INTERNATIONAL ATOMIC ENERGY AGENCY
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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O. B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - I

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SPRING COLLEGE ON PLASMA PHYSICS

(25 May - 19 June 1987)

THE REVERSED FIELD PINCH

H. BODIN
Culham Laboratory
Oxfordshire U.K.

THE REVERSED FIELD PINCH

H A B BODIN

CULHAM LABORATORY

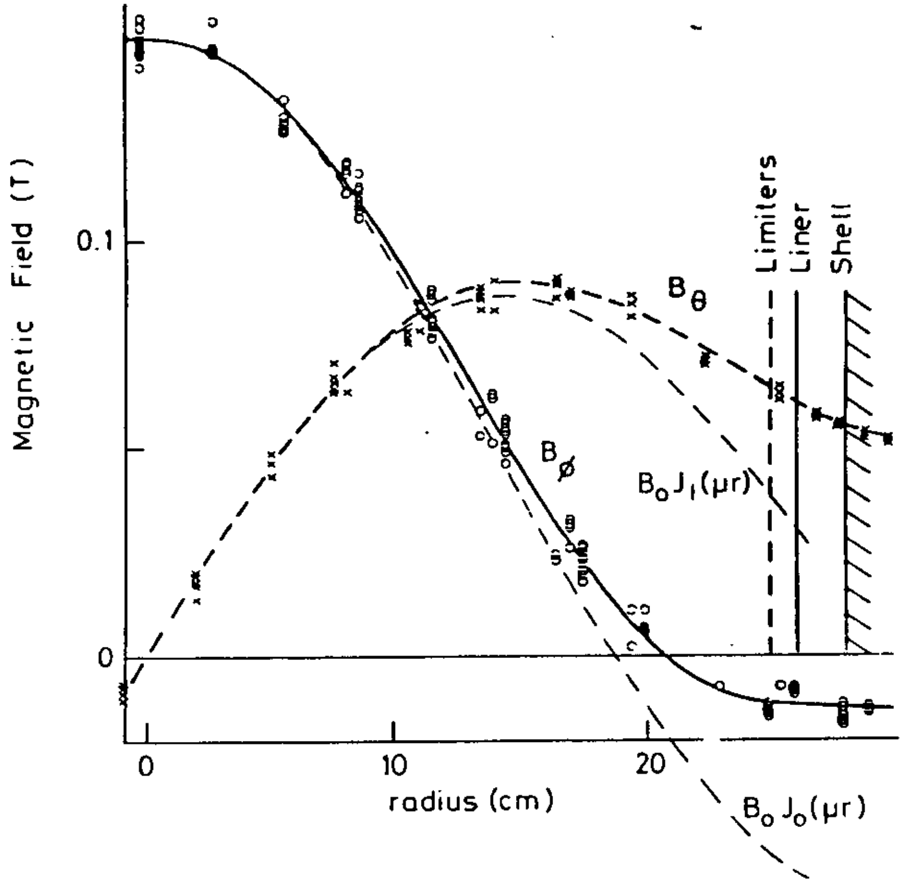
Two lectures presented at the Spring College on Plasma Physics

Trieste, June 1987

TOPIC 1

REVERSED FIELD PINCH (RFP)

INTRODUCTION



EXPERIMENTAL AND THEORETICAL (BFM)
FIELD PROFILES

Basic Principles of RFP

- Equilibrium is a near minimum energy "Relaxed State" (Taylor's Theory)
- These equilibria are self generated by the plasma. "self reversal"
- The configuration only depends on

$$\theta \sim \frac{\text{plasma current}}{\text{toroidal flux}}$$

- If θ, ie current, is maintained the reversed field configuration is sustained as a steady state

Basic Principles of RFP (cont)

- Good stability at high-β because little free energy to drive unstable modes
- Powerful ohmic heating possible to ignition because current high
- $B_\phi \sim B_\theta$, $q(a) << 1 \sim 1/10$
- Field lines have short pitch near wall (influences limiter design)

- Differences cf Tokamak (eg edge physics, radiation effects)

INTERNATIONAL RFP RESEARCH

- 1980-84 Five machines
  a = 12-25 cm
  I = 100-500 kA
  timescale = 1-20 msec

- 1986 Fifteen operating or building
  RFX at Padua (a = 50 cm, I = 2 MA)
  CFPR Los Alamos (design phase)

- Plasma parameters

	1980	1986
T	50-100 eV	0.5 keV
τ_E	10's μsec	0.5-1 ms
β_θ	—— 5-25% ——	

Present Day Plasma Parameters

$T_e \sim T_i \lesssim$ 0.1-0.5 keV

$n_e \sim$ 10^{19}-10^{20} m^{-3}

$\beta_\theta \sim$ 5-25%

$\tau_E \sim$ 0.1-1 ms

- RFP much less advanced than Tokamak

- Expanding field - one other RFX scale machine being designed (Los Alamos)

TOPIC 2

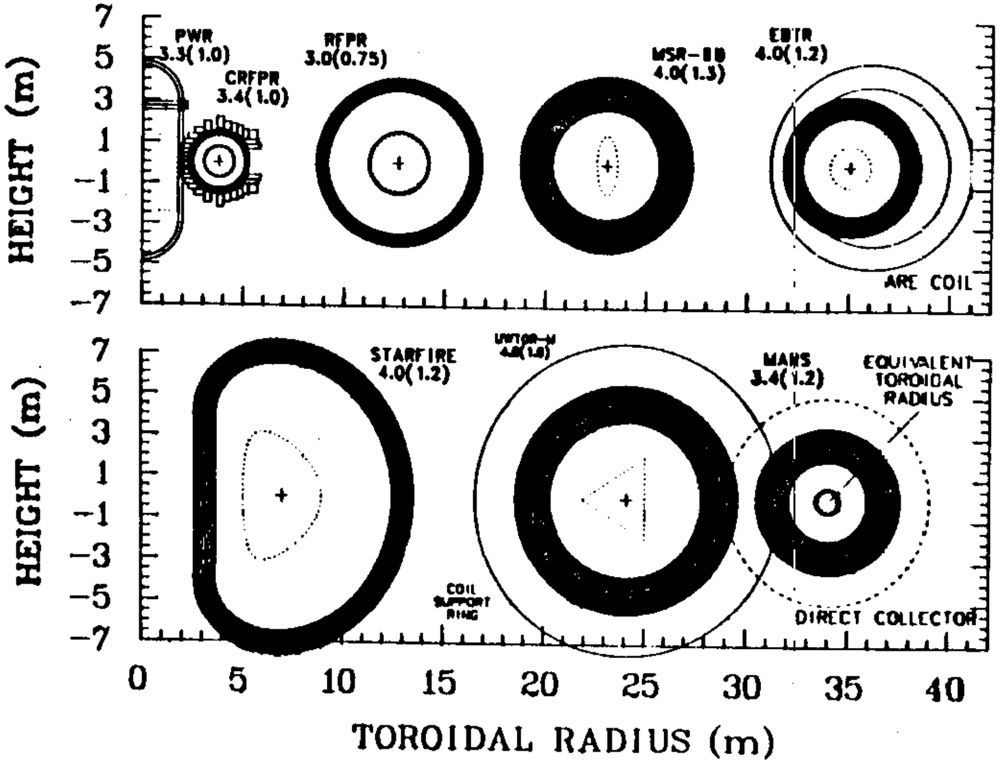
COMPACT RFP REACTOR

COMPACT RFP REACTOR

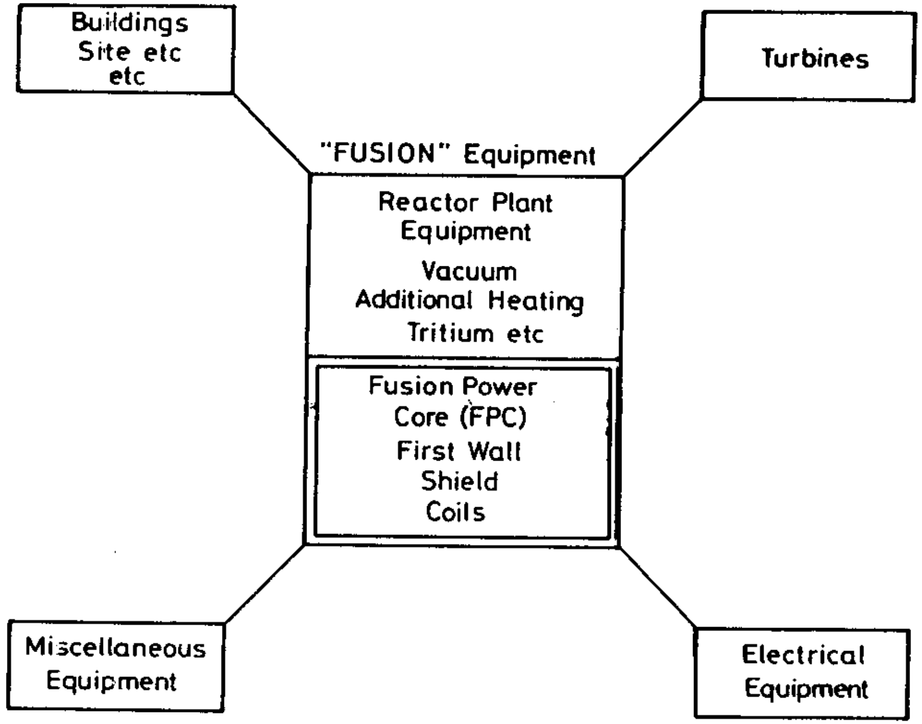
- High Energy Density same as Fission Reactor
- Small size
- Normal coils
- Ohmic Heating
- High wall loading But same fluence
- Good volume and mass utilisation
- Fusion power core cost 3-4% of total (cf 30%)
- Less expensive development path

- Major new (inter-laboratory) US study starting CONN

Compact Reactors can be designed for many systems including Tokamak BUT BECAUSE OF THE LOW FIELD AND HIGH-β IN THE RFP this system is particularly favoured.



Cost Breakdown in Fusion Power Station



	Starfire Tokamak	Compact RFP
$\frac{\text{Cost of FPC}}{\text{Cost of Total Plant}}$ %	25	5

TOPIC 3

RELAXED STATES

TAYLOR'S THEORY OF RELAXED STATES

PRINCIPLE:

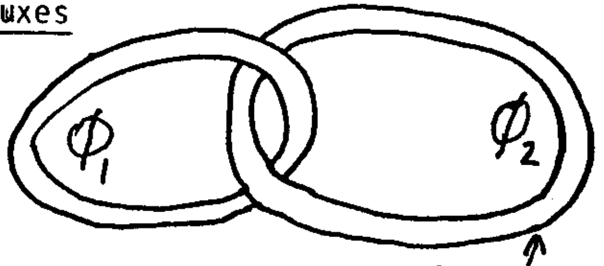
Minimise energy with single constraint that total magnetic helicity k_0 is invariant

MAGNETIC HELICITY

- $k = \int A.B \; dV$

  A = vector potential; B = magnetic field

- Helicity is Topological Linkage of Fluxes



FLUXTUBE

$k = 2\phi_1\phi_2$ LINKED
$k = 0$ UNLINKED

- Conservation of global helicity
  K INVARIANT (Taylor)

  True even in resistive plasma although local helicity can be destroyed

- Helicity injection

$$\dot{K} = 2 \Psi V$$

V = voltage across insulating gap
Ψ = flux linking gap

TAYLOR'S THEORY OF RELAXED STATES

- Relaxation of a plasma with small but finite resistivity

- Relaxed state is obtained by minimising the energy with respect to the single constraint, the total magnetic helicity

$$K_0 = \int_V \underline{A}.\underline{B} \; d\tau$$

is invariant ($\underline{B} = \nabla \times \underline{A}$ where A = vector potential)

- Solution (toroidal flux conserved) is force-free configuration, ie j parallel to B, β=0 which satisfies

$$\nabla \times \underline{B} = \mu \underline{B}$$

μ uniform across the plasma

TAYLOR'S THEORY OF RELAXED STATES

- In a cylinder the solution is Bessel-function (BFM) distribution:

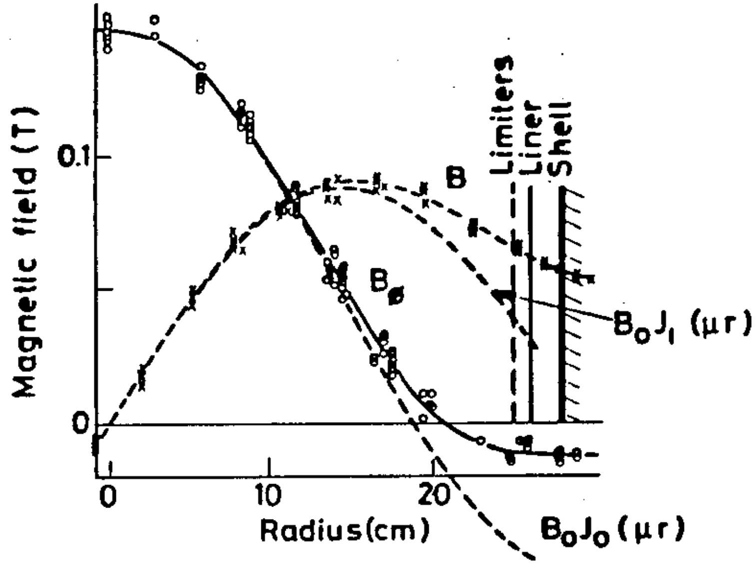
  $B_\phi = B_0 J_0(\mu r)$, $B_\theta = B_0 J_1(\mu r)$, $B_r = 0$

  where

  $\mu = 2\theta/a$, a = radius

- Field reversal when $\theta > 1.2$

- Second, helical, relaxed state when $\theta = 1.6$



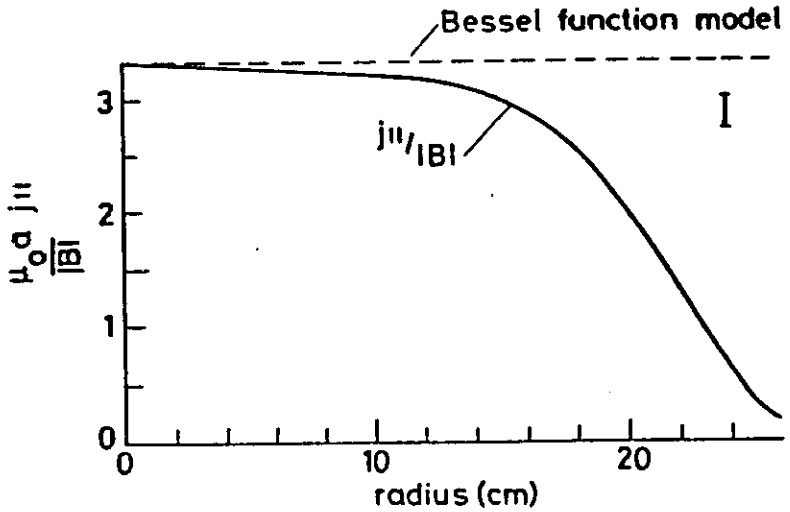
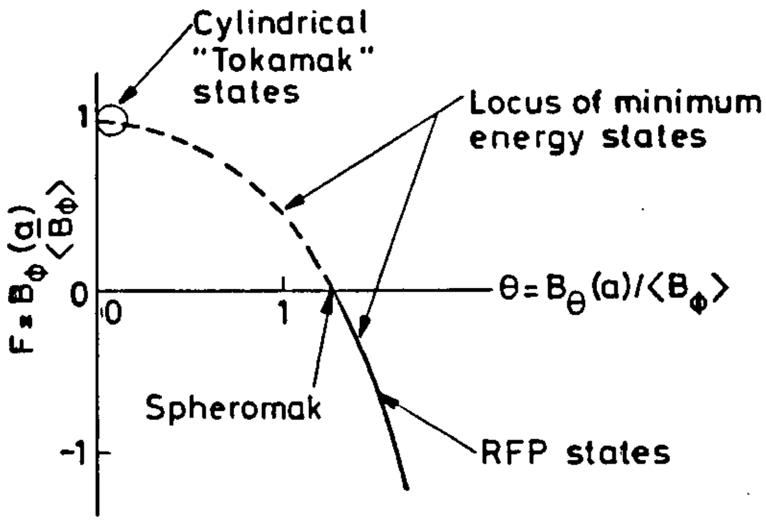


Fig 6.1

F-θ DIAGRAM



- All states on F-θ curve have minimum energy and are stable
- Need for REVERSED FIELD comes from stability theory
  - High-β
  - Vacuum region between plasma and wall

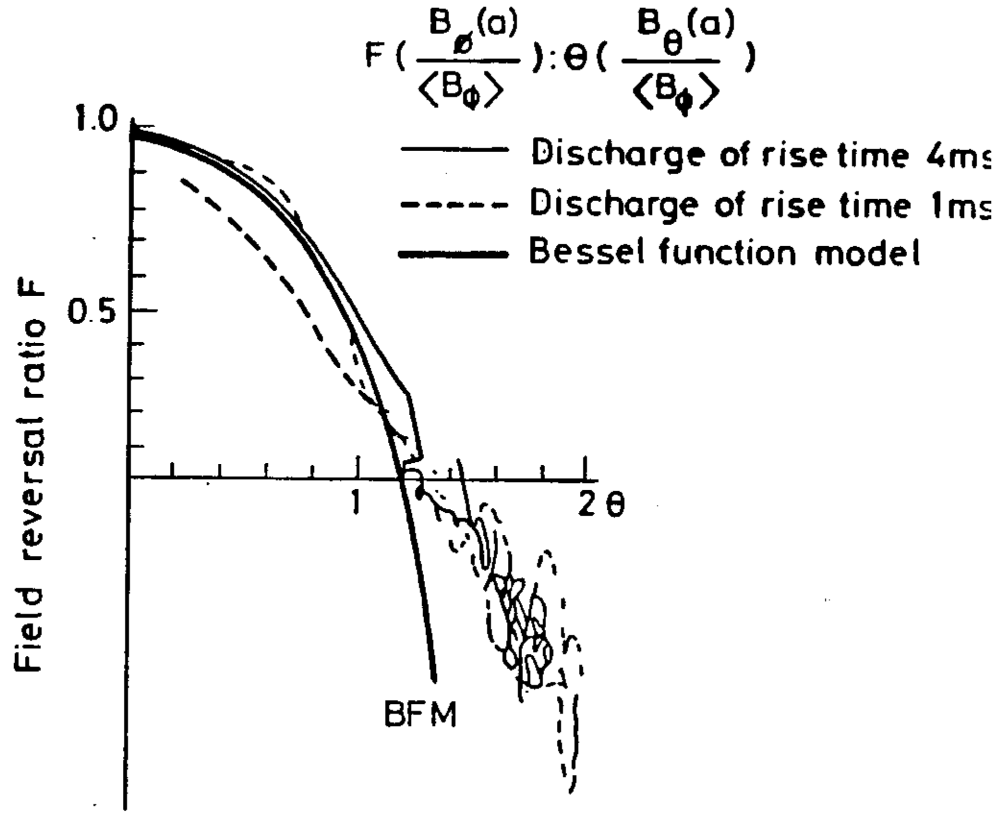


Fig 6.3

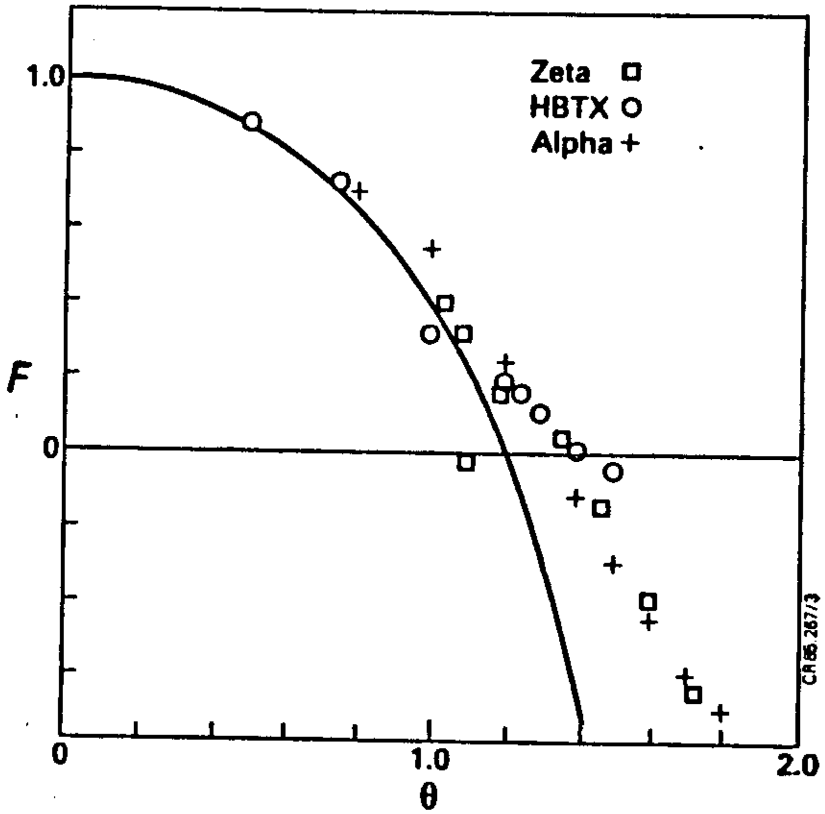
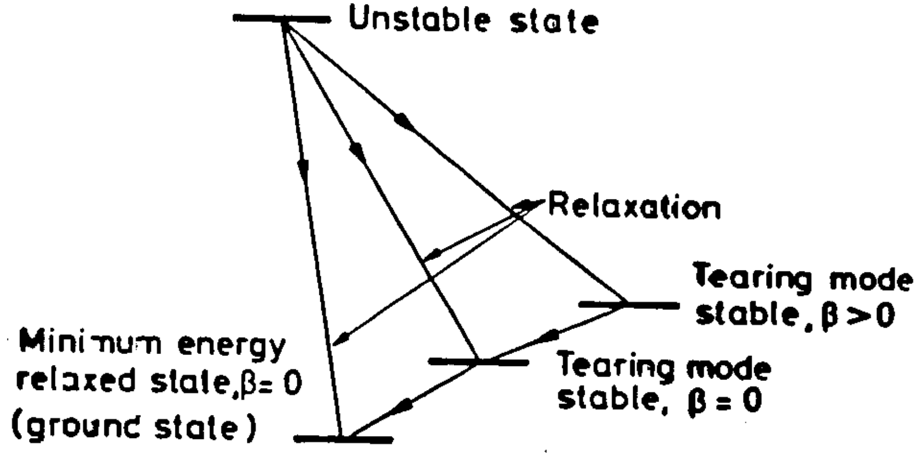


FIG. 3. F-θ diagram. Data from HBTX1, ALPHA, and ZETA and theoretical curve.

STABILITY OF RELAXED STATES



- Within error measured time averaged profiles are either stable or nearly so to ideal and tearing modes BECAUSE RELAXATION ACTS TO MAINTAIN IT SO
- Large amplitude gross modes almost never observed; $\beta_\theta \gtrsim 10\%$

CONSEQUENCES OF RELAXED STATE THEORY

I CONTINUOUS REVERSED FIELD GENERATION

Since the configuration depends on current and average B_ϕ, ie on θ

- If current is maintained (and B_ϕ is fixed) the configuration is SUSTAINED AS A QUASI-STATIONARY STATE

- New reversed field is generated which just compensates tendency to decay by diffusion (DYNAMO)

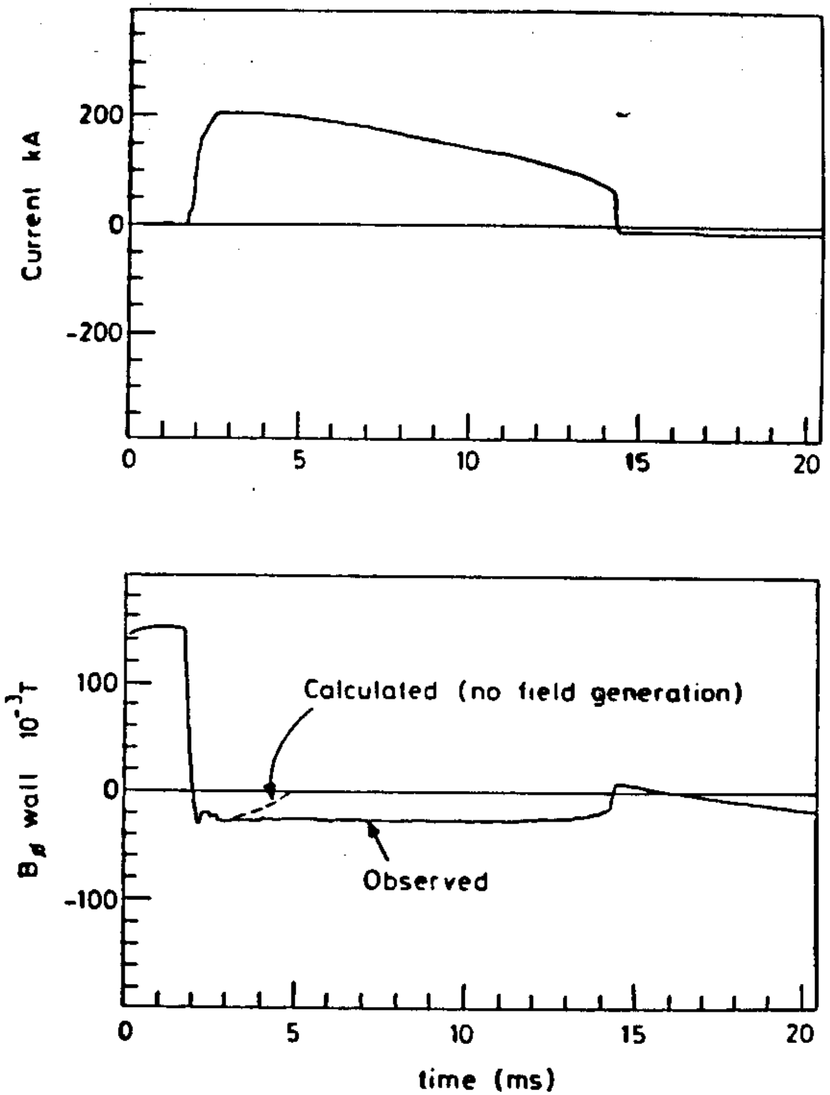


FIGURE 12

SUSTAINMENT OF REVERSED FIELD
EVIDENCE FOR "DYNAMO"

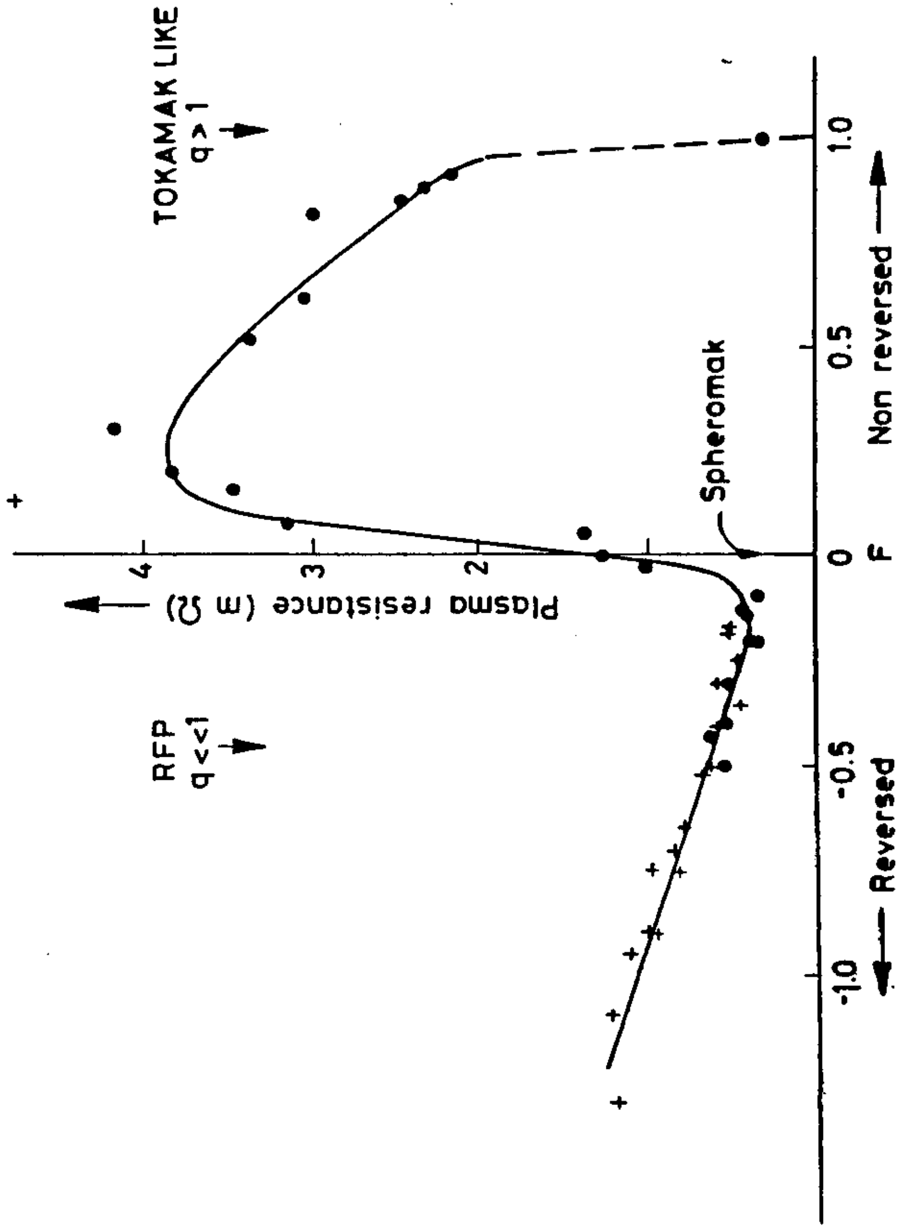

TOKAMAK LIKE
q > 1
RFP
q <<1
Plasma resistance (m Ω)
Spheromak
Non reversed
Reversed
F
1.0
0.5
0
-0.5
-1.0
4
3
2

Fig 6.8

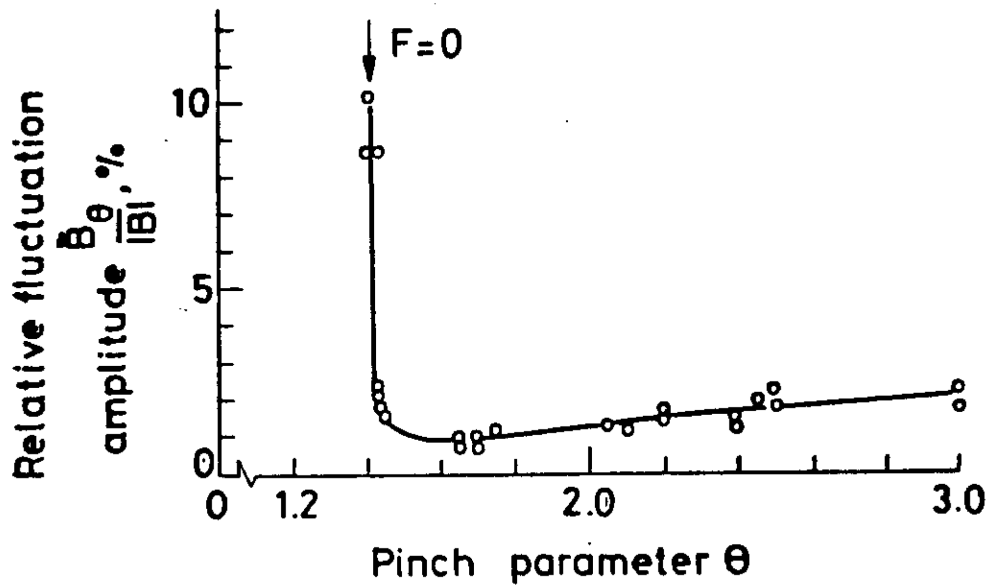

F=0
Relative fluctuation amplitude $\frac{\tilde{B}_\theta}{|B|}$, %
10
5
0
0
1.2
2.0
3.0
Pinch parameter Θ

Fig 6.9

TOPIC 4

MECHANISMS FOR REVERSED FIELD GENERATION

REVERSED FIELD GENERATION

- Basic mechanism is generation of positive (toroidal) flux in the core

- Reversal occurs when total flux (toroidal) is conserved - outer region field reversed to balance new positive core flux

FIELD GENERATION (DYNAMO)

According to Ohm's law in a stationary distribution

$$J_\theta = 0, \text{ when } B_\phi = 0$$

Problem is to explain what drives poloidal J_θ current to support reversal at $B_\phi = 0$ surface

MECHANISMS FOR FIELD GENERATION

- Problem:- what drives j_θ at the reversal surface?
- This cannot occur in steady state on ohms law when $E_\theta \propto d\phi/dt = 0$

$$B_\phi = 0$$

$$E_\parallel = 0$$

$$\text{but} \quad j_\parallel \neq 0$$

$\therefore \underline{E} + \underline{v} \times \underline{B} = \eta \underline{j}$ NOT SATISFIED

FIELD GENERATION (cont)

Two general kinds of mechanism

TYPE 1 Add a new term to Ohm's law (Dynamo term)

TYPE 2 Abandon concept of local Ohm's law because fields stochastic

FIELD GENERATION (DYNAMO) (cont)

Two kinds of model

(1) The E_θ field which drives j_θ comes from non-linear effects of instabilities eg α-effect (Gimblett)

(2) When field lines are stochastic (wander about; no closed, nested, surfaces) a global Ohm's law applie and j_θ is driven by electric fields originating elsewhere in plasma, eg Tangled Discharge (Rusbridge)

EXAMPLES OF MECHANISMS FOR FIELD GENERATION

Type 1

: The "α-effect"

Modify Ohm's law

$$\eta \underline{j} = \underline{E} + \alpha \underline{B} - \beta \underline{j}$$

: Simple large amplitude kink

: Inverse reconnection

Type 2

: Tangled Discharge

: Kinetic mechanism

1) Initial column with conserved B_ϕ

2) Becomes m=1 unstable
Flux enhanced at centre
⟹ reverses at wall

3) Adjacent loops of plasma reconnect
⟹ axisymmetric RFP

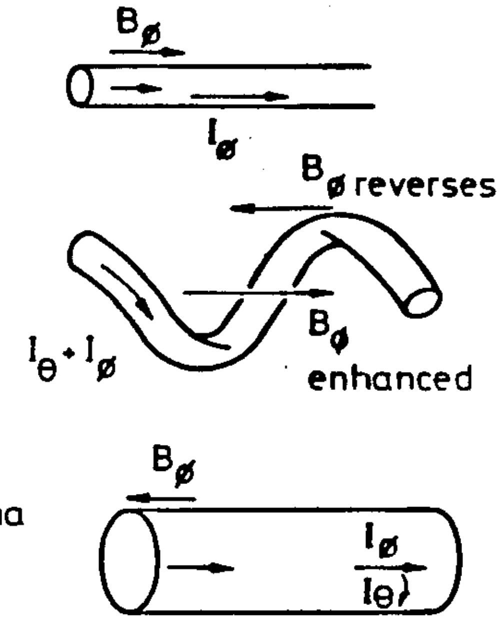


Fig 6.13

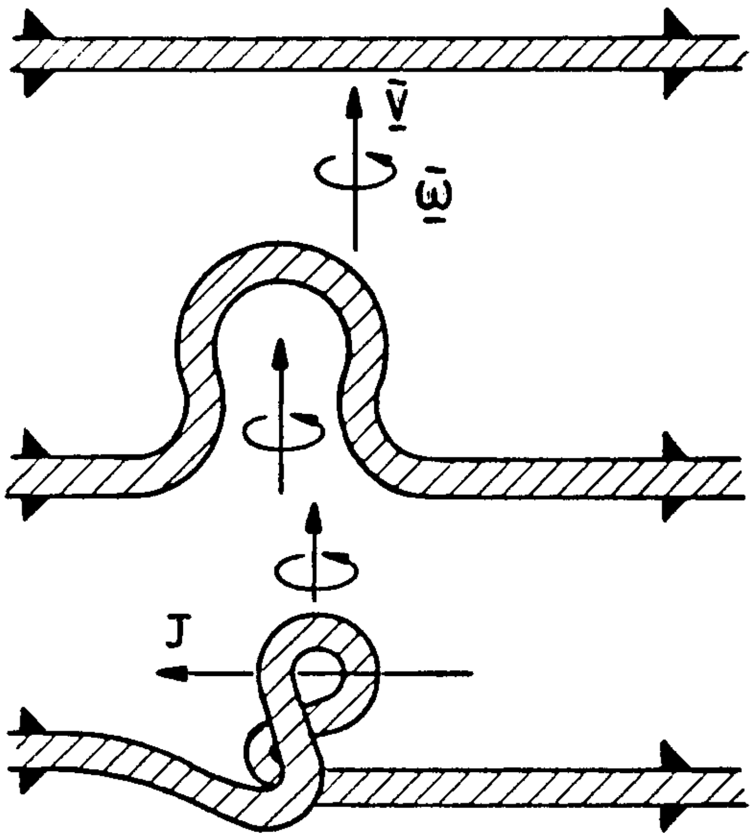


Fig 6.12

TOPIC 5

RFP THEORY

- Results for Basic Equilibrium, Stability and Transport Theory
- Helicity Balance Considerations
- 3-D MHD Code Calculations

EQUILIBRIUM

Radial Equilibrium

Pressure balance

$$\beta_\theta I^2 = \frac{8\pi}{\mu_o} Nk \,(T_e + T_i)$$

where $N = \pi a^2 n$

Toroidal Equilibrium

- Equilibrium by conducting shell and/or vertical field B_v
- Shafranov Eq

Outward force =

$$\frac{\mu_o I^2}{2}\left(\frac{\beta_\theta}{2} + \frac{\beta_\theta - 1}{2} + \ln\frac{8R}{a} - 1 + \frac{l_i}{2}\right)$$

↑ pressure ($\frac{\beta_\theta}{2}$), ↑ ∇B_ϕ ($\frac{\beta_\theta - 1}{2}$), ↑ Hoop force of I_ϕ ($\ln\frac{8R}{a}$)

Displacement δ =

$$\frac{b^2}{2R}\left[\left(\beta_\theta + \frac{l_i - 1}{2}\right)\left(1 - \frac{a^2}{b^2}\right) + \ln\frac{b}{a}\right] - \frac{bB_v}{B_\theta(b)}$$

where a = plasma radius, b = shell radius

STABILITY (cont)

- Ideal MHD
- Resistive MHD
  - Tearing modes ($\nabla j_{\parallel}$)
  - g-modes (∇p)
- Stability depends on $B_\theta(r)$, $B_\phi(r)$-pitch profile $q(r)$
- High-β

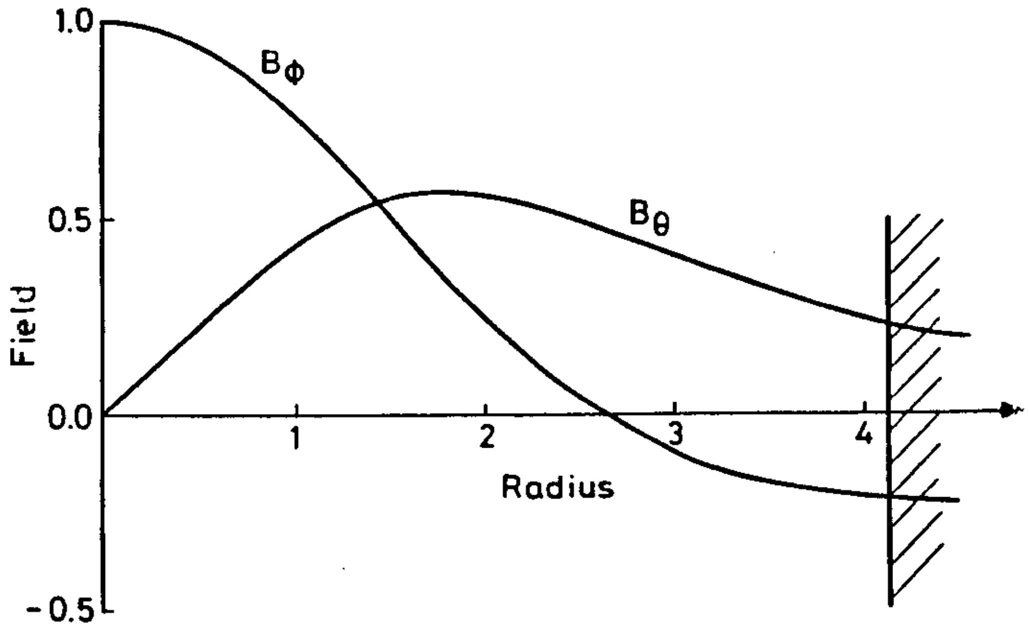


Fig 6.19

STABILITY OF RELAXED STATES

- All minimum energy relaxed states are STABLE
- In practice equilibria are NEAR MINIMJM ENERGY

  - Finite β

  - $\mu(r) \neq$ constant near walls

- Models for "realistic distributions" eg $\mu \alpha \left[1-(r/a)^{\alpha}\right]$
- Stability theory and relaxation theory are complimentary

  eg Importance of reversal - stability theory

TRANSPORT - BASIC IDEAS

- Basic Eq $nv_{\perp} = -D_{\perp} \nabla n$
- Particle picture

$$D_{\perp} \simeq r_{ce}^2 \nu_{ei} \rightarrow \frac{1}{T_e^{1/2} B^2}$$

- Fluid picture

$$D_{\perp} \sim \frac{nkT}{B^2} \frac{1}{\sigma} \rightarrow \frac{1}{T^{1/2} B^2}$$

TRANSPORT

- Classical ion cross field transport $D_\perp^{cl,i}$
- Energy confinement in experiment
- Transport due to resistive fluid turbulence; stochastic fields; magnetic islands

CLASSICAL ION CROSSFIELD TRANSPORT

$$D_{\perp class}^{ions} = \left(\frac{m_i}{m_e}\right)^{1/2} \frac{\beta_e}{\mu_o \sigma_\parallel}$$

$$\tau_E \propto \frac{a^2}{D_\perp}$$

$$\therefore \qquad \tau_{Eclass}^{ion} = \left(\frac{m_i}{m_e}\right)^{1/2} \frac{\mu_o \sigma_\parallel (a/\alpha)^2}{\beta_e}$$

NOTES - Resistive field diffusion time
$\tau_R \propto \mu_o \sigma a^2$

- Neoclassical effects small

ENERGY CONFINEMENT TIME IN EXPERIMENT

$$\tau_E^{EXP} = \frac{\text{plasma energy}}{\text{Ohmic heating rate}} = \frac{3NkT}{I^2R}$$

$T = T_e = T_i$

or

$$\tau_E^{EXP} = \frac{3}{16} \mu_0 \beta_\theta \sigma a^2$$

$$\frac{\tau_E^{EXP}}{\tau_{Eclass}^{ion}} \propto \frac{1}{\beta_\theta^2} \sim \frac{1}{50} - \frac{1}{100} \text{ for } \beta_\theta = 10\%$$

TRANSPORT THEORIES BASED ON RESISTIVE FLUID TURBULENCE AND FLUCTUATIONS

- Conner-Taylor (g-modes)

$$\beta_\theta = (m/M)^{1/6} \sim \text{const} \quad T \tilde{\propto} I$$

- Diamond et al (tearing modes)

$$\beta_\theta \simeq a^{-1/6}(I/N)^{-1/3} I^{-1/3}$$

$$T \underset{\propto}{\sim} I^{0.7}$$

- Stochastic Field Line Diffusion

$$\tau_E \sim (\tilde{B}/B)^{-2}$$

$\tilde{B}/B$ falls with current (observed)

$T \tilde{\propto} I$ (from fluctuation data)

THEORY

1. Thin shell calculations (HBTX1C)

2. 3D code

- Single fluid; incompressible
- Input parameters (Expt); s, $\eta(r)$
- Predicts F-θ, $\mu(r)$, $\tilde{B}/B$ (S)
- "Dynamo Term" $(\underline{v} \times \underline{B})_\theta = v_r B_\phi - v_\phi B_r$
  $v_\phi B_r$ dominates

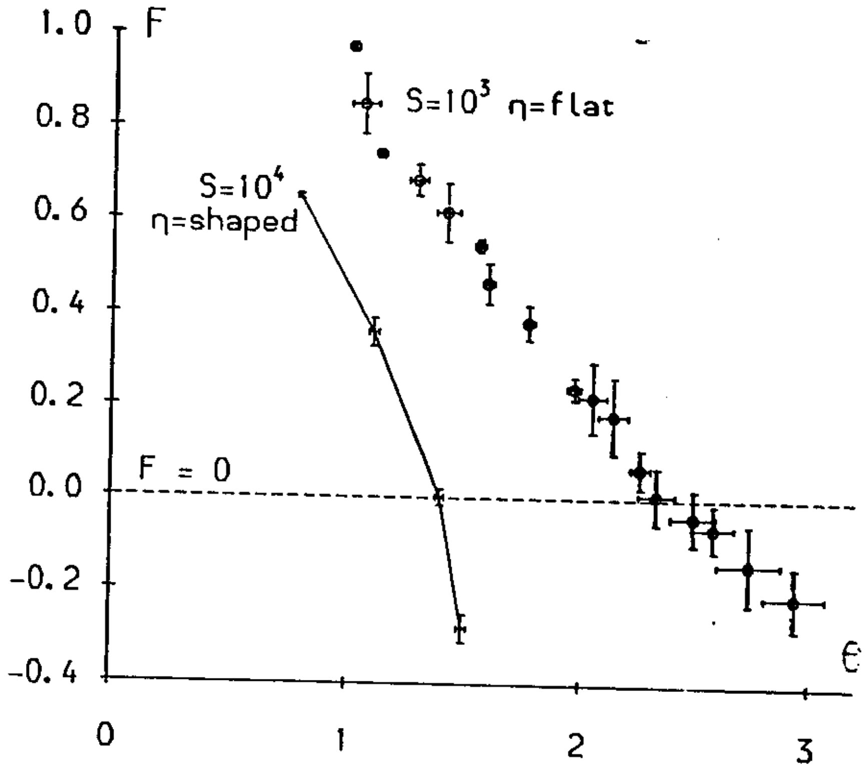
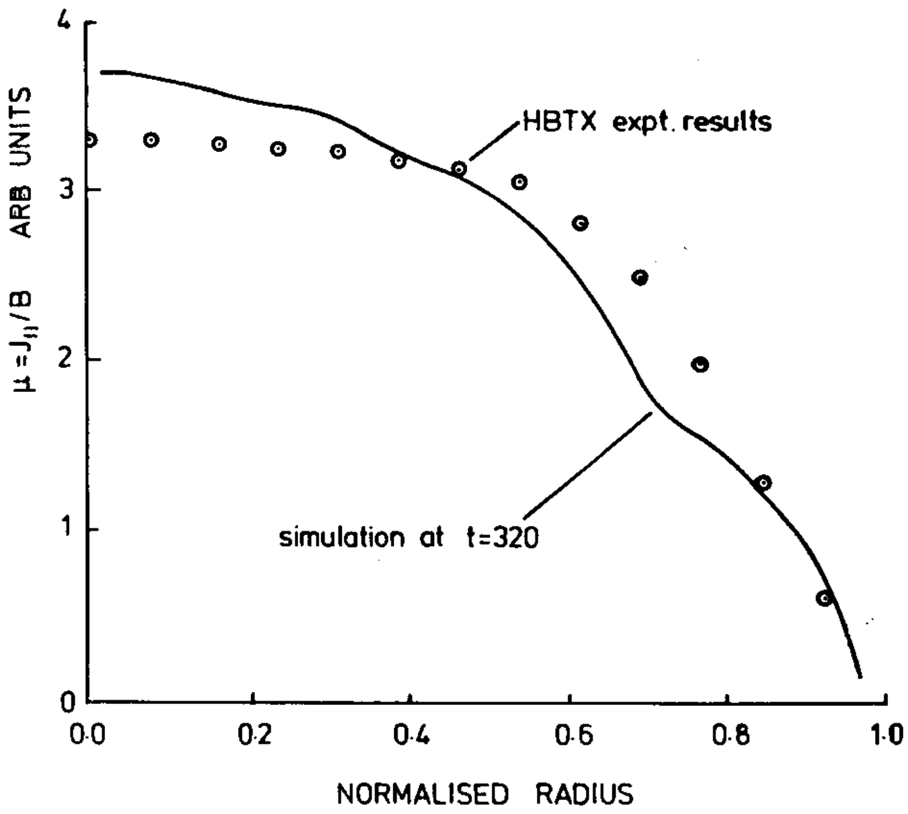


Fig. 2 F vs. theta in the steady state.
Bars show fluctuation amplitudes.
(Cases: $S=10^3$, η=flat and $S=10^4$, η=shaped

RADIAL μ- PROFILE 3D CODE AND HBTX EXPERIMENT.



SIMPLE OHMIC RESISTIVITY

$$\eta^{c}(0) = \frac{V_\phi}{I_\phi}\frac{\pi a^2}{2\pi R}\frac{[j_\phi]}{j_\phi(0)}$$

ENERGY RESISTIVITY

$$\frac{dW_m}{dt} = V_\phi I_\phi - V_\theta I_\theta - \int E\cdot j\, d^3x$$

$$\eta(0) = \frac{V_\phi I_\phi - \int \eta\langle \tilde{j}^2\rangle - \langle \underline{\tilde{u}}\times\underline{\tilde{B}}\rangle\cdot \underline{j}_o - \langle \underline{\tilde{u}}\times \underline{B}_o\cdot \underline{\tilde{j}}\rangle\, d^3x}{\int \frac{\eta(r)}{\eta(0)}\, j_o^2\, d^3x}$$

Neglect fluctuations

$$\eta^W(0) = \frac{V_\phi}{I_\phi}\,\frac{\pi a^2}{2\pi R}\,\frac{[j_o]^2}{[j_o^2\eta(r)/\eta(0)]}$$

HELICITY RESISTIVITY

$$\frac{dk}{dt} = 2\gamma V_L - 2\int E\cdot B\, d^3x$$

k is helicity $= \int \underline{A}\cdot\underline{B}\, d^3x$, $\underline{B} = \nabla\times\underline{A}$

ϕ is toroidal flux V_L is loop voltage

$$\eta(0) = \frac{\Phi V_\phi - \int \eta\langle \underline{j}\cdot\underline{B}\rangle\, d^3x}{\int \frac{\eta(r)}{\eta(0)}\, \underline{j}_o\cdot\underline{B}_o\, d^3x}$$

Neglect fluctuations and

$$\eta^k(0) = \frac{V_\phi}{I_\phi}\,\frac{\pi a^2}{2\pi R}\,\frac{[B_\phi]\,[j_\phi]}{[\underline{j}_o\cdot\underline{B}_o\eta(r)/\eta(0)]}$$

HELICITY AND ENERGY BALANCE - RESISTIVITY AND LOOP VOLTAGE

(when $\underline{B}_0 \cdot \underline{n} = 0$)

HELICITY BALANCE

$$V_L \phi = \int \underline{E} \cdot \underline{B} \, d^3x$$

ENERGY BALANCE

$$V_L I = \int \underline{E} \cdot \underline{j} \, d^3x$$

It is necessary to include <u>fluctuations</u>

$$\underline{E} = \underline{E}_0 + \underline{\tilde{E}} \text{ etc}$$

HELICITY

$$V_L \phi = \int [\eta \underline{j}_0 \cdot \underline{B}_0 + \underbrace{\langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot B_0}_{0}] \, d^3x$$

ENERGY

$$V_L I = \int [\eta j_0^2 - \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0 - \underbrace{\langle \underline{u} \times B_0 \cdot j \rangle}_{0}] d^3x$$

- Fluctuations do not dissipate helicity
- Taylor state μ=const $\int \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0 d^3x = 0$

HELICITY AND ENERGY BALANCE - RESISTIVITY AND LOOP VOLTAGE

One obtains

HELICITY

$$V_L \phi = \int \eta \underline{j}_0 \cdot \underline{B}_0 \, d^3x$$

ENERGY

$$V_L I = \int [\eta j_0^2 - \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0] d^3x$$

↑ DYNAMO TERM

$$V_{loop} = V_L^W \text{ (Spitzer)} + V_L(\underline{\tilde{u}} \times \underline{\tilde{B}})$$

$$V_{loop} = V_L^k \text{ (Spitzer)}$$

If fluctuations neglected

$$\eta^c > \eta^W \geq \eta^k$$

η^c is from simple Ohm's law
V_L^W, η^W, η^K and V_L^k mean different things.
η^k "most accurate"

TOPIC 6

THE HBTX RFP EXPERIMENT

GENERAL INTRODUCTION

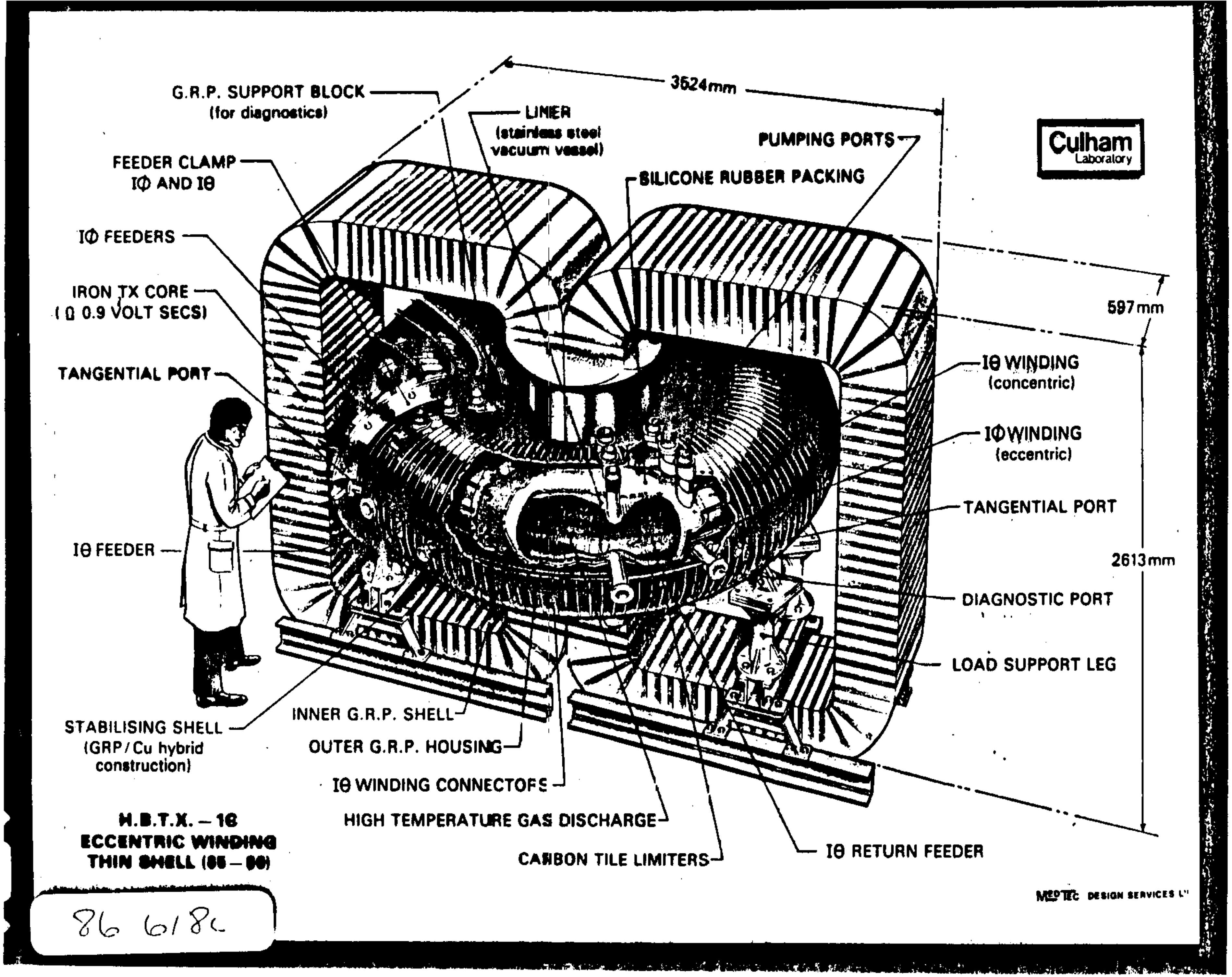
HBTX1B REVERSED FIELD PINCH

Parameters of HBTX1B

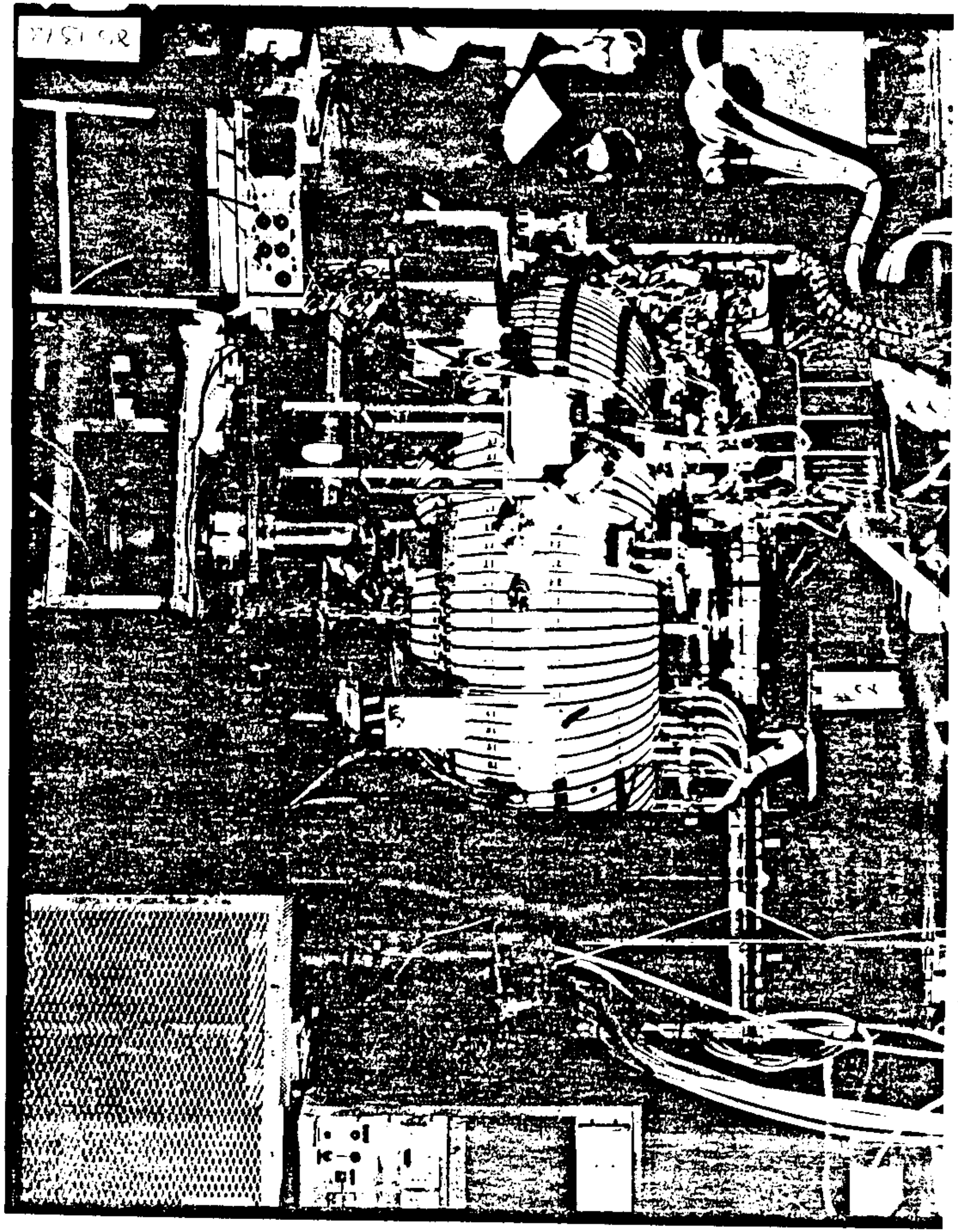
R/a	0.8m/0.26
I_{max}	520 kA
τ_{rise}	~ 0.5 ms
τ_{pulse}	~ 10 ms

Carbon tile limiters (8%)

55

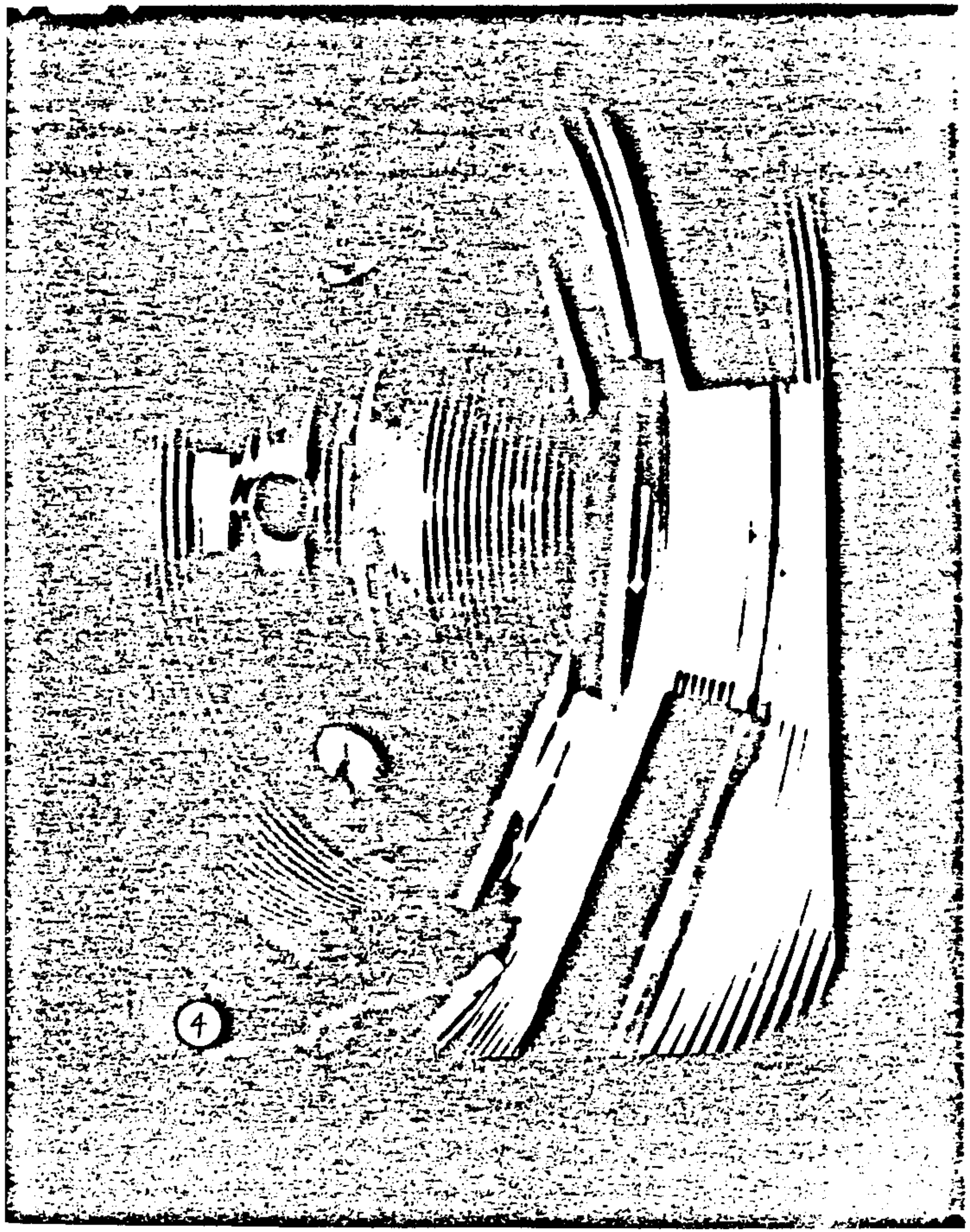

G.R.P. SUPPORT BLOCK (for diagnostics)
LINER (stainless steel vacuum vessel)
3524mm
PUMPING PORTS
Culham Laboratory
SILICONE RUBBER PACKING
FEEDER CLAMP IΦ AND Iθ
IΦ FEEDERS
IRON TX CORE (Ω 0.9 VOLT SECS)
597mm
TANGENTIAL PORT
Iθ WINDING (concentric)
IΦ WINDING (eccentric)
TANGENTIAL PORT
Iθ FEEDER
2613mm
DIAGNOSTIC PORT
LOAD SUPPORT LEG
STABILISING SHELL (GRP/Cu hybrid construction)
INNER G.R.P. SHELL
OUTER G.R.P. HOUSING
Iθ WINDING CONNECTORS
HIGH TEMPERATURE GAS DISCHARGE
CARBON TILE LIMITERS
Iθ RETURN FEEDER
H.B.T.X. – 1B
ECCENTRIC WINDING
THIN SHELL (85 – 90)
MEDTEC DESIGN SERVICES L

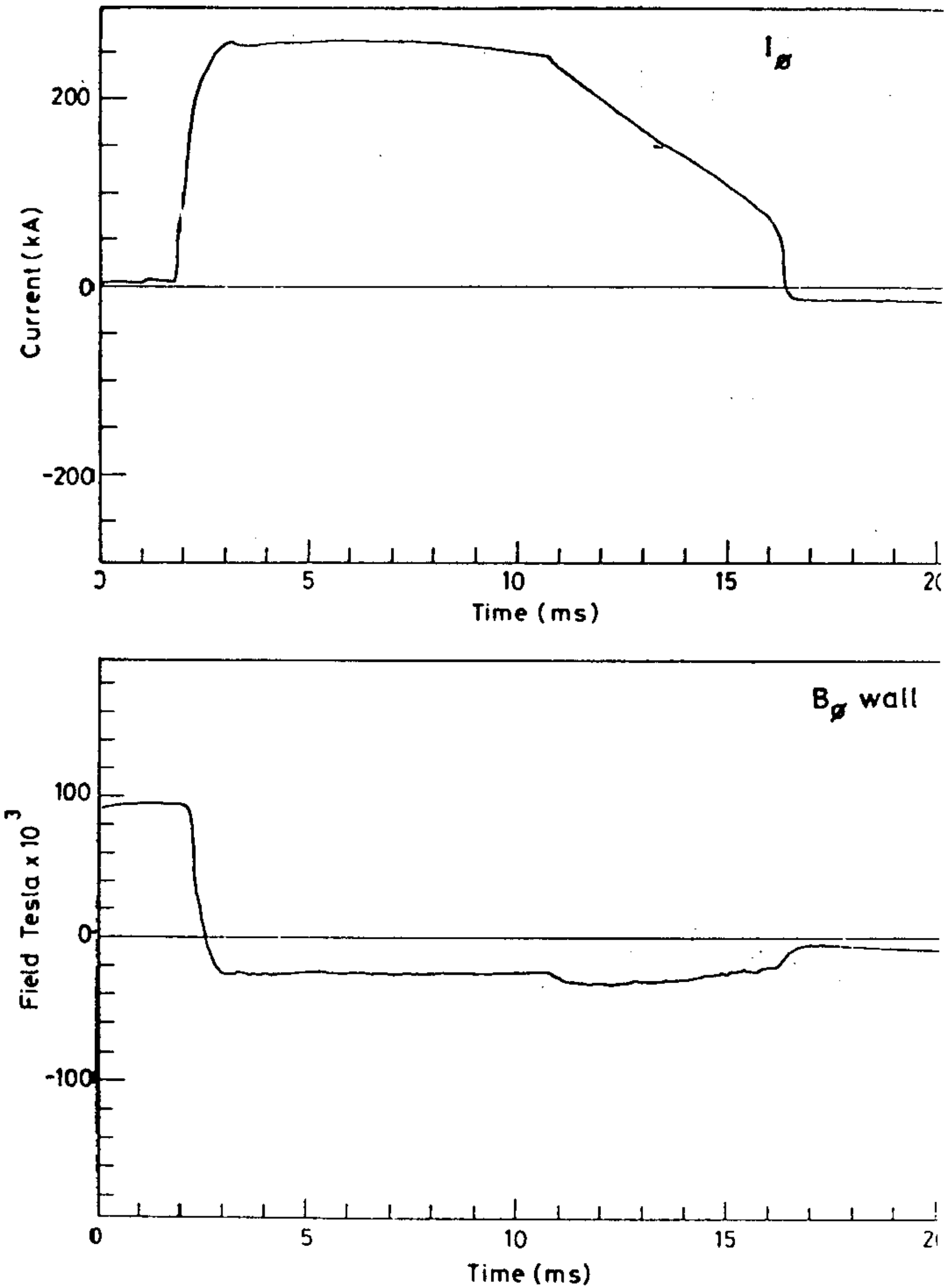
86 6/8c



HBTX1B - MAIN FEATURES

- Carbon Tile Limiters (200, 10% coverage)
- Poloidal Gap correction and DC vertical field
- Setting Up - Matched (or Self Reversal only)
- Density Control by wall preconditioning
- Approximately steady state conditions 5-10 ms
- Controlled current rundown





HBTX1B Waveforms

TOPICS STUDIED ON HBTX 1986/87

• Plasma parameters - scaling database	Alper
• Loop voltage effects	Alper Tsui Newton
• Ion heating, rotation	Carolan Bunting Tsui
• Limiter removal	Newton et al

TOPICS STUDIED ON HBTX 1986/87 (cont)

• Radiation and impurities - Radiation is not a major energy loss; impurity concentrations, Z_{eff} (important) and transport determined	Carolan et al Bunting
• Fluctuations - New phenomena at high-θ and with limiters removed - Large amplitude "more coherent" phenomena (m=0, m=1) - Taylor's second (helical) state?	Tsui Evans et al
• Density control by wall loading and improved puffing; pellets	Alper Noonan
• Ramping, controlled rundown, decaying plasmas	Noonan Gimblett Newton

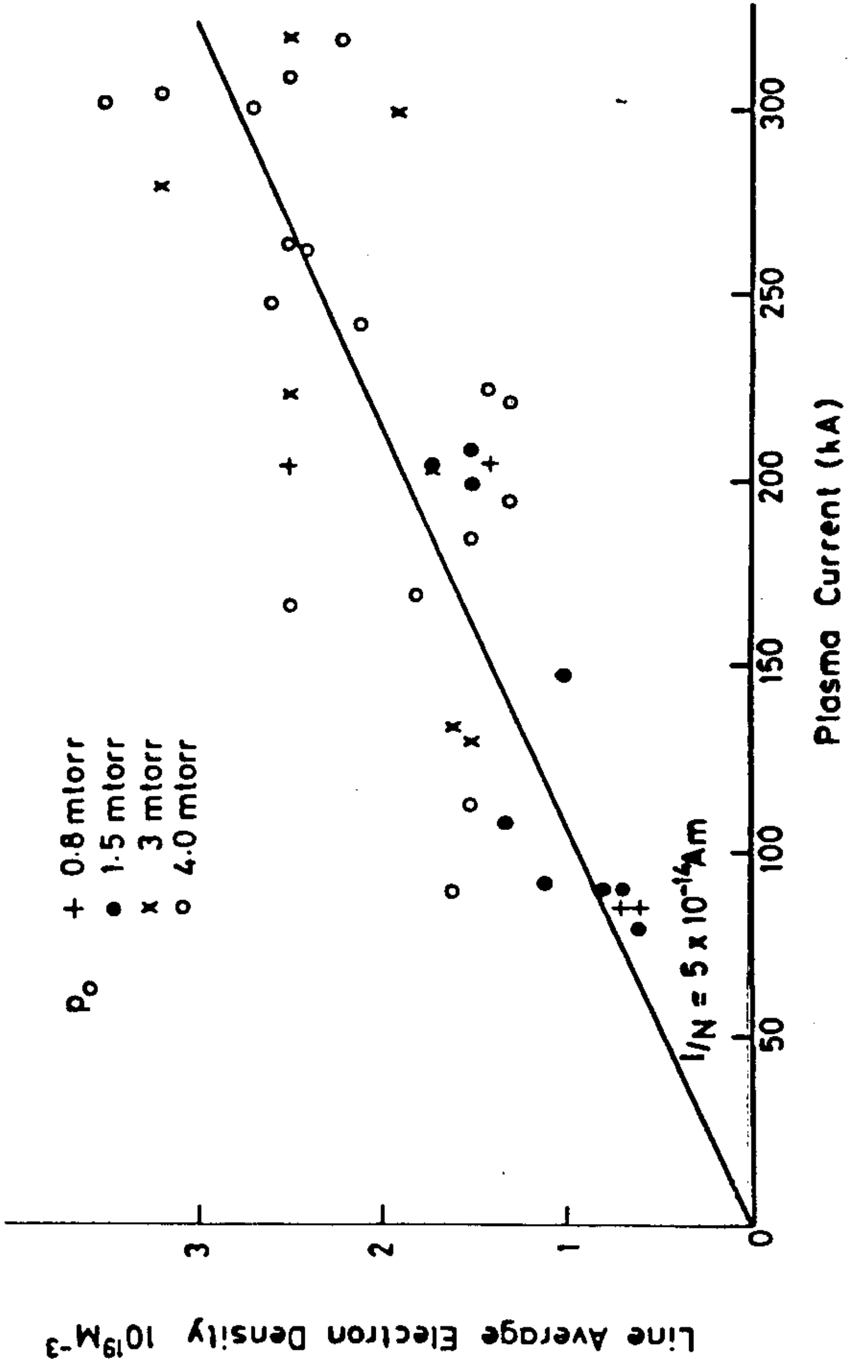
HBTX DIAGNOSTICS

Electrical & Magnetic Measurements	- Noonan Tsui+ Cunnane+
Temperature	
T_e soft X-rays	- Alper Hayden+
Thomson Scat	- Wilcock
T_i Neutral Particle Analyser	- Field+
Density CO_2 Interferometer (3 channel)	- Storey+
Total Radiation Bolometer (3 channel)	- Bunting
Spectroscopy (Carolan)	
Polychromator (40 channel)	- Patel+
Multichord spectrometer (20 channel)	- Schneider+
Z_{eff} monitor)	- Manley+
Normal inc spec with OMA (400-3500 Å))	
Vac UV	- Hawkes
Fluorescent scattering	- Forrest Imp Col
Surface Barrier Diode Arrays	- Gee+
First wall monitors	- Firth

+Attached staff from universities

HBTX1B - PLASMA PARAMETERS

T_e (Si(Li))	100-450 eV
T_i (NPA)	$(1 \pm 0.2)T_e$
n_e (Linear)	$1 - 5 \times 10^{19}\ m^{-3}$
I/N (Parab)	$4 - 15 \times 10^{-14}$ a.m
τ_E (Parab)	0.2-0.4 ms
β_θ Typical value	10%
Range	5-25%

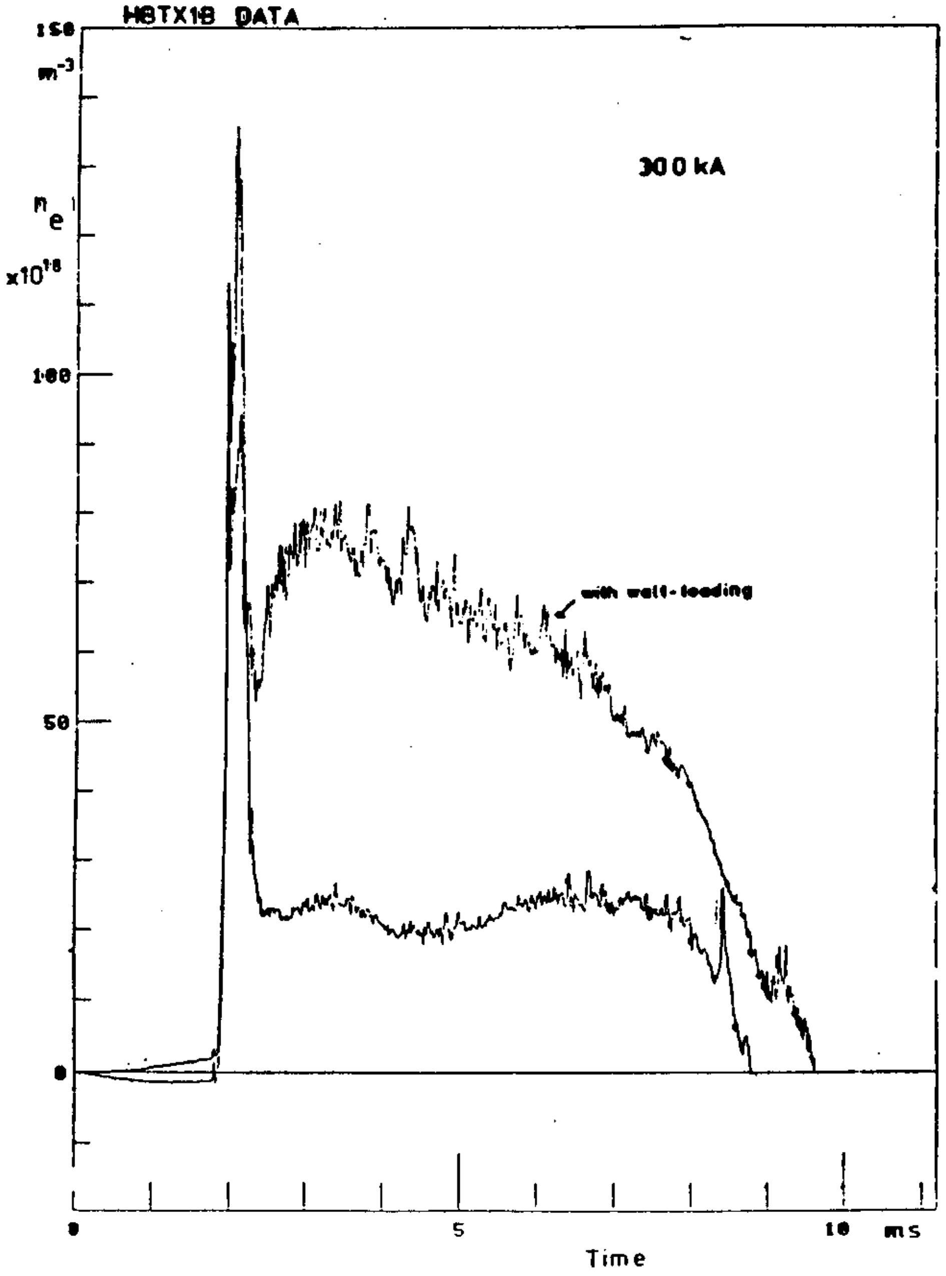


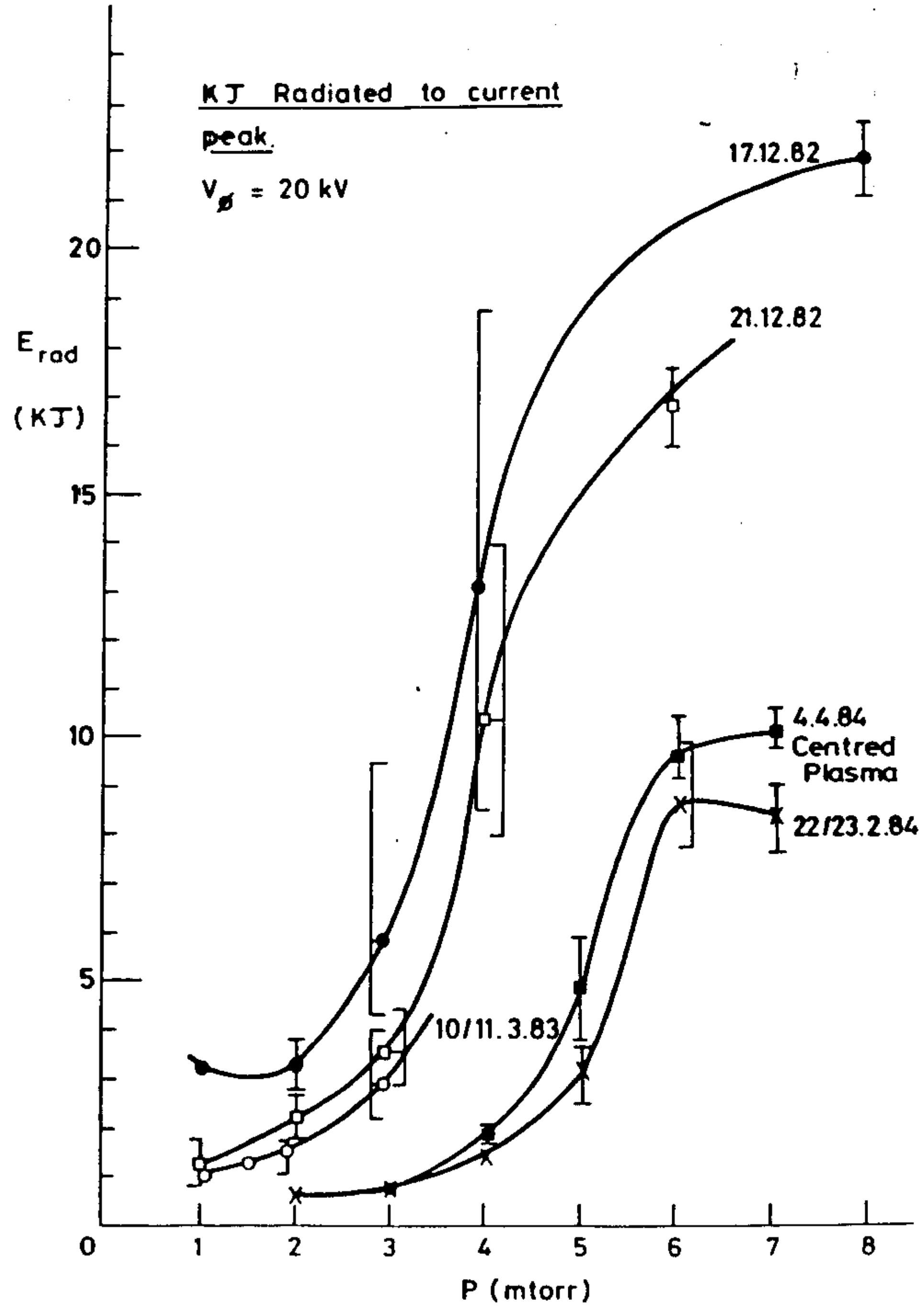
DENSITY BEHAVIOUR II

With Density Control by Wall Pre-Conditioning

- The carbon tile limiters (~ 8% surface area) are preloaded with gas
- Preloading described by numerical simulation
- Density and current flat tops 5-10 ms
- Density can also be controlled by
  - injecting puffs of D_2 gas
  - injecting pellets of solid, frozen D_2

DENSITY CONTROL BY WALL PRE-CONDITIONING





HIGH FILLING DENSITY LIMIT

- As p_0 raised radiation increases
- Discharges become resistive - RFP will not form
- Due to radiation cooling by light elements (eg 1-2% O, N)
- Except at very high density

  $P_{rad}/P_{ohmic} \gtrsim$ 5-10% (HBTX)

ANOMALOUS RESISTANCE

The resistance

- Cannot be explained in a simple way by impurities taking into account
  - Radial profiles of:- T_e, n_e, ion species, Z_{eff}
  - Total radiation
- Depends little on T_e (fixed I)
  eg R = 152±12 μohm, 220 eV$<T_e<$470 eV
- Does not correlate systematically with impurities
- Depends sensitively on size of "edge region" defined by limiters, field errors, equilibrium position

$$V_{loop} = I\ R_{(Spitzer+impurities)}$$

$$+\ V\ \text{(due to edge helicity dissipation where field lines intersect material objects)}$$

RESISTANCE ANOMALY FACTOR

$$Z^*_{eff} = \frac{\text{Resistivity on axis, } \eta_o \text{, from } V_{loop}}{\text{Spitzer value for } T_e(0)}$$

(For η_0 - $j(r)$ profile based on experiment assumed)

MAGNETIC FIELD GEOMETRY, RESISTANCE AND CONFINEMENT

Reduced field errors and accurate centering

- Decreases the resistance
- Has little effect on β,T

Increased τ_E due to reduced R, $\tau_E \sim \beta/R$

TOPIC 7

ION HEATING

ION HEATING

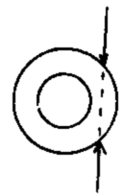
(Deuterium - NPA; Carbon - OMA Doppler spectrometer viewing opposed tangential ports)

DEUTERIUM

- $T_i = T_e \pm 20\%$, $200 < T_i < 450$ eV
- T_i (from collisions + impurity effects) $\sim T_e/10$
  Anomalous ion heating

CARBON

- T(CV) $\sim$ T(D)
- Rotation (ion current direction)

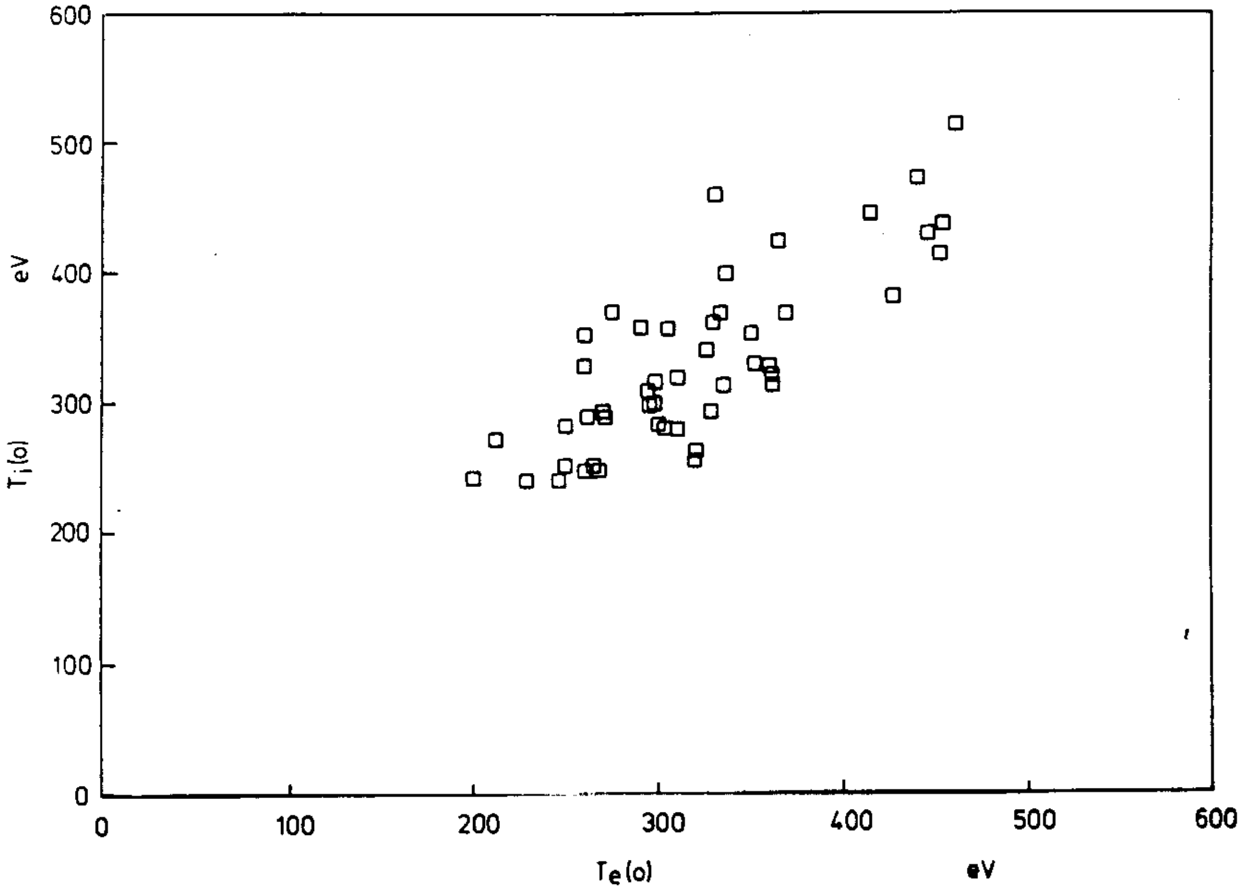


$$v_\phi \gtrsim 1\text{-}4 \times 10^4 \text{ ms}^{-1}$$

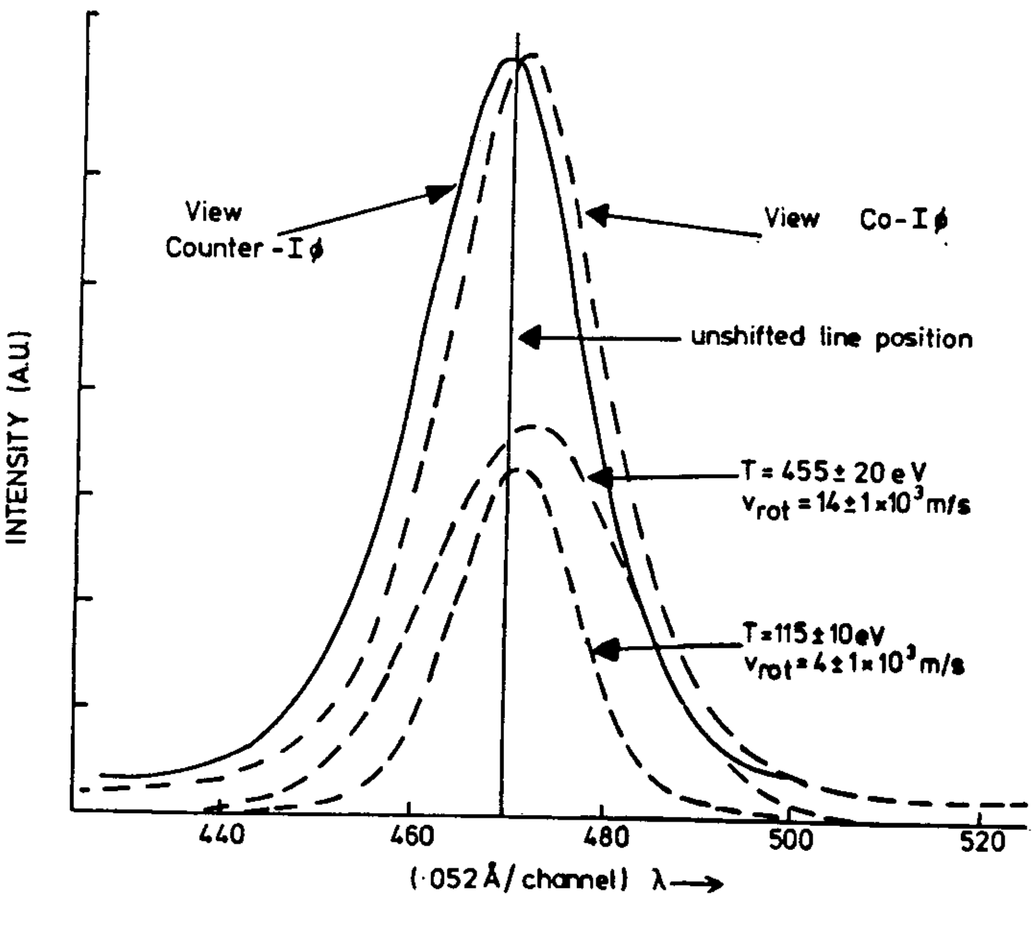
$$v_\theta \gtrsim 4 \times 10^3 \text{ ms}^{-1}$$

- Direct ion heating from E_ϕ
  - significant for carbon (1 keV/ms)
  - small for deuterium

ION VS ELECTRON TEMPERATURE



TANGENTIAL CV (2271) SPECTRA AND GAUSSIAN T_i FITS



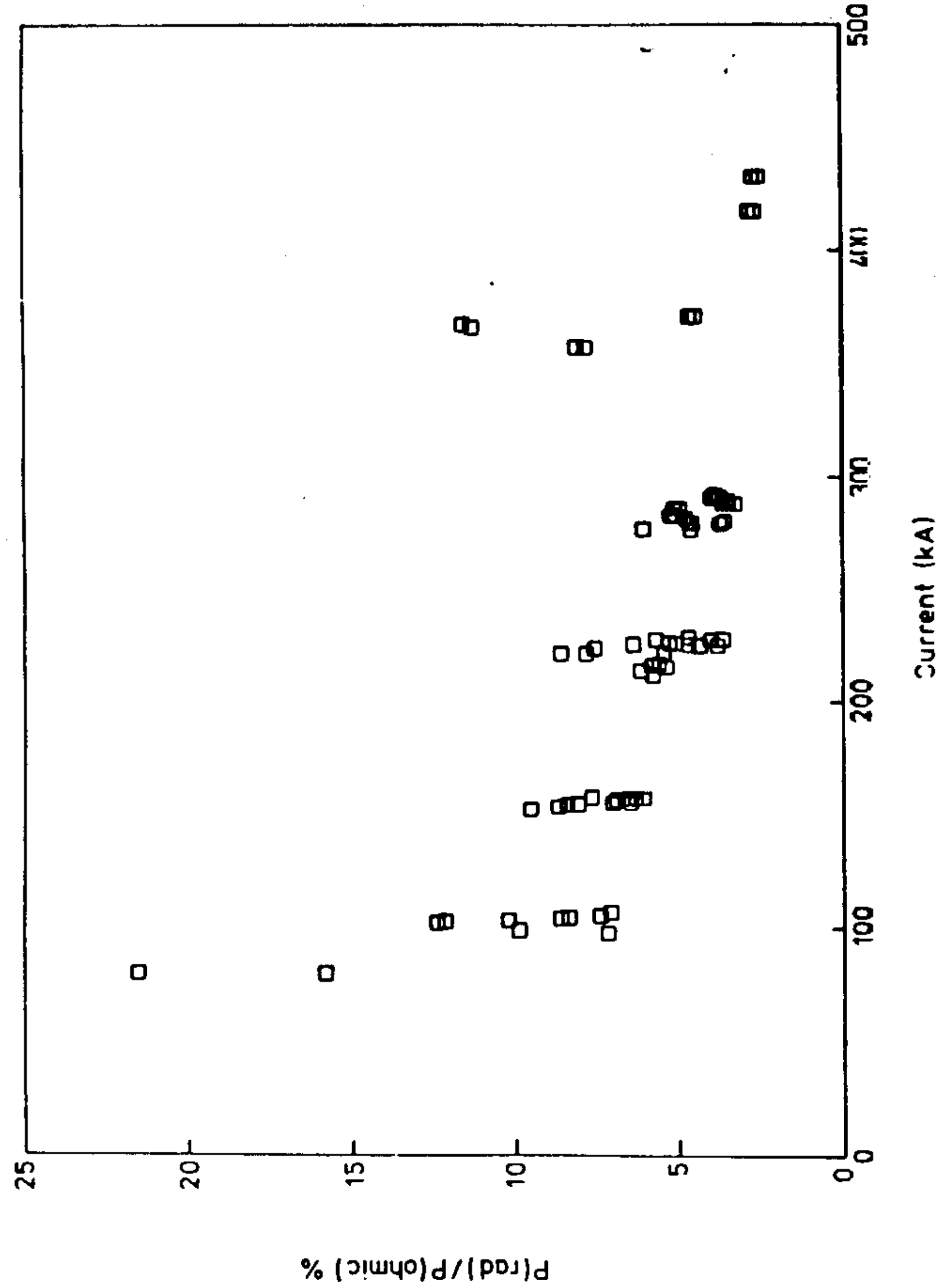
TOPIC 8

RADIATION AND IMPURITIES

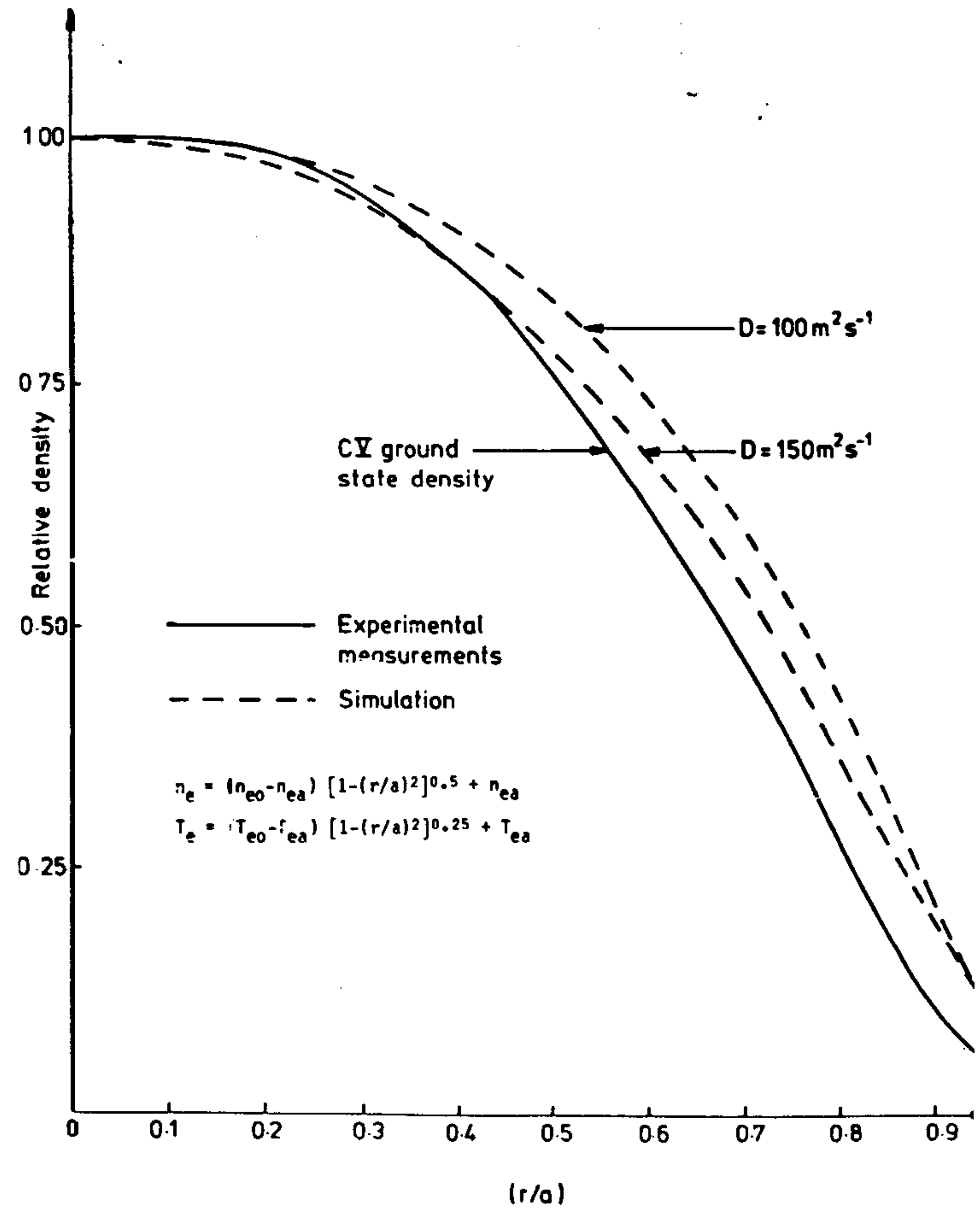
RADIATION AND IMPURITIES

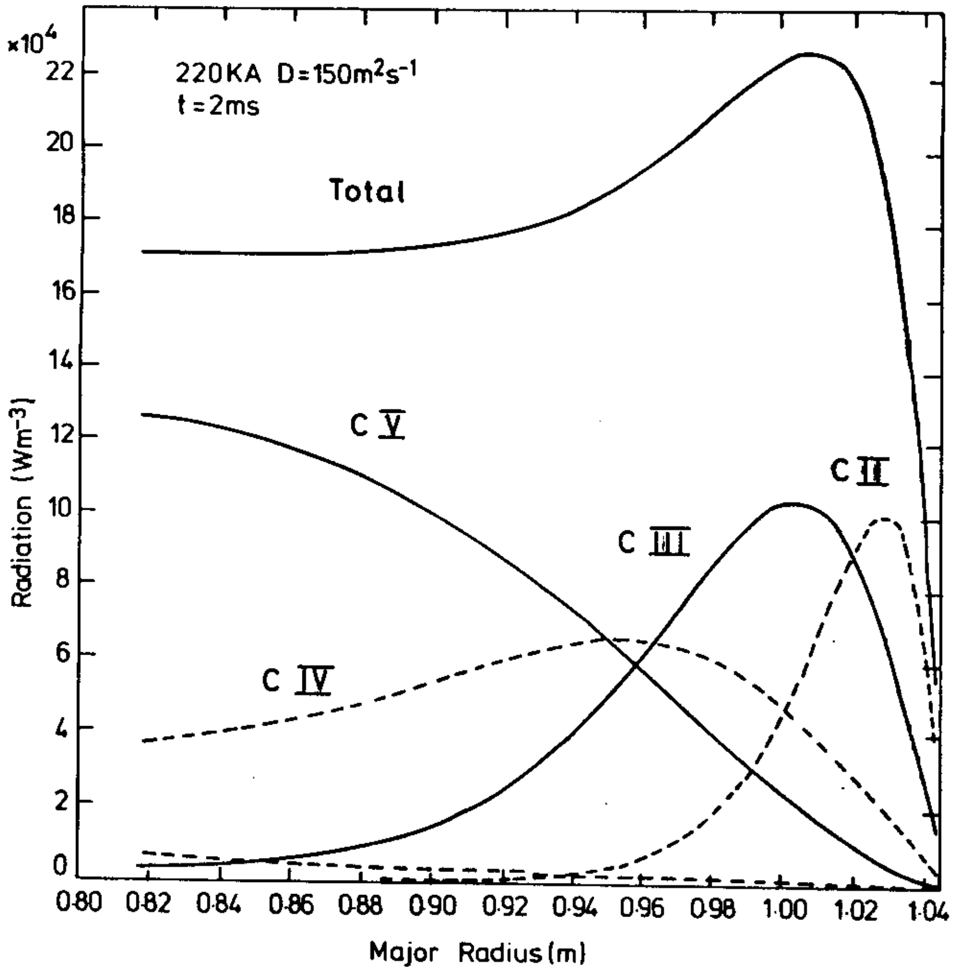
- Impurity concentration 1-2% low Z, 0.1% metals
- P_{rad}/P_{ohmic} (typically 4% at 300 kA) falls with I. Unimportant in energy balance
- No radiation cooled mantle controlling T_{edge} as in Tokamak
- Impurity diffusion
  - $D(CV) \sim 100\text{-}150\ m^2s^{-1}$
  - $n_e\tau(CV) \sim n_e\tau_E$

RADIATED POWER/OHMIC POWER vs CURRENT



CV PROFILE - EXP AND THEORY WITH DIFFERENT $D_\perp$





×10⁴
220KA D=150m²s⁻¹
t=2ms
Total
C V
C II
C III
C IV
Radiation (Wm⁻³)
0
2
4
6
8
10
12
14
16
18
20
22
0·80 0·82 0·84 0·86 0·88 0·90 0·92 0·94 0·96 0·98 1·00 1·02 1·04
Major Radius (m)

TOPIC 9

RFP SCALING

SCALING II

Pressure and energy Balance for Ohmic Heating

(Assumes I/N, Z^*_{eff}, profiles const)

Pressure Balance: $T \propto \beta_\theta (I/N) I$

- $T(I) = f(\beta_\theta)$
- If β_θ = const with current, size
  $T \propto I$

Energy Balance: $\tau_E \propto a^2 \beta_\theta T_e^{3/2}/Z^*_{eff}$

- If β_θ = const $\tau_E \propto a^2 I^{3/2}/Z^*_{eff}$
- If $\beta_\theta = \beta_\theta(I)$,

  $\tau_E \propto a^2 \beta_\theta^{5/2} I^{3/2}/Z^*_{eff}$

Importance of $\beta_\theta(I)$ - scaling, physics

ENERGY CONFINEMENT TIME SCALING

In an ohmically heated pinch, simple energy balance gives

$$\tau_E = \frac{3}{8}\mu_0 \text{ (major radius) } \frac{\beta_\theta}{\text{(plasma resistance)}}$$

ie $\tau_E \propto a^2 \beta_\theta T_e^{3/2}/\eta_A$

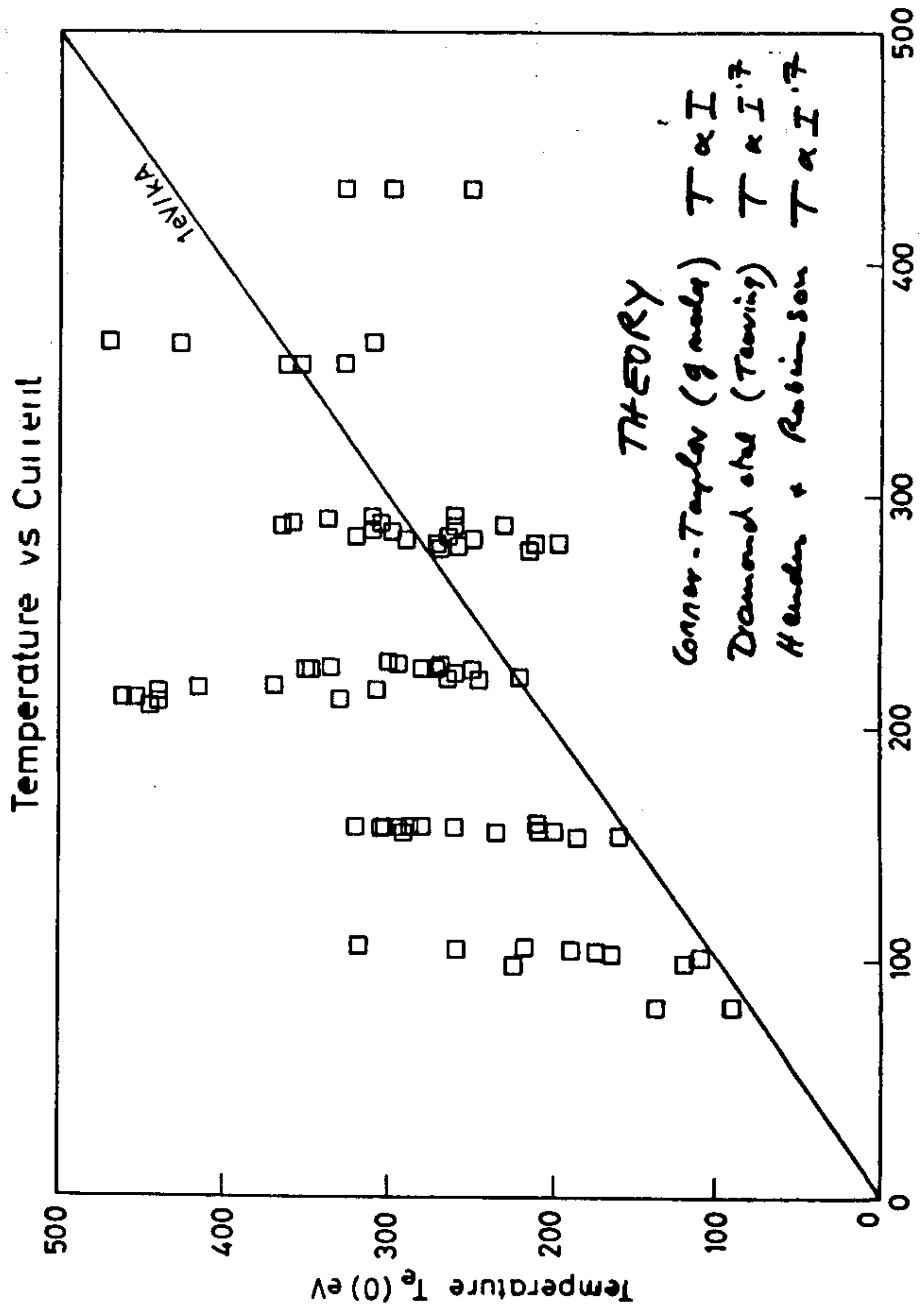
η_A is resistance anomaly

Standard Scaling

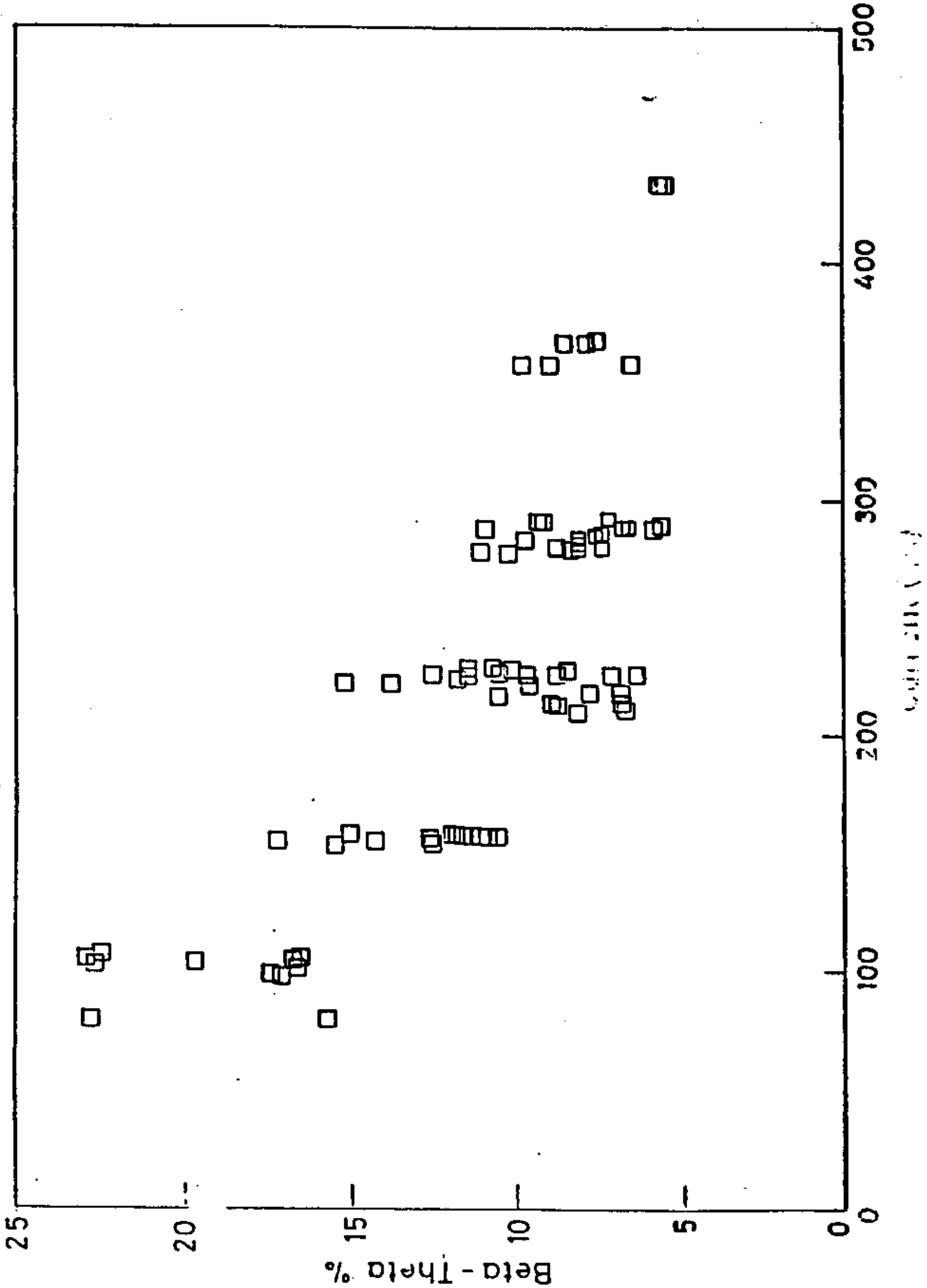
Use $T \propto \beta_\theta (I/N) I$

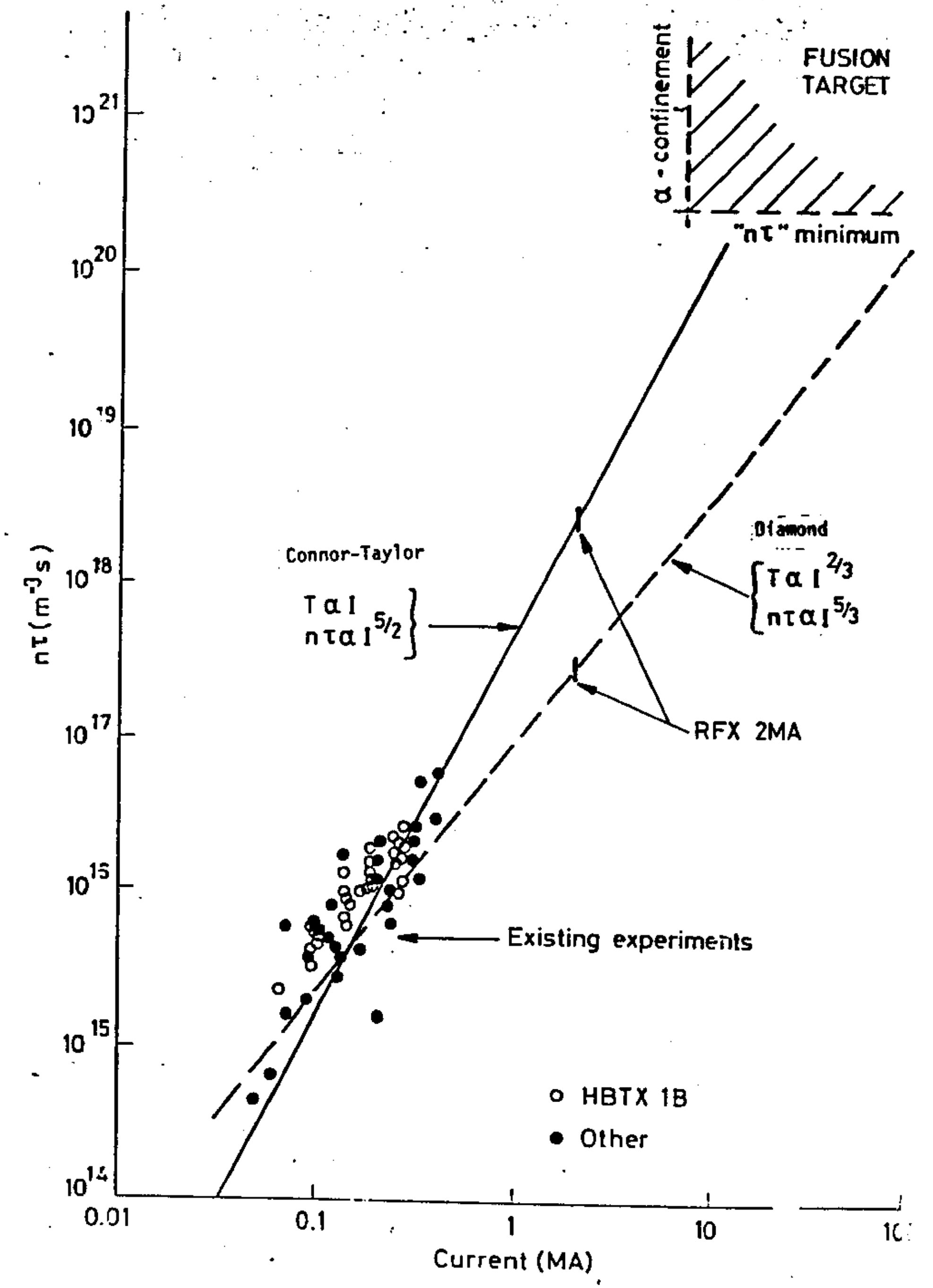
Fix I/N, then (experiment) β_θ, $\eta_A \sim$ const

- $\tau_E \propto a^2 I^{3/2}$
- $n\tau_E \propto I^{5/2}$



Poloidal-Beta vs Current





Lawson Parameter vs Current

RFP SCALING - EXPERIMENT AND TRANSPORT THEORY

Classical Theory (Cylinder, Ions)

$$\tau_E(\text{class}) = (m_i/m_e)^{1/2}\ \mu_0 (a/\alpha)^2 \sigma_\parallel/\beta_e \underset{\propto}{\approx} T_e^{3/2}$$

$$\tau_E(\text{exp})/\tau_E(\text{class}) \propto \beta_\theta^2(\text{expt}) \sim \frac{1}{100}$$

RFP SCALING - EXPERIMENT AND TRANSPORT THEORY

Experiment

$T \propto I^\alpha$, $0.5<\alpha<1$

$\beta_\theta \propto I^\beta$ $\beta \lesssim 0$ at $I \gtrsim 300$ kA

Anomalous Transport due to Resistive Instabilities

(Connor/Taylor, Diamond et al, Hender & Robinson, Yamagishi etc)

eg

- g-modes (Connor/Taylor) $T \propto I$, $\beta_\theta = \text{const}$
- Tearing modes (Diamond) $T \propto I^{0.7}$, $\beta_\theta \propto I^{-1/3}$

- Tokamak-Pinch comparison

RFP SCALING - EXPERIMENT AND TRANSPORT THEORY

Summary

- Experiment and theory in approximate agreement at I<0.5 MA
- $\tau_E \sim a^2 \beta_\theta^{5/2} I^{2/3} / Z^*_{eff}$

  will scale to reactor conditions if β_θ, Z^*_{eff} are approximately constant with current and size and I/N can be controlled
- Need high I - RFX

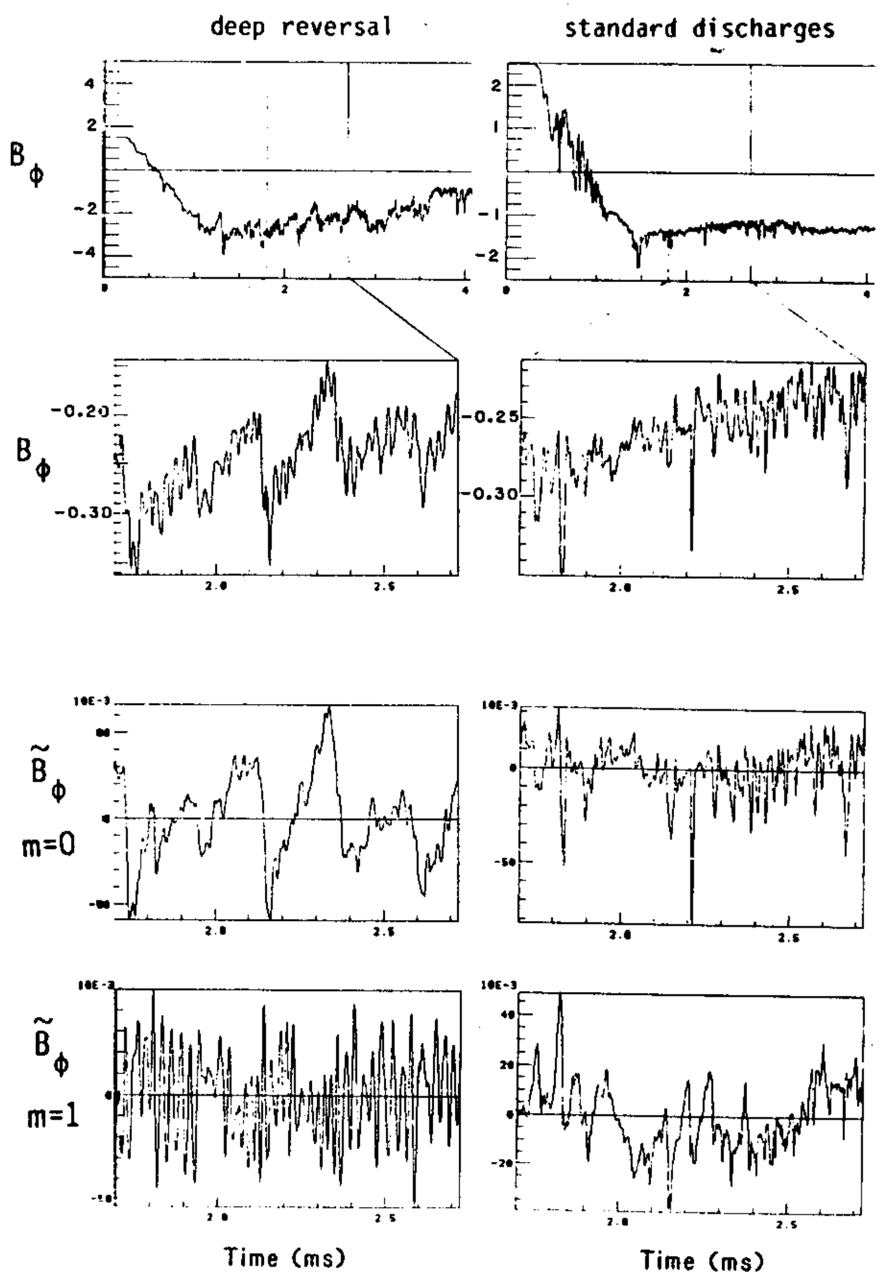
SCALING (80-430 kA)

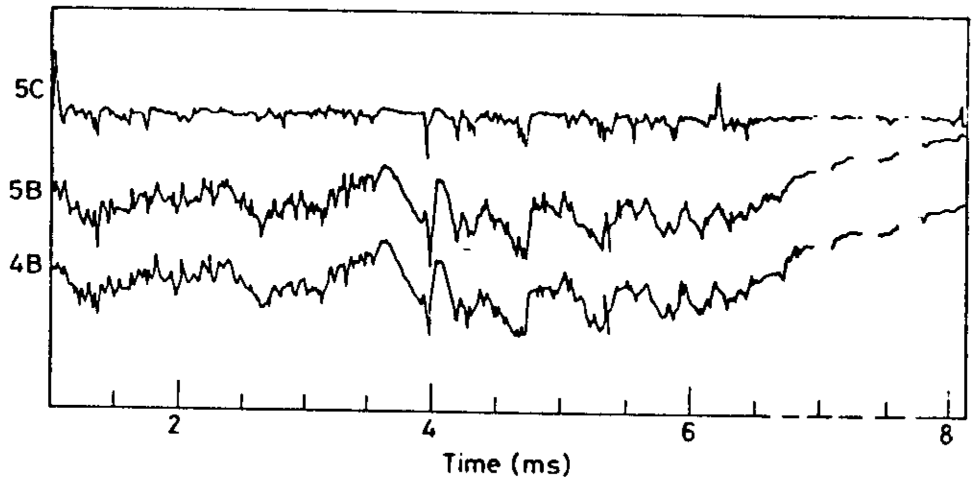
- T_e increases as I^n, $0.5 < n < 1$ (fixed I/N)
- T_e decreases as $n^{-0.6}$ (fixed I)
- "Best Fit" $T \propto I^{0.78} n^{-0.55}$
- β_θ falls from 20% at 80 kA to 10% at 220 kA and slowly thereafter possibly saturating
- $n\tau$ increases with I
  cf Theory $I^{5/2}$ (g modes), $I^{5/3}$ (tearing modes)
- τ_E depends on size of edge region

TOPIC 10

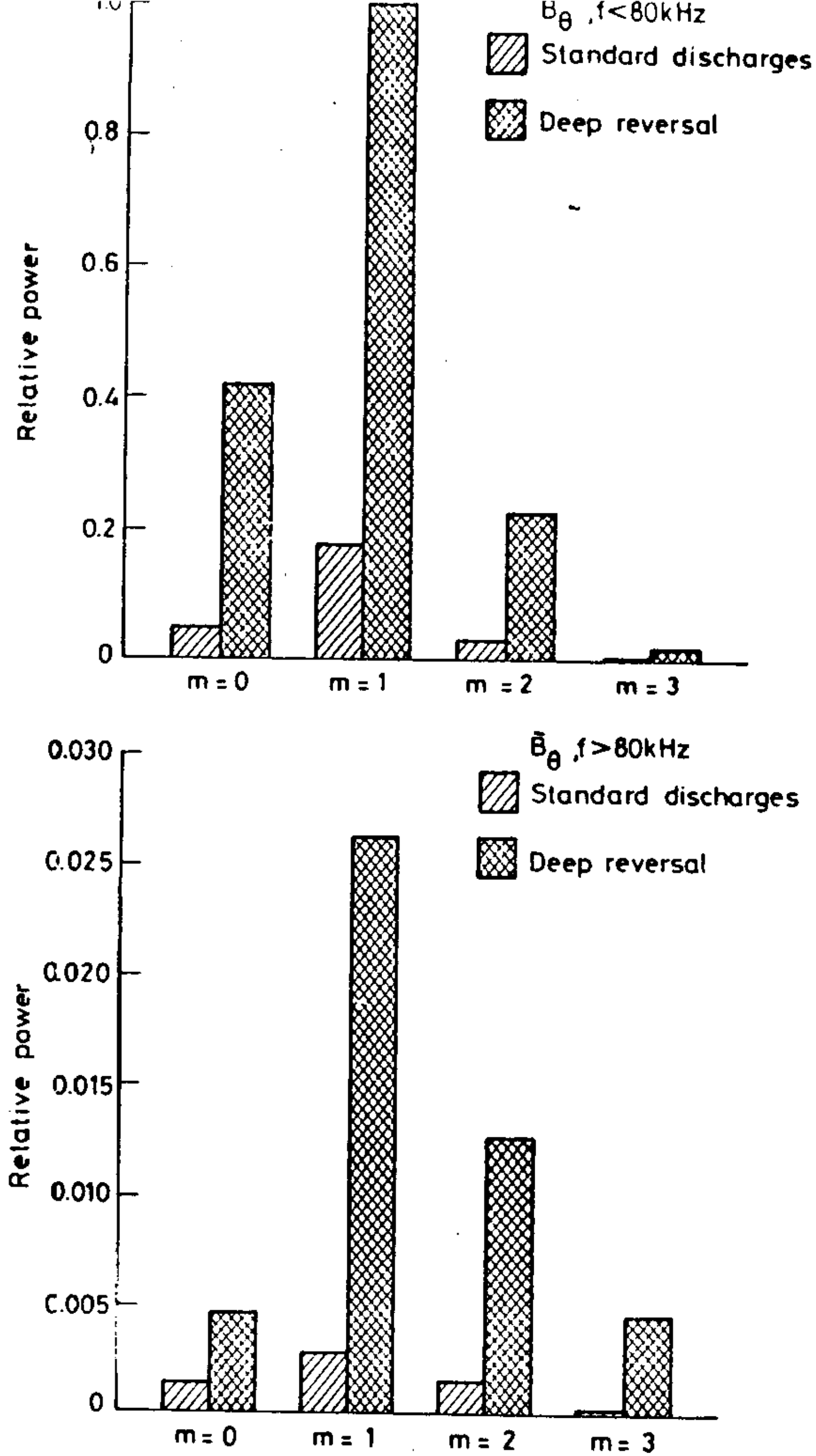
FLUCTUATIONS

Magnetic Field Fluctuations





Signals from SBD Arrays



Poloidal mode spectra - $\tilde{B}_\theta$

m=1 MAGNETIC FLUCTUATIONS

Standard	Deep Reversal
$F > -0.25$	$F < -0.35$
$\tilde{B}/B \sim 1\text{-}2\%$	$\tilde{B}/B \sim 5\text{-}10\%$ More coherent
Resonant Inside $B_\phi=0$	Resonant Outside $B_\phi=0$
Broad n spectrum Peak $\lvert n \rvert \simeq 10\text{-}12$	Single $n \simeq 6$ constant in time and from shot to shot
$v_\phi = 5 \times 10^4\ ms^{-1}$ $v_\theta = 3 \times 10^4\ ms^{-1}$	v_ϕ, v_θ vary in time

- Rotating n=6 helical structure interpreted as Taylor's second relaxed state

TOPIC II

MACHINE IMPROVEMENTS (REDUCED FIELD ERRORS, ACCURATE EQUILIBRIUM) GIVE INCREASED PARAMETERS

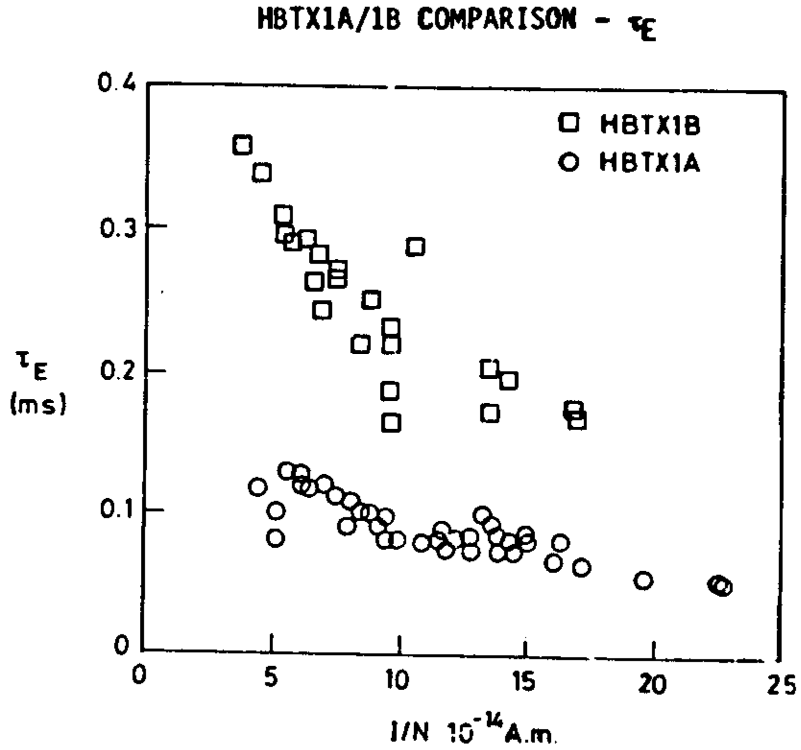
PLASMA PARAMETERS WITH MACHINE IMPROVEMENTS HBTX1A and HBTX1B

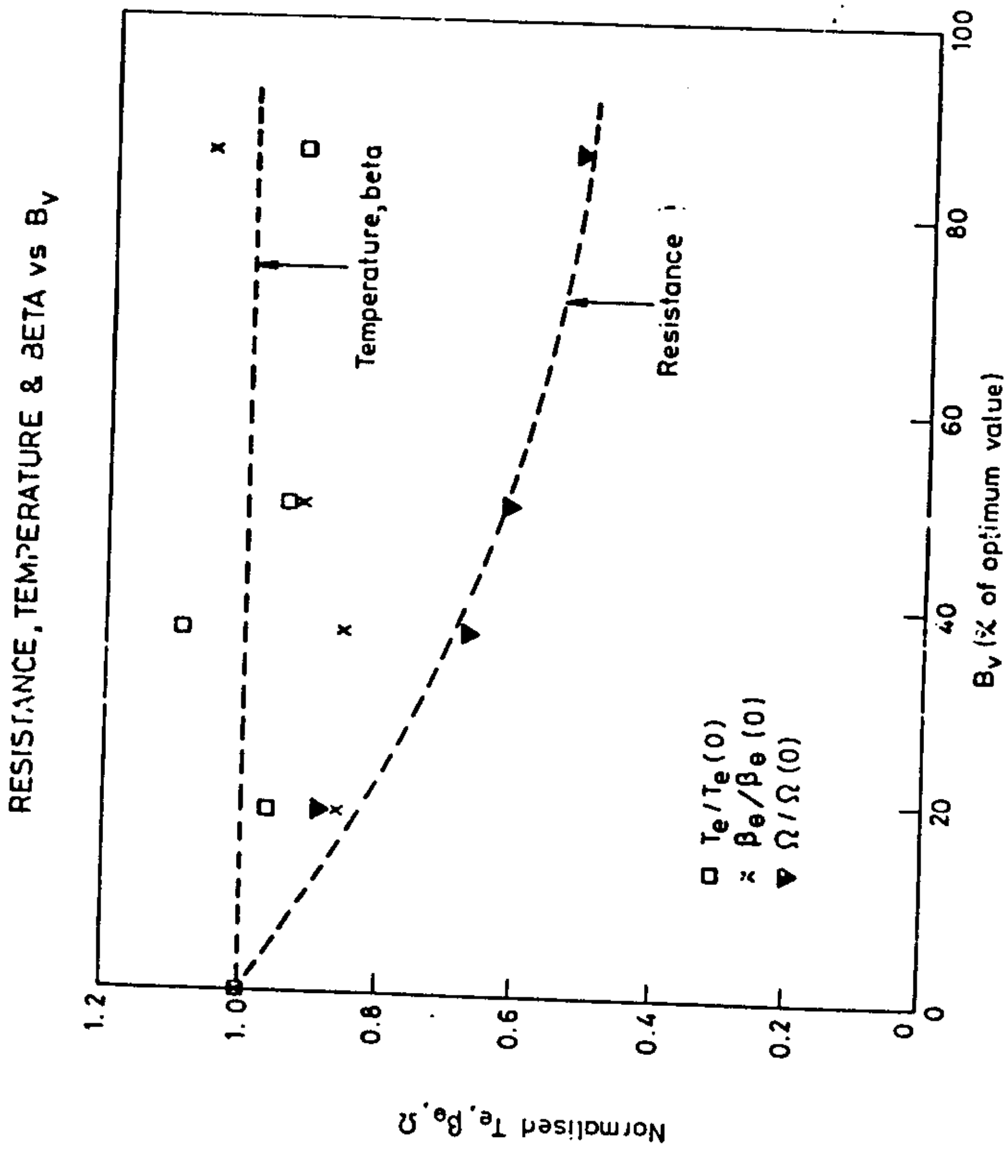
MACHINE

- Reduced field errors from ports and windings
  Equivalent error area/liner area 0.31% to 0.02%
- Gap flux correction (pulse length); DC B_v

PLASMA

- Resistance decreased
- Confinement, $\tau \propto \beta_\theta / R_p$, increased (x~3-5)
- β_θ unchanged - 10-15% at 250 kA


HBTX1A/1B COMPARISON - τE
τE (ms)
□ HBTX1B
○ HBTX1A
I/N 10^-14 A.m.


RESISTANCE, TEMPERATURE & BETA vs Bv
Temperature, beta
Resistance
□ Te/Te(0)
x βθ/βθ(0)
▼ Ω/Ω(0)
Bv (% of optimum value)
Normalised Te, βθ, Ω

TOPIC 1a

NEW RESULTS ON ANOMALOUS RESISTANCE

(LOOP VOLTAGE) AND ION HEATING

- Proposed New interpretation of RFP

RECENT RESULTS

*Increased parameters with machine improvements ($I \sim 200$ kA, flat top, best values)

Limiters In	Limiters Out
• $\tau_E \sim 0.35$ ms	0.5-1
• $T_e \sim 300$-400 eV	800-900 eV
• $T_i \sim 300$-400 eV	100-250 eV
• $V_{loop} \sim 33$ V	$\sim$ 15-18 V
• $\beta_\theta \sim 10$-15%	10-15%

*New facts and new interpretations of how RFP works, especially V_{loop} and T_i which can be greater, equal to or less than T_e

EXPERIMENTAL FACTS TO EXPLAIN I

V_{loop}

- Except at low T_e, V_{loop} is dominated by a non Spitzer component (eg 3:1)
- Sensitively dependent on field errors and equilibrium displacement, and on first wall surface (eg obstructions)
  - Decreases: reduced field errors, equilibrium shift; removal of limiters (although Z_{eff} increases)
  - Increases: insertion of objects
- $\delta V_{loop} \approx\propto$ area of material surface intercepted by field lines
- τ_E depends on V_{loop}

EXPERIMENTAL FACTS TO EXPLAIN II

Ion Temperature

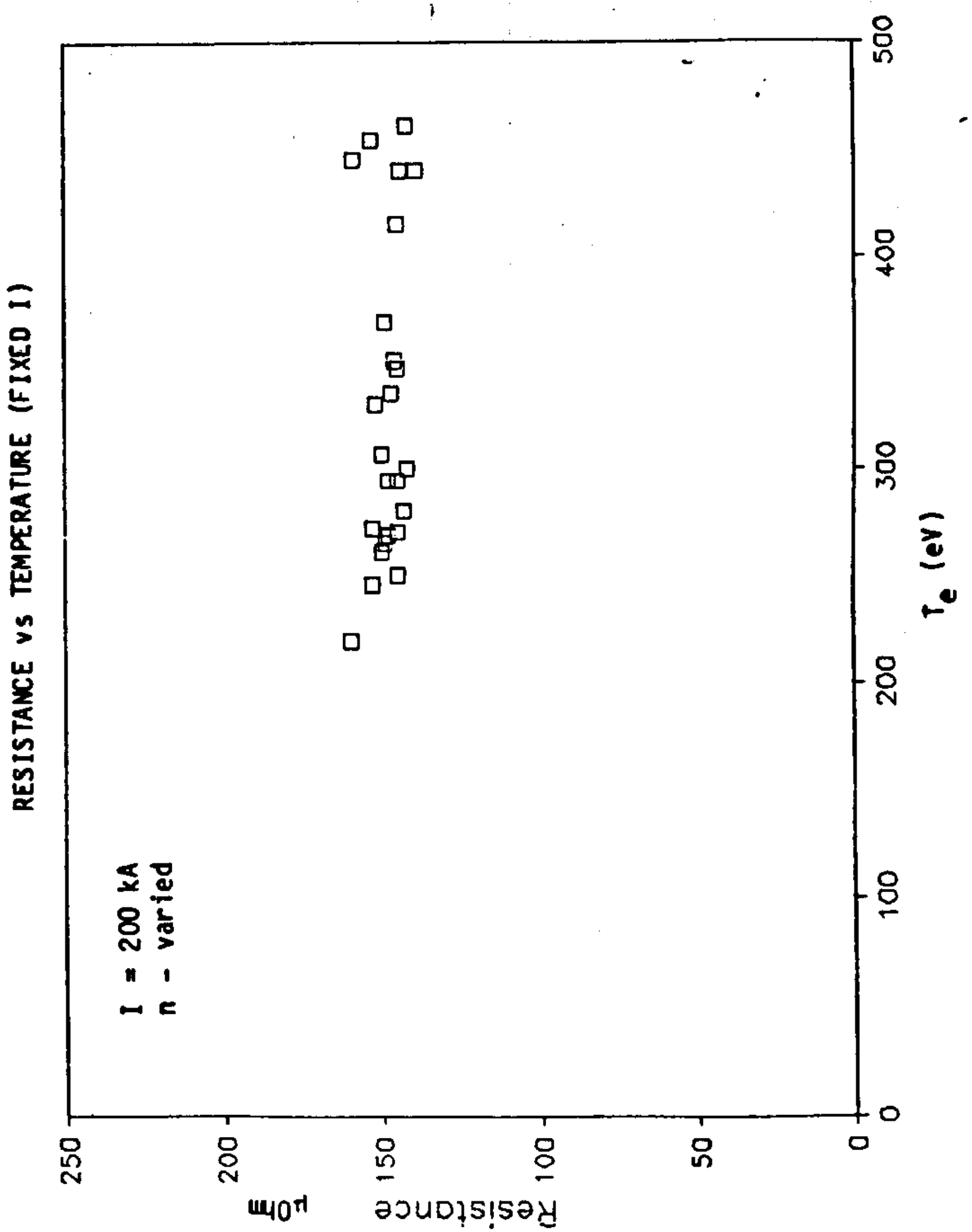
- $T_i/T_e \sim 0.1\text{-}2$
- T_i is correlated with δV_{loop}
  - Decreases: on removal of limiters
  - Increases: on insertion of objects and at high θ
- τ_E depends on T_i

HBTX1B REVERSED FIELD PINCH

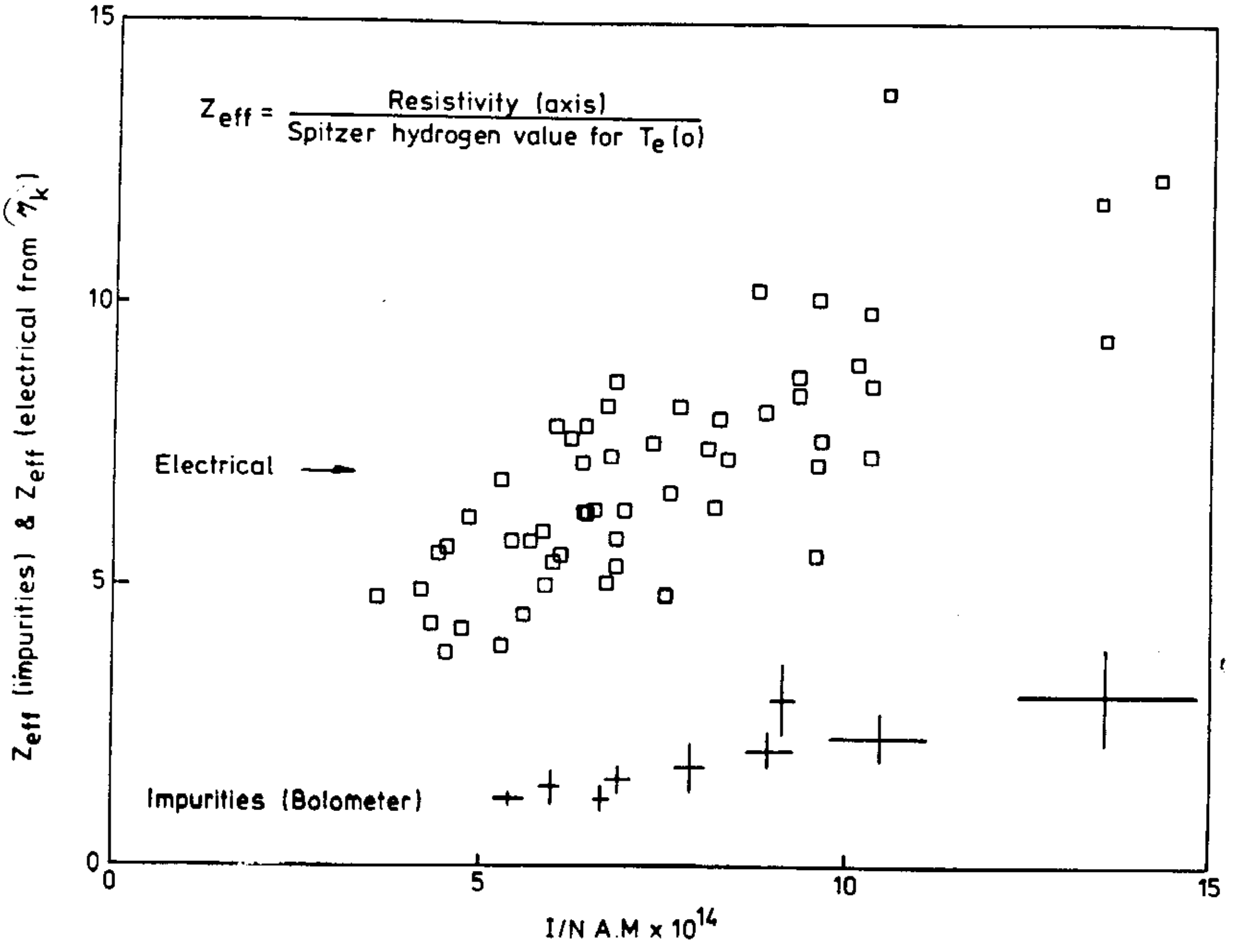
Parameters of HBTX1B

R/a	0.8m/0.26
I_{max}	520 kA
τ_{rise}	~ 0.5 ms
τ_{pulse}	~ 10 ms

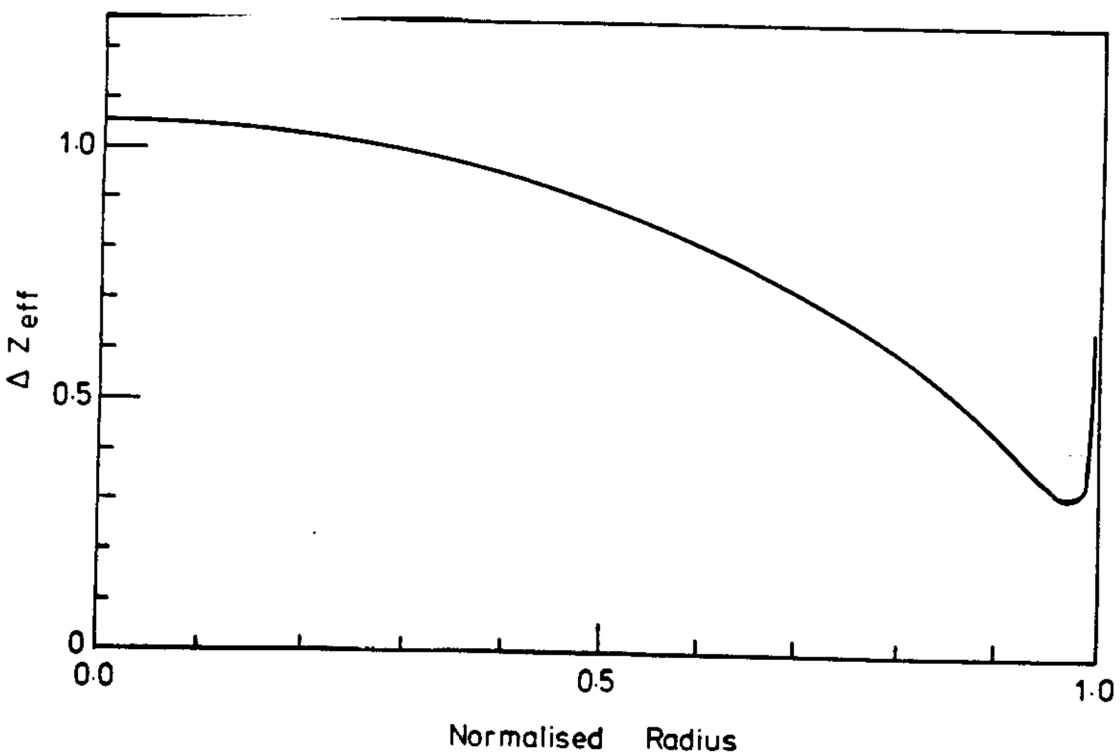
Carbon tile limiters (8%)



Z_{eff} ELECTRICAL & IMPURITIES vs $I/_N$

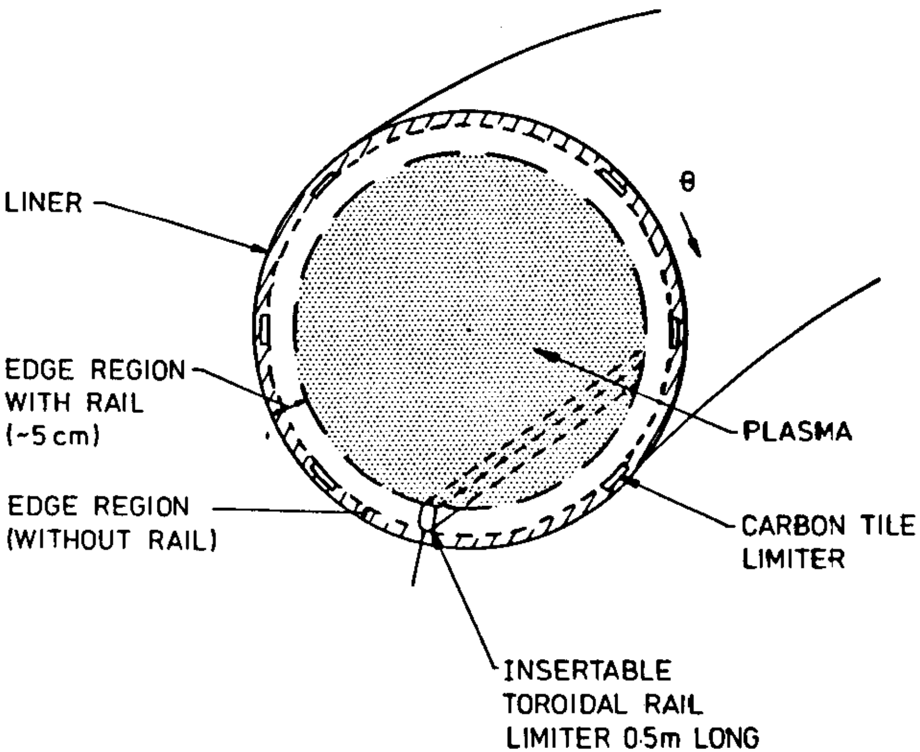


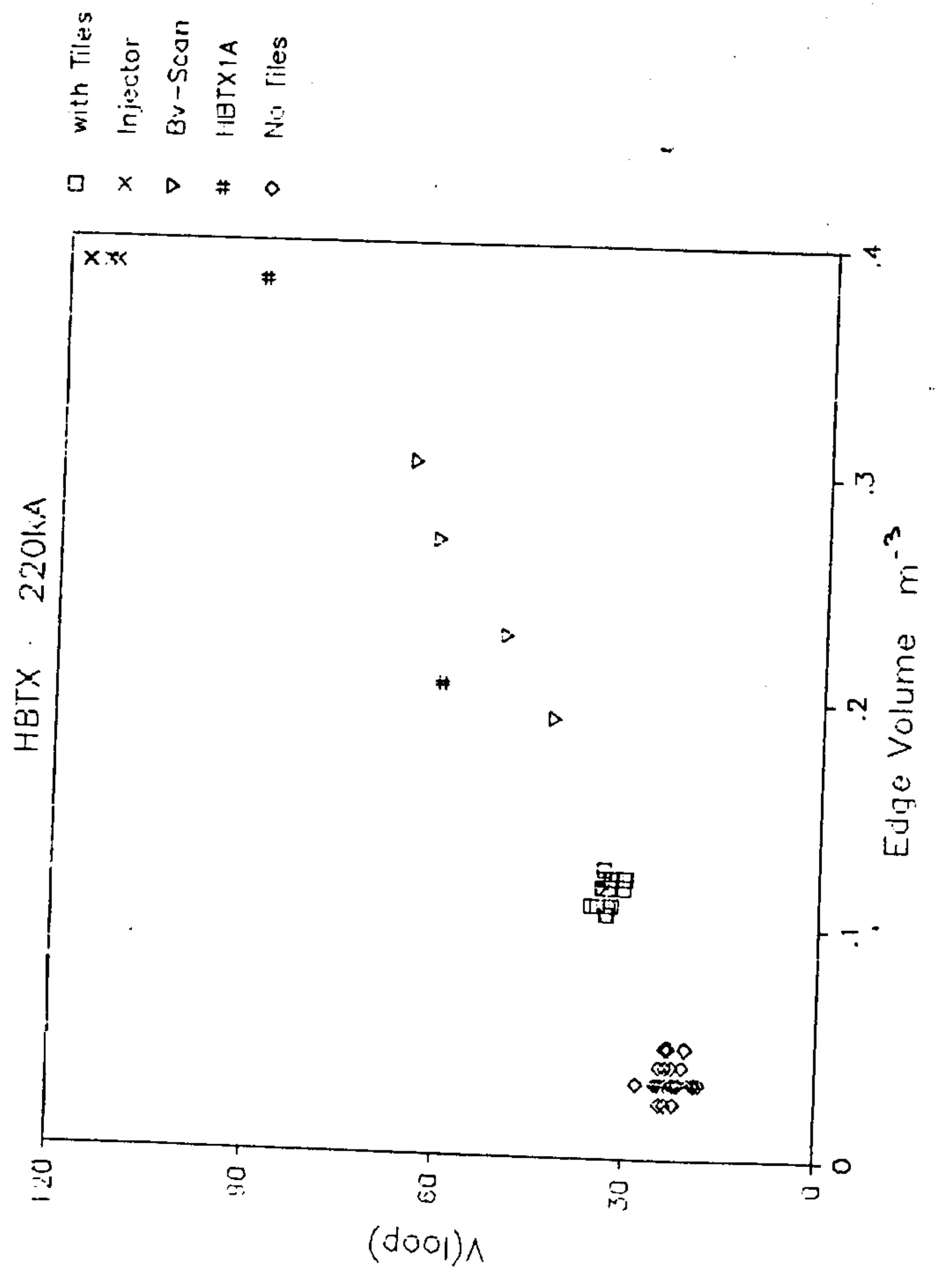
RADIAL VARIATION OF Δ Z_{eff} (CARBON)

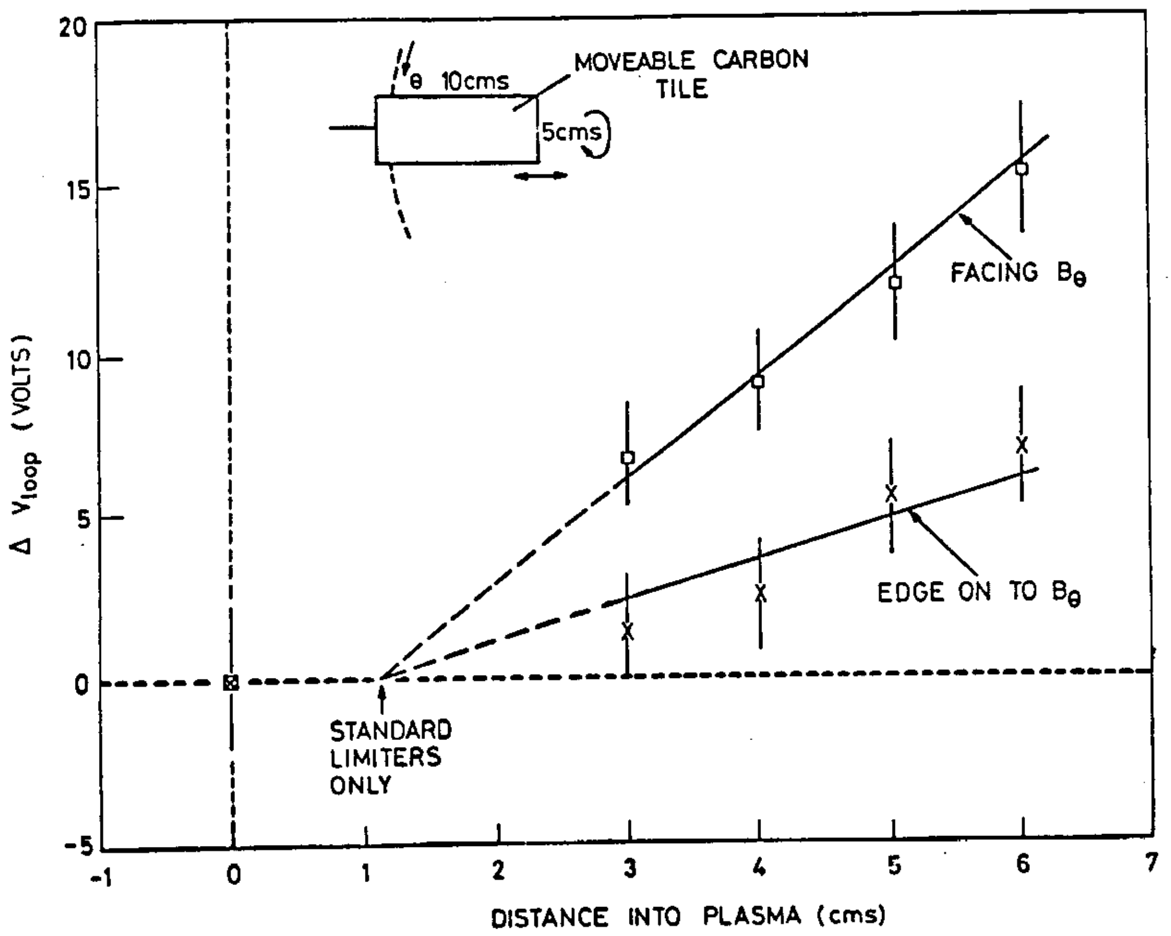


INFLUENCE OF EDGE REGION ON RESISTANCE

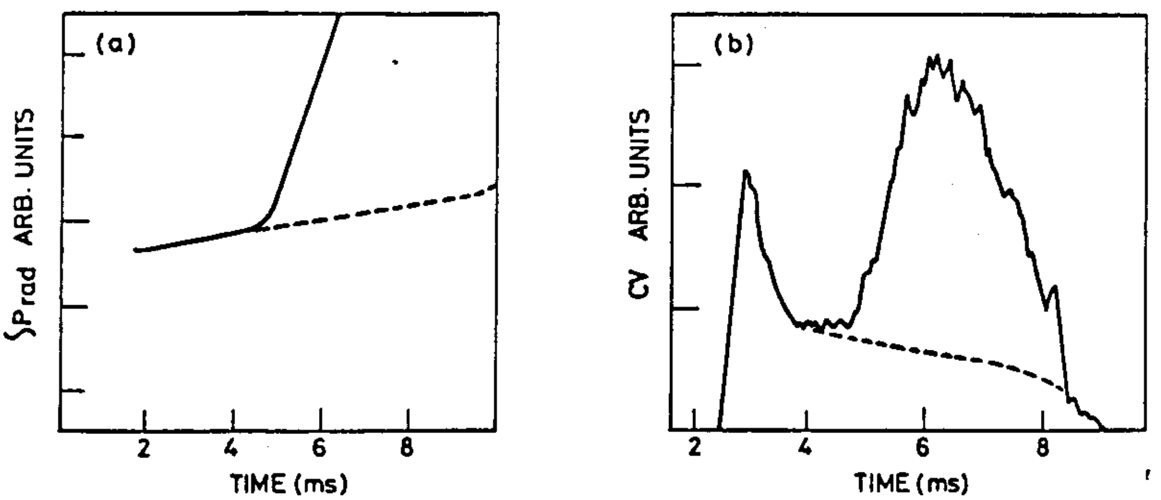
SCHEMATIC DIAGRAM OF RAIL LIMITER EXPERIMENT



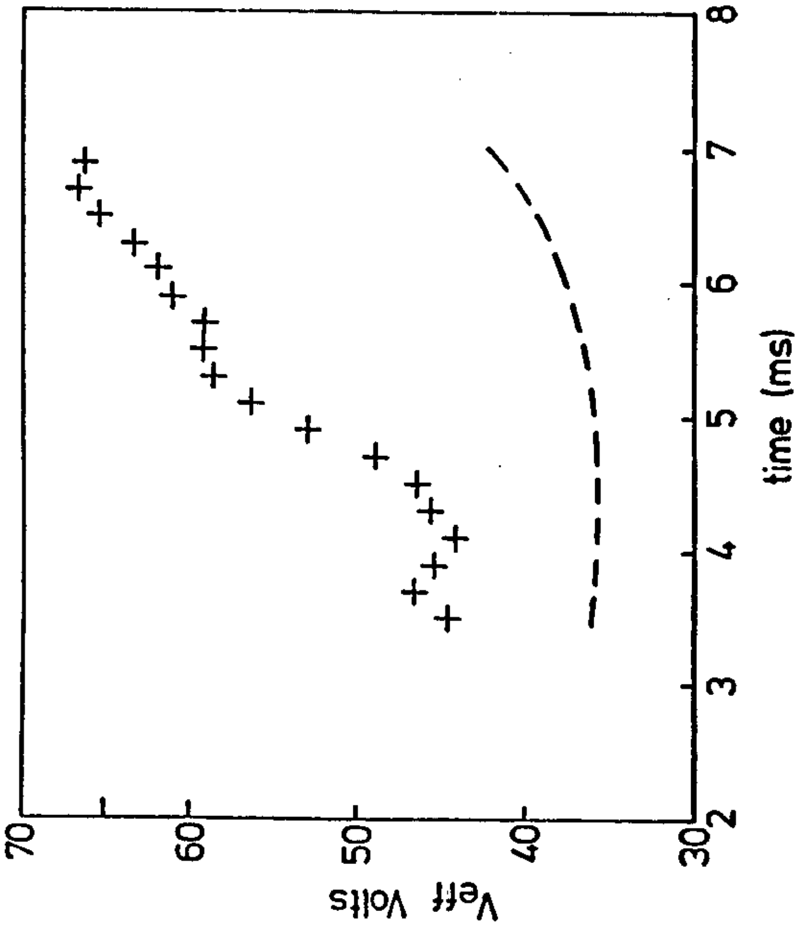




MOVEABLE CARBON TILE
10cms
5cms
FACING Bθ
EDGE ON TO Bθ
STANDARD LIMITERS ONLY
Δ V loop (VOLTS)
DISTANCE INTO PLASMA (cms)



(a)
∫Prad ARB. UNITS
TIME (ms)
(b)
CV ARB. UNITS
TIME (ms)



HELICITY AND ENERGY BALANCE - RESISTIVITY AND LOOP VOLTAGE

(when $\underline{B}_0 \cdot \underline{n} = 0$)

HELICITY BALANCE

$$V_L \phi = \int \underline{E} \cdot \underline{B} \, d^3x$$

ENERGY BALANCE

$$V_L I = \int \underline{E} \cdot \underline{j} \, d^3x$$

It is necessary to include fluctuations

$$\underline{E} = \underline{E}_0 + \underline{\tilde{E}} \text{ etc}$$

HELICITY

$$V_L \phi = \int [\eta \underline{j}_0 \cdot \underline{B}_0 + \underbrace{\langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot B_0}_{0}] \, d^3x$$

ENERGY

$$V_L I = \int [\eta j_0^2 - \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0 - \underbrace{\langle \underline{u} \times B_0 \cdot j \rangle}_{0}] \, d^3x$$

- Fluctuations do not dissipate helicity
- Taylor state μ=const $\int \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0 \, d^3x = 0$

HELICITY AND ENERGY BALANCE - RESISTIVITY AND LOOP VOLTAGE

One obtains

HELICITY

$$V_L \phi = \int \eta \underline{j}_0 \cdot \underline{B}_0 \, d^3x$$

ENERGY

$$V_L I = \int [\eta j_0^2 - \langle \underline{\tilde{u}} \times \underline{\tilde{B}} \rangle \cdot j_0] d^3x$$

↑ DYNAMO TERM

$V_{loop} = V_L^W$ (Spitzer) + $V_L(\underline{\tilde{u}} \times \underline{\tilde{B}})$

$V_{loop} =$ V_L^k (Spitzer)

If fluctuations neglected

$\eta^c > \eta^W \geq \eta^k$

η^c is from simple Ohm's law
V_L^W, η^W, η^K and V_L^k mean different things.
η^k "most accurate"

LOOP VOLTAGE IN RFP

Two energy flow channels

V_{loop} = $V^k_{Spitzer}$ (Helicity Balance) + $V_{(\text{due to edge helicity loss})}$

$V^W_{Spitzer}$ (Energy balance) + $V(\underline{\tilde{u}} \times \underline{\tilde{B}})$ + $V_{edge}(\underline{\tilde{u}} \times \underline{\tilde{B}})$

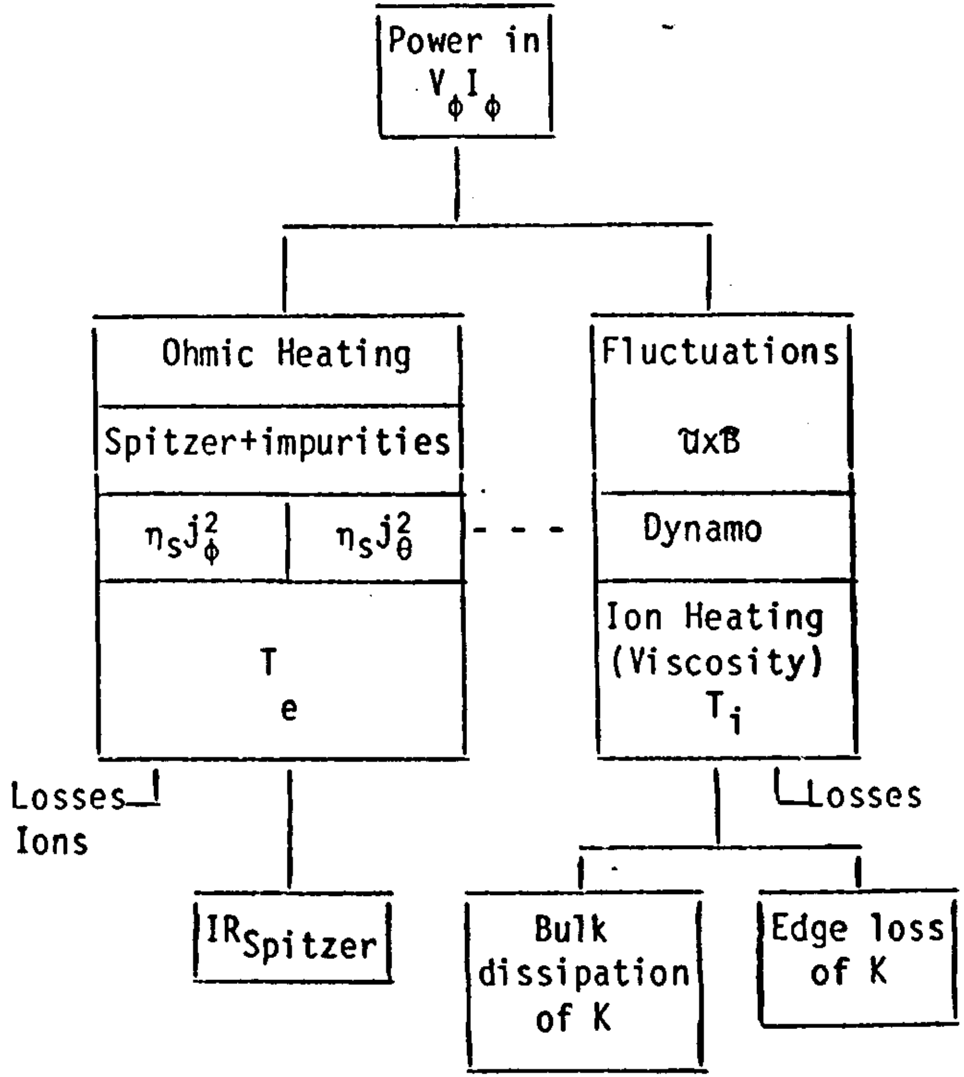
Heats Electrons — Dynamo Heats ions — Enhanced dynamo, ion heating

					Tiles
30V	7.5	[10]	2.5	20	In
20V	6-4	[8]	2-4	12	Out

$V^{k,W}_{Spitzer} = V(T_e, Z_{eff}, I)$; $V(\underline{\tilde{u}} \times \underline{\tilde{B}}) = V(\mu, I)$
V_{edge} - Helicity loss when lines intersect material objects (limiters, field errors, equilibrium)

Ion Heating - "Perfect" edge ($V_{edge=0}$):- $V(\underline{\tilde{u}} \times \underline{\tilde{B}})$
Practical edge:- $V(\underline{\tilde{u}} \times \underline{\tilde{B}}) + V_{edge}$

TWO ENERGY FLOW CHANNELS



$$V_{loop} = V_{Spitzer}(\text{Energy}) + V(\tilde{v}\times\tilde{B}) + V_{edge}(\tilde{v}\times\tilde{B})$$

$$= V_{Spitzer}\ (\text{Helicity}) + V_{edge}$$

THEORY OF EXCESS RESISTANCE DUE TO CURRENT OBSTRUCTIONS (Pease)

- It is assumed that disc-like obstructions which intersect the current, such that the flow around the disc excites torsional Alfvén waves, give an impedance, V_A

- Excess Resistance is

$$R^* \underset{\sim}{\propto} V_A\ (a/r_o)^4 (j_\parallel/j_o)^2$$

a = disc radius r_o = plasma radius

- $\delta V \sim \phi_{arc}$ f(geometry)

  $\phi_{arc} \sim 20$ V

cf Tsui Jarboe/Alper

THEORY OF ANOMALOUS LOOP VOLTAGE BASED ON HELICITY BALANCE

Jarboe/Alper

$$V_{L\phi} = \int_{\substack{\text{Bulk}\\\text{Plasma}}} E\cdot B d^3x + \int_{\substack{\text{Edge}\\\text{Plasma}}} E\cdot B d^3x$$

2nd Term

$$\boxed{\delta V = E\ (\theta/\pi a^2)\ V_{(edge)}}$$

V_{edge} = Edge volume (eg limiter shadow)

E = Average edge electric field

THEORY OF ANOMALOUS LOOP VOLTAGE BASED ON HELICITY BALANCE

Tsui

$$V_{L\phi} = \int_{\substack{\text{Bulk}\\\text{Plasma}}} E\cdot B d^3x + \int_{\text{Surface}} \chi B\cdot n d^2x$$

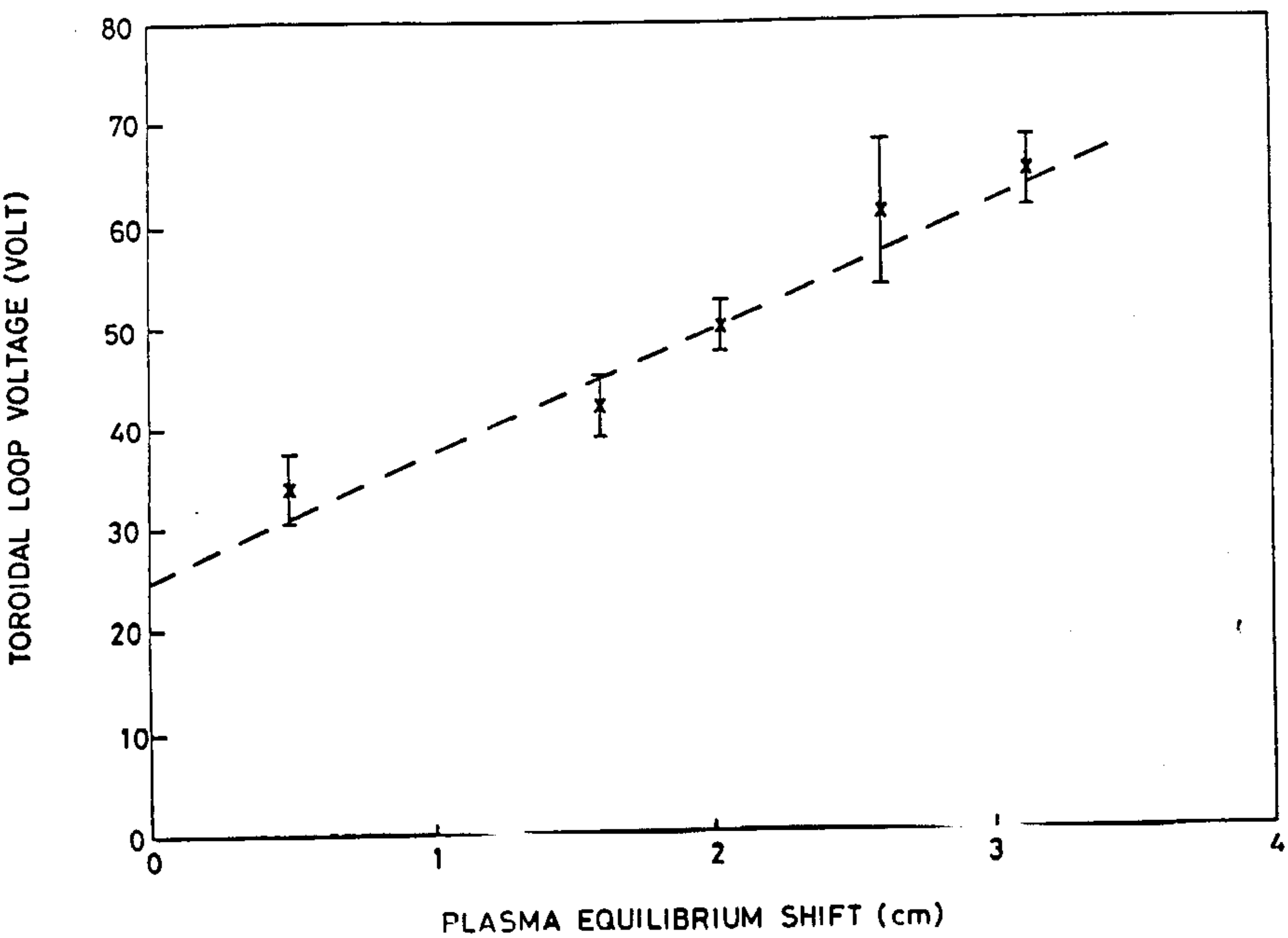
2nd Term

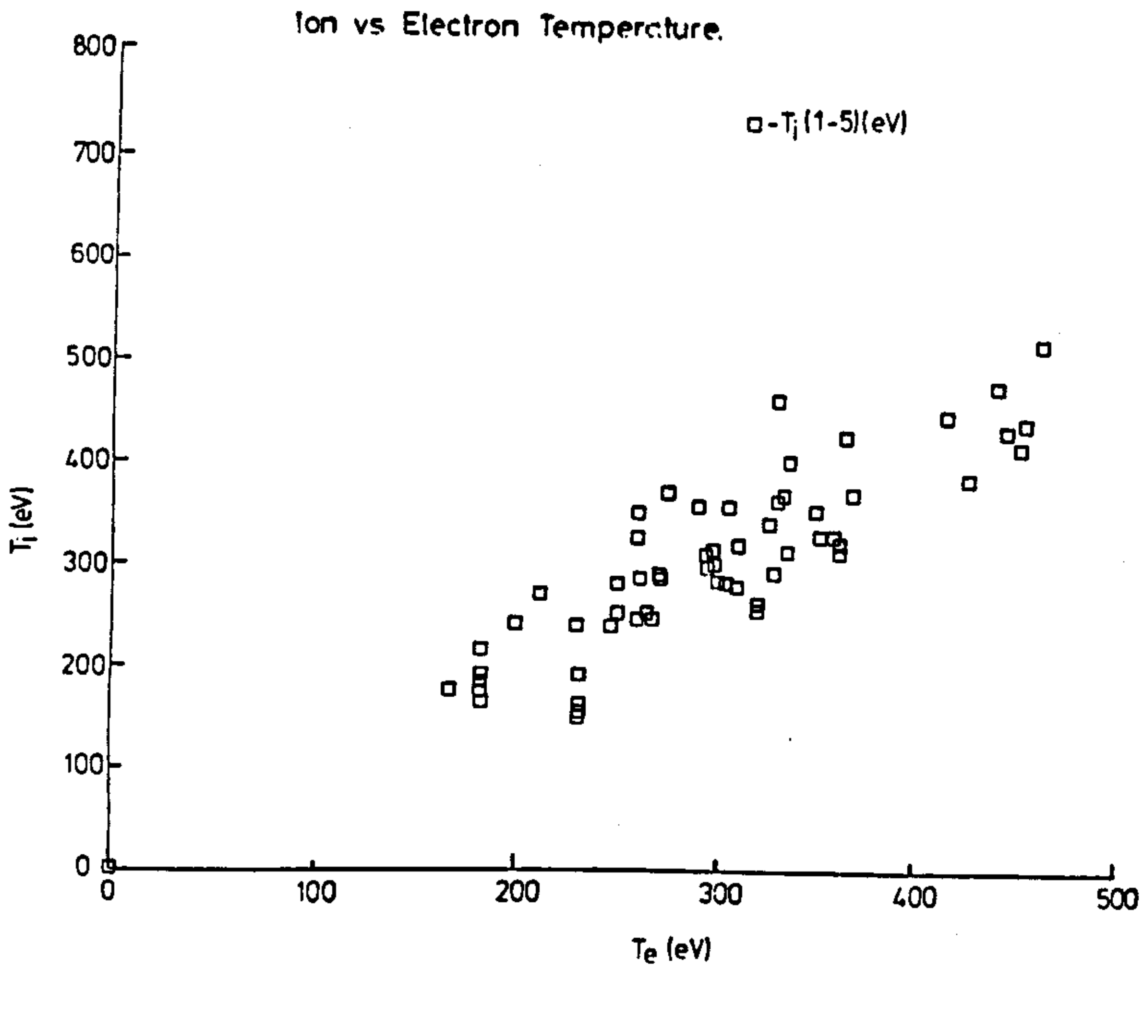
$$\boxed{\delta V = \delta\chi(\theta/\pi a^2)A}$$

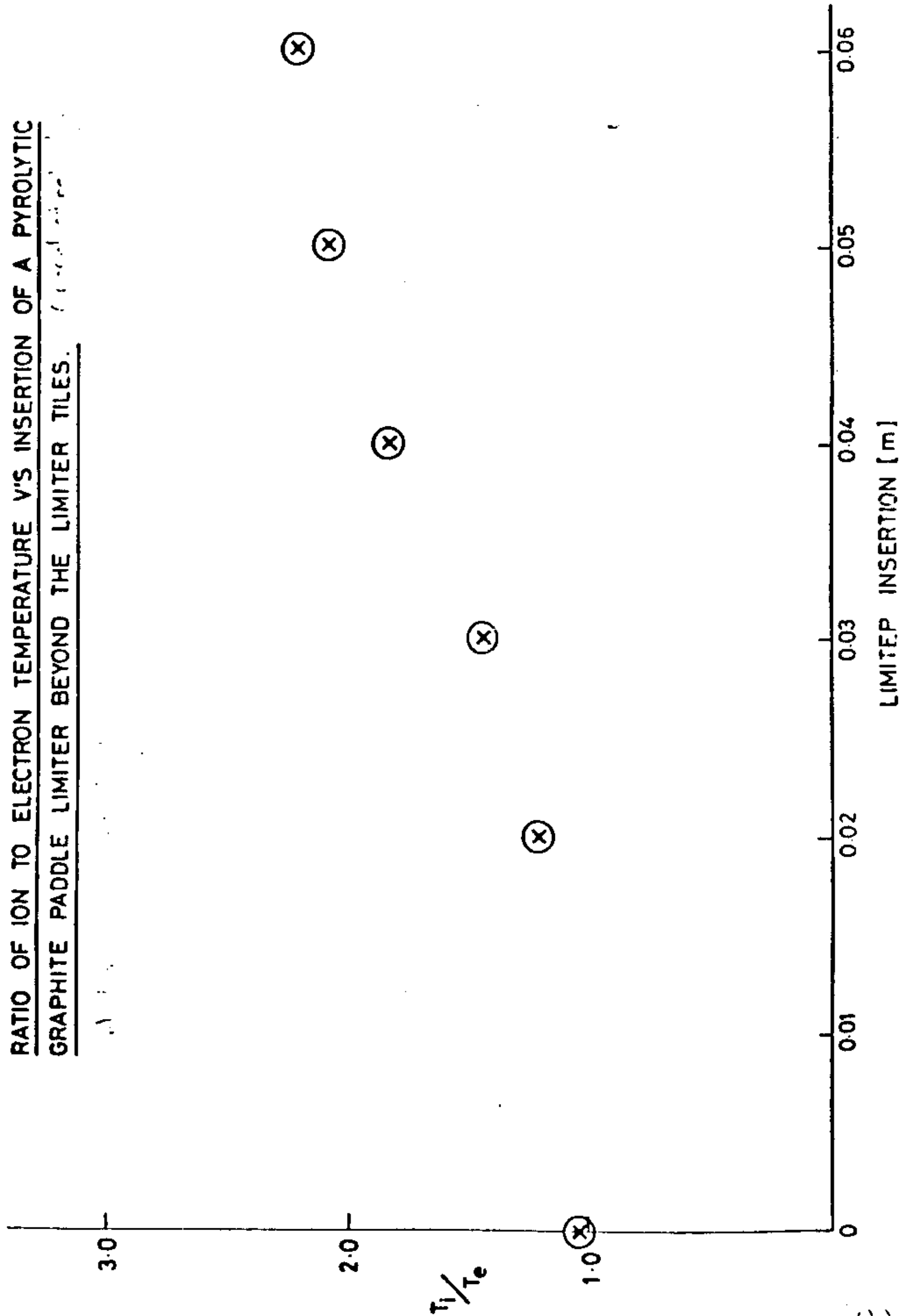
$\delta\chi$ = PD between surfaces where field lines enter and leave ($\delta\chi = f(T_e) \sim 1.8kT_e/e$)

A = Area intercepted

NOTE Area A can be defined for inserted objects, field errors and equilibrium - equivalent


TOROIDAL LOOP VOLTAGE (VOLT)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
PLASMA EQUILIBRIUM SHIFT (cm)


Ion vs Electron Tempercture.
□ - Ti (1-5)(eV)
Ti (eV)
0
100
200
300
400
500
600
700
800
0
100
200
300
400
500
Te (eV)



ION HEATING MODEL I

Power Balance

$$P_{in} = \underline{E}\cdot\underline{j} = \eta \underline{j}^2 - \underline{u}\times\underline{B}\cdot\underline{j}$$

When there are fluctuations
$\underline{j} = \underline{j}_0 + \underline{\tilde{j}}$ etc

$$\boxed{P_{in} = \eta j_0^2 - \langle \underline{\tilde{u}}\times\underline{\tilde{B}}\rangle\cdot\underline{j}}$$

$P_{in}(\text{electrons}) = \eta j_0^2,$
$\eta = \eta_{Spitzer}(T_e, Z_{eff})$

Dynamo Field $= \langle \underline{\tilde{u}}\times\underline{\tilde{B}}\rangle$

$P_{in}(\text{ions}) = \langle \underline{\tilde{u}}\times\underline{\tilde{B}}\rangle\cdot\underline{j}$ ASSUME

ION HEATING MODEL II
Loop Voltage

$$V_{loop} = V_{Spitzer} + V(\tilde{u} \times \tilde{B}) + V_{edge}(\tilde{u} \times \tilde{B})$$

$V_{Spitzer}$ (energy balance) → ELECTRON HEATING

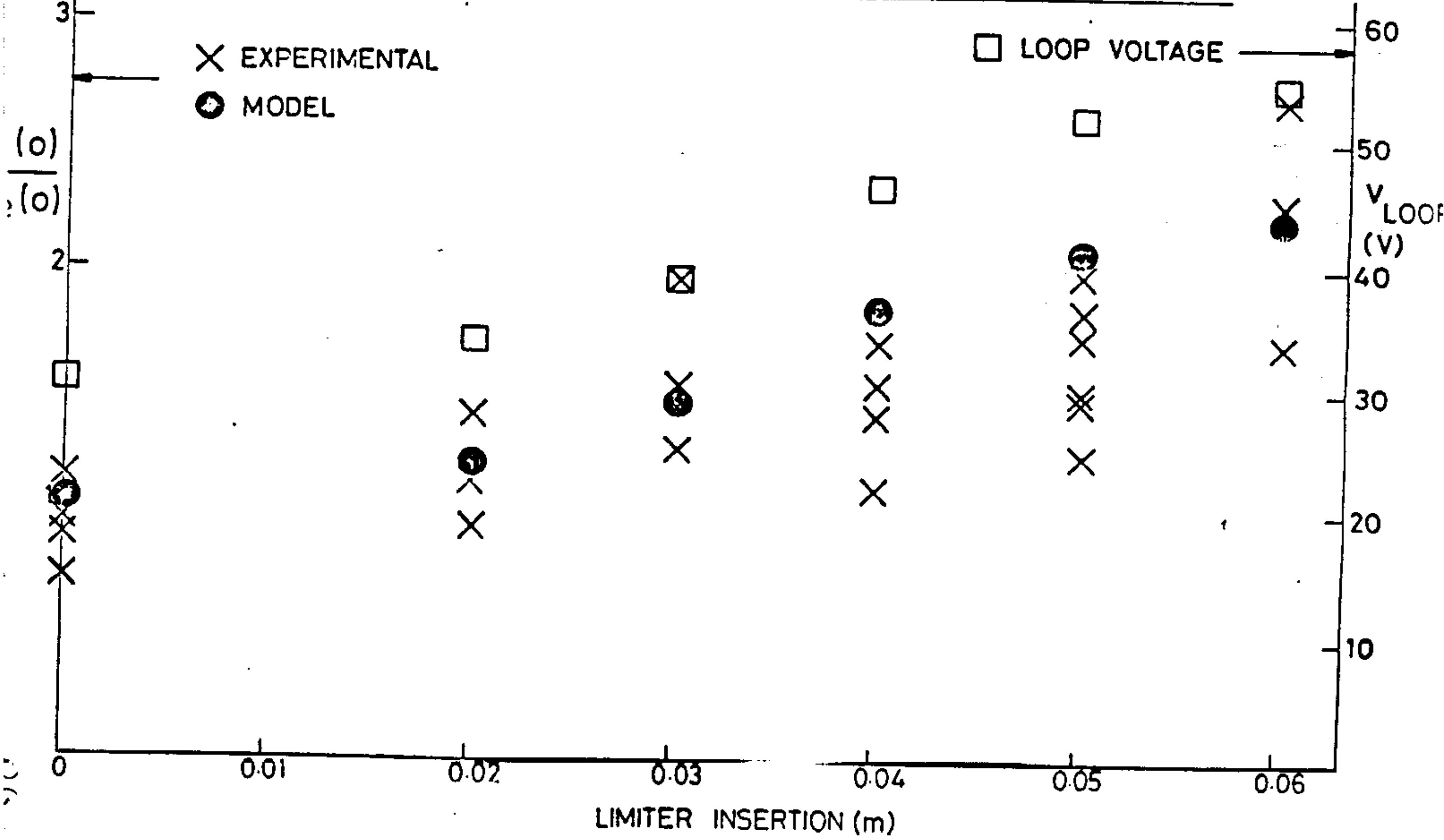
$V_{Spitzer}$ (Helicity Balance) = $V_{Spitzer}$ (energy balance) + $V(\tilde{u} \times \tilde{B})$

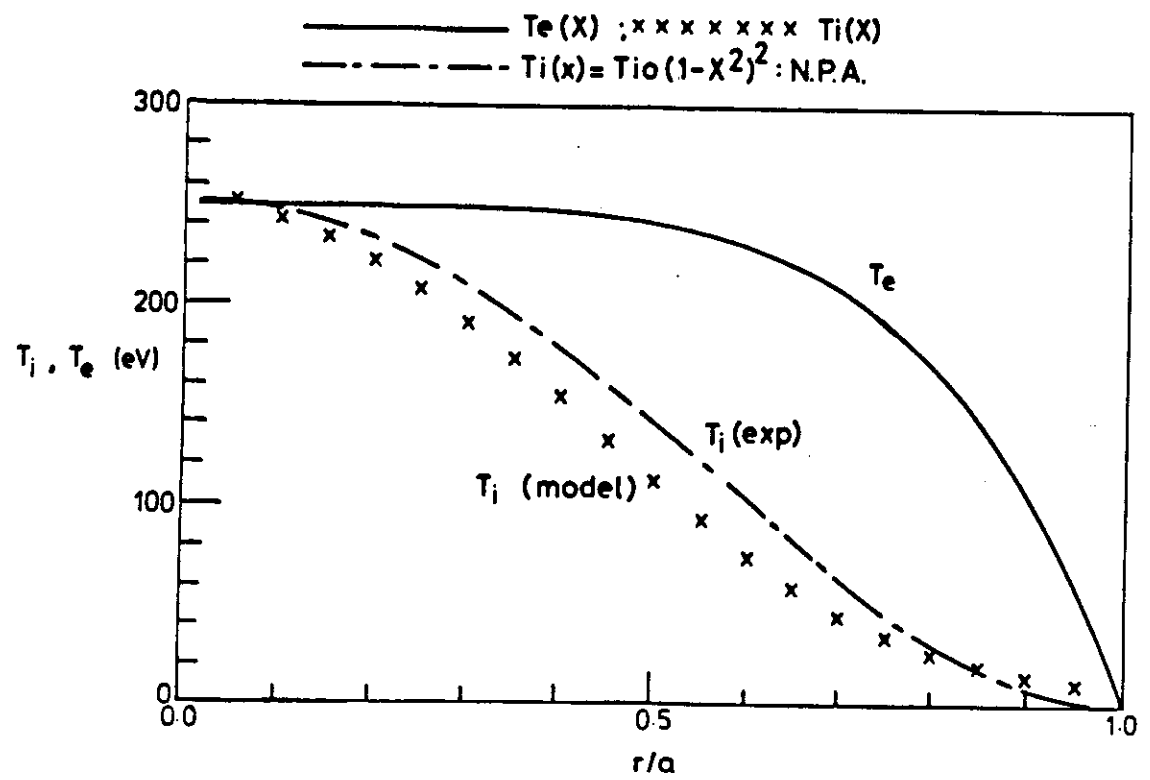
$V(\tilde{u} \times \tilde{B})$ + $V_{edge}(\tilde{u} \times \tilde{B})$ → ION HEATING

ION HEATING III
Ion Transport Loss

- Evaluate $D_{\perp e}(0)$ from experimental data assuming "Diffusion" > "Conduction" [$n_e(r)$ more peaked than $T_e(r)$]
- Assume ambipolarity to get $D_{\perp i}(0)$
- Use measured (relative) $n_0(r)$ - particle source - from fluorescent scattering and Monte Carlo calculations to give $D_{\perp i}(r)$ and $D_{\perp(e)}r$
- Recheck assumption that Diffusion > Conduction

RATIO OF ION TEMPERATURE TO ELECTRON TEMPERTURE V'S INSERTION OF A PYROLYTIC GRAPHITE PADDLE LIMITER BEYOND THE LIMITER TILES.

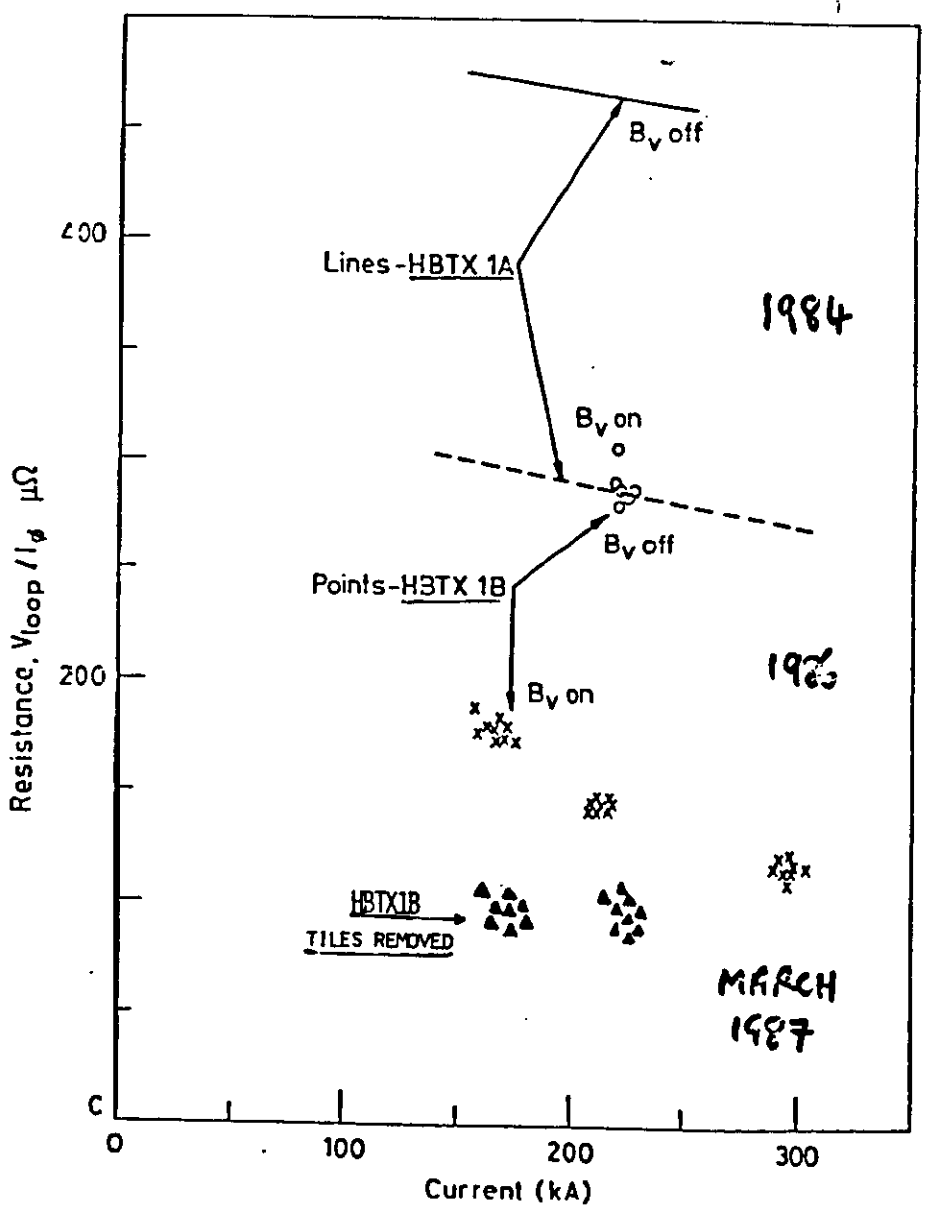




HBTX LIMITER REMOVAL

		Predicted	Observed
V_{loop}	Reduced	33V→22V	33V→18 V
Z_{eff}	Increased	-	2→3
τ_E	Increased	$\tau_E \propto \beta_\theta / V_L$ ~50%	~50% to ~0.5 ms
T_i	Reduced	T_i falls as V_{loop}	300-400→ 100-250 eV
T_e	Increased	-	300-400→ 600-900 eV
β_θ	(10-15%)	Unchanged?	Unchanged

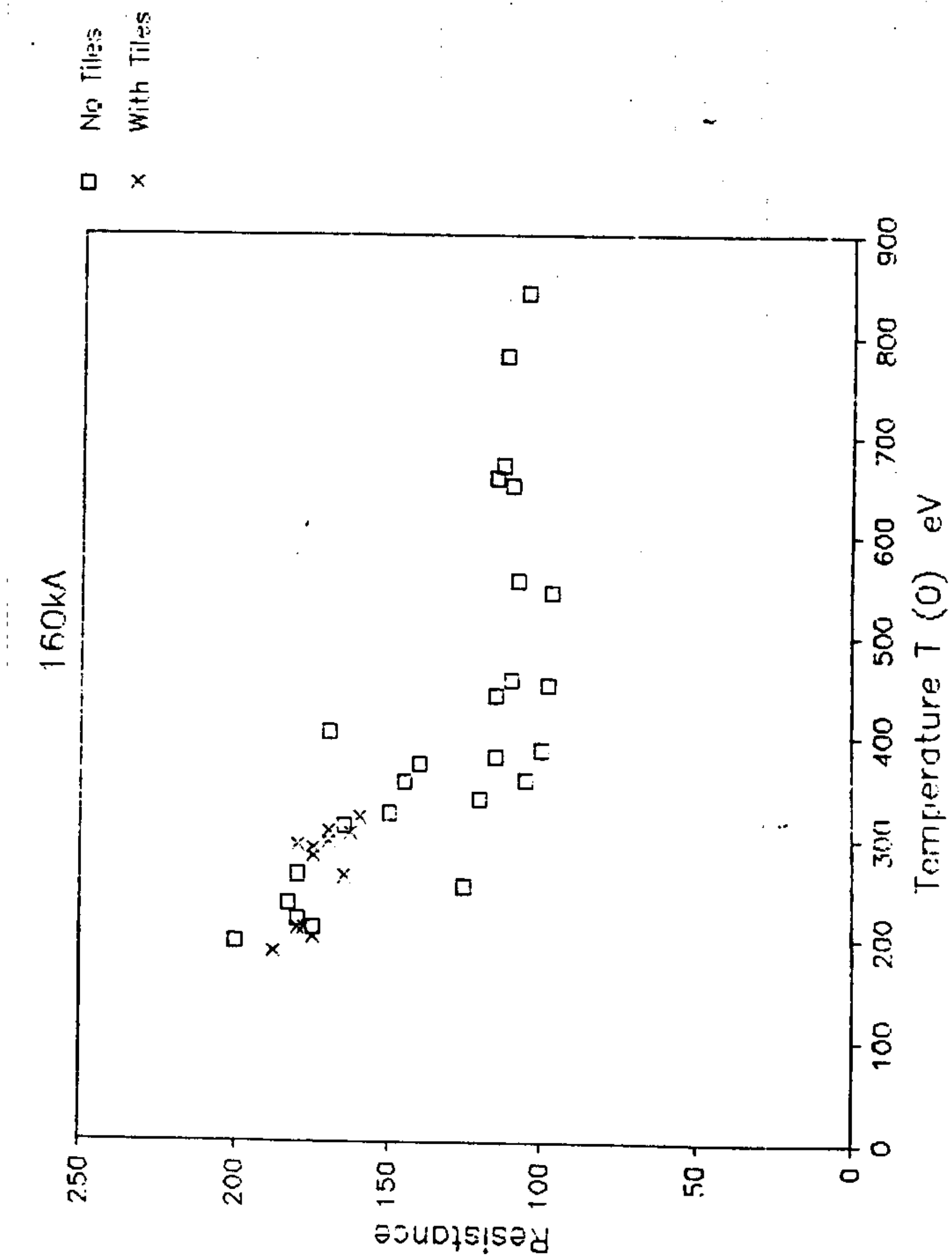
HBTX 1A/1B COMPARISON-RESISTANCE vs CURRENT



SCALING DATA BASE

- β_θ falls with I from 20% at I<100 kA to 10-15% at 200-300 kA and more slowly thereafter, possibly saturating with S

- Scaling laws assuming $R_p \propto T_e^{-3/2} Z_{eff}$ will not apply until the anomalous loop voltage (resistance) approaches the Spitzer value. WITH NO TILES SPITZER VARIATION MOVES TO HIGHER TEMPERATURES



TOPIC 13

EUROPEAN RFP PROGRAMME

PRESENT AND FUTURE

2 MA RFX MACHINE

EUROPEAN REVERSED FIELD PINCH (RFP) PROGRAMME

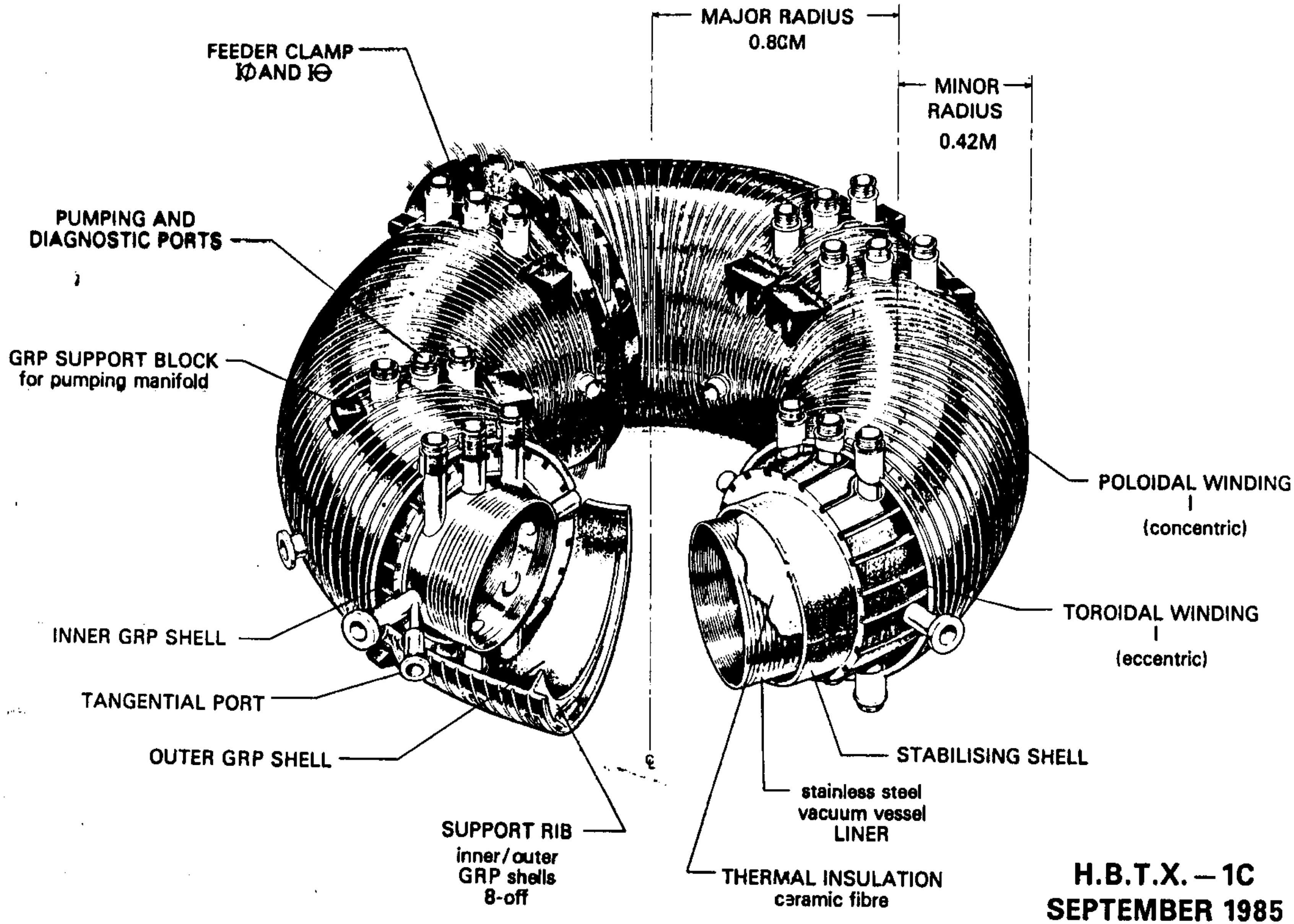
Instituto Gas Ionizzati del CNR, Padua - EURATOM/CNR Fusion Assoc

Culham Laboratory - EURATOM/UKAEA Fusion Assoc

Machines

	R(m)	a(m)	I MA	τ_p msec
ETA BETA II (Padua)	0.65	0.125	0.25	2
HBTX1A* (Culham)	0.8	0.26	0.3-0.4	10-15
RFX (Padua)	2	0.5	2	250

*Improved design with reduced field errors now operating - HBTX1B



H.B.T.X. — 1C
SEPTEMBER 1985

86 86c

MAIN OBJECTIVES OF RFX
[From Proposal (RFX R2)]

Build large high current machine
Importance of high I and high n

- Obtain nearer reactor conditions

- Test T, β, τ_E scaling with size and current

A big step planned, first proposed by Culham/Padua staff mid 1970's

IS THIS AIM STILL RELEVANT?

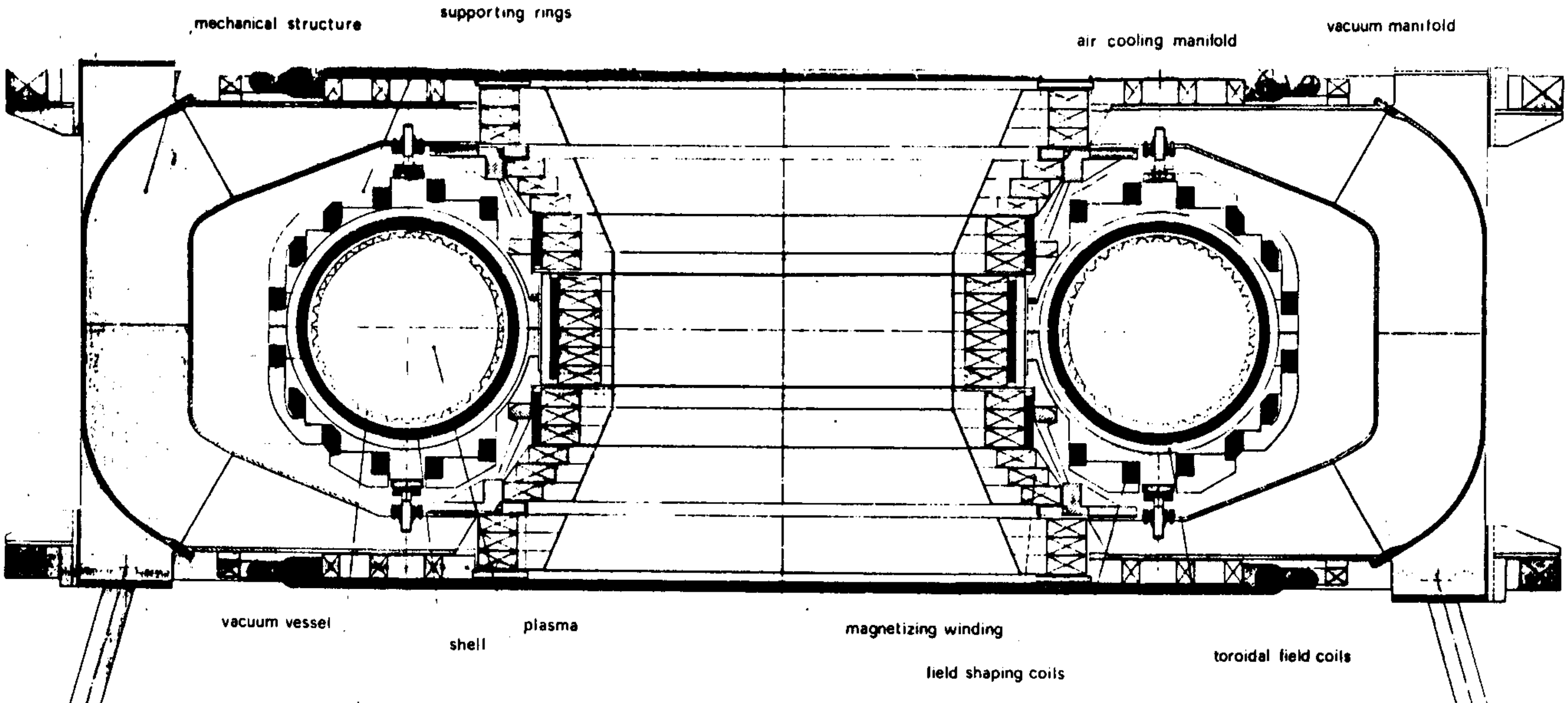
PARAMETERS OF RFX

Machine Parameters

$R = 2$ m
$a = 0.5$ m
$I = 2$ MA
$\tau_p = 0.25$ sec

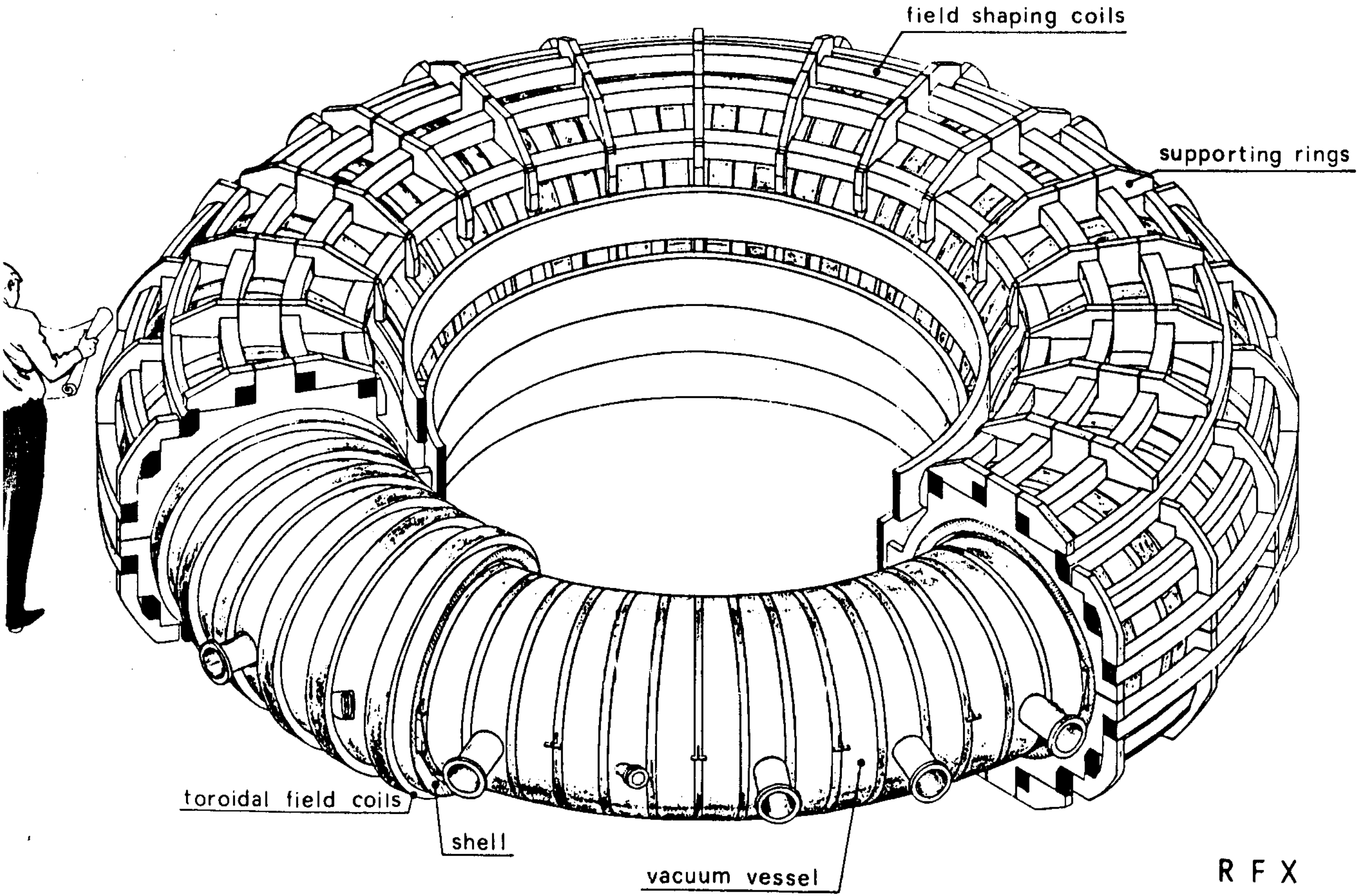
Representative Plasma Parameters

$T \sim 1$ keV
$n \sim 10^{20} m^{-3}$
$\beta_\theta \sim 10\%$
$\tau_E \sim 10$ ms



R F X

load assembly



R F X

Inner Load Assembly

RFX

- Good progress after early (organisational) delays. Completion date 1989

- Scientific specification frozen April 1985
- Financially on target

- Tenders placed or actioned for major components; buildings

- Remaining 25% funds released
  Build to full 2 MA specification (total 36 MEUA)

- Culham contributions
  - Engineering (~ 3-4 AGMY), power supplies, switching, protection
  - Physics ($\lesssim$ 1 AGMY), physics planning; diagnostic development (ion temperature, total radiation)