# NCSX GOALS and PROJECTED PLASMAS

M.C. Zarnstorff, R. Goldston, L-P Ku, Z. Lin,
R. Majeski, H. Mynick, H. Neilson, M. Redi, A. Reiman,
D. Spong, and the NCSX Team

PPPL, ORNL

1999 APS/DPP
Seattle, WA

NCSX is a medium-scale quasi-axisymmetric stellarator, designed to achieve $\beta \sim 4\%$ at aspect ratio $A \sim 3.4$ with passive stability to the ballooning, external kink, vertical, and neoclassical-tearing instabilities via 3D shaping without a conducting wall. The proposed experiment will test these theortical predictions of stability and whether plasmas can be obtained near the beta-limit without disruptions. The quasi-axisymmetric optimization of the magnetic field gives orbit-confinement and neoclassical transport similar to tokamaks. This should allow tokamak-like manipulation of $E \times B$ flow-shear for controlling turbulent transport. Target plasma parameters have been projected using empirical scaling and numerical calculations of fast ion and thermal-plasma neoclassical losses. They indicate that the $\beta \sim 4\%$ goal can be attained using 6MW of NBI assuming a confinement enhancement 2.3 times ISS-95 scaling or 1.6 times ITER-89P scaling. Projections for several configurations and confinement levels will be presented.

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# The Compact Stellarator Design Team

R. D. Benson, ORNL
L. A. Berry, ORNL
B. Blackwell, ANU
A. H. Boozer, Columbia U.
A. Brooks, PPPL
T. G. Brown, PPPL
M. Cole, ORNL
W. Cooper, CRPP
M. Drevlak, IPP-Greifswald
G. Y. Fu, PPPL
P. Garabedian, NYU
A. Georgievskiy, Raytheon
R. J. Goldston, PPPL
P. Goranson, ORNL
J. Hanson, Auburn U.
P. Heitzenroeder, PPPL
S. P. Hirshman, ORNL
W. Houlberg, ORNL
M. Isaev, Kurchatov
C. E. Kessel, PPPL
L.-P. Ku, PPPL
H. Kugel, PPPL
E. Lazarus, ORNL
Z. Lin, PPPL
J. F. Lyon, ORNL
R. Majeski, PPPL
P. Merkel, IPP-Greifswald
M. Mikhailov, Kurchatov
D. Mikkelsen, PPPL
W. Miner, U. Texas
D. A. Monticello, PPPL
H. Mynick, PPPL
N. Nakajima, NIFS
G. H. Neilson, PPPL
B. E. Nelson, ORNL
C. Neuhrenberg, IPP-G.
M. Okamoto, NIFS
N. Pomphrey, PPPL
M. H. Redi, PPPL
W. T. Reiersen, PPPL
A. H. Reiman, PPPL
G. Rewoldt, PPPL
R. Sanchez, CIEMAT
J. A. Schmidt, PPPL
J. Schultz, MIT
R. T. Simmons, PPPL
D. A. Spong, ORNL
D. Strickler, ORNL
A. Subbotin, Kurchatov
P. Valanju, U. Texas
K. Y. Watanabe, NIFS
R. B. White, PPPL
D. A. Williamson, ORNL
M. C. Zarnstorff, PPPL
I. Zatz, PPPL

**Auburn U., Columbia U., ORNL, PPPL, U. Texas-Austin, U. Wisconsin.**

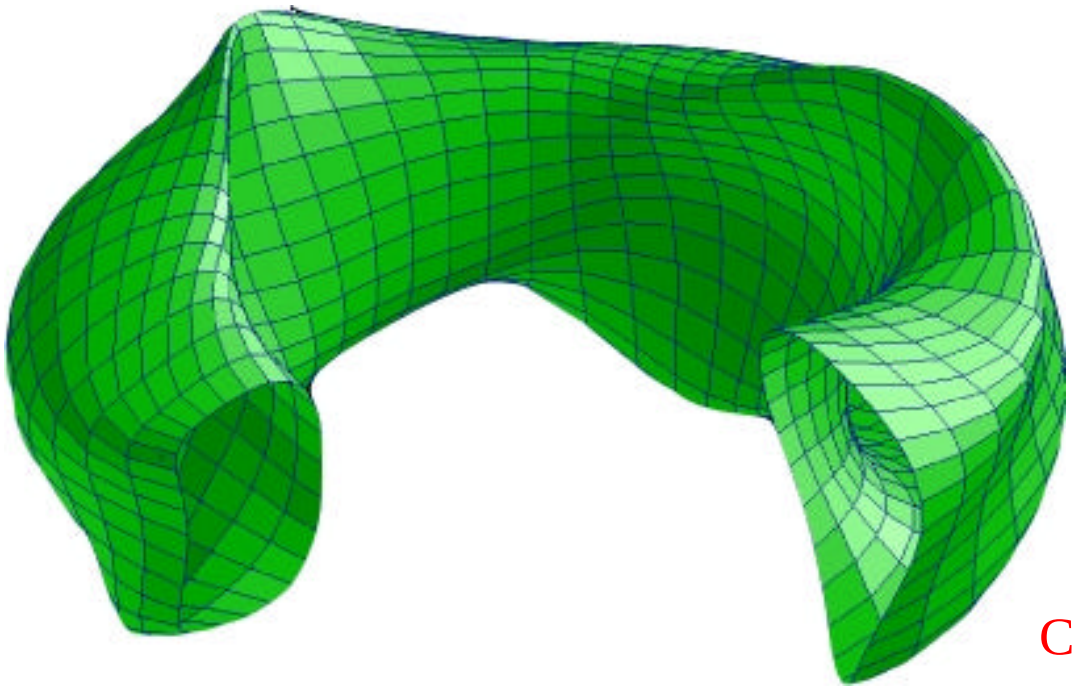
**Germany, Switzerland, Russia, Japan, Australia**

# NCSX Research Goals

- High-beta disruption-free operation, compatible with bootstrap & external transform, at low aspect ratio (A < 4)
- Determine beta limits and limiting mechanisms
- Reduction of neoclassical transport by quasi-axisymmetric (QA) design
- Reduction of anomalous transport by flow-shear control, using reduced flow damping by QA design
- Equilibrium island and neoclassical tearing-mode stabilization by design of magnetic shear
- Test compatibility with power and particle exhaust methods

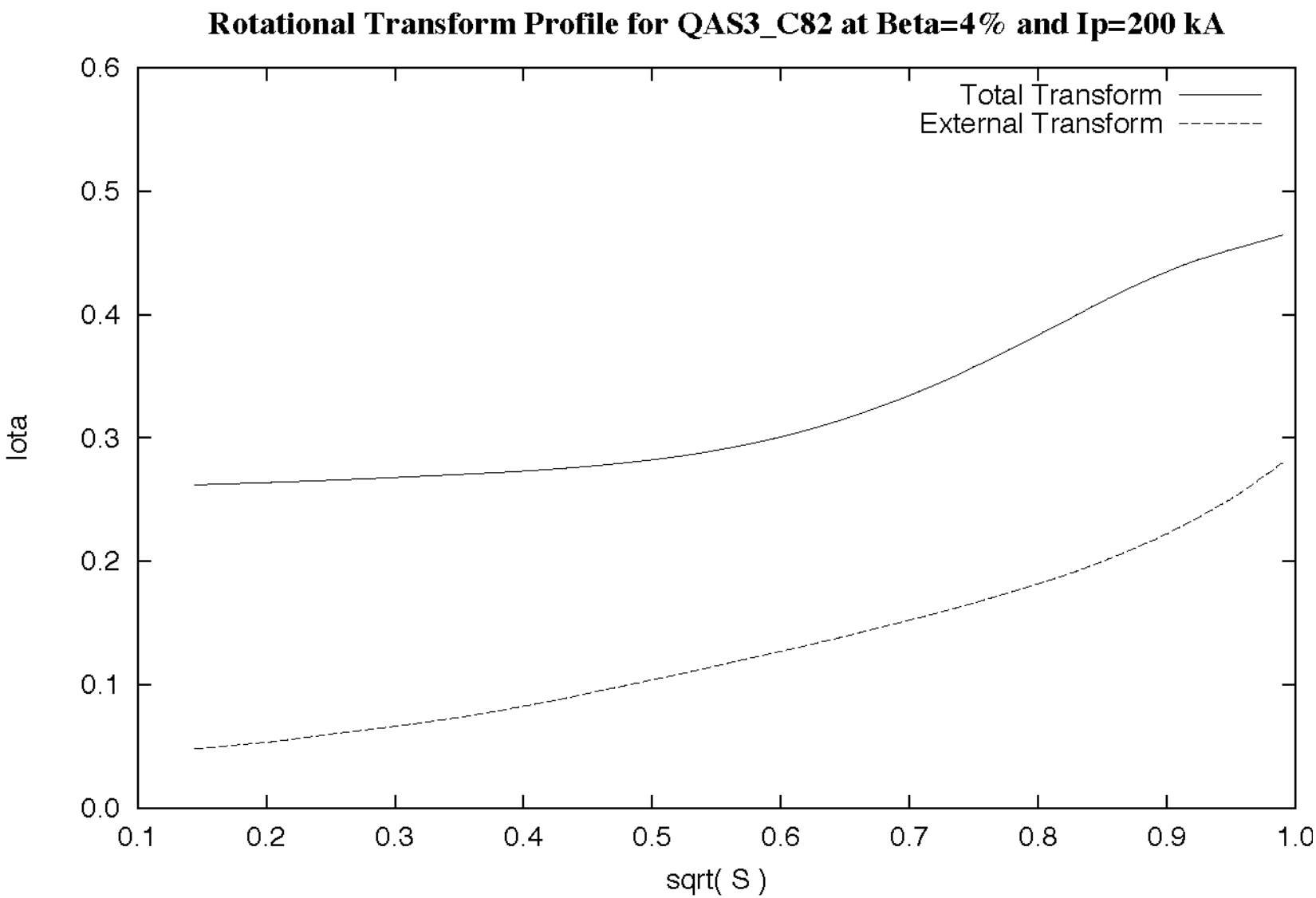
NCSX: Proof-of-Principle facility for integrated testing of compact stellarator plasmas

# NCSX Configuration Stable at $\langle\beta\rangle$ = 4%

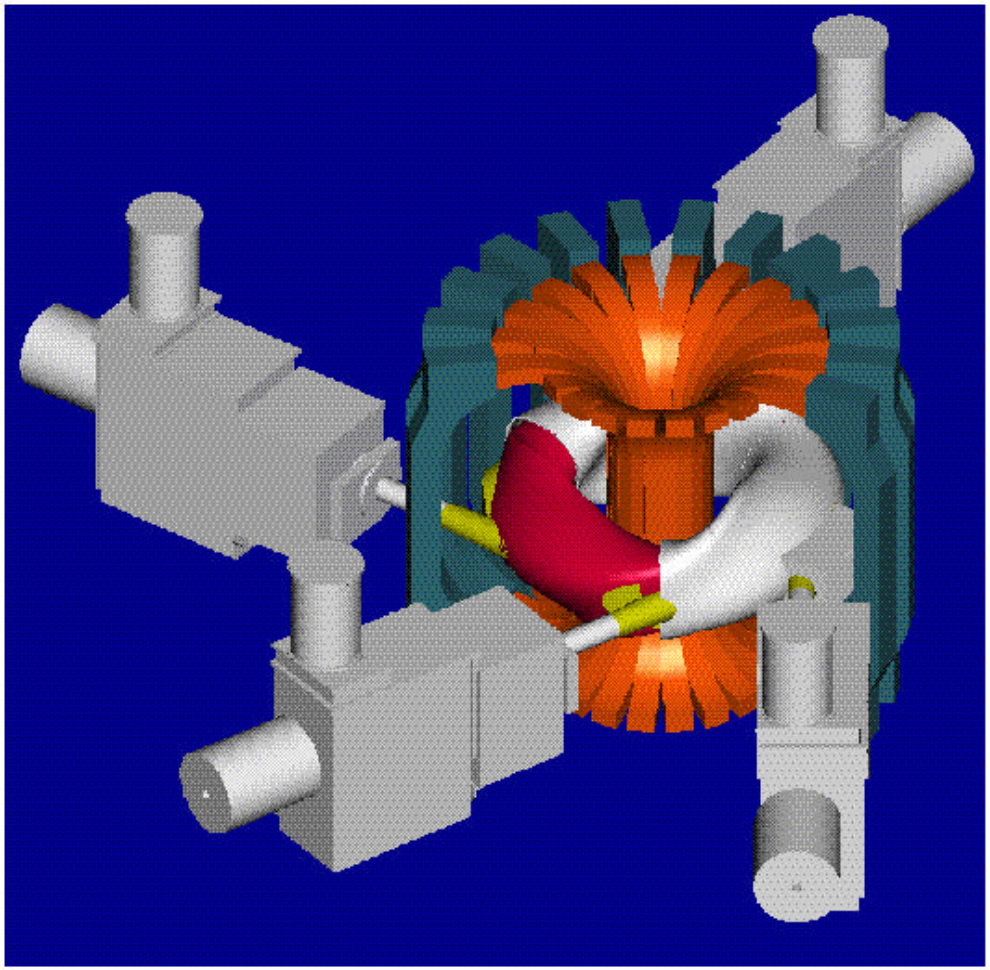


C82

- 3 periods, $\langle A\rangle$=3.4, Quasi-axisymmetric
- Stable to ballooning, kink,vertical, mercier modes at $\langle\beta\rangle$=4% without nearby conducting wall
- Bootstrap-like current profile, increases iota. $I_P$ ~ 200 kA at B=1 T.
- Stellarator shear ($dq/dr < 0$), for neoclassical island stabilization
- Configuration c10 is predecessor with lower kink beta limit, but better confinement.


Rotational Transform Profile for QAS3_C82 at Beta=4% and Ip=200 kA
Total Transform
External Transform
Iota
sqrt( S )
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

# The NCSX Construction Cost Will Be Reduced By Re-Using PBX-M Magnets and Neutral Beams



**Machine Parameters**

- R=1.45 m, ⟨a⟩=0.42 m
- B≥1.2 T / $t_p$≥0.5 s

**Plasma Heating:**

- NBI: 6 MW
- ICRF: 6 MW available

- Also re-use existing diagnostics, power supplies, C-site infrastructure at PPPL.

# NCSX Beam-Ion Confinement

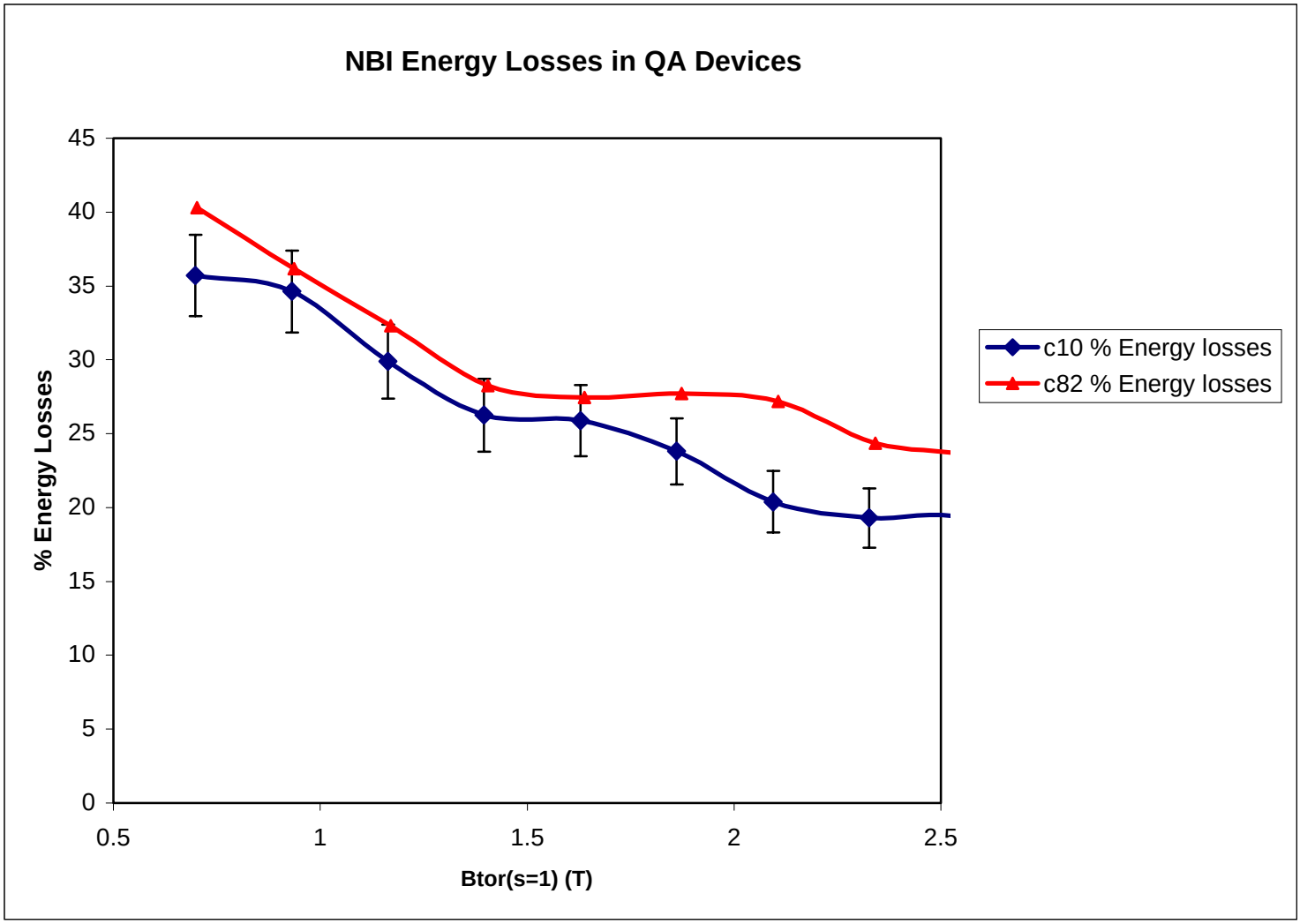
- Simulated using Monte-Carlo codes in full 3-D geometry, using model plasma parameters and profiles
- Two codes
  - Spong's: full collision operator
  - Orbitmn: pitch-angle scattering and slowing down rate (taken as independent of energy)

- Deposition profile is from simulation by Transp, using the oblate poloidal cross-section geometry (as a 2-D calculation)

- Losses are accumulated until particles slow-down to $^3/_2$ $T_I$
  or for a fixed number of slowing-down times (Orbitmn)

- Emphasis on $H^0$ injection into $H^+$ plasma
  $D^0$ losses are $\sim \sqrt{2}$ higher

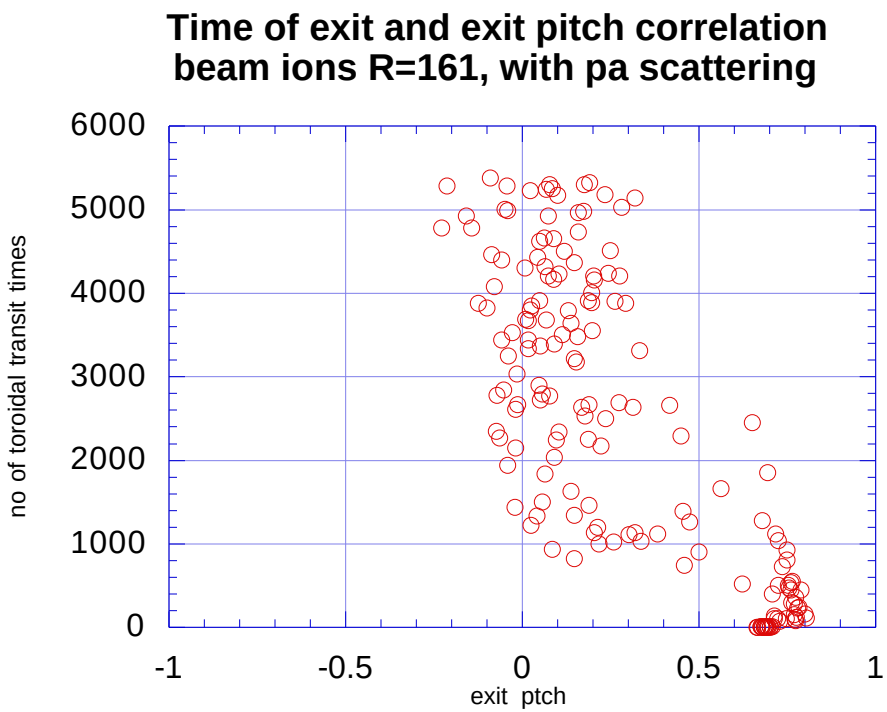
# Similar NB Losses Calculated for all NCSX Configurations




D. Spong

- Full 3D orbit following calculation, with full collision operator

- $H^0 \rightarrow H$, co-only NBI


Time of exit and exit pitch correlation
beam ions R=161, with pa scattering
no of toroidal transit times
6000
5000
4000
3000
2000
1000
0
-1
-0.5
0
0.5
1
exit ptch

M. Redi

# Thermal Neoclassical Transport Calculated by 3D Monte-Carlo Code

Use GTC (gyrokinetic) Monte-Carlo code to simulate neoclassical losses for each species.

- $\delta f$ simulation for electrons
- $f$ simulation for ions

- Use $e\Phi = -T_i (r/a)^2$ to approximate ion-root $E_r$ solution
  increases confinement by ~30%

- Electron neoclassical transport negligible compared to ion transport

- Scales as ~ $B^2$ (c10)
  - Use in 0D spreadsheet model to identify operating points, or

  - Iterate profiles $\rightarrow \tau_{Ei}^{neo}$ in 1D transport solution, using empirical Te or anomalous transport simulation

H. Mynick, Z. Lin, I. Zatz

# NBI Operating Points in NCSX (c10)

R=1.45 m, $\langle a \rangle$=0.42 m, $Z_{eff}$=2

| Scenario | 4% $\langle\beta\rangle$ | Reactor collisionality |
|---|---|---|
| Magnetic field, B (T) | 1.2 | 1.2 |
| Injected power, P (MW) | 5.3 | 5.5 |
| Volume-avg. beta $\langle\beta\rangle$ (%) | 4.0 | 3.0 |
| Volume-avg. density, n ($10^{19}$ $m^{-3}$) | 10.1 | 5.4 |
| Central temperature, $T_0$ (keV) | 1.4 | 2.0 |
| Collisionality parameter ($nR/T^2$) | 7.3 | 2.0 |
| $\tau_E$ (ms) | 45 | 33 |

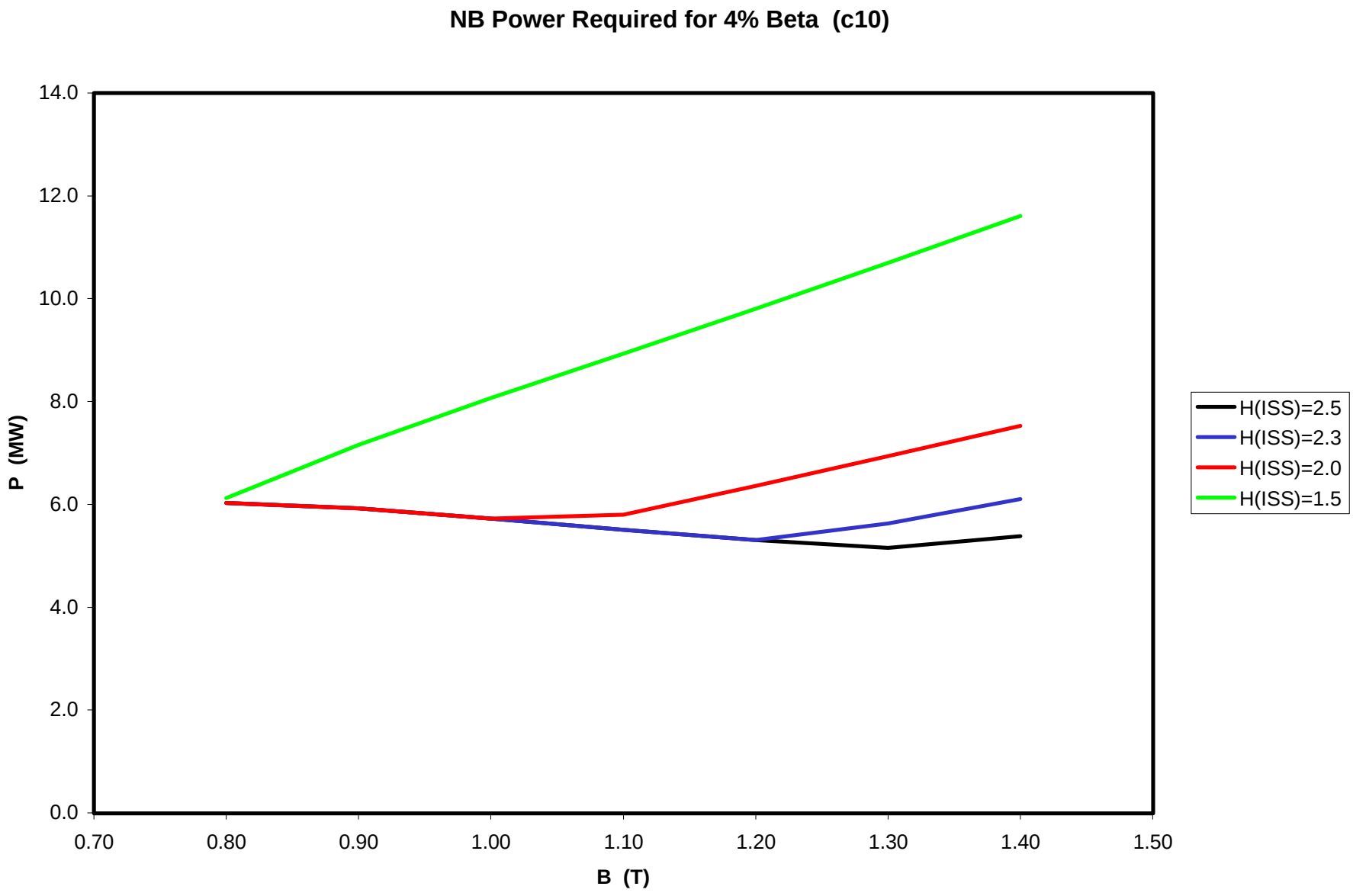
- $\tau_E^{assumed} = \min(2.3\times\tau_E^{ISS95}, \tau_E^{neo}/2)$
- NBI orbit losses per Monte Carlo calculations
- Neoclassical confinement times per gyrokinetic simulations.
- Density less than Sudo limit, by constraint.
- Includes 10% beam beta.

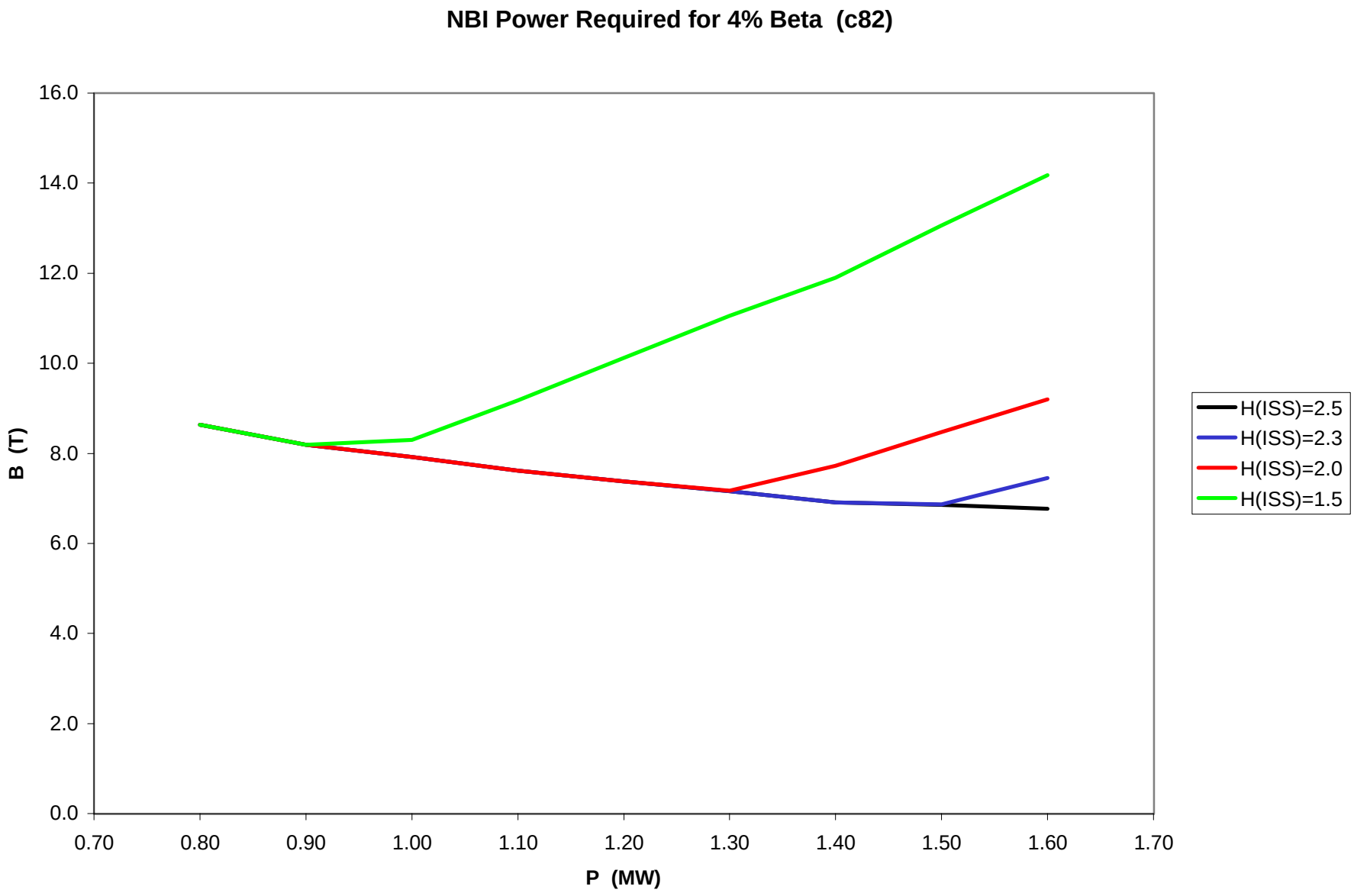
# NBI Operating Points in NCSX (c82)

R=1.45 m, $\langle a \rangle$=0.42 m, $Z_{eff}$=2

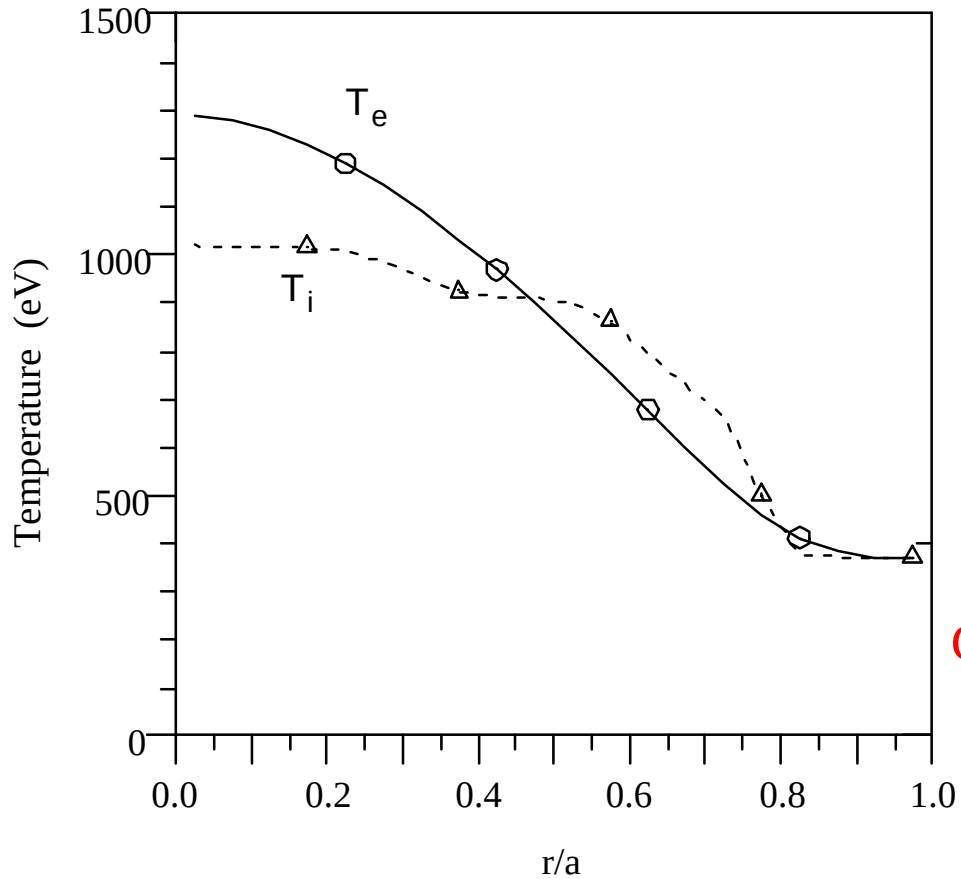
| Scenario | max $\langle \beta \rangle$ | Reactor collisionality |
|---|---|---|
| Magnetic field, B (T) | 1.5 | 1.5 |
| Injected power, P (MW) | 5.5 | 5.5 |
| Volume-avg. beta $\langle \beta \rangle$ (%) | 3.2 | 2.6 |
| Volume-avg. density, n ($10^{19}$ $m^{-3}$) | 11.3 | 6.6 |
| Central temperature, $T_0$ (keV) | 1.6 | 2.2 |
| Collisionality parameter ($nR/T^2$) | 6.4 | 2.0 |
| $\tau_E$ (ms) | 53 | 43 |

- $\tau_E^{assumed} = \min(2.3 \times \tau_E^{ISS95}, \tau_E^{neo}/2)$
- NBI orbit losses per Monte Carlo calculations. Includes 10% beam beta.
- Neoclassical confinement times per gyrokinetic simulations.
- Density less than Sudo limit, by constraint.
- Need 6.9 MW to get to 4% beta.


NB Power Required for 4% Beta (c10)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
P (MW)
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
B (T)
H(ISS)=2.5
H(ISS)=2.3
H(ISS)=2.0
H(ISS)=1.5


NBI Power Required for 4% Beta (c82)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
B (T)
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
P (MW)
H(ISS)=2.5
H(ISS)=2.3
H(ISS)=2.0
H(ISS)=1.5

# Transport Simulation for 1D Profiles




C82

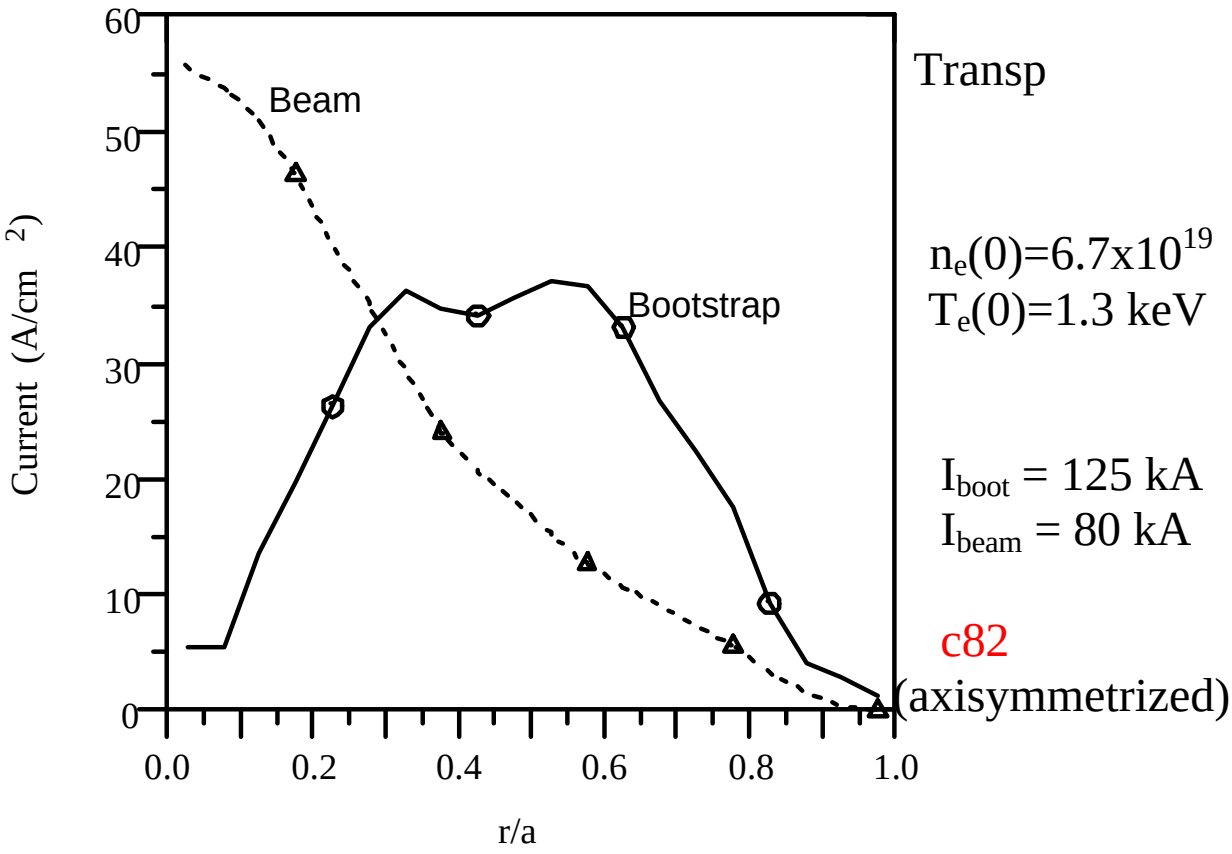
- Example with $n_e(0) = 6.7 \times 10^{13}$
- $\chi_e$ from Lackner-Gotardi, with H=2.3
- $\chi_i$ matching $\tau_{Ei}^{neo}$ from GTC gyrokinetic simulation

– Profiles not fully converged between GTC and transport-solver

Exploring range of densities and profiles

May add ITER transport models

# Beam-Driven Currents




- Concern: Co-NBI produces large, peaked driven current. May impede ability to make reactor-like broad current profiles and thus high β

- Will give shear control via core current-drive

⇒ Examine RF heating options, to give separate control of heating, CD, and rotation.

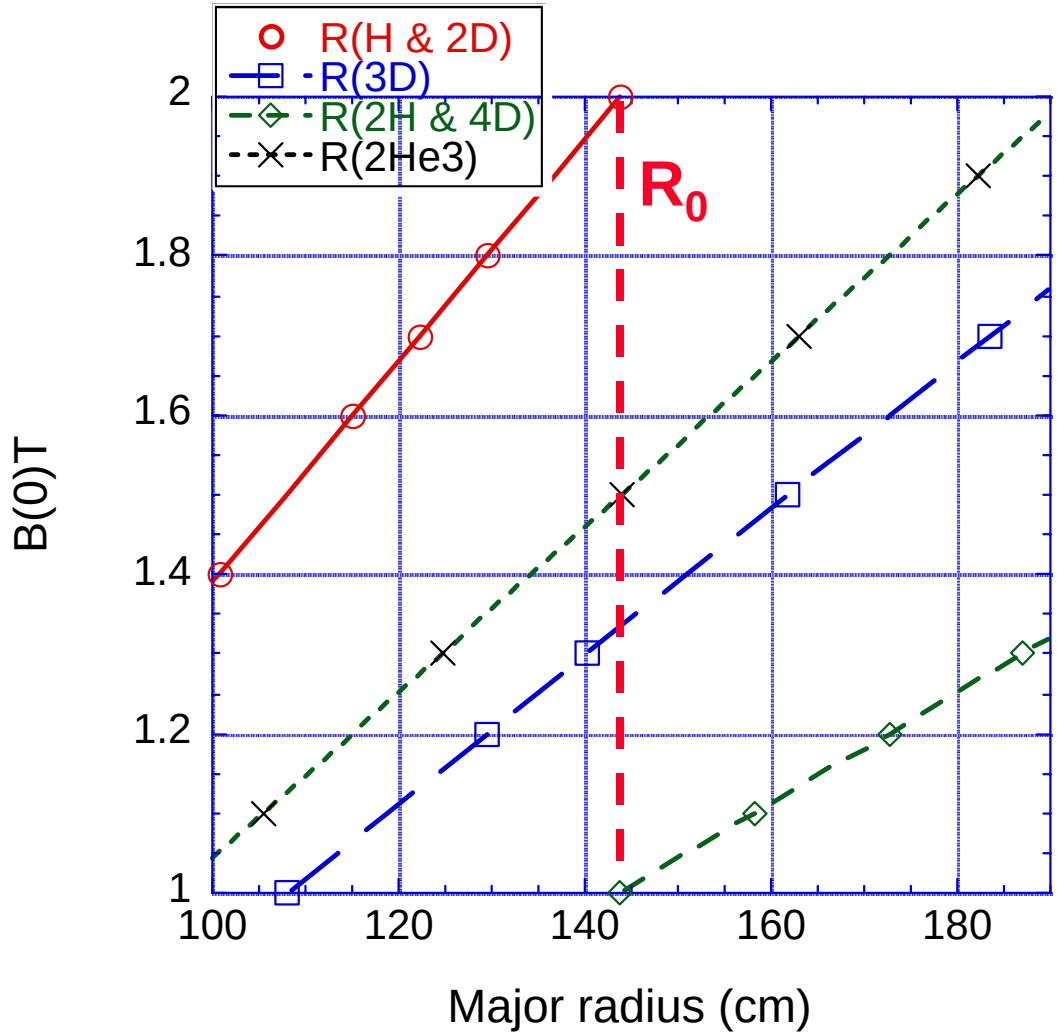
# ICRF Scenarios for NCSX

Possibilities examined:

- 30MHz
  - existing NSTX HHFW heating system
  - 6 transmitters: 6 MW for 5 sec, 12 MW for 2 sec
  - But: <u>frequency is fixed</u>
    - » Major mechanical modifications necessary to retune.
- Lower frequencies
  - requires new RF sources
  - large antennas
  - poor absorption
- High harmonic fast wave, 350MHz:
  - requires new RF sources
  - compact antennas, increased plasma-launcher separation

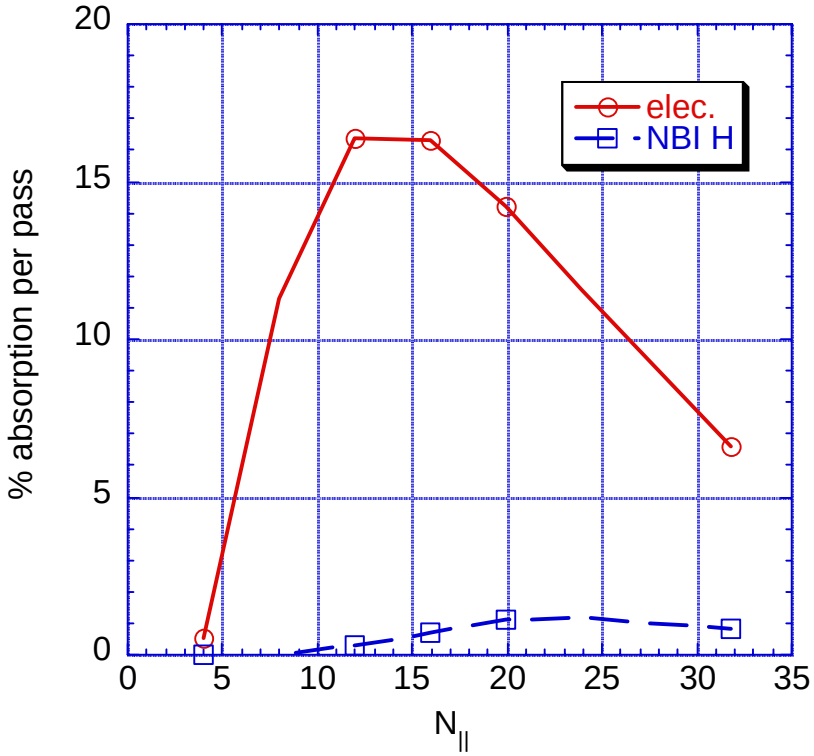
# No useful ion resonances at 30 MHz for NCSX with $B_0 \sim 1.2 - 1.6$ T

⇒ Consider direct electron heating

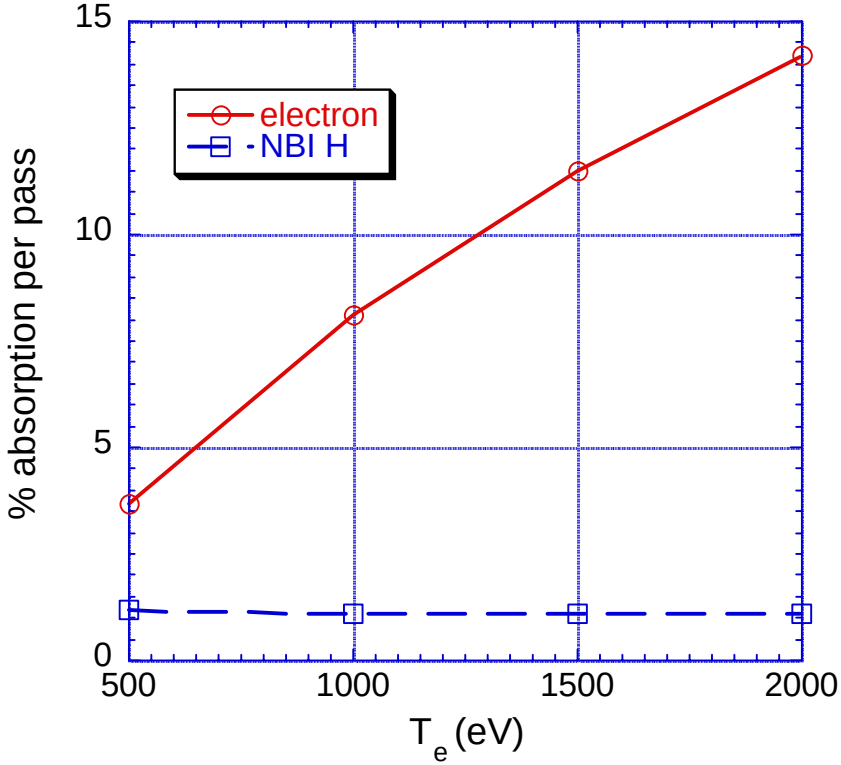


# Direct electron absorption at 30 MHz in NCSX is marginal

30 MHz, $n_e(0) = 6 \times 10^{19}\ m^{-3}$ (parabolic$^{0.5}$),
$T_e(0) = T_i(0) = 2$ keV, $B_0 = 1.4T$, 2%NBI H




$N_{||} = 20$



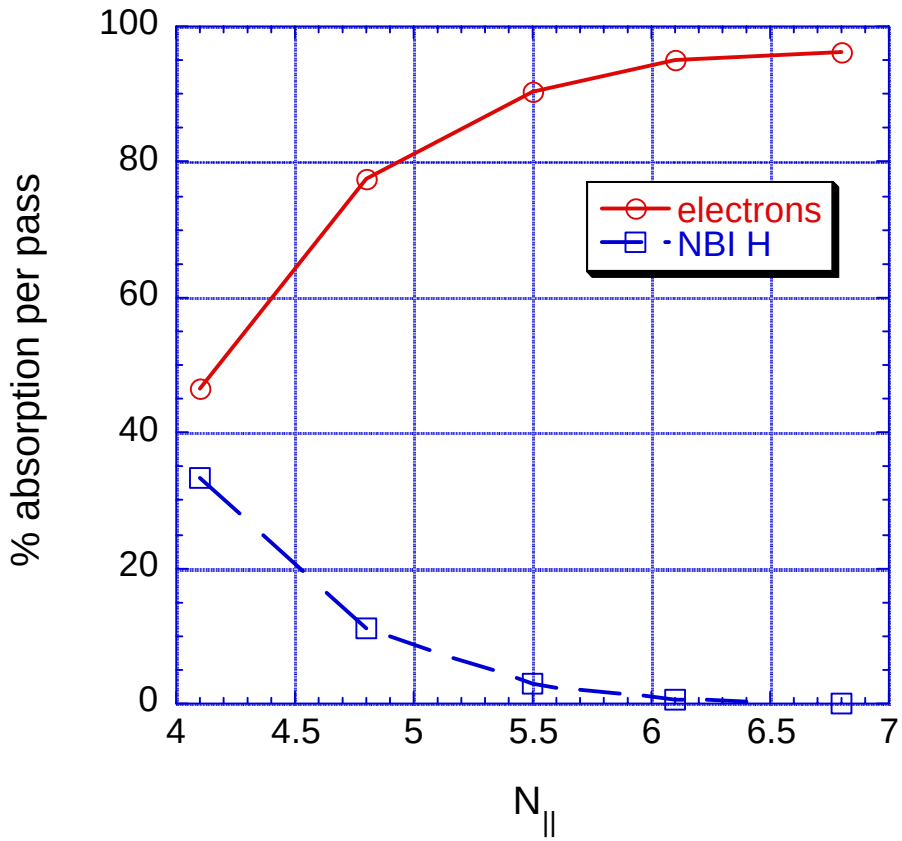

1-D results from METS

# High harmonic fast wave (HHFW) heating for NCSX

- HHFW heating and current drive is being implemented on NSTX
- NCSX will typically operate at moderately susceptibility ($\omega_{pe}^2/\Omega_{ce}^2 \sim 5$)
- Very high frequency fast waves can be strongly damped
- High power, CW sources are available for frequencies > 300 MHz
- Here we look at 350 MHz HHFW heating for NCSX
  - Compact launchers, probably folded waveguide
  - Isolators can be implemented at this frequency
    - » Reduces sensitivity of the system to changes in the plasma edge
  - Current drive capability is significant
  - Sources are typically CW, > 1 MW per tube

# 350 MHz HHFW strongly absorbed in NCSX

350 MHz, $n_e(0) = 6 \times 10^{19}\ m^{-3}$ (parabolic$^{0.5}$), $T_e(0) = T_i(0) = 2$ keV, $B_0 = 1.2$T, 2%NBI H

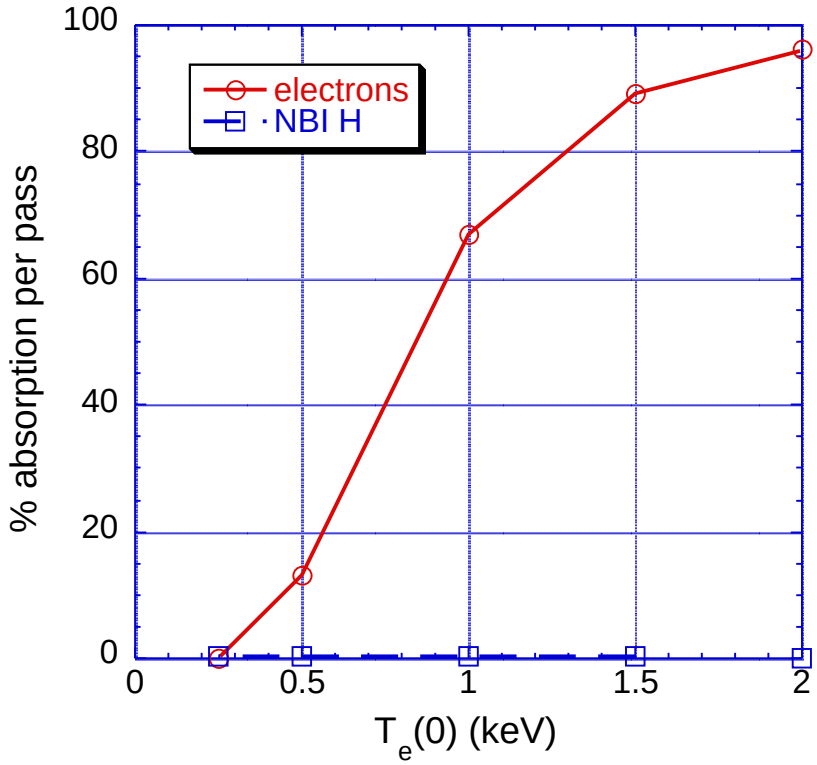



- High $N_{||}$ <u>not</u> required for strong absorption
- Significant noninductive current drive capability
  - ~0.03 - 0.05 A/W (TORIC)
  - Accurate estimate requires detailed geometry

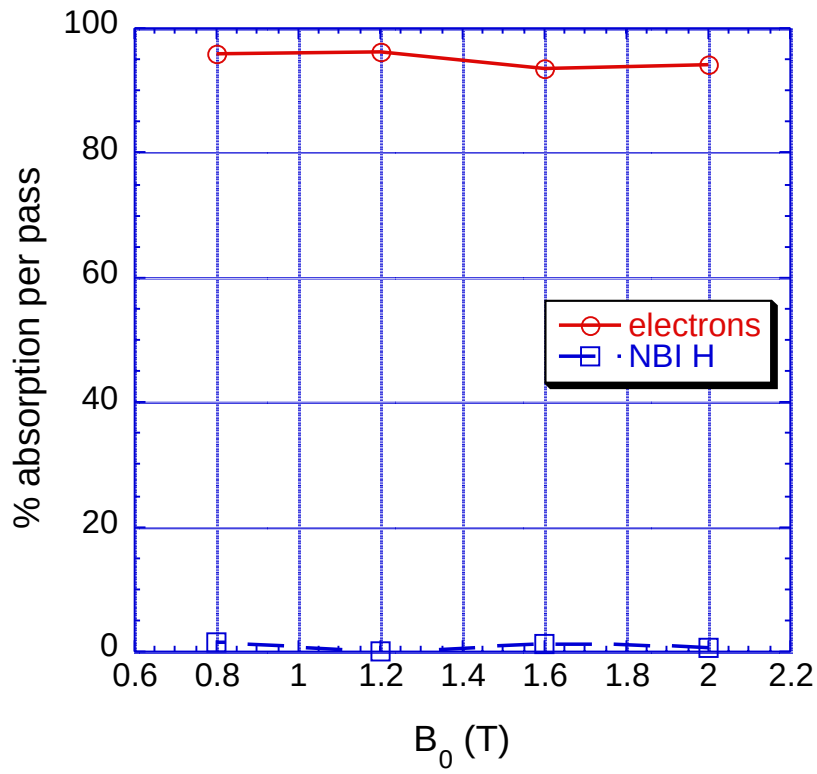
1-D results from METS

# HHFW absorption is strong over a wide range in $T_e$, $B_0$

350 MHz, $n_e(0) = 6 \times 10^{19}\ m^{-3}$ (parabolic$^{0.5}$), $T_e(0) = T_i(0)$, $N_{||} = 6.8$, $B_0 = 1.2T$, 2%NBI H




350 MHz, constant $\beta$, $N_{||} = 6.8$, 2%NBI H



# Summary

- NCSX will test whether a compact QA stellarator can operate disruption free at $\langle\beta\rangle \sim 4\%$

- NCSX has been designed to be passively stable to ballooning, kink, vertical, and neo-tearing instabilities.

- Initial transport assessments indicate that $\langle\beta\rangle = 4\%$ should be accessible (in c10) using the PBX-M beam-set assuming that a confinement enhancement of 2.3 x ISS95 (or ~1.6 x ITER-89P) is accessible.

  For c82, only $\langle\beta\rangle = 3.2\%$ may be accessible with NBI. Would need additional ~ 1.4MW of RF to access 4%.

- Initial calculations indicate that high-harmonic fast-wave heating is the most attractive ICRF heating scenario, offering good absorption and central deposition.