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MAGNETIC DIAGNOSTICS FOR THE PROTO-ETA TOKAMAK

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Magnetic Diagnostics for the Proto-Eta Tokamak

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1 Introduction

THE PURPOSE OF THIS WORK IS TO GIVE A GENERAL VIEW OF THE MAGNETIC DIAGNOSTICS THAT WILL BE USED IN THE PROTO-ETA TOKAMAK. THESE DIAGNOSTICS WILL BE USEFUL TOOLS TO MEASURE CURRENTS, ELECTRIC AND MAGNETIC FIELDS INVOLVED IN THE PLASMA MAGNETIC CONFINEMENT. THE DETERMINATION OF THE MAGNITUDE OF THESE PARAMETERS IS ESSENTIAL TO THE STUDY OF PLASMA MHD EQUILIBRIUM AND INSTABILITIES. THE EXPERIMENTAL PLASMA RESEARCH ON THIS FIELD WILL BE SPECIALY RELEVANT BECAUSE UP TO NOW, THERE ARE NO EXPERIMENTAL DATA OF PLASMA MAGNETIC CONFINEMENT ON SMALL ASPECT RATIO TOKAMAK.

2 Major Features

CONTROL OF HIGH CURRENTS AND VOLTAGES FROM THE POWER SOUCERS SUCH AS CAPACITORS BANKS, FLY WHEELS AND SO ON.

MAPPING OF MAGNETIC FIELDS INSIDE THE TOROIDAL CHAMBER (WITHOUT PLASMA) TO DETERMINE THE SPACE PROFILE OF MAGNETIC FIELDS PRODUCED BY TOROIDAL FIELD COILS, VERTICAL FIELD COILS, SHAPING COILS AND OHT FIELD CORRECTION COILS

PLASMA CURRENT MEASUREMENT

TOROIDAL ELECTRIC FIELD MEASUREMENT

PLASMA SHAPE DETERMINATION

PLASMA POSITION CONTROL

MEASUREMENTS OF DIAMAGNETIC AND PARAMAGNETIC EFFECTS (DETERMINATION OF THE β PARAMETER)

DETERMINATION OF SURFACES OF CONSTANT MAGNETIC FLUX INSIDE THE PLASMA

MAGNETIC FIELDS FLUCTUATIONS AND MHD INSTABILITIES DETECTION

3 Main Difficulties

ELETRIC NOISE AND SPURIOUS MAGNETIC FIELDS PERTUBATIONS DUE TO THE HIGH CURRENTS AND FIELDS INVOLVED

HIGH VOLTAGE INSULATION

A LARGE NUMBER OF COILS SHOULD BE INSERTED INTO THE TOROIDAL VACUUM CHAMBER AND MAY INCREASE THE LEVEL OF IMPURITIES. THE REASONS ARE:

-ABSENCE OF SPACE BETWEEN THE OHT AND THE INNER VACUUM CHAMBER WALL

-NECESSITY TO DECREASE TO A MINIMUM THE SIGNAL ATTENUATION AND THE MAGNETIC COILS TIME RESPONSE.

DUE TO THE HIGH PLASMA CURRENTS INVOLVED IN THIS EXPERIMENT THE CONTACT BETWEEN THE PLASMA SURFACE AND THE INTERNAL MAGNETIC DIAGNOSTICS MUST BE AVOIDED

SHAPE AND POSITION CONTROL ON ETA TOKAMAK WILL REQUIRE FEEDBACK SYSTEMS MORE COMPLEX THAN THE ONES USED IN CIRCULAR CROSS SECTION TOKAMAKS

SIMULTANEOUS MEASUREMENTS OF A LARGE NUMBER OF SIGNALS FROM THE MAGNETIC COILS WILL LEAD TO A LARGE NUMBER OF CAMAC STORAGE UNITS AND MEMORIES

NON CIRCULAR CROSS SECTION TOKAMAK PLASMAS WILL REQUIRE SPECIFIC COMPUTER CODES TO THE DETERMINATION OF THE PLASMA EQUILIBRIUM PARAMETERS

4 Pulsed Magnetic Field Measurements With Active Circuits

THE VOLTAGE INDUCED IN THE MAGNETIC COIL IS GIVEN BY:

$$V = NA\frac{dB}{dt} \quad (1)$$

AFTER INTEGRATION BY AN ACTIVE CIRCUIT THE SIGNAL WILL BE PROPORTIONAL TO THE MAGNETIC FIELD B

$$V_I = \frac{NAB}{\tau} \quad (2)$$

WHERE τ IS THE INTEGRATOR TIME CONSTANT $(\tau) = RC$, N THE NUMBER OF TURNS AND A THE COIL AREA

LIMITS FOR THE COIL SIGNAL RESPONSE

-LOW FREQUENCY SIGNALS $(\omega_{min}) >> 1/(\tau)$

-HIGH FREQUENCY SIGNALS $(\omega_{max}) << R/L$

WHERE L IS THE COIL INDUCTANCE

-CABLES AND CONECTIONS SHOULD BE COMPATIBLE WITH THE FREQUENCIES OF THE DETECTED SIGNALS

Magnetic field measurements

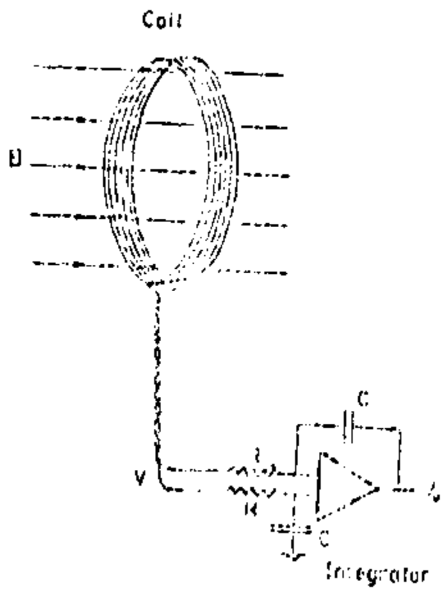

Figure 1: Typical magnetic coil and integrating circuit

5 High Current Measurements

IN TOKAMAKS HIGH CURRENTS ARE NECESSARY TO PRODUCE HIGH MAGNETIC FIELDS AND TO HEAT THE PLASMA. THE BEST KNOWN METHOD TO MEASURE THESE CURRENTS IS BY USING THE SO CALLED ROGOWSKI COIL.

OBS:THE NUMBER OF TURNS PER UNIT LENGHT n SHOULD BE BIGGER THAN THE MAGNETIC FIELD VARIATIONS $n >> \delta B/B$

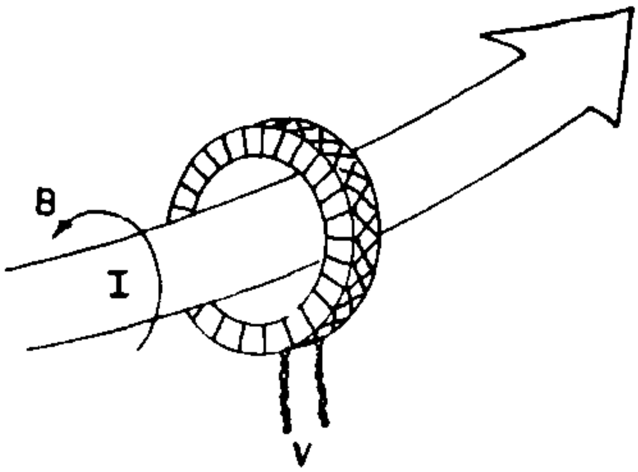

Figure 2: The Rogowsky Coil is a solenoide with a toroidal geometry and an uniform coil around a current conductor. The time varying voltage induced after integration is diretly proportional to the flowing current I in the conductor $V_I = N(\mu)AI/(\tau)$

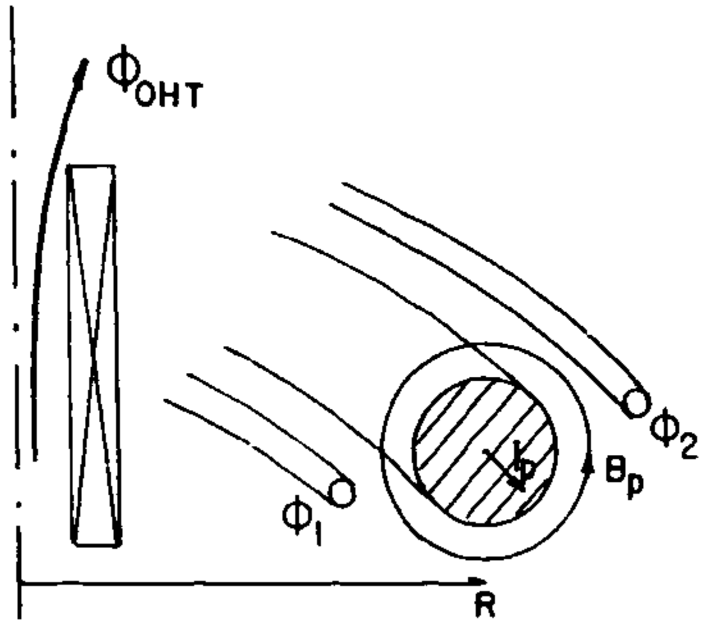

Figure 3: Loop wire system to measure the voltage induced along the plasma

6 Loop Voltage Measurement

THE VOLTAGE DROP ALONG THE PLASMA TORUS IS MEASURED BY SINGLES LOOP WIRES POSITIONEL ALONG THE SURFACE OF THE TOROIDAL VACUUM CHAMBER

THE VOLTAGE INDUCED ALONG THE PLASMA IS GIVEN BY:

$$V_p = -\frac{d(\phi_p)}{dt} \qquad (3)$$

WHERE $\phi_p = \phi_i + \phi_e$

ϕ_i DEPENDS ONLY ON THE MAGNETIC FLUX OF THE OHT COIL .

ϕ_e WILL DEPEND ON THE INTERNAL PLASMA INDUCTANCE, VERTICAL B_v FIELD AND ON THE SHAPING B_s FIELD. SPURIOS FIELDS WILL ALSO BE CATCHED BY THE EXTERNAL LOOP VOLTAGE COIL.

THE FOLLOWING PARAMETERS CAN BE ESTIMATED FROM THE LOOP VOLTAGE MEASUREMENT:

-TOROIDAL ELECTRIC FIELD

-PLASMA TORUS INDACTANCE

-PLASMA RESISTIVITY AND OHMIC POWER DELIVERED TO HEAT THE PLASMA

FROM THE PLASMA RESISTIVITY, THE ELECTRON TEMPERATURE CAN ALSO BE ESTIMATED THROUGH THE SPITZER FORMULA FOR RESISTIVITY

$$\eta_p = \frac{5.53 \times 10^{-8}}{T_{kev}{}^{3/2}} \qquad (4)$$

7 Plasma Position and Shape Control by Poloidal Flux Loops and Coils

THE PLASMA POSITION CONTROL IN THE OLD TOKAMAKS WAS MADE ONLY BY MAGNETIC PROBES LOCATED AROUND THE PLASMA COLUMN IN THE POLOIDAL DIRECTION (MIRNOV PROBES).

FOR STRONGLY SHAPED PLASMAS WITH NON CIRCULAR CROSS SECTION, THIS METHOD DOES NOT GIVE ENOUGH ACCURACY.

IT IS USUAL TO EMPLOY NUMERICAL SOLUTIONS OF THE MHD EQUILIBRIUM EQUATIONS VIA COMPUTER CODES TO FIND OUT PLASMA SHAPE AND POSITION, BUT THIS METHOD IS NOT FAST ENOUGH TO CONTROL THESE PARAMETERS DURING THE DISCHARGE.

FOR THE PROTO-ETA TOKAMAK IT WILL BE DESIRABLE TO USE SYSTEMS OF PLASMA SHAPE AND POSITION CONTROL SIMILAR TO THE ONES USED IN THE ASDEX AND JET TOKAMAKS.

THESE SYSTEMS USE A MODIFIED FORM OF THE MIRNOV COIL SYSTEM TO MEASURE VERTICAL AND HORIZONTAL SHIFTS OF THE MAGNETIC AXIS. DISPLACEMENTS OF THE PLASMA TORUS AS A WHOLE AND SHAPE CHANGING ARE DETECTED BY POLOIDAL FLUX LOOPS IN FORM OF SADDLE COILS.

8 Measurements of the β parameters

THE β PARAMETER IS DEFINED AS THE RATIO OF KINETIC PRESSURE TO MAGNETIC PRESSURE GIVEN BY:

$$\beta = \frac{< P >}{\frac{(B_T)^2}{2(\mu_o)}} \tag{5}$$

THE VARIOUS β PARAMETERS FOR THE PROTO-ETA TOKAMAK ARE THE FOLLOWINGS:

TOROIDAL BETA β_t

$$\beta_t = \frac{1.76}{(q_a)^2} \tag{6}$$

FOR $q_a = 3$ $\beta_t = 0.20$

POLOIDAL BETA

$$\beta_p = \left(\frac{2\pi a B_t}{\mu_o I_p}\right)^2 \left(\frac{k^2+1}{2}\right) \tag{7}$$

FOR $\beta_t = 0.20$ $\beta_p = 0.86$

CRITICAL BETA FOR STABILITY CALCULATED FROM TROYON SCALING LAW β_c

$$\beta_c = 0.035 \frac{I_p}{a(B_t)} \tag{8}$$

FOR $I_p = 0.45$ MA AND $B_t = 0.65$ T , $\beta_c = 0.12$

*THE SUCCESS OF THE MEASUREMENTS WILL DEPEND ON THE USE OF COILS WITH PROPER GEOMETRY AND MECHANICAL STABILITY

THE POLOIDAL AND THE TOROIDAL BETA CAN BE EXPRESSED ONLY IN TERMS OF THE POLOIDAL AND THE TOROIDAL FIEDS WHEN THERE IS EQUILIBRIUM

$$\beta_p = 1 + \frac{B_{ta}^2 - < B_t^2 >}{B_{pa}^2} \tag{9}$$

$$\beta_t = 2\frac{(B_{ta} - < B_t >)}{B_{ta}} \tag{10}$$

IN A GOOD CALIBRATED DIAMAGNETIC LOOP SYSTEM THE VOLTAGE INDUCED SHOULD BE CLOSE TO ZERO WITHOUT THE PLASMA.

AFTER INTEGRATION THE SIGNAL OF THE DIAMAGNETIC LOOP SYSTEM V_I WILL BE PROPORTIONAL TO CHANGE IN THE TOROIDAL FLUX DUE TO THE PLASMA $\Delta\phi$

$$\Delta\phi = A_{DL}(B_{ta} - < B_t >) \tag{11}$$

FOR $< B_t > < B_{ta}$ THE PLASMA IS DIAMAGNETIC AND $\beta_p > 1$

FOR HIGH PLASMA CURRENTS THE MAGNETIC PRESSURE OF THE POLOIDAL FIELD IS CONSIDERABLE AND $< B_t > > B_{ta}$. IN THIS CASE THE PLASMA IS PARAMAGNETIC $\beta_p < 1$ WHICH IS WHAT IT IS BEEN EXPECTED TO OCCUR IN PROTO-ETA.

TO CANCEL EFFECTS FROM IMAGE CURRENTS PRODUCED BY THE PLASMA CURRENT, A FINAL CORRECTION SHOULD BE MADE

*THE DIAMAGNETIC LOOP β MEASUREMENTS AND THE TOROIDAL FIELD B_{to} MEASUREMENTS AT THE MAJOR RADIUS R_o CAN BE COMBINED TO GIVE THE ENERGY CONFINEMENT TIME τ_{Eoh} OF A QUASISTATIONARY OHMICALLY HEATED PLASMA.

$$\tau_{Eoh} = \frac{kinetic\ energy}{ohmic\ power} \sim A\beta_p B_t \tag{12}$$

WHERE A IS THE ASPECT RATIO (R_o/a)

PLASMA EQUILIBRIUM DIAGNOSTICS BY MAGNETIC FLUX SURFACES RECONSTRUCTION

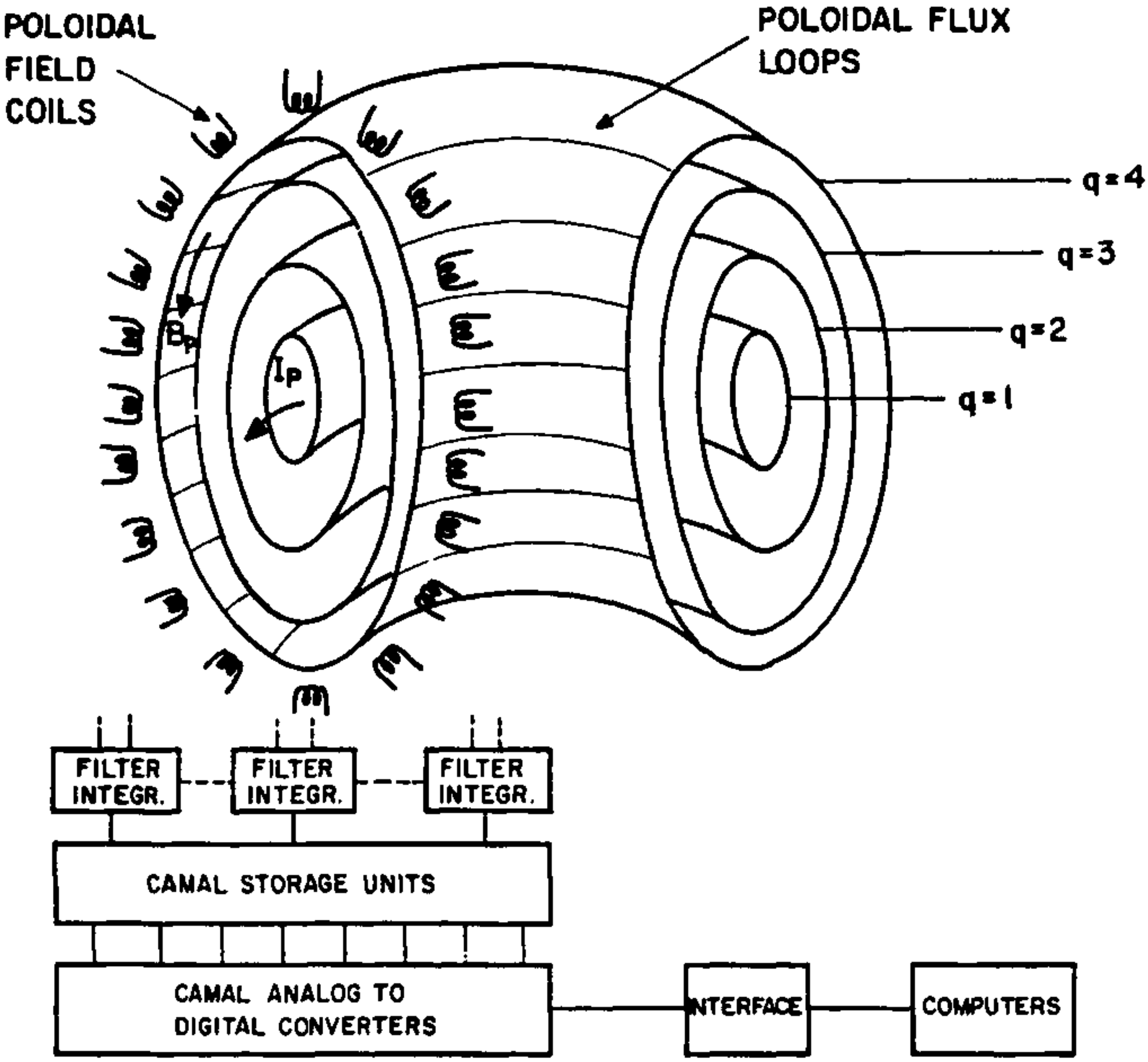

Figure 8: Magnetic Coils Array and Poloidal Flux Loops Systems used to produce boundary values to equilibrium computer codes. These codes are responsible for the calculations of the plasma cross section lines of constant magnetic flux or constant q values.

9 Plasma Equilibrium Diagnostics Based on Magnetic probes Located at the Plasma Edge

THE FUNDAMENTAL QUESTION FOR A GOOD TOKAMAK OPERATION IS WHETHER THE MAGNETIC CONFINING FIELDS ARE CORRECT TO PRODUCE THE PLASMA TORUS EQUILIBRIUM.

THE SAFETY FACTOR q SPACE AND TEMPORAL PROFILE MEASUREMENT IS ESSENTIAL TO DO THIS TASK.

BY DEFINITION THE q VALUE IS THE NUMBER OF TIMES A MAGNETIC FIELD LINE WINDS IN THE POLOIDAL DIRECTION DIVIDED BY THE NUMBER OF TIMES IT WINDS AROUND THE TOROIDAL DIRECTION AND IT IS RELATED TO THE TOROIDAL AND POLOIDAL FIELDS BY:

$$q = \oint \frac{B_t dl}{\nabla\psi} \tag{13}$$

WHERE $\nabla\psi$ IS RELATED WITH THE POLOIDAL FIELD BY:

$$B_p = \frac{\nabla\psi}{2\pi R} \tag{14}$$

*THESE COILS CAN BE USED ALL TOGETHER AS A ROGOWSKY COIL.

10 Magnetic Fields Fluctuation Measurements

MHD INSTABILITIES ARE LARGE SCALE OR MACROSCOPIC FLUCTUATIONS OF THE PLASMA TORUS

THE DRIVING MECHANISMS FOR THIS INSTABILITIES ARE GRADIENTS OF MAGNETIC PRESSURE AND OF CURVATURE OF THE FIELD LINES

IN TOKAMAKS THE MOST COMMON ARE THE KINK INSTABILITIES THAT CAN BE DETECTED ALSO BY MAGNETIC COILS AROUND THE POLOIDAL DIRECTION.

NEVERTHELESS TO DETECT THE FLUCTUATIONS THE COILS AND THE ELECTRONICS SHOULD BE ADEQUATED TO HIGHER FREQUENCIES SIGNALS

THE PERTUBATIONS ON THE MAGNETIC FIELDS ARE GIVEN BY:

$$\delta B = A_{mn} exp(i\omega_{mn} - m\theta - n\varphi) \qquad (15)$$

WHERE θ AND φ ARE TOROIDAL AND POLOIDAL ANGLES. THE TOROIDAL AND POLOIDAL MODE NUMBERS n AND m ARE RELATED WITH THE SAFETY FACTOR BY:

$$q = \frac{m}{n} \qquad (16)$$

THE MOST COMMON METHOD TO MEASURE m AND n IS TO INFER THE HELICITY BASED ON THE FOURIER ANALYSIS OF THE PROBE SIGNALS. THIS IS CALLED THE PHASE CORRELATION METHOD.

THE POLOIDAL NUMBER IN PROTO-ETA WILL BE DETERMINATED BY THE VARIATION OF THE AMPLITUDE PERTUBATION WITH THE POLOIDAL ANGLE. THE FREQUENCY OF THESE FLUCTUATIONS ARE DETERMINED BY THE DIAMAGNETIC DRIFT FREQUENCY OF ELECTRONS. FOR THE PROTO-ETA THIS FREQUENCY SHOULD BE AROUND 50 kHz TO 100 kHz.

FOR NON CIRCULAR CROSS SECTION PLASMA COLUMN IT WILL BE IMPORTANT TO INCLUDE THE DISTANCE BETWEEN THE PLASMA EDGE AND THE MAGNETIC AXIS, BECAUSE IT IS NOT CONSTANT ALONG THE POLOIDAL DIRECTION

11 Summary-Magnetic Diagnostics For Proto-Eta

Diagnostic	*Parameter to be measured*	*Number of Coils*
SMALL ROGOWSKY COILS	CURR. USED TO PROD. CONFINING FIELDS	5 UNITS
HIGH VOLTAGE PROBES	CAP. BANKS DISCHARGE VOLT.	> 5 UNITS
BIG ROGOWSKY COIL	PLASMA CURR. INSIDE CHAMBER	1
VOLTAGE LOOP	PLASMA TOROIDAL VOLT. DROP	4
MAGNETIC COILS-POS.	PLASMA AXIS POSITION	4
SADDLE COILS	PLASMA SHAPE AND GLOBAL POS.	> 4 UNITS
MAGNETIC MIRNOV COILS-q	MHD EQU q PROFILES	18 Coils + 18 Pol FL Coils
POLOIDAL FLUX LOOPS - ψ	MHD EQU. ψ PROFILES	> 4
DIAMAGNETIC LOOP SYSTEM	β, CONFINEMENT TIME	1
MAGNETIC PICK UP COILS	MHD INSTABILITIES	$4X16 = 64$ Pol +4 Tor

VOLTAGES AND CURRENTS DIAGNOSTICS FOR PROTO-ETA

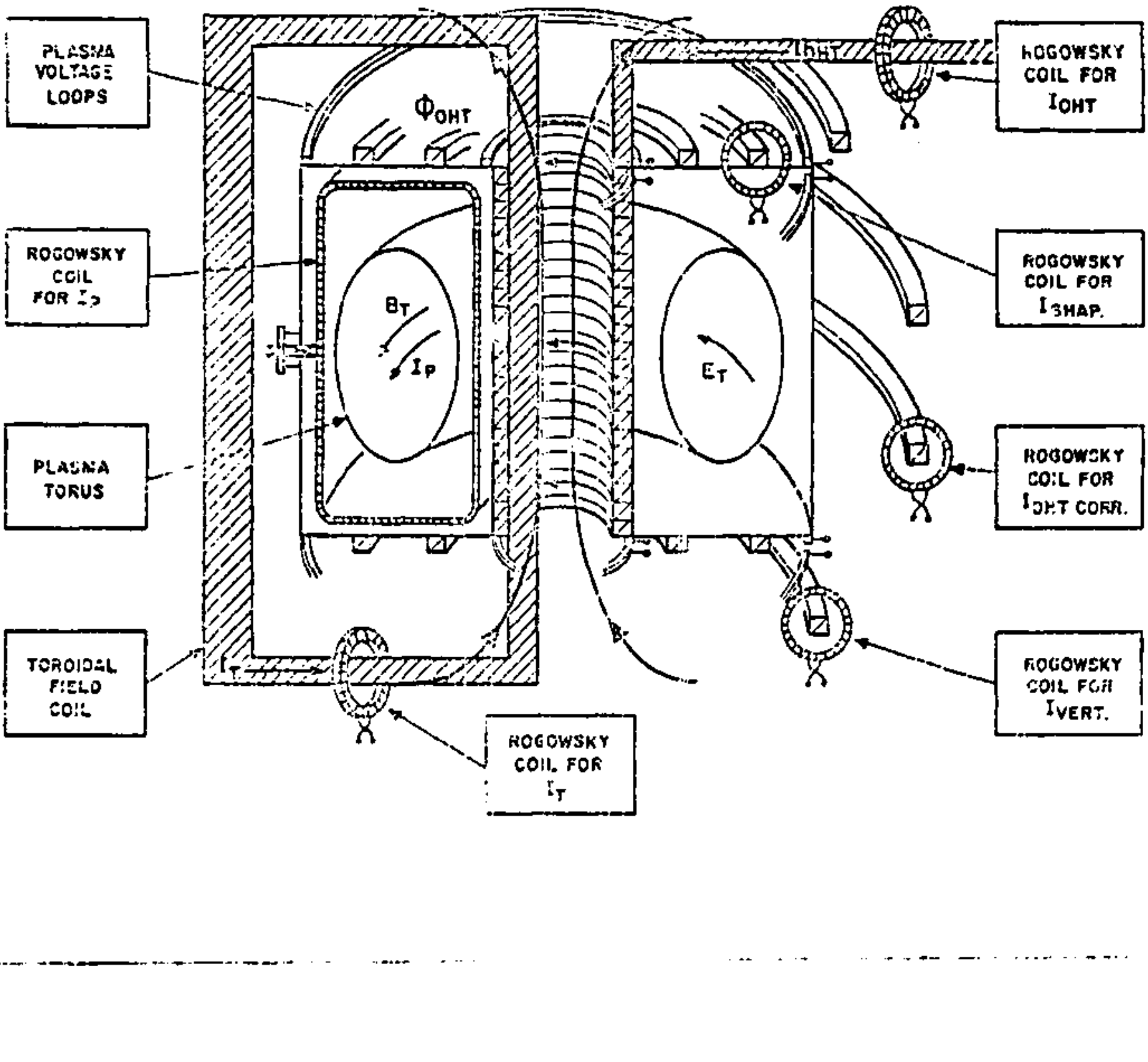

Figure 4: General View of The Proto-Eta Tokamak Showing the Rogowsky Coils and the Loop Voltage Coils.

PLASMA POSITION SHAFE CONTROL

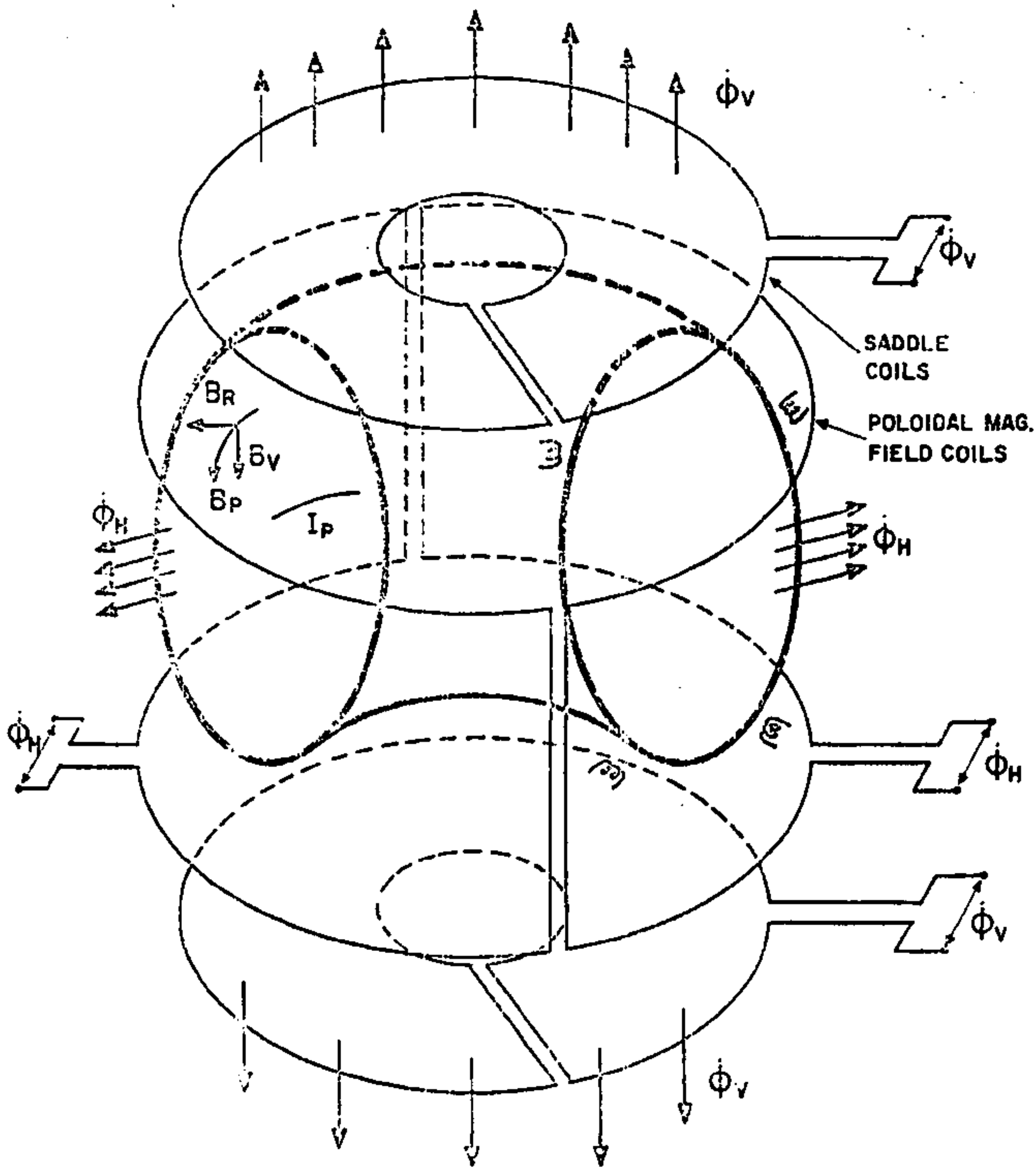

Figure 5: Plasma Position and Shape Control Coils

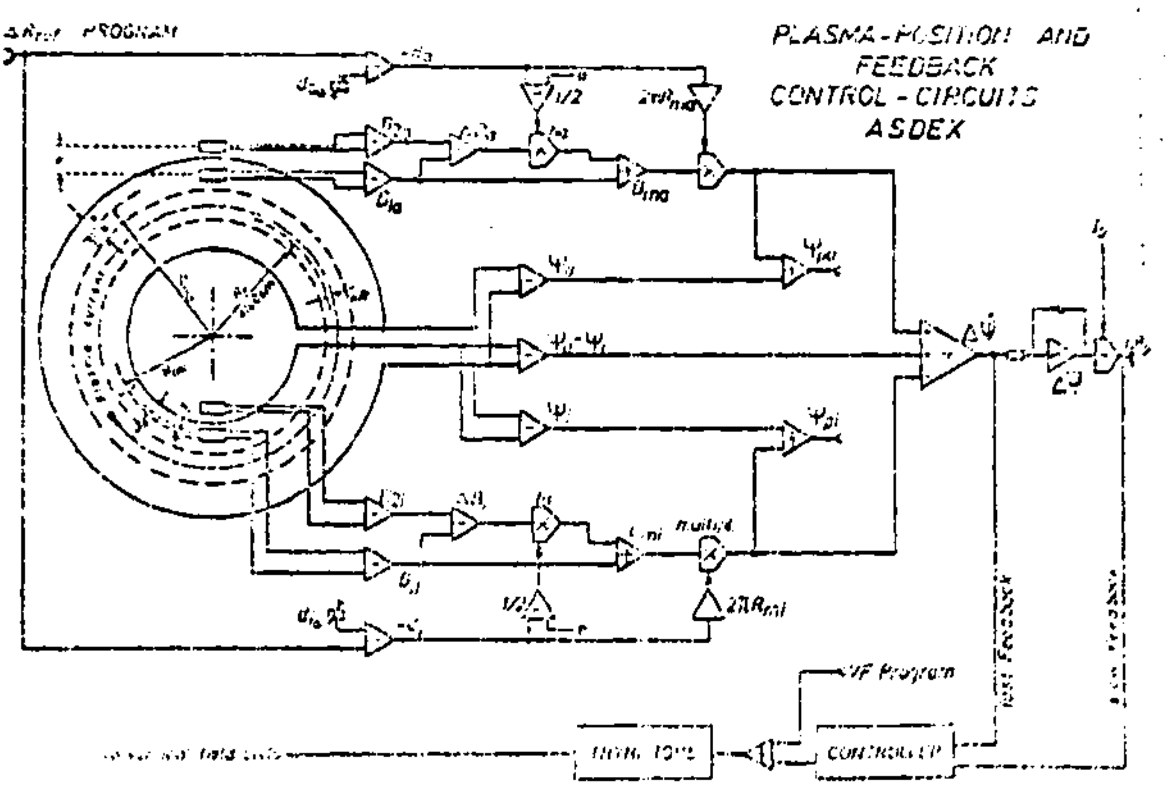

Figure 6: Position and Shape Control Circuit used in ASDEX Tokamak

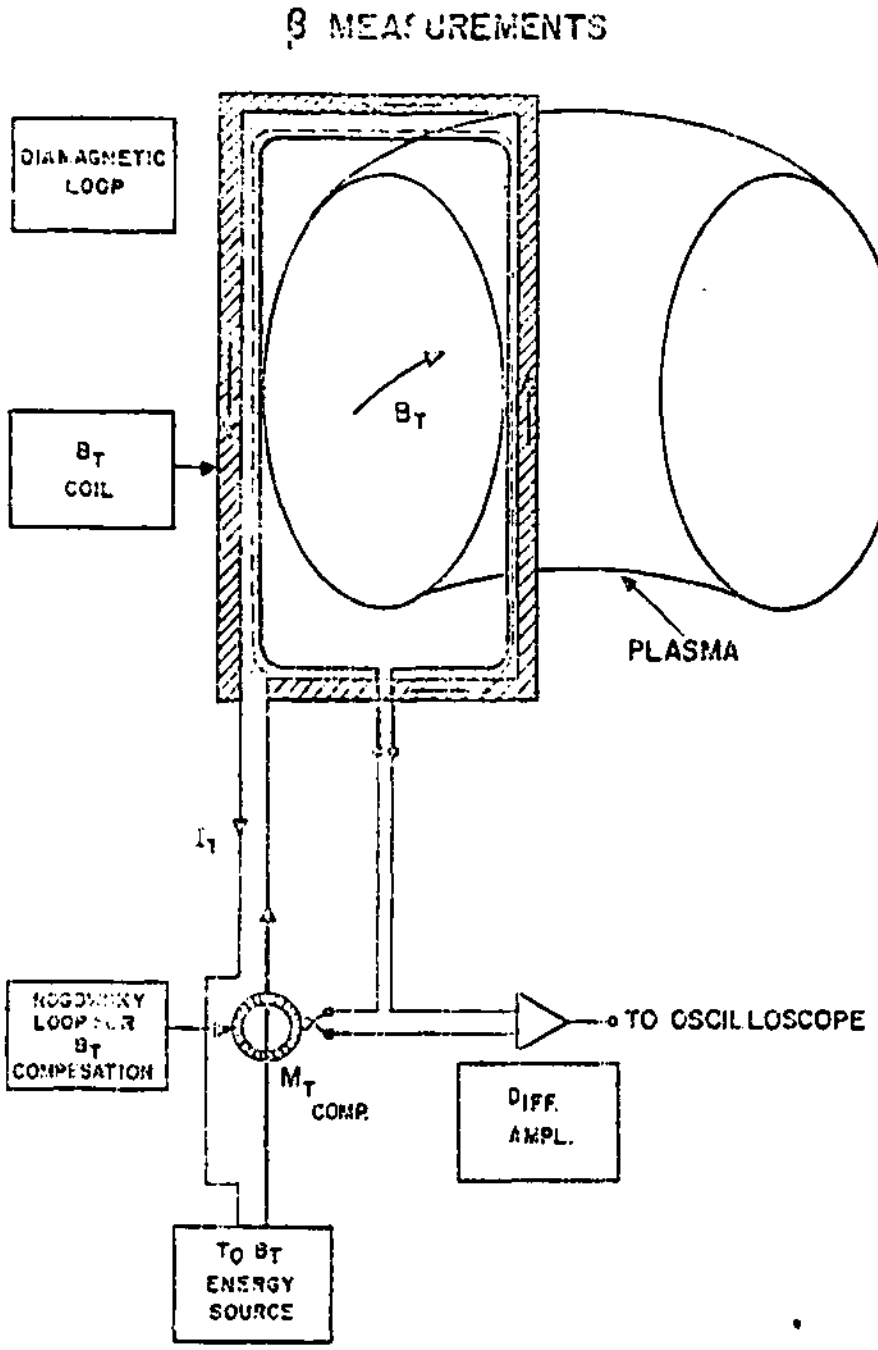

Figure 7: Diamagnetic Loop system to measure small variations on the toroidal magnetic field flux $\Delta\phi$.

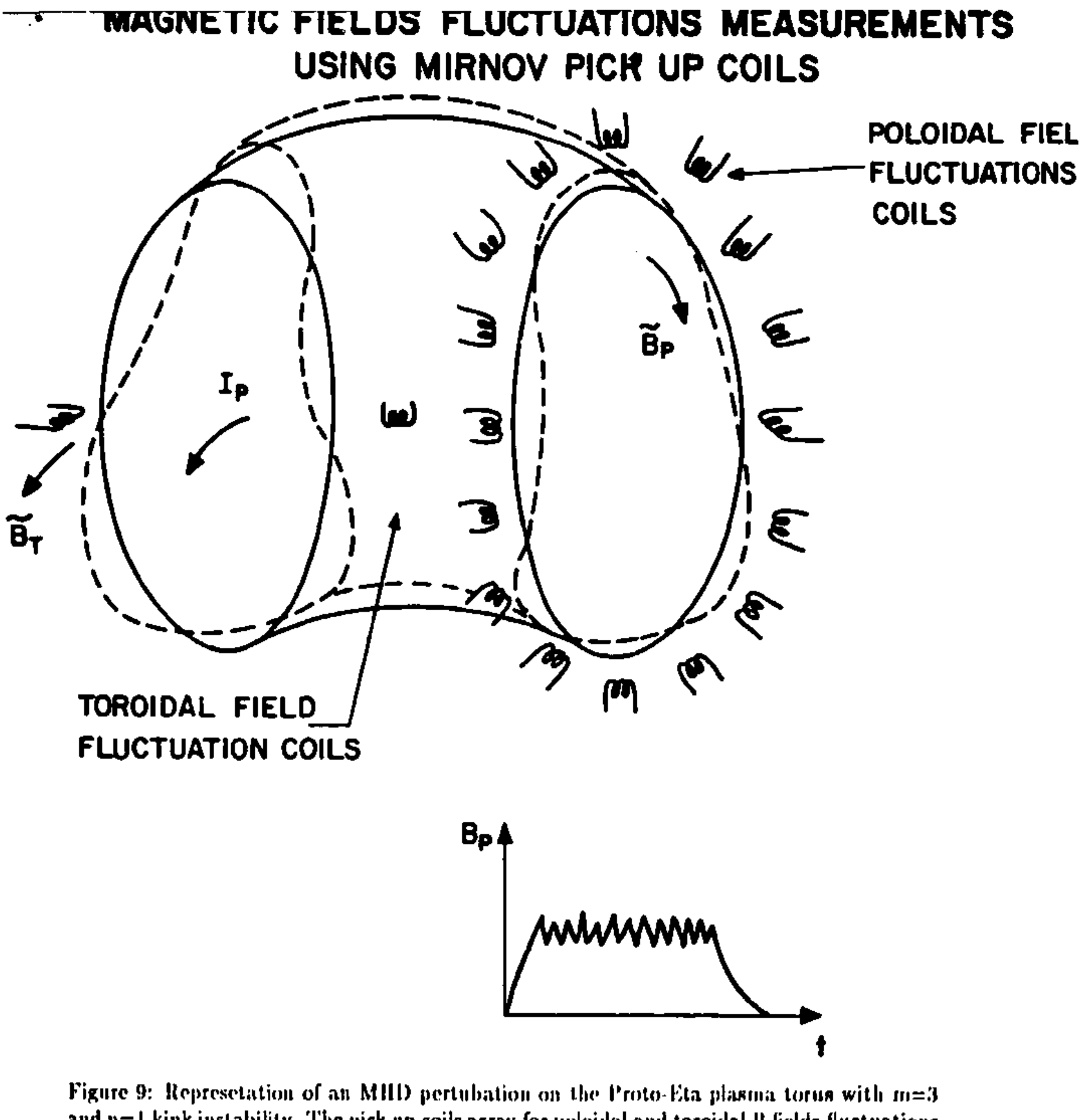

Figure 9: Represetation of an MHD pertubation on the Proto-Eta plasma torus with m=3 and n=1 kink instability. The pick up coils array for poloidal and toroidal B fields fluctuations and the signal detected by the coils during the discharge is also shown.

REFERÊNCIAS

LUDWIG, G.O.; MONTES, A.; SAKANAKA, P.H. "Preliminary Design of a Small Aspect Ratio Tokamak". Research Using Small Tokamaks, IAEA-TEC Doc. 519. Proc. of a Technical Committee Meeting Organizaed by IAEA, Nice, France, 10- 11 Oct., 1988.

Equipe TFR "Tokamak Plasma Diagnostics". Review Paper on Nuclear Fusion (18) 647, 1978.

HUTCHINSON, I.H. in "Principles of Plasma Diagnostics". Cambridge University, Press 1st edition, 1987.

SCHNEIDER, F. "Novel Method of Determining the Plasma Position and its Application to the Asdex Feedback System" int. publication, Max-Planck-Institute fur Plasma Physik Euratom . IPP Association.

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