Perturbing QA stellarators: What helps & what hurts confinement

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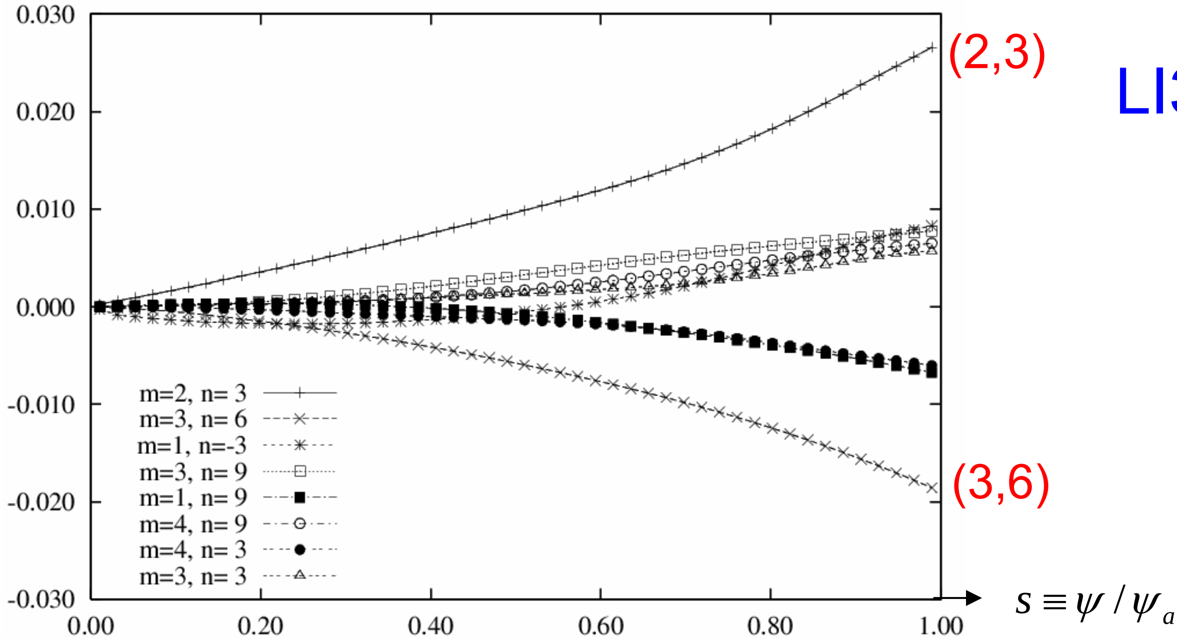
-Thanks to:
N. Pomphrey, M. Zarnstorff

(I)We compare some related QA designs to better understand the differences in their confinement properties, & identify some design rules on that basis. [See Mynick, Boozer, Ku, PPPL-4162, to appear in Phys.Plasmas (2006).]

-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?

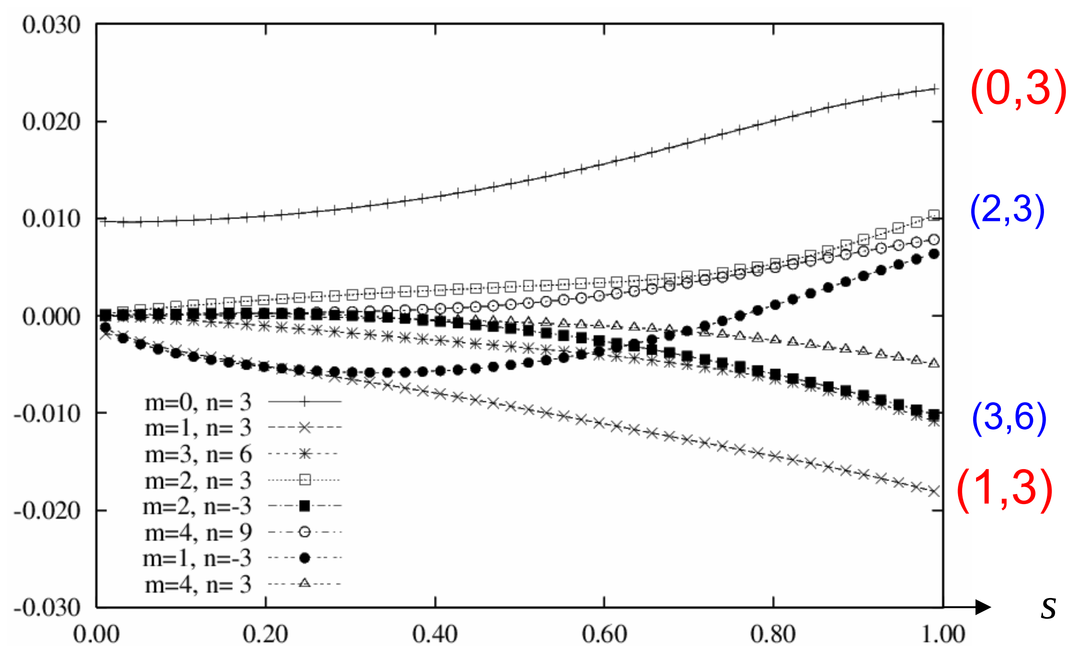
-Harmonic composition (From L.P.Ku, 2005):



LI383 (NCSX):

Designed using

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

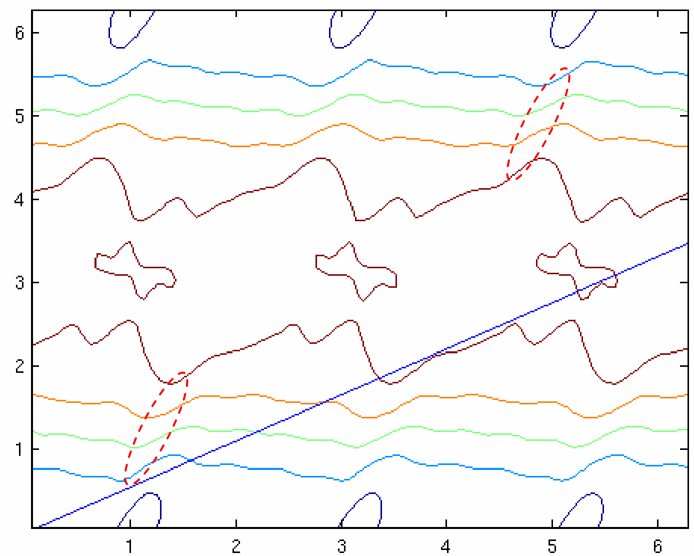


N3ARE:

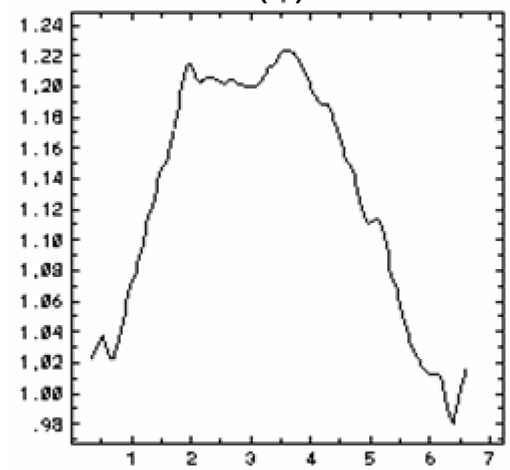
Magnetic field structure:

LI383 (NCSX):

B(θ,ζ)

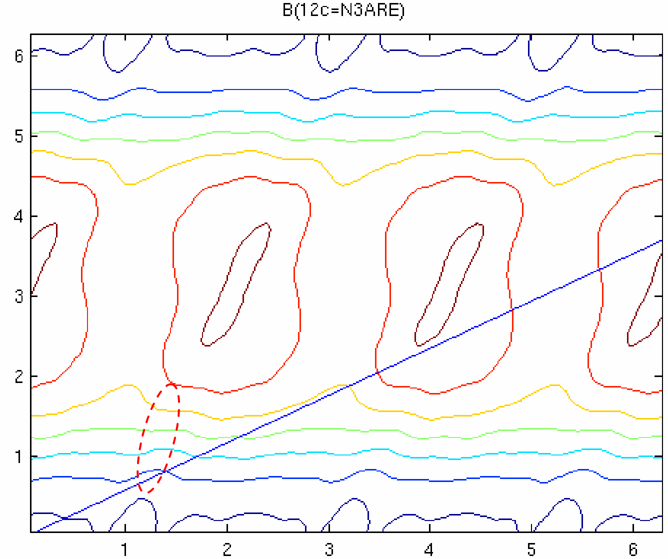


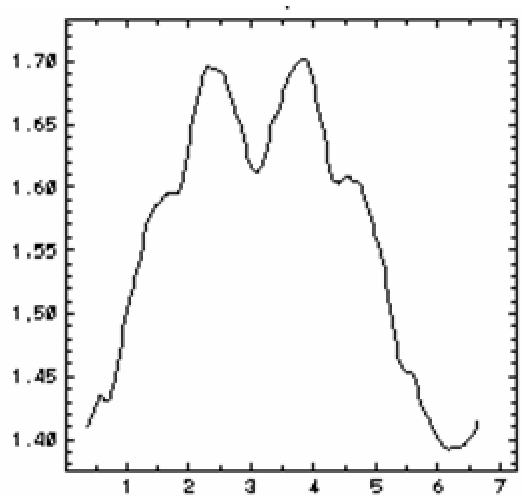
B(s)



N3ARE:

B(12c=N3ARE)

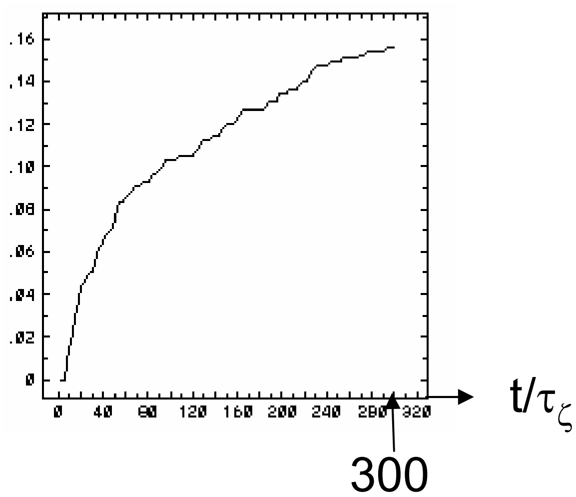




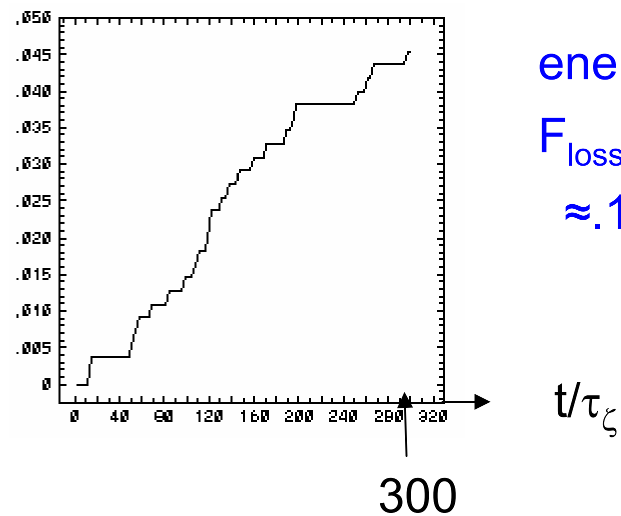
N3ARE has much better α-confinement:

-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:

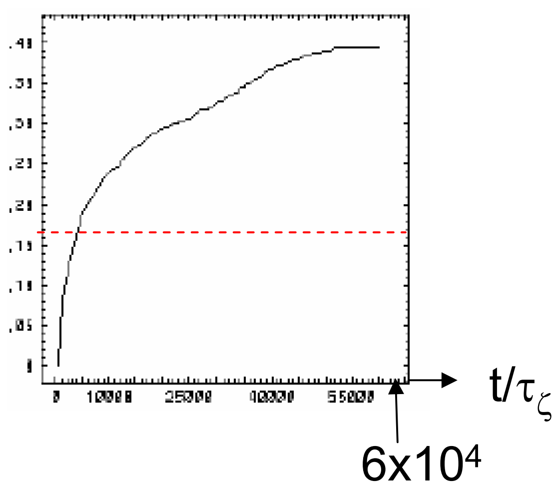


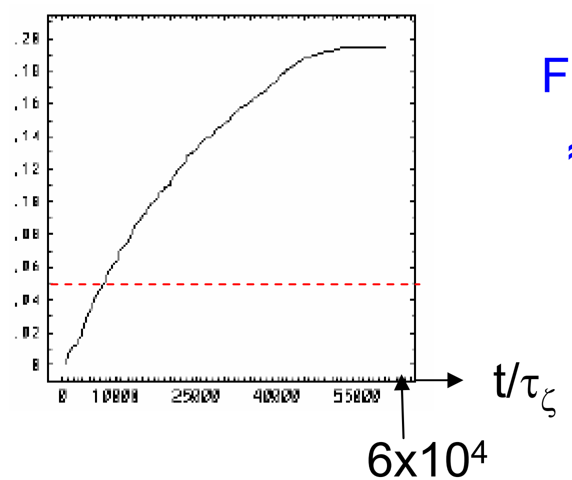
N3ARE:



energy loss fraction ratio

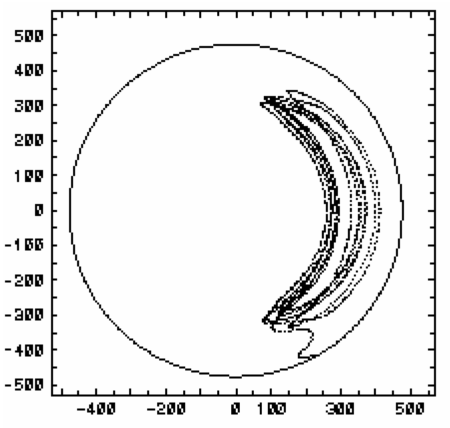
F_{loss}(LI383)/ F_{loss}(N3ARE) $\approx$.16/.045 $\approx$ 3.55

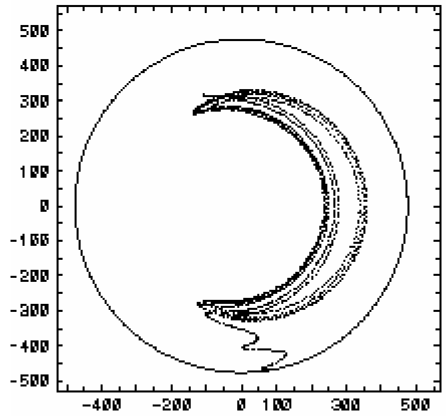




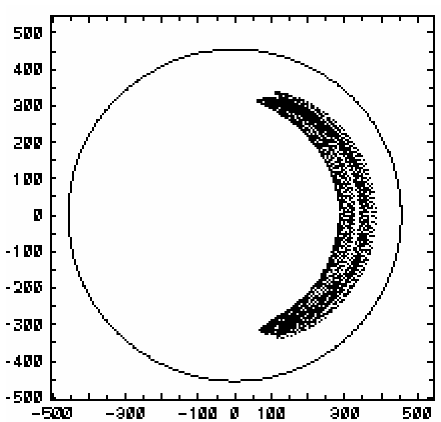
F_{loss}(LI383)/ F_{loss}(N3ARE) $\approx$.27/.10 $\approx$ 2.7

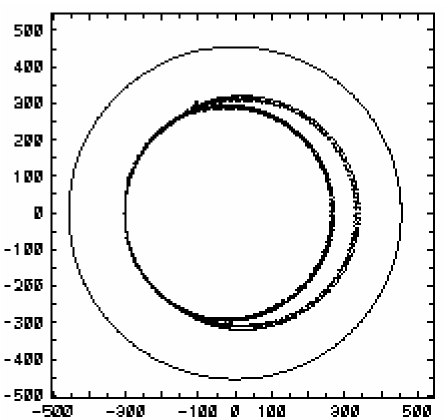
-Typical α-loss in LI383 are from $\tau = t \rightarrow r$ transition:





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

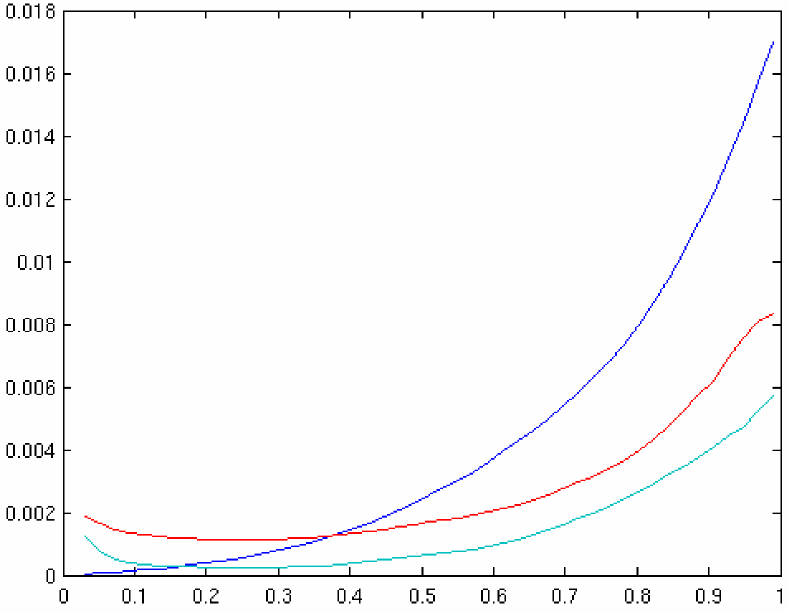




→LI383 has extra "hole" in it from ripple trapping.

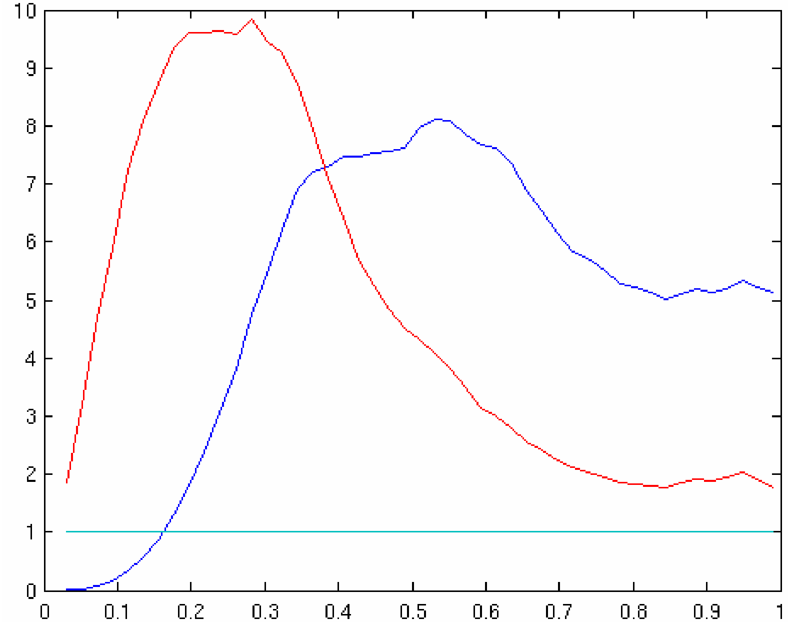
N3ARE has appreciably improved ε_{ef}, a measure of $1/\nu$ transport: $D_{-1} \sim \varepsilon_{ef}^{3/2}/\nu$:

ε_{ef} [LI383,T8G,N3ARE]



$s \equiv \psi / \psi_a \longrightarrow$

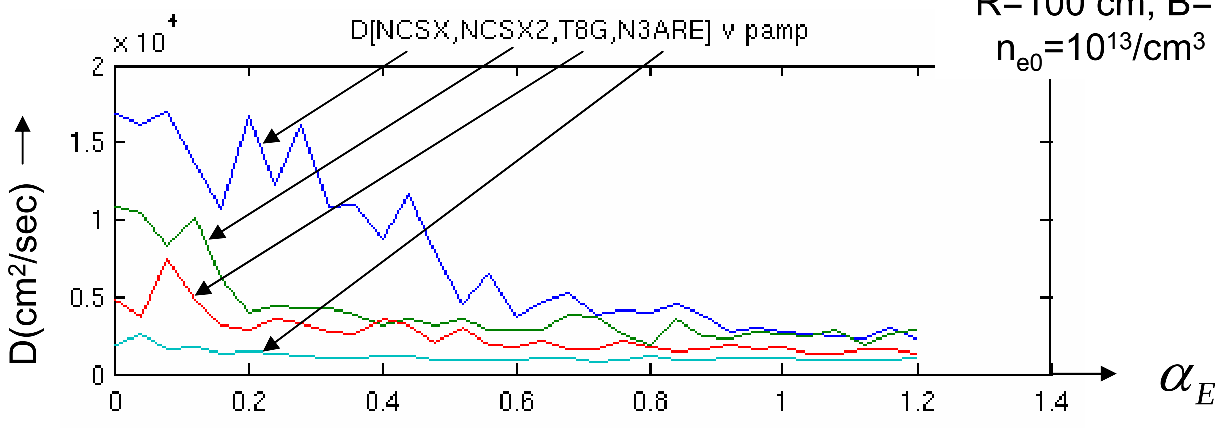
D_{-1}[LI383,T8G,N3ARE]/ D_{-1}[N3ARE]



$s \longrightarrow$

Similar results from Monte-Carlo calculations for thermal transport:

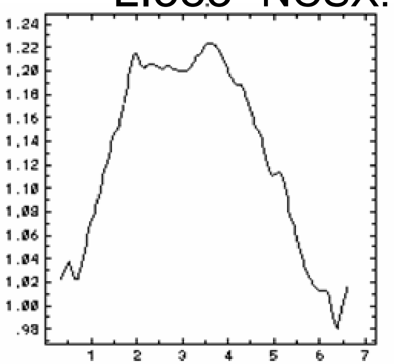
R=100 cm, B=15 kG, $n_{e0}=10^{13}/cm^3$



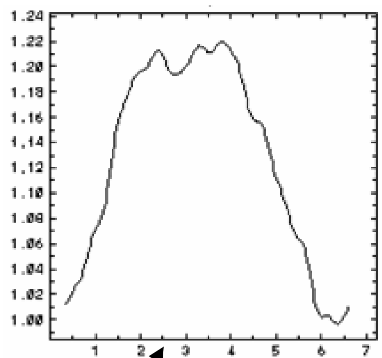
$$e\Phi(s)/T = \alpha_E(1-s)$$

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

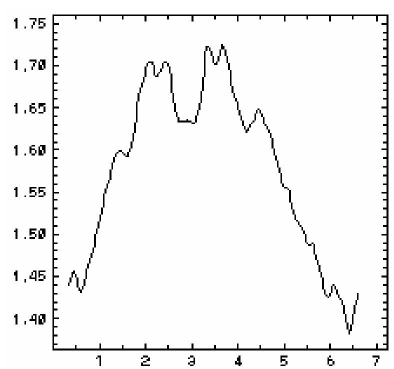
LI383=NCSX:



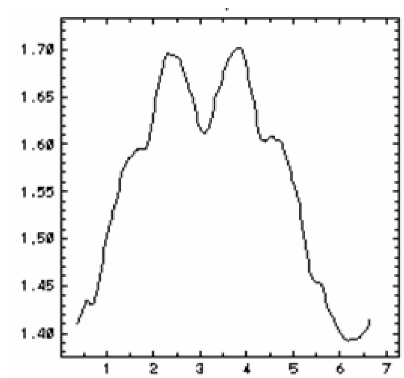
NCSX2:



T8G:



N3ARE:

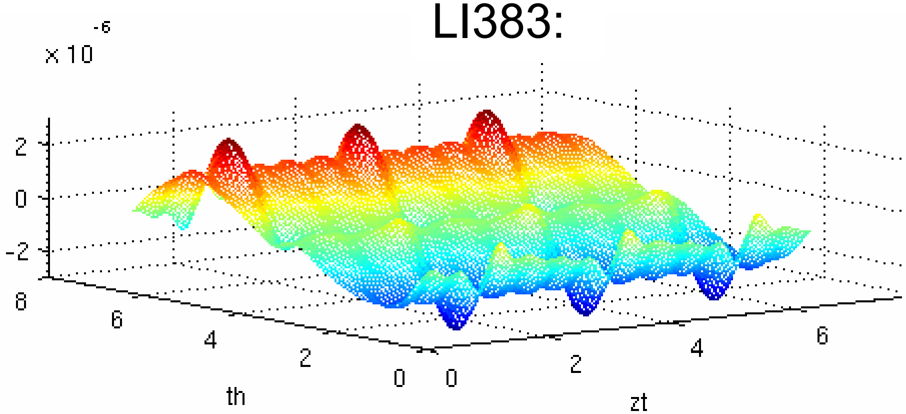


(8-harmonic approx to NCSX)

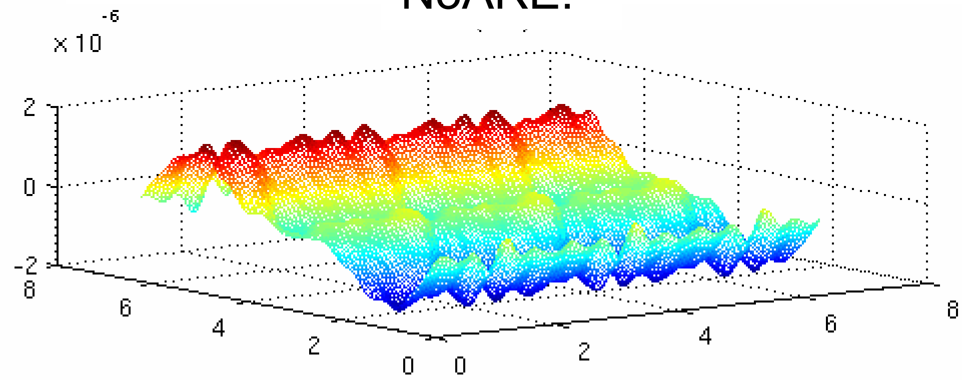
$\dot{\psi}$ of comparable size for these devices:

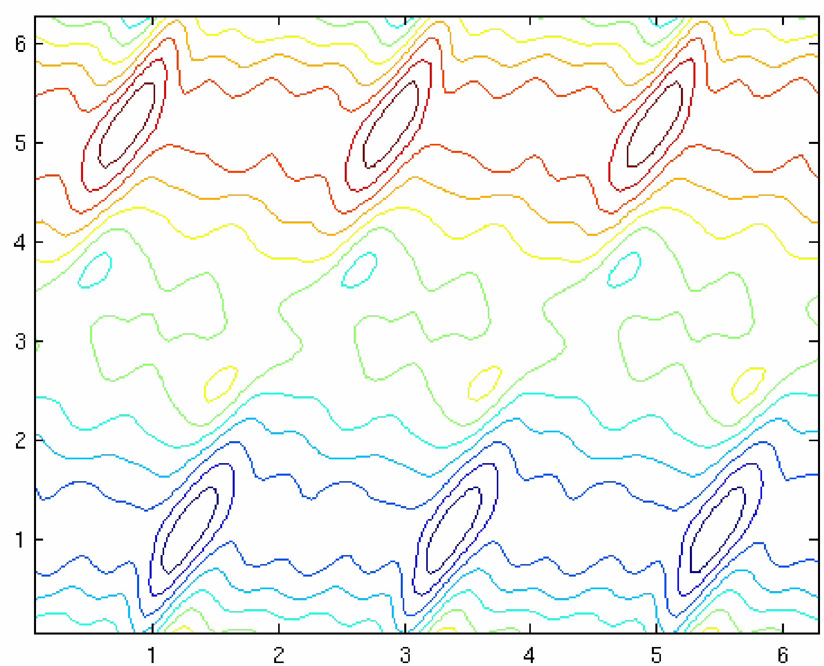
-Plot over flux surface:

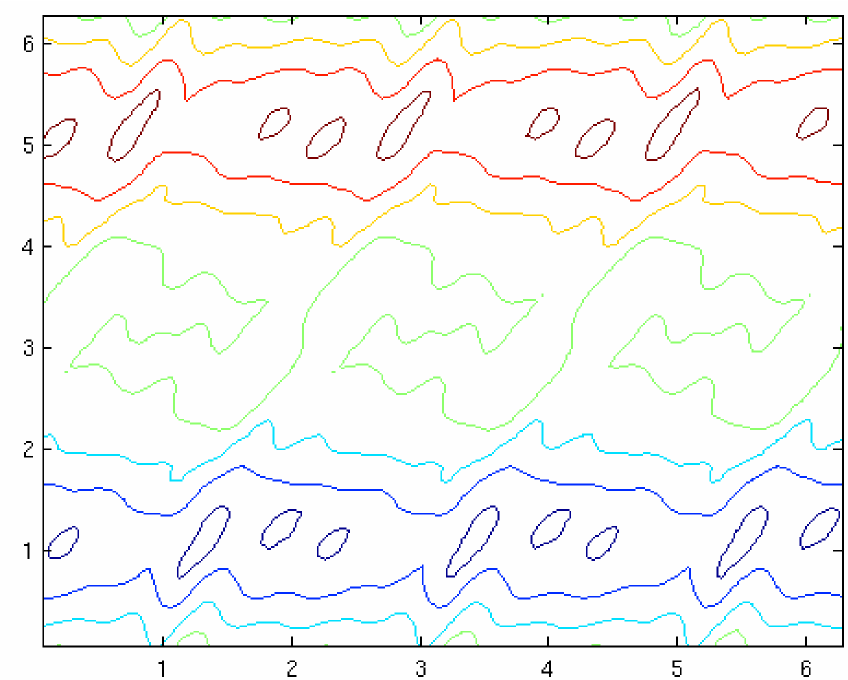
LI383:



N3ARE:

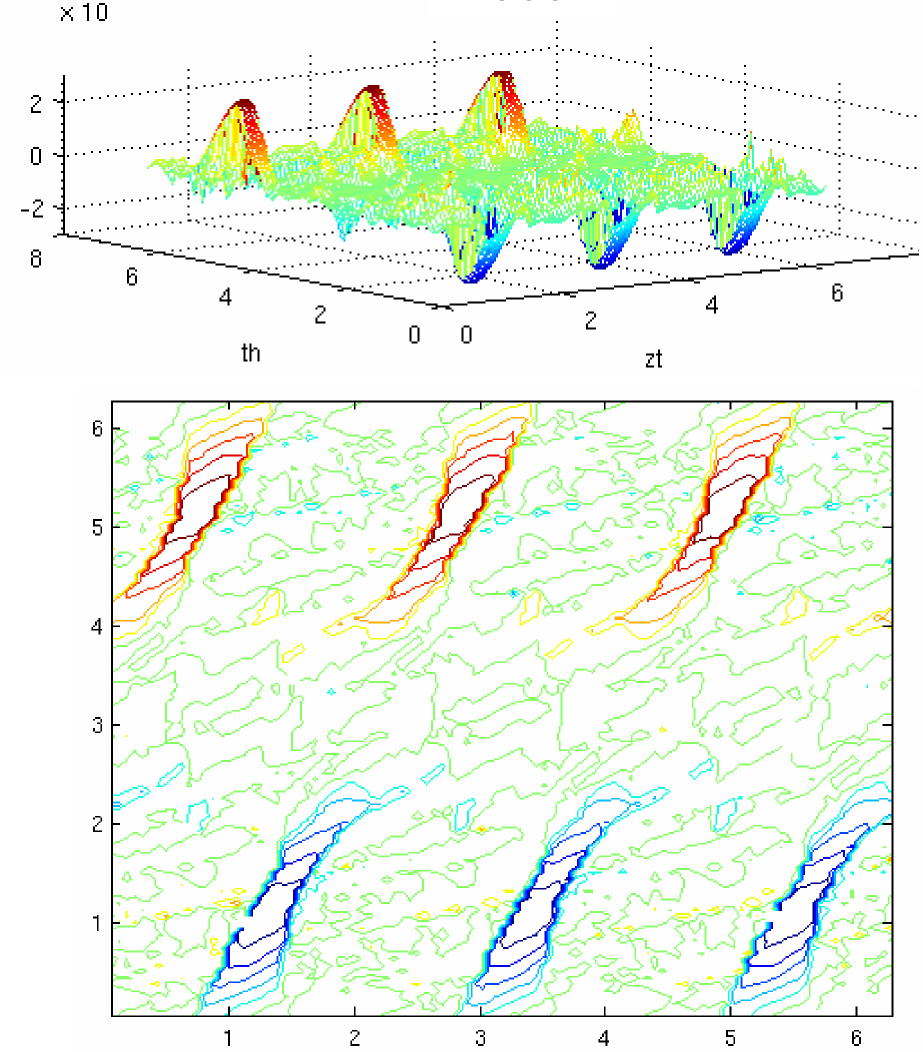




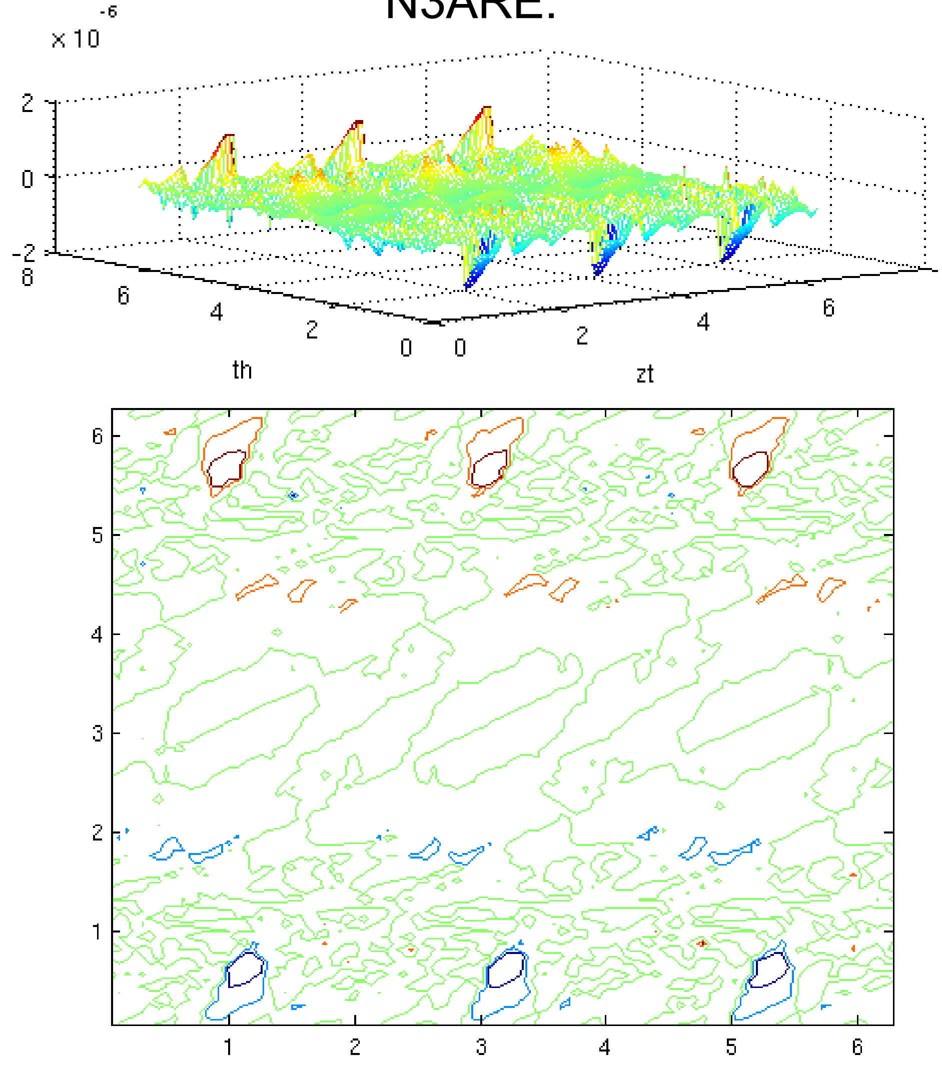


$\overline{\dot{\psi}}$ =bounce-avged $\dot{\psi}$ reduced by factor ~ 2 for N3ARE, not at all for LI383:

LI383:

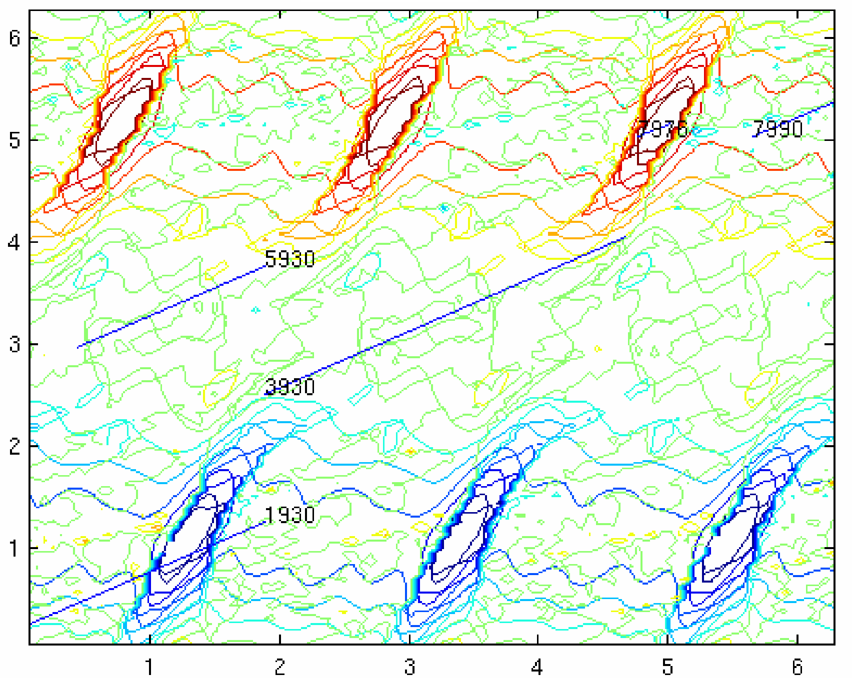


N3ARE:



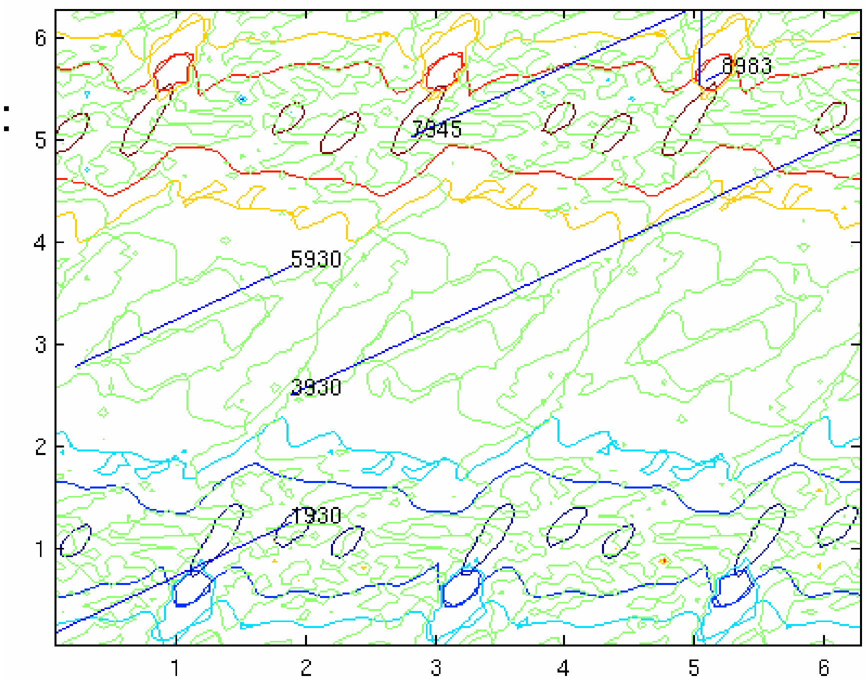
-Overlay contour plots to see why:

LI383:



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

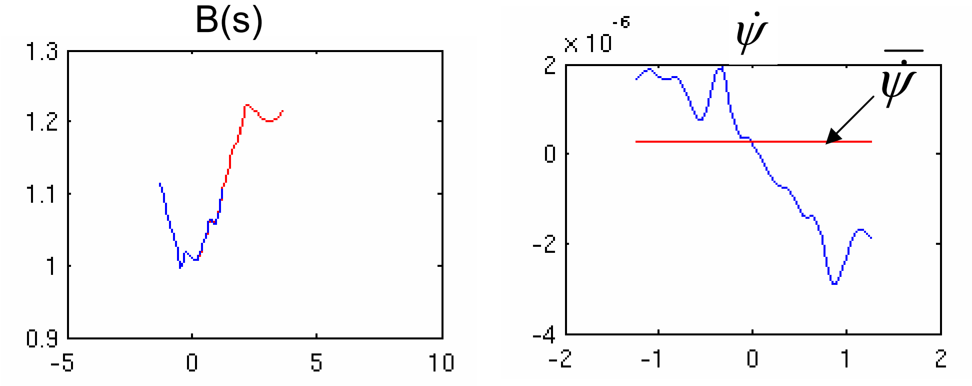
N3ARE:



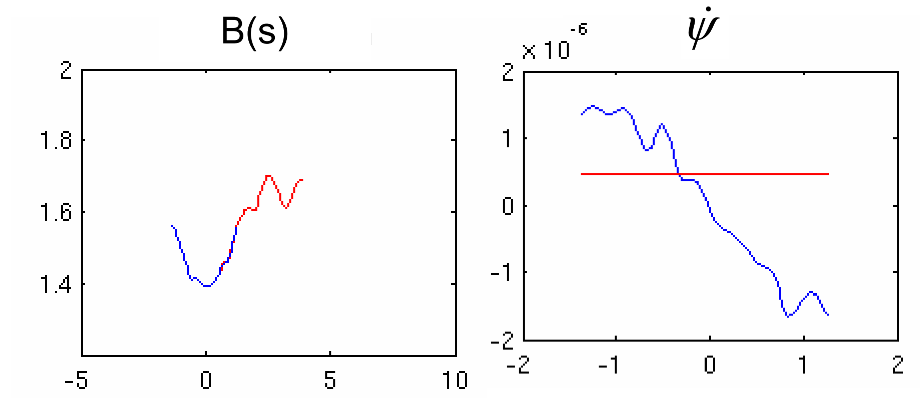
-Find $\left\langle \dot{\psi}^{2} \right\rangle^{N3ARE} / \left\langle \dot{\psi}^{2} \right\rangle^{LI383} \approx 0.5,$ while $\left\langle \overline{\dot{\psi}}^{2} \right\rangle^{N3ARE} / \left\langle \overline{\dot{\psi}}^{2} \right\rangle^{LI383} \approx 0.12$

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

LI383:

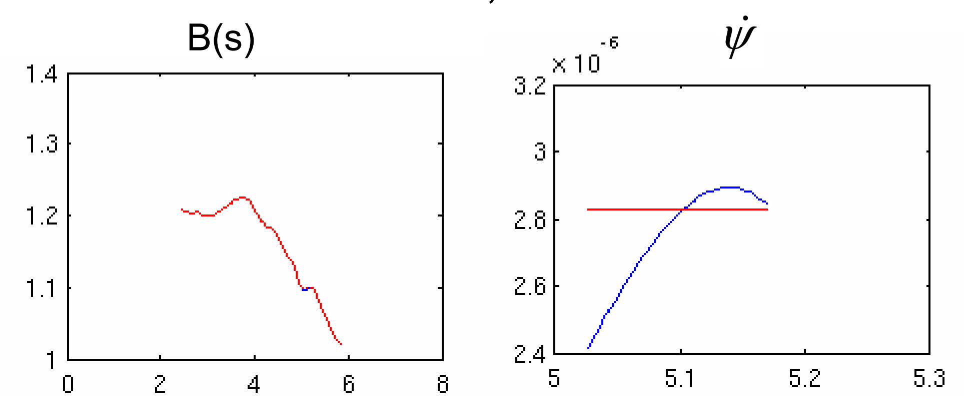


N3ARE:

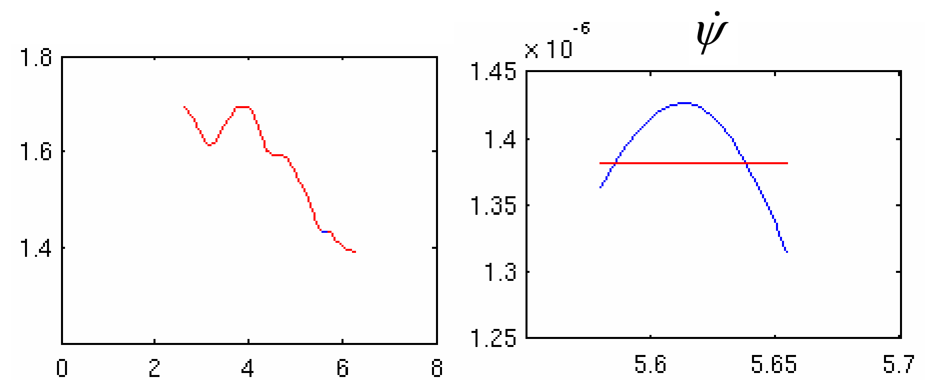


-Ripple-trapped particles have $\overline{\dot{\psi}} \approx \dot{\psi}$, so can be large where $\dot{\psi}$ is:

LI383, k=7976



N3ARE, k=8983



-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.

-N3ARE has greatly reduced such inflections from LI383, removing this extra loss channel.

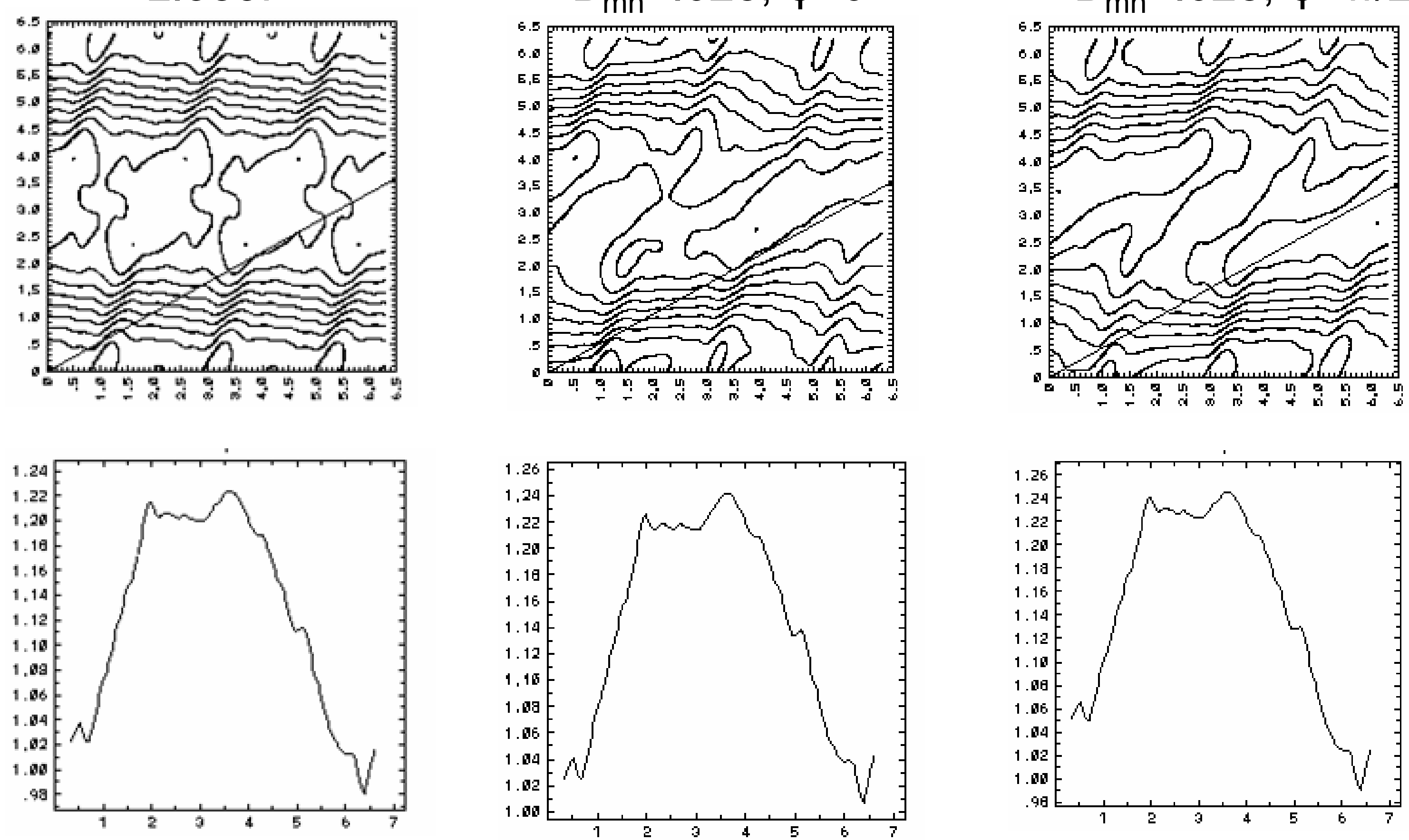
-While T8G’s B(s)-profile looks more jagged than LI383, its ripple wells occur away from problematic θ –values, making its confinement Intermediate between LI383 and N3ARE.

-T8G can be created using the same (E04) coil set to be used in NCSX. Still better approximations to N3ARE may be created using In addition the trim coils now being designed.

(II)Another issue: Is stellarator symmetry important to particle confinement?

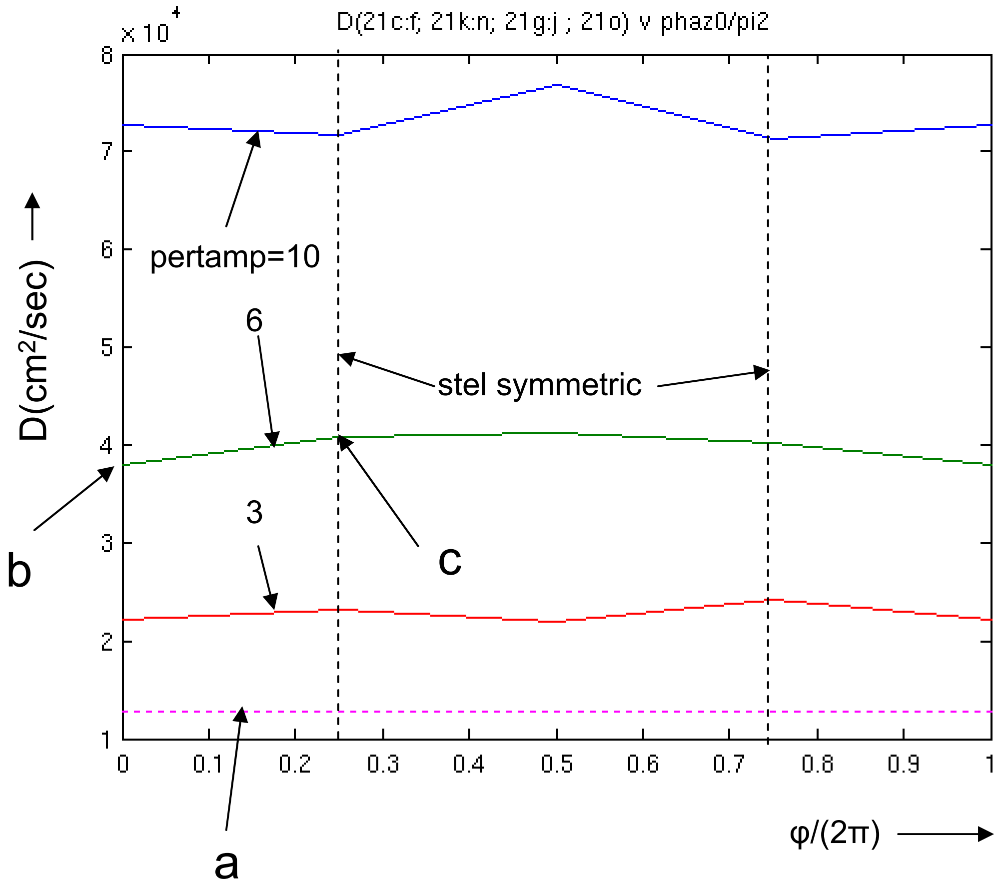
>Study by adding perturbation ~ $B_{mn}\cos(n\varsigma - m\theta - \varphi)$ to background LI383 fields. Take (m,n)=(2,1):

LI383: B_{mn}=.028, φ=0 B_{mn}=.028, $\varphi=\pi/2$



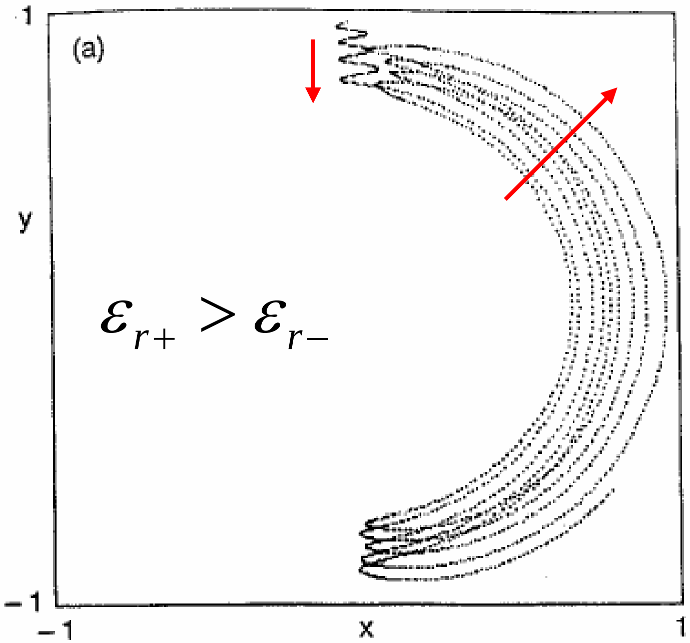
(a)stel symm (b)not stel symm (c)stel symm

Monte-Carlo results from scan in φ :



-See configs with stellarator symmetry are not better or worse than those without it.

-However, Yushmanov [Yushmanov, Shasharina, Cary, Nucl.Fusion **33**,1293 (93)] suggest that some symmetry-breaking , such as loss of up/down symmetry, can degrade confinement:



$$\varepsilon_r \approx \varepsilon_r^{\ sym}(r)\exp(n\Delta z \sin\theta / R_0)$$

-Find can enhance transport at low ν, but not at higher ν, where ripple & toroidally trapped fluxes cancel.

-Can approximate this ε_r with a simple generalization of the "σ-configuation" model, for which α = 0 :

$$\varepsilon_r \approx \varepsilon_r^{\ sym}(1+\sigma\sin\theta) = \varepsilon_r^{\ sym}[1-\sigma\cos(\theta+\alpha)],$$
$$\sigma \equiv n\Delta z / R_0, \alpha \rightarrow \pi/2$$

-Summary:

(I)

-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.

(II)

-Loss of stellarator symmetry per se does not degrade or enhance confinement.

-However, has been argued that certain symmetry-loss, such as of up/down symmetry, can degrade confinement. Needs testing.