[redacted]

(140)

pt. 1

Cours/Lecture Series

1983 - 1984 ACADEMIC TRAINING PROGRAMME

SPEAKER	: R. S. PEASE / Culham Laboratory
TITLE	: Fusion reactors
DATES	: June 4, 5, 6, 7, 8 ,1984
TIME	: 11.00 hours to 12.00 hours
PLACE	: Auditorium

ABSTRACT

1. The basic possibilities.
2. High temperature matter.
3. Magnetic confinement principles.
4. Survey of current confinement experiments.
5. Fusion reactor engineering.

Secretariat : Tel. 2844.

DOC/PU/ED
Distr. Interne + Externe

COPIES OF TRANSPARENCIES

TABLE 1

Fusion Reactions

Solar Reactions

$H + H \rightarrow D + e^{+} + \nu + 0.9$ MeV

$D + H \rightarrow {}^{3}H_{e} + \gamma + 5.5$ MeV

Possible for Practical Terrestial Thermonuclear Fusion

Reaction	σ_{max} (barns)
$D + D \rightarrow {}^{3}H_{e} + n + 3.1$ MeV	0.08
$D + D \rightarrow {}^{3}H + p + 3.75$ MeV	0.09
$D + T \rightarrow {}^{4}H_{e} + n + 17.6$ MeV	5.0
$T + T \rightarrow {}^{4}H_{e} + 2n + 11.3$	0.1
$D + {}^{3}H_{e} \rightarrow {}^{4}H_{e} + p + 18.3$ MeV	0.8
$D + {}^{6}L_{i} \rightarrow {}^{4}H_{e} + {}^{4}H_{e} + 22.4$ MeV	0.026
$p + {}^{11}B \rightarrow 3\ {}^{4}H_{e} + 8.7$ MeV	0.8
$p + {}^{6}L_{i} \rightarrow {}^{4}H_{e} + {}^{3}H_{e} + 3.7$ MeV	0.25

Tritium Breeding

$n + {}^{6}L_{i} \rightarrow {}^{4}H_{e} + T + 4.8$ MeV

$n + {}^{7}L_{i} \rightarrow {}^{4}H_{e} + T + n - 2.5$ MeV

Neutron Multiplicator

$n + {}^{9}Be \rightarrow 2H_{e} + 2n + e - 1.85$ MeV

(Crocker et al CLM-P240, 1970)

O N Jarvis, Eur.Appl.Res.Rept. - Nucl.Sci.Technol. Vol.3, No.1 and 2, pp127-352, 1981.

WORLD ENERGY REQUIREMENTS AND FUSION FUEL RESERVES

Present total energy utilization	$\simeq$ 0·2 Q/year
Estimated total energy requirement in 21st century	$\simeq$ 1 Q/year
Deuterium in the oceans	$\equiv 3 \times 10^{10}$ Q
Known land-based lithium reserves	$\equiv$ 1,000 Q (approximately 50% in North America and 50% in Africa)
Lithium reserves in Meldon Dyke, Devon	$\simeq 10^5$ tonnes (approximate British energy requirement for 1,000 years)

$Q = 10^{21}$ J

81.658 1 Tonne of Li $\sim 10^{17}$ J. But $^6Li : {}^7Li$ usage! 1.2

Reaction Cross-section

$$\sigma = \frac{\Lambda^2}{4\pi} \times$$

$$\operatorname{Exp}\left[-\frac{2\pi e^2 Z_1 Z_2 \sqrt{MA}}{\hbar\sqrt{E}} + \frac{4e\sqrt{2MAZ_1Z_2R}}{\hbar}\right] \times$$

$$\Gamma MAR^2/\hbar^2 .$$

Where

$A = A_1A_2/(A_1+A_2)$

M = nucleonic mass

$R \simeq 1.7 + 1.22\times10^{-13}(A_1+A_2)^{1/3}$

= Radius of compound nucleus

$\Lambda = h/\sqrt{2MAE}$

From Gamow

Simplified Formulae

$$\sigma = \sigma_1 \beta^2 / E \,.\, \mathrm{Exp}(-\beta/\sqrt{E}),$$

Where

For D-D $\begin{cases} \sigma_1 = 0\cdot14 \text{ barn and} \\ \beta = 1448 \quad (eV)^{1/2}. \end{cases}$

E is kinetic energy in eV

For D-T $\begin{cases} \sigma_1 = 11 \text{ barns and} \\ \beta = 1404 \quad (eV)^{1/2}. \end{cases}$

W.P. Allis 1960

E in lab. frame, stationary T

Thermonuclear Reactions

A/ $\sigma_{sc} \simeq 10^{12} Z_1^2 Z_2^2 / E^2$, barns

E in eV

$\gg$ Reaction cross-sections for $E \lesssim 10^5$ eV

B/

$$dN = \frac{4 n_1 n_2 \, \sigma(E) \, \mathrm{Exp}(-E/kT) \, E dE}{A_1 A_2 \sqrt{2\pi A} \, . \, (MkT)^{3/2}}$$

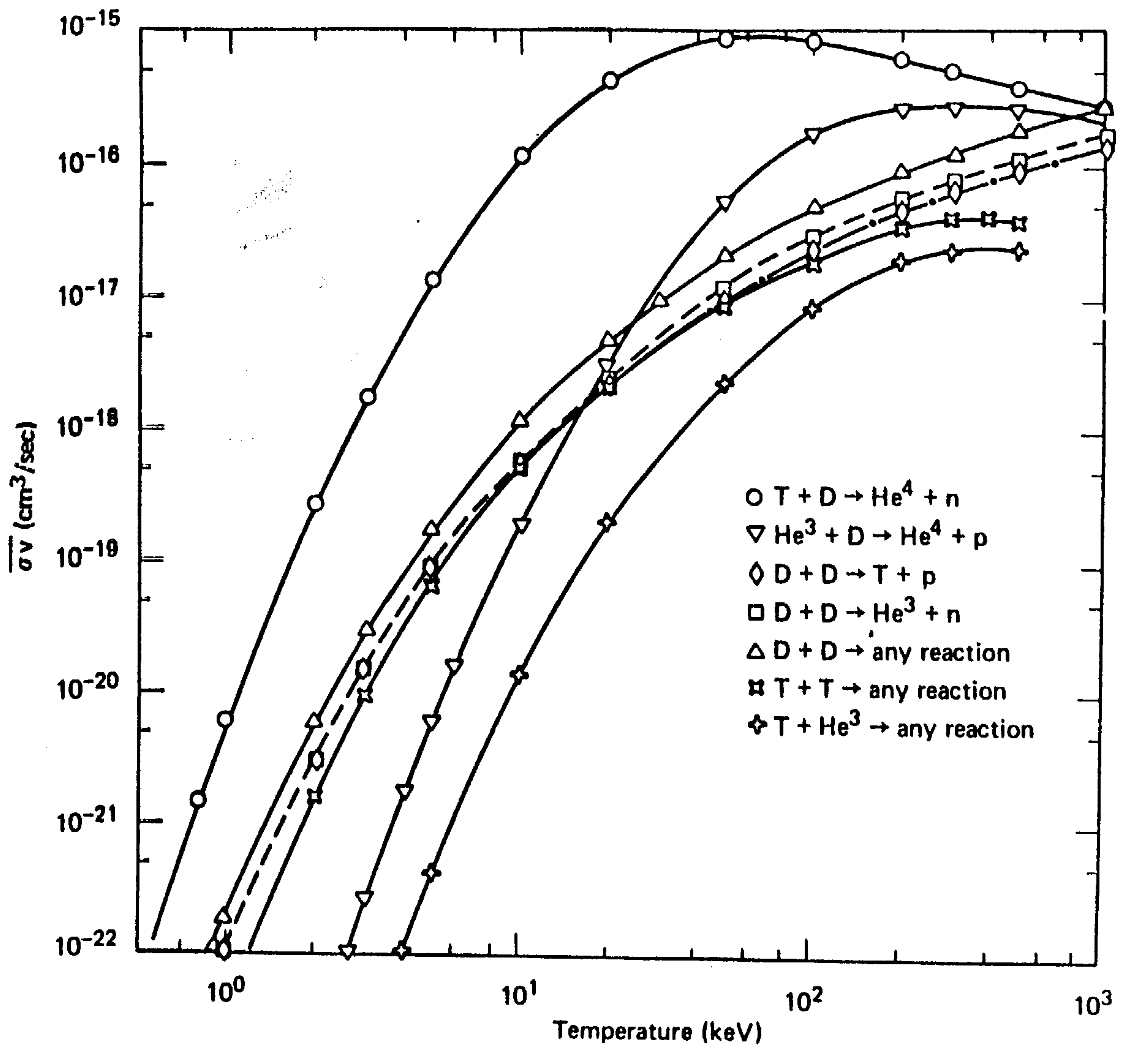
reactions per unit volume per sec. with collision energy E and E+d

C/ After integration, simplified formulae

$$N = a n_1 n_2 \left(b/T^{1/3} \right)^2 e^{-b/T^{1/3}}$$

H - H , $a = 0.64 \times 10^{-46}$ cm^2/s
$b = 149$ $(eV)^{1/3}$

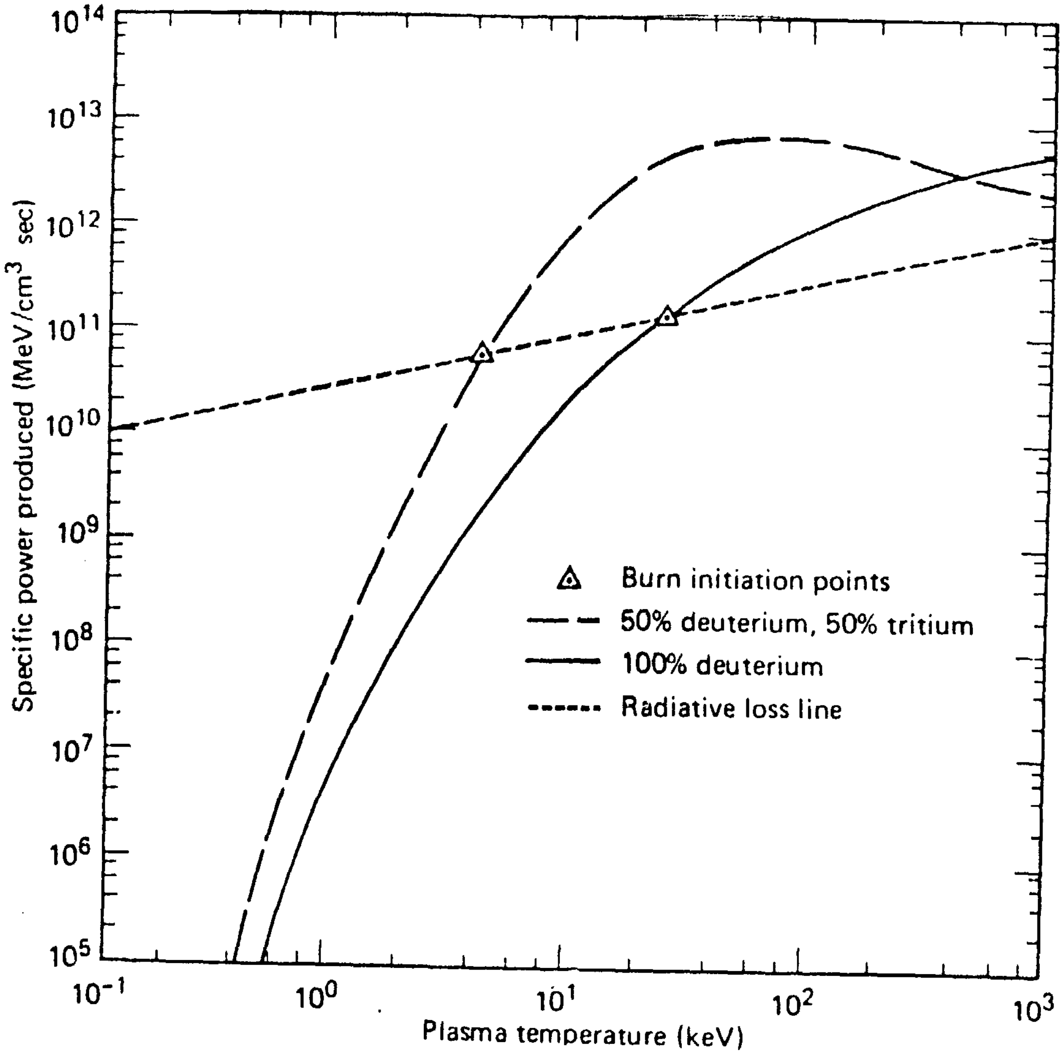
D - D $a = 75 \times 10^{-22}$ cm^3/s
$b = 188$ $(eV)^{1/3}$



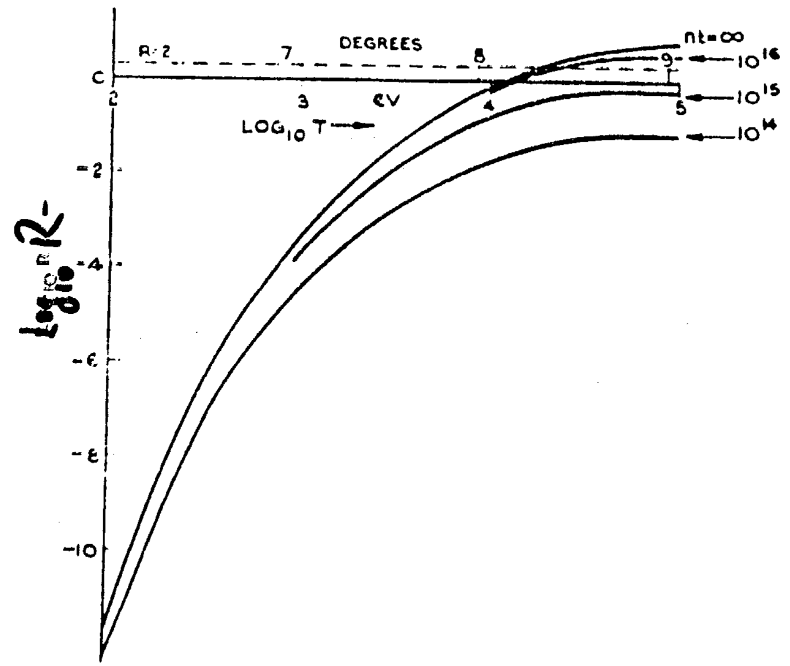
Maxwell-averaged cross sections for some thermonuclear reactions of light isotopes.

1eV
11,600

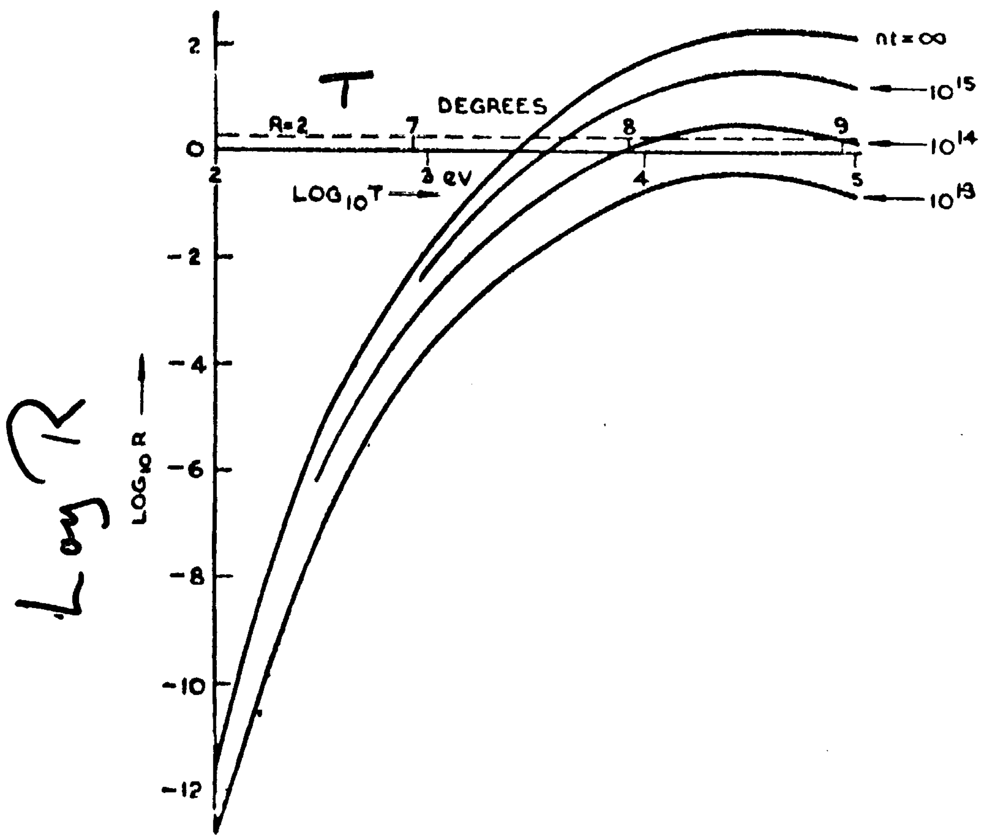
84.997


Specific power produced (MeV/cm^3 sec)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Plasma temperature (keV)
Burn initiation points
50% deuterium, 50% tritium
100% deuterium
Radiative loss line

84.984



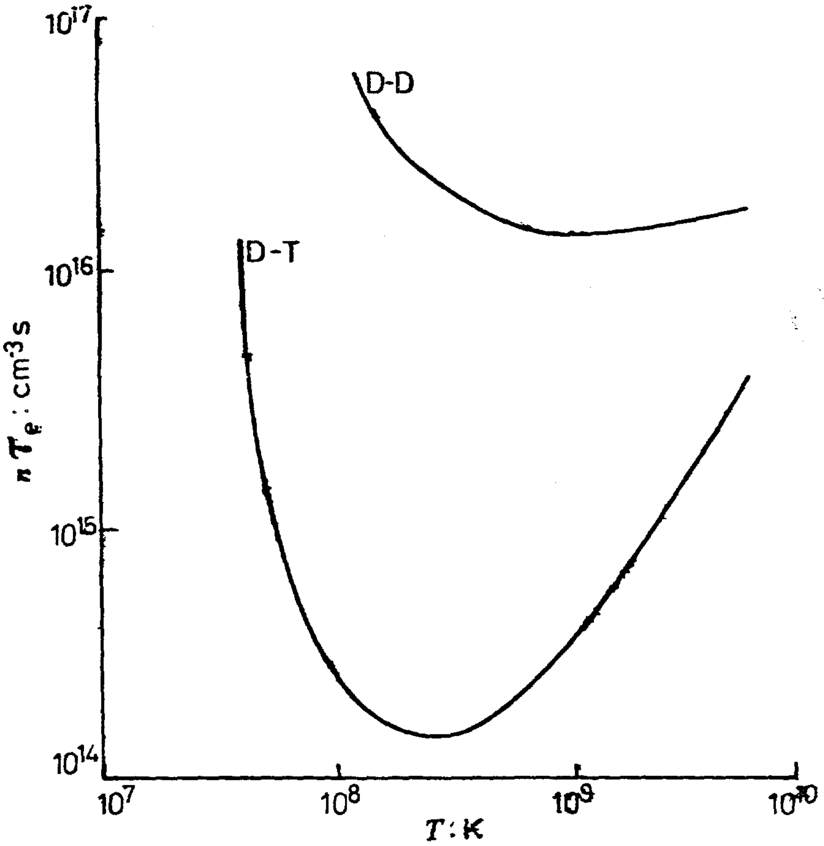
Variation of R with T for various values of nt for D·D reaction.



Variation of *R* with *T* for various values of *nt* for T–D reaction.

$$R = \frac{\text{Nuclear energy output / cc}}{3nkT + \tau P_{BS}} \geq 2.$$

84.996



Product of density and energy containment time as a function of temperature for the D–D and D–T fusion reactions . Ignition.

$$\tau_e = \frac{\text{Total Thermal Energy}}{\text{Total energy loss} - P_{BS}}$$

84.988

TABLE

Fuel Cycle	Max Q	$n\tau_e$ for Q = 2 (cm^{-3} sec)	Comments
D-T	∞	$10^{13} - 10^{14}$	Tritium breeding required
D-D	∞	6×10^{14}	No breeding
cat D-D	∞	$\sim 2 \times 10^{14}$	No breeding
D - ^{3}He	∞	6×10^{14}	Availability of ^{3}He? Not clean cycle since there are neutrons from D-D reaction
p - B^{11}	0.95	-	Q too small
p - ^{6}Li	0.1	-	Q too small
cat p - ^{6}Li	3	5×10^{15}	Q still small
^{3}He - ^{3}He	0.6	-	Q too small
p - ^{9}Be	< 1	-	Q too small

INERTIAL CONFINEMENT

Conf. Time $\tau \simeq \xi . r . 10^{-8}$ s.

Substitute in Lawson

$$\xi r n > 10^{22} \text{ cm}^{-2}$$

Nuclear yield is ~ 1% of $r^3 n Q$ at Lawson

$$\text{Yield} \propto 1/\xi^2 n^2$$

i.e. for small, manageable yield, n very large

e.g. $10^4 \times$ Liquid ~ 5×10^{26} cm^{-3}

Magnetic Confinement

$$\nabla p = j \times B$$

In plane slab geometry

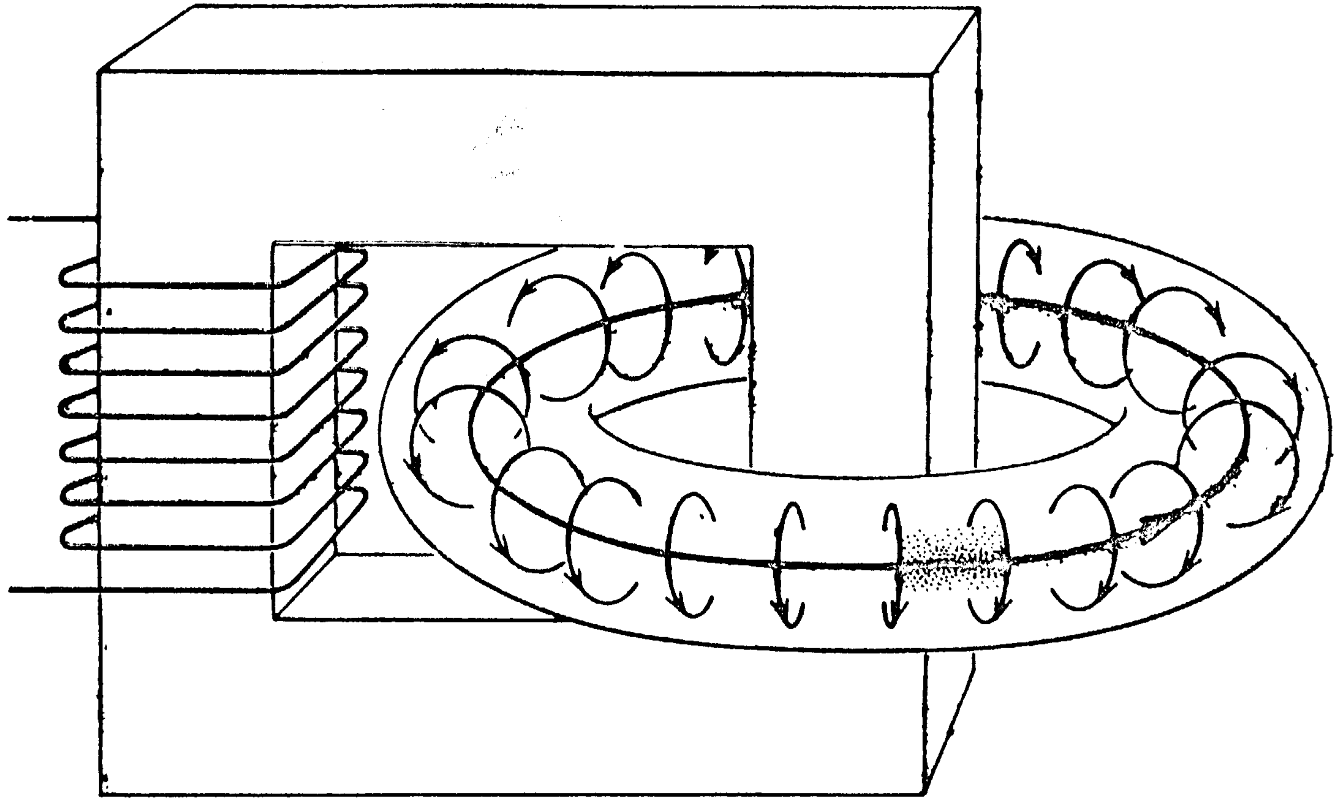
$$[p]_o^i = [B^2/8\pi]_i^o$$

$$p / B^2/8\pi \equiv \beta$$

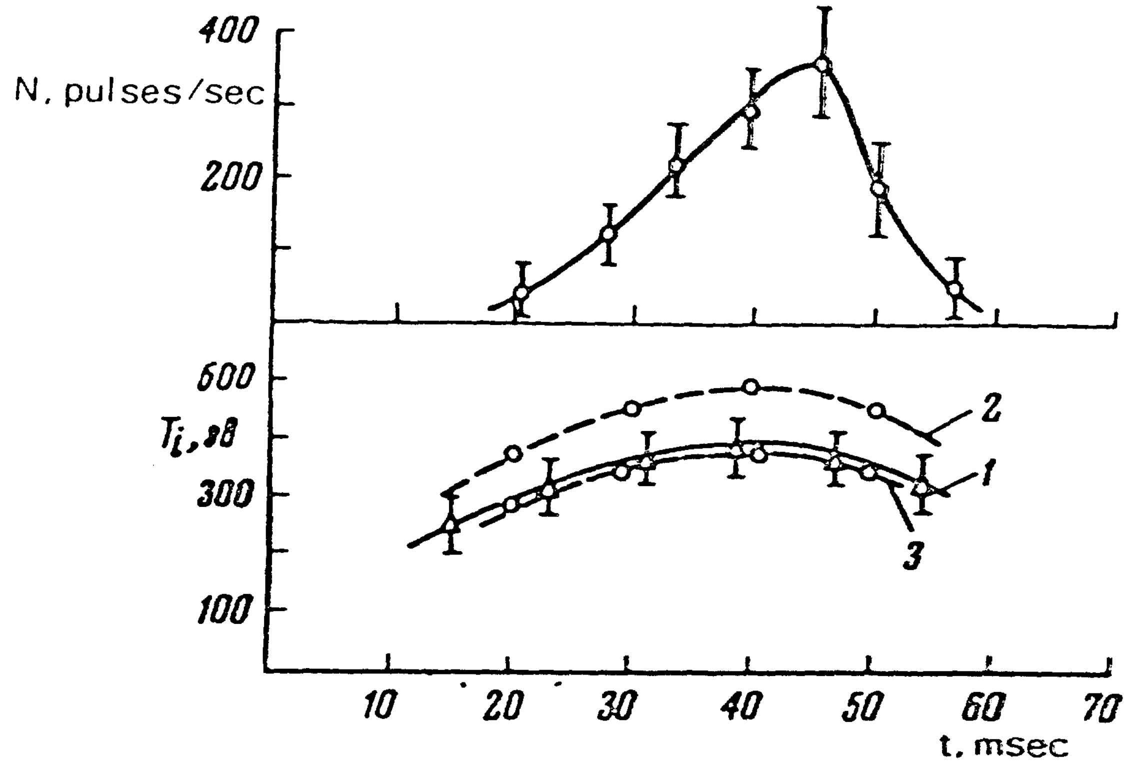
$$B^2/8\pi \sim 1 \text{ atmosphere}$$

when $B = 5$ k gauss.

$\beta \gtrsim 5\%$ for Reactor.



Schematic representation of the unstabilized toroidal pinch



Ion temperature and neutron emission in Tokomak T-3.
Top: intensity of neutron emission as a function of time.
Bottom: variation of ion temperature with time.
Curve 1 - from the spectrum of the charge exchange atoms.
Curves 2 and 3 - from the intensity of the neutron emission.

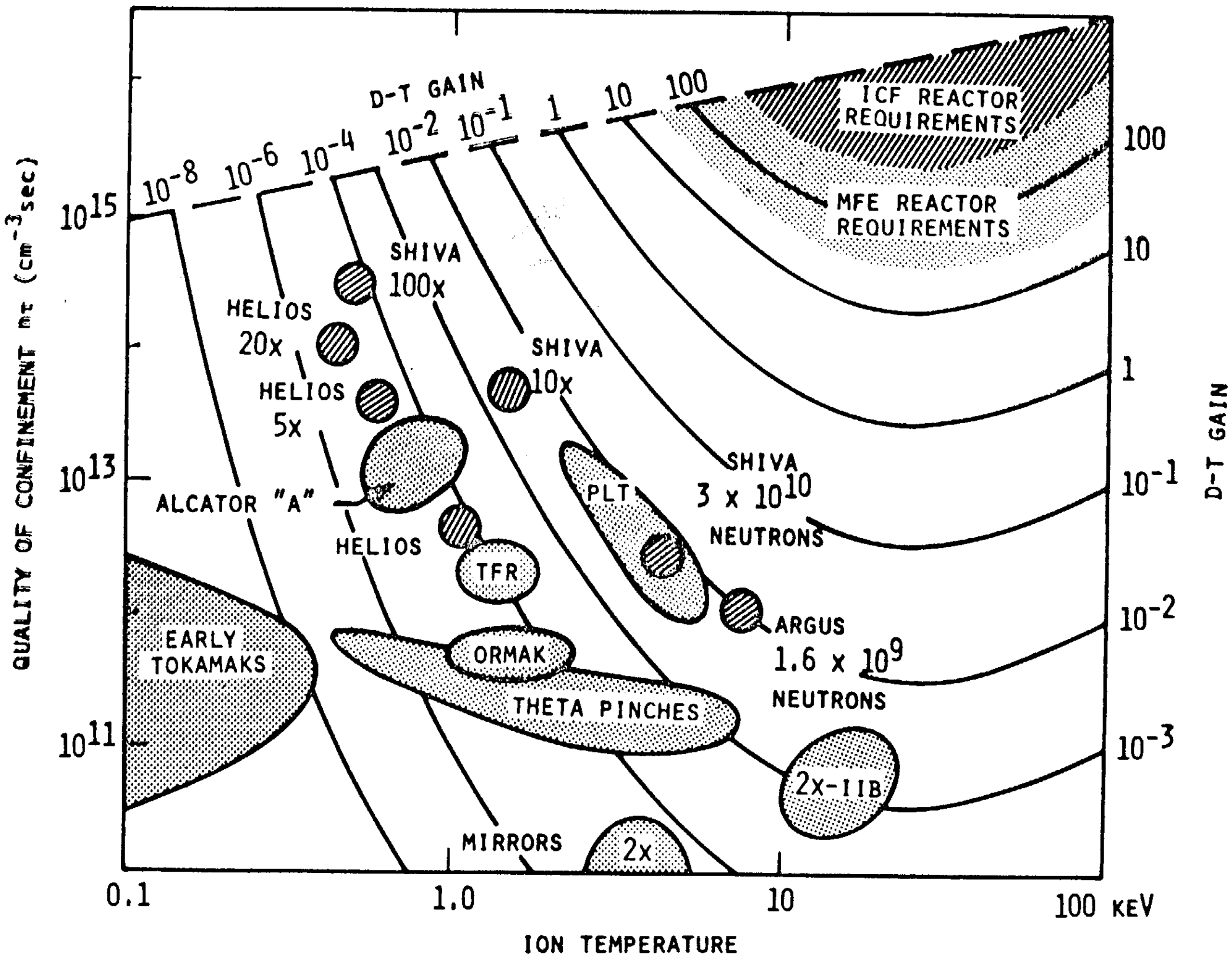
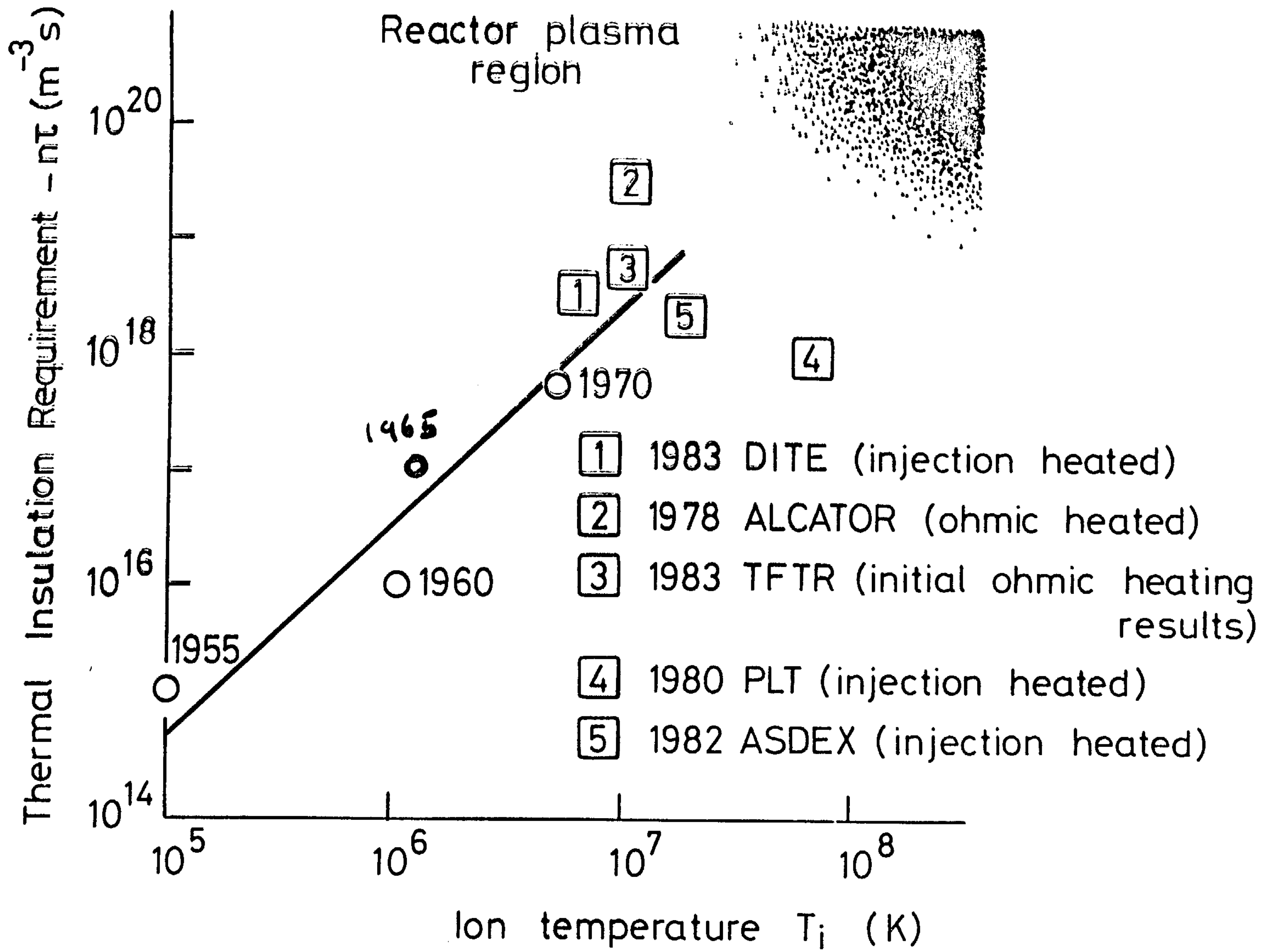
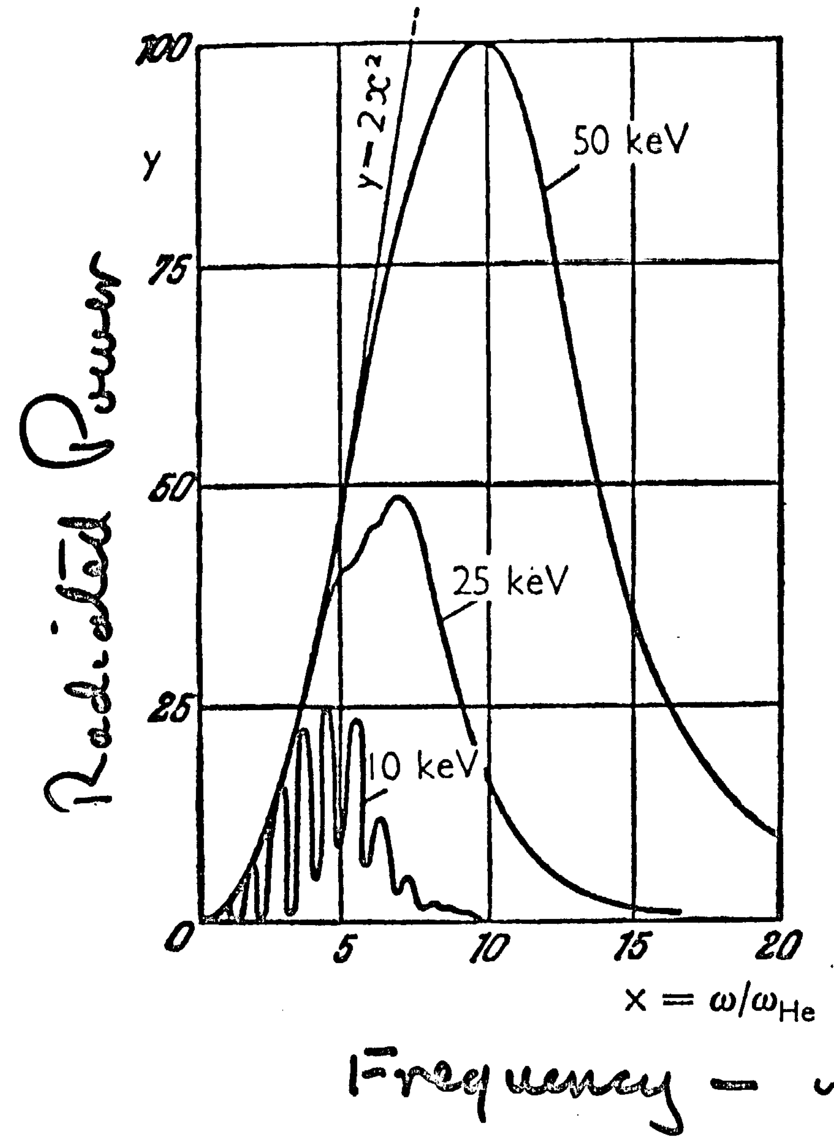


Figure 4 Plasma conditions achieved in Inertial Confinement experiments, using pulsed lasers. Magnetic confinement results from these experiments are also plotted (from Maniscalco (1980)) [1]


Reactor plasma region
Thermal Insulation Requirement – nτ (m⁻³ s)
10^20
10^18
10^16
10^14
1955
1960
1965
1970
1
2
3
4
5
1 1983 DITE (injection heated)
2 1978 ALCATOR (ohmic heated)
3 1983 TFTR (initial ohmic heating results)
4 1980 PLT (injection heated)
5 1982 ASDEX (injection heated)
10^5
10^6
10^7
10^8
Ion temperature Ti (K)

PLASMA PARAMETERS ACHIEVED IN TOROIDAL PINCHES

	Confinement Time (τ_e) (s)	Ion Temperature (T_i) (K)	Lawson Parameter ($n\tau_e$) (m^{-3} s)	Sustainment Time (s)
1955	10^{-5}	10^5	10^{15}	10^{-4}
1960	10^{-4}	10^6	10^{16}	3×10^{-3}
1965	2×10^{-3}	10^6	10^{17}	2×10^{-2}
1970	10^{-2}	5×10^6	5×10^{17}	10^{-1}
1980	10^{-1}	8×10^7	3×10^{19}	3
1983	$1{\cdot}5 \times 10^{-1}$; 3×10^{-1}	8×10^7	8×10^{19}	10
Needed for a reactor	10^0	10^8	10^{20}	> 100



$$A = \frac{4\pi ne}{H}a,$$

= Dimensionless length

$= 10^4$

Magnetic radiation spectrum; the various curves correspond to different values of the electron temperature

From L.A. Artsimovitch Book

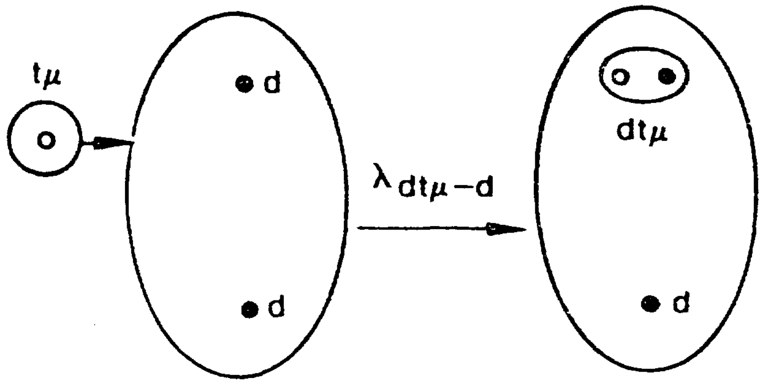


FIG. 1. Resonant production of $dt\mu$ molecules.

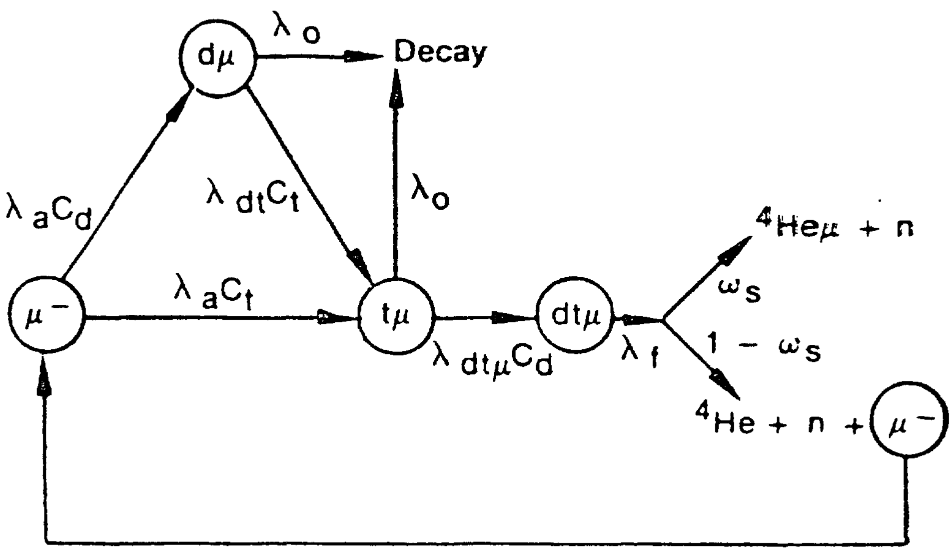


FIG. 2. Muon catalysis in a mixture of deuterium and tritium.

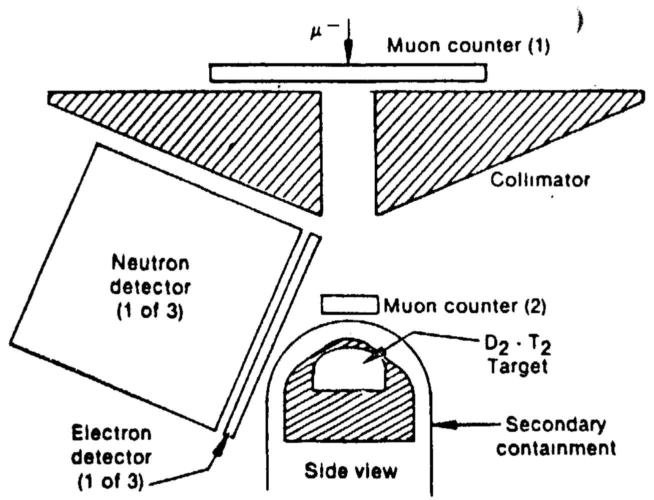


FIG. 3. Layout of the experiment.

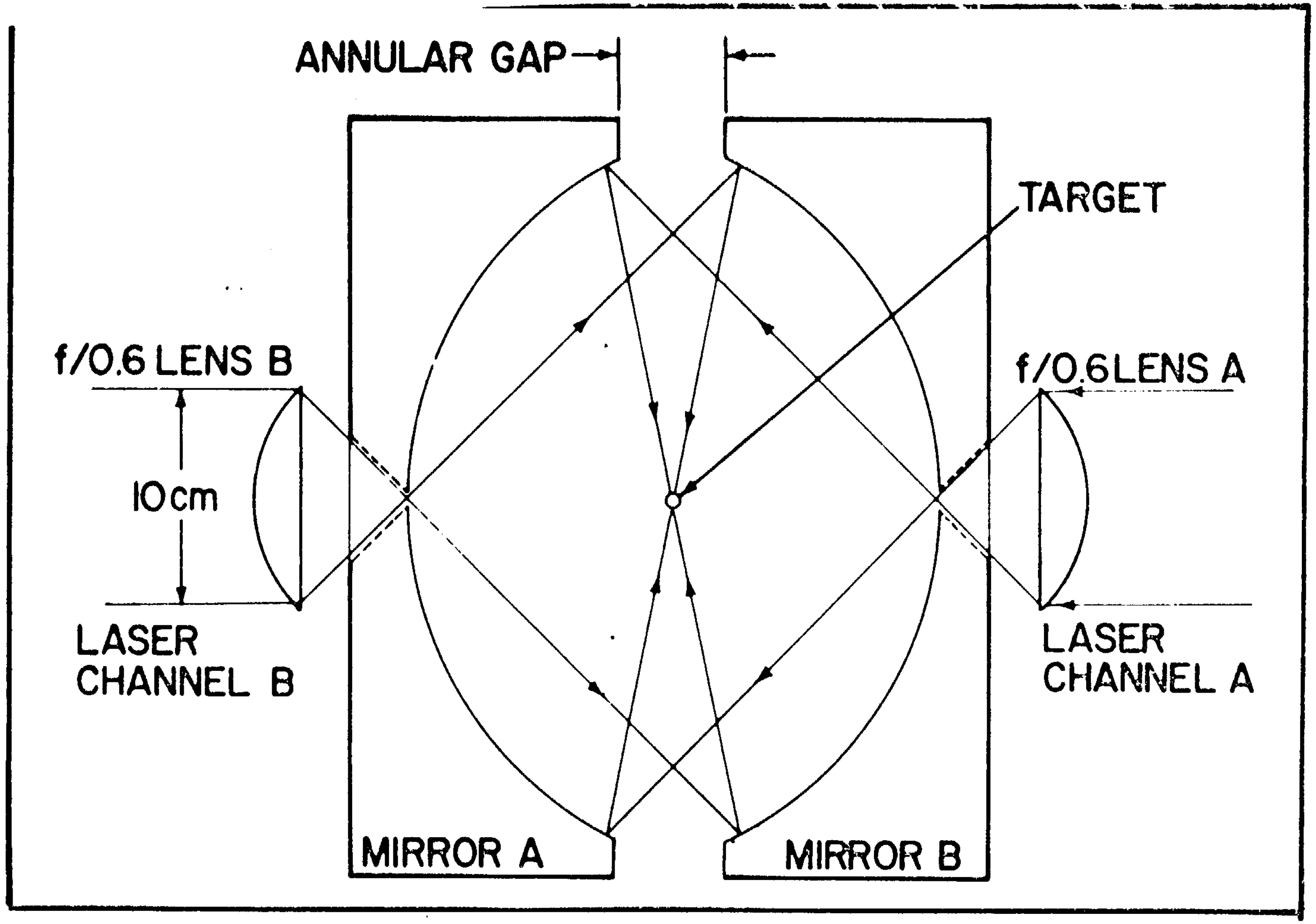
TABLE I. Parameters of muon catalysis in deuterium-tritium mixtures.

	λ_{dt} (s^{-1})	$\lambda_{dt\mu}$ (s^{-1})	ω_s	ω_{He}	λ_{dHe} (s^{-1})	λ_{tHe} (s^{-1})	$\bar{n}$
Theory	2×10^8 [b]	$\sim10^8$ [c]	0.86% [d] 0.91% [e]	~1 [f]	1.5×10^8 [g]	5.6×10^8 [g]	$\sim10^2$ [c]
Previous experiment [a]	$(2.9\pm0.4)\times10^8$	$>10^8$	...	...	...	...	...
Present experiment	$(2.8\pm0.3)\times10^8$	see Fig. 5	(0.77 ± 0.08)%	1 ± 1	$(2\pm1)\times10^8$	$(7\pm2)\times10^8$	90 ± 10

[a] Ref. 7.
[b] Ref. 8.
[c] Ref. 5.
[d] Ref. 11.
[e] Ref. 12.
[f] Ref. 14.
[g] Ref. 13.

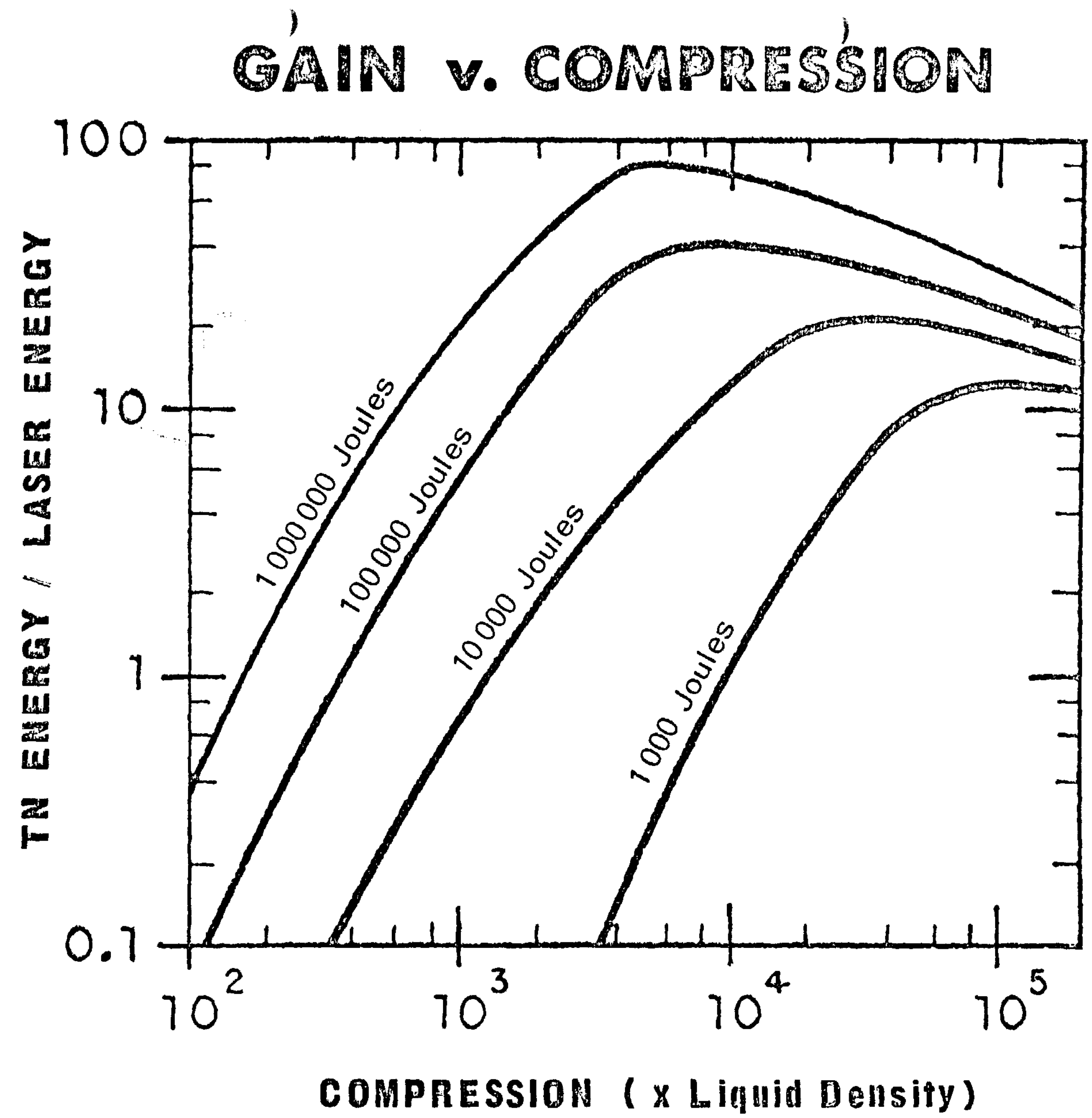
S. E Jones et al, Phys Rev. Lett. 51 1757 ('83) 1.21

LMP84-907



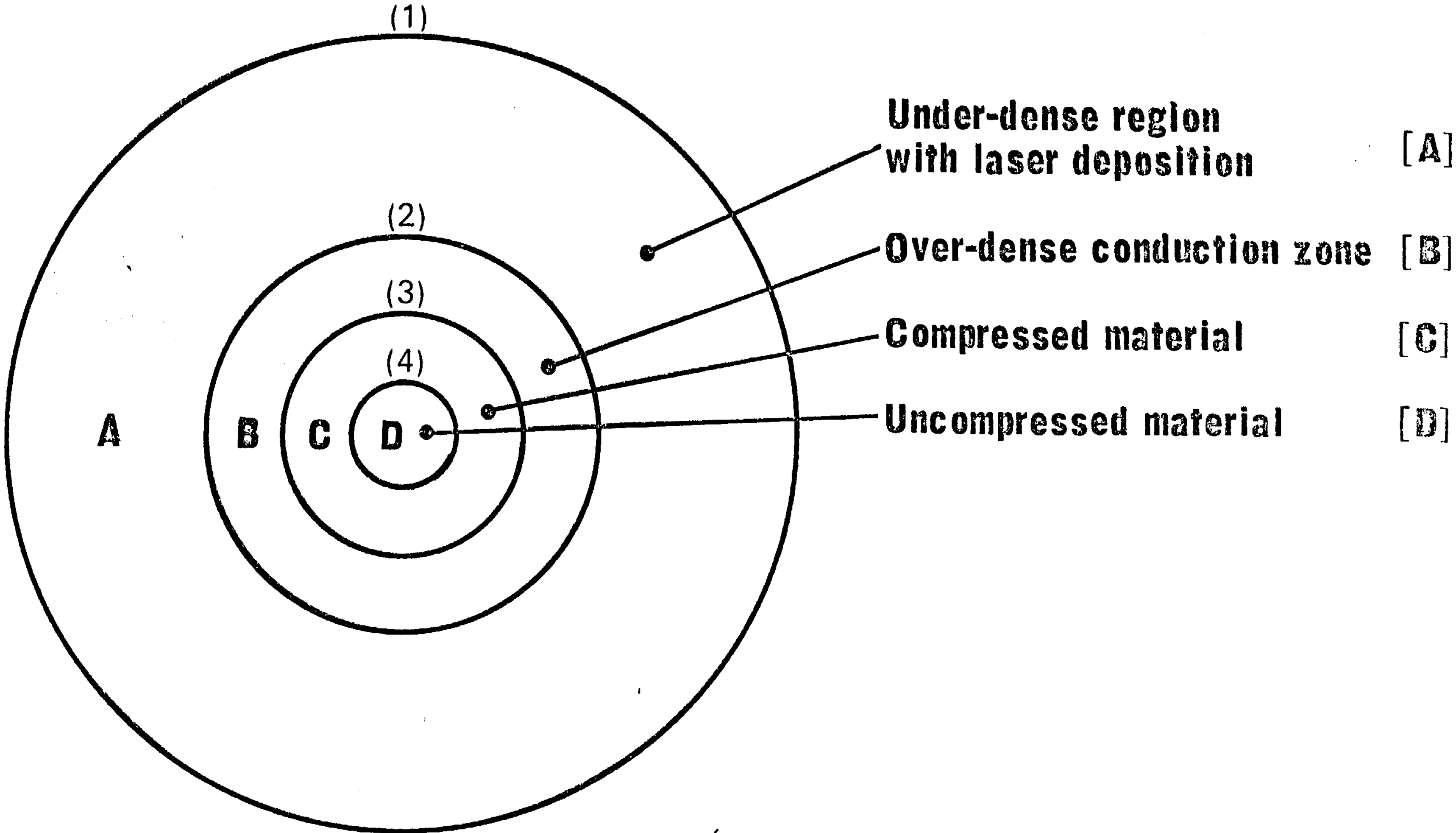
TARGET-ILLUMINATION CHAMBER uses aspheric lenses and ellipsoidal mirrors to illuminate most of a pellet's surface with two beams

75.407 K.M.S. (Brueckner et al 1975)


GAIN v. COMPRESSION
100
10
1
0.1
10^2
10^3
10^4
10^5
1 000 000 Joules
100 000 Joules
10 000 Joules
1 000 Joules
TN ENERGY / LASER ENERGY
COMPRESSION (x Liquid Density)

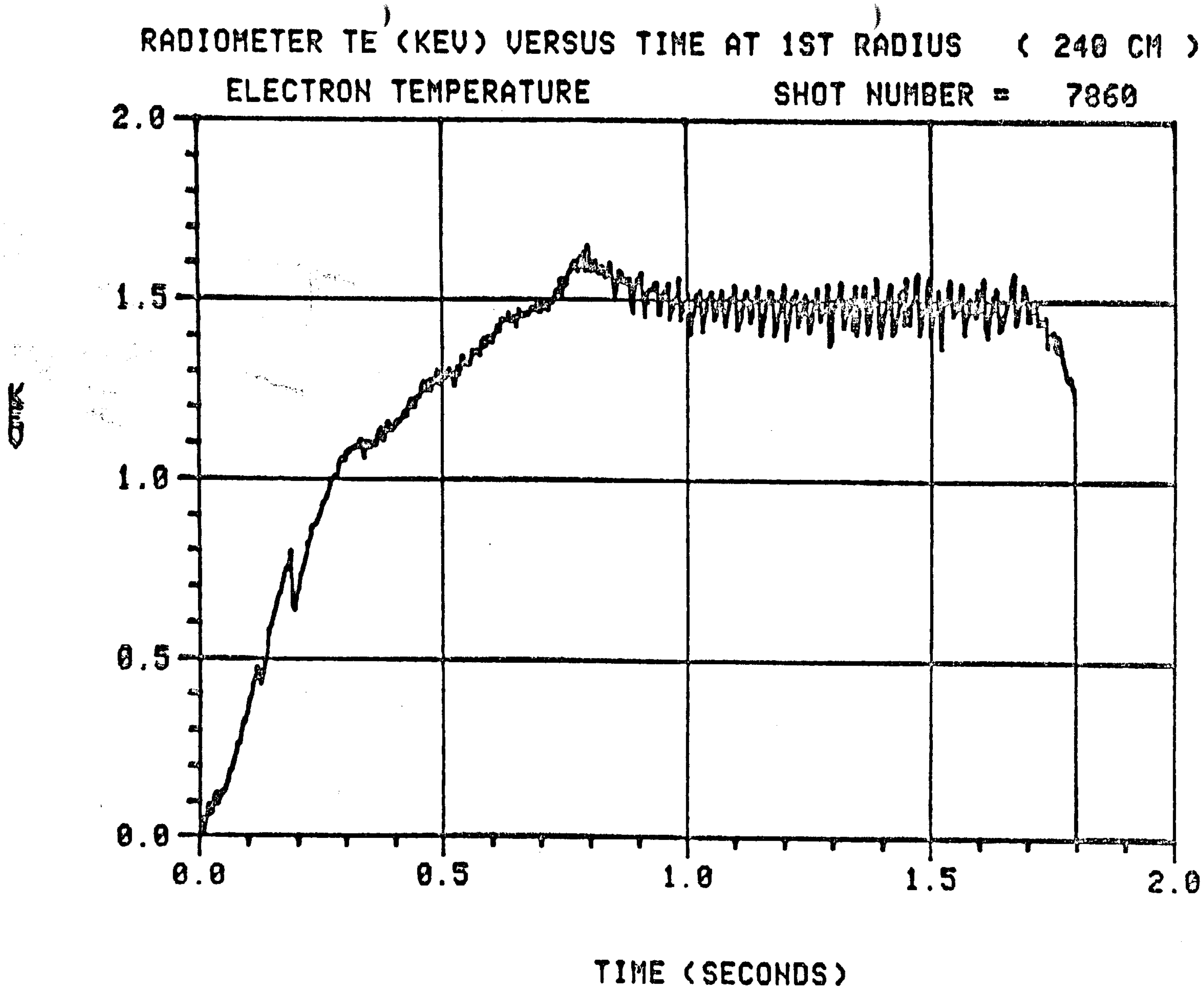
73,133

STRUCTURE OF IMPLODING PELLET

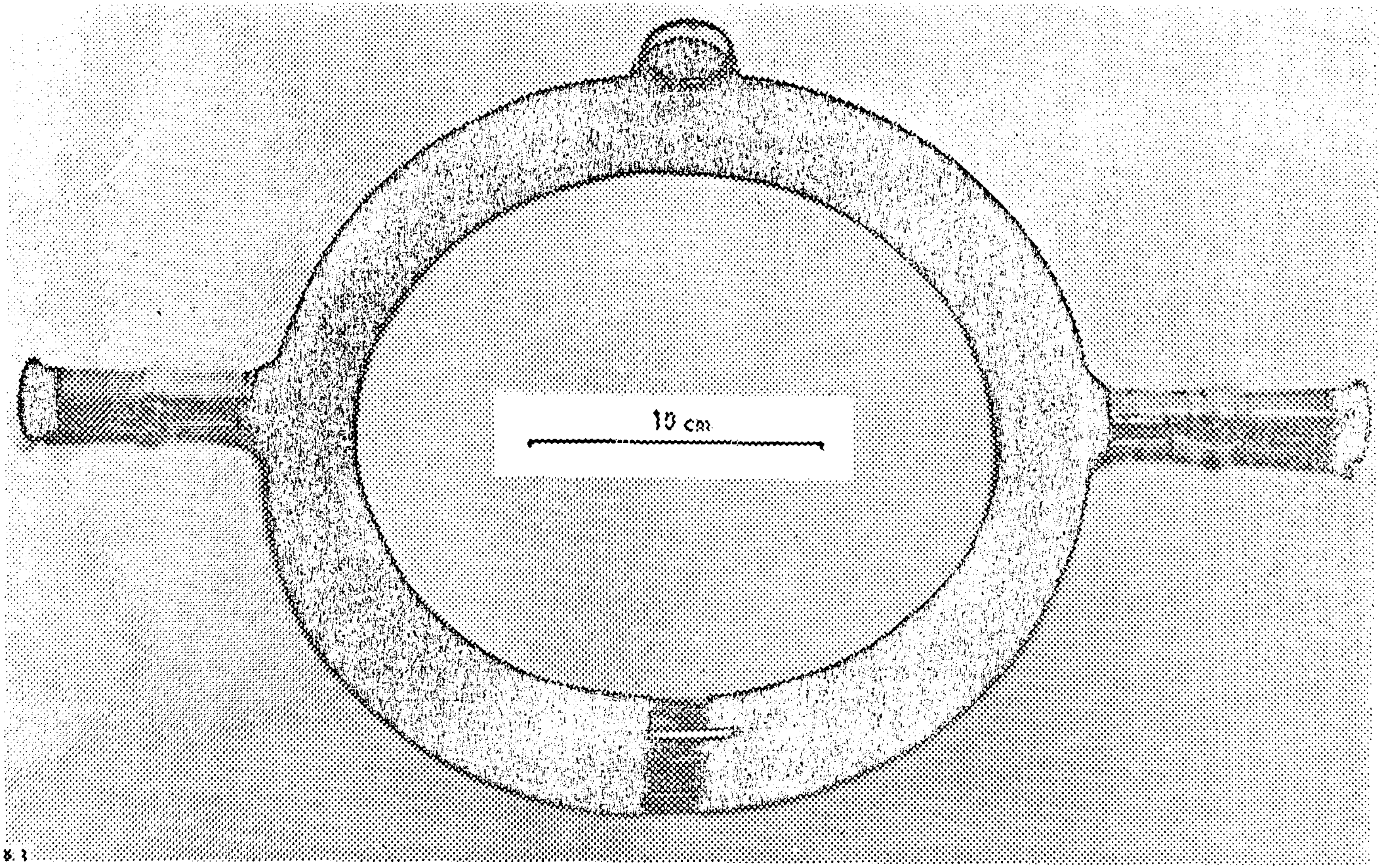


BOUNDARIES:

(1) Expanding under-dense plasma front
(2) Critical density surface
(3) Front of thermal conduction wave
(4) Front of compression wave



Electron Temperature in TFTR (Young et al 1984)



Toroidal Discharge Apparatus (Ware, 1951)

PLASMA PHYSICS : Cook's Tour.

Spitzer 1962

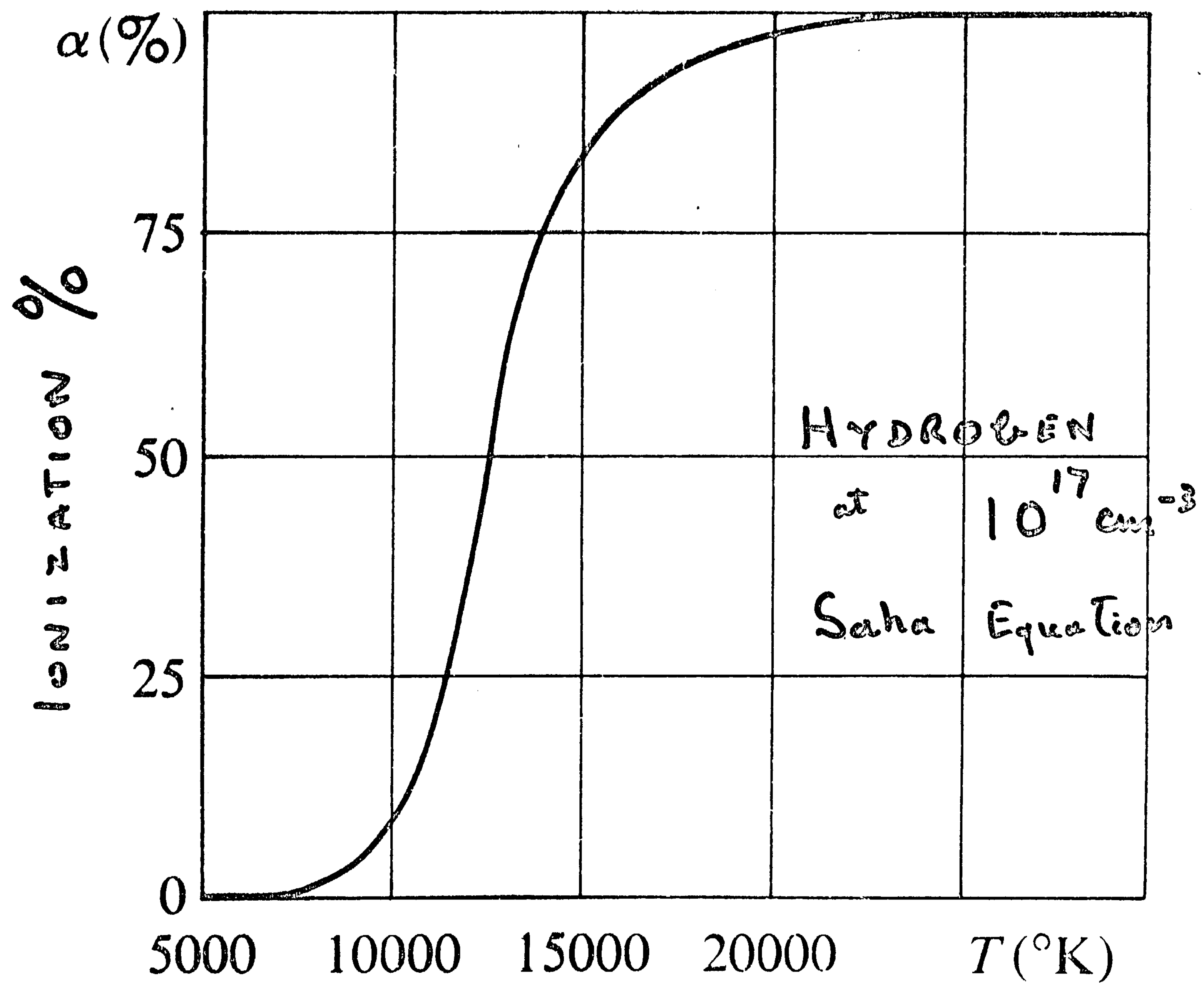
— Composition

— Electric Neutrality

— Why we believe theoretician.
(Debye Length)

— Plasma in B
(i) MHD / Alfvén
(ii) Two Fluid

— Plasma Production
& Heating


α(%)
IONIZATION %
75
50
25
0
5000
10000
15000
20000
T(°K)
HYDROGEN
at 10^17 cm^-3
Saha Equation

Ionization : Coronal Equilibrium

Assumes $f(v_e)$ maxwellian

Radiation not absorbed.

Then
electron impact ionization versus
(Radiative) recombination

Electron Impact Ion^{sn}.

$$\sigma(E) \sim 4\pi a_0^2 \frac{E_R^2}{E\chi_r}\left(1-\chi_r/E\right)$$

$\uparrow$ $10^{-16}\,cm^2$

$$\text{Rate} = S_r n_e n_r$$

$$S_r \sim 10^{-8}\, r\, T_e^{1/2} \chi_{eV}^{-2} e^{-\chi/kT}$$

Recombination

$$\text{Radiative } \sigma \sim \frac{hc}{e^2}\left(\frac{e^2}{mc^2}\right)^2$$

$2\times10^{-22}\,cm^2$

$$\text{Rate} = \alpha\, n_e n_{r+1}$$

$$\alpha \simeq 2\times10^{-11} Z^2 T^{-1/2} \phi\left(\frac{h\nu_0}{kT}\right)$$

$$\frac{n_{r+1}}{n_r} \simeq S/\alpha \sim 10^3 \frac{T}{\chi} \frac{e^{-\chi/kT}}{\phi}$$

Degree is less than Saha

Degree of Ionization :

Thermal Equilibrium — Saha Eqn.

n_r of r- times ionized atoms

n_{r+1} of $(r+1)$- times .. ..

Then

$$n_{(r+1)} = n_r \left[\frac{U_{r+1}}{U_r}\right] \cdot \frac{2}{n_e} \cdot \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \cdot \times \text{Exp}\left(-\chi_r / kT\right).$$

χ_r = ionization energy for $r \longrightarrow r+1$

$$U_r \equiv \text{Partition Function of ion} = \sum_{k=1}^{k=\infty} g_{rk} \, \text{Exp}\left(-E_{rk} / kT\right)$$

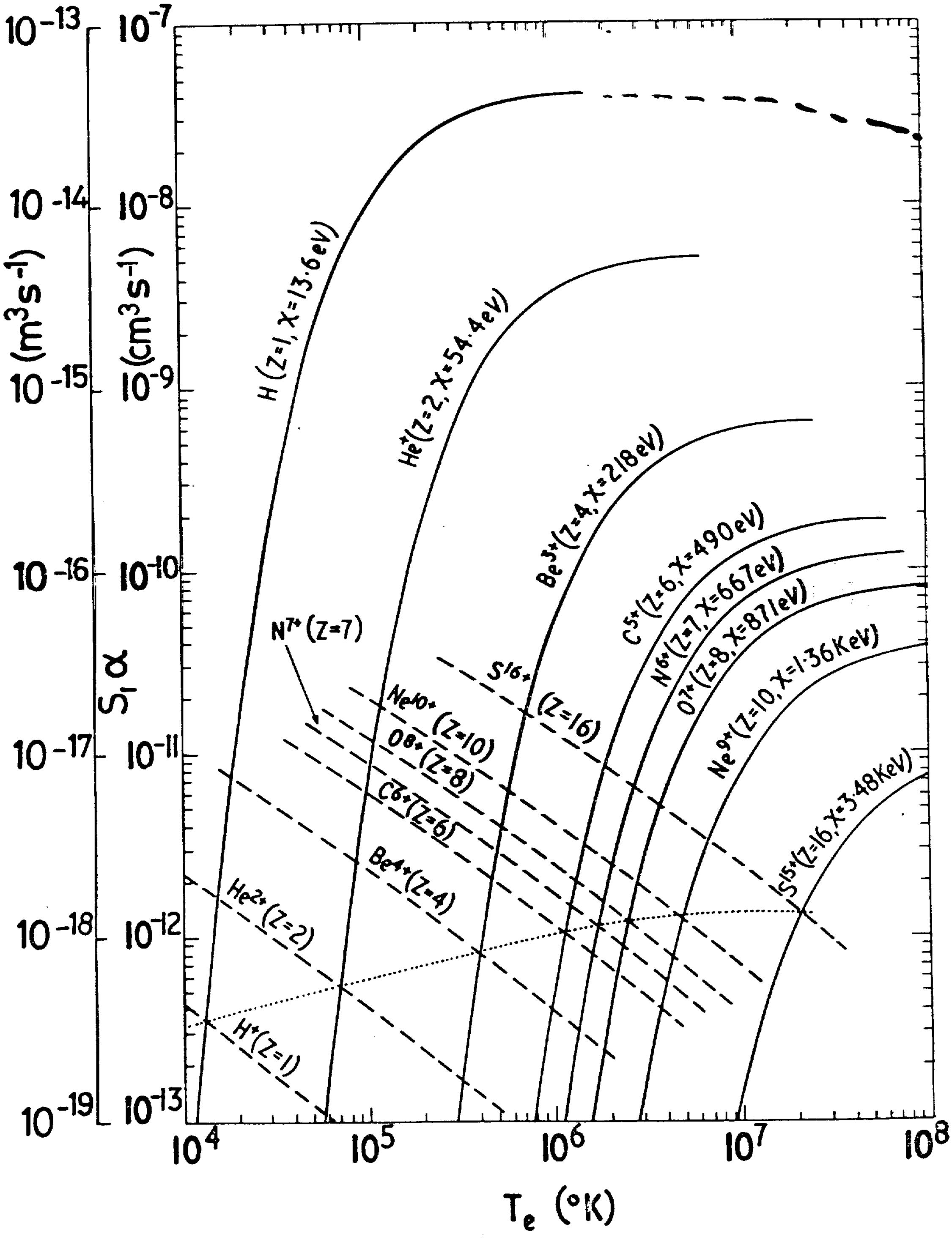
↑ stat. Weight ↑ Energy of k.

For Ground states, $\frac{U_{r+1}}{U_r} \simeq 1/2$.

$$\left(2\pi m_e kT / h^2\right)^{3/2} \cong \left(\text{de Broglie } \lambda\right)^{-3}$$

For classical plasmas $\gg n_e$

$\therefore n_{r+1} \gg n_r$ for $kT \sim \chi_r$

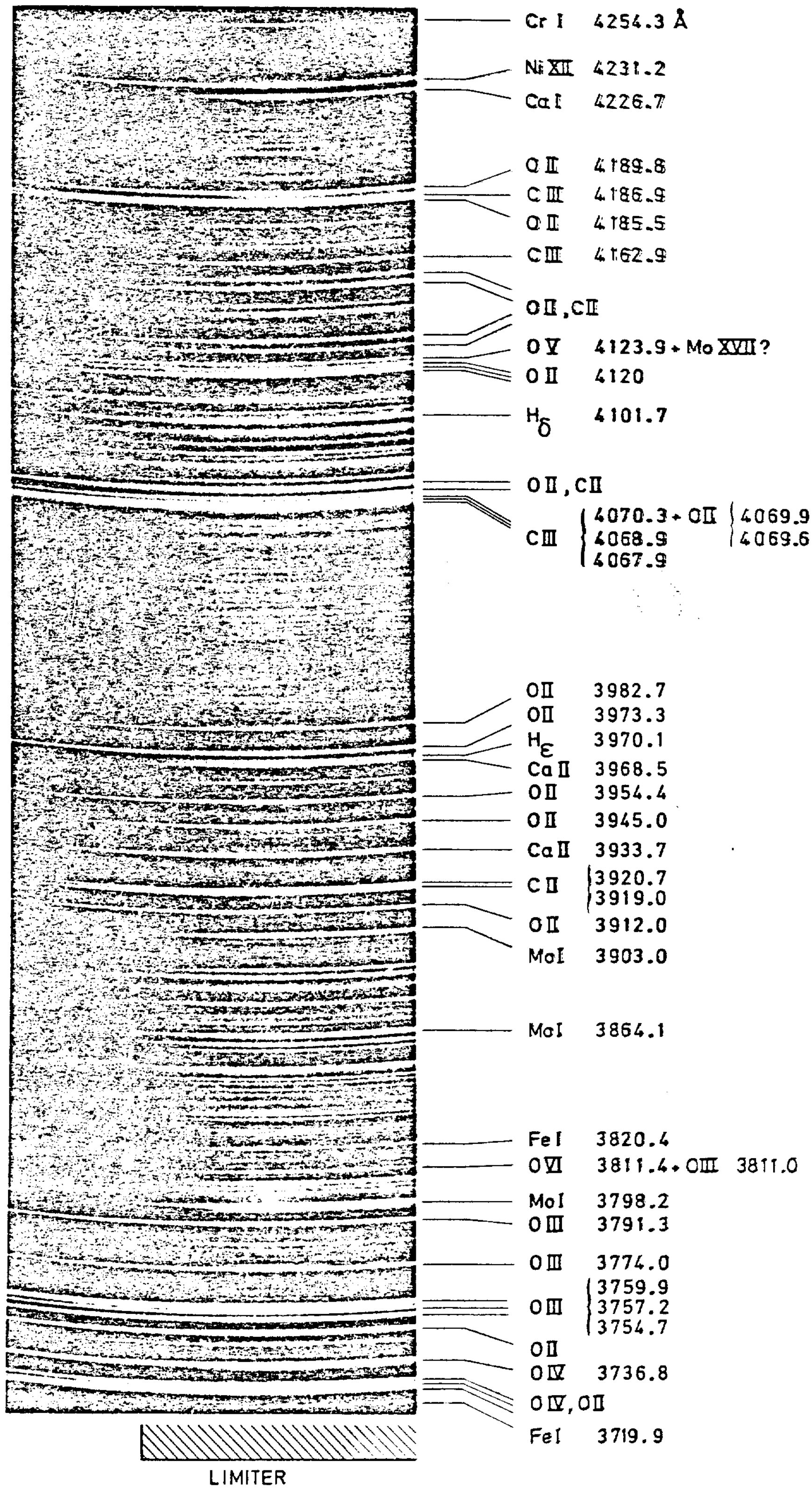


Ionization and recombination coefficients for hydrogen-like io[illegible] the limit of low electron density. (From Bates et al., 1962a.)

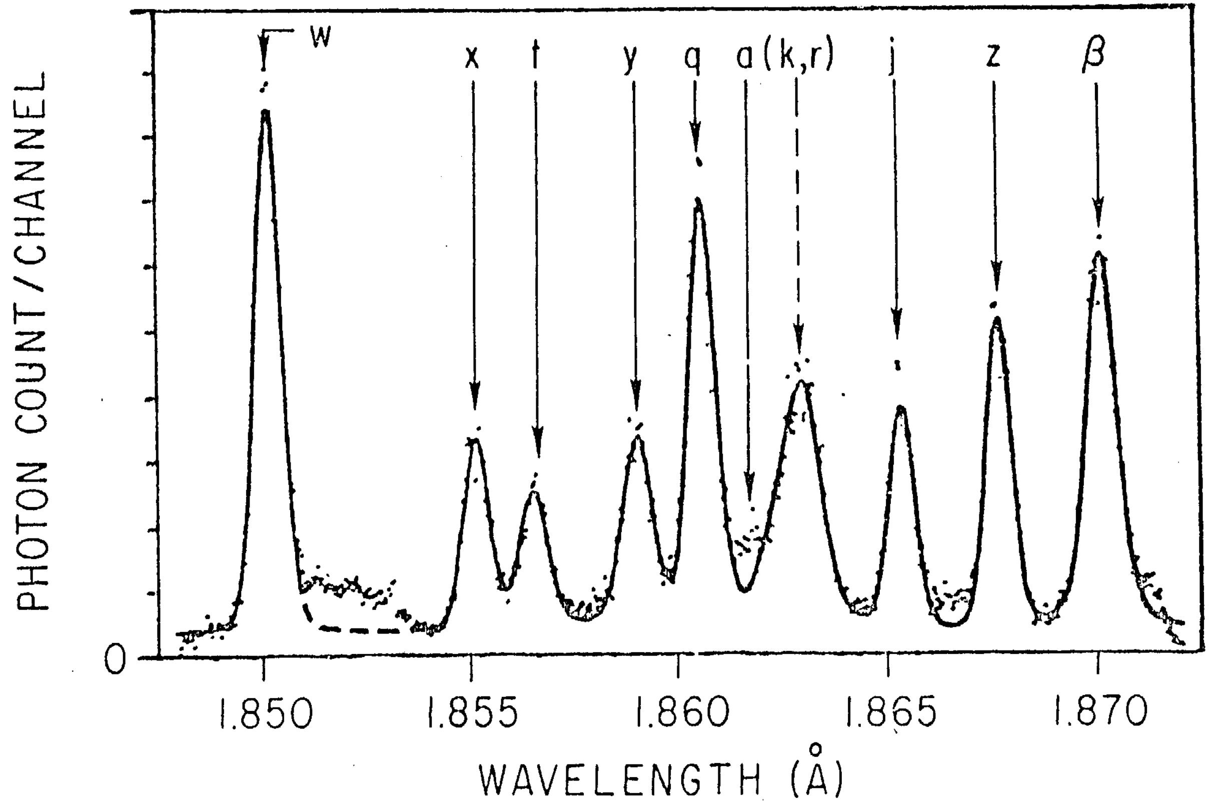
4

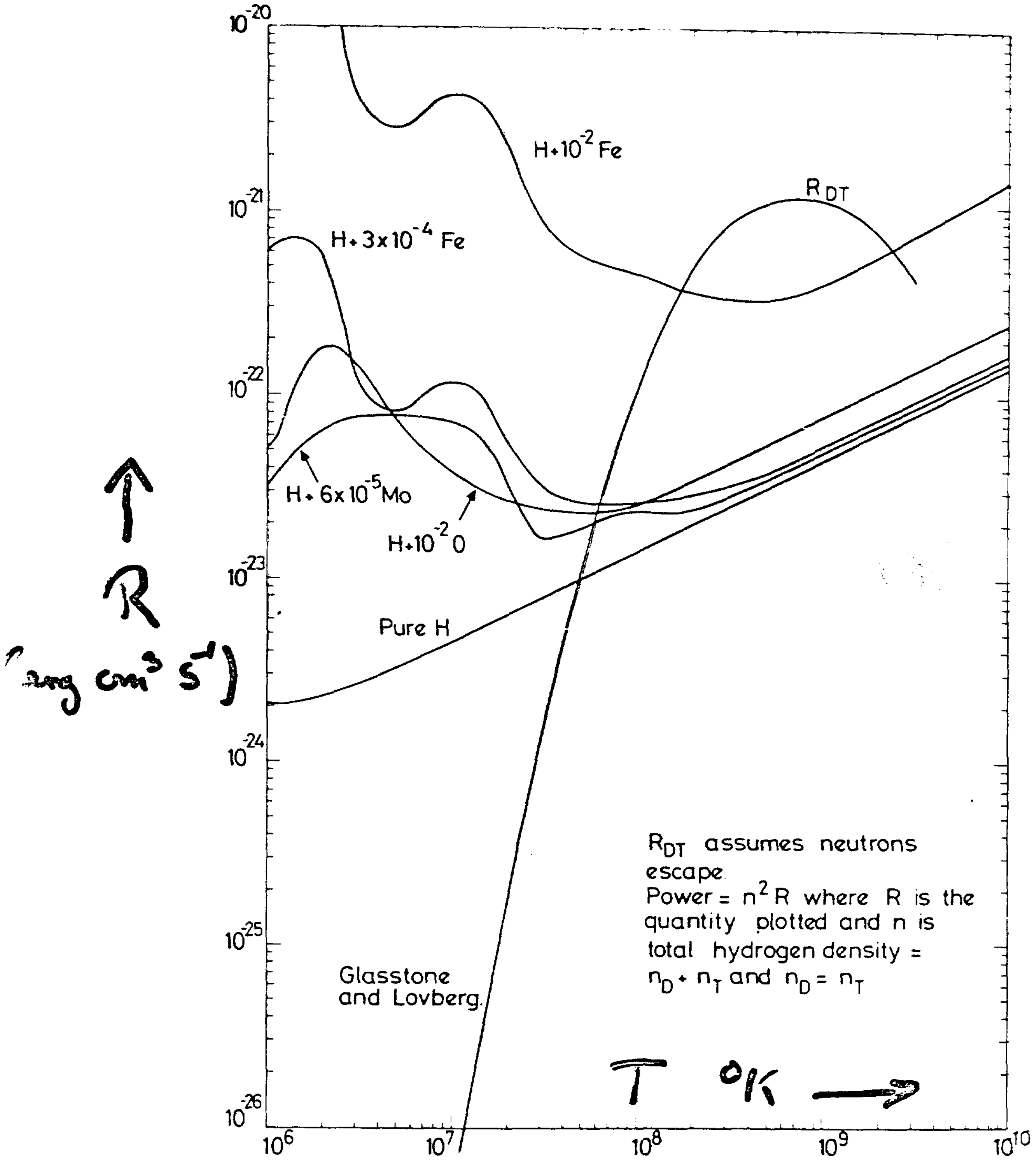
2-6

JET UV SPECTRUM



Fe XXV Spectra
(Bitter et al 1979)

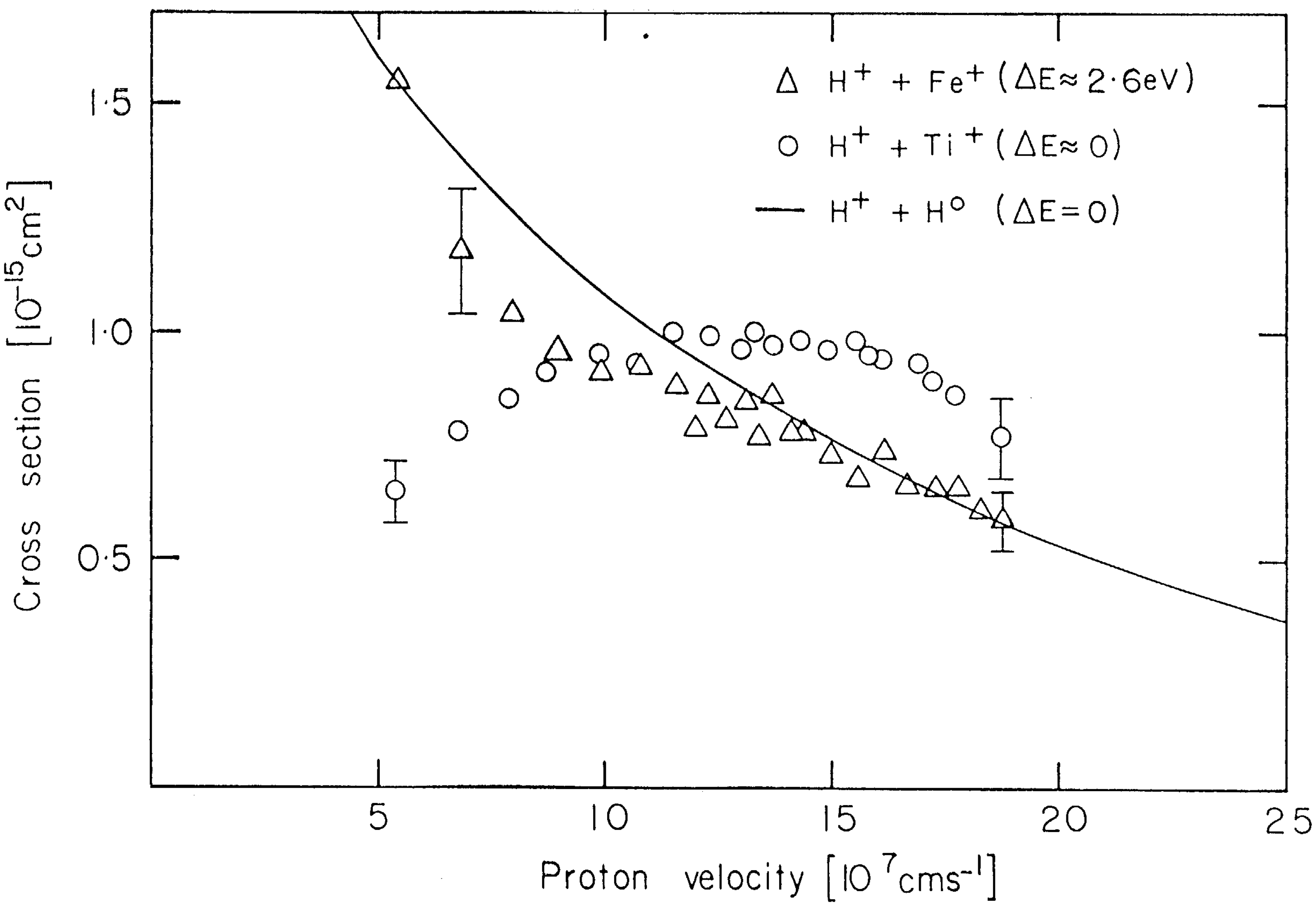




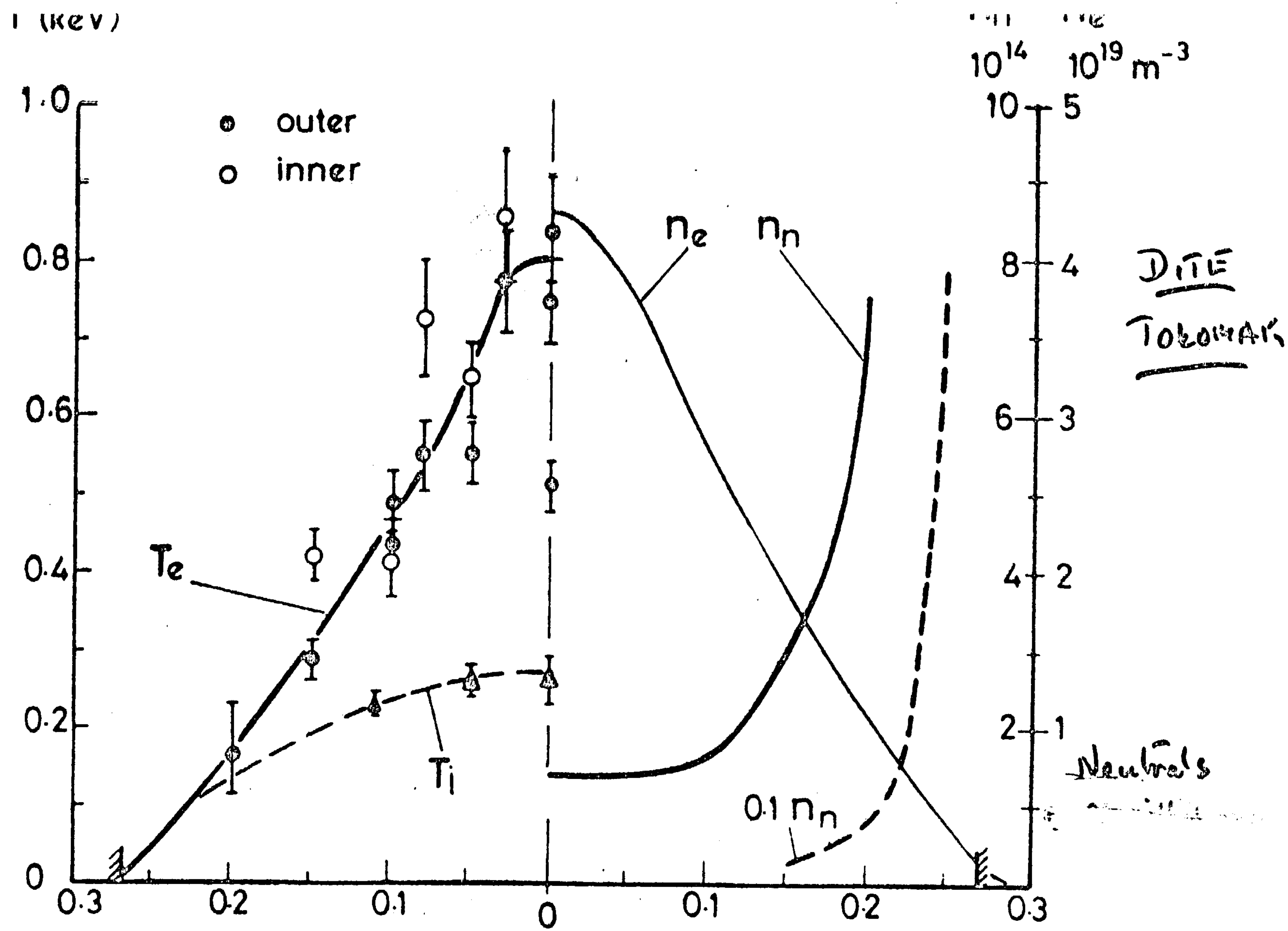
Radiated power loss for various impurity concentrations. The curve labelled R_{DT} is the power produced by the D—T reaction assuming the loss of all the neutrons.

McWhirter 1981 in Plasma Phys. Nuclear Fusion (Academic Press

.986



Charge Exchange Cross - sections
(Harrison & Montague 1984)



(J. Paul et al 1978)

FIG.4. *Typical radial profiles for $I_p = 2$ 4, (n_n = neutral hydrogen density).*

2.10

PLASMA

Electrical Neutrality

$$\sum z_i n_i e \doteq n_e e ,$$

n = number density ;
e = value of electronic charge in e.s.u. (usually!).

Scale-length of neutrality :

Plane slab with $n_i = 0$, n_e = const.

Poisson says

$$\frac{d^2V}{dx^2} = 4\pi n e$$

$$\text{P.E.} = eV = 2\pi n e^2 x^2$$

Take P.E. $\simeq \frac{1}{2} kT$

$$x = \left(\frac{kT}{4\pi n_e e^2}\right)^{1/2} \equiv \lambda_d$$

$\equiv$ Debye Length.

$$\lambda_d = 6.9 \left(T/n_e\right)^{1/2} , \quad T \text{ in } {}^\circ K$$

Why believe in λ_d ?

1/ Studies at Plasma Edge
(Langmuir and many others)

2/ Fundamental Theory of Liquids
(BBGKY) $\longrightarrow$ $N_d \equiv n_e \lambda_d^3$
Model o.k. for $N_d \gg 1$
(Rosenbluth & Rostocker 1962)

3/ In Bulk of Plasma, Expts
on Laser Light scattering
see Evans & Katzenstein
Rep Prog Phys. 1979

4/ Expts on "Landau
damping" of Waves

5/ Expt v. Theory on
Transport collisions

Waves in Plasma ($B = 0$)

1/. Sound waves

$$V_s^2 = \gamma k (T_e + T_i)/m_i$$

$\gamma = 1$ (iso thermal approx)

2/ Damping : strongly Damped when $T_i \gtrsim T_e$ because $v_i = v_s$ for all λ

3/ Electron Plasma Oscillations

$$\omega_{pe}^2 = 4\pi n_e e^2/m_e$$

Full Dispersion equation

$$V_{pe}^2 = \frac{\lambda^2 \omega_{pe}^2}{4\pi^2} + 3kT_e/m_e$$

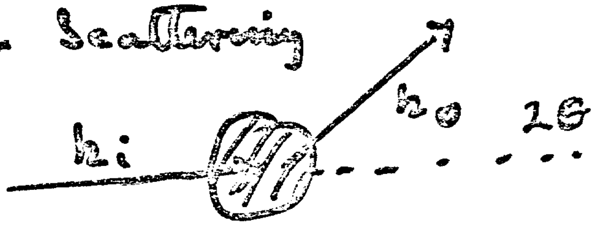
For $\lambda \simeq \lambda_d$,

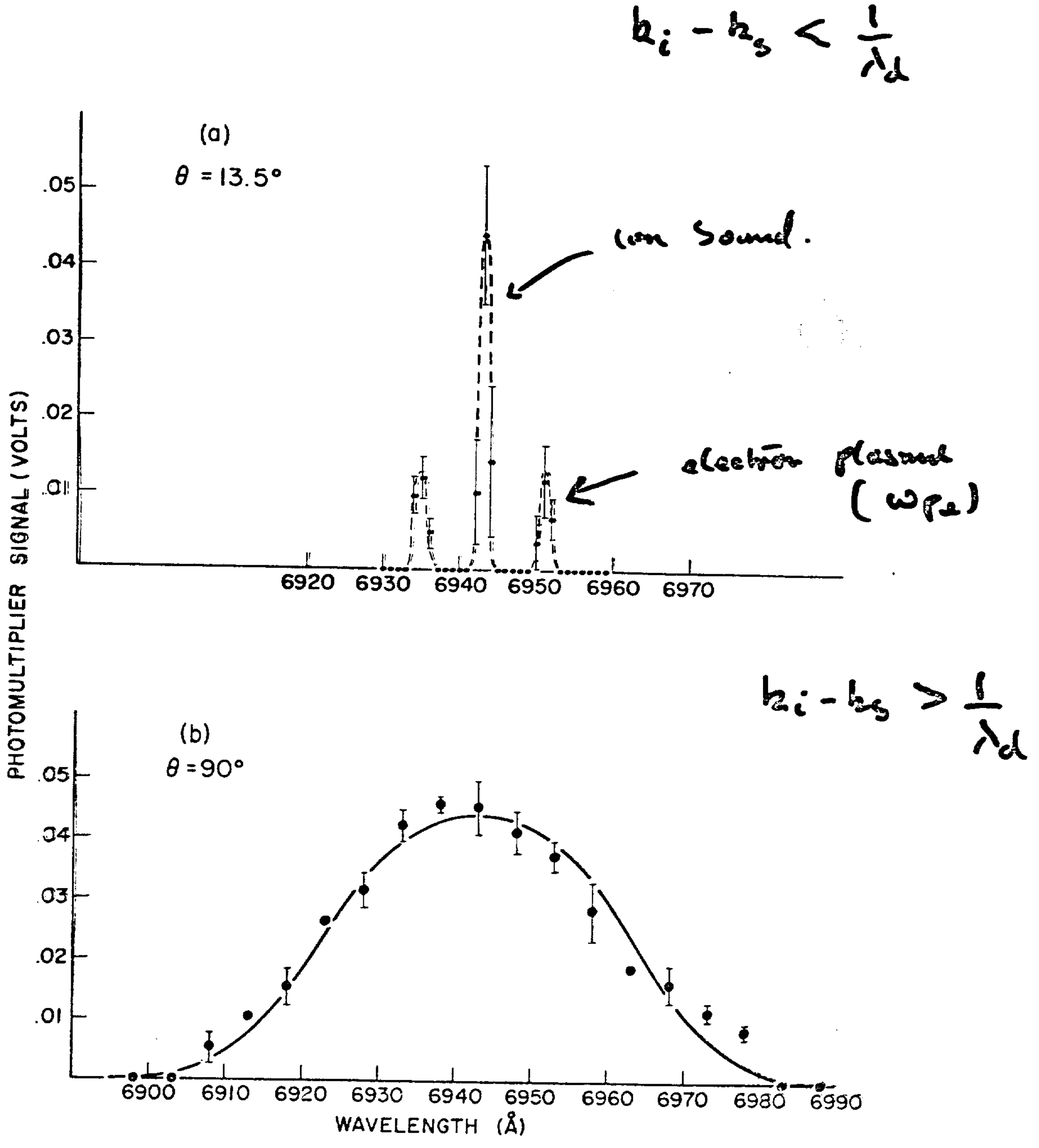
$$V_{pe}^2 \sim kT_e/m$$

$\therefore$ $\lambda \ll \lambda_d$ no waves

$\lambda > \lambda_d$ waves

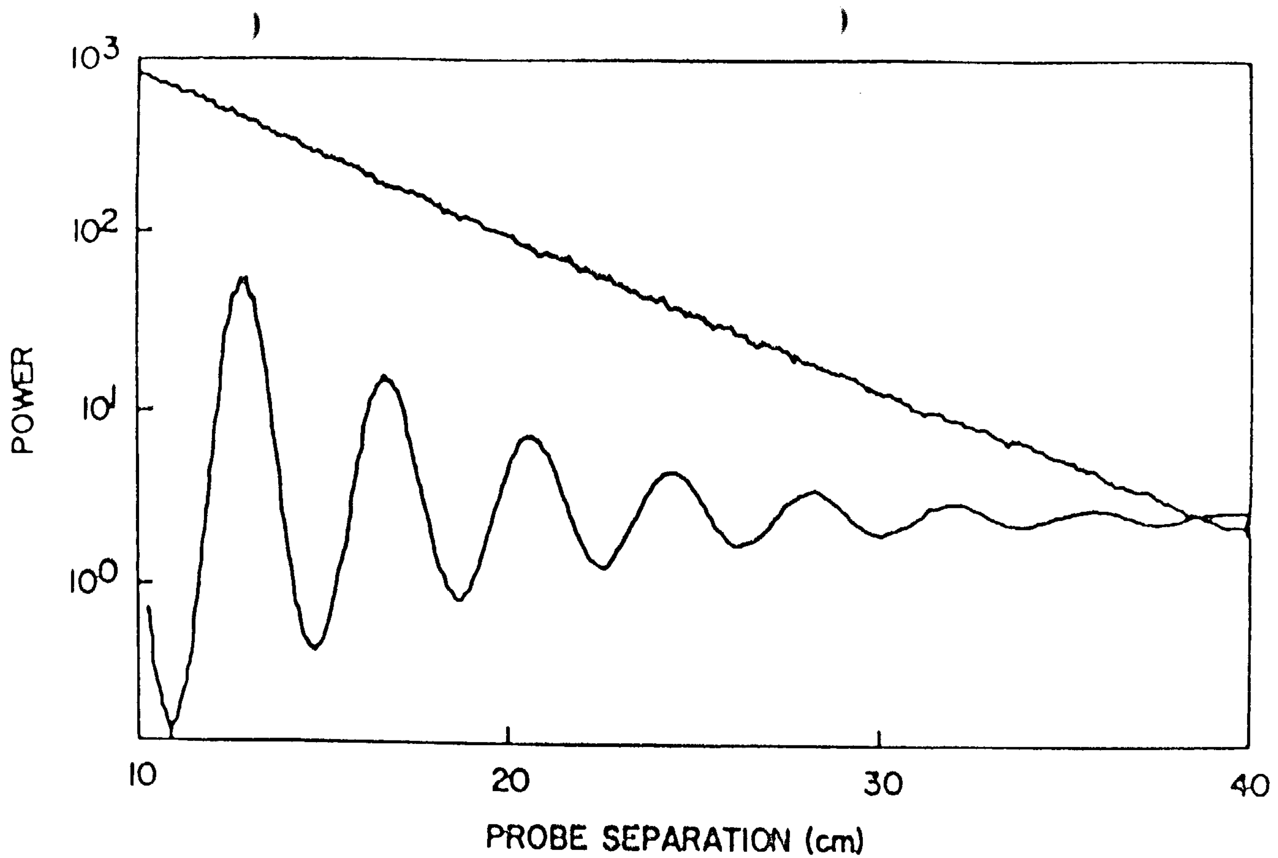
4/ Laser Scattering



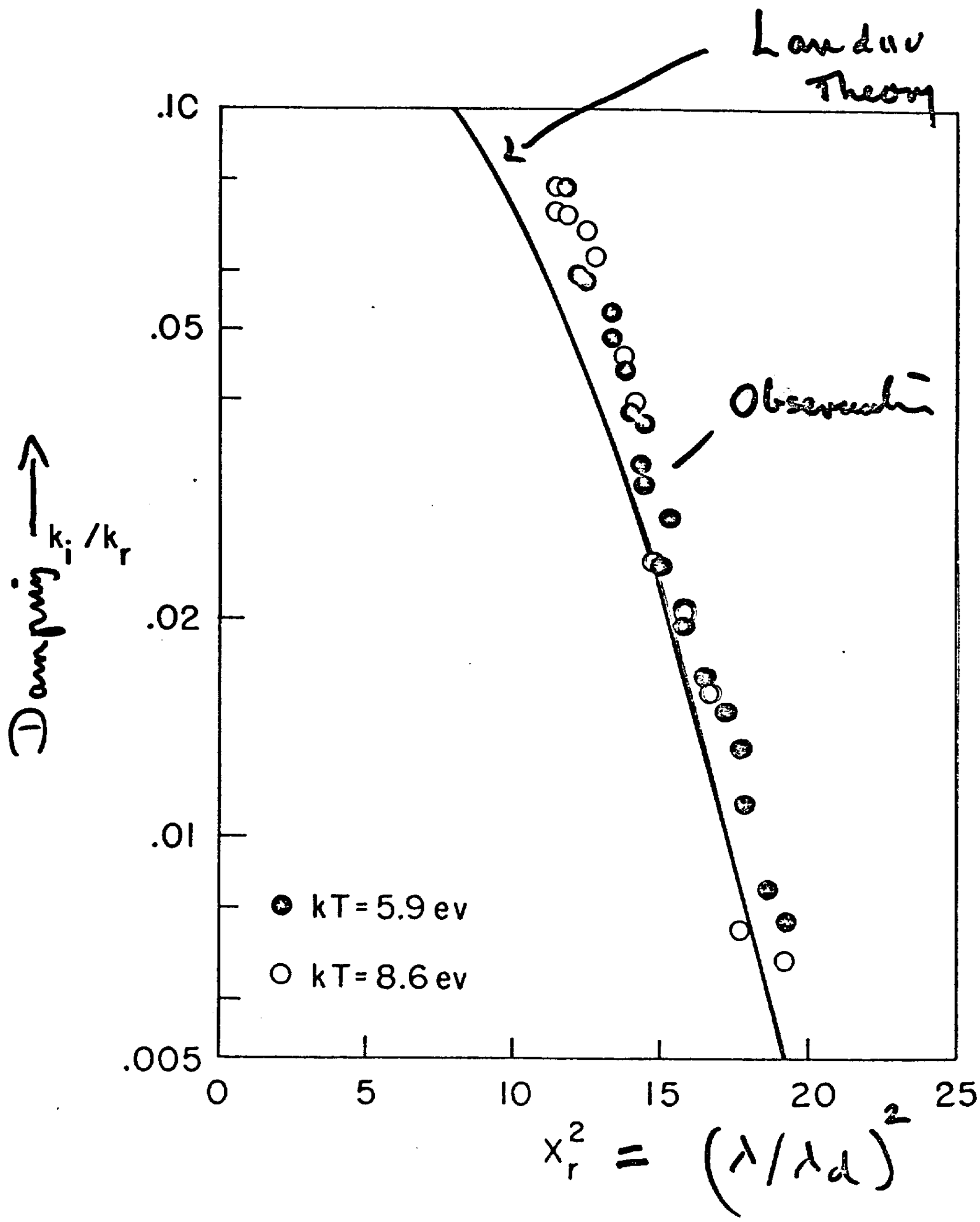


Scattering of Ruby Laser Light
(Ramsden et al 196?)

-2 68.232



Landau damping of electron plasma oscillations in a hydrogen plasma. The received signal and power as a function of distance from the exciting probe. The upper curve is the logarithm of the received power. The lower curve is the output from a coherent detector. Malmberg & Wharton 1966



k_i/k_r vs. x_r^2.

Landau Damping of Electron Plasma Oscillations.

<u>Landau Damping</u> (Landau 1946 Fiz Zh 10 2

$f(V_{\parallel})$ = Velocity Distribution of e

In longitudinal wave, electrons see a travelling wave electric field

$$E_{\parallel} \simeq \frac{\tilde{n}}{\bar{n}_e} \cdot \frac{kT}{e\lambda}$$

If $\frac{\partial f}{\partial V_e} < 0$ when $V_e = V_{ph}$

Then damping. For Maxwell

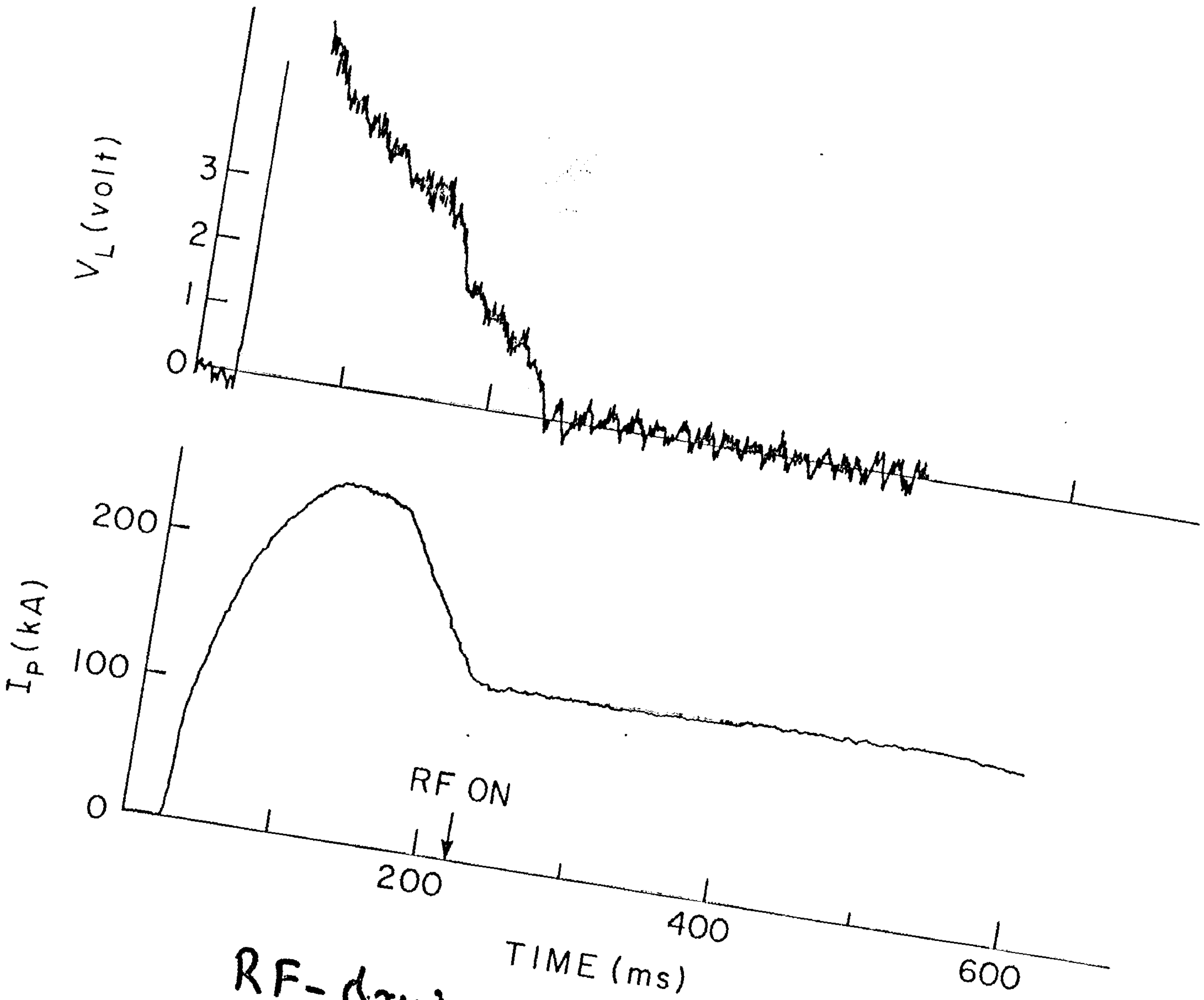
Damping decrement $\equiv \gamma$

$$\gamma \sim \frac{\omega_{pe}}{(k\lambda_d)^3} \operatorname{Exp}\left(-\frac{1}{2(k\lambda_d)^2} - \frac{3}{2}\right)$$

Stops when $\frac{\partial f}{\partial V_e} = 0$ $\longrightarrow$ collisions ultimately dissipate.

Echos.

Macroscopic Currents driven in special waves (lower Hybrid)



RF-driven Currents in PLT Tokamak
(W. Hooke et al 1980, IAEA conf.)

84.999

Collisions

"Encounters" Spitzer 1962

Effective Cross Section : Screened Coulomb

$$\frac{dV_{\parallel}}{V_{\parallel}} = -\frac{dx}{L} \quad ; \quad L = \frac{1}{n_i \sigma_{ei}}$$

$$\sigma_{ei} \simeq 4\pi \frac{Z_i^2 e^4}{(kT)^2} \ln(\lambda_d / p_0)$$

where

$$p_0 = \frac{3kT_e}{2e^2}$$

↑ 10 – 20

see Spitzer 1962, Braginskii (1960) and Chapman & Cowling (1939)

<u>Resistivity</u> $\eta = 6.5 \times 10^3 \, Z_i \ln\Lambda / T^{3/2}$

T in °K Ohm-cm

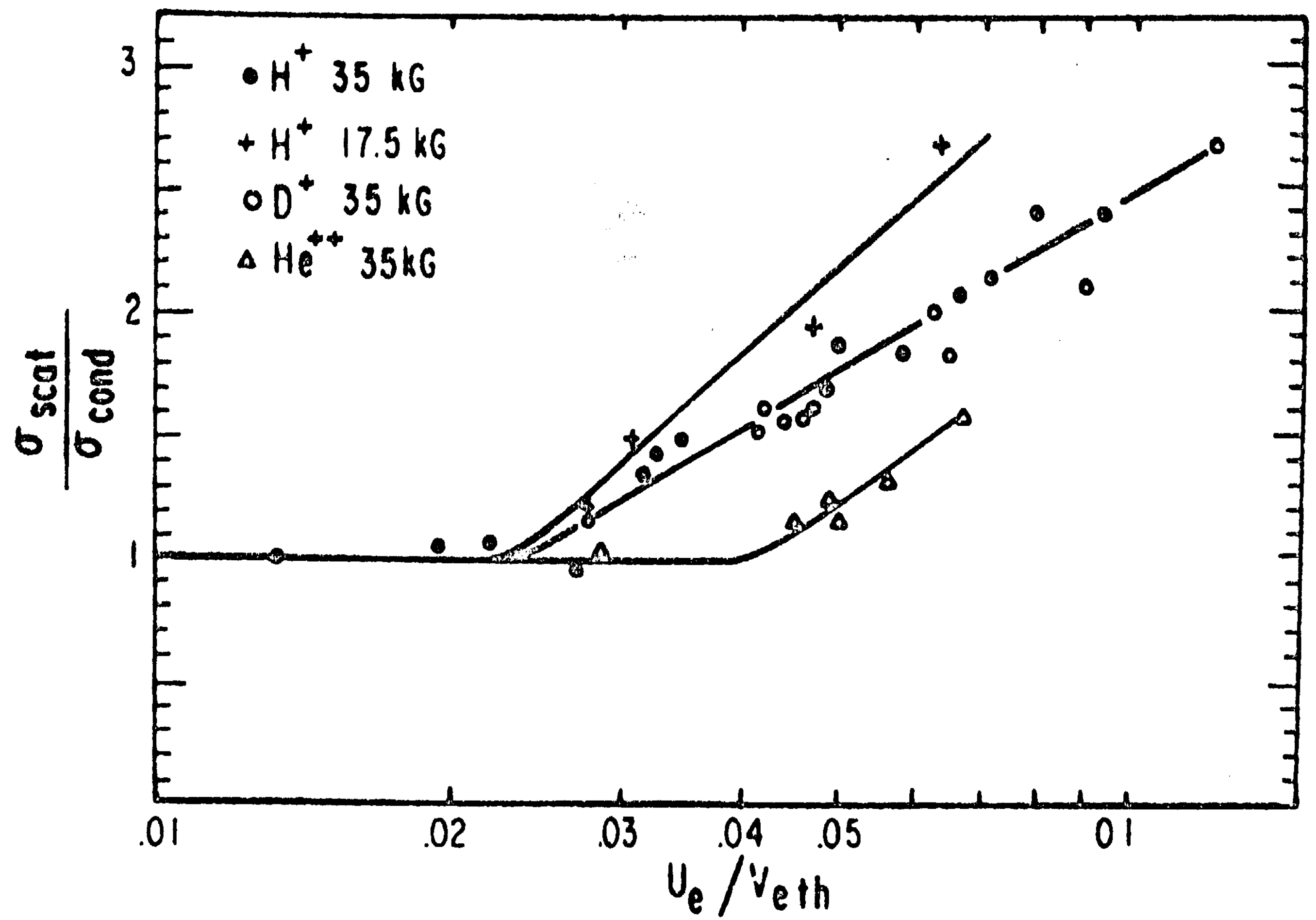
But $ej/ne \ll \sqrt{kT_e/m}$:

Runaway electrons (see Dreicer 1959)

Ion – Electron Equilibrium

$$\frac{dT_i}{dt} = \frac{T_e - T_i}{\tau_{ie}} , \quad \text{then } n_e \tau_{ie} = 17 A Z^2 T_e^{3/2}$$

sec., °K.



Ratio of measured to theoretical plasma resistivity as a function of the ratio of electron drift to thermal velocity.

$T_e \sim 50-100\,eV$

(C - Stellarator group c 1967)

2.20

Plasma in Magnetic Fields

Particles move in helices

$\omega \sim \omega_{ce}, \omega_{ci}$ $\frac{eB}{mc}$

↑ 20 – 200 GHz ; 10 – 100 MHz

Single Fluid

$\omega < \omega_{ci}$

$$\rho \frac{dv}{dt} = j \times B - \nabla p$$

$\rho = n_i m_i$; $p = nk(T_e + T_i)$ $(Z=1)$

v = fluid velocity

$$E + v \times B = \eta j \quad \text{Resistive MHD}$$

$$= 0 \quad \text{Ideal MHD}$$

$$\text{Curl } E = -\frac{\partial B}{\partial t}$$

$$\therefore \frac{\partial B}{\partial t} = \text{Curl } v \times B$$

Plasma 'Frozen to lines of force'

Alfven 1942

Waves. $\omega < \omega_{ci}$

$$V_a^2 = H^2/4\pi n m_i$$

Torsional, Transverse Alfven waves

$\underline{V}, \underline{E} \perp \underline{B}$, $k \parallel B$

Compressional Alfven Waves

$$V^2 = (p + H^2/8\pi n m_i)$$

For $\omega \xrightarrow{\omega_{ci}} \omega_{ci}$ Cyclotron damping

Stix, 1960

Diffusion

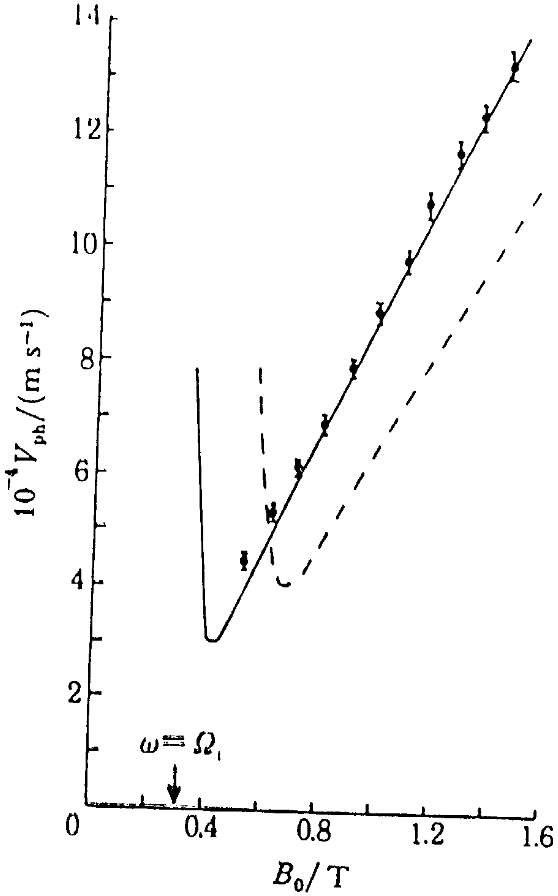
$$V_\perp = -\eta \nabla p / B^2$$

1/ For one species of ion, cross field diffusion depends only on ion-electron collisions

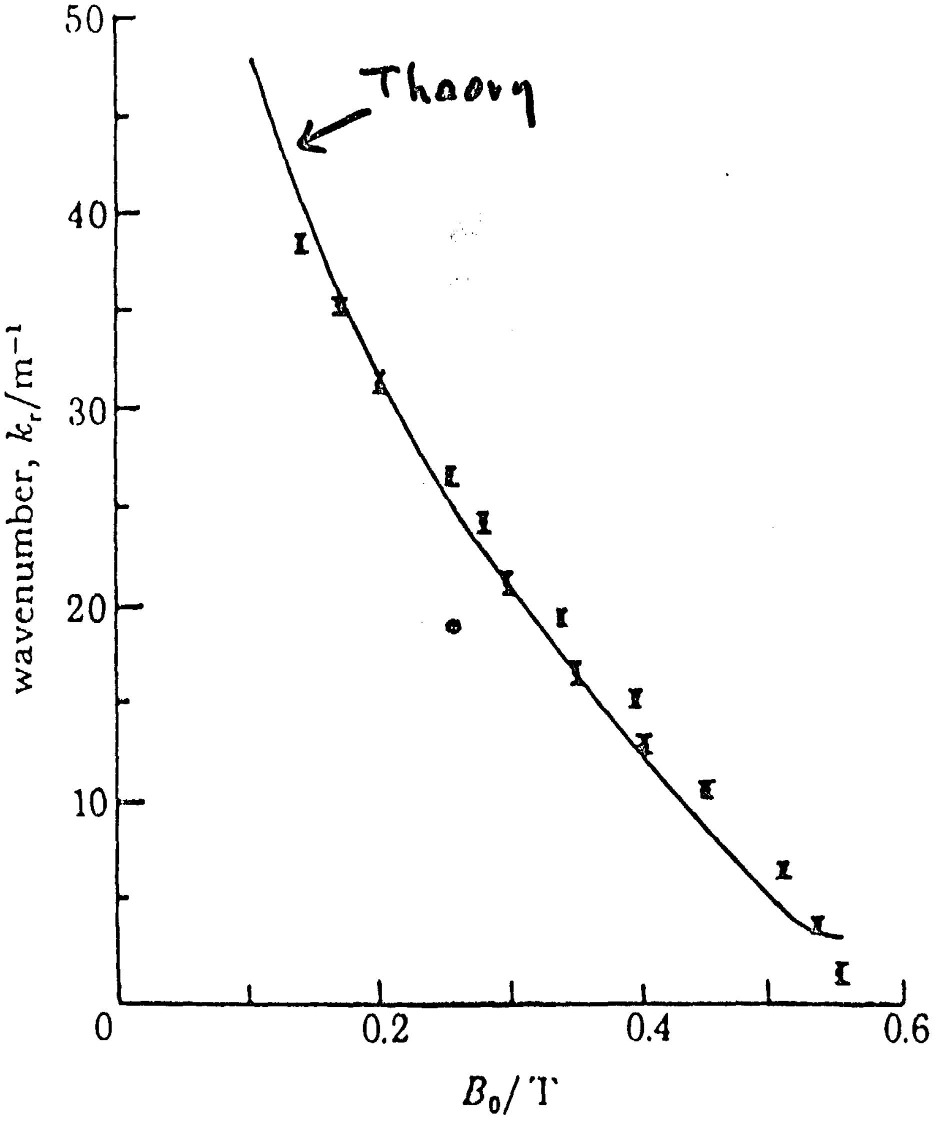
2/ ~ "Stein diffusion effect" × β

∴ slow

2.23



Measured phase velocity of shear Alfvèn waves. —, Theoretical, taking into account collisions between ions and neutral atoms; $n_i = 10^{21}\ \mathrm{m}^{-3}$; $n_0 = 1.5 \times 10^{20}\ \mathrm{m}^{-3}$. – – –, Experimental, $n_i = 10^{21}\ \mathrm{m}^{-3}$; $n_0 = 8 \times 10^{20}\ \mathrm{m}^{-3}$. (From D. F. Jephcott & P. M. Stocker 1962 *J. Fluid Mech.* **13**, 587.)



Measured wavenumber against magnetic field for fixed frequency compressional Alfvèn wave. .coretical prediction. (From D. F. Jephcott & A. Malein 1964 *Proc. R. Soc. Lond.* A 278, 243.)

2.24

Plasmas in Magnetic Fields (ii)

$\omega_{ci} < \omega < \omega_{ce}$

Two Fluid Model.

Electrons still have helices
Ions 'ignore' B
Appleton - Hartree Dispersion
equation (ionosphere)

Whistler Waves.

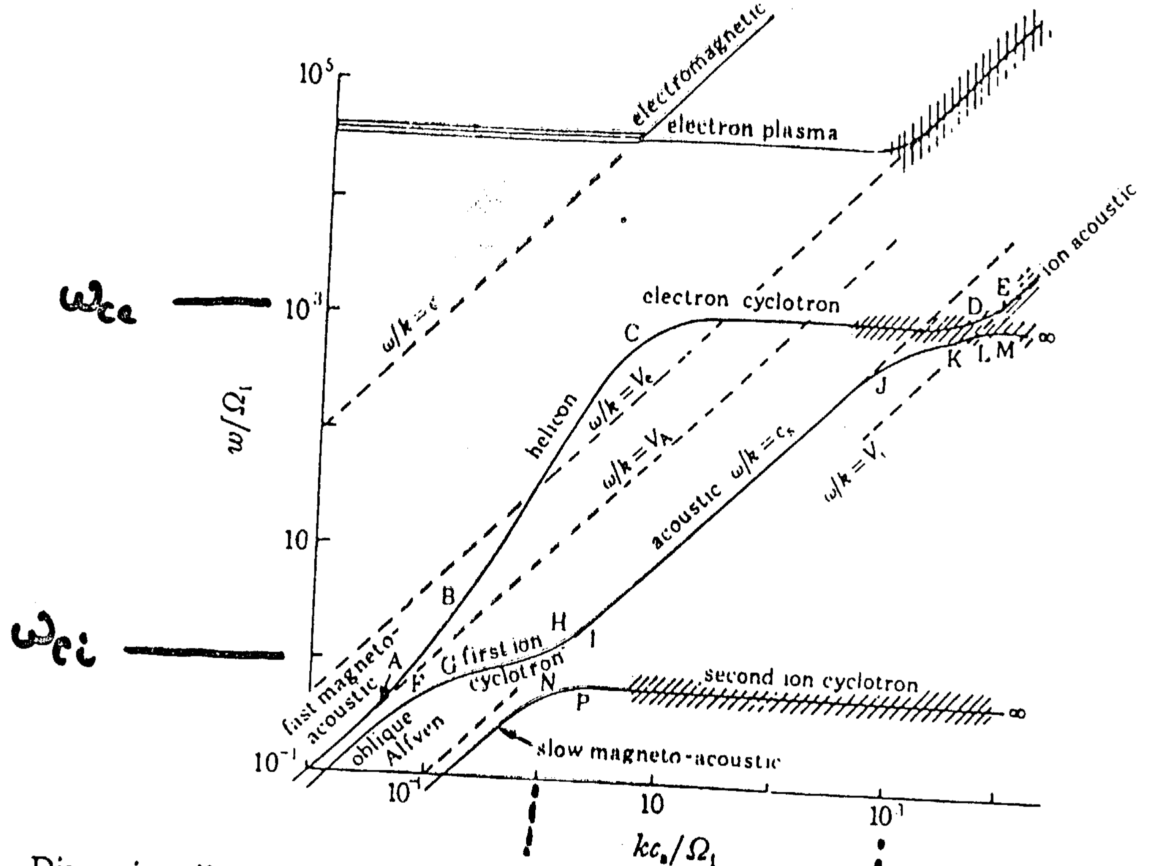
$E \perp B$, $v_e = \frac{E \times B}{B^2} \rightarrow j = \frac{env_e}{c}$.

"Helicon Waves"

$$R.I = \mu^2 = 1 - \frac{\omega_{pe}^2/\omega^2}{1 \pm \frac{\omega_{ce}}{\omega}\cos\theta}$$

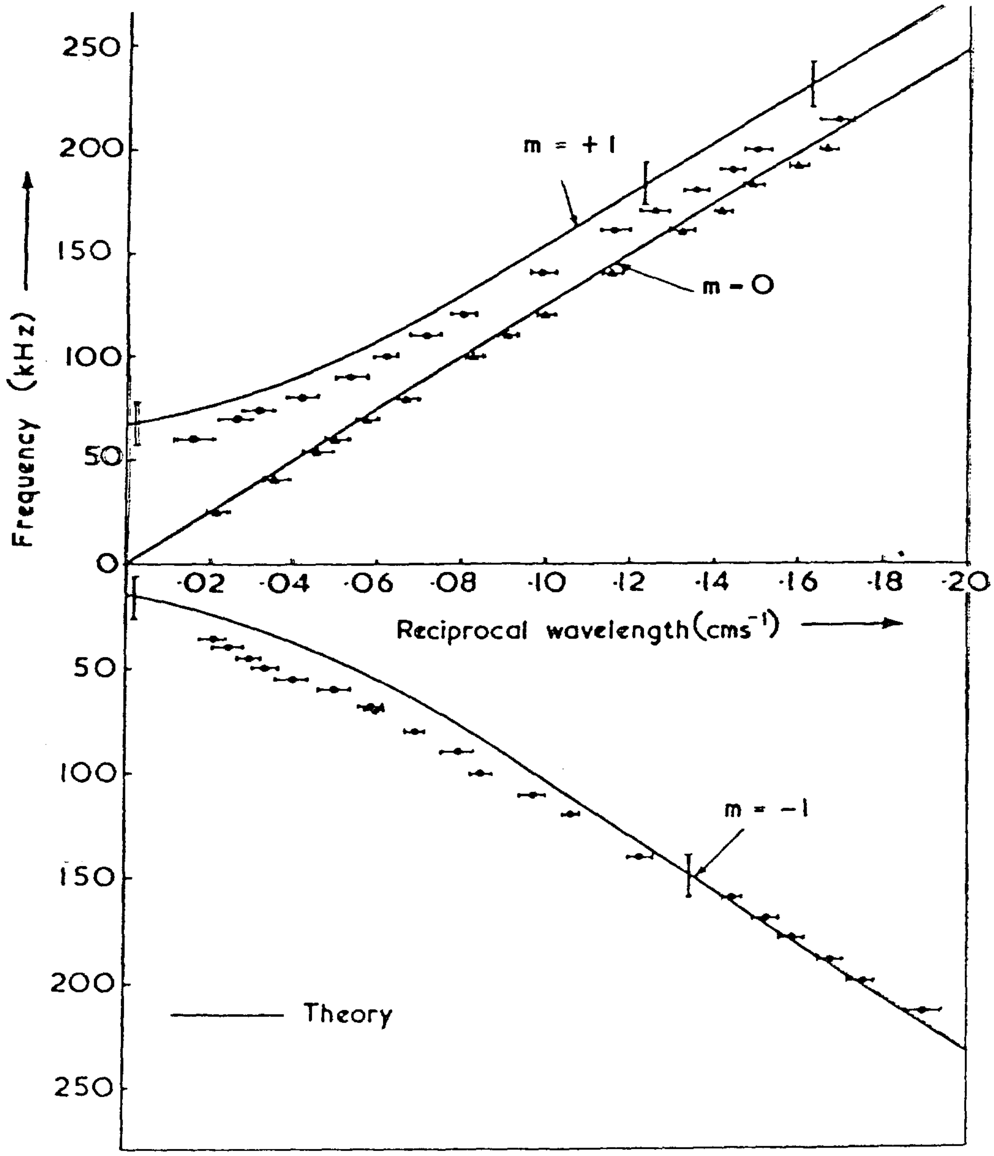
$$= 1 + \frac{\omega_{pe}^2}{\omega\omega_{ce}} \gg 1$$

V. dispersive, basis of LH
current drive. Observed 1914 &
Storey 1952



Dispersion diagram for waves in a low β-hydrogen plasma propagating at 45° to the magnetic field. (From T. E. Stringer 1963 *Plasma Phys.* **5**, 89 and J. J. Sanderson 1974 In *Plasma physics*. London: The Institute of Physics.)

"Drift" Waves in gradient of Density
Two Fluid model, but $\omega < \omega_{ci}$



Comparison of experimental (circles and triangles) with theoretical dispersion relations (full lines) for drift waves in helium arc plasma. B. E. Keen (1970)

$$\omega \equiv \omega^* = \frac{kT_e}{eB} k_y \frac{1}{n}\frac{dn}{dx}, \quad B = B_z$$

See Corden 1981

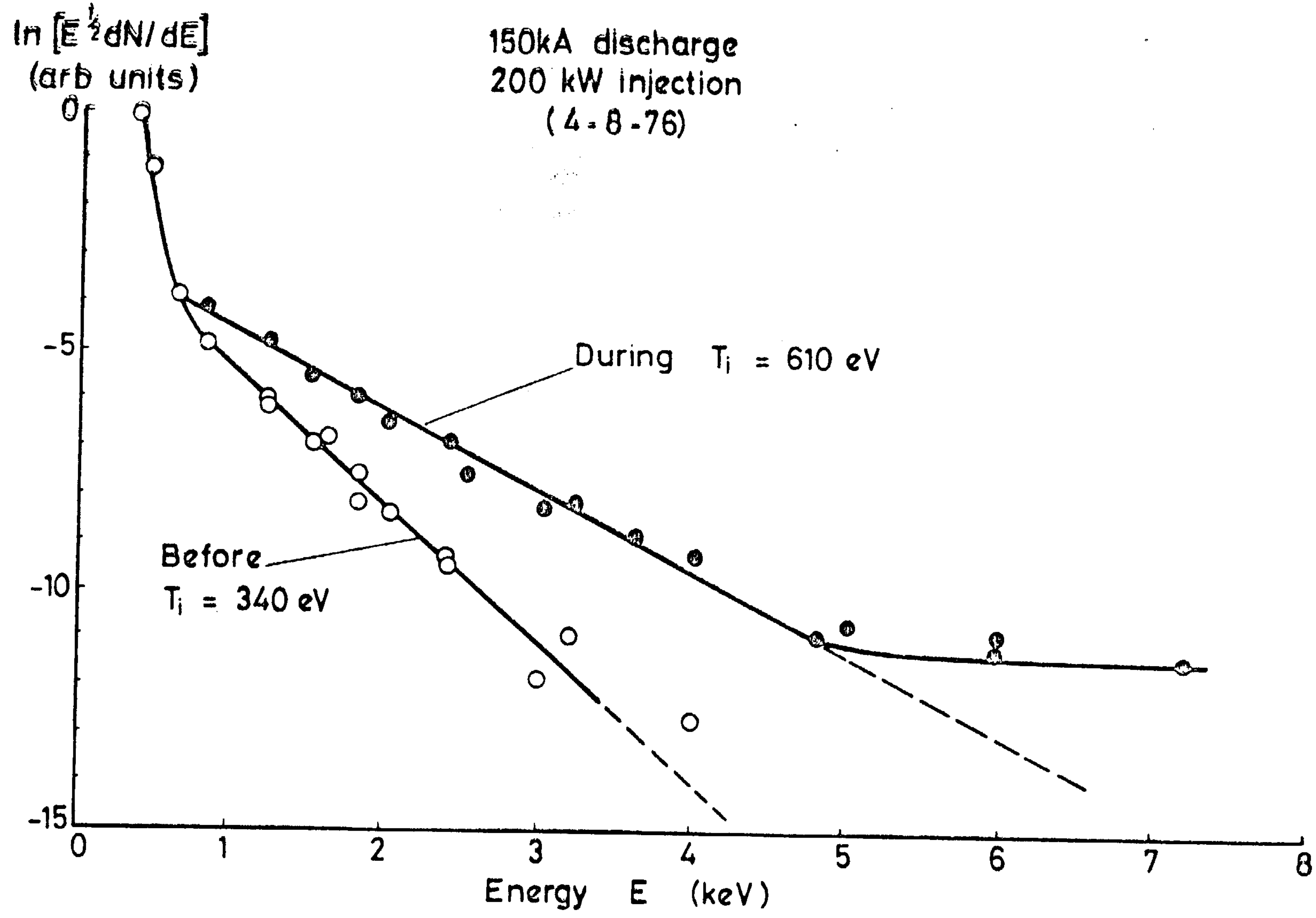
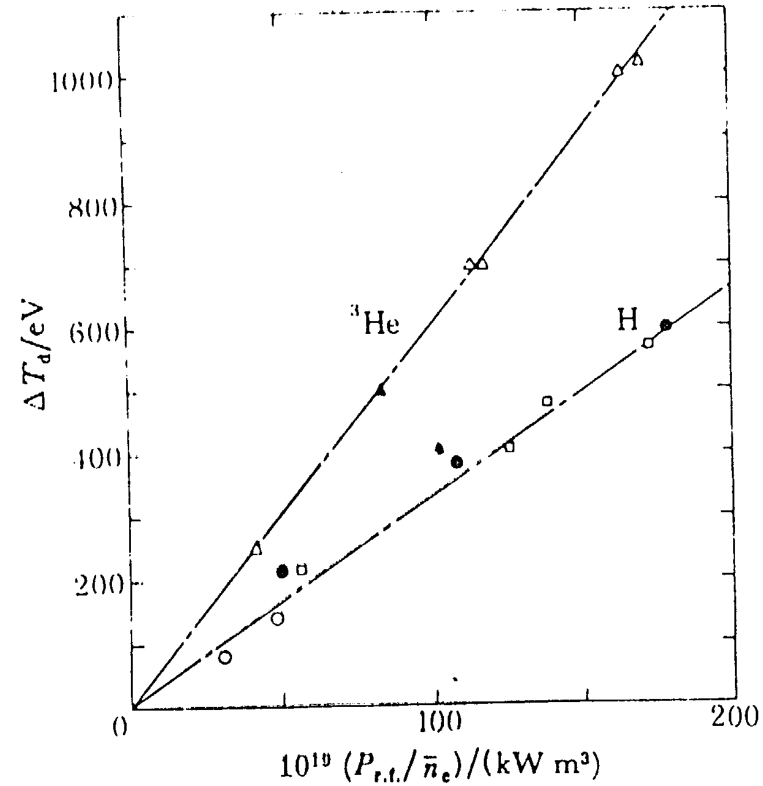


FIG.6. Thermal-ion spectrum for 200 kW into a 150-kA discharge.

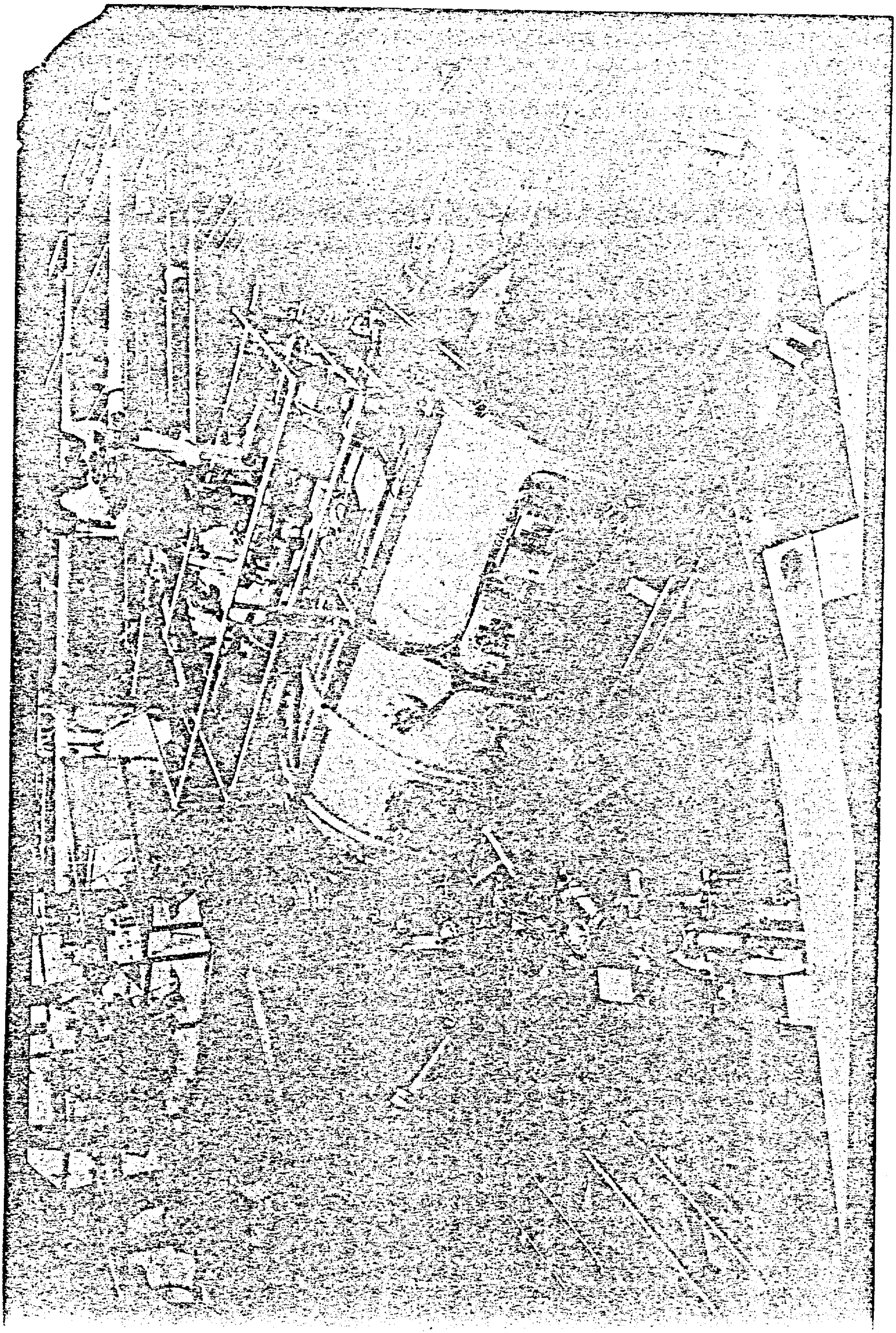
2.28

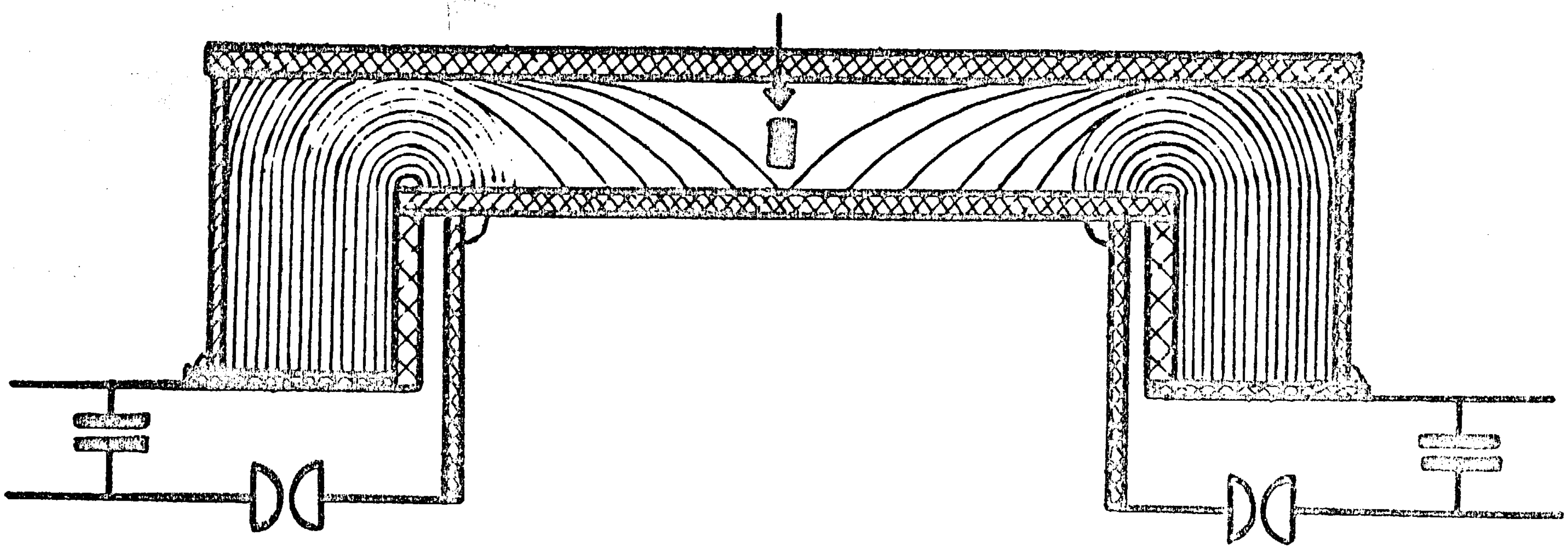
Paul et al (1978)



Radio-frequency heating at the ion cyclotron frequencies of various minority ions in a P.L.T. deuterium plasma produces deuteron temperature rises ΔT_d that compare favourably with those obtained by neutral-beam injection at the same power.

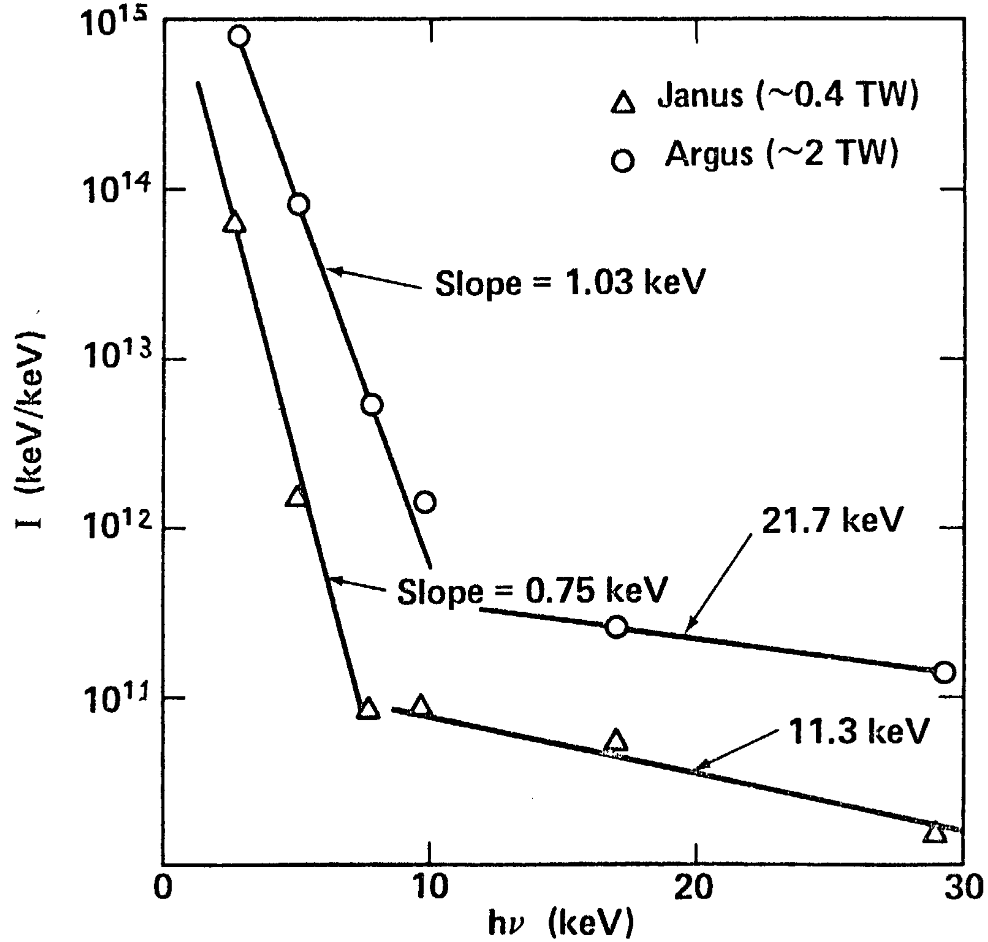
Princeton Corp. ~1981





Design of the installation for obtaining "the plasma focus"

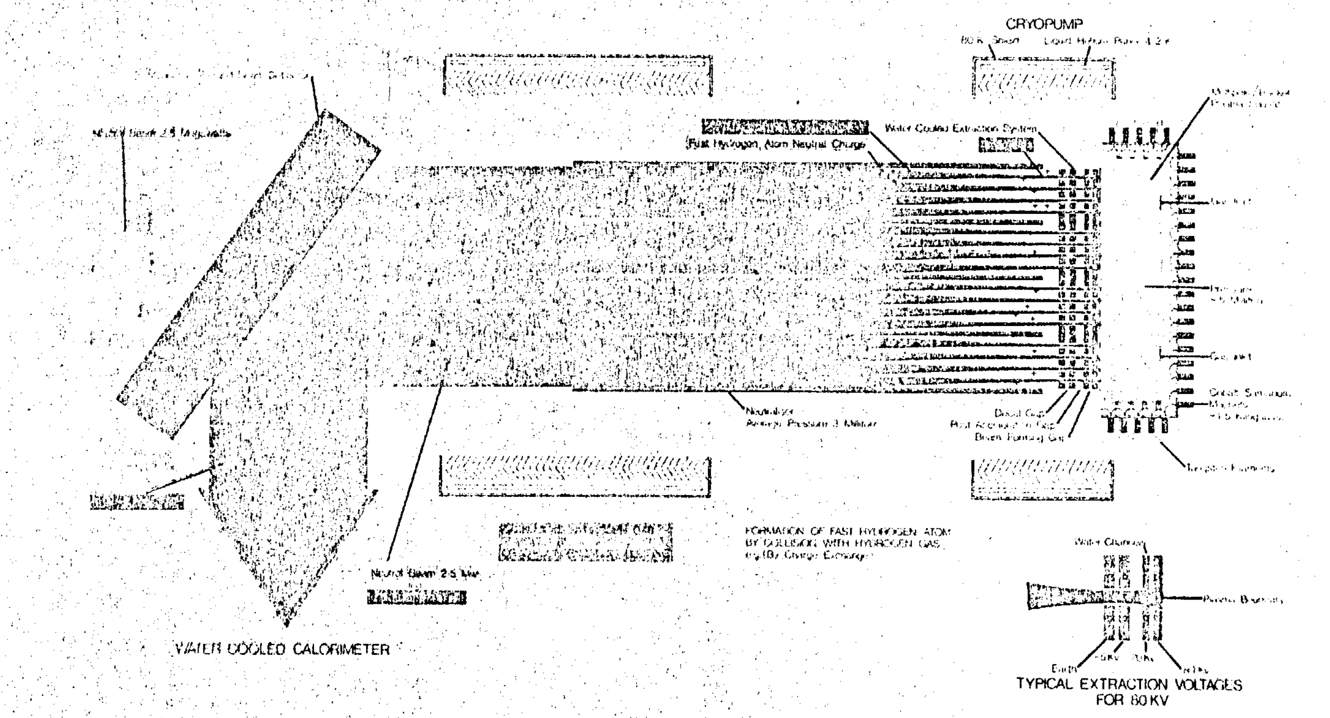
X-RAY SPECTRUM FOR 0.4 AND 2 TW EXPERIMENTS



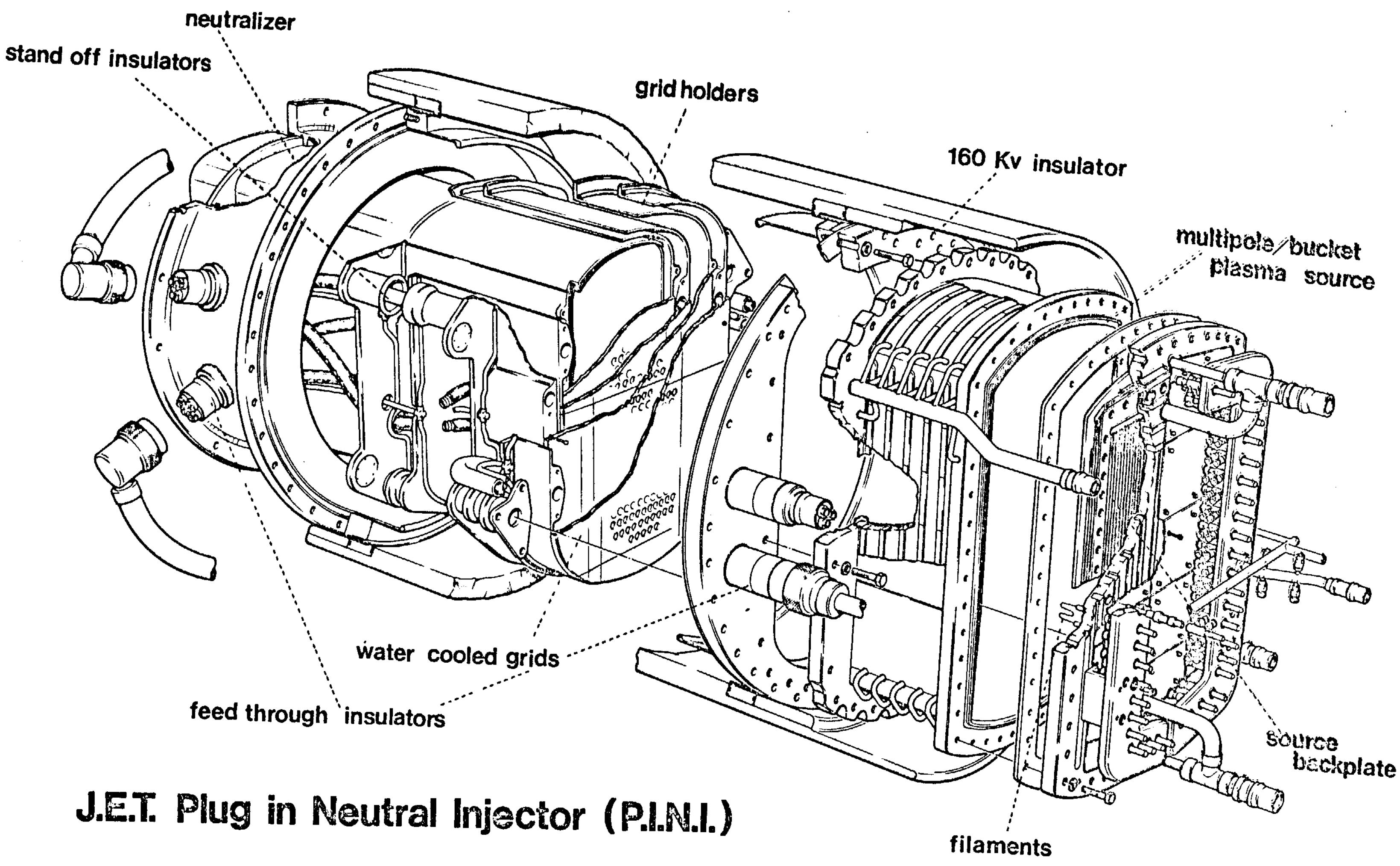
11/76

Electron Energies Produced in Laser Compression Expts.
(Livermore, 1976)

77.313



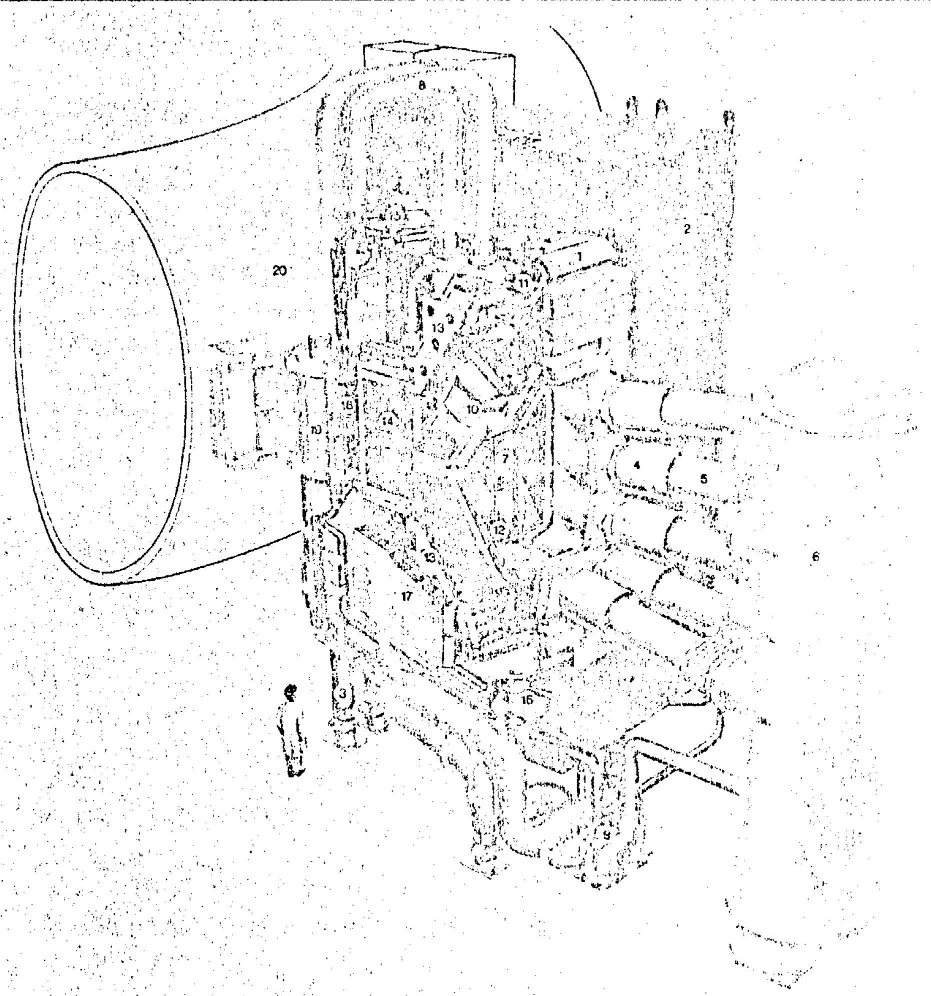
NEUTRAL INJECTOR FOR MULTIMEGAWATT BEAMS (SCHEMATIC)



J.E.T. Plug in Neutral Injector (P.I.N.I.)

JET Neutral Injection System

1 Vacuum Tank
2 Magnetic Shielding
3 Support Structure
4 PINI [illegible]
5 High Voltage [illegible]
6 High Voltage [illegible]
7 Central Support Column
8 [illegible]
9 Coolant Supply [illegible]
10 [illegible]
11 [illegible]
12 [illegible]
13 [illegible]
14 [illegible]
15 [illegible]
16 [illegible]
17 [illegible]
18 [illegible]
19 [illegible]
20 JET [illegible]



82.1033c

2.25

MAGNETIC CONFINEMENT
(INTRODUCTION)

- Simple Example
- Particle motion & Confinement
- Configurations used
- Rules for stability
- Self-Stabilization of Toroidal discharges

MAGNETIC CONFINEMENT

Simple Systems

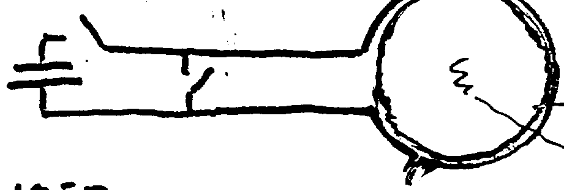
Plane Slab

$$\nabla p = j \times B$$

$$p + B^2/8\pi = \text{const}$$

Modelled in θ - pinch

$B = B_z = B_z(r)$ only



Tuck, Quin et al 1958

Bodin et al 1968 8 - metre long, $r \sim 7$ cms

B_z rises in 2 - 3 μs. 10 - 20 kg.

Principal Result — $n_e \sim 10^{16}$

$T_e \sim T_i \sim 200$ eV

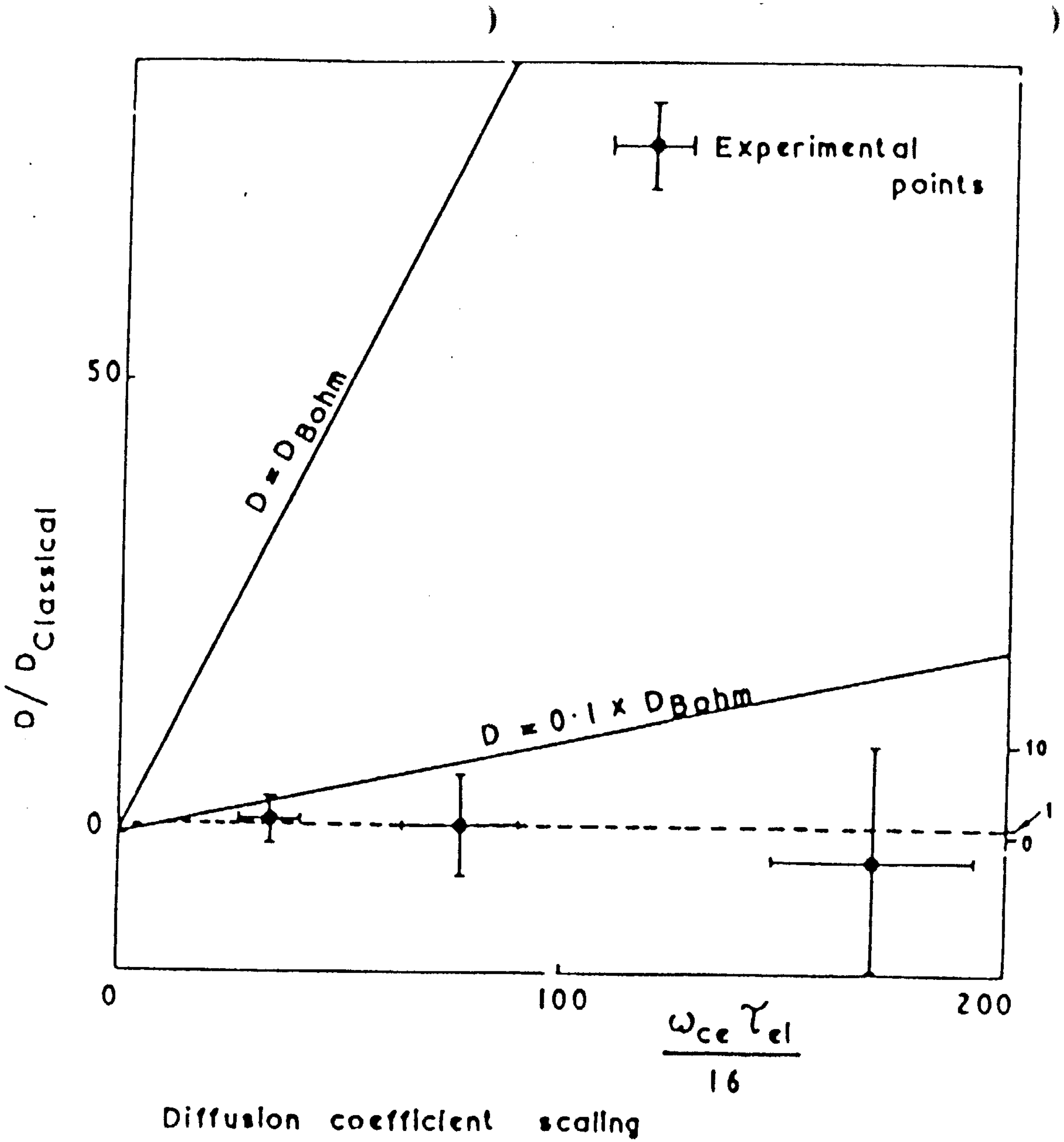
Cross field Diffusion agrees Classical

$$V_{diff} = \eta \nabla p / B^2$$

$$(\text{or } D = \eta \beta / 8\pi)$$

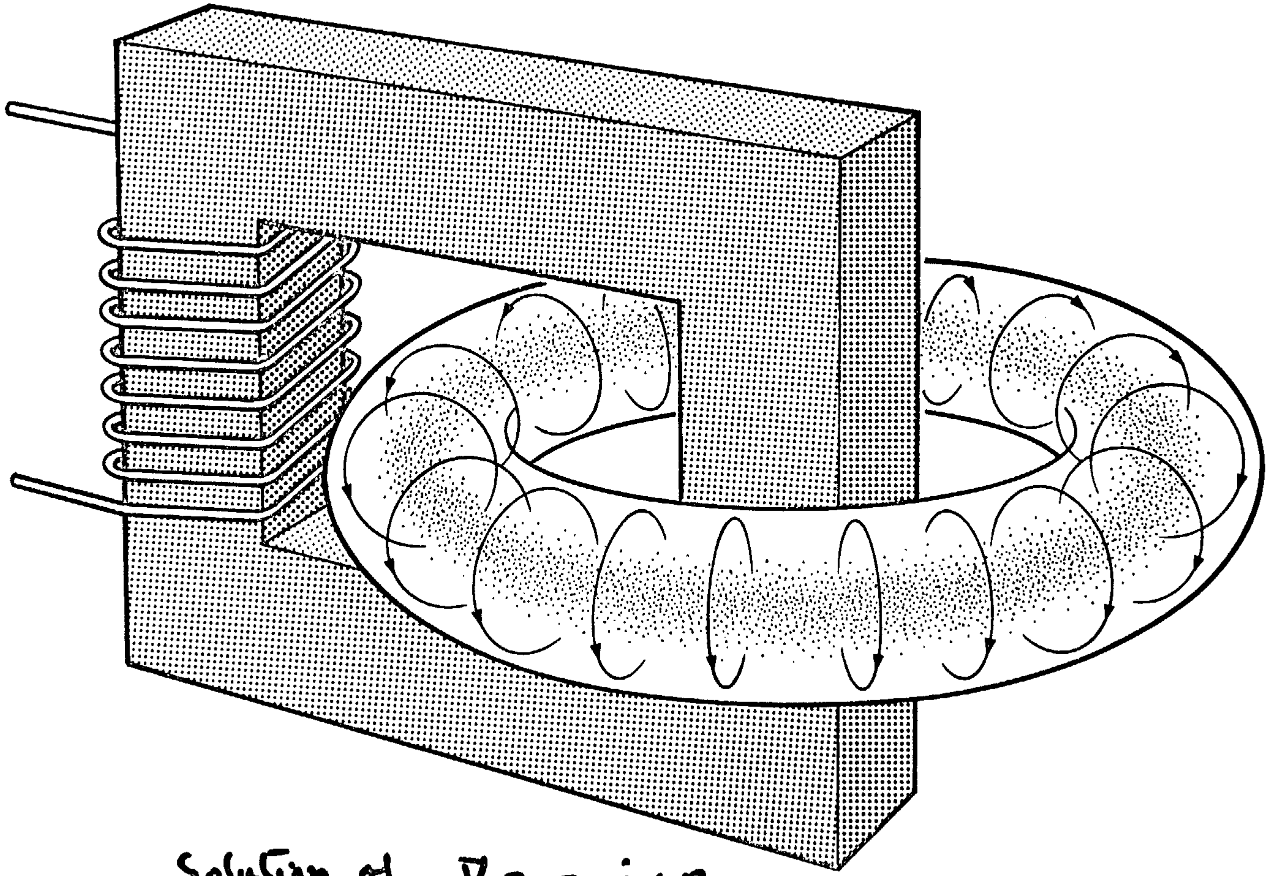
compared with Bohm Diffusion

$$D_{Bohm} = \frac{1}{16} \frac{k T_e c}{e B}$$



Density profiles and diffusion measured and calculated in the 8-metre theta-pinch.

3.3



Solution of $\nabla p = j \times B$

$$I^2 = 2\pi (N_i k \bar{T}_e + N_i k \bar{T}_i)$$

(Bennet)

With B_ϕ present, $Z_i = 1$

$$I^2 \beta_\theta = 4\pi N k \bar{T}$$

Large Aspect ratio $R \gg r$

78.1123

3.4

Guiding centre drifts in B.

(See Spitzer 1962)

1/ Electric Field E

$$v_d = E \times B / |B^2|$$ — Exact

Same sign

2/ Gravity g — or other gen. force.

$$v_d = m g_\perp / (\pm e B)$$ Opposite sign

e.g. on a line of force radius R, $g = v_\parallel^2 / R$

→ charge separation

→ current —

'Favourable' or 'Unfavourable' curvature for stability

3/ $B = B_z$ only but grad B

$$v_d = \rho_H \frac{\text{grad}\, B}{B} \times v_\perp$$

Opposite drift for ions and electrons

4/ Curved lines Radius R, e.g. $B_\theta = \frac{2I}{R}$

$$v_d = (\rho_H / R)(v_\perp/2 + v_\parallel^2/v_\perp)$$

3/ and 4/ NOT exact. requires $\rho_H/\rho \ll 1$

~~I[illegible]~~ Motion $\parallel B$

$-\mu$ = diamagnetic moment $= \dfrac{W_\perp}{B}$ = const

for $\rho_H \ll R$.

Hence Magnetic mirror Reflection

Assembly of moving particles at B_0

Then "loss cone" in velocity space

$$\sin\alpha_0 = \sqrt{B_0 / B_{max}}$$

But with a potential difference between B_0 and B_{max}

$$\sin^2\alpha_0 = \left(1 - \frac{e\phi}{W_0}\right) B_0 / B_{max}$$

$W_0 = \frac{1}{2}mv^2$ at B_0.

$\longrightarrow$ Electrostatic trapping $\longrightarrow$ Tandem Mirror Machine.

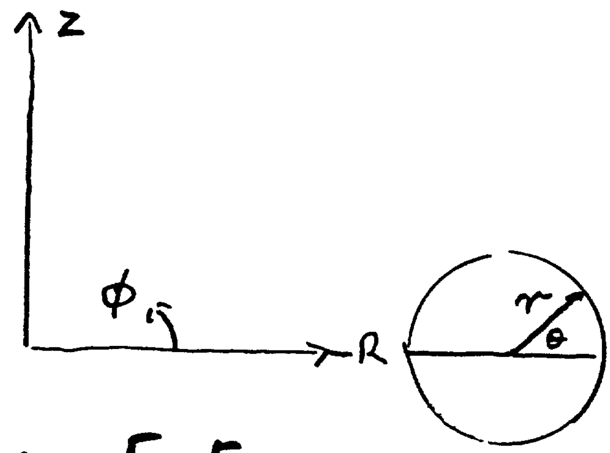
(Also electrostatic enhancement of losses in other mirror cases).

Finally with isotropic velocity distribution at B_0, proportion of particles trapped

$$= \sqrt{\Delta B / B_{max}}$$

$\longrightarrow$ 'B[illegible]' [illegible]

Motion in Axisymmetric Systems



- Two exact constants

1/ $V^2 = \text{const}$

2/ $eRA_\phi + mRV_\phi = \text{const}$

when $\dfrac{\partial}{\partial\phi} = 0$

$B = \text{Curl}\,A$: $RA_\phi = \text{const}$ defines line of force.

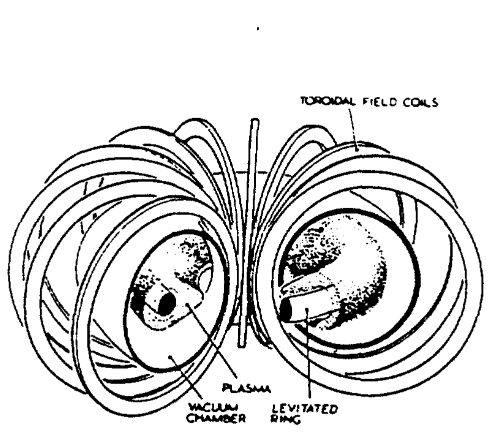
Then, because V_ϕ cannot vary by more than $-V < V_\phi < +V$,

Δ = distance of departure from a line of force

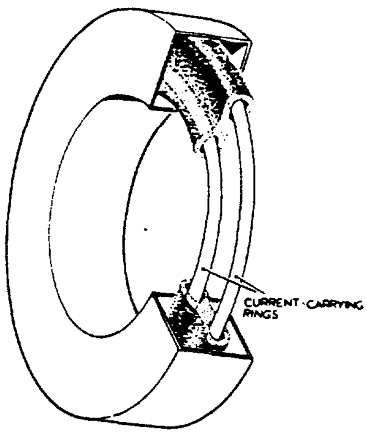
$$= \frac{mV}{e\sqrt{B_R^2 + B_Z^2}} = \rho_{H\theta}$$

= The Larmor radius in poloidal field.

TAMM (1951) – (Acad Nauk 19[illegible])

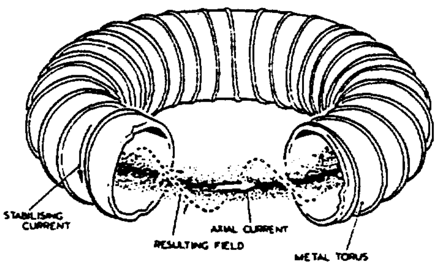


LEVITRON

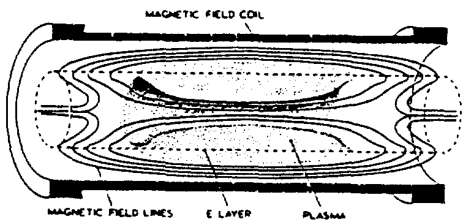


QUADRUPOLE

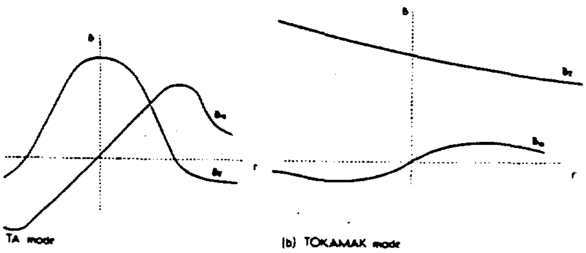
(b) Plasma confinement geometries - closed-line systems;



TOROIDAL PINCH

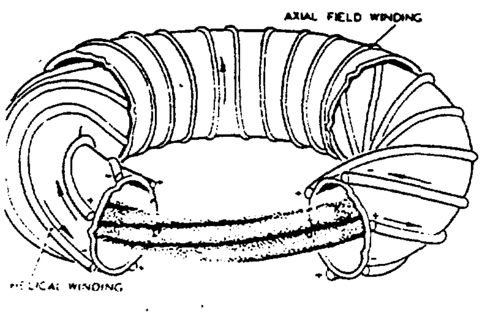


ASTRON

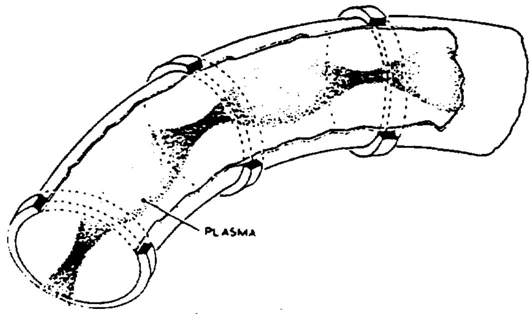


Modern form is Spheromak. (Furth 1988)

(c) Plasma confinement geometries - closed-line systems;



STELLARATOR



BUMPY TORUS

(d) Plasma confinement geometries - closed-line systems.

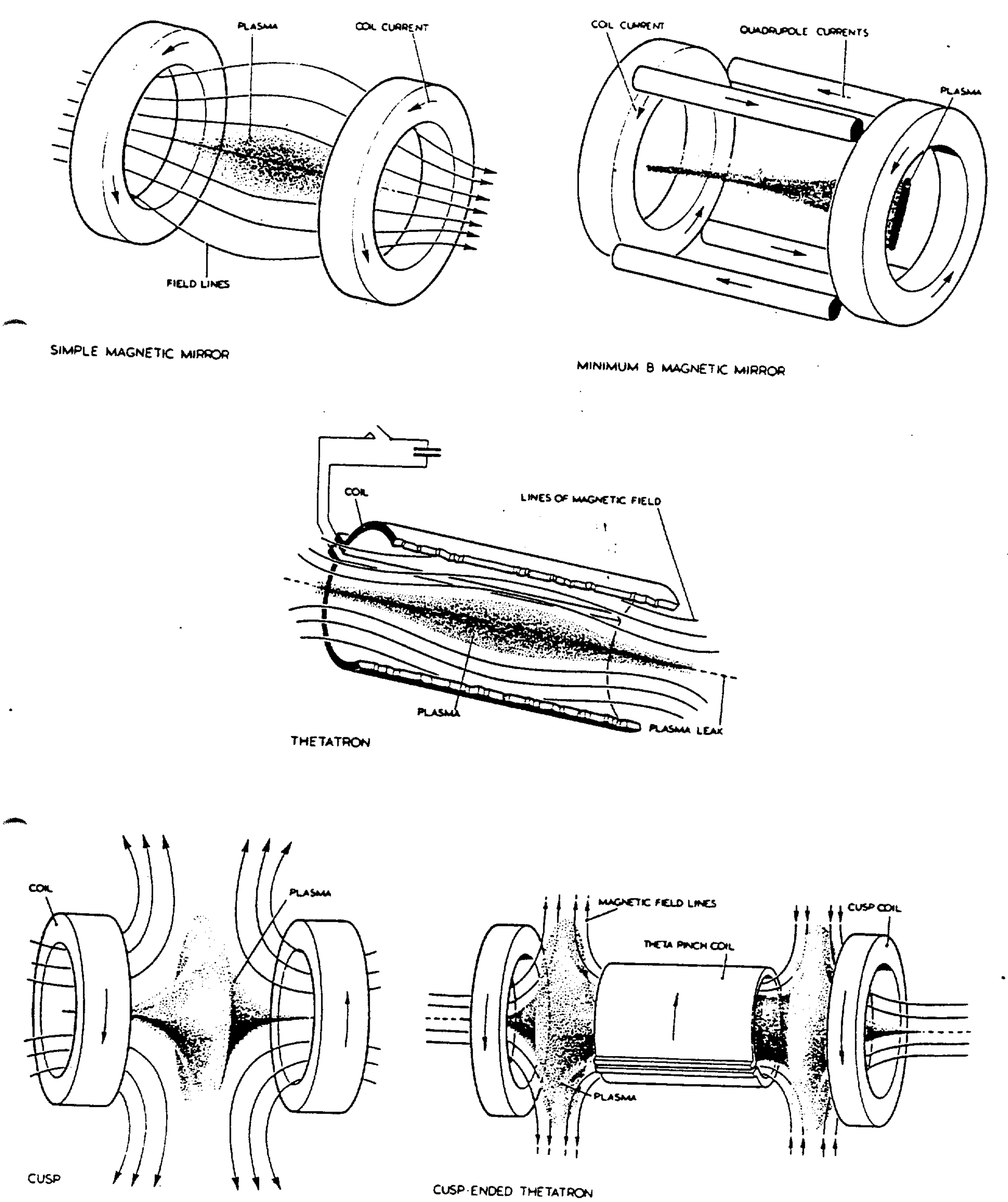


Fig.3 (a) Plasma confinement geometries - open-ended systems;

Instabilities

1/ Flute Instability (Pressure driven)
- field gradient unfavourable

a/ grad p . grad B < 0 everywhere for stability

e.g. Magnetic Well mirror machine.

(Kadomtsev, Joffe)

J.B. Taylor)

b/ Average well

$U = \oint \frac{dl}{B}$ ≈ Volume of Tube of Force

Then $\frac{dp}{dU} < \frac{\gamma p}{|U|}$ for stability. ($\gamma = c_p/c_v$)

e.g. Toroidal Multipoles   eg. Kadomtsev 1966

c/ But liable to "Ballooning" in local regions where R unfavourable.

$\beta_c \lesssim rR/(\text{Connection length})^2$

↑ (heuristic)

d/ Also may be resistive MHD unstable

e/ Shear stabilized

$$-\frac{dp}{dr} < (1-q^2)\frac{B_\phi^2}{32\pi r}\left(\frac{d \ln q}{d \ln r}\right)^2$$

$$q \equiv \frac{rB_\phi}{R B_\theta} > 1 \quad \text{Suydam}$$

4 continued

$$q \equiv \frac{\text{Pitch length of magnetic lines of Force}}{\text{Major circumference}}$$

$\therefore$ $q > 1$ prevents major $m=1$ "kinks"

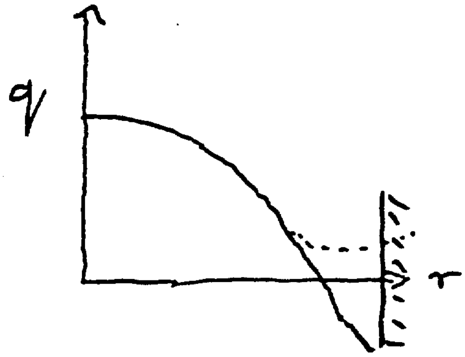
Also $q > 1$, Tokomak is an "average magnetic well.

For $q < 1$ e.g. Levitron, R.F.P., Curvature nearly always unfavourable

4/ Then liable to resistive g-mode"

2/ Kink and Tearing modes.

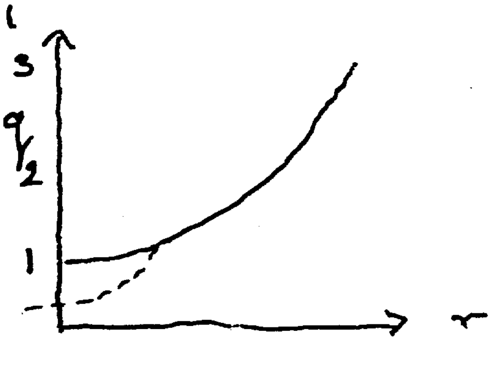
a/ Shear $q' \neq 0$ $q'' < 0$ on axis. Metal walls



RFP case
$q < 1$

Conducting wall

b/ $q > 1$



- - - - = Unstable profile

Self-Stabilization (Relaxation)

(J. B. Taylor 1974,6)

Objective of an instability → minimize $\int B^2/8\pi \, dV$

Ideal constraint $\oint A \cdot B \, dl$ = const for each line of force.

Relaxed constraint (finite η) $\int A \cdot B \, dV$ = const

Then, with conducting walls $\int B_\phi . 2\pi r \, dr = \text{const}$

configuration is

$$\text{Curl } B = \mu B$$

where μ is a constant everywhere.

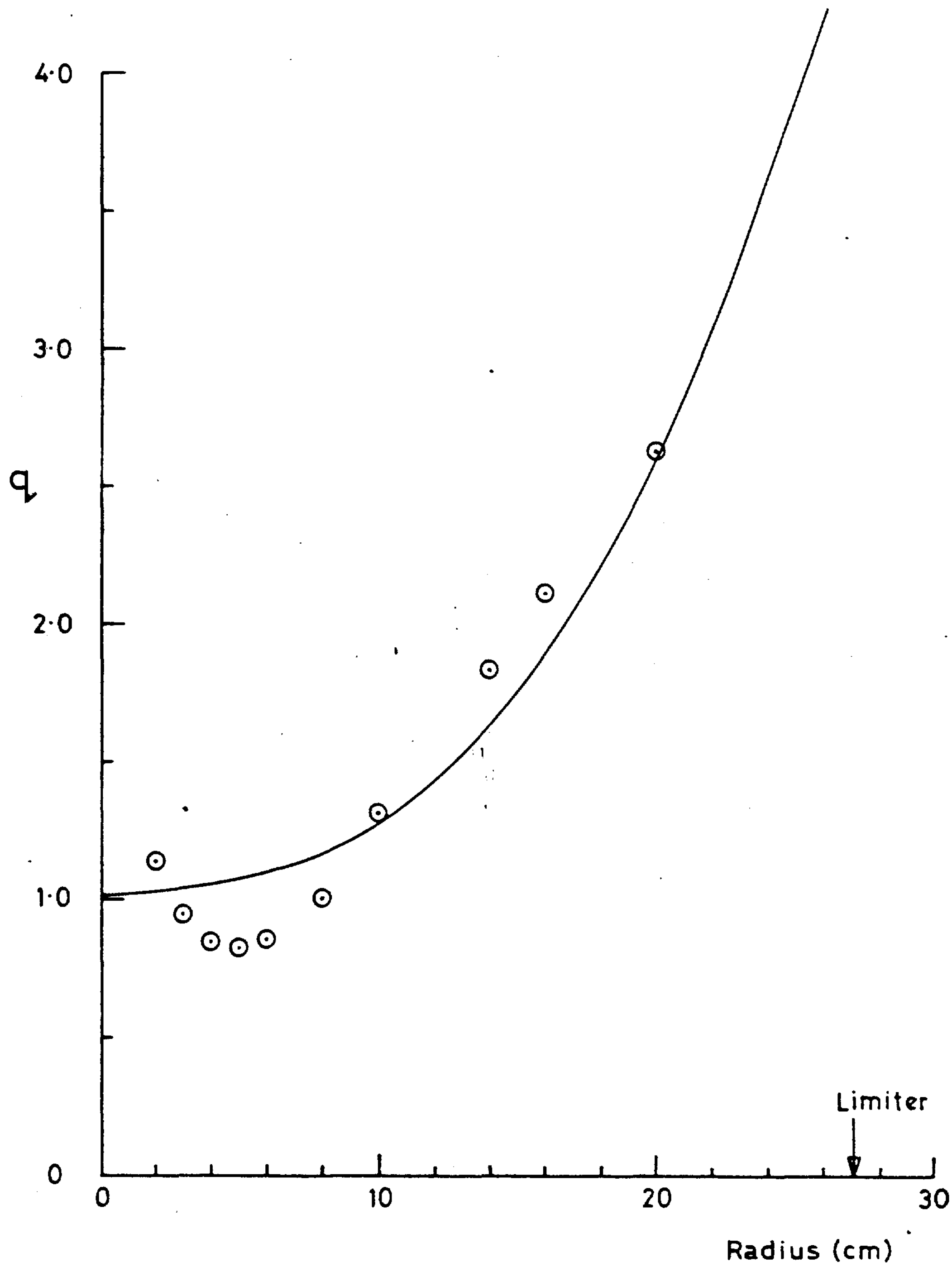
Simple cylindrical solution

$$\left.\begin{aligned} B_\phi &= B_0 J_0(\mu r) \\ B_\theta &= B_0 J_1(\mu r) \end{aligned}\right\} \text{ Bessel Function Model}$$

Provided discharge not too pinched.

Departures – e.g. finite pressure or $j_{\parallel} \neq \mu B$, treated with linear theory.

Finite β ideal MHD stable for Tokomak and Reverse Field Pinch



⊙ – from Laser scattering measurements of pitch angle of magnetic surfaces.

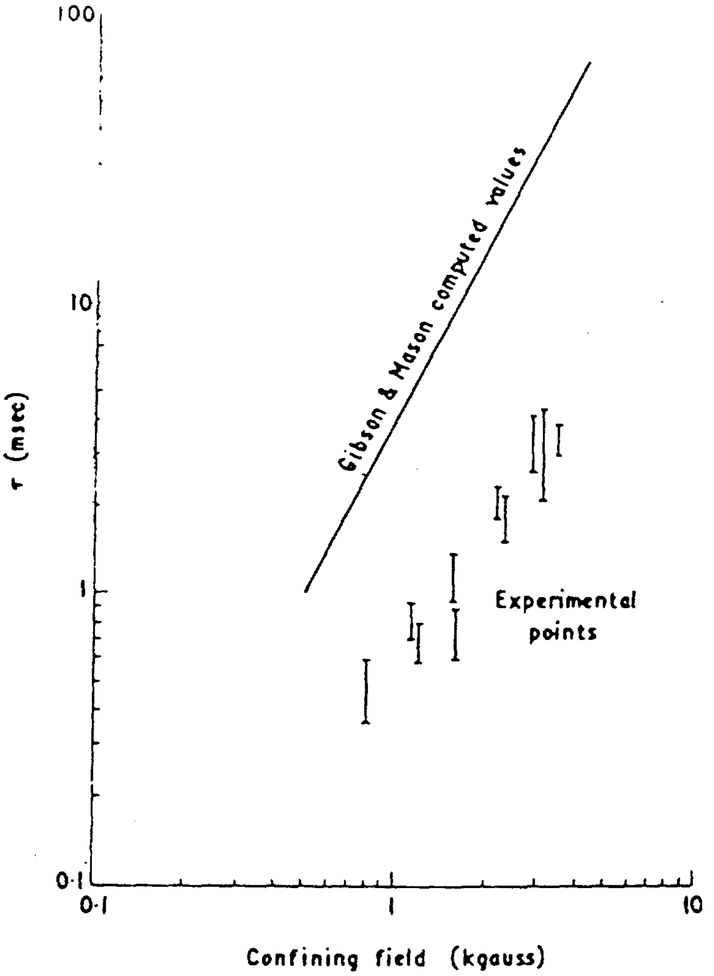
DITE; 70 millisec, $I = 130$ kA, $B_Z = 2$ T
gettered discharges.

—— from electron temperature profiles, assuming $j \propto T_e^{3/2}$ and constant $Z_{eff}(r)$ in similar plasma conditions

77.1722

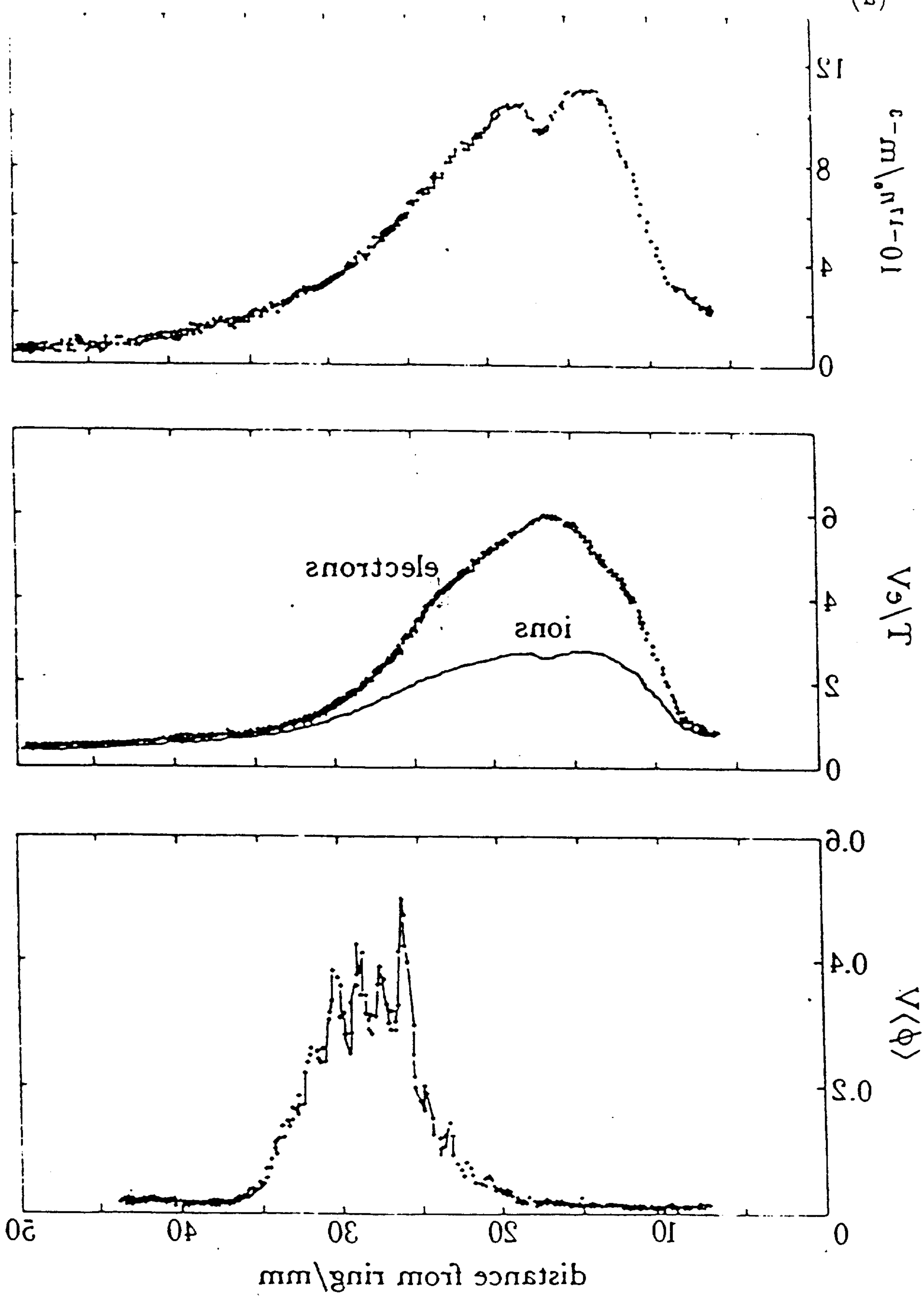
3.14

$\tau_e \sim B^2$



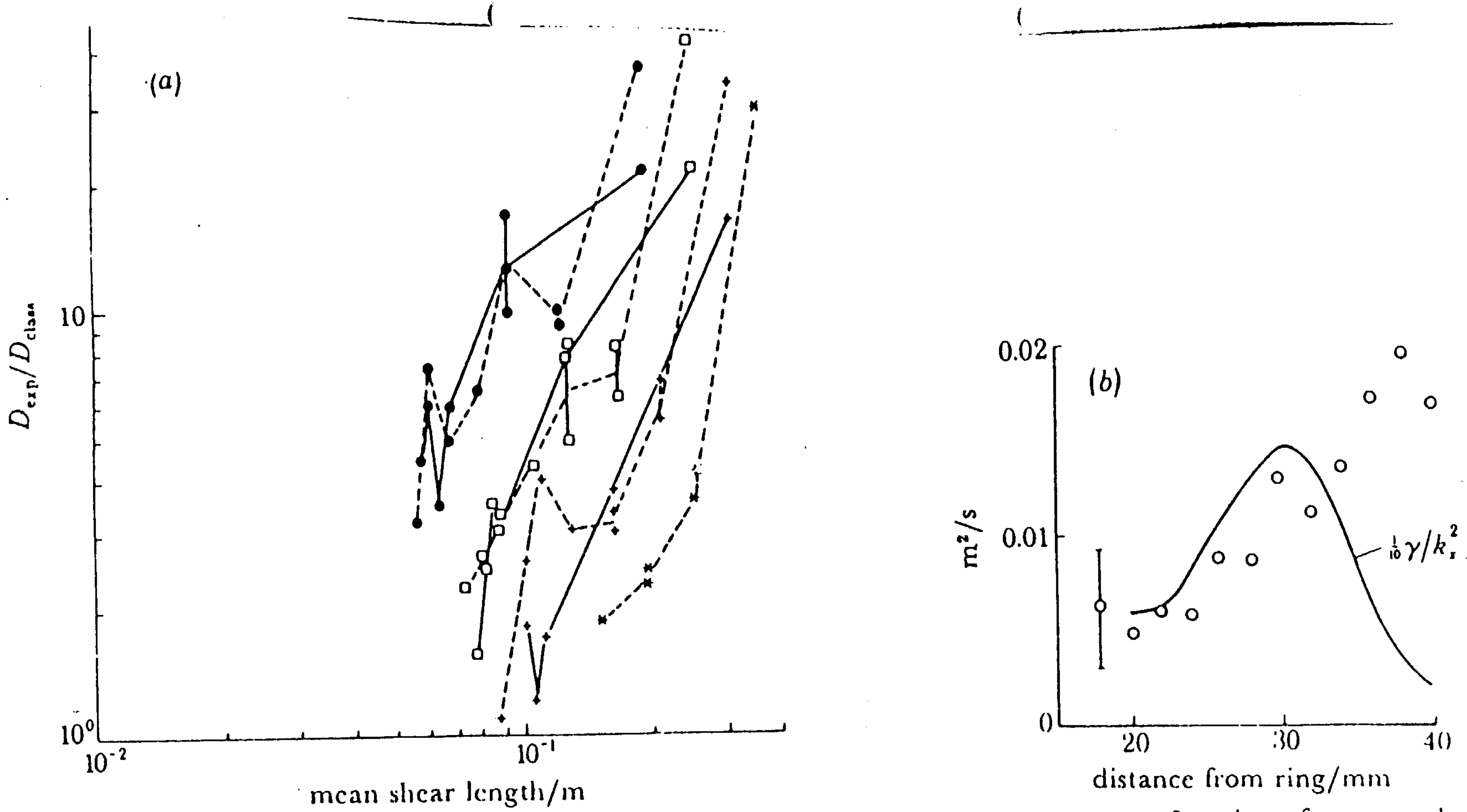
Confinement in stellarators: observed and calculated confinement times in the Proto-Cleo stellarator (Culham). Hydrogen plasma $T_{ce} \sim 5$ eV $n_e \sim 10^{10} cm^{-3}$.

3.15

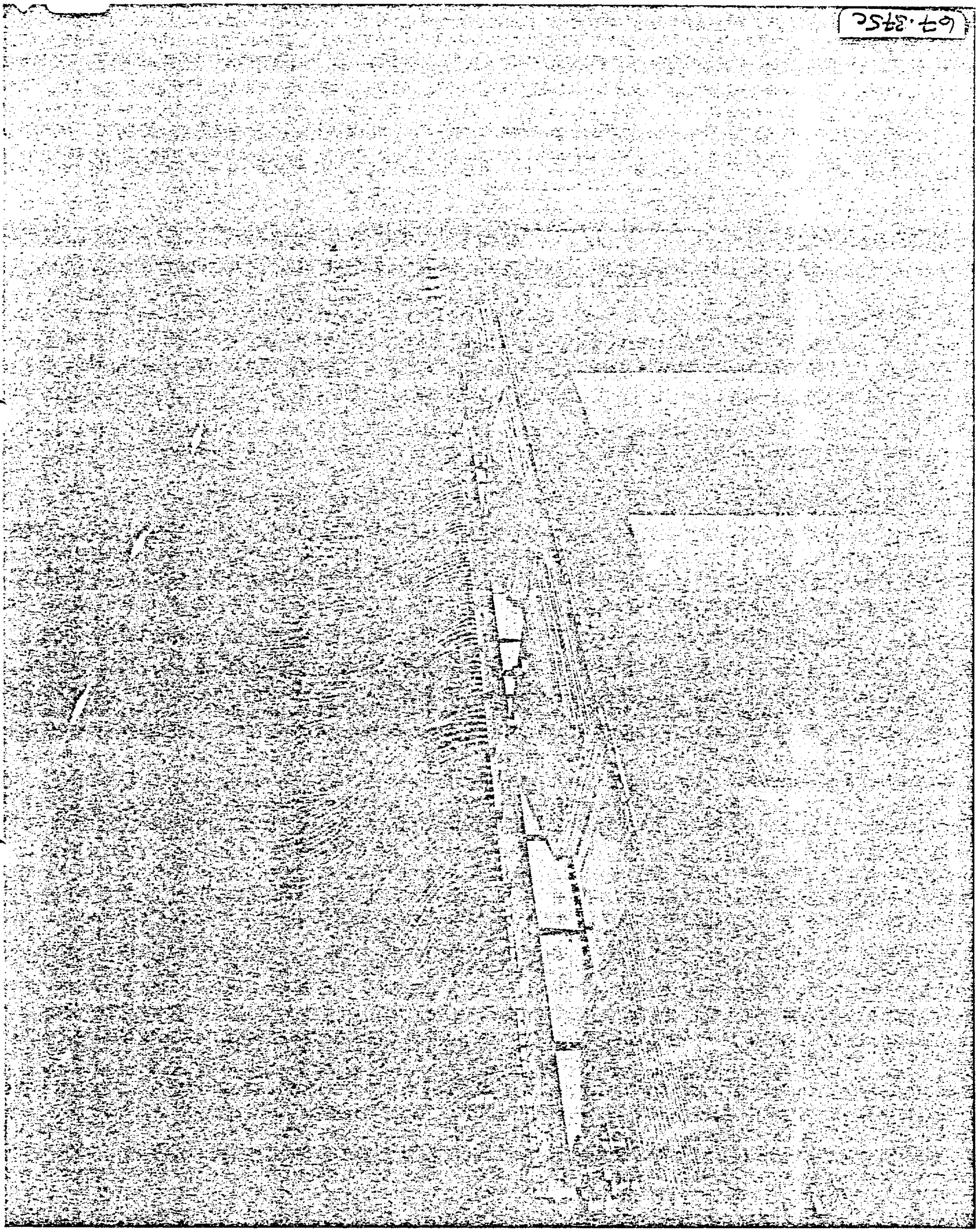


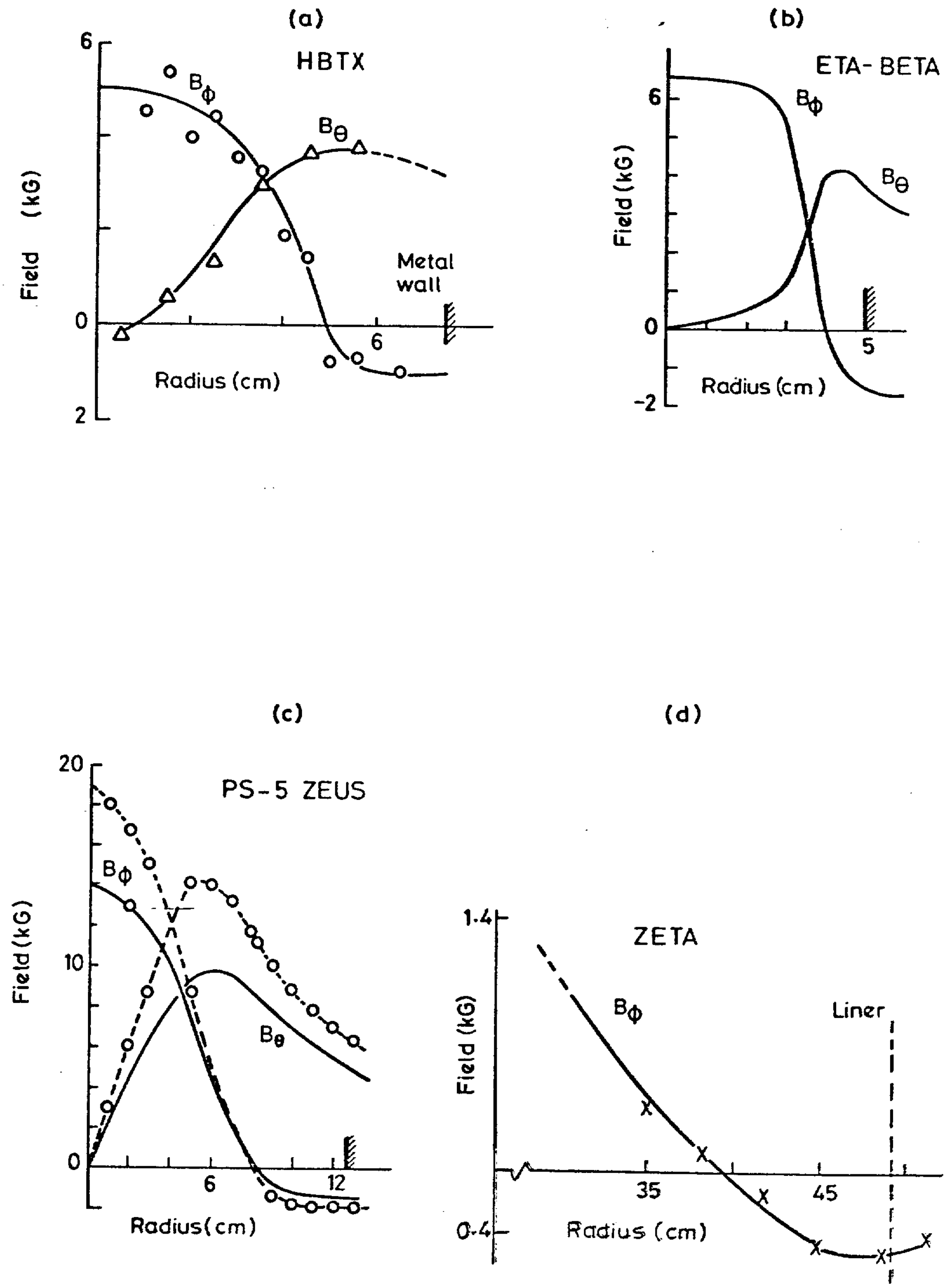
Electron density, temperature and fluctuation amplitude profile in the Culham levitron. (Ainsworth *et al.* 1978.)

3.16



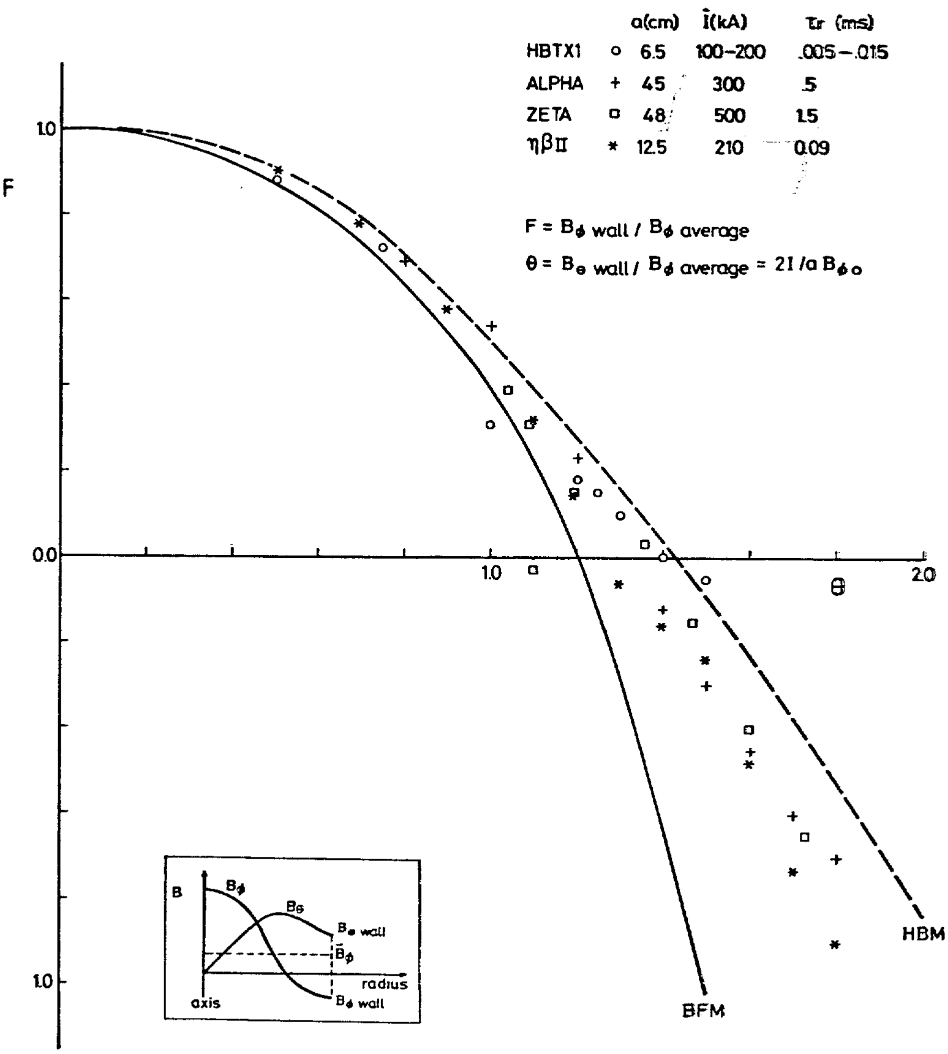
(a) Ratio of experimental to classical diffusion coefficients, D_{exp}/D_{class}, as a function of average shear length for ring currents of 180 kA (——) and 110 kA (- - -), and the following distances from the ring: ★, 20 mm; +, 25 mm, □, 30 mm; ●, 35 mm. (b) Profile of D_{exp} compared with the corresponding predictions of γ/k_x^2 from the resistive-g instability theory of Cordey *et al.* (1980).





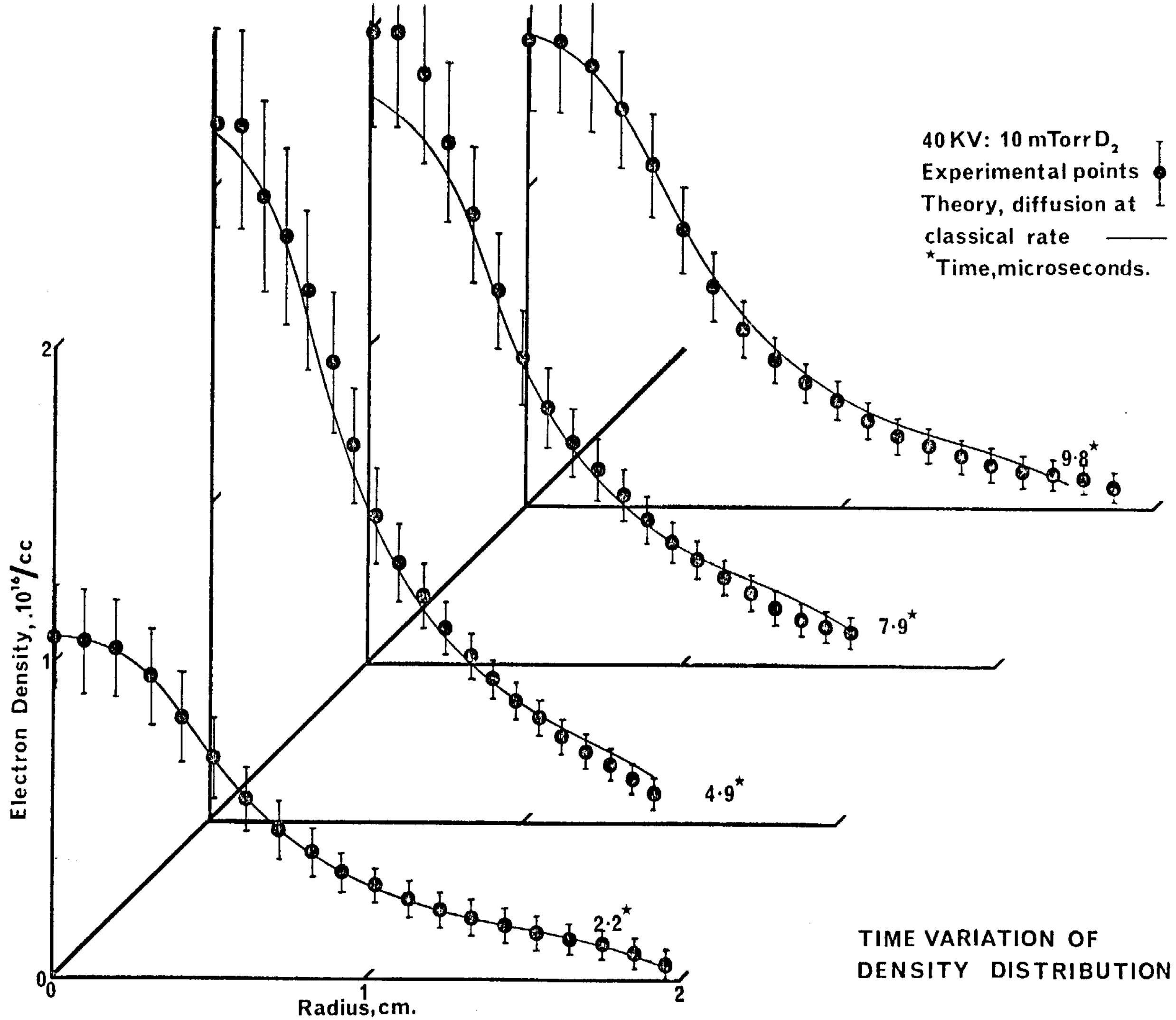
Experimental field distributions

Bodin et al



Universal F-θ Curve, showing Data
from Four Machines.

J.B. Taylor 1975



TIME VARIATION OF DENSITY DISTRIBUTION

CR68.161B

Bodin et al 1968