Runaway Bremsstrahlung Spectra in Pulsator Tokamak+

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Abstract

Runaway bremsstrahlung spectra in the hard X-ray region are investigated under different plasma conditions.

The spectra obtained during the initial stage of the discharge and during the current plateau part are discussed, where the electron density has been increased by fast gas input at 30 ms. The spectra of the current plateau are compared with a theory for runaway production and losses.

I. Introduction

We address ourselves to two important questions regarding the presence of runaway electrons in a Tokamak discharge:

1. What is the relative importance of the runaways produced in the initial stage versus those produced later on during the rest of the discharge?

2. Are the observed spectra compatible with the current theories for the runaway production rate and additional assumptions on runaway loss rates?

We report here the results of our investigations on the Pulsator Tokamak in which we studied both the initial stage of the discharge and the current plateau part. The measurements were performed utilizing a 3" Na-J-crystal and a pulsed-height-analysis system for the hard X-rays above 50 keV. The observation direction was normal to the toroidal magnetic field and the bremsstrahlung could be scanned over the minor radius.

Most of the paper is centered around one type of the discharge where in addition to the stationary filling pressure of 2 x 10^{-4} torr, a fast gas input is added, 30 ms into the discharge, thereby increasing the electron density by usually more than factor of two.

II. Discharge Beginning

The development of the discharge and the hard X-rays in the first five ms are shown in the Fig.1. In the figure the hard X-ray pulses are shown on the upper polaroid picture and on the lower one the time development of the loop voltage, plasma current and the horizontal displacement are shown. Several points can be noted:

a) The main bulk of the runaways is produced in less than 200 μs at the very beginning of the discharge, where the loop voltage is about 60 V.

b) The bremsstrahlung comes in several bursts separated by about 500 μs. These bursts and their timing are very reproducible and are observed over the whole discharge radius.

c) These bursts are correlated with small changes in the loop voltage.

Time resolved pulse-height-analysis shows that during the first ten ms the bremsstrahlung spectra are of rectangular form and after that time the spectra show a typical exponential decay. One can define the characteristic energy and characteristic intensity for these two types of spectra. E_c is the cut-off energy for the rectangular spectrum and E_k is the characteristic energy of the exponentially decaying spectrum. The characteristic intensity is the intensity of the spectrum extrapolated to zero energy.

Figure 2 shows the time development of these characteristic energies. The cut-off energy of the ractangular spectrum E_c peaks at about 3 ms in discharge and decreases after that. The characteristic energy of the exponential spectrum E_k increases steadily with time. Both values are peaked at the center of the plasma.

The characteristic intensities as a function of time are shown in Fig. 3. Again the intensity of the initial rectangular spectrum increases to about 2.5 ms and thereafter decreases by a factor of about 10. The characteristic intensity of the subsequent exponential spectrum increases in time. The radial dependence of both intensities shows again peaking in the center of the plasma.

III. Discharge Plateau

Now we will discuss the discharge plateau. The time development of the plasma parameters important in setting the runaway production rate are shown in Fig.4. These plasma parameters are the electron temperature T_e, average electron density n_e, loop voltage U_l and Z_{eff}. At $t = 30$ ms the hydrogen gas is added to the discharge and a steady increase in the electron density and decrease in Z_{eff} and electron temperature are observed.

In this type of discharge we again observe exponentially decaying bremsstrahlung spectra with large characteristic energies during the plateau part.

The characteristic intensities of these discharges are shown in Fig.5 again as a function of time and also as a function of the radial position (without Abel-inversion). The bremsstrahlung shows a very strong initial burst of radiation which is then after 10 ms followed by a quiet period, where the intensity falls by more than four orders of magnitude. Shortly after that the intensity increases again and becomes maximum about 10 ms later, when the electron density shows a minimum (about 40 ms in the discharge). While the density is increasing, the hard X-ray intensity decreases by almost an order of magnitude. It is interesting to note that the influence of the fast gas input is first felt at the plasma edge and that this minimum in the hard X-ray intensity moves toward the center of the plasma in about 20 ms. During this time a drop in electron temperature is observed. For times later than 60 ms the spectrum is distorted by hard X-rays coming from the limiter.

IV. Comparison with Theory

Calculations of the runaway production rates are made on the basis of the theory of Connor and Hastie /1/(using $C_R = 0.42$) which also includes relativistic effects. The theoretical results can be assumed to be most reliable for low production rates. This situation is met in experiments with pulsed gas input, where the electron density is well above $10^{13} cm^{-3}$.

Since the runaway production depends very sensitively on the ratio n_e/T_e we have also the radial profiles of n_e and T_e to take into account. From the Thomson scattering data we calculate the production rate for various radial positions as a function of time.

Results are to be seen in Fig.6. The runaway production rate $S_R(X, t)$ peaks at the plasma center and changes rapidly in time. At 90 ms in discharge the production reaches a minimum which is preceded by an exponential decay with a time constant of 15 ms.

The variation of the runaway production in time changes not only the intensity but also the shape of the spectrum. High energetic quanta are created by runaway electrons which were born earlier and have been freely accelerated since then. Thus the bremsstrahlung spectrum can be strongly influenced by the history of the discharge. There is, however, empirical evidence for runaway loss mechanism. In this study we assumed a loss mechanism that can be described by an exponential decay in time with a time constant τ_{run}. τ_{run} is the runaway confinement time.

Using this concept we calculate the runaway distribution function at 60 ms and also the runaway bremsstrahlung spectrum by integrating over electron energies and the observation chord length.

Figure 7 shows these spectra for different values of τ_{run} and the measured spectrum. Comparing the theoretical curves with experiment a runaway confinement time of about 5 ms is deduced. It should be emphasized that there is no discrepancy between absolute values from theory and experiments as it has been found in former investigations. The broad peak around 500 keV is ascribed to 511 keV photon from the pair building and annihilation in the detection system.

V. Summary and Conclusion

In conclusion one can stress the following points regarding Pulsator results:

1. There is a strong production of runaways during the first couple hundred μs, but they are soon lost. Thus the initial phase of the discharge is of minor importance. During this initial time the hard X-rays come in reproducible bursts separated by approximately 500 μs. These bursts correlate to changes in loop voltage indicating presence of an instability.

2. Subsequent to initial stage, the runaways are produced during the rest of the pulse. By increasing the density by a factor 3 to 4 the bremsstrahlung intensity decreases by almost three orders of magnitude. Runaways are produced over most of the discharge diameter; however, the production is concentrated in the center of the discharge.

3. For the high density case both the absolute value and the form of the hard X-ray spectrum is compatible with the theory by assuming a runaway confinement time of about 5 to 10 ms.

References:

/1/ Connor, J.W., Hastie, R.J., Nuclear Fusion, 15, 415 (1975)

/2/ Koch, H.W., Motz, J.W., Rev.Mod.Phys.,31,4,920(1959)

Appendix

A. Calculation of the distribution function

The runaway distribution function f_R in momentum space $q = p/mc$ is to be calculated by integration over the time of birth t_o

$$f_R(x,q,t) = \int_0^t S_R(x,t_o) \cdot w(t-t_o) \cdot \delta(q - q(t,t_o))\, dt_o \qquad (1a)$$

where

$$w(t-t_o) = \exp[(t_o - t)/\tau_{run}] \qquad (1b)$$

is the assumed probability that a runaway electron born at time t_o is still in discharge at the time of observation t. The normalized momentum $q(t,t_o)$ is obtained by integrating the electric field.

$$q(t,t_o) = q_c + \frac{e}{mc} \int_{t_o}^{t} E(t')\, dt' \quad . \qquad (1c)$$

q_c is the critical momentum an electron must have in order to run away. Substituting

$$t_o = g(q) \qquad (1d)$$

from eq.(1c) into eq.(1a) we get

$$f_R(x,q,t) = \begin{cases} - S_R(x, g(q)) \cdot g'(q) \cdot \exp[-(t - g(q))/\tau_{run}] \\ 0 \qquad \text{if } q < q_c \text{ or } q > q_{max} \end{cases} \qquad (2)$$

with $q_{max} = q(t,t_o)$ and $g' = dg/dq$.

In case of constant electric field and with

$$S_R(x,t_o) = A(x) \cdot \exp(-t_o/\tau_s) \qquad \text{equation (2)}$$

simplifies to

$$f_R(x,q,t) = \begin{cases} \tau \cdot S_R[t-\tau(q-q_c)] \cdot \exp[-\tau(q-q_c)/\tau_{run}] \\ 0 \quad \text{if } q < q_c \text{ or } q > q_{max} \end{cases} \qquad (3)$$

where $\tau = mc/e\mathcal{E}$ is a characteristic acceleration time.

B. Runaway bremsstrahlung spectrum

We define the bremsstrahlung spectrum as

$$B(E,t,\theta) = \frac{\dot{N}\,\Delta E}{E\,\Delta S\,\Delta\Omega}$$

where E is the photon energy, θ the angle between electron momentum and direction of observation ($\sim 90^{\circ}$ in Pulsator), and $\dot{N}$ is the number of observed quanta per second that fall into the space angle $\Delta\Omega$ from a surface element ΔS . The Function B is obtained from

$$B(E,t,\theta) = c\int_{-l/2}^{l/2} dx \sum_j n_j(x,t)\, Z_j^2 \int_{T=E}^{T_{max}} Q(E,T,\theta)\cdot f_R(x,q(T),t)\, dT \qquad (4)$$

where a transformation to kinetic energies according to

$$E_{kin}/mc^2 = T(q) = (1+q^2)^{1/2} - 1 \qquad (5)$$

and

$$f_R(q)\, v(q)\, \frac{dq}{dt}\, dT = f_R(T)\cdot c\, dT \qquad (6)$$

is implied. $Q(E,T,\theta) = E d\sigma/dEdTd\Omega$ is the bremsstrahlung cross-section (/2/, eq. 2BN) and n_j, Z_j are the ionic and atomic densities and their nuclear charges, respectively. Since most of the impurity is made up from oxygen, which is fully ionized in the center of the plasma, we use the relation

$$\sum_j n_j(x,t)\, Z_j^2 = n_e(x,t)\, Z_{eff}(t) \qquad (7)$$

in equation (4).

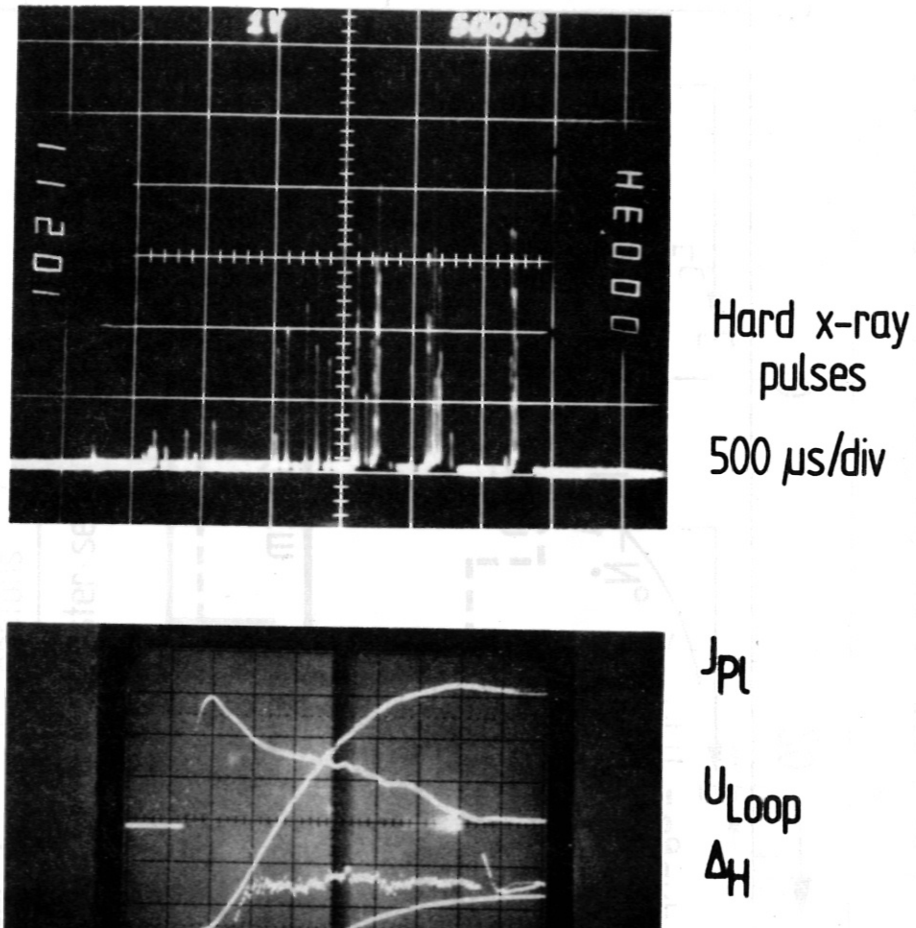

Fig.1: a) Hard X-ray pulse during the first five ms in discharge (horz.: 500 µs/div, vert.:150 keV/div).
b) Loop voltage Uloop, plasma current, I_{pe}, and horizontal displacement, Δ_H, during the first five ms in discharge (horz.: 500 µs/div, vert.: 20 V/div and 10 kA/div).

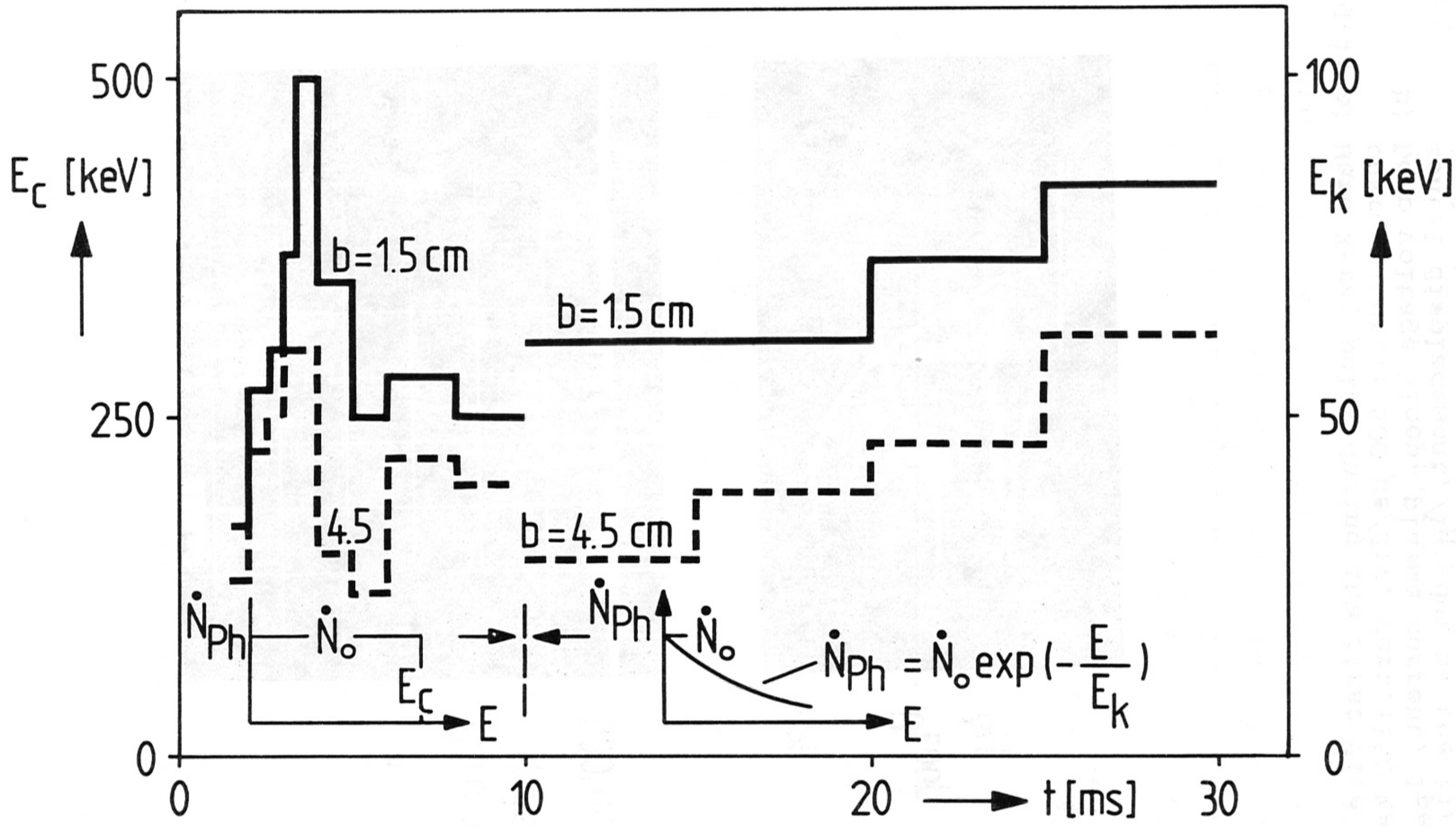

Fig.2: Variation of E_C and E_K with time and radial position b : (limiter radius 11 cm), E_C is the cut-off energy for a rectangular spectrum and E_K is the characteristic energy of an esponential spectrum.

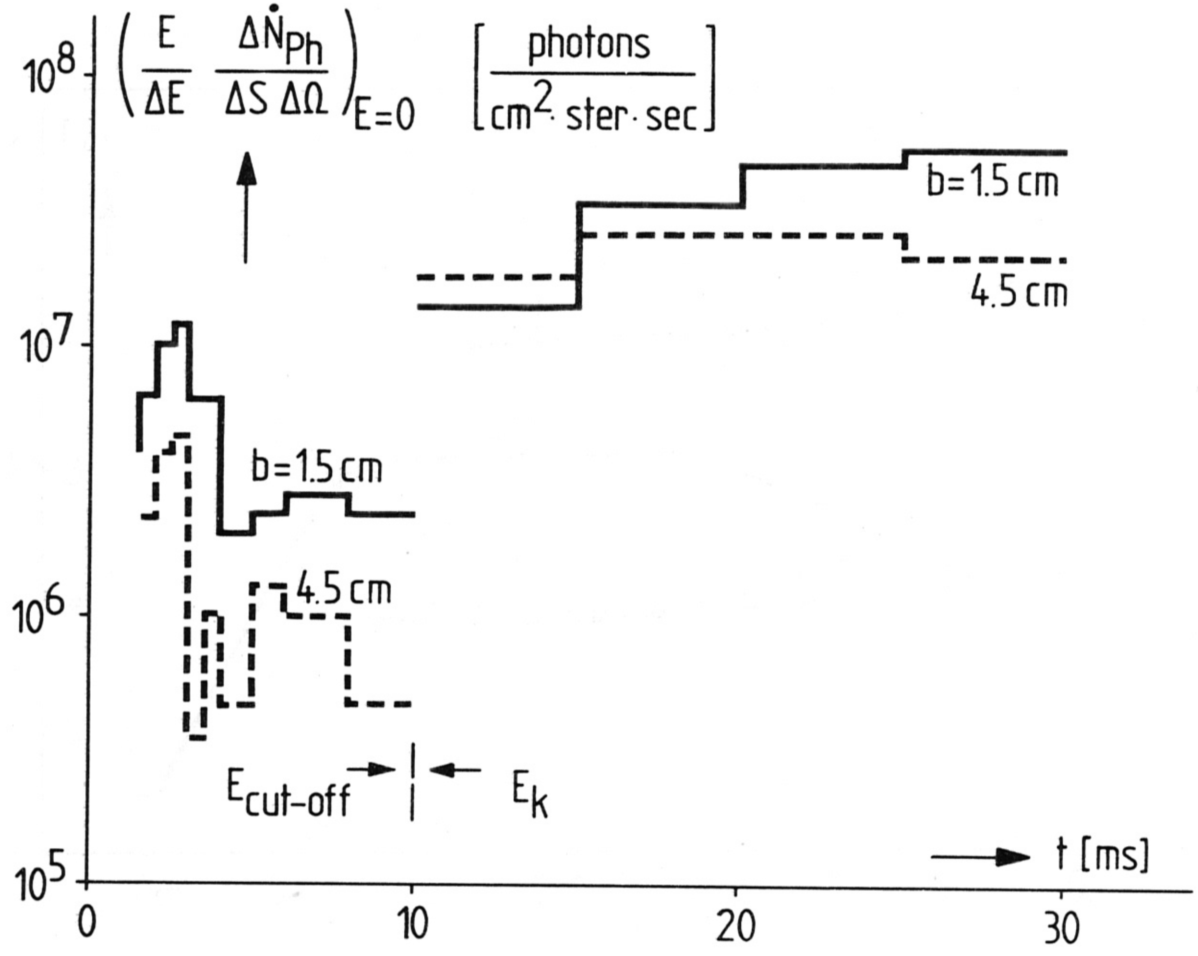

Fig.3: Hard X-ray intensity as a function of time and radial position.

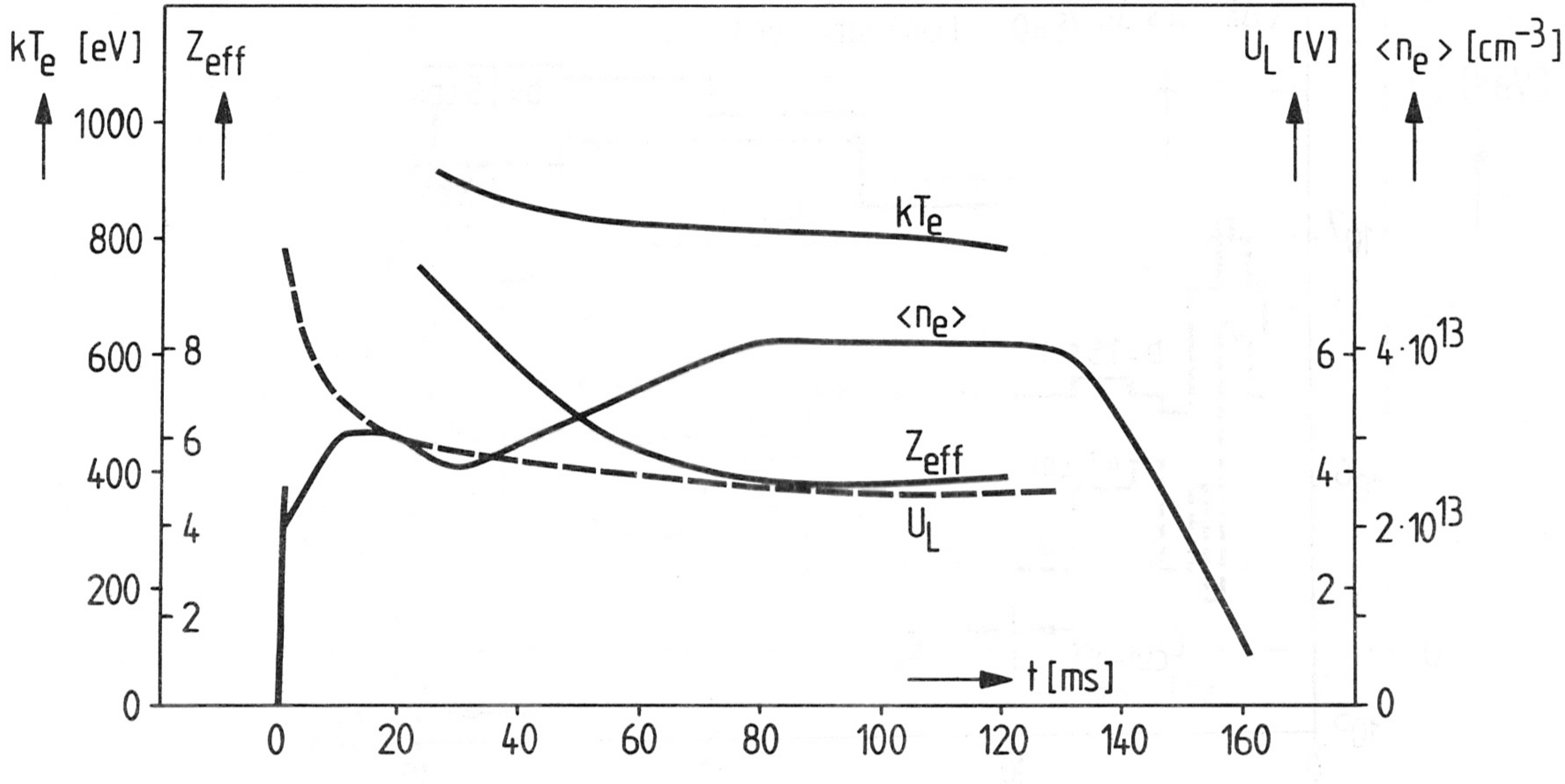

Fig.4: Loop voltage U_L, mean electron density $\langle n_e \rangle$, peak electron temperature T_e and Z_{eff} vs time for pulsed gas input at 30 ms.

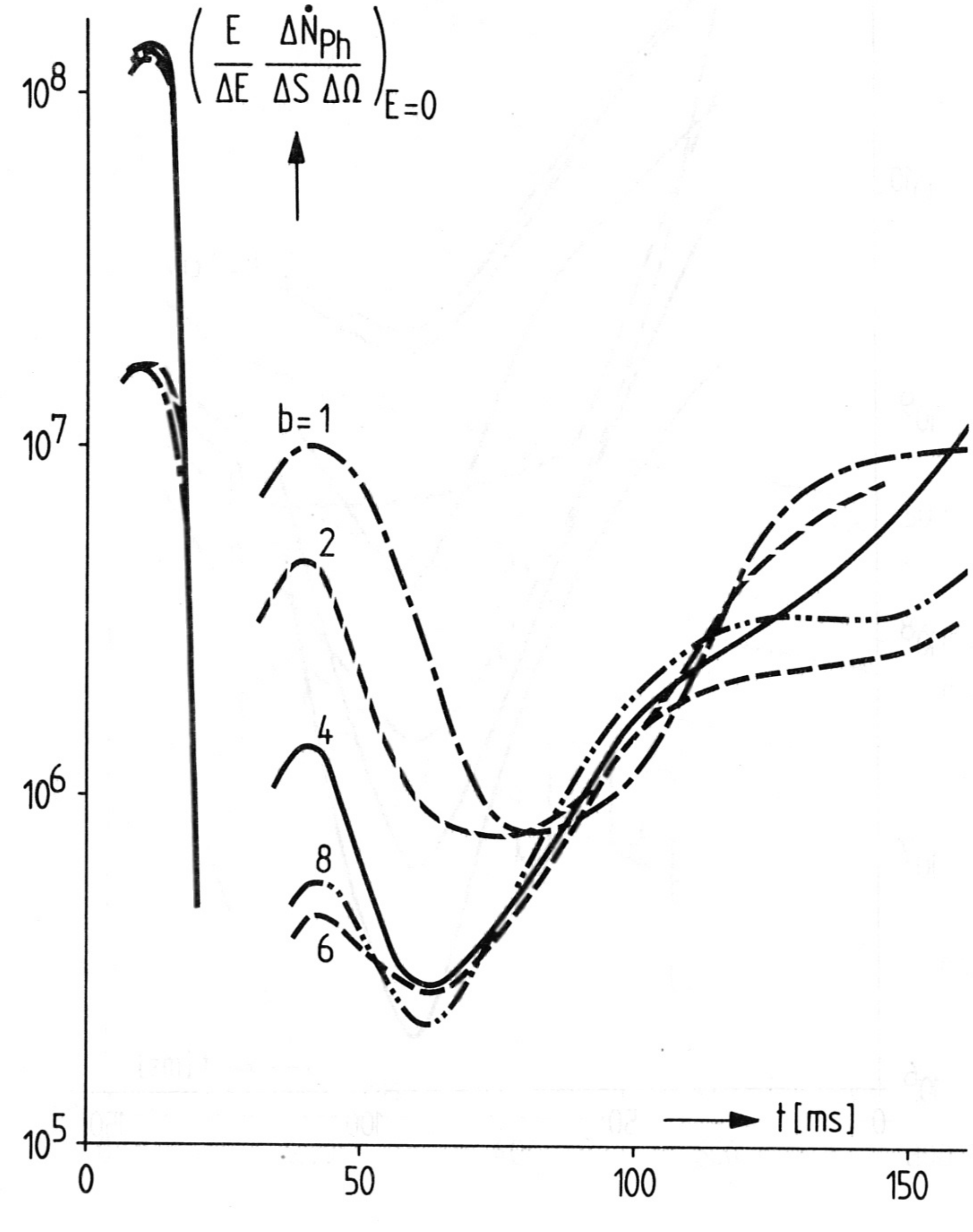

Fig.5: Variation of the bremsstrahlung intensity with time and radial position. Pulsed gas inlet at t = 30 ms.

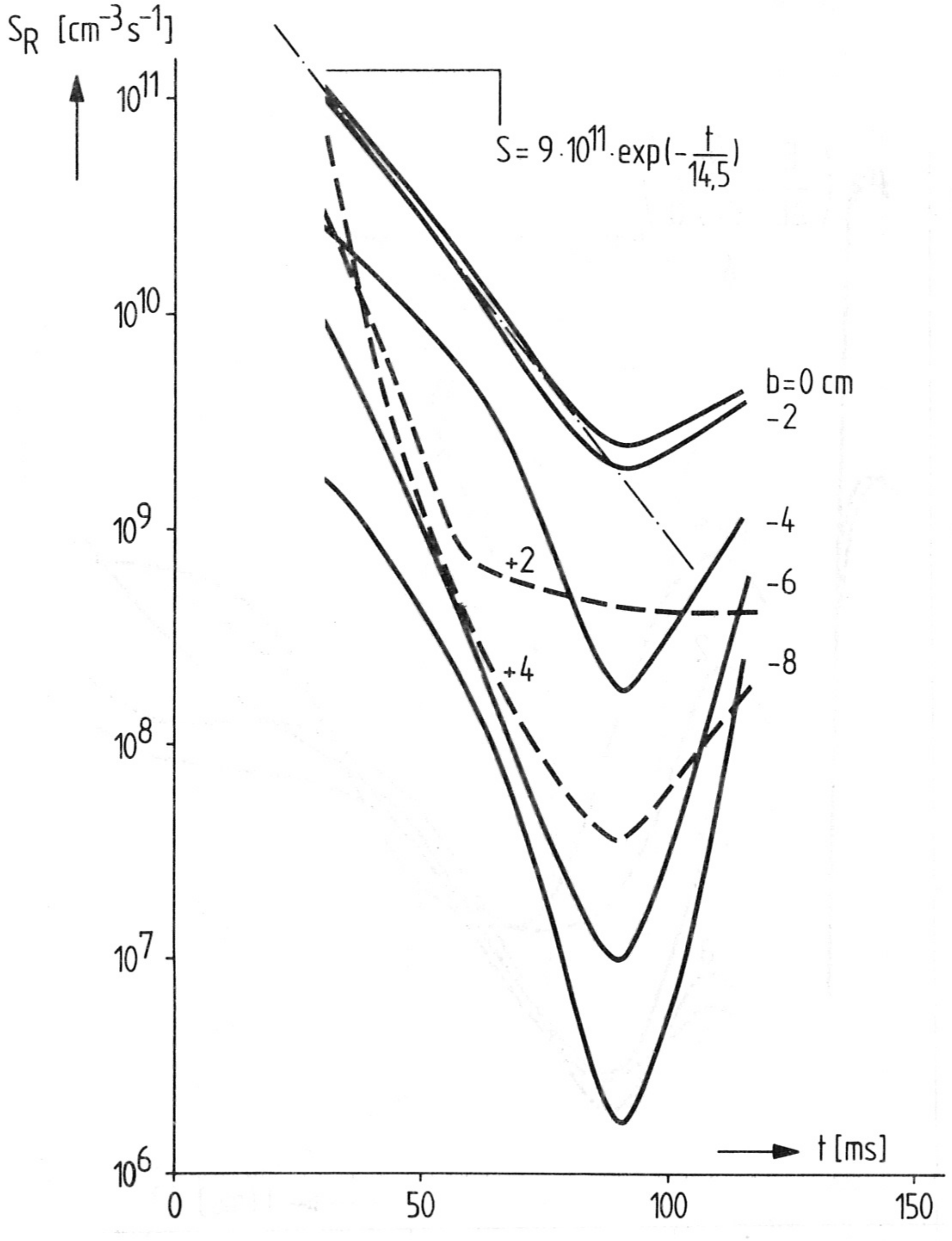

Fig.6: Calculated runaway production rate at different radial positions as a function of time. Thomson scattering data for T_e, n_e and Z_{eff} are used.

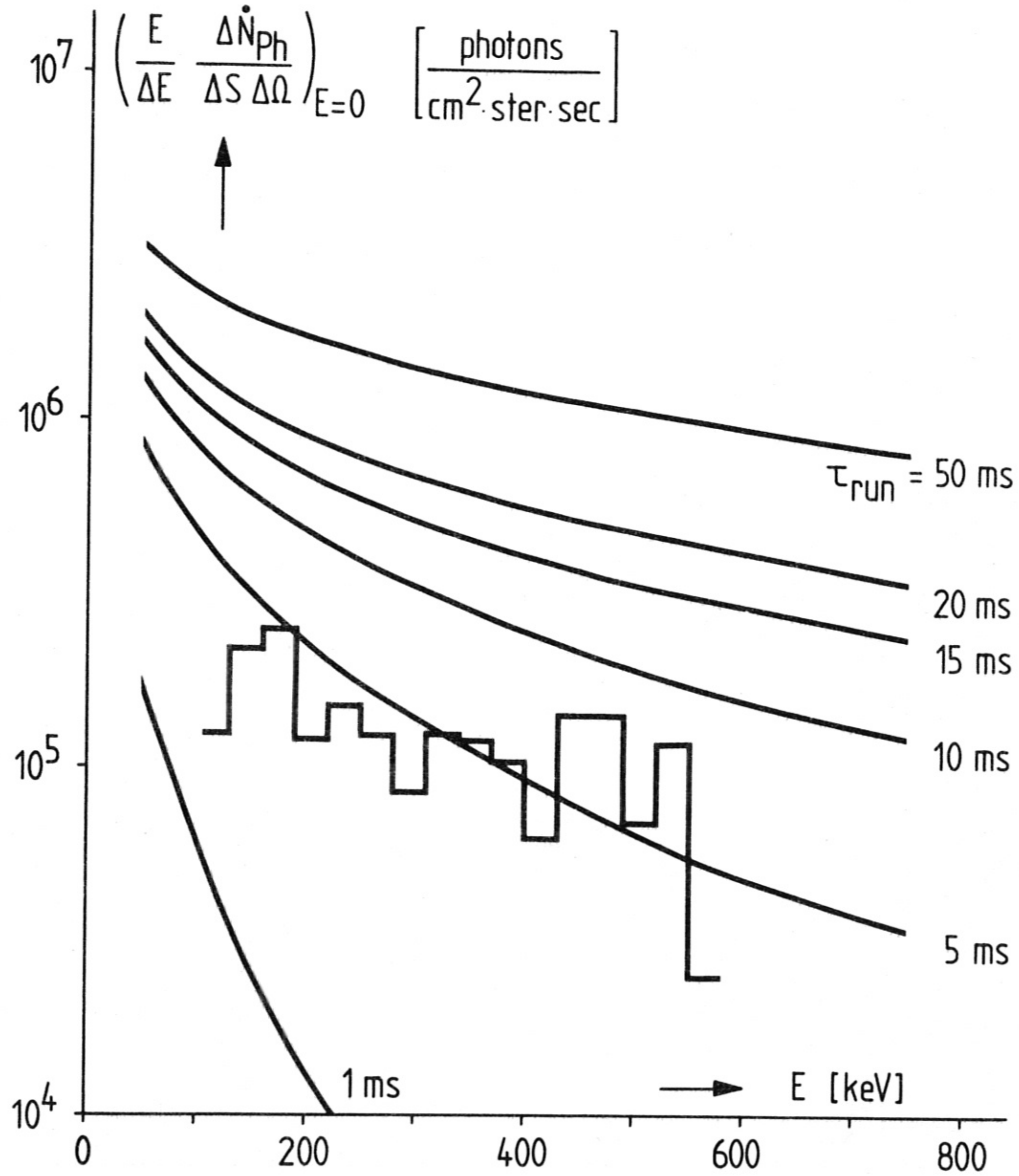

Fig. 7: Theoretical and measured runaway spectra at 60 ms in discharge. τ_{run} is the assumed runaway confinement time.