MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO DE PESQUISAS ESPACIAIS

BR8818547

8. Title — INPE-4241-PRE/1116

DESIGN, CONSTRUCTION AND OPERATION OF A SMALL RFP FOR TURBULENT PLASMA STUDIES

9. Authorship

Y. Aso
R.M.O. Galvão
M. Ueda

Responsible author Yoshiyuki Aso

1. Publication Nº
INPE-4241-PRE/1116

2. Version

3. Date
July, 1987

5. Distribution
☐ Internal ☒ External
☐ Restricted

4. Origin: LAP
Program: PMAG

6. Key words - selected by the author(s)
REVERSED FIELD PINCH
RFP
CECI
TURBULENT PLASMA
DYNAMO EFFECT
SELF-REVERSAL

7. U.D.C.: 533.9

8. Title INPE-4241-PRE/1116

DESIGN, CONSTRUCTION AND OPERATION OF A SMALL RFP FOR TURBULENT PLASMA STUDIES

10. Nº of pages: 12

11. Last page: 11

12. Revised by
Gerson Otto Ludwig

13. Authorized by
Marco Antonio Raupp
Director General

9. Authorship
Y. Aso
R.M.O. Galvão
M. Ueda

Responsible author

14. Abstract/Notes

A small RFP (Reversed Field Pinch) apparatus for turbulent plasma studies, which is called CECI (Configuração de Estrição a Campo Inverso), is described. The apparatus has a major radius of 12cm and a minor radius of 4.2cm. First plasma experiments are scheduled to start in October 1987.

15. Remarks

To be presented in the "Energy Independence Conference: Fusion Energy and Plasma Physics", August 17-21, 1987, Rio de Janeiro, Brazil.

DESIGN, CONSTRUCTION AND OPERATION OF A SMALL RFP FOR TURBULENT PLASMA STUDIES

Y. Aso, R.M.O. Galvão, and M. Ueda
Laboratório Associado de Plasmas
Instituto de Pesquisas Espaciais - INPE
12225 - São José dos Campos, SP, Brazil

ABSTRACT

A small RFP (Reversed Field Pinch) apparatus for turbulent plasma studies, which is called CECI (Configuração de Estrição a Campo Inverso), is described. The apparatus has a major radius of 12cm and a minor radius of 4.2cm. First plasma experiments are scheduled to start in October 1987.

1 - INTRODUCTION

A Reversed Field Pinch (RFP) plasma has the unique feature that a stable magnetic configuration is formed from a turbulent state through a relaxation process. The initial turbulent state is produced by a large plasma current along the lines of force of the toroidal magnetic field inside the flux conserver, forming a configuration which is highly unstable to magnetohydrodynamic (MHD) modes. After a few ten Alfvén transit times, the plasma relaxes to a stable state. This final state is the minimum energy state pointed out by J.B. Taylor[1], which corresponds to the condition of a force-free magnetic configuration, i.e.:

$$\nabla \times \vec{B} = \lambda \vec{B} \ , \qquad (1)$$

where λ is a single constant having the same value on all field lines. If we use a cylindrical coordinate system (r, θ, z), the solution of equation (1) is given by the Bessel-function as follows:

$$B_\phi(r) = B_0 J_0(\lambda r) \; , \qquad B_\theta(r) = B_0 J_1(\lambda r) \; , \tag{2}$$

where B_ϕ and B_θ are toroidal and poloidal fields, respectively, and B_0 is the toroidal field on the minor axis. Figure 1 shows these field distributions. From Fig. 1, it is found that when $\lambda r > 2.4$ the toroidal field reverses. The reversal of toroidal field may be related to the pinch parameter θ which is defined by

$$\theta = \frac{B_\theta(b)}{\overline{B}_\phi} \; ,$$

where $\overline{B}_\phi$ is the mean toroidal field and $B_\theta(b)$ is the poloidal field at the wall. From the Bessel-function model (BFM) described above, the relation between λ and θ is given by $\lambda r = 2\theta$. On the other hand, the reversal ratio (F) of the toroidal field is defined by $F = B_\phi(b)/\overline{B}_\phi$. Using this ratio, the RFP configuration can be characterized on the F-θ diagram as shown in Fig. 2. It is clear f.om the figure that when $\theta > 1.2$ in BFM, which corresponds to the above relation $\lambda r > 2.4$, the RFP configuration can be obtained. Here, it may be mentioned that the F-θ diagram is also useful to show that RFP can be classified under the same category as the plasma confinement systems of Tokamak and Spheromak. However, the distinctive feature of the RFP configuration is the reversal of the toroidal field inside the flux conserver, which means that a toroidal field is generated within the plasma itself; this process is called the dynamo effect.

Some mechanisms have been proposed for the dynamo effect[2]; for example, a solenoidal current model based on a large-amplitude $m = 1$ helical kink instability, a model of magnetic reconnection by the $m = 1$ internal helical kink instability, MHD turbulence model and so on. The last MHD turbulence model includes two mechanisms: one is the production of an electric field along the poloidal magnetic field caused by the turbulent plasma flow. The presence of this electric field causes a poloidal current to flow which drives the reversal of the toroidal field. This effect is known as the α-effect. The other mechanism, known as the β-effect, is the enhancement of plasma resistivity by MHD turbulence which accelerates the relaxation process to the minimum energy state. In addition to the above mechanisms, nonlinearly driven reconnection model[3] was also recently proposed.

For these theoretical models, the experimental evidence is insufficient. Our experiment was proposed to study the mechanisms that are relevant to explain the self-reversal of the toroidal field.

2-EXPERIMENTAL OBJECTIVES

Recently, as Table I clearly shows, RFP experiments are being actively carried out, because its possibility as an alternative to Tokamak for being a fusion reactor has been boosted by the achievement of high electron temperature[4]. Consequently, most of these experiments are aimed to confirm the confinement scaling (CS) in ever larger experimental devices. On the other hand, the RFP plasma presents some interesting basic problems that are not yet completely solved, as the generation of toroidal field inside the flux conserver described in the preceding section. Moreover, many experiments show that the ion and the electron temperatures are almost the same, which suggests the presence of an anomalous heating for ions, viz., turbulent heating and so on. The small RFP experiment described in this paper was planned to investigate such basic problems, namely the following objectives are pursued:

1) studies on the generation of field reversal;

2) studies on the behavior of the plasma edge;

3) studies on the toroidal divertor and the high current density in short discharge times.

Considering the first problem, the current rise time of the poloidal coil system can be selected by properly changing the coil connections to be either 84μs or 170μs. This allows a separation of the two possible macroscopic instabilities that can lead to a relaxation or reconnection process causing the field reversal, namely, the ideal MHD modes that have a characteristic growth time $\tau_{MHD} \approx 90$ns and the resistive modes that have a corresponding time $\tau_r \approx 180\mu s$, for the predicted parameters of CECI. By carefully measuring the structure of magnetic fluctuations during the discharge evolution and by verifying its trajectory in the F - θ diagram [2], we can expect to get an insight into which mechanisms are dominant for the phenomenon of field reversal.

With respect to the second topic of research, in the ZT-40M experiment[5], the ion flow in the peripheral region of the plasma was observed to have a characteristic speed roughly of the order of the ion thermal speed in the direction antiparallel to the toroidal plasma current. Although it was proposed as the possible explanation for this flow that the mass flow arises as the result of thermal ion momentum transfer to the wall[6], in this experiment the relation of ion flow to the relaxation process will be examined.

To investigate the effectiveness of a toroidal divertor in a high current density regime, the device has a DC external toroidal field and a multiturn air core transformer as a poloidal coil to induce the plasma current, as described in next section.

3 - EXPERIMENTAL APPARATUS

The basic configuration of CECI[7] is shown in Fig. 3 and the main parameters are listed in Table II. CECI is a small toroidal device with a small aspect ratio ($\frac{R}{a}$ = 2.9 where R and a are major and minor radii, respectively) which has two characteristic features: firstly, the pyrex toroidal discharge tube with R = 12cm and a = 4.2cm is closely wrapped by double copper bands with a single electrical break in the toroidal direction and no breaks in the poloidal direction. This copper shell allows the conservation of a toroidal magnetic flux with decay times of about 3.4ms. Secondly, a multiturn air core transformer, exciting a magnetomotive force up to 220kAT, is used to induce the plasma current. Since the copper shell has no breaks in the poloidal direction, a toroidal magnetic field of up to 700G is excited by a D.C. toroidal coil system using water cooled copper pipes. Consequently, the RFP configuration is produced in the self-reversal mode, i.e., the toroidal flux is nearly conserved during the plasma discharges. Due to this mode, the poloidal current in plasma causing the reversal field is produced only by the dynamo effect in plasma. It is mentioned, here, that a toroidal magnetic divertor configuration may be produced at a break region of copper shell because the direction of external field is always the same, even when the field inside the copper shell reverses.

On the other hand, the multiturn poloidal coil system is wound along the toroidal direction around the copper shell with a quasi superconductor current distribution. Figure 4 shows the field profile on the equatorial plane produced by the poloidal coil. The leakage field inside the poloidal coil is shown in Fig. 5[8]. A merit of this type of coil configuration is that a better matching with the condenser bank can be obtained, especially in a small toroidal machine with a small aspect ratio, than using an ordinary single turn coil of the shell type. By this feature, it may be hoped that a high current density operation may be possible, which is one of our experimental objectives.

The variation in the working gas species (H_2, He, Ar and N_2) will let us study a relation between the relaxation process and the magnetic Reynolds number S[9] (= τ_D/τ_A, where τ_D and τ_A are a diffusion time and Alfvēn transit time, respectively). Before the discharge, the gas is locally preionized by the J x B gun that takes the advantage of the D.C. toroidal field.

The diagnostics used in this experiment are mainly of the standard types, except for a directional probe, as shown in Table III. The directional probe[10] which is an asymmetric double probe to measure an ion current is employed in RFP experiment for the first time. Through this measurement, the plasma flow in the peripheral region and, if possible, in the inner region of plasma will be measured to study the relation between the relaxation process and the plasma flow.

The experimental device is being constructed and tested[8]. Plasma experiments are planned to start in October 1987.

REFERENCES

[1] J.B. Taylor, Phys. Review Lett. 33, (1974) 1139.

[2] H.A.B. Bodin, A.A. Newton, Nucl. Fusion, 20, (1980) 1255.

[3] K. Kusano, T. Sato, Nucl. Fusion 26 (1986) 1051.

[4] Y. Hirano, T. Shimada, Y. Maejima, K. Ogawa, Nucl. Fusion 22 (1982) 1613.

[5] A.R. Jacobson, M.G. Rusbridge, L.C. Burkhardt, LANL Report, LA-UR-1541 (1983).

[6] J.P. Mondt, Plasma Phys. 25 (1983) 1461.

[7] Y. Aso, SBPC, 38th Annual Meeting, July 09-16, 1986, Curitiba, Brazil.

[8] M. Ueda, Y. Aso, R.M.O. Galvão, SBPC, 39th Annual Meeting, July 12-19, 1987, Brasília, Brazil.

[9] Z. Yoshida, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1984 (Proc. 10th Int. Conf. London, 1984), Vol. 2, IAEA, Vienna (1985) 467.

[10] R.D. Bengtson, S.A. Eckstrand, A.G. Sgro, C.W. Nielson, Phys. Rev. Lett. 39 (1977) 884 or
Ch. Wu, Y. Aso, S. Himeno, S. Yamaguchi, M. Okamoto, K. Hirano, J. Phys. Soc. Japan 52 (1983) 1215.

TABLE CAPTIONS

Table I Reversed Field Pinch (RFP) Experiments.

Table II Machine Parameter in CECI Apparatus.

Table III Diagnostics in CECI Experiment.

FIGURE CAPTIONS

Fig. 1 The distributions of toroidal field B_ϕ and poloidal field B_θ in RFP, based on the Bessel Function Model.

Fig. 2 F-θ diagram.
The solid curve indicates a locus of minimum energy state based on the Bessel Function Model.

Fig. 3 Schematic drawing of CECI apparatus.

Fig. 4 Field distribution on an equatorial surface produced by the D.C. poloidal coil current.

Fig. 5 Leakage field inside the poloidal·coil.

Table I - Reversed Field Pinch (RFP) Experiments

COUNTRY Institution	Device Name	YEAR COMPLETED	Plasma Size: Minor Radii a(m) or a(m)/b(m)	Plasma Size: Major Radius R(m)	Magnetics: Poloidal Field at Wall B_θ(kG)	Magnetics: Toroidal Plasma Current I_p(MA)	Magnetics: Discharge Duration (ms)	Plasma Parameters: Peak Temperatures T_e(eV)/T_i(eV)	Plasma Parameters: Average Density $\bar{n}$ (10^{14} cm^{-3})	Plasma Parameters: Energy Confinement Time T_E (ms)	Plasma Parameters: Poloidal Beta β_p (%)	Objectives
EC												
Culham, UK	HBTX-1A	1982	0.26	0.8	3.8	0.5	8	100/NA	0.2	0.03	5	CS, PMI, FE, PS
Padua, ITALY	Eta Beta II	1979	0.13	0.65	2.4	0.15	3	80/NA	1.0	0.1	10	CS, PMI, FE, PS
Instituto sui Gas Ionizzati	RFX	1989	0.5	2	8	2	250	1KeV*	2-3*		10-20*	CS, PMI, FE, PS
USA												
LANL	ZT-40M	1981	0.2	1.14	4	0.4	6	500/500	0.3	0.25	8	CS, PMI, CD, FE, PS
					3.4	0.34	2.5	300/300	0.8	0.5	17	
					1.2	0.12	25	230/NA	0.1	0.25	13	
	ZT-P	1984	0.07	0.45	7	0.25	3*					FE, PMI, HCD, S, MD
Colorado U.	REVERSATRON	1981	0.03	0.5	0.7	0.05	2*					S
GA/Phillips	OHTE	1981	0.19	1.24	5	0.5	8	500/500	3	0.25	24	CS, PMI, PS
	Multipinch	1984	0.10/0.25	0.525	3	0.3	1					Note 1, S, Note 2
JAPAN												
ETL	TPE-1R(M)	1980	0.09	0.50	3	0.13	1	600/NA	0.4	0.12	10	CS, PMI
	TPE-1RM(15)	1985	0.15	0.70	3	0.25						CS, PMI, FE
IPP Nagoya	STP-3M	1984	0.1	0.5	9	0.4	10					HCD
Kyoto U.	STE-RFP	1983	0.1	0.25	0.5	0.02	0.05	10/NA	1	0.1		Note 3
Hiroshima U.	KIT-1	1984	0.05	0.25	2	0.1						PMI, FE
Tokyo U.	REPUTE-1	1984	0.2	0.82	4	0.4	10					FE, CS, Note 4
Nihon U.		1984	0.1/0.4	0.15	8	0.6	1					Note 1
BRAZIL												
INPE	CECI	1987	0.042	0.12	2*	0.05*	0.2*					PMI, MD, HCD

Note 1: Non-circular RFP physics.
Poloidal divertor physics.

Note 2: Boundary conditions studies.

Note 3: Investigation of non-axisymmetric separatrices in RFP plasmas.
Toroidal divertors.

Note 4: OHTE operation.
Equilibrium physics.
Shell stability physics.

* Projected Values.

CD : Current Drive
CS : Confinement Scaling
FE : Field Error
HCD: High Current Density
MD : Magnetic Divertor
PMI: Plasma-Material Interaction
PS : Profile Sustainment
S : Conducting Shell

Table II - Machine Parameters in CECI Apparatus

Machine Parameters	
Major radius R:	12cm
Minor radius a:	4.2cm
Copper shell	
Major radius R:	12cm
Minor radius b:	4.5cm
Diffusion time for toroidal field	3.4ms
Poloidal coil (air core transformer of 40 or 80 turn)	
Condenser bank	16.85μF (20kV, 3.4kJ)
Current rise time	84μs for 40 turns
	170μs for 80 turns
Maximum loop voltage	500V for 40 turns
	250V for 80 turns
Toroidal coil (D.C. coil of 72 turns)	
Maximum toroidal field	700G
Working gas	H_2, He, Ar, N_2

Table III - Diagnostics in CECI Experiment

Diagnostics	
Magnetic probe:	Distributions of toroidal field $B_\phi(r)$ and poloidal field $B_\theta(r)$.
Rogowski coil:	Plasma and coil currents.
One turn loop:	Loop voltage.
Fourier coils:	MHD activity for poloidal mode number $m \leq 4$ and toroidal mode number $n \leq 12$.
Directional probe:	Direction of a plasma flow.
Faraday cup:	Plasma flux.
Spectrometer:	Behavior of impurity, and ion and electron temperatures.

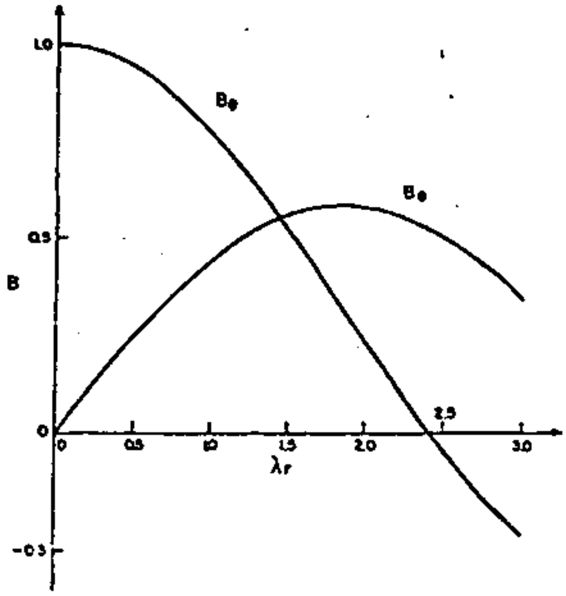

Fig. 1 - The distributions of toroidal field B_ϕ and poloidal field B_θ in RFP, based on the Bessel Function Model.

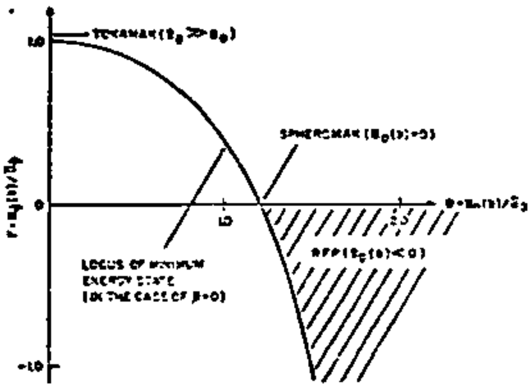

Fig. 2 - F-θ diagram. The solid curve indicates a locus of minimum energy state based on the Bessel Function Model.

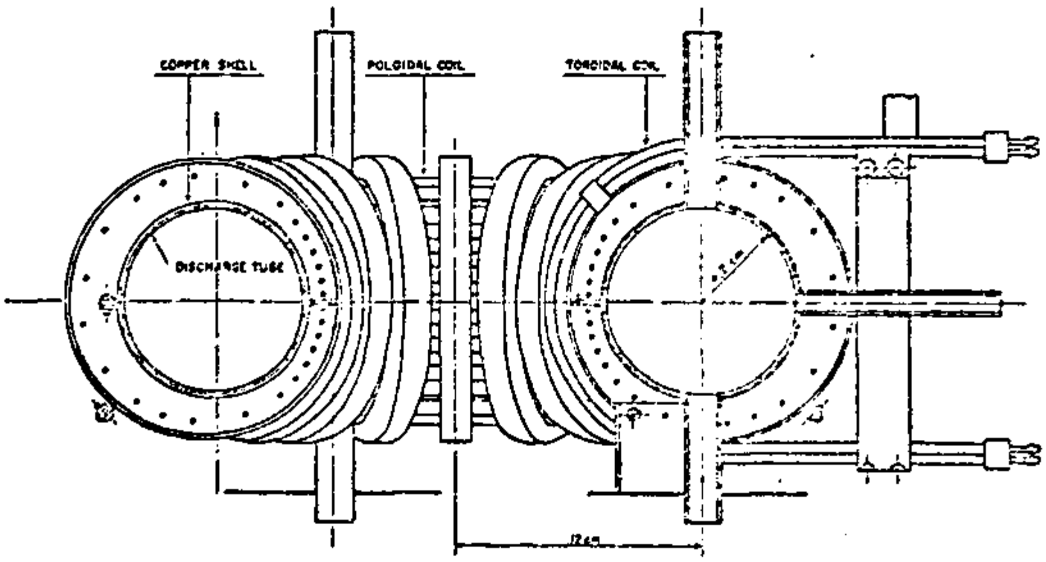

Fig. 3 - Schematic drawing of CECI apparatus.

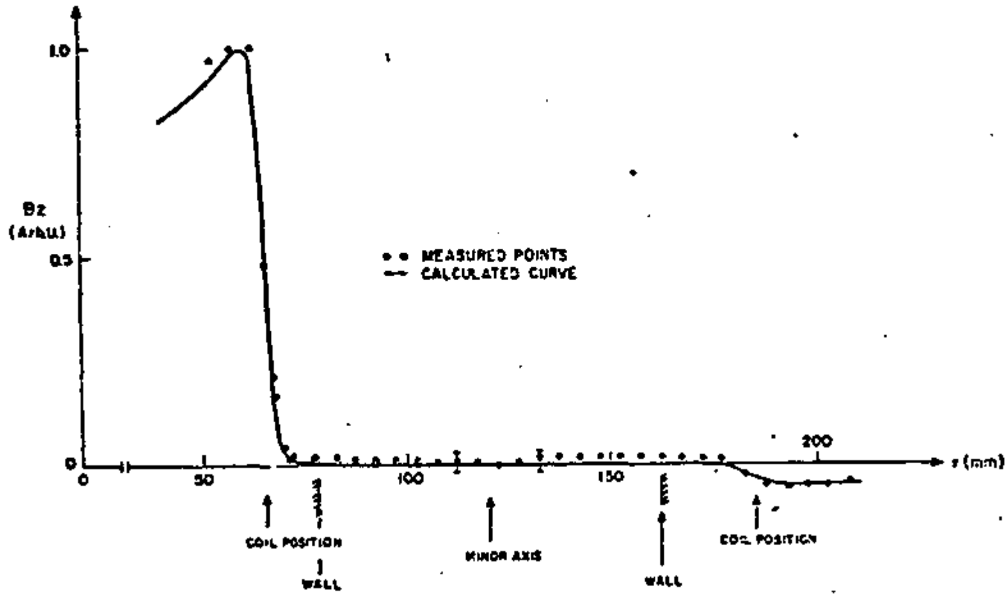

Fig. 4 - Field distribution on an equatorial surface produced by the D.C. poloidal coil current.

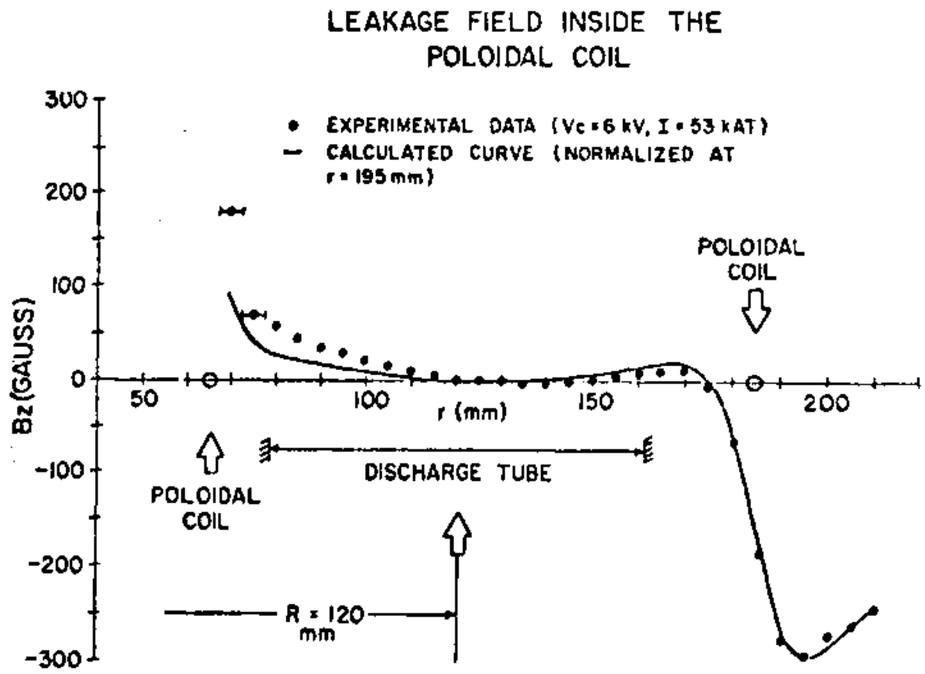

Fig. 5 - Leakage field inside the poloidal coil.