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Photodiode measurements in Nucte-II

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Abstract Direct measurements of light emission from plasma produced by a field reversed theta-pinch NUCTE-II have been performed by using a set of photodiode detectors. The analysis shows that the plasma light emission can be related to the bremsstrahlung radiation and it is used to identify n = 2 rotational instability parameters as rotation direction, angular velocity, and radia! and axial displacement of the plasma column. A rough estimate for the temporal behaviour of the electron temperature has also been obtained by using the photodiode signal together with He-Ne laser interferometer and flux excluded signals.

1. Introduction

Theta-pinch machines have been operating in many places for some decades. A particular version of this machine, namely the field reversed configuration (FRC) type, is currently the preferred one and several advances have been reported in recent years[1,2,3]. This configuration produces compact toroidal plasmas with very large aspect ratio and small or zero toroidal magnetic field, which usually display an n = 2 rotational instability during the first 30μs of their equilibrium phase[3,4].

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This instability deforms the plasma column elliptically until it reaches the wall of the discharge tube and destroys the plasma confinement. Although instability suppression techniques for this n = 2 instability have already been succesfully used, it still is the subject of continuing investigation as its origins are not yet fully understood[3,4,5].

This instability can be monitored in many ways, such as laser interferometry and light emission analysis with a spectrometer or with photodiode arrays[6]. Among these, photodiode arrays are the cheapest and the most straightforward diagnostic tool.

In this paper we present the results of photodiode array measurements taken in NUCTE-II[7]. This diagnostic technique can measure precisely the continuum light emission from the plasma and indicates clearly when deformation of the column due to the n = 2 instability begins, as the light emission is modulated by the deformation. Furthermore, when coupled with interferometric and external niagnetic probe data, this technique ailows the electron temperature to be estimated. Also the rotational velocity and the approximate radial and axial size of the plasma column can be inferred from these measurements.

This technique can be further used in other machines, as in USP's small tokamak TBR-I[8], where the bremsstrahlung radiation is confirmed by X-ray diagnostics and the plasma body is dominated by mode oscillations[9].

NUCTE-II produces a FRC plasma via a theta-pinch discharge with reversed bias in which a small toroidal field is generated by an internal axial current discharge. A schematic drawing of the machine is shown in fig.1. The full length and inner diameter of the solenoid coil are 170 cm and i6 cm respectively. The vacuum vessel is made of quarts and is evacuated to a base pressure of 2 to 4×10^{-7} Torr by a turbomolecular pump. Deuterium gas is used at 12 mTorr in a 14 cm discharge tube. NUCTE-II has a 24 kJ slow bank and a 54 kJ fast bank for the main compression field. The plasma is preheated with an oscillating discharge of axial current I_{z1} of 35 kA peak value as shown in fig. 2. When the negative bias field reaches a value of - 630 G the main compression is fired with.rise time, peak field value, and e-folding time of 2μs, 12 kG, and 65μs, respectively. A second discharge

of the internally applied axial current, I_{z2}, is used to study the enhancement of the trapped flux and the effects of a weak toroidal field on the equilibrium phase. Further details on the parameters and the operation of the machine are presented elsewhere[7].

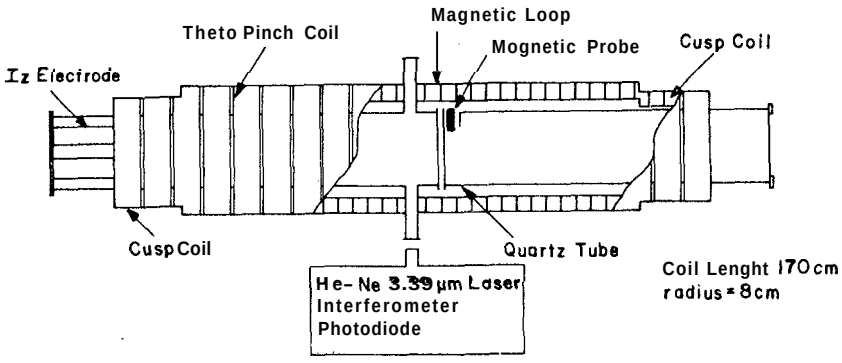

Fig.1 - Experimental apparatus of NUCTE-II.

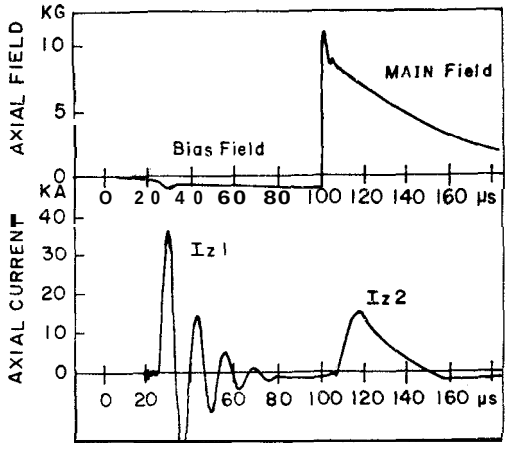

Fig.2 - Time sequence of axial field and current.

2. Experimental results

In this section we analyse the data obtained with a photodiode array in the visible region. The n = 2 instability is clearly seen and comparison with other disgnostics. He-Ne laser interferometry and excluded flux probes, shows that this technique is a good, reliable, routine diagnostic tool, easy to install and to operate. Fig.3 shows the photodiode set up together with a typical discharge signal, where the n = 2 instability appears clearly 25μs into the equilibrium phase. All the photodiodes used in the array are from EG & G, type **SGD - 100 A.**

The light emitted from the plasma and captured by the photodiode array can be thought of as originating from two regions: **(1)** from the whole plasma body along the radial line of sight, or **(2)** from a thin layer on the surface of the plasma column. With the assumption that all elementary plasma volume are light emitters of equal intensity, these two hypotheses can be distinguished by an analysis of the length of the region (ta) which emits the light captured by the photodiodes. Also, assuming the plasma to be a rotating elliptical rigid body, as in the n = 2 instability phase, with an eccentricity $E = b/a$ and equivalent area radius r, $= (a/b)^{1/2}$, the variation of the emission length ta as a function of the rotating angle θ can be plotted as shown in fig. 4. The continuous line represents the case of light emitted from the whole plasma volume, and the dotted line the case of emission from a thin external layer of thickness H = 0.2.

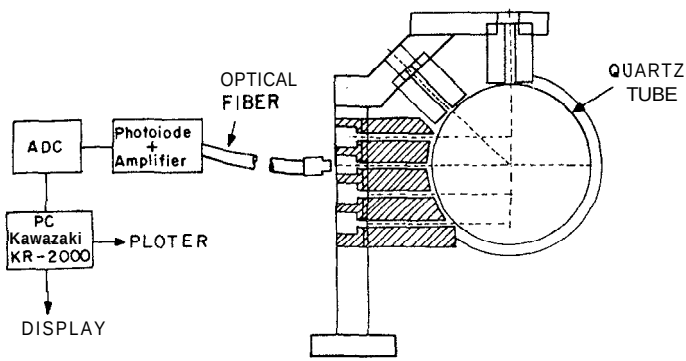

Fig.3.A - Photodiode sensor setup and collection system.

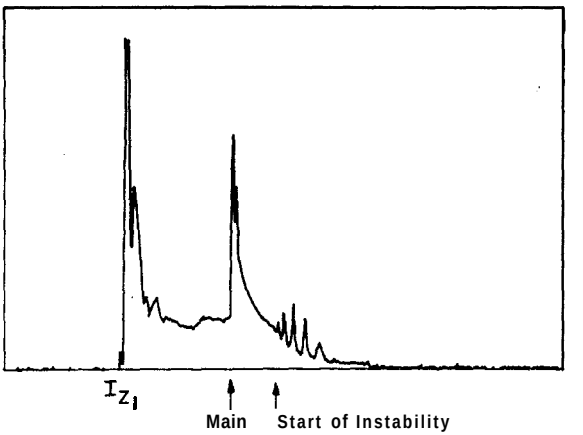

Fig.3.B - Typical photodiode signal with N = 2 instability (full scale 400 μs).

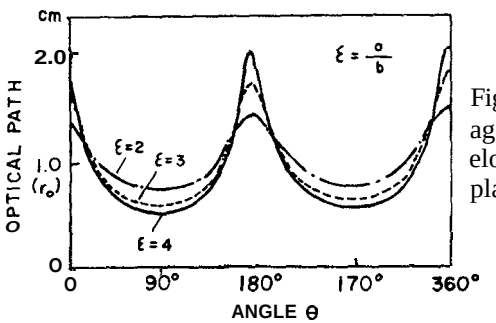

Fig.4.A - Variation of optical path against θ of rotating ridig body with elongation $\epsilon = a/b$ for line integrated plasma.

Comparison of this figure with the experimental photodiode signals in the instability interval, as in fig. 5, leads to the conclusion that the light captured by the photodiode comes from the whole plasma body and not from a thin surface layer. (The experimental data do not have the dip at the peak of the curve and the upper and lower peaks of instability are very similar to theoretical results). Note that the growth of the instability was ignored in our analysis for the sake of simplicity. Therefore we can associate the photodiode signals with an elliptically deformed plasma column of major and minor axis a and b.

The separatrix radius r, can be determined as a function of time, while the instability is present, by taking the r_s as $r_s = (ab)^{1/2}$ and a (and b) are read from

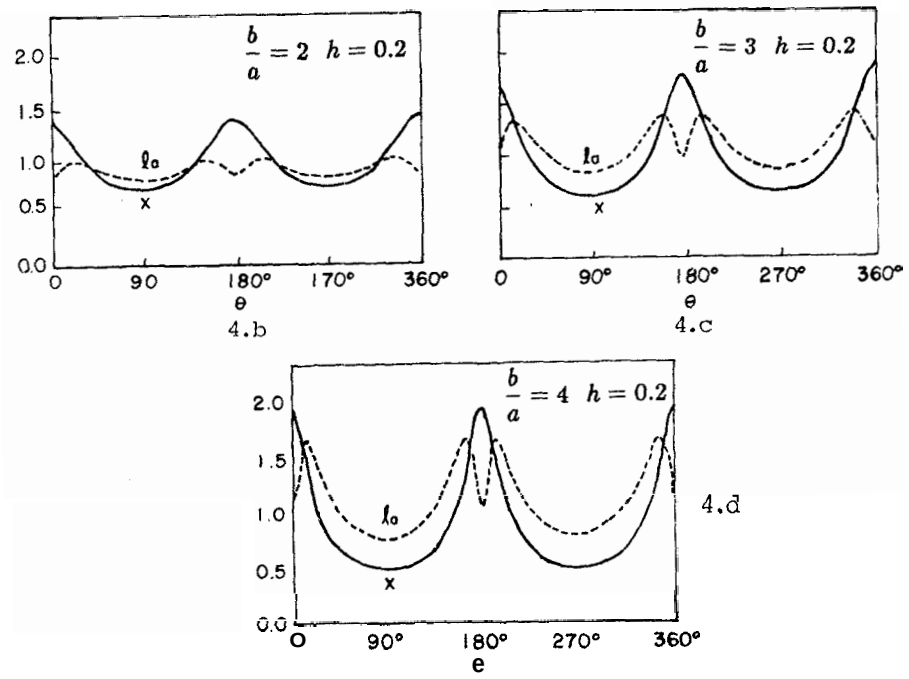

Fig.4.B, C, D - Variation of optical path against 0 of rotating rigid body for surface emission with different elongation.

the upper (and lower) intensity values taken from the photodiode signal. The equivalent r, value is also plotted in the fig. 5. Furthermore a comparison can be made with the data from a He-Ne 3.39μm laser interferometer. Since both diagnostics represent line integrated signals, they should represent the same kind of behavior, and this is indeed seen in fig. 6. The 180^0 phase difference seen there is due to the 90^0 difference in the radial position of each detector.

The light detected by the photodiode can be thought of as continuum light emission by bremsstrahlung radiation, which in the semiclassical treatment is given by[10]

$$W(P)d\nu \simeq 6.3\,10^{-53} Z^2 \left(\frac{1}{T_e}\right)^{1/2} n_e n_i \exp\left(-\frac{h\nu}{T_e}\right) d\nu (W/m^3) \qquad (1)$$

where the term on the left is the power radiated per unit volume of plasma between the frequencies Y and $\nu + \mathrm{dv}$, and T_e is given in eV. For the case of $n_e \cong n_i, Z_i = 1$

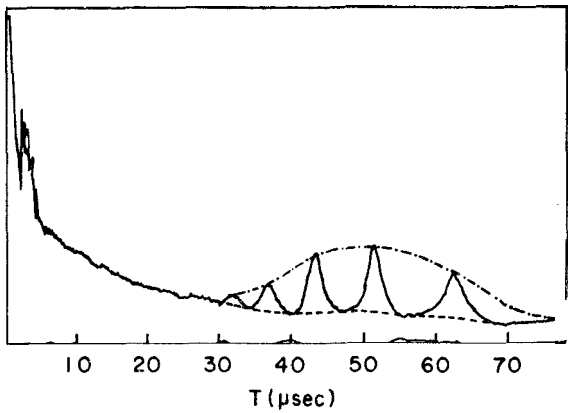

Fig.5.A - Typical photodiode signal with plotting of enveloped upper and lower curves, (T=0 for main bank start time).

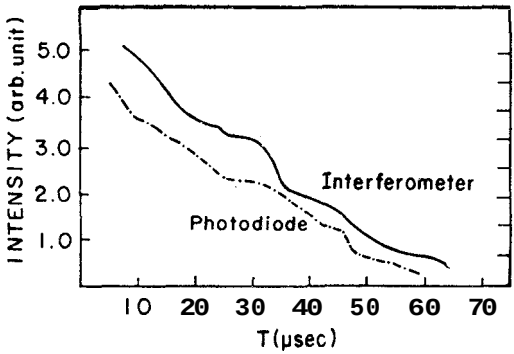

Fig. 5.B - Time dependence for photodiode and interferometer signal using geometric average values for envelope region.

(deuterium plasma) and $h\nu << kT_e$, the above equation can be rewritten in the form of a line integrated intensity as

$$I = An^2 r_s T^{1/2} \tag{2}$$

and here n is the electron density, r_s the separatrix radius, T is the electron temperature in electron volts and A is a calibration constant.

In order to compare eq.(2) with the photodiode signals, the time variation of the density, the separatrix radius and the electron temperature are needed. They

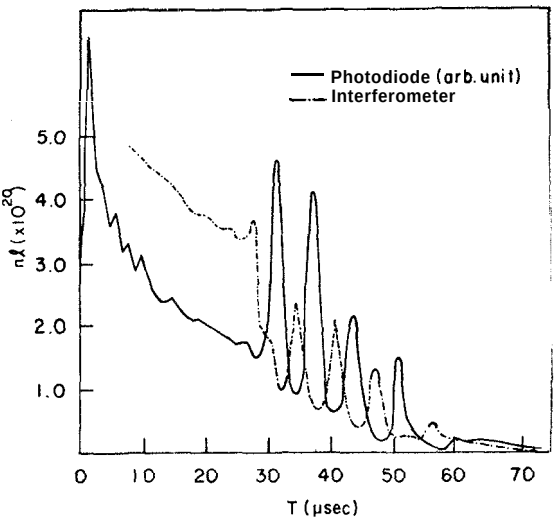

Fig.6 - Comparison between interferometer and photodiode signal.

can be obtained from other diagnostics such as interferometer data for n_e and flux excluded signals for r,; the temperature dependence can be obtained from

$$< \beta >= 1 - \frac{1}{2}\left(\frac{r_s}{r_w}\right)^2 \tag{3}$$

where r, is the radius of the quartz wall and

$$< \beta >= \frac{nk < T >}{B_{ext}^2/2\mu_0}$$

We have then

$$< T >= \frac{B_{ext}^2}{2\mu_0}\frac{1}{nk}\left(1 - \frac{1}{2}\frac{r_s^2}{r_w^2}\right) \tag{4}$$

and all quantities on the RHS are known. The plots of n,, r,, B_{ext} and T versus time are shown in fig. 7. These values are then used in eq.(2) and the light intensity is obtained as a function of time, within the assumption that the emission cames from bremsstrahlung radiation.

This function is plotted together with the photodiode signals in fig. 8. The agreement is remarkable and the differences seen, mainly in the unstable region, are probably due to the use of an average temperature in eq.(2).

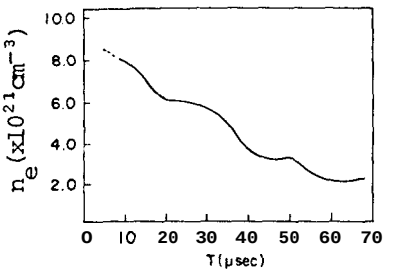

Fig. 7.A - N_E value from interferometry.

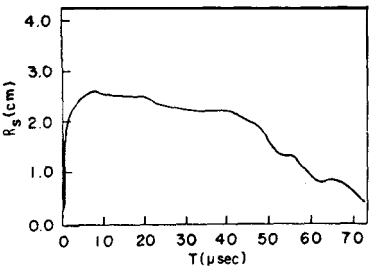

Fig. 7.B - R_S value from excluded flux signal.

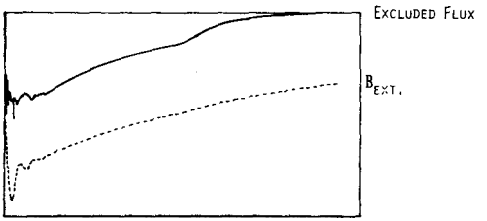

Fig.7.C - Signals from B_{ext} and $\Delta\phi$ excluded flux loops.

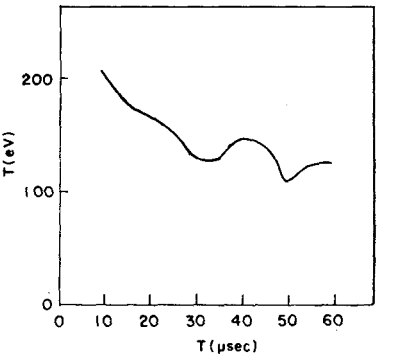

Fig. 7.D - $< T >$ curve from $< \beta >$ calculation.

Therefore if we accept the photodiode signal as being from bremsstrahlung radiation we can estimate the electron temperature with the equation

$$T_e = \left(\frac{I_{photo}}{An^2 r_s}\right)^2 \qquad (5)$$

As before, the density is obtained from interferometric data and the separatrix radius r, from flux excluded probe. The constant A is a calibration constant

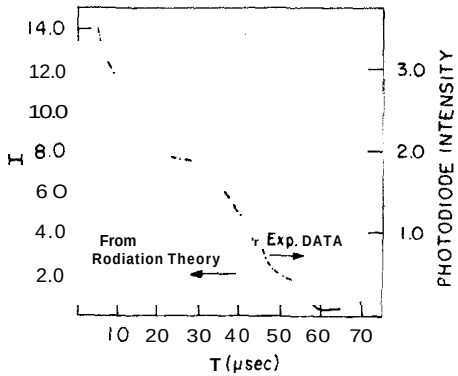

Fig.8 - Curves from photodiode and bremsstrahlung radiation theory.

to be determined for each setup with a calibrated source, or else, eq.(5) can be used to obtain the relative electron temperature in arbitrary units as seen in the fig. 9. This represents a very easy method to estimate the electron temperature, when compared with other techniques such as Thomson scattering, and gives more details than averaged temperature obtained from $< \beta >$ value.

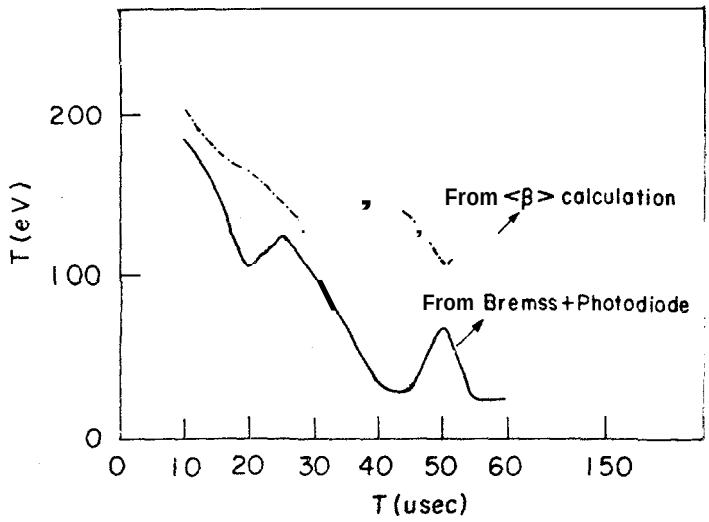

Fig.9 - Temperature obtainned by $< \beta >$ value (upper) and bremsstrahlung photodiode signal.

The angular velocity of the rotating plasma column can also be easily determined using two photodiodes displaced by 45^0 on the radial plane. The result for

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NUCTE-II is shown in fig. 1.0, which yields a velocity of 5 x 10^5 cm/s in the ion diamagnetic direction as seen also in other machines[12]. Also the radial position of the plasma column and its length can be monitored by placing several diodes at suitable locations determined by shot to shot basis. The radial position of the column is monitored using three photodiodes displaced by 2.5 cm in the radial plane. The position is defined by the observation of the $n = 2$ instability for each channel. The results are shown in fig. 11, and indicate a quite well centered plasma column up to 45μs into the discharge. The differences seen on the $n = 2$ instability at the center (r = 0 cm) and at r = ±2.5 cm, are due to the edge observations of elliptically deformed plasma.

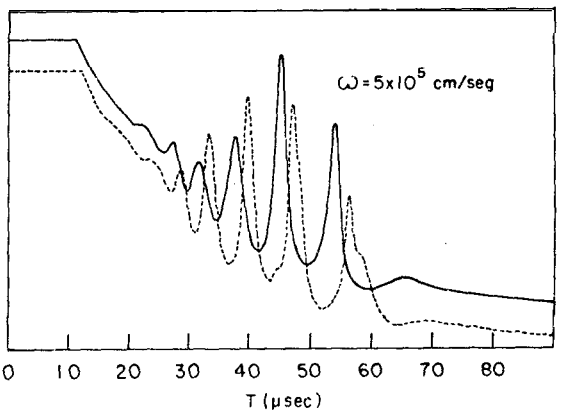

Fig.10 - Plasma rotation determined by instability signals taken with two radial 45° displaced photodiodes.

The length of the column is monitored with three diodes, at $z = +80.0$ cm, $z = 0$ cm and $z = -80.0$ cm. The results are shown in fig. 12. Again the final position has been obtained by shot to shot basis by monitoring the n = 2 instability. The plasma column length is found to be around 150 cm, shifted slightly to the left side; also, that plasma rotation appears earlier at the extremes of the column, leading to the speculation of a shear in the angular velocity, probably associated with a density profile in the z-direction.

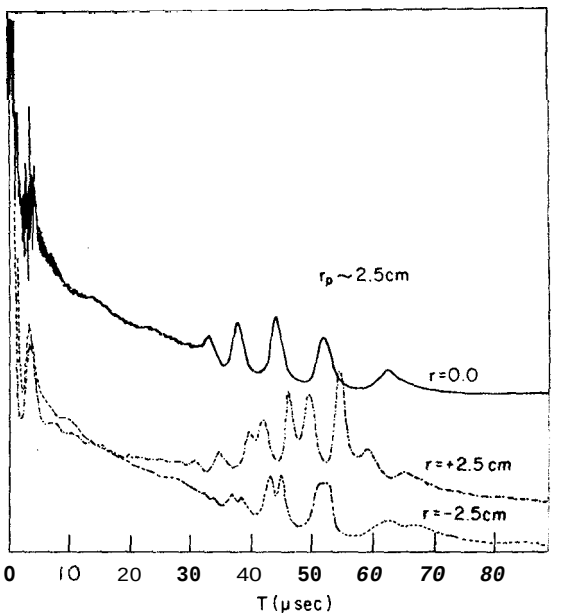

Fig. 11 - Signals from three radially displaced photodiodes for Z=0.0.

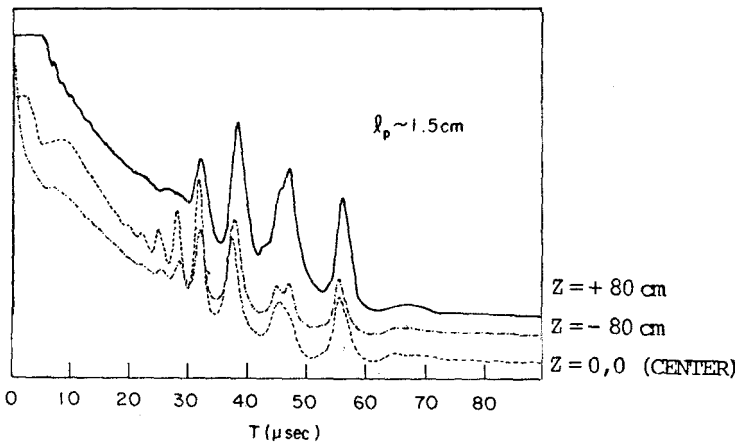

Fig.12 - Signals from three axially displaced photodiodes for R=0.0.

3. Conclusion

We have shown that the light detected by the photodiode is radiated from the

whole plasma body and displays the characteritics of bremsstrahlung radiation. The detected intensity then can be used to determine the relative electron temperature as a function of time where the absolute calibration procedures, not used here, are necessary for more accurate temperature measurements. The detected signals agree very well with those obtained with laser interferometry. Appropriate positioning of several diodes allows an unambiguous determination of the rotation of the column and its angular velocity. The radial and axial displacements of the plasma column during the discharge also can be monitored with this technique.

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Resumo

Utilizando um conjunto de detetores tipo fotodiodo foi analisada a luz emitida pelo plasma produzido em um theta-pinch de campo reverso NUCTE-II. A análise mostra que a emissão de luz pelo plasma pode ser relacionada com a radiação bremsstrahlung e isto pode ser utilizado para obter parâmetros da instabilidade rotacional $n = 2$ tais como direção de rotação, velocidade angular, deslocamentos axiais e longitudinais da coluna do plasma. A variação da temperatura eletrônica do plasma também foi obtida quando utilizado em conjunto com outros diagnósticos tais como interferometria com laser H-Ne e sondas de fluxo excluído.