NCSX GOALS and PROJECTED PLASMAS

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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 other confinement levels and for ICRF heating will also be presented.

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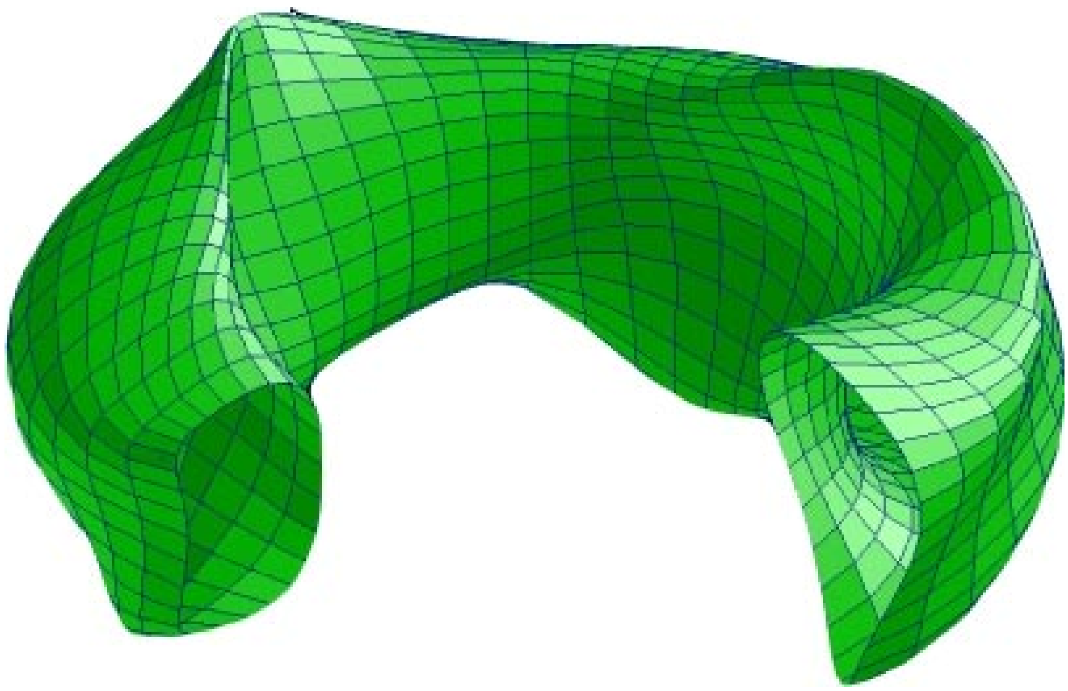
NCSX Research Goals

- 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 $\langle\beta\rangle = 4\%$

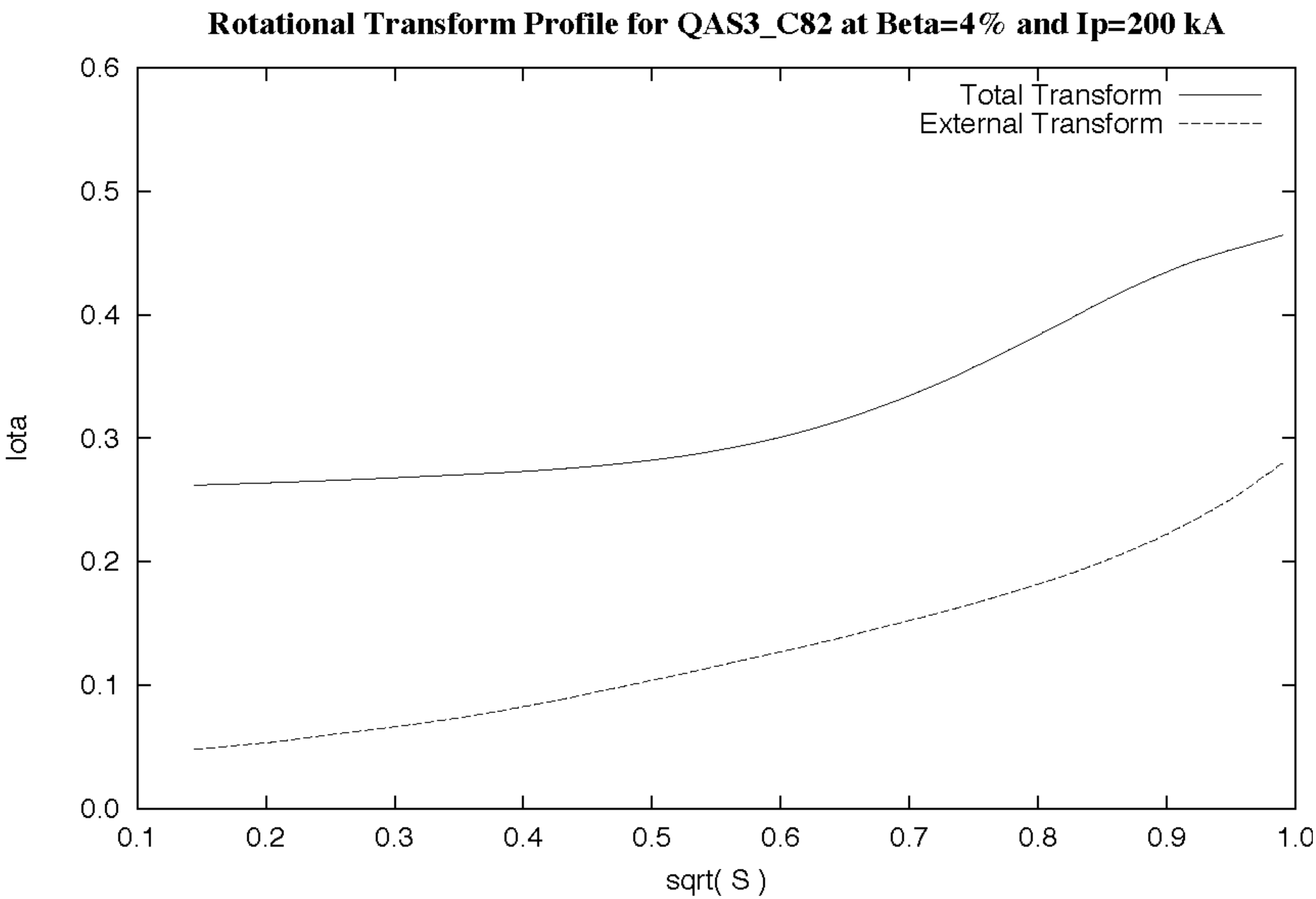


- 3 periods, $\langle A\rangle$=3.4, Quasi-axisymmetric

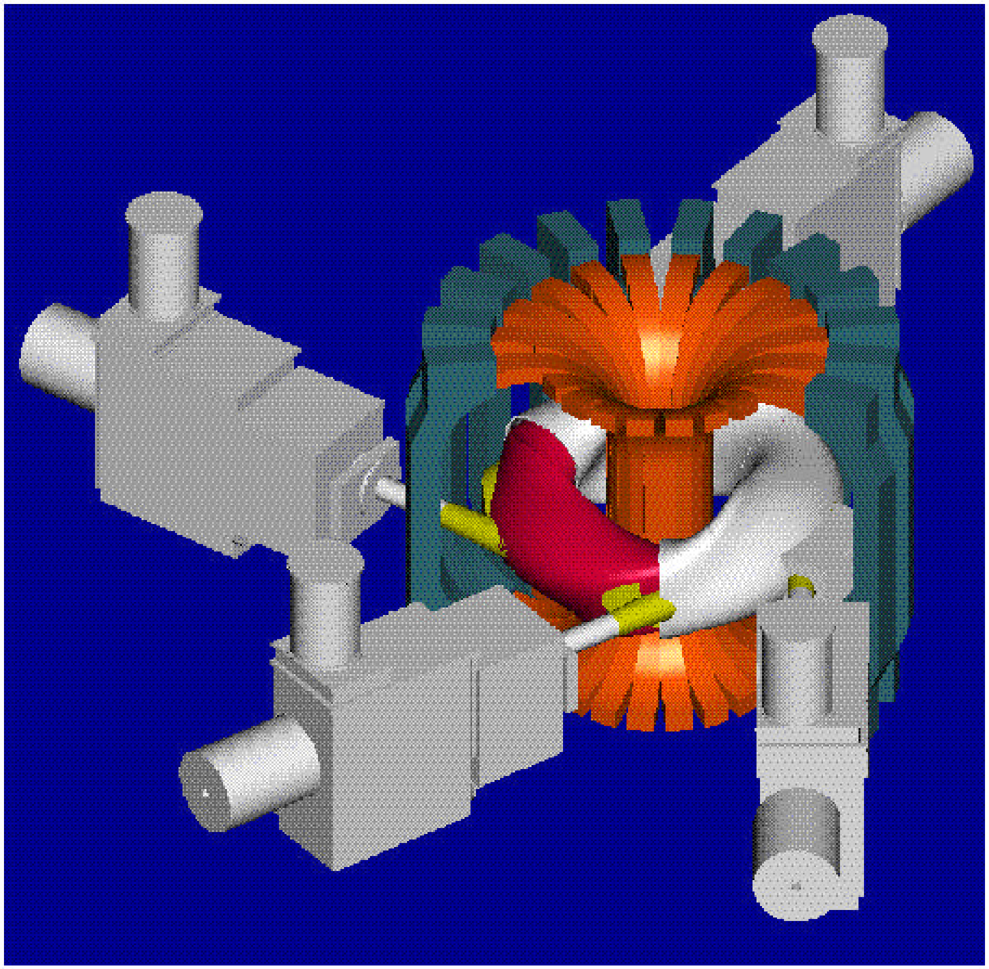
- Stable to ballooning, kink,vertical, mercier modes at $\langle\beta\rangle$=4% without nearby conducting wall

- Bootstrap-consistent current profile, increases iota. $I_P \sim 200$ kA at B=1 T.

- Stellarator shear ($dq/dr < 0$), for neoclassical island stabilization


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
0.7
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

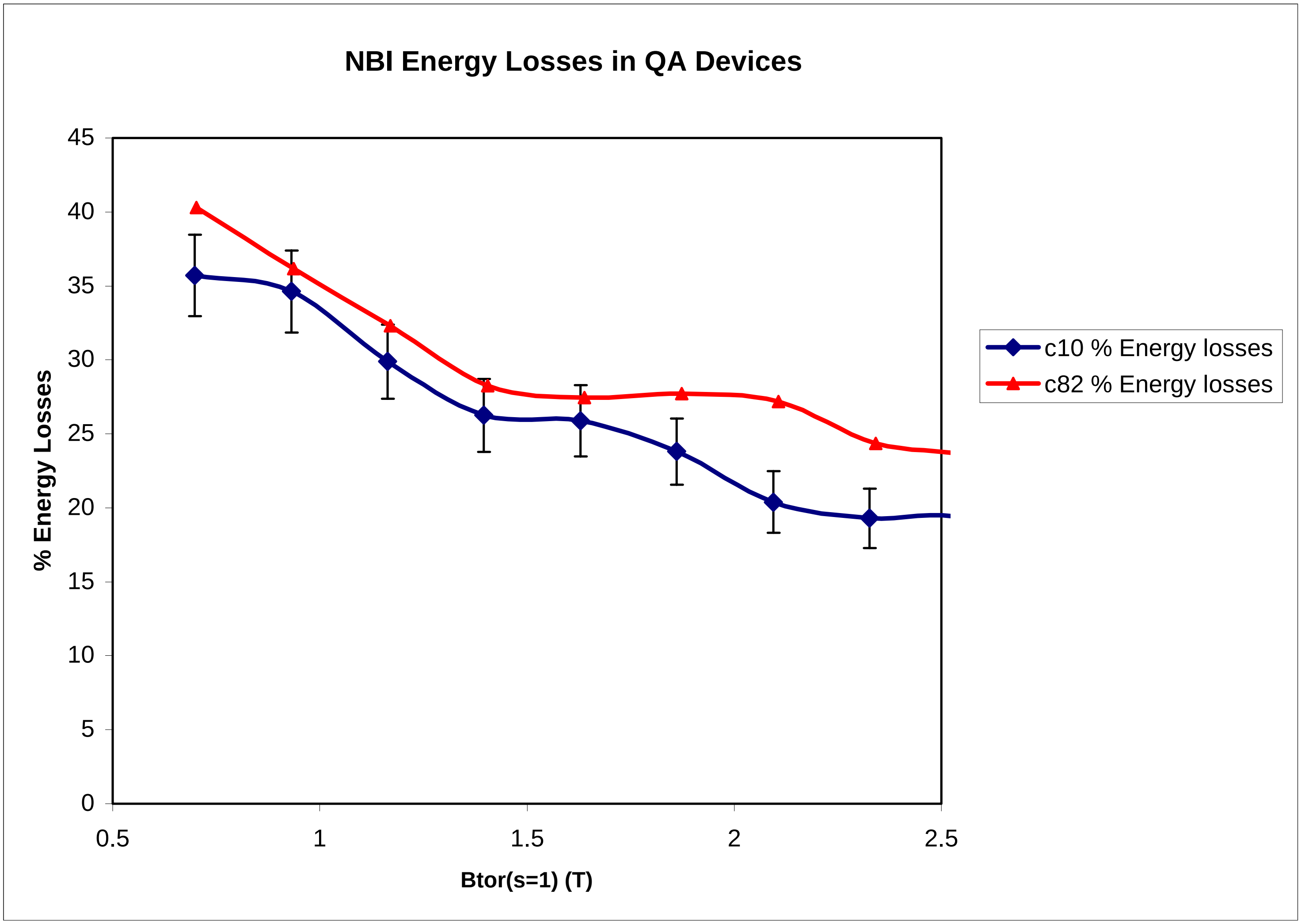
- Simulated using Monte-Carlo codes in full 3-D geometry, using model plasma parameters and profiles
- Two codes
  - Spong's: full collision operator
  - Orbitmn: pitch-angle scattering and slowing down rate (taken as independent of energy)

- 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

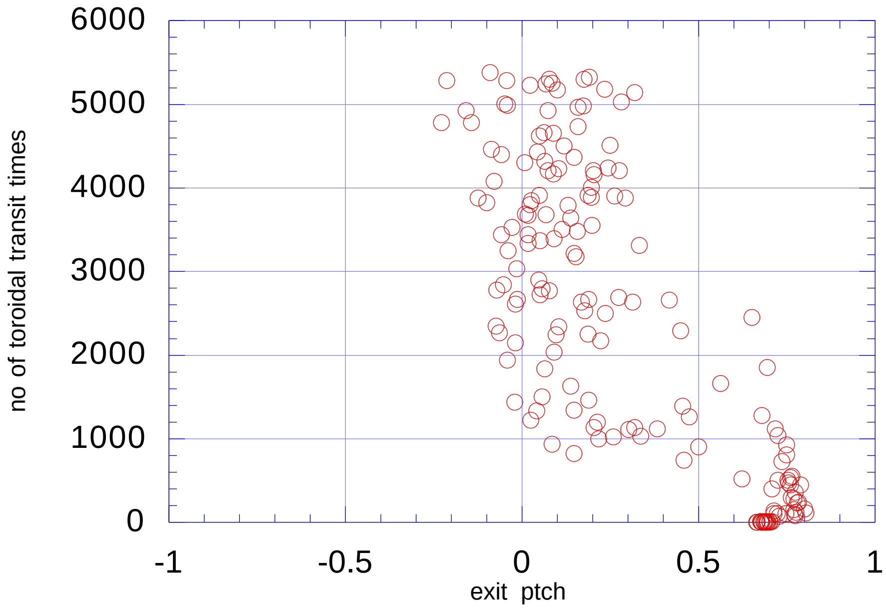


D. Spong

- 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



M. Redi

Thermal Neoclassical Transport Calculated by 3D Monte-Carlo Code

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

- δf simulation for electrons
- f simulation for ions

- Use $e\Phi = T_i$ to approximate electric field effect 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 → τ_{Ei}^{neo} in 1D transport solution, using empirical Te or anomalous transport simulation

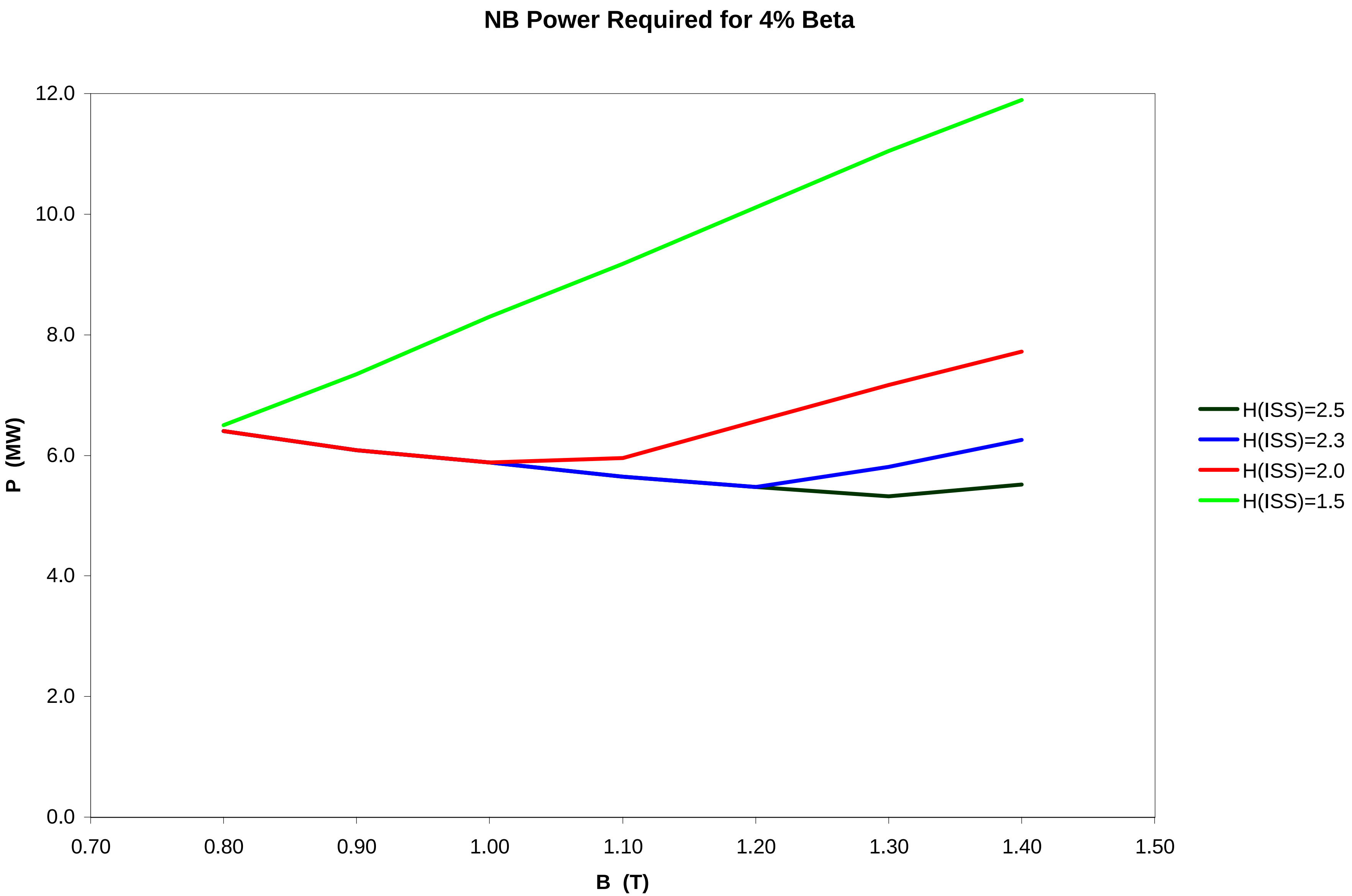
H. Mynick, Z. Lin, I. Zatz

Operating Points in NCSX

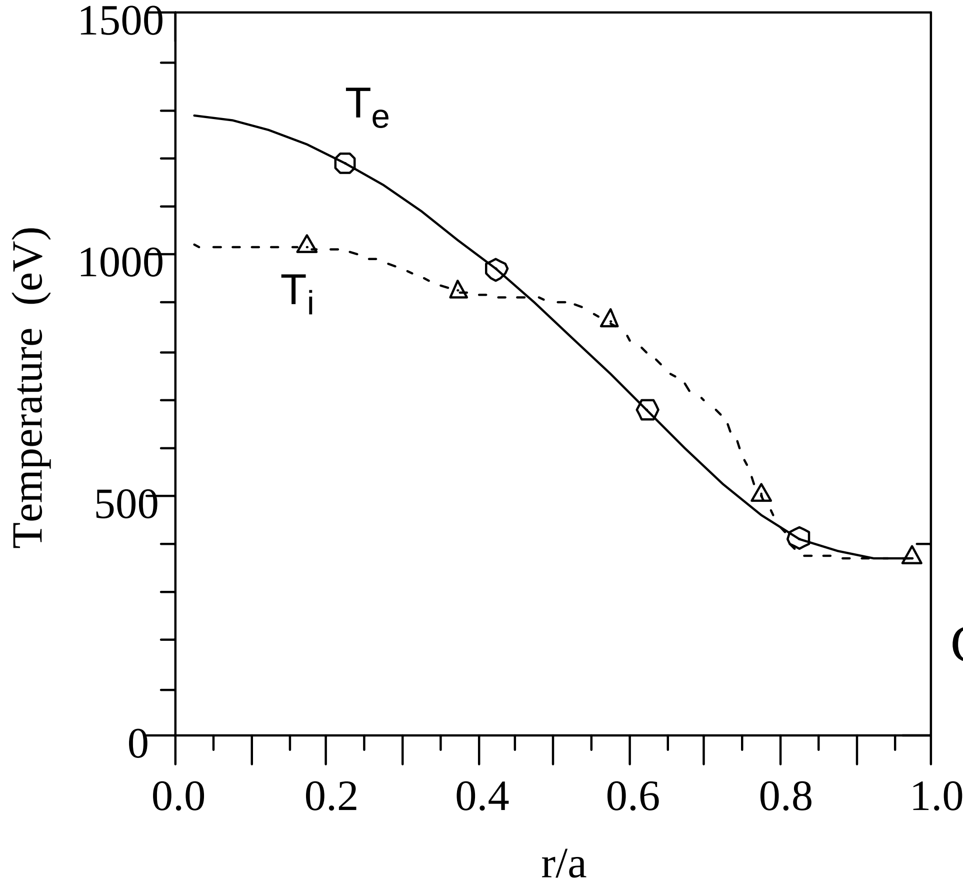
R=1.45 m, a =0.42 m, Z_{eff}=2

Scenario	4% $\langle\beta\rangle$	Reactor collisionality
Magnetic field, B (T)	1.2	1.2
Injected power, P (MW)	5.5	5.5
Volume-avg. beta β (%)	4.0	2.7
Volume-avg. density, n (10^{19} m^{-3})	10.2	4.6
Central temperature, T_0 (keV)	1.4	2.1
Collisionality parameter (nR/T^2)	7.4	1.5
τ_E (ms)	45	31

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


NB Power Required for 4% Beta
P (MW)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
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

Transport Simulation for 1D Profiles



C82

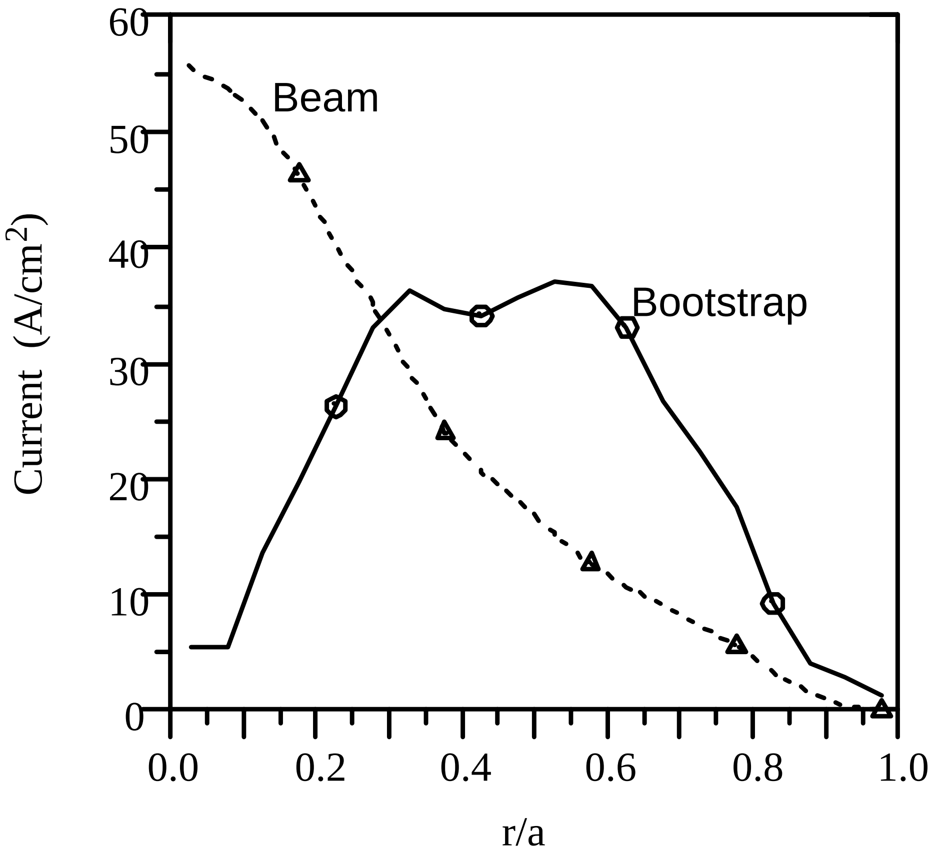
- Example with $n_e(0) = 6.7 \times 10^{13}$
- χ_e from Lackner-Gotardi, with H=2.3
- χ_i matching τ_{Ei}^{neo} from GTC gyrokinetic simulation

– Profiles not fully converged between GTC and transport-solver

Exploring range of densities and profiles

May add ITER transport models

Beam-Driven Currents



$n_e(0)$=6.7x10[19]
$T_e(0)$=1.3 keV

I_{boot} = 125 kA
I_{beam} = 80 kA

c82

- 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

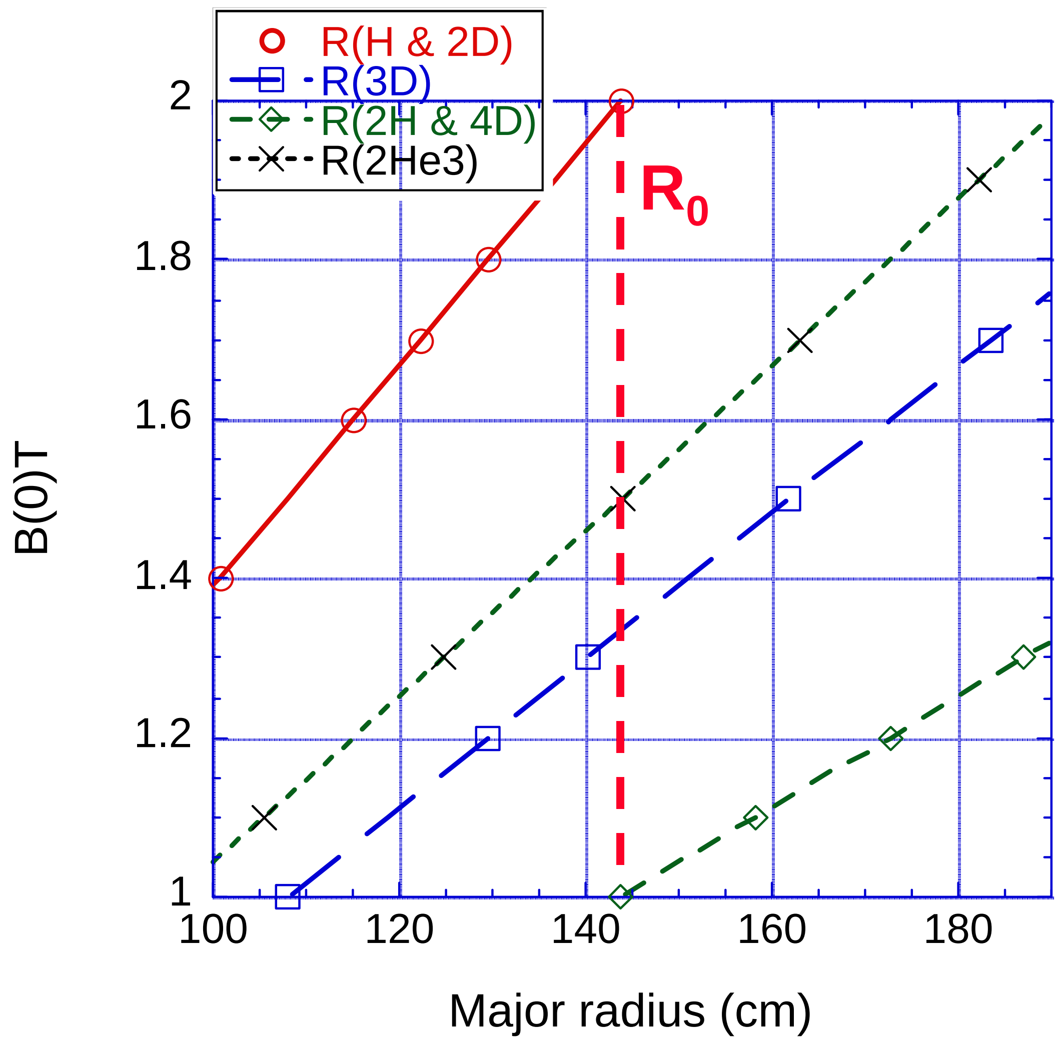
Possibilities examined:

- 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

PPPL

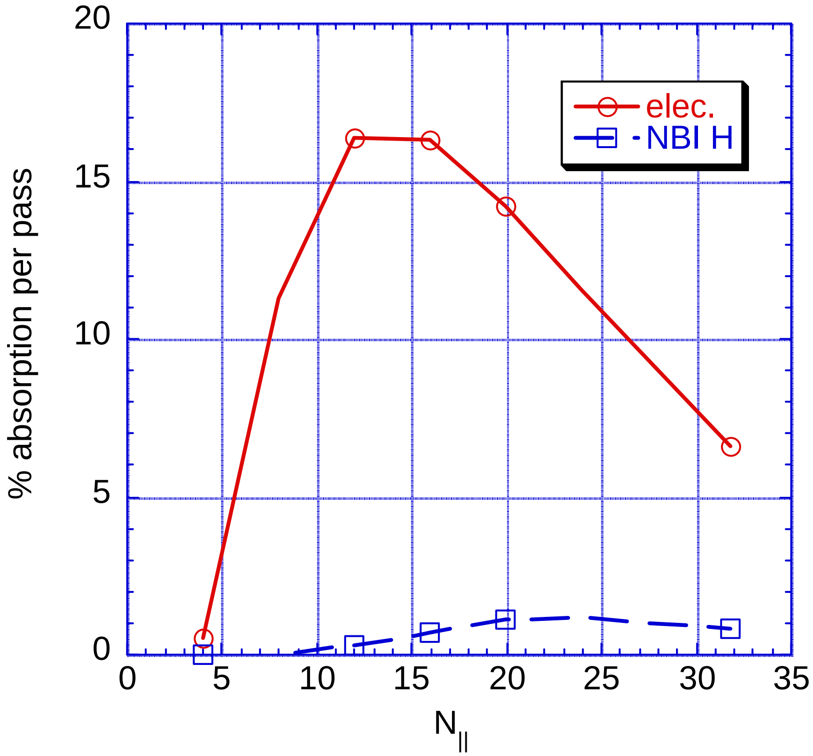
No useful ion resonances at 30 MHz for NCSX with $B_0 \sim 1.2 - 1.6$ T

⇒ Consider direct electron heating

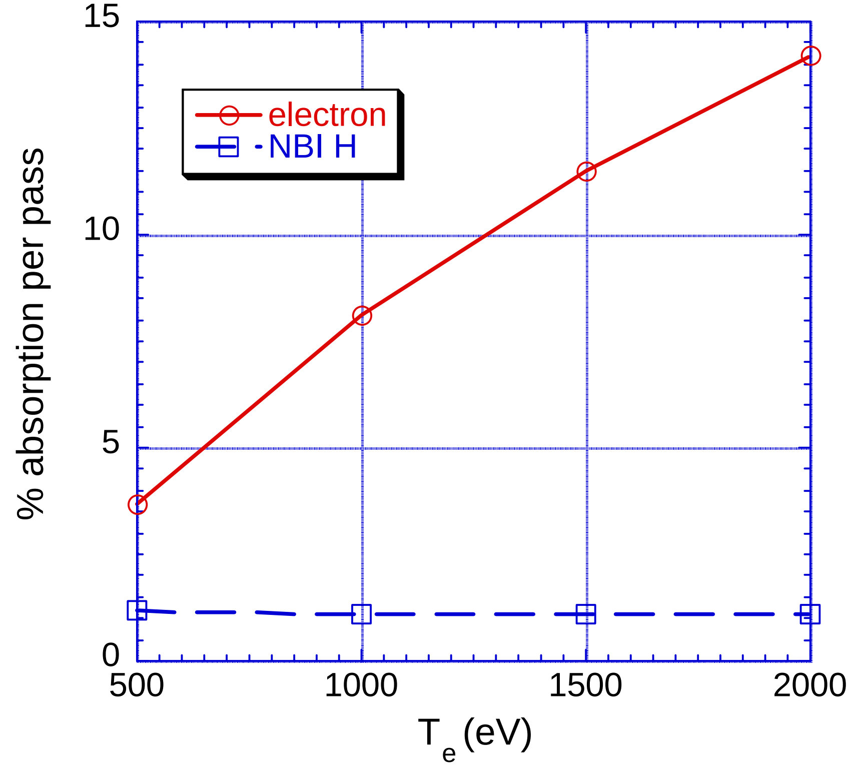


Direct electron absorption at 30 MHz in NCSX is marginal

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

PPPL

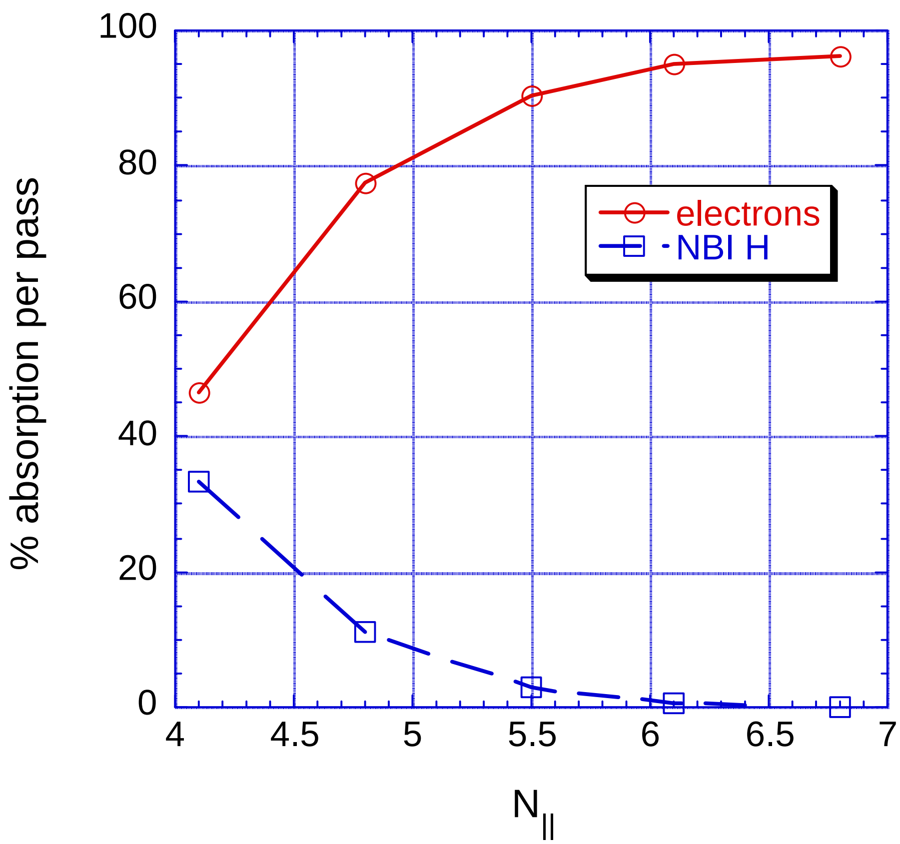
High harmonic fast wave (HHFW) heating for NCSX

- 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

PPPL

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



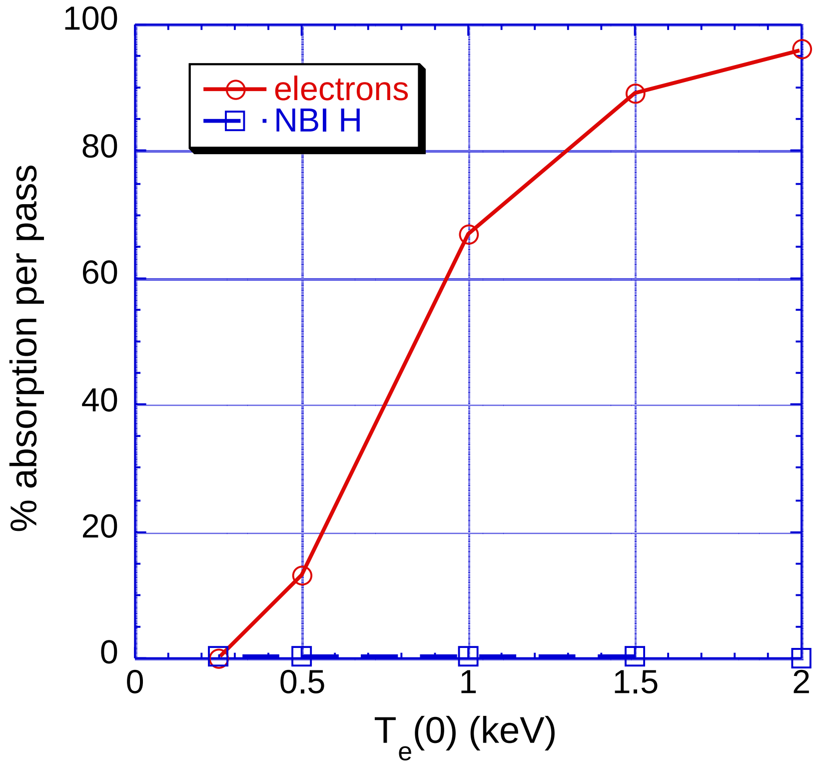
- High $N_{||}$ not required for strong absorption
- Significant noninductive current drive capability
  - ~0.03 - 0.05 A/W (TORIC)
  - Accurate estimate requires detailed geometry

1-D results from METS

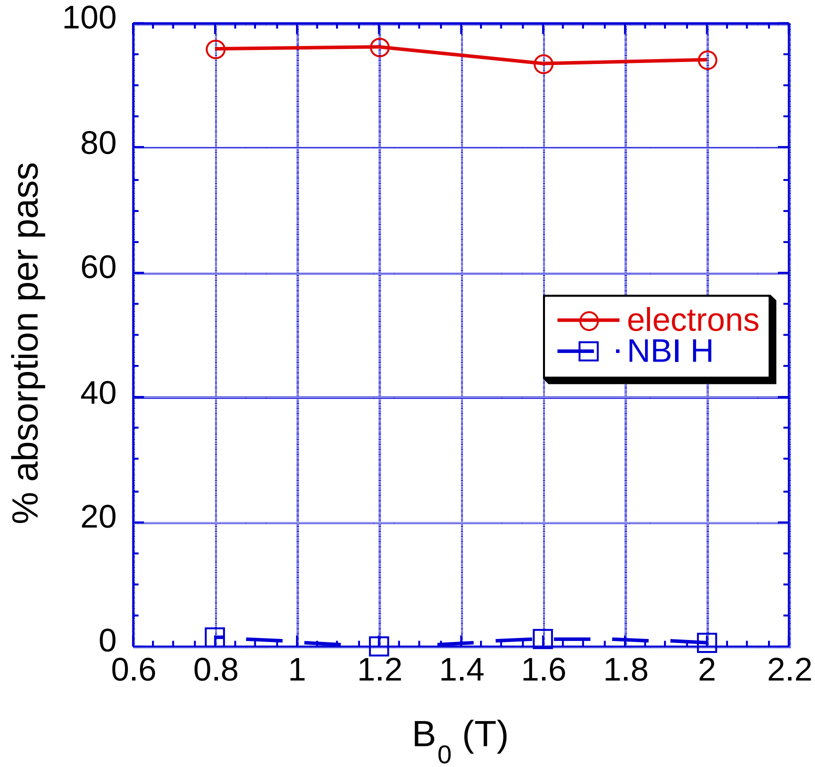
PPPL

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$^{0.5}$), $T_e(0) = T_i(0)$, $N_{||} = 6.8$, $B_0 = 1.2$T, 2%NBI H



350 MHz, constant β, $N_{||} = 6.8$, 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 using the PBX-M beam-set assuming that a confinement enhancement of 2.3 x ISS95 (or ~1.6 x ITER-89P) is accessible.

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