Motivation for NSTX Upgrade and selection of design point

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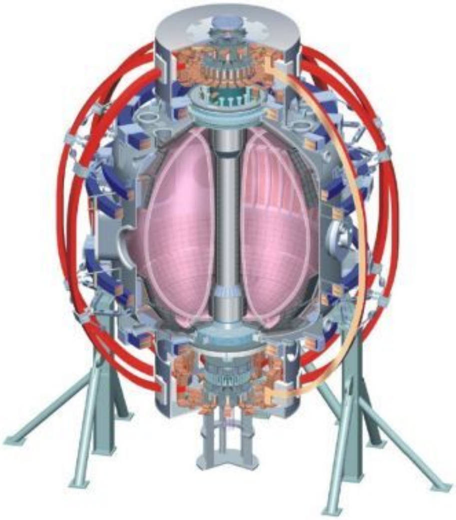
NSTX Upgrade Project
Conceptual Design Review
LSB, B318
October 28-29, 2009



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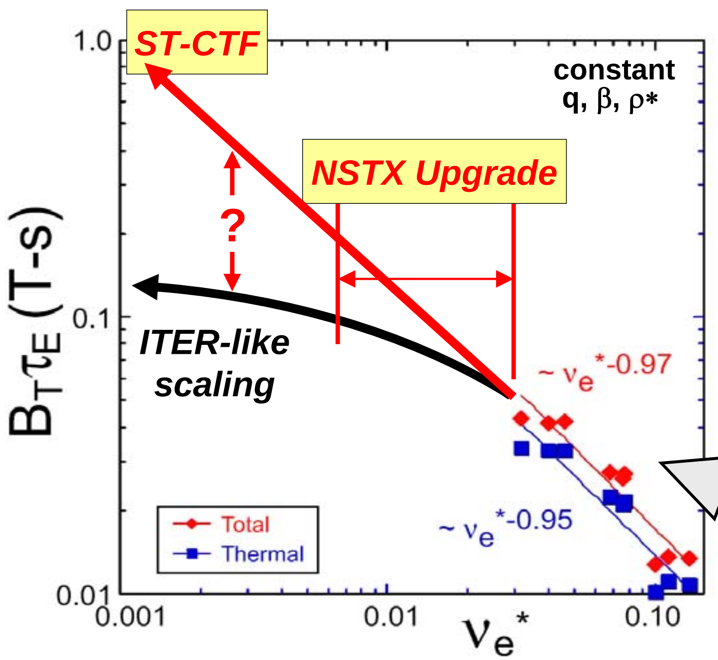
Outline

- Physics Motivation
- Design Point Selection Process
- General Requirements Document, Design Point Info
- Assessment of Impact of Operational Scenarios

Access to reduced collisionality is needed to understand underlying causes of ST transport, scaling to next-steps



Normalized electron collisionality $\nu_e^* \propto n_e / T_e^2$

- Future ST's are projected to operate at 10-100× lower normalized collisionality ν*
- Conventional tokamaks observe weak inverse dependence of confinement on ν*

ITER $B\tau_E$ (e-static g-Bohm) $\propto \rho_*^{-3}\, \beta^0\, \nu_*^{-0.14}\, q^{-1.7}$

Petty et al., PoP, Vol. 11 (2004)

- NSTX observes much stronger scaling vs. ν*
  - Does favorable scaling extend to lower ν* ?
  - What modes dominate e-transport in ST ?
    - Electrostatic or electromagnetic?

- Higher toroidal field & plasma current enable access to higher temperature
- Higher temperature reduces collisionality, but increases equilibration time

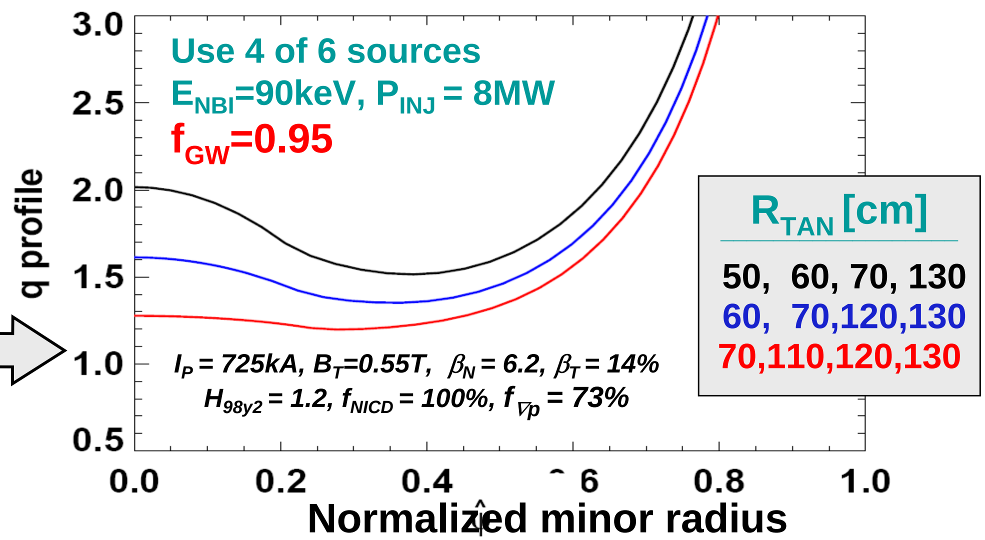
- **Upgrade: Double field and current for 3-6× decrease in collisionality → require 3-5× increase in pulse duration for profile equilibration**

Increased auxiliary heating and current drive are needed to address ST start-up, sustainment, and boundary issues

- Need additional heating power to access high temperature and β at low ν^*
  - → 4-10MW, depending on confinement scaling
- Need increased <u>current drive</u> to access and study 100% non-inductive
  - → 0.25-0.5MA current drive compatible with ramp-up, sustainment plasmas
- Need to learn to manage ≥ ITER→FNSF-level high-heat-flux challenge
  - → high divertor power density (P/R ≤ 20MW/m) + flexible divertor PF coil set

- **Upgrade: Double neutral beam power + more tangential injection**
  - More tangential injection → up to 2 times higher efficiency, current profile control

- q(r) profile very important for global stability, electron transport, Alfvénic instability behavior
  - Variation of mix of NBI tangency radii would enable core q control

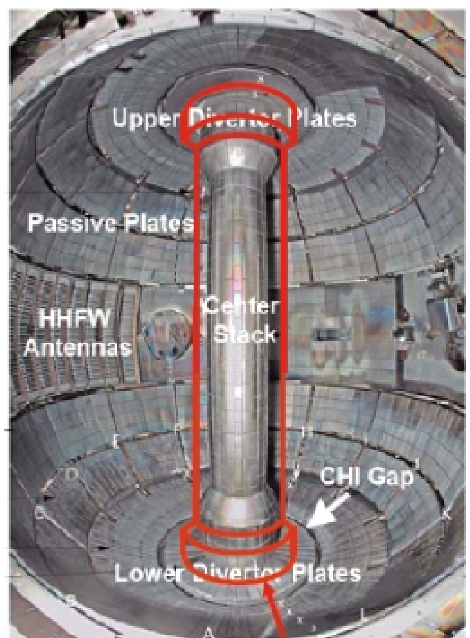


Upgrades provide major step along ST development path

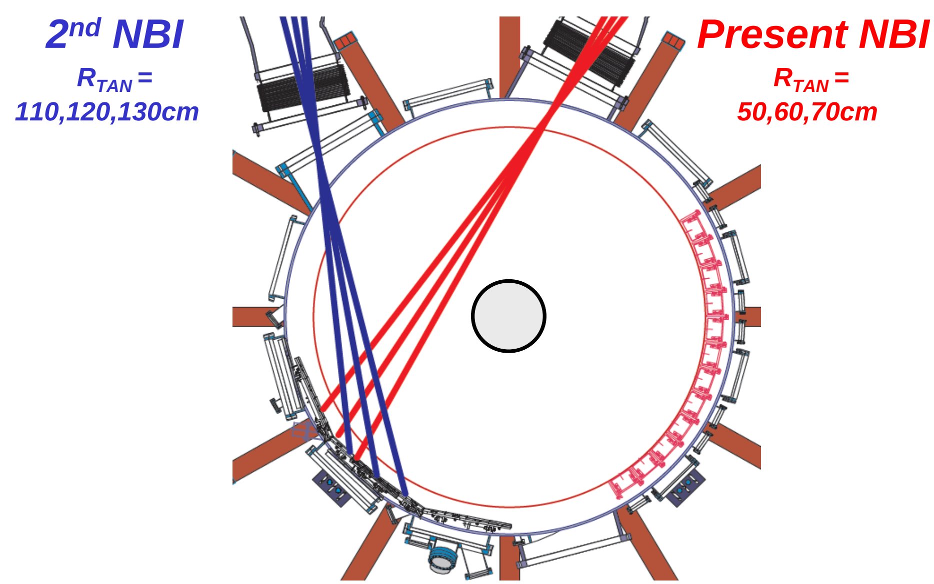
(next factor of 2 increase in current, field, and power density)

	NSTX	NSTX Upgrade	High Heat Flux Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	$\geq$ 1.3	$\geq$ 1.5	$\geq$ 1.7	$\geq$ 1.5
Plasma Current (MA)	1	2	3.5	10
Toroidal Field (T)	0.5	1	2	2.5
P/R, P/S (MW/m,m^2)	10, 0.2*	20, 0.4*	40, 0.7	40-60, 0.8-1.2

***** Includes 4MW of high-harmonic fast-wave (HHFW) heating power***



Approximate outline of new Center-Stack



Design Point Selection Process (1)

- Design point spreadsheet studies were initiated in April ‘08
- Guiding assumptions:
  1. Completely replace center stack
  2. New TF same dZ as average turn of original
  3. New OH same dZ as old
  4. Retain existing TF outer legs
  5. TF at flat top for full duration of Ip
  6. Provide OH flux sufficient for I_P ramp in 1st swing
     - Conservative dI_P / dt = 2MA/s – assumes 2× higher T_e with upgrade
  7. Use OH 2nd swing as thermal/stress permits
  8. Retain existing PF outer coils
  9. Coil temperature range* 12-100C, adiabatic, allow for L/R decay
  10. Simple formulae for TF von Mise stress**, OH hoop stress*** (peak)
      - VM allowable stress 133 MPA, peak allowable stress 200MPA
  11. 1kV TF, 8kV/24kA OH, 1 MG
  12. Two TFTR NBI systems imposing MG loads

* TF adiabatic allowable slightly above 100C to account for entrained water benefit
** neglects tension due to force from outer leg
*** neglects interaction with PF coils and plasma

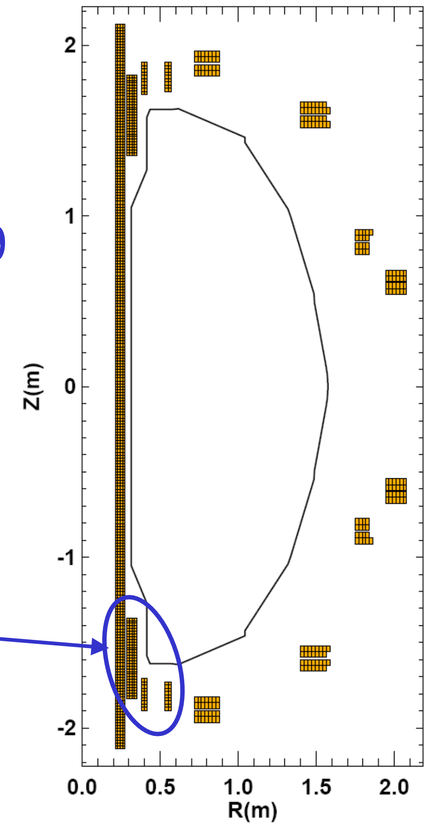
Design Point Selection Process (2)

- Spreadsheet modeling features:
  - TF and OH conductor sizing
    - Adiabatic conductor heating models (G-function)
    - Allowance for "fill factor" due to conductor cooling hole, corner radii, electrical insulation
  - Simple formulae for TF inner leg Von Mises stress and OH peak hoop stress
    - Not included are TF inner leg torsion, TF outer leg, VV, etc.
    - Full OH Von Mises/Tresca stress calculation w/axial stress is not included
  - Full OH waveform including plasma loop voltage and flux requirement
    - Accounts for flux consumption during plasma initiation
    - Computes ramp and flat top flux using Hirshman-Neilson formulation
  - Simplified linear models for AC/DC converter behavior
  - TF and OH L-R circuit models V = L • dI/dt + I• R w/ temperature dependent R's
  - MG power and energy models

- XL Solver (non-linear optimizer) is used to compute design point…
  - finds radius of TF necessary to meet B_T and pulse length requirement
  - designs OH coil to meet flux requirement of 1st swing, maximizes 2nd swing within thermal constraints

Design Point Selection Process (3)

- Initial approach was aggressive (e.g. 2kV TF, 10kV OH, 2 MG) at A ~ 1.5-1.6 to understand possible operating envelope
  - Found that maximum usage of center stack area (based on spreadsheet analysis) would allow I_P=3 MA with 5 sec flat top at B_T=1.4T
  - But this ignored TF joint design, PF forces on TF, PF interaction forces, …
- Decided to limit to 1kV TF, 8kV OH, 1 MG → I_P=2MA, 5 flat-top, B_T = 1T and investigate design concepts in detail
  - First design point proposed in November 2008
  - Physics analysis performed to confirm assumptions
  - First "official" design point for engineering study issued 2/10/09
- Recent iterations in summer/fall 2009:
  - TF conductor details based on manufacturing considerations
  - OH coil wound directly on TF - eliminates "tension tube", gap
  - Refinements in insulation thicknesses (more conservative)
  - Refined design of inner PF coils (PF1a/b/c coils)
  - Added short pulse double swing scenario
  - Inclusion of force influence matrices and force calculations

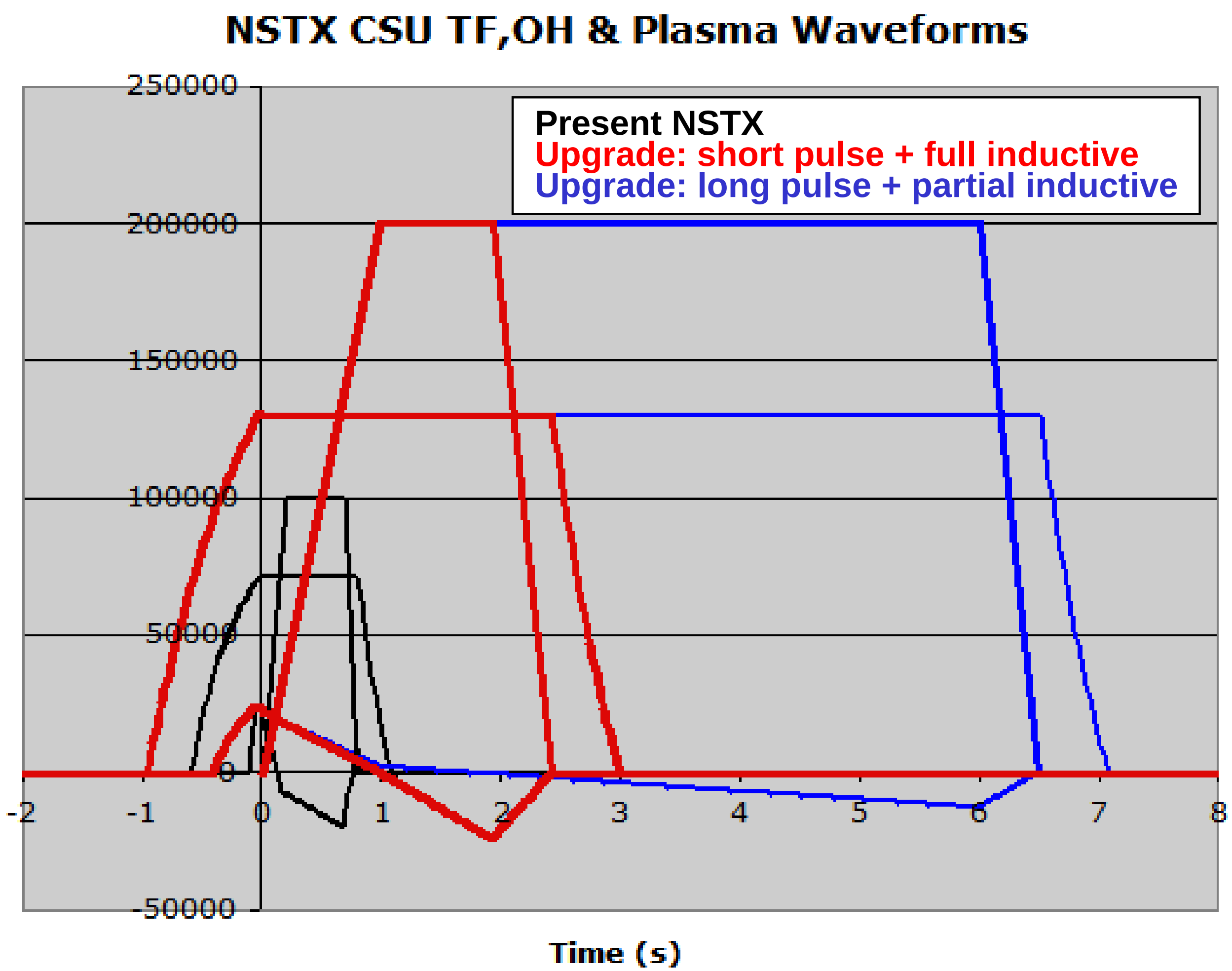


Design Point Parameters and Waveforms

Relative performance of Upgraded NSTX vs. Base:

- ***Center-stack radius increased 13cm – A=1.3 → 1.5***
- ***Field doubled at same major radius***
- ***Available OH flux increased 4-fold***
- ***Inter-shot cool-down period doubled***

	Base NSTX	NSTX Upgrade
R_0 [m]	0.854	0.934
Min. aspect ratio	1.28	1.5
I_p [MA]	1	2
B_T [T]	0.55	1
T_{pulse} [s]	1	5
$T_{repetition}$ [s]	600	1200
$R_{center\_stack}=R_0$-a [m]	0.185	0.315
$R_{antenna}=R_0$+a [m]	1.574	1.574
Total OH flux [Wb]	0.75	3



General Requirements Document (GRD) and Web-based Design Point Information for Centerstack Upgrade

- GRD was signed and issued on March 30
- Contains top level mission performance requirements
  - Includes appropriate level of specificity for mission performance
  - Refers to web-based design point data as vehicle for tracking/coordinating details subject to iteration
- Organized according to original NSTX WBS structure
  - Changes required to each WBS element are described
  - Ensures that no work scope is overlooked

- Comprehensive design point data is also maintained on web site to ensure coordination of all design activities
  - NSTX CSU design team is notified when new data is posted
  - Changes indicated in “blue, records of prior revisions maintained
- Web data contains both base NSTX with CS upgrade data
  - Useful for comparing “old” vs. “new” - MKS and English units

  http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

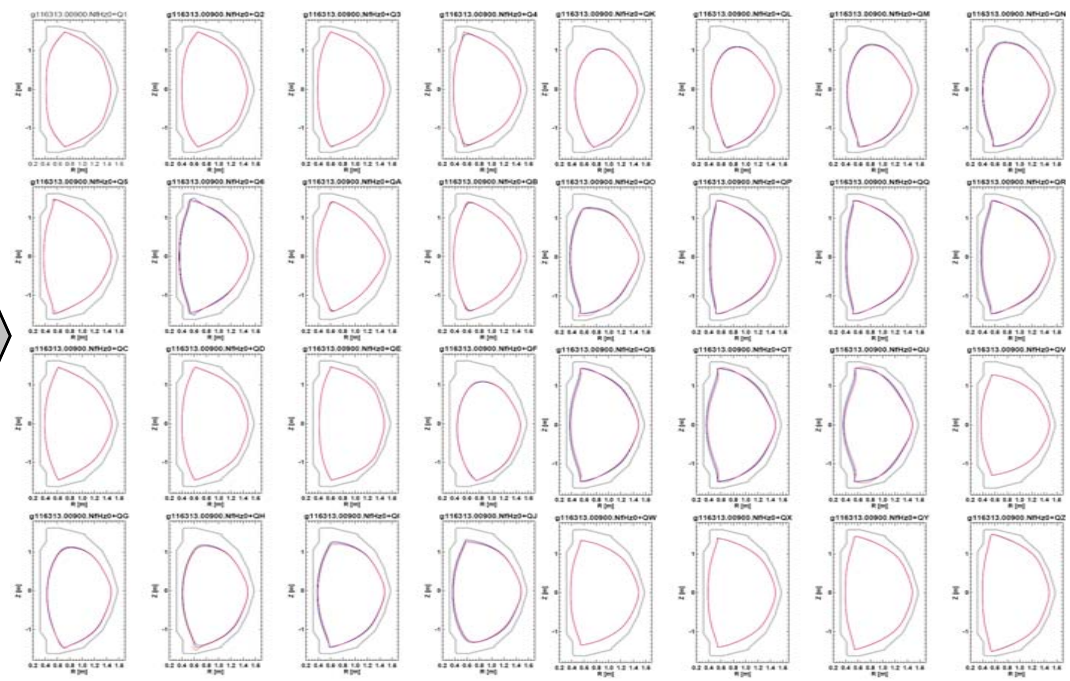
TF supports and "PF cage" design have been based on most conservative physics and engineering assumptions

1. Compute PF current requirements based on wide range of equilibria that provide *more shaping flexibility/capability* than present NSTX
2. Assume all power supplies can access worst-case force combinations

Free boundary equilibrium parameters:

- Aspect ratio A: 1.6 – 1.9
- Internal inductance l_i: 0.4 – 1.1
- Elongation κ: 2.1 – 2.9
- Triangularity δ: 0.2 – 0.7
- Squareness ζ: -0.15 – 0.12
- Magnetic balance: -1.5 – 0cm
- I_{OH}: zero and +/- supply limit
  - For computing PF needed for cancellation of OH leakage flux

32 free boundary equilibria × 3 OH conditions = 96 cases



Narrower operating range ($\delta \geq 0.4$, $\zeta \sim 0.1$, $l_i \leq 0.8$)* + advanced coil protection could simplify PF support design – analysis underway...

****this operating range similar to that of highest-performance present NSTX plasmas***

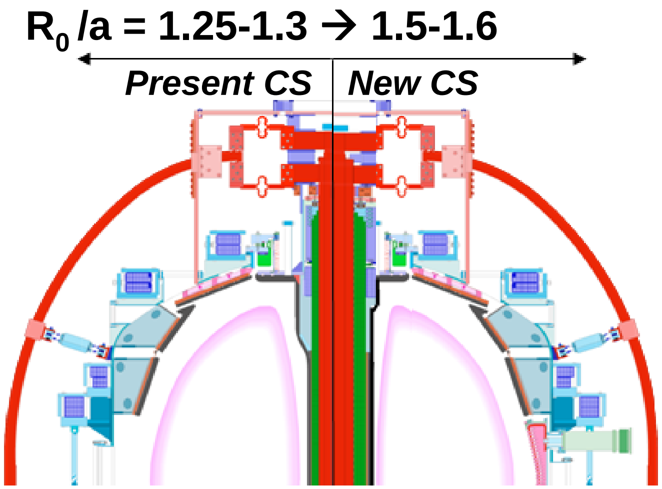
Summary: NSTX Upgrades will greatly expand the research capabilities of NSTX and narrow key gaps to future STs/tokamaks

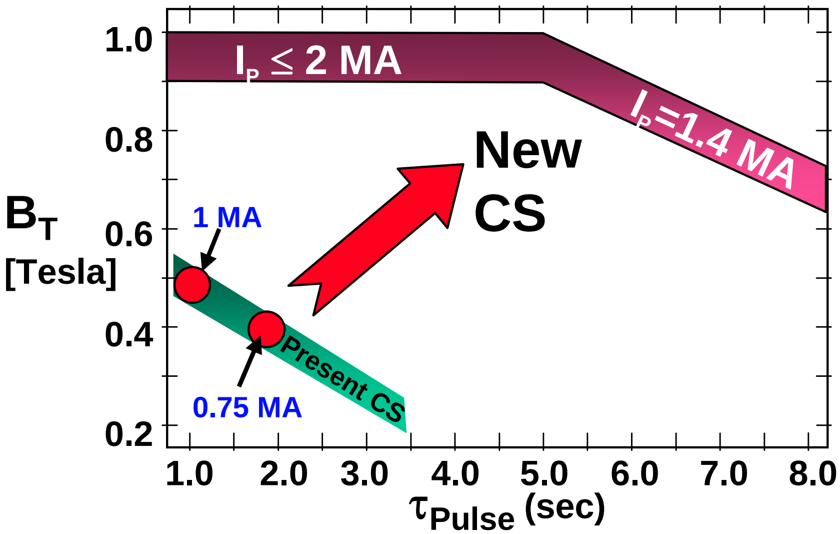
- Design doubles B_T, I_P, P_{NBI}, and extends pulse 3-5×
  - Access and understand impact of reduced collisionality
  - Access fully non-inductive ramp-up and sustainment
  - Assess plasma-material interface solutions for FNSF/Demo
- Design point is feasible from engineering standpoint
  - See subsequent presentations
- Next activity is to further assess trade-offs between physics performance and complexity/estimated cost

Backup Slides

Major facility upgrades are proposed to bridge performance and understanding gaps between present and next-step STs

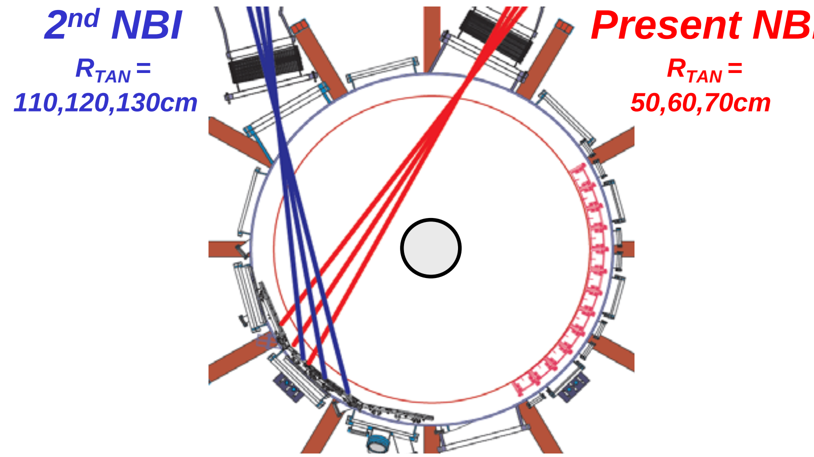
New center stack for 1T, 2MA, 5s to access reduced ν*, 100% non-inductive ST plasmas

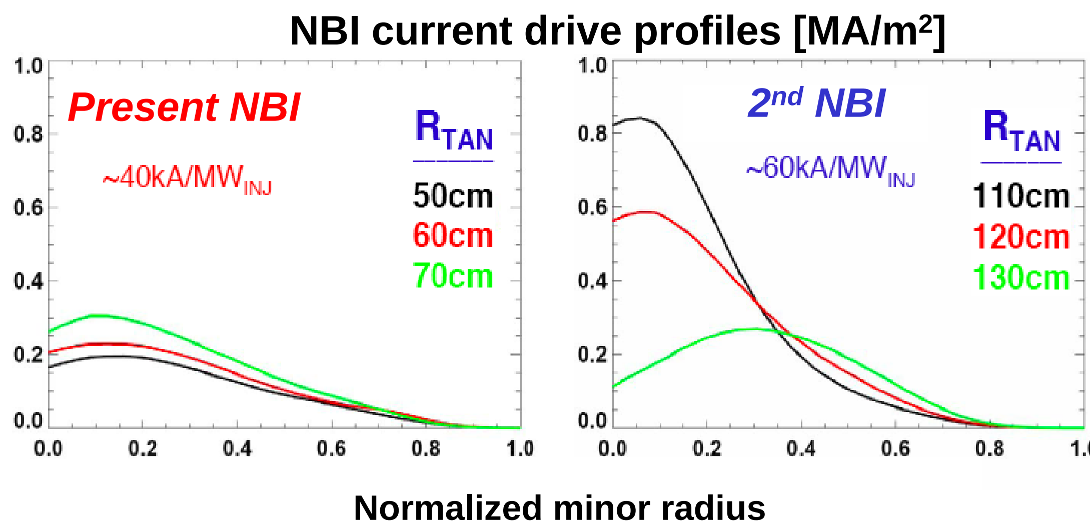




Magnet operation at ~1T (vs. 0.55T) → within a factor of 2 of next-step STs

2nd NBI with larger $R_{tangency}$ for sustained and controllable 100% NICD + high β at low ν*





Up to 2 times higher NBI current drive efficiency, current ramp-up with NBI, current profile control

Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

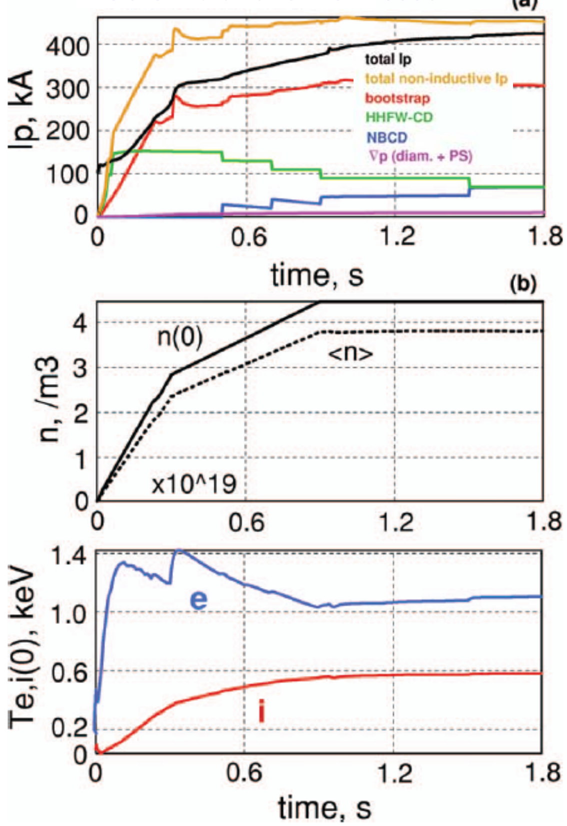
Ramp to ~0.4MA with fast wave heating:

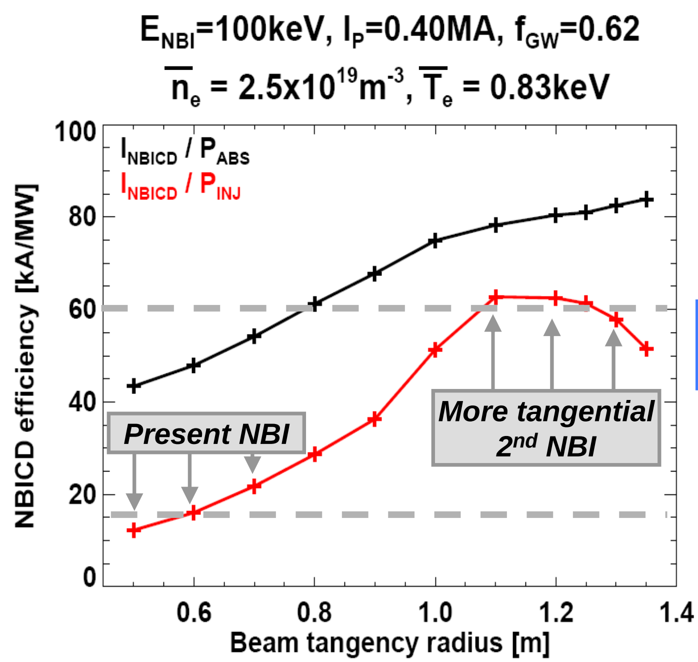
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

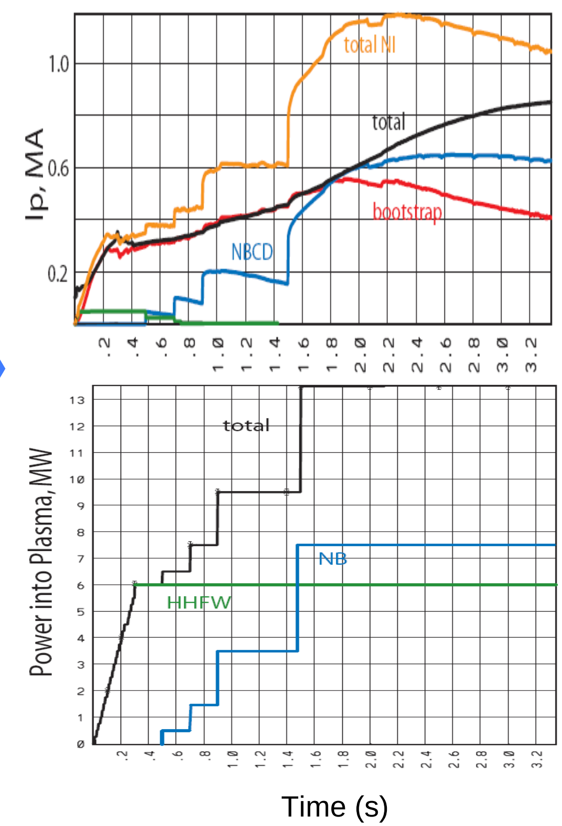
Extend ramp to 0.8-1MA with 2nd NBI:

- Benefits of more tangential injection:
  - Increased NBI absorption = 40→80% at low I_P
  - Current drive efficiency increases: ×1.5-2
- New CS needed for ~3-5s for ramp-up equilibration
  - Higher field 0.5→1T also projected to increase electron temperature and NBI-CD efficiency

TSC Simulations – C. Kessel



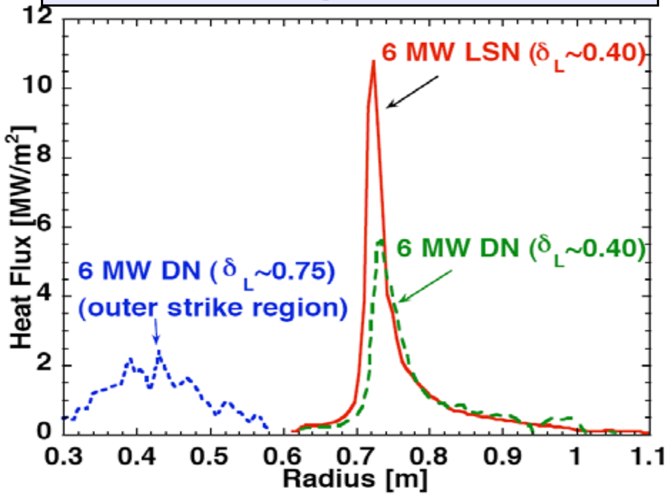




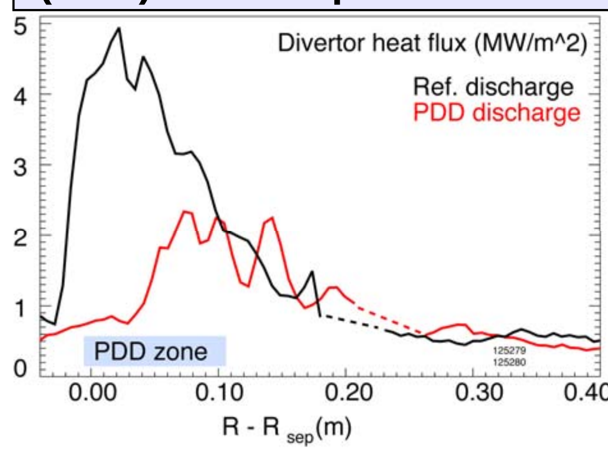
Additional PF coils of new CS would provide flexibility to control flux-expansion for heat flux control

Present NSTX:

Magnetic geometry strongly influences peak heat flux

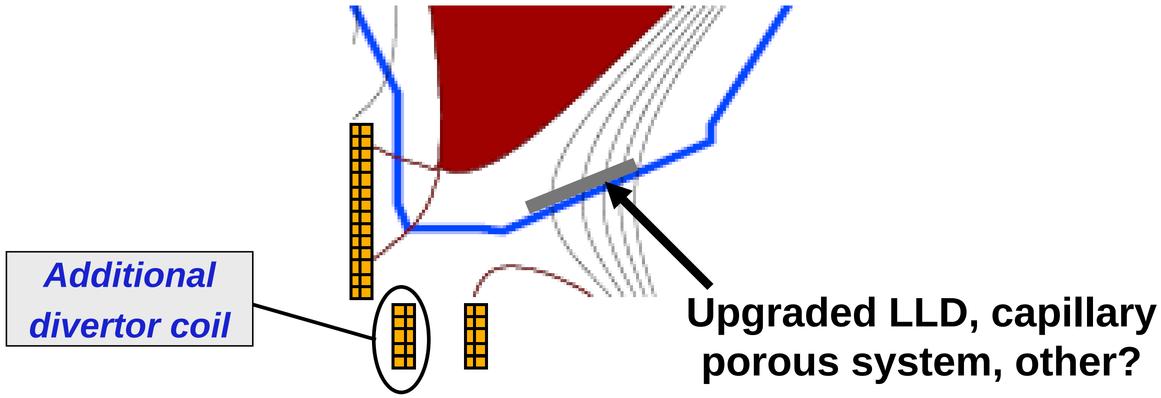


Partial divertor detachment (PDD) reduces peak heat flux

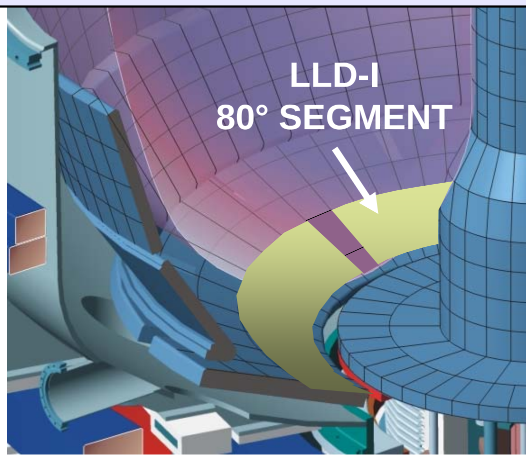


NSTX with new CS:

New divertor poloidal field coils on new CS would extend present high flux expansion ~20 to 40-60



Upgraded NSTX would test compatibility of high flux expansion, PDD, a liquid lithium divertor (LLD), and up to 5× longer pulse-length and 2-3× higher divertor heat flux

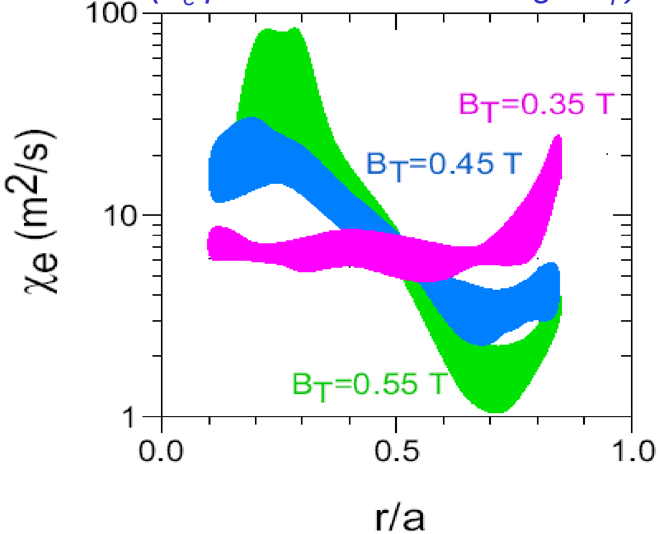


NSTX Upgrades needed to extend ST confinement scaling studies to higher field and current and lower collisionality

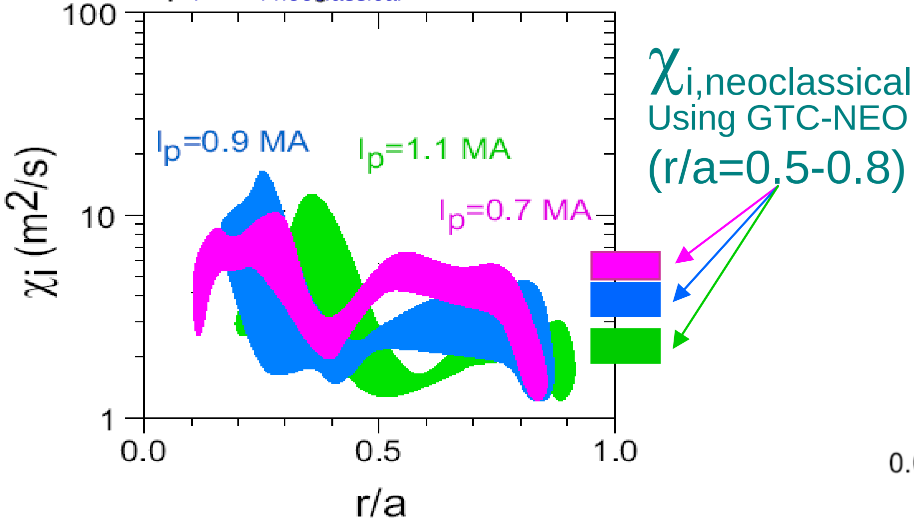
- **NSTX H-mode thermal confinement scaling differs from higher aspect ratio scaling:**

$\tau_{E,NSTX} \propto B_T^{0.9}\ I_p^{0.4}$ → strong B_T scaling $\qquad \tau_{E,98y,2} \propto B_T^{0.15}\ I_p^{0.93}$ → weak B_T scaling

Electrons largely responsible for B_T scaling of confinement *(T_e profile broadens at high B_T)*

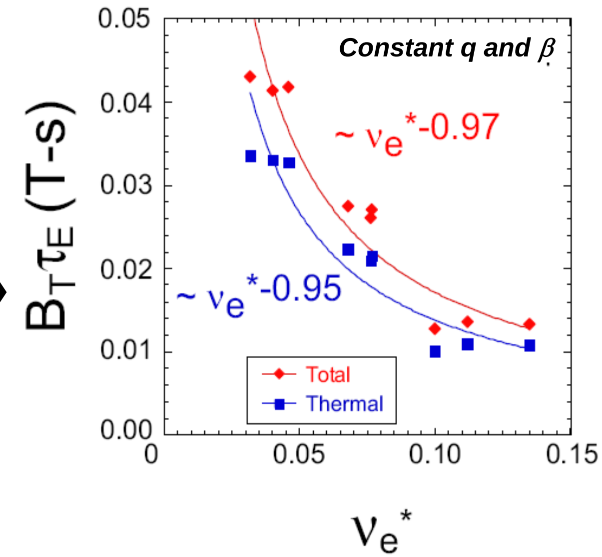


Ions largely responsible for I_p scaling of confinement *($\chi_i \approx \chi_{i\text{-}neoclassical}$ at large r/a)*



New CS with 1T, 2MA operation:

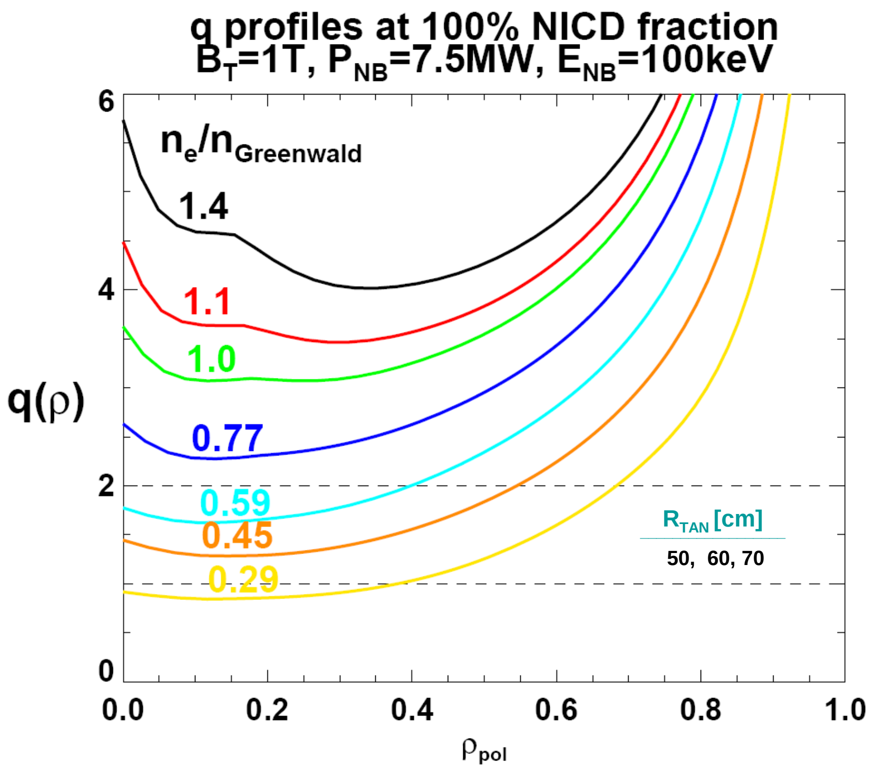
- Increased range of B_T, I_P variation from 1.6 to nearly a factor of 3
- Does strong confinement dependence on ν* extend to lower ν*?
- Assume $\tau_E \propto B_T^{1.3}$ at fixed q, $\tau_E \propto P_{heat}^{-0.5\text{ to }-0.7}$, and $n_e/n_{gw} \propto I_P^{-0.5}$
  - Present NBI + 4MW RF, access ~ 0.75-0.9× present β, 3-4× lower ν*
  - Present + 2nd NBI + 4MW RF: access ~0.9-1.1× present β, 4-6× lower ν*



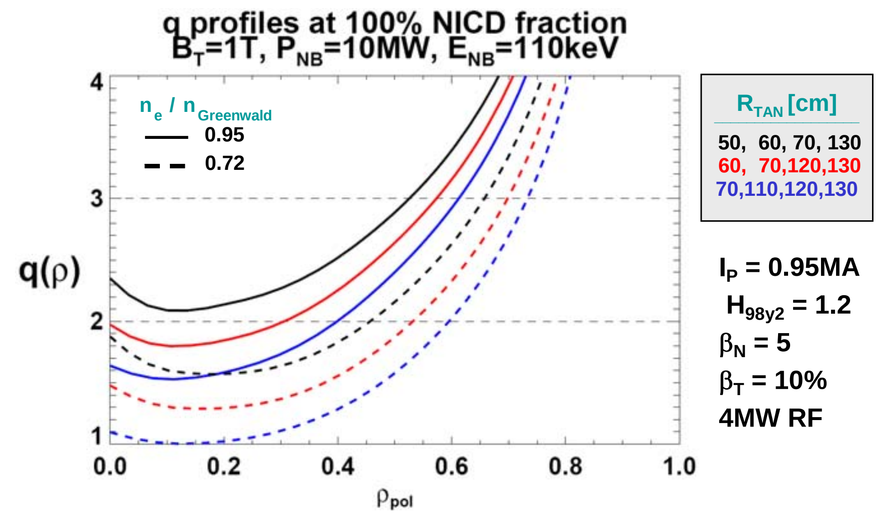
Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- Use present NBI-CD + fast wave heating
- Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)
- State sustained for 1-1.5s (~1 τ_{CR})
  - NBI duration limited to 2s at 7.5MW

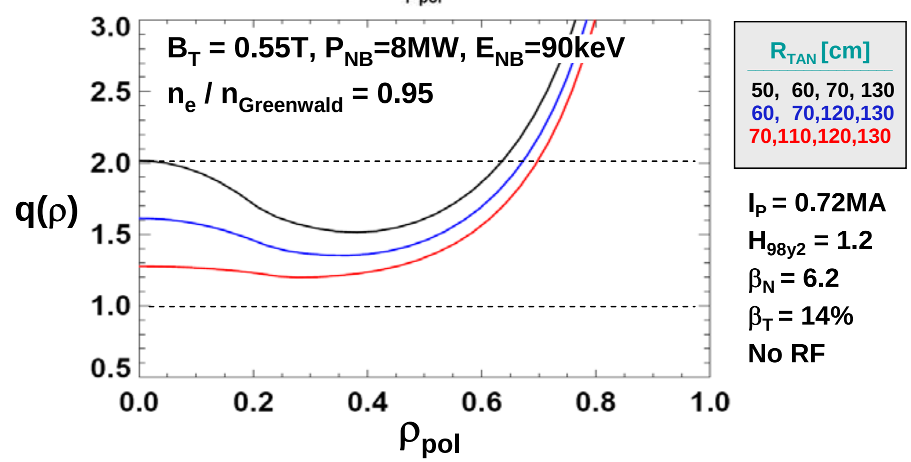
- Addition of 2nd NBI would enable:
  - Longer NBI duration → profile relaxation
    - 10MW NBI available for 5s → 3-4 τ_{CR}
  - Control q_{min} & q-shear with NBI source and B_T
  - Study long-pulse MHD stability, PMI performance



I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4
β_N = 4.5-5, β_T = 10-12%, 4MW RF



I_P = 0.95MA
H_{98y2} = 1.2
β_N = 5
β_T = 10%
4MW RF



I_P = 0.72MA
H_{98y2} = 1.2
β_N = 6.2
β_T = 14%
No RF