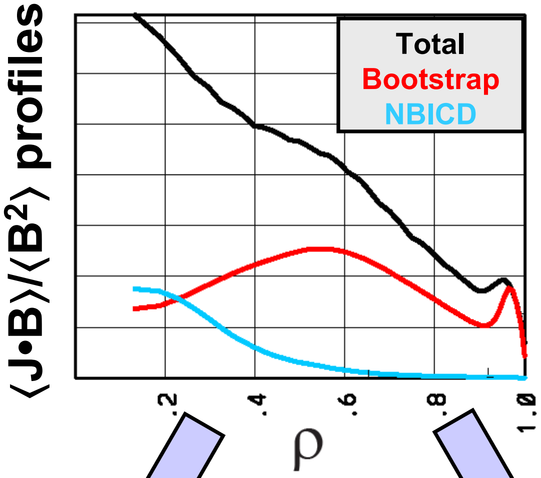


Real-time MSE, CHERS available by FY11

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

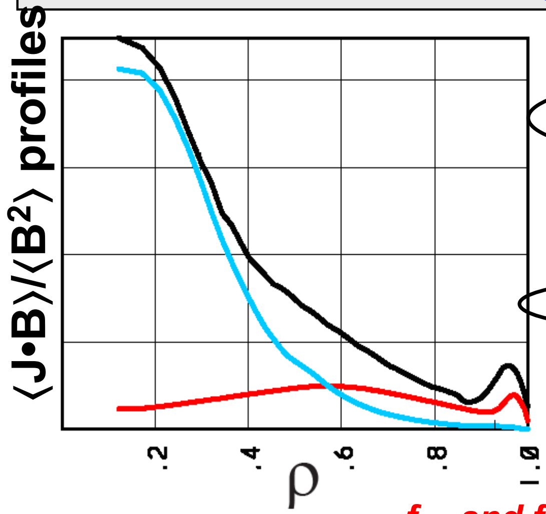


<u>Starting point - NSTX highest f_{NICD}</u>

$n_{20}(0) = 0.85$
$\kappa = 2.2$
$H_{98} = 1.1$
$\beta_N = 5.7$
$q(0) \approx 1.2$
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?

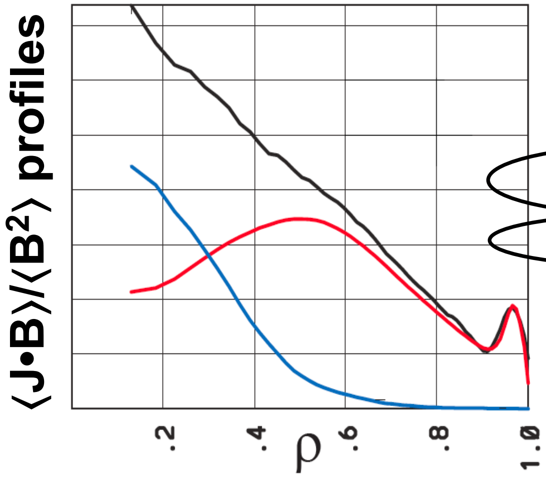
- **High density, high-β_N, high-f_{BS}**
  - Control n_e, broaden T_e, increase H_{98} with LLD?
  - Increase $W_{electron}$, β_N, f_{BS} with HHFW?



<u>Low-n_e, high-f_{NBICD}</u>

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

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



<u>High β_N, high-f_{BS}</u>

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

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