Transport Status

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NCSX Project Meeting, 3/23-24/00

·Issues
·Tools
·Current Status, Plan

Issues:

(1) Insensitivity of τ_E's from GTC to ripple level:
The standard transport assessments with GTC have produced results with only small differences in τ_E for large variations in quasiaxisymmetry measure $\chi^2_{QA}(s) = \sum_{m,n\neq 0} B^2_{mn}/B^2_{00}$, counter to simple expectations from standard 3D neoclassical transport theory.

(2) Impact of issue-1 on configuration:
Since χ^2_{QA} is an integral part of the optimizer's objective function, Allan R has pointed out that this has important implications for the NCSX design: If the GTC results are to be believed, transport considerations alone might lead us to configurations (such as PG2) with far greater ripple δ than up to now.

(3) Other constraints on δ:
However, thermal confinement is not the only issue which provides a constraint on δ. Energetic confinement, and a toroidal rotational damping rate ν_ζ small enough to permit study of tokamak-like enhanced-confinement regimes, also set limits on δ.

(4) Credible determination of ν_ζ and E_{r0}:
ν_ζ is closely related to the equilibration rate ν_Φ for the ambipolar potential $\Phi(r)$, or equivalently for the radial electric field E_r. Especially for $s = i$, the ambipolar value E_{r0} of E_r strongly affects issue-1. Determining ν_ζ and E_{r0} requires being able to compute the non-ambipolar radial current $J_r(E_r)$, which requires the non-axisymmetric parts $\Gamma^{na}(E_r)$ of the particle fluxes Γ.

(5) Credible determination of $\Gamma_s^{na}(E_r)$.

○Tools:

·Analytic theory

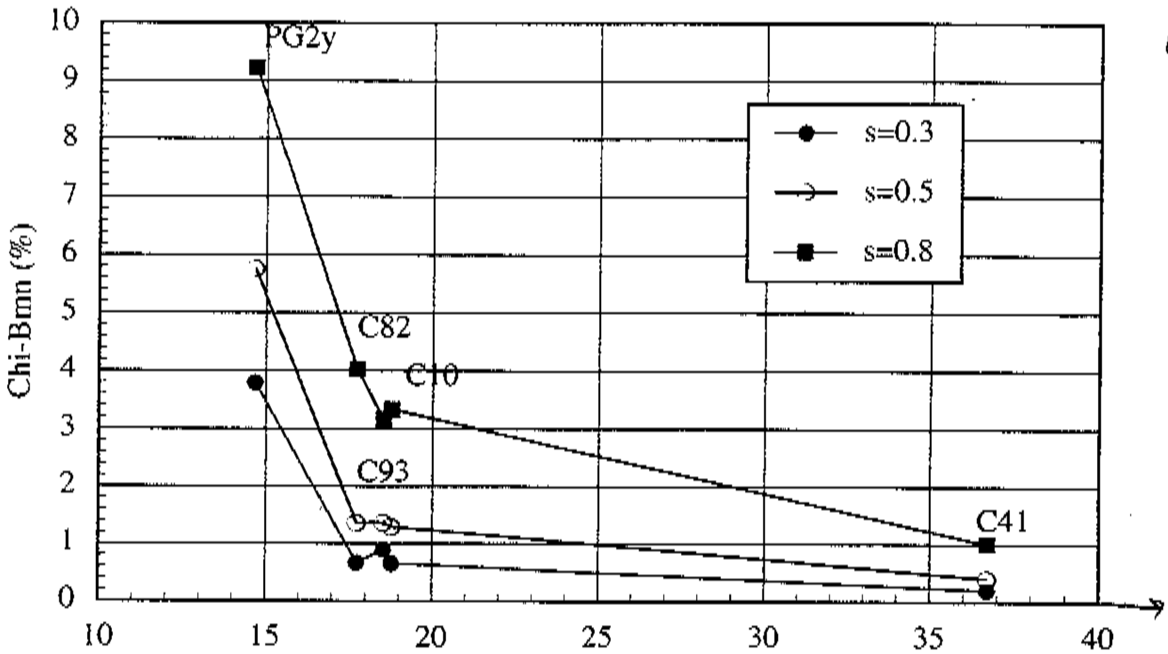
·Codes extending analytic theory
(*e.g.*, Nemov code 'NEO')

·Codes solving the kinetic equation
(*e.g.*, MC codes, DKES)

·Different ones of these have different virtues, *e.g.*, speed, ability to compute Maxwellian-avged results, closeness to analytic theory, diagnostics for physical insight, non-statistical answers.

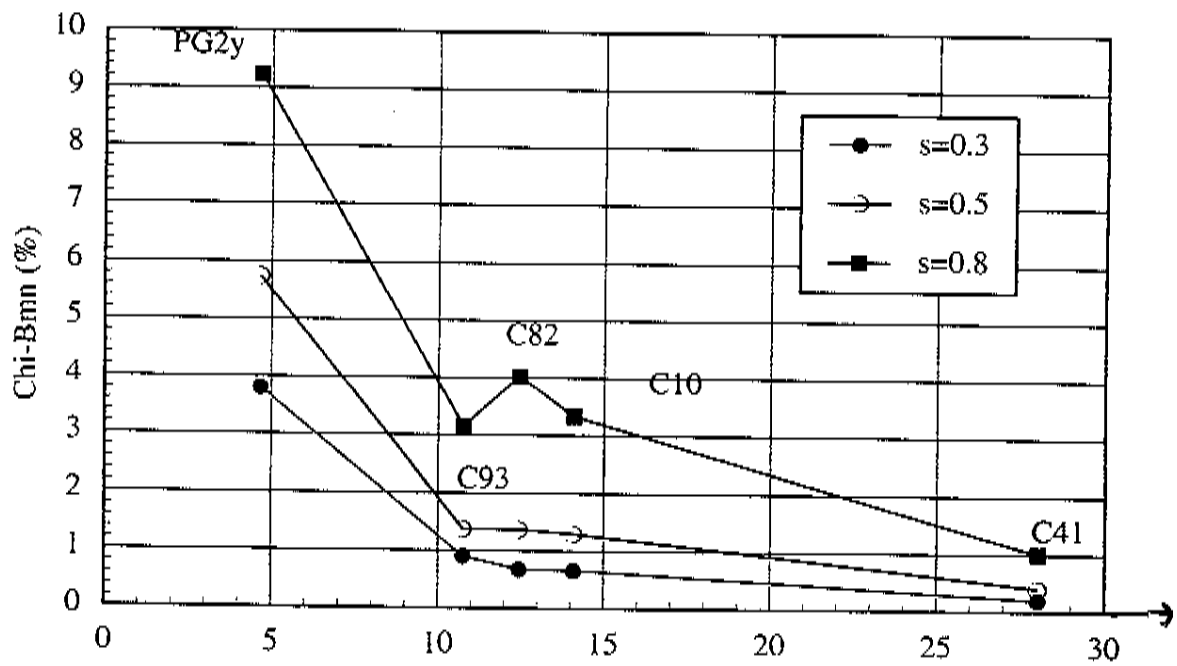
○Issue-1: Insensitivity of τ_E's to ripple level in standard GTC assessments:

[From L-P Ku]



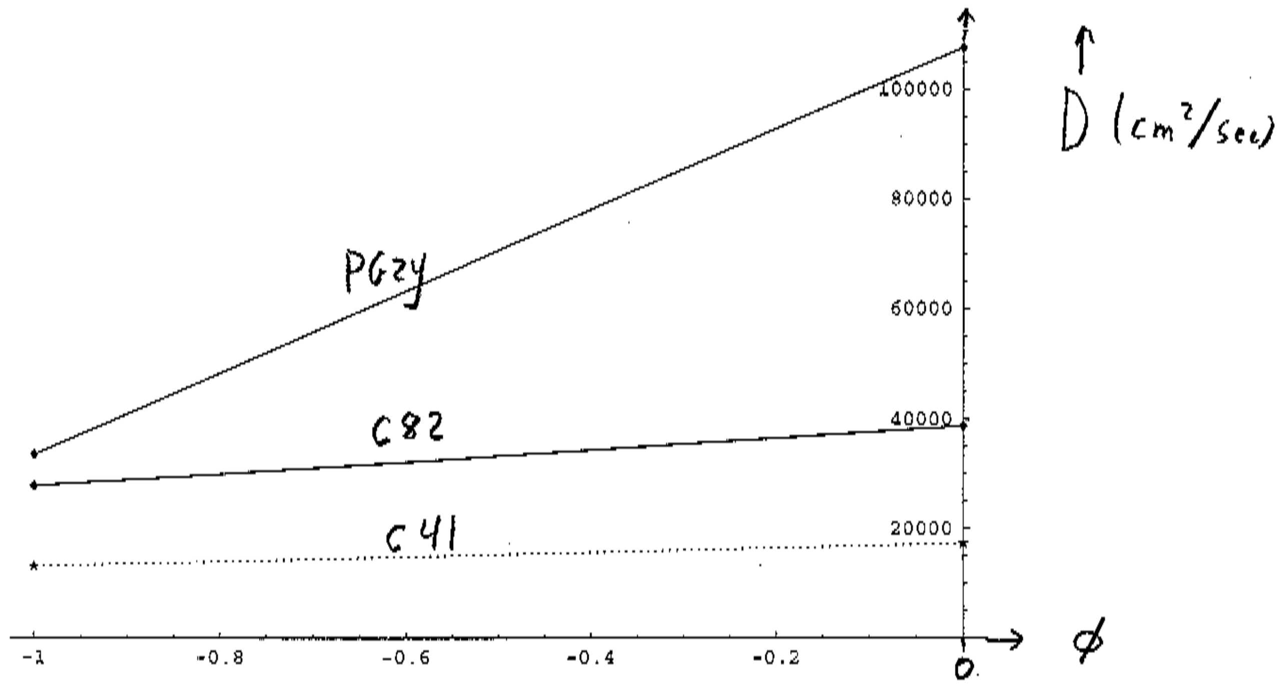
$\alpha = 1$, in $\frac{e_i \Phi}{T_i} = \alpha \, \Psi / \Psi_a$

○Older eval'ns using GC3 showed expected sensitivity to ripple. **Difference:** GC3 eval'ns took $\phi \equiv e_i a E_r / T_i = 0$, GTC's use $\phi \sim 1$ ($\alpha = 1$ in $\phi \simeq -2\alpha r/a$). Then τ_E's from GTC, GC3 consistent:

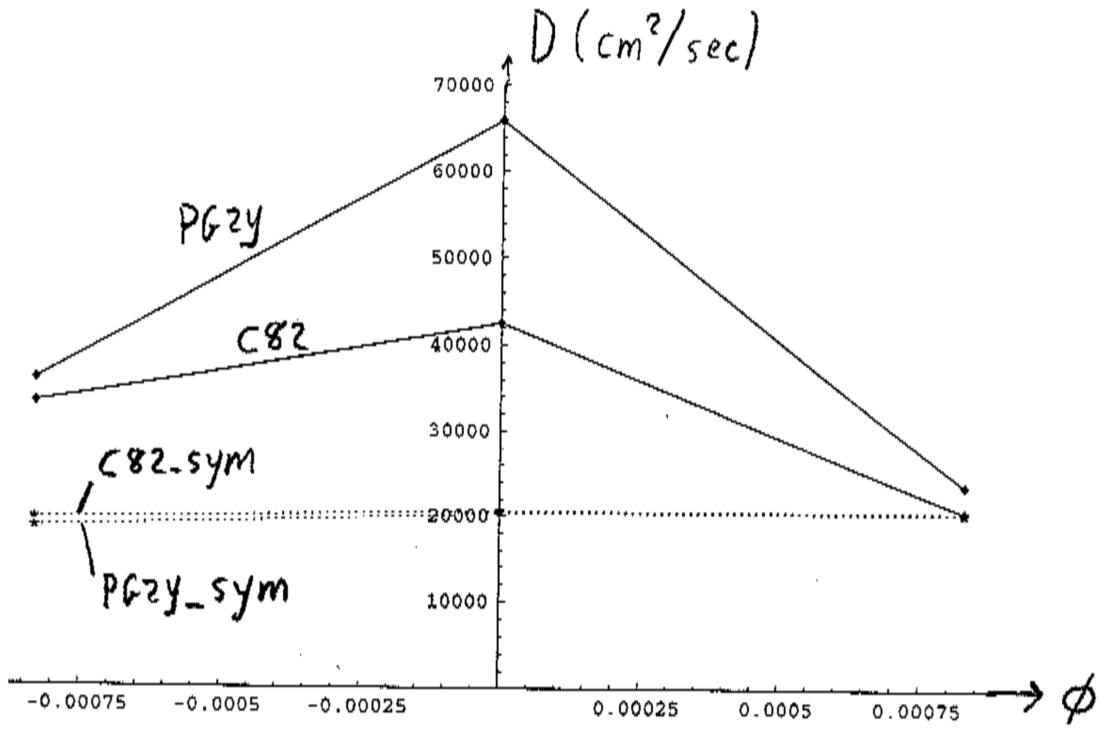


$\alpha = 0$

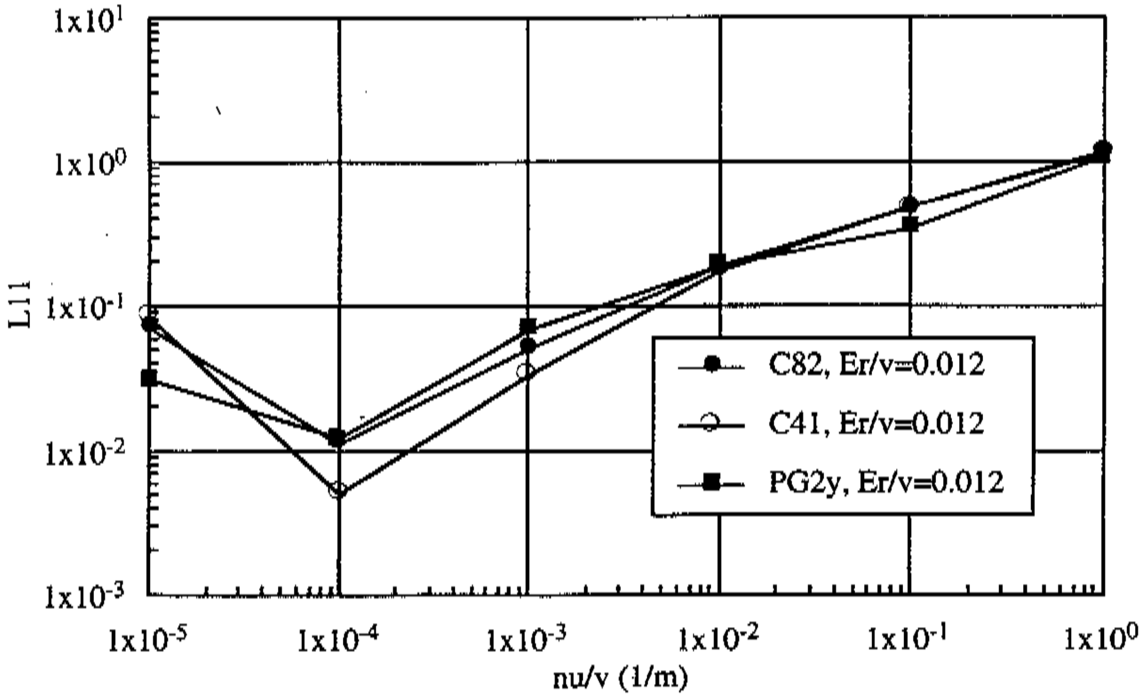
∘From these GTC numbers, sketch $D \equiv a^2/(4\tau_E)$ versus ϕ, using c41 as a proxy for the equivalent tokamak:



∘Compare with comparable GC3 results (but monoenergetic, D computed directly):

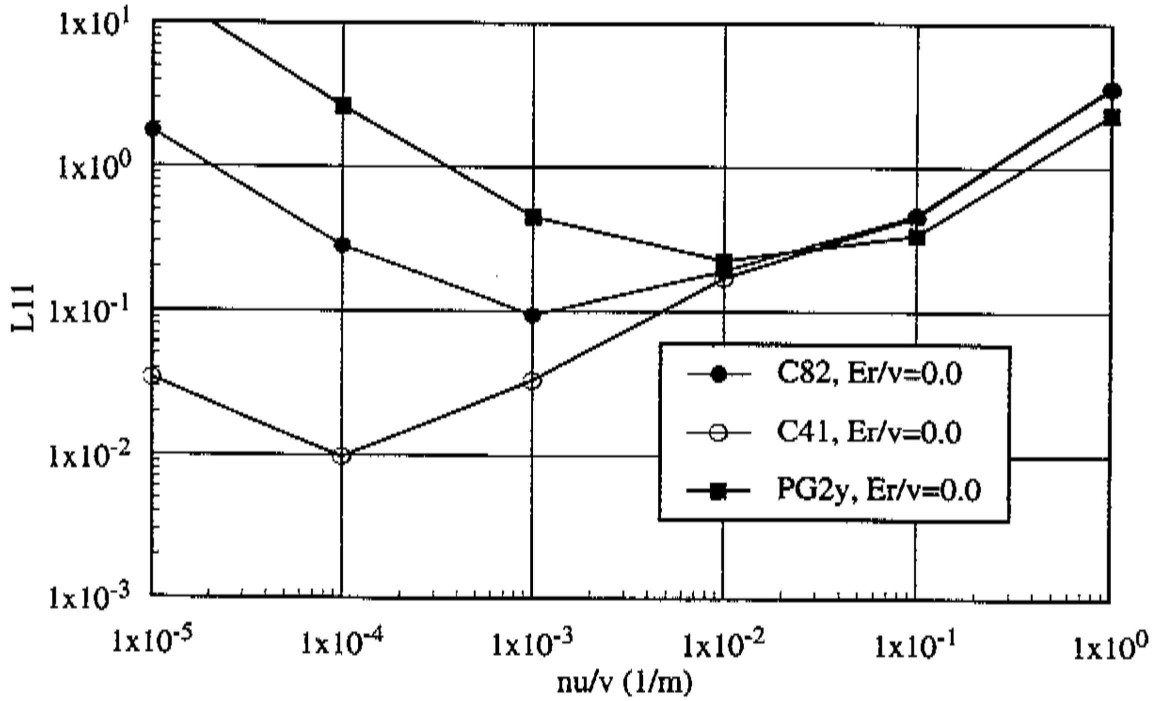


∘ D(DKES) shows a similar lack of sensitivity to δ for $\phi \sim 1$: [From L-P Ku]



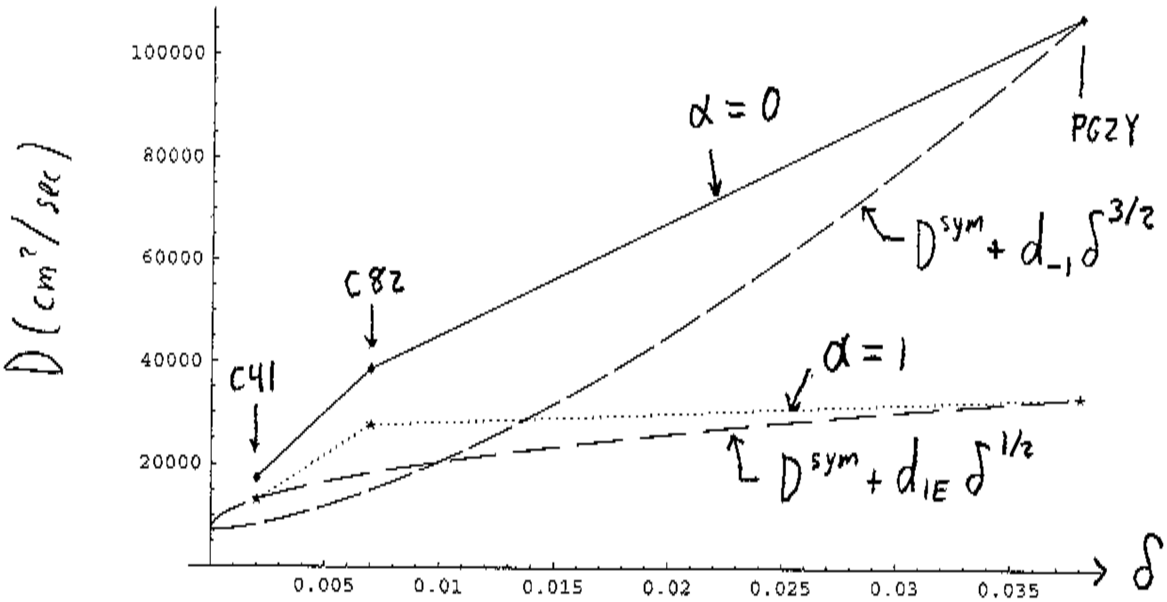
$\frac{E_r}{v} = .012$

$\phi \sim 1$



$\phi = 0$

○ δ-dependence of D(GTC) weaker than analytic expectation:

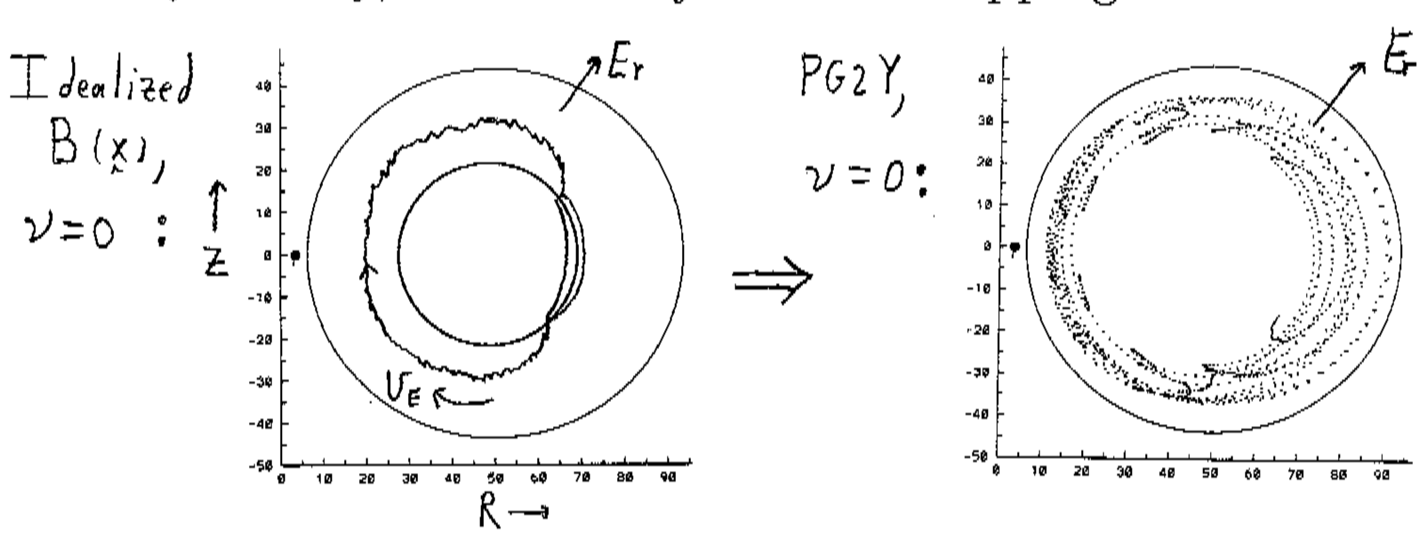


○Theory says $D_{-1} \sim \delta^{3/2}$, $D_{1E}^{sb} \sim \delta^{1/2}/\phi^2$, $D_{1E}^{bd} \sim \delta^2/\phi^2$.
⇒Theory can serve as a useful guide for expectations, but often not quantitatively valid for NCSX configurations.

○Deficiencies of theory:

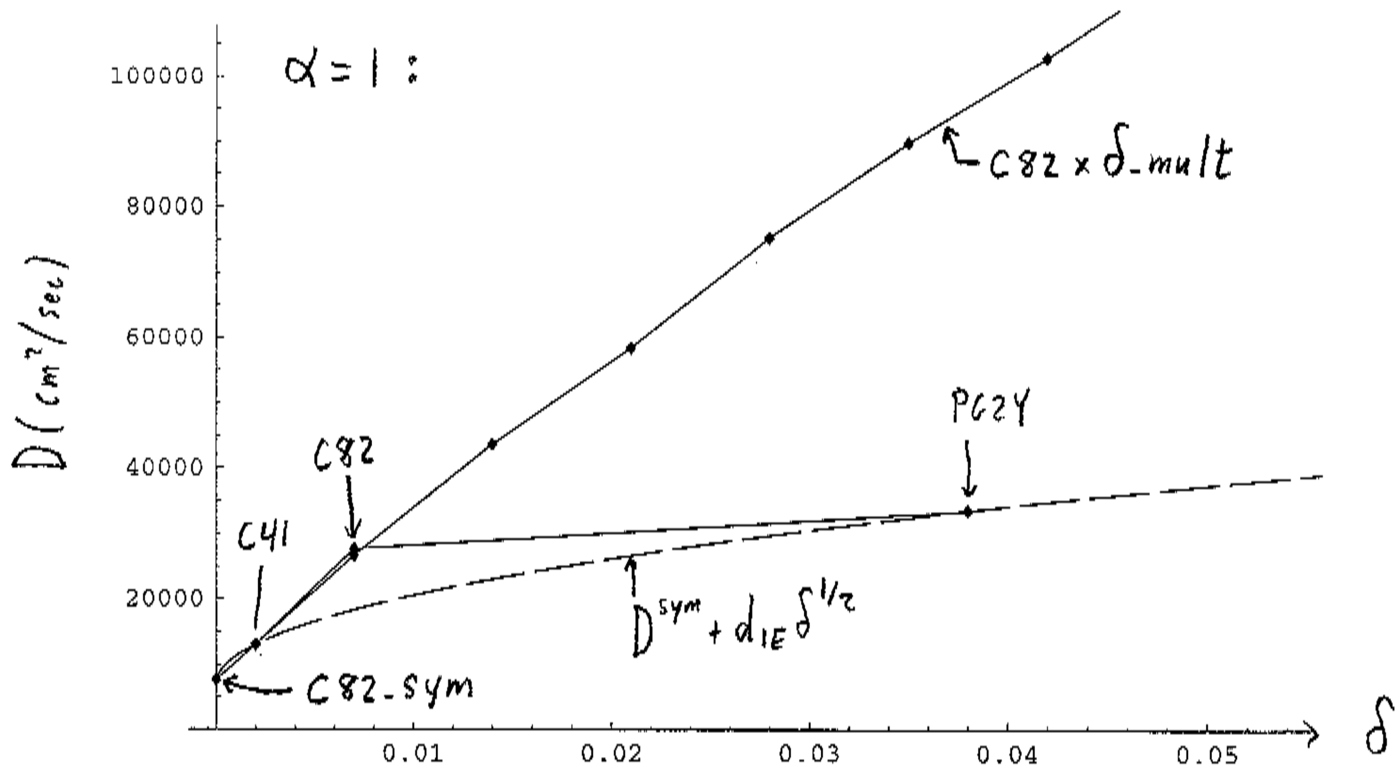
·Diffusion only. Neglects direct (nonstochastic) loss.

·Assumes idealized $B(\mathbf{x})$, and clean separation of transport mechanisms. Results in ν-less orbits with simple symmetry, unbroken by ν-less detrapping.



○ Recent GTC results [F.Dahlgren]: Artificially sweep c82 ripple strength, for more apples-to-apples comparison:

○ Shows much stronger δ-dependence.

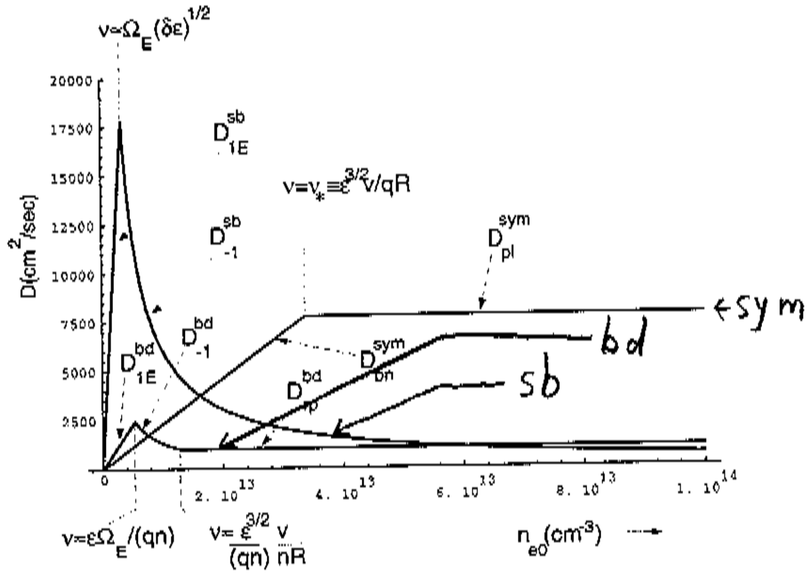


○ Electrons a better gauge of transport sensitivity to δ:

○Whether dominated by diffusive or direct–loss, Γ_i must adjust itself (via E_r) to equal Γ_e.
○Electrons in $1/\nu$ regime $\Rightarrow \Gamma_e \simeq (d_e \delta^{3/2})(F_0 - \phi)$ much less sensitive to E_r than Γ_i.
○Electrons better satisfy assumptions of analytic theory: diffusive transport, more collisional, $\rho_b \simeq 0$.
○For the $1/\nu$ regime, NEO removes one of the remaining deficiencies of analytic theory (*viz.*, the complicated distribution of the ripple over a flux surface), hence provides a refinement of our current χ^2_{QA} for use in the optimizer.
○NEO does *not* account properly for banana–drift transport, nor of effects of collisionless detrapping and lack of clean separation of transport mechanisms at the low ripple levels ($nq\delta/\epsilon \sim 1$) QA devices have.

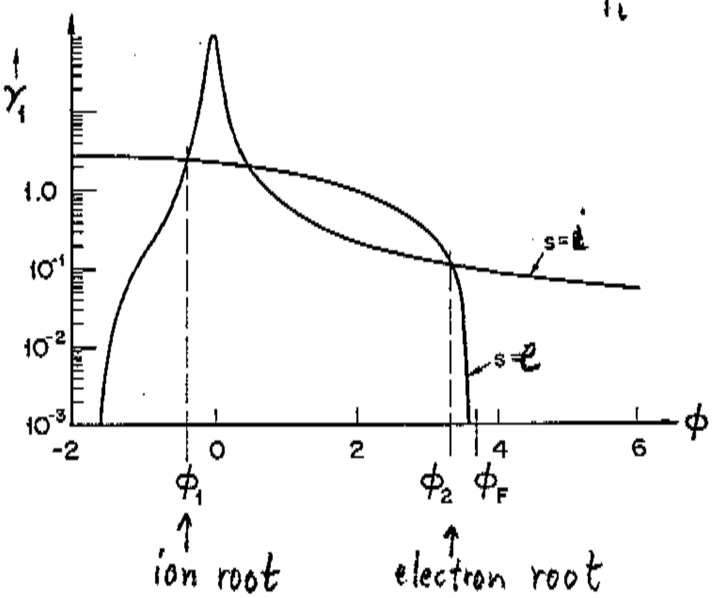
○Benchmarking of GTC against NEO for electrons needed, to
(a)establish that it DOES connect to theory when theory should hold (larger–δ, possibly simplified B_{mn} spectrum),
(b)find at what δ the $1/\nu$ theory deviates from numerical results. [F. Dahlgren, M. Redi?].

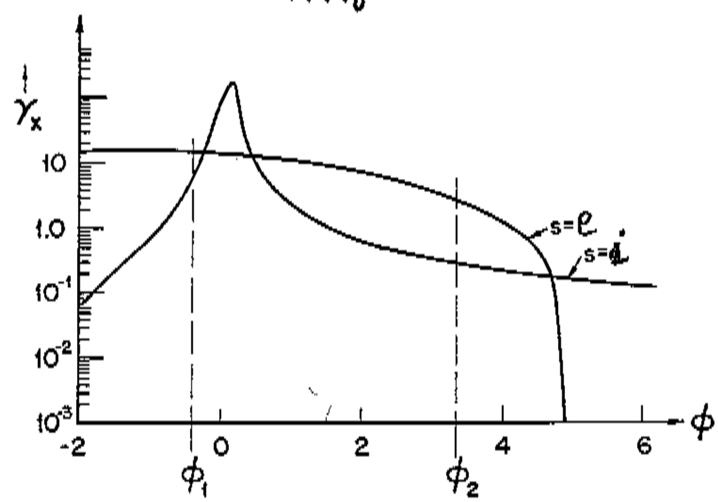
○Analytic theory:



[From: Mynick, Hitchon, NF 23 ('83)]

$$\phi \equiv \frac{e_i a E_r}{T_i}, \quad \gamma_{1,x} \equiv \frac{[\Gamma, Q/T]}{a n_0} \quad (\mathrm{sec}^{-1})$$





○Deficiencies of theory:

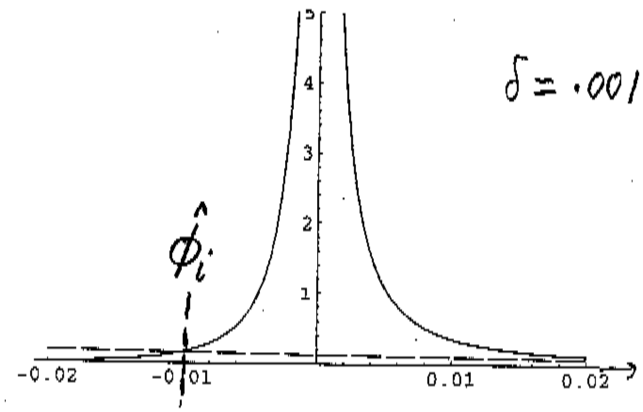
·Diffusion only. Neglects direct (nonstochastic) loss.

·Assumes highly idealized $B(\mathbf{x})$, and clean separation of transport mechanisms.

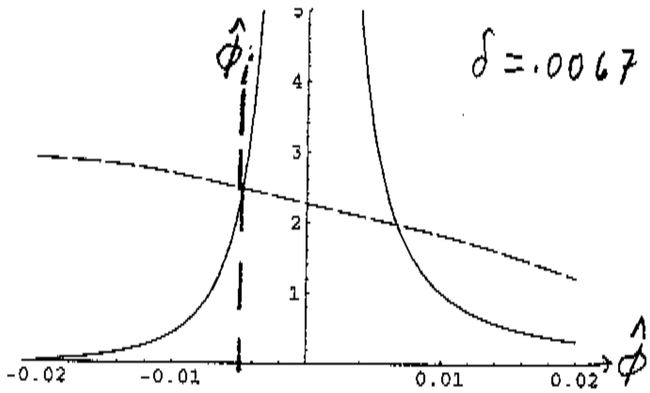
⇒Can serve as a useful guide for expectations, but often not quantitatively valid for NCSX configurations.

∘Analytic theory: Ambipolarity:

$T = 3.5$ keV, $n_e = 1.4e20$ (.75)



$\hat{\phi} \equiv \phi \overbrace{\left(\frac{R}{a}\frac{T_i}{E_d}\right)}^{.0034}$

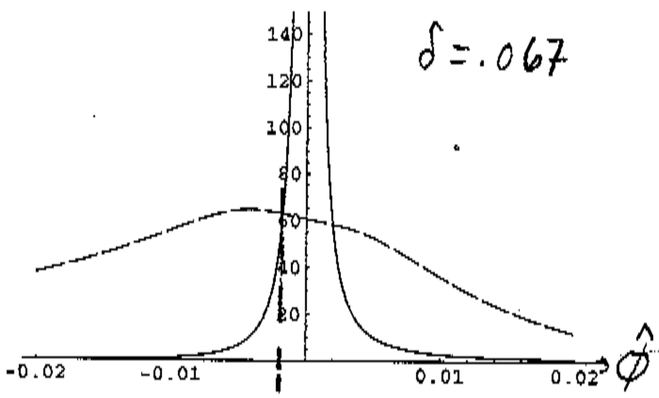


$$\Gamma_i^{na} = \Gamma_e^{na}$$

$$\Gamma_i^{na} \simeq \left(d_i \delta^{1/2}/\phi^2\right)\left(F_{0i} \overset{\text{drop}}{\boxed{+\phi}}\right)$$

$$\Gamma_e^{na} \simeq \left(d_e \delta^{3/2}\right)\left(F_{0e} \boxed{-\phi}\right)$$

$$\Rightarrow \phi \simeq \left[\frac{d_i F_{0i}}{d_e F_{0e} \delta}\right]^{1/2}$$



○Assessing the tradeoff between reducing Q^{na} by ripple reduction, vs Q^{sym} by ι enhancement. Short–term method:

○Have $Q_i^{sym} \gtrsim Q_i^{na}(E_r) \sim Q_e^{na} \gg Q_e^{sym}$,

$$\Gamma_i^{na}(E_r) = \Gamma_e^{na}$$

⇒Compute $Q_e \simeq Q_e^{na}$

$$\Rightarrow Q_i^{na}(E_r) = Q_e^{na} \underbrace{\frac{Q_i^{na}(E_r)}{\Gamma_i^{na}(E_r)}}_{\text{theory}} \underbrace{\frac{\Gamma_e^{na}}{Q_e^{na}}}_{\text{theory}},$$

Compute Q_i^{sym}

$$\Rightarrow Q_i(E_r) = Q_i^{sym} + Q_i^{na}(E_r).$$

∘ Issues-3-5: Credible calculation of $\nu_\zeta, E_{r0}, \Gamma^{na}$:

∘To compute these, need the radial current from the nonambipolar fluxes $J_r = \sum_s e_s \Gamma_s = \sum_s e_s \Gamma_s^{na}$.

∘Previous direct attempts to compute J_r with δf codes using the full Γ_s unsuccessful for QA configurations, because $\Gamma_i^{na} \sim \Gamma_i^{sym,t.p.}$ for these, and since $\Gamma_i^{sym,t.p.} \gg \Gamma_e^{sym}$, obtaining $\Gamma_i^{sym} = \Gamma_e^{sym}$ numerically requires very good statistics, long run times and/or loading close to the value of the equilibrated distribution function.

∘Fluid-equation formulations [*e.g.*, Boozer (76), Shaing (86), Coronado & Wobig (87), Coronado & Talmadge (93), Kovrizhnykh (99)] of nonsymmetric transport theory provide prescriptions for Γ^{na} and equilibration rates from taking 2 components in a flux surface of the momentum equation. Thus,

$$\langle \nabla V \cdot \partial_t \mathbf{E} \rangle = -4\pi \langle \nabla V \cdot \mathbf{J} \rangle,$$
$$\langle \nabla V \cdot \mathbf{J} \rangle = \textstyle\sum_s e_s (\Gamma_s^{na} + \Gamma_s^{pl} + \Gamma_s^{ex}), \text{ with}$$
$$\Gamma_s^{na} \equiv (c/e_s \chi' \psi') \langle \mathbf{B}_t \cdot \nabla \cdot \boldsymbol{\pi}_s \rangle, \boldsymbol{\pi} = (p_\parallel - p_\perp)(\hat{b}\hat{b} - \mathbf{I}/3)$$
$$\Gamma_s^{pl} \equiv (c/e_s \chi' \psi') \langle \mathbf{B}_t \cdot \partial_t \mathbf{u}_s \rangle,$$
$$\Gamma_s^{ex} \equiv (c/e_s \chi' \psi') \langle \mathbf{B}_t \cdot \mathbf{R}_s \rangle.$$

∘Evaluating Γ_s^{na} analytically is difficult, especially in low-ν regimes. Recently, Williams and Boozer have evaluated this for simple model stellarator fields using a δf code, and used this to find ν_ζ, the E_{r0} satisfying ambipolarity, and the fluxes there.

⇒Plan: Implement this method into GTC, for larger-scale runs needed for realistic QA configurations.

[Lewandowski, Lin, Mynick, Williams]

◦ Summary:

◦Our numerical tools show consistent trends for τ_{Ei}. DKES does not include direct loss while GTC, GC3, ORBIT, DELTA do, making their $\phi = 0$ scalings further from analytic theory, but more realistic.

◦The difference in δ-scaling between theory and GTC asessments is only partly understood, but not very surprising: a number of assumptions of analytic theory are violated by QA configurations.

◦This disparity for ions is also not as critical as might be supposed, because E_r will bring the ion fluxes down to the level of the electron fluxes, which are insensitive to E_r, and whose transport should be easier to compute.

◦Theoretical assumptions best satisfied for electrons, in the $1/\nu$ regime. Since Γ_e^{na} is insensitive to ϕ, one may expect the electron and ion nonsymmetric fluxes to roughly display the $1/\nu$ dependence $\Gamma^{na} \propto \delta^{3/2}$, not far from the present figure of merit χ^2_{QA} used 'til now in the optimizer. NEO would impart a similar, but better, figure of merit. Further benchmarking of GTC against NEO needed to verify agreement of MC results with theory when theory should hold.

∘The method of Williams and Boozer for computing Γ^{na} alone, isolated from Γ^{sym}, offers a promising way to compute credible values of ν_ζ and E_{r0}, and through it, τ_{Ei}. An effort to do this has been initiated, with participation from Lewandowski, Lin, Mynick, and Williams.