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A CAMERA FOR IMAGING HARD X-RAYS FROM SUPRATHERMAL ELECTRONS
DURING LOWER HYBRID CURRENT DRIVE ON PBX-M

BY

S. VON GOELER, S. JONES, R. KAITA, ET AL.

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A Camera for Imaging Hard X-rays from Suprathermal Electrons during Lower Hybrid Current Drive on PBX-M.

S. von Goeler, S. Jones[†], R. Kaita, S. Bernabei, W. Davis, H. Fishman,
G. Gettelfinger, D. Ignat, F. Paoletti[†], G. Petravich^{††}, F. Rimini^{†††},
P. Roney, J. Stevens, W. Stodiek,

*Plasma Physics Laboratory, Princeton University, Princeton NJ.
08543*

Abstract: During lower hybrid current drive (LHCD), suprathermal electrons are generated that emit hard X-ray bremsstrahlung. A pinhole camera has been installed on the PBX-M tokamak that records 128×128 pixel images of the bremsstrahlung with a 3 ms time resolution. This camera has identified hollow radiation profiles on PBX-M, indicating off-axis current drive. The detector is a 9" dia. hard X-ray image intensifier. A detailed account of the construction of the Hard X-ray Camera, its operation, and its performance is given.

1. Introduction.

The goal of the modified Princeton Beta Experiment PBX-M is to find geometric configurations and plasma scenarios which allow tokamaks to operate at higher values of beta. Calculations of MHD instabilities^{1,2} in particular of ballooning modes, have indicated that shaping of the radial profile of the safety factor q , or more precisely a lowering of the plasma current density in the center and an increase of the current density near the plasma edge, can significantly improve the MHD stability of high beta plasmas. In order to control the current profile, a high power Lower Hybrid Current Drive (LHCD) system³ was installed on PBX-M. This system was put into operation in the fall of 1991, and the first results on the modification of the current profile in the presence of the LH waves have been observed and reported^{4,5}. During previous lower hybrid current drive experiments on the PLT tokamak, it was found that the lower hybrid waves couple to suprathermal electrons in the plasma

presumably through the process of Landau damping⁶. The diagnosis of the suprathermal electrons and the investigation of their production mechanism and their transport across the magnetic field is a critical element of the PBX-M program.

During lower hybrid current drive experiments on the PLT tokamak^{7,8}, X-ray techniques^{9,10} were developed to diagnose the suprathermal electrons that are generated by the lower hybrid waves and are responsible for the production of plasma currents. In the PLT experiments single detectors were used. Radial profiles of the hard X-ray emission were obtained by an array of seven detectors viewing the plasma on vertical chords perpendicular to the magnetic field. "Tangential" profiles, in which the angle between the magnetic field and the sight-line of the x-ray emission was varied, were obtained by scanning horizontally across the plasma changing the angle on a shot to shot basis. The detectors consisted of 3" $\times$ 3" NaI(Tl) scintillator crystals each optically coupled to a photo multiplier tube. Similar measuring systems were adopted for other LH experiments, for instance on the Versator and Alcator tokamaks¹¹, JET¹², and JT60¹³.

For the lower hybrid current drive experiments that are currently carried out on the PBX-M tokamak, we have constructed and installed a tangential viewing Hard X-ray Camera¹⁴ that represents a large advance in hard X-ray techniques on tokamaks. The camera utilizes a medical X-ray image intensifier as the detector and delivers 2D images of the hard X-ray emission at a rate of approximately 300 frames per sec. Radial and tangential scans, which previously required data from numerous discharges, are now obtained in a single plasma shot. The camera allows one to actually see pictures of the suprathermal electron cloud that is produced by the lower hybrid waves, and it provides immediate feedback after a plasma shot to judge the performance of the LH current drive. The main task of the lower hybrid current drive is to increase the plasma current density at the plasma edge and to lower it near the plasma center; the studies with the Hard X-ray Camera on PBX-M have shown, that the initial hard X-ray profile in many discharges is indeed hollow - a first indication that the lower hybrid can modify the current profile¹⁵. This paper describes the features and the performance of the Hard X-ray Camera in detail.

The paper is organized in the following way: Section 2 shows the physical layout of the Hard X-ray Camera. Section 3 discusses its data acquisition system, which was taken over from the so-called

Soft X-ray Pinhole Camera of PBX-M¹⁶. In Section 4, we analyze the performance of the system as far as spatial resolution, temporal resolution, intensity, and spectral efficiency is concerned. We also report on the calibration of the camera. In Section 5, we show actual images obtained with the camera during lower hybrid current drive on PBX-M.

2. Mechanical Layout of the Hard X-ray Camera.

The bremsstrahlung emission from suprathermal electrons in forward direction is noticeably larger than the backward emission, even for mildly relativistic electrons. In order to illustrate this effect, we show in Fig. 1 bremsstrahlung emission cones for electrons of various energies⁸. The electrons are assumed to go from left to right, and the distance from the origin to a point on one of the cones is proportional to the radiated power in that particular direction, at the photon energy indicated on each cone. The figure shows that most of the bremsstrahlung is emitted in the flow direction of the suprathermal electrons. Ideally, therefore, one would like to look at the plasma from all directions, but, with only one camera available, a tangential view in the direction opposite to the current is the preferred setup.

Fig. 2 shows a mechanical layout of the Hard X-ray Camera, which is fundamentally a pinhole camera. The interchangeable aperture is made from lead: a 1/4" opening was used for most experiments. The camera looks at the plasma through a circa 2 mm thick aluminum vacuum "window". The detector is a medical X-ray image intensifier from Hamamatsu Photonics Corporation with a 9" diameter sensitive area; it will be described in detail below. The 2.2 mm Al vacuum window - together with the 1.5 mm thick aluminum entrance window of the Hamamatsu tube, and two 0.004" thick CO-NETIC metal foils in front of the Hamamatsu tube (that serve as magnetic shielding) - give rise to a 45 keV low-energy cut-off for X-ray photons. The view is such that the camera sees the whole plasma and also part of the PBX-M pusher coil armor, as shown in Fig. 2. The imaging tube creates a 20 mm diameter image on its phosphor output screen. This image is transferred by two lenses onto the front face of an 8 × 8 mm coherent fiber optic bundle. The bundle is fiber-optically coupled to a visible light intensifier (Varo

5772) which in turn is fiber optically connected to a 128×128 self scanning diode array.

A layout of the Hamamatsu tube (Model V2465P) is shown in Fig. 3. The incoming X-rays pass through the 1 mm thick aluminum entrance window and create scintillations in the approximately 0.3 mm thick cesium iodide (CsI) screen. The CsI layer has a fiber optic structure and guides the visible light generated by the X-rays to a photocathode where photoelectrons are generated (Fig. 3b). The photoelectrons are accelerated to 30 keV and imaged on a 20 mm diameter P-20 phosphor screen. The mass surface density of the cesium iodide scintillator is 134 mg / cm^2 , and, as a consequence, the photon detection efficiency drops gradually for photons with energies above 65 keV, the X-ray energy at which the absorption e-folding length equals the CsI layer thickness.

Each of the manually interchangeable "pin-hole" apertures has a bi-conical hole in a 1.5 inch thick lead plug. They are mounted in a 8" deep lead slug, which provides protection from the hard X-ray background that originates from limiters and other vacuum vessel components hit by suprathreshold electrons. Right in front of the aperture, a foil drive is installed which carries three different absorber foils (0.52 mm copper [Cu], 0.95 mm molybdenum [Mo], and 2.03 mm silver [Ag]). Without any absorber foil, the aluminum vacuum window, the aluminum entrance window of the X-ray image intensifier, and the CO-NETIC magnetic shielding foil in front of the image intensifier contribute to a low energy cut-off of 45 keV. The low energy X-ray cutoffs with the additional copper, molybdenum and silver absorber foils are 67 keV, 115 keV, and 176 keV, respectively. The foils allow determination of an effective temperature of the photon spectrum with the absorber foil method. The motion of the foil drive is accomplished by a computer-controlled stepping motor; thus foils can be changed in between shots.

The image on the 20 mm dia. phosphor screen of the Hamamatsu tube is optically transferred to the 8×8 mm fiber optic bundle by two lenses. The first lens was supplied with the Hamamatsu tube and is a f/1.2 Kowa lens with a focal distance of 85 mm. Since the image has to be demagnified, we chose a f/0.95 Bell&Howell video lens with a focal distance of 25 mm . Clearly we lose a lot of light in the process of demagnification. This could be

avoided if the demagnification were performed after the image intensification. During the first phase of operation we did not want to tamper with the working experimental setup of the original Soft X-ray Pinhole Camera¹⁶; however, we plan to change the setup for the next running period of PBX-M. In the process we also hope to substantially improve the spatial resolution of the camera, which we presume to be limited by the poor resolving power of the fiberoptic bundle and the Varo image intensifier for 8×8 mm pictures. The Varo 5772 image intensifier and the 128×128 self-scanning Reticon diode array (model MC9128) with a $60 \mu\text{m}$ center-to-center pixel spacing have also been part of the PBX Soft X-ray Pinhole Camera, and are described in detail in a PhD. thesis¹⁷

Operation of an X-ray image intensifier tube in a tokamak environment is highly susceptible to magnetic field perturbations, and thus requires careful magnetic shielding. We have surrounded the Hamamatsu imaging tube by a double-walled iron box with a total iron thickness of 1.5 inches. Magnetic field lines can still enter the iron box through a large entrance hole. The imaging tube was set back 4" from the entrance hole, and, in order to reduce the magnetic flux through the entrance hole even further, a soft-iron snout was placed around the hole. Although the tube is supplied by the manufacturer with a μ -metal shield, it proved necessary to place two additional 0.004" μ -metal foils over the input window of the tube in order to eliminate image distortions. For the detection of image distortions, we placed a grid in front of the tube. The grid was made of soldering wire, which contained a large amount of lead, and had a half-inch spacing. A piece of the grid was cut out in the middle to mark the center of the tube. The grid was also very useful for establishing a scaling between the X-ray images on the computer and the actual geometry in the tokamak.

All hard X-ray diagnostics are highly susceptible to neutron noise, and the Hamamatsu tube is no exception. The neutrons create an approximately constant background. In order to reduce noise, we have surrounded the camera by a standard neutron shield of 8 inches of boronated polyethylene and 4 inches of lead. The lead has also the function to inhibit the γ -ray background radiation from neutron activation (n - γ reactions) and the hard X-ray background radiation from the PBX-M limiters. Because the CsI layer is so thin, however, X-ray image intensifier tubes seem to be much less sensitive to neutrons than most other hard X-ray detectors. For instance, the $3 \times$

3 " sodium iodide detectors on PLT exhibited neutron noise when the number of neutrons generated by the machine exceeded $\approx 10^{10}$ neutrons per second, whereas the Hard X ray Camera on PBX-M began to show a small uniform neutron background for approximately 10^{13} neutrons per second.

3. Data Acquisition of the Hard X-ray Camera.

The data acquisition system for the Hard X-ray Camera was part of the PBX-M Soft X-ray Pinhole Camera. Although it has been documented previously^{16,17}, for completeness we want to summarize briefly its essential features. A diagram of the components is shown in Fig. 5. The Reticon diode array is read out by the Reticon model MB9000 Video Formatter, which is placed on the PBX-M platform. The timing and synchronization electronics are also located on the platform, as well as the power and high voltage supplies for the Varo image intensifier and the Reticon diode array. Some of the supplies can be controlled from the PBX-M control room. The non-standard video signal is send via fiber optics to the primary data acquisition module, a TRAPIX model 55/256 image processor from Recognition Concepts Incorporated in the PBX-M data acquisition room. The TRAPIX has an 8 bit-8 MHz non-standard video digitizer. The digitized signal is stored as 512×512 8-bit frames. Each frame contains 16 images. Since 16 frames can be acquired, a total of 256 images can in principle be stored in the TRAPIX; to date the maximum number of images stored during one shot was 64. The 512×512 frames are displayed by the TRAPIX immediately after a plasma shot on a video monitor. The TRAPIX is controlled on-line by a MicroVAX computer that is part of the PPPL VAX cluster. Execution time for the control program limits the data taking rate at the present time to 200 images per sec. We attempted to take data with 330 images/sec; the images looked fine, except that the processor randomly skipped a few images during processing. This is thought to be a problem that can be solved by improving the control program. In addition to its control function, the MicroVAX acquires and stores the data after the shot. Finally, the foil drive is also part of the data acquisition system. Its stepper motor is computer controlled via a CAMAC highway, and the position of the foil drive is read from a shaft encoder.

4. Performance of the Hard X-ray Camera.

In this section we discuss data that reflect all of the main performance characteristics of the Hard X-ray Camera. The topics treated sequentially are spatial resolution, time resolution, spectral resolution, photon detection efficiency, detection linearity, and calibration. We want to point out at the start, that the performance data as well as the testing procedures are not optimized yet and further improvements are in progress.

The spatial resolution of a pinhole camera is determined by two factors, the diameter a_1 of the pinhole and the spatial resolution a_2 of the detector. If d is the distance between pinhole and detector screen and D the distance between plasma and detector screen, then a simple calculation shows that the full-width half-maximum resolution R_{FWHM} in the plasma is

$$R_{FWHM} = \frac{D}{d} a_1 \quad \text{if } a_2 \leq \frac{D}{D-d} a_1$$
$$R_{FWHM} = \frac{D}{2d} a_1 + \frac{D-d}{2d} a_2 \quad \text{if } a_2 > \frac{D}{D-d} a_1$$

The diameter of the pinhole a_1 has been 0.25 inches in practically all of our experiments. The a_2 of the detector is not limited by the Hamamatsu tube, which has excellent spatial resolution. The manufacturer quotes 4 line pairs / mm, i.e. 0.01 inches. If we divide the width of the input screen of the tube (9 inches) by the number of pixels (113), we obtain 0.08 inches. Looking at the image of the lead wire grid, that we placed in front of the tube, we found that the resolution is only about 2 to 3 pixels, i.e. a_2 is comparable in size to a_1 . [This low value for the resolution a_2 is thought to be due to the fiberoptic coupling and the optical image intensifier. The image intensification is done on the very small 8×8 mm images of the fiber bundle. If the resolution of the fiber bundle and the optical intensifier were in the range 5 - 10 line pairs / mm, it would explain the data.] In any case, since the spatial resolution a_2 of the detector is comparable or smaller than the pinhole diameter a_1 , the first of the two formulas above is applicable, and the pinhole diameter determines the spatial resolution of the Hard X-ray Camera. Since $d = 19.3''$ and $D \cong 102''$ at the tangency point of the sight line that touches the magnetic axis, the spatial resolution R_{FWHM} in the plasma approximately equals 3.3 cm.

The temporal resolution of the Hard X-ray Camera is determined by three factors: (a) intensity considerations, (b) the decay constants of the phosphors in the optical intensifier and the X-ray intensifier tube, and (c) the speed of the data acquisition system. It seems that (b) and (c) are the limiting factors for our system, and that intensity considerations do not play a decisive role. This is manifest by the fact that we have operated with sufficient intensity at the highest data acquisition speed of 333 Hz, - although it was at the highest permissible voltages on the optical intensifier. However, as we discussed earlier, the optical coupling between the Hamamatsu tube and the fiber optical bundle is not optimized yet, and substantial gains in intensity are possible. Finally, we can trade off spatial resolution for intensity by increasing the aperture. On the other hand, the X-ray intensifier tube has a P20 phosphor, which decays initially with a time constant 2 ms but then has a long drawn out tail, as shown in Fig. 6. The 8 MHz read out speed of the Reticon diode array limits the framing rate to 488 Hz. So far the time resolution was actually limited by the speed of the TRAPIX control program to a framing rate to 200 Hz. Improvements in the control program should bring this value up to 350 Hz.

Another subject related to the intensity question is the photon detection efficiency, which in turn is related to photon noise. The manufacturer of the X-ray image intensifier quotes a quantum efficiency of 60% for 60 keV X-rays. However, this value was obtained in an ideal set up, where the total light from the phosphor screen was focused on a photo-multiplier tube. In our set-up, we have never reached such a high photon detection efficiency. We have measured the photon detection on an X-ray test stand shown in Fig. 7. X-rays emitted from an X-ray tube can reach the X-ray image intensifier through five 1 cm dia. holes drilled into a lead plate. The energy of the impinging X-rays can be varied by changing the high voltage of the X-ray tube and by placing suitable absorber foils in front of the X-ray intensifier. The spectrum and the number of photons is measured by replacing the X-ray imaging tube with a 3×3" NaI detector and performing pulse height analysis. Typical X-ray spectra are shown as an insert in Fig. 7. The determination of the photon detection efficiency proceeds in several steps: First the signal of the X-ray intensifier behind one of the holes is recorded. Usually we take the average of a 9×9 sub-matrix of the 128×128 image and subtract the background (the average of a neighbouring submatrix from a region shielded from X-rays). Then the intrinsic noise level of

the camera is established by subtracting background signals taken at different times and at different locations. The photon detection efficiency is then the inverse of the number of photons necessary to produce the photon detection level. For 50 keV photons the photon detection efficiency that we determined for the Hard X-ray Camera from these experiments was only 3%. This relatively poor detection efficiency can be improved by changing the optical coupling between the X-ray imaging tube and the visible image intensifier, as we mentioned before. However, even those improvements would not bring the efficiency up to the 60% level quoted by the manufacturer. The same measurements permit us also to estimate the photon noise for the camera. In the experiments, the noise level was approximately 0.5 bits. The photon noise for a 100 bit signal is consequently approximately 1% or 1 bit. These measurements were performed with a framing time of 100 ms and maximum amplification (1400 V) on the optical image intensifier.

Measurements on the linearity of the signal and on the dependence of the signal on high voltage of the optical image intensifier were performed by positioning the screen of a standard light source (Optronics Laboratories Inc., model 420) in front of the coupling lens and by observing the variation of the signal as a function of the distance between the tungsten halogen lamp and the aperture to the integrating sphere. The illumination is varying with the inverse square of the distance. It was found (Fig. 8) that the signal varied approximately linear with density up to approximately bit 200, and then showed a slight sign of saturation for the 50 remaining bits of the 8 bit conversion. It is presently not known where the saturation comes from. In the experiments on PBX-M, the gain (i.e. the high voltage of the optical image intensifier) is varied to adjust the camera sensitivity to the plasma hard X-ray source. Therefore it was important to know the dependence of the signal strength on intensifier high voltage. These data were again inferred from the measurements with the standard light source, and the result is shown in Fig. 9, which shows the gain as a function of image intensifier voltage. The gain is normalized to its value at the highest voltage (1400 V).

Another topic is the spectral sensitivity of the X-ray imaging tube. In Fig. 10 we show calculations of the detection efficiency of the Hard X-ray Camera versus photon energy, using the McMaster Tables¹⁸ for X-ray absorption. Plotted is the formula

$$\eta = \exp[-\mu_{Al}(h\nu)d_{Al} - \mu_{\mu m}(h\nu)d_{\mu m} - \mu_{af}(h\nu)d_{af}] \times (1 - \exp[-\mu_{CsI}(h\nu)d_{CsI}])$$

where μ denotes the x-ray absorption coefficients for the aluminum windows (subscript Al), the mu-metal foils (μm), the absorber foils (af), and the cesium iodide scintillator screen (CsI), whereas d denotes the respective thicknesses. The decrease in efficiency at low energies is due to the aluminum windows and the μ -metal foil. The steps at 35.9 and 33.2 keV are due to the K-edges in the CsI scintillator. The fall-off of the efficiency at higher photon energies is due to the fact that the CsI layer becomes more transparent to X-rays of higher energy. We also show the efficiency curves for the three different absorber foils that can be inserted into the X-ray path. Experimentally, we tried to check these calculations on the test stand. However, the experimental data showed a large random scatter of up to a factor of almost two, which we attributed to the fact that - in order to perform the measurement - the X-ray imaging tube had to be removed from the test stand and replaced by a sodium iodide detector. Within the scatter, the measurements agreed with the computations shown in Fig.10.

Finally, we want to discuss the spatial homogeneity of the detection efficiency of the Hard X-ray Camera. We already found during the optical testing with the standard calibration lamp, that the sensitivity for the optical part of the camera was not very uniform. We then tried to do a calibration with an X-ray tube. This turned out to be a difficult measurement because our X-ray tube does not emit isotropically but sends out a comparatively narrow (6 degree) beam. We therefore moved the beam across the imaging tube. Since this procedure takes about an hour and since the X-ray tube drifts during this time, the calibration is not very accurate. However, it is the only calibration method we have to date. A contourplot of the calibration file is shown in Fig. 11. It represents a matrix of multiplicative factors with which the pixels of a raw image have to be multiplied in order to get correct data. Figure 11 shows that the raw signal on the right side, i. e. the large major radius region of the plasma, is registered too faintly. The sensitivity of the tube also decreases near the outer edge of the image. The correction factor on the right side near the outer edge amounts to a factor of more than two. We want to emphasize that the correction factor encompasses all the components of the Hard X-ray Camera, and that the main contribution to the inhomogeneity seems to stem from the optical

components - from the optical coupling, optical image intensifier, and diode array - and not from the X-ray imaging tube itself.

5. Example of Images taken with the Hard X-ray Camera.

Finally we want to show three typical images that have been taken during lower hybrid current drive on PBX-M. The examples have been chosen to illustrate the variety and usefulness of data that can be obtained with this diagnostic, and also to point out some additional limitations. The quantitative interpretation and analysis of the data, and the interesting and complex physics that can be extracted from the measurements are given in concurrent publications ^{19,4,5,20,21,22,23}.

The first image that we want to discuss is Fig. 12. It shows what we call a "hollow profile". The hard X-ray bremsstrahlung radiation from the plasma has a minimum in the center of the plasma, increases with minor radius until it reaches a maximum, and then decreases and vanishes. The X-ray image is, of course, the result of a chord integration of the bremsstrahlung emission, and Fig. 13 explains how the chord integration leads to the characteristic sickle shape that strikes the eye in Fig. 12. Figure 13 represents a top view of the PBX-M tokamak: A toroidal shell volume of hard x-ray emission produced by suprathreshold electrons is indicated by the shaded region. The pusher coil, which obstructs sight lines on the inboard (small major radius) side is sketched solid black. Chord (a) has no signal. Once the line of sight intersects the shell, the signal starts to increase until it reaches a maximum for chord (b). Further inward the signal decreases because the path length through the shaded area becomes shorter. The path-length is a minimum for chord (c). From that point on the intensity increases again and reaches a maximum for chord (d). The intensity for chord (d) is larger than for chord (b) because chord (d) intersects the emitting region three times. Further to the left the signal decreases again. At the position of chord (e) the signal decreases by a factor two, because the pusher coil obscures the view on the emission region behind the coil. This effect produces the shadow of the pusher coil in Fig. 12. The strongest intensity in Fig. 12 actually occurs above or below the mid plane near the end of the sickle. If one draws pictures analogous to Fig. 13 for chords that intersect the shell above or below the midplane, one finds that the longest path length through the shell occurs for certain chords above and below the midplane. All these

features have been quantitatively modeled with a computer code, the PBXRAY code (Ref. 19). Another noteworthy feature in Fig. 12 is the shadow of the lead grid in front of the X-ray image intensifier tube that was inserted into the X-ray path in order to monitor deformations of the image. The lead grid is not sharp but is strongly blurred because of the poor optical resolution of the camera. The contours in Fig. 12 were created by changing the greyscale of the display for certain bit values..

The second image (Fig.14) has been obtained from a circular discharge. In the midplane of PBX-M, the plasma normally extends from the pusher coil out to the outside limiter. As a consequence, the height of a circular plasma is much smaller than the height of a bean-shaped discharge. A comparison of Fig. 12 and Fig. 14 shows that this is indeed the case. Fig.14 does not exhibit the characteristic sickle shape; this particular discharge had a broadly peaked X-ray emission profile with a flat top.

Finally we want to discuss Figure 15, which was recorded during a discharge in which strong MHD activity (locked modes and disruptions) led to an increase in the transport of suprathermal electrons to the plasma edge. The "hot spots" in Fig. 15 are regions of very high hard X-ray emission that occur because suprathermal electrons hit physical obstacles near the plasma boundary. The hot spots are located always at the same place, and the obstacles have been identified as the armor of the pusher coil which often serves as plasma limiter, the "Mirnov Dens Pack" array, a magnetic diagnostic that is located close to the plasma edge in view of the Hard X-ray Camera, and graphite protection bars on the PBX-M stabilizer plates. These hot spots interfere with the plasma bremsstrahlung measurements. However, since they occur only in abnormal discharges and are easily recognized because they occur only at certain well defined locations, the occasional presence of hot spots has not been a serious problem. On the contrary, they seem to provide a unique opportunity to study the MHD induced transport of suprathermal electrons to the plasma edge.

6. Summary.

The feasibility of 2D hard X-ray imaging to diagnose suprathermal electrons during lower hybrid current drive has been demonstrated on PBX-M. We have constructed and operated a hard

X-ray pinhole camera with a tangential view of the plasma. The detector consists of a 9" dia. medical X-ray image intensifier. 64 images are recorded during one plasma shot, which have approximately a 3 cm spatial resolution in the plasma and a 3 ms temporal resolution. The camera has identified discharges with hollow X-ray emission profiles. The camera is used to study the coupling of lower hybrid waves to plasma electrons and to investigate the physics of suprathermal electrons in tokamak plasmas.

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- †† CRIP, Budapest, Hungary.
- ††† JET, Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, U.K.
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Figure Captions

Fig. 1: Bremsstrahlung emission cones for electrons with energies of 20, 50, 100, 200 and 500 keV. Parameter of the curves is the energy of the bremsstrahlung photons. Electrons go from left to right. Consider a vector from the origin to a point on a curve; the angle between it and the x-axis be θ . The length of the vector is proportional to the bremsstrahlung power emitted in direction θ at the photon energy associated with the particular curve.

Fig. 2: Mechanical layout of the Hard X-ray Camera. The pinhole camera provides a tangential view of the PBX-M plasma through a 2 mm thick aluminum vacuum window. The lead aperture (pinhole) is interchangeable. The absorber foil drive has four positions: (1) open, (2) .05 mm Cu, (3) 1.0 mm Mo, and (4) 2.0 mm Ag. The detector is a 9" diameter X-ray image intensifier (Hamamatsu V2465P). The X-ray imaging tube is surrounded by a double walled iron box for magnetic shielding. The 4" lead shielding and the 8" borated polyethylene shielding provide attenuation for the neutron, γ -ray, and hard X-ray background. The visible output from the X-ray intensifier is imaged on a fiber optic bundle, amplified by an optical image intensifier and recorded by a self scanning Reticon diode array.

Fig. 3: X-ray image intensifier. (a) X-ray photons entering the tube through the 1 mm thick aluminum input window produce scintillation light in the input phosphor screen. The light is converted into electrons at the photo cathode. The electrons are accelerated to 30 keV and electrostaticly imaged on the output phosphor screen. (b) and (c): Details of the input phosphor screen. The CsI has a fiber optic structure that guides the scintillation light to the photo cathode. (Courtesy of Hamamatsu Photonics Corporation).

Fig. 4: Photograph of the Hard X-ray Camera on PBX-M, showing the Hamamatsu tube as it is put into the iron box, the polyethylene shielding, (on the left) the lens that couples the visible image to the fiber optic bundle, and the tracks that allow to split the shielding apart for easy access to the imaging tube.

Fig. 5: Schematics of the data acquisition system of the Hard X-ray Camera on PBX-M.

Fig. 6: Decay of the P20 phosphor in the X-ray image intensifier. (Courtesy of Hamamatsu Photonic Cooperation).

Fig. 7: X-ray Test Stand for the X-ray imaging intensifier. The inset shows spectra that were obtained when we replaced the X-ray image intensifier by a NaI(Tl) detector and performed pulse height analysis.

Fig. 8: Camera signal vs. light intensity. The light intensity was varied by changing the distance between the screen of a standard light source and the coupling lens. The signal varies linearly with intensity approximately up to bit 200. For higher intensity saturation occurs.

Fig. 9: Comparative gain in the linear region vs. high voltage on the optical image intensifier. The gain was normalized on the maximum permitted gain (high voltage equals 1400 V).

Fig. 10: Calculated photon detection efficiency versus photon energy. (Solid curve without foils, dotted curve Cu-foil, dashed curve Mo-foil, dashed-dotted curve Ag-foil).

Fig. 11: Contourplot of the Hard X-ray Camera calibration file. This file was produced by illuminating the X-ray image intensifier with 40 keV X-ray radiation from an X-ray generator tube. The X-ray beam from the generator was pointed at different spots of the image intensifier. In an iterative procedure a calibration factor was determined for each pixel, by which the intensity has to be multiplied in order to obtain a homogenous image for uniform illumination.

Fig. 12: Hard X-Ray image from a discharge with a hollow radiation profile. The center of PBX-M is on the left side. "Pusher Coil" refers to the shadow of the pusher coil armor that is caused by the obstruction of the X-ray line of sight behind the pusher coil. "Grid" refers to the shadow produced by a lead wire grid. The stem, i. e. the somewhat brighter area in the lower left corner, is not real; it is generated while the computer rotates the image.

Fig. 13: Chords through a plasma with a hollow radiation profile in the mid plane of the plasma torus.

Fig. 14: Image of a circular discharge.

Fig. 15 Image of a discharge showing "hot spots", i.e. points of strong hard X-ray emission which are produced by energetic electrons that leave the plasma and hit obstacles near the boundary of the discharge, for instance the pusher coil, limiters on the stabilizer plates, and the so called "Mirnov dense-pack", a magnetic diagnostic located close to the plasma edge.

83X0130

Fig. 1

HARD X-RAY CAMERA ON PBX-M

Fig. 2

Photo: Electron Microscope Photograph
of CsI Input Phosphor Screen

X-RAY IMAGE INTENSIFIER

Fig. 3

FIG. 4

Fig. 5

Fig. 6

X-RAY TEST STAND

PHOTON SPECTRUM MEASURED WITH 3×3" NaI DETECTOR

Fig. 7

Fig. 8

Fig. 9

Fig. 10

PPPL#93X0034

Fig. 11

Plasma Center

INTEGRATION PATHLENGTHS FOR HOLLOW PROFILE

Fig. 13

Shot 291488 Frame 59

Pusher Coil

Mimov Densepack

Shot 290299 Frame 27

Pusher Coil Armor

Stabilizer Plate
Protector Bars

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