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?

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 $H_{ISS\text{-}95}$=2.0 for $\dot{W}_{dia} < 0.05 P_{abs}$,

and $H_{ISS\text{-}95}$=2.4 for $\dot{W}_{dia} < 0.13 P_{abs}$

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 $\iota\!\!-$ with the toroidally averaged NCSX shape: $I_p^{eff} = (\frac{B_o}{1.2T})(\frac{R_o}{1.4m})0.5$ MA.

Confinement enhancement techniques

- NCSX will employ standard techniques:

Wall conditioning.

Edge biasing.

Unbalanced neutral injection to generate flow shear.

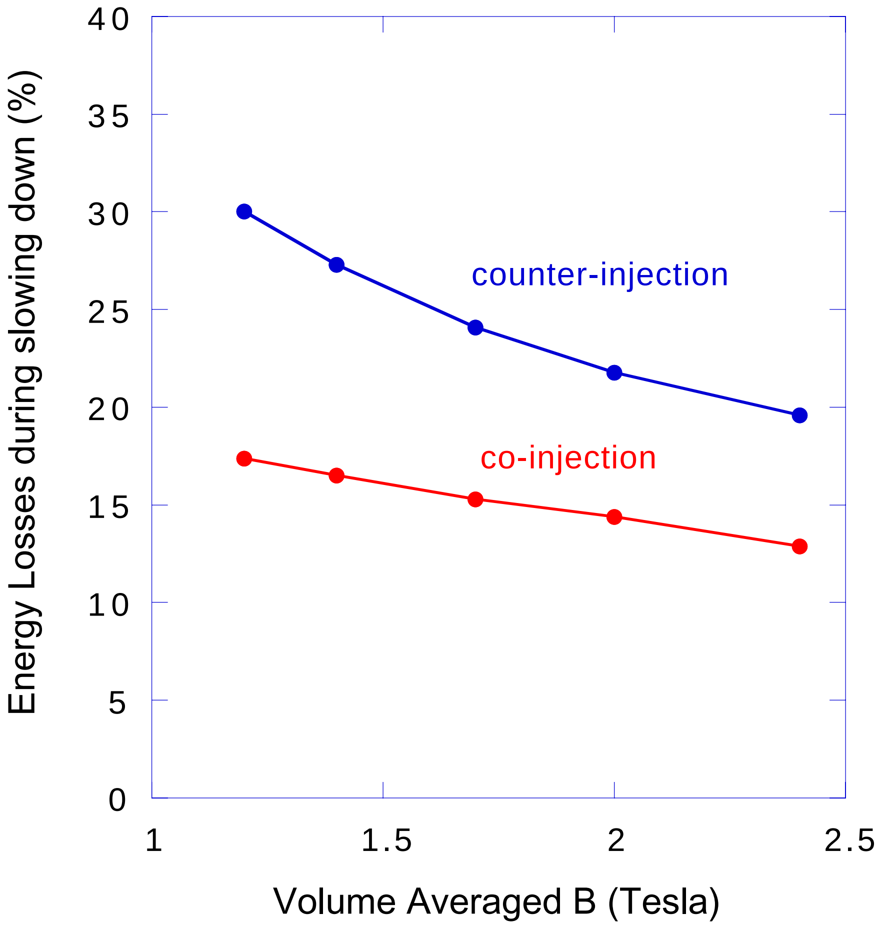
Pellet injection.

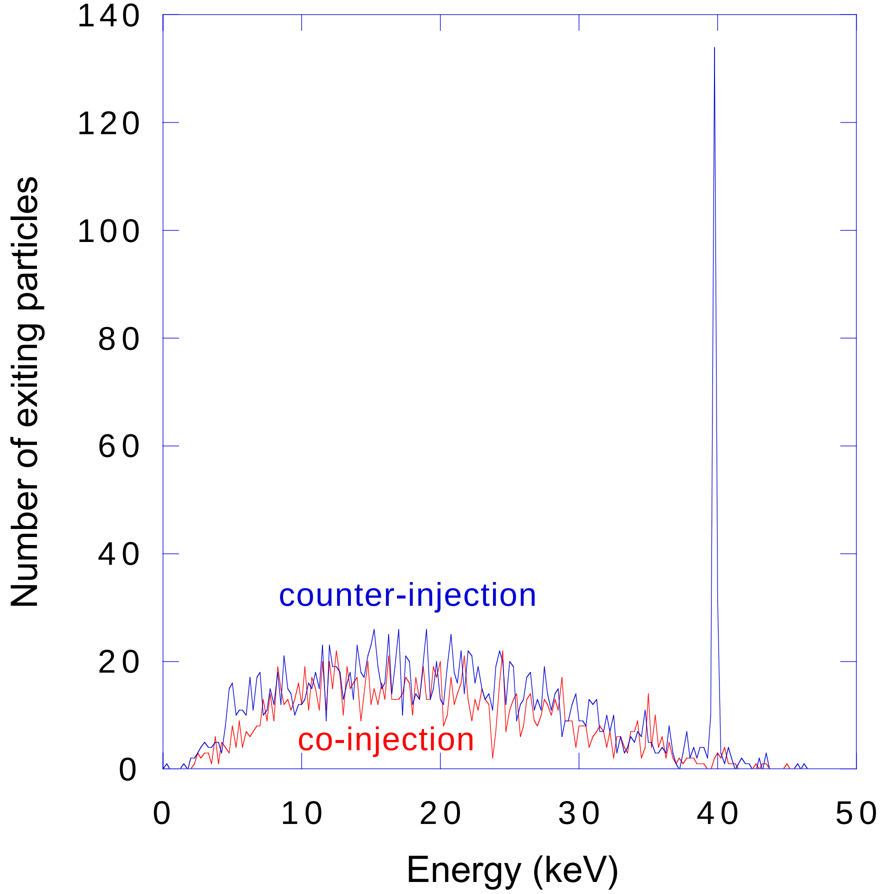
Limiter placement in region of high flux expansion to reduce cx losses.

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

Fast ion confinement; net heating power

D. Spong’s orbit calculations use 3-D geometry and predicted profiles.
All co losses are due to imperfect quasi-axisymmetry.
Thermal transport is less sensitive to ripple than fast ion orbits.
Orbit losses place a lower bound on the product $B_oR_o \propto I_p^{eff}$.
For B_o=1.2 T, and R_o=1.4 m, balanced injection orbit loss ~24%.





Global confinement model

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

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

High $<\beta>$ ⇔ high $H_{ISS\text{-}95}$.

Normalized collisionality,

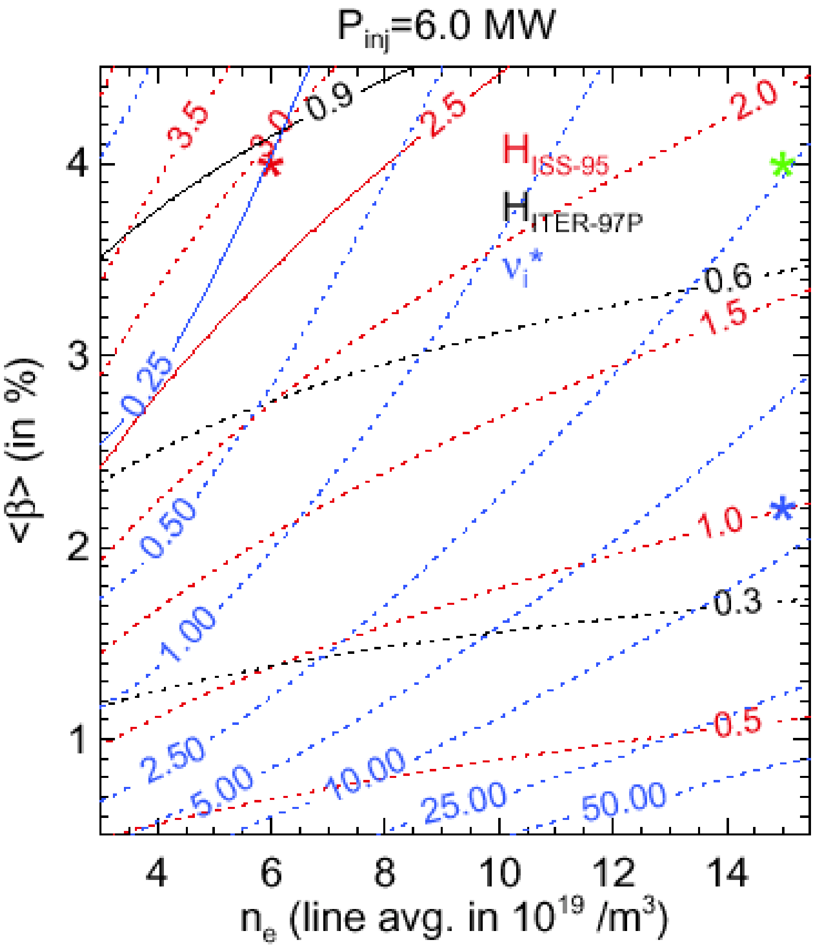
$$\nu_i^* = \nu_{coll}/\nu_{bounce} \propto \; n/T^2 \; \propto \; n^3/B_o^2<\beta>^2,$$

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

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

Maximum density is at the Sudo density ‘limit’.

<β> limits are testable



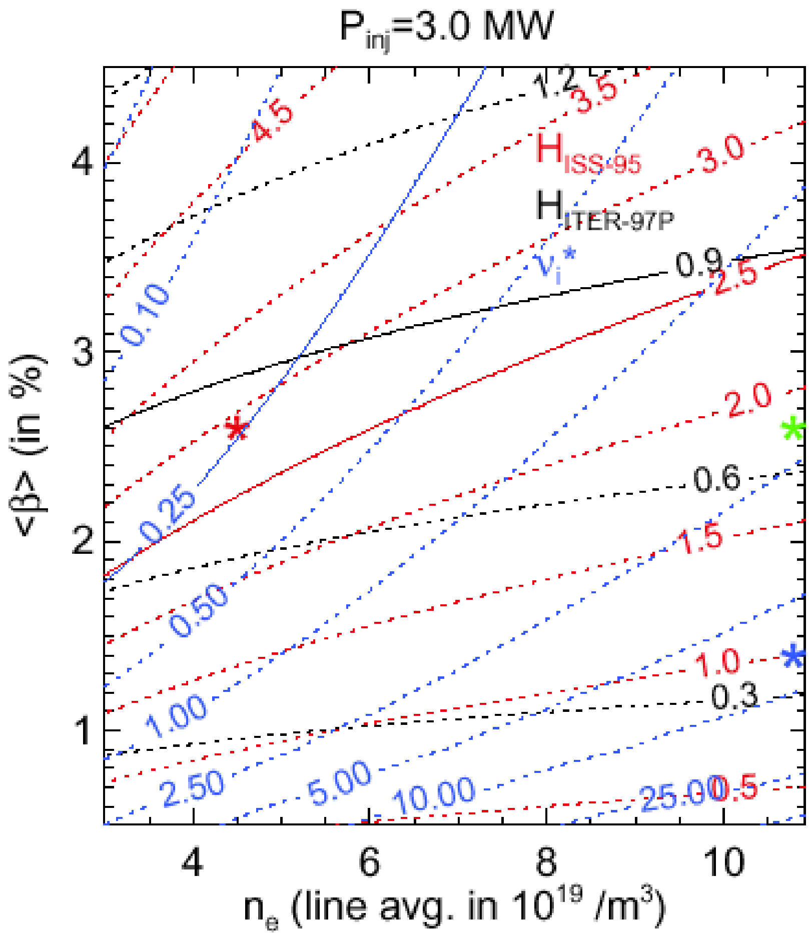
H_{ISS-95}=1 allows <β> up to 2.2%; sufficient to test predictions of MHD stability for de-optimized shapes.

<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*

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

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*

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,

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

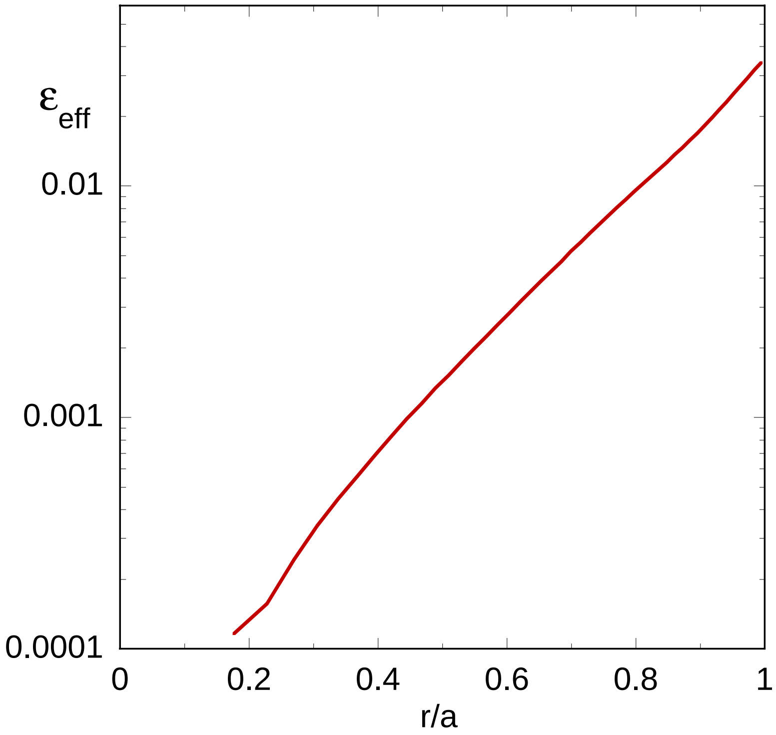
neoclassical ripple and axisymmetric transport, and ‘anomalous’ transport

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 <β>, or $H_{ISS\text{-}95}$;
$q_{anom.}$ 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.

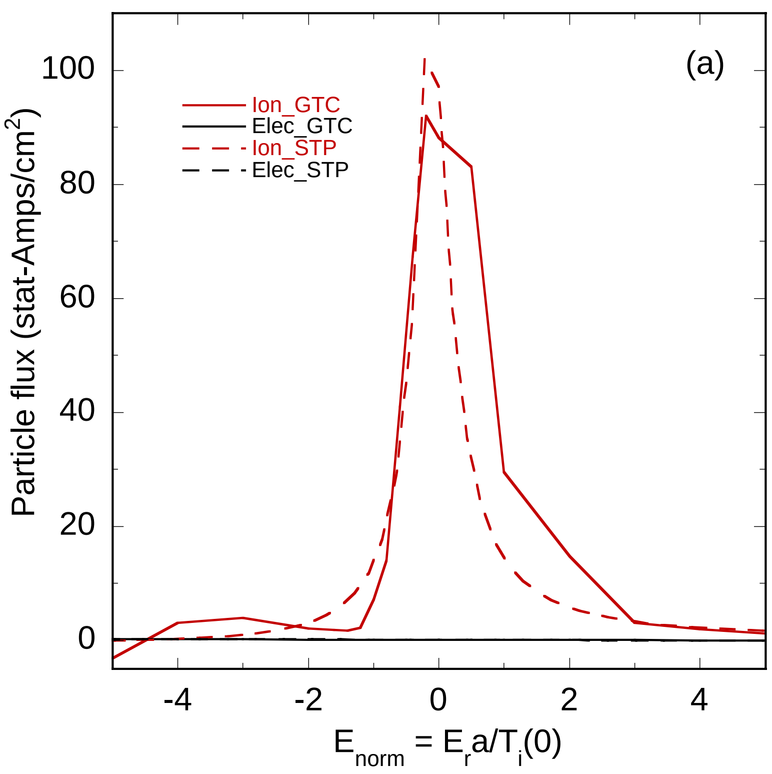
Neoclassical ripple transport is not intrinsically ambipolar, so the plasma charges up until it finds an E_r that does produce ambipolar particle flux. This E_r is very important in reducing the ion's ripple transport.

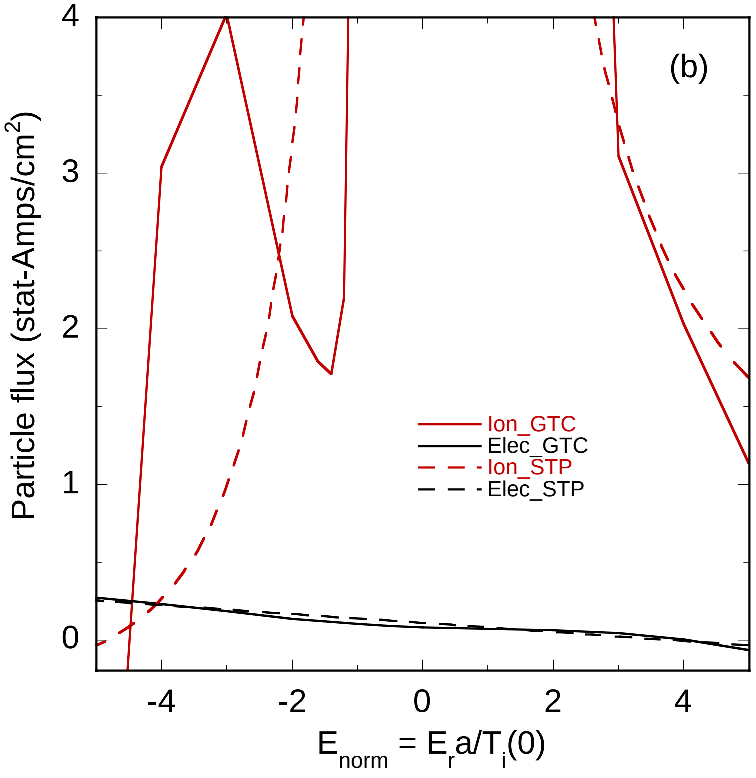
In the 1/ν regime with the 'ion root' $q_{ripple}^{neo} \propto T^{\frac{9}{2}}$, so high density is favorable. The electrons are in the 1/ν regime of validity, but not the bulk ions.

Benchmark validates analytic ripple model

The Monte Carlo code GTC calculates transport fluxes using the full 3-D magnetic geometry, with no assumption about the collisionality regime.
GTC benchmarked with single helicity theory and axisymmetric theory.
E_r is prescribed; particle fluxes vs. E_r are compared (Lewandowski).

Analytic and numerical predictions of ambipolar E_r are close to each other
Electron fluxes are close, so ambipolar fluxes are close.



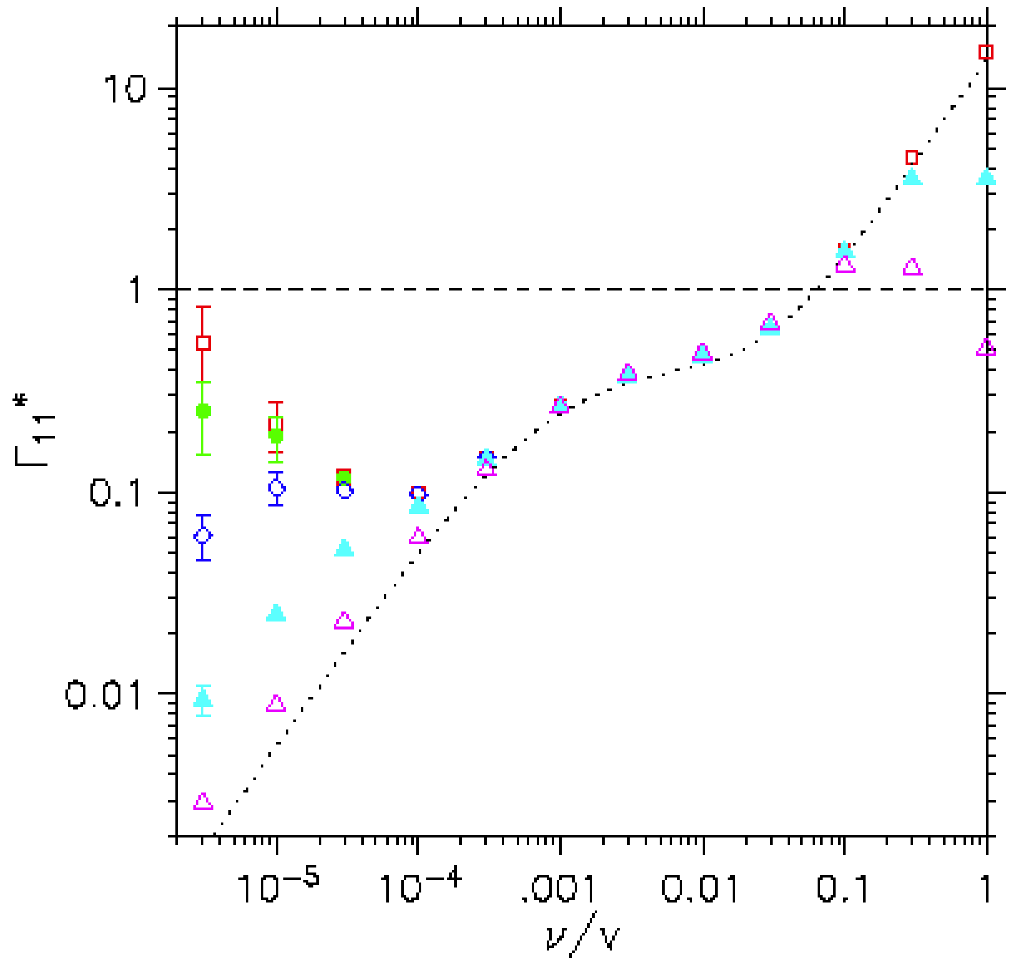


DKES confirms axisymmetric transport is dominant

DKES code (Hirshman) predictions confirmed by W7-AS (Maaßberg).

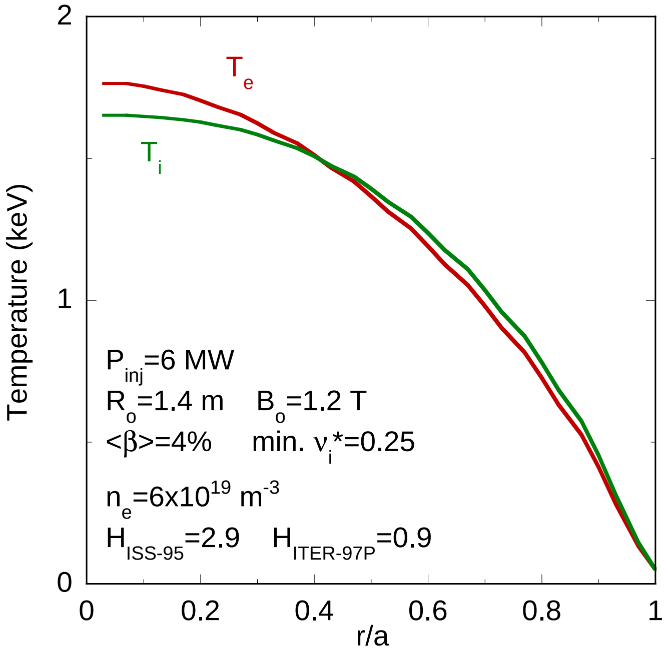
Monoenergetic diffusivities are strongly reduced by E_r; and asymptotically approach the axisymmetric result.

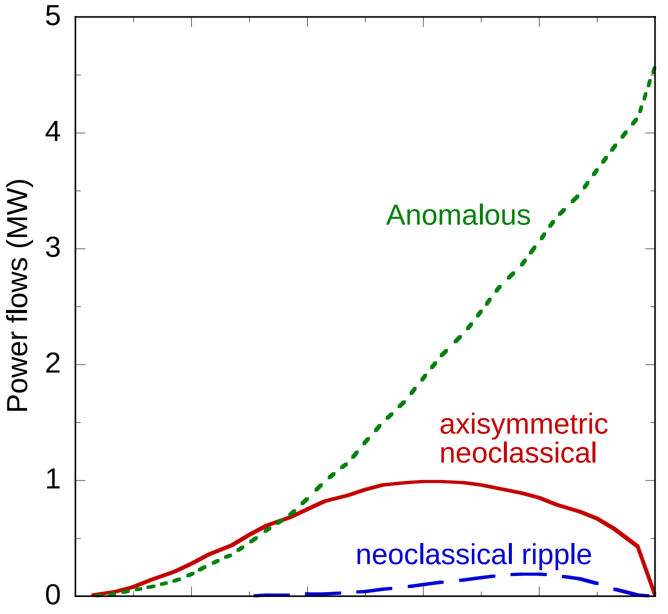
With the ambipolar E_r the neoclassical ripple transport is negligible.



E_r/Bv= 0
1x10-4
3x10-4
1x10-3
3x10-3

Large margin for anomalous transport





High <β> and moderate ν_i*

$\langle\beta_{thermal}\rangle=2.9\%$, $\langle\beta_{fast}\rangle=1.2\%$

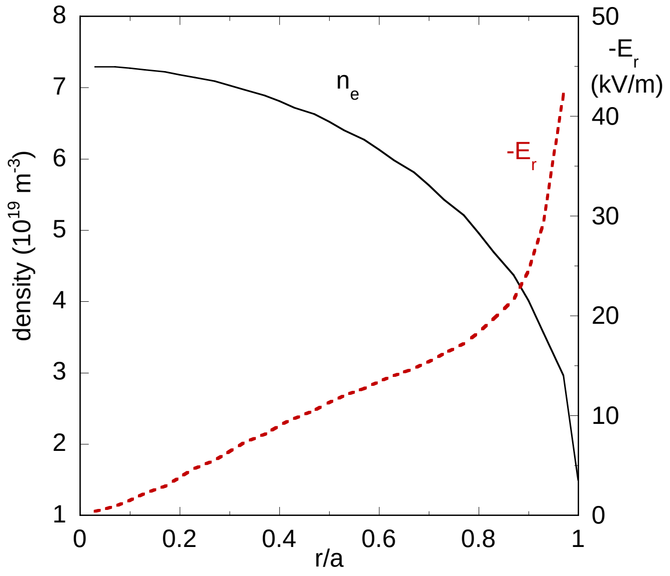
$q^{neo}_{axisym.}$ normalized to THRIFT/NCLASS

$q^{neo}_{ripple} << q^{neo}_{axisym.}$

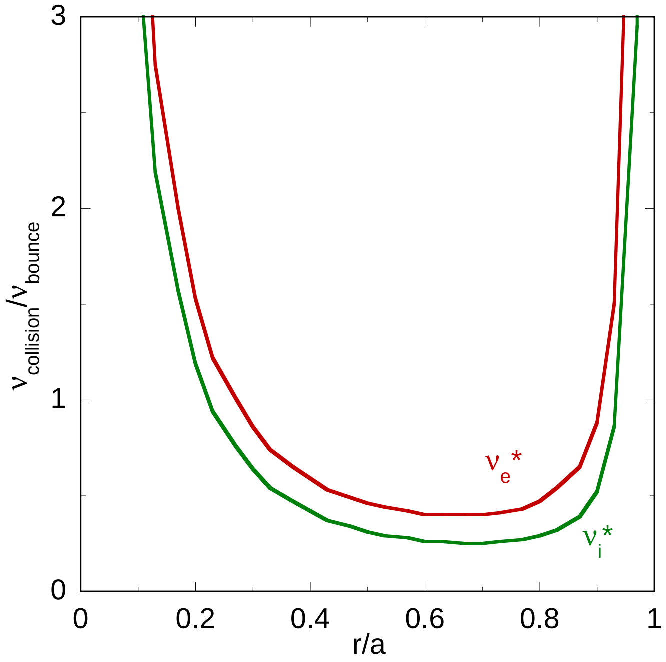
Spatially constant $\chi_{anom}=1.7\ \mathrm{m^2/s}$

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

$\langle\beta\rangle$=4%, moderate ν_i*, (cont'd)



Ambipolar E_r is used in ripple transport calculation.



minimum ν_i*=0.25

minimum ν_e*<0.5

CX losses not serious

Neutral transport simulation (Stotler) used n_e, T_e, T_i profiles similar to those shown above.

Neutrals launched from outboard midplane (or tip) of crescent cross sectio

Neutral influx is normalized by assumed $\tau_p = \tau_E$.

Thermal P_{cx}~0.04 (0.01) MW

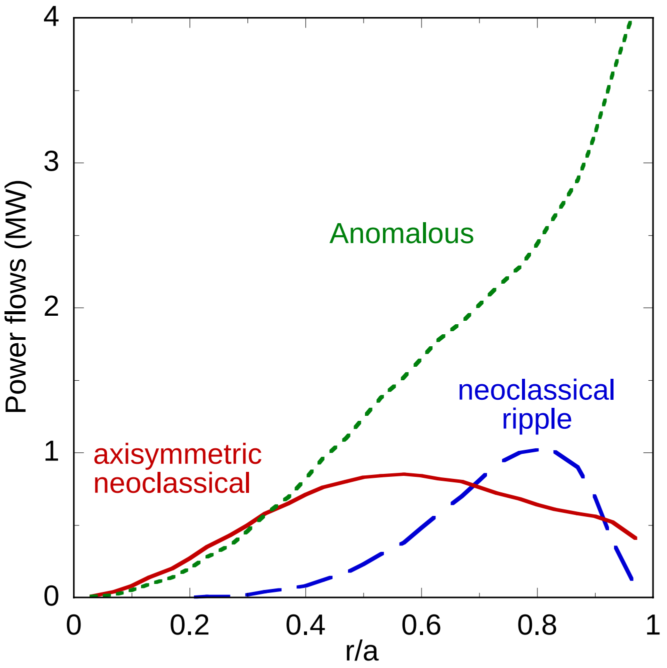
Fast ion cx losses ~0.3 (<0.1) MW

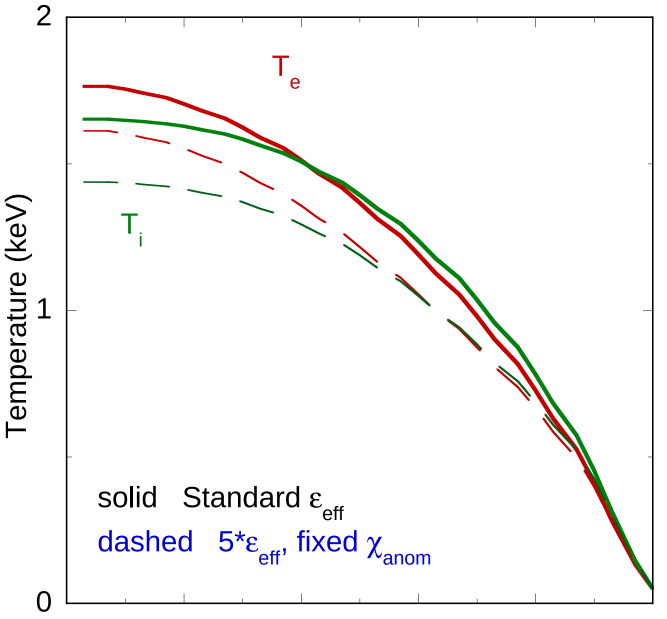
For either limiter placement charge exchange losses are acceptable.

Plan to place limiter near crescent tip to reduce cx losses.

More detail in P. Mioduszewski's talk.

Spoiled quasi-axisymmetry: 5 times higher ε_{eff}





Typical configuration changes raise effective ripple ≤2 times nominal value.

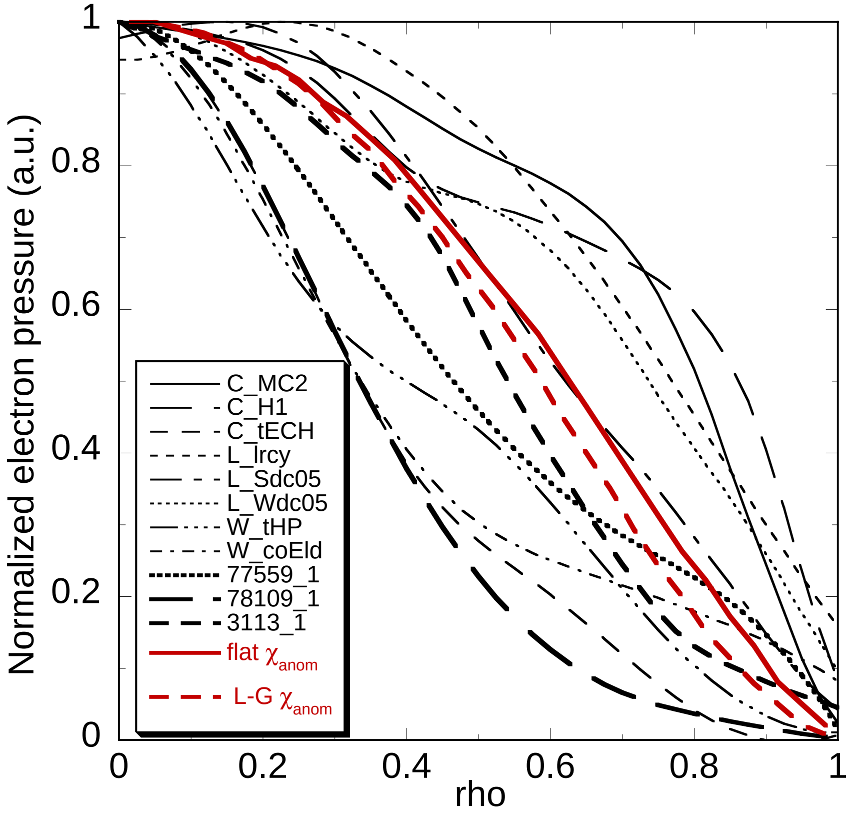
Intentional efforts can raise effective ripple by ~5 times.

With χ_{anom} fixed, $<\beta_{th}>$ drops from 2.9 to 2.5%. Ripple transport still negligible for r<a/2.

Temperature change would be marginally detectable.

Increased ripple is a potential problem for fast ions and flow damping.

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.

Summary

- Confinement is expected to allow tests of $<\beta>$ limit predictions.
Even with $H_{ISS\text{-}95}=1$, $<\beta>$ 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 $<\beta>=2\%$.

Challenging a more optimized $<\beta>$ limit ~4% requires $H_{ISS\text{-}95}=1.8$, but $\nu_i^* \geq 3$.
$\nu_i^*\sim 0.25$ *and* $<\beta>\sim 4\%$ 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.