Improving confinement in QA stellarators

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-Thanks to: L.P. Ku, PPPL

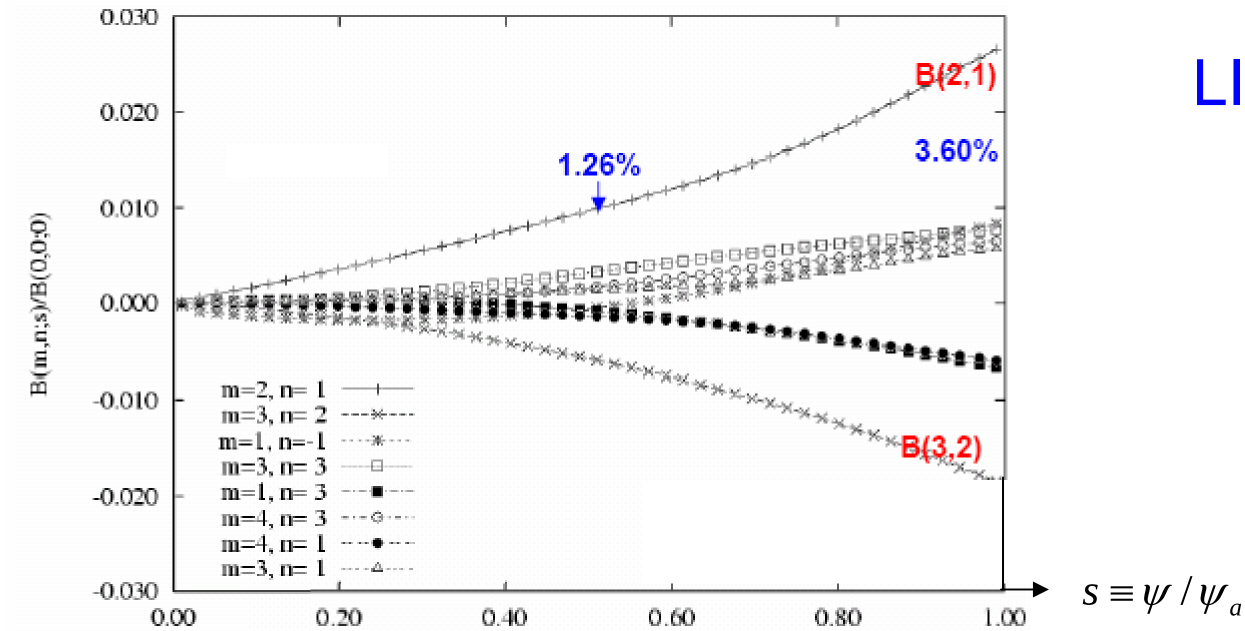
-We compare some related QA designs to better understand the differences in their confinement properties, & identify some design rules on that basis.

-The LI383 (NCSX) QA design has good thermal confinement properties. Its energetic ion confinement is more problematic.

-The descendant N3ARE design [Ku, Garabedian, 2005] reduces the dominant B_{23}, B_{36} in LI383, in exchange for larger B_{03}, B_{13}, & achieves substantially better energetic & thermal confinement. WHY?

-Harmonic composition (From L.P.Ku, 2005):

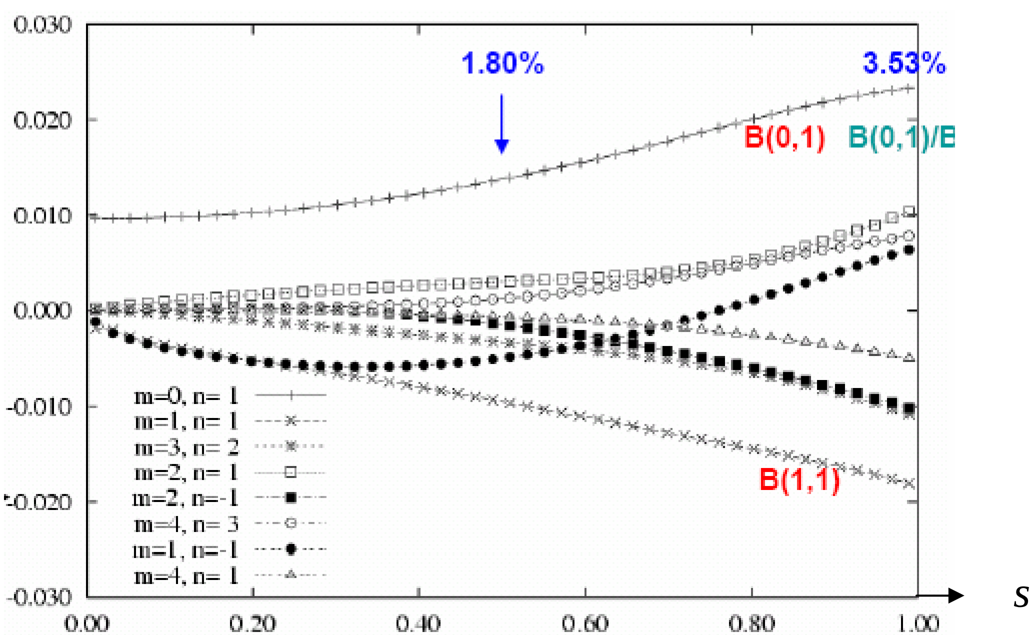
LI383 (NCSX):



Designed using

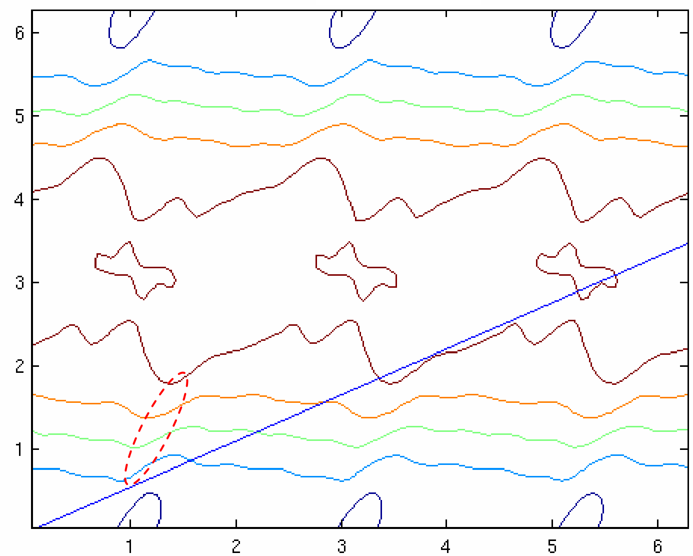
$$F_{Bmn} \equiv \left\langle \sum_{m,n\neq 0} B_{mn}^2 / B_{00}^2 \right\rangle_s$$

N3ARE:

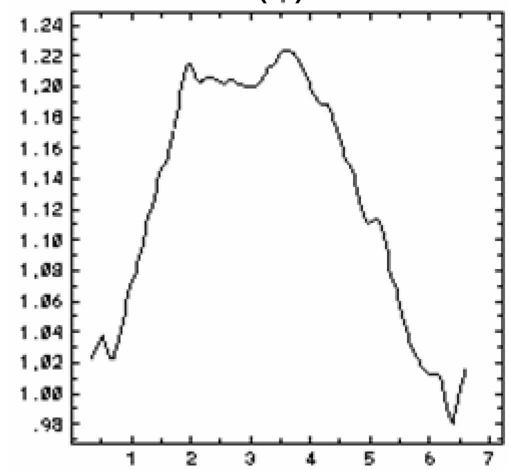


Magnetic field structure:

B(θ,ζ)

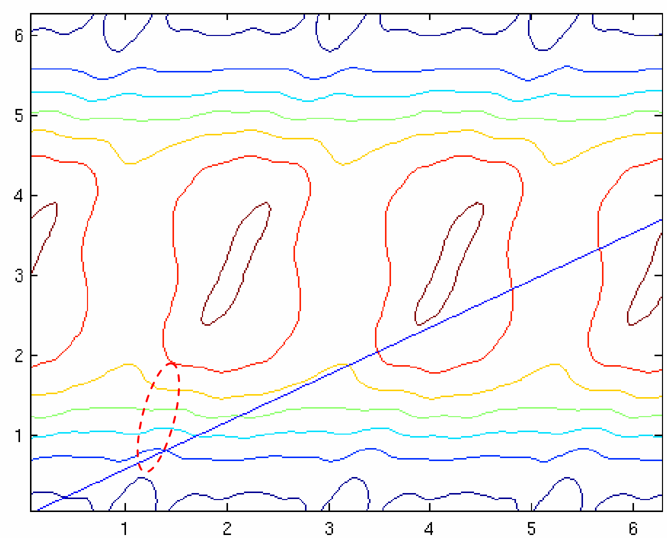


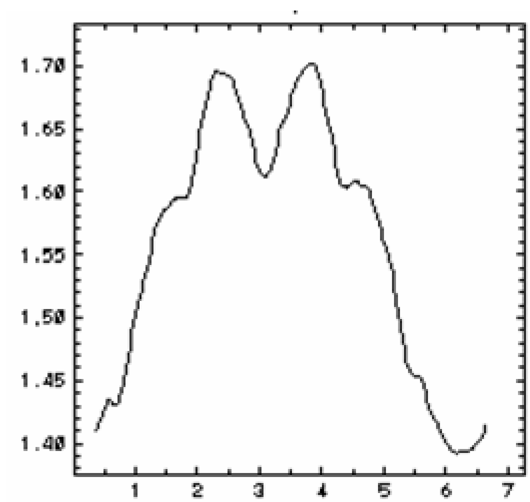
B(s)



LI383 (NCSX):

B(12c=N3ARE)

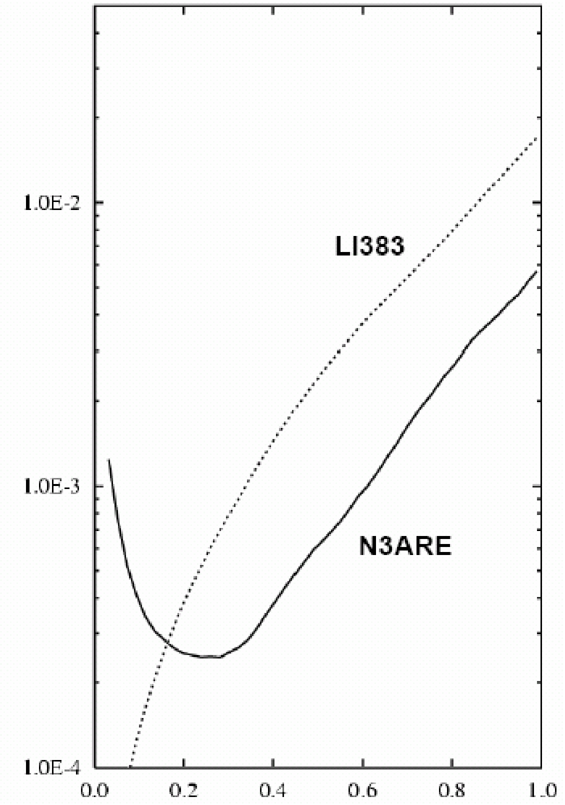




N3ARE:

N3ARE has appreciably improved ε_{ef}, a measure of $1/\nu$ transport: $D_{-1} \sim \varepsilon_{ef}^{3/2}/\nu$:

(From L.P.Ku, 2005):

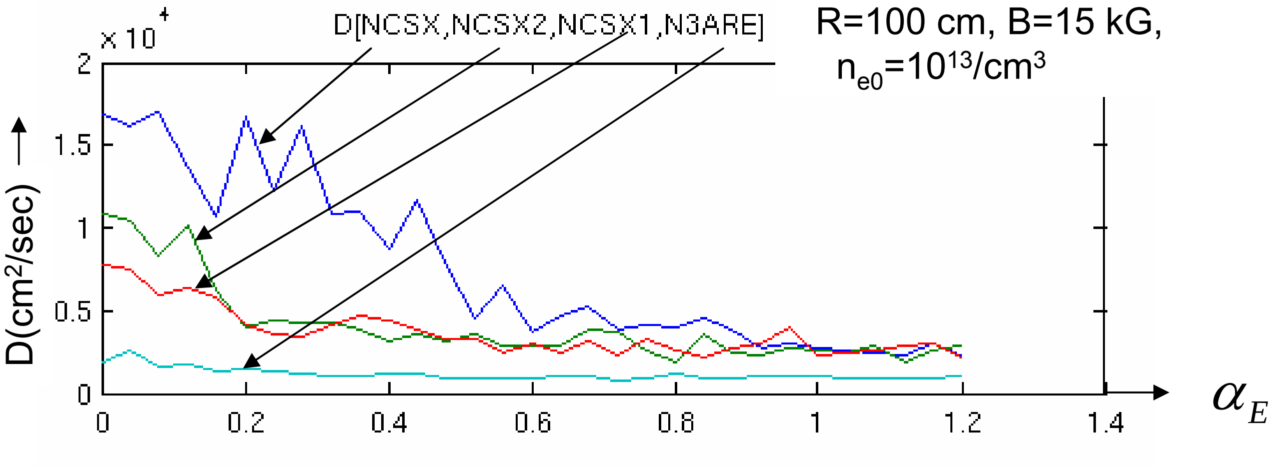


$s \equiv \psi / \psi_a$

$$\varepsilon_{ef}^{3/2}(\mathrm{LI383}) / \varepsilon_{ef}^{3/2}(\mathrm{N3ARE}) \approx (.016/.006)^{3/2} = 4.36$$

Similar results from Monte-Carlo calculations for thermal transport:

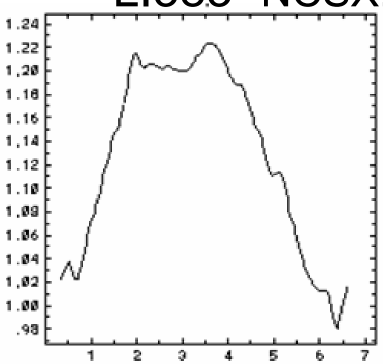
R=100 cm, B=15 kG,
$n_{e0}=10^{13}/cm^3$



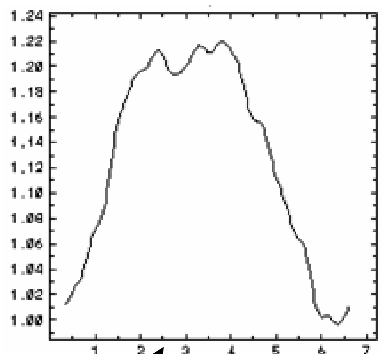
$$e\Phi(s)/T = \alpha_E(1-s)$$

$$\Rightarrow eaE_r/T \approx 2\alpha_E(r/a)$$

LI383=NCSX:

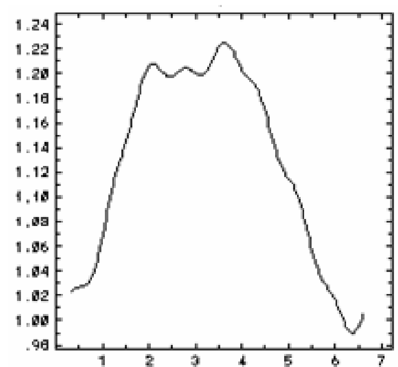


NCSX2:



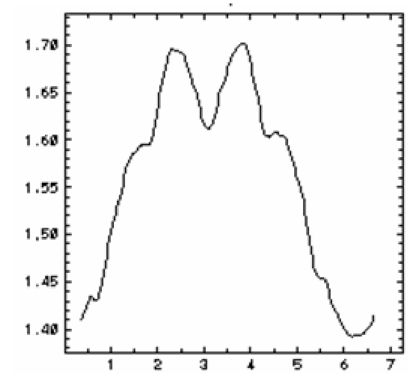
(8-harmonic approx to NCSX)

NCSX1:



(2-harmonic approx to NCSX)

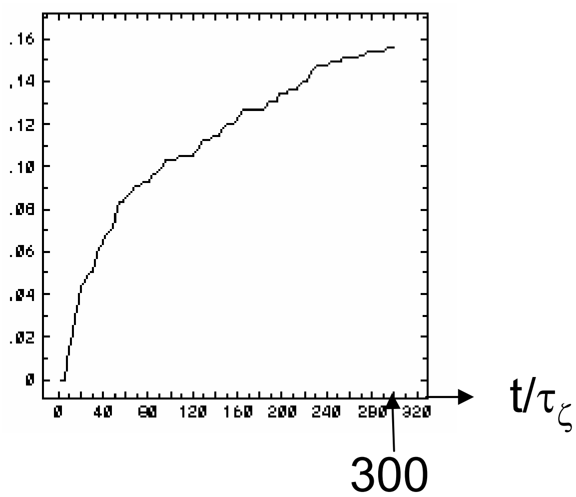
N3ARE:



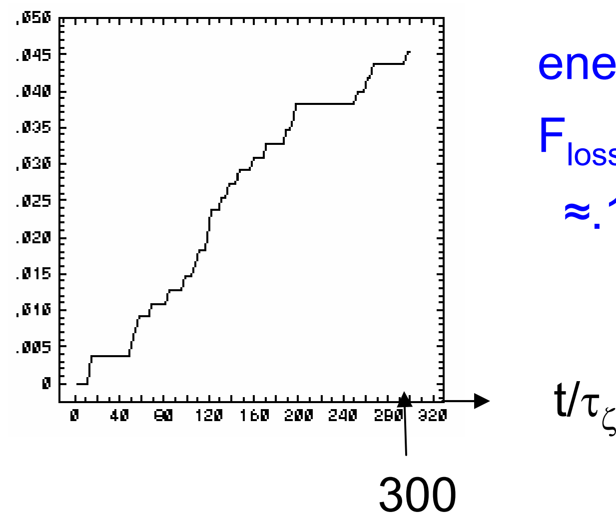
N3ARE also has much better α-confinement:

-Look at loss fraction F_{loss} for modest number (N_p=550) of α's in reactor-sized device (R=825 cm, B=65 kG):

LI383:



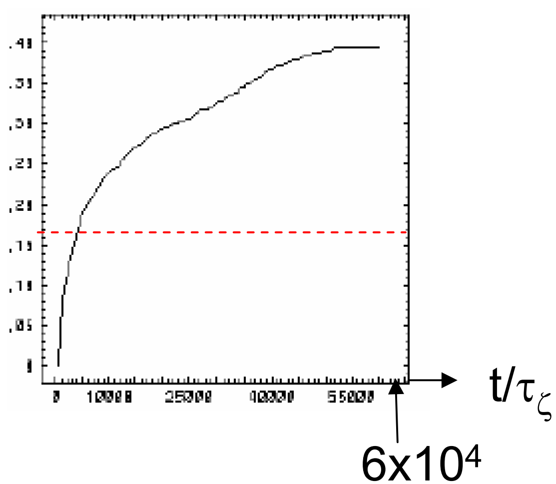
N3ARE:

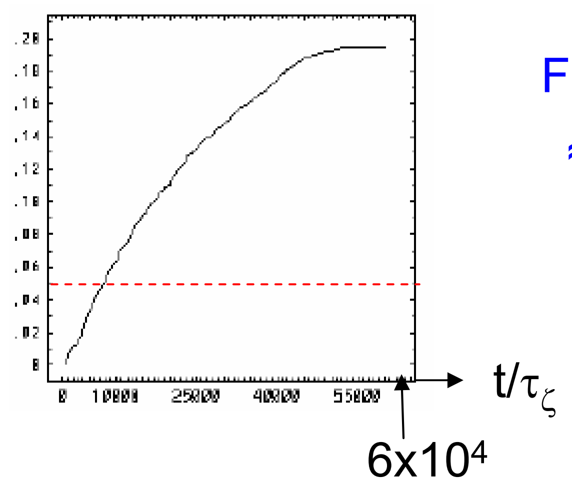


energy loss fraction ratio

F_{loss}(LI383)/ F_{loss}(N3ARE)

≈.16/.045 ≈ 3.55





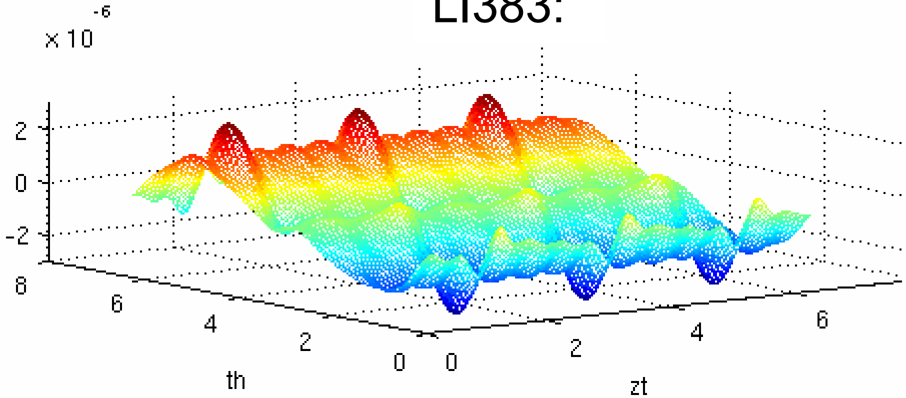
F_{loss}(LI383)/ F_{loss}(N3ARE)

≈.27/.10 ≈ 2.7

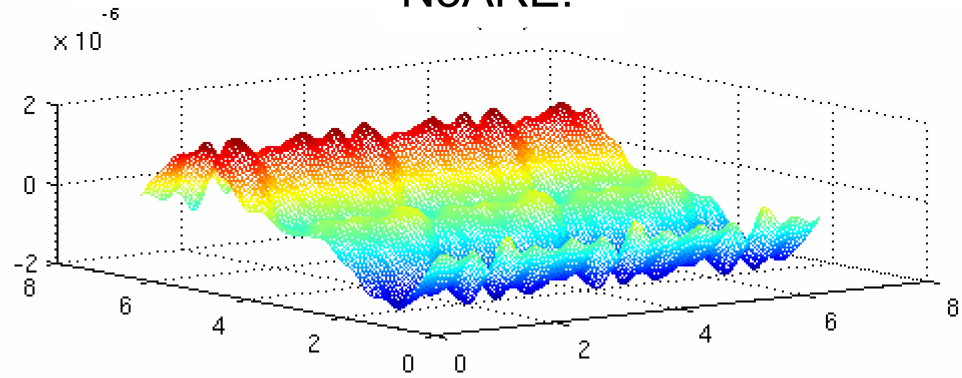
$\dot{\psi}$ of comparable size for these devices:

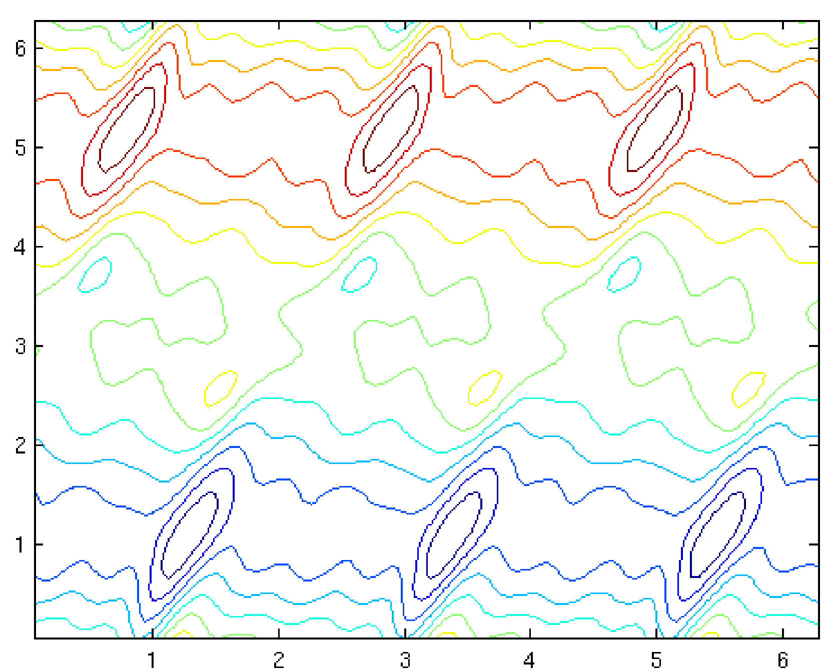
-Plot over flux surface:

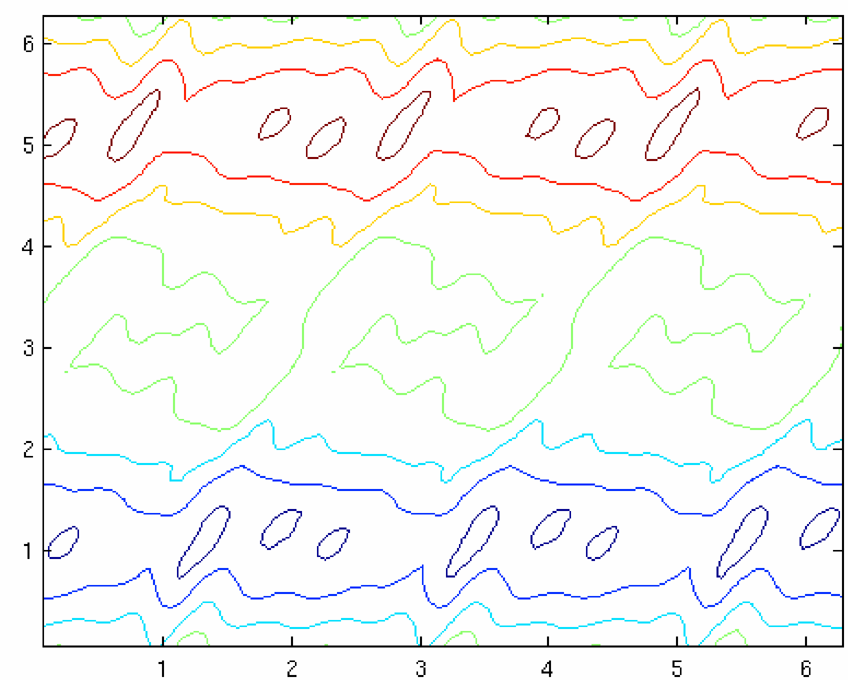
LI383:



N3ARE:

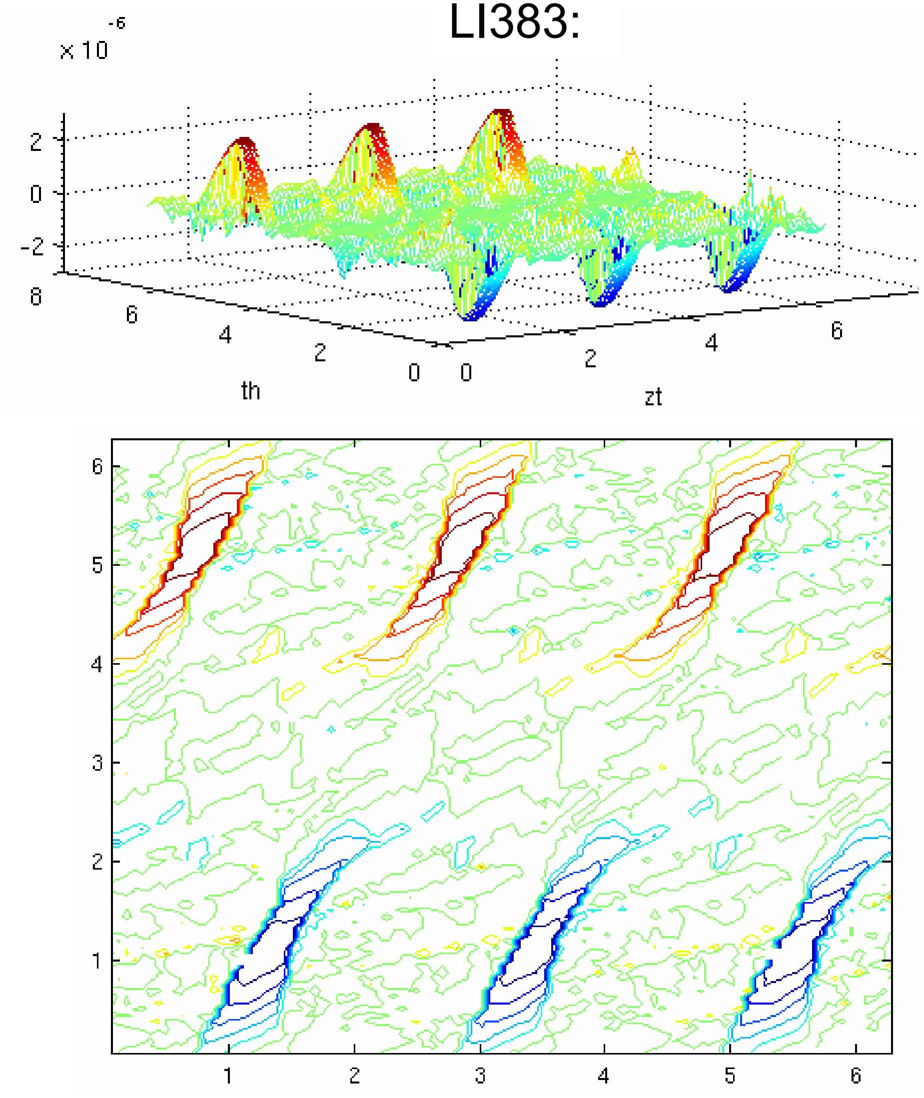




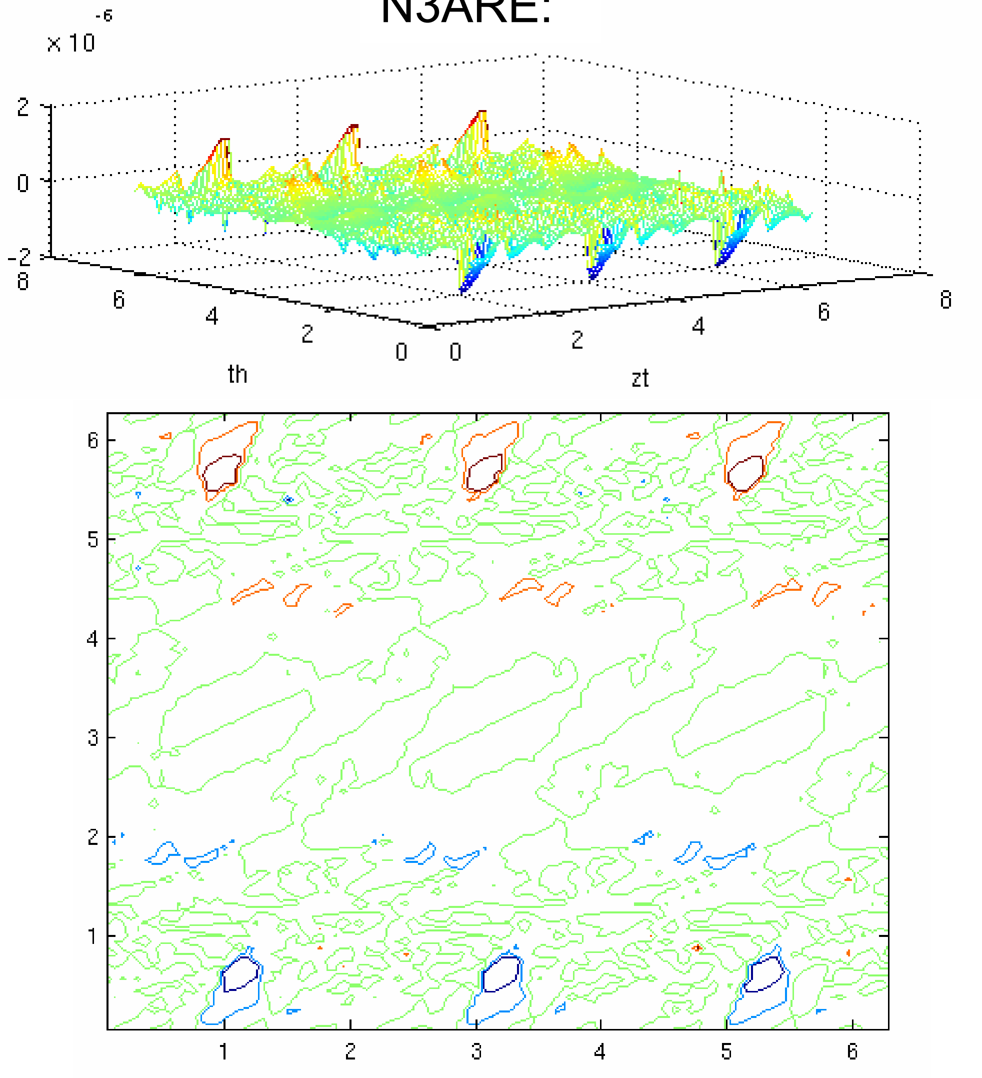


$\overline{\dot{\psi}}$ =bounce-avged $\dot{\psi}$ reduced by factor ~ 2 for N3ARE, not at all for LI383:

LI383:

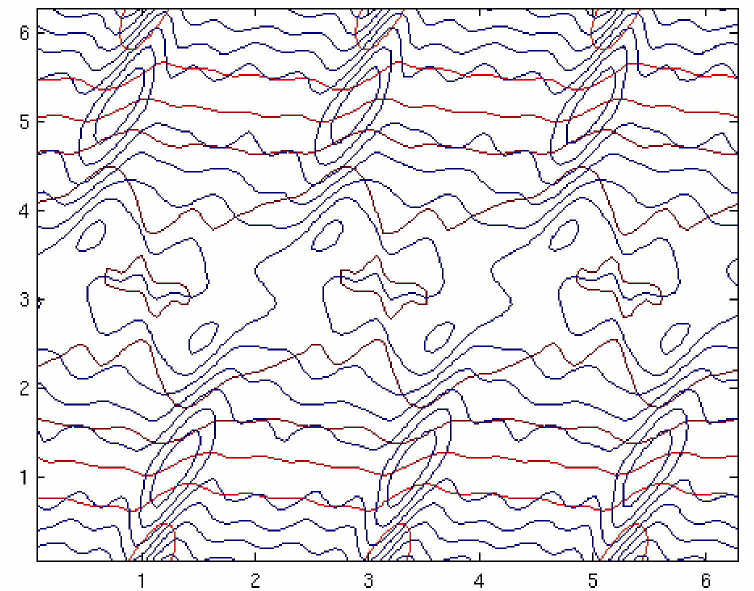


N3ARE:

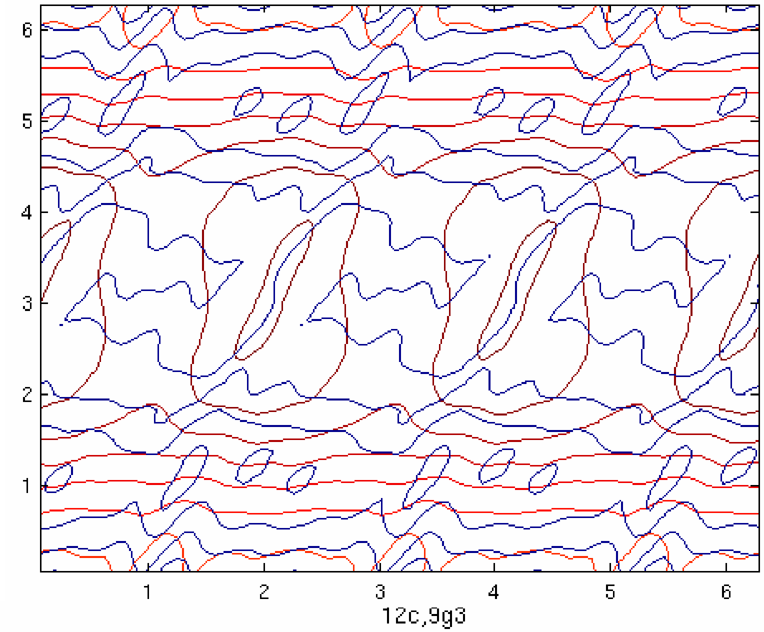


-Overlay contour plots to see why:

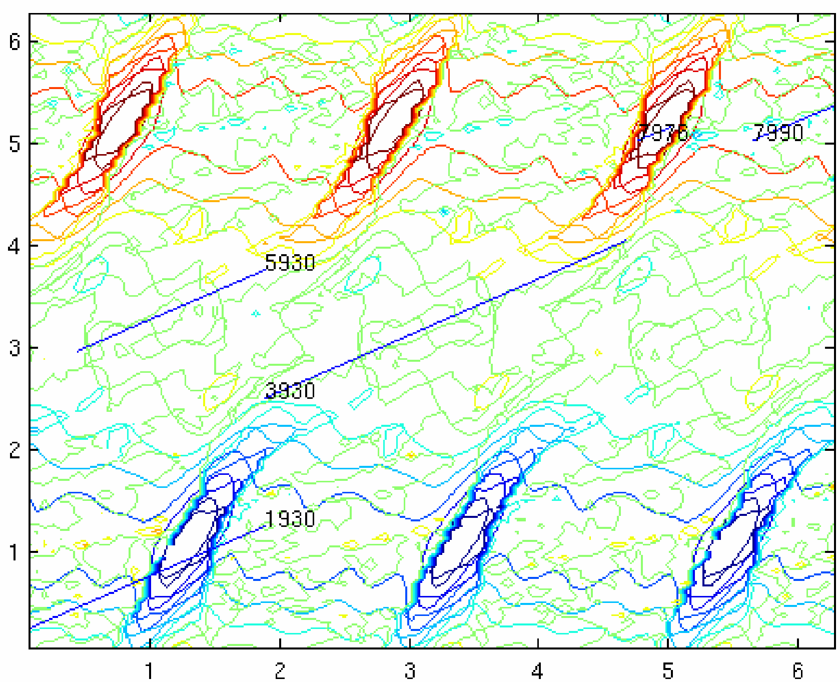
LI383:



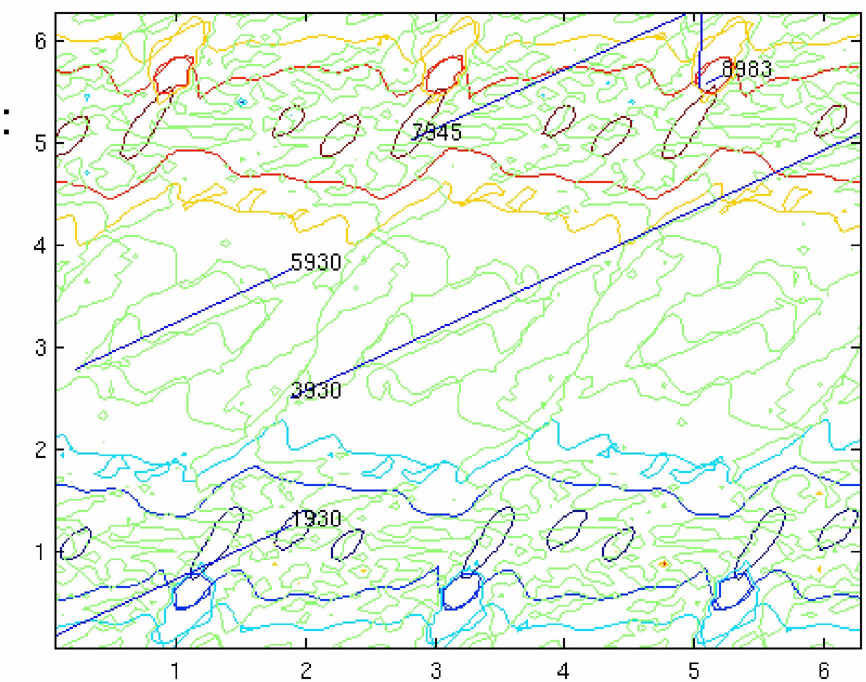
N3ARE:



$\dot{\psi}$ on B:

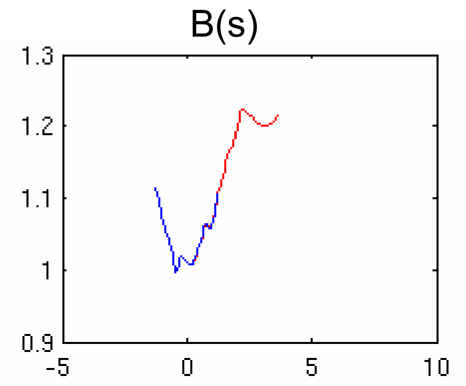


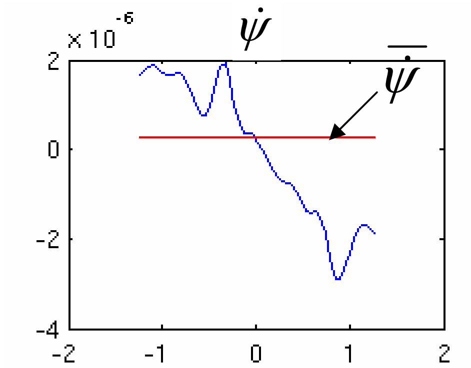
$\overline{\dot{\psi}}$ on $\dot{\psi}$:



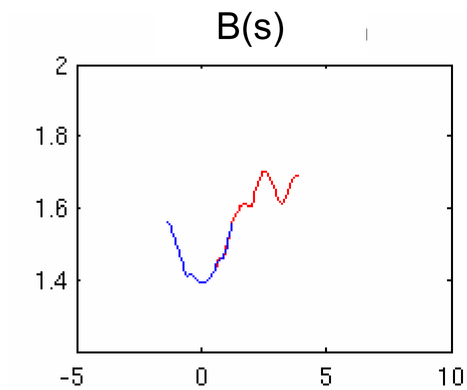
-Particles like k=1930 pass through large values of $\dot{\psi}$, but not ripple-trapped, so $\dot{\psi}$ much smaller:

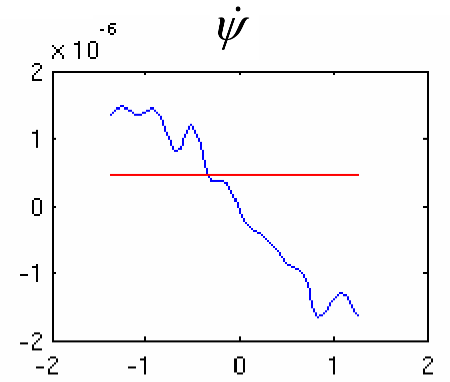
LI383:





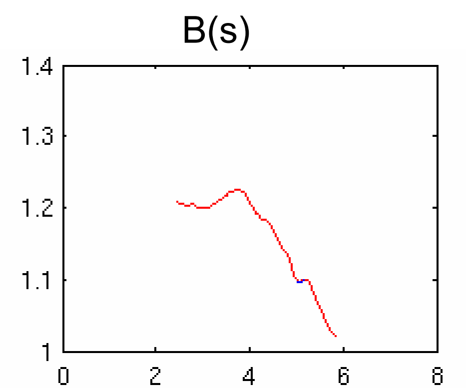
N3ARE:

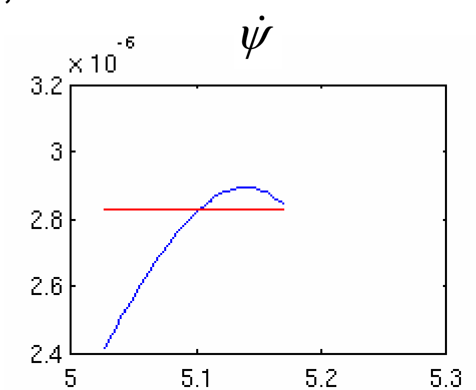




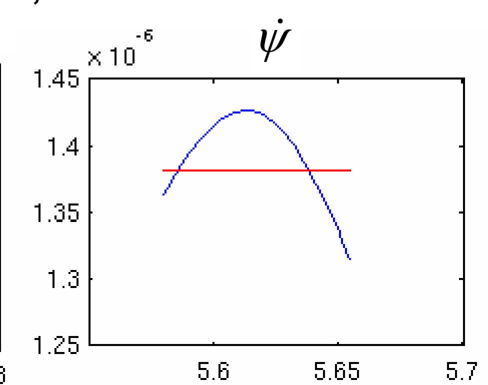
-Ripple-trapped particles have $\overline{\dot{\psi}} \approx \dot{\psi}$, so can be large where $\dot{\psi}$ is:

LI383, k=7976

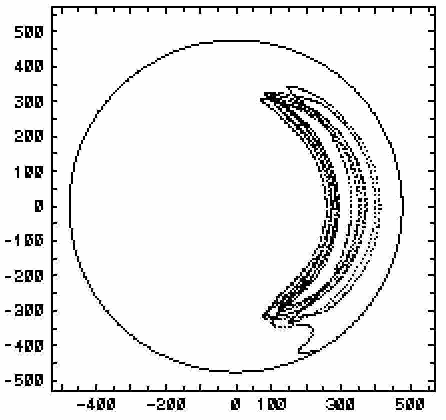


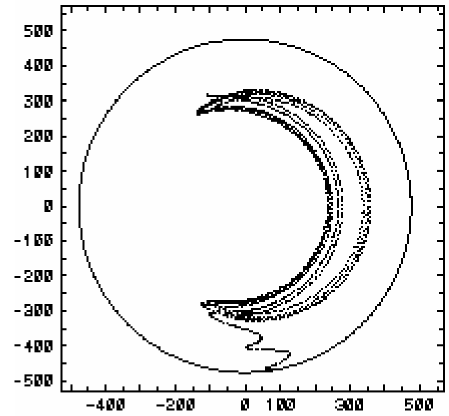


N3ARE, k=8983

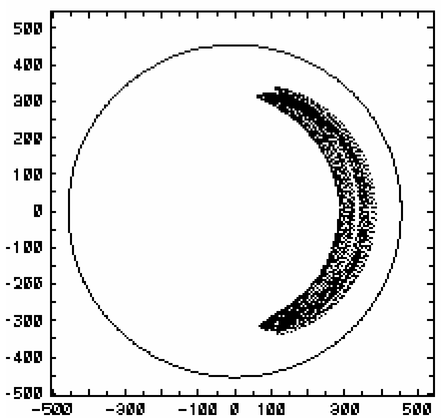


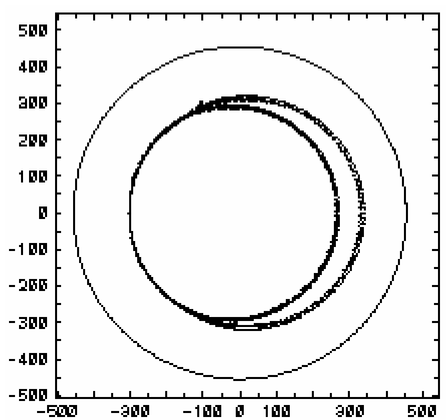
-Typical α-loss in LI383 are from $\tau = t \rightarrow r$ transition:





-Such loss orbits very seldom occur in N3ARE.
Loss tends to be of “banana-drift” type:





$\rightarrow$LI383 has extra “hole” in it from ripple trapping.

-Some general rules:

-Ripple wells on the toroidal slope of B are dangerous for QAs, providing “holes” for trapped particles to make large radial excursions.

-”Left”-inflections in field lines in B(θ,ζ) plot produce such wells.

-Some transport figures of merit:

semi-analytic:

$F_{Bmn} \equiv \left\langle \sum_{m,n\neq 0} B_{mn}^2 / B_{00}^2 \right\rangle_s$, used to design NCSX

W = “water measure”

$\varepsilon_{ef}^{3/2}$ from NEO, GIOTA

$\Gamma_{v,w}$ =new ε_{ef}-like

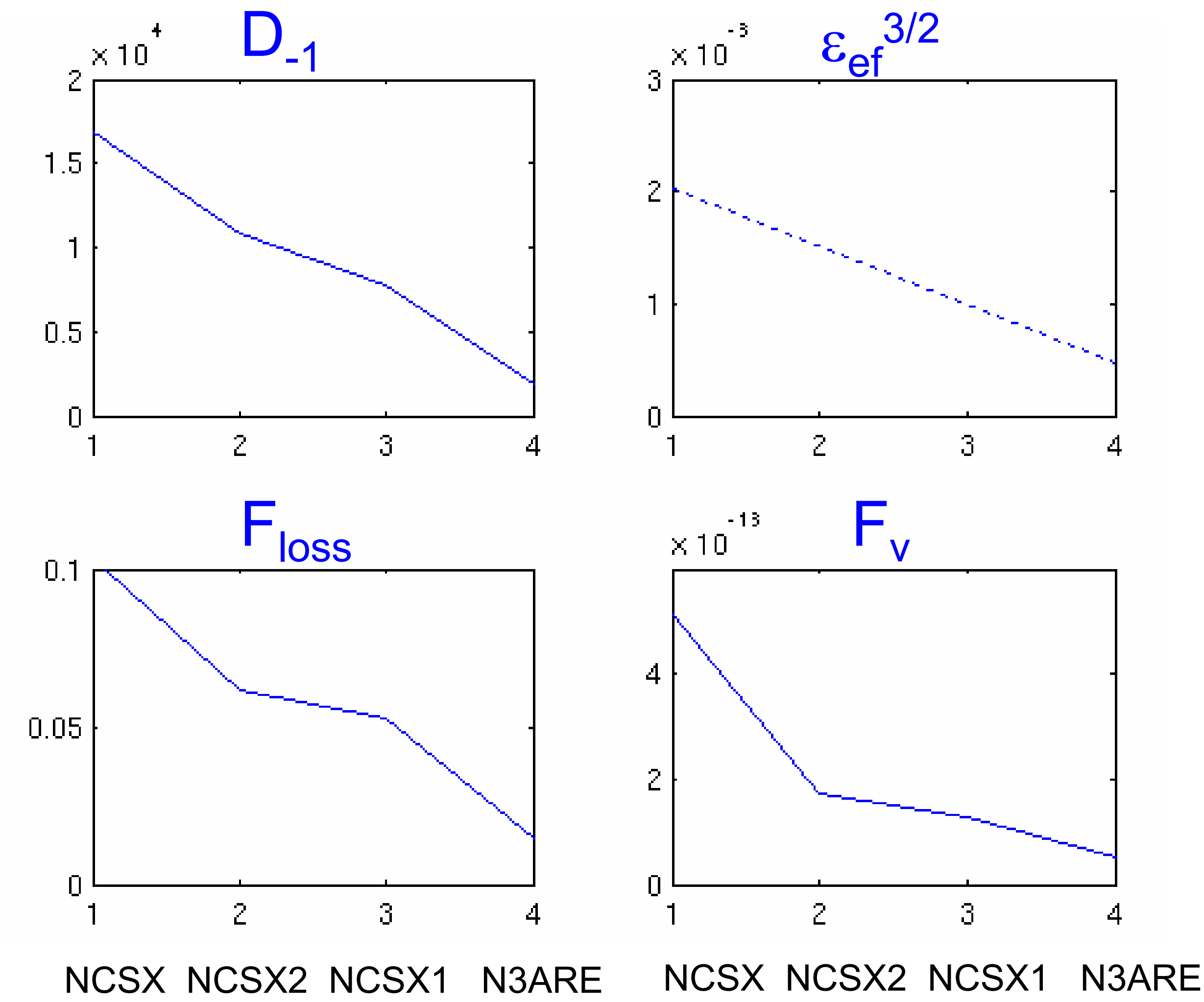
$F_v \equiv \sum_{i,j} \dot{\psi}^2(\theta_i, \zeta_j) / N_g$

numerical:

D_{-1}

F_{loss}

-Compute D_{-1}, $\varepsilon_{ef}^{3/2}$, F_{loss}, F_v for the set of configurations above:



-Summary:

-By comparing a set of related QA designs, we have distilled some rules for features deleterious to confinement, especially for energetic particle confinement:

-Ripple wells on the toroidal slope of B are dangerous for QAs, providing “holes” for trapped particles to make large radial excursions.

-Left-inflections in field lines in B(θ,ζ) plot produce such wells.

-LI383 has larger such holes than N3ARE, occuring more on the toroidal slope, resulting in its much worse alpha confinement.

-Some existing semi-analytic transport figures of merit, involving similar flux-surface averages of $\overline{\dot{\psi}^2}$, capture much of this effect.

-However, only the numerical figures of merit, eg, F_{loss}, currently capture the radial “connectivity” of these holes.