Physical Properties of Plasmas in the L=1 Heliotron (Heliotron-J)

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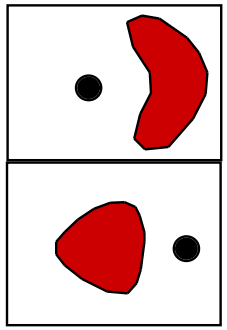
Introduction

- Physical properties of a specific L=1 / M=4 Helical Axis Heliotron (Heliotron-J) are studied.
- One of the main purposes of this machine is to do the basic study of configuration optimization experimentally.
- A continuous helical coil winding is adopted by considering experimental flexibility and plasma accesibility (diagnostics, heating and divertor) in a relatively small size of experimental device.
- Two sets of TF coils with a different power supply are used to control the toroidal mirror component of magnetic field strength to verify the “Linked Mirror” concept.
- The results we have obtained up to now will be shown.

Characteristics of L = 1 / M = 4 Helical Axis Heliotron

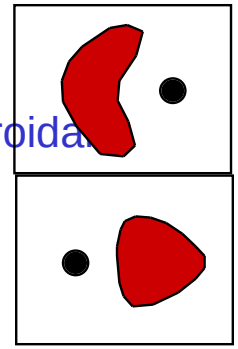
The effect of the modulation of the helical coil winding α

α > 0



- reduction of ε_t
- large unfavorable toroidal mirror component $\varepsilon_b / \varepsilon_h > 1$
- magnetic hill
- high aspect ratio

α < 0

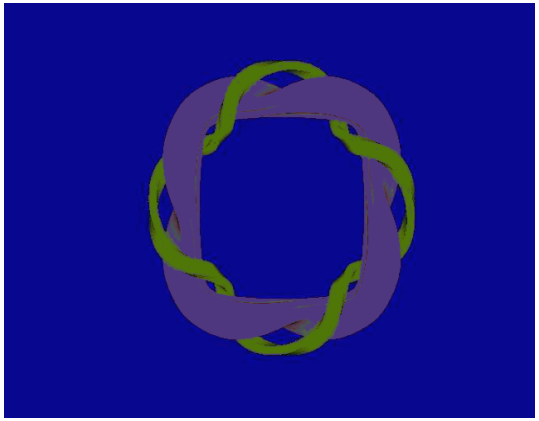


- ε_t is not reduced
- small unfavorable toroidal mirror component $\varepsilon_b / \varepsilon_h < 1$
- magnetic well
- smaller aspect ratio

Helical coil winding law :

$$R = R_c + a_c \cos$$
$$Z = a_c \sin$$
$$= + (M / L) - \sin(M / L)$$

definition : $\varepsilon_h = B_{1,4} / B_{0,0}$
$\varepsilon_t = B_{1,0} / B_{0,0}$
$\varepsilon_b = B_{0,4} / B_{0,0}$



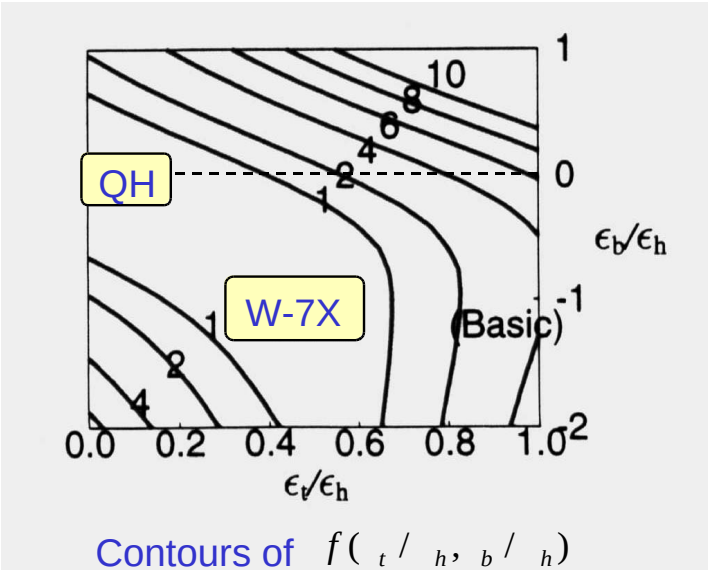
Reduction of neoclassical ripple transport by toroidal mirror component (bumpy field)

Model field

$$B = B_0(1 - {}_t\cos(\quad) + {}_h\cos(L \quad - M \quad) + {}_b\cos(M \quad))$$

→ Shaing-Hoking formula for 1/ν neoclassical transport

$$\Gamma \quad f({}_t / {}_h, {}_b / {}_h)$$



Contours of $f({}_t / {}_h, {}_b / {}_h)$

→ Toroidal effects (breaking quasi-helical symmetry) on N-C ripple transport can be reduced by the bumpy field

Coil Configuration

- Helical field coil (HF coil)

  winding law :

  $R = R_c + a_c \cos$

  $Z = a_c \sin$

  $= +(M / L) - \sin(M / L)$

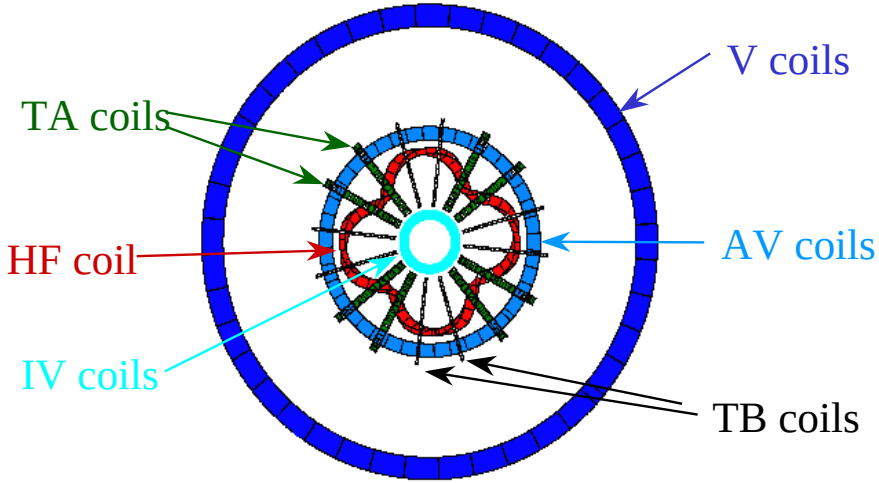
  $R_c = 12\,\text{m},\ a_c = 022\,\text{m}$

  $= -04$

- Three sets of PF coils
  - V coils
  - AV coils
  - IV coils
- Two sets of TF coils
  - TA coils
  - TB coils

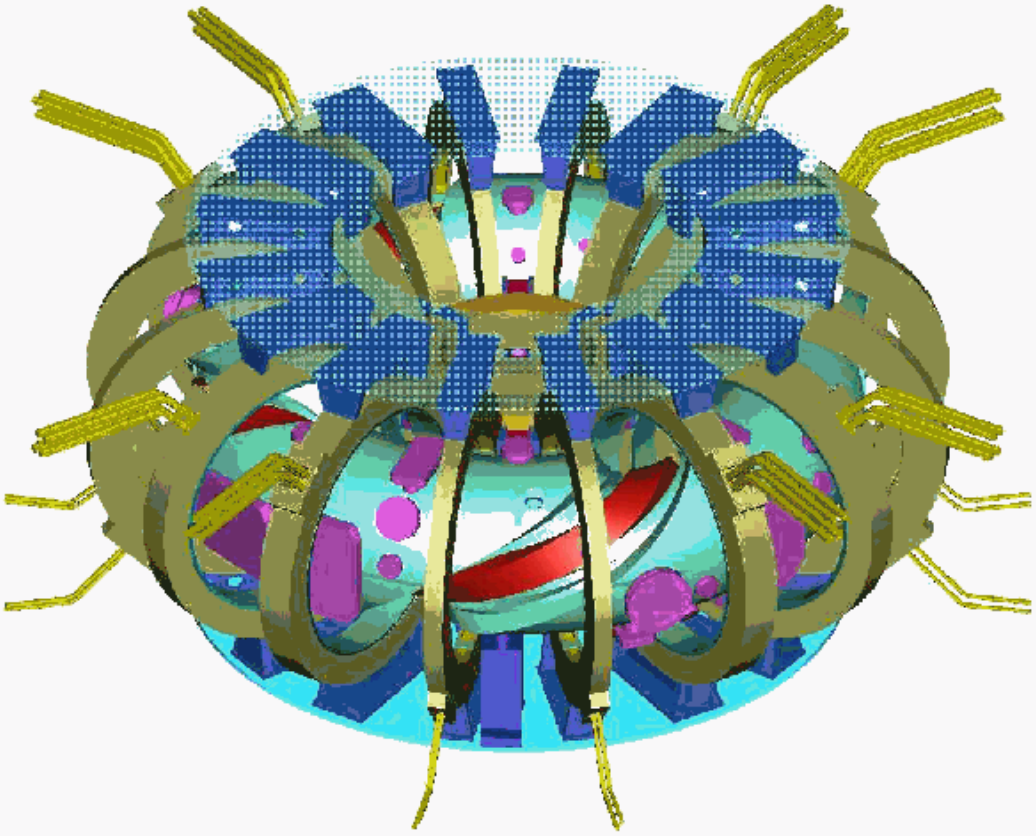
- $I_{HF} : I_V = 8:7$ is fixed.
  - ← power supply
- I_{AV} → plasma position
- $I_{AV} + I_{IV}$ → plasma shaping
- $I_{TA} + I_{TB}$ → rotational transform

  toroidal mirror ratio



Top View of Coil Configuration

Coils and Vacuum Vessel of Heliotron-J



Properties of Vacuum Magnetic Surfaces (1)

- Typical Vacuum Magnetic Configuration

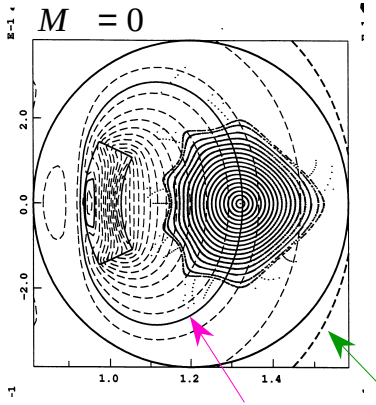
$$I_{HF} = 0.96\text{MA}$$
$$I_{V} = 084\,\text{MA}$$

$$I_{TA} = 0.50\text{MA}$$
$$I_{TB} = 0.20\text{MA}$$

$$I_{AV} = I_{IV} = 0\text{MA}$$

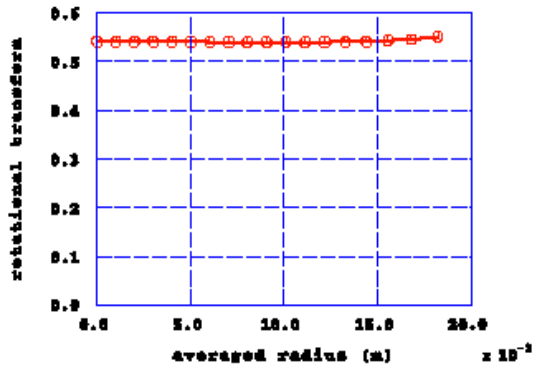
KMAG code

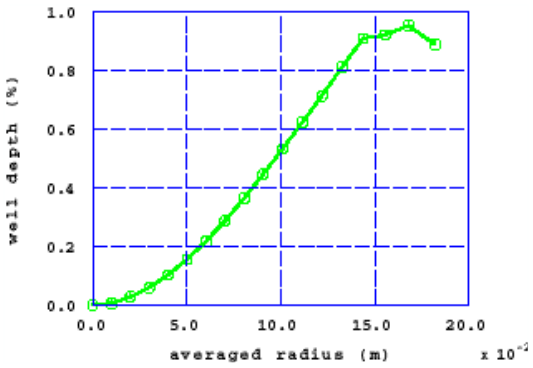
- Averaged plasma minor radius = 0.1m - 0.2m



|B|=1.5T |B|=1.0T

Poincare Plot & |B| Contours



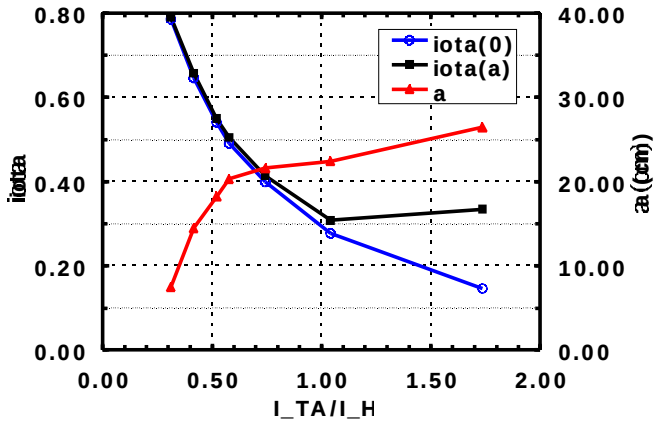


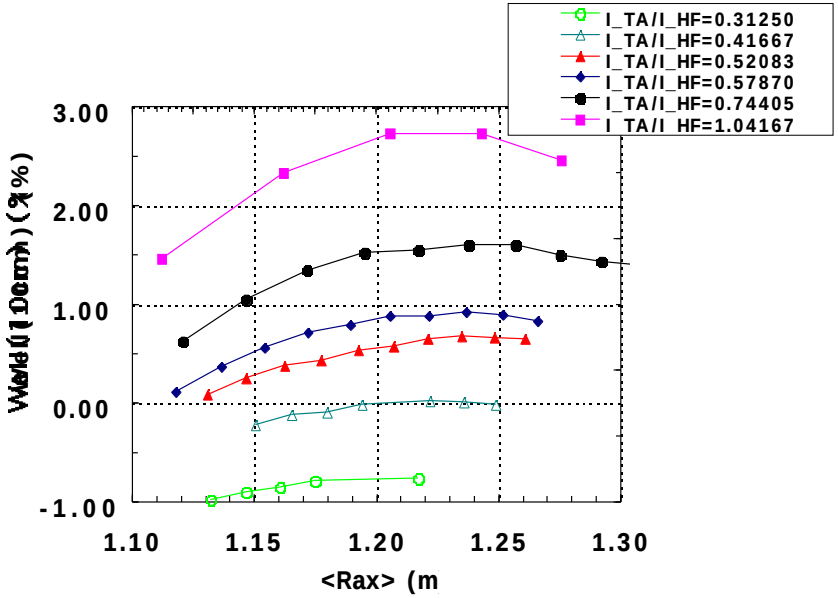
Properties of Vacuum Magnetic Surfaces (2)

- Control of Rotational Transform by TF coils
  - Change of Magnetic Well Depth with Rotational Transform

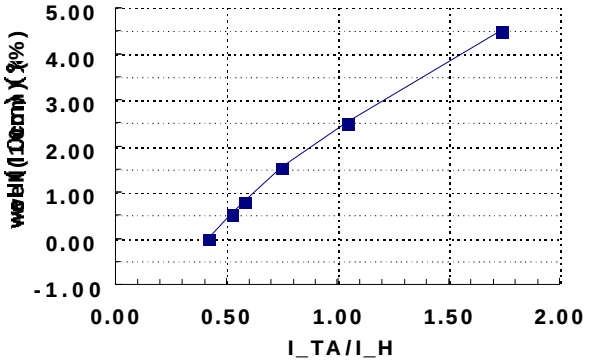
well $[V'(0) - V'(r = 10\text{cm})] / V'(0)$

R_{ax} =1.19 – 1.20 m





R_{ax} =1.19 – 1.20 m

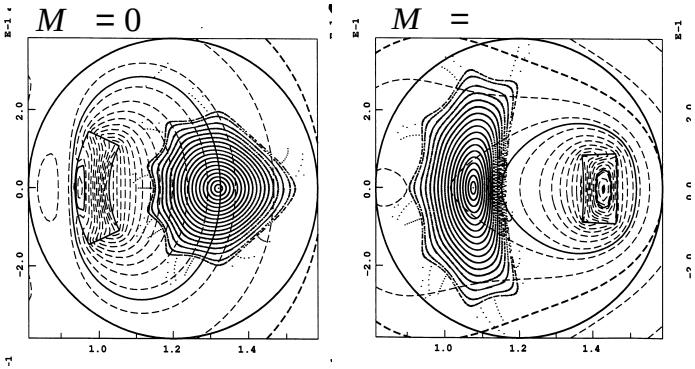


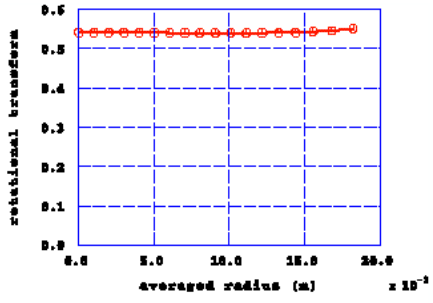
Properties of Vacuum Magnetic Surfaces (3)

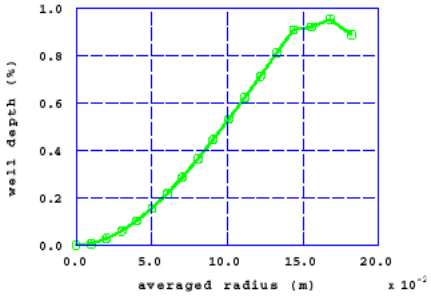
- Control of Toroidal Mirror Component of |B| by TF coils $I_{TA} / I_{TB} = 1.0$

$\rightarrow \varepsilon_b / \varepsilon_h = +0.8$ (r/a=0.5)

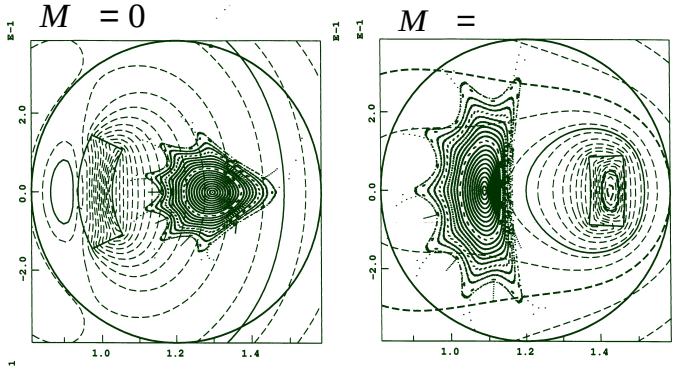
$I_{TA} / I_{HF} = 0.52083$ (0.5:0.96) $I_{TA} / I_{TB} = 2.5$ (5:2) $\rightarrow \varepsilon_b / \varepsilon_h = -0.5$ (r/a=0.5)

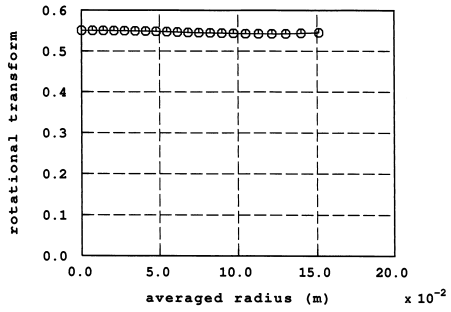


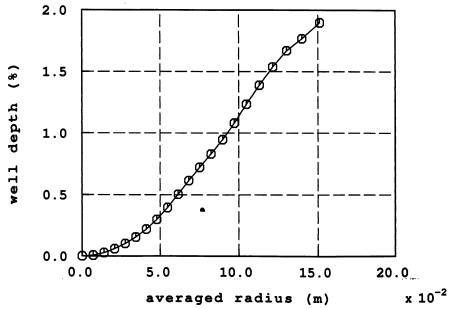




$I_{TA} / I_{HF} = 0.83333$ (0.8:0.96) $I_{TB} = 0.0$ $\rightarrow \varepsilon_b / \varepsilon_h = -2.5$ (r/a=0.5)







MHD Equilibrium and Mercier Stability

- MHD Equilibria are Calculated by the VMEC Code

  radial grids ; $N_s = 101$

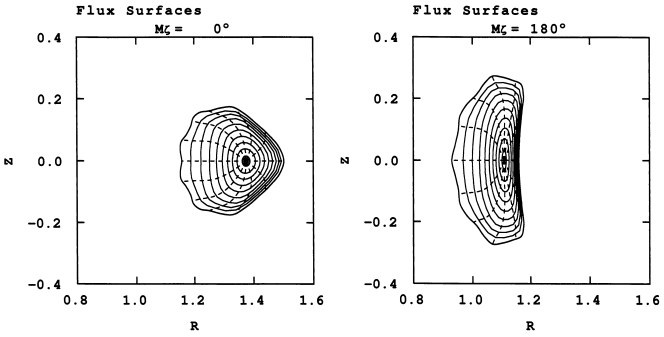
  Fourier modes ; $m = 0 \sim 11$

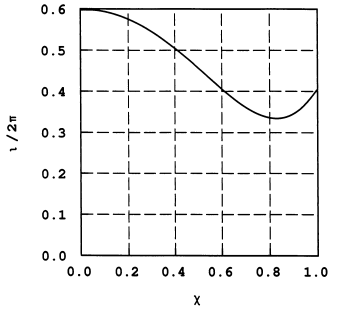
  $n = -12 \sim 12$

  Fixed Boundary Condition

  ↓

  $_{eq} > 3\%$



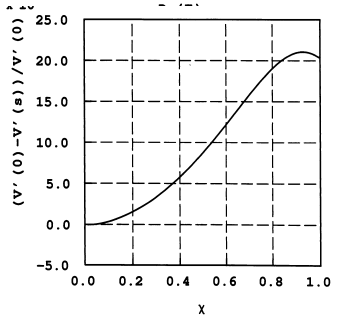


- Mercier Criterion

  Mercier criterion is evaluated by neglecting resonant parallel currents due to the rational surfaces.

  (← If it cannot be neglected, we need to do equilibrium calculation without assuming nested flux surfaces.)

  Typical equilibrium is stable against Mercier modes.

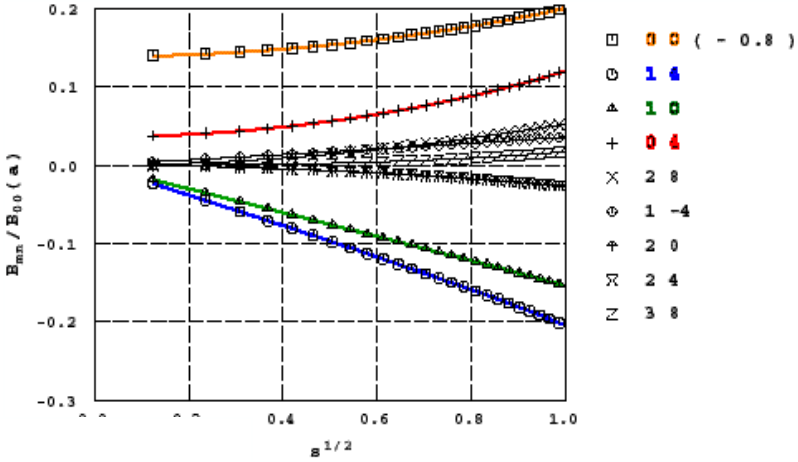


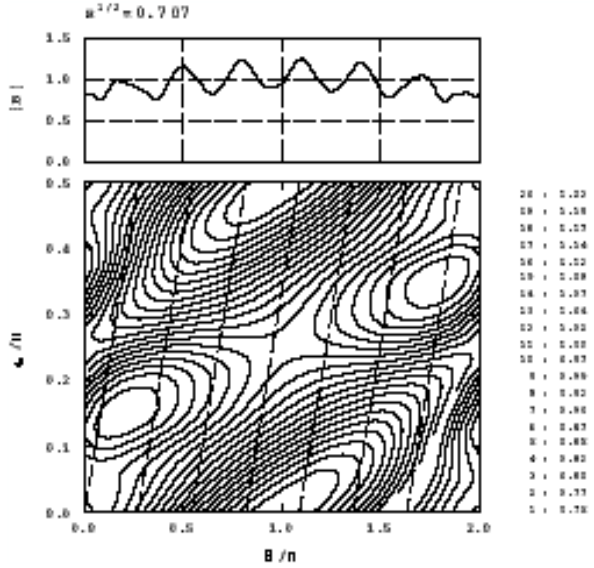
Structure of Magnetic Field Strength (1)

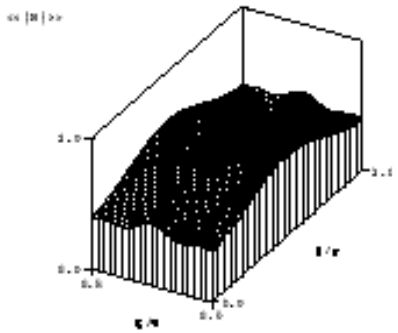
- Fourier Spectra of Magnetic Field Strength in Boozer Coordinates

Dominant Fourier Components are ;

- $B_{0,0}$
- $B_{1,4}$; helical component
- $B_{1,0}$; toroidal component (toroidicity)
- $B_{0,4}$; toroidal mirror component



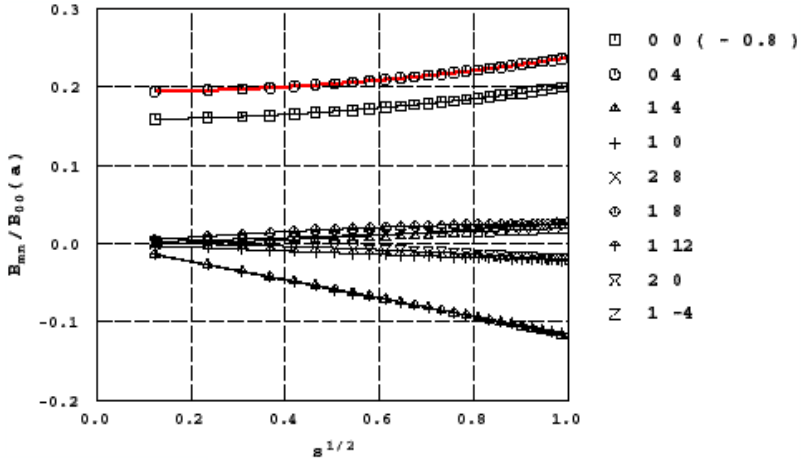


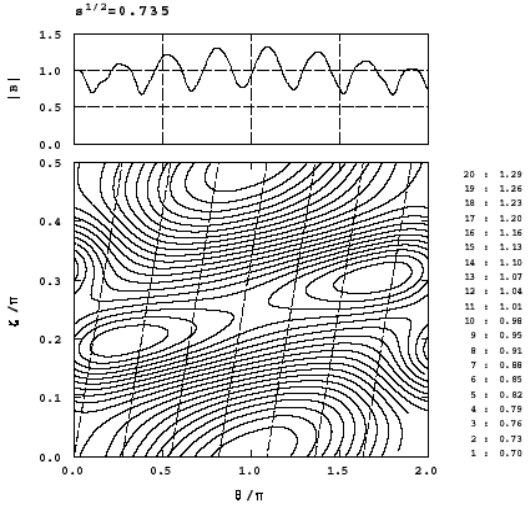


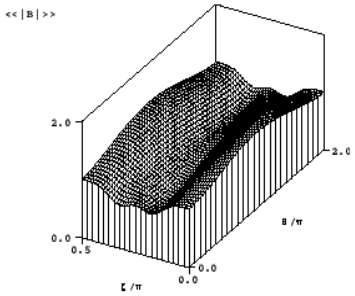
$I_{TA} / I_{TB} = 2.5$

Structure of Magnetic Field Strength (2)

- Fourier Spectra of Magnetic Field Strength in Boozer Coordinates







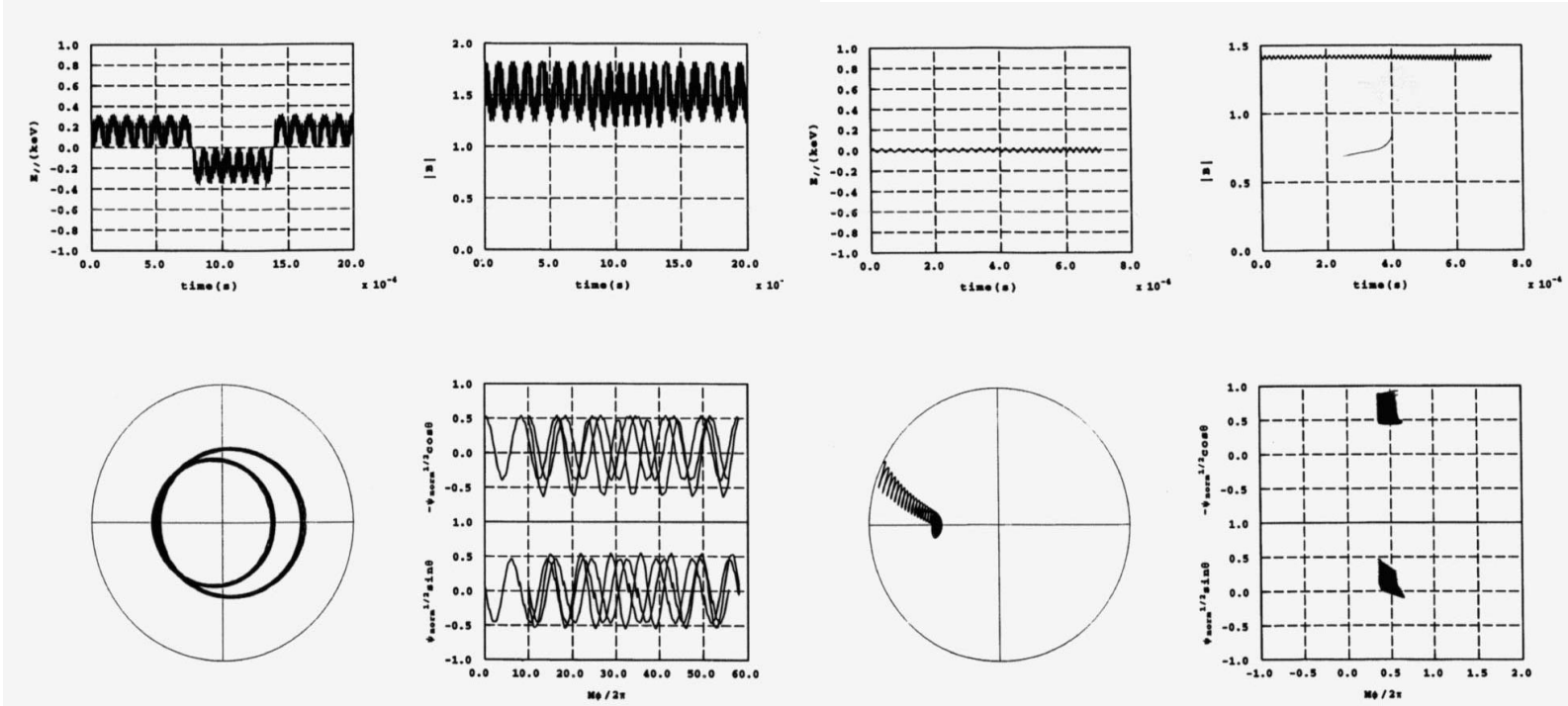
$I_{TB} = 0.0$

↓

tends to *Linked Mirror" configuration close to the Quasi-Poloidal Symmetry

Collisionless Particle Orbit (1)

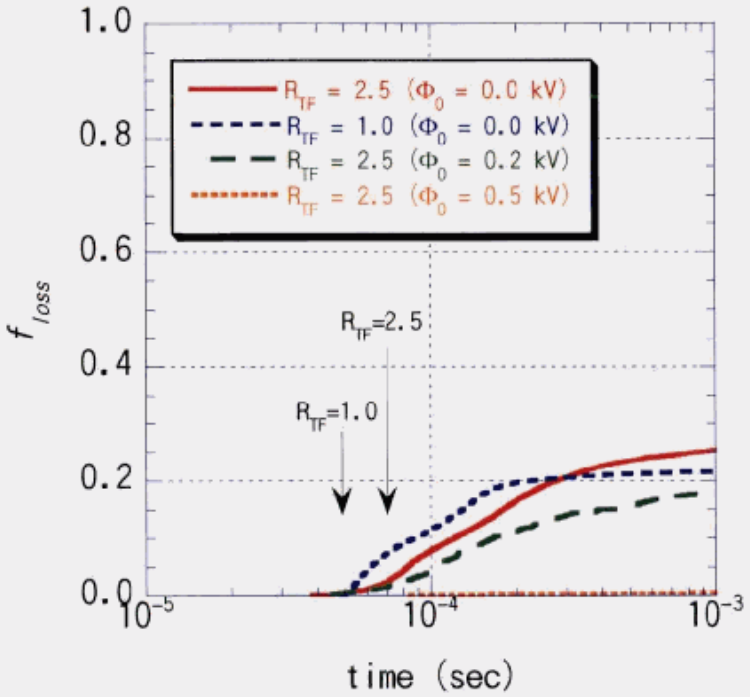
1 keV proton / B_0 = 1T / $v_{//}$ (t = 0) = 0 $I_{TA} / I_{TB} = 2.5$



Trapped particles are located at the faborable position where we can expect slow grad-B drift.

Collisionless Particle Orbit (2)

Time evolution of the loss rate of 1keV protons launced at <r>/a = 0.5 flux surface with uniform distribution in space and pitch angle (B_0 = 1T).



- favorable bumpy field gives slower orbit loss
- weak radial electric field improves particle confinement significantly.

These are consistent with slow grad-B drift.

Neoclassical Transport (1)

Neoclassical transport calculation by DKES code

Definitions for the calculation with monoenergetic distribution function

mean free path ; $\Lambda = \nu / v$
half connection length ; $L_c = \pi R_0 / \iota$
nomalized mean free path ; $L_* = \Lambda / L_c = 1 / \nu^*$

Simple estimation of diffusion coefficient in plateau regime ($(r/R_0)^{3/2} < \nu < 1$)

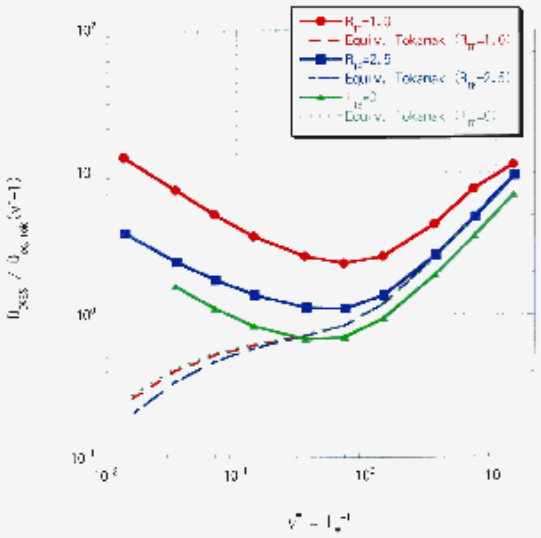
$D_{plateau} = (\rho^2 v) / (\iota R_0)$ $\rho = (mv) / (eB_0)$

Diffusion coefficient calculated from DKES(monoenergetic) output Γ_{11}

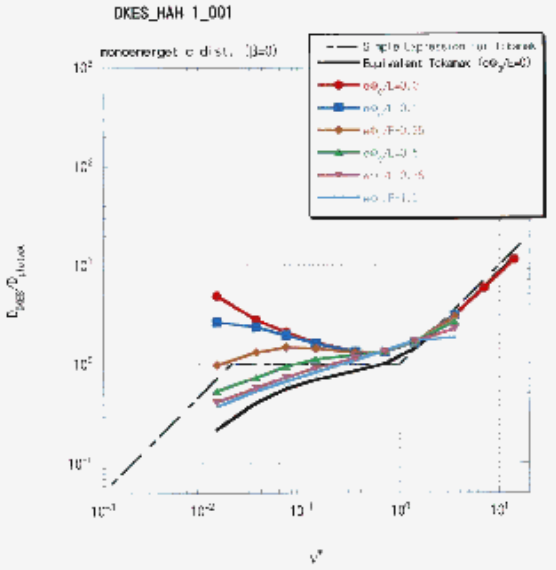
$D_{DKES} = v(vB_0/\Omega_c)^2\Gamma_{11}$

Neoclassical Transport (2)

DKES code



neoclassical diffusion can be reduced by bumpy field



significant reduction can be expected by the radial electric field

Concluding remarks

- There are a lot of studies to be done.

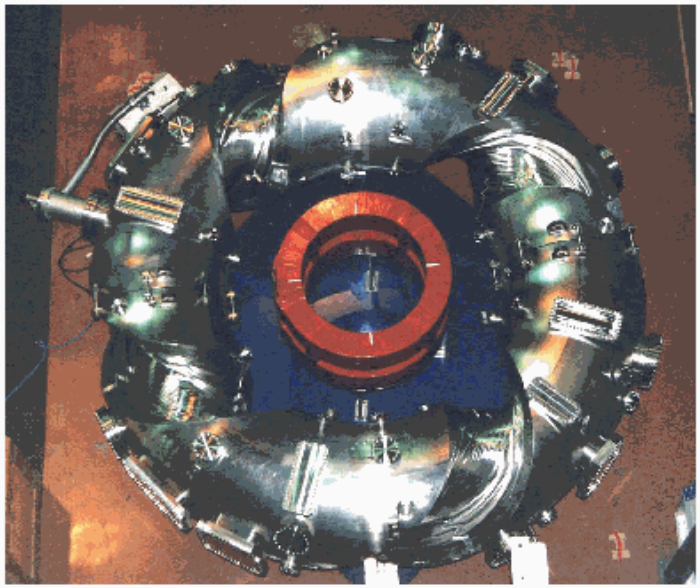
  Ballooning stability
  Global stability (free boundary)
  Magnetic islands due to finite beta effect
  Ambipolar neoclassical transport
  Divertor study (island divertor?)
  Plasma shaping by IV coils.
  etc.

- Theoretical predictions have to be verified by experiments !!

Present Status of Heliotron-J

Heating, diagnostics systems and power supply are those of Heliotron-E.
Same site of Heliotron-E --> Heliotron-E will be removed.
We already made TF coils, IV coils, and Vacuum vessel.

TF coils (TA and TB coils)



Vacuum vessel and IV coils

Construction will be finished at the end of FY-99 (April, 99 - March, 2000).

----> first plasma can be expected at the beginning of 2000!