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NSTX Upgrade Motivation and Elements

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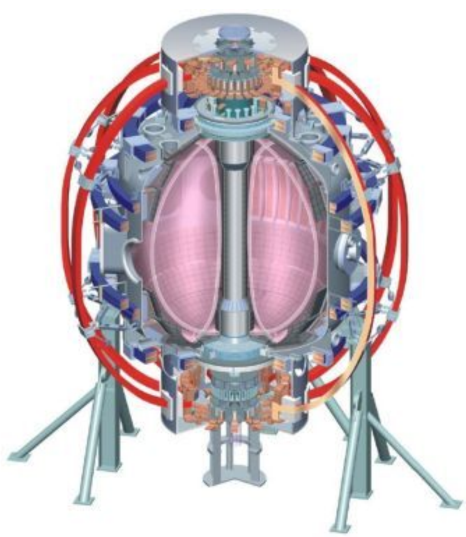
J. Menard, PPPL

For the NSTX Research Team

NSTX Physics Meeting

February 8, 2010
LSB-B318, PPPL



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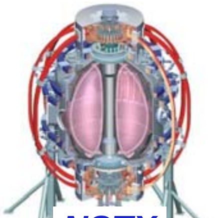
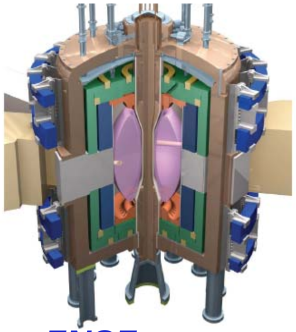
NSTX Upgrade will contribute strongly to toroidal plasma science and preparation for a fusion nuclear science (FNS) program

- NSTX:
  - Providing foundation for understanding ST physics, performance
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality
    - Vital for understanding confinement, stability, start-up, sustainment
  - Assess full non-inductive current drive operation
    - Needed for steady-state operating scenarios in ITER and FNS facility
  - Prototype solutions for mitigating high heat, particle exhaust
    - Can access world-leading combination of P/R and P/S
    - Needed for testing integration of high-performance fusion core and edge
- NSTX Upgrade contributes strongly to possible next-step STs:
  - ST Fusion Nuclear Science Facility (FNSF)
    - Develop fusion nuclear science, test nuclear components for Demo
    - Sustain $W_{neutron}$ ~ 0.2-0.4 → 1-2MW/m^2, τ_{pulse} = 10^3 → 10^6s
  - ST Plasma Material Interface Facility (PMIF)
    - Develop long-pulse PMI solutions for FNSF / Demo (low-A and high-A)
    - Further advance start-up, confinement, sustainment for ST
    - High P_{heat}/S ~1MW/m^2, high T_{wall}, τ_{pulse} ~ 10^3s

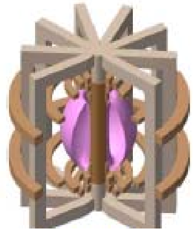


NSTX

NSTX-U



FNSF (ST-CTF)



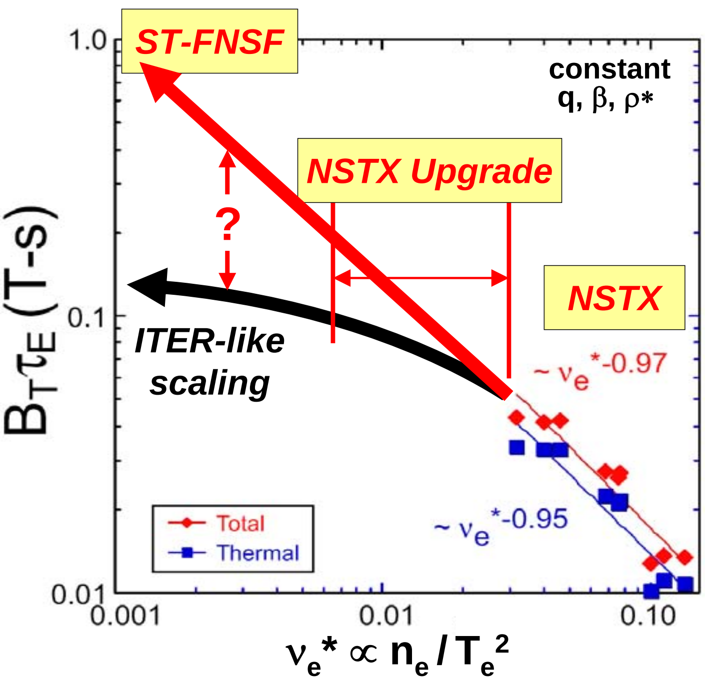
PMIF (NHTX)

NSTX Upgrade will address many important questions for fusion

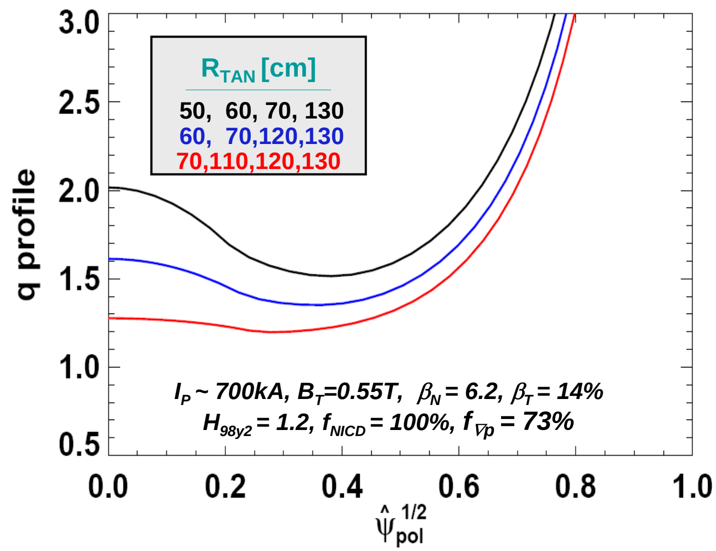
How does confinement vary with normalized temperature, pressure?

Can we create, sustain, and control high β, low l_i ST plasmas without induction?

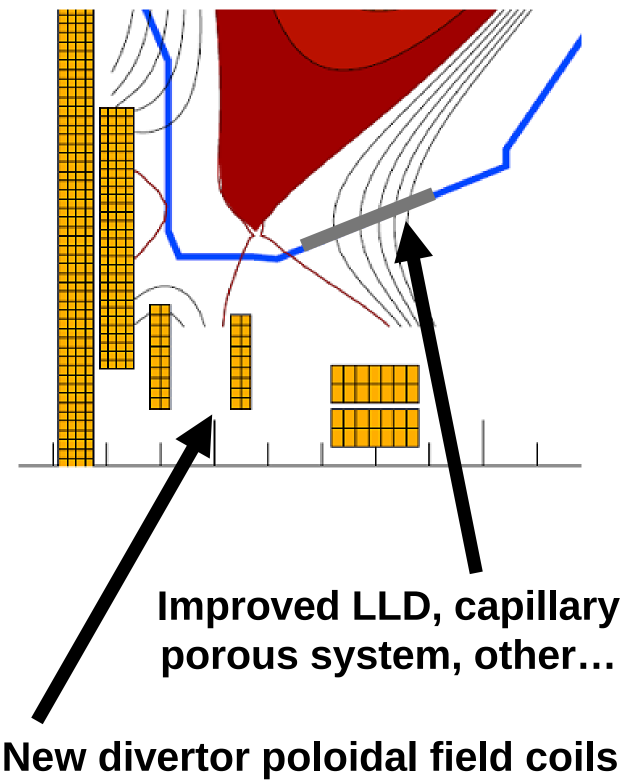
Can we manage the power & particle exhaust of high-performance plasmas?



Normalized electron collisionality reduction from higher temperature from higher field, current, heating

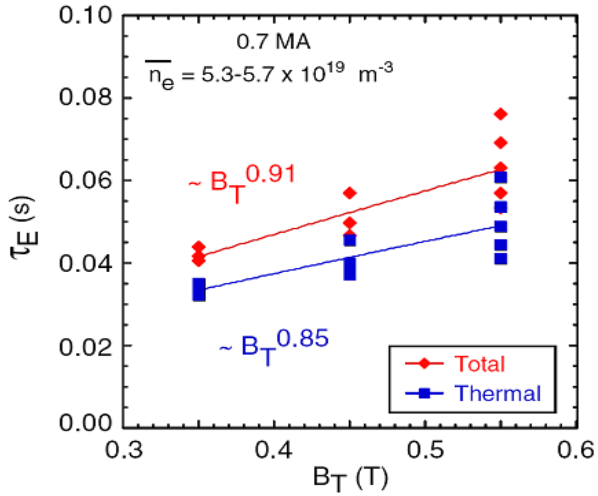


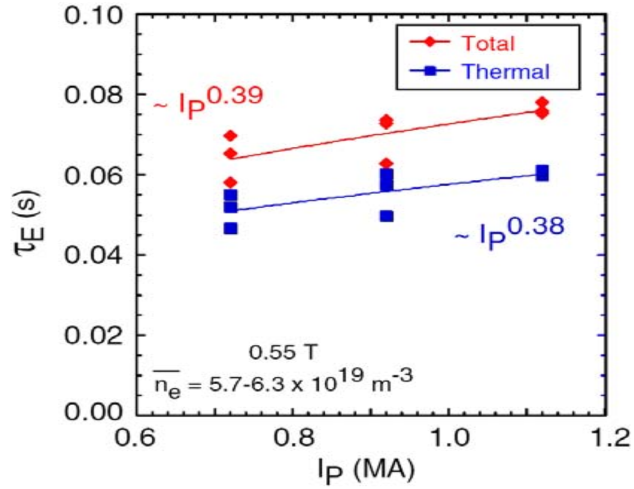
q profile control in 100% non-inductive plasma using mix of existing and additional NBI sources



Access to higher field and current is needed to understand scaling of ST confinement, implications for next-steps

NSTX Data





- NSTX (and MAST) energy confinement time τ_E scales much more strongly with magnetic field and more weakly with current than ITER scaling

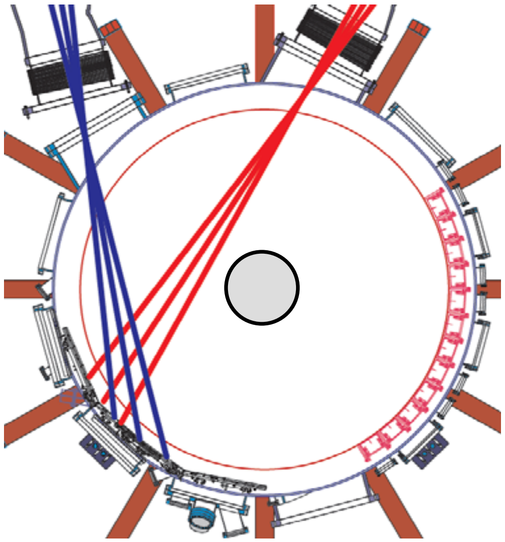
ST H-mode: $\tau_E \propto B_T^{1.2} I_P^{0.6} n^{0.2} P^{-0.6}$ **ITER H-mode: $\tau_E \propto B_T^{0.15} I_P^{0.9} n^{0.4} P^{-0.7}$**

- For scaling from NSTX to NSTX-U assume:
  - $n / n_{Greenwald}$ decreases 30% (~1 → ~0.7) via planned density control
  - Toroidal, normalized beta held ~constant: increase -20% (ITER) to +10% (ST)

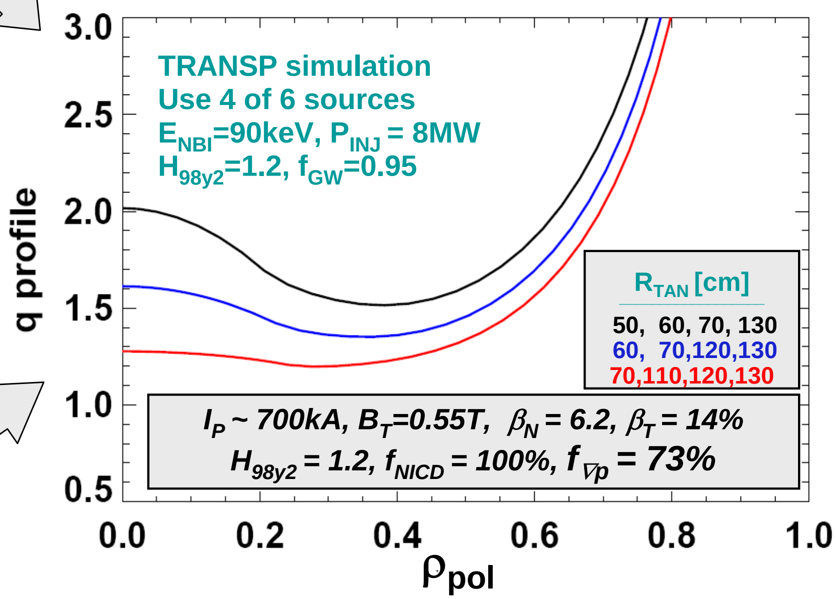
- **To achieve: 3-6× reduction in collisionality →**
  - Field and current must double, heating power P = 6MW increases to 10-16MW
  - Also require 3-5× increase in pulse duration for profile equilibration

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

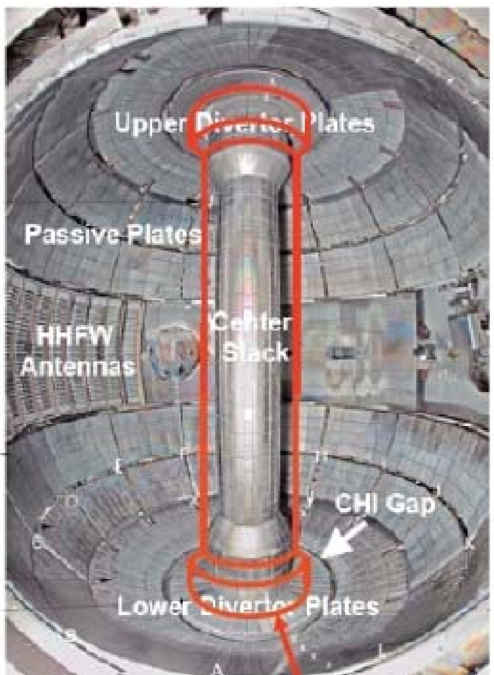


- q(r) profile variation and control very important for global stability, electron transport, Alfvénic instability behavior

Upgrades provide major step along ST development path
(next factor of 2 increase in current, field, and power density)

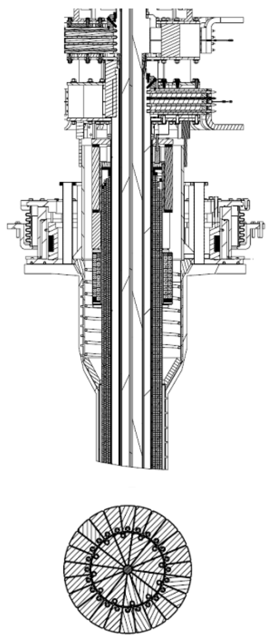
	NSTX	NSTX Upgrade	Plasma-Material Interface Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.7	≥ 1.5
Plasma Current (MA)	1	2	3.5	10
Toroidal Field (T)	0.5	1	2	2.5
P/R, P/S (MW/m,m^2)	10, 0.2*	20, 0.4*	40, 0.7	40-60, 0.8-1.2

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



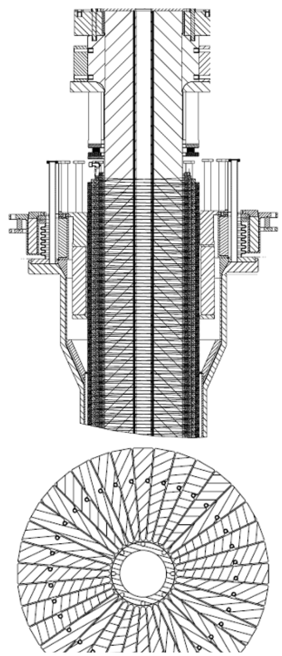
Outline of new center-stack (CS)

Present CS



TF OD = 20cm

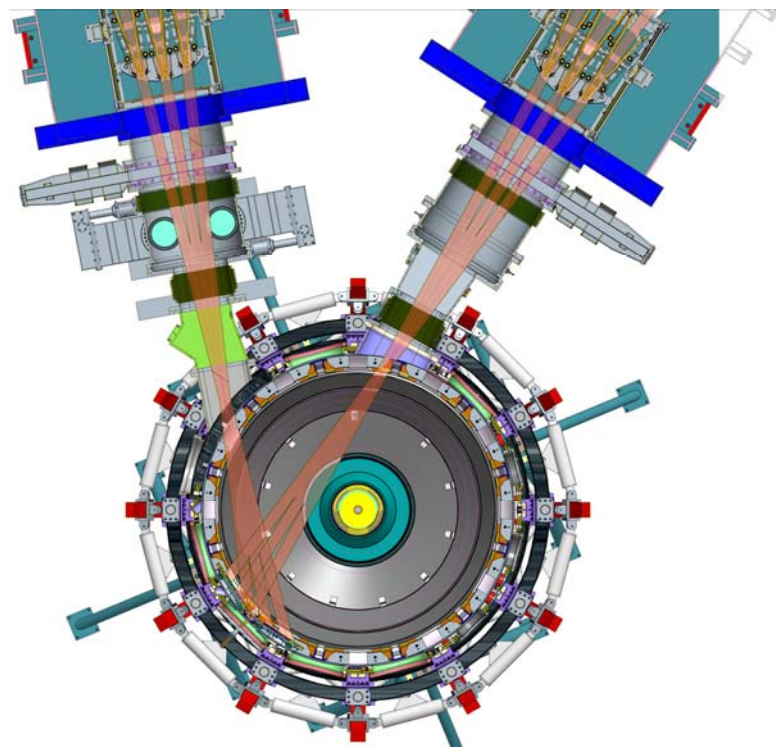
New CS



TF OD = 40cm

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

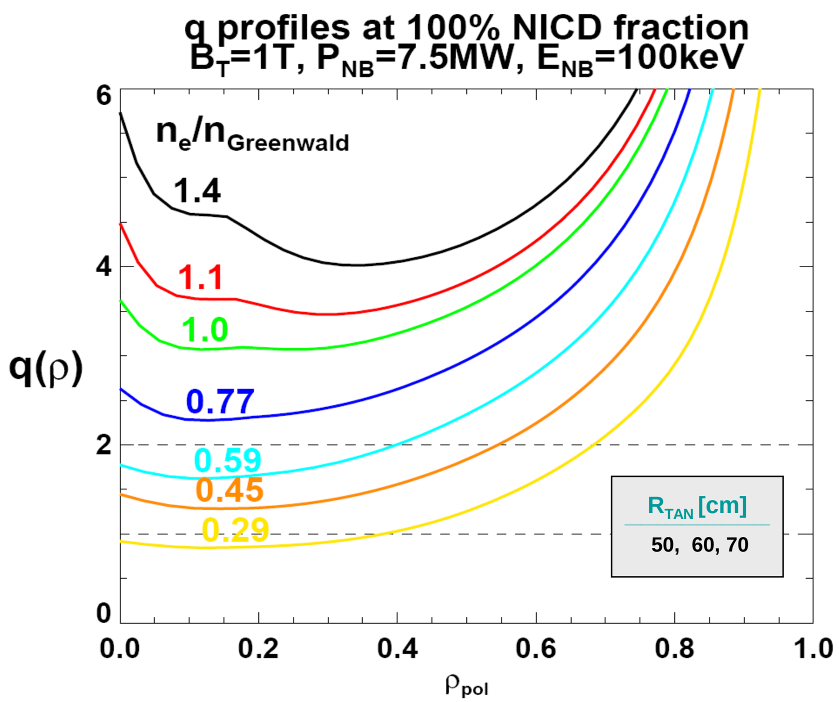
Present NBI *(R_{TAN}= 50, 60, 70cm)*



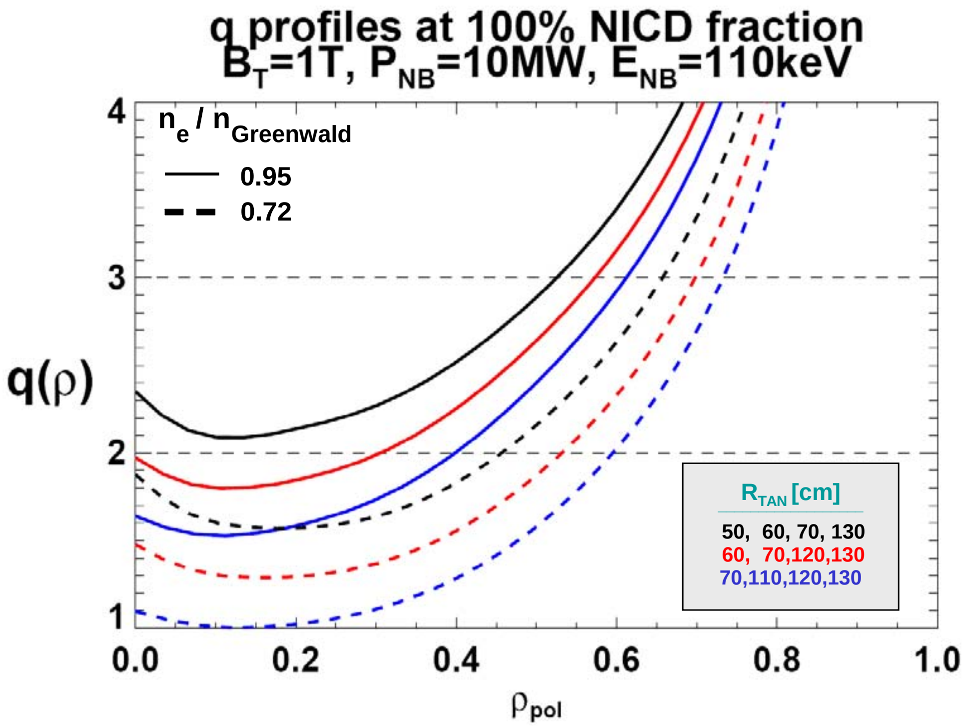
Higher field B_T=1T from new CS + 2nd NBI would enable access to wide range of 100% non-inductive scenarios

- **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

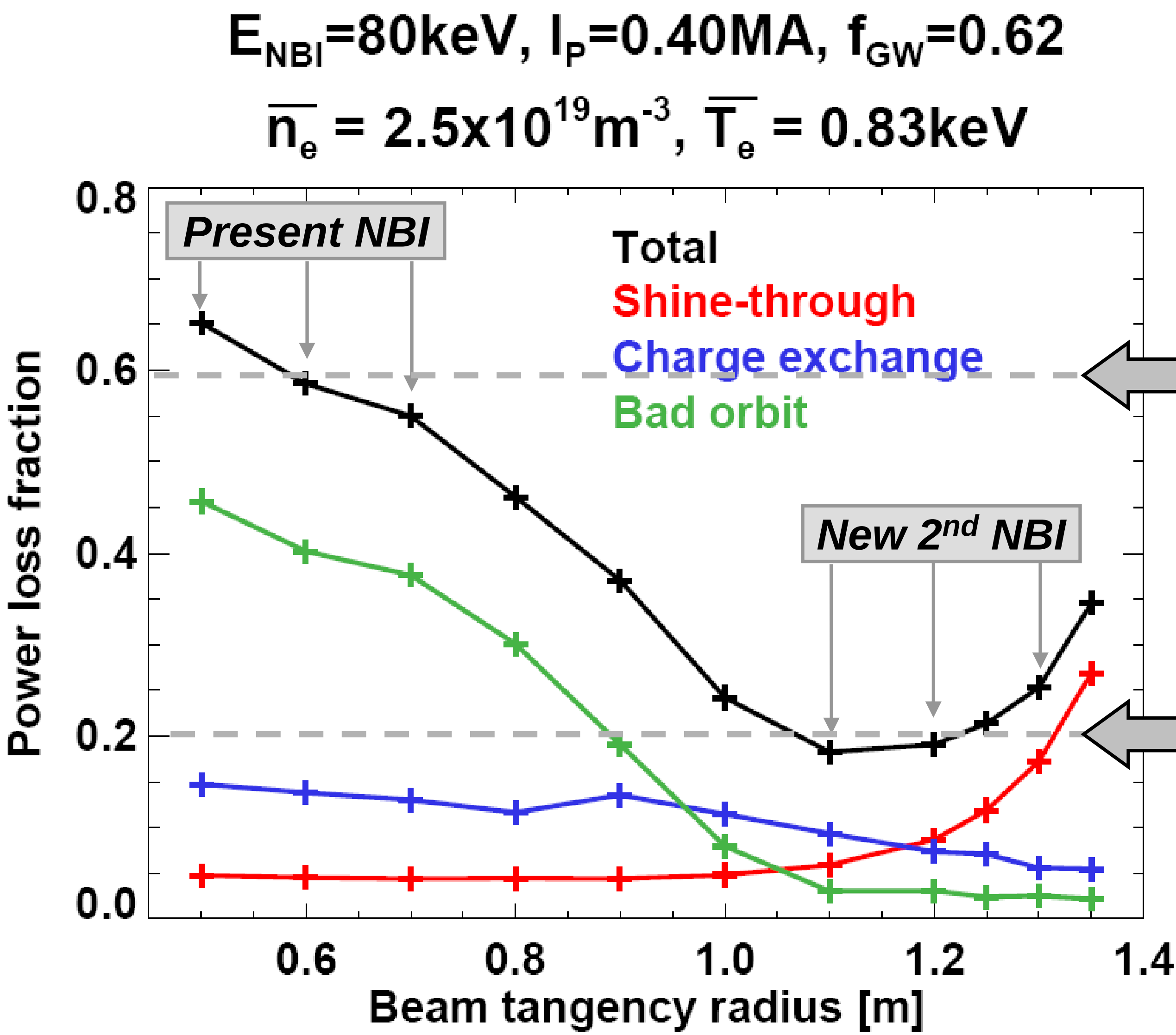


I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4, β_N = 4.5-5, β_T = 10-12%, 4MW RF



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

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



- 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*

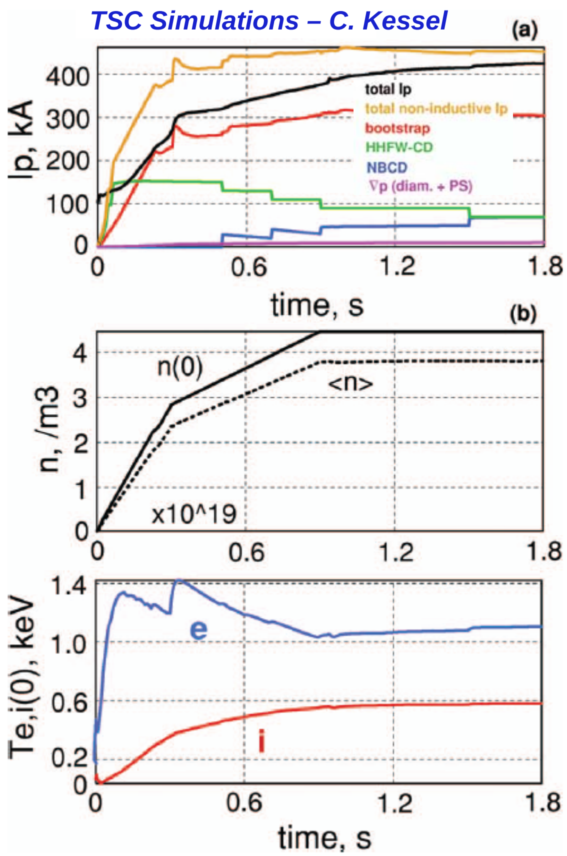
Non-inductive ramp-up to ~0.4MA possible with RF + new CS, ramp-up to ~1MA possible with new CS + more tangential 2nd NBI

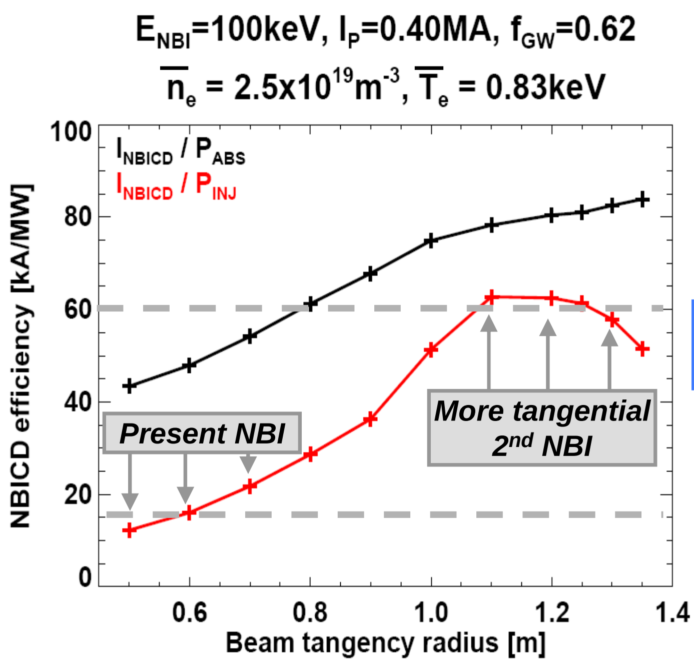
Ramp to ~0.4MA with fast wave heating:

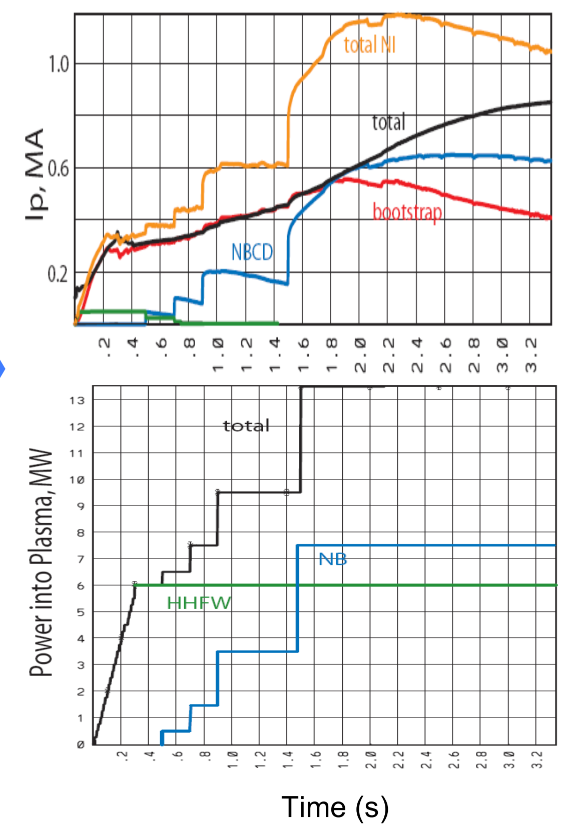
- High field ≥ 0.5T needed for efficient RF heating
- ~2s duration needed for ramp-up equilibration
- Higher field 0.5→1T projected to increase electron temperature and bootstrap current fraction

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





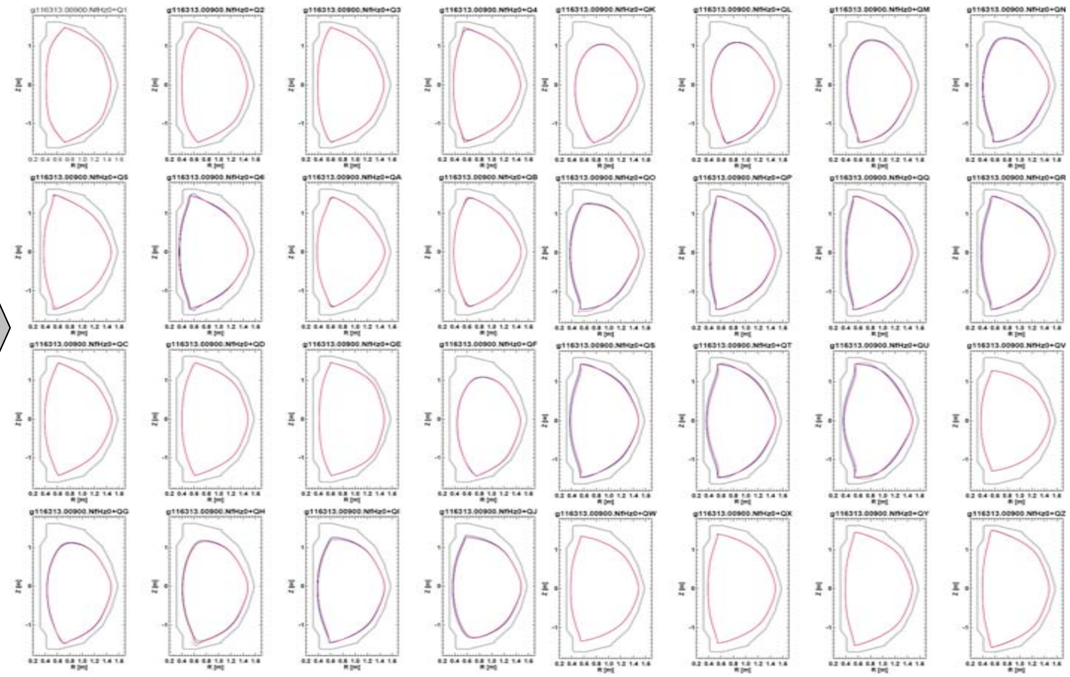


Range of I_P = 2MA free-boundary equilibria generated to support design of TF and PF coil support structures

Free boundary equilibrium parameters:

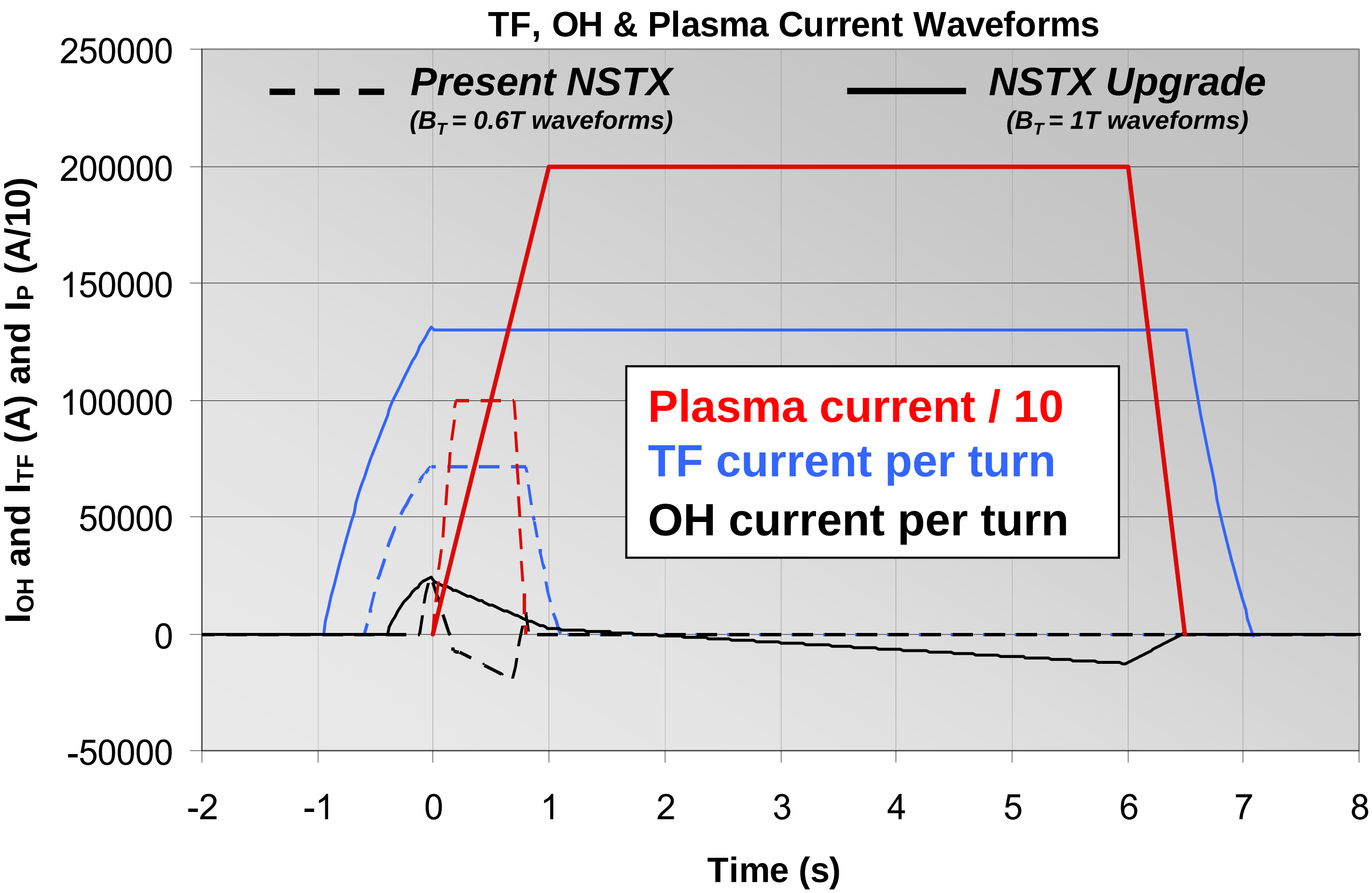
- Aspect ratio A: 1.6 – 1.9
- Internal inductance l_i: 0.4 – 1.1
- Elongation κ: 2.1 – 2.9
- Triangularity δ: 0.2 – 0.7
- Squareness ζ: -0.15 – 0.12
- Magnetic balance: -1.5 – 0cm
- I_{OH}: zero and +/- supply limit
  - For computing PF needed for cancellation of OH leakage flux
- Pressure variation: β_N = 1, 5, 8

32 free boundary equilibria × 3 OH conditions = 96 cases



- NOTE: Negative “squareness” boundary shape cases are included:
  - More shaping flexibility/capability than in present NSTX (requires PF4 usage)
  - Expect could be important for controlling edge stability (NSTX will test in FY2010)
- With coil/machine protection system + nominal operating currents, analysis indicates enhanced vertical field coil structure can support above scenarios

Upgrade provides substantial increase in device performance

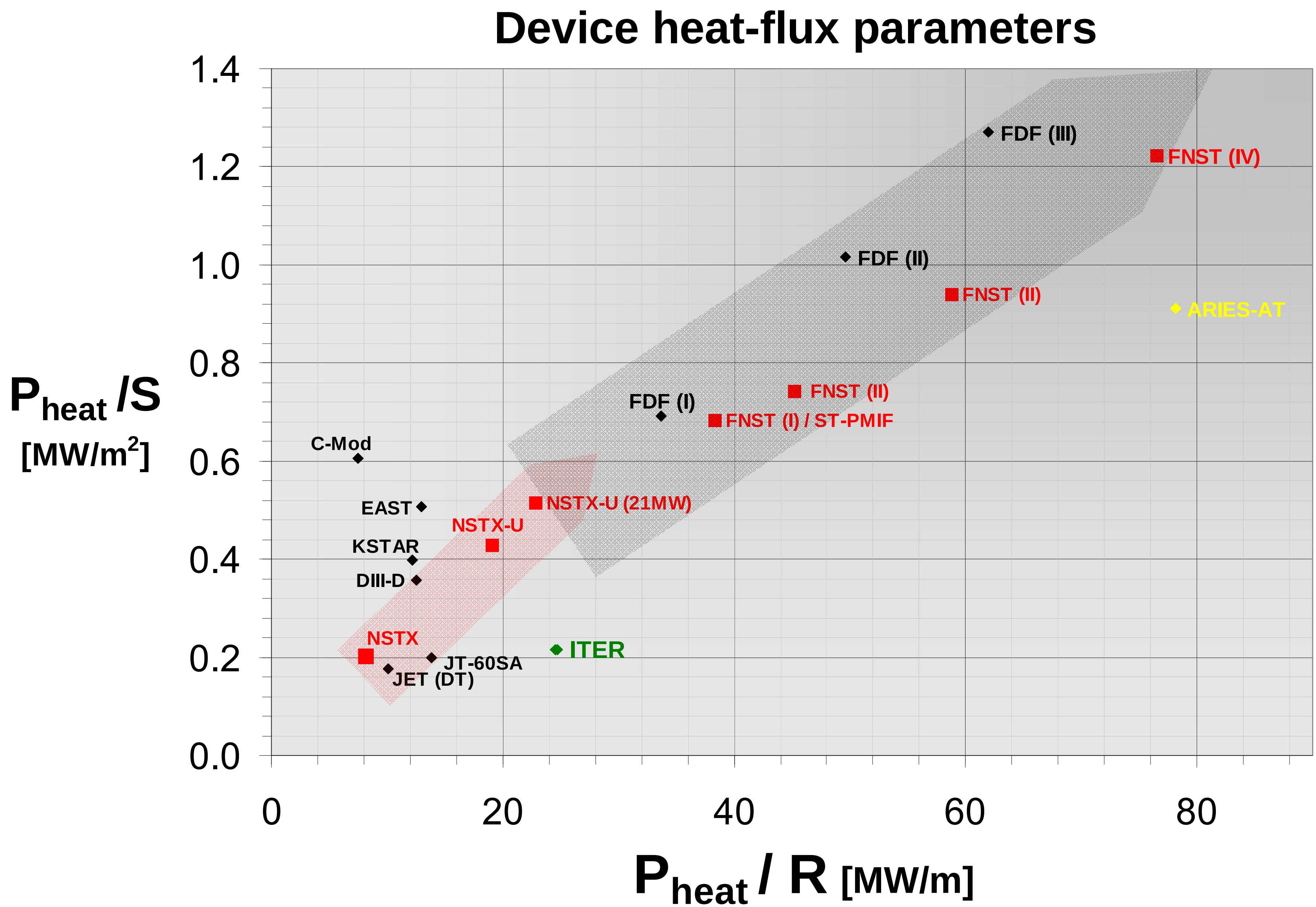


	Base NSTX	NSTX Upgrade
R_0 [m]	0.854	0.934
Min. aspect ratio	1.28	1.5
I_p [MA]	1	2
B_T [T]	0.55	1
T_{pulse} [s]	1	5
$T_{repetition}$ [s]	600	1000
$R_{center\_stack}=R_0$-a [m]	0.185	0.315
$R_{antenna}=R_0$+a [m]	1.574	1.574
Total OH flux [Wb]	0.75	2.1

Relative performance of Upgraded NSTX vs. Base:

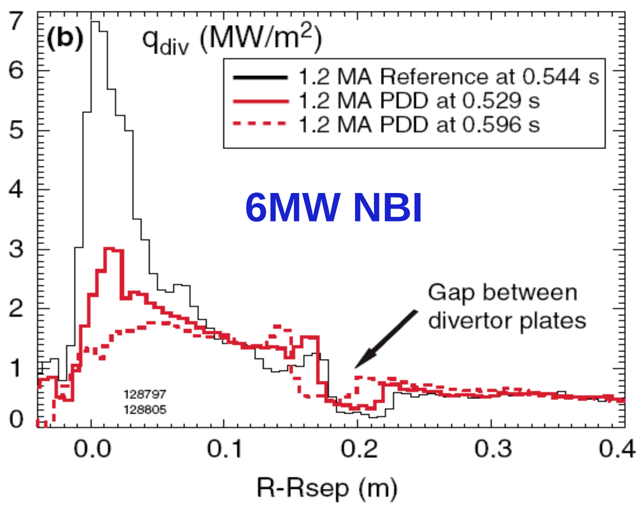
- Center-stack radius increased 13cm → A=1.3 → 1.5
- Available OH flux increased 3×, 3-5× longer flat-top
- I_P increased 2×, B_T increased 2× at same major radius
- Plasma stored energy increased up to 4× (0.25→ 1MJ)

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

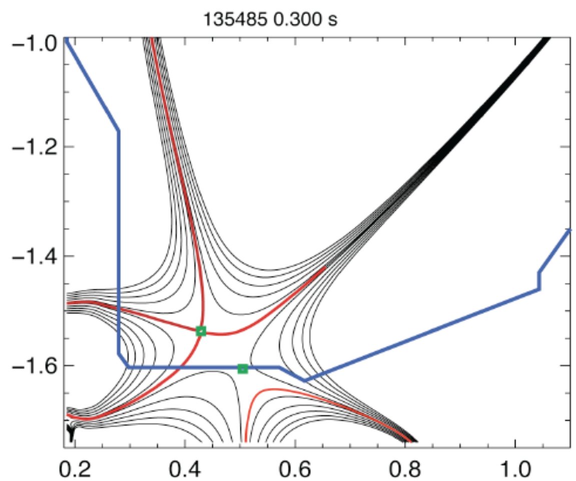


A combination of advanced PMI solutions will likely be required to manage the power exhaust of NSTX Upgrade

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



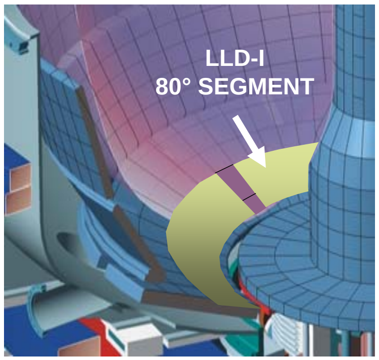
- **NSTX has demonstrated the formation of high flux-expansion "snowflake" divertor**



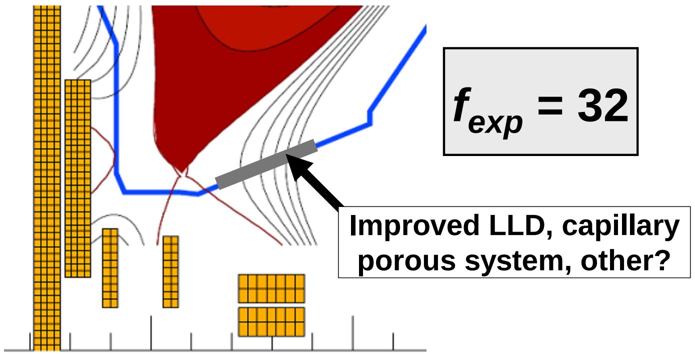
- **The PDD operating regime and other PMI solutions will be challenged in NSTX-U due to:**
  - 2-3× higher input power
  - 30-50% reduction in Greenwald fraction
  - 3-5× longer pulse duration, leading to substantial increase in $T_{divertor}$

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

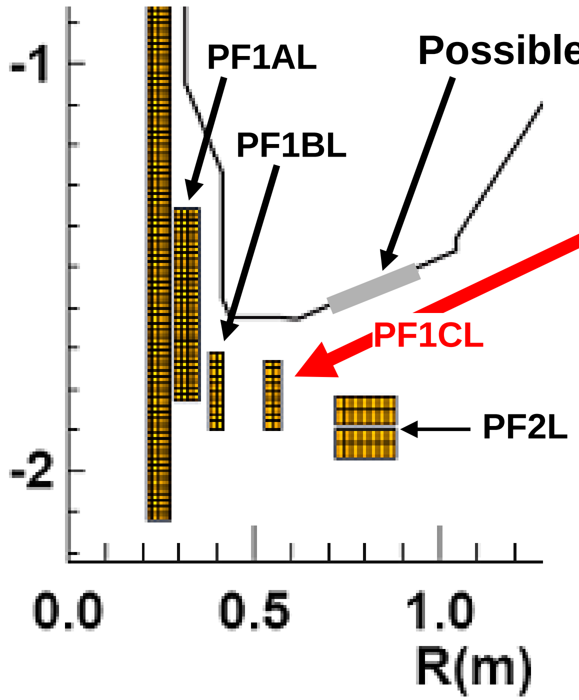
- NSTX LLD



- NSTX-U high flux expansion:



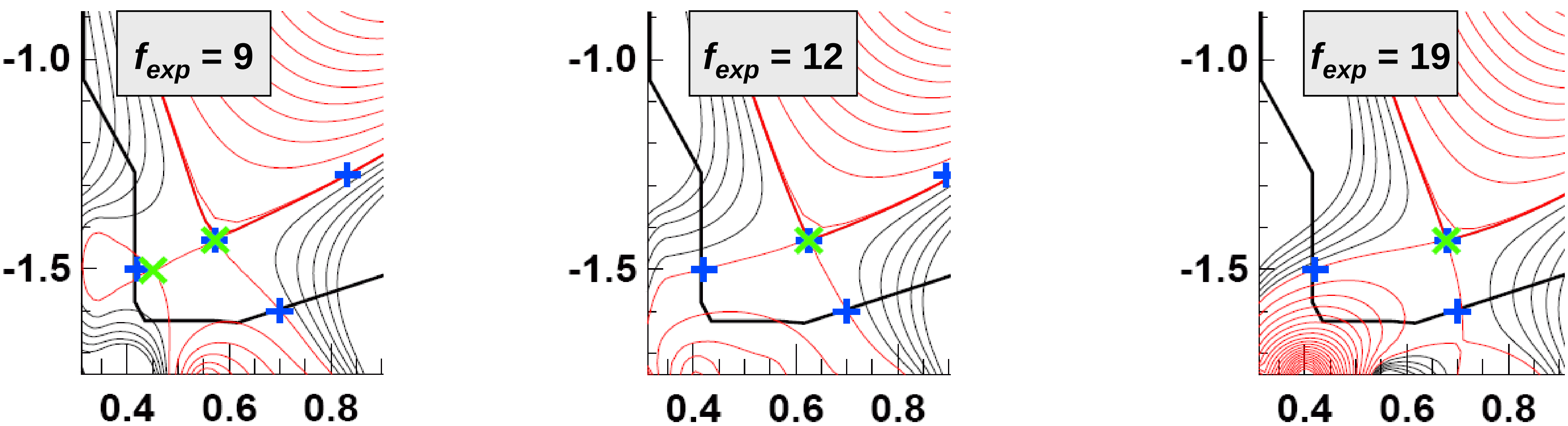
Divertor PF coil system for NSTX Upgrade includes additional coil to enhance control of power exhaust (and support CHI)



Additional coil added = PF1C

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

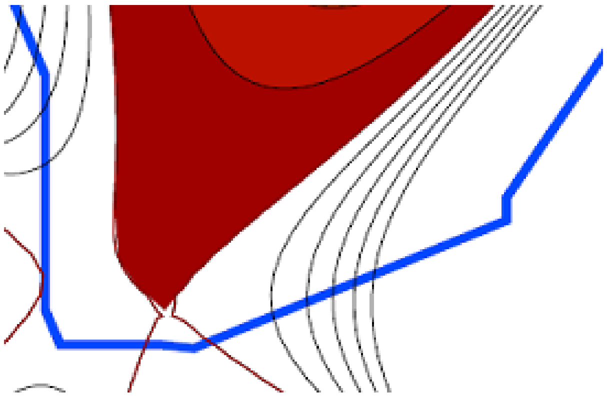
Outboard poloidal flux expansion factor $f_{exp} \equiv |\nabla\psi|_{mid\text{-}plane} / |\nabla\psi|_{strike\text{-}point}$



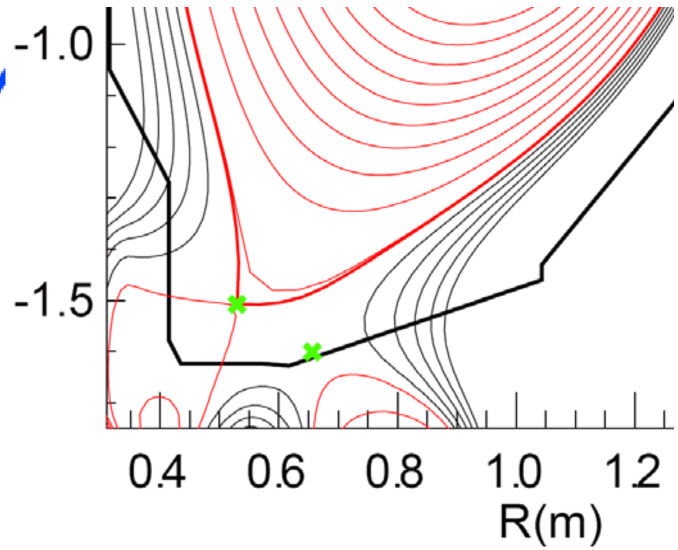
Center-stack Upgrade divertor coil set supports conventional, snowflake, and X/Super-X divertor options

- **Implication:** CS divertor coil location and configuration now finalized

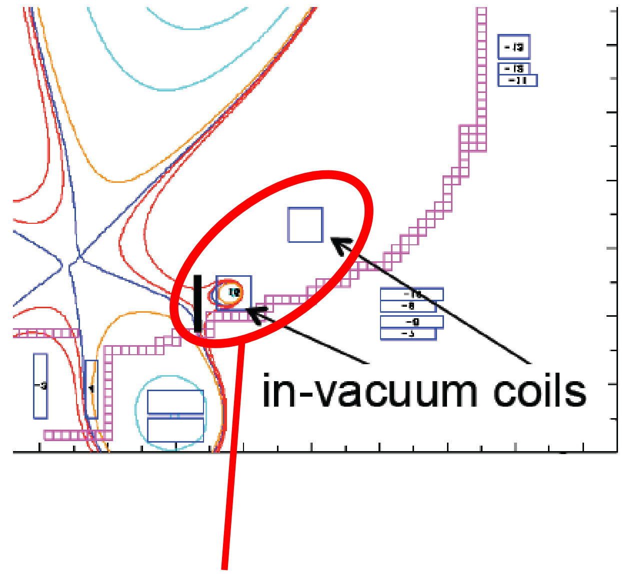
Conventional



Snowflake



X/Super-X



Possible location for cryo-pumps?

- X/Super-X requires in-vessel PF coils which are **<u>NOT</u>** part of Upgrade project
- Design/analysis of Upgrade divertor is collaborative effort (ORNL, LLNL, UT, PPPL)

- NSTX-U divertor design will be strongly influenced by NSTX LLD results
  - To be prepared for possible favorable results from LLD, NSTX is initiating a conceptual design study of heated inboard Mo divertor tiles to support test of high-δ LLD-pumped plasma

NSTX → NSTX Upgrade research goals strongly support research actions identified in ReNeW ST Thrust 16:

1. Develop MA-level plasma current formation and ramp-up
   - CHI start-up and fast-wave ramp-up in NSTX, **NBI ramp-up to ~1MA in Upgrade**
2. Advance innovative magnetic geometries, first wall solutions (liquid metals)
   - **"Snowflake" divertor, detachment, solid/liquid PFCs in NSTX and Upgrade**
3. Understand ST confinement and stability at fusion-relevant parameters
   - Understand μ-turbulence and AEs in NSTX, **extend to lower ρ^* and ν^* in Upgrade**
4. Develop stability control techniques for long-pulse disruption-free operation
   - Advanced mode-ID and rotation control in NSTX, **q(r) optimization in Upgrade**
5. Employ energetic particle beams, plasma waves, particle control, and core fueling techniques to maintain the current, control plasma profiles
   - High $f_{non\text{-}inductive} \leq 70\%$ in NSTX (FW+NBI+BS), **100% NI + J(r) control in Upgrade**
6. Develop normally-conducting radiation-tolerant magnets for ST applications
   - **Design and utilize higher-field TF magnet (0.5T → 1T) in Upgrade**
7. Extend ST performance to near-burning-plasma conditions
   - **NSTX and Upgrade + tokamak program provide physics basis for next-step STs**