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NSTX

Scenario Integration and Control Progress and Plans

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NSTX PAC-23 Meeting

LSB B318, PPPL

January 22-24, 2008

This presentation (with others) addresses all PAC-21 recommendations for scenario integration research

- PAC21-31
  - Have close coupling between ELM control and stability & boundary research
    - Initiated cross-group effort to develop and execute RMP experiments for ITER design support
- PAC21-32
  1. Consider increasing emphasis of development of techniques for off-axis CD
     - Proposed 2nd NBI with large R_{TAN} during FY2010-11 outage to provide off-axis CD
  2. Give higher priority to obtaining higher central safety factor in start-up phase
     - Developed high-κ start-up to access higher q_{min} discharges in 2007
  3. Analyze risks & benefits of LLD for development of steady state scenarios
     - Describe potential LLD benefits in this presentation – see also Boundary and LLD presentations
- PAC21-33
  - Complement DIII-D work on RMP ELM suppression for ITER physics basis
    - See response to PAC21-31 above
- PAC21-34
  - Develop and articulate a plan to systematically integrate higher β_N, T_e, etc…
    - This presentation will articulate a plan to integrate key elements of full-NICD scenarios
- PAC21-35
  - Give attention to understanding the redistribution of beam ions by MHD
    - Have milestone on redistribution physics in FY09, obtained detailed *AE avalanche results in 2007
  - Consider compatibility of highly shaped plasmas w/ tolerable divertor heat-flux
    - Boundary physics + overview presentations discuss flux expansion, radiative divertor results

Primary purpose of this presentation is to articulate a plan to integrate various program elements into advanced scenario(s)

OUTLINE

- Scenario integration goals
- Review of integrated modeling results
- Approaches to achieving these goals
- Supporting experimental results from 2007
- Role of 2^{nd} NBI in long-term integration goals
- Control system status and plans
- Summary and timelines

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

GOALS: reduce density, increase NBICD, increase thermal confinement

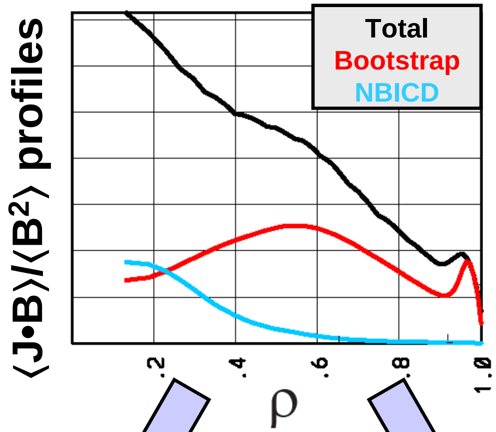
Present high-f_{NICD}	NSTX	NHTX	ST-CTF
A	1.53	1.8	1.5
κ	2.6-2.7	2.8	3.1
β_T	14%	12-16%	18-28%
β_N [%-mT/MA]	5.7	4.5-5	4-6
f_{NICD}	0.65	1.0	1.0
f_{BS}	0.54	0.65-0.75	0.45-0.5
f_{NBICD}	0.11	0.25-0.35	0.5-0.55
f_{GW}	0.8-1.0	0.4-0.5	0.3-0.5
H_{98y2}	1.1	1.3	1.5
Dimensional/Device Parameters:			
Solenoid Capability	Ramp-up + flat-top	Ramp-up to full I_P	No/partial ramp-up
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

Integrated modeling has identified two approaches to increase non-inductive current fraction that will be tested in NSTX

NSTX

TSC modeling
(C. Kessel)

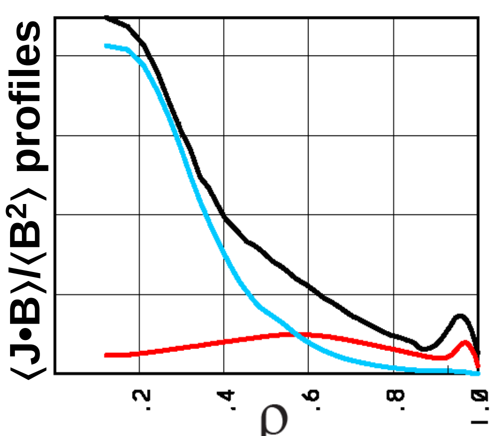
Scenarios have:
I_P=0.68-0.7MA
B_T=5.2-5.5kG



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%

- **Low density, high NBICD fraction**
  - Reduce n_e, broaden T_e with LLD
  - Determine if J_{NBI} redistribution → q(0) > 1

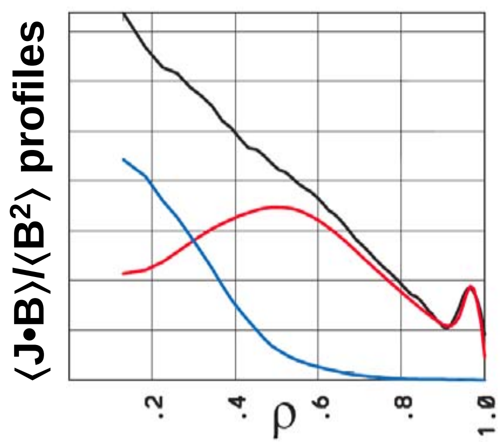


Low-n_e, high-f_{NBICD}

- $n_{20}(0)$ = 0.36
- H_{98} = 1.1
- κ = 2.2
- 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

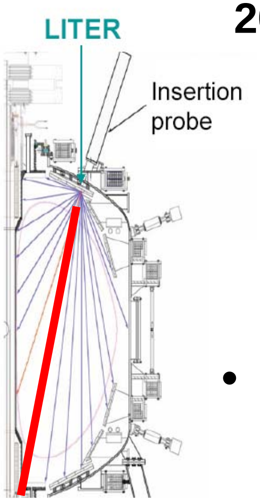


High β_N, high-f_{BS}

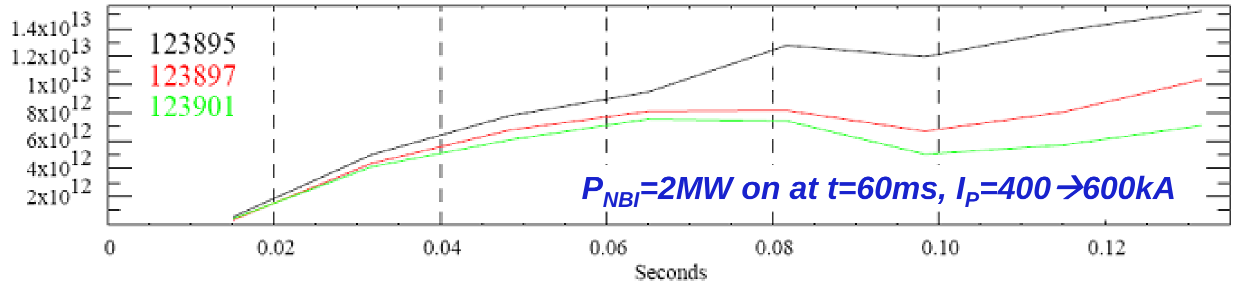
- $n_{20}(0)$ = 0.75
- κ = 2.6
- H_{98}= 1.4
- β_N = 6.6
- q(0) = 1.4 to 2.4
- f_{BS} = 75%
- f_{NBICD} = 25%
- f_{NICD} = 100%

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

Plan for developing low density, high-NBICD scenario



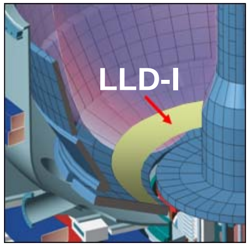
2007 - Early n_e decreased w/ increased Li deposition, but pumping lasts < 300ms



20mg
200mg
400mg

PAC21-32-3

- 2008 – Characterize NICD fraction versus n_e, shaping, q
  - Increase D pumping via more Li plus more complete coverage (dual-LITER)
  - Improve fueling control (SGI) to reduce density rate of rise
- 2009-10
  - Characterize D pumping w/ LITER, LLD-I, II – FY09 milestone
  - Study pedestal & ELMs vs. ν^* – FY10 milestone
    - *ELM suppression observed with Li from LITER (2007)*
  - Characterize J(r) redistribution from MHD – FY09 milestone
    - *PhD thesis on fast-ion redistribution from MHD modes*



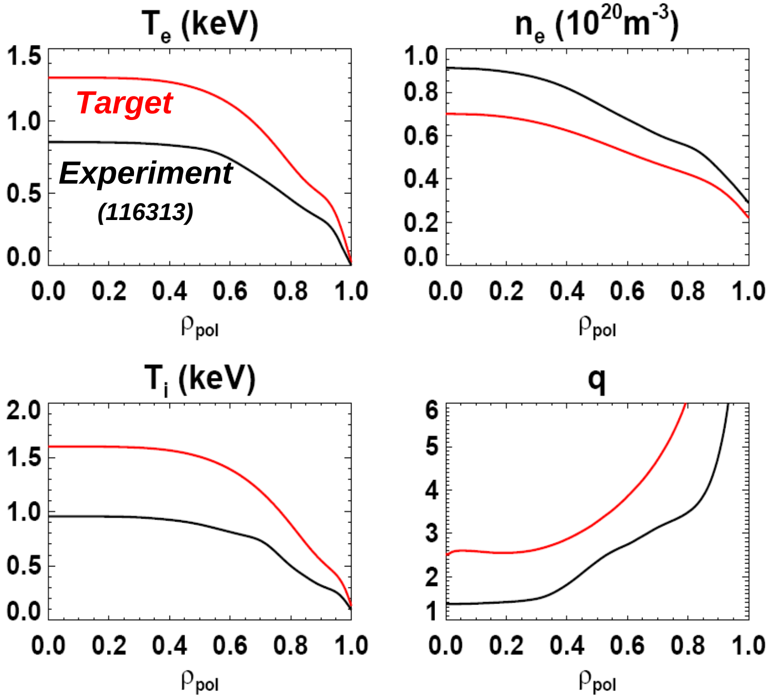
PAC21-35

- With only 2 years (FY08-09), cannot access lowest density scenarios (LLD-II) or assess possible NBICD redistribution at low density
- 2011-13
  - 2^{nd} NBI with more tangential injection (similar to NHTX/ST-CTF)
  - Density pumping and control with long-pulse divertor
  - Develop methods of controlling mode-induced NBICD redistribution

High β_N, high-f_{BS} scenario requires increased confinement, strong shaping, and elevated q to increase ideal-wall limit

NSTX

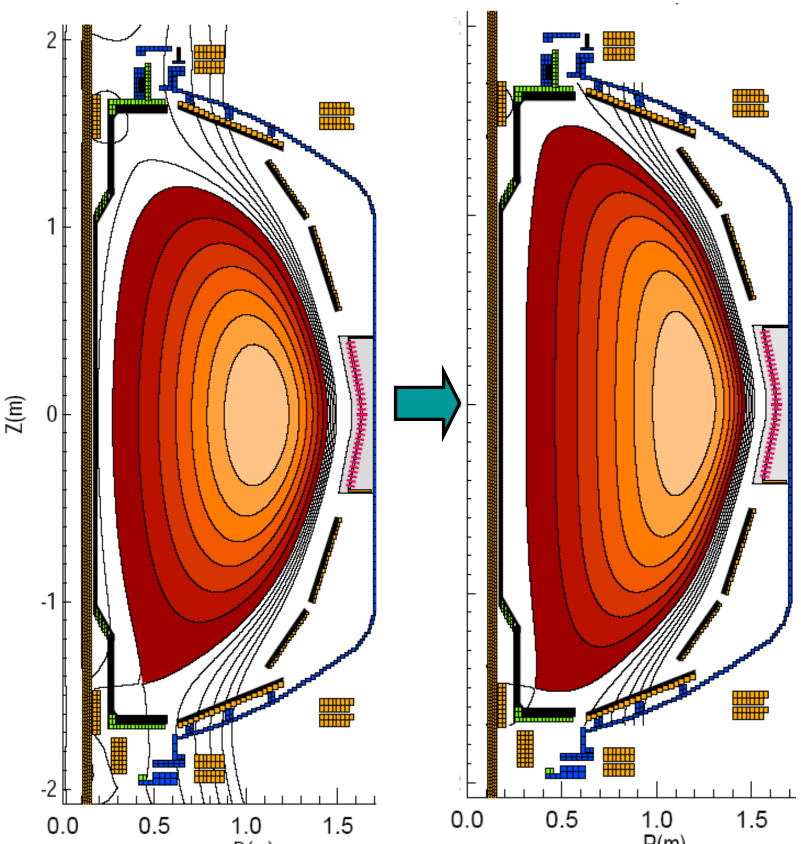
- $T_{e,i}$ increase 50,70%, n_e ↓ 25%, H_{98}= 1.1→1.35-1.45
  - Increases f_{BS} & NBICD consistent w/ desired q(r)
    - **Use LLD for lower n_e & higher H_{98}, use HHFW for higher T**



- Will optimize q_0, q_{min} (1.4 – 2.4) to maximize f_{NICD}
  - q_{min} ≈ 1.4 with-wall β_N limit ≈ 6, need 6.6 for f_{NICD}=100%
  - q_{min} ≈ 2.4 with-wall β_N ≈ 7.2, but significant bad-orbit loss
    - **HHFW and/or very high H_{98} needed for high β_N**

- Higher κ for higher q, β_P, f_{BS}
- High δ for improved kink stability

κ= 2.3, δ_{X-L} = 0.75, δR_{SEP} = -1cm → **κ= 2.6, δ_{X-L} = 0.85, δR_{SEP} = -2mm**



Goals & status of high β_N, high-f_{BS} scenario development

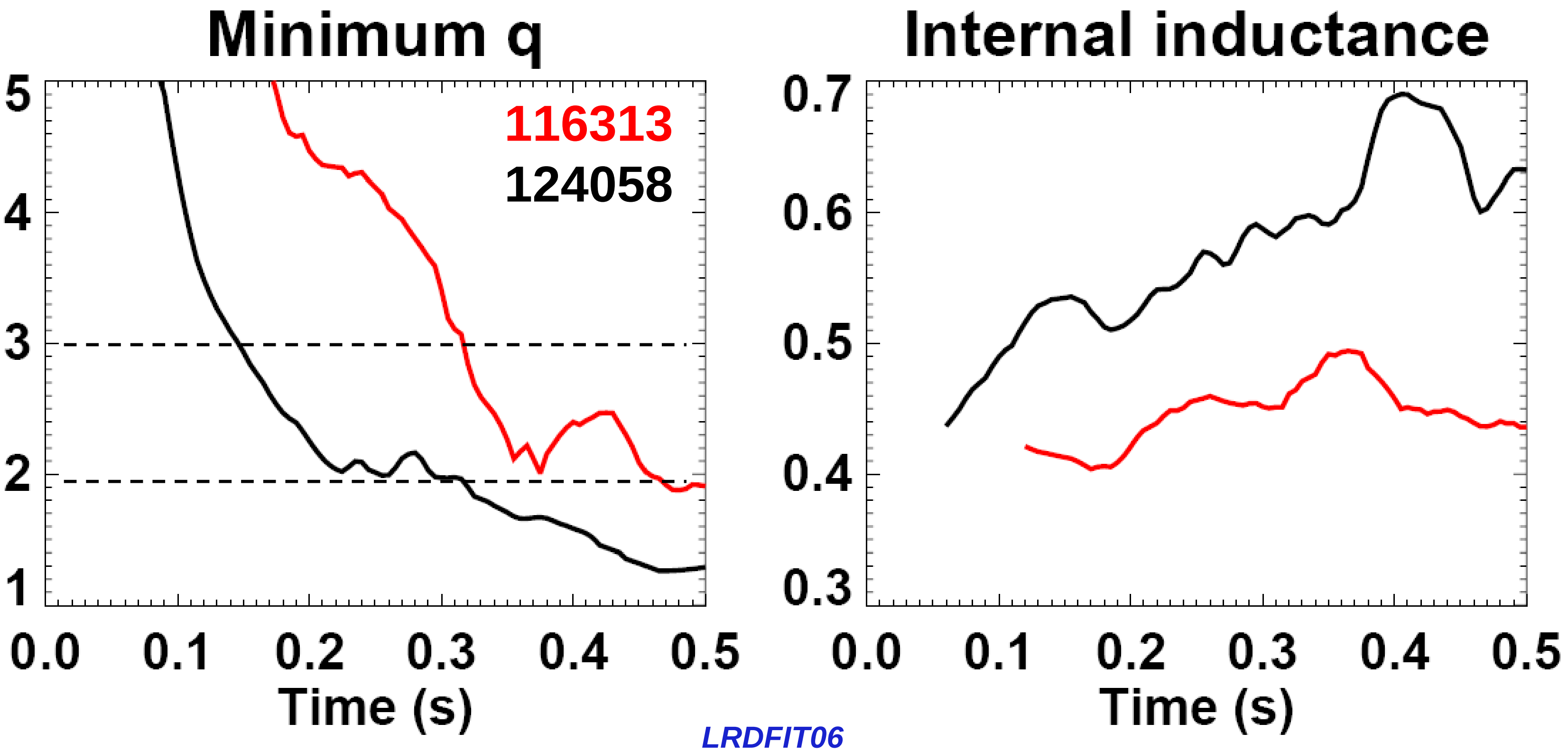
NSTX

- Goal 1: Achieve elevated q(r) profile – target is q_{min} = 2.4
  - Accessed elevated q with modified breakdown and ramp-up (2007)
  - Based on stability calculations, core shear reversal likely too strong
  - → **Future:** Vary current ramp and heating timing to flatten core shear
- Goal 2: Achieve & control LSN boundary with high κ and δ
  - Achieved with rt-EFIT (2007)
- Goal 3: Access high β_N, β_P, f_{BS} with elevated q(r)
  - No evidence of disruptive MHD during push to high β_P
  - Did not achieve target β_N > 6.5 (insufficient heating and/or confinement)
  - Very low l_i = 0.4-0.5 & low I_P=700kA → 30% bad orbit loss (TRANSP)
  - Saturated n=1 TM activity when q_{min}=1.6-1.8 - limits β_P → want q_{min} > 2
  - → **Future:** Test lower voltage on highest-loss NBI source (or turn off)
    Test ability of HHFW to increase electron stored energy
    Test ability of Li (LITER/LLD) to increase confinement

PAC21-34

High-κ breakdown scenario + LITER (15-20mg/min) successfully elevated safety factor *q* early in discharge

- In first 300ms, high q_{min} > 3, l_i = 0.45, κ = 2.6-2.7
  - Previous long-pulse shots (116313) had q_{min} → 2 by t=0.2s



PAC21-32-2

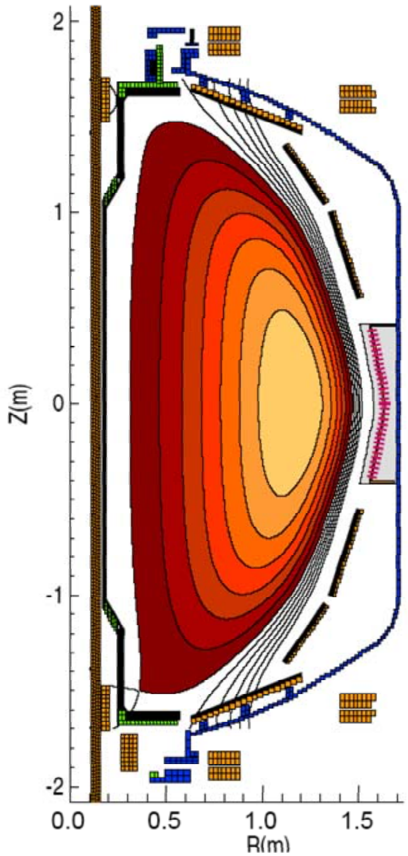
rt-EFIT isoflux control algorithm achieves and maintains shape very close to desired target shape

NSTX

High q_{min} TARGET

κ= 2.6, $\delta_{X\text{-}L}$ = 0.85

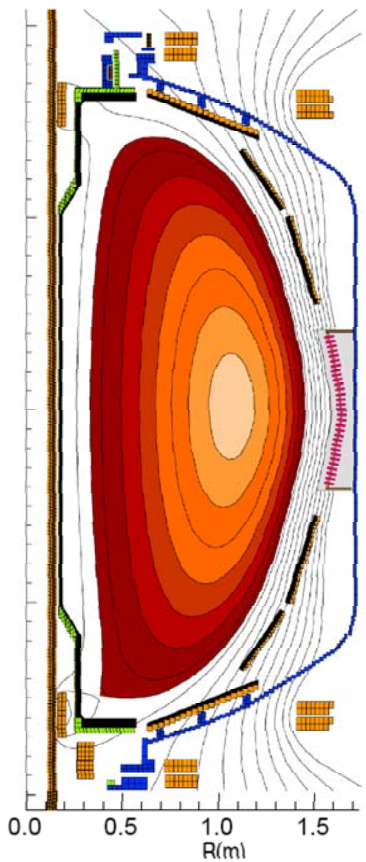
δR_{SEP} = -2mm



124058, 600ms (LRDFIT06)

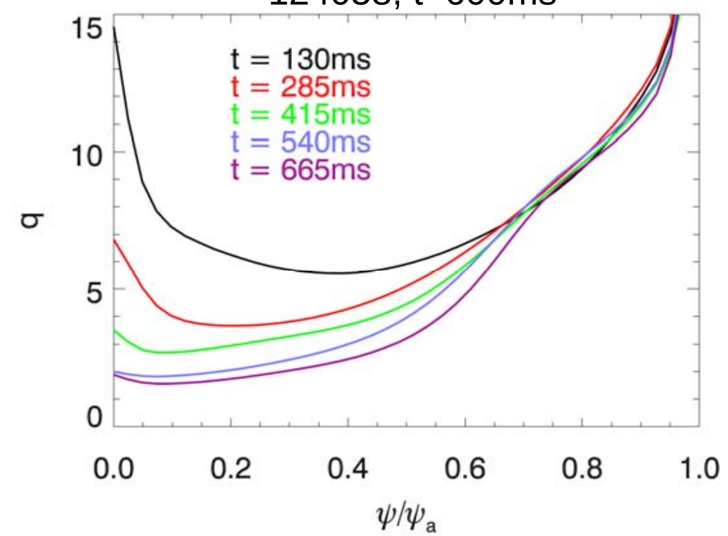
κ= 2.65, $\delta_{X\text{-}L}$ = 0.8

δR_{SEP} = -1.0cm



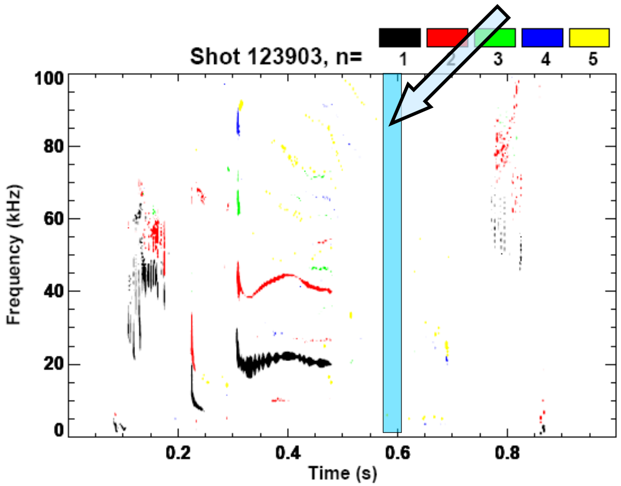
- In 2006 achieved world record plasma elongation
  - κ = 3
- In 2007 maintained κ = 2.7
- High κ in flat-top combined with high-q startup results in elevated q_{min} and low l_i~0.4

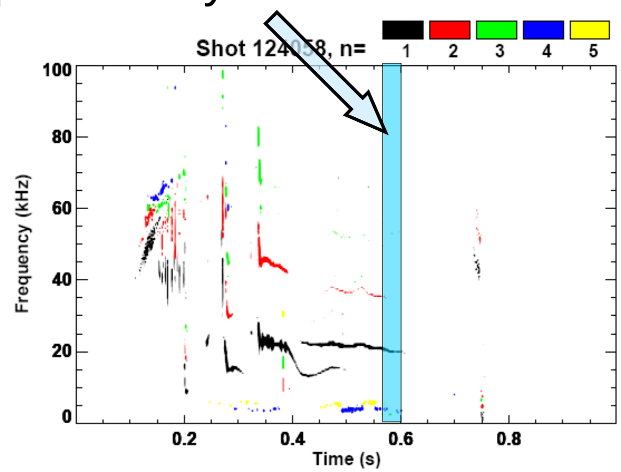
MSE reconstructed q-profile
124058, t=600ms

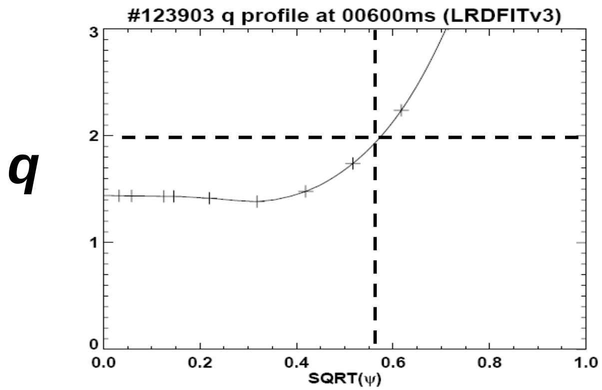


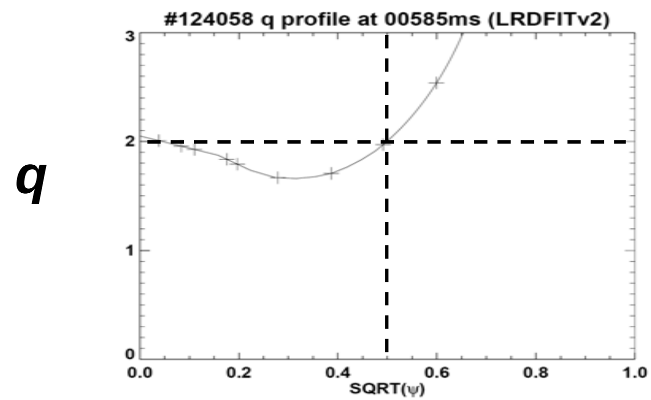
Elevated q_{min} experiments indicate core magnetic shear is important parameter influencing β-limiting MHD activity

- β-limiting mode frequency matches rotation at q=2 surface → 2/1 NTM or DTM
- Mode absent for monotonic shear → RS q-profile may destabilize mode





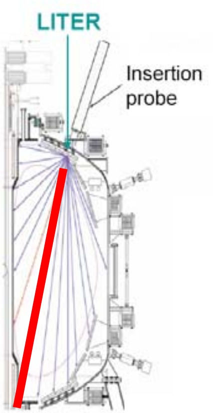




Reversed-shear discharge limited to β_P < 1.5 by this core *n*=1 MHD

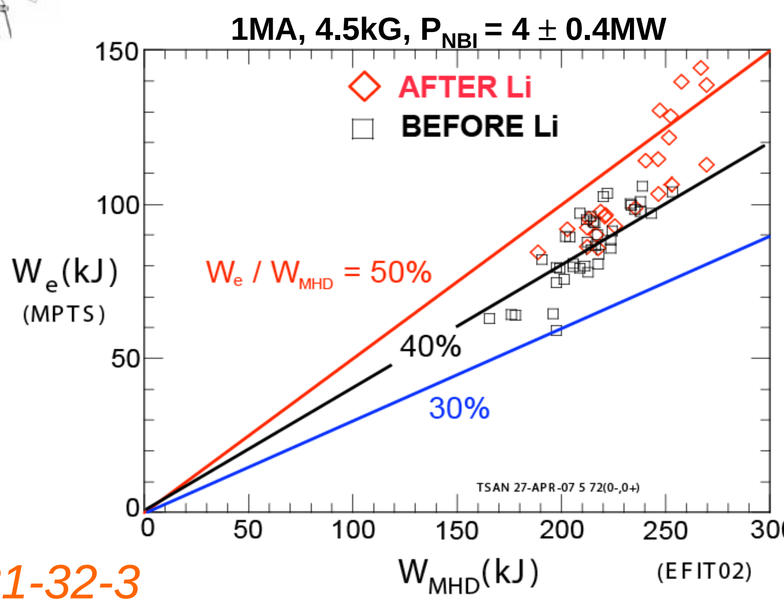
→ Test HHFW heating & current drive in ramp-up and flat-top for elevating q_{min} > 2

Tools for further developing fully non-inductive scenarios



LITER/Lithium can increase electron thermal confinement

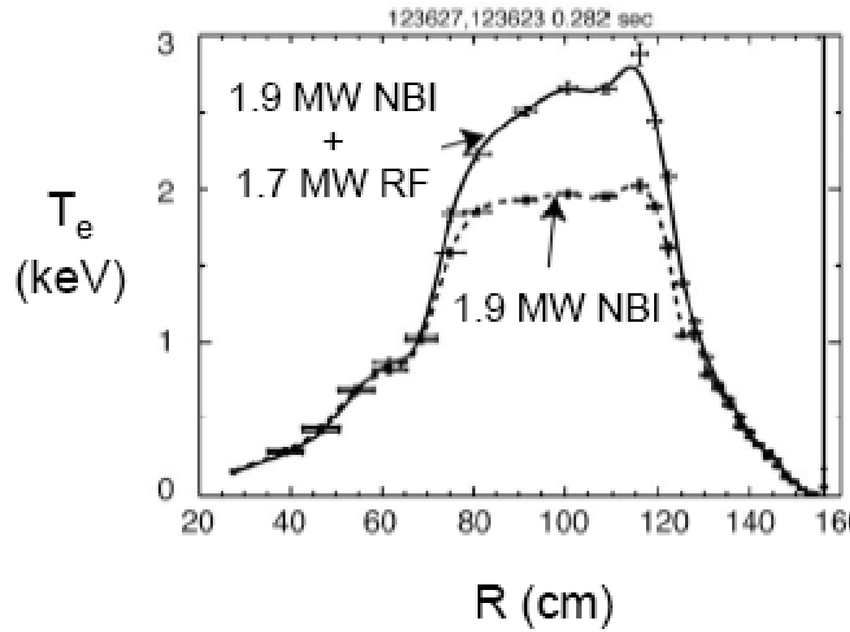
- τ_E increases 10-20%
- Electron stored energy fraction increases ≥ 20% (**45% → 55%)** from T_e profile broadening



PAC21-32-3

- Further increases with LLD?

Significant core HHFW e-heating obtained in L-mode at B_T=5.5kG with CD phasing and during NBI



- Need to extend to H-mode

→ Upgrading HHFW system for higher V, P_{RF}, ELM resilience

Plans for developing high β_N, high-f_{BS} scenario

NSTX

- 2008

  PAC21-34
  - Assess confinement, ELM, thermal profile modifications from dual-LITER
  - Develop HHFW in deuterium H-modes for advanced scenario applications
  - Incorporate n=1 RWM/RFA and n=3 EFC control into scenarios
- 2009-10 GOAL: increase f_{NICD} = 65-70%→80-90% for $\tau \sim \tau_{CR}$
  - Assess confinement, ELM, thermal profile modifications from LLD-I and LLD-II
  - Increase NBICD using lower n_e, higher/broader T_e from LLD
  - Use higher-power HHFW with ELM resilience to increase W_e, f_{BS}, and f_{NICD}
  - Perform high-elongation wall-stabilized plasma operation – FY09 milestone
    - Conditions: κ up to 2.8, $\tau \geq \tau_{CR}$, low-n_e for high NBICD fraction, high β_N for high f_{BS}
  - Integrate ELM reduction techniques into scenarios (Mid-plane coil RMP, Lithium)
  - Utilize NBI β-feedback to controllably operate near ideal-wall limit
- With only 2 years (FY08-09), cannot fully assess HHFW and LLD for improving advanced scenarios
- 2011-13 GOAL: increase f_{NICD} → 100% with J profile control for $\tau >> \tau_{CR}$
  - Long pulse (2s ⇔ $4\tau_{CR}$) at full B_T=5.5kG w/ sub-cooled TF/OH, long-pulse LLD
  - HHFW q(0) control, full-NICD + J(r) control w/ 2nd NBI, off-midplane RMP coils

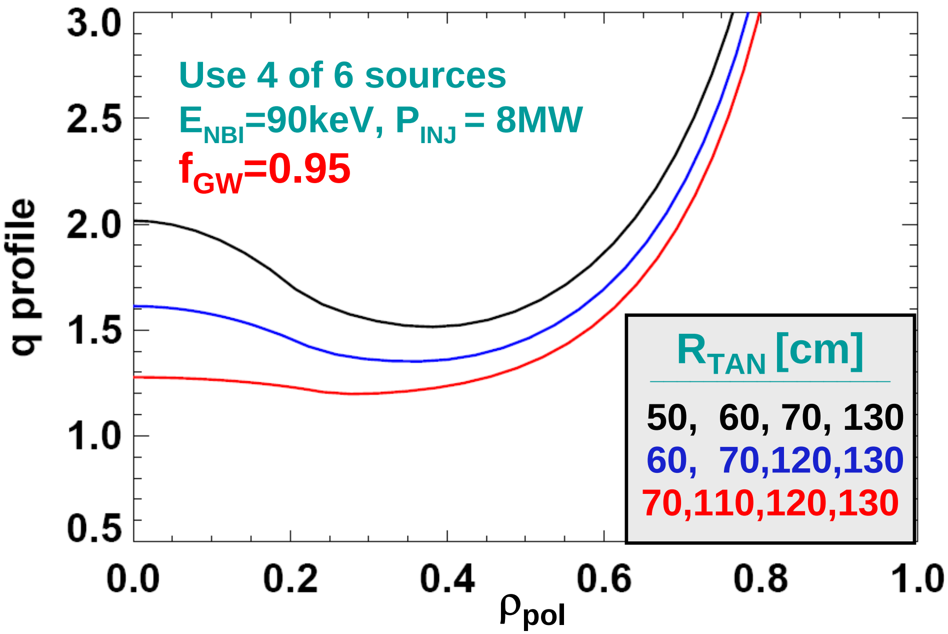
2^{nd} NBI (FY11-13) would enable full non-inductive current drive w/ only small extrapolation from present NSTX performance

NSTX

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%

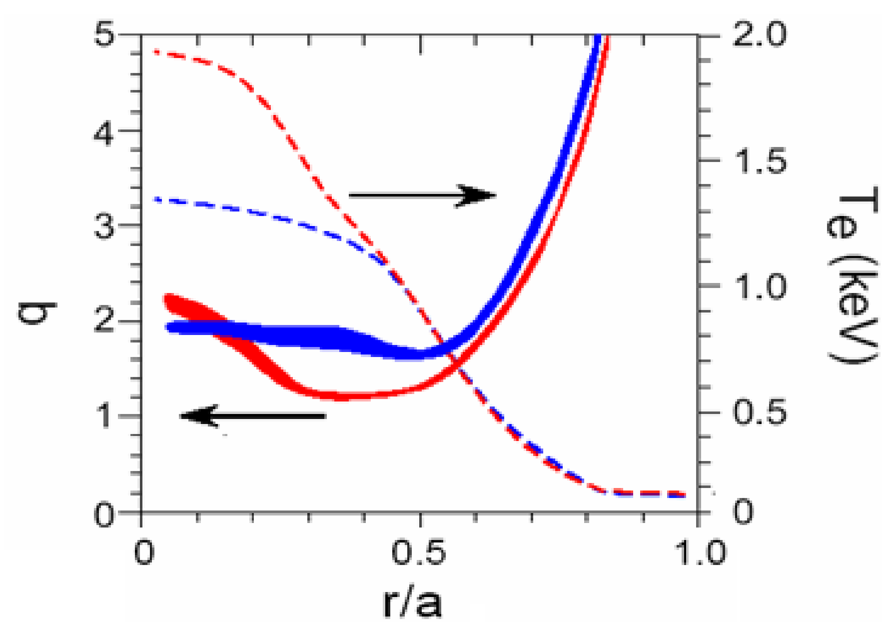
PAC21-32-1

- 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



(TRANSP simulation)

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



(Experiment)

Plasma control is the primary tool by which advanced scenarios are realized

- Improved vertical position control (2004)
  - Elongation key to achieving steady state with high f_{bs}
- Improved plasma shape control has yielded important benefits for NSTX operations (2005)
  - Improved stability
  - Improved HHFW coupling
- Non-axisymmetric control has led to several important new areas of research for NSTX (2006)
  - Error field control, RWM feedback
  - Non-resonant magnetic braking, neoclassical toroidal viscosity
- Recent computer hardware upgrades (2008) will enable new control areas
- Future:
  - Neutral beam control/β-feedback (2009), density control using SGI (2010)
  - Rotation control (beams + braking) (2010/11)
  - Advanced RWM control, real-time MSE (2011), HHFW q(0) control (2011-12)
  - Current profile control with additional NBI (incremental 2011-12)

Control science on NSTX is a growing collaborative research field

- Plasma control system (PCS) has been developed at PPPL in collaboration with GA
  - This successful collaboration has led to GA exporting the PCS to MAST, KSTAR, EAST
  - Incorporated vessel eddy currents into rt-EFIT for NSTX
  - Collaborated with GA on EAST control system and operation
- RWM control developed in collaboration w/ Columbia Univ.
  - Optimized RWM control development in progress
- New collaborations underway with LeHigh University and Princeton University
  - NSF CAREER Award for Prof. E. Schuster at Lehigh supports graduate student on NSTX - Optimized shape control development.
    - Proposal to develop optimized rotation control
  - New post-doc working on optimized vertical control on NSTX from Princeton University.
    - Proposal to develop optimized current profile control

Development of scenarios that integrate high non-inductive fraction w/ high confinement & stability crucial for next-step STs

- 2008-10 **Goal:** Reduce uncertainty in extrapolation to next-steps by achieving 80-90% NICD fraction for $\tau \sim \tau_{CR}$
  - LITER/LLD to reduce n_e and test NBICD redistribution physics
  - Characterize long-pulse τ_E and core and edge stability vs. n_e & ν^*
  - Use higher-power HHFW w/ ELM resilience to increase f_{BS} and f_{NICD}
  - Characterize high-elongation wall-stabilized plasma operation

- With only FY08-09, cannot realistically assess impact of LLD, NBICD redistribution, or HHFW for advanced scenarios

- 2011-13 **Goal:** Significantly reduce uncertainty in extrapolating to next-steps by demonstrating 100% NICD for $\tau >> \tau_{CR}$ with J(r) control
  - Long pulse (3-4 τ_{CR}) at full B_T=5.5kG (sub-cooling), long-pulse LLD
  - Full-NICD + J(r) control w/ 2^{nd} NBI, HHFW q(0) control, ELM control
  - Develop methods of controlling mode-induced NBICD redistribution

Integrated Scenario Research Timeline – FY08-10 plan

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

- **Understand, increase, control Li pumping**
- **Assess J_{NBICD} & redistribution vs. n_e**
- **Assess H_{98}, ELMs, β_N vs. n_e & Lithium**
- **Increase β_N, f_{BS}, f_{NICD} with HHFW**
- **Maximize β_N, f_{BS}, f_{NICD} vs. q and dq/dr**
- **Control β, n=0, RWM, EF to operate near ideal-wall limit**
- **ELM control w/ mid-plane RMP, Lithium**

Transient ($\leq 1\,\tau_{CR}$) demo of high NICD:

$I_P \approx 0.7$MA
f_{GW} = 0.5-1
f_{NBICD} = 25-50%
H_{98y2} = 1-1.4

f_{NICD} = 80-90%
β_N up to 6.6
β_T = 15-20%
$\tau_{flat} \leq 1\,\tau_{CR}$
Small/no ELM

Tools

- **Dual LITER**
- **Liquid Li Divertor (LLD)**
- **HHFW V_{ANT}, P_{RF} upgrade**
- **HHFW ELM resilience**
- **β control**
- **n_e control**

Integrated Scenario Research Timeline – FY08-13 (base)

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

FY08–10:
- Understand, increase, control Li pumping
- Assess J_{NBICD} & redistribution vs. n_e
- Assess H_{98}, ELMs, β_N vs. n_e & Lithium
- Increase β_N, f_{BS}, f_{NICD} with HHFW
- Maximize β_N, f_{BS}, f_{NICD} vs. q and dq/dr
- Control β, n=0, RWM, EF to operate near ideal-wall limit
- ELM control w/ mid-plane RMP, Lithium

FY11–13:
- Long-pulse n_e control (pumping & fueling)
- Develop control of J_{NBI} redistribution
- Assess long-pulse H_{98}, ELMs, β_N vs. n_e
- Develop q(0) control with HHFW CD
- Improved control of ELM/RWM/EF/rotation

Extended duration approaching full NICD:

- $I_P \approx$ 0.7MA
- f_{GW} = 0.3-1
- f_{NBICD} = 25-50%
- H_{98y2} = 1.2-1.4
- f_{NICD} = 90-100%
- β_N up to 6.6
- β_T = 15-20%
- $\tau_{flat} \sim$ 1-2τ_{CR}
- No ELM

Tools

FY08–10:
- Dual LITER
- Liquid Li Divertor (LLD)
- HHFW V_{ANT}, P_{RF} upgrade
- HHFW ELM resilience
- β control
- n_e control

FY11–13:
- Long-pulse divertor and core fueling
- TF/OH sub-cooling
- Off-midplane control coils
- real-time v_ϕ
- v_ϕ control
- rt - MSE
- HHFW q(0) control
- 2nd NBI

Integrated Scenario Research Timeline – FY08-13 (+10%)

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

FY08–10:
- Understand, increase, control Li pumping
- Assess J_{NBICD} & redistribution vs. n_e
- Assess H_{98}, ELMs, β_N vs. n_e & Lithium
- Increase β_N, f_{BS}, f_{NICD} with HHFW
- Maximize β_N, f_{BS}, f_{NICD} vs. q and dq/dr
- Control β, n=0, RWM, EF to operate near ideal-wall limit
- ELM control w/ mid-plane RMP, Lithium

FY11–13:
- Long-pulse n_e control (pumping & fueling)
- Control J_{NBI} w/ multiple NBI sources and from redistribution
- Assess long-pulse H_{98}, ELMs, β_N vs. n_e
- Develop q(0) control with HHFW CD
- Improved control of ELM/RWM/EF/rotation

Long-pulse full NICD with J(r) control:

- $I_P \approx$ 0.7-0.8MA
- f_{GW} = 0.3-1
- f_{NBICD} = 25-50%
- H_{98y2} = 1.2-1.4
- $f_{NICD} \leq$ 100%
- β_N up to 7
- β_T = 15-25%
- $\tau_{flat} \leq 3\text{-}4\tau_{CR}$
- No ELM

Tools

- Dual LITER
- Liquid Li Divertor (LLD)
- HHFW V_{ANT}, P_{RF} upgrade
- HHFW ELM resilience
- β control
- n_e control
- real-time v_ϕ
- 2[nd] NBI
- v_ϕ control
- Real-time MSE
- Long-pulse divertor and core fueling
- TF/OH sub-cooling
- Off-midplane control coils
- NBI J(r) control