Relaxing Confinement Behaviour of Metal Limiter in High Density Tokamak Discharges

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract: Electron density fluctuations measured with $\lambda = 2$ mm waves radiating the plasma through several limiter chords of the Pulsator Tokamak have been correlated with sawtooth fluctuations of soft X-rays emitted along crossing chords. These studies and the similar sawtooth relaxation beaviour of other parameters during external disruption of off-centered discharges reveal that the observed fluctuations arise from relaxing plasma-limiter interactions, i.e. they are not caused by kink--mode oscillations as previously reported.

Fluctuations in soft X-ray intensity first observed in the ST Tokamak show characteristic sawtooth behaviour. This beaviour has been identified as an internal disruption /1/. Each internal disruption is preceded by growing sinusoidal oscillations which have been identified as kink-mode instabilities m=1, n=1 and/or m=2, n=1 and are believed to be the probably cause of the disruption /1/,/2/,/3/,/4/.
However, the lack of correlating data, such as soft X-ray intensity fluctuations from crossed limiter chords, time evolution of the plasma density and of the temperature distribution during the relaxation processes and the similar, hithertho not well understood, relaxation processes of the external current disruptions has not allowed a clear statement to be given about the origin of these phenomena.

In the following, electron density fluctuation measurements along several limiter chords crossing at 90° the line integrated emission chords of the soft X-rays yielded the first surprising result that the core of the so-called "internal" disruptions is shifted topologically towards the outer limiter.

Other surprising results (in open discrepancy to the well - established interpretation /1/,/2/,/3/,/4/, of sawtooth and sinusoidal oscillations of soft X-ray data) are obtained by a correlation study of these data with the fluctuations of i) discharge current, ii) electron density, iii) loop voltage and position current signals during "external" disruption of off-centered discharges.

Instead of "kink mode" instabilities generating "internal"

disruption, the observed relaxation processes can be related to a scraping of the limiter by the plasma as a naturally confining process for both low and high-density discharges.

Each time the limiter is scraped a short sputtering pulse of impurity gas diffuses, sharply decreasing in amplitude, from the plasma boundary towards the centre of the discharge.

Each impurity pulse rapidly cools the plasma, the electron temperature slowly recovering until the next impurity pulse cools it again, thus generating the observed sawtooth-like fluctuations of the line integrated soft X-ray emission.

As will be seen, this finding is supported by the inverse sawtooth-like oscillations of both soft X-ray and $\lambda = 2$ mm wave fluctuations and by the electron density and temperature profiles.

Figure 1 shows schematically the seven $\lambda = 2$ mm vertical channels /6/ crossing the nine soft X-ray channels /7/ of the Pulsator Tokamak.

Figure 2(a) and (b) shows the time evolutions of, respectively, the Abel inverted density distribution measured with $\lambda = 2$ mm waves /6/ and of the electron temperature profile as derived from Thomson scattering of laser light /4/, for a typical set of high-density discharge parameters, i.e. $B_\varphi = 27$ kG, $q(a_L) = 3.5$, $I = 65$ kA.

Note in Fig. 2(a) the initial off-centered growth of the density after the pulsed gas inlet at t=40 ms and the step density profile of the discharge near the outer limiter edge for t>70 ms.

The cooling of the plasma boundary by the pulsed gas inflow

in the initial stage of the high-density discharge is also evident from Fig. 2(b). /4/

Starting from t = 70 ms sawtooth-like density variations of increasing period and amplitude, as shown in Fig. 3(a), are observed for the central millimetre wave channels 5, 4 and 3 (see Fig. 1).

In going from the outer channel 5 towards the internal channels, the density fluctuation amplitude decreases, being almost zero for channel 3.

For t > 70 ms the density of the outermost channels 1, 2 and 6, 7 (see Fig. 1), cannot be measured owing to the refraction losses of the $\lambda = 2$ mm waves /5/.

However, for the relatively low value of the density at the beginning of the high-density discharge, 40 ms < t < 60 ms, it is possible to observe, under particular discharge conditions, the variation of the density of the outermost channel 7, as shown in Fig. 3(a).

The increasing density of this channel shows alternately a rapid and a slow increment.

Figure 3(b) shows the density fluctuations of the three channels obtained by subtracting the almost linear density increase from the total density variations of Fig. 3(a).

From Fig. 3(b) we see that the density fluctuations of the vertical outer channels of the $\lambda = 2$ mm interferometer, have an "inverted" sawtooth shape very similar to that of the horizontal outer soft X-ray channels as reported in Ref. /1/, /2/, /4/ and /7/ and as shown for convenience in Fig. 3(c) for the X-ray channels 4 and 7 of Fig. 1. /7/.

For the central millimetre wave channels 4 and 5, the relatively low value ΔN_e of the density sawtooth fluctuations, $\Delta N_e/N_e < 5\%$, added to the steeply increasing density gives the observed sawtooth-like phase-shift variation of the $\lambda = 2$ mm wave shown in Fig. 1(b) for the channel 4.

Figure 4 shows that the region II of the sawtooth-like fluctuations, as measured with the $\lambda = 2$ mm beams crossing the emission chords of the available soft X-ray data, is shifted towards the outer limiter wall.

Region I is that corresponding to the "inverted" sawtooth fluctuations, which are also observed for the innermost $\lambda = 2$ mm channel 1. However at the beginning of the pulsed high density discharge the amplitude of this "inverted" sawtooth is too small to excite sawtooth fluctuations for the inner channels.

Considering the density profile of Fig. 2(a) for $t > 70$ ms, it looks as if the source of the fluctuations is localized at the outer limiter edge whereby the density fluctuations, which surround the core of the discharge, sharply decrease in amplitude towards the torus axis.

To understand the "inverted" sawtooth shape of the soft X-rays , it should be recalled that the silicon surface-barrier detectors are sensitive to X-ray fluctuations which are caused by fluctuations of electron density, electron temperature and impurity concentration.

Considering the low temperature contribution of the plasma surrounding the core of the discharge, the fluctuations of the soft X-rays emitted from region I of Fig. 4 must be mainly due to fluctuations of density.

The following observations indicate that the "inverted" sawtooth fluctuations of region I for both $\lambda = 2$ mm waves and soft X-rays are actually due to impurities which are sputtered-off periodically by a relaxing interaction of the discharge current with the metal limiter or liner walls.

Figure 1(c) shows the "inverted" sawtooth shape of large density pulses measured in conditions of low refraction losses, i. e. at densities $\bar{N}_e \approx 3 \times 10^{13} cm^{-3}$, by means of $\lambda = 2$ mm channel 8 (not shown in Fig. 1) positioned only <u>one</u> cm from the outer edge of an r= 12 cm limiter.

Similar pulses of somewhat lower amplitude were measured with the innermost channel 1 during "external" current disruption of off-centered discharges. The amplitudes of these pulses at the plasma boundary can amount to 30 % of the total density of the central channel but only a few per cent of this reaches the discharge axis with pulse shaping similar to that shown in Fig. 3(b). This first detailed study of density pulses from the plasma boundary to the discharge axis is well related to the observed impurity evolution in several Tokamak discharges /8/, /9/. As will be seen in the following, this finding is also supported by the relaxations of i) electron density, ii) soft X-ray intensity, iii) loop voltage and iv) intensity and position of the discharge current during disruption of high-density discharges.

A correlation of this quantities in a single shot is shown in Fig. 5, where a rare combination of three alternate relaxation processes clearly illustrate these phenomena.

In Fig. 5 each of the several strong relaxations which are

characteristic of external disruptions is followed by several weaker relaxations, all involving the above listed plasma quantities.

The difference between these two relaxations during current disruption and the "internal" one before the onset of disruption, studied before, is that the latter is too weak to cause observable relaxations of the current intensity and position and of the loop voltage.

We are also confronted with three similar relaxation processes differing in amplitude only.

Note in Fig. 5 that the characteristic decrease of the sawtooth period shortly before a large disruption also applies, on enlarged scale, to this strong plasma-wall interactions. Bearing in mind all the previously reported relaxation properties of the electron density and X-ray fluctuations along the various limiter chords, especially the density pulse near the limiter walls shown in Fig. 1(c) and 3(b), one can deduce from Fig. 5 that each disruption is caused by a pulsed sputtering of impurities from the discharge walls; i.e. limiter or liner. These impurities change the current distribution/10/, thus causing all the observable relaxation processes shown in Fig. 5. Going back to Fig. 3(c), one can now explain the sawtooth behaviour of the observed soft X-ray emissions of the central limiter chords: the impurity pulses of region I shown in Fig. 3(b) for the $\lambda = 2$ mm waves and in Fig. 3(c) for channels 4, 7, of the soft X-rays periodically cool the central region of the plasma, the temperature recovering after further ionization and heating of the incoming pulse of impu-

rities.

With regard to the sharp density profile towards the outer limiter wall shown in Fig. 2(a) for $t > 70$ ms, one can now understand the increasing amplitude and period of the sawtooth relaxations of Fig. 3: the increasing off-centered growth of the density interacts with the outer limiter edge, thus generating sputtering impurity pulses of increasing amplitude until the first of the strong interactions shown in Fig. 5 involving all other discharge parameters occurs.

The process is repeated again till extinction of the accumulated energy in the plasma.

Regarding the observed $m = 1$, $n = 1$ and/or $m = 2$, $n = 1$ X-ray oscillations of growing amplitude /1/, /2/, /7/ it must be added that they are also seen in the electron density relaxation processes. However, they exibit spurious density fluctuations which, observed in an enlarged time scale, seem characteristic of finely structured impurity sputtering from the walls at the fast rise or drop of the sawtooth density fluctuation.

A detailed description of the $\lambda = 2$ mm wave measurement of these oscillations will be treated elsewhere since it would exceed the scope of this report.

In conclusion, the extensive new data reported in this work on sawtooth oscillations of electron density measured with $\lambda = 2$ mm waves indicate that the observed sawtooth oscillations of soft X-rays may be excited by impurity influxes originated by the interactions of the plasma with the confining metal limiter or liner walls.

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Figure captions.

Fig. 1. Experimental arrangement of the $\lambda = 2$ mm wave channels of the Pulsator Tokamak. The density sawtooth oscillations (b) for the central channel 4 and the "inverted" sawtooth oscillation (c) for an outermost channel at $r = 11$ cm are from different shots, the latter being made at low density discharge in order to avoid the refraction losses of the outermost $\lambda = 2$ mm wave beam.

Fig. 2. Radial profile of (a) electron density from $\lambda = 2$ mm waves, Abel-inverted, and of (b) electron temperature from laser data of Ref. 4.

Fig. 3. Sawtooth fluctuations of (a,b) electron density from vertical $\lambda = 2$ mm wave channels and of (c) soft X-ray line integrated emission along horizontal limiter chords.

Fig. 4. Regions of (I) "inverted" sawtooth and of (II) sawtooth fluctuations of soft X-ray intensity and $\lambda = 2$ mm phase-shift fluctuations.

Fig. 5. Sawtooth relaxation processes involving several discharge parameters. Up to 77 ms the relaxation is only observable with the $\lambda = 2$ mm waves and with soft X-rays. The current disruption beginning at 77 ms exibit alternate relaxations of different amplitude.

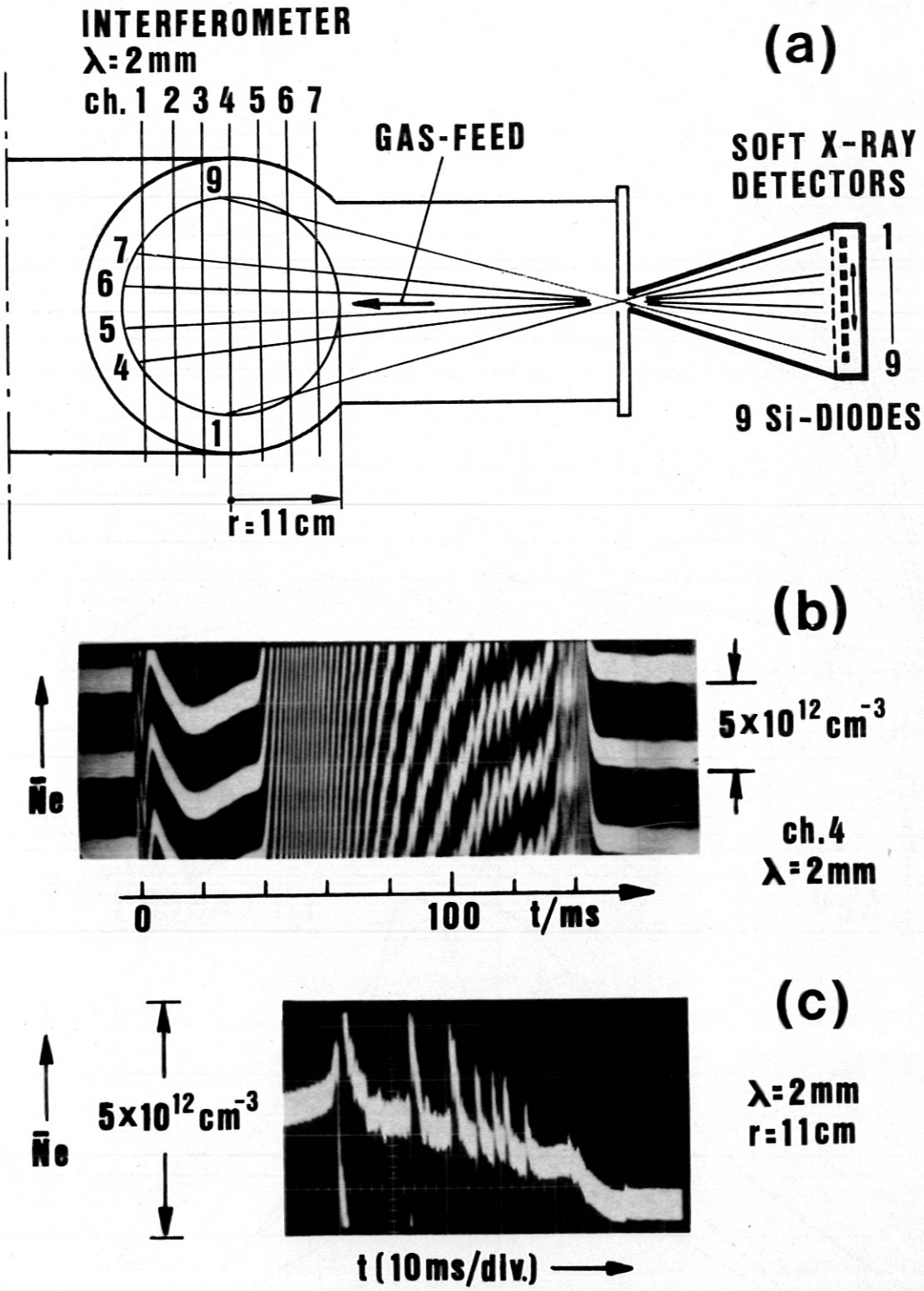
INTERFEROMETER
λ=2mm
ch. 1 2 3 4 5 6 7
GAS-FEED
(a)
SOFT X-RAY
DETECTORS
9
7
6
5
4
1
1
9
9 Si-DIODES
r=11cm
(b)
Ñe
5×10^12 cm^-3
ch.4
λ=2mm
0
100
t/ms
(c)
Ñe
5×10^12 cm^-3
λ=2mm
r=11cm
t(10ms/div.)

Fig. 1

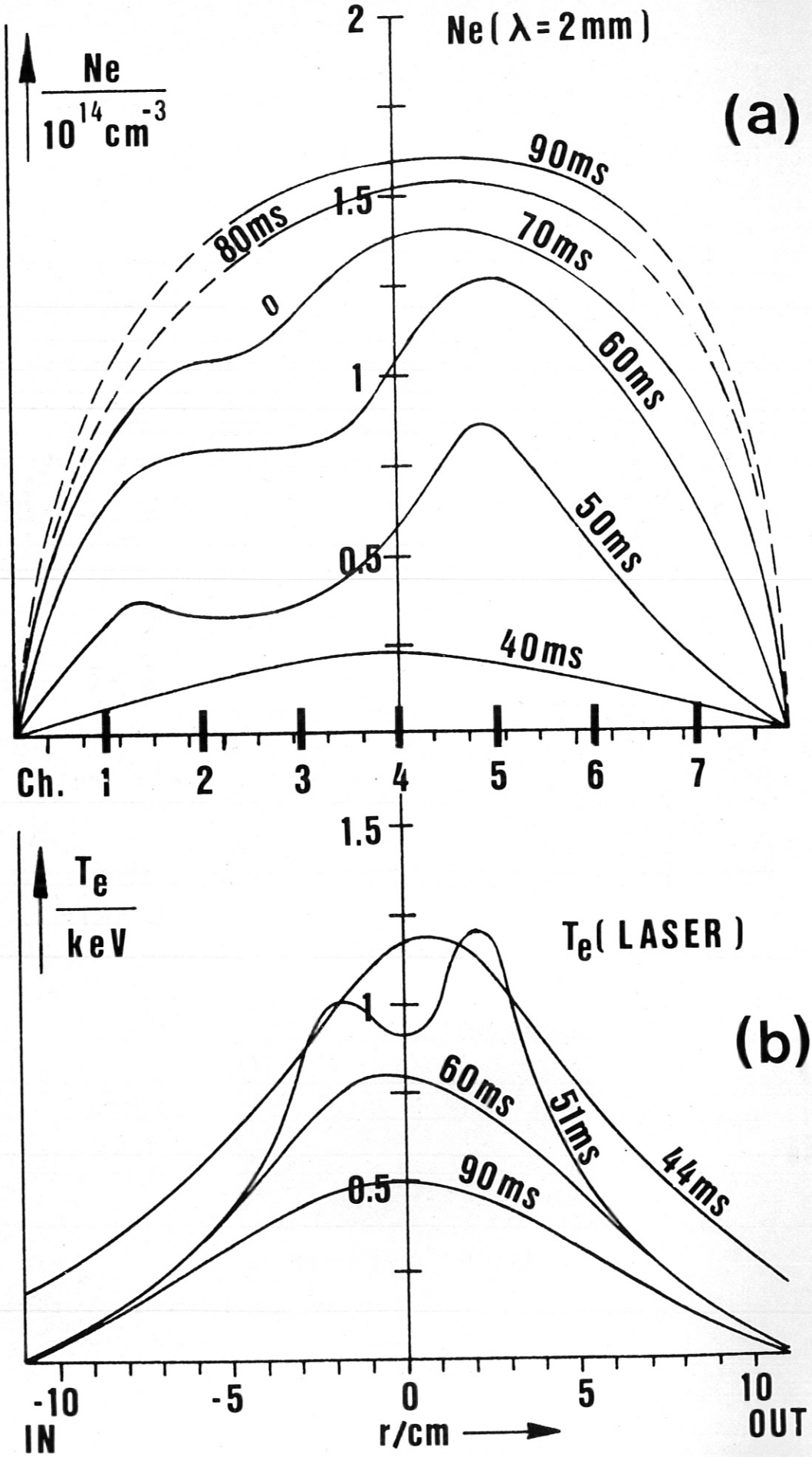
Ne
10^14 cm^-3
Ne (λ = 2mm)
(a)
2
1.5
1
0.5
90ms
80ms
70ms
60ms
50ms
40ms
0
Ch. 1 2 3 4 5 6 7
Te
keV
Te (LASER)
(b)
1.5
1
0.5
60ms
51ms
44ms
90ms
-10 -5 0 5 10
IN
r/cm
OUT

Fig. 2

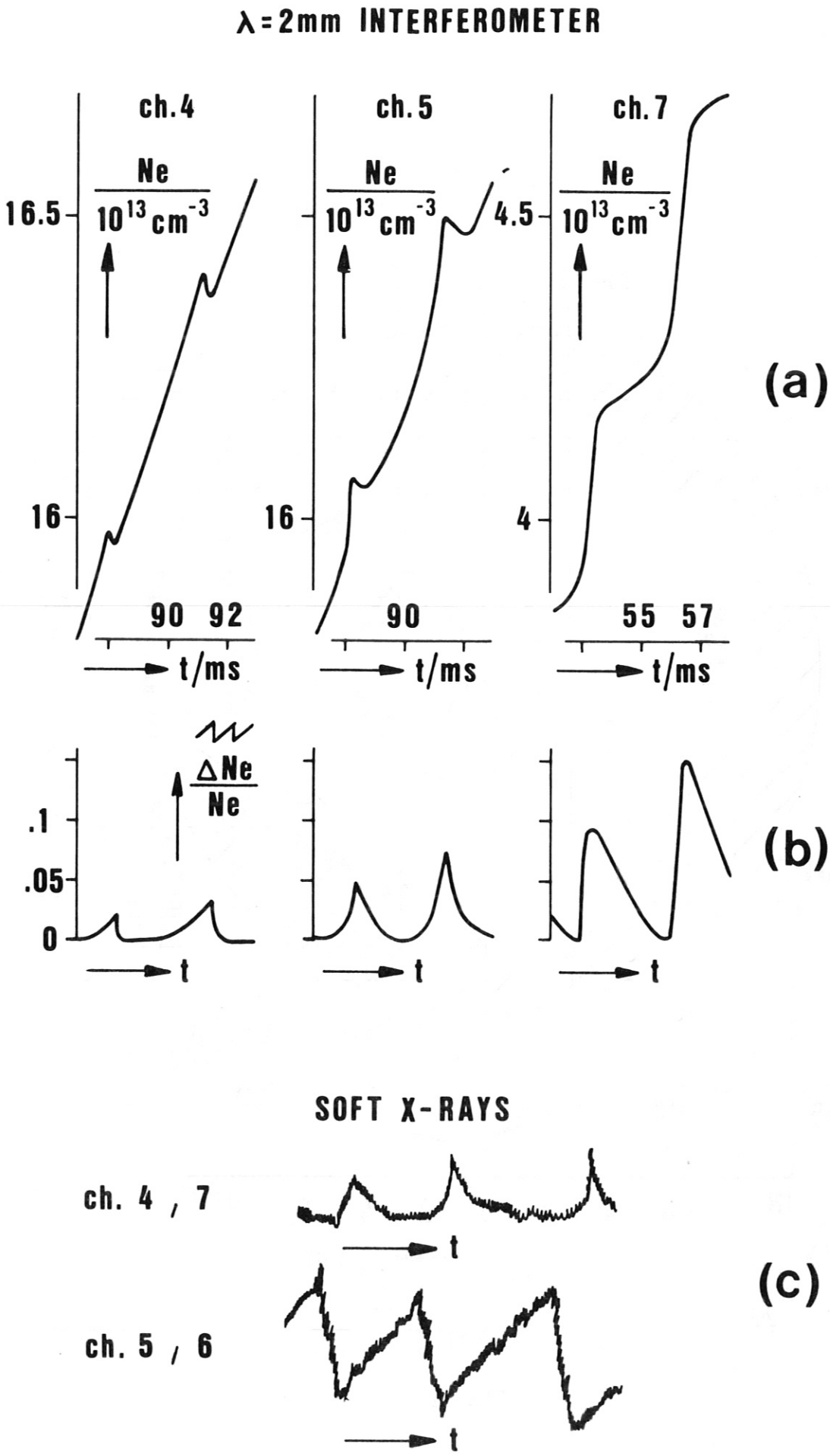
λ = 2mm INTERFEROMETER
ch.4
ch.5
ch.7
Ne / 10^13 cm^-3
16.5
16
4.5
4
90 92
90
55 57
t/ms
(a)
ΔNe / Ne
.1
.05
0
t
(b)
SOFT X-RAYS
ch. 4 , 7
ch. 5 , 6
t
(c)

Fig. 3

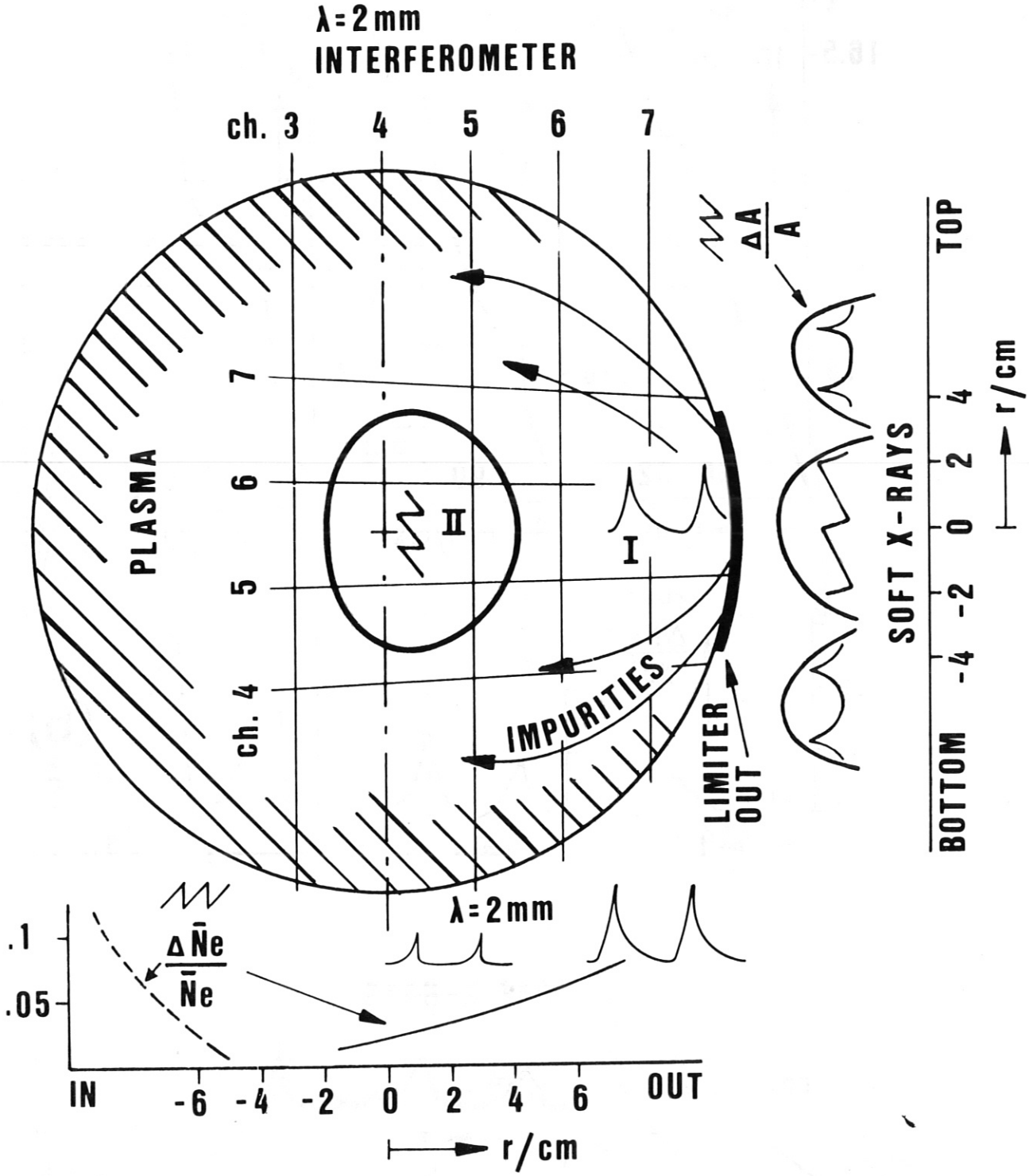
λ = 2 mm
INTERFEROMETER
ch. 3
4
5
6
7
PLASMA
II
I
IMPURITIES
LIMITER
OUT
ΔA/A
SOFT X-RAYS
TOP
BOTTOM
r/cm
λ = 2 mm
.1
.05
ΔNe/Ne
IN
-6
-4
-2
0
2
4
6
OUT
r/cm

Fig. 4

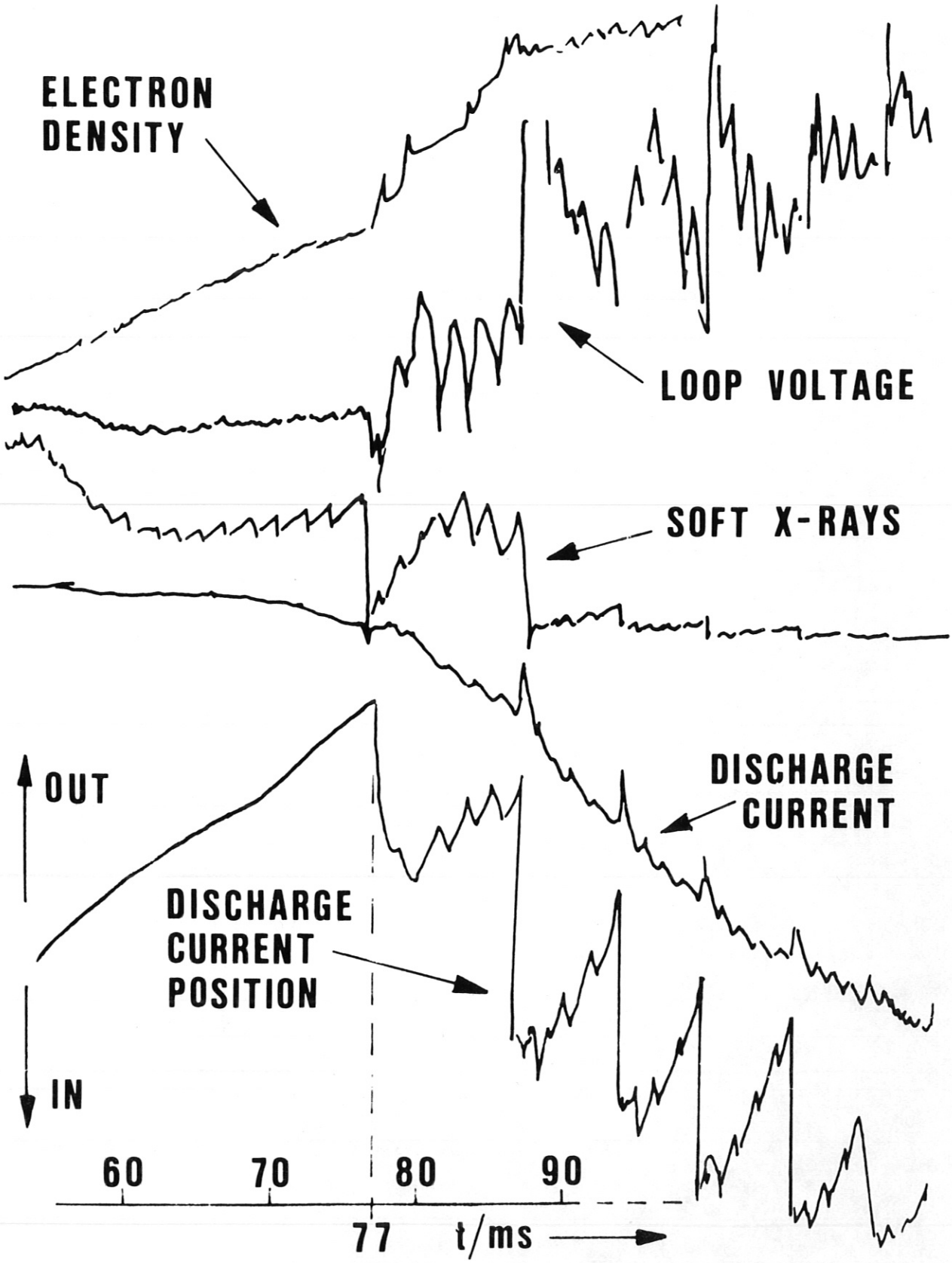
ELECTRON
DENSITY
LOOP VOLTAGE
SOFT X-RAYS
DISCHARGE
CURRENT
OUT
IN
DISCHARGE
CURRENT
POSITION
60
70
80
90
77
t/ms

Fig. 5