2. Stellarators

A. Features

- B_p by external helical windings (or twisted-coil system)
  (Adjustable ι, Unstable mode control, Built-in poloidal divertor)
- Unnecessary ohmic current (No OH coils)
  - High A design → easy maintenance & access
  - Steady-state operation
  - Free of disruptive termination (No major disruption)
  - No fatigue problem, Simple blanket
  - NBI, RF CD and heating
- Capable of ignition & low recirculating power
- Complex non-axisymmetric field configuration
  - Rotation of flux surface cross-section
- Easier control (Confining field formation before plasma generation
  → minimum plasma-wall interaction, no feedback control
  Separative control of heating & confinement)
- Limited experimental basis

B. Configurations

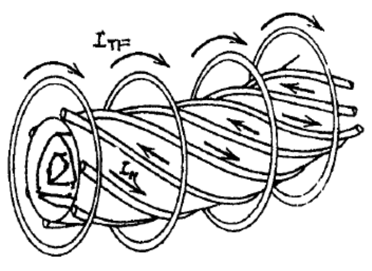
1) Stellarator

***l* pairs of helical windings** with alternatively anti-paralleled current flows

$$\Rightarrow \quad \boldsymbol{B}_\theta \quad (\overline{B_\phi}=0,\ \overline{B_V}=0)$$

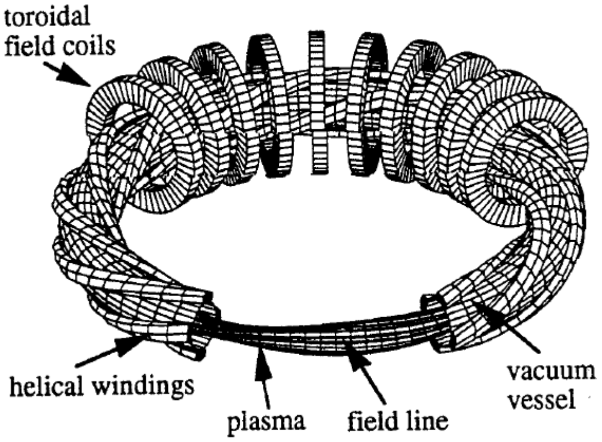
TF coils ⇒ $\boldsymbol{B}_\phi$

No VF coils



Stellarator (l = 3)

Stacy[4] Fig. 4.3.1



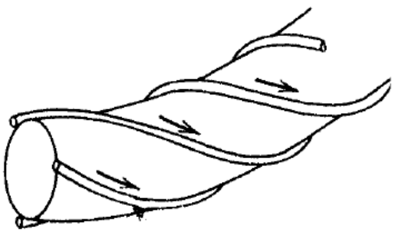
Shown is a classical stellarator (W7-A) with helical windings and additional toroidal field coils. Plasma and field lines are also shown.

2) Torsatron

l helical windings (instead of l paris) with parallel current flows + No TF coils

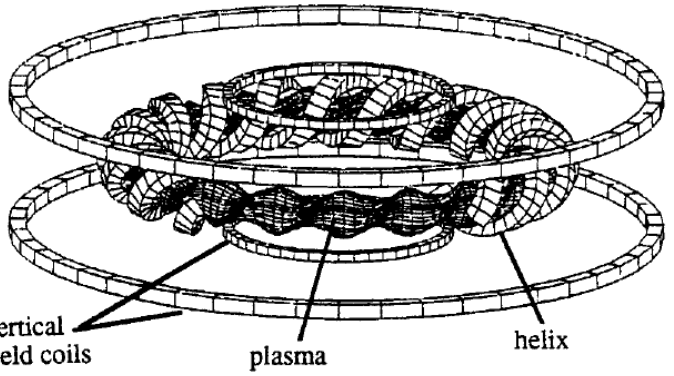
$\Rightarrow \quad B_\Phi + B_\Theta + B_V$

VF coils to cancel self-generated B_V



Torsatron (l = 3)

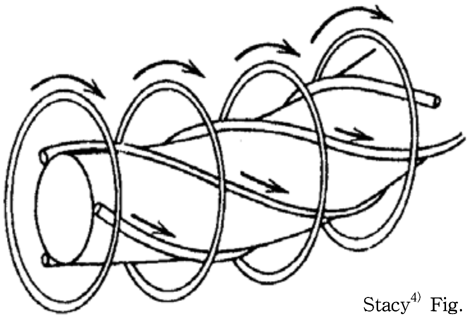
Stacy[4] Fig. 4.3.1



Plasma and coil system of a torsatron (HeE)

3) Heliotron

Torsatron windings + **TF coils** $\Rightarrow$ high ι & shear

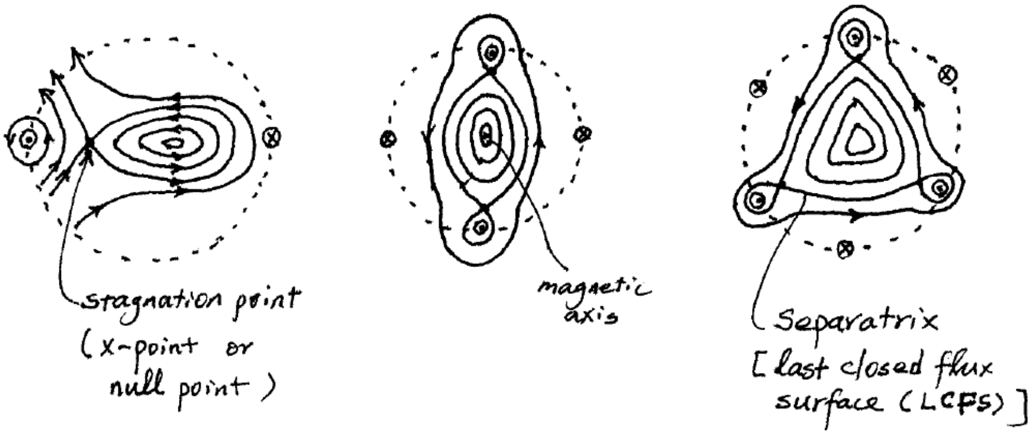


Stacy[4] Fig. 4.3.1

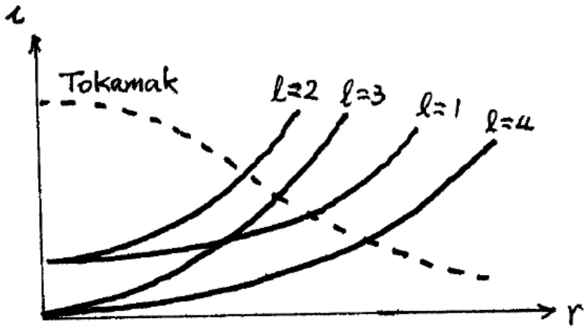
Heliotron (l = 3)

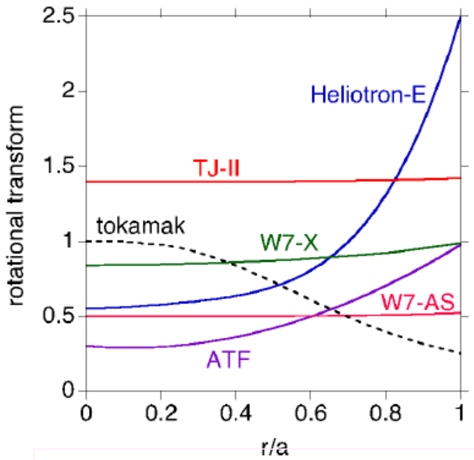
C. Plasma cross sections

l = 1 l = 2 l = 3



D. Rotational transform





(R. Brakel, MP-IPP Summer Univ. (2005), Fig. 11.4)

No shear is possible up to large r for $l \leq 2$

E. Magnetic field & Particle orbits

$$B = B_o[1 - \varepsilon_t \cos\Theta - \varepsilon_h \cos(l\Theta - m\Phi)]$$

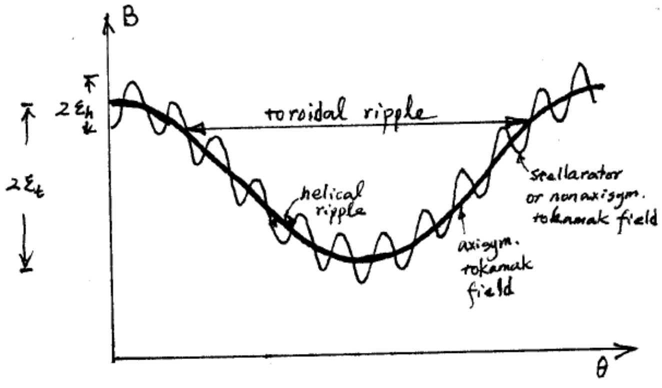
↓ ↓

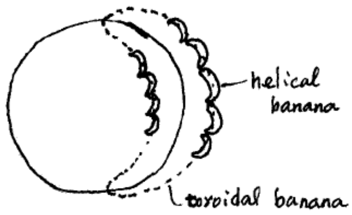
Toroidal term due to toroidal geometry ($\varepsilon_t \propto r/R$)

Nonaxisymmetric term due to helical windings

⇓ ⇓

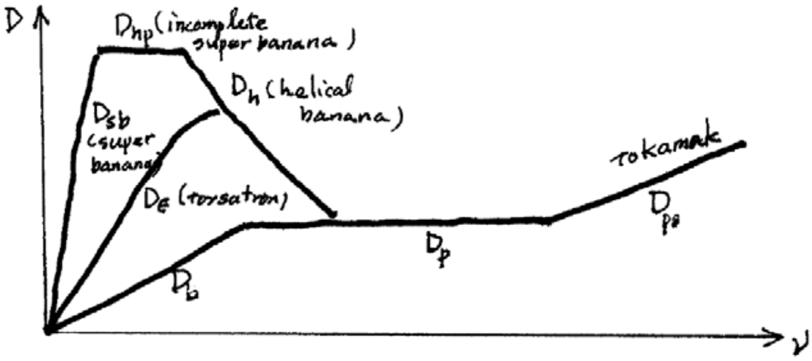
toroidal banana + helical banana = super banana



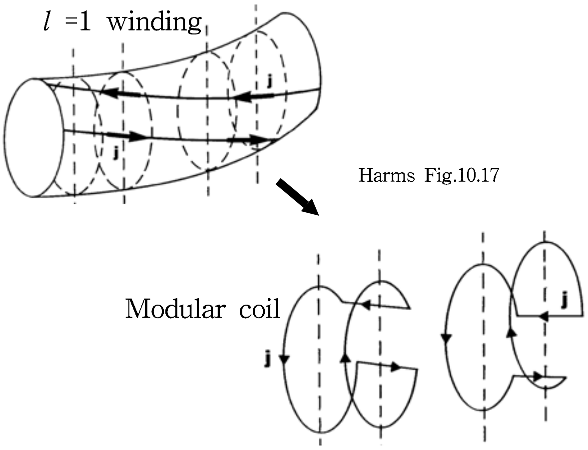


* No super banana orbits in torsatrons due to no mag. well.

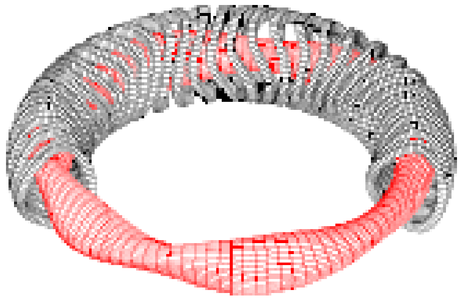
F. Neoclassical diffusion



G. *Modular design of stellarator coils* *for easy assembly & disassembly*

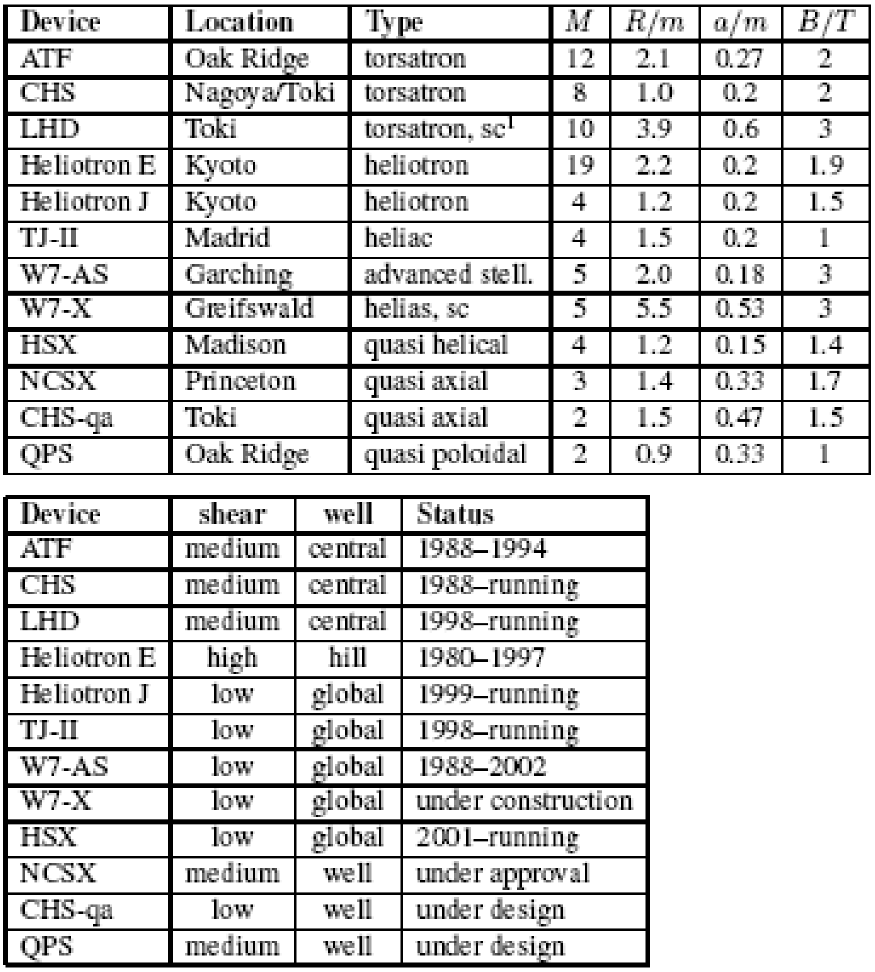


Harms Fig.10.17



Advanced modular coil (W7-X)
(R. Kleiber, MP-IPP Summer Univ. (2005), Fig. 10.4)

H. *Stellarators in the world* with plasma volume ≥ 1 m^3

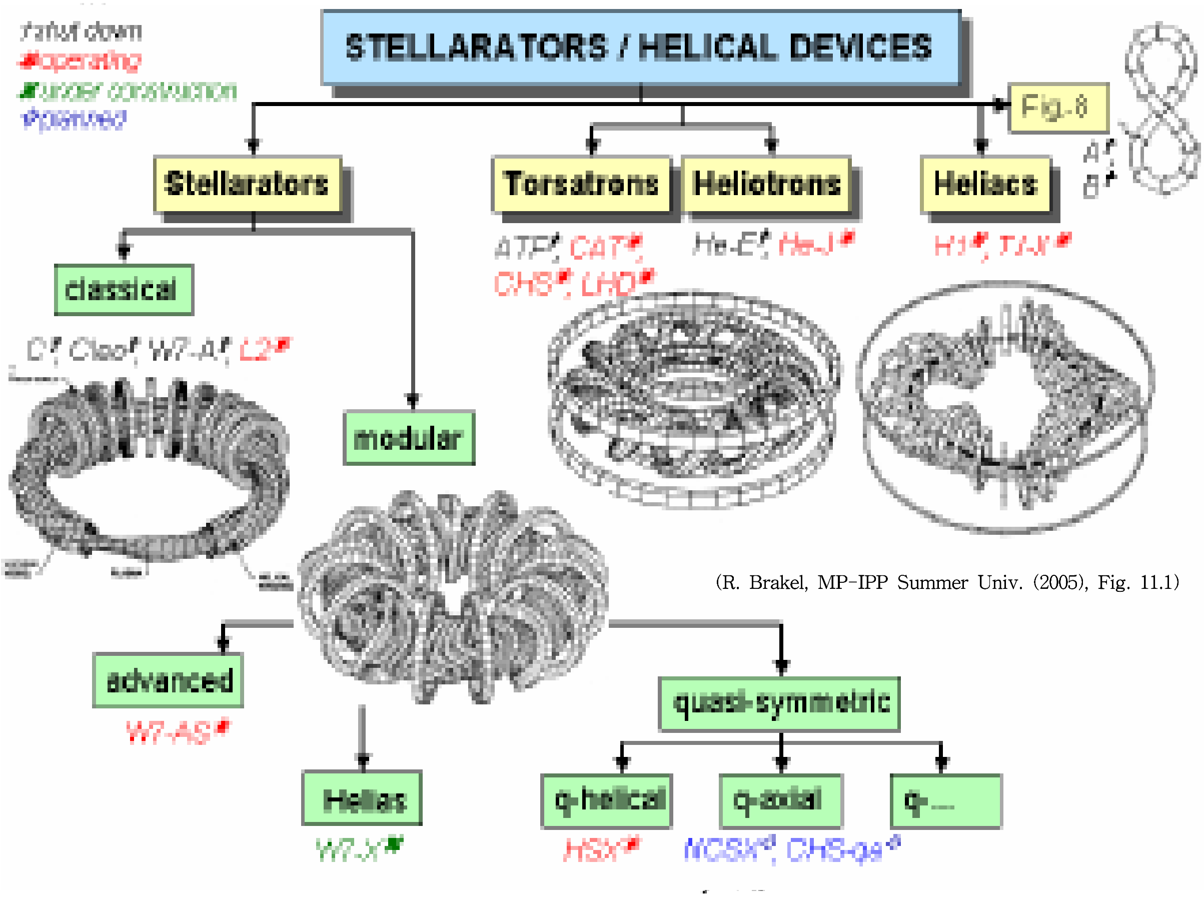


Device	Location	Type	M	R/m	a/m	B/T
ATF	Oak Ridge	torsatron	12	2.1	0.27	2
CHS	Nagoya/Toki	torsatron	8	1.0	0.2	2
LHD	Toki	torsatron, sc[1]	10	3.9	0.6	3
Heliotron E	Kyoto	heliotron	19	2.2	0.2	1.9
Heliotron J	Kyoto	heliotron	4	1.2	0.2	1.5
TJ-II	Madrid	heliac	4	1.5	0.2	1
W7-AS	Garching	advanced stell.	5	2.0	0.18	3
W7-X	Greifswald	helias, sc	5	5.5	0.53	3
HSX	Madison	quasi helical	4	1.2	0.15	1.4
NCSX	Princeton	quasi axial	3	1.4	0.33	1.7
CHS-qa	Toki	quasi axial	2	1.5	0.47	1.5
QPS	Oak Ridge	quasi poloidal	2	0.9	0.33	1

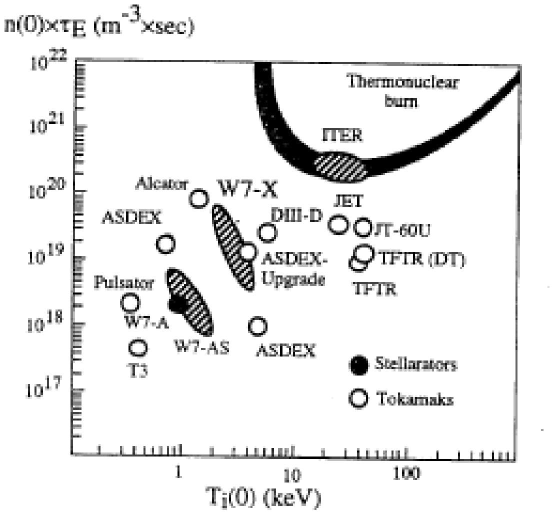
Device	shear	well	Status
ATF	medium	central	1988–1994
CHS	medium	central	1988–running
LHD	medium	central	1998–running
Heliotron E	high	hill	1980–1997
Heliotron J	low	global	1999–running
TJ-II	low	global	1998–running
W7-AS	low	global	1988–2002
W7-X	low	global	under construction
HSX	low	global	2001–running
NCSX	medium	well	under approval
CHS-qa	low	well	under design
QPS	medium	well	under design

Table 11.1: Some stellarators and helical devices (M: number of field periods, R: major radius, a: minor radius, B: maximum magnetic field) (R. Brakel, MP-IPP Summer Univ. (2005))

* heliac = helical axis



(R. Brakel, MP-IPP Summer Univ. (2005), Fig. 11.1)



$n\tau_E$ versus ion temperature for tokamaks and stellarators. Expected placing of W7-X (Courtesy of MP-IPP[23])

3. Alternate closed configurations

A. Bumpy torus

Elmo(EBT) - ORNL (EBT-1, EBT-S)

Nagoya(NBT) - Nagoya Univ. (NBT)

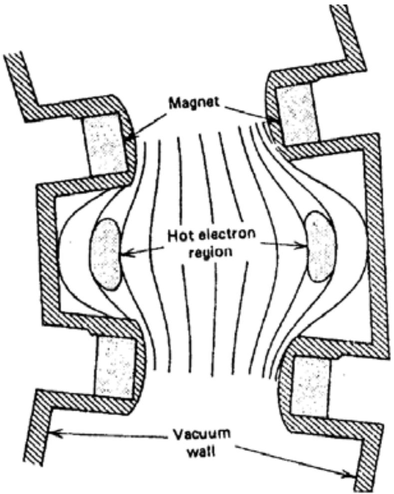
Toroidally-linked mirrors

(reduced end losses,

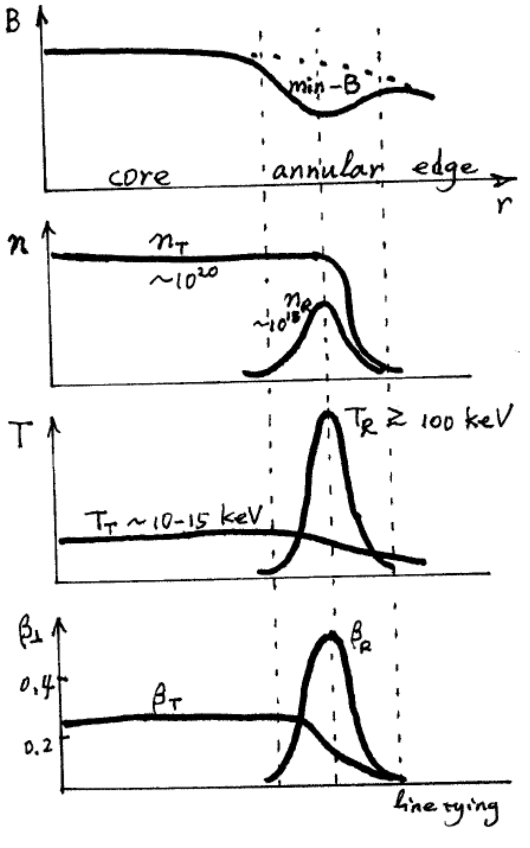
stabilizing hot ring by cooling → $\nabla p \downarrow$)

+ High-β annular hot-electron rings

(min-B) by ECRH



Stacy[4] Fig. 4.3.2



$n_R \leq 0.1 n_T$ ⇒ Stable annulus

(Stabilization of hot e by cooler toroidal core plasmas)

$\beta_T(\sim 20-30\ \%) \leq \beta_R(\geq 10-40\ \%)$

: Stable against MHD instab.

Engineering aspects :

High β → high power density, low B cost

Steady state

Large aspect ratio → simple design + maintenance

Limited experiments

*B. **RFP** (Reversed-Field Pinch)*

High β axisymmetric toroidal magnetic configuration with strongly sheared field in outer plasma region produced by reversal of $B_\phi(\sim B_\theta)$

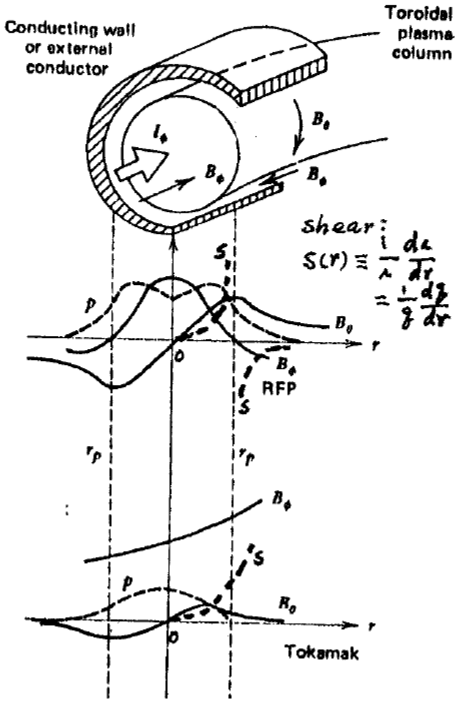
(cf) Linear Z-pinch (electrode problem)

↱ Tokamak($B_\phi \gg B_\theta$): USSR

⇒ Toroidal Z pinch (stability problem)

↳ RFP($B_\theta \sim B_\phi^{in} \swarrow\!\!\nearrow B_\phi^{out}$): UK

1) RFP configuration



Stacy[4)] Fig. 4.3.3

$$\mathbf{B} = \mathbf{B}_\theta + \mathbf{B}_\phi, \qquad B_\theta \sim B_\phi$$

↗ ↗ (short pitch)

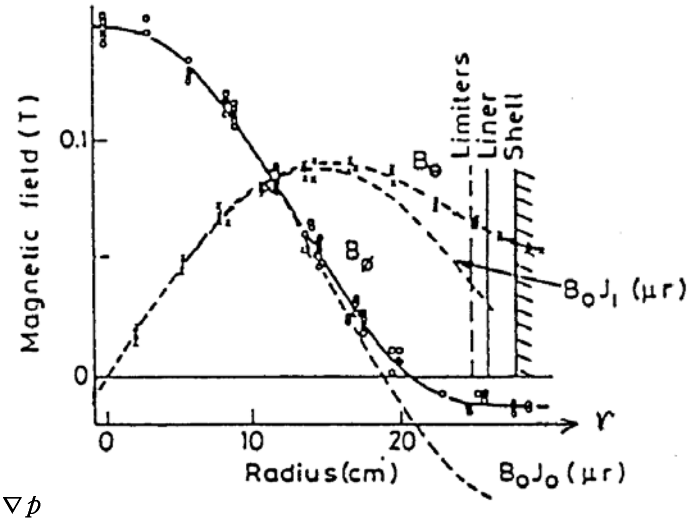
I_ϕ $\quad I_{TF} + I_\theta$

$$\iota(r) \equiv \frac{2\pi R}{r}\frac{B_\theta(r)}{B_\phi} = \frac{2\pi}{q(r)} > 1$$

$q < 1 \Rightarrow$ low $B_\phi \rightarrow \beta \approx 3-10\ \beta_{tok} \leq 0.3$

large R_0/a than in tokamak

$I_\phi \uparrow$: No K-S limit



2) RFP equilibrium

$\mathbf{j}_\perp \times \mathbf{B}$ supports ∇p : $\quad \mathbf{j}_\perp \times \mathbf{B} = \nabla p$

$\mathbf{j}_\parallel$ generates reversed B_ϕ configuration:

$\mathbf{j}_\parallel \times \mathbf{B} = \mathbf{0}$ (force-free state) $\qquad$ * Phys. Rev. Lett. **33**, 1139 (1974)

$\Rightarrow \mu_o \mathbf{j} = \nabla \times \mathbf{B} = \alpha \mathbf{B}$: Taylor minimum energy condition*

$\Rightarrow \nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = \mathbf{0}$

$\Rightarrow B_z = B_o J_o(\alpha r) \rightarrow B_\phi$: Bessel function model

$B_\theta = B_o J_1(\alpha r) \rightarrow B_\theta \qquad$ (BFM)

3) Formation of RFP configuration

a. Self-field reversal

Plasma passing in a turbulent phase during starting up

→ spontaneous production of $\boldsymbol{B_{\Phi R}}$

(tearing, m=1 → turb. E_Θ → I_Θ → $B_\Phi \uparrow$ (core) → $\exists\ B_\Phi$(out) for flux conservation)

Not fully understood

Taylor theory : Natural tendency of plasma discharge inside flux conserving wall to relax towards a min. pot. energy state if there is energy dissipation

b. Field programming

Setting up $B_{\Phi R}$ during pinch formation($\tau < \tau_{instab.}$) by programming

$\boldsymbol{j_\Theta}$ ext. winding

c. Aided self-reversal or semiprogramming

Combination of 1) & 2)

4) Features

① High-β operation (~30 %)

② OH to ignition temperature (q < 1 → $I_\Phi \uparrow$: No K-S limit)

③ Large aspect ratio (5~10) → modular design

- Min. impurity due to current free region between plasma & wall/limiter
- $B_\Theta \propto 1/r$, low $B_{\Phi R}$ at wall and coil → min. mag. stress in coils
- Pulsed operation & short burn time (1-20 s)
- MHD Stabilization & self-reversal by conducting shell
- Large energy losses during start up
- Uncertain reverse-field setting up

5) RFPs in the world with $I_{plasma} \geq 0.5\ MA$

DEVICE	Institution / Country	Geometry: R (m) / a (m)	Plasma current I_p (MA)	Pulse length (ms)	Start of Operation
MST	Univ. Wisconsin /USA	1.5/0.52	0.65	40	1988
EXTRAP-T 2	Association Euratom-NFR / Sweden	1.24/0.18	0.5	20	1994
RFX	Assoc. Euratom-ENEA-CNR / Italy	2.0/0.48	≤2	250	1991
TPE-RX	ETL / Japan	2.0/0.5	1		(1997)

C. Compact fusion reactor concepts

① Compact RFP Reactor (CRFPR) - LANL (0.75/4.3 m, 18.5 MA, 3.35 GW_{th})

② Ohmically Heated Toroidal Exp. (OHTE) - GA, Philips (0.74/5.91, 3.8 GW)

③ Spheromak - PPPL

④ Compact Tokamak Reactor-Riggatron - INESCO (0.34/0.85 m, 1.325 GW_{th})

Homework : Harms Problems 10.2, 10.7