Supported by Office of Science

Physics and Engineering Design Considerations for NHTX

National High-power advanced Torus eXperiment

Presented by:

J. Menard, PPPL

With contributions from:

G.-Y. Fu, R. Goldston, N. Gorelenkov, S. Kaye, G. Kramer,
R. Maingi, C. Neumeyer, S. Sabbagh, V. Soukhanovskii,
R. Woolley, and the NSTX Research Team

The development of advanced fusion reactors will require the integration of key areas of fusion science

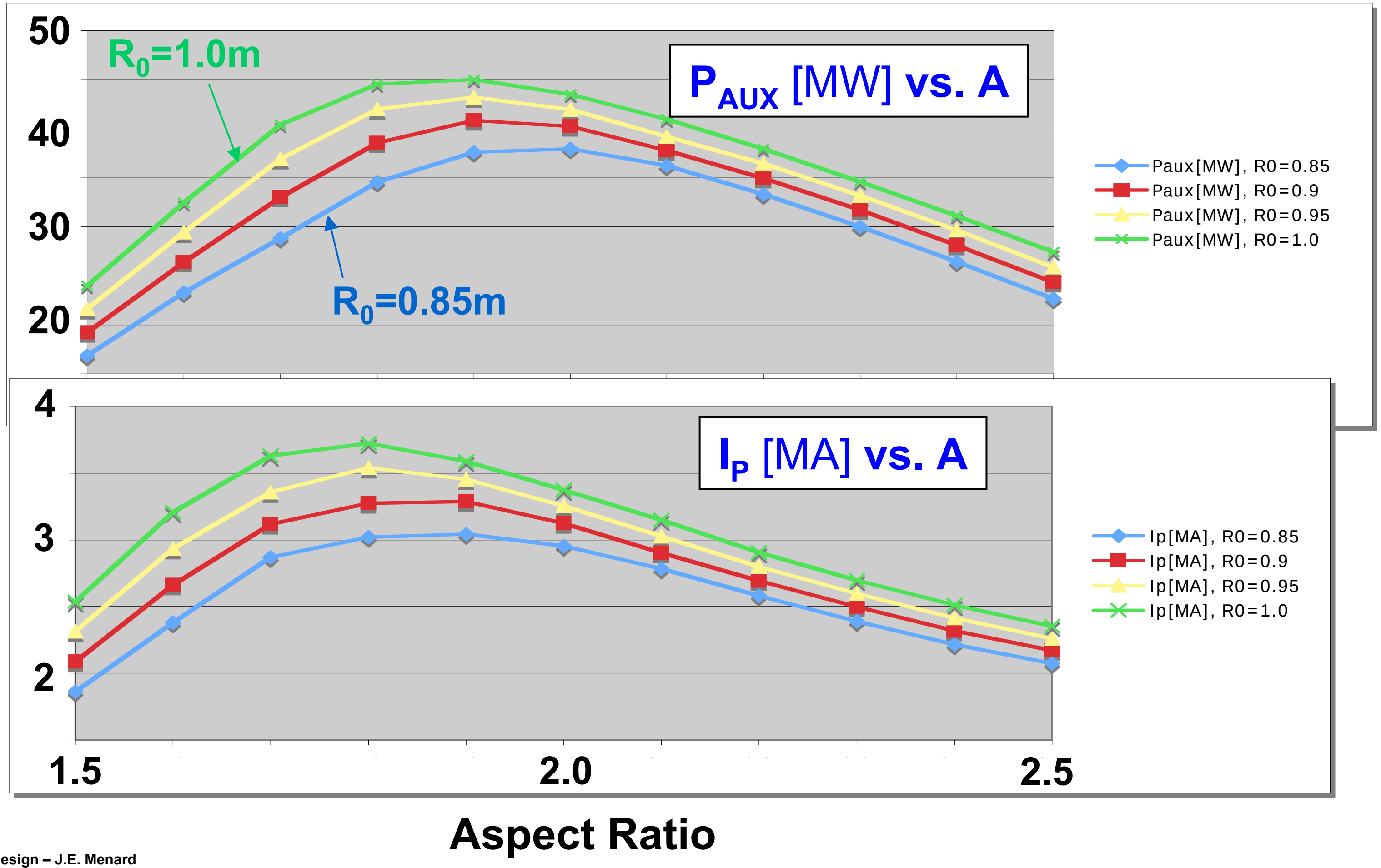
- **NHTX mission:**

  "To study the integration of high-confinement, high-beta, long-pulse non-inductive plasma operation with a fusion-relevant high-power plasma-boundary interface."

- Metrics for the four key fusion areas:
  1. High thermal confinement → **H-mode with HH > 1**
  2. High plasma beta → **at or above no-wall limit**
  3. Steady state operation → **$f_{BS} \geq 0.7$ + NBI, RF CD → n_e control**
  4. Reactor-level heat-flux-handling compatible w/ above → need innovation

Systems code identifies optimal aspect ratio A=1.8-2 based on NHTX mission and design

- A=1.8-2 maximizes P/R and I_P (or $I_P \times A$) at fixed magnet power
  - Fixed $HH_{98y2}=1.3$, use $\kappa(A)$ and **n=1 no-wall limit** $\beta_N(A)$ scalings
  - I_P from BS and NBI – additional LHCD, ECCD/EBW to be assessed



NHTX Heating and Current Drive

- Total auxiliary heating and current drive power = 50MW
  - Neutral beams: 32 MW, 110 kV D_0 NBI, steerable off axis
  - 18 MW RF – type to be determined

- Results from NSTX, C-MOD, DIII-D will be critical to selection of RF system(s)
  - EBWCD: High efficiency, remote coupling.
  - LHCD: High efficiency, intimate coupling.
  - ECCD: Inside-launch 120 GHz 2nd harmonic: lower efficiency, more complex access.
  - ICRF: Cost-effective electron or ion heating, intimate coupling

- 2MA bootstrap current at operating point

- For confidence in 3.5 MA steady-state operation, desirable to be able to drive ~ 1.5 MA with beams + RF (R_0 = 1m)

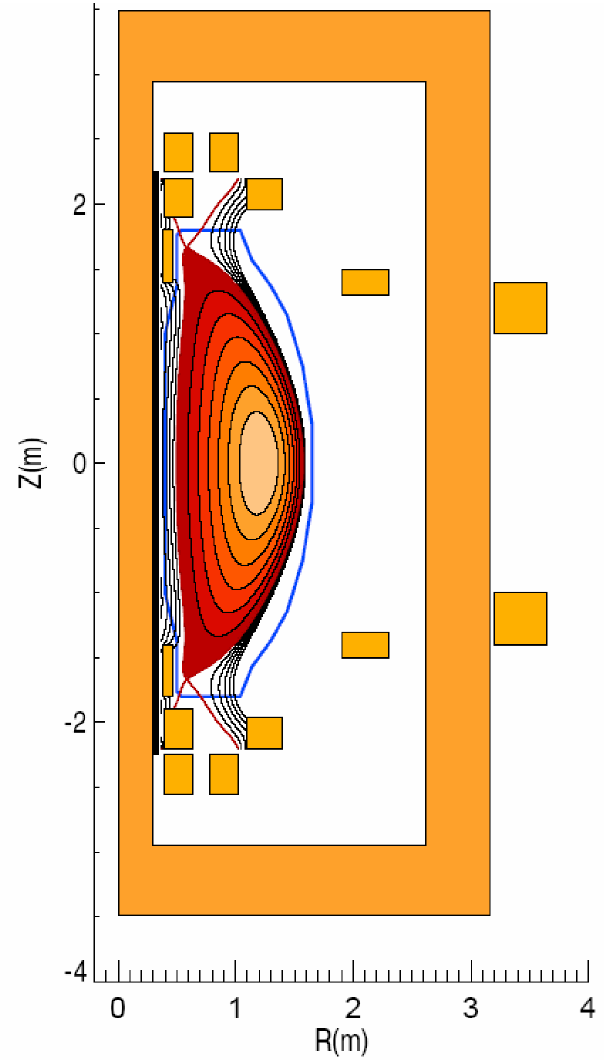
Overview of NHTX design progress

- Systems code has identified favorable design point:
  - A=1.8-2, R_0=1m, I_P=3-4MA, B_T=2T, κ=2.7-3, fully non-inductive
  - Maximizes I_P, $I_P \times A$, and P/R for given magnet power
  - $HH_{98Y} = 1.3$, β_N=4.5, β_T=15%, f_{BS}= 65%, f_{GW}=0.4-0.5
  - High β possible with Ω_ϕ & feedback stabilization of RWM
- Favorable PF coil configuration identified
  - Divertor flexibility without PF coil modification
  - Strong shaping flexibility (κ, δ, squareness, flux expansion)
  - Large midplane vertical gap for beam steering (ΔZ), diagnostics, access
- NBI current drive efficiency & profiles studied with TRANSP
  - R_{TAN} and Z_{TAN} variations allow for J_{NBI} profile control
  - NBICD scalings used in systems code are reasonable

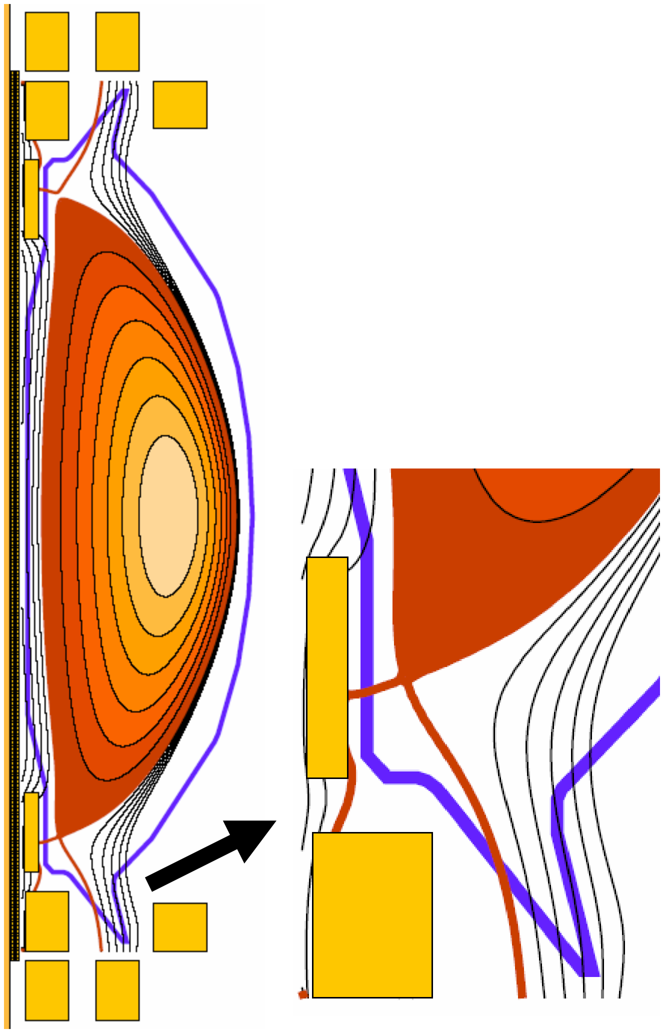
Single coil set supports range of divertor configurations

Example configurations:

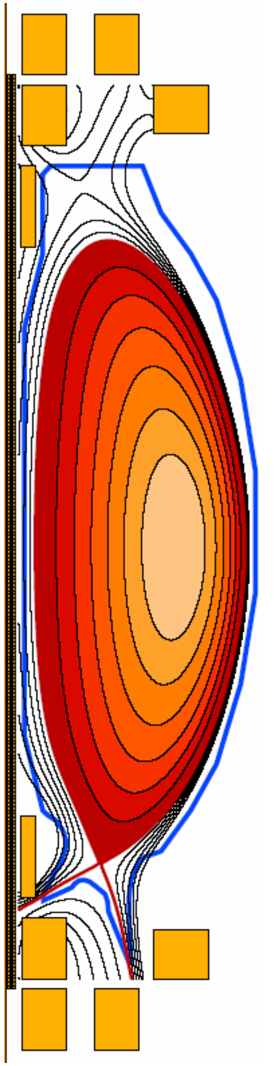
Open DN divertor



Pumped DND, JET-like

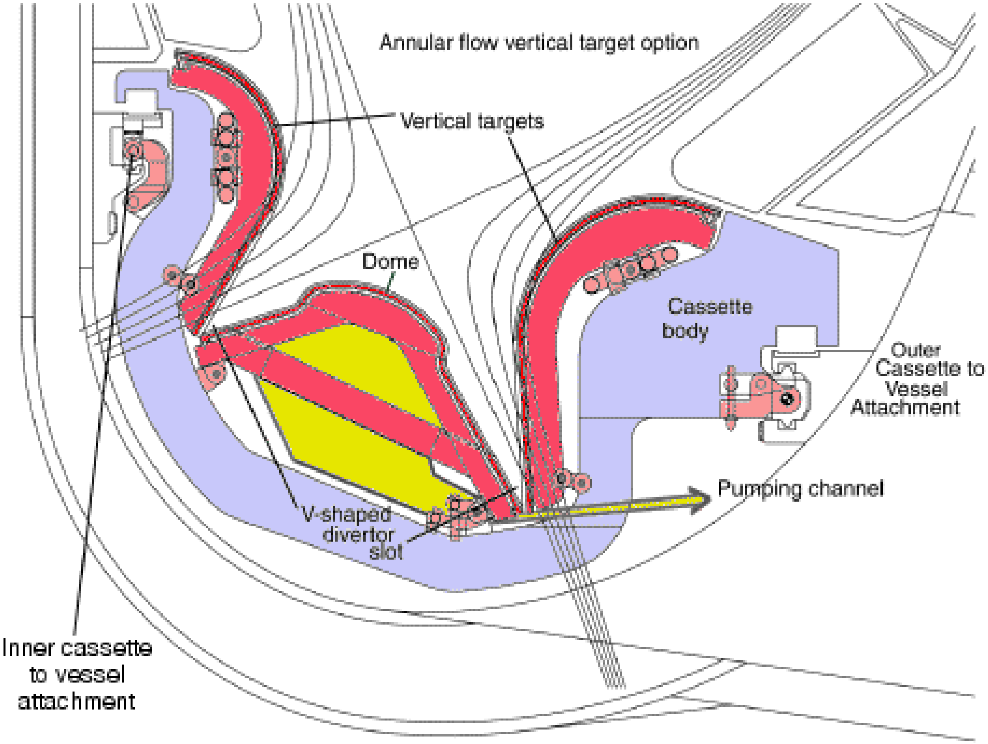


ITER-like LSN divertor

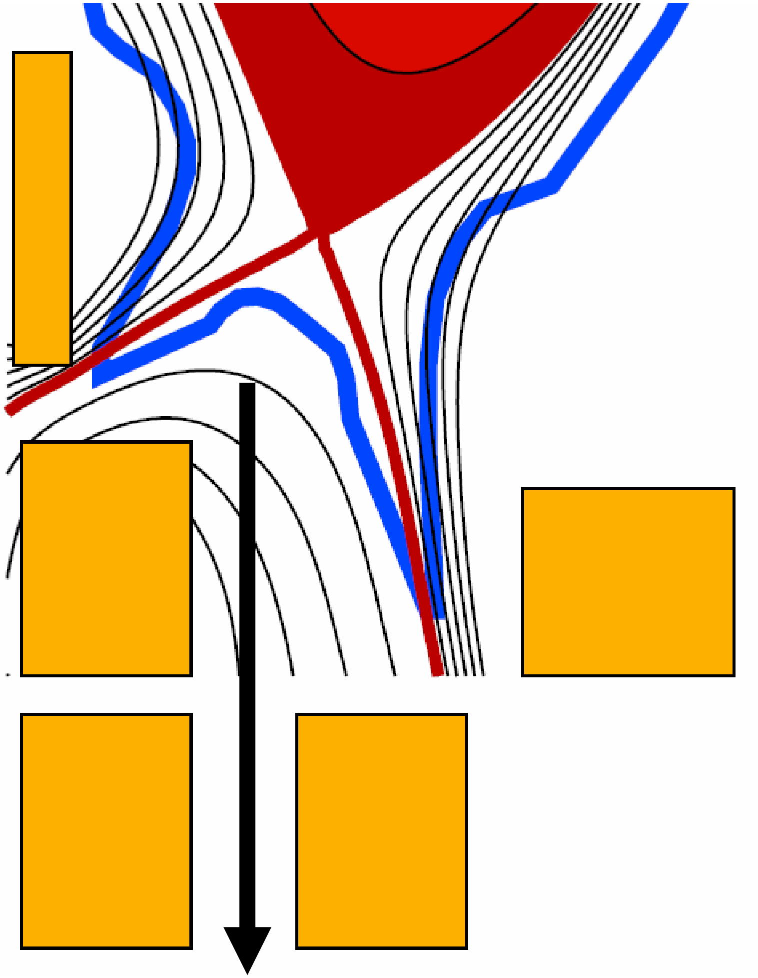


NHTX coil set supports ITER-like LSN divertor

ITER



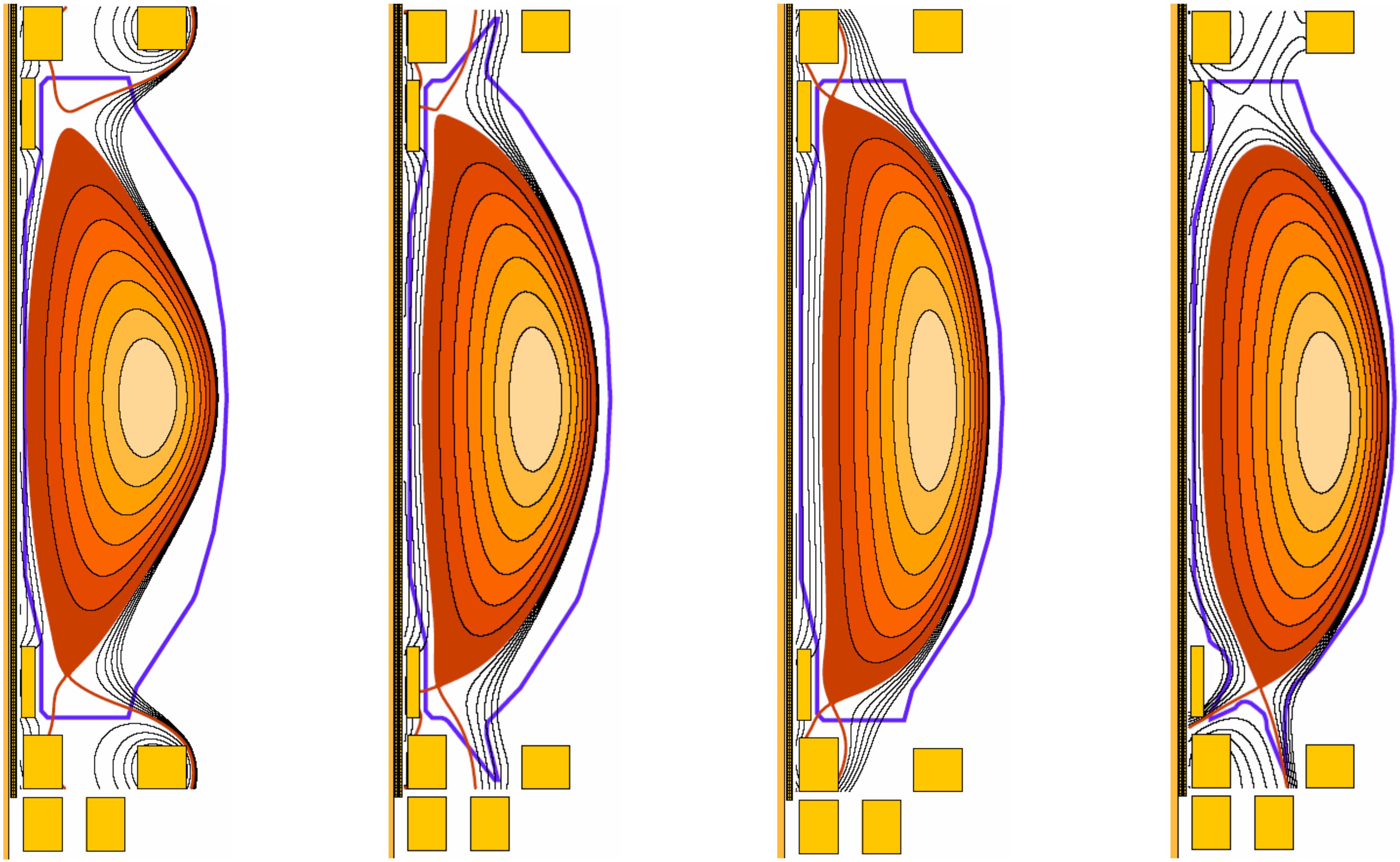
NHTX



Pumping channel from dome

Coil set supports wide range of boundary shapes

- Shaping plays important role in determining global and ELM stability



DND w/ negative squareness ζ ≈ -0.15

DND w/ near zero squareness

DND w/ positive squareness ζ ≈ 0.25

Example LSN shape

Divertor coil set supports wide range of flux expansion

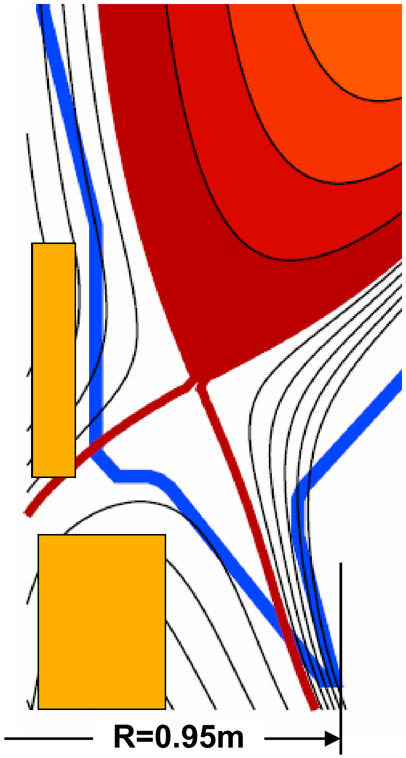
Poloidal flux expansion factor $f_{exp} \equiv |\nabla\psi|_{\text{mid-plane}} \,/\, |\nabla\psi|_{\text{strike-point}}$

Poloidal B-field angle of incidence into target plate $\equiv \alpha_p$

Total B-field angle of incidence into target plate $\equiv \alpha_t$

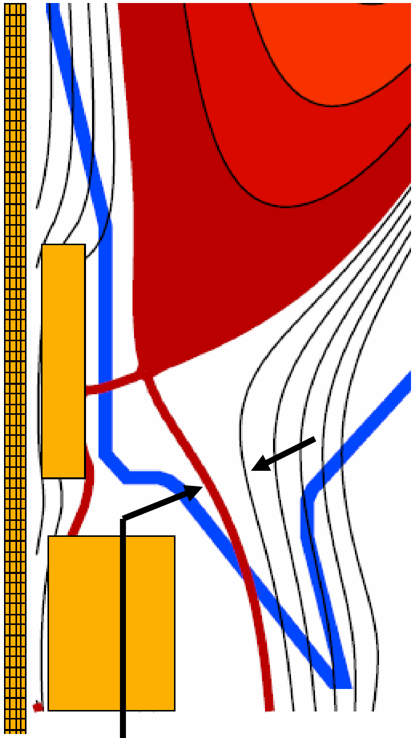
f_{exp} = 2.8

α_p=22° α_t=5.1°



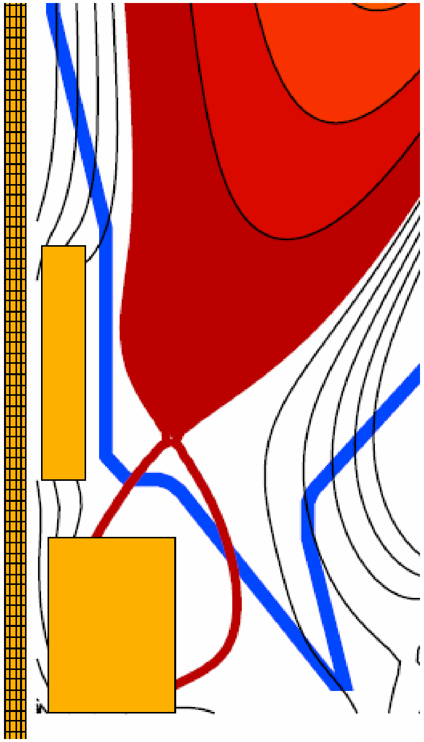
f_{exp} = 9

α_p=23° α_t=1.8°



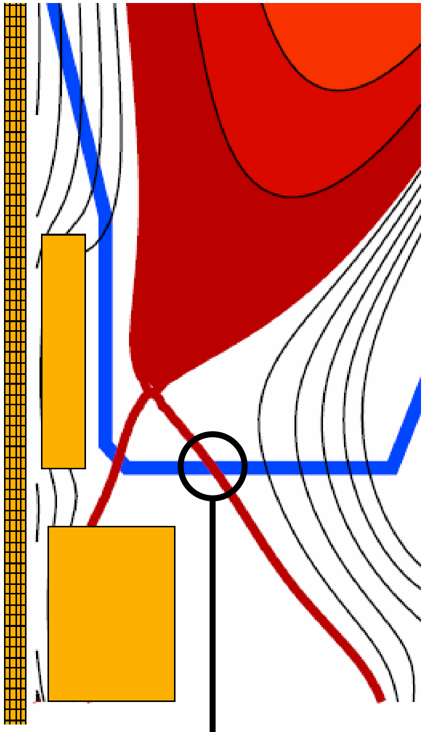
f_{exp} = 17

α_p=25° α_t=1.0°



f_{exp} = 35

α_p=64° α_t=1.1°

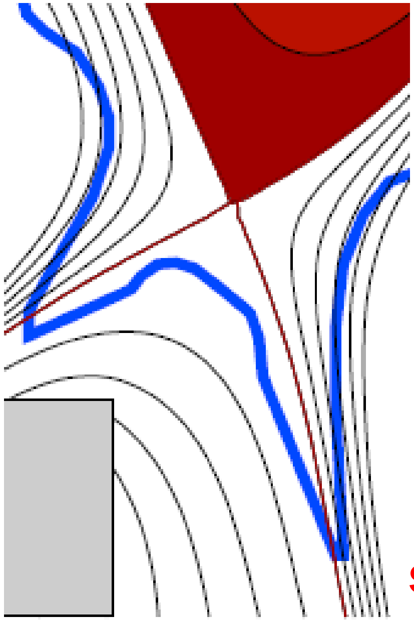


Flux contours have 5mm separation at midplane

f_{exp}, α values computed at strike-point

Operation w/ LSN and low flux expansion challenging

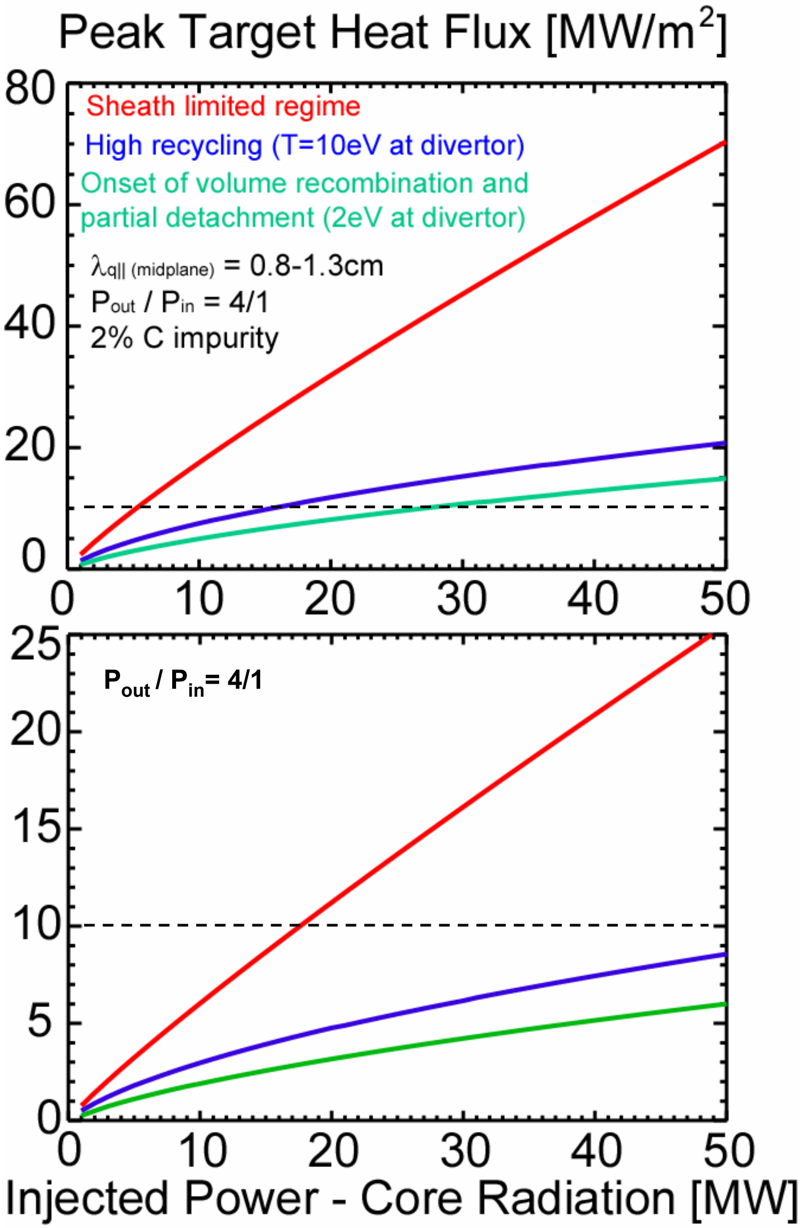
Note: ITER designed for $q_{div} \leq 10 MW/m^2$

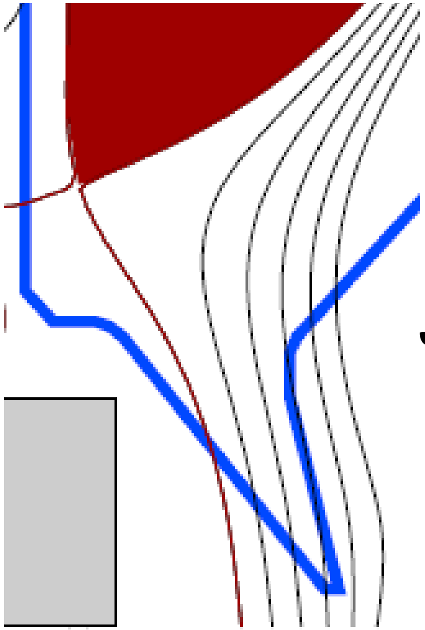


ITER-like div. - LSN

f_{exp} = 3 at strike-pt

Compatible with solid divertor material?





JET-like div. – DND

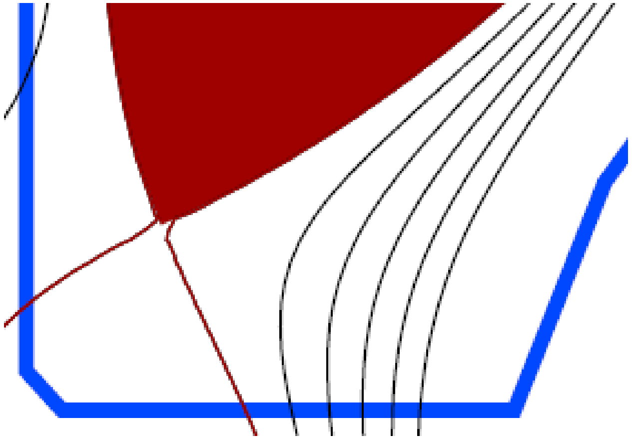
f_{exp} = 9 at strike-pt

Compatible with efficient pumping?

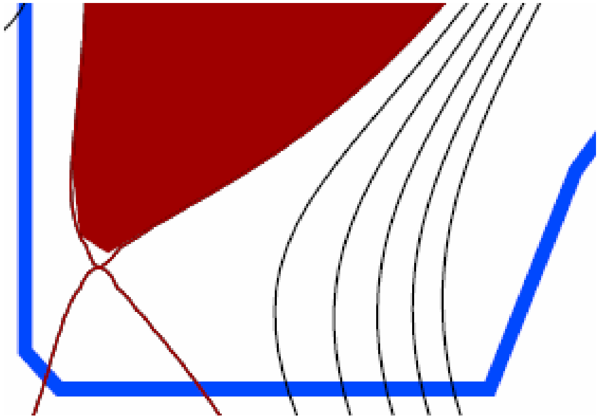
Large flux expansion and/or plate-tilt is attractive…

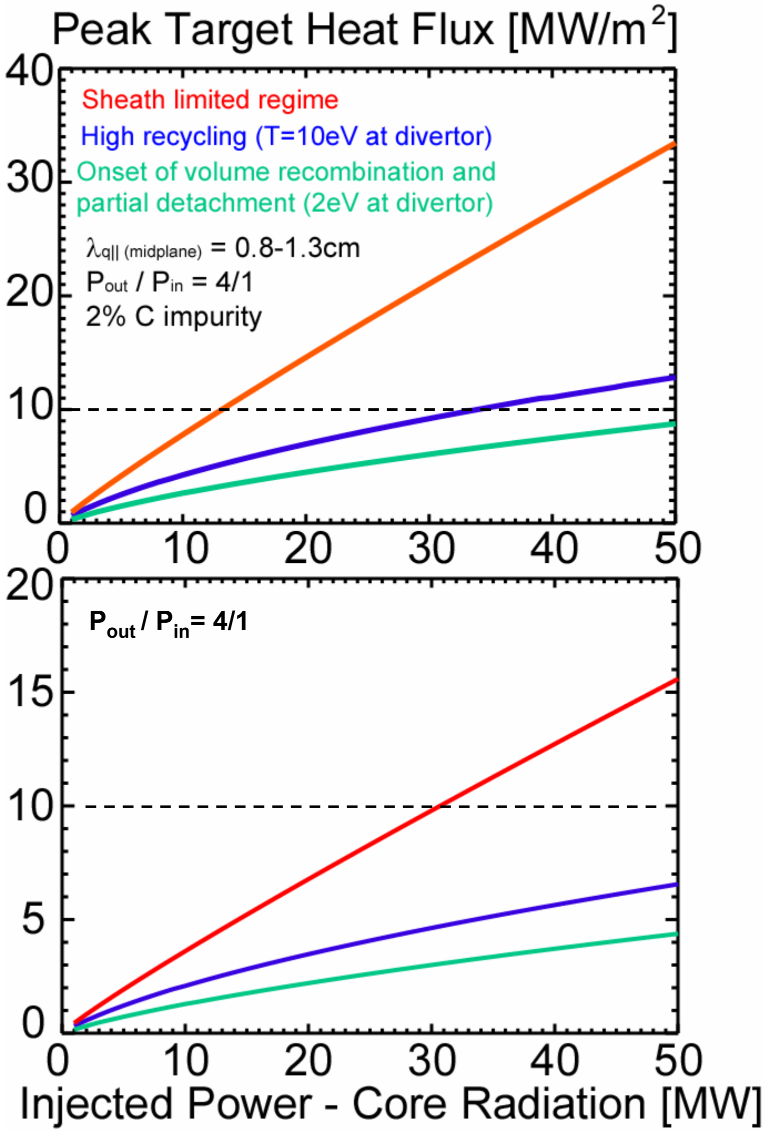
…but can one pump over large surface area? (liquid lithium?)

DND - f_{exp} = 10 at strike-point



DND - f_{exp} = 35 at strike-point



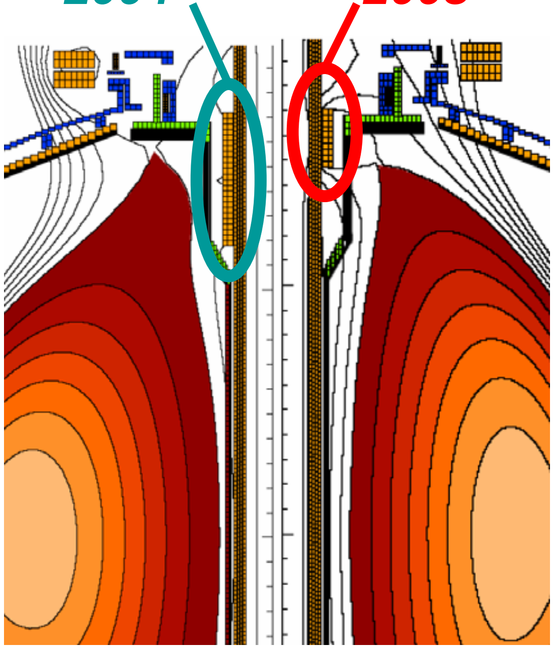


NHTX requires advanced control of high κ/δ boundary, strike point placement, and flux expansion

- NSTX: Sustained $\kappa \geq 2.8$ (reached $\kappa = 3$) for many τ_{WALL} using rtEFIT isoflux control
- High κ n=0 stability research important for NHTX and CTF/FDF design studies

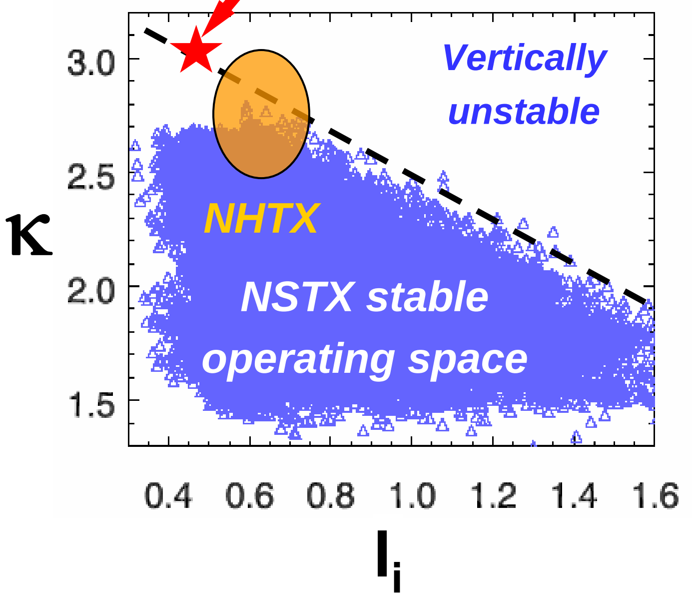
Divertor coil upgrade

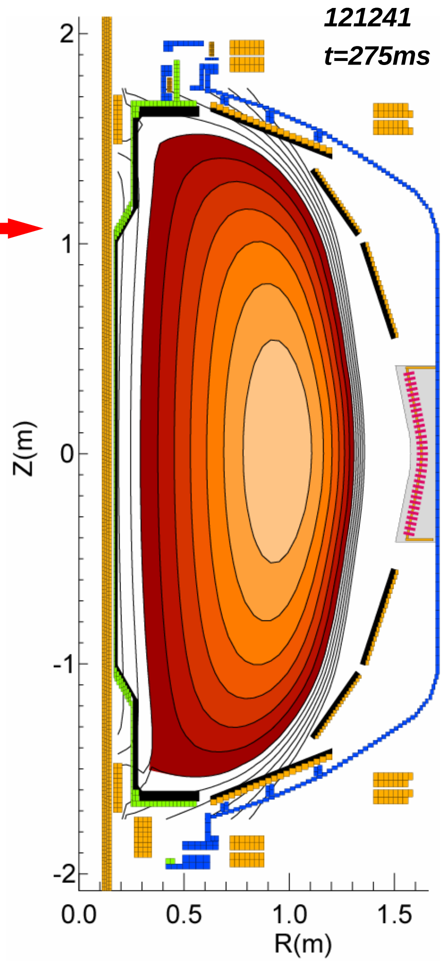
2004 **2005**



2006: $\kappa = 3.0$, $\delta_X = 0.8$

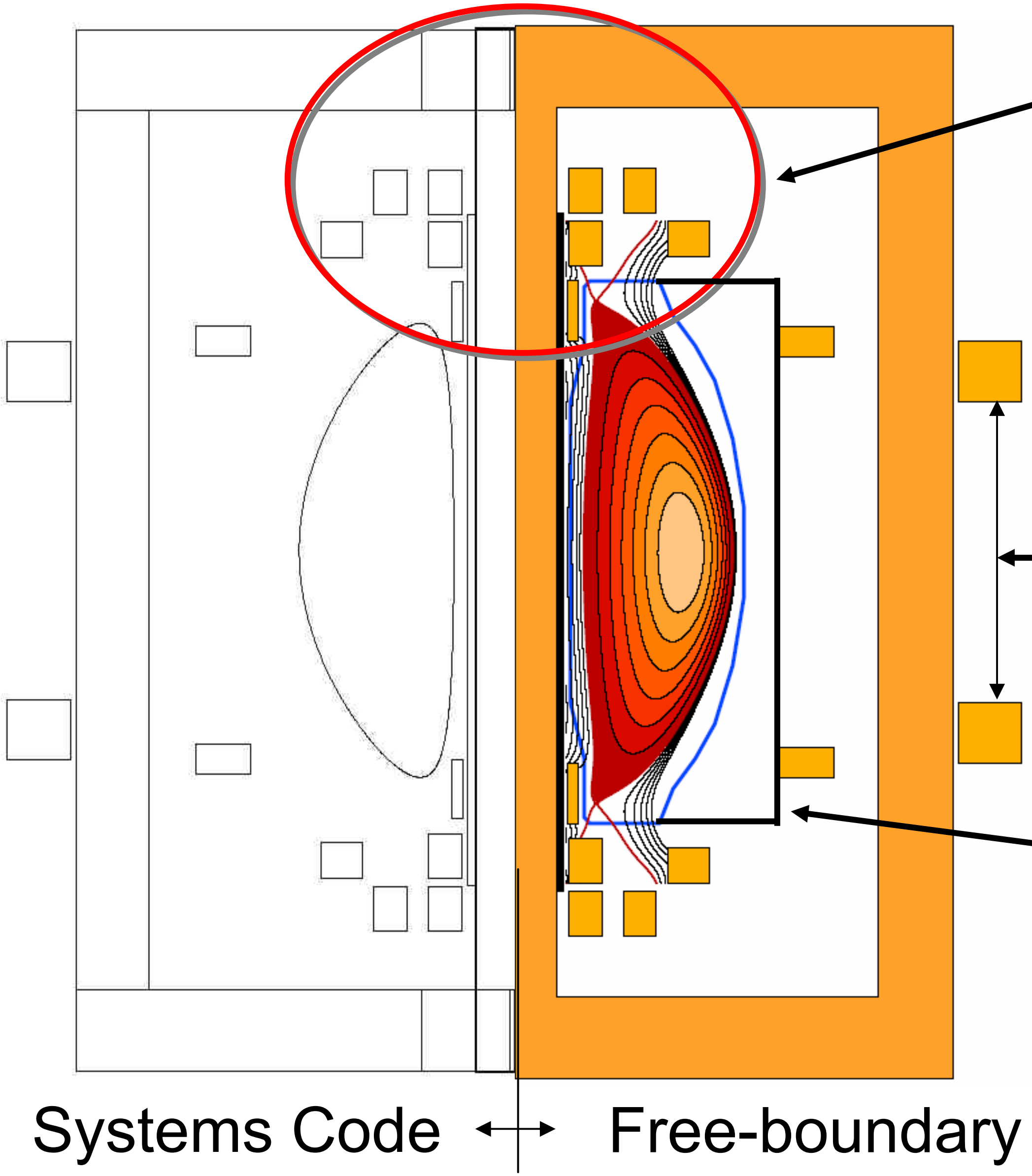
$l_i = 0.45$





*Gates, et al., PoP **13** (2006) 056122*
*Gates, et al., NF **46** (2006) 17*

Many engineering issues remain to be addressed



Critical area for physics and engineering design:

- Space for many divertor options
- Manifolds for heat removal
- B_{PF} & J_{PF} optimization
- TF jointing and structure

Tall mid-plane ports offer several potential advantages:

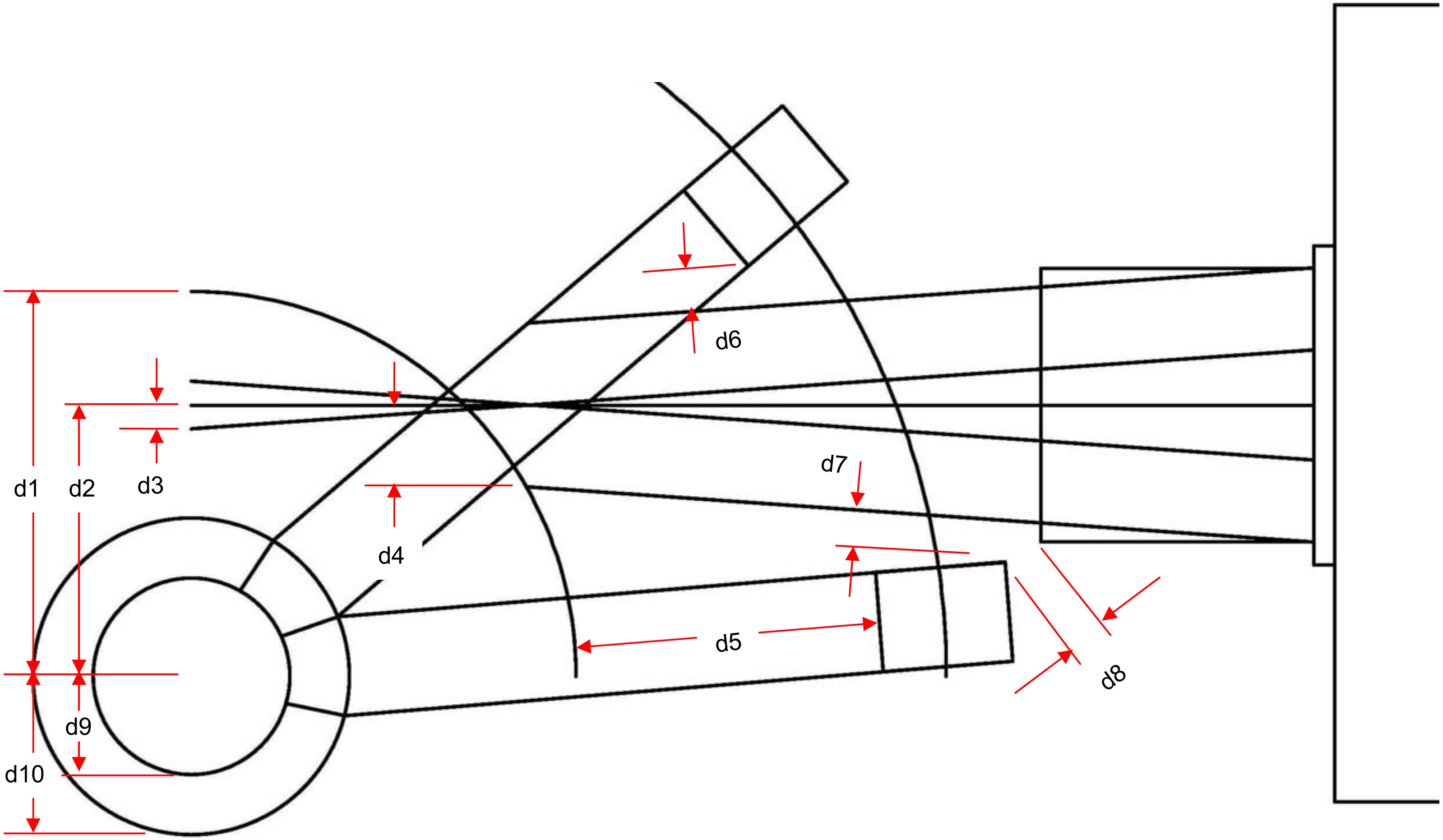
- Beam vertical shift for J control
- Access for maintenance

Cylindrical vacuum vessel has potential advantages:

- Facilitates top (crane) access
- Simplicity of fabrication

Systems Code ↔ Free-boundary equilibrium

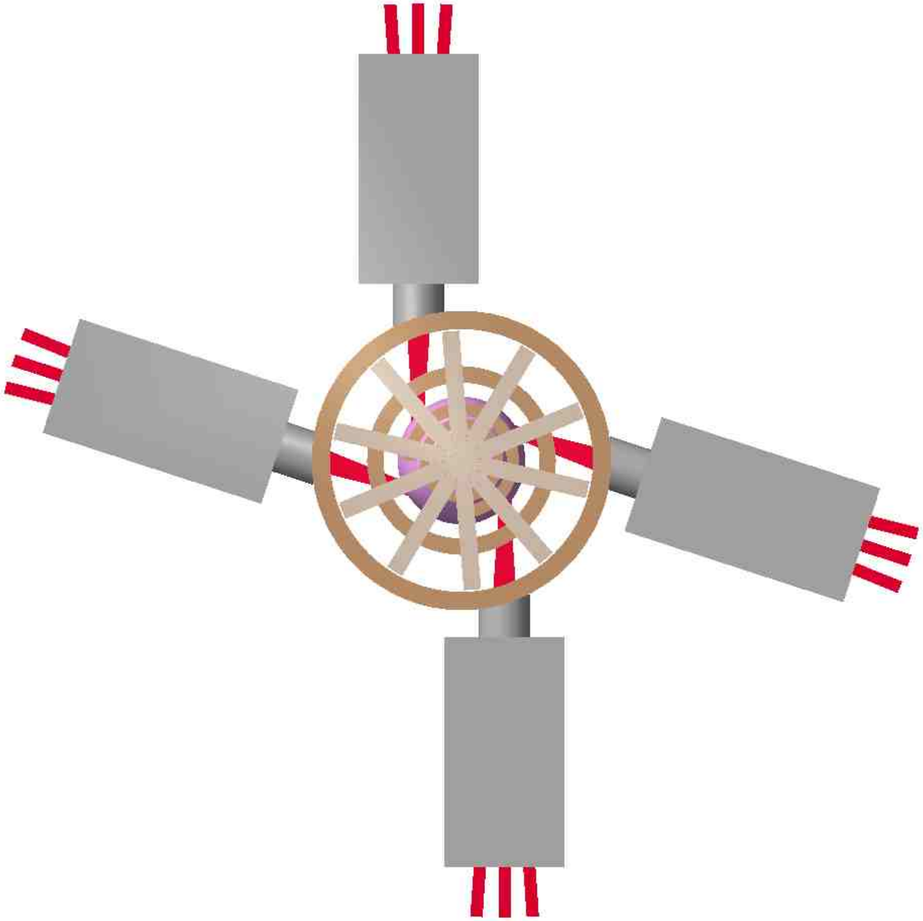
Systems code incorporates NBI geometry, TF ripple < 0.5%, and J_{TF} limits into TF outer leg layout and sizing

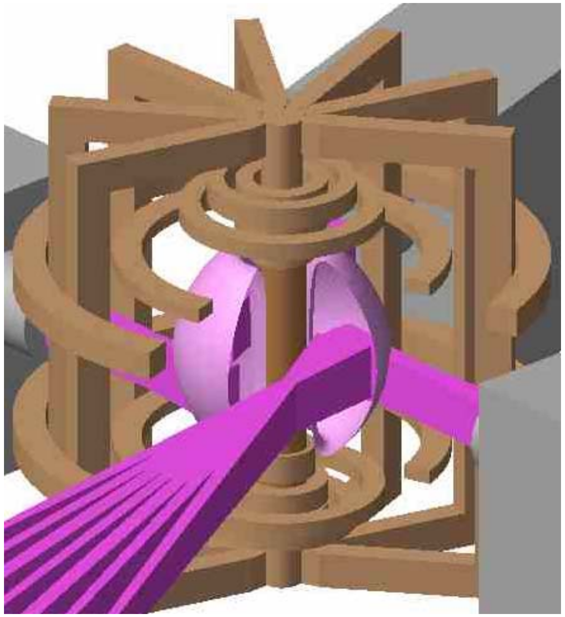


d1 = R0+a
d2 = R_tangency
d3 = beam centerline spacing around R_tangency
d4 = extent of beam duct w.r.t. beam centerline

d5 = gap R0+a to TF outer leg
d6, d7 = gaps TF outer legs to beam duct
d8 = gap TF outer leg to beam nozzle
d9 = radius of TF inner leg
d10 = radius of TF outer leg taper

TF coil layout (10 coils) and sizing allows for R_{TAN} variation of NBI for J-profile control

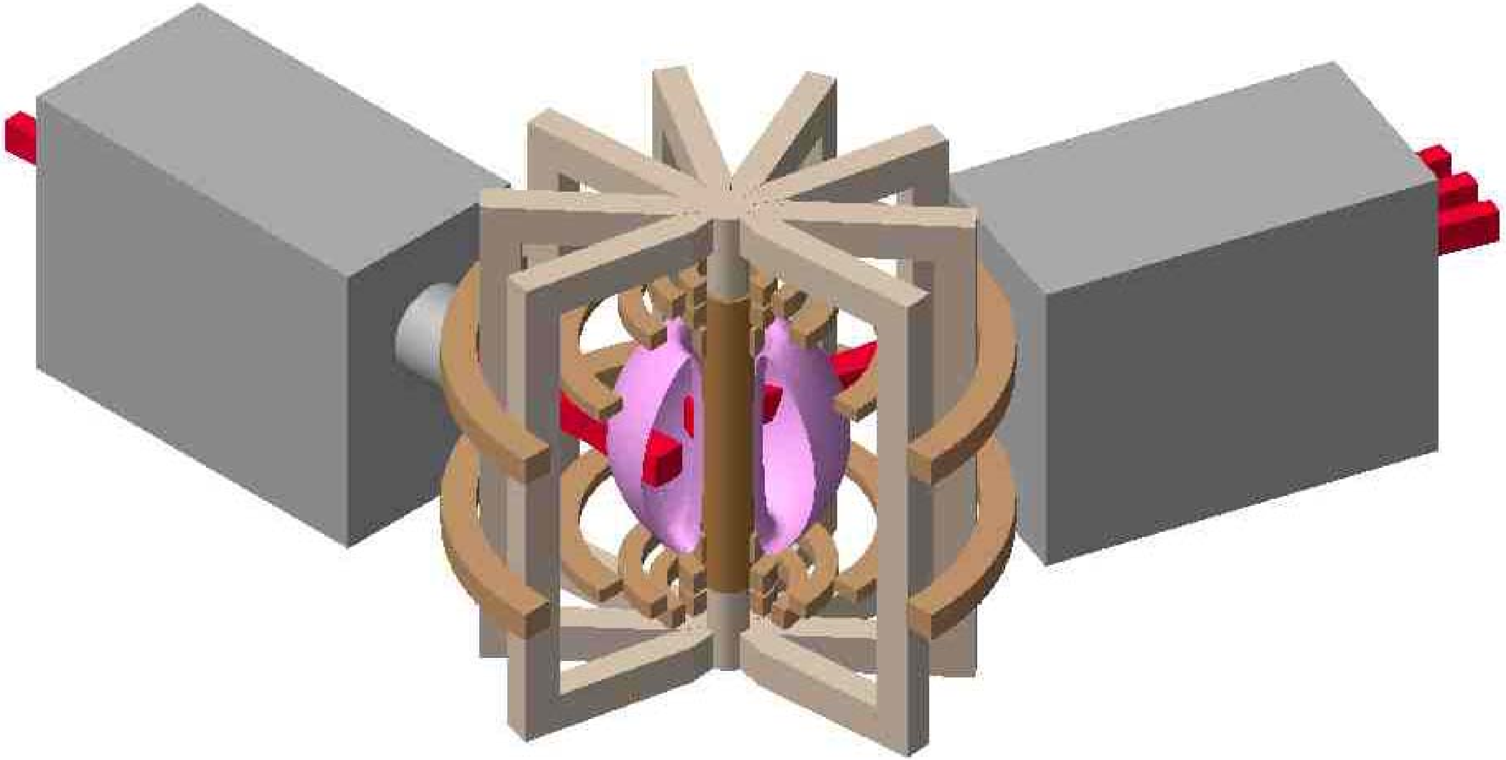




- R_{TAN} range = 1m ± 0.2m possible with cross-over point at vessel entrance
  - Analyzing access port and beam dump layouts

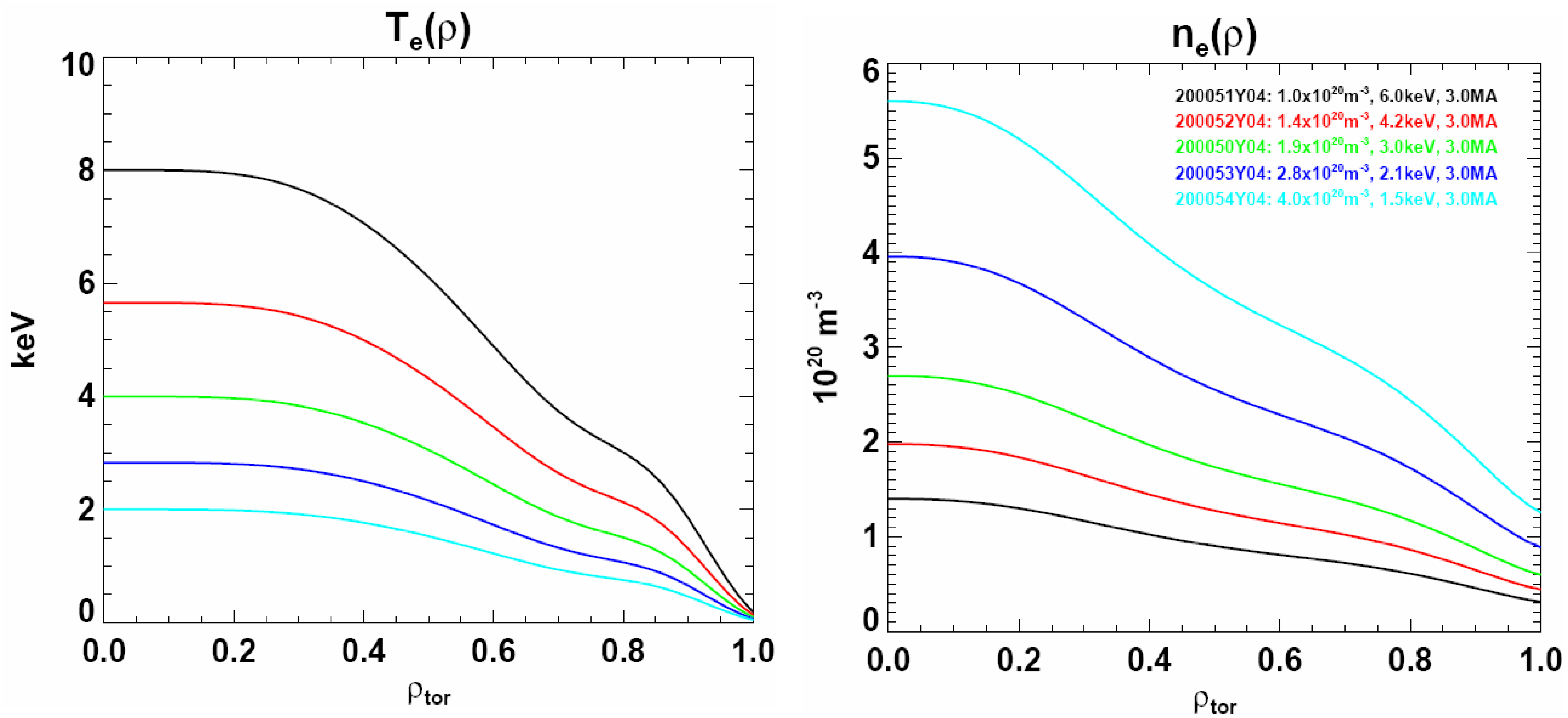
Large vertical gap between outer PF coils also allows for *vertical* shifting of NBI for J-profile control

- High κ capability requires outer-most PFs to be outside TF
- If R_{TAN} variation is chosen, these PFs could have smaller R
  - Reduces PF power consumption, but…
  - Lose accessibility of large vertical midplane gap



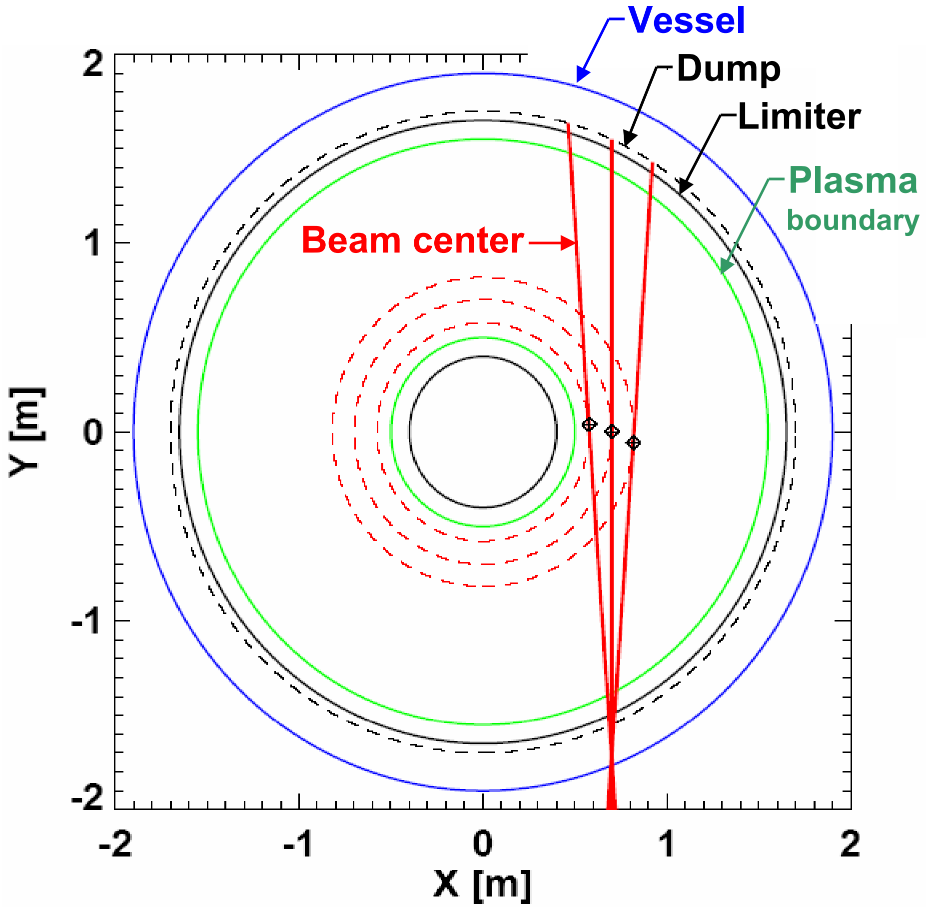
NBICD assessment w/ TRANSP uses thermal profile shapes based on high f_{NI} = 60-70% NSTX discharges

- Scale n_e, T_e profiles from 116313 - fixed T_i / T_e = 1.5, β_T=14%

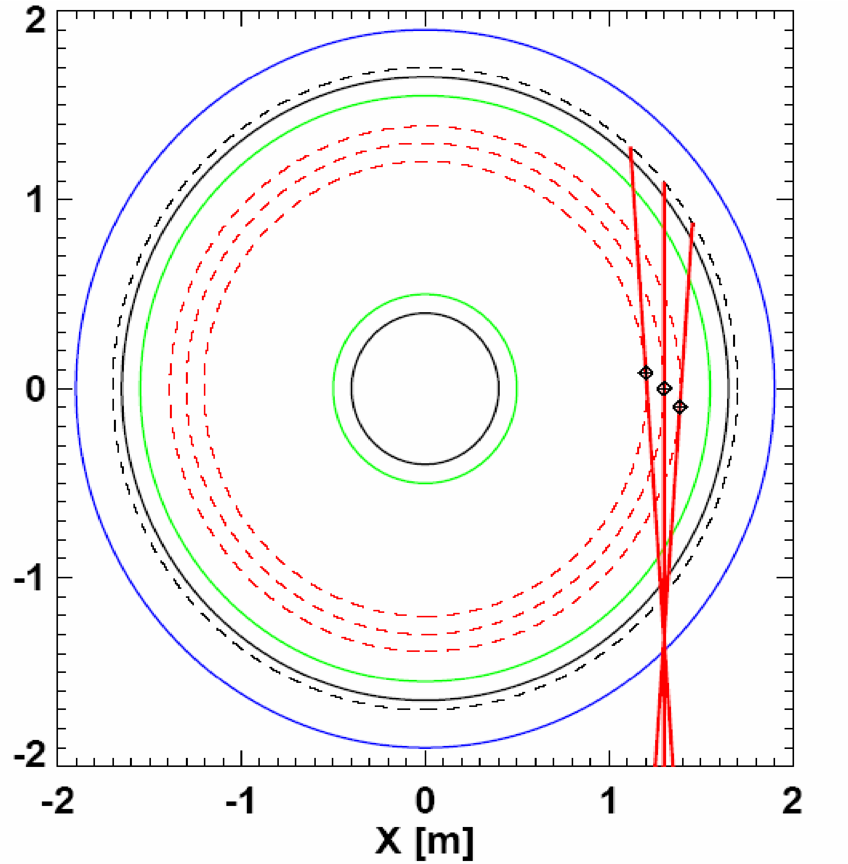


Scan R_{TAN} within range $R_0 \pm 30$cm to assess NBICD efficiency and profiles

- Fix source cross-over radius at $R_{CO} = 1.85$m to be near vessel entrance
- Simulates horizontal beam-line swing with bellows near vessel



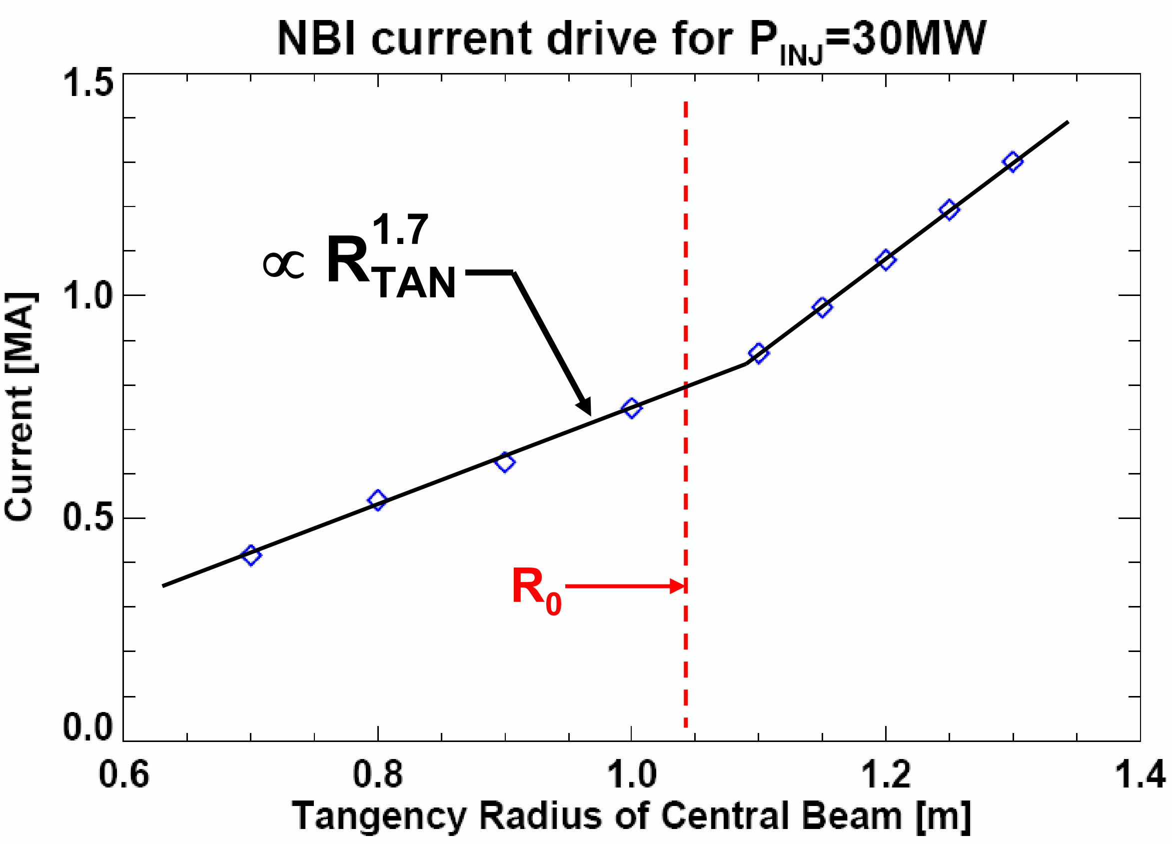
Tangency radius = 70cm for central source



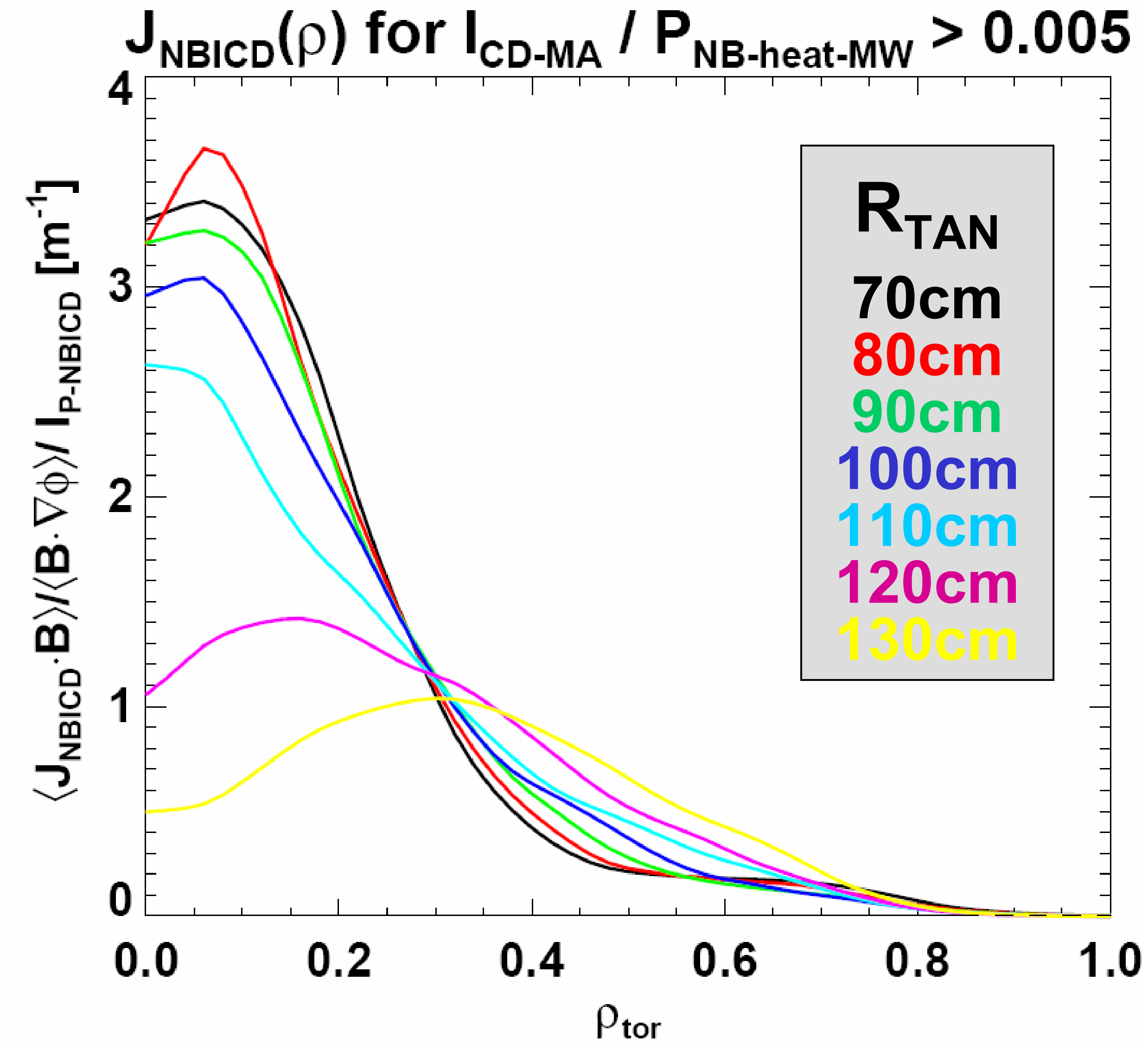
Tangency radius = 130cm for central source

Driven current increases × 3 for $R_{TAN}=0.7 \rightarrow 1.3$m and increases more quickly w/ radius for $R_{TAN} > R_0$

NBICD for $\overline{n}_e = 1.4\times10^{20}$m^{-3}, $\overline{T}_e$=4.2keV, f_{GW} = 0.43

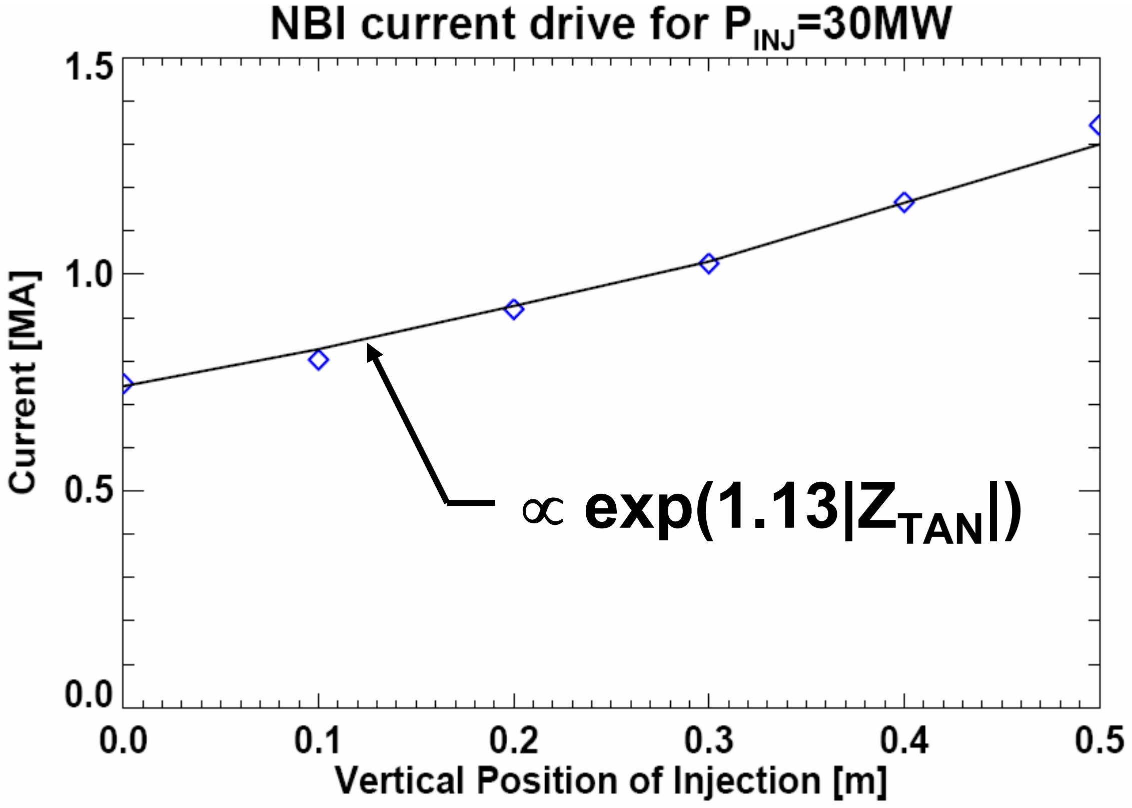


Beam tangency radius variation would enable control of core current and *q* profile

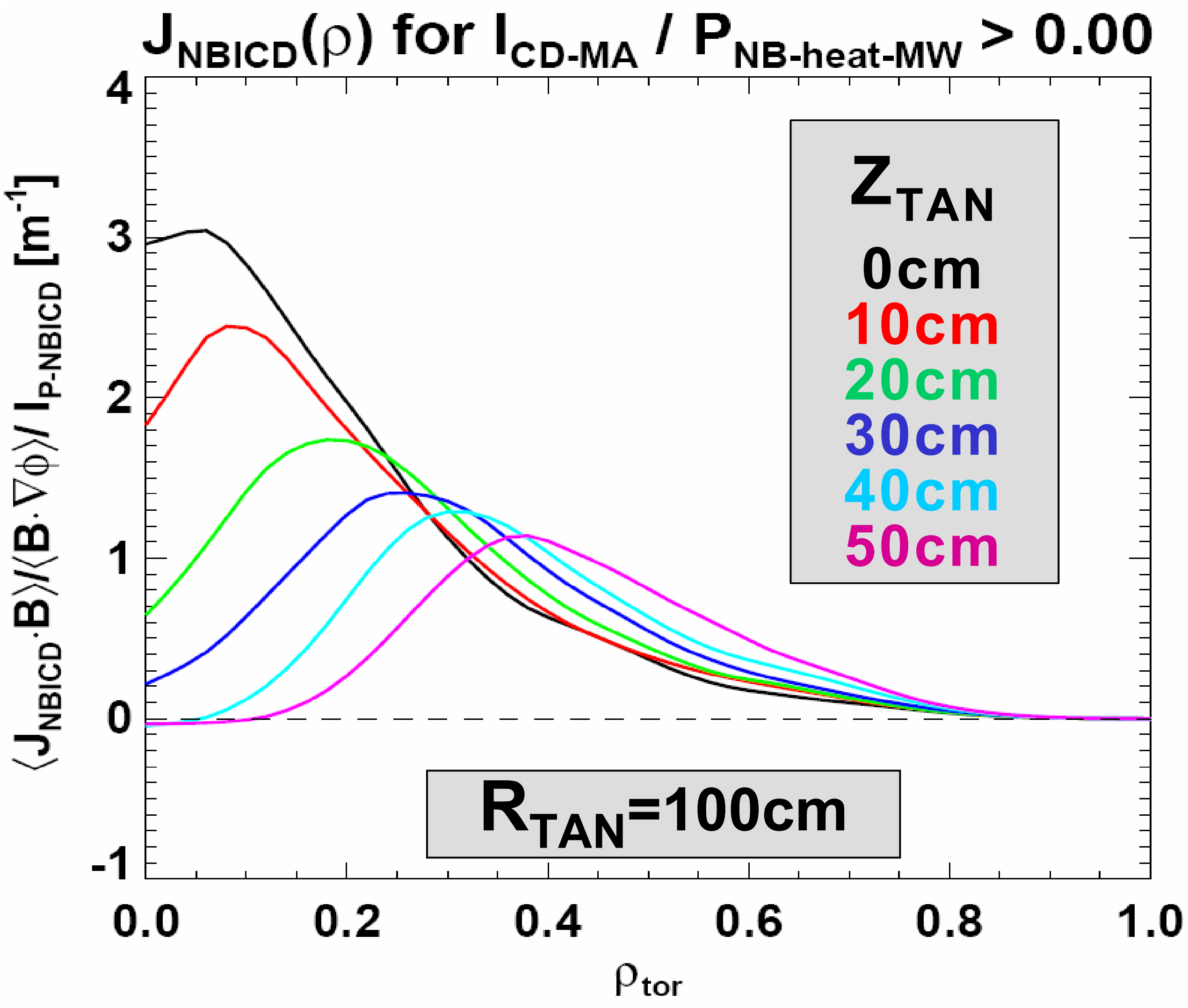


Driven current increases × 1.8 for Z_{TAN}=0.0 → 0.5m for R_{TAN} = 1.0m

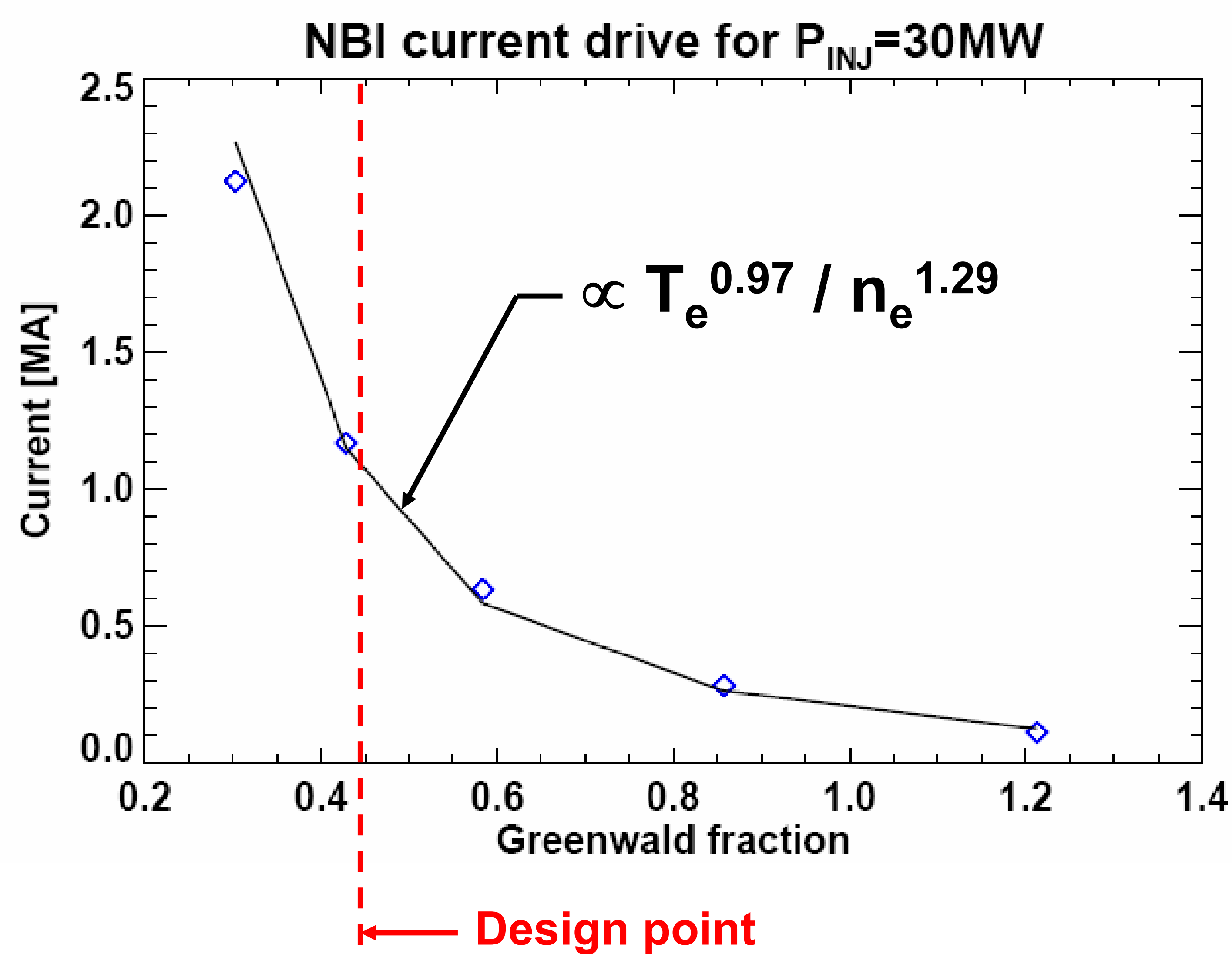
NBICD for $\overline{n}_e = 1.4\times10^{20}m^{-3}$, $\overline{T}_e$=4.2keV, f_{GW} = 0.43



Beam vertical position (Z_{TAN}) variation would also enable control of core current and *q* profile



Ability to control density and operate at $f_{GW} < 0.5$ crucial for high NBICD efficiency



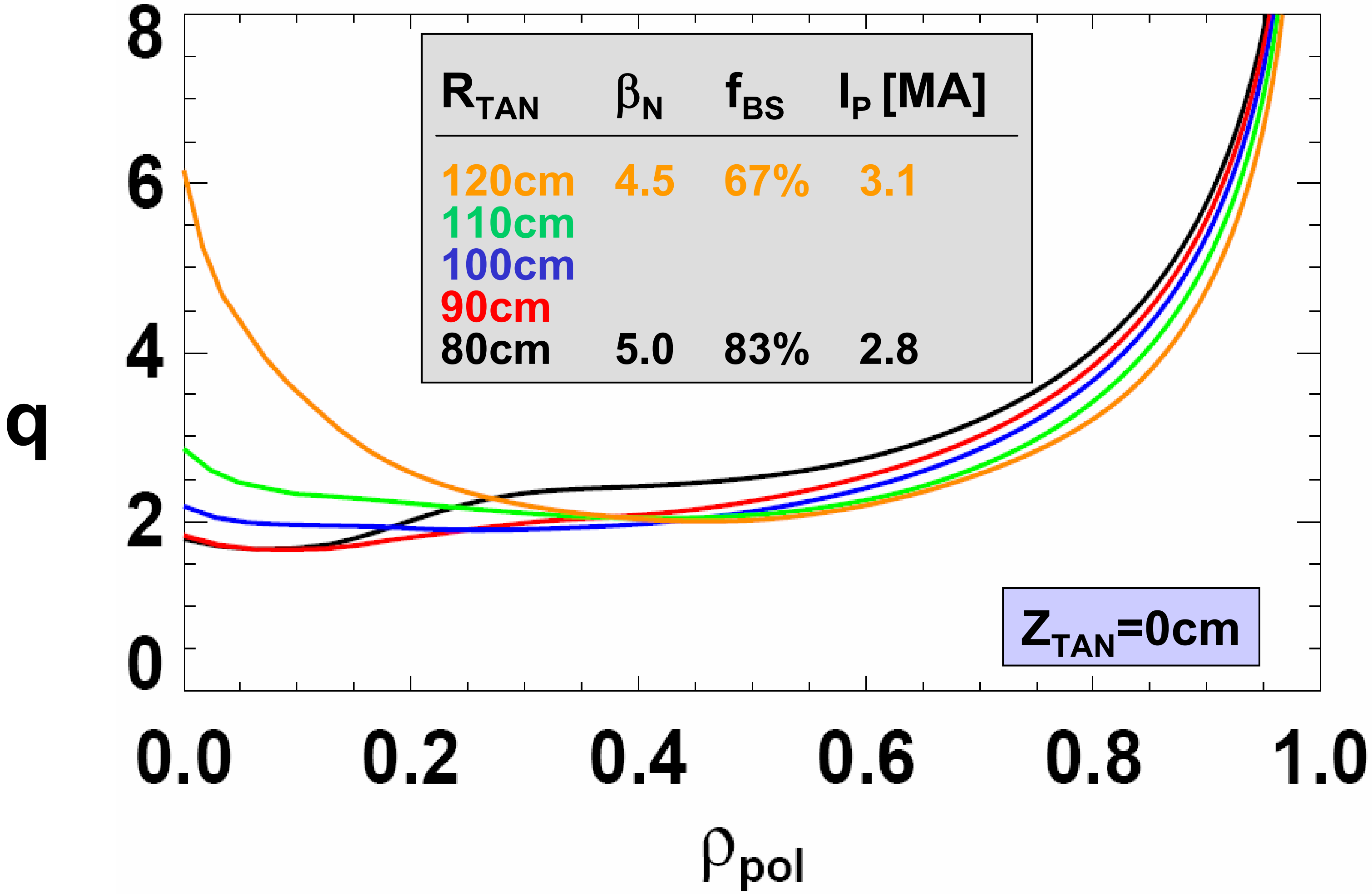
NBI current drive for P_{INJ}=30MW

$\propto T_e^{0.97} / n_e^{1.29}$

Design point

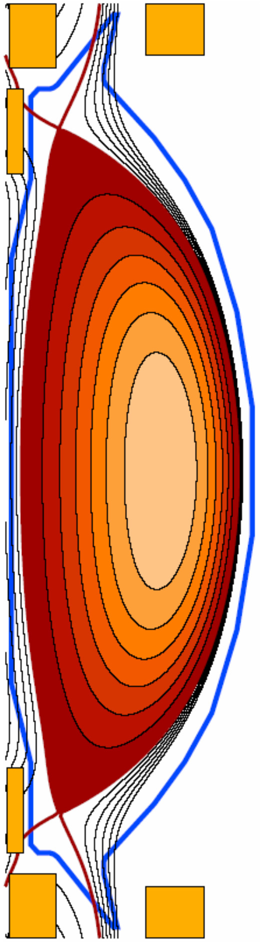
At design point, tangency radius of injection controls degree of shear reversal and radius of q_{MIN}

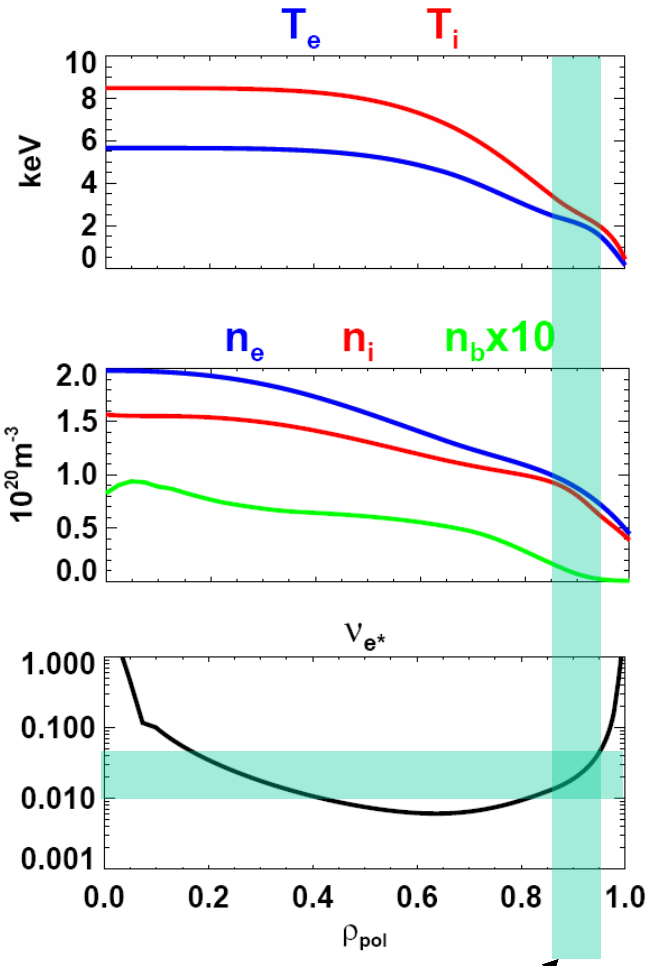
$\overline{n}_e = 1.4\times10^{20} m^{-3}$, $\overline{T}_e = 4.2 keV$, $f_{GW} = 0.43$, $\beta_t = 14\%$



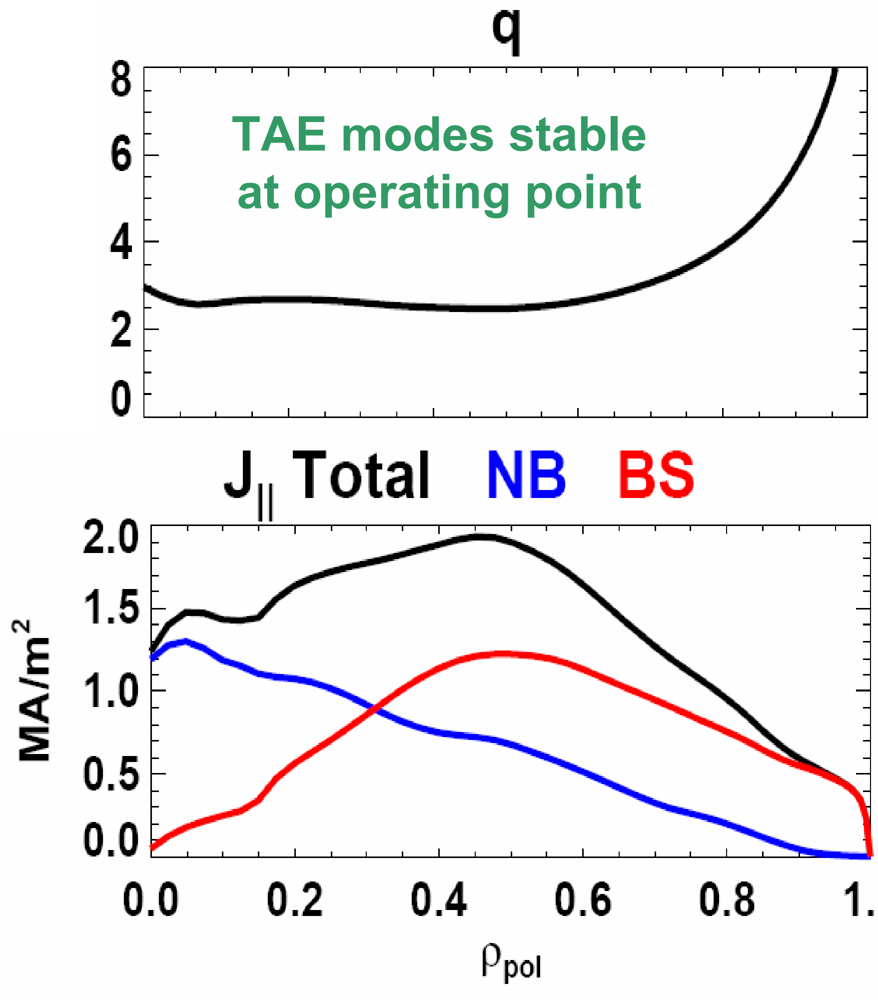
R_{TAN}	β_N	f_{BS}	I_P [MA]
120cm	4.5	67%	3.1
110cm			
100cm			
90cm			
80cm	5.0	83%	2.8

A=1.8, κ=2.85, I_P=3MA target plasma with self-consistent $J(\rho)$ from NBI and BS with q_{MIN} > 2.4





Pedestal ν_{e*} comparable to ITER

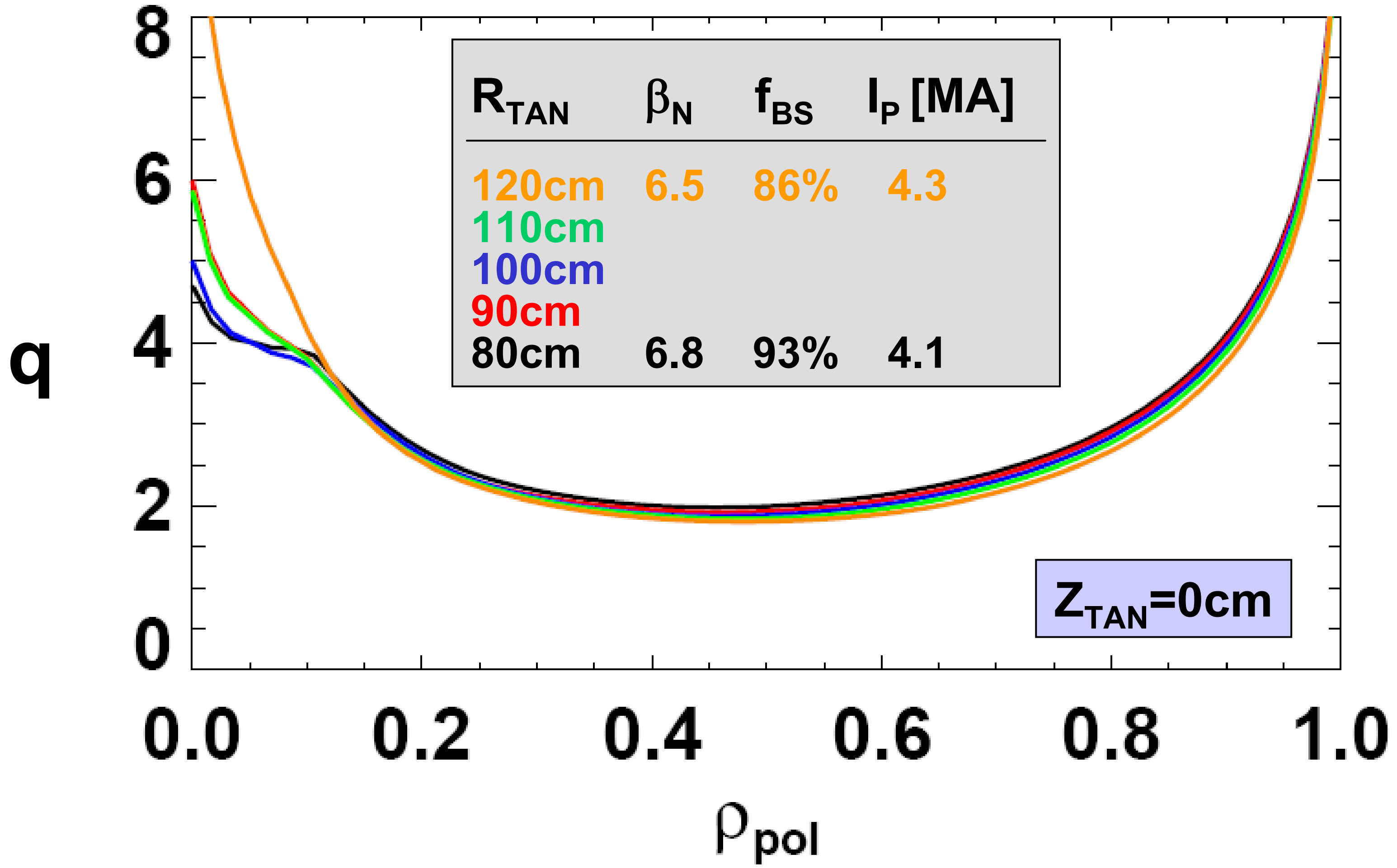


TAE modes stable at operating point

R_{TAN} = 115cm, Z_{TAN}= 0cm

If β_t is doubled, bootstrap current dominates NBI-driven current, and R_{TAN} controls only q(0)

$\overline{n}_e = 2.0\times10^{20}\mathrm{m}^{-3}$, $\overline{T}_e$=6.0eV, f_{GW} = 0.46, β_t = 28%



R_{TAN}	β_N	f_{BS}	I_P [MA]
120cm	6.5	86%	4.3
110cm			
100cm			
90cm			
80cm	6.8	93%	4.1

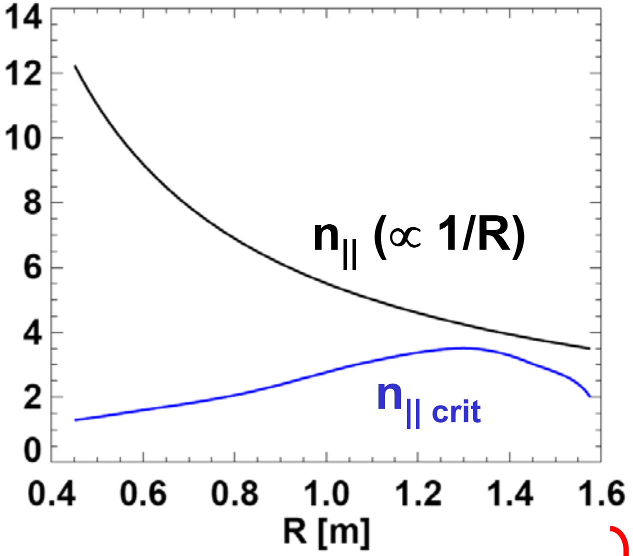
Next step: assess stability and sensitivity to n,T profile shapes

LHCD for lower-density operating points and current ramp-up appears promising

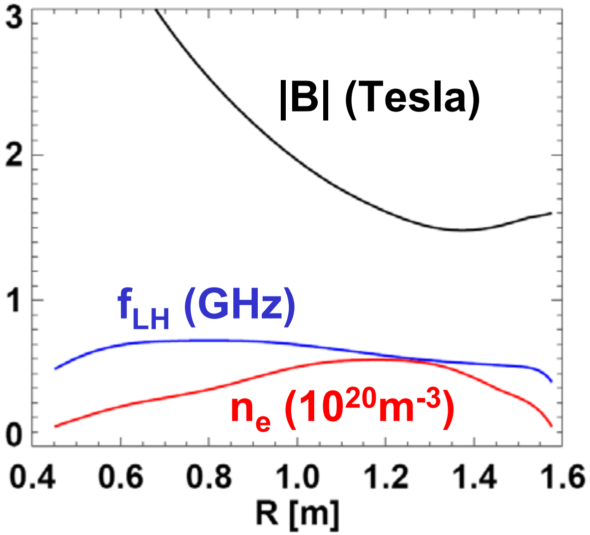
- Require $n_{||} > 3.5$ for $n_e(0) = 6\times10^{19}\,\mathrm{m}^{-3}$
- Find $v_{ph} / v_{the} = 1.5$-3 for $T_e(0) = 3\,\mathrm{keV}$

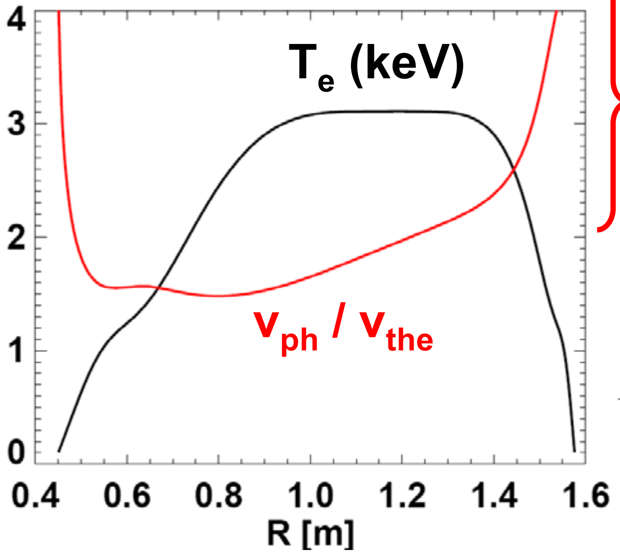
Core LHCD efficiency = 0.1 A/W

1MA of I_P for 10MW delivered



$$n_{||crit} \approx \frac{\omega_{pe}}{|\Omega_e|} + \sqrt{S}$$





v_{ph} / v_{the} for high η_{CD}

$$\frac{I}{P} \simeq \frac{(v_{\rm ph}/v_T)^2}{30}\left[\frac{T_{10}}{R_1 n_{14}}\right]\ \mathrm{A/W}$$

Summary

- Systems code has identified favorable design point:
  - $A=1.8\text{-}2$, $R_0=1\text{m}$, $I_P=3\text{-}4\text{MA}$, $B_T=2\text{T}$, $\kappa=2.7\text{-}3$, full NICD
  - $HH_{98Y} = 1.3$, $\beta_N=4.5$, $\beta_T=15\%$, $f_{BS} \geq 65\%$, $f_{GW}=0.4\text{-}0.5$
  - High β possible with Ω_ϕ & feedback stabilization of RWM
- Favorable coil geometry found for maximum flexibility
  - Divertor flexibility critical element of NHTX mission
- NBI Z_{TAN} and R_{TAN} variations allow control of J_{NBICD}
  - Analyzing engineering tradeoffs of ΔR vs. ΔZ beam shift
- Beginning studies of additional heating & CD sources
  - Up to 18MW of additional RF power

Backup slides

Systems Code Method

- XL-based - uses non-linear optimizer (“Solver”)
- Jardin/Kessel algorithms used for NSST were starting point for Systems Code
- Continued evolution with Peng, Rutherford, Kessel for CTF studies
  - See PPPL Report 4165 “Spherical Torus Design Point Studies”
- Engineering & physics algorithms tailored to suit NHTX

Physics Assumptions in Systems Code

A	1.5-3.0	100% flux surfaces
R0	0.9-1.0m	
kappa	3.674/SQRT(A)	Goldston
delta	0.6	Fixed
qcyl	4/3*(12.259-13.58*A+6.4286*A^2-1.0417*A^3)	Multiple of Menard
beta_N	<= limit 6.43-1.02*A	Fit to Menard no-wall limit
α_n=α_T	(0.64-0.3/A)/2	Menard model
peaking factor (pf)	ŗ(1-(r/a)^2)^α_n*(1-(r/a)^2)^α_T	
kBS	0.344+0.195*A	Menard model
fBS	Beta_P*kBS*pf^0.25/SQRT(A)	
Confinement	Ti=Te, HH98=1.3	Also examined Ti .ne. Te w/HHe=0.7-1.3
Solenoid Flux	85% Hirshman-Neilson flux, ramp-up only	85% factor matches formula to Menard data
Non-inductive CD	Bootstrap + NBI (4*8=32MW) @ 110keV	
Paux	32MW (NBI) + 6MW (RF) = 38MW	Beta limited
NBI alignment	Normalized to 90,100,110 cm tangency for R0=0.95m, A=1.8 case	Kaye
PF Currents	Amp-turns scaled from Menard equilibrium @ 3MA (A=1.8)	

Engineering Assumptions in Systems Code

TF Inner Leg Heating	Jcu_avg <= 5.75kA/cm^2	dz=kappa*a+1.425m, packing fraction f(Jcu_avg,dZ) based on KCOOL, v=10m/s, Tcu_max=100C
TF Inner Leg Stress	Radial stress <=138MPA	Insulation shear stress is tracked
TF Outer Leg Heating	Minimize J but maximizing CSA of outer legs within available space, considering NBI alignment	
TF Outer Leg Stress	Not Modeled	
OH Heating	G-function adiabatic	dz=f(kappa*a)
OH Stress	Hoop stress <=138MPA	
PF Heating	Jcu_avg <= 2.5kA/cm^2	KCOOL analysis assumes conductor area per turn 1.5*CSA of existing PF coils, 10 turns per cooling path, 15kA per turn
PF Stress	Not Modeled	
Center Stack Casing (VV) Heating and Radial Build	25% of Paux impinges on CS over dZ=2*kappa*a	Radial build based on heat flux, ferritic steel w/15% cooling fraction, 400C, 4MPa He cooling at 150m/s
PFC Heating	Not Modeled	
PFC Stress	Not Modeled	
Transrex Capacity	15kA/PSS, 3.25kA rms	Irms is limiting (Trep~20min)
MG	TF/PF/OH Loads W<=4.5GJ, CCV on during pulse	
Grid	NBI/MG/BOP Loads P<=200MW	Approved by PSE&G for TPX, requires local D-site substation and p.f. correction
Cooling Water Systems	Total flow requirement based on total energy dissipation, rep rate limited by 20MW heat removal	60-10=50C rise typ. deltaT

Beyond high P/R, NHTX provides high $P/P_{L\rightarrow H}$ required for testing radiative power dispersal techniques

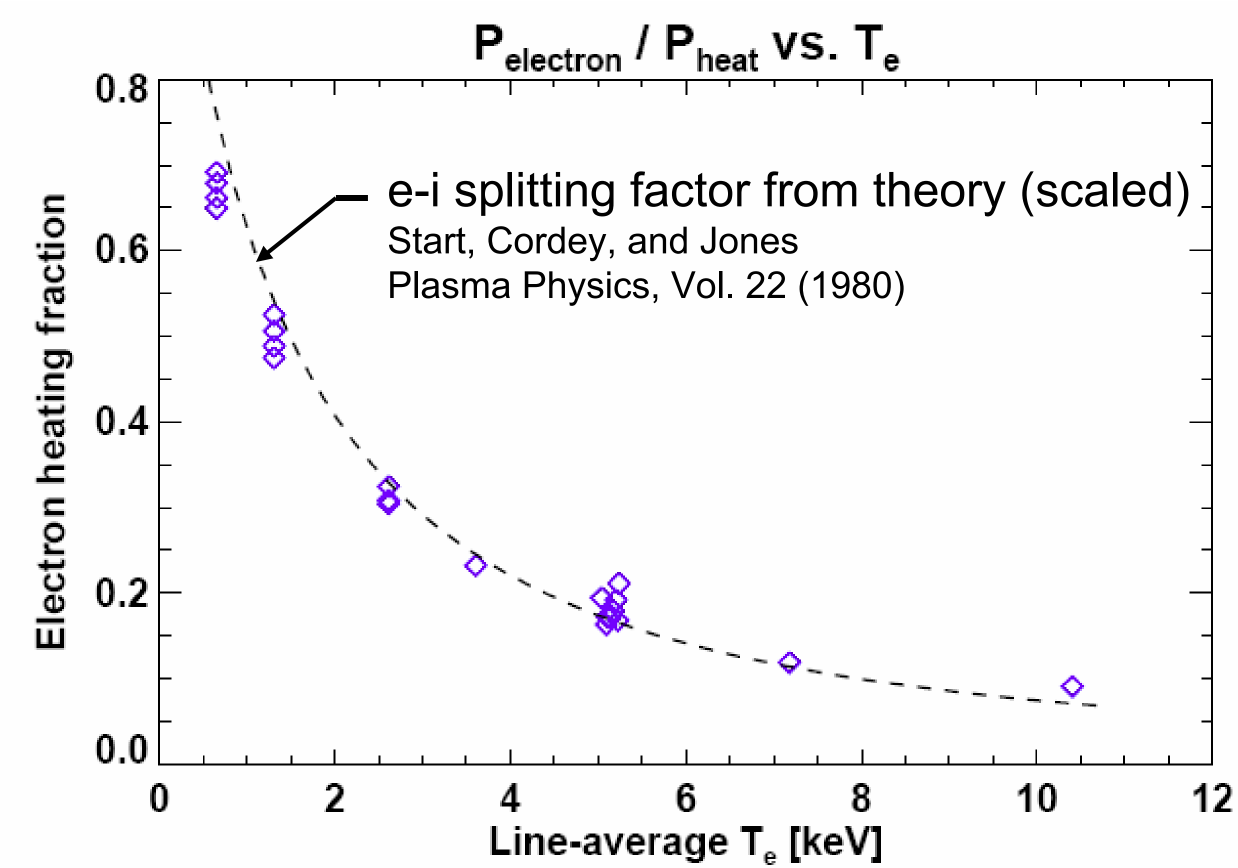
- Can fusion plasmas operate at high τ_E and β with 90% core radiated power, to reduce divertor heat flux?
- Physics test requires input power exceeding H-mode threshold power by a very large factor ~ 10.
- NHTX has unique capability to test the Demo-relevant physics in this area:

	$P_{in}/P_{L\rightarrow H}$ @ $0.85 \times n_{gw}$
ITER	**3.6**
JT-60SA	**4.9**
ARIES-AT	**11**
NHTX	**12**

The solution to the power-dispersal problem has order-unity impact on CTF/FDF and Demo design

NBICD assessment with TRANSP tests CD efficiency scalings from analytic theory used in 0D optimizations

- Expect $\eta_{CD} \propto I_{NBICD} / P_{heat} \propto T_e^{3/2} / n_e$ (i.e. τ_s) × e-i splitting factor × e-shielding factor
- At high T, fast ions lose energy primarily to thermal ions → J_{circ} should be reduced
- **e-i splitting factor from theory scales like e-heating fraction from TRANSP**



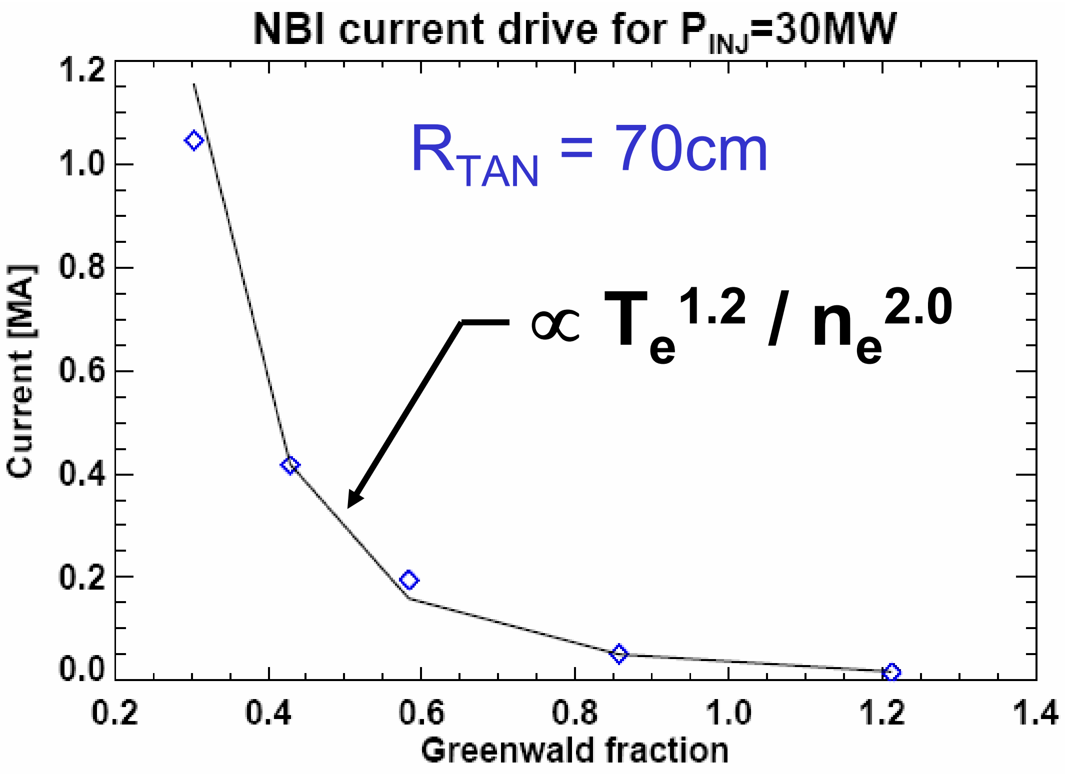
e-i splitting factor from theory (scaled)

Start, Cordey, and Jones

Plasma Physics, Vol. 22 (1980)

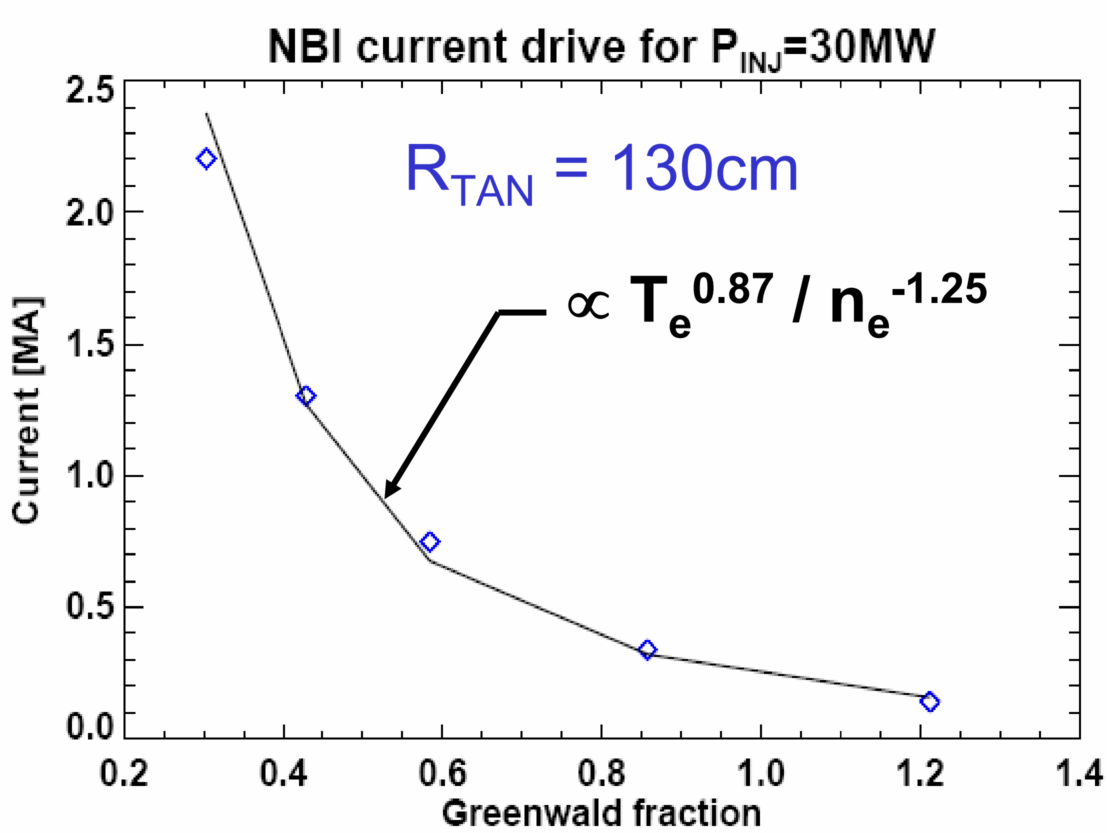
For $R_{TAN} < R_0$, TRANSP predicts T_e / $\mathbf{n_e^2}$ CD efficiency scaling when line-averaged T, n parameters are used:

- Expect faster than $1/n_e$ scaling from broadened deposition into lower local T_e when n_e is increased
- However, NSTX studies w/ ***flat*** core profiles find similar scaling

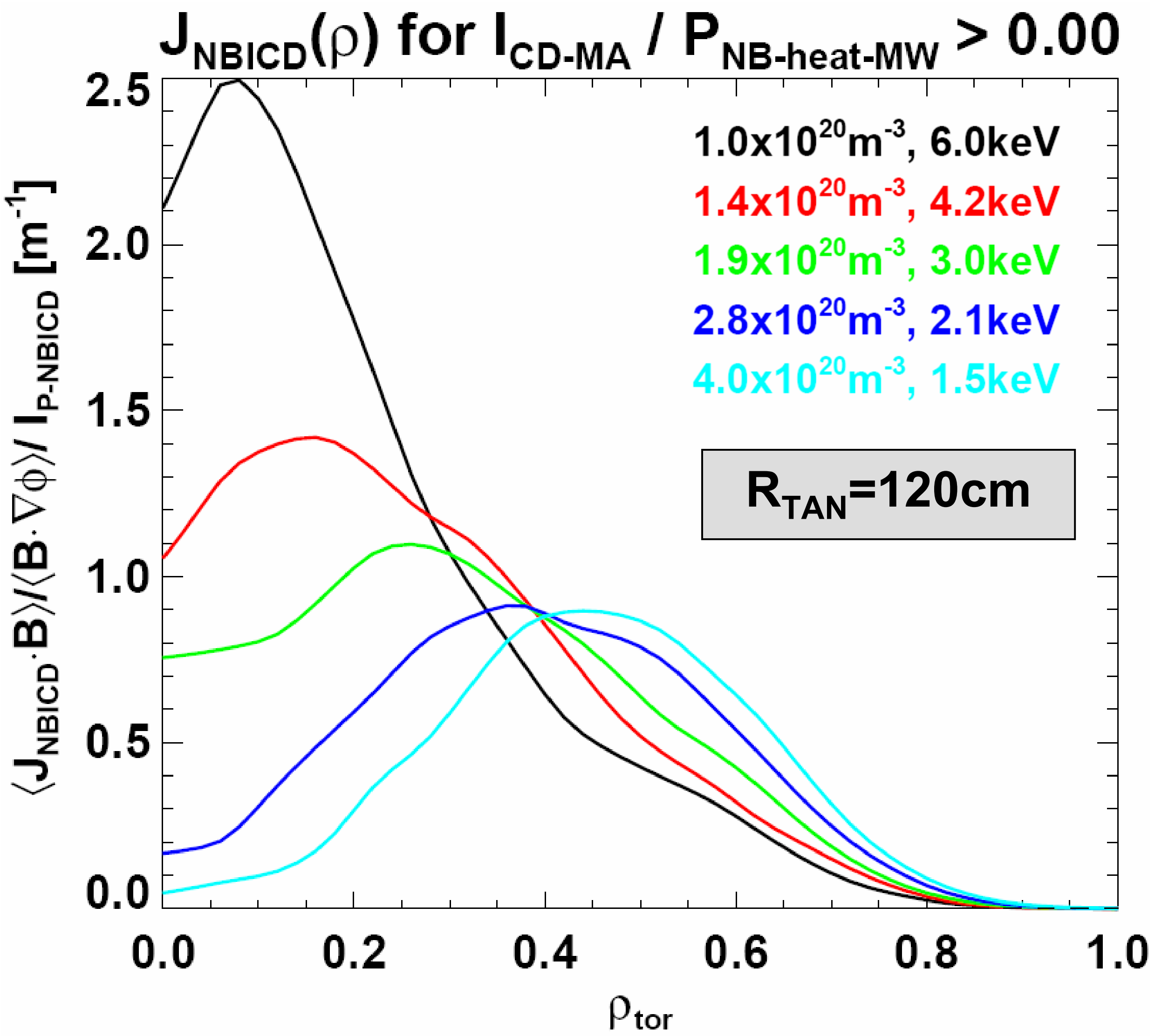


For $R_{TAN} > R_0$, TRANSP predicts CD efficiency scaling closer to $\mathbf{T_e / n_e}$

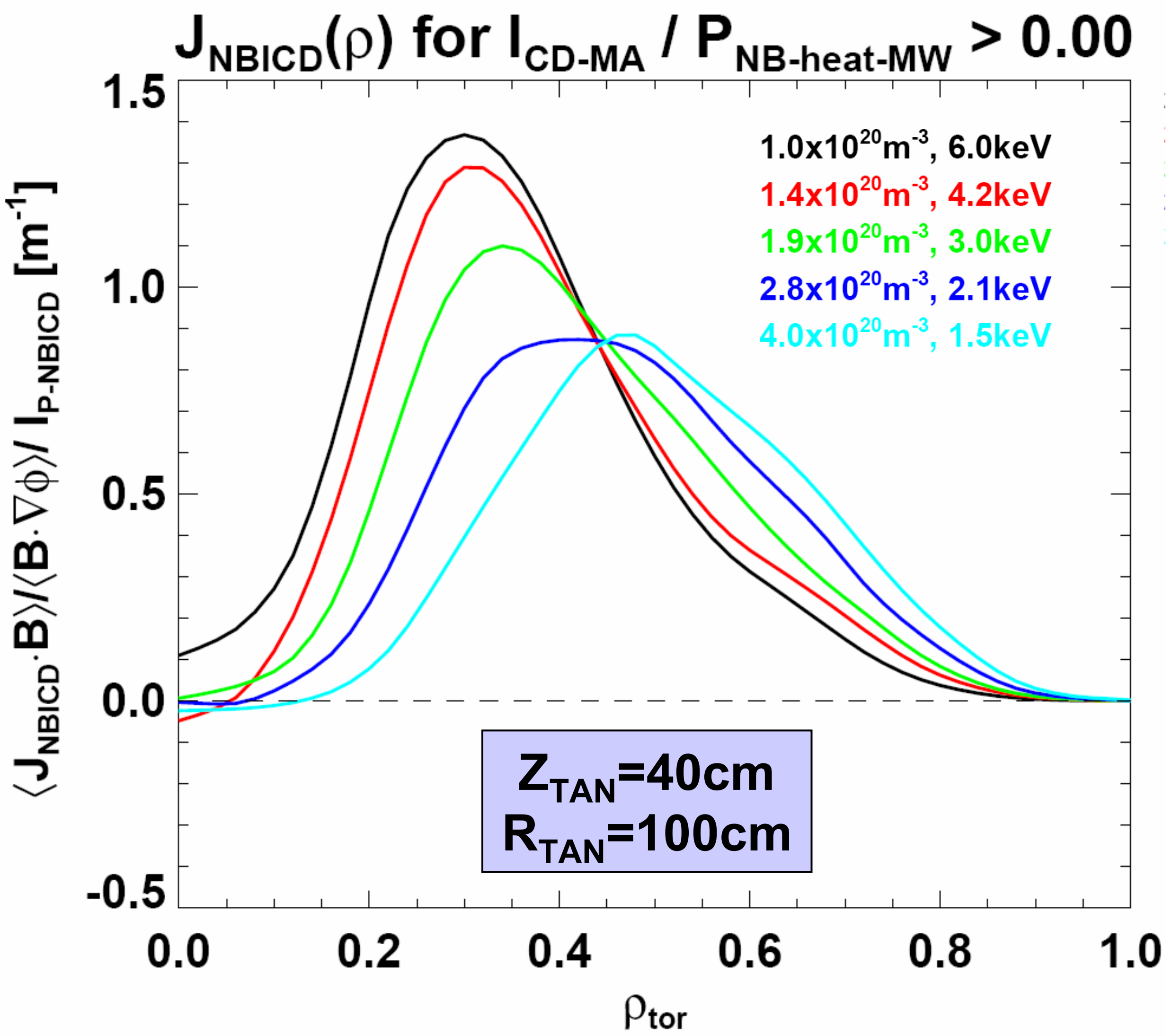
- Implies injection geometry more important than profile effects
- Possible explanation: small R_{TAN} produces increasingly ⊥ fast ions as n_e increases and deposition profile broadens



For outboard beam tangency radius, driven current profile broadens significantly at high density



For vertically shifted beams, driven current profile shape is less sensitive to variations in density



Additional LHCD at nominal operating point could be challenging due to LFS accessibility requirement

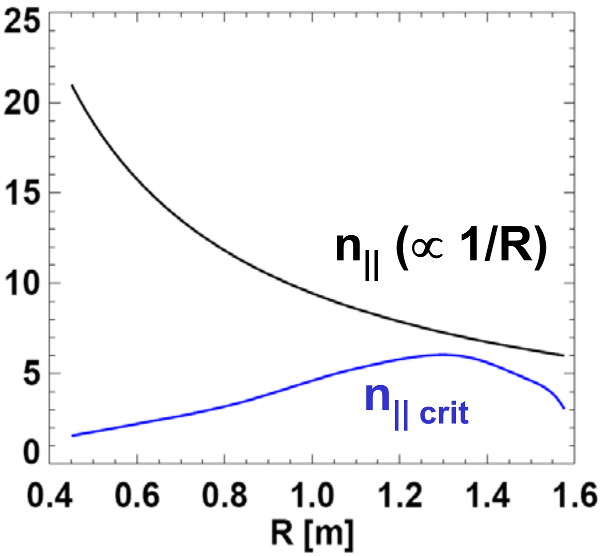
- Require $n_{||} > 6$ assuming $k_{||} \propto 1/R$
- Find $v_{ph} / v_{the} < 1$ inside $\rho < 0.8$
- Want v_{ph} / v_{the} = 2-5 for high η_{CD}

Core LHCD efficiency = 0.01 A/W

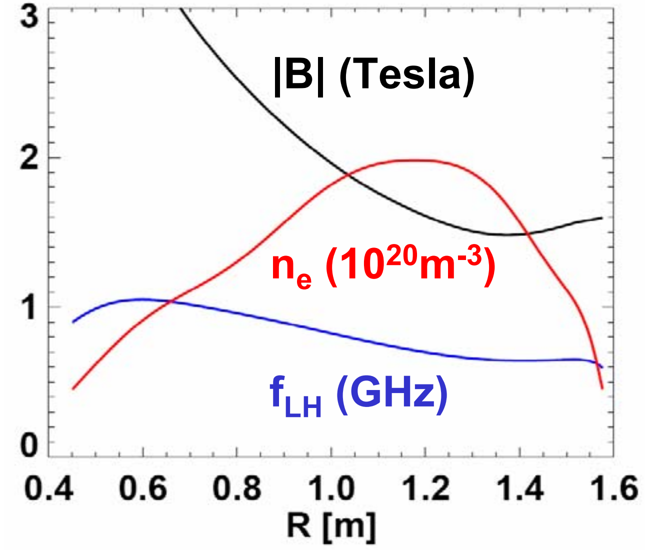
0.1MA of I_P for 10MW delivered

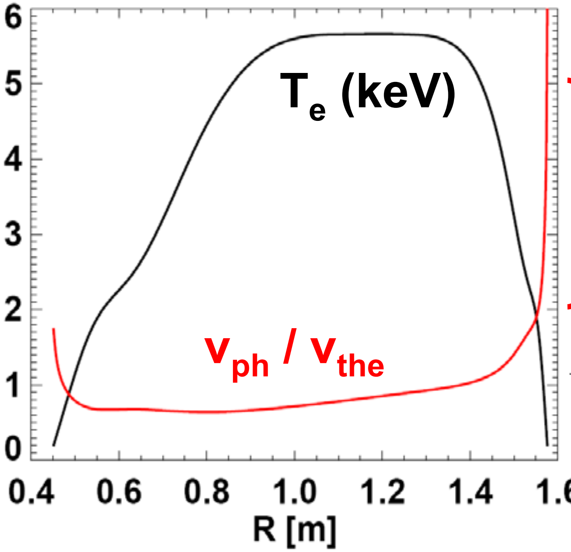
Use LH for bulk heating w/o torque?

- **Try poloidally directed launch at LFS + $k_{||}$ downshift at HFS? (need ray-tracing)**



$$n_{||crit} \approx \frac{\omega_{pe}}{|\Omega_e|} + \sqrt{S}$$





v_{ph} / v_{the} for high η_{CD}

$$\frac{I}{P} \simeq \frac{(v_{ph}/v_T)^2}{30} \left[\frac{T_{10}}{R_1 n_{14}} \right] \text{A/W}$$