Transport Assessment

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• Will confinement be adequate to test <β> limit predictions?
Can the optimized <β> limit of 4% to be challenged?
Can low collisionality and high <β> be achieved simultaneously?

• Will thermal neoclassical ripple transport be negligible?

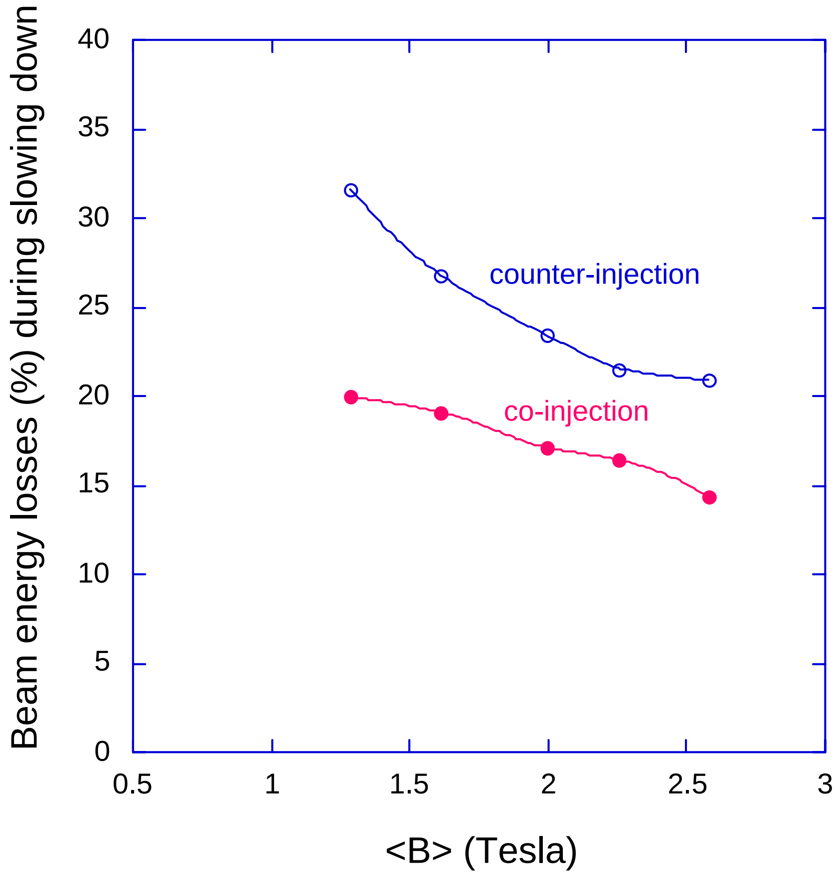
• Will the pressure profile shape be inside the stability envelope?

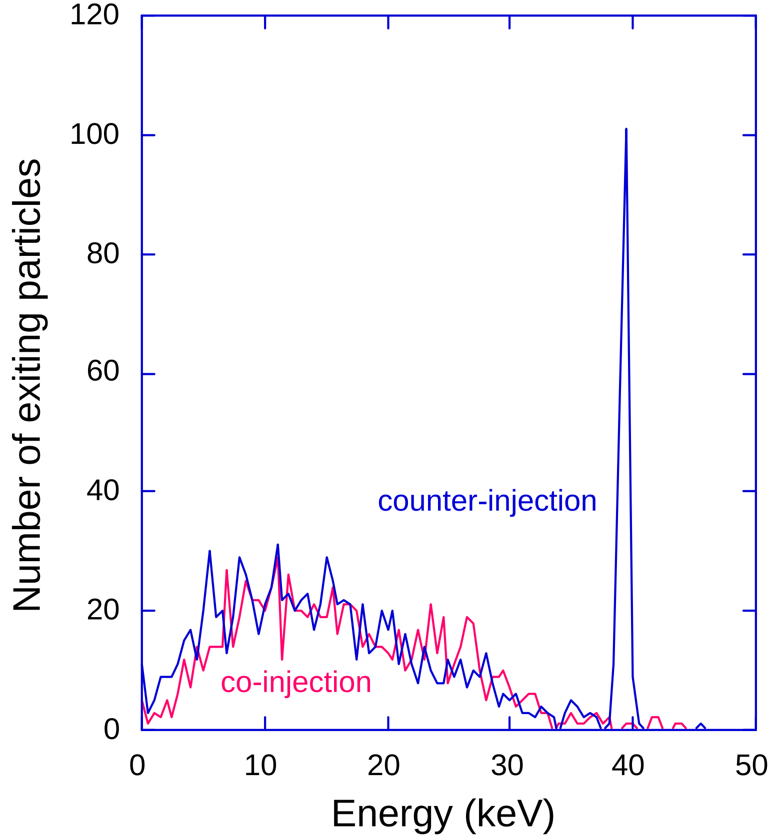
• Will the flow-damping be low?

Two methods used:
1) global confinement scaling
2) transport modeling

Fast ion confinement; net heating power

- D. Spong's orbit calculations use 3-D geometry and predicted profiles.
- Thermal transport is less sensitive to ripple than fast ion orbits.
- Orbit losses place a lower bound on the product $B_o R_o \propto I_p^{eff}$.
  For B_o=1.2 T, and R_o=1.4 m, balanced injection orbit loss ~26%.





- NB CX Losses calculated to be ~5%   (300kW / 6 MW)

Global confinement model

Energy confinement is directly related to $<\beta>$:

$$\tau_E = W_{tot}/P_{heat}; \;\; W_{tot} = 1.5<\beta> (B_o^2/2\mu_o)V_p; \;\;\; V_p = 2R_o(\pi a)^2.$$

Normalized collisionality,

$$\nu_i^* = \nu_{coll}/\nu_{bounce} \propto n/T^2 \propto n^3/B_o^2<\beta>^2,$$

is scaled from profiles shown below (from the minimum of the ν_i^* profile).

Low ν_i^* $\Leftrightarrow$ low density and high $<\beta>$.

Maximum density is taken to be the Sudo density ‘limit’.

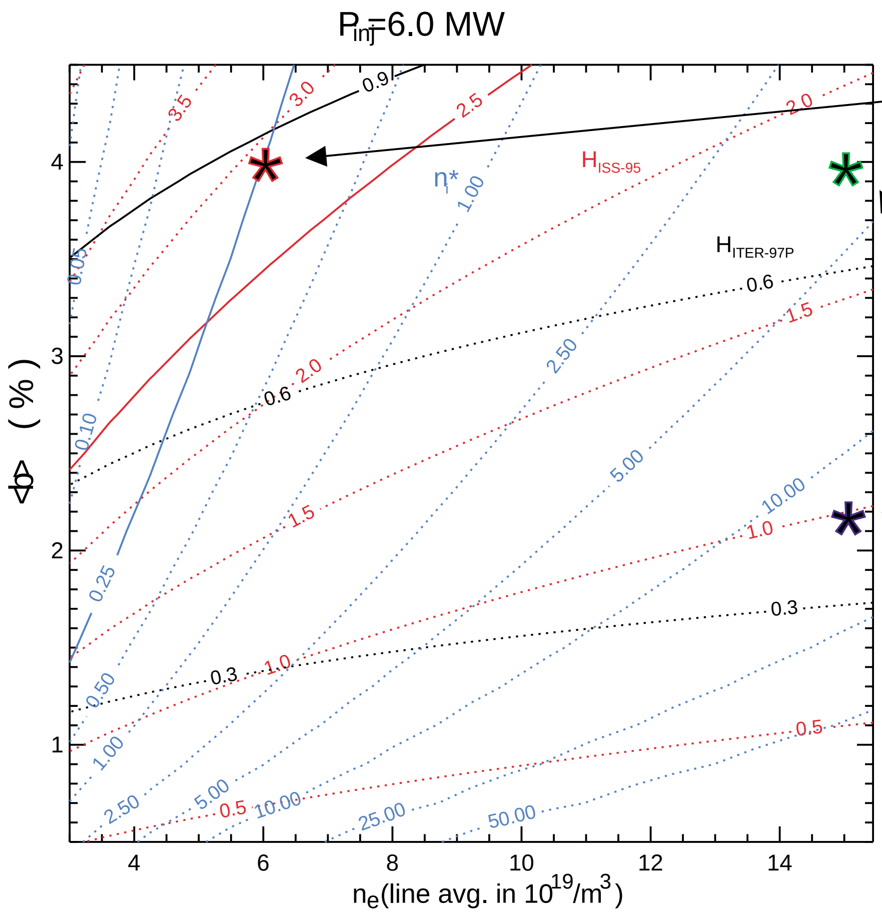
Global confinement scalings

• ISS-95 scaling of typical energy confinement (no H-modes,…).
Five stellarators not optimized for low neoclassical ripple transport.
Ripple transport is typically larger than axisymmetric transport.
Based on total stored energy, so τ_E can be directly related to $\langle\beta\rangle$.
NCSX is largely within the parameter range of the ISS-95 database.

LHD represents a large extrapolation beyond ISS-95 stellarators, and it immediately exceeded the ISS-95 prediction.
LHD record $H_{ISS\text{-}95}$ is 2.4
W7-AS record $H_{ISS\text{-}95}$ is 2.5

• ITER-97P scaling of L-mode energy confinement in 13 tokamaks.
NCSX is largely within the parameter range.
Use the effective plasma current that produces the same edge ι with the toroidally averaged NCSX shape: $I_p^{eff} = (\frac{B_o}{1.2T})(\frac{R_o}{1.4m})0.5$ MA.

<β> limits are testable



* <β>=4% at ν_i*=0.25 requires H_{ISS-95}=2.9; $H_{ITER-97P}$ =0.9

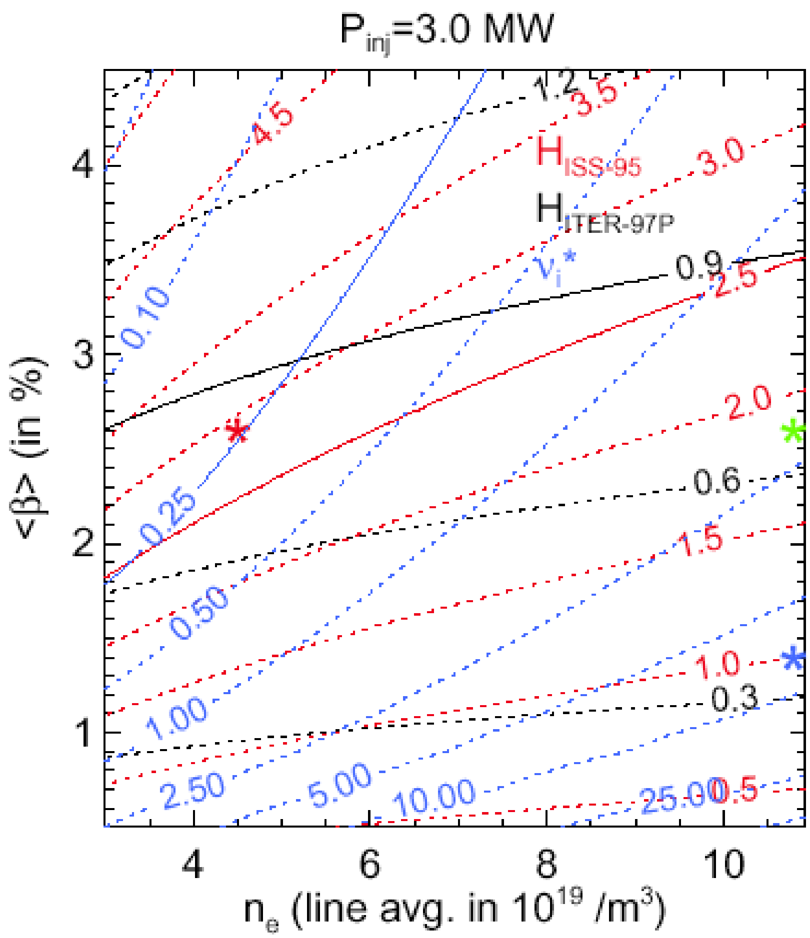
* <β>=4% possible at H_{ISS-95}=1.8, but with large ν_i*

* H_{ISS-95}=1 allows <β> up to 2.2%; sufficient to test predictions of MHD stability for de-optimized shapes.

B_o=1.2 T; R_o=1.4 m; a=0.32 m

Contours of H_{ISS-95}, $H_{ITER-97P}$, and ν_i*

Lower <β> limits are testable even at Pinj= 3 MW



* ν_i*=0.25 and H_{ISS-95}=2.9 ⇒ <β>~2.6%

* H_{ISS-95}=2.9 ⇒ <β>~2.6%; but large ν_i*

* H_{ISS-95}=1 allows <β> up to 1.4%, but with large ν_i*

Contours of H_{ISS-95}, $H_{ITER-97P}$, and ν_i*

Profile prediction methodology

The electron and ion power balance equations are each of the form

$$\frac{1}{V'}\frac{\partial}{\partial\rho}(<|\rho|> V' q_{tot}) = Q_{heat} \pm Q_{ie}$$

Q_{heat} is based on TRANSP; power fluxes are divided into three parts,

$$q_{tot} = q_{ripple}^{neo} + q_{axisym.}^{neo} + q_{anom.}$$

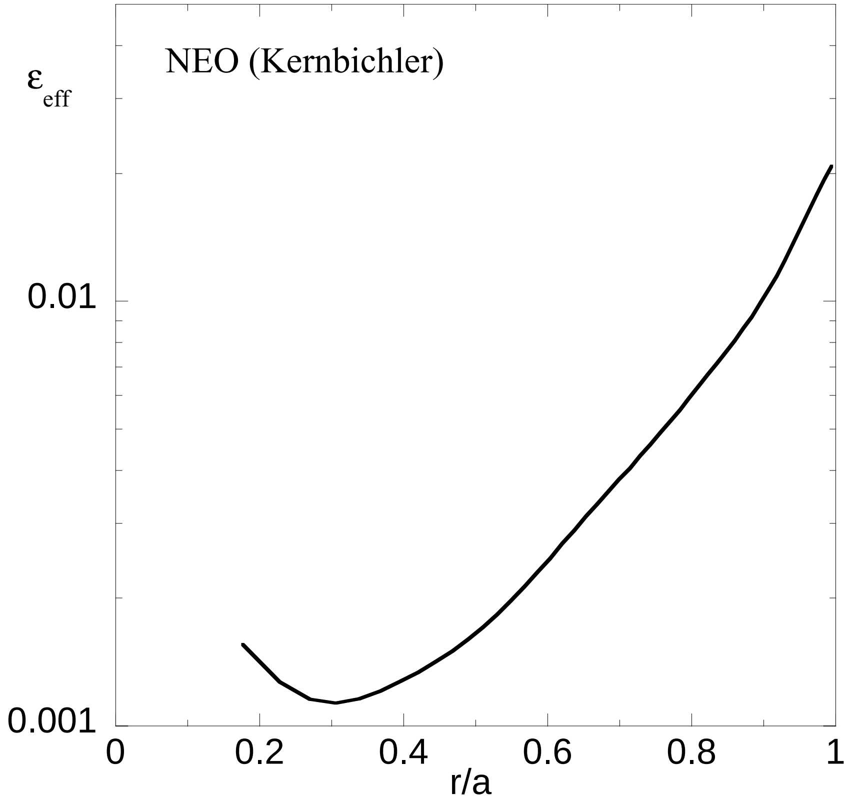
neoclassical ripple and axisymmetric transport, and ‘anomalous’ transport.

The analytic neoclassical ripple model is discussed on the following page.
The Chang-Hinton model is used for neoclassical axisymmetric transport, and has been re-normalized to THRIFT/NCLASS (Strand/Houlberg).
Stellarator plasma cores are frequently close to neoclassical predictions.

Anomalous transport is modeled with either a radially uniform diffusivity, or the version of the Lackner-Gottardi model that has been applied to W7-AS.

An anomalous multiplier is adjusted to match a target $<\beta>$, or H_{ISS-95};
$q_{anom.}$ is compared to $q_{ripple}^{neo} + q_{axisym.}^{neo}$ to assess anomalous transport margin.

Effective ripple is very low



Single helicity theory can be extended in the 1/ν regime, where $q_{ripple}^{neo} \propto \varepsilon_{eff}^{\frac{3}{2}}$, ε_{eff} is the effective ripple amplitude.

ε_{eff} is calculated by the NEO code using the 3-D magnetic configuration (Nemov, Kernbichler).

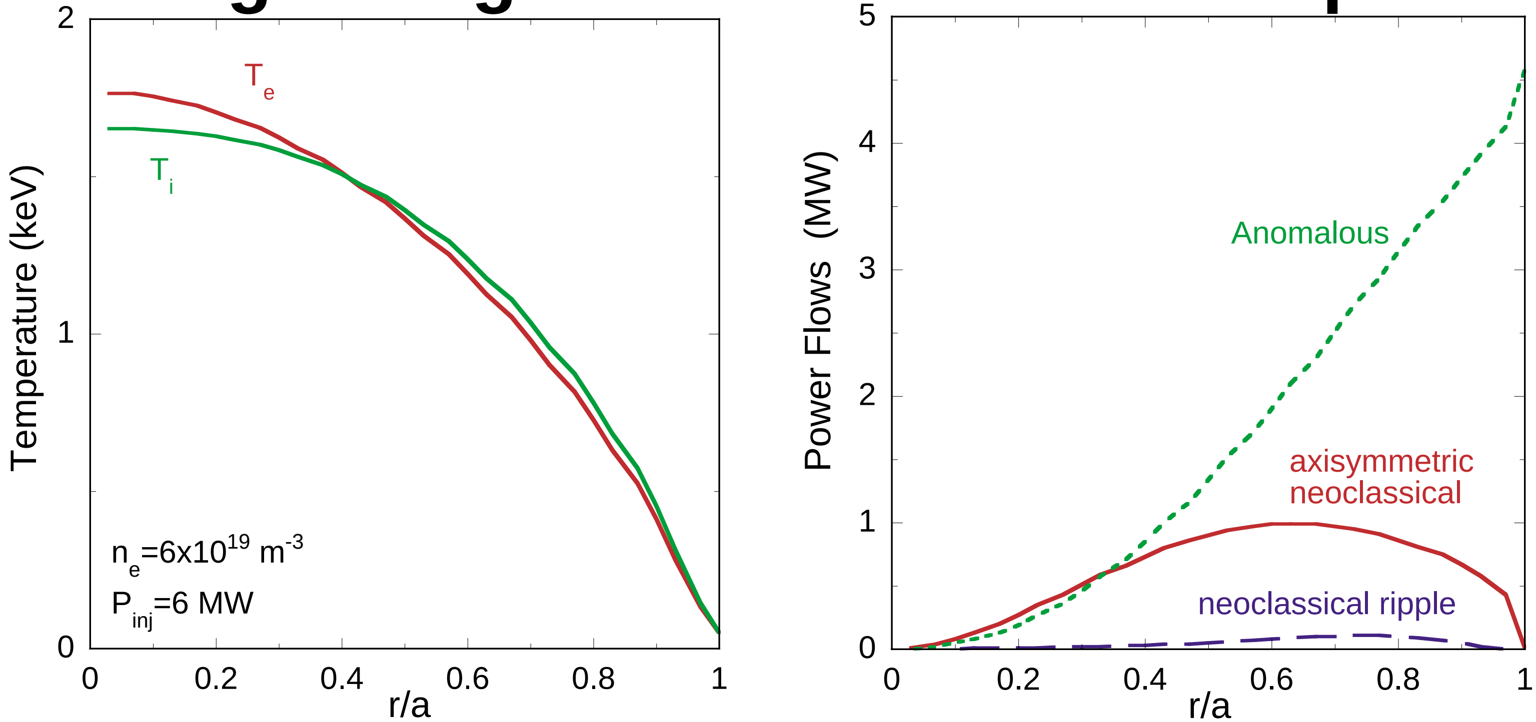
In W7-X ε_{eff} ~ 0.01 at all radii.

Fast ions and flows determine the allowable level of ripple.

Neoclassical ripple transport is not intrinsically ambipolar, so the plasma charges up until it finds an E_r that does produce ambipolar particle flux. This E_r is very important in reducing the ion's ripple transport.

In the 1/ν regime with the 'ion root' $q_{ripple}^{neo} \propto T^{\frac{9}{2}}$, so high density is favorable.
The electrons are in the 1/ν regime of validity, but not the bulk ions.

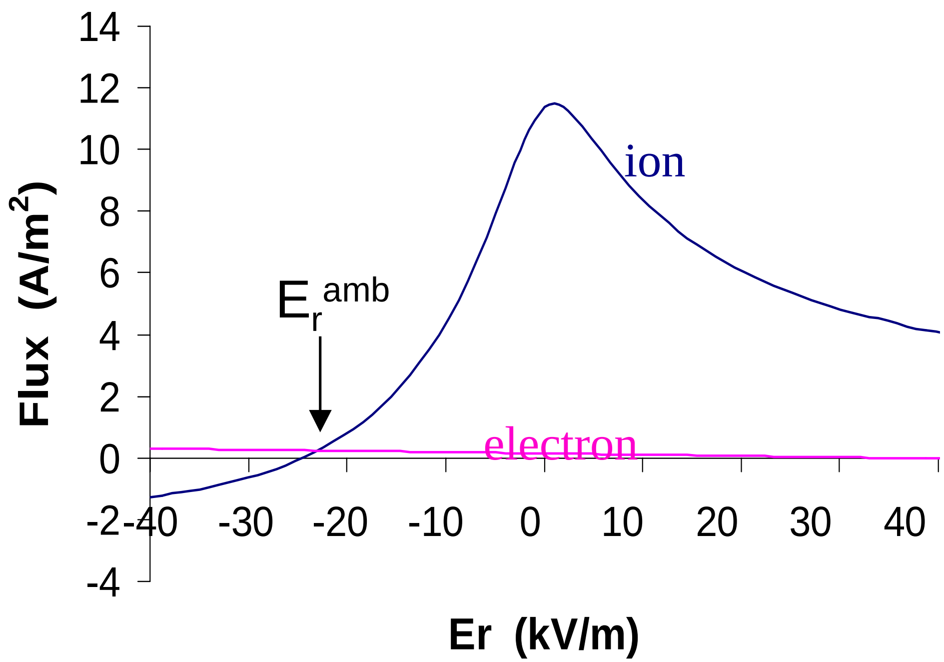
Low ripple transport
Large margin for anomalous transport

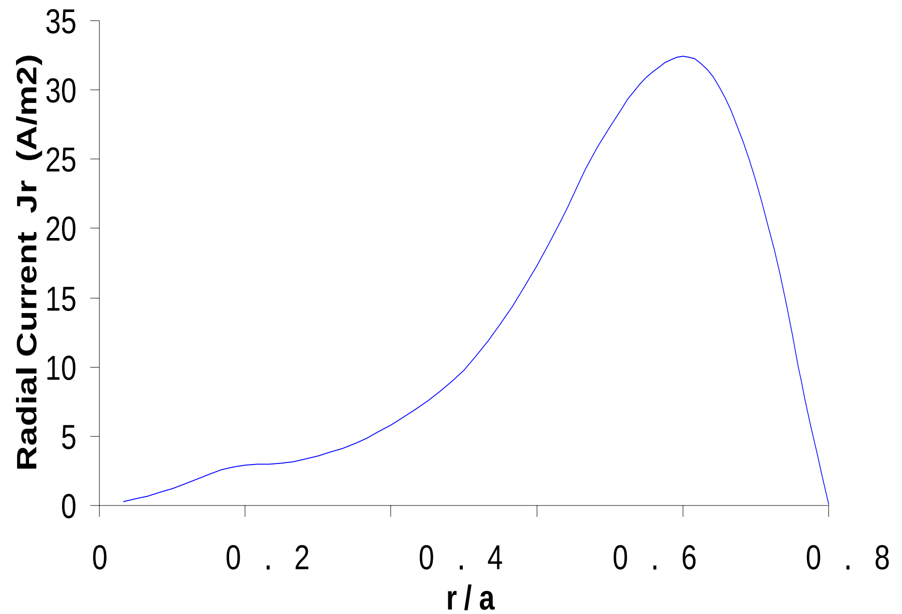


- High <β> and moderate ν_i^* ~ 0.25 $\langle\beta_{thermal}\rangle$=2.9%, $\langle\beta_{fast}\rangle$=1.2%
- $q^{neo}_{axisym.}$ normalized to NCLASS
- $q^{neo}_{ripple} << q^{neo}_{axisym.}$, confirmed by DKES & GTC
- Spatially constant χ_{anom}=1.7 m^2/s

$$q_{anom} > q^{neo} \quad \text{for } r > a/3$$

Ripple driven flux peaks for E_r=0, near edge



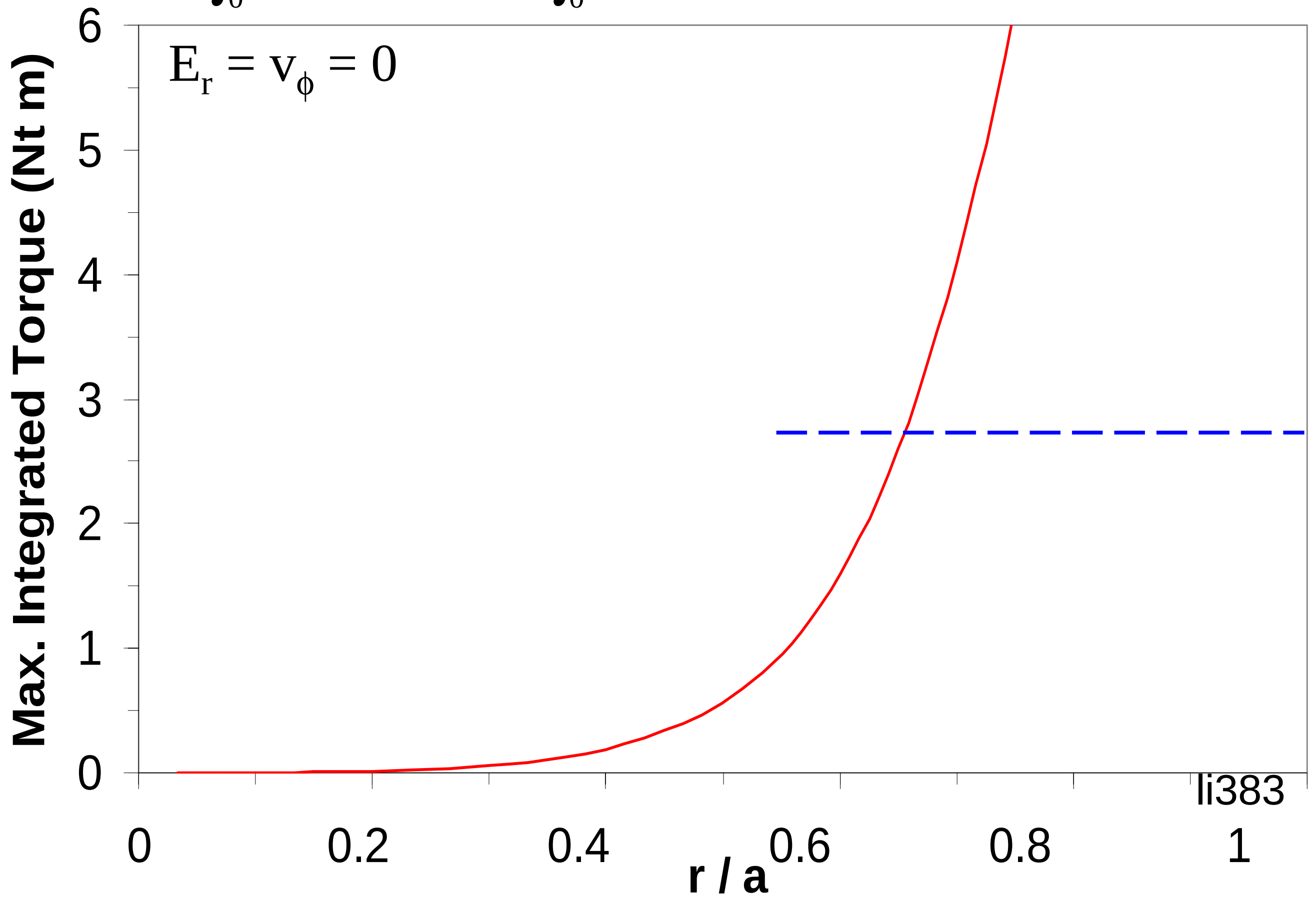


- Ripple-neoclassical model predicts radial currents for $E_r \neq E_r^{amb}$, due to deviations from quasi-axisymmetry; benchmarked to Monte-Carlo (GTC)
- For $E_r \neq E_r^{amb}$, $J_r \propto (\Gamma_i - \Gamma_e)$ acts to restore E_r^{amb} and damp rotation, $J_r \times B_P$ back to ambipolar value.
- At each radius, peak , $J_r \propto (\Gamma_i - \Gamma_e) \sim \Gamma_i$ occurs for $E_r = 0$

Core rotation is un-damped

Integrated maximum (E_r = 0) ripple-damping toroidal-torque from axis to given radius

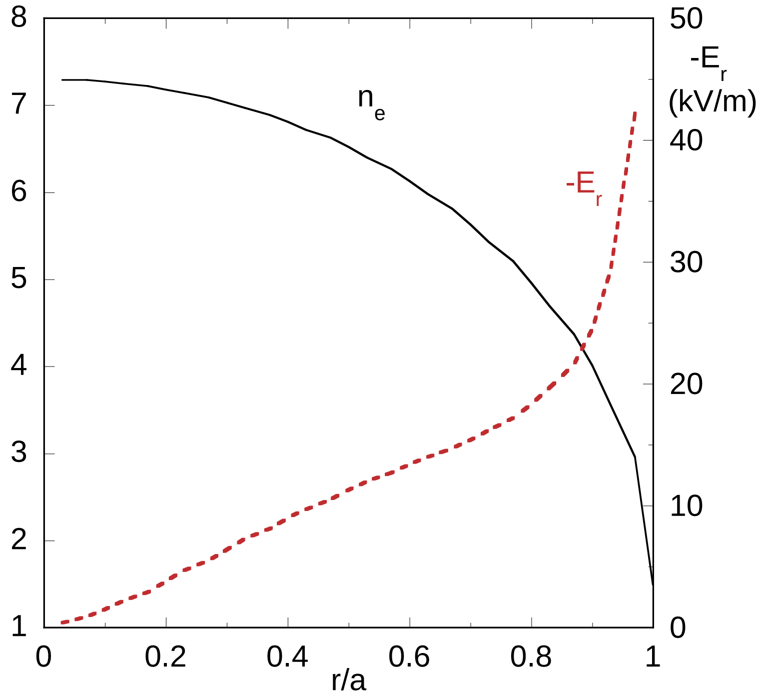
$$\int_0^r J_r B_P R\, d\underline{v}' \sim \int_0^r \overline{J}_r(r')\,\overline{B}_P(r')\,R_0\, d\underline{v}'$$

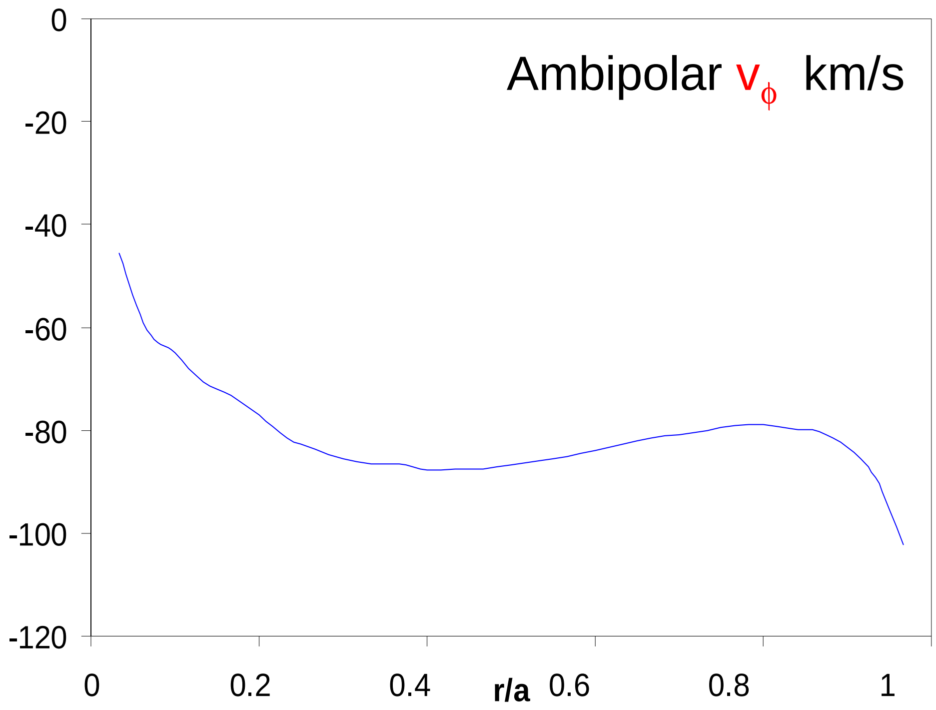


- 6MW balanced NBI planned
- 3MW unidirectional NBI ~ 2.7 Nt-m

Beams cannot bring edge velocity to zero; it will probably be constrained to counter-rotation

Ambipolar $E_r \Rightarrow$ large v_ϕ





- No applied torque
- Ambipolar E_r peaks at edge due to edge ripple
- Assumes poloidal damping much faster than toroidal, $\Rightarrow$ tokamak-like solution $v_\phi \sim E_r/B_P$.
- v_ϕ preliminary: want to verify with Monte-Carlo codes

Summary

• Confinement is expected to allow tests of $\langle\beta\rangle$ limit predictions.
Even with $H_{ISS\text{-}95}$=1, $\langle\beta\rangle$ up to 2.2% would be possible with P_{inj}=6 MW.
With P_{inj}=3 MW, $H_{ISS\text{-}95}$=1.5 is needed to reach $\langle\beta\rangle$=2%.

Challenging the reference $\langle\beta\rangle$ = 4% requires $H_{ISS\text{-}95}$=1.8, but $\nu_i^* \geq 3$.
For ν_i^*~0.25 *and* $\langle\beta\rangle$~4% requires $H_{ISS\text{-}95}$=2.9, but $H_{ITER\text{-}97P}$ is only 0.9.

Large margin for anomalous transport even with high $H_{ISS\text{-}95}$.
$H_{ITER\text{-}97P} \leq 1$ across the operating range considered here.

• Neoclassical ripple transport expected to be small.

• Pressure profile shapes are not unusual, and in stability envelope.

• Flow damping is very low in the core, but significant at edge.

Confinement enhancement techniques

NCSX will employ standard techniques:

– Shaping

– Wall conditioning.

– Unbalanced neutral injection to generate flow shear.

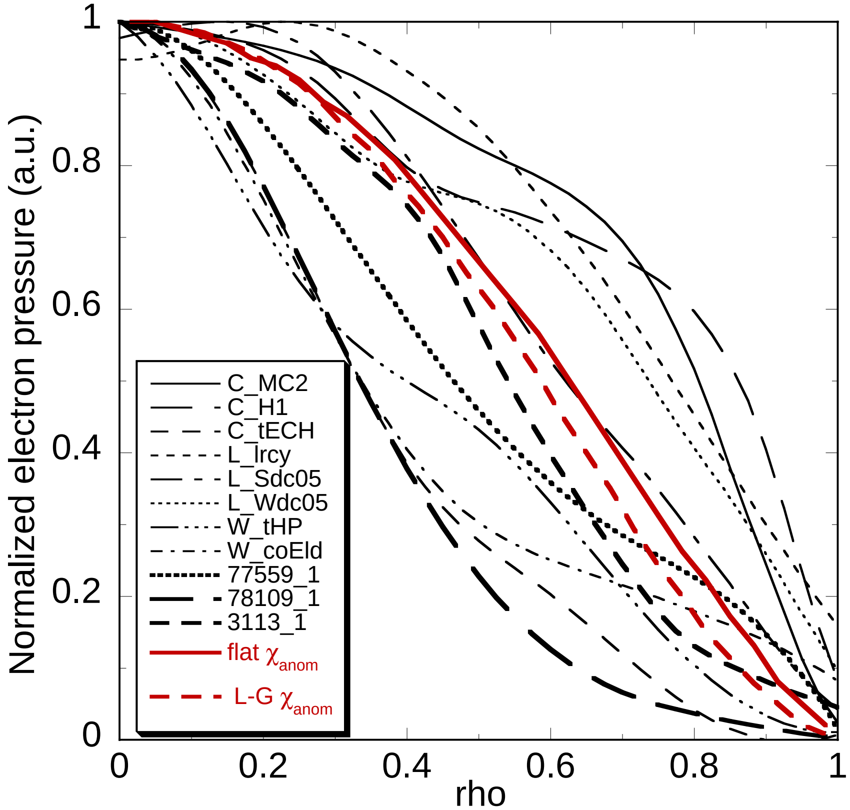
– Pellet injection.

– Limiter placement in region of high flux expansion to reduce cx losses.

– Edge biasing.

H-mode power threshold scaling: <1 MW.
Small enhancement in stellarators, will NCSX be more like a tokamak?

• Pressure profile shapes within envelope of stellarator and tokamak experiments



Lackner-Gottardi model produces a slightly more peaked pressure than the spatially uniform χ_{anom}.

Predicted pressure profile shapes also in the range used in flexibility study.