US/Japan workshop on Stellarator/Helical System
Concept Improvement (ORNL) Sep.23-24, 1999

ROLE OF THE BUMPY FIELD ON CONFINEMENT AND THE POSSIBILITY OF QUASI-POLOIDALLY SYMMETRIC (QPS) STELLARATOR CONFIGURATION

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NIFS

The bumpy field appears in several helical axis configurations

⇒ The role of the bumpy field should be clarified in systematic way

⇒ The guidance to improve further the collisionless particle confinement such as in Heliotron-J

based on
the model magnetic field including the bumpy field & mod-B_{min} structure

- Radial shift of closed mod-B_{min} with the appropriate bumpy field (Madison)
- Enhancement of poloidal drift due to the radially increasing bumpy field ⇒ Collisionless particle confinement improvement compatible with the increase of β in Heliotron-J

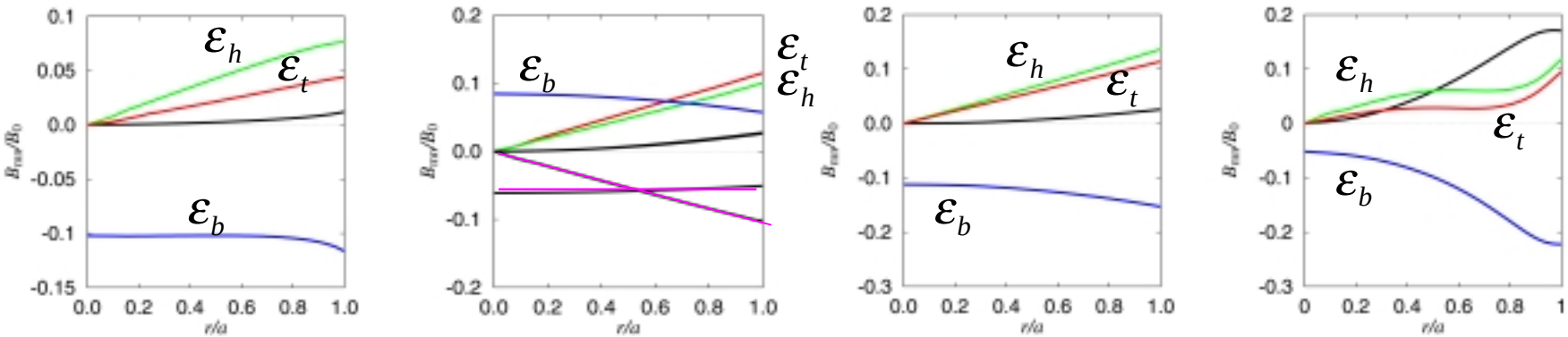
However, this improvement is rather weak compared with W7-X

⇓

Considering the reason of this difference

⇒ the possibility of further improvement of collisionless particle confinement in Heliotron-J

Magnetic field components in several helical axis configurations (Boozer coordinates)



W7-X H-1 Heliotron J

$\langle\beta\rangle = 0\%$ $\langle\beta\rangle = 2.9\%$

—— $B_{00}(r/a) - B_{00}(0)$

Bumpy field appears in several helical axis systems

Model Magnetic Field (Boozer coordinates)

The frequently used magnetic field model for planar axis helical systems:

$$B/B_0 = 1 - \underbrace{\varepsilon_t \cos\theta_B}_{\text{toroidicity}} - \underbrace{\varepsilon_h \cos(L\theta_B - M\zeta_B)}_{\text{helicity}}$$

$$\Downarrow$$

The bumpy field appears in helical axis systems:

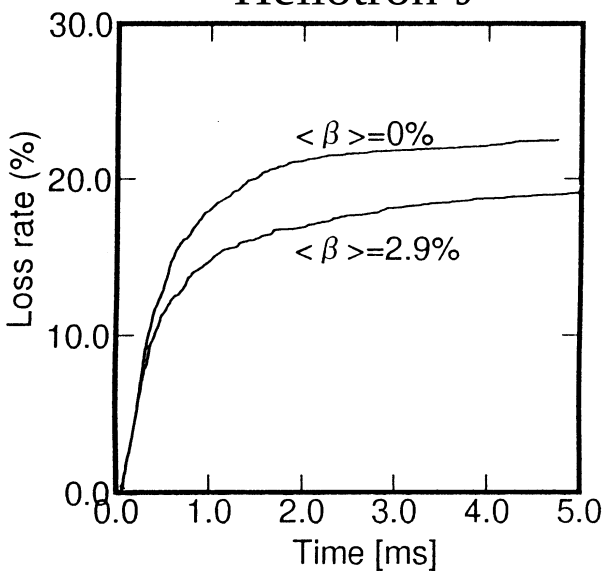
$$B/B_0 = 1 - \varepsilon_t \cos\theta_B - \varepsilon_h \cos(L\theta_B - M\zeta_B) - \underbrace{\varepsilon_b \cos(M\zeta_B)}_{\text{bumpy}}$$

For convenience,

$$\varepsilon_t = \varepsilon_{ta}(r/a), \quad \varepsilon_h = \varepsilon_{ha}(r/a)$$

Improvement of collisionless particle confinement compatible with increase of β

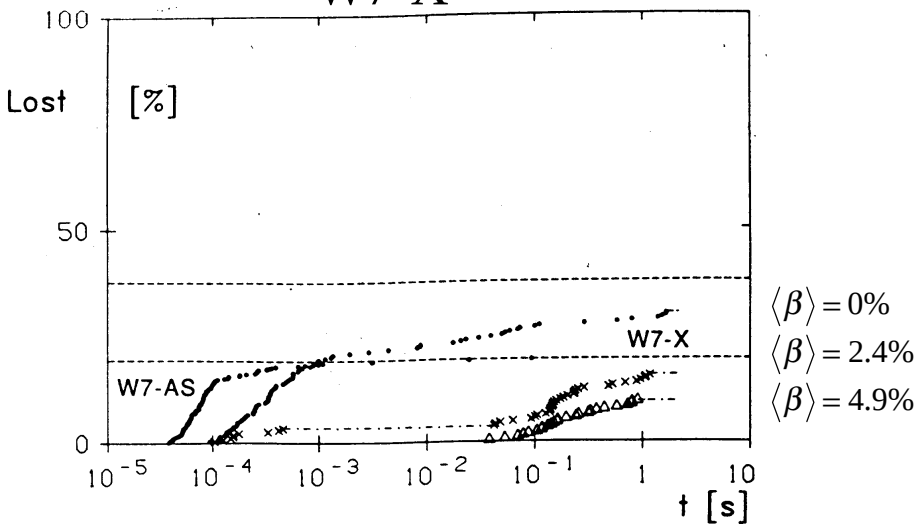
Heliotron-J



[M.Yokoyama et al., 16th IAEA Vol.2 p.175]

slightly improved

W7-X

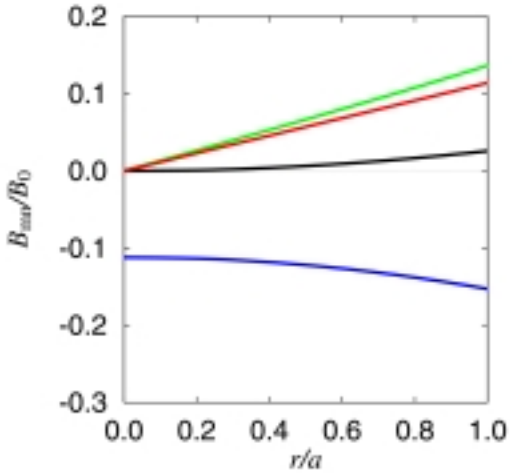


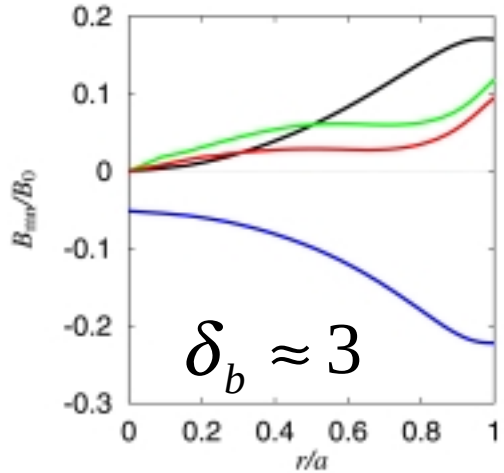
[G.Grieger et al., Phys.Fluids B4(1992)2081.]

significantly improved

What causes this difference ?

Role of radial variation of the bumpy field



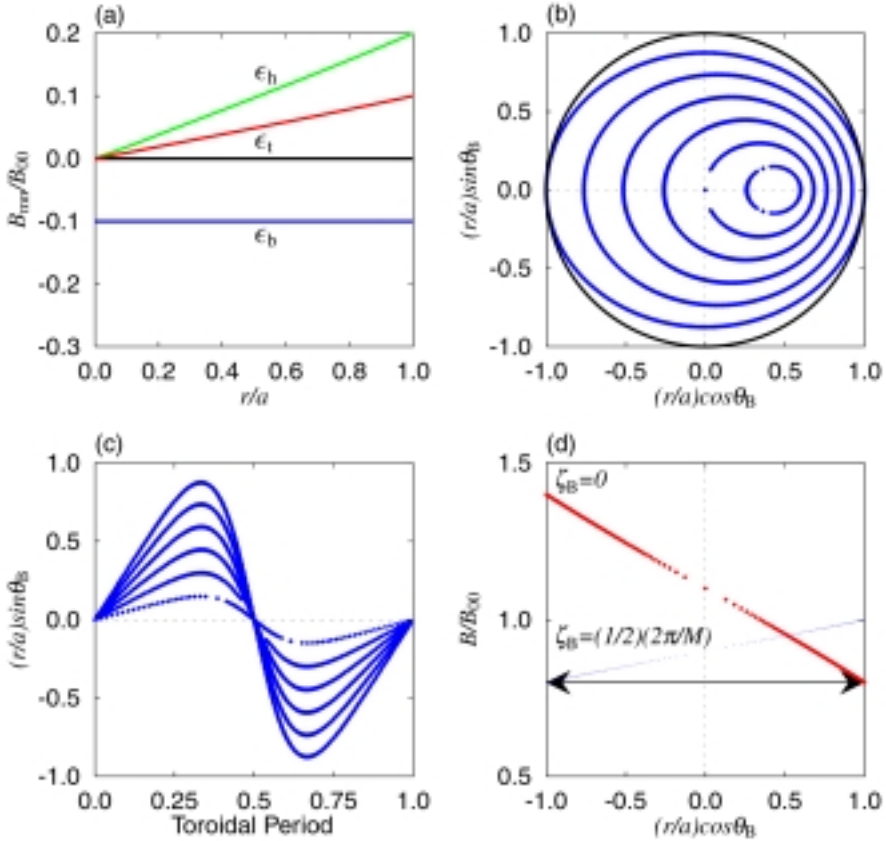


Heliotron-J

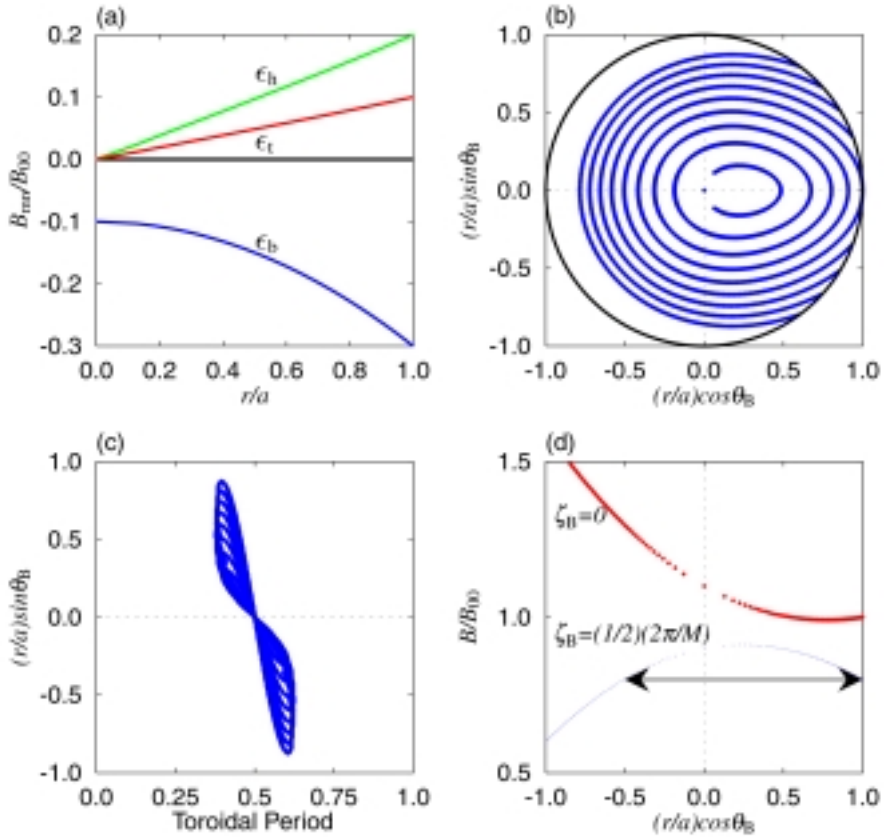
$\langle \beta \rangle = 0\%$ $\langle \beta \rangle = 2.9\%$

$$\varepsilon_b \Rightarrow \varepsilon_b(0)\left[1+\delta_b (r/a)^2\right]$$

$\delta_b = 0.0$



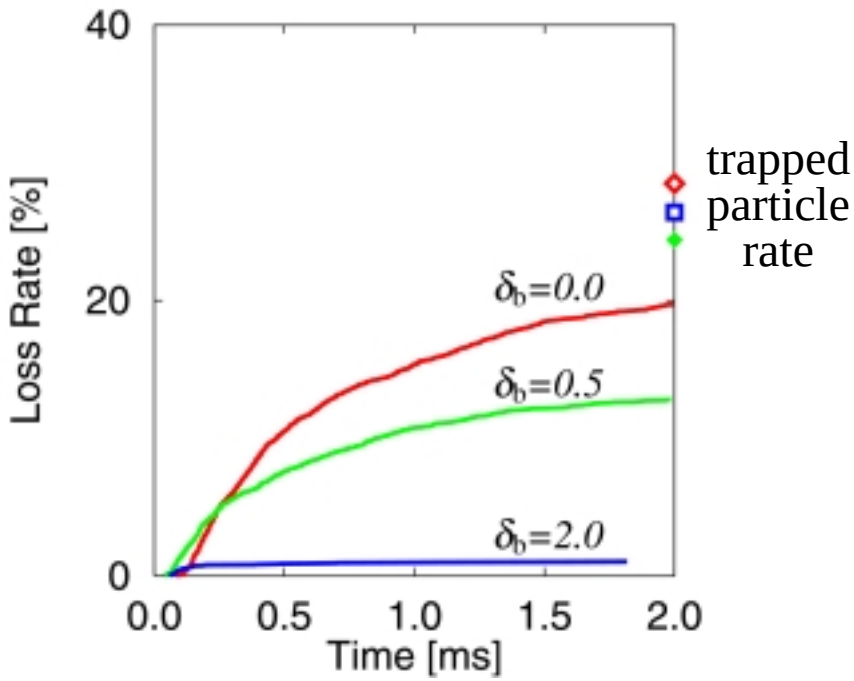
$\delta_b = 2.0$



- **separation of B between ζ_B=0 and ζ_B=(1/2)(2π/M)**
- **toroidally localized mod-B_{min} with maximum B at its center**

Particle loss rate

- $T_i(r/a)=1.0[1-(r/a)^2]$ keV
  ($\rho_i/a \sim 2.4\times10^{-2} \rightarrow$ 70keV proton in W7-X)
- Launched from r/a=0.25, 0.5 and 0.75 with uniform distribution in Boozer coordinates
- 2 msec or until crossing the outermost magnetic surface
- Vacuum without radial electric field
- B_0=1 T on the magnetic axis



Significant improvement as δ_b is increased

G.C.eqs. in Boozer coordinates

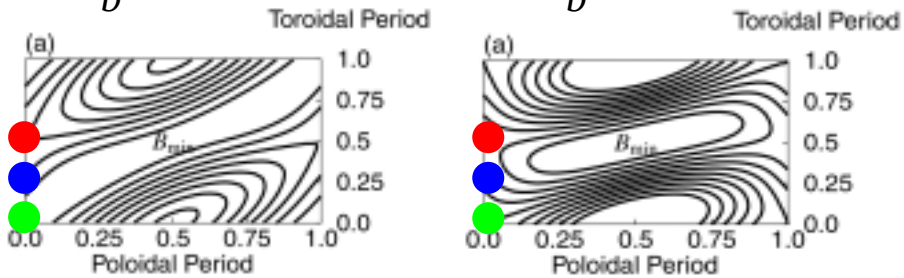
$$\dot{\psi} = \frac{\delta}{\gamma}\left(\frac{\partial B}{\partial \phi_B} I - \frac{\partial B}{\partial \theta_B} g\right)$$

$$\dot{\theta}_B = \frac{g}{\gamma}\left(\delta \frac{\partial B}{\partial \psi} + e\frac{\partial \Phi}{\partial \psi}\right) - \frac{e^2 B^2}{m}\rho_c\left(\frac{\rho_d g' - \iota}{\gamma}\right)$$

Magnetic topography at r/a=0.75

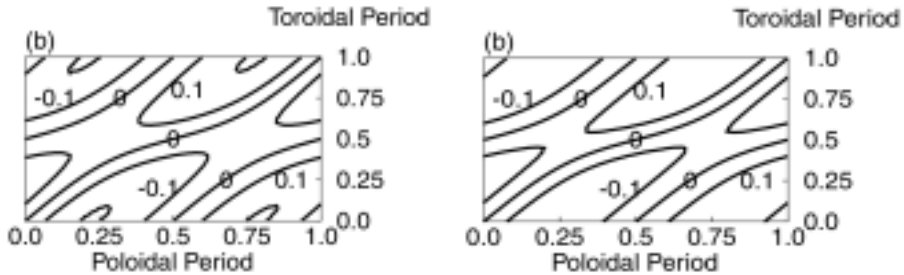
$\delta_b = 0.0$ $\delta_b = 2.0$

B



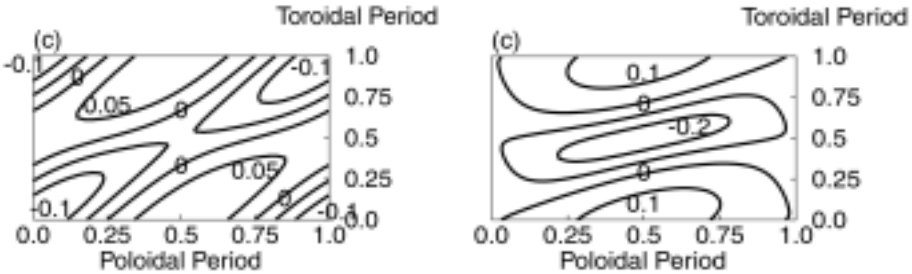
toroidally localized B_{min}

$$\frac{1}{B}\frac{\partial B}{\partial \theta_B} \propto \dot{\psi}$$



No change with bumpy field
(Bumpy field does not have poloidal angle dependence)

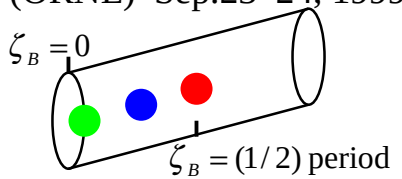
$$\frac{\psi}{B}\frac{\partial B}{\partial \psi} \propto \dot{\theta}_B$$



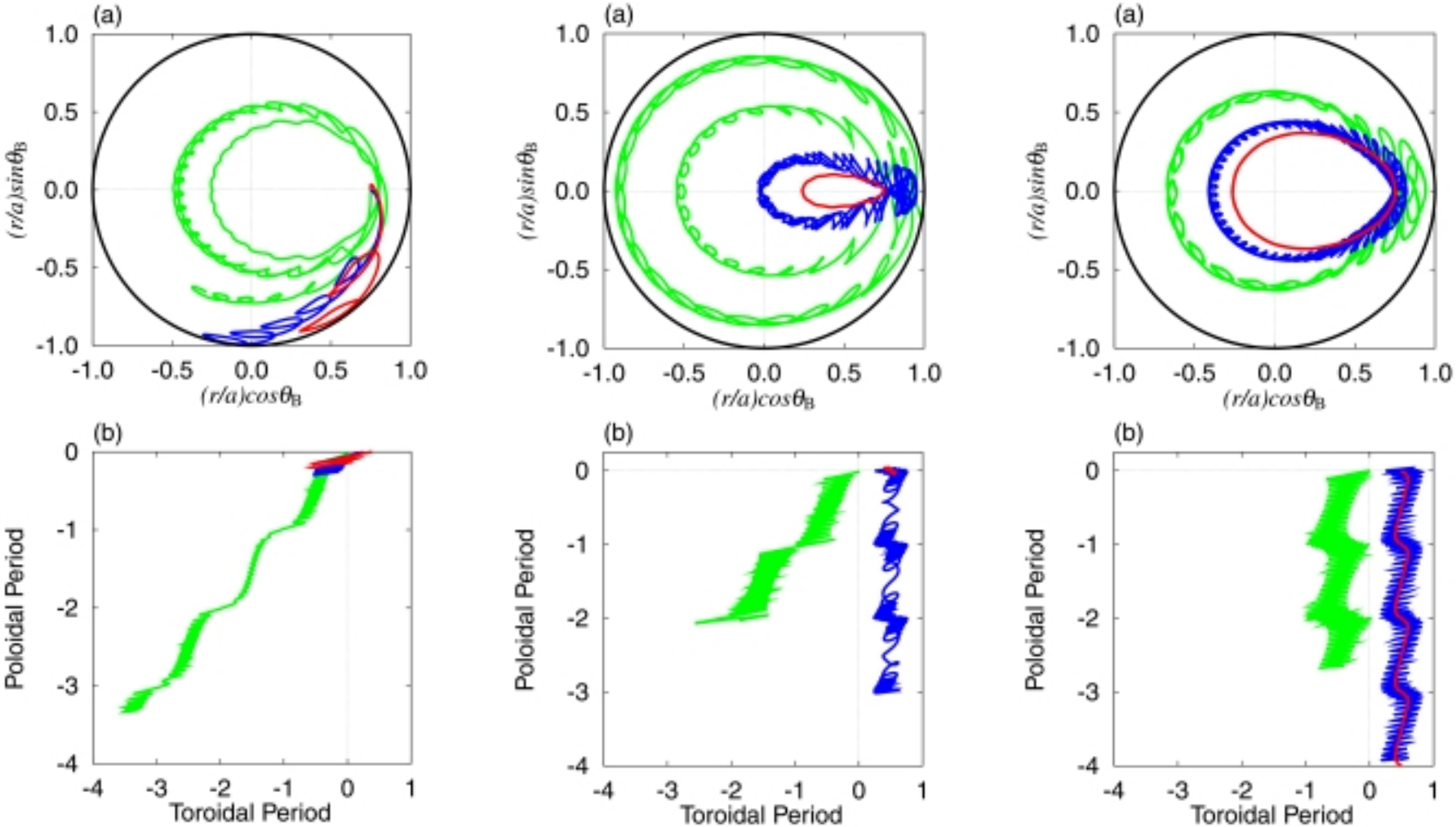
Enhancement of poloidal drift
(well alignment to B_{min} region)

Radial variation of the bumpy field
$\Rightarrow$ enhancement of poloidal drift with radial drift unchanged

Typical Collisionless trapped particle orbits ($v_{//}$=0 initially)

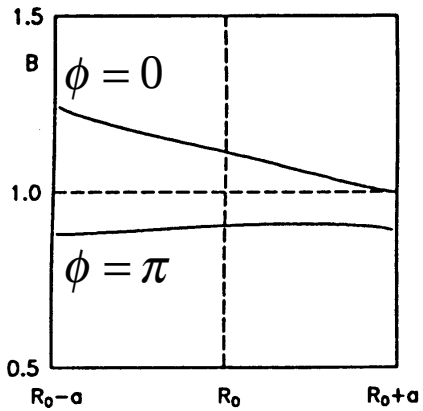


$\delta_b = 0.0$ $\delta_b = 1.0$ $\delta_b = 2.0$

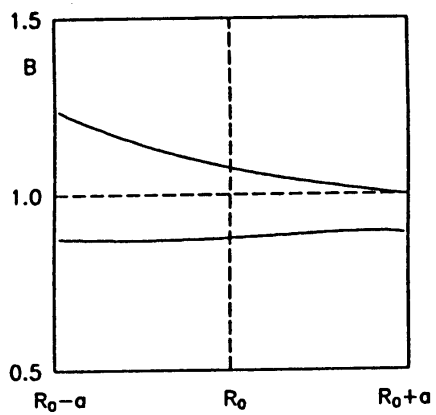


Improvement of α particle confinement for finite beta equilibria in W7-X

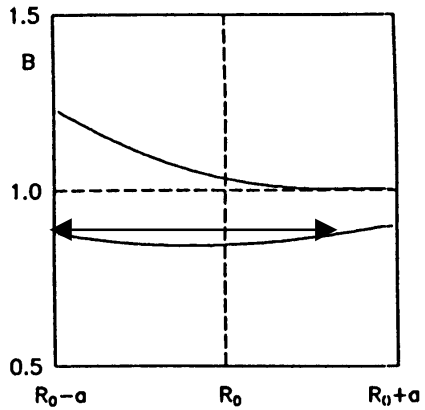
[W.Lotz et al., Plasma Phys. Contr. Fusion 34(1992)1037.]



$\langle \beta \rangle = 0.0\%$

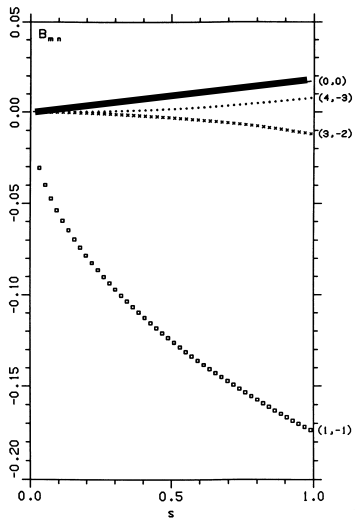


$\langle \beta \rangle = 2.5\%$



$\langle \beta \rangle = 4.9\%$

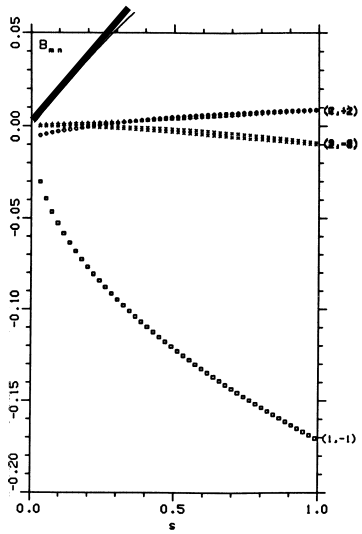
Absolute minimum of *B*



diamagnetic effect

⇒ absolute minimum of *B* at $\phi \approx \pi$

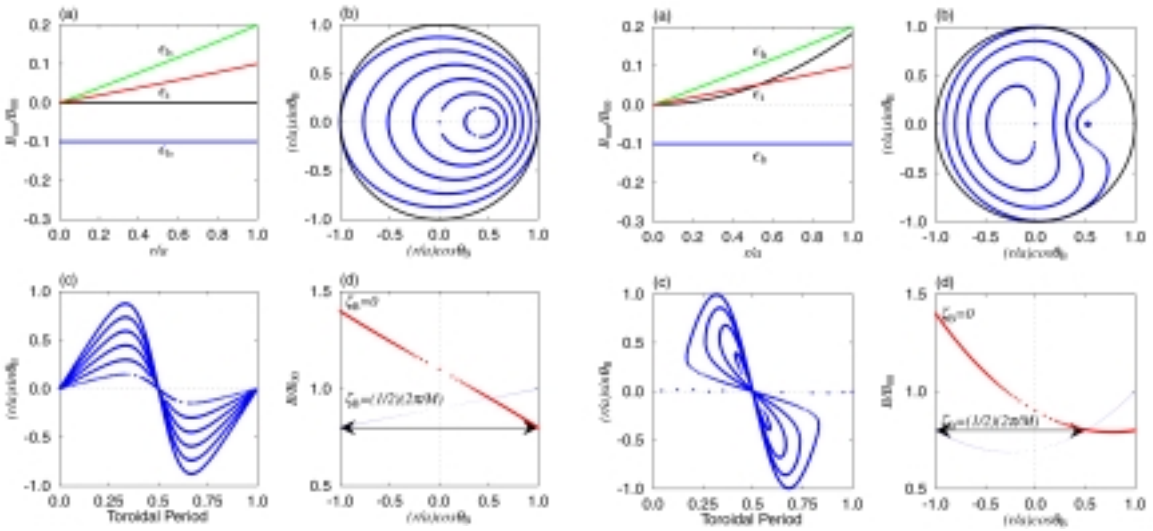
[2nd workshop on W7-X (1988)]

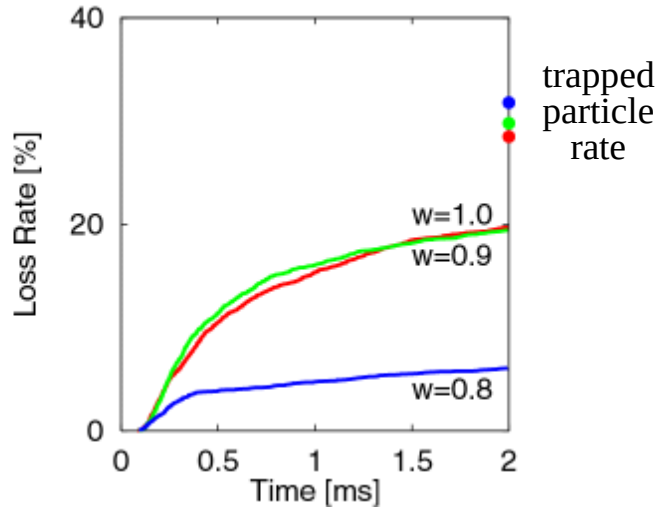


Role of diamagnetic effect on collisionless particle confinement

$$B_0 \Rightarrow B(0)\left[w + (1-w)\left(\frac{r}{a}\right)^2\right] \qquad w < 1 \text{ for magnetic well}$$

w=1.0 w=0.8





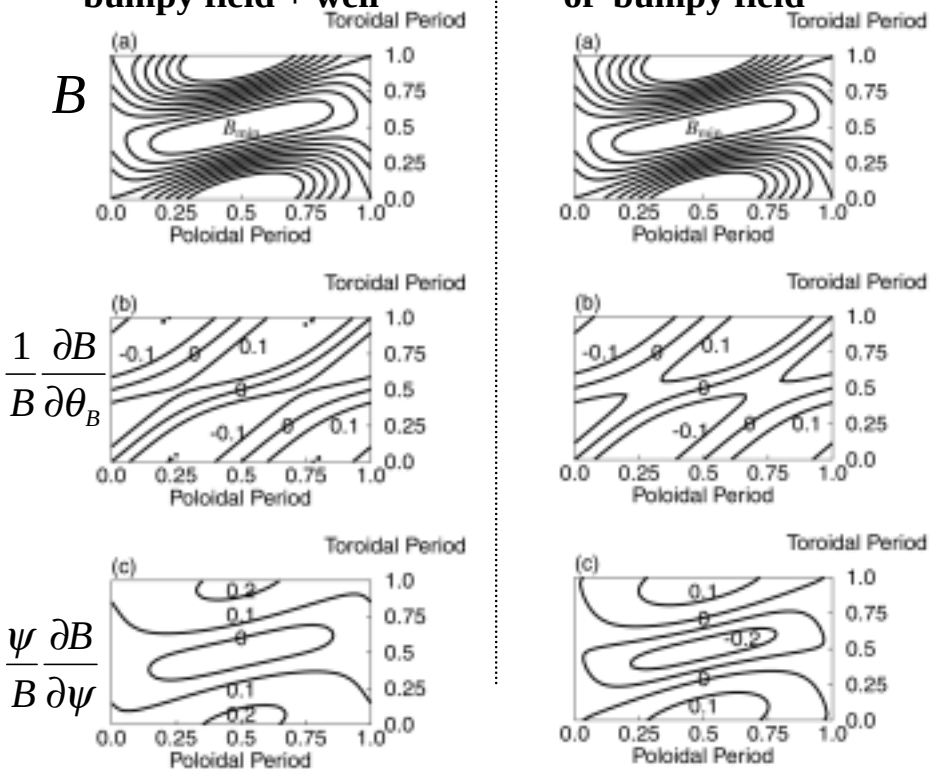
toroidally localized mod-B_{min} but with minimum B at its center (different from radially increasing bumpy field induced one)

significant improvement

Radial variation of the bumpy field and simultaneous diamagnetic effect

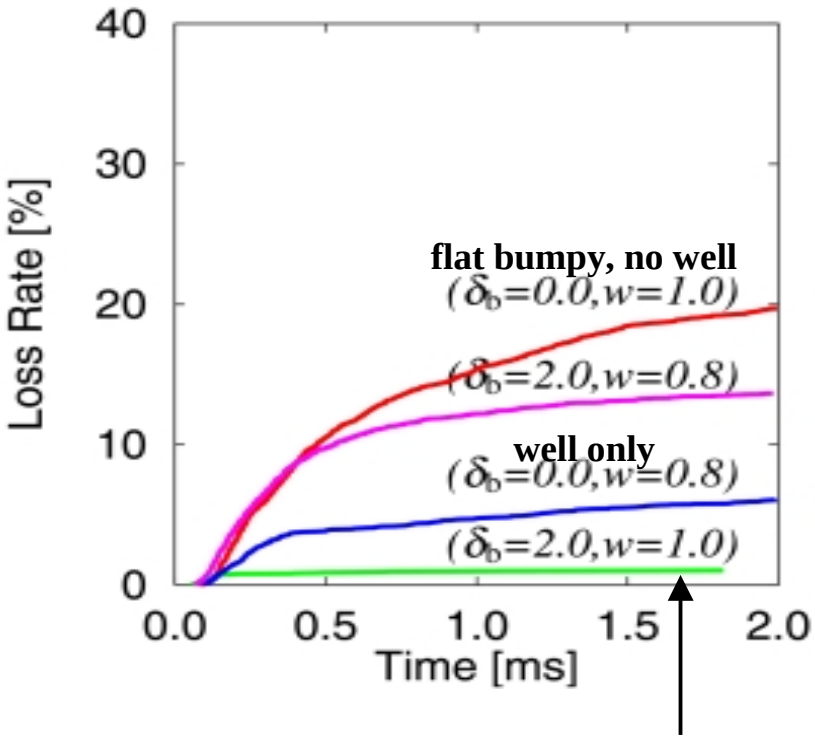
$(\delta_b = 2.0, w = 0.8)$
radial variation of bumpy field + well

$(\delta_b = 2.0, w = 1.0)$
only radial variation of bumpy field



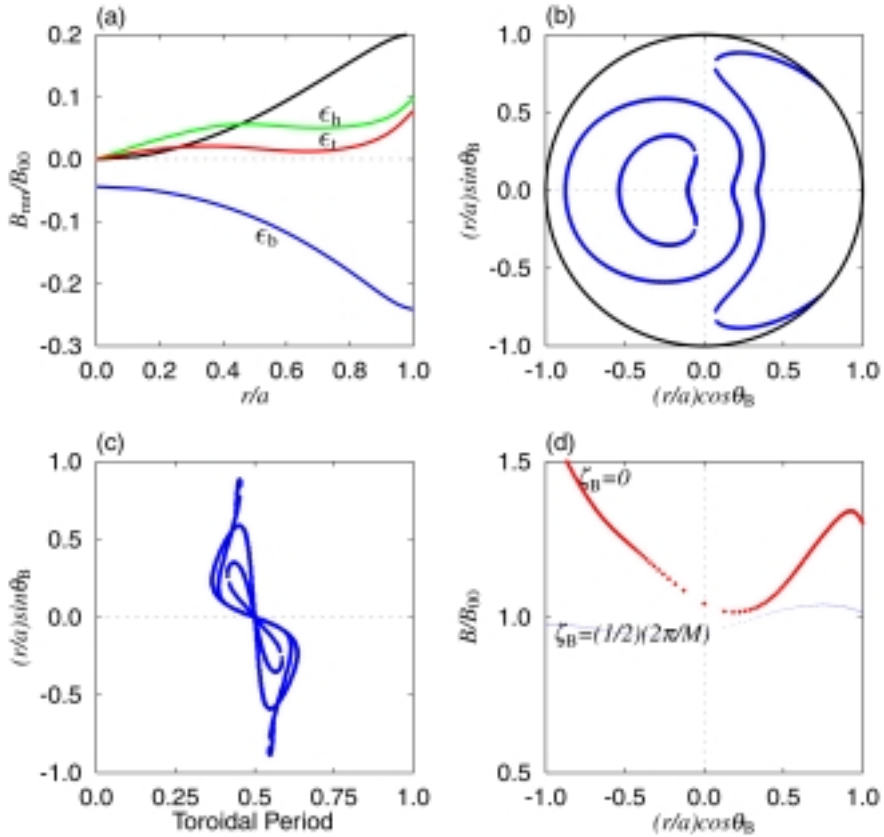
$\Downarrow$

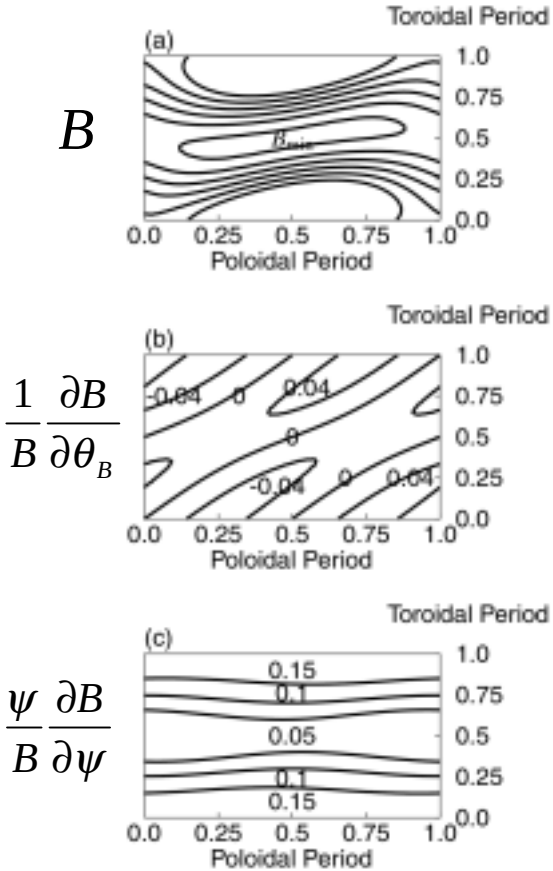
The region of enhanced poloidal drift deviates from B_{min} region
$\Rightarrow$ improvement becomes weaker (the situation as in Heliotron-J)



only radial variation of bumpy field

Finite β equilibrium in Heliotron-J $\langle\beta\rangle = 2.9\%$





The radial variation of the bumpy field and the diamagnetic effect occur simultaneously ⇒ The region of enhanced poloidal drift deviates from B_{min} region

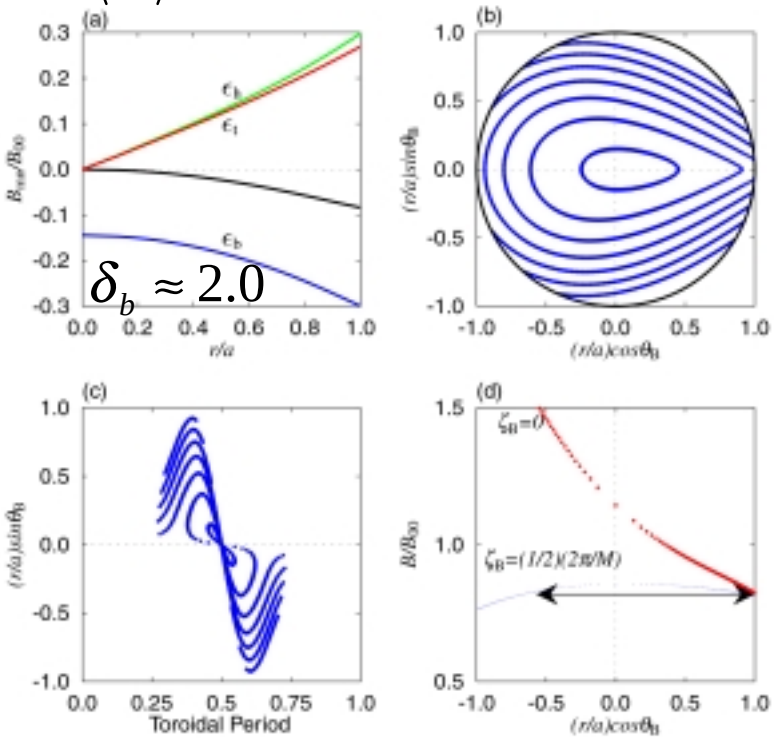
The weaker improvement of collisionless particle confinement in finite β equilibria in Heliotron-J

Some trials have been made for further improvement in Heliotron-J

- Stronger radial variation of the bumpy field even at vacuum

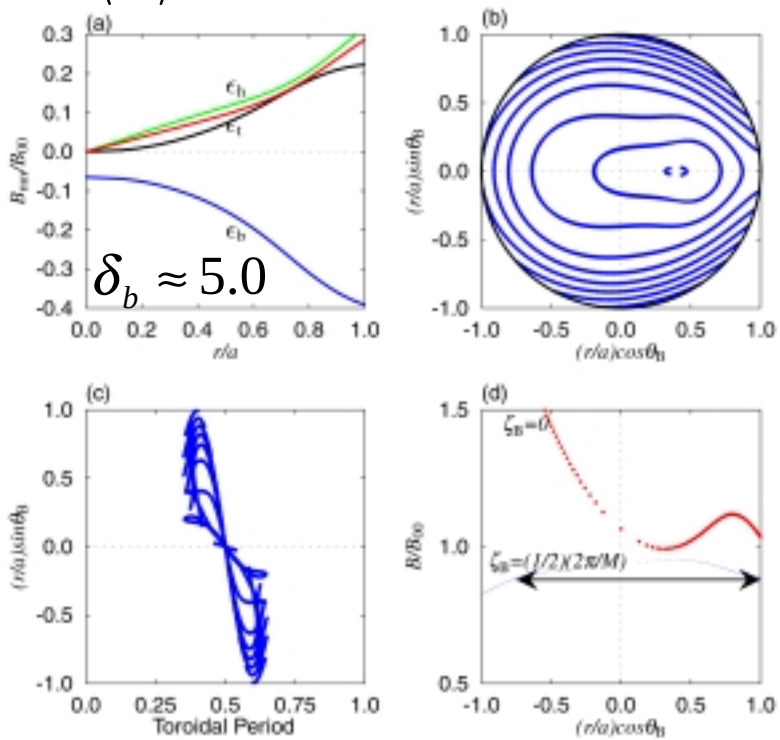
  ex.) increase of I_{AV}

$\langle \beta \rangle = 0\%$



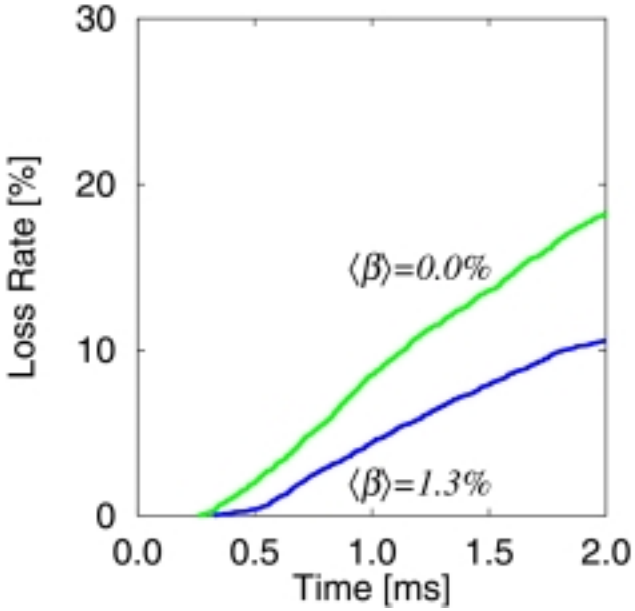
toroidicity is also enhanced

$\langle \beta \rangle = 1.3\%$



The toroidally localized mod-B_{min} formed with the bumpy field overcoming the diamagnetic effect

Particle loss rate for this configuration

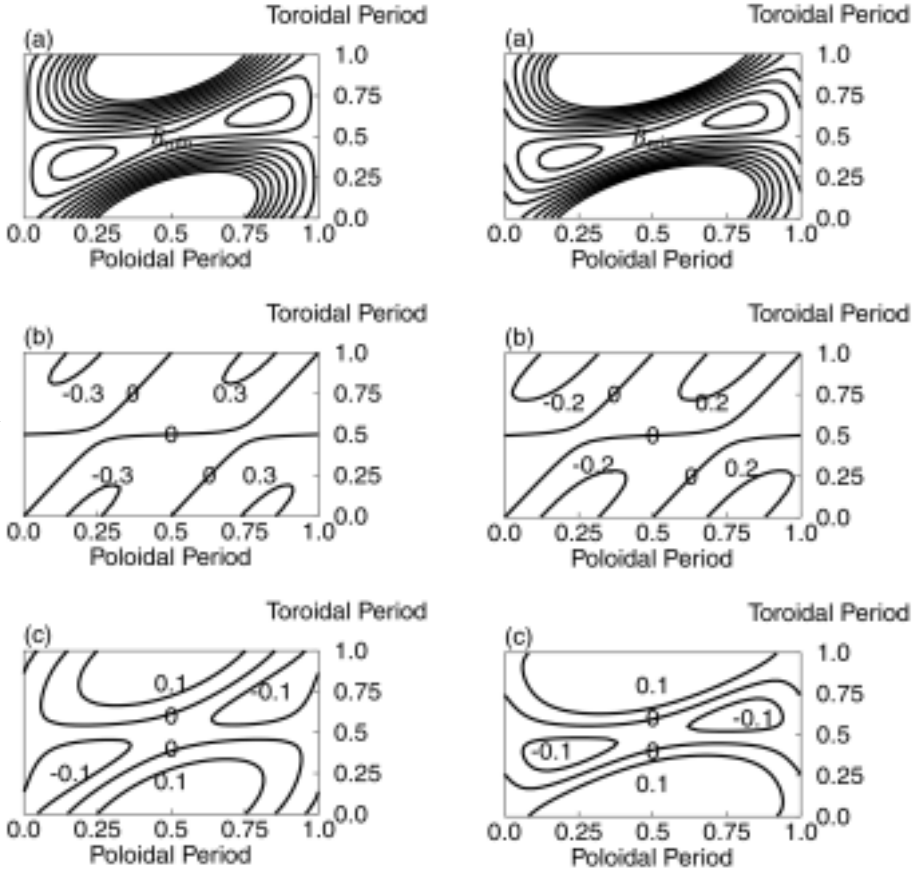


$\langle\beta\rangle = 0\%$ $\langle\beta\rangle = 1.3\%$

B

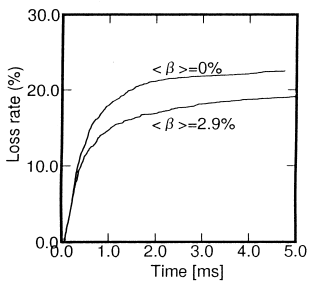
$\frac{1}{B}\frac{\partial B}{\partial \theta_B}$

$\frac{\psi}{B}\frac{\partial B}{\partial \psi}$



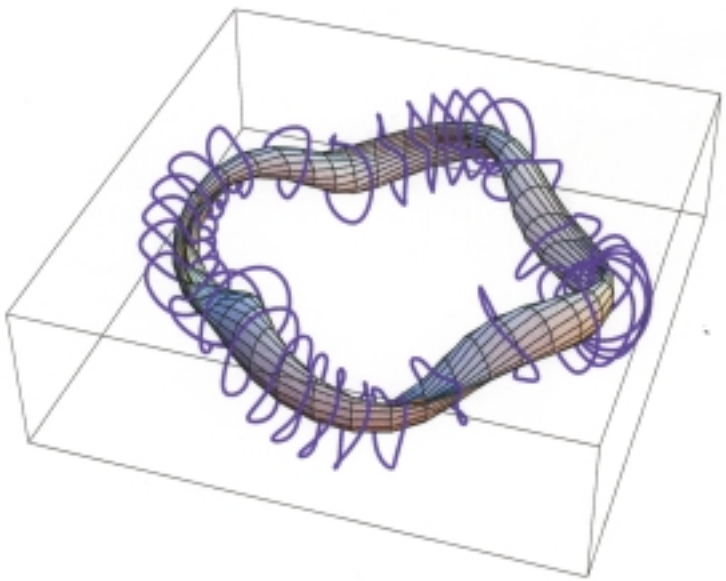
Successful improvement

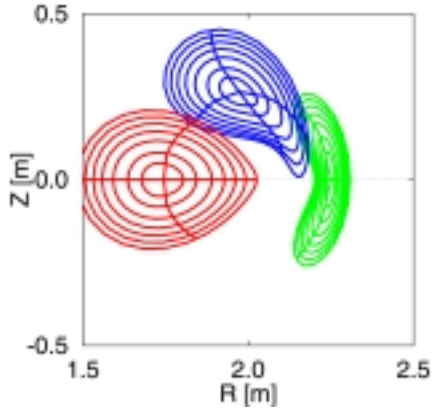
- loss rate decreases
- slow loss beginning

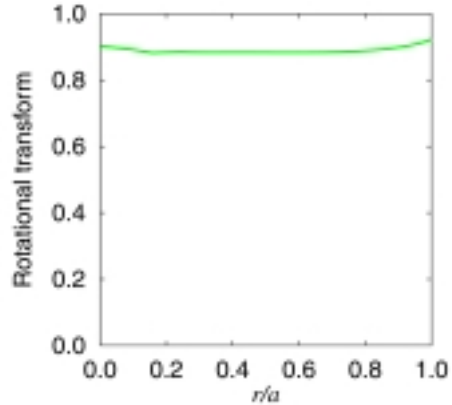


The possibility of Quasi-Poloidally Symmetric (QPS) Configuration

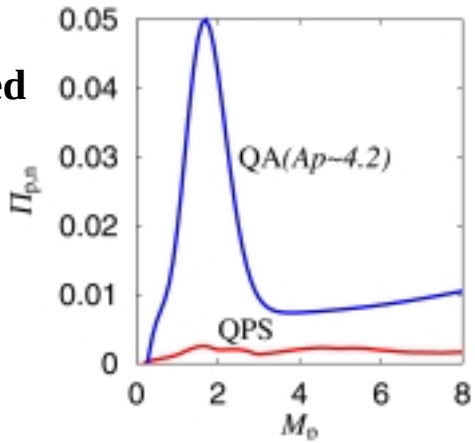
(in collaboration with Auburn Univ.)







Significantly reduced poloidal viscosity



- **QPS ⇒ the magnetic pumping is minimized in the poloidal directio**
⇒ experimental test of ITB formation in stellarators
- **techniques to generate localized poloidal shear flow, such as IBV may be very efficient in reducing anomalous transport.**
- **Studies of driven rotation in the QPS configuration should clarify the roles of neoclassical and anomalous poloidal viscosity on the effectiveness of ITB in all toroidal plasmas.**

Summary

- The role of radial variation of the bumpy field
  - The toroidal localization of B_{min} region (localization of deeply trapped particles) due to the bumpy fleld itself
  - The enhancement of poloidal drift due to the radial variation of the bumpy field with keeping the radial drift unaffected

  → well alignment of these regions improves collisionless particle confinement

- The improvement of collisionless particle confinement compatible with increase of β in W7-X(significant) and Heliotron-J(weak)
  - [W7-X] The diamagnetic effect ⇒ formation of absolute B_{min} (toroidally localized closed mod-B_{min} with the minimum B at its center)
  - [Heliotron-J] Radially increasing bumpy field (toroidally lozalized closed mod-B_{min} with the maximum B at its center) + diamagnetic effect

    ⇒ the improvement due to the radial variation of the bumpy field is weaken with the simultaneous diamagnetic effect

- Some trials have been made for further improvement in Heliotron-J based on this study ⇒ Experimental test

- The possibility of QPS is shown --- the last quasi-symmetry in 3D systems --- significantly reduced poloidal viscosity for poloidal rotation enhancement or maintaining