Princeton Plasma Physics Laboratory

PPPL- 4283

PPPL- 4283

Development of a High Resolution X-Ray Imaging Crystal Spectrometer for Measurement of Ion-Temperature and Rotation-Velocity Profiles in Fusion Energy Research Plasmas

K. W. Hill, M. L. Bitter, Ch. Broennimann,
E. F. Eikenberry, A. Ince-Cushman, S. G. Lee,
J. E. Rice, S. Scott, and R. Barnsley

January 2008

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

Development of a High Resolution X-Ray Imaging Crystal Spectrometer for Measurement of Ion-Temperature and Rotation-Velocity Profiles in Fusion Energy Research Plasmas*

K. W. Hill[1], M. L. Bitter[1], Ch. Broennimann[2], E. F. Eikenberry[2], A. Ince-Cushman[3], S. G. Lee[4], J. E. Rice[3], S. Scott[1], and R. Barnsley[5]

[1]*Princeton University Plasma Physics Laboratory, Princeton, NJ, USA*
[2]*SLS, Paul Scherrer Institute, Villigen, Switzerland*
[3]*PSFC, MIT, Cambridge, MA, USA*
[4]*NFRC, Korea Basic Science Institute, Daejeon, Korea*
[5]*Queen's University Belfast and EFDA/JET*
(Received 6 December 2006 / Accepted day month year)

A new imaging high resolution x-ray crystal spectrometer (XCS) has been developed to measure continuous profiles of ion temperature and rotation velocity in fusion plasmas. Following proof-of-principle tests on the Alcator C-Mod tokamak and the NSTX spherical tokamak, and successful testing of a new silicon, pixilated detector with 1 MHz count rate capability per pixel, an imaging XCS is being designed to measure full profiles of T_i and v_ϕ on C-Mod. The imaging XCS design has also been adopted for ITER. Ion-temperature uncertainty and minimum measurable rotation velocity are calculated for the C-Mod spectrometer. The affects of x-ray and nuclear-radiation background on the measurement uncertainties are calculated to predict performance on ITER.

Keywords: ion-temperature, rotation velocity, diagnostic, x-ray, crystal spectrometer, detectors, C-Mod, ITER.

1. Introduction

Measurement of radial profiles of ion temperature (T_i) and toroidal rotation velocity (v_ϕ) are extremely important for understanding and modeling thermal and impurity transport toward optimizing fusion performance. Historically two main techniques have been used for these measurements, charge exchange recombination (CXR) spectroscopy and x-ray crystal spectroscopy (XCS). For large, high density plasmas such as those in ITER, however, the neutral beam required for CXR will be severely attenuated in the plasma core, resulting in low signal intensity. Thus, it is important to develop the XCS technique for reactors. Previous XCS systems had only 1 – 5 single chord views of the plasma, requiring multiple instruments and providing poor spatial resolution [1,2].

Recently, however, a new type of imaging XCS has been developed, which can measure continuous radial profiles of high resolution impurity x-ray spectra using only a single, spherically bent crystal and a single 2-dimensional x-ray detector [3]. Proof-of-principal experiments were done on the Alcator C-Mod and TEXTOR tokamaks and the NSTX spherical tokamak. The time resolution of the imaging XCS in these experiments, however, was severely limited by the low global count-rate capability (< 400 kHz) of the available 2d multiwire proportional counters (MWPC). For example, in the C-Mod measurements, less than 0.5% of the available intensity of Ar XVII line radiation was sufficient to saturate the MWPC. Also the position resolution of the earliest MWPC detectors (>0.5 mm) was marginal for providing high resolution spectra suitable for Doppler-broadening T_i measurements ($\lambda/d\lambda > 5000$).

The count-rate limitation problem was solved by the development of a revolutionary new 2d x-ray detector, which has recently become available. This is the Pilatus II detector, which has several orders of magnitude higher count-rate capability and better position resolution than the 2d MWPC used for our imaging XCS experiments [4]. The Pilatus II is a pixilated silicon detector, having ~ 100,000 pixels of dimensions 0.172 x 0.172 mm^2 and an overall size of about 8 x 3.4 cm. The high count-rate capability results from separate processing and counting electronics for each pixel with count-rate capability of 1 MHz per pixel. With these detectors one should be able to

author's e-mail: khill@pppl.gov

use the full intensity available from the C-Mod tokamak, resulting in total count rates of several 10s of MHz to 100 MHz. The spectral image then should be divisible into 30 spectra from continuous radial chords of < 1 cm width with >10,000 counts accumulated in 10 ms. Following successful testing of a Pilatus II detector with Ar XVII x rays at 3.1 keV, it was decided to build an imaging XCS for measurement of full profiles of T_i and v_ϕ on C-Mod using 3 Pilatus detectors.

The imaging XCS has also been chosen as the design to use on ITER, and designs, performance calculations and neutronics calculations have been done to predict the performance of such a spectrometer on a burning-plasma reactor [5]. The fact that very high intensity signals were available from small area crystals on the high density tokamak, C-Mod, suggests that small crystals, of order a few centimeters, can be used for ITER, thus enabling small area neutron collimators to minimize neutron streaming.

2. Imaging XCS proof-of-principle test results

Images of high resolution spectra from +/- 10 cm in C-Mod and from +/- 40 cm in NSTX have been measured, and the results have been presented previously [3,6]. A sample of a spatially imaged spectrum of Ar XVII Kα x rays is shown in Fig. 2 to illustrate the type of data obtained from the imaging XCS. The image has very good spatial and spectral resolution. Analysis of the width of the line w in Fig. 1 has enabled determination of T_i.

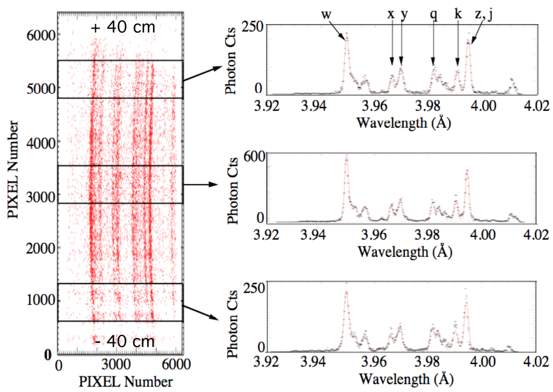

Fig. 1 (left) Image of high resolution Ar XVII Kα spectra from NSTX spatially resolved from 40 cm below midplane to 40 cm above midplane. (right) Spectra from 3 spatial regions obtained by vertically summing data within boxes on image at left side.

3. Testing of Pilatus detector

The Pilatus II detector, however, was developed for protein crystallography experiments on synchrotron radiation beamlines, which are done mainly at 8-12 keV x-ray energy, and the Ar XVII lines are near 3.1 keV. Thus, a Pilatus II detector was tested on an existing C-Mod HIREX spectrometer chord to prove its applicability to low energy x rays. Figure 2 shows an image of the spectrum from the Pilatus II detector integrated over a C-Mod discharge.

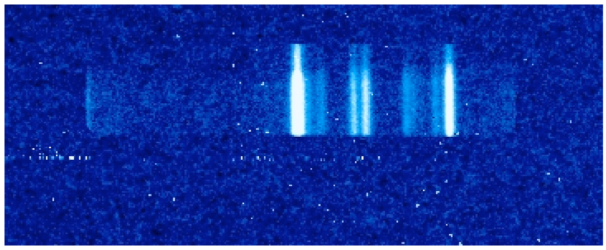

Fig. 2 Pilatus II image of x-ray spectrum from HIREX spectrometer integrated over a C-Mod discharge.

Figure 3 shows a comparison of the spectrum from Fig. 2 normalized and compared with a spectrum from another HIREX spectrometer using the usual position-sensitive proportional counter, but viewing a slightly different plasma chord. The Pilatus spectrum is very similar to that of the MWPC.

The time history of the line w from the Pilatus II detector spectrum is compared with the stored energy in Fig. 4. Figure 5 shows that the background count rate, derived from the lower half of the image of Fig. 2, which was not exposed to x rays, is proportional to the plasma neutron source strength, and is, thus, due to the neutrons and associated gamma rays.

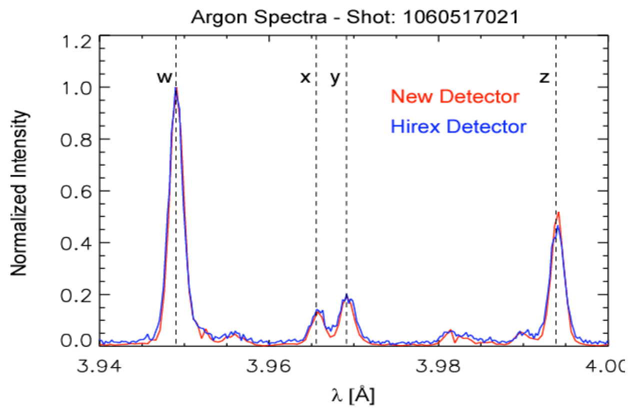

Fig. 3 Comparison of Pilatus II spectrum on a C-Mod HIREX spectrometer with that of a proportional counter on a neighboring spectrometer.

4. Imaging XCS for Alcator C-Mod and ITER tokamaks

Following proof-of-principle demonstrations of the imaging XCS, this concept was adopted as the configuration for the ITER XCS. Also, following successful testing of a Pilatus II detector on C-Mod, it was decided to build an imaging XCS using Pilatus detectors

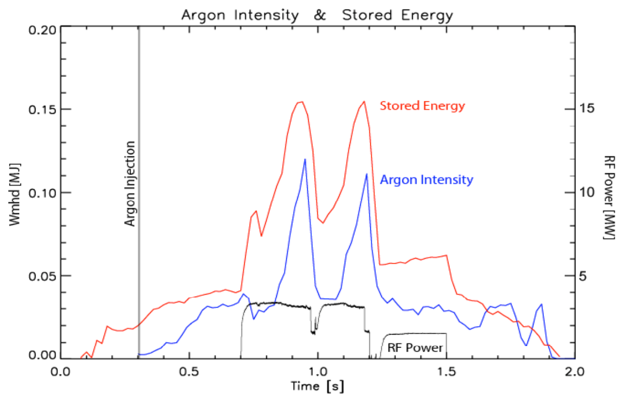

Fig. 4 Comparison of time history of line w with that of the plasma stored energy.

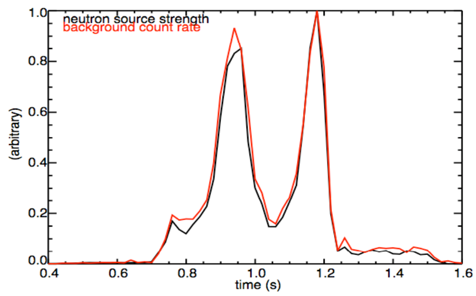

Fig. 5 Comparison of time history of Pilatus II background (red) with the plasma neutron rate (black).

detectors for measurement of full radial profiles of T_i and v_ϕ on C-Mod.

Figure 6 shows the range of view anticipated using 3 Pilatus II detectors and 2:1 demagnification. The detectors are on the left, and the plasma is depicted by the red curve on the right.

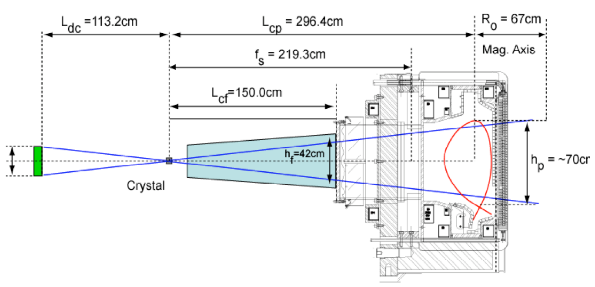

Fig. 6 Schematic of imaging XCS view of C-Mod plasma cross section.

5. Effects of background on performance of XCS

It is important to minimize uncertainties in measurement of T_i and v_ϕ. Ti is determined from the width of a spectral line, and v_ϕ is measured from the line wavelength shift. Multiple factors contribute to the uncertainties, such as inherent spectrometer resolving power, binning by the detector of the continuous spectral line intensity distribution into strips of finite width, statistical uncertainty from fitting a Gaussian function to the spectral line, and background from x-ray continuum or nuclear radiation (neutrons and gamma rays). In this section we consider only the statistical and line-background contributions.

The statistical contributions to the uncertainty in measurement of the line position and width are given by Eqs 1 and 2, respectively [7],

$$\sigma_\mu = \frac{\sigma_I}{\sqrt{N_I}}\sqrt{1+\frac{\sigma_B{}^2 N_B}{\sigma_I{}^2 N_I}} \quad (1)$$

$$\sigma_S = \frac{\sigma_I}{\sqrt{2N_I}}\sqrt{1+\frac{\sigma_B{}^4 N_B}{\sigma_I{}^4 N_I}} \quad (2)$$

where σ_μ and σ_S are, respectively, the uncertainties in the position and width of the Gaussian, σ_I and σ_B are the width parameters for the line and background, and N_I and N_B are the number of counts in the line and background. Numerical simulations were done in IDL in which a random Gaussian distribution of N_I counts, using the procedure RANDOMN, was binned into a finite number of intervals, using the procedure HISTOGRAM. The resulting synthetic approximately Gaussian line shape was then fit with a Gaussian function using the procedure GAUSSFIT. This procedure was repeated a large number of times, typically 10,0000 times, and the mean and standard deviation of the fitted Gaussian position and width were determined. Fortunately the numerical simulations agreed with equations 1 and 2 without background (N_B=0). Thus, Eqs. 1 and 2 were used to predict the performance of the C-Mod imaging XCS without background. Then the same numerical experiments were done, but now including the addition of background counts using RANDOMU. Different ratios of peak height to background height were considered. The results of these calculations are shown in Fig. 8 and will be discussed later.

Figure 7 shows the results of using Eq. 1, with N_B=0, to calculate the minimum toroidal velocity measurable, assumed to be equal to the statistical uncertainty in the v_ϕ measurement, for the C-Mod spectrometer, with crystal radius of curvature of 1.4 m, a Bragg angle of 60.535 degrees, and assuming a 33% view of the toroidal component of plasma rotation. These calculations neglect any other possible contributions to the uncertainty in measurement of the line position, which may further increase the minimum measurable velocity.

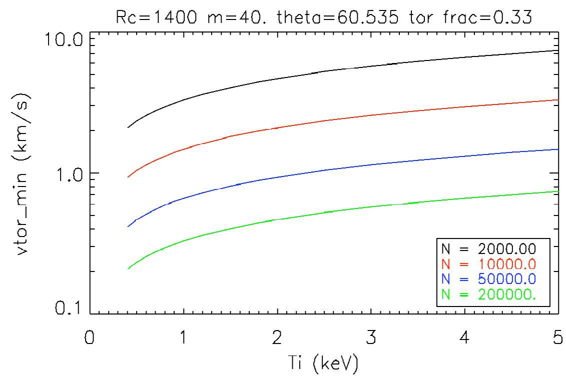

Fig. 7 Calculations of minimum measurable toroidal rotation velocity for the C-Mod imaging XCS as a function of the ion temperature and number of counts in the x-ray line.

To estimate the statistical uncertainty in the T_i measurement for lines with no background we use the fact that T_i is proportional to σ_S^2. From this relation and from Eq. 2, with $N_B = 0$, we derive

$$\frac{dTi}{Ti} = \frac{2d\sigma_I}{\sigma_I} = \sqrt{\frac{2}{N}}. \qquad (3)$$

Thus, the statistical contribution to the Ti measurement becomes of order 1% when N becomes about 10,000.

We used numerical simulations of a Gaussian peak with a random uniform background, as discussed earlier, to calculate the increase in uncertainty in measurement of the position and width of the Gaussian, when background is added, relative to the uncertainties without background. The results are shown in Fig. 8.

From Fig. 8 we see that the uncertainties in measurement of centroid position and line width are increased by factors of 2 and 3, respectively, for a background height equal to the peak height, relative to the case of no background. Thus, since $T_i \sim \sigma_I^2$, $dT_i \sim 2d\sigma_I$, and we expect the increase in certainty in measuring T_i is about 6 times. So for a line with 10,000 counts, the uncertainty in T_i would increase from 1% to 6%.

6. Conclusions

An imaging x-ray crystal spectrometer successfully measured profiles of Ar XVII spectra on NSTX and C-Mod.

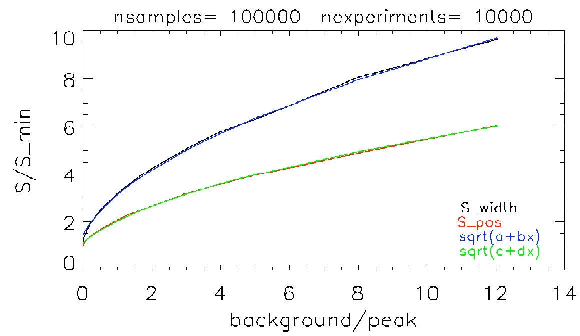

Fig. 8 Relative increase of uncertainty in measurement of Gaussian width and position as a function of ratio of background height to height of Gaussian by itself, normalized to values with no background.

A new, very fast detector with good position resolution will enable use of the full intensity available from C-Mod, and should enable measurement of 20-40 points on the profile with 10 ms time resolution. With these developments, an imaging XCS is being built to measure full profiles of T_i and v_ϕ on C-Mod. Designs and neutronics calculations are being done for a set of imaging XCS systems for ITER.

* Work supported by U. S. Department of Energy under contract number DE-AC02-76-CHO-3073 and grant number 1083.

References

[1] J. E. Rice *et al.*, Rev. Sci. Instrum. **66**, 752 (1995)
[2] M. Bitter et al., TFTR vertical XCS array paper
[3] M. Bitter *et al.* Rev. Sci. Instrum. **75**, 3660 (2004)
[4] Ch. Broennimann *et al.*, J. Synchotron Radiation **13**, 120 (2006)
[5] R. Barnsley et al., Rev. Sci. Instrum **75**, 3743 (2004); and report from this conference.
[6] M. Bitter *et al.*, presented at the 15th International Room Temperature Semiconductor Workshop, October 29 – November 4, San Diego, CA
[7] I. H. Hutchinson, "Statistical Uncertainty in Line Shift and Width Interpretation," unpublished report.

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov