Research on High-Beta Plasmas Based on Two-Fluids Relaxation Theory

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and

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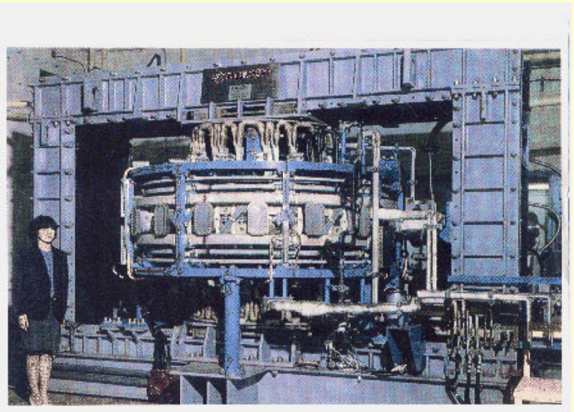
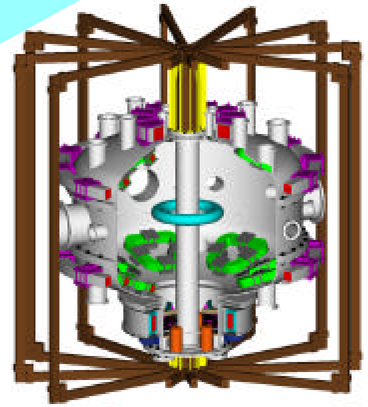
Exploration of new relaxation states for high beta plasmas

RFP → ULQ → High β



REPUTE-1

Proto-RT



S-RT

Taylor State

- Current (electron fluid)
- Low(zero) beta plasmas

Mahajan－Yoshida theory

- Two fluids (electron & ion)
- Ultra high beta plasmas

Two-fluid Relaxation Theory

S.M. Mahajan and Z. Yoshida, Phys. Rev. Lett., **81** (1998) 4863.

• Two-fluid MHD Equation

$$0 = \vec{E} + \vec{V}_e \times \vec{B} + \frac{1}{en} \nabla p_e$$

$$\frac{\partial \vec{V}_i}{\partial t} + \left(\vec{V}_i \cdot \nabla\right)\vec{V}_i = \frac{e}{M}\left(\vec{E} + \vec{V}_i \times \vec{B}\right) - \frac{1}{Mn} \nabla p_i$$

These two-fluid MHD equations are rewritten as follows;

$$\frac{\partial \vec{A}}{\partial t} = \left(\underline{\hat{V} - \nabla \times \hat{B}}\right) \times \underline{\hat{B}} + \nabla\left(\hat{p}_e - \phi\right)$$

$$\frac{\partial}{\partial t}\left(\hat{V} + \vec{A}\right) = \underline{\hat{V}} \times \left(\underline{\hat{B} + \nabla \times \hat{V}}\right) - \nabla\left(\frac{1}{2}\hat{V}^2 + \hat{p}_i + \phi\right)$$

• MHD Relaxation Equilibrium

$$\hat{B} = a\left(\hat{V} - \nabla \times \hat{B}\right) \qquad \hat{B} + \nabla \times \hat{V} = b\hat{V}$$

• Beltrami/Bernoulli Condition

$$\hat{p}_e - \phi = const. \qquad \frac{1}{2}\hat{V}^2 + \hat{p}_i + \phi = const.$$

$$\boxed{\hat{V}^2 + \beta = const.}$$

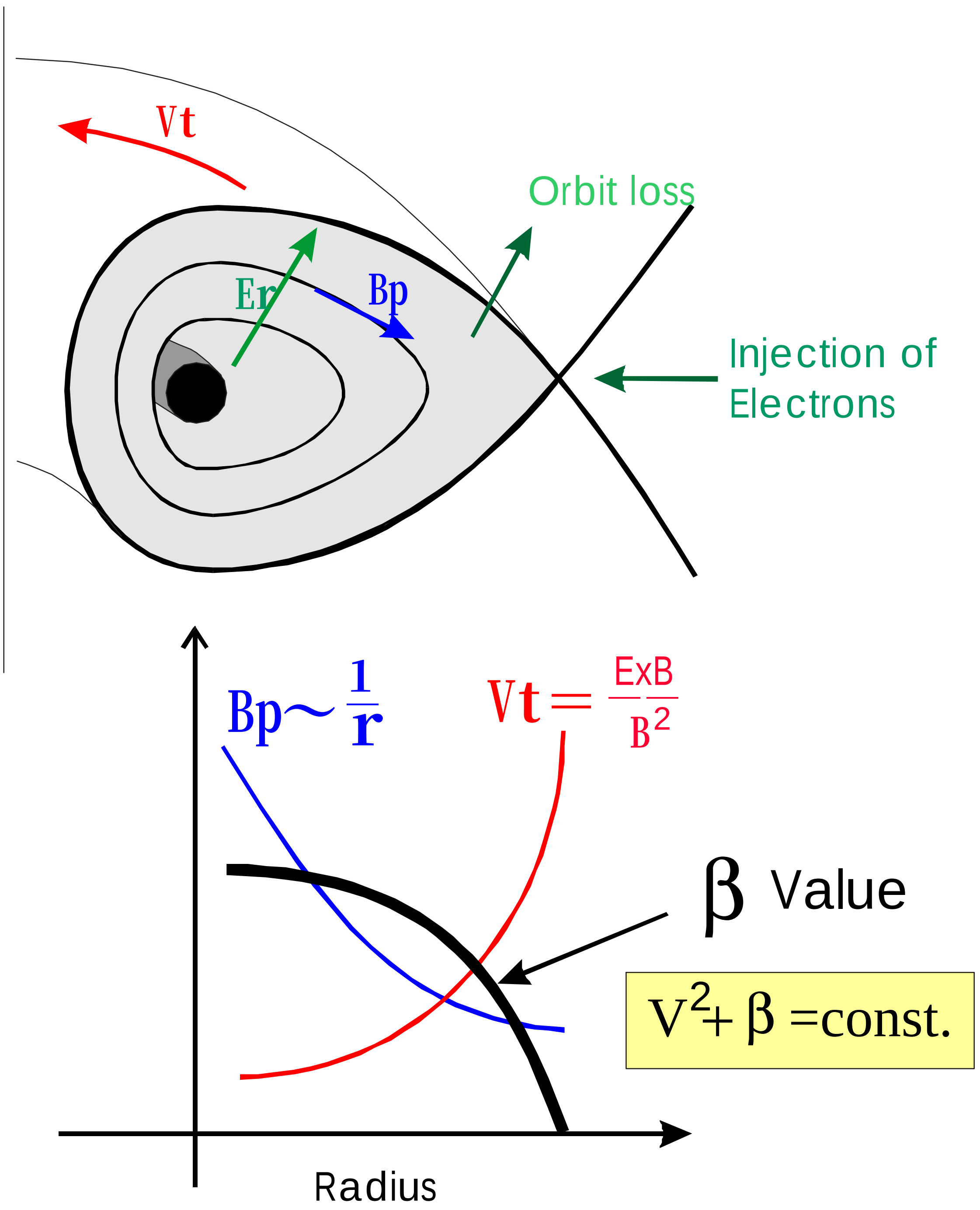
Concept for Confining a New High Beta Plasma

@ Internal Ring Device

* toroidal flow velocity : Vt = Er/Bp
(Er ~ const. , Bp ~1/r)

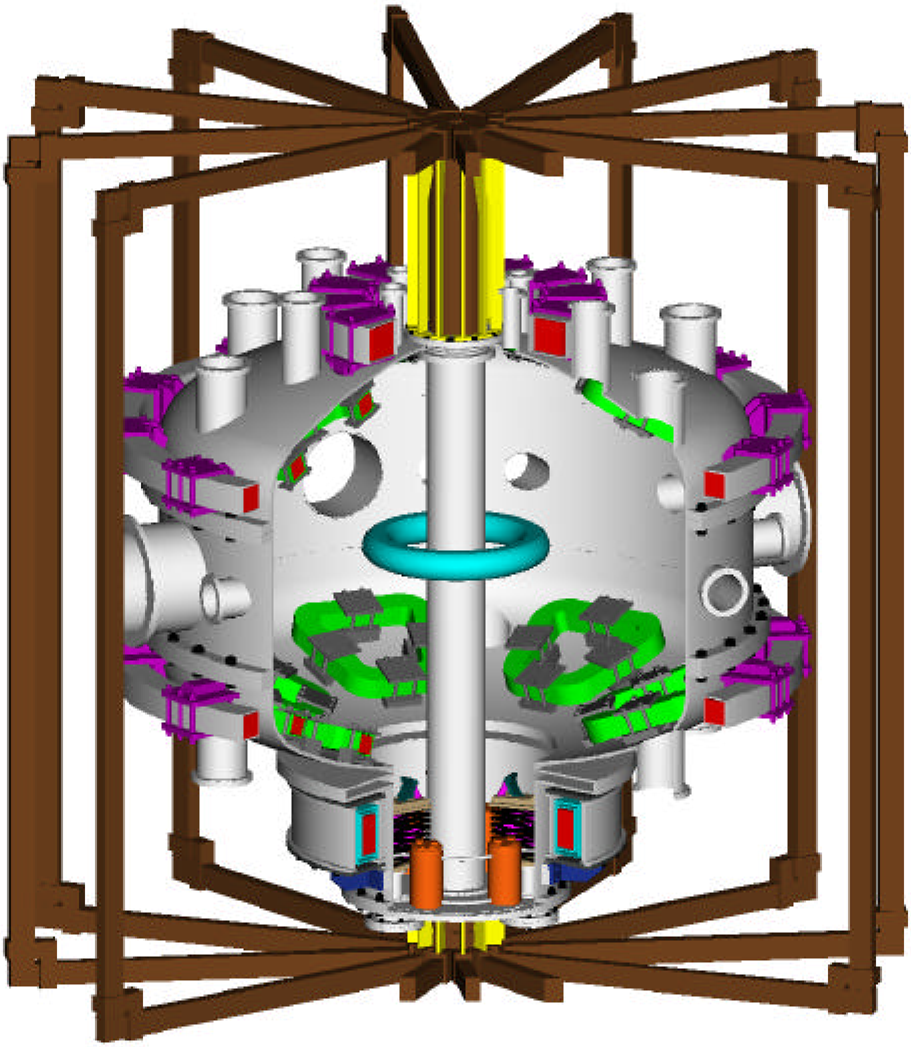
@ Non-neutralized Plasma

* Injection of electrons through separatrix
* Orbit loss of high energy electrons

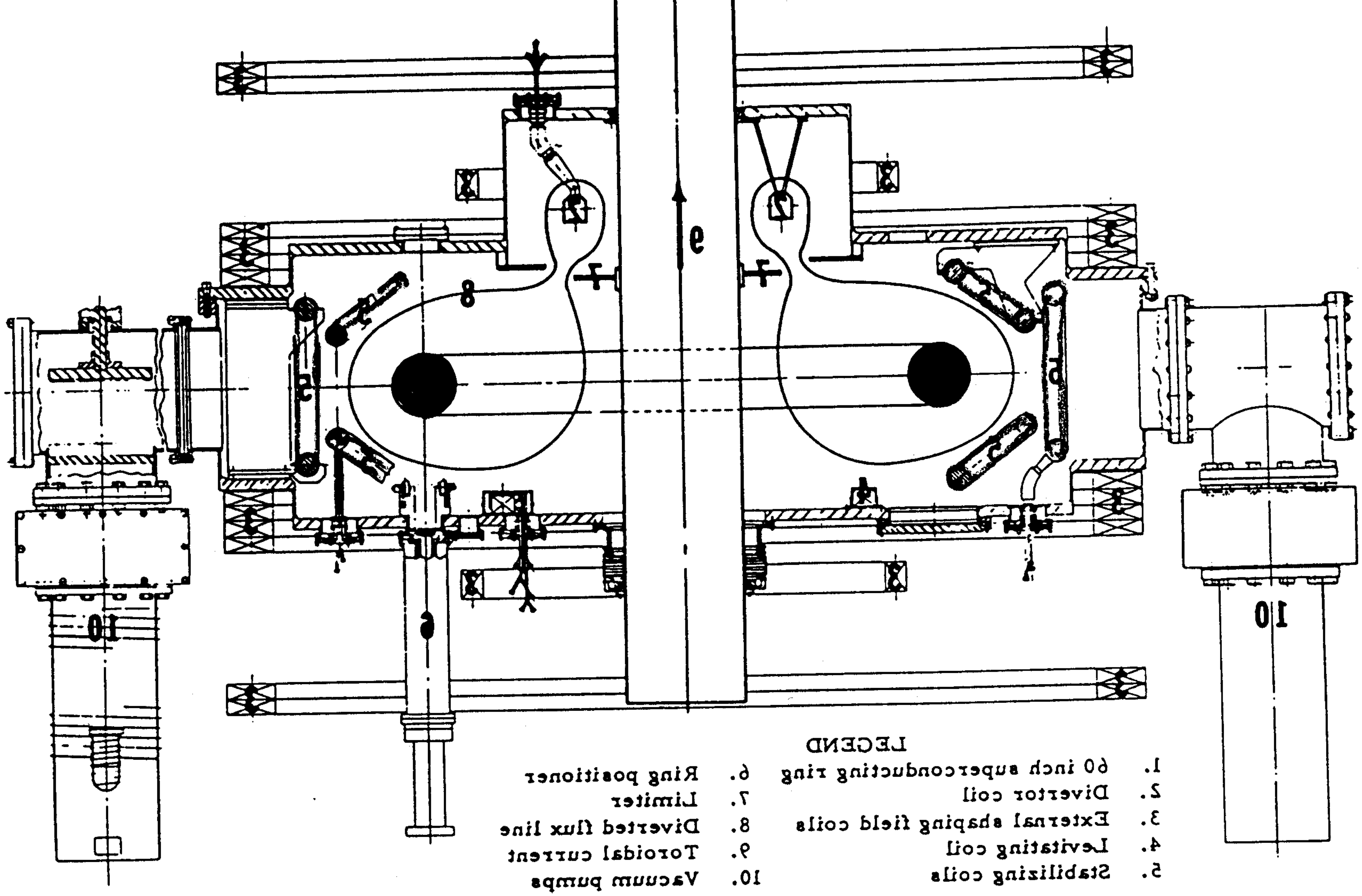


A Bird's-eye view of an internal coil device with an superconductor floating coil

(Superconductor Ring Trap : S-RT)



FM-1 Spherator



LEGEND

1. 60 inch superconducting ring
2. Divertor coil
3. External shaping field coils
4. Levitating coil
5. Stabilizing coils
6. Ring positioner
7. Limiter
8. Diverted flux line
9. Toroidal current
10. Vacuum pumps

FIG.18. Cross-sectional view of FM-1 spherator. The superconducting ring is levitated magnetically by a levitating coil and mechanically stabilized by 5 sets of asymmetric stabilizing coils by feedback. The divertor is also provided.

LDX Base Case Configuration

(Levitated Dipole EXperiment)

LDX - Base Case Parameters

Compression Ratio:	512
Adiabatic Pressure Ratio:	32,768
Minimum B at Ring:	0.24 T
Maximum B at Ring:	3.95 T

Linear Ring Stability:

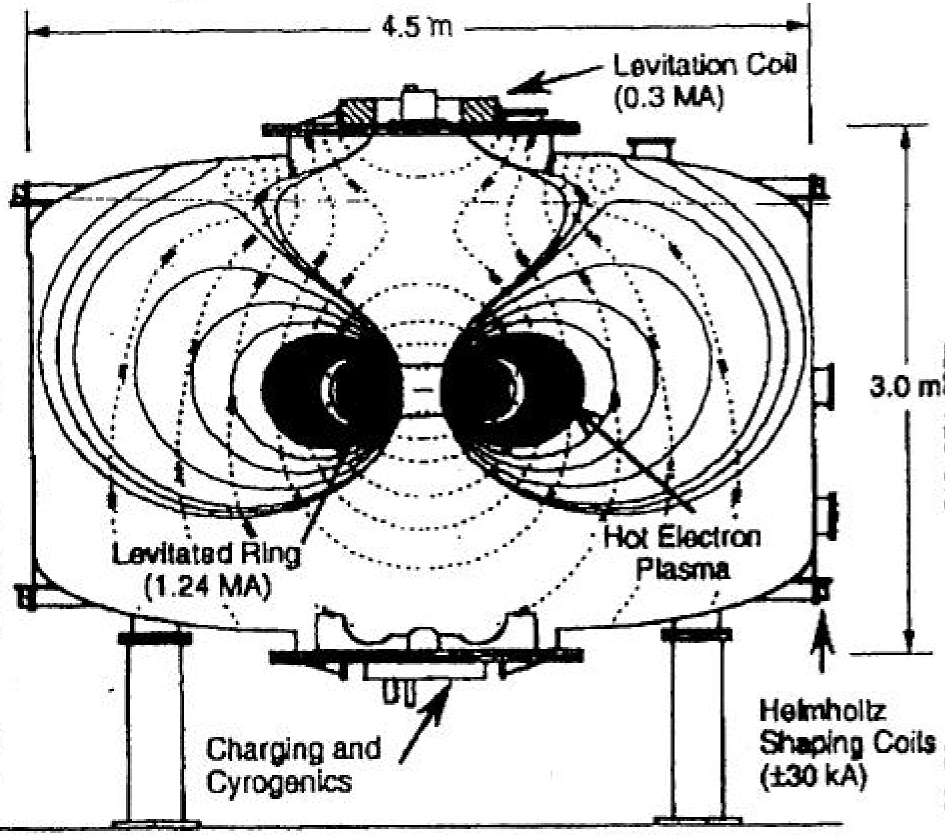
Axial Growth Rate:	5 1/s
Horizontal Wobble:	0.5 Hz
Tilt Wobble:	1.6 Hz

Hot Electron Parameters:

Hot Electron Temp:	250 keV
Peak Density :	1-5 E11 /cm3
Outer Field Strength:	1.7 kG
Hot Electron Beta:	>20%

Plasma Parameters:

Peak Density :	> 1 E13 1/cm3
Plasma Beta	> 10%



by. M. Mauel in Columbia Univ.
& J. Kesner in MIT

Basic research for fusion plasmas
– with internal ring devices –

In the past (~ 1970)

Multipole
Levitron
Spherator

→

Confinement
Min-B
Magnetic shear

Contemporary Research

Relaxation physics in fusion plasmas
(high beta configurations)

- **Two-fluids (electron and ion) relaxation**
  (ref. S.M. Mahajan and Z. Yoshida, Phys. Rev. Lett., 81 (1998) 4863.)

  ーー>S-RT(Superconducting-Ring Trap)：the Univ. of Tokyo

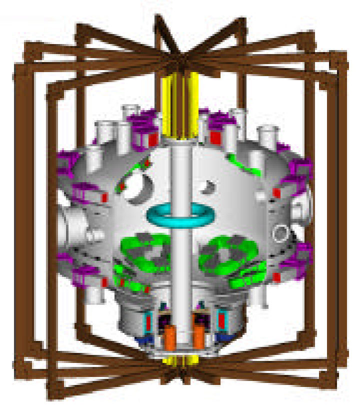
- **Kinetic relaxation under μ and J conservation**
  (ref. A. Hasegawa, et al., Nucl. Fusion, 30 (1990) 2405.)

  ーー>LDX（Levitated Dipole Experiment)：MIT/Columbia

Research on Two-fluid Relaxation

With an Internal Ring Device,
exploring a new high beta plasma

S-RT

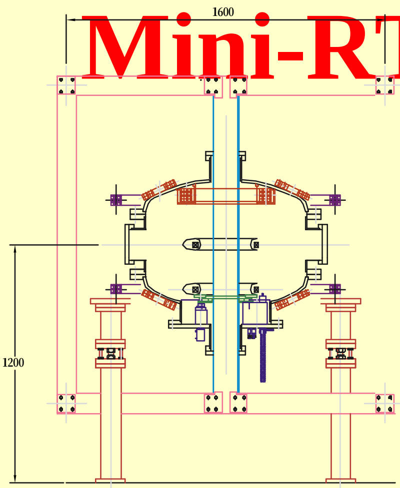


- PoP Experiment
- Floating Ring Coil
- **Rc=40cm,Ic=500kAT**
- (Proposal)

Proto-RT

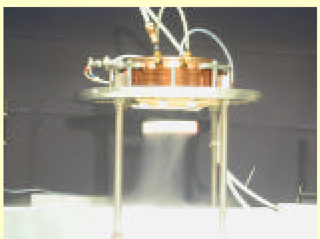
- Normal conductor Coil
- **Rc=30cm,Ic=10kAT**
- Operating for high beta study

Mini-RT

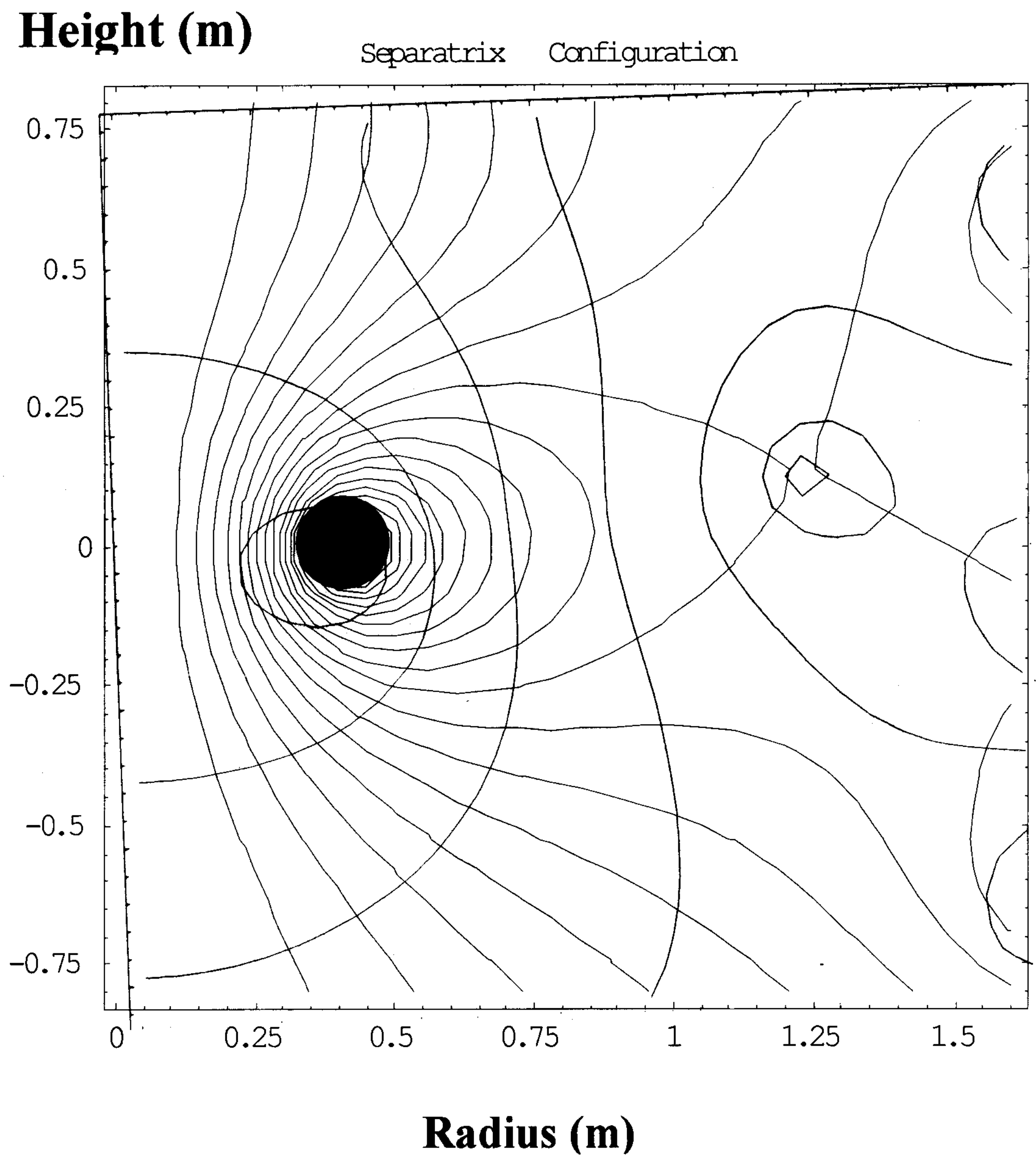


- High Tc Floating Coil
- **Rc=15cm,Ic=50kAT**
- Under Construction

FB-RT



- Feedback Study
- High Tc coil
- **Rc=4cm,Ic=2.6kAT**



Height (m)
Separatrix Configuration
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
0
0.25
0.5
0.75
1
1.25
1.5
Radius (m)

Expected Plasma Parameters in the S-RT Device

@ Radial Electric Field E_r

$$\left(\frac{V_p}{V_A}\right)^2 + b = const. \qquad \text{and} \qquad V_P = \frac{\vec{E}\times\vec{B}}{B^2}$$

$$\therefore \quad E_r(V/m) = \frac{B^2}{\sqrt{m_0 n_i m_i}}\sqrt{b}$$

@ Plasma non-neutrality

$$\nabla\cdot\vec{E} = \frac{e\Delta n}{e_0} \qquad \therefore \quad \Delta n = \frac{e_0}{e}\frac{E}{a}$$

@ Plasma parameters

β(%)	Density Temperature	Radial Electric Field : *Er*	Non-neutrality $\Delta n/n$
100 %	$n = 10^{18}$ m^{-3} T = 12 keV	220 kV/m	2.4X **10**$^{-5}$
100 %	$n = 10^{19}$ m^{-3} T = 1.2 keV	69 kV/m	0.08X **10**$^{-5}$
10 %	$n = 10^{18}$ m^{-3} T = 1.2 keV	69 kV/m	0.76X **10**$^{-5}$

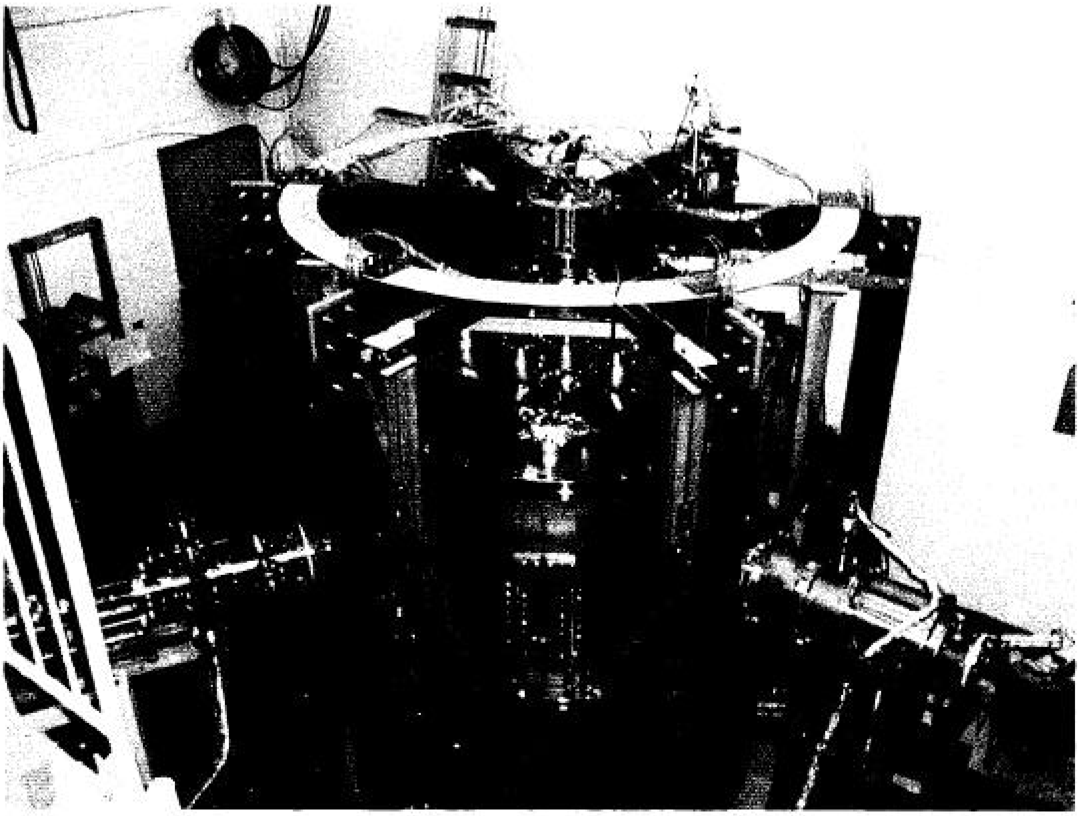
(at Bp = 0.1 T and a = 0.5 m)

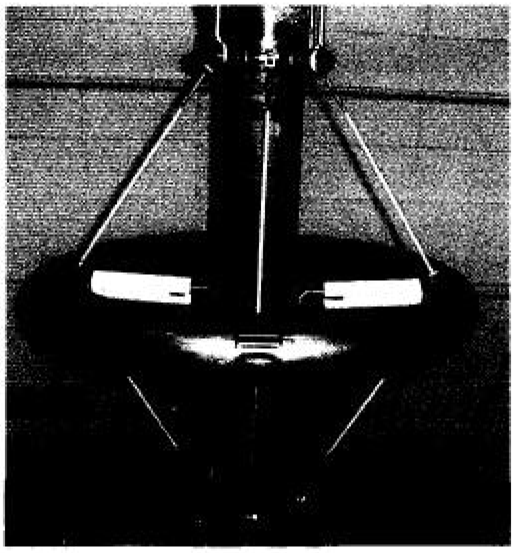
@ Energy confinement time
required for above-mentioned plasma parameters

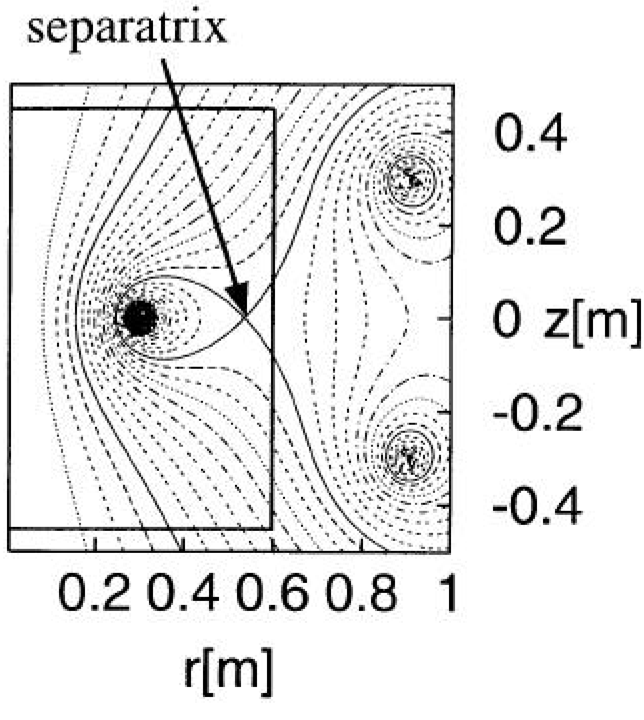
$$P = \frac{W_p}{t_E}$$

$$\therefore \quad t_E = 120\ m\sec \quad \text{at} \quad b = 100\%, \quad P = 100kW$$

Proto-RT Device

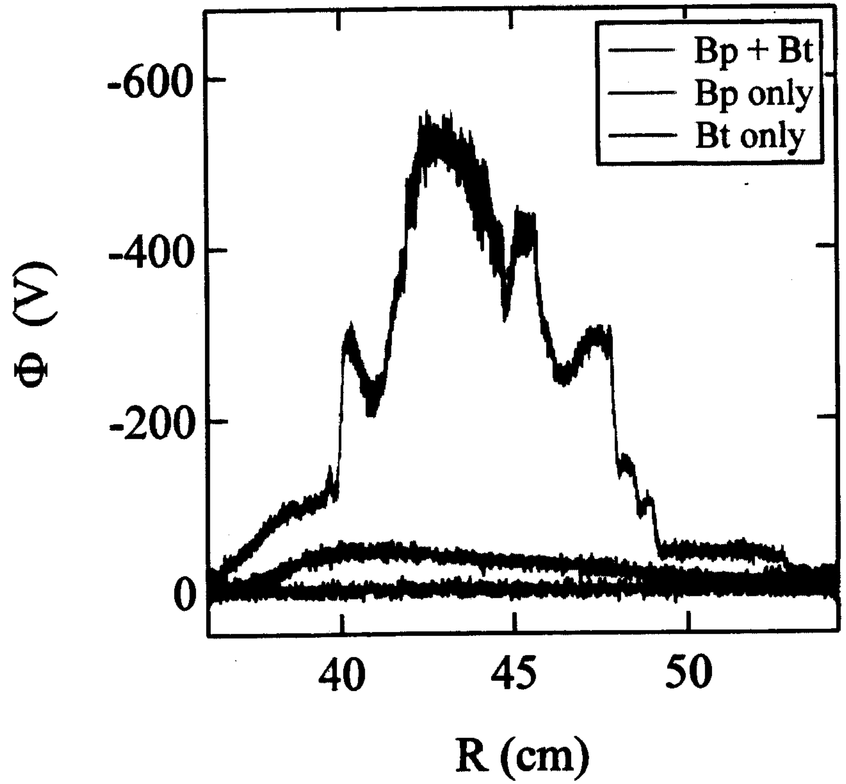




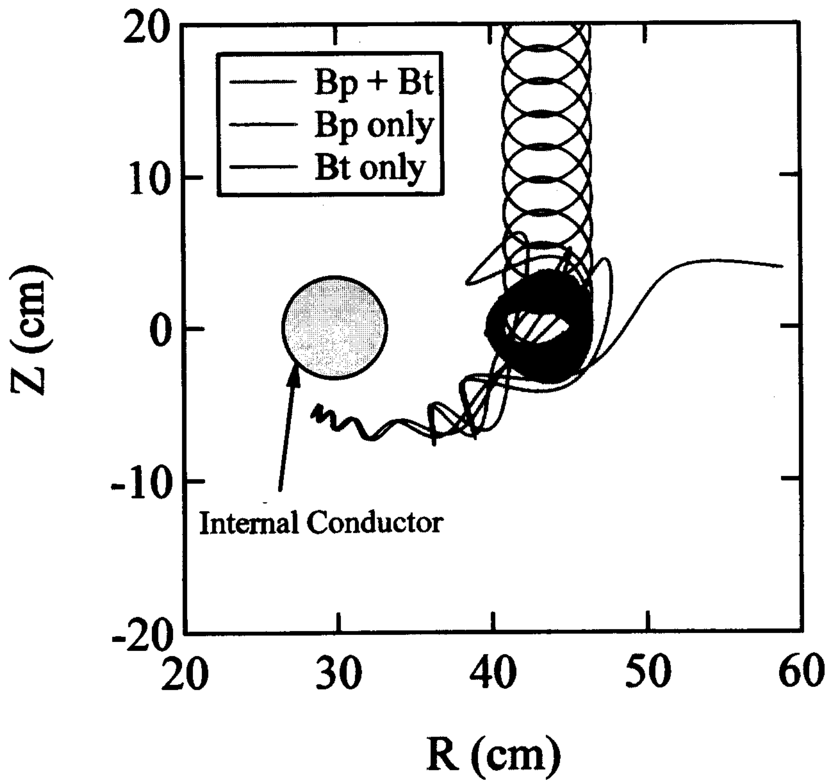


6The shape of Φ profile of pure electron plasmas seems to depend on the orbits of electrons injected from the e-gun

a) Measured radial profiles of the electrostatic potential Φ for three different B-configs.

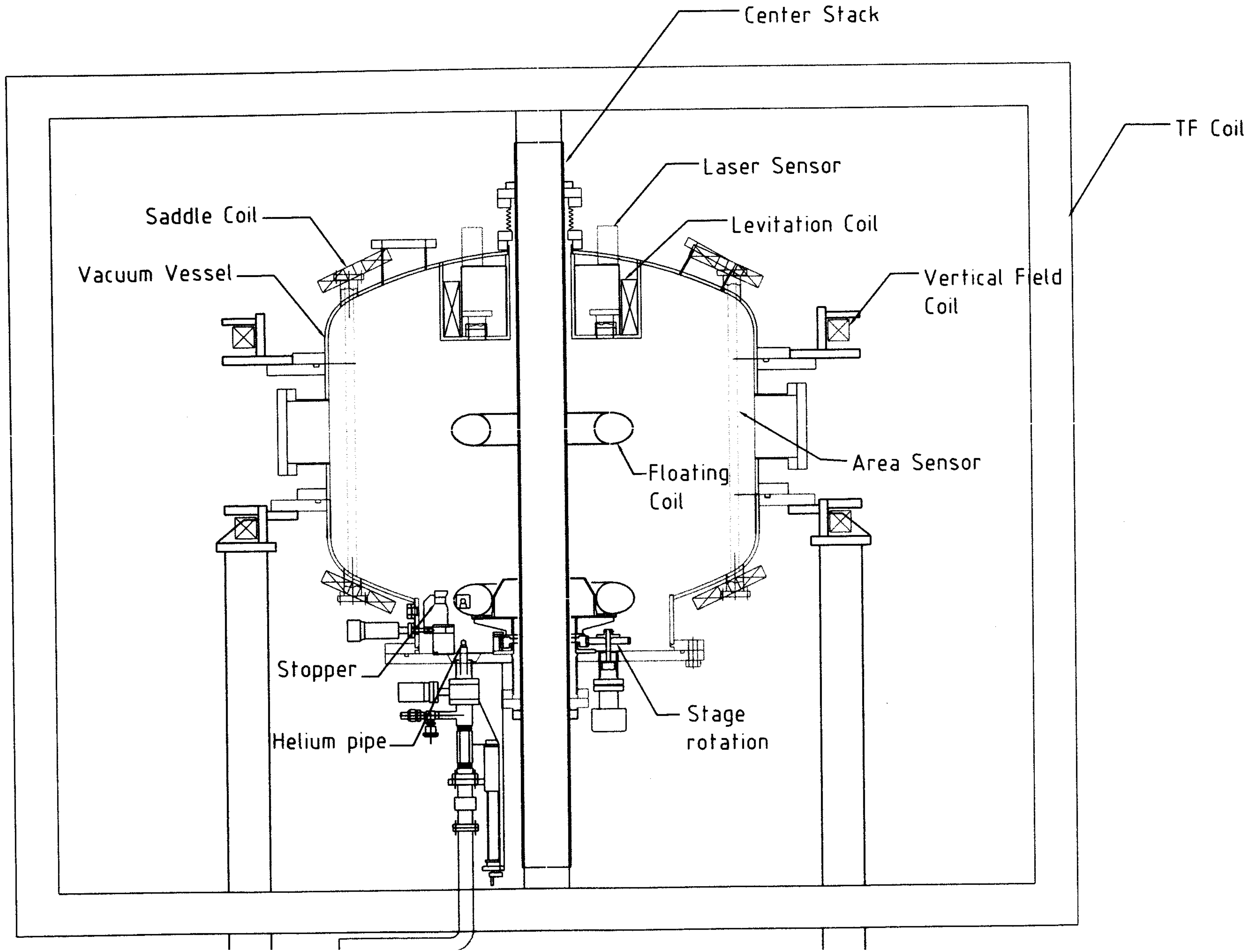


b) Electron orbit trajectories calculated in the same B-configs. as left.



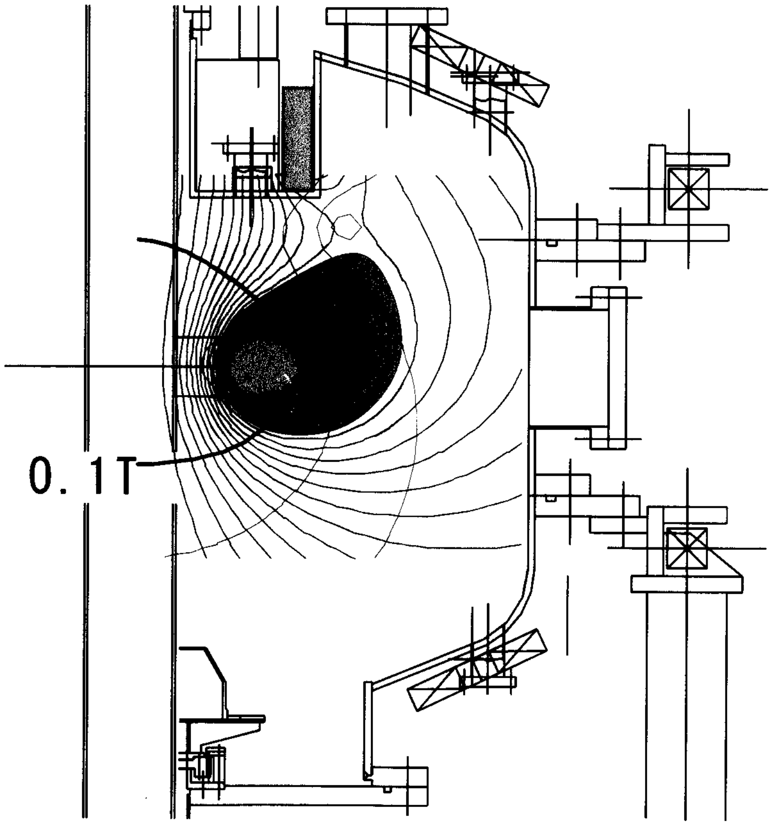
Data indicate that in the X-point configuration, the pitch angle of electrons against the magnetic fields is quite important to confine the electrons inside the separatrix.

Mini-RT Device



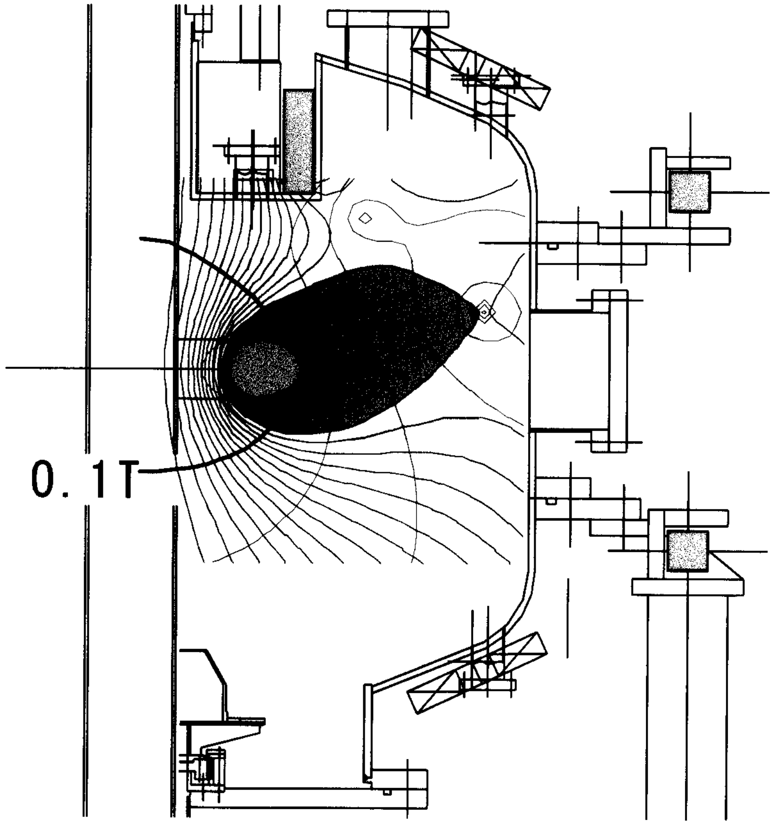
Mini-RT磁場配位

ダイポール配位



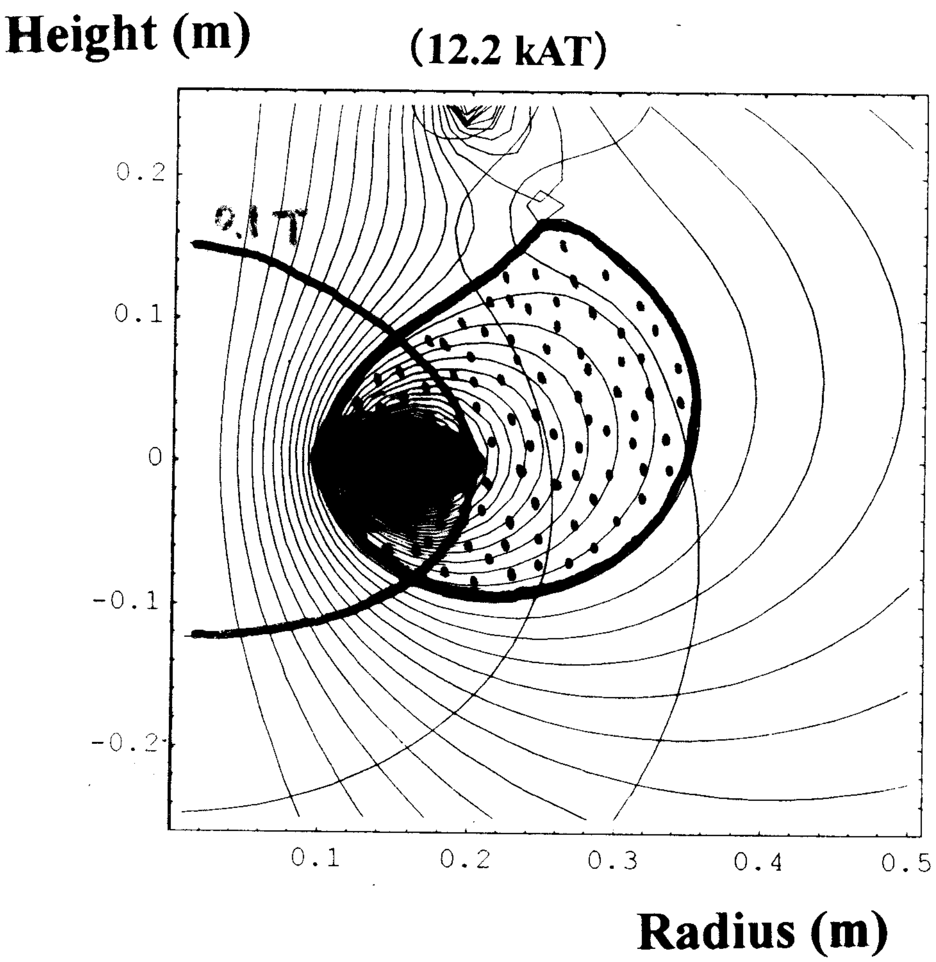
I_F=50kAT, I_L=15kAT, I_V=0kAT

セパラトリクス配位



I_F=50kAT, I_L=15kAT, I_V=3kAT

Plasma Characteristics of a Mini-RT device



@ The high density neutral plasma will be produced by 2.45 GHz ECH ($B_{resonance} = 0.0875$ T)

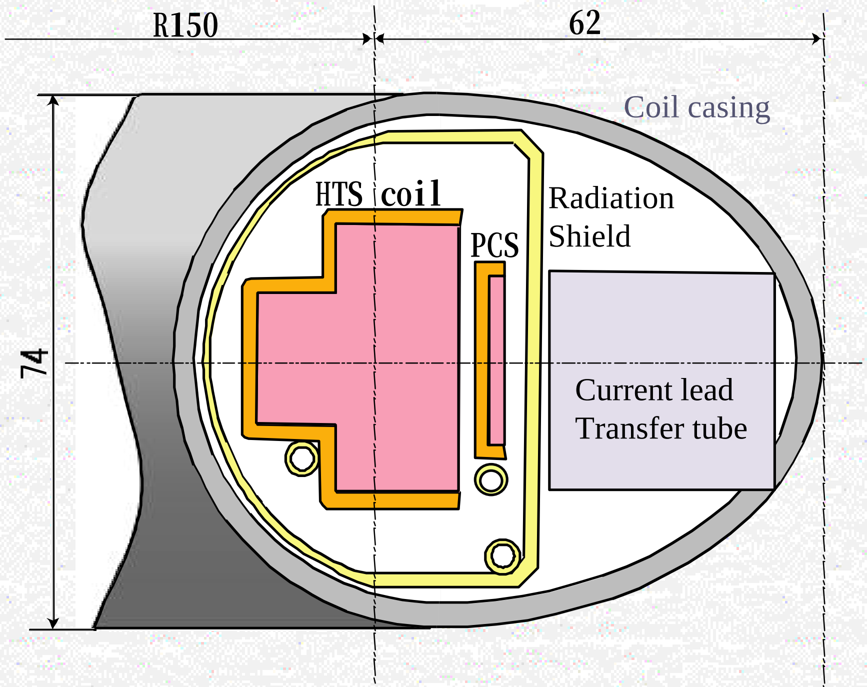
@ A non-neutral plasma (i.e., radial electric field) will be produced through several methods;

- Injection of electrons through the separatrix
- Orbit loss of high energy electrons produced by 2.45 GHz ECH
- Direct insertion of the electrode into the plasma

Characteristics of Mini-RT

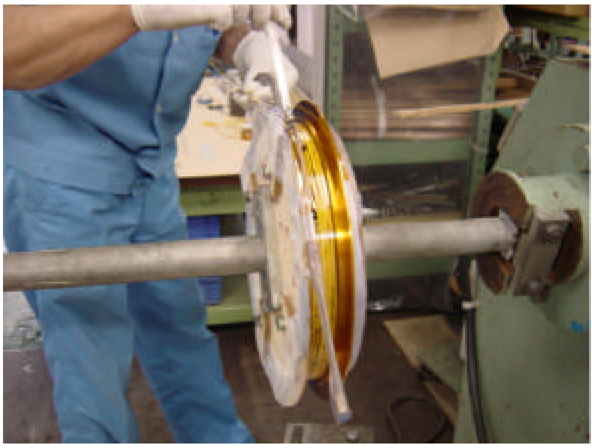
- High Tc Superconductor (HTS) Floating Coil
  - Advantages
    - High operation temperature：20 K - 40 K
    - High heat capacity yields a long time operation
    - No liquid helium : small refrigerator, easy maintenance
  - Disadvantages
    - Critical current density is not so large.
    - Decay of permanent current due to a flow resistance
- Persistent Current Switch (PCS) by HTS
  - No induction coil
  - Current lead with less heat input
- Removable current lead
- Removable transfer tube

Specification of a floating coil



Major/minor radii	150 mm / 28 mm
Total coil current	50 kA
HTS tape	BSCCO-2223
Operation current	115 A
Operation temperature	20 K – 40 K
Critical current, 77K s. f.	108 A
Stored energy	600 J
Inductance	0.09 H
Max. magnetic field	Bx:0.57 T, By:0.75 T
Total weight	20 kg
Current decay time	174hr (20 K)

Fabrication of the HTS coil for the Mini-RT device



Winding of the HTS coil

Ag-sheathed Bi-2223 tape
(4.3 mm × 0.26 mm)
I(coil) = 117 A
I(total) = 50 kAturns

Persistent Current Switch

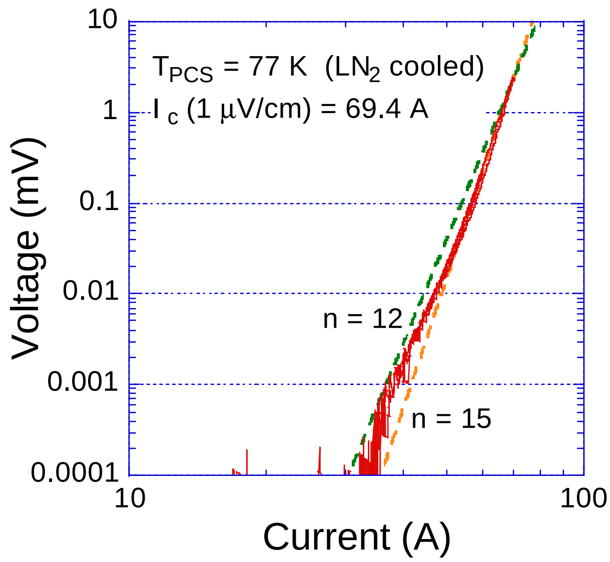
Ag-sheathed Bi-2223 tape
with 0.3wt% Mn
R_{Ω}(turn off) = 0.27 Ω

the Floating Coil (mock-up)

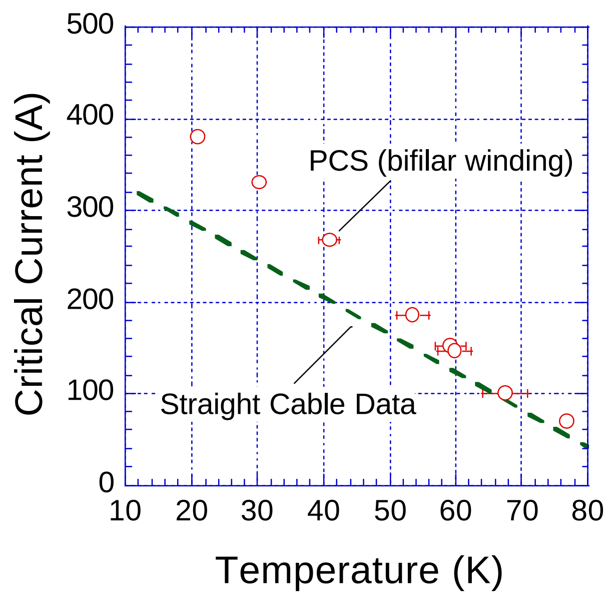
R = 15 cm
Weight = 20 kg

Development of the Persistent Current Switch (PCS)

Cable Type	(Ag-0.3wt%Mn sheathed) Bi-2223
Cable Width / Thickness	3.8 / 0.26 mm
Silver Ratio	1.9
Winding Method	Bifilar
Cable Length	21.24 m
Critical Current (77K, self-field)	53 A
Turn-off Resistance	0.27 Ω
Heater	ϕ0.5 mm Manganin

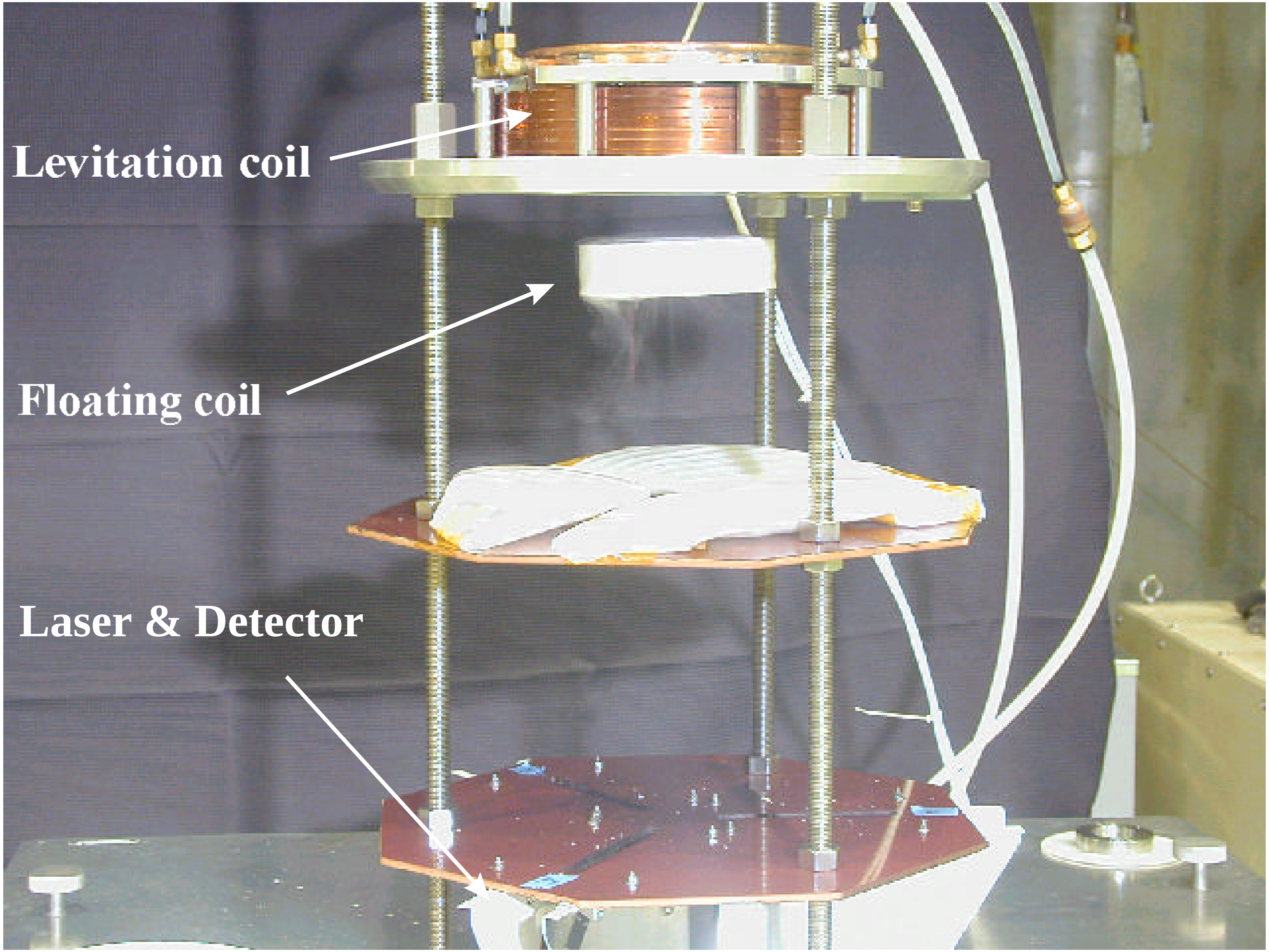


Voltage vs. current curve measured for the HTS-PCS cooled by liquid nitrogen. Two curves determined by the *n*-value of 12 and 15 are indicated by dashed lines.



Dependence of the measured critical current on the PCS temperature. Critical current for a straight sample is deduced for the present conductor based on the empirical scaling.

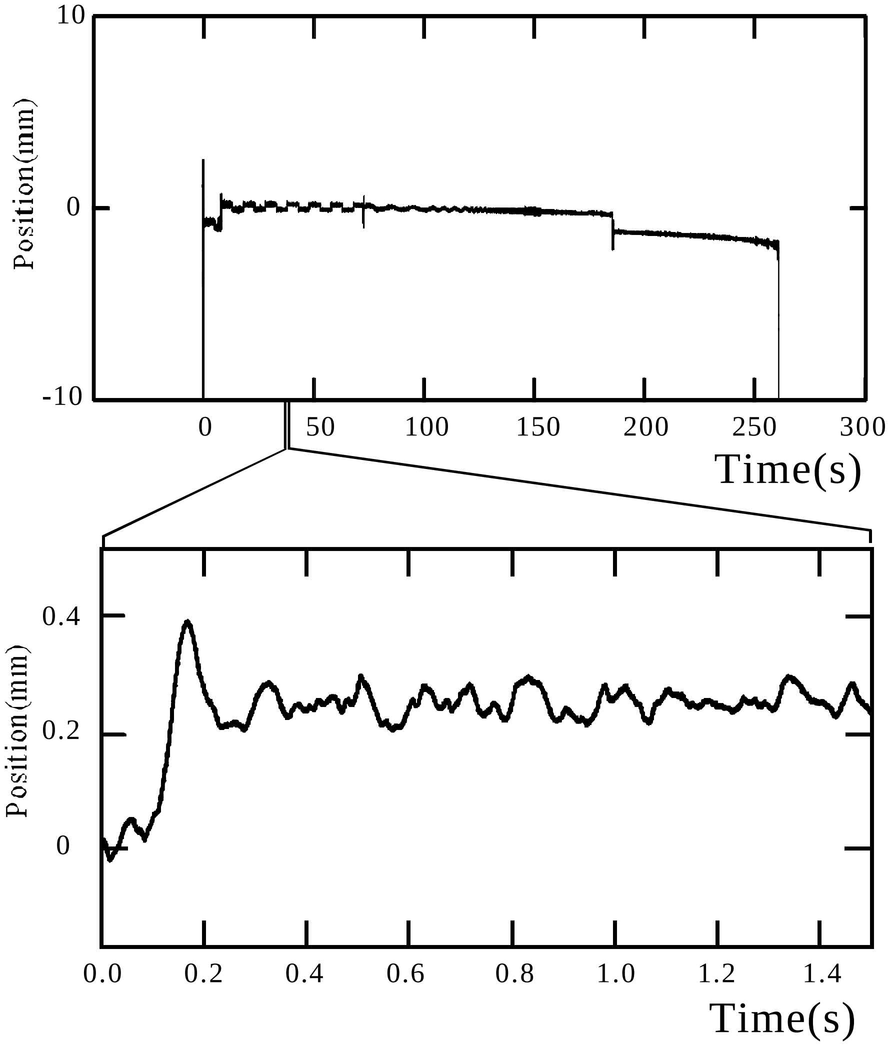
Levitation Experiment of HTS coil



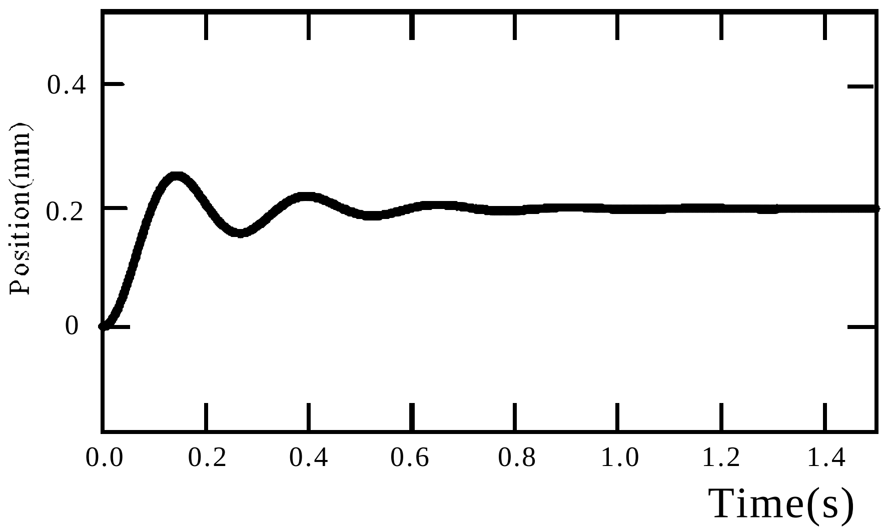
Levitation of a HTS coil

(The coil position is artificially changed, so as to examine the dynamic response of the HTS coil.
The levitation more than 4 minutes has been demonstrated.)

(a)Experimental Data



(b)Calculation Result



Summary

@ A new relaxation state based on two-fluids plasma theory has been proposed by Mahajan-Yoshida, and a possibility for confining high-beta plasmas has been pointed out.

@ To explore this new relaxation state experimentally, a toroidal device with an internal coil is suitable, where the strong plasma flow in the toroidal direction is induced by $\boldsymbol{E}\times\boldsymbol{B}$ drift by introducing a radial electric field. Since the $\boldsymbol{E}\times\boldsymbol{B}$ flow velocity increases as the minor radius is increased, the high-beta plasma could be confined at the core region.

@ A torus device with a floating superconductor coil, called S-RT, is proposed, and the engineering design and expected plasma parameters are discussed.

@ A device with a normal conductor, called Proto-RT, has been constructed, and the build-up of plasma potential up to ~ 1 keV has been achieved.

@ A small-scale torus device with a high temperature superconductor (HTS) coil, called Mini-RT, are under construction. This is a first challenge to explore a feasibility of HTS coils for fusion plasma devices.

@ Persistent Current Switch (PCS) with the HTS tape has been developed for the Mini-RT device. A miniature HTS coil have been successfully levitated within an accuracy of 20~30 micrometers.