TRITA-PFU-89-06

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Stockholm, November 1989

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ABSTRACT

Electron temperature and density measurements on a high beta discharge in the EXTRAP-T1 device have been performed with Thomson scattering. It was found that the signal levels were low and the plasma background radiation high. The spread of the measured temperatures and densities was large. A computer code was developed to investigate whether this spread in measured temperatures was due to shot to shot variations or to photon stastistics. The code showed that the scattered data could be explained by photon statistics.

1. Introduction

The EXTRAP-T1 is a toroidal high beta experiment [1,2] which is shown in Fig.1. The major radius of the device is 0.45 m and the discharge radius is aproximately 0.04 m. The plasma current channel is bounded by a separatrix with 4 x-points in the poloidal field produced by current in the 4 rings outside the discharge current channel. The plasma current as well as the ring currents are induced in parallel as the secondary of an iron core transformer. The toroidal magnetic field and a vertical, nearly homogenous field, used to control the equilibrium position of the plasma, are produced by coils outside the stainless steel vacuum vessel. Typical values of the toroidal field and the vertical field are B_ϕ = 0.05 to 0.2 T and B_V= 0 to 0.01 T. The induced plasma current pulse has a duration of about 100 µs.

In order to measure the plasma density and temperature, Thomson scattering [3] can be performed. Laser light is scattered by the free electrons in the plasma, and density and temperature are obtained by analysing the frequency-broadened, scattered light. In the EXTRAP-T1 experiment, the plasma density is of the order of 10^{21} m^{-3} and is surrounded by a large region of low density, low temperature plasma. This region contributes to a large background radiation in the wavelength region around the laser wavelength, λ_0 = 6943 Å, where the Thomson scattering measurements are performed.

The diagnostics will be treated in Sec. 2. In Sec.3 the method of evaluating the data is described. The results of the measurements are presented in Sec. 4 and a discussion of the validity of the results follows in Sec. 5.

2. The Thomson scattering diagnostics

An overview of the Thomson scattering system is shown in Fig. 2. The present experimental set up of the Thomson scattering system was originally designed for the EXTRAP-L1 experiment, and is described in detail elsewhere [4]. To adapt the equipment to the EXTRAP-T1 experiment the laser beam guiding optics were modified. A QUANTEL double-pulse ruby laser capable of 10 J in a single pulse of 20 ns have been used. In the EXTRAP-T1 device the laser beam is guided by 4 mirrors and focused down to a diameter of 2 mm inside the plasma. Due to lack of space, the laser dump consists of blue glass, orientated at the Brewster angle, mounted on a vacuum port where the laser beam exits the vacuum chamber. Although the laser dump is a simple construction, the stray light level is not a problem. The receiving optics include a camera lens which images the 1×5 mm^2 end of a 25 m long, coherent fibre bundle onto a 2×10 mm^2 rectangle at the postion of the laser light beam in the plasma. The long side of the image rectangle is parallel with the beam. The other end of the fibre bundle is imaged onto the entrance slit of a f/10, 1-m, spectrometer. At the output slit of the spectrometer an array of optical quartz fibrres provides the usual spectral resolution as well as the possibility for spatial resolution of the 10 mm length of the scattering volume into 3 regions [4] However, the plasma density of about 1×10^{21} m^{-3} was typically 5 times lower for the present EXTRAP-T1 experiment than on the EXTRAP-L1 experiment the number of photons collected were not enough to use the possibility for spatial resolution. Therefore photons collected from the entire scattering volume, were added using quartz fibre optics to increase the signal level.

3. Data evaluation

3.1 Calibration

Three types of calibration measuremeents have been carried out: 1) Relative calibration of the detector channels which is necessary to evaluate the electron temperature. 2) Rayleigh scattering which is necessary for obtaining the electron density. 3) An absolute calibration which is necessary for photon statistical analysis.

The relative calibration of the channels was performed by pulsing a light diode, having a maximum emission at 6600 Å, with 50 ns pulses. This LED was placed in front of the plasma end of the fibre bundle and the spectrometer was scanned through λ so that each channel to be calibrated received a constant source strength. The signal level from each channel detector then provided the the relative calibration.

In additon, in order to be able to measure the density, a calibration by the means of Rayleigh scattering on N_2 was performed. This technique is standard and is not described in detail here.

The third calibration is more unususal for a Thomson scattering diagnostic. In order to carry out a better statistical analysis, an absolute calibration was done relating the number of photoelectrons to the detector signal. In our case the detector signal is the digital output of an integrating ADC (Le Croy 2250L). The basis for this calibration is now described.

If S denotes the signal and N the number of photoelectrons then

$$S = C\,N \qquad (1)$$

where C is the constant to determined. The number of photoelectrons is taken to be Poisson distributed. If the mean of the number of photoelectrons is $\langle N \rangle$ then the standard deviation is $\Delta N = (\langle N \rangle)^{1/2}$. If we accordingly denote the mean of the signal by $\langle S \rangle$ and the standard deviation by ΔS we get

$$\Delta S = C\,\Delta N = (C \langle S \rangle)^{1/2} \qquad (2)$$

or

$$C = (\Delta S)^2 / \langle S \rangle \qquad (3)$$

If a PMT is illuminated with light pulses of constant magnitude and shape, ΔS can be estimated as well as $\langle S \rangle$ and C is easily obtained from Eq.(3). The calibration factor C is used for the analysis of the data which will be treated later.

3.2 Stray light and plasma background radiation

The detected signal come from sources in addition to Thomson scattered laser light. One such source is stray light which originates from the scattering of the incoming laser light by the input window and imperfections in the laser dump. This light has the laser wavelength but cannot be totally discriminated by the spectrometer. In our case it was found to be of minor importance; its contribution to the signal is typically about 15% of the signal in the channel closest to the laser wave length.

The plasma background radiation is of more importance. Depending on the plasma parameters it could be of the order of 50% of the signal. In Fig.3 we show a typical stray light, plasma background and Thomson scattered light spectra. Also in this figure we see the width of the detector channels and their position in the spectral coordinate λ. The number of Thomson scattered photoelectrons is

$$N(\lambda) = N_t(\lambda) - N_s(\lambda) - N_b(\lambda) \qquad (4)$$

where N_t denotes the total number of photoelectrons, N_s the stray light photoelectrons and N_b the plasma background radiation. To evaluate N we must estimate N_s and N_b. The stray light was constant if the laser optics were not changed. This measurement was made periodically to check the level. In order to estimate N_b, three plasma shots without laser light, at the parameter values of interest were taken. The standard deviation in N due to photon statistics, will according to Eq.(4), depend on the standard deviations in N_t, N_s and N_b in the following way;

$$\Delta N = \sqrt{(\Delta N_t)^2 + (\Delta N_s)^2 + (\Delta N_b)^2} = \sqrt{<N_t> + <N_s> + <N_b>} \quad (5)$$

where ΔN represents the standard deviation of N.

3.3 Temperature analysis

The signal levels are measured at 5 equidistant wavelengths, $(\lambda_i = \lambda_0 - i\,\Delta\lambda)_{i=1,5}$, with a channel width $\Delta\lambda_d$. This is illustrated in Fig.3 where the sample wavelengths λ_i, the channel separation $\Delta\lambda$ and the channel width $\Delta\lambda_d$ is seen. We have $\lambda_0 = 6943$ Å, $\Delta\lambda = 25$ Å and $\Delta\lambda_d = 16$ Å. We measure the signal levels and calculate N_{ti}, N_{si} and N_{bi}, where the index i denotes the number of photoelectrons in the i:th channel. Then N_i and ΔN_i are obtained from Eq.(4) and Eq.(5). Theoretically the non-relativistic Thomson spectra has the form

$$f(\lambda) = A \frac{n}{\sqrt{T}} e^{-\frac{B(\lambda-\lambda_0)^2}{T}} \quad (6)$$

where A and B are constants (B is a known constant and A is calculated from Rayleigh scattering) and n is the electron density. If the measured N_i is fitted to the theoretical expression above, it is possible to evaluate T as well as the density n. This is achieved by minimizing the sum

$$\sum_{i=1}^{5} \frac{(f(\lambda_i) - N_i)^2}{\Delta N_i^2} \quad (7)$$

with the help of a non-linear least squares fitting routine (E04HFF in the NAG Mark 11 library). Note that by dividing with ΔN_i^2 in the sum of Eq.(7) more weight is given to the measured N_i with a low standard deviation ΔN_i. It is also possible to use a linear fitting routine by minimizing $(\ln(f_i) - \ln(N_i))^2$ instead of $(f(\lambda_i) - N_i)^2$ in the sum of Eq.(7) but then special care has to be taken to the errors ΔN_i^2 [5].

4. Results

The data from EXTRAP-T1 presented here were taken with the following ranges of parameters: the plasma current I_p from 15 to 38 kA and filling pressure p_{fill} from 4 to 20 mTorr. The purpose of the measurements was to investigate the scaling of n and T with I_p and p_{fill}. The time dependence of I_p from a typical shot is shown on Fig 4. It was found that the highest temperatures ocurred when I_p had its maximum and therefore the measurements presented here was taken at this time. In general the signal level was low and the background high. The background was independent of wavelength in the range where light was collected but increased with increasing I_p. The stray light was low, about 15% of the signal in the channel nr 1, closest to the laser wavelength, and neglible in the other channels. Typical absolute photoelectron levels in channel nr 1 were found to be N_{t1}= 50, N_{s1} = 5 and N_{b1} = 20, which, according to Eq.(4) and Eq.(5) give N_1 = 25 and ΔN_1 = 9. Because the background is independent of wavelength whereas the signal decreases according to the Gaussian distribution in Eq.(6) the stastical fluctuations $\Delta N/N$ increases for the channels farther from the laser wavelength. For some shots the distribution of N_i was such that no tmperature could be evaluated, i.e. no minimum of the sum in Eq.(7) could be found or the minimum obtained gave a negative T. The number of shots where no T could be obtained increased with increasing I_p.

The electron temperature T has been evaluated over the range of plasma currents. This has been done at different filling pressures. The temperature data are plotted in Fig.5 show that T increases with I_p with a scaling factor of about 0.5 eV/kA. In Fig. 6 we show T vs p_{fill} and, as expected, T has a tendency to decrease with increasing p_{fill}. Also shown are the dependencies of n upon I_p and p_{fill}. For a more detailed description of the scalings see Ref.[6]

The large spread of the Thomson scattering data points for the graphs shown motivates an analysis of the photon statistics to investigate whether the observed spread in the data is due to shot to shot variation or to photon statistics of the diagnostics? The remainder of this paper is therefore devoted to a discussion of this question.

5. Discussion

The stastical fluctuations of the single channels affect the evaluation of the electron temperature. This problem has been treated by Hart et.al.[7] who developed a computer code. We have also constructed a code based on the same principles but adapted to our particular parameters. The basic idea of this code is to have a plasma of constant temperature and to simulate a number of shots where the number of photoelectrons is picked according to photon statistics. Then it is possible to predict the spread in temperature due to photon stastics. The average number of photoelectrons from Thomson scattering and plasma background in the channel closest to the laser wavelength, $\langle N_l \rangle$ and $\langle N_{bl} \rangle$, are given. As for the other channels $\langle N_{bi} \rangle$ was taken to be constant whereas $\langle N_i \rangle$ was calculated from the Gaussian ditribution. Since the stray light is low, it has not been accounted for in the code. Then the code simulated a number of shots and for each shot picking N_i and N_{bi} for the channels according from Poisson distributions with the corresponding means $\langle N_i \rangle$ and $\langle N_{bi} \rangle$. Then the code made a non linear least squares fit to data for each shot. In this way the effect of photon stastistics upon the measured temperatures could be estimated. Fig. 9 shows the frequency distribution for the typical case $T = 20$ eV, $\langle N_l \rangle = 25$ and $\langle N_{bl} \rangle = 20$. The accumulated freqency distribution for the same parameters is shown on Fig.10. There it is seen that slightly below 20% of the shots gave a temperature below zero. The reason for this is that for some shots a distribution was picked such that no temperature could be evaluated or a negative temperature was obtained and they are represented by this percentage. Also from Fig.10 it is seen that 15% of the shots resulted in positive temperatures below 10 eV and almost 20% gave temperatures higher than 30 eV. The low overall signal levels as well as the high background radiation contributed to the large spread in T, only 45% of the simulated shots resulted in temperatures in the interval 20 ± 10 eV. These results indicate that the spread in the measured temperatures could entirely be explained by the effect of photon stastistics. The code also predicts that the spread in temperatures increases with T as well as the fraction of shots for which no T could be obtained. This is in agreement with the experimental results. It is important to note, however, that this also means that the measurements of higher temperatures is difficult. It is a high probability that a high T could not be determined.

6. Acknowledgements

The author is indebted to Mr. J. Tonks who has constructed many of the mecano-optical components of the diagnostics and to Dr. B. Wilner who has designed the optical guide for the laser beam. Professor J.R.Drake has contributed with valuable comments on the manuscript.

References

1. Drake, J.R., Brunsell, P., Brzozowski , J., Hedin, E.R., Karlsson, P., Lehnert, B., Li, J., Ohlsson, M., Sätherblom, H.E., Tennfors, E. and Wilner B.. Twelfth International Conference on Plasma Physics and Controlled Nuclear Fusion Reasearch, Nice, France, October 12-19, 1989, paper C-V-19.

2. Drake, J.R., Hedin, E.R., Karlsson, P., Li, J., Sätherblom, H.E., To be published in Physica Scripta.

3. Sheffield, J., Plasma scattering of electromagnetic radiation (Academic Press, New York, 1975).

4. Karlsson, P., Nucl. Instr. and Meth. **A257**, 391 (1987).

5. Nicholson, M.G., Plasma Phys. **26**, 1035 (1984).

6. Drake, J.R., Hedin, E.R., Karlsson, P., Li , J. and Sätherblom, H.E., Royal Institute of Technology, Stockholm, TRITA-PFU-89-01.

7. Hart, G.W., Levinton, F.M. and McNeill, D.H.. Rev.Sci. Instrum. **57**, 2218(1986).

Figure Captions

Fig. 1 Overview of the EXTRAP-T1 device.

Fig. 2 The Thomson scattering experimental set up. Along the path of the laser beam we have: L1 is a plano-concave lens f = -200 mm, L2 is a plano-convex lens f = 300 mm, M1-M3 are high energy laser mirrors, L3 is a plano-comvex lens f = 1000 mm and LD is the laser dump. The detection optics incude: VD is the viewing dump, L4 is a camera lens f = 85 mm/1.8, P is a sheet polarizer, L5 is a camera lens f = 50 mm/1.4, L6 is a camera lens f=58 mm/1.8, FM is the fibre matrix and PM(1) - PM(5) are photomultiplier tubes. For triggering the detection optics a 400 μm optical fibre (OF) and a photodiode (FD) is used.

Fig. 3 A typical spectrum from a Thomson scattering measurement is sketched. The plasma background radiation is almost independent of wavelenght, the non relativistic Thomson scattered radiation and the stray light contribute to the detected signals.

Fig. 4 The plasma current versus time.

Fig. 5 The plasma temperature versus plasma current.

Fig. 6 The plasma temperature versus filling pressure.

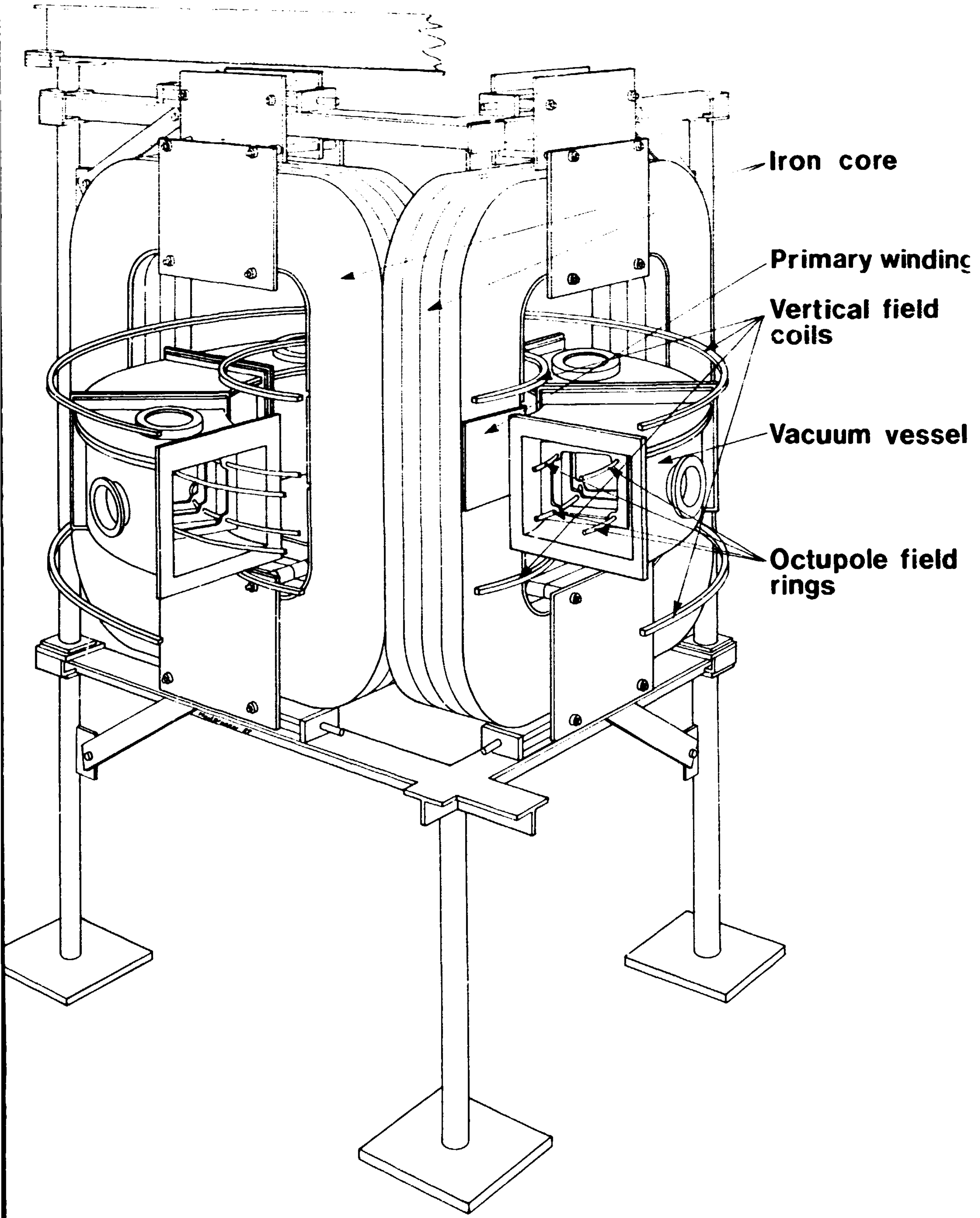
Fig. 7 The plasma density versus plasma current.

Fig. 8 The plasma density versus filling pressure.

Fig. 9 Frequency versus temperature for simulations with the parameters $<N_1> = 25$, $<N_{b1}>= 20$ and T = 20 eV.

Fig.10 Accumulated frequency versus temperature for simulations with the parameters $<N_1> = 25$, $<N_{b1}>= 20$ and T = 20 eV.

Fig.1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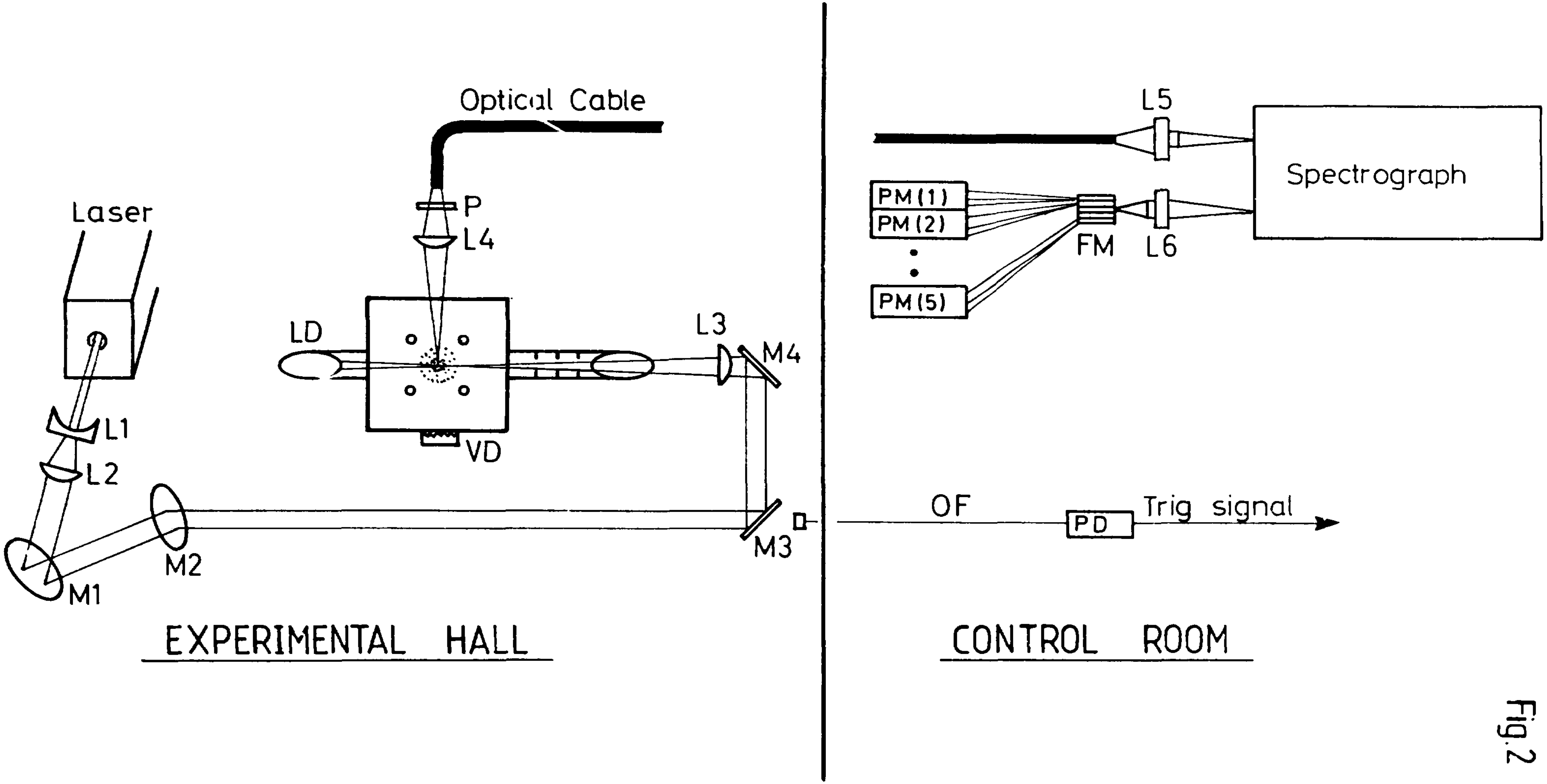
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Laser
P
L4
LD
L3
M4
L1
VD
L2
M2
M3
M1
EXPERIMENTAL HALL
L5
Spectrograph
PM (1)
PM (2)
PM (5)
FM
L6
OF
PD
Trig signal
CONTROL ROOM

Fig. 2

Fig. 3

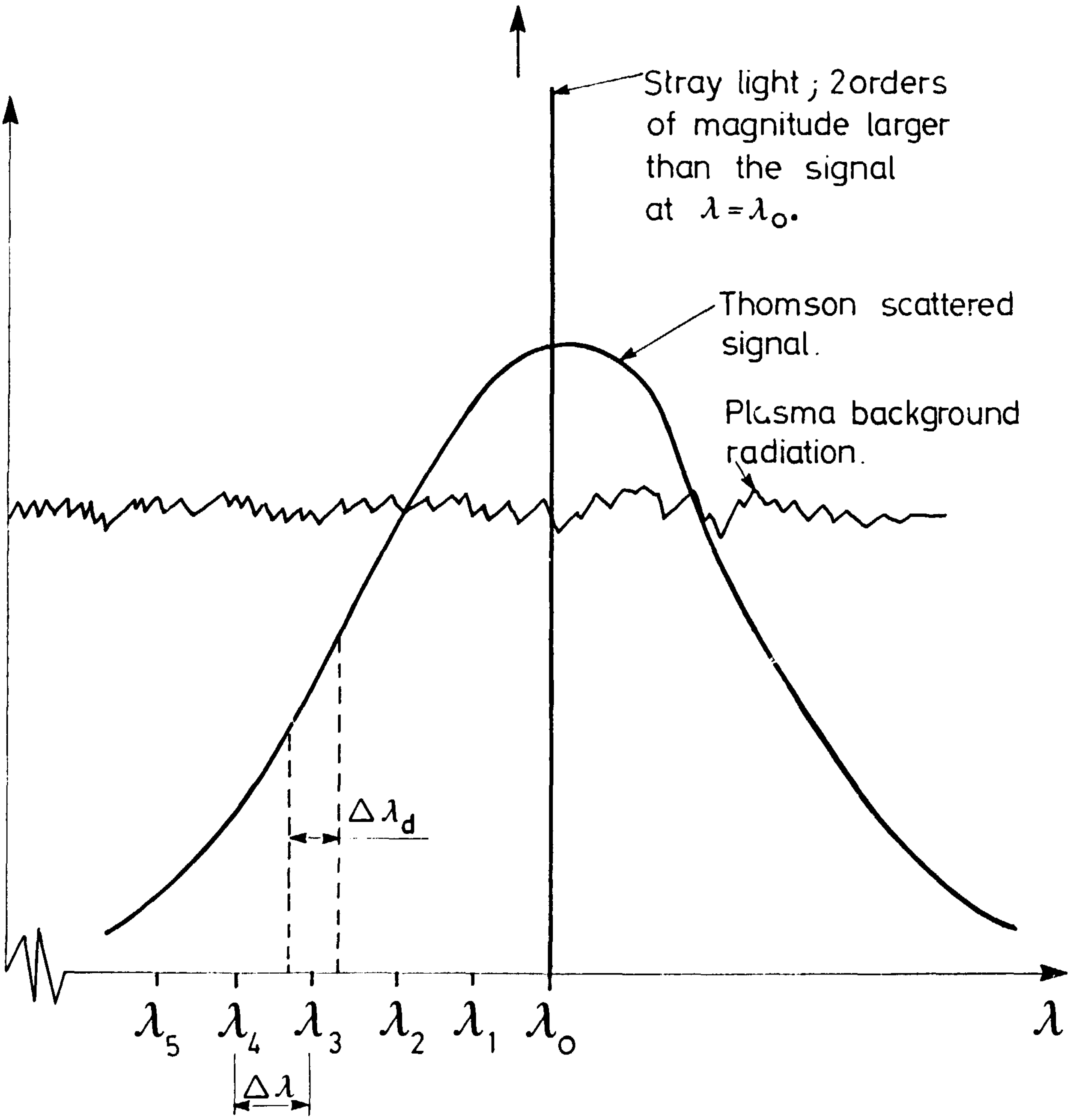

S
Stray light ; 2orders of magnitude larger than the signal at $\lambda = \lambda_0$.
Thomson scattered signal.
Plasma background radiation.
$\Delta\lambda_d$
λ_5
λ_4
λ_3
λ_2
λ_1
λ_0
λ
$\Delta\lambda$

Fig.4

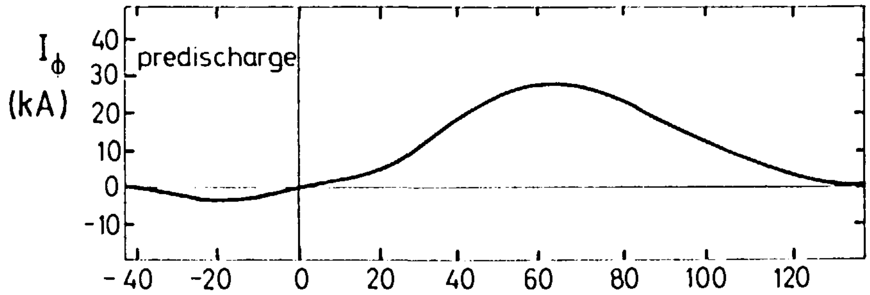
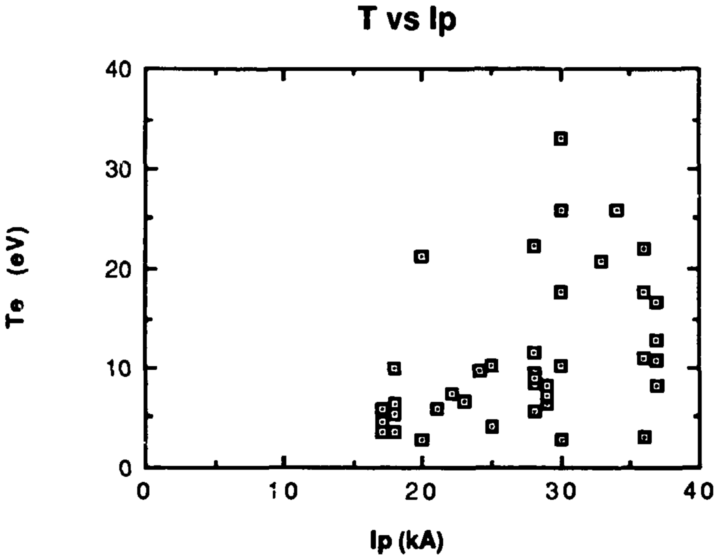
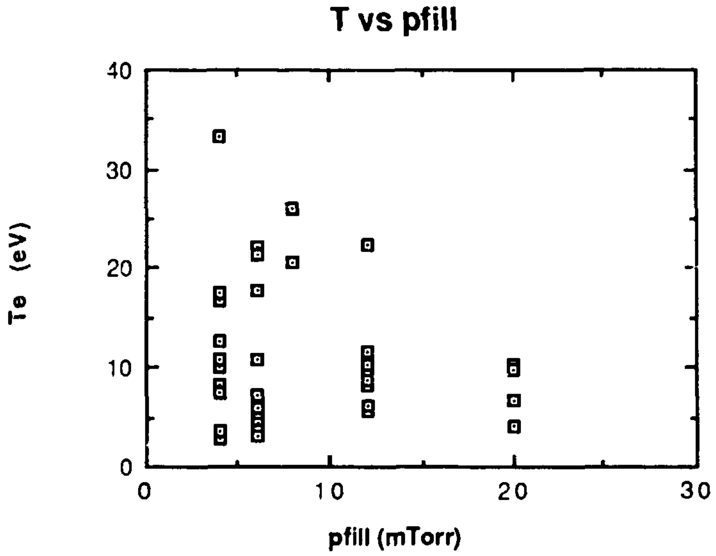


Fig.5




T vs pfill
Te (eV)
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10
20
30
40
pfill (mTorr)
0
10
20
30

Fig.7

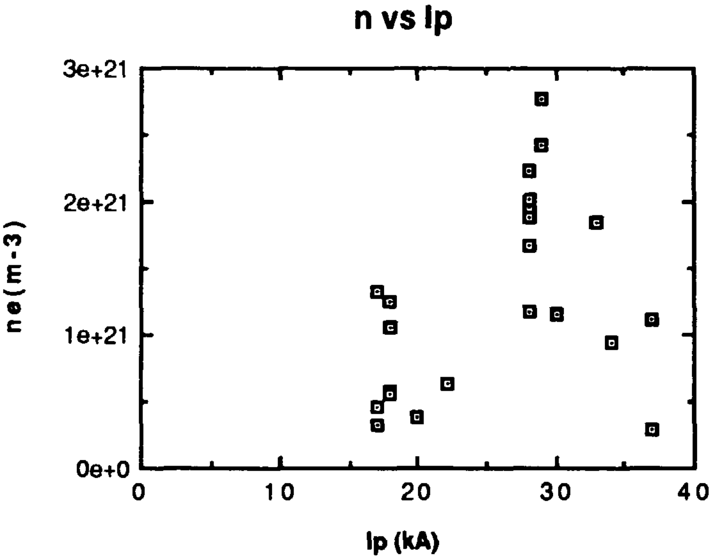


Fig.8

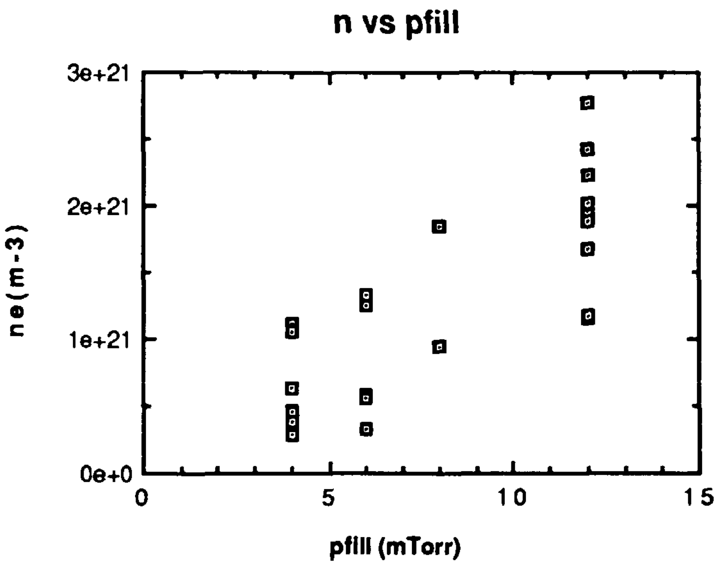


Fig. 9

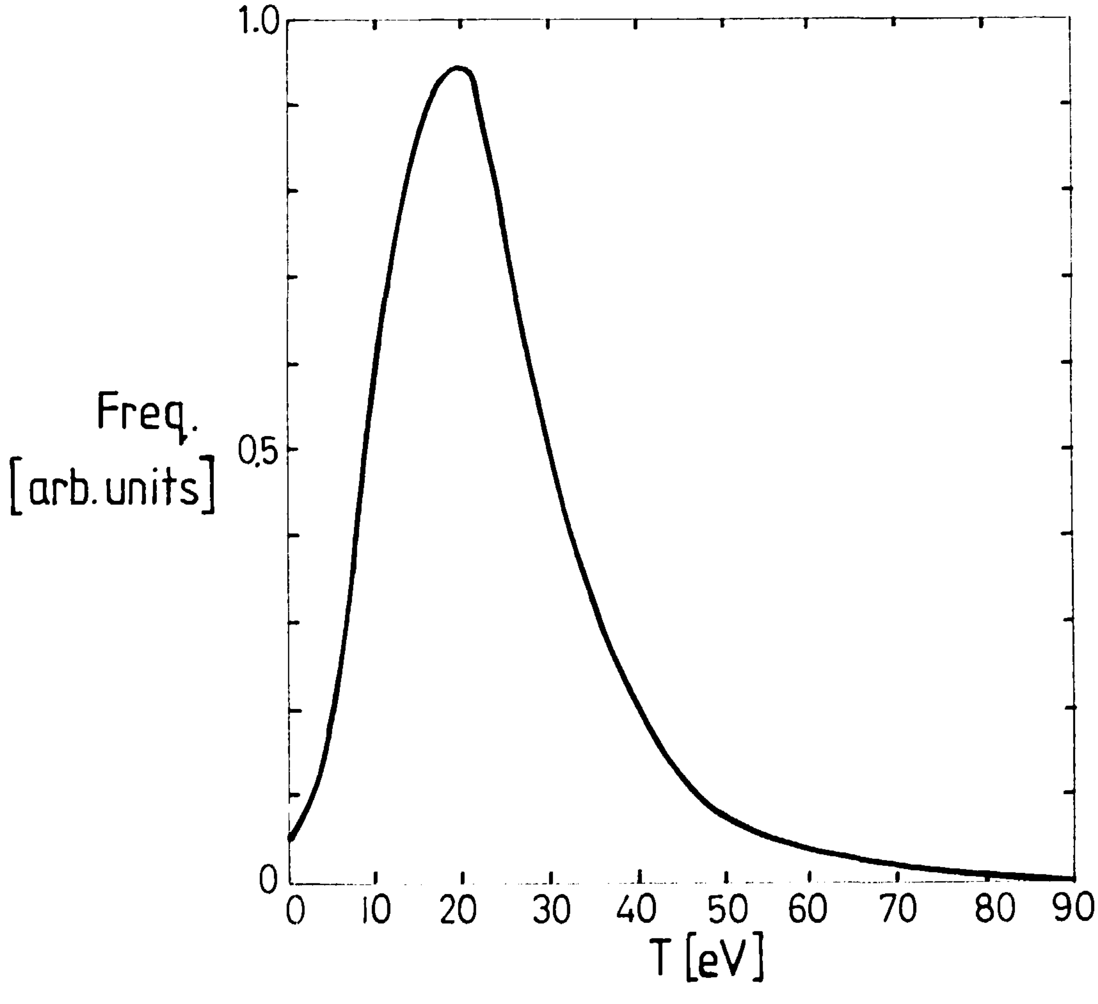
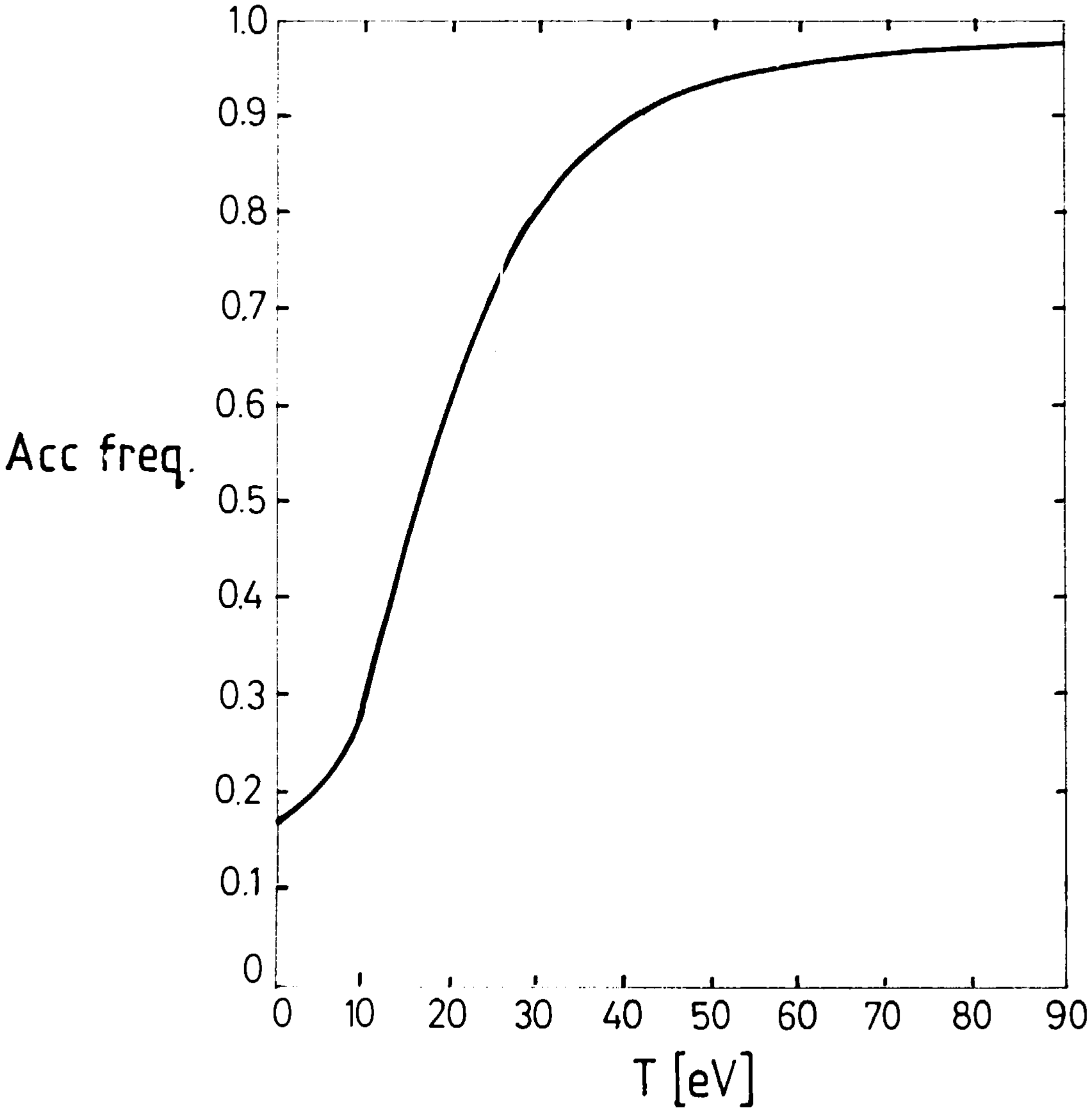


Fig.10


1.0
0.9
0.8
0.7
0.6
0.5
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0.3
0.2
0.1
0
Acc freq.
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10
20
30
40
50
60
70
80
90
T [eV]

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Key Words : Z-pinch, Extrap, Thomson scattering, temperature measurement, data evaluation