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JUNE, 1993

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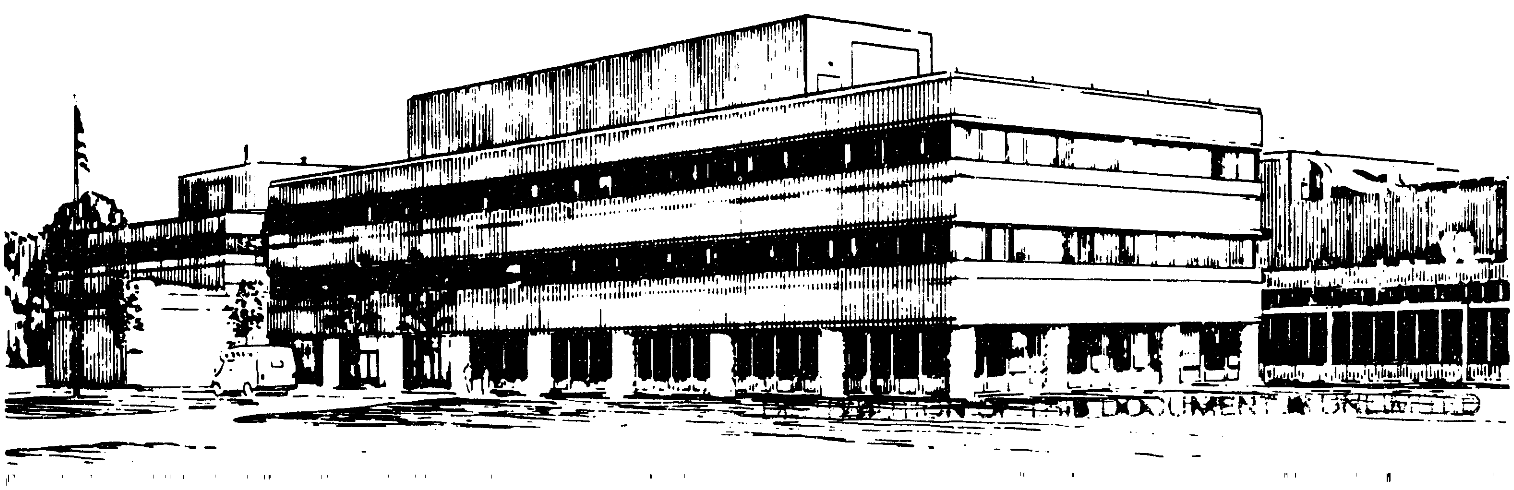

DETERMINATION OF THE ENERGY OF SUPRATHERMAL ELECTRONS DURING LOWER HYBRID CURRENT DRIVE ON PBX-M*

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S. VON GOELER, S. BERNABEI, W. DAVIS, D. IGNAT, S. JONES, R. KAITA, G. PETRAVICH, F. RIMINI, P. RONEY, J. STEVENS

ABSTRACT

Suprathermal electrons are diagnosed by a hard X-ray pinhole camera during lower hybrid current drive on PBX-M. The experimental hard X-ray images are compared with simulated images, which result from an integration of the relativistic bremsstrahlung along lines-of-sight through the bean-shaped plasma. Images with centrally peaked and radially hollow radiation profiles are easily distinguished. The energy distribution of the suprathermal electrons is analyzed by comparing images taken with different absorber foils. An effective photon temperature is derived from the experimental images, and a comparison with simulated photon temperatures yields the energy of the suprathermal electrons. The analysis indicates that the energy of the suprathermal electrons in the hollow discharges is in the 50 to 100 keV range in the center of the discharge. There seems to exist a very small higher energy component close to the plasma edge.

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Determination of the Energy of Suprathermal Electrons during Lower Hybrid Current Drive on PBX-M.

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1. Introduction. The Lower Hybrid Current Drive (LHCD) experiment on the PBX-M tokamak attempts to modify and optimize the radial current profile in order to find new tokamak operating regimes with a higher value of beta.[1,2] The lower hybrid waves interact with the plasma electrons and generate a suprathermal electron tail,[3] presumably via Landau damping. In order to elucidate and test the physical mechanism of the wave-plasma interaction, we have installed on PBX-M a hard X-ray Camera[4,5] that produces images of the hard X-ray bremsstrahlung created in collisions of the suprathermal electrons with plasma ions. The first results from the Hard X-ray Camera were reported at the Innsbruck EPS conference.[5] In that paper, hard X-ray images from the camera are compared with computer-simulated images from the PBXRAY code. It was shown that the radial the location of the suprathermal electrons can be determined quite accurately. In particular it was found that LHCD with -90° or -105° phasing of the grill at high plasma densities generated a hollow ring of suprathermal electrons, a result that is considered crucial for the effort to modify the current profile. The present paper concentrates on the determination of the energy of the suprathermal electrons. We shall show that the suprathermal electrons in the high density regime have very low energies, (less than 100 keV). This result seems to support the notion that the electrons in the hollow discharges are in a regime where collisional slowing-down dominates acceleration by the electric field, and where low-$n_{\parallel}$ LH waves, that tend to accelerate electrons to high energies, cannot penetrate to the plasma center because of accessibility.

The paper is organized as follows: In Sect. 2 we discuss the absorber foil method for the determination of the electron energy, which is well known for soft X-rays, but, to our knowledge, has not been applied to hard X-ray measurements. Modeling with the PBXRAY code will illustrate its merits - and its subtleties. In Sect. 3 we present results for a PBX-M high density discharge.

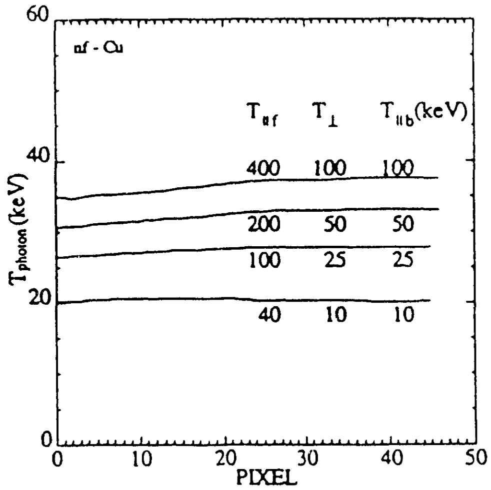

Fig. 1: Horizontal profiles of T_{photon} for different electron tail temperatures.

2. The Absorber Foil Method for Hard X-rays. The Hard X-ray Camera has an imaging tube that integrates over photon energies. In order to determine the X-ray energy, we place various absorber foils in front of the pinhole of the camera in between shots, and compare the intensity I_{foil1} from a shot with absorber foil #1 to the intensity

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I_{foil2} from a shot with foil #2. In analogy with the well-known absorber foil method for soft X-rays, we plot an effective "temperature" of the photon spectrum T_{photon}

$$T_{photon} = \frac{E_{foil2} - E_{foil1}}{\ln(I_{foil1}) - \ln(I_{foil2})} ,$$

where E_{foil1} and E_{foil2} are the low energy cut-offs for foil #1 and foil #2. If the spectrum of the emitted bremsstrahlung falls off with energy like an exponential function, then T_{photon} is the negative reciprocal slope of the spectrum in a semilog plot. The absorber foils consist of copper (0.52 mm), molybdenum (0.95 mm), and silver (2.03 mm). Without any absorber foil, the aluminum vacuum window, the aluminum entrance window of the X-ray tube, and the connectic magnetic shielding foil in front of the imaging tube contribute to a low energy cut-off of 45 keV. The cutoff energies with an additional Cu, Mo , or Ag foil are 67 keV, 115 keV, and 176 keV, respectively.

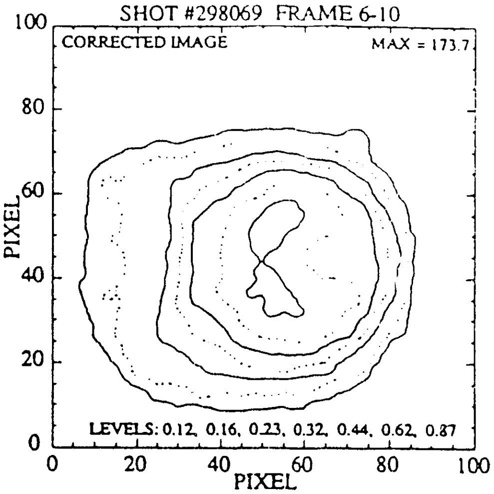

Fig. 2: Contour plot of a hollow discharge.

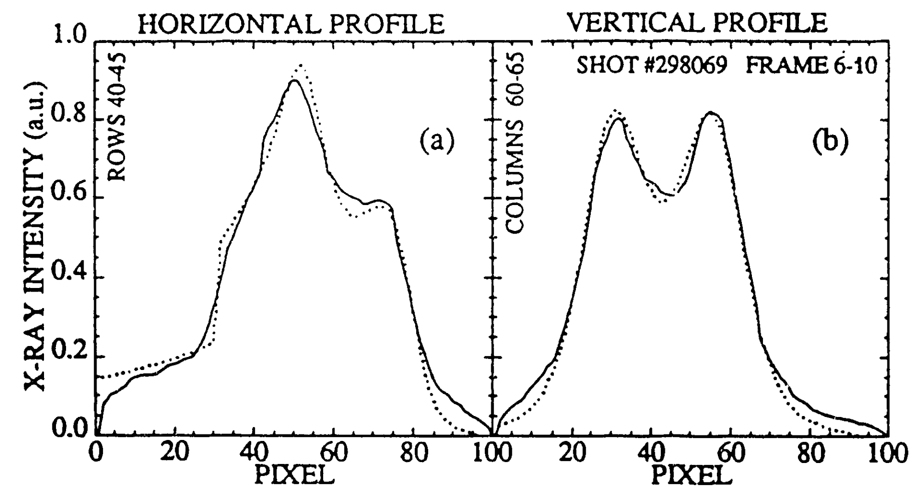

Fig.3: Horizontal (a) and vertical (b) profile for a hollow discharge. Solid curves experiment, dotted curves simulation. Input for simulation is shown in Fig. 6.

The quantity T_{photon} is only indirectly related to the energy (or temperature) of the suprathermal electrons. We now want to use the PBXRAY code to establish such a relationship. Simulated horizontal profiles of photon temperature T_{photon} are shown in Fig. 1 for four different hot-electron velocity distributions. ["Horizontal profile" is our nomenclature for a horizontal slice through the center of an image]. In the computation that lead to Fig.1, the electron tail distribution function was assumed to be a Gaussian characterized by three parameters, the parallel forward temperature $T_{\parallel f}$, the perpendicular temperature $T_{\perp}$, and the parallel backward temperature $T_{\parallel b}$. For each of the four curves, the tail temperature was the same on all flux surfaces; the density of suprathermal electrons, though, changed. For the four cases shown in Fig. 1, the temperatures varied by a factor of 10; however, the ratio of the three temperatures $T_{\parallel f}$, $T_{\perp}$, and $T_{\parallel b}$ was kept the same. It is remarkable how little the photon temperature changes across the image in Fig. 1, although the angle between the sight-line and the magnetic field varies significantly from the left side of the image to the right side. The photon temperature increases with increasing energy of the suprathermal electrons, however, the increase amounts only to a factor 2, and

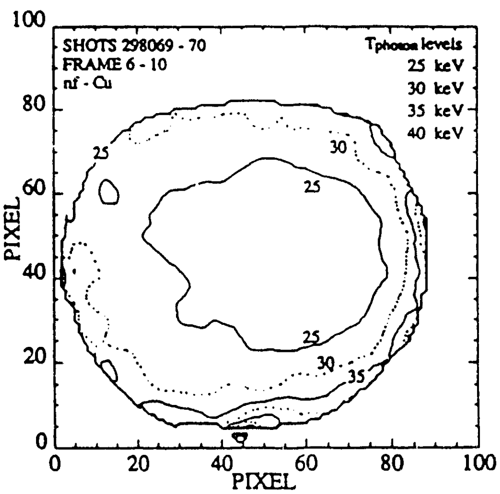

Fig. 4: Contour plot of the photon temperature in a hollow discharge.

the values for the photon temperature are considerably smaller than the values for the temperature of the suprathermal electrons. As a consequence, we believe that the photon temperature can be directly related in an approximate but simple fashion to the energy of the suprathermal electrons. However, a warning should be posted: The number of suprathermal electrons depends strongly on plasma density, and small changes in density may cause large variation in hard X-ray intensity. Therefore, the photon temperature can be measured only for plasma shots that are identical.

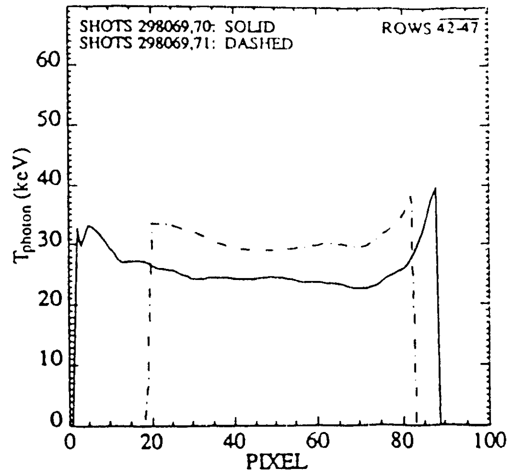

Fig. 5: Horizontal profile of T_{photon}.

3. High Density Discharges. In this section we want to discuss the analysis of three nearly identical discharges with a hollow hard X-ray radiation profile, PBX-M shots #298069 - 71. The plasma current for these shots was about I_p = 190 kA and the plasma density $n_e = 1.6 \times 10^{13}$ cm^{-3}. LHCD with -90° phasing and 185 kW of power took place from time 250 ms to time 650 ms. Simultaneously, neutral beams were injected with 2.2 MW power. As soon as the RF started, hard X-ray images were observed. The hard X-ray intensity rose quickly for 50 ms and then settled into an approximately stationary state. The hard X-ray vertical profile was very hollow initially and remained hollow, albeit somewhat flatter, for the rest of the LHCD period. A contour plot of an X-ray image from the early stage is shown Fig. 2; it is an average of 5 frames from time 270 to 295 ms of shot #298069. The figure exhibits the characteristic crescent-like shape that is typical for "hollow" discharges on PBX-M. Figure 3a and 3b show the vertical and horizontal profiles from this image (solid curves). The experimental data are overlaid with computer simulations from the PBXRAY code (dotted curves). The velocity distribution and radial profile of the hot electrons that went into the simulations, will be discussed below. A comparison of these results with the data shown at the Innsbruck Conference (Ref. 5), shows that there exists now a much better agreement between simulations and experiment. The improvement is mostly due to the fact that we have completed a calibration of the Hard X-ray Camera. In particular the right "shoulder" of the horizontal profile in Fig. 3a has now the correct height.

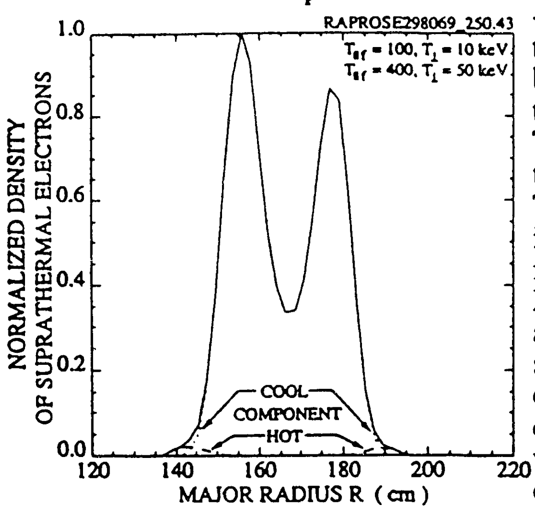

Fig. 6: Density of suprathermal electrons.

For shot #298070 and shot #298071, the copper (Cu) foil and the molybdenum (Mo) foil, respectively, were placed in front of the pinhole of the X-ray Camera. In Fig. 4, we show a contour plot of the photon temperature that was determined from the no-foil shot (nf) and the copper foil shot (Cu) during the time interval 270 -295 ms. The photon temperature is 25 keV in the central region of the discharge, and rises towards the outside to about 40 keV on the large major radius side. Near the edge, the X-ray intensity becomes very small, and the measurement was truncated when the signal became smaller than 3 bits. The photon temperature from the nf - Mo

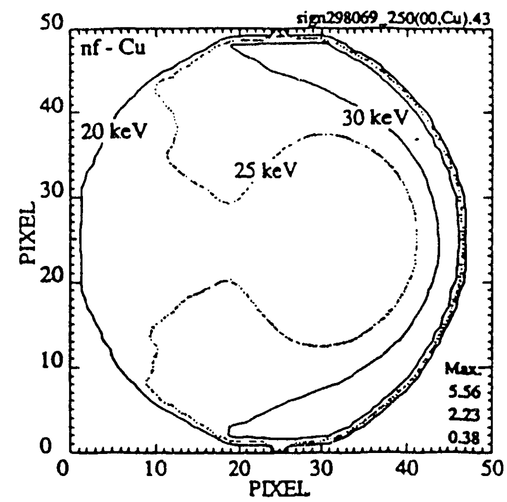

Fig. 7: Simulation of the photon temperature

shots looks very much like Fig. 4. The hard X-ray intensity is much weaker for the Mo shot, however, and the measurement has to be truncated further inside. In Fig. 5, we show horizontal profiles of the photon temperature for the nf- Cu case and the nf-Mo case. The nf-Mo case gives slightly higher photon temperatures. The fact that the photon temperature rises towards the large major radius side means that we cannot simulate the discharge with only one distribution function, in other words, the distribution function changes as a function of radius.

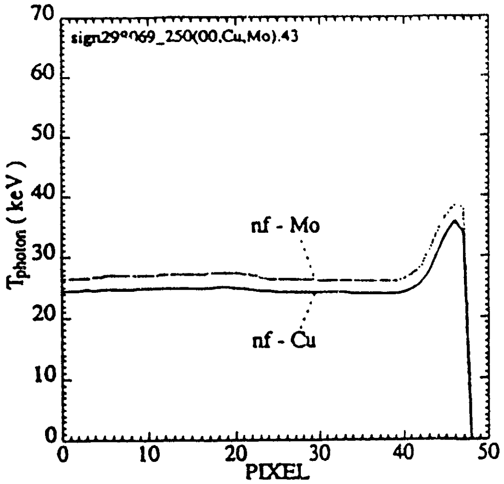

Fig. 8: Simulated horizontal profile of the photon temperature

We have attempted to model the discharge with two distribution functions. The radial profile factors of the two distributions are shown Fig. 6. In the plasma center a "cool" component ($T_{\parallel f}$ = 100 keV, $T_\perp$ = 10 keV, $T_{\parallel b}$ = 10 keV) dominates. At the plasma edge there seems to exist a small hot component ($T_{\parallel f}$ = 400 keV, $T_\perp$ = 50 keV, $T_{\parallel b}$ = 50 keV), which may be produced by electron runaway. The maximum density of the hot component is only 2 percent of the maximum density of the cool component. Therefore, the hot component makes only a small contribution to plasma current and energy. These distribution functions were also used to compute the two curves of the simulated hard X-ray intensity in Fig. 3a and 3b. In Fig. 7, we show a contour plot of the modeled photon temperature for the nf - Cu case, and, in Fig. 8, the horizontal profiles of the simulated photon temperature for the nf-Cu and the nf- Mo case. The simulations nicely reproduce the rise of the photon temperature on the right (large major radius) side of the image (Fig. 4 or Fig. 5). However up to now, we have no explanation for the small increase of the photon temperature on the left side of the image.

The analysis can now be done not only for one frame, but for a whole shot. In Fig. 9, we show the photon temperature in the central plasma region as a function of time for the nf-Cu case and the nf-Mo case. At time t=400 ms the photon temperature for the nf-Cu case seems to drop suddenly, whereas the nf-Mo temperature stays unchanged. At the time of the drop the plasma density for shot #298070 (the Cu shot) starts to deviate by 5% from the density for the other two shots. Therefore, we think that the drop is not a real change of the photon temperature, but reflects the sensitivity of the absorber foil method to density variations.

The fact that the photon temperature - and consequently the energy of the suprathermal electrons - is so low for the hollow discharge on PBX-M represents a significant new finding. As we mentioned in the introduction,these resuluts depart from our former PLT measurements and from data of other machines. Of course the experimental techniques used on the earlier machines were also different. We plan to repeat the experiment using pulse-height-analysis techniques during the next PBX-M run.

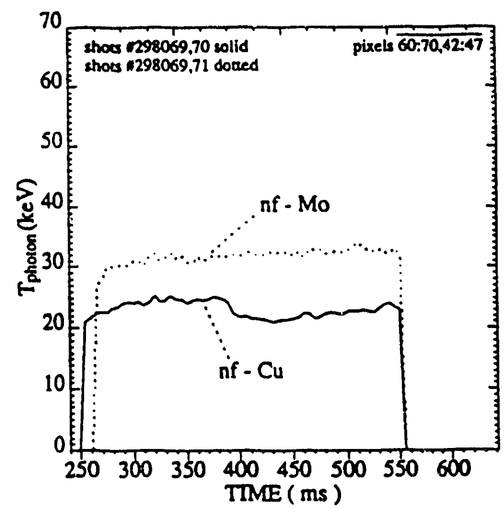

Fig. 9: Photon temperature vs. time.

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