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M. Siegrist, R. Behn, D. Dicken*, B. Duval, J. Hackmann,* B. Joye, J. Lister, C. Nieswand, A. Pochelon, G. Soumagne, D.C. Yuan

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
21, Av. des Bains, CH-1007 Lausanne/Switzerland

*Institut für Laser- und Plasmaphysik, Universität Düsseldorf, West Germany

ABSTRACT

Collective Thomson scattering, using a high-power pulsed D_2O laser at 385μm and a heterodyne receiver system, has provided local ion temperature (T_i) measurements of the plasma in the TCA tokamak. Recent improvements in the noise-equivalent power (NEP) of the Schottky barrier diode mixers permitted us to achieve a typical precision of ±12% for a single shot measurement at densities above $10^{20}m^{-3}$. Even at densities of standard TCA discharges ($5x10^{19}m^{-3}$) the uncertainty is better than ±25%.

For the interpretation of the measured spectra and the evaluation of T_i the local value of the electron temperature (T_e) is an important parameter. Therefore, T_e was measured simultaneously by incoherent Thomson scattering at 0.694μm during a series of shots. The density was obtained from a far-infrared interferometer. An independent measurement of T_i on TCA can be obtained from a neutral particle analyzer (NPA). Comparison of the results from the two methods showed good agreement.

The precision of a T_i-measurement depends strongly on the plasma density. Since an uncertainty of ±25% at standard densities may still not be regarded as satisfactory, further investigations using a numerical simulation code have been carried out to find ways of improvement.

INTRODUCTION

Last year we reported the first single shot ion temperature measurements in a tokamak by collective Thomson scattering (CT) [1]. The precision was estimated to be of the order of 25%. This could not yet be considered as sufficient accuracy compared to other T_i diagnostics and hence improvements were required. Making use of the latest improvements in the field of Schottky diodes and optimising the frequency coverage of the detection system, it is now possible to achieve a measurement precision of 12% at plasma densities of 1.2 10^{20} m^{-3}. This degrades to 17% at half this density, and the previously reported accuracy of 25% is achieved at densities of 5 $10^{19} m^{-3}$.

On the other hand, two important questions still had to be answered: (1) are the observed spectra indeed produced by scattering from thermal velocity distributions and (2) is the ion temperature obtained from collective Thomson scattering in agreement with results from other diagnostics.

In this paper we report measurements which were undertaken to investigate these points.

First we present the measurements of sensitivity of the latest diodes. We then investigate the predominantly statistical nature of the measurement accuracy in conjunction with simulation results and discuss possible further improvements and finally we report the results of a series of plasma discharges where all required plasma diagnostic systems were operational. For the interpretation of spectra obtained from collective Thomson scattering, the electron density and temperature are required. These were measured simultaneously by a far-infrared interferometer and by ruby laser scattering, respectively. An independent measurement of T_i on TCA can be obtained from a neutral particle analyzer [2] with five energy channels with an accuracy of the order of 5%.

APPARATUS

The experimental set-up has been described in detail in ref [1]. We will only briefly recall the main components: A CO_2 laser which delivers 600J on the 9R(22) line in a 1.4µs long single mode pulse is used for optical pumping of a 4m long unstable resonator containing 6.5mbar of D_2O vapor. The far infrared laser produces 0.5J during 1.4µs at the wavelength of 385µm.

The D_2O laser emission is focused to a 3mm waist close to the plasma center via a set of off-axis parabolic mirrors. The scattered light is collected at 90^o to the incident beam in a solid angle of 4.3×10^{-3} sr.

For detection and spectral analysis of the scattered radiation we use a heterodyne receiver with an optically pumped CD_3Cl laser as local oscillator. Its emission is combined with the scattered radiation in an optical diplexer and mixed in a Schottky barrier diode. The resulting IF signal around 3.6 GHz, is amplified and split into twelve channels with a bandwidth of 80 MHz each. Thereafter the signals are integrated and digitized.

A considerable improvement of the sensitivity of our detection system has been achieved through a collaboration with groups at the University of Düsseldorf and the MPI für Radioastronomie, Bonn, which provided the mixer. Our diodes are manufactured by the Semiconductor Device Laboratory, University of Virginia, Charlottesville, USA. The latest chip used for these measurements comprises two epi-layers of thicknesses 0.06µm and 1µm, doped with $4x10^{17}cm^{-3}$ and $5x10^{18}$ cm^{-3} GaAs respectively. The 120µm thick substrate with a surface of 100µm * 100µm is covered with a layer of SiO_2 which is only 0.17µm thick. The Pt-Au Schottky contacts have a diameter of 0.5µm and a separation of 1.5µm from each other. The small dimension of the Schottky contact results in a reduced capacitance of the junction of 0.6fF. This does not only result in a high cutoff frequency, but also in an increased sensitivity [3], as was confirmed by our measurements.

SYSTEM NOISE TEMPERATURE MEASUREMENTS

The system noise temperature of the heterodyne detection system is measured routinely using thermal radiation sources (ECCOSORB sheets at room temperature and at the temperature of liquid nitrogen). Since the sources are placed close to the receiver system, the system noise temperatures obtained from the standard Y-factor method [4] include the losses of the diplexer but not those encountered in the beam path between the receiver and the tokamak vessel (distance ≈ 10m). We estimate the total losses to 50% when a beam duct filled with dry nitrogen is used to avoid attenuation by humidity in the air.

An impedance matching circuit has been added to the mixer for better adaptation to the 50Ω input impedance of the first IF amplifier.

Fig. 1 shows the system noise temperature (DSB) in the IF-band covered by our receiver. From a comparison with earlier results, using a different diode type, we find that an improvement of about 20% has been achieved.

Since T_{sys} depends on local oscillator (LO) power and bias current, it is important to optimise these parameters. The dependence on LO-power at fixed bias current (I_B = 0.5mA) is shown in Fig. 2. The noise temperature as a function of LO-power decreases to 5000°K at 0.5mW and then enters a plateau region (up to 3mW) where changes in LO-power have only very little effect. The fact that these diodes reach their optimum performance at rather low LO-power offers more flexibility in the choice of a suitable LO-source, since now also weaker FIR laser transitions could be used. On the other hand, the stability of the CD_3Cl LO-laser used in our scattering experiment is much better at low power levels.

MEASUREMENT PRECISION AND NOISE CONSIDERATIONS

In the heterodyne detection system used in our experiment, the signal to noise ratio (S/N) of the output of each channel of spectral width df, after integration, is related to the power P_{in} incident onto the Schottky diode by [5]

(1) $$(S/N)_{df} = P_{in} / (P_{in} + P_{noise}) \sqrt{(1 + \tau\ df)}$$

where τ is the integration time or the laser pulse duration respectively. Independent of its origin the noise power will be denoted by P_{noise}. The expectation value of the observed signal E(S) is proportional to the input power P_{in}. In fact, if the overall gain of the system is g

(2) $$E(S) = g\ P_{in},$$

and the signal-to-noise ratio of eq. (1) is simply the ratio of the expectation value to the standard deviation σ of the output signal

(3) $$E(S)/\sigma(S) = P_{in} / (P_{in} + P_{noise}) \sqrt{(1 + \tau\ df)}$$

Replacing E(S) in (3) by equation (2) we find for $\sigma(S)$

(4) $$\sigma(S) = g\ (P_{in} + P_{noise}) / \sqrt{(1 + \tau\ df)}$$

In the absence of an external signal, the result of data acquisitions during the integration time τ produce an output with an expectation value of E(N) = 0 and a standard deviation of

(5) $$\sigma(N) = g\ P_{noise} / \sqrt{(1 + \tau\ df)}$$

During a single shot measurement we obtain with our experimental set-up a sample value S for each channel, as well as a reasonable estimates of $\sigma(N)$ for each channel. The latter is obtained from a statistical analysis of 9 pre- and 9 post-acquisitions in the presence of the local oscillator, but without the scattered laser pulse. An estimation of (S/N) according to equation (1) or (3) is only obtainable if it can be expressed in terms of E(S) and $\sigma(N)$, since no information is available on the standard deviation of the signal $\sigma(S)$. In fact, E(S) is not obtained in a single shot either and must be replaced by the sample value S, a standard procedure if a value can only be determined by a single measurement. We obtain from equations 2, 3 and 5

(6) $$E(S)/\sigma(S)=[E(S)/\sigma(N)*\sqrt{(1+\tau\ df)}]/[E(S)/\sigma(N)+\sqrt{(1+\tau\ df)}]$$

For a channel width of 80 MHz and an integration time of τ = 1.4μs (equal to the laser pulse duration) $\sqrt{(1 + \tau\ df)}$ = 10.6. Fig 3 shows the signal-to-noise ratio as a function of the measured ratio of signal to the standard deviation of background.

At the highest densities (n_e = 1.2 $10^{20} m^{-3}$) ratios $E(S)/\sigma(N)$ of 25 to 30 have been achieved, corresponding to signal-to-noise ratios of 7 to 8. Equation (1) and Fig 3 show that for the given τ df, the maximum signal-to-noise ratio that can be obtained is 10.6. While a further increase of the detector sensitivity or laser power would still improve the signal-to-noise ratio, the slope of the curve in Fig 3 is already quite low at the current operating conditions and it could be more effective to increase the laser pulse duration, although S/N is only proportional to the square root of τ.

For plasma temperatures which are typical for TCA (T_e = 700eV, T_i = 400eV) and a range of densities we present in Fig. 4 the predicted accuracy of a T_i measurement obtained from a Monte Carlo simulation [6] and the ratio $E(S)/\sigma(N)$ for 3 representative channels (*). The fact that neither T_e, z_{eff}, B_F (the magnetic field) nor the plasma density are precisely known has been included (**). At the highest density an accuracy of 25% is achieved, less than 30% accuracy is still obtained at n_e = $6x10^{19} m^{-3}$ whereas below that density the signal-to-noise ratio precludes an interpretation of the measured spectra.

We have already discussed earlier [7] that our frequency channels are not optimally distributed with respect to the spectrum to be recorded. Fig 5 shows the results of simulations for a fixed number of 12 (*) channels, but arranged to cover different regions of the spectrum. The predicted accuracy is plotted as function of the lowest offset frequency (cutoff frequency). The accuracy can be improved by 50% by operating in the frequency range from 640 to 1520 MHz. Since this requires only a small modification of our detection system, the following simulation uses this more suitable frequency coverage.

Fig 6 shows the predicted precision of a T_i measurement resulting from a large number of simulations (over 300 per point). Curve 1 represents the current system using the adjusted frequency coverage. Some preliminary experiments indicate that it should be possible to increase at least the CO_2 pulse duration to about 5μs. However, two important points require further investigations: (1) It is not certain that the D_2O laser pulse will follow the pump laser pulse shape for such a long pulse. The well known bottleneck effect [8] might preclude this. (2) The laser power is probably reduced with increasing pulse duration. If the current laser power could be maintained, curve 2 shows the expected improvement of an ion temperature measurement. At the higher densities it is below 10%. If, however, longer pulses can only be achieved at reduced power, curve 3 indicates that the effort is completely wasted. We have assumed that the laser energy is constant, so that the 3.5 fold increase in pulse duration is only achieved by a corresponding decrease in average power. The real situation is probably somewhere between these extremes. Finally curve 4 shows that doubling the diode sensitivity (probably feasible with cooled mixer systems) is nearly as promising as longer pulses at constant power, and certainly easier to achieve.

MEASUREMENTS

So far we have analyzed collective scattering data from several hundred plasma discharges. The observed spectra could all be interpreted assuming thermal density fluctuations taking into account the influence of impurity ions and the magnetic field. There is no indication that non-thermal fluctuations contribute to the spectrum in the parameter range of interest (Δk = 230 cm^{-1}, $\Delta\omega > 3 \times 10^9$ s^{-1}).

Table I shows the results of 8 plasma shots with fairly reproducible plasma parameters. The diagnostic systems for n_e, T_e and the NPA were all operational. It is immediately obvious that while n_e, T_e and T_i^{NPA} (the ion temperature measured by the neutral particle analyser) are very similar, thus proving that the plasmas were indeed reproducible, T_i^{CT} (the ion temperature measured by collective Thomson scattering) shows large fluctuations. This indicates that the signal-to-noise ratio was not as good as was usually the case for this particular series.

For the centermost channel (400MHz from line center) we show in table I the ratio of the scattered signal S to the standard deviation of acquisitions in the absence of a signal $\sigma(N)$, as obtained from 18 acquisitions immediately before and after the laser pulse. Simulations for the corresponding experimental conditions indicate that this ratio has to be greater than 13 in order to achieve an accuracy of better than 30% in T_i. There is a reasonable correlation between the difference $\Delta T_i = T_i^{CT} - T_i^{NPA}$ and the ratio $S/\sigma(N)$.

The last column in table I shows the FIR laser energy in arbitrary units. In general, high accuracy is correlated with high laser pulse energy.

Based on the assumption that the plasma conditions for the 8 shots were reproducible, we averaged the measured signals in all channels. Fig 7 shows the resulting spectrum with the standard deviation from the averaging process. The spectrum is now quite smooth and can be fitted with a calculated spectrum based on the measured average plasma parameters (n_e = 1.2 x 10^{20} m^{-3}, T_e = 415 eV, z_{eff} = 2.5 (estimate)). The resulting ion temperature is 305 eV which is in excellent agreement with the average ion temperature measured by the NPA for these 8 shots: 310 eV.

In Fig 8 we present the results from an individual shot. The shaded area is $\sigma(N)$, the points are the measured signals and the curve is the fit with T_i = 280 eV. For the ratio of $S/\sigma(N) \approx 14$ at 400 MHz we expect an accuracy of ≈ 28% from simulation results. The deviation from T_i^{NPA} is less than this value.

DISCUSSION AND CONCLUSIONS

Collective Thomson scattering of far-infrared radiation is a powerful tool for the determination of T_i in a tokamak since the measurements provide excellent temporal and spatial resolution. In the parameter range investigated during our experiments on TCA we have never observed any contributions from non-thermal fluctuations to the spectrum.

A comparison with ion temperatures measured with the NPA showed very good agreement. In the temperature and density range studied, the NPA is expected to have an absolute accuracy of 5% on the density plateau. The NPA measures the ion temperature of the high energy tail of the Maxwellian velocity distribution which is mainly from the plasma core. The collective Thomson scattering system samples the bulk of the velocity distribution and was aligned to observe the plasma center as well. Its accuracy is density dependent and approaches 10% for densities around 10^{20} m^{-3}. Further improvements are still possible, e.g. by using cooled Schottky diodes.

FOOTNOTE

(*) Our detection system comprises 12 channels to cover the range of 280 to 1240 MHz offset from the laser line to higher frequencies. During the experiments reported here only 11 channels were used.

(**) In our numerical simulations the following uncertainties were assumed: 5% for n_e, 10% for T_e, 30% for the impurity concentrations, and 10% for the magnitude of the magnetic field.

TABLE I

The measured plasma parameters of 8 reproducible TCA plasma discharges

shot #	n_e ($*10^{19}$ m^{-3})	T_e (eV)	T_i^{NPA} (eV)	T_i^{CT} (eV)	$\lvert\Delta T_i\rvert/T_i^N$ (%)	$S/\sigma(N)$ (@400MHz)	E_L (AU)
37720	12.2	450	310	260	16	6	60
37721	11.7	450	320	290	9	9	80
37722	12.2	400	315	370	17	16	70
37725	12.2	450	310	220	29	13	85
37726	11.9	420	300	160	47	5	55
37727	11.9	450	310	280	10	9	90
37728	11.8	380	300	180	40	3	105
37730	11.3	330	330	300	9	14	105
average over series of shots	12	415	310	260	22	9	80
averaged spectrum	12.0	415	310	305			

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FIGURE CAPTIONS

FIG 1: Measured double sideband system noise temperature T_{sys}(DSB) as a function of the intermediate frequency, (A) for the mixer diode of ref [1] and (B) for the current diode

FIG 2: Dependence of T_{sys} on the local oscillator laser power

FIG 3: Signal-to-noise ratio (after integration) as a function of the ratio of the scattered signal S to the standard deviation of the receiver noise σ(N) for heterodyne detection with an integration time τ = 1.4μs and a channel bandwidth of df = 80MHz

FIG 4: Curve 1: the precision of a T_i measurement as function of plasma density for a 11 channel system covering the IF range from 400 to 1200 MHz, as obtained from simulation results (T_e = 700 eV, T_i = 400 eV). Curves 2 - 4: the ratio of E(S)/σ(N) for the frequency channels centered at 400, 800, 1200 MHz, resp.

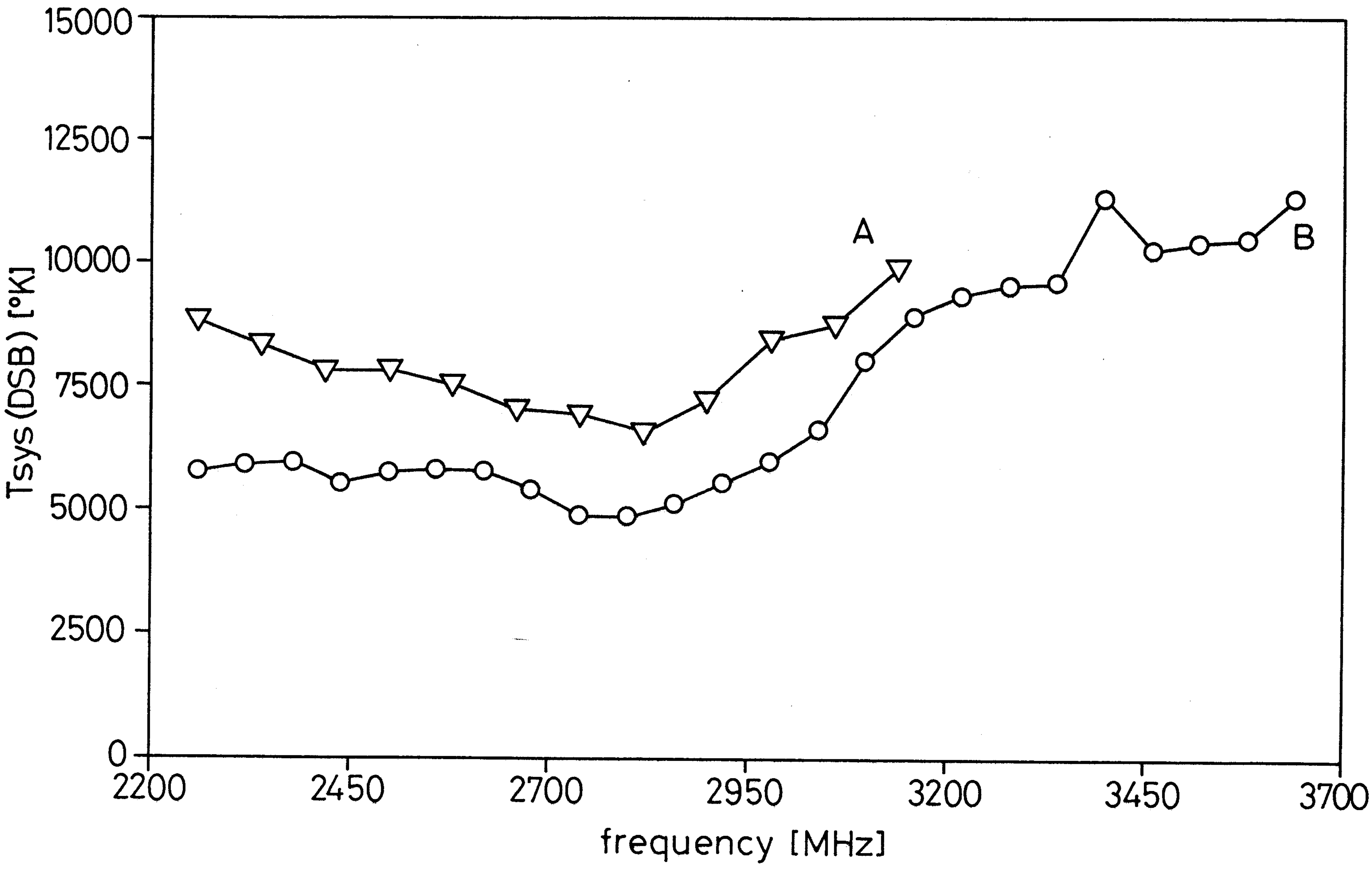
FIG 5: Predicted precision of a T_i measurement as a function of the lower cut-off frequency of the IF band. The spectral region covers a fixed total bandwidth of 12 x 80 MHz. The plasma parameters are: $n_e = 10^{20}$ m^{-3}, T_e = 700 eV, T_i = 400 eV.

FIG 6: The predicted precision of a T_i measurement as function of plasma density:

	laser power	pulse duration	detection sensitivity
curve 1	100kW	1.4μs	2 x 10^{-19} W/Hz
curve 2	100kW	5 μs	2 x 10^{-19} W/Hz
curve 3	28 kW	5 μs	2 x 10^{-19} W/Hz
curve 4	100kW	1.4μs	1 x 10^{-19} W/Hz

FIG 7: The average intensity and its standard deviation of 8 measured spectra obtained from reproducible plasma discharges. The plasma parameters are those given in table I. The solid line is a least square fit, yielding T_i = 305 eV.

FIG 8: Fit to a spectrum recorded in a single shot with time resolution of 1.4μs. The shaded region is σ(N) (see text). Measured plasma parameters: n_e = 7.2 x 10^{19} m^{-3}, T_e = 500 eV, T_i^{NPA} = 320 eV, z_{eff} = 2.5. The fit (solid line) yields T_i^{CT} = 280 eV.



15000
12500
10000
7500
5000
2500
0
Tsys (DSB) [°K]
2200
2450
2700
2950
3200
3450
3700
frequency [MHz]
A
B

Fig. 1

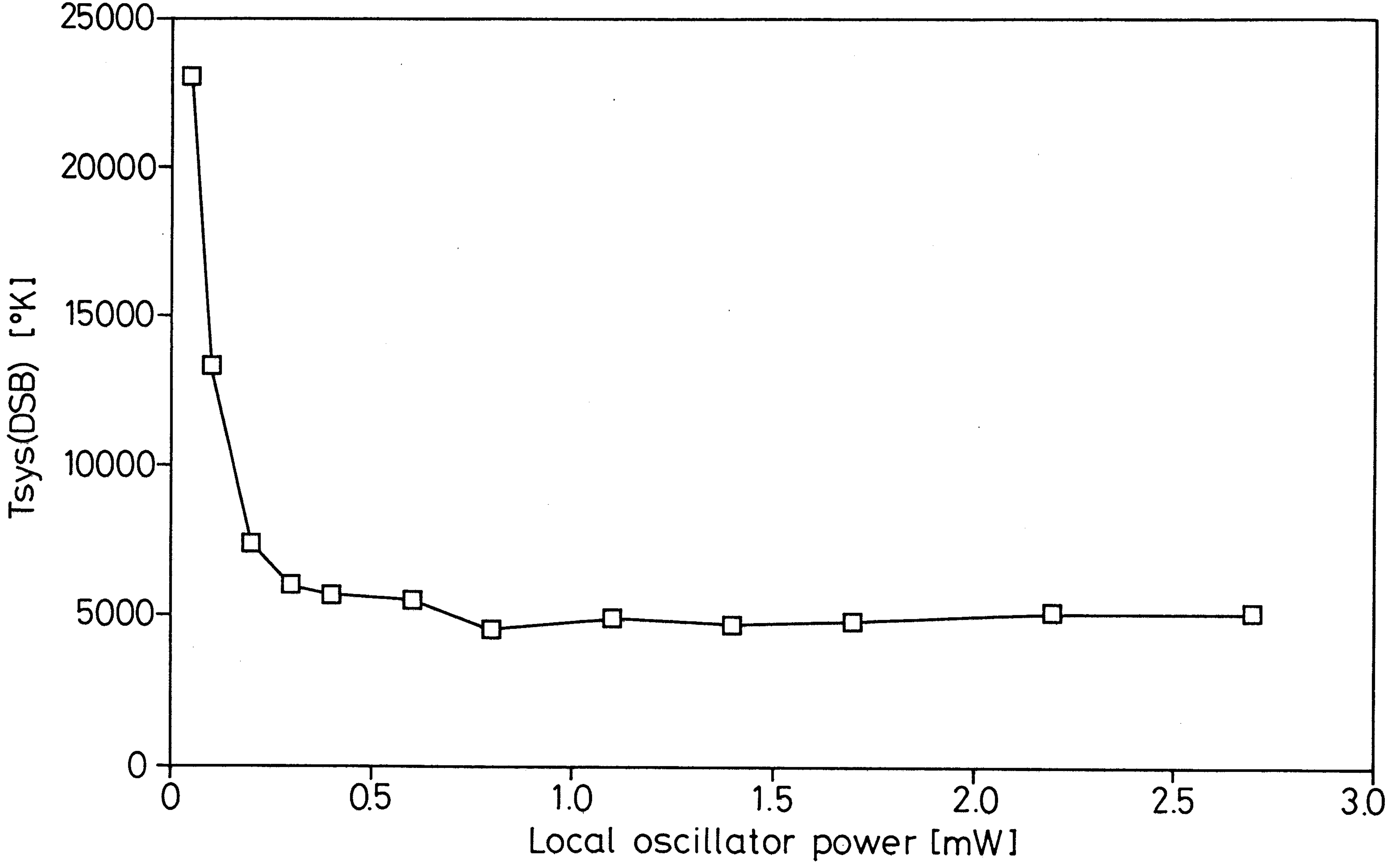
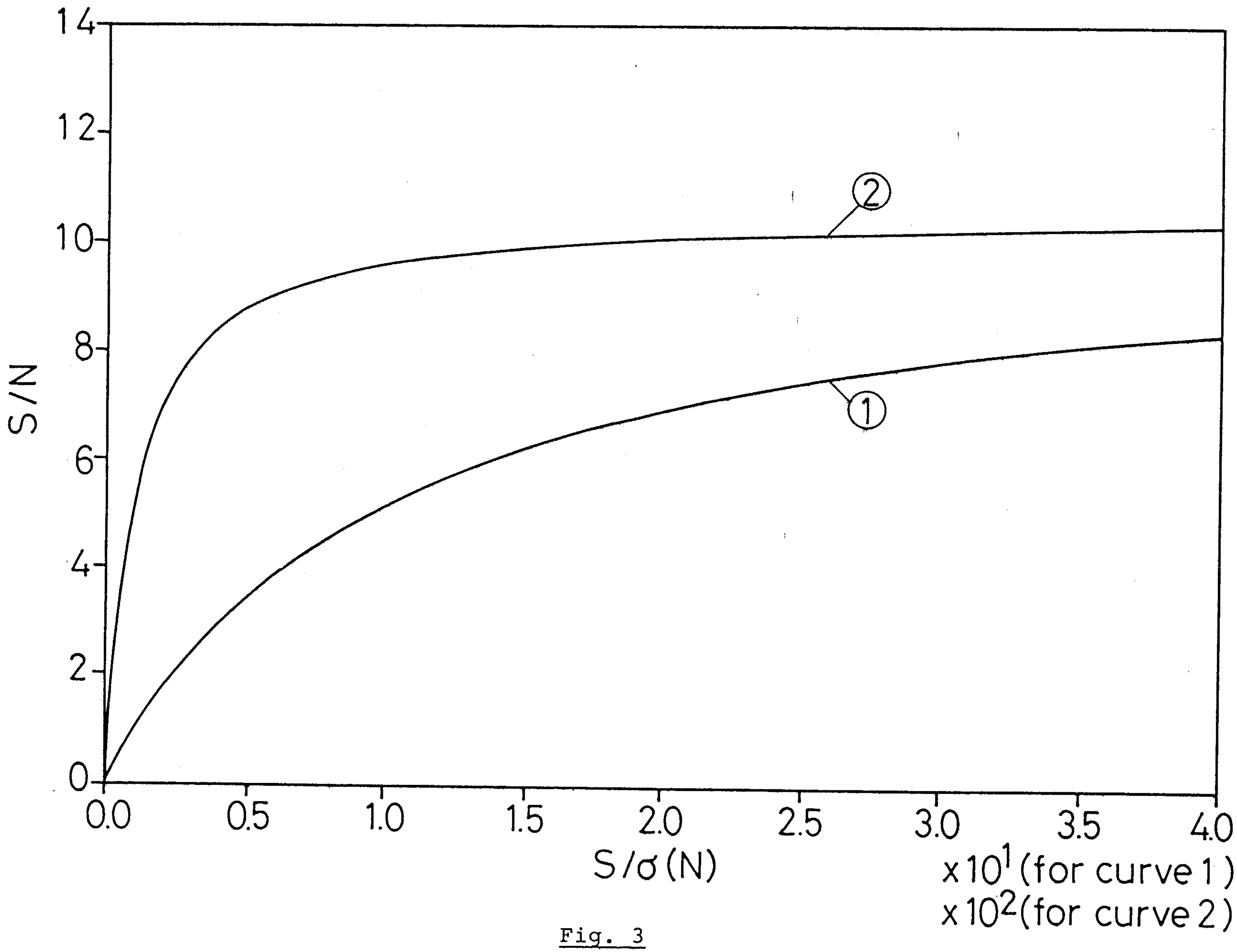
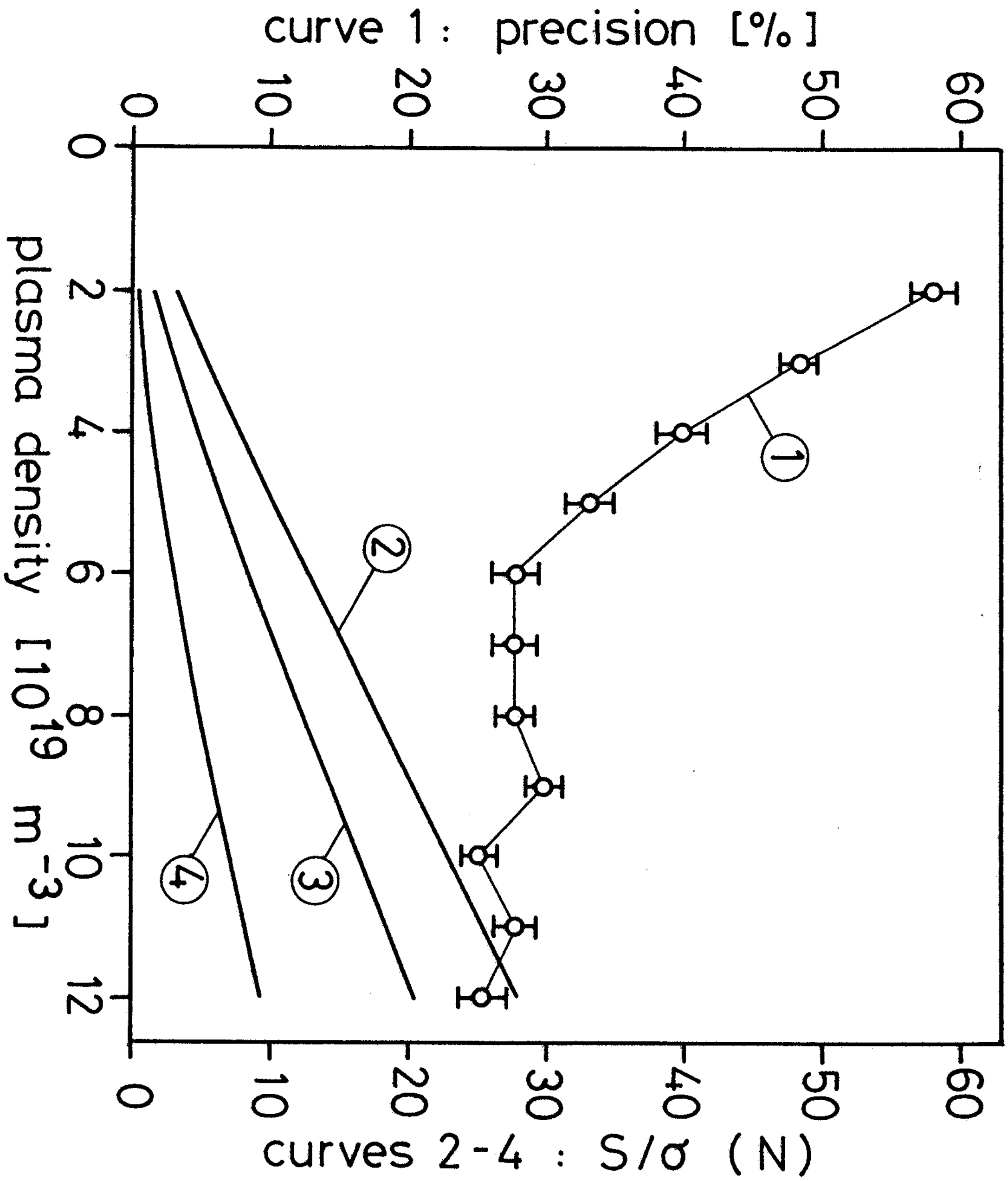

25000
20000
15000
10000
5000
0
Tsys(DSB) [°K]
0
0.5
1.0
1.5
2.0
2.5
3.0
Local oscillator power [mW]

Fig 2



14
12
10
8
6
4
2
0
S/N
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
S/σ(N)
x10¹(for curve 1)
x10²(for curve 2)
2
1

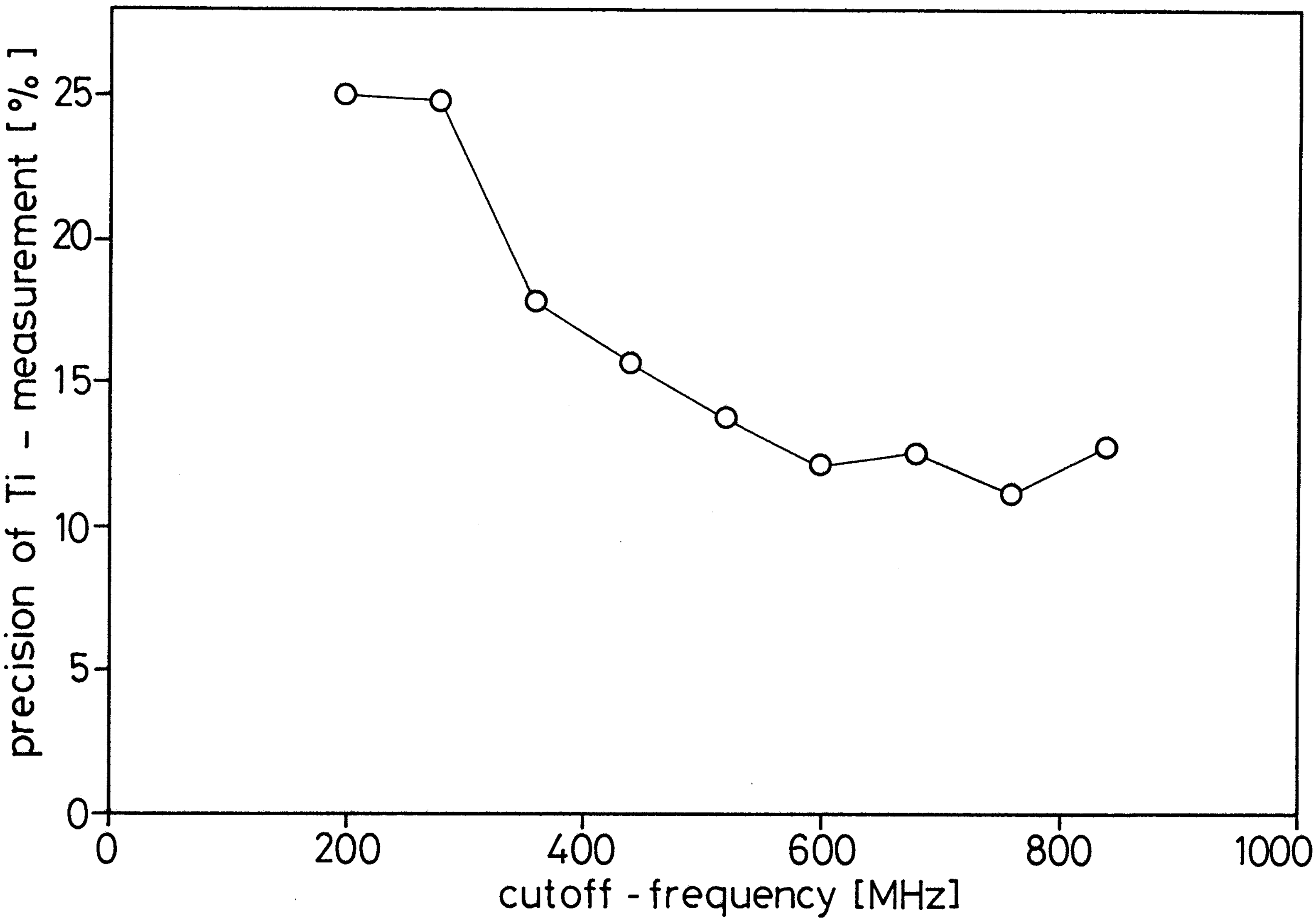
Fig. 3



curve 1: precision [%]
curves 2-4 : S/σ (N)
plasma density [10^19 m^-3]
0
10
20
30
40
50
60
0
2
4
6
8
10
12
1
2
3
4

Fig. 4

Fig. 5



precision of Ti - measurement [%]
25
20
15
10
5
0
0
200
400
600
800
1000
cutoff - frequency [MHz]

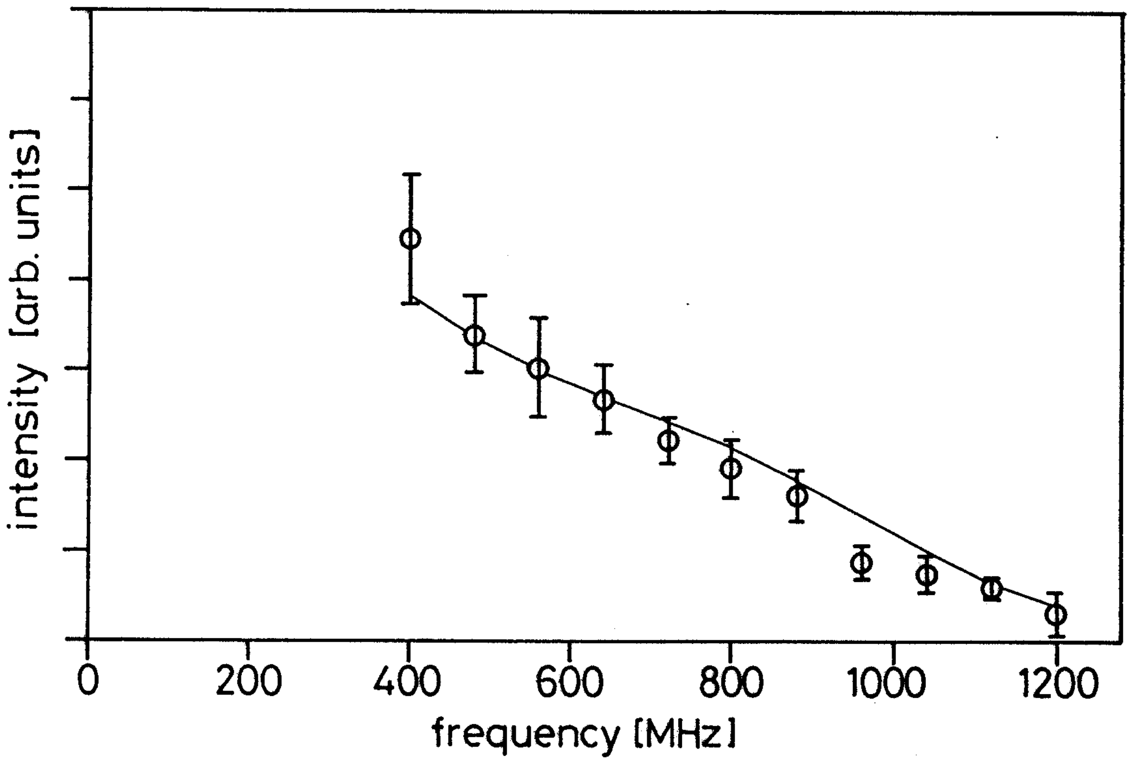

intensity [arb. units]
0
200
400
600
800
1000
1200
frequency [MHz]

Fig. 7

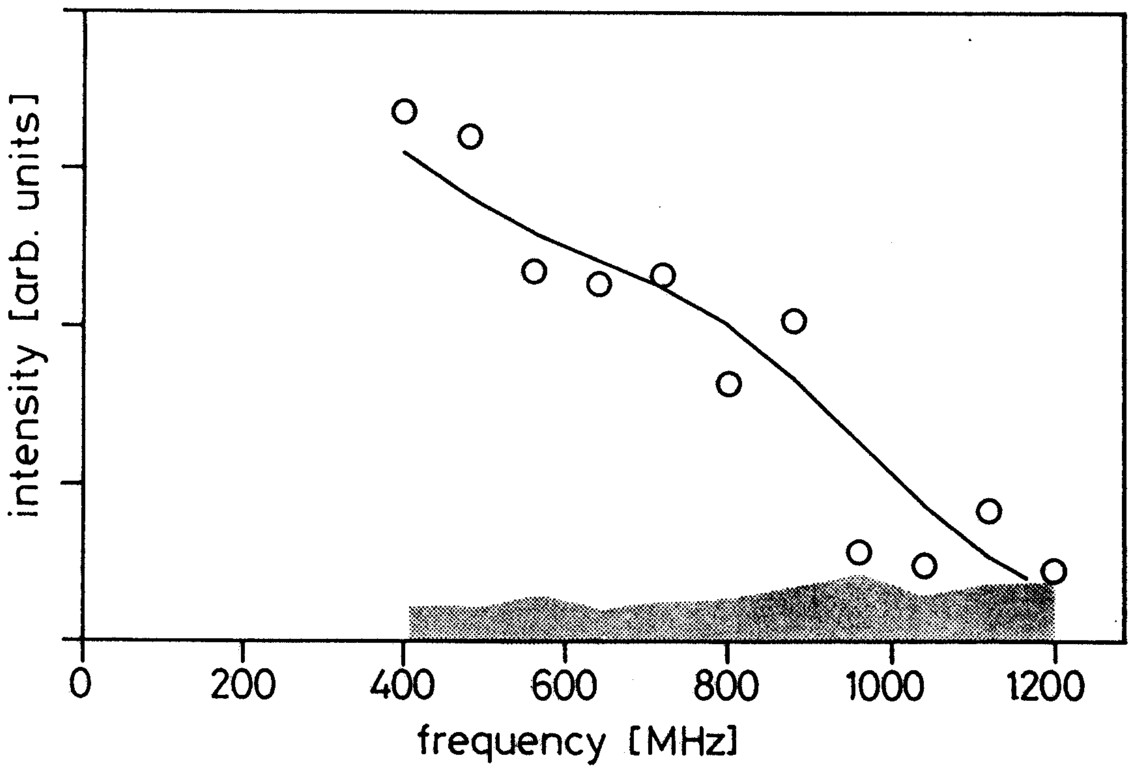

intensity [arb. units]
0
200
400
600
800
1000
1200
frequency [MHz]

Fig. 8