Physics design of the NSTX Upgrade

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For the NSTX Research and NSTX Upgrade Project Teams

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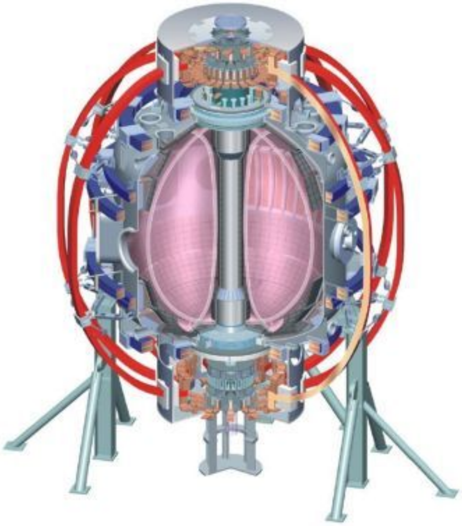

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Abstract

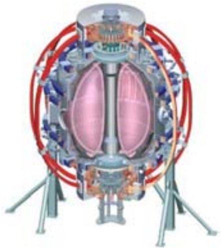
Access to low collisionality is important to more fully understand transport, stability, and non-inductive start-up and sustainment in the ST. For example, NSTX and MAST observe a strong (nearly inverse) scaling of normalized confinement with collisionality, and if this trend holds at low collisionality, high fusion neutron fluences could be achievable in very compact ST devices. Such considerations motivate the proposed upgrade of NSTX to higher field, current, and heating power. To enable engineering design of the upgrade, systematic free-boundary equilibrium calculations have been performed to determine the upgrade poloidal field requirements as a function of plasma shape, magnetic balance, internal inductance, and beta. Additional poloidal field coils in the divertor region are proposed to provide very high flux expansion for reduction of high predicted divertor heat flux. TRANSP simulations indicate that more tangential neutral beam injection (NBI) can increase NBI current drive efficiency by up to a factor of two, enable control of the core q profile, and ramp-up the plasma current to near mega-ampere levels. These and other physics design activities will be discussed.

Outline

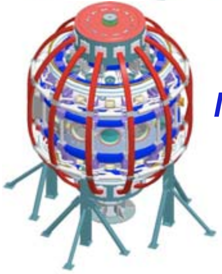
- Motivation for upgrades
- Overview of center-stack and NBI upgrades
- Free-boundary equilibrium studies
- NBI current drive studies for sustainment, ramp-up

NSTX, NSTX Upgrade, and proposed future ST facilities emphasize preparation for fusion Demo

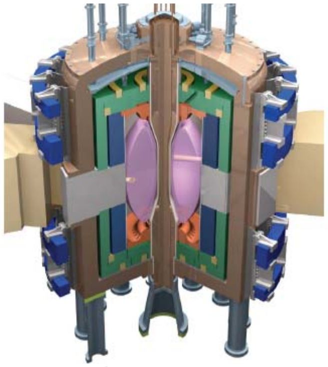
- NSTX:
  - Providing foundation for understanding ST physics and performance
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality – important for further understanding confinement, stability, start-up, current drive
  - Assess full non-inductive current drive operation – needed for steady-state ST applications and ITER advanced operating scenarios
  - Prototype heat and particle exhaust solutions for next-step facilities
- Fusion Nuclear Science Facility - ST (FNST)
  - Develop/test nuclear components for Demo
  - Sustain $W_{neutron} \sim 0.2\text{-}0.4 \rightarrow 1\text{-}2\,\mathrm{MW/m^2}$, $\tau_{pulse} = 10^3 \rightarrow 10^6\,\mathrm{s}$
- ST Plasma Material Interface Facility (ST-PMIF)
  - Develop PMI solutions for FNSF/Demo (low and high-A)
  - Advance start-up, confinement, sustainment for ST
  - High $P_{heat}/S \sim 1\,\mathrm{MW/m^2}$, high T_{wall}, $\tau_{pulse} \sim 10^3\,\mathrm{s}$
- Burning Plasma ST (BPST)
  - Burning plasma science for ST-Demo, high $W_{neutron}$ FNST
  - Advance start-up, confinement, PMI for FNST/ST-Demo
  - High β_T=20-40%, high v_{fast}/v_{Alfven}, $\tau_{pulse}=10^2\text{-}10^3\,\mathrm{s} \rightarrow$?



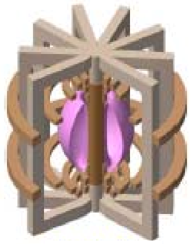
NSTX



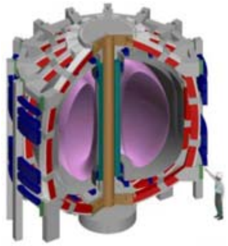
NSTX-U



FNST (FNSF/ST-CTF)



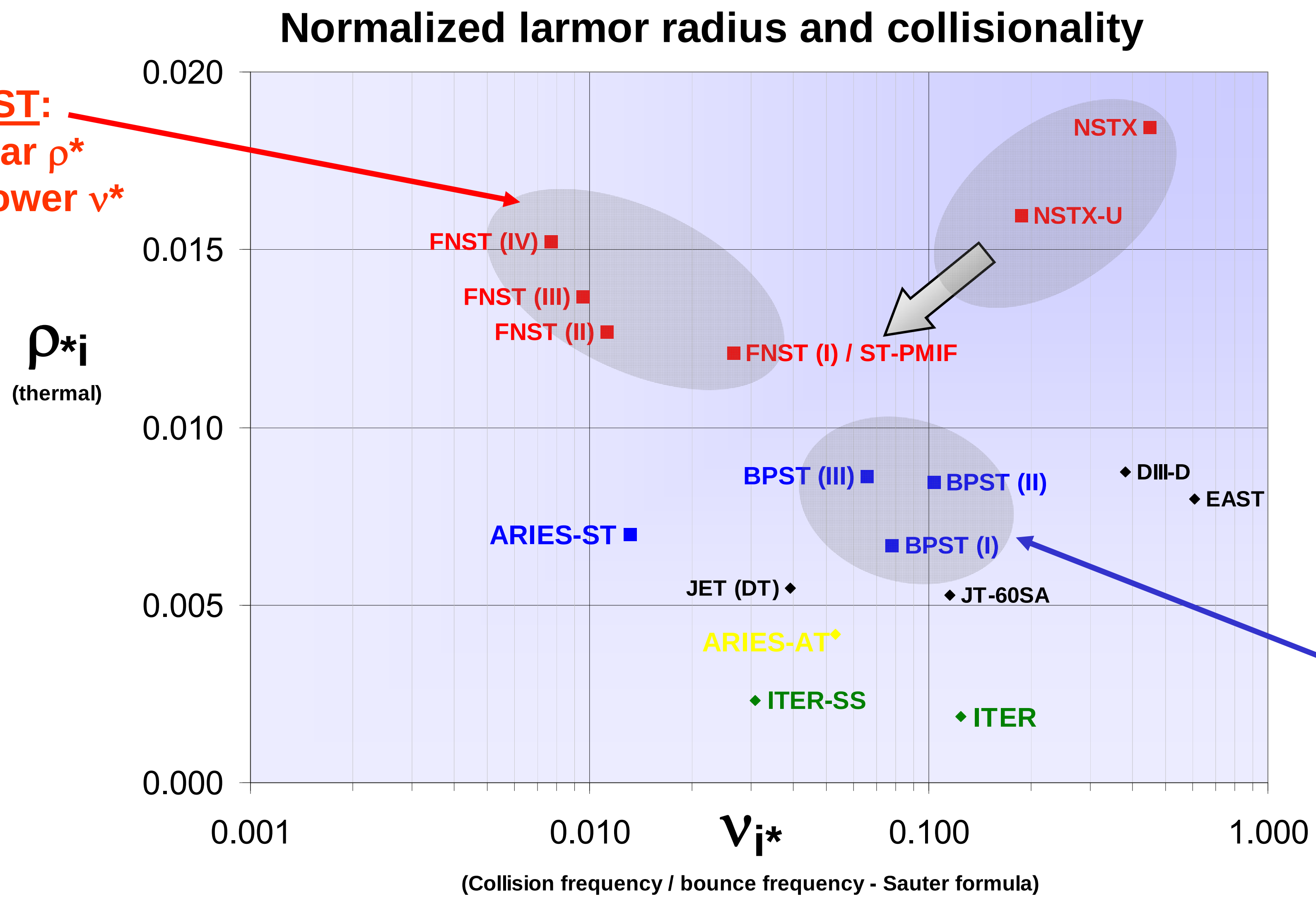
ST-PMIF (NHTX)



BPST (NSST)

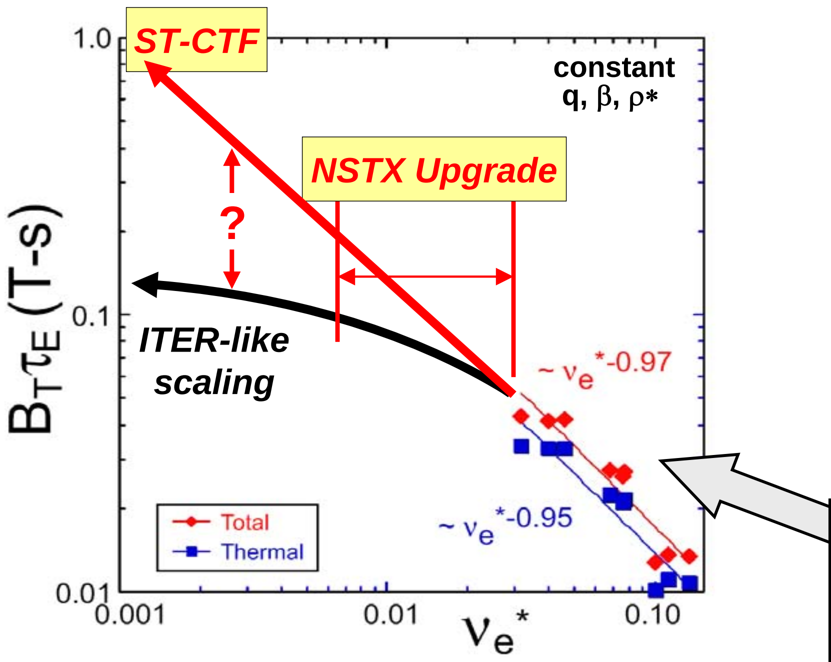
NSTX Upgrade lowers ρ* and ν* toward next-step ST values

FNST:
Similar ρ*
4-20× lower ν*



BPST:
2× lower ρ*
similar ν*

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) $\propto \rho_*^{-3}\ \beta^0\ \boxed{\nu_*^{-0.14}}\ q^{-1.7}$

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

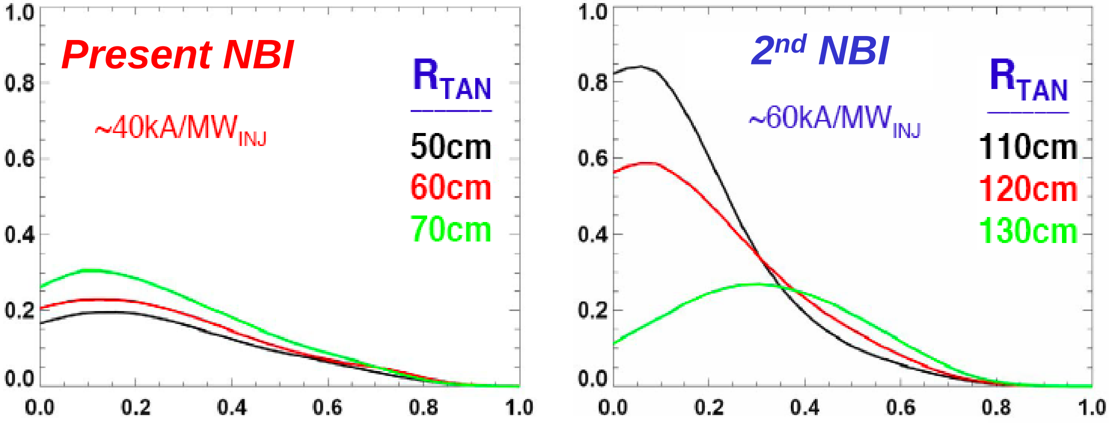
- **Upgrade:** **Double field and current for 3-6× decrease in collisionality → require 3-5× increase in pulse duration for profile equilibration**

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 more heating, depending on confinement scaling
- Need increased current drive to access and study 100% non-inductive
  - → 0.25-0.5MA more current drive compatible with ramp-up, sustainment plasmas
- Need to learn to manage $\geq$ ITER→FNSF-level high-heat-flux challenge
  - → high divertor power density ($P/R \leq 20$MW/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

NBI current drive profiles [MA/m²]



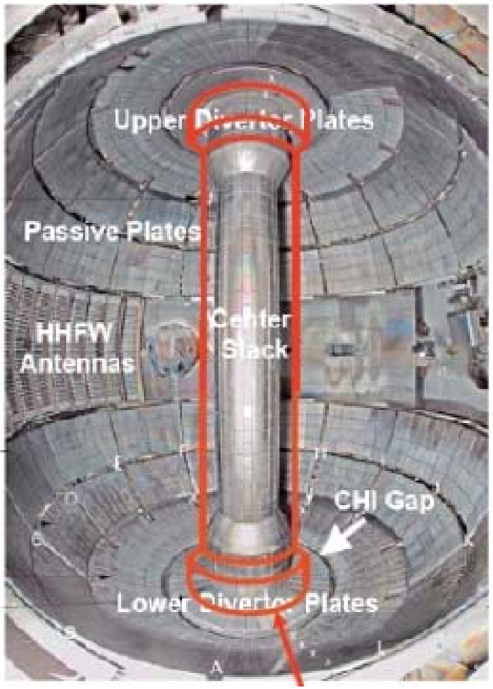
Normalized minor radius

Upgrades provide major step along ST development path

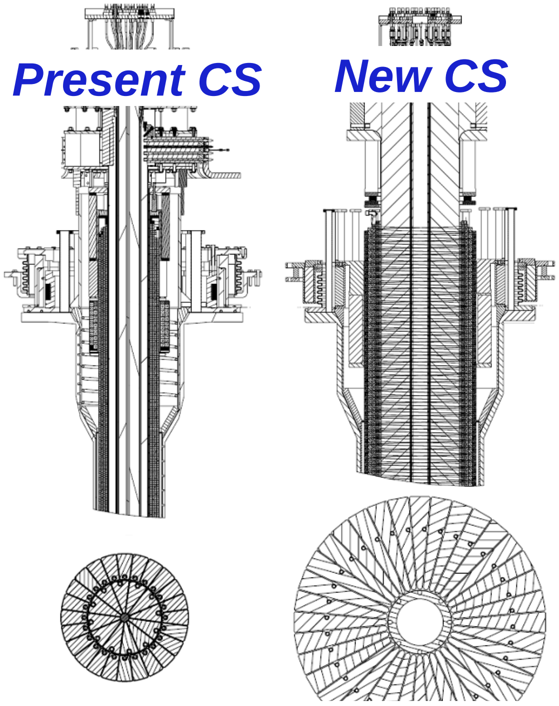
(next factor of 2 increase in current, field, and power density)

	NSTX	NSTX Upgrade	Plasma-Material Interface Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.7	≥ 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***



Outline of new center-stack (CS)



TF OD = 20cm

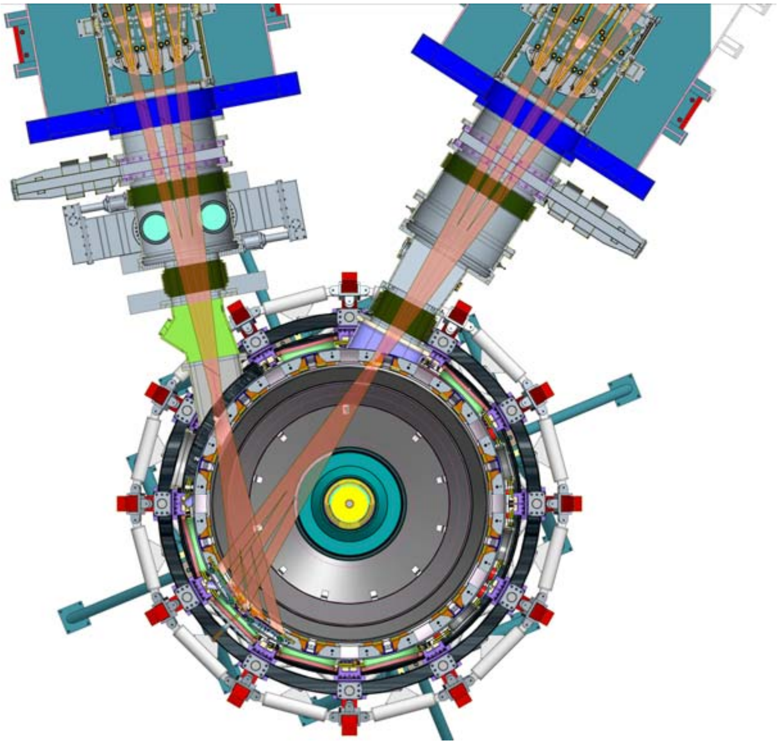
TF OD = 40cm

New 2^{nd} NBI

(R_{TAN}=110, 120, 130cm)

Present NBI

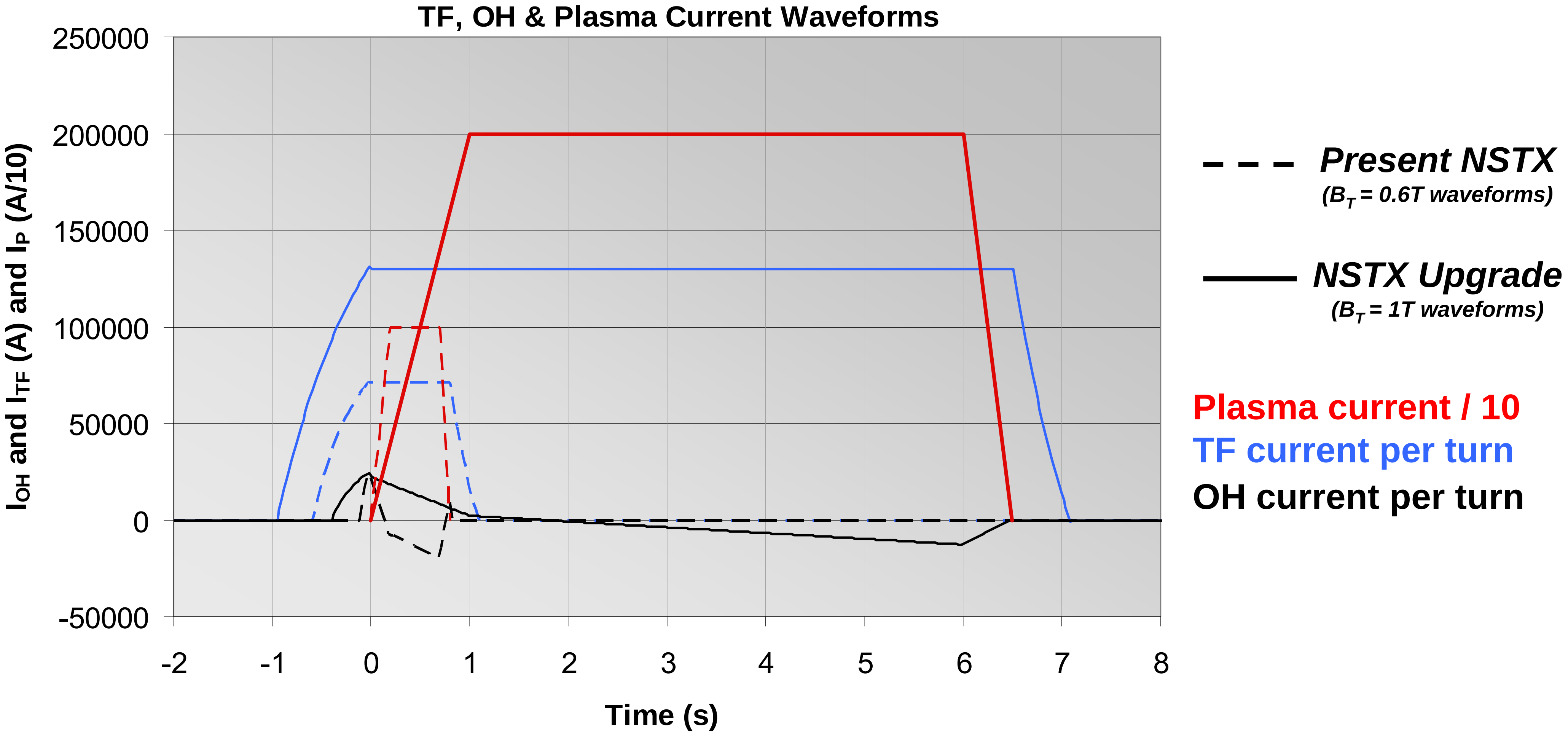
(R_{TAN}= 50, 60, 70cm)



Comparison of NSTX and NSTX Upgrade current waveforms:

Relative performance of Upgraded NSTX vs. Base:

- ***Center-stack radius increased 13cm → A=1.3 → 1.5***
- ***Available OH flux increased 4×, 3-5× longer flat-top***
- ***I_P increased 2×, B_T increased 2× at same major radius***
- ***But, inter-shot cool-down period increased 2 to 4-fold***

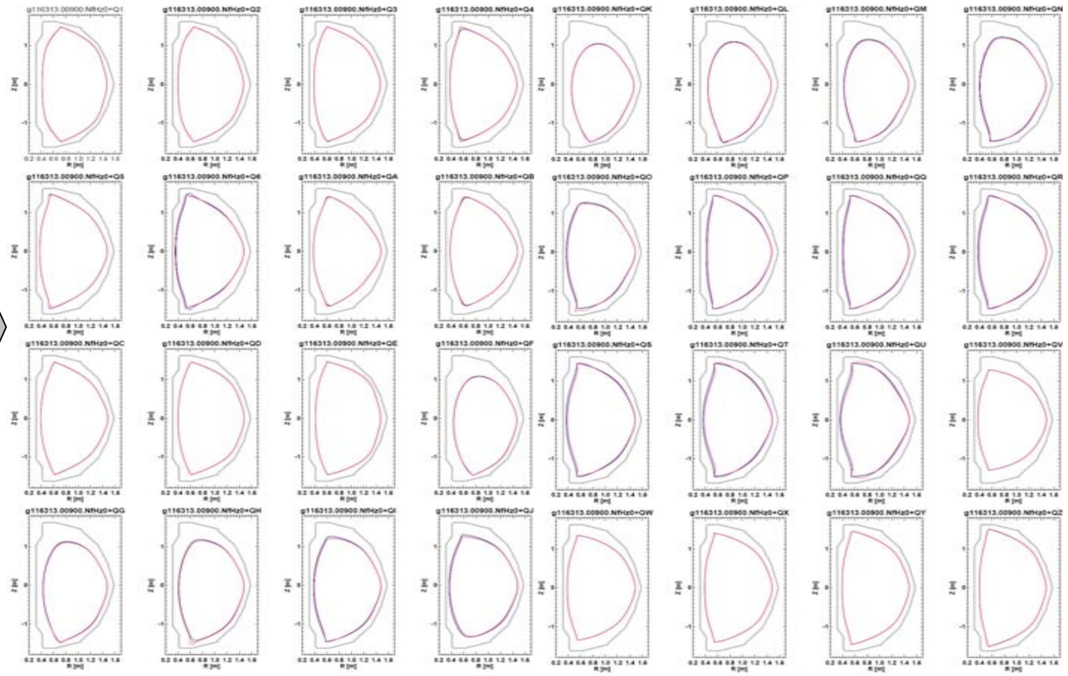


Range of I_P = 2MA free-boundary equilibria generated to support design of TF and PF coil support structures

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
- Pressure variation: β_N = 1, 5, 8

32 free boundary equilibria × 3 OH conditions = 96 cases

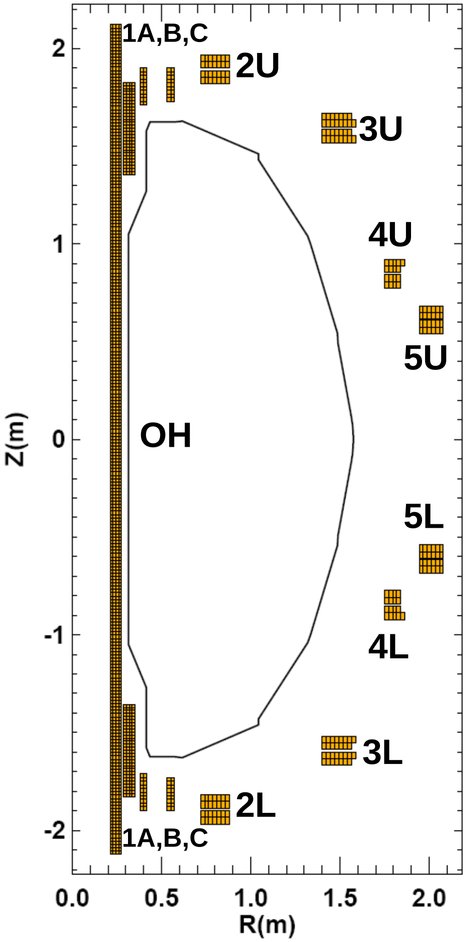


- NOTE: Negative squareness cases are included
  - More shaping flexibility/capability than in present NSTX **(requires PF4 usage)**
  - Likely requires substantial inter-coil support structure, which could be challenging
- Narrower operating range ($\delta \geq 0.4$, $\zeta \sim 0.1$, $l_i \leq 0.8$)* + advanced coil/machine protection is being assessed to simplify PF support design

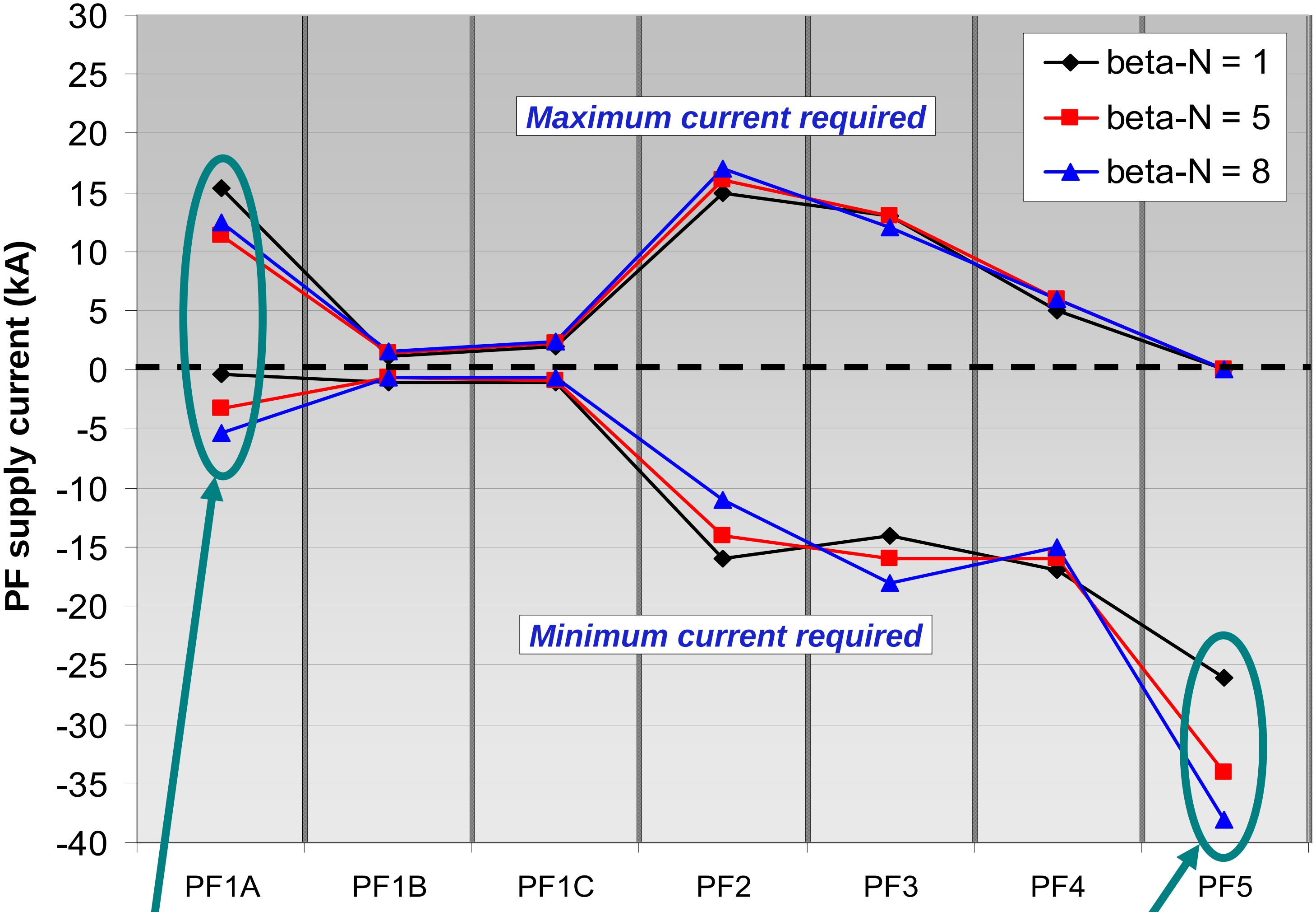
**** this operating range similar to that of highest-performance present NSTX plasmas***

High β_N increases vertical field requirement, and shifts primary divertor coil (PF1A) current requirement to bipolar

Note: all current limits are 10% above current required for actual equilibrium



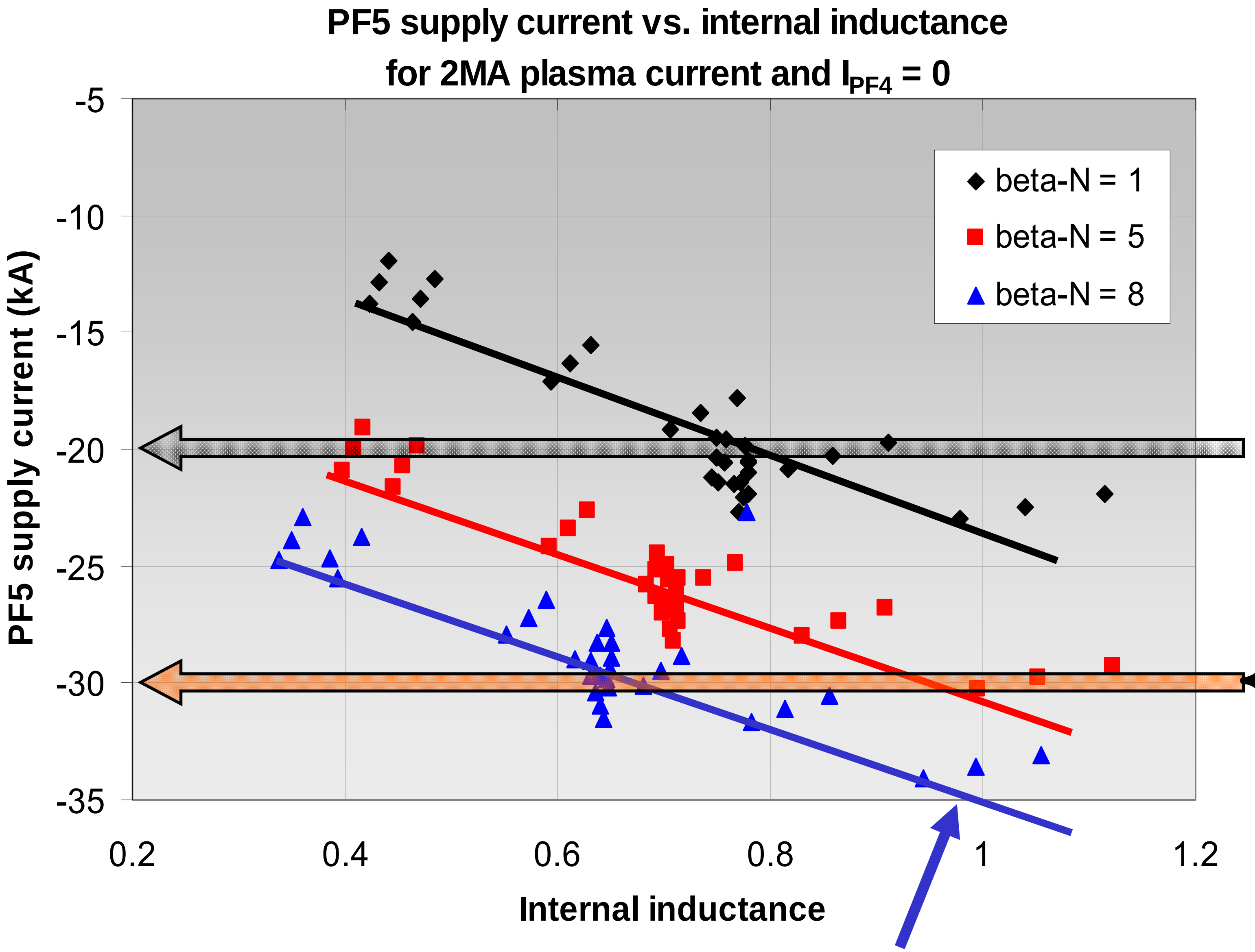
PF supply limits - 2MA, expected OH operation, full PF



Primary divertor field (PF1A) requires -5kA reduction at high β_N

Vertical field (PF5) required increases ~50% from low to high β_N

Vertical field upgrade being designed to support $\beta_N = 5$, $l_i \leq 1$ and $\beta_N = 8$, $l_i \leq 0.6$ at I_P = 2MA

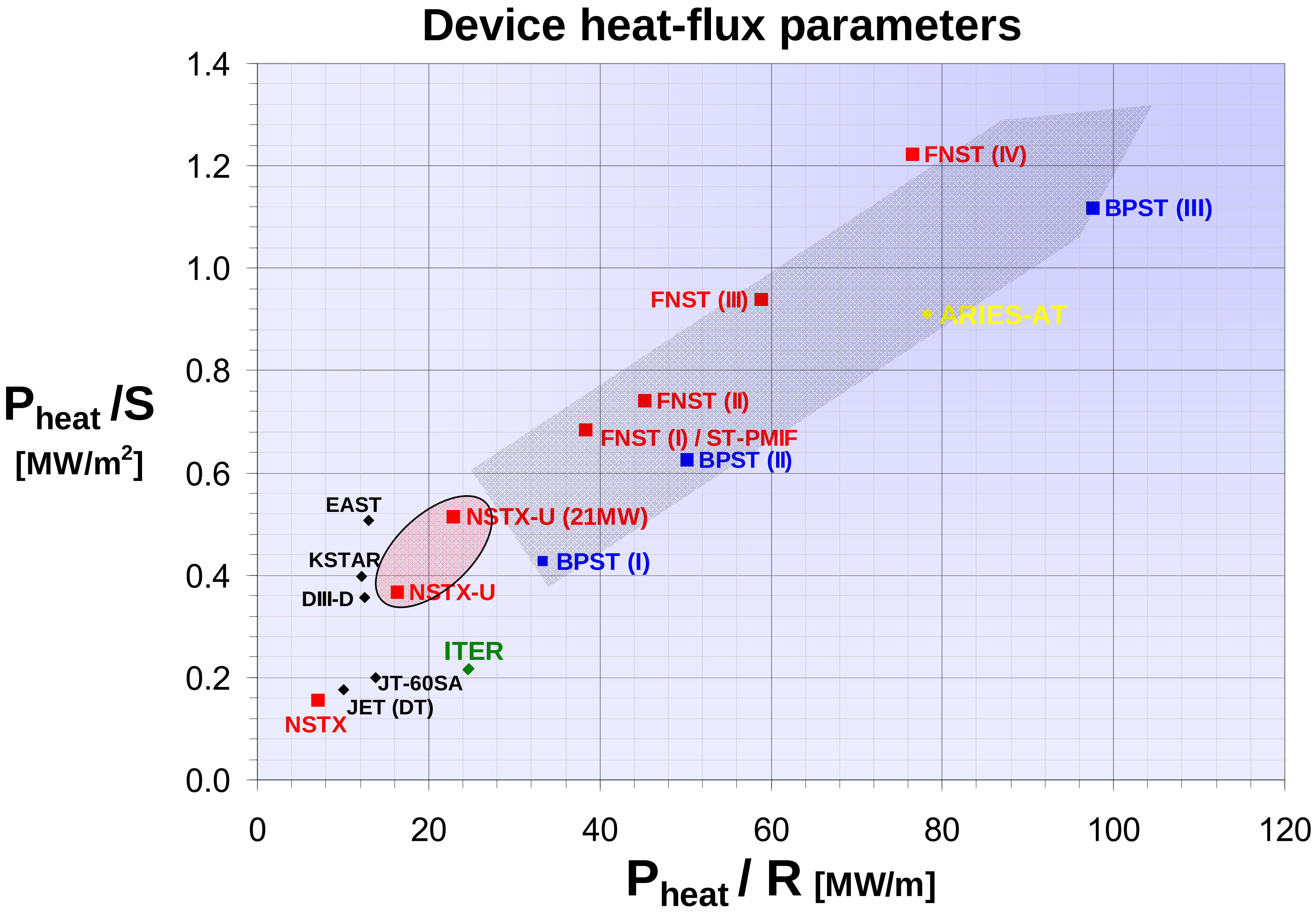


Present PF5 limit

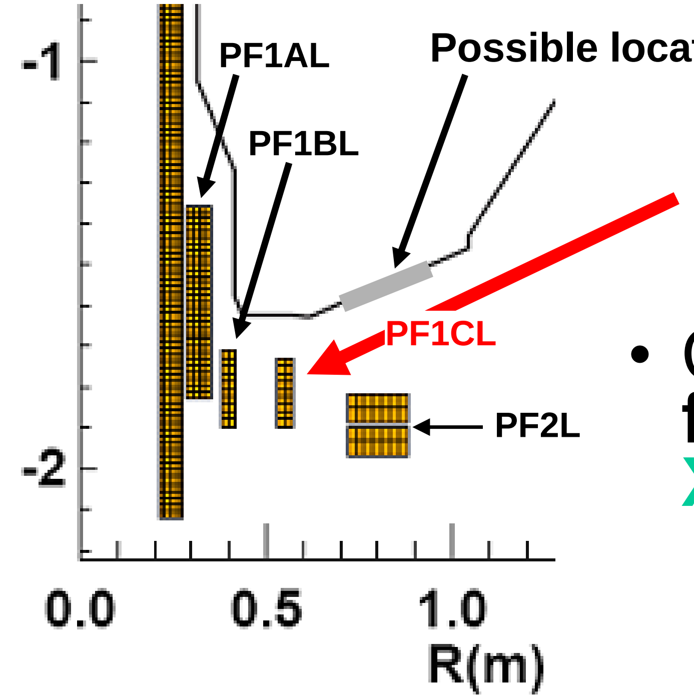
Upgrade design targets $I_{PF5} \leq$ 30kA with 10% current margin for radial position control

High l_i, high-β_N scenarios determine maximum PF5 current required

NSTX Upgrade will extend normalized divertor and first-wall heat-loads much closer to next-step ST and Demo regimes



The divertor PF coil system for NSTX Upgrade includes an additional coil to enhance control of power exhaust

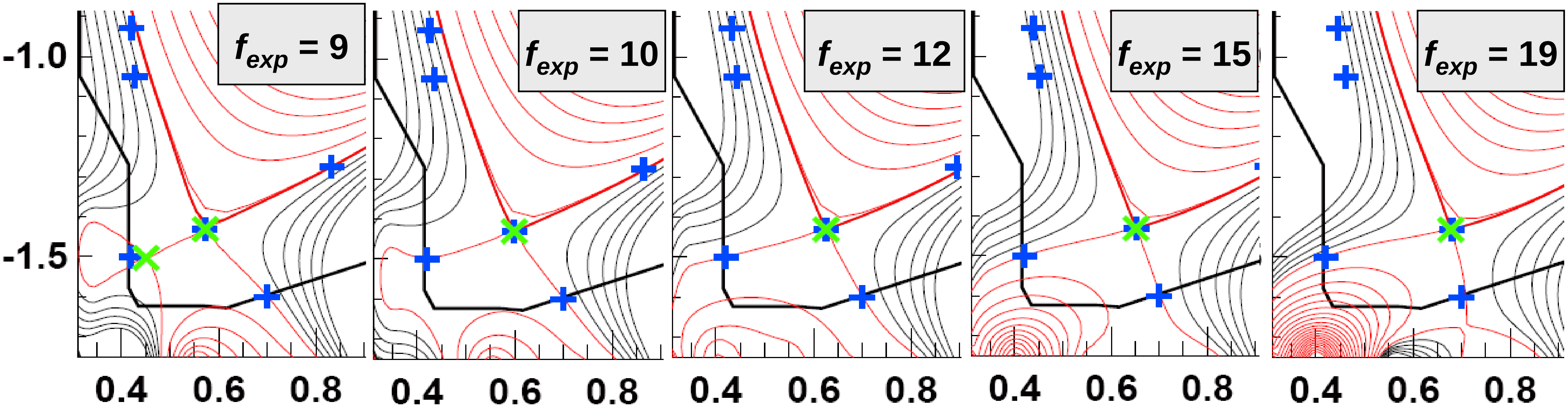


Possible location of liquid lithium divertor

Additional coil added = PF1C

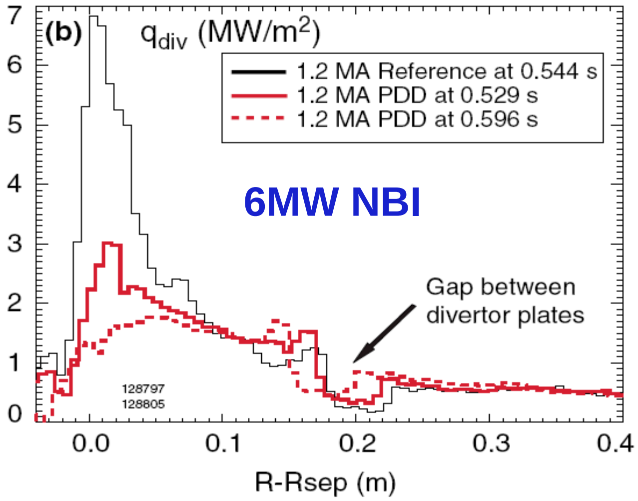
- Combination of PF1A,B,C + PF2 enables **flux expansion variation** with fixed X-point height and strike-point location:

Outboard poloidal flux expansion factor $f_{exp} \equiv |\nabla\psi|_{\text{mid-plane}} / |\nabla\psi|_{\text{strike-point}}$

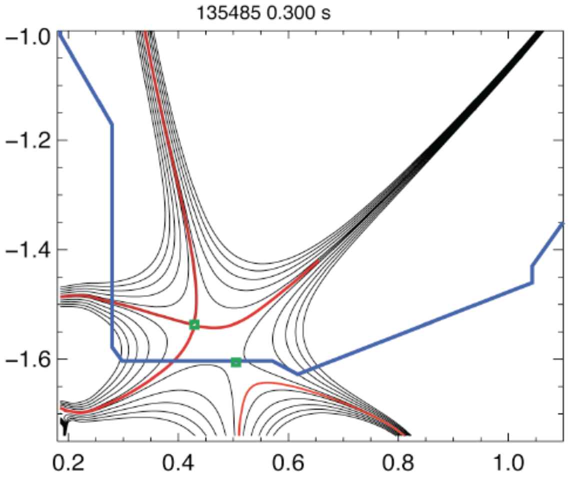


A combination of advanced PMI solutions will likely be required to manage the power exhaust of NSTX Upgrade

- **High divertor heat flux can be reduced in NSTX with partially detached divertor (PDD)**



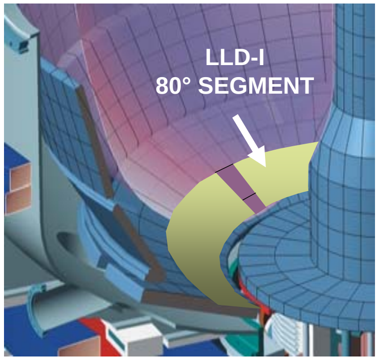
- **NSTX has demonstrated the formation of high flux-expansion "snow-flake" divertor**



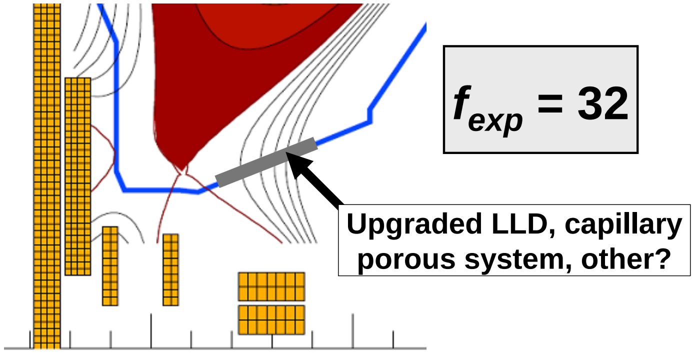
- **The PDD operating regime and other PMI solutions will be challenged in NSTX-U due to:**
  - 2-3× higher input power
  - 1.5-2× lower Greenwald fraction
  - 3-5× longer pulse duration, leading to substantial increase in $T_{divertor}$

- **NSTX and NSTX-U will test the compatibility of high flux expansion, PDD, and a liquid lithium divertor (LLD) at higher power/energy**

- NSTX LLD

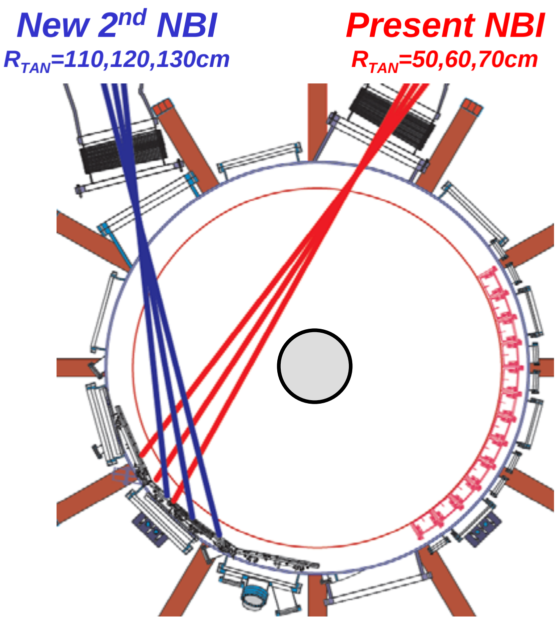


- NSTX-U "snow-flake":

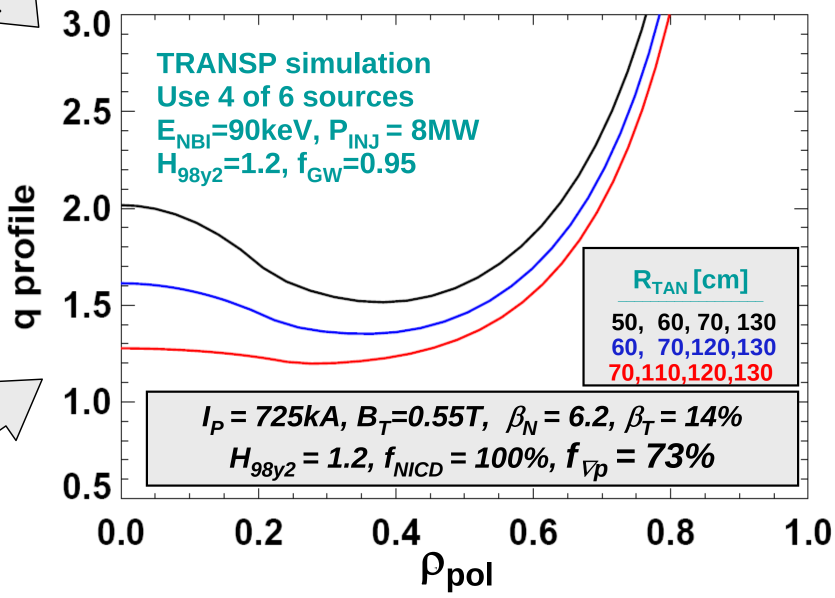


Upgrade 2nd NBI injecting at larger $R_{tangency}$ will greatly expand performance and understanding of ST plasmas

- Improved NBI-CD and plasma performance
  - Higher CD efficiency from large R_{TAN}
  - Higher NBI current drive from higher P_{NBI}
  - Higher β_P, f_{BS} at present $H_{98y2} \leq 1.2$ from higher P_{HEAT}
  - Large R_{TAN} → off-axis CD for maintaining $q_{min} > 1$
  - Achieve 100% non-inductive fraction (presently < 70%)
  - Optimized $q(\rho)$ for integrated high τ_E, β, and f_{NI}



- Expanded research flexibility by varying:
  - *q*-shear for transport, MHD, fast-ion physics
  - Heating, torque, and rotation profiles
  - β, including higher β at higher I_P and B_T
  - Fast-ion $f(v_{||},v_{\perp})$ and *AE instabilities
    - 2nd NBI more tangential – like next-step STs
  - Peak divertor heat flux, SOL width

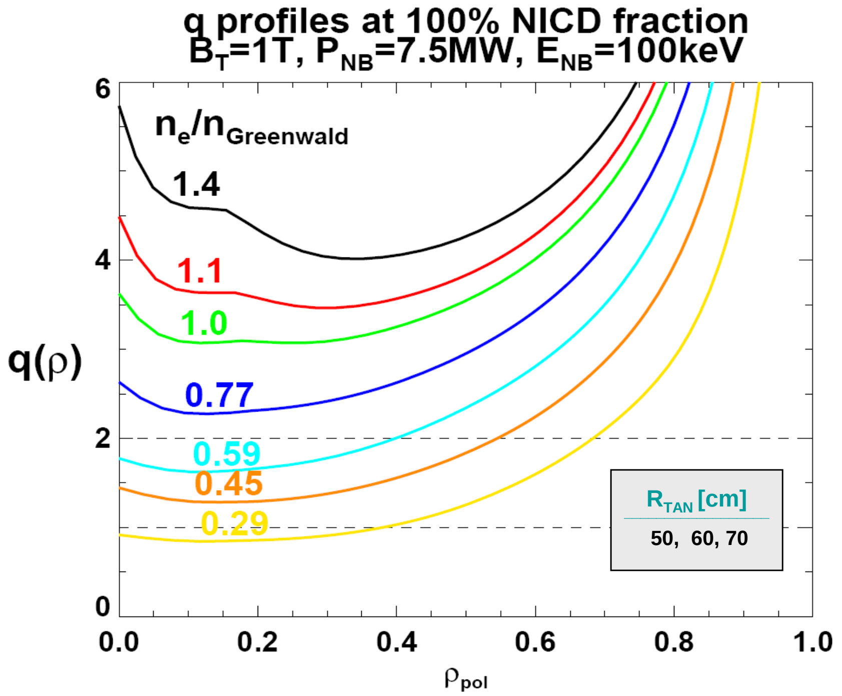


- q(r) profile variation and control very important for global stability, electron transport, Alfvénic instability behavior

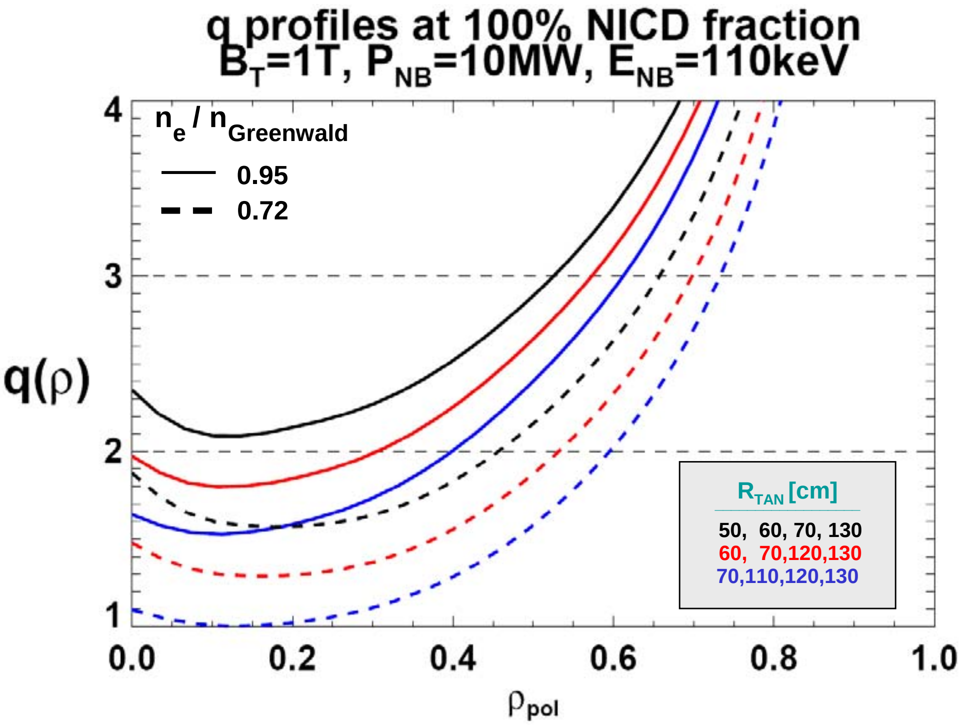
Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- **New CS + present NBI-CD + fast wave:**
  - Study confinement scaling vs. I_P and B_T
    - Limited range of auxiliary power levels
  - 100% non-inductive for 1-1.5s (~1 τ_{CR})
    - NBI duration limited to 2s at 7.5MW
    - Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)

- **Addition of 2nd NBI would enable:**
  - Study confinement scaling vs. I_P and B_T with:
    - Full range of auxiliary power available
    - Assured access to high-β at reduced ν*
  - 100% non-inductive for 3-4 τ_{CR} → relaxed J(r)
    - 10MW NBI available for 5s
    - Control q_{min} & q-shear w/ NBI source, n_e, & B_T
    - Study long-pulse NTM stability with q > 2
  - Study compatibility of high-β w/ PMI solutions



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

2nd NBI also needed to support long-pulse (5s) high-I_P partial-inductive scenarios at high-power at full TF ($B_T = 1T$)

- Higher current expected to expand range of accessible T and ν^*
  - Accessible ν^* will depend on how confinement scales at higher field and current

- Access to higher current important for variety of physics issues – examples:
  - High-β_T physics at lower ν^* (RWM, NTV) – requires access to high I_P/aB_T
  - Core transport and turbulence at reduced ν^*, reduced $\chi_{i\text{-neoclassical}}$
  - Pedestal transport/stability, SOL width, heat flux scaling vs. current, …

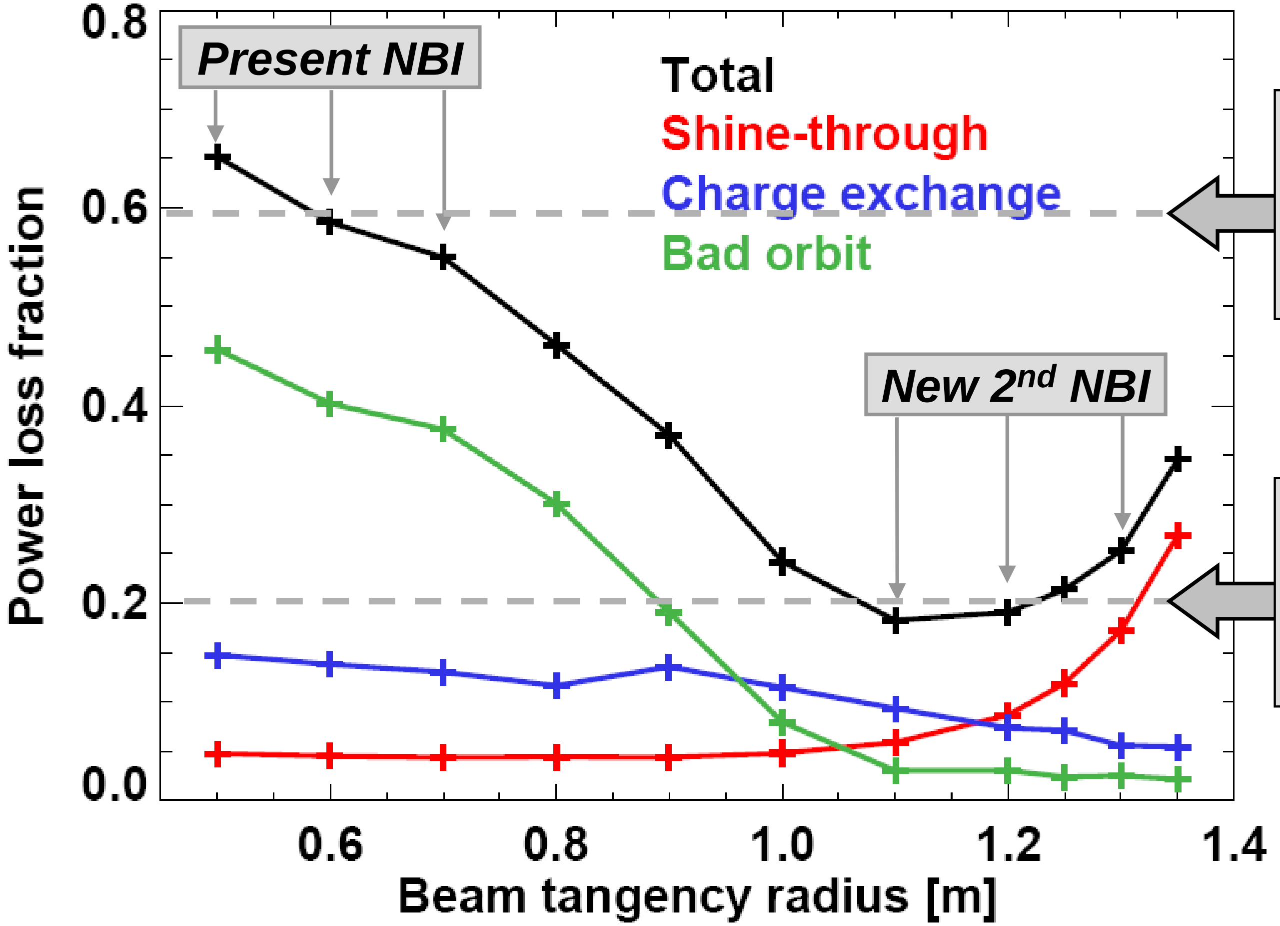
- I_P =1.6-2MA and B_T = 1T partially-inductively driven scenarios identified:
  - f_{NICD} = 50-65% with **q_{min} > 1**, β_N = 4-5, NBI profile computed with TRANSP
    - Similar to present high NI-fraction discharges, but with 2× field and current
  - These scenarios also require $\geq$ 8MW of NBI heating power for $H_{98} \leq 1.2$

- Solenoid in new CS can support 2MA plasmas for 5s (flat-top $\Delta\Phi_{OH}$~1.5Vs)

For NBI I_P ramp-up, more tangential 2nd NBI has 3× lower power loss than present NBI at low I_P = 400kA

E_{NBI}=80keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n_e}$ = 2.5x$10^{19}$$m^{-3}$, $\overline{T_e}$ = 0.83keV



- 60% of power of present NBI lost
  - Absorb 2 of 5 MW (80kV)

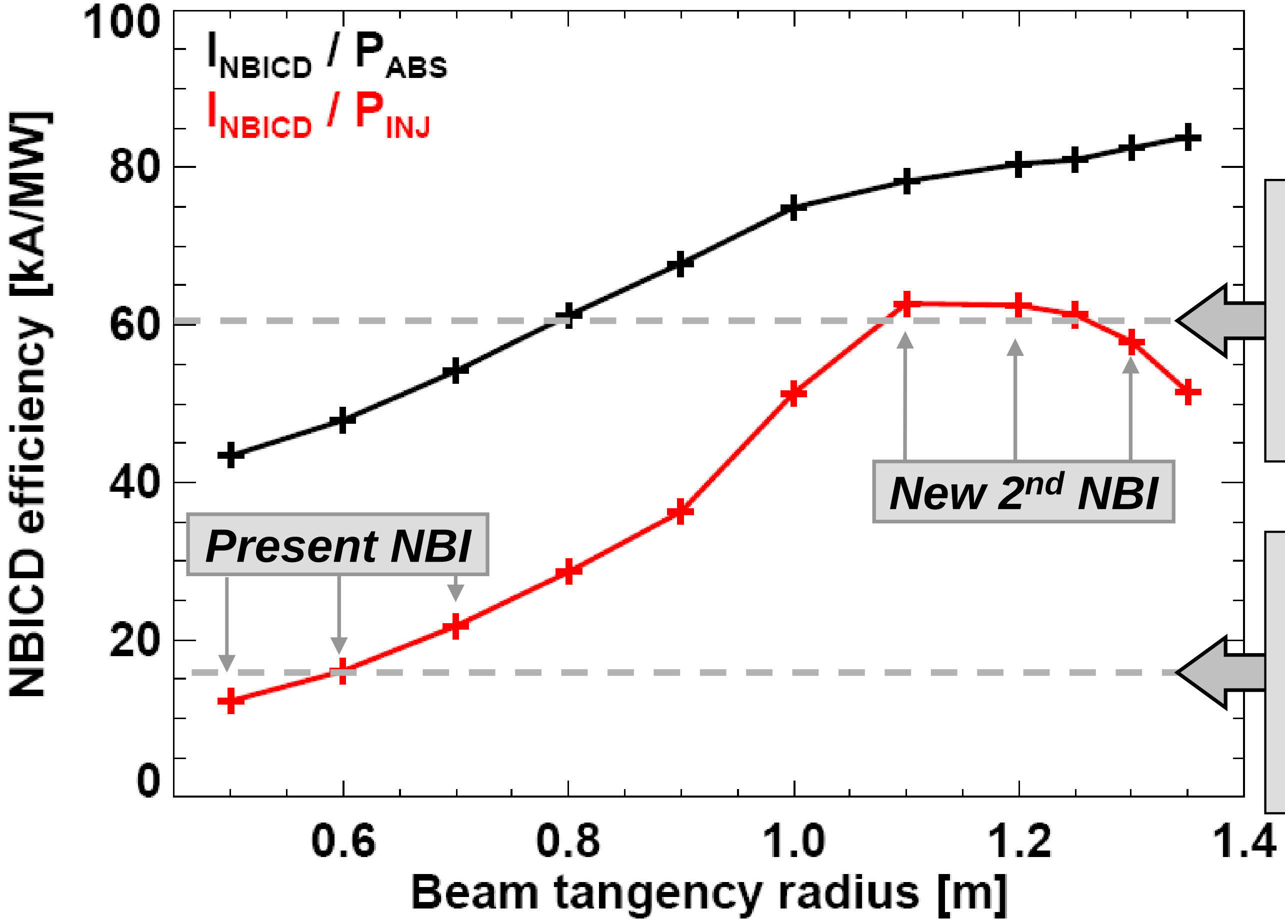
- 20% of power of new 2nd NBI lost
  - Absorb 4 of 5 MW (80kV)

→ *2nd NBI can efficiently heat 400kA HHFW-driven ramp-up plasma*

For NBI I_P ramp-up, more tangential 2nd NBI has 4× higher NBI-CD than present NBI at low I_P = 400kA

E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5\text{x}10^{19}\text{m}^{-3}$, $\overline{T}_e$ = 0.83keV



- 2nd NBI → 60kA/MW current drive efficiency
  - 450kA CD for 7.5MW injected at E=100keV

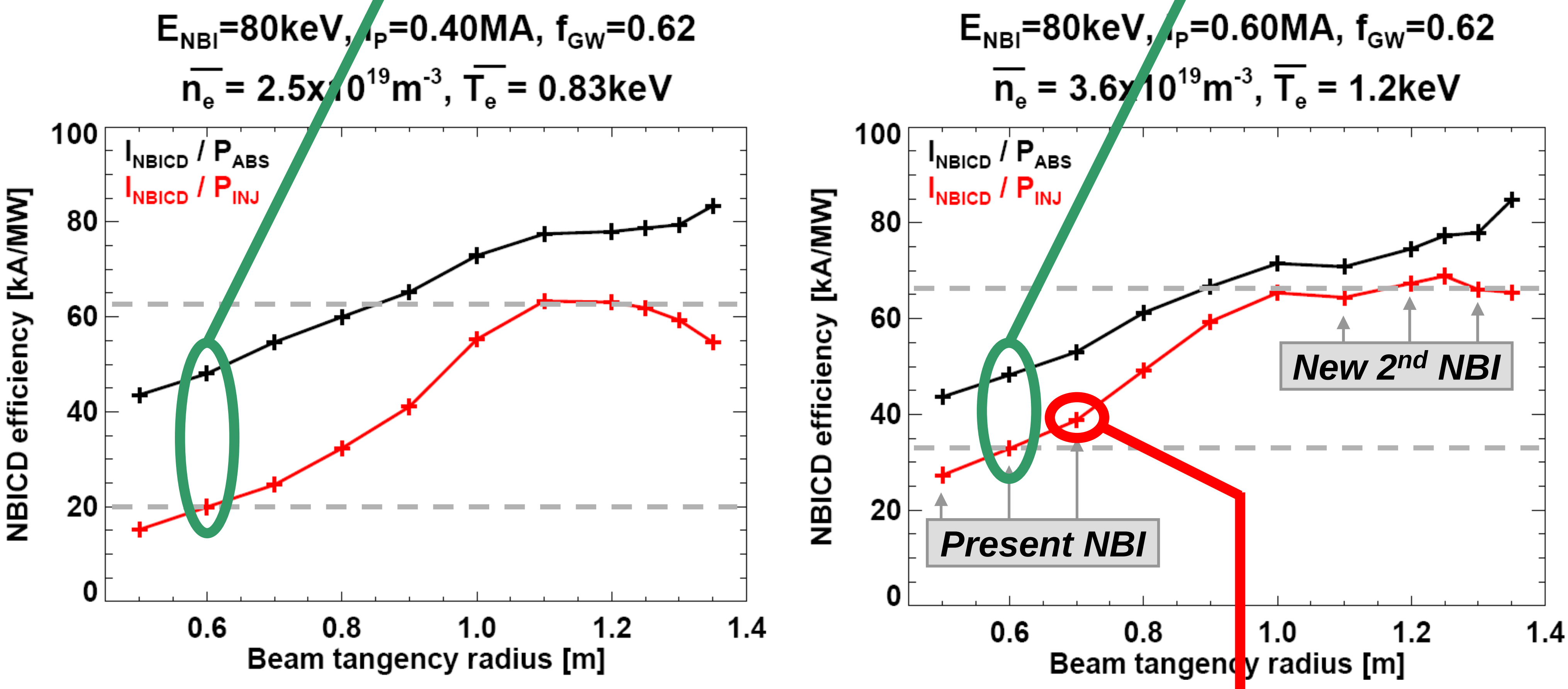
- Present → 15kA/MW current drive efficiency
  - 110kA CD for 7.5MW injected at E=100keV

→ 2nd NBI can provide sufficient current for ramp-up to ~800kA

For NBI I_P ramp-up, absorbed fraction and CD of *present* NBI increases by factor of 1.7 for plasma current = 400kA→600kA

- I_P = 400kA, present NBI:
  - 60% loss, 20kA/MW

- I_P = 600kA, present NBI:
  - 32% loss, 33kA/MW



Most tangential of present sources has > 70% absorption for $I_P \geq$ 600kA and would be the most effective of the present sources for ramp-up

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

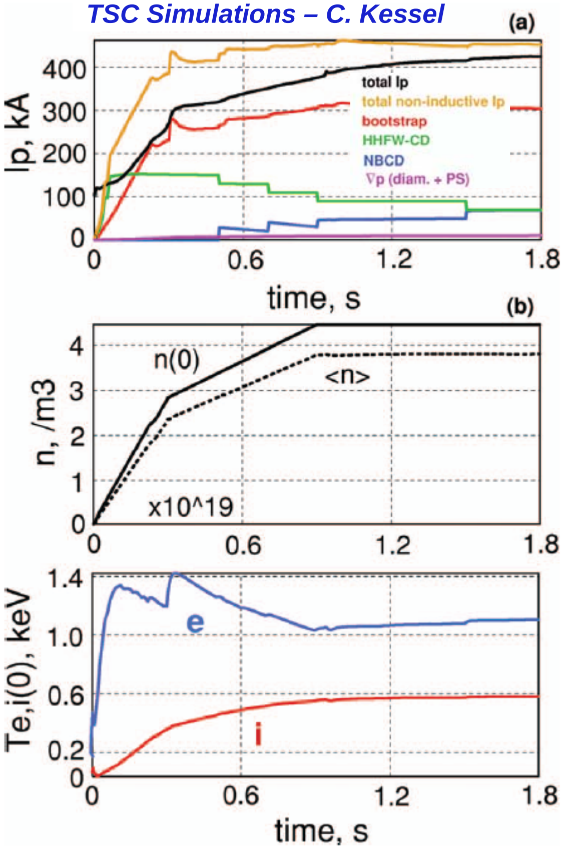
Ramp to ~0.4MA with fast wave heating:

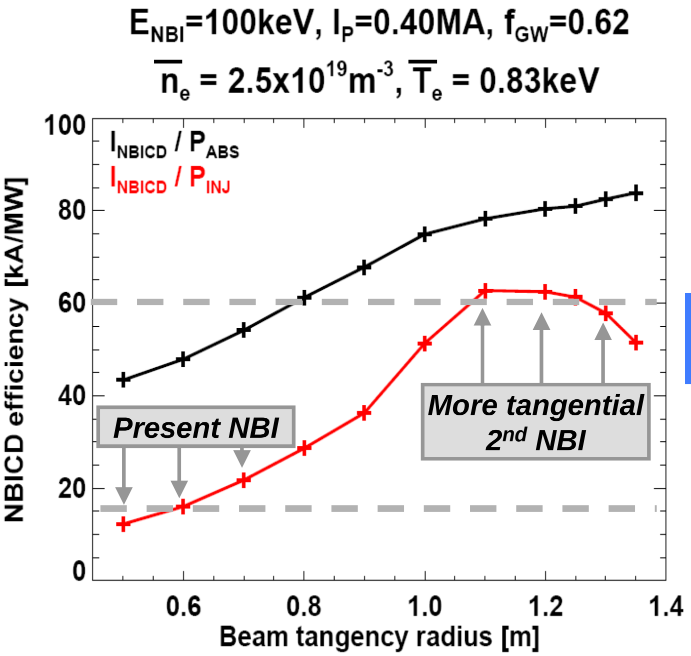
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

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

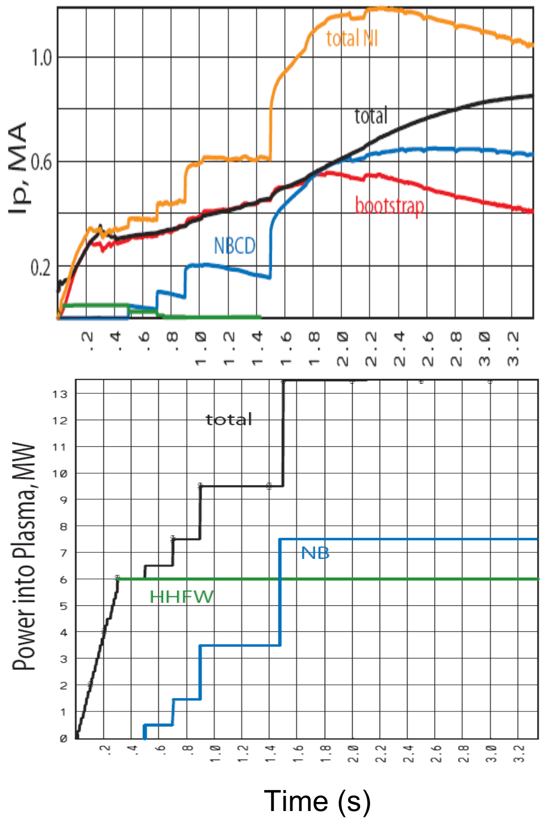
- Benefits of more tangential injection:
  - Increased NBI absorption = 40→80% at low I_P
  - Current drive efficiency increases: ×1.5-2
- New CS needed for ~3-5s for ramp-up equilibration
  - Higher field 0.5→1T also projected to increase electron temperature and NBI-CD efficiency

TSC Simulations – C. Kessel




E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e$ = 2.5x10^{19}m^{-3}, $\overline{T}_e$ = 0.83keV



Summary

- Free-boundary equilibrium calculations have been performed to determine the coil currents to support $B_T = 1T$, $I_P = 2MA$, high β_N – **largest change is for VF**
- **Additional divertor PF coils** have been optimized and incorporated to provide **enhanced power exhaust flexibility** - including high flux expansion
- TRANSP calculations indicate NB injection at **large tangency radius** is favorable for **increased current drive efficiency**, especially at reduced I_P
- Summary of physics and performance enabled by NSTX Upgrade:
  - New CS with $B_T = 1T$, $I_P = 2MA$ (with induction), $t_{flat\text{-}top} = 5s$ to provide:
    - Extended range of field, current, β, collisionality to obtain unique data to aid development of first-principles understanding of turbulent transport
    - Longer pulse to assess RF ramp-up, 100% non-inductive sustainment at ~1MA
    - Higher field to stably accept high power for edge heat/particle transport studies
    - Magnet operation at ~1T (vs. 0.55T), within factor of 2 of next-step STs
  - More tangential 2nd NBI to provide:
    - Up to 2 times higher current-drive efficiency, current profile control, tests of NBI ramp-up to ~1MA
    - World-leading capabilities for plasma boundary physics at high heat flux
    - Increased heating power to access very high β at low collisionality – important for fundamental studies of transport and global stability

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