X-Ray Spectroscopy

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X-Ray Imaging Crystal Spectrometer for measurements of Ti and Te profiles and ionization equilibrium

Proposed in 1998: M. Bitter, K. W. Hill, A. L. Roquemore, et al., Rev. Sci. Instrum. **70**, 292 (1999)

Patented in 2001: US Patent 6,259,763 B1

Funded in 2002: by a grant from the Department of Energy for the Development of Diagnostic Systems for Magnetic Fusion Energy Sciences Experiments, LAB 01-25

A prototype will be built in 2003 at NSTX. - Large 2D detectors are developed in collaboration with G. Smith and P. Beiersdorfer from the Brookhaven and Livermore National Laboratories, S. G. Lee from KSTAR, G. Bertschinger from TEXTOR, and O. Siegmund, Sensor Sciences LLC, Pleasant Hill, CA 94523.

Outline

I. **Advantages of X-ray spectroscopy**

II. **Results from the present NSTX X-ray crystal spectrometer** *and* performance estimates for an upgraded X-ray imaging crystal spectrometer

III. **Imaging properties of a spherical crystal** *and* instrumental parameters for the upgraded X-ray imaging crystal spectrometer at NSTX

IV. **Developments of large 2D position-sensitive detectors**

V. **ITER-relevant experiments with krypton at JET** to test the performance of X-ray imaging crystal spectrometers for ITER

VI. **Conclusions**

I. Advantages of X-ray spectroscopy *(Introduction)*

- **High resolution X-ray spectroscopy has made invaluable contributions** to tokamak experiments by providing data on the **central** ion and electron temperatures, **$T_i(0)$** and **$T_e(0)$,** the **central toroidal** plasma **rotation**, **$v_t(0)$**, and the **ionization equilibrium**. *It has also been important for experimental verifications of atomic theories and interpretation of stellar flares.*

- **However, with respect to the measurement of radial profiles** of plasma parameters, X-ray spectroscopy has not been competitive with optical methods, such as the Charge-Exchange Recombination Spectroscopy (CHERS) - due to the lack of lenses, mirrors, and fiber bundles for the X-ray region.

- **This longstanding problem will be solved** with the proposed new type of X-ray imaging crystal spectrometer, which can provide spectra from an, in principle, unlimited number of sightlines through the plasma **with only one spherically bent crystal**, – so that one can obtain profiles *and gradients* of plasma parameters.

The main advantages of X-ray spectrometer are:

- **It can be used for all experimental conditions**, which include plasmas with pure ohmic heating as well as plasmas with RF and neutral-beam heating.

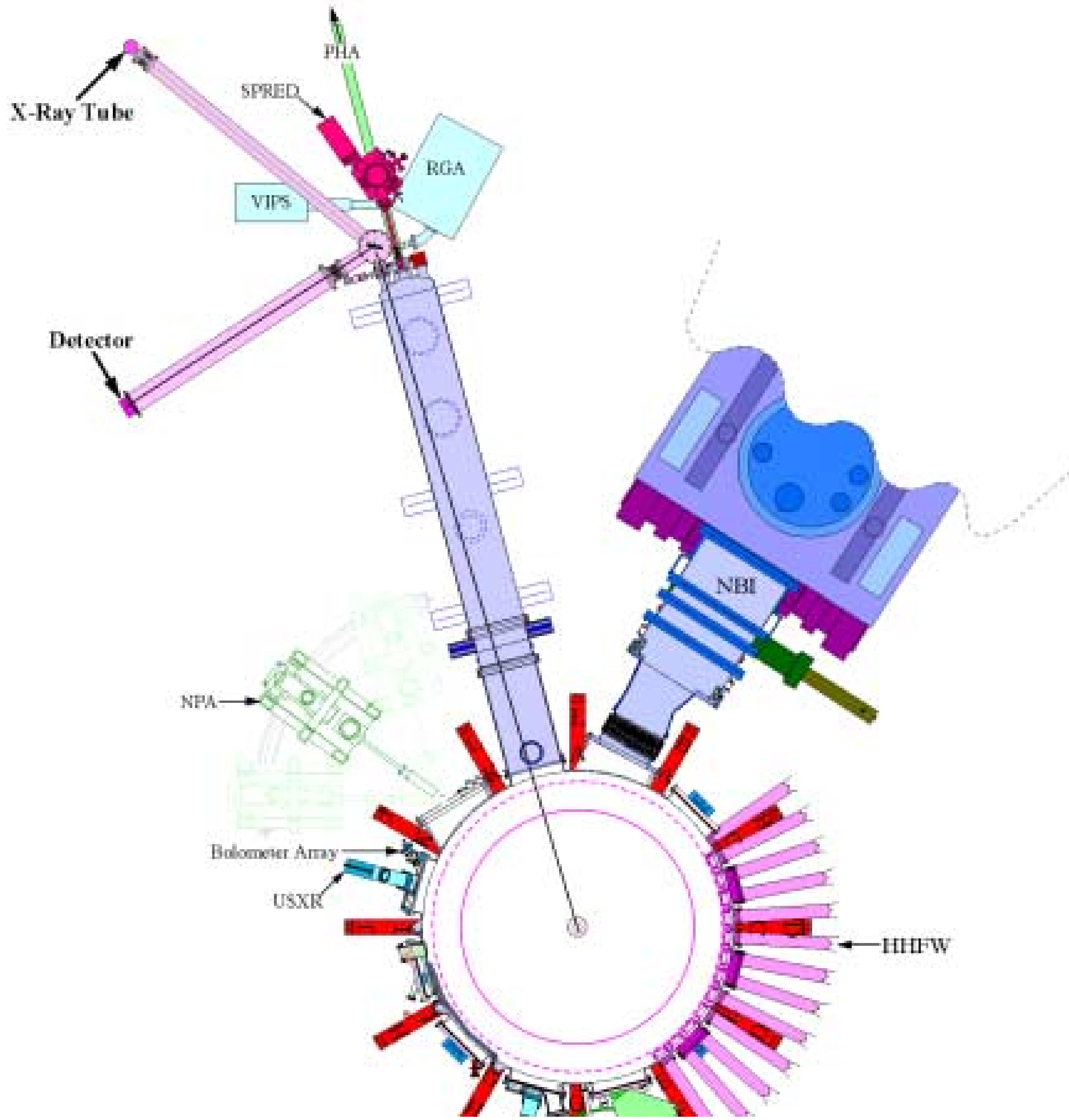
- **A cross-calibration of the spectra from the different lines of sight through the plasma will not be necessary**, since all the spectra are obtained by the same crystal, and measurements of radial profiles of line ratios will therefore be very reliable.

- **Contrary to CHERS, X-ray spectroscopy does not require a neutral beam** - which in many cases perturbs the plasma and which will not penetrate to the center of the plasma of future large tokamaks, such as ITER.

- **For these reasons, X-ray spectroscopy is attractive** for the diagnosis of plasmas without neutral beams, such as ohmic and RF heated plasmas, - and as a Ti diagnostic for future large tokamas, such as ITER.

- **In addition to the** *(proof-of-principle)* **prototype instrument at NSTX, further X-ray imaging crystal spectrometers are planned** for TEXTOR, KSTAR and W7-X Stellarator. ITER-relevant experiments with krypton at JET are proposed to test the performance of an imaging crystal spectrometer for ITER.

II. **Results from the present NSTX X-ray crystal spectrometer** and performance estimates for an upgraded imaging spectrometer.



II. Instrumental parameters of the existing crystal spectrometer

- **The present NSTX X-ray crystal spectrometer consists of a spherically bent 110 quartz crystal** and a conventional 1D position-sensitive multi-wire proportional counter. It is mounted at the end of the NSTX pump duct and records spectra of ArXVII at a Bragg angle of 54° from a central line of sight through the plasma.

- **A small argon gas puff** is applied at –500 ms for a duration of 10 ms before a NSTX discharge. This gas puff is seen as a small pressure blip of 10^{-7} Torr on a fast ion gauge and does not perturb the plasma.

- **An *in situ* calibration** can be performed with an X-ray by rotating the crystal by 72°.

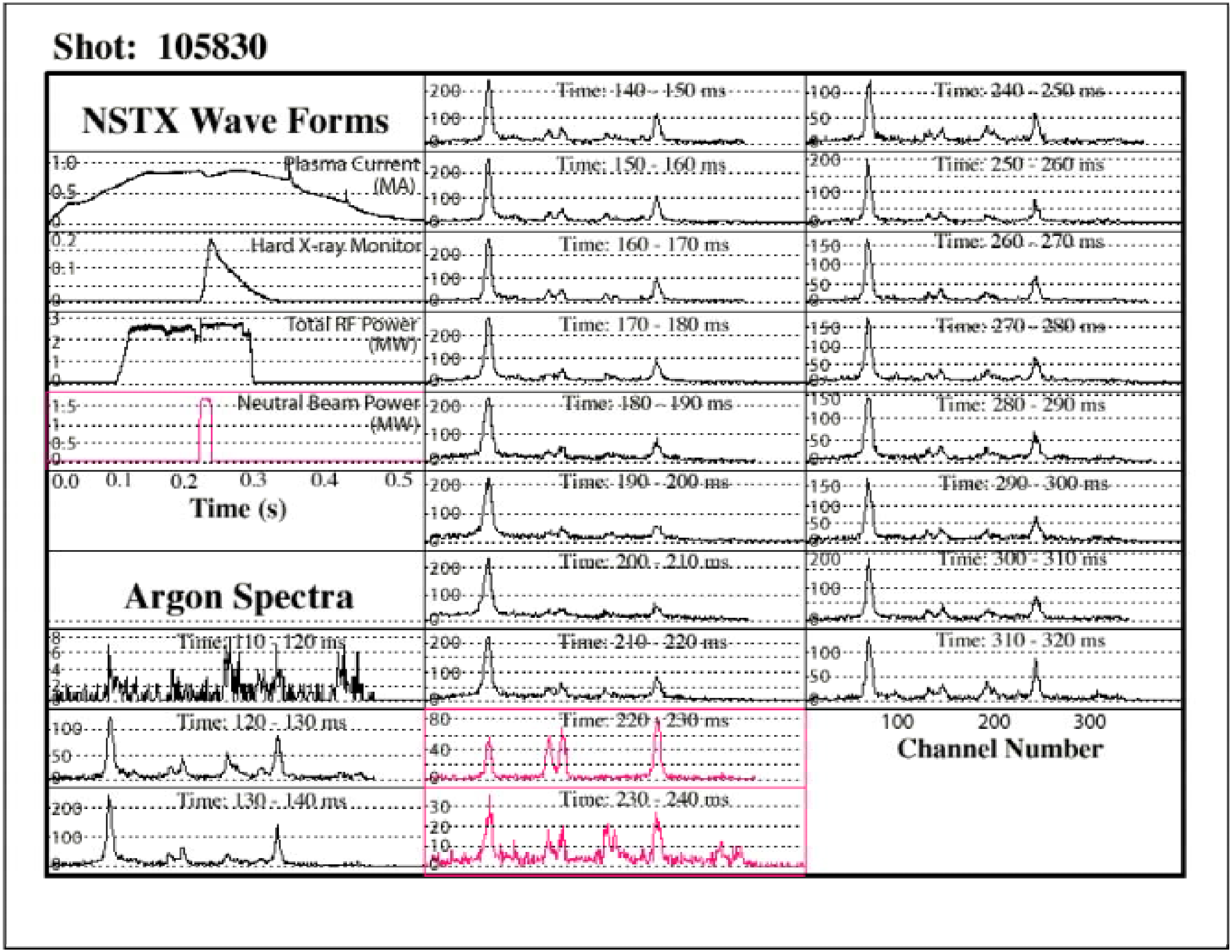
- **The spectrometer will be upgraded** to an imaging spectrometer by replacing the 1D detector with a 10 cm x 30 cm large 2D position-sensitive multiwire proportional counter with a count rate capability of 500 kHZ. 2D detectors with higher count rates of several MHZ are presently developed.

- **providing spatial resolution** in the plasma in a direction perpendicular to the horizontal mid-plane of NSSTX.

Experimental Results

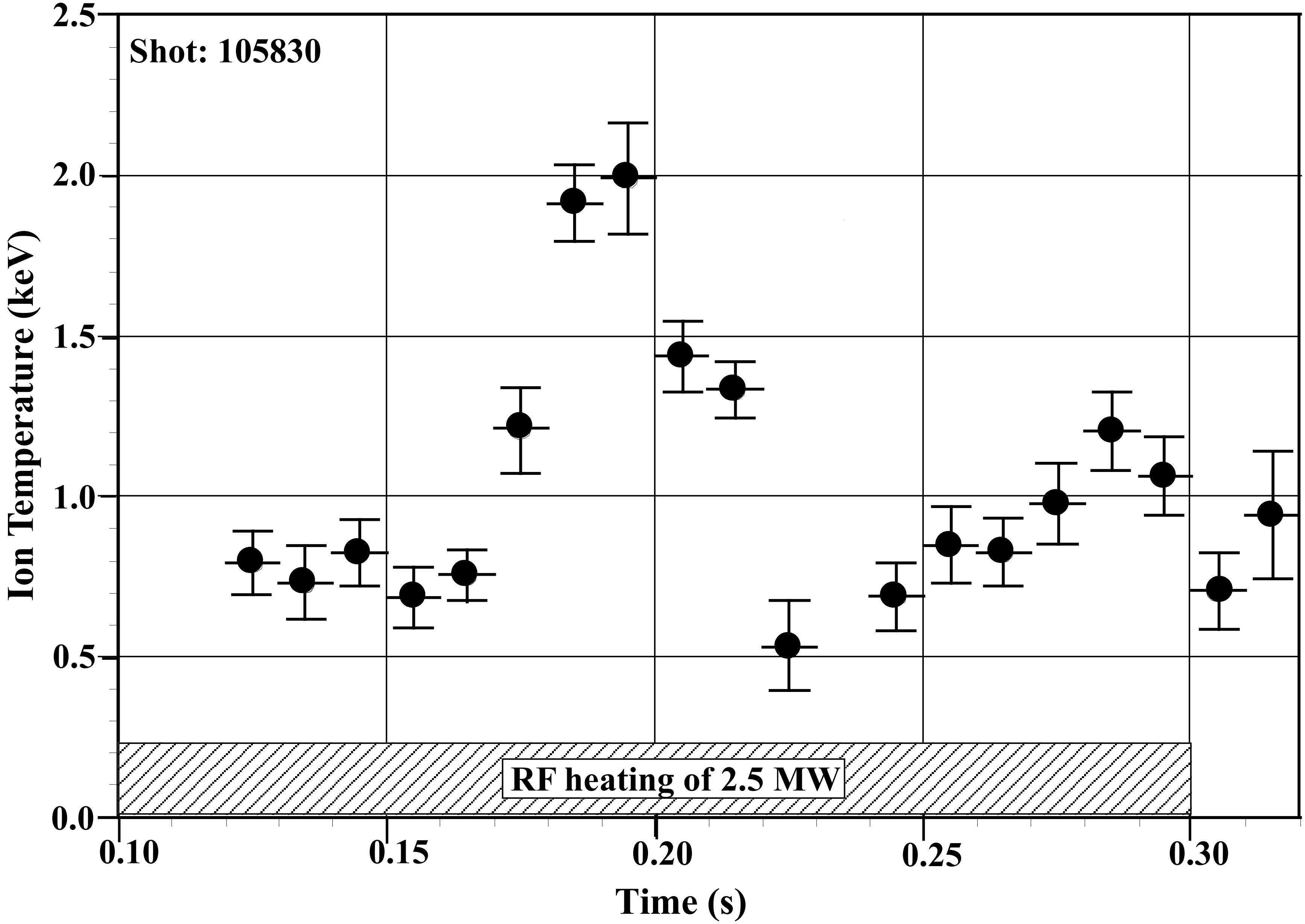
- **The following figure shows raw spectral data** from shot 105830. An RF (High Harmonic Fast Wave) heating pulse of 2.5 MW was applied from 0.1 to 0.3 s and a neutral beam was injected during the period from 220 to 240 ms to facilitate measurements of a Ti profile by CHERS. Spectra of the helium-like lines of ArXVII and associated lithium-like satellites of ArXVI were obtained with a time resolution of 10 ms.

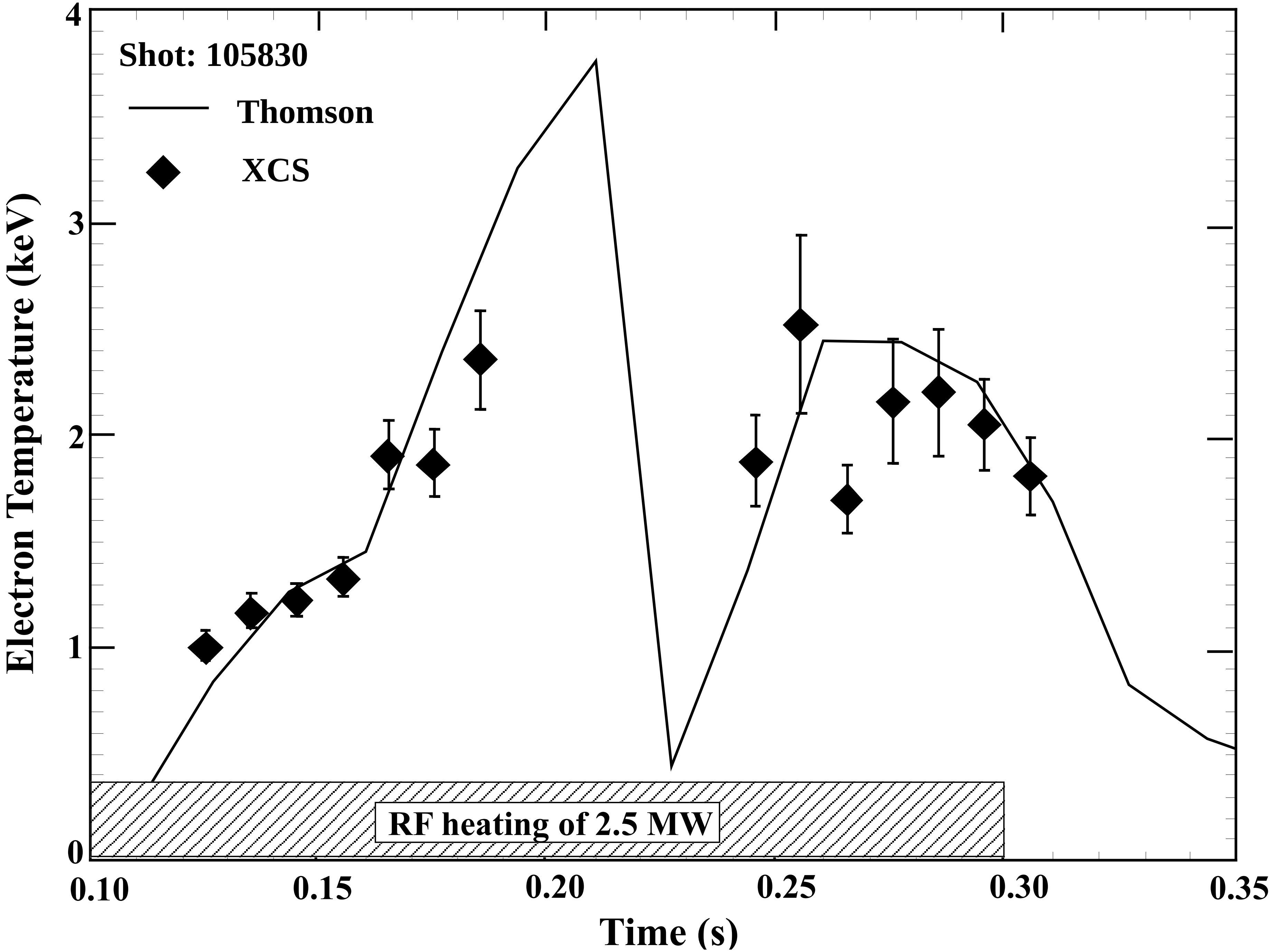
- **The neutral beam used by CHERS greatly perturbs the ionization equilibrium and possibly other plasma parameters.** Note that the spectrum obtained during the period from 220 to 230 ms shows only the helium-like lines of ArXVII but none of the numerous dielectronic satellite lines of ArXVI. This spectrum must be due to charge-exchange recombination of hydrogen-like argon, ArXVIII, with the injected energetic deuterium atoms from the neutral beam. Since no dielectronic satellites are present, we the helium-like and lithium-like argon, ArXVII and ArXVI, must have been entirely recombined to lower charge states. **Because of these severe perturbations of the plasma by the neutral beam, CHERS is not the appropriate diagnostic for purely RF and ohmically heated plasmas**.



Shot: 105830
NSTX Wave Forms
Plasma Current (MA)
Hard X-ray Monitor
Total RF Power (MW)
Neutral Beam Power (MW)
Time (s)
Argon Spectra
Time: 110 - 120 ms
Time: 120 - 130 ms
Time: 130 - 140 ms
Time: 140 - 150 ms
Time: 150 - 160 ms
Time: 160 - 170 ms
Time: 170 - 180 ms
Time: 180 - 190 ms
Time: 190 - 200 ms
Time: 200 - 210 ms
Time: 210 - 220 ms
Time: 220 - 230 ms
Time: 230 - 240 ms
Time: 240 - 250 ms
Time: 250 - 260 ms
Time: 260 - 270 ms
Time: 270 - 280 ms
Time: 280 - 290 ms
Time: 290 - 300 ms
Time: 300 - 310 ms
Time: 310 - 320 ms
Channel Number

- **The shortcomings of CHERS as a Ti-diagnostic for purely RF heated discharges** are also evident from the following figures showing the time histories of the ion and electron temperatures for shot 105830. The experimental points for Ti and Te which include statistical error bars were obtained from the Doppler width of the argon lines and argon line ratios, respectively. Also shown for comparison are the electron temperature data from Thomson scattering. Note the sharp drop of Te and Ti during the period of neutral beam injection. The Ti-value of 500 eV obtained during this period from the Doppler width of the argon lines was in good agreement with the peak value of the ion temperature profile measured by CHERS. **However, it should be noted that the CHERS measurement of the Ti-profile is an instantaneous measurement made at a single predetermined time to keep the perturbations of the RF heated plasma by the neutral beam to a minimum. CHERS may therefore entirely miss an interesting time evolution of the ion temperature.** Also note that due to the absence of dielectronic satellites during the time of neutral beam injection it was not possible to obtain a Te-measurement from the argon spectra. For electron temperatures above 2.5 keV, the satellite-to-resonance line ratios are too weak for reliable Te-measurements from the argon spectra – further explanations are given below.

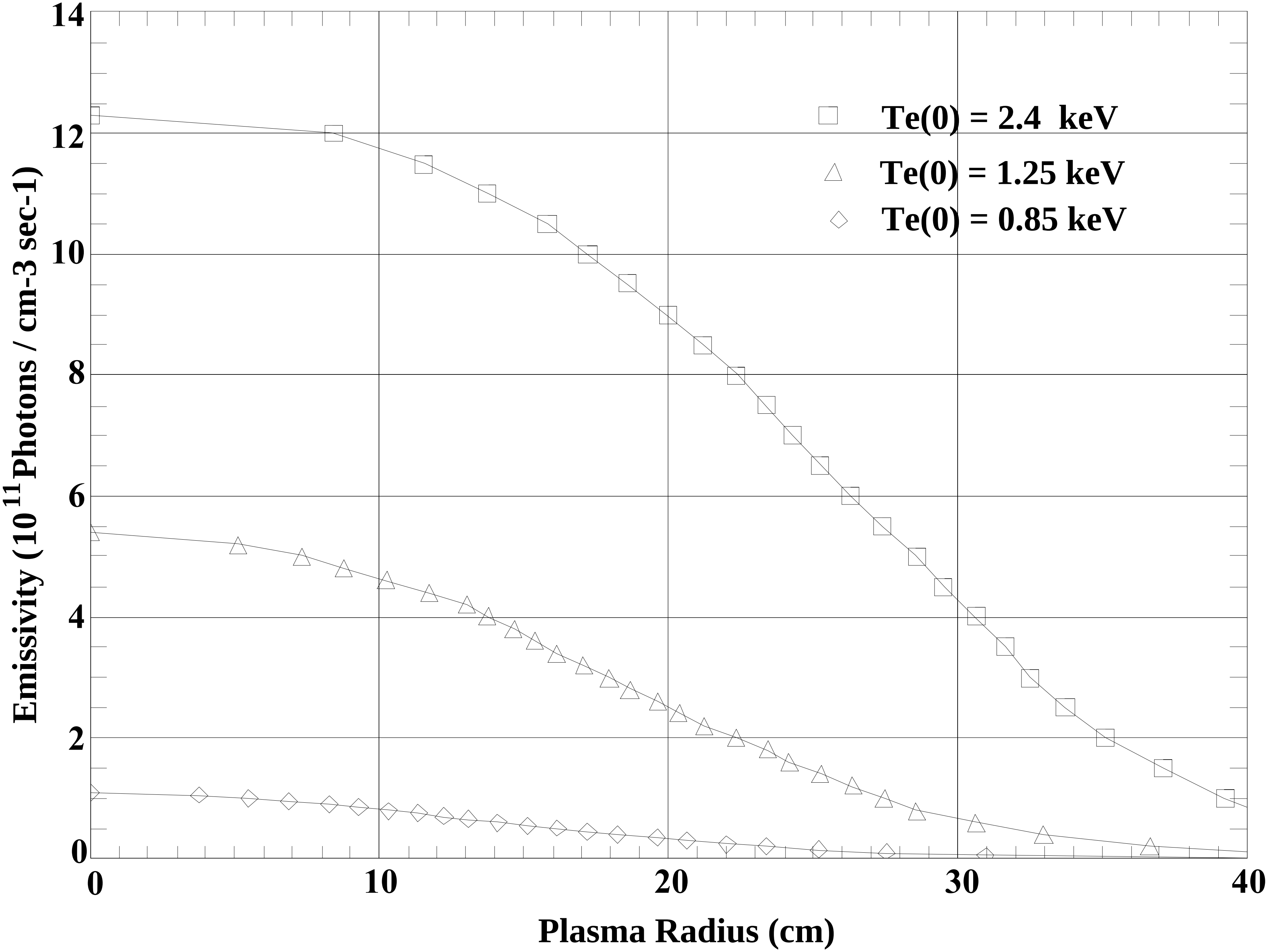

Shot: 105830
Ion Temperature (keV)
2.5
2.0
1.5
1.0
0.5
0.0
0.10
0.15
0.20
0.25
0.30
Time (s)
RF heating of 2.5 MW


Shot: 105830
Thomson
XCS
RF heating of 2.5 MW
Electron Temperature (keV)
Time (s)
0
1
2
3
4
0.10
0.15
0.20
0.25
0.30
0.35

- **Estimates of the throughput and achievable time and spatial resolution for the upgraded spectrometer** were obtained from MIST transport code calculations of radial emissivity profiles of the ArXVII resonance line for central electron temperatures, Te(0) = 0.85, 1.25, and 2.4 keV, using the spectral data from shot 105830 and the Te and ne profiles from Thomson scattering as input parameters. The results are shown in the following Figure.

- **According to these estimates** it will be possible to record argon spectra with **spatial resolution of 2.5 cm and time resolution of 10 ms** when the central electron temperature is about and above 1 keV.

- **Note that it is possible to choose the time and space resolution** by binning the data according to the statistical requirements after a shot at the time of the data analysis.


14
12
10
8
6
4
2
0
0
10
20
30
40
Emissivity (10^11 Photons / cm-3 sec-1)
Plasma Radius (cm)
Te(0) = 2.4 keV
Te(0) = 1.25 keV
Te(0) = 0.85 keV

Te Measurements

● **The satellite-to-resonance line ratios of ArXVI and ArXVII are a very sensitive to Te for electron temperatures in the range 0.5 $\leq$ Te $\leq$ 1.5 keV and provide a very valuable independent Te measurement, in addition to Thomson scattering**. Measurements of these line ratios have been important during the last NSTX experimental campaign to solve a discrepancy of the Te measurements. These discrepancies were partly due to a calibration error in the Thomson scattering system and partly due to an inaccuracy in Vainshtein's theoretical predictions for the intensity of the n$\geq$3 dielectronic satellites of ArXVI *–see M. Bitter et al.,* ***GP1 129*** *- 44th Annual Meeting of the APS Meeting, Orlando, Florida, Nov. 11-15, 2002.*

● **This theoretical uncertainty**, which led to small differences between the Te-values obtained from the ratios of the n=2 and n=3 satellites with respect to the resonance line **w**, **has been removed** in **new atomic physics calculations** by Ming Feng Gu, whose new theory now yields **consistent Te results** from all the spectral features.

● **The new theoretical results** by Ming Feng Gu, which have been experimentally verified at NSTX, may also be **important for the interpretation of astrophysical spectra.**

The following figures show:

- **the theoretically predicted dependence** of the satellite to resonance line ratios **k/w** and (resolved n=3 satellites)/**w** on Te,
- **two experimental spectra**, obtained at electron temperatures of 0.6 and 1.2 keV, which confirm the predicted strong variation of these line ratios with Te,
- **a least squares fit of a synthetic spectrum from Ming Feng Gu's theory** to the experimental data,
- **comparisons** for two NSTX shots of the **time histories of the electron temperature data** from the **XCS** with the maximum Te value and a 3-point spatially averaged Te value of the Te profiles obtained by **Thomson scattering**,
- **a comparison of the Te results from the XCS and Thomson scattering for a series of NSTX discharges.** Note that the XCS data represent a time-average over several ms and that the Thomson scattering data represent instantaneous measurements, which vary significantly from time point to time point if MHD events are present. <u>This general comparison of the Te results therefore provides less information than a comparison of the time histories.</u>

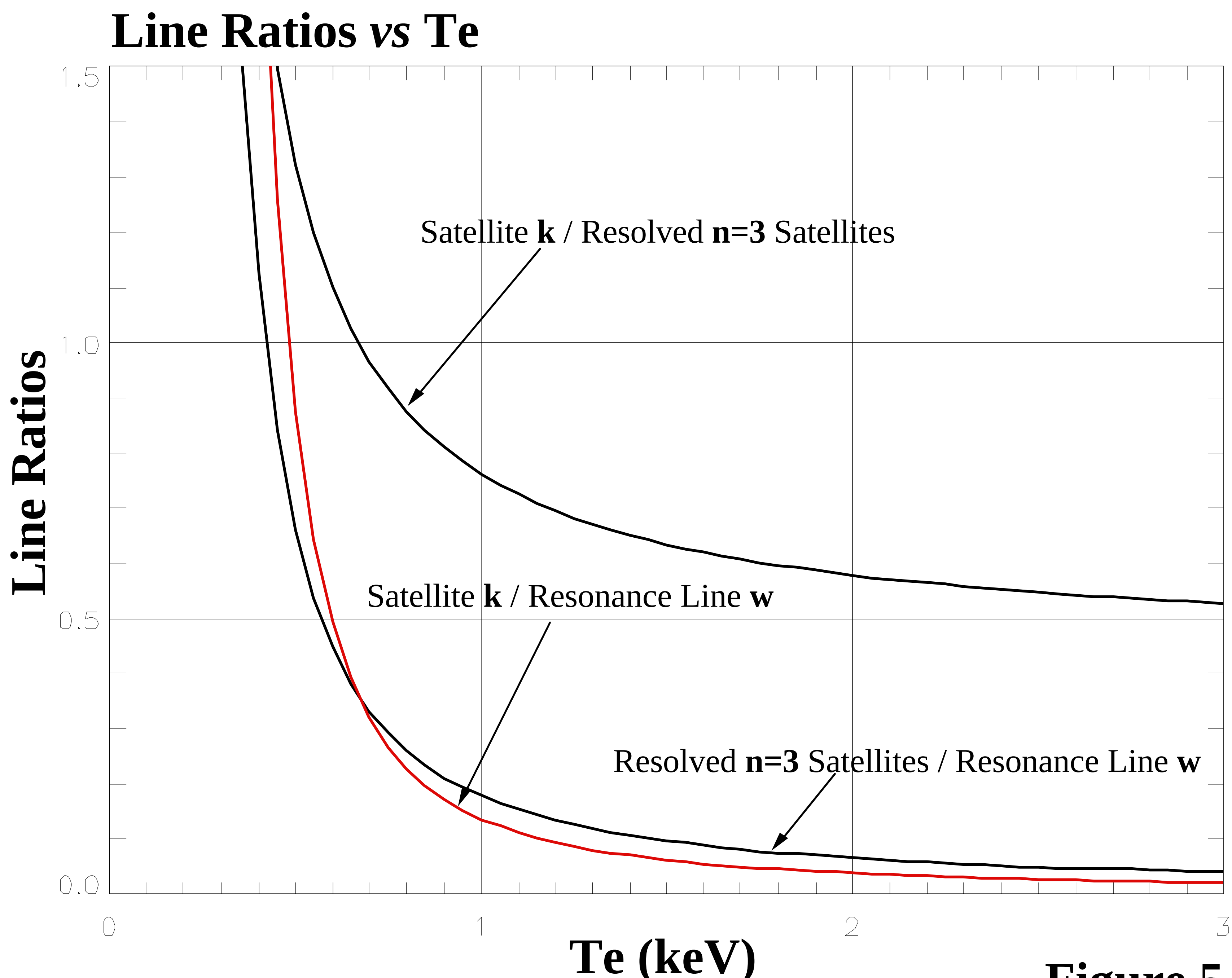
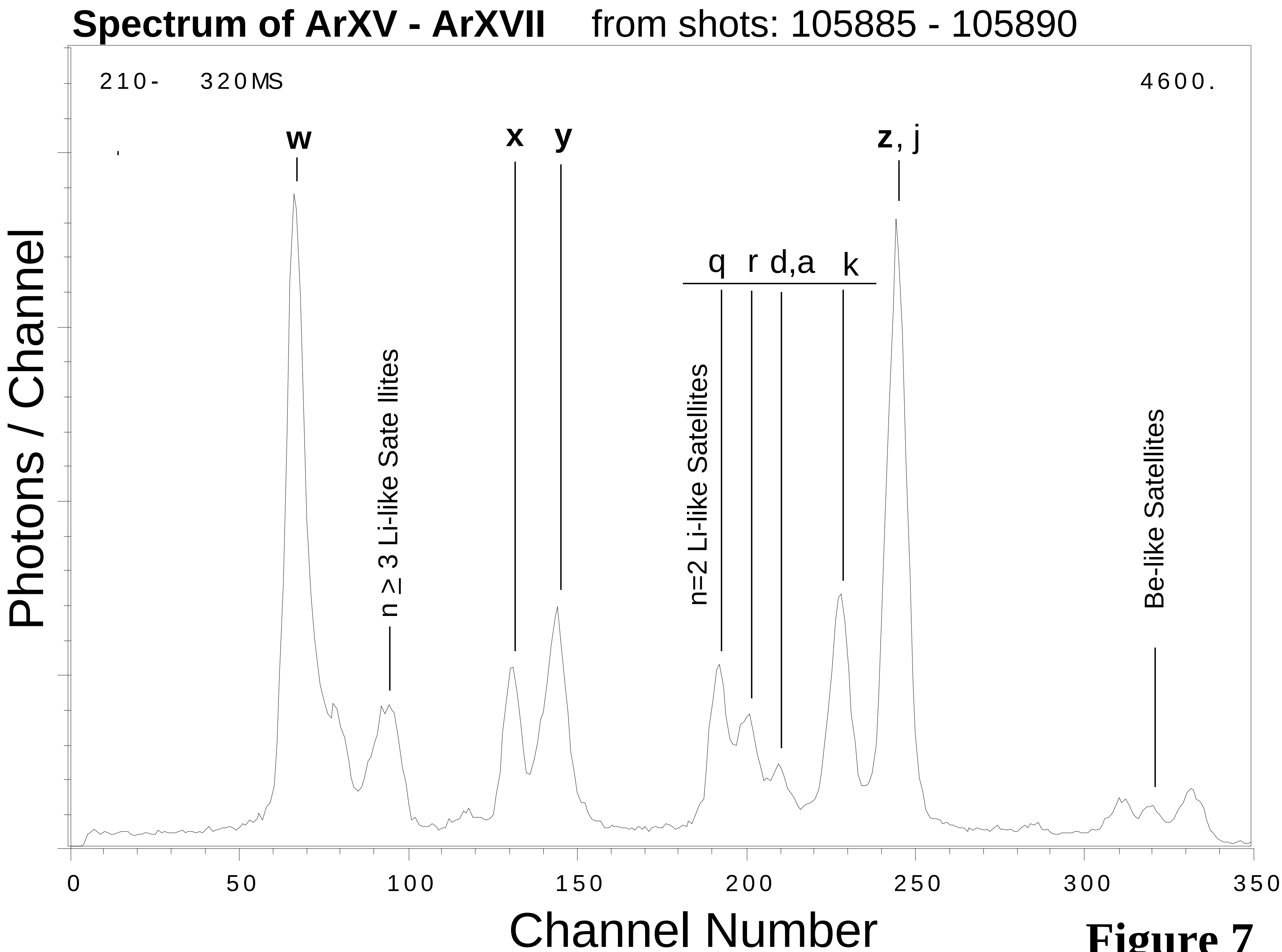

Line Ratios *vs* Te
1.5
1.0
0.5
0.0
0
1
2
3
Line Ratios
Te (keV)
Satellite **k** / Resolved **n=3** Satellites
Satellite **k** / Resonance Line **w**
Resolved **n=3** Satellites / Resonance Line **w**

Figure 5



Spectrum of ArXV - ArXVII from shots: 105885 - 105890
210- 320MS
4600.
w
x
y
z, j
q
r
d,a
k
n ≥ 3 Li-like Sate llites
n=2 Li-like Satellites
Be-like Satellites
Photons / Channel
0
50
100
150
200
250
300
350
Channel Number

Figure 7

Spectrum of ArXV -ArXVII from shot 107906 ; Time 255 - 510 ms

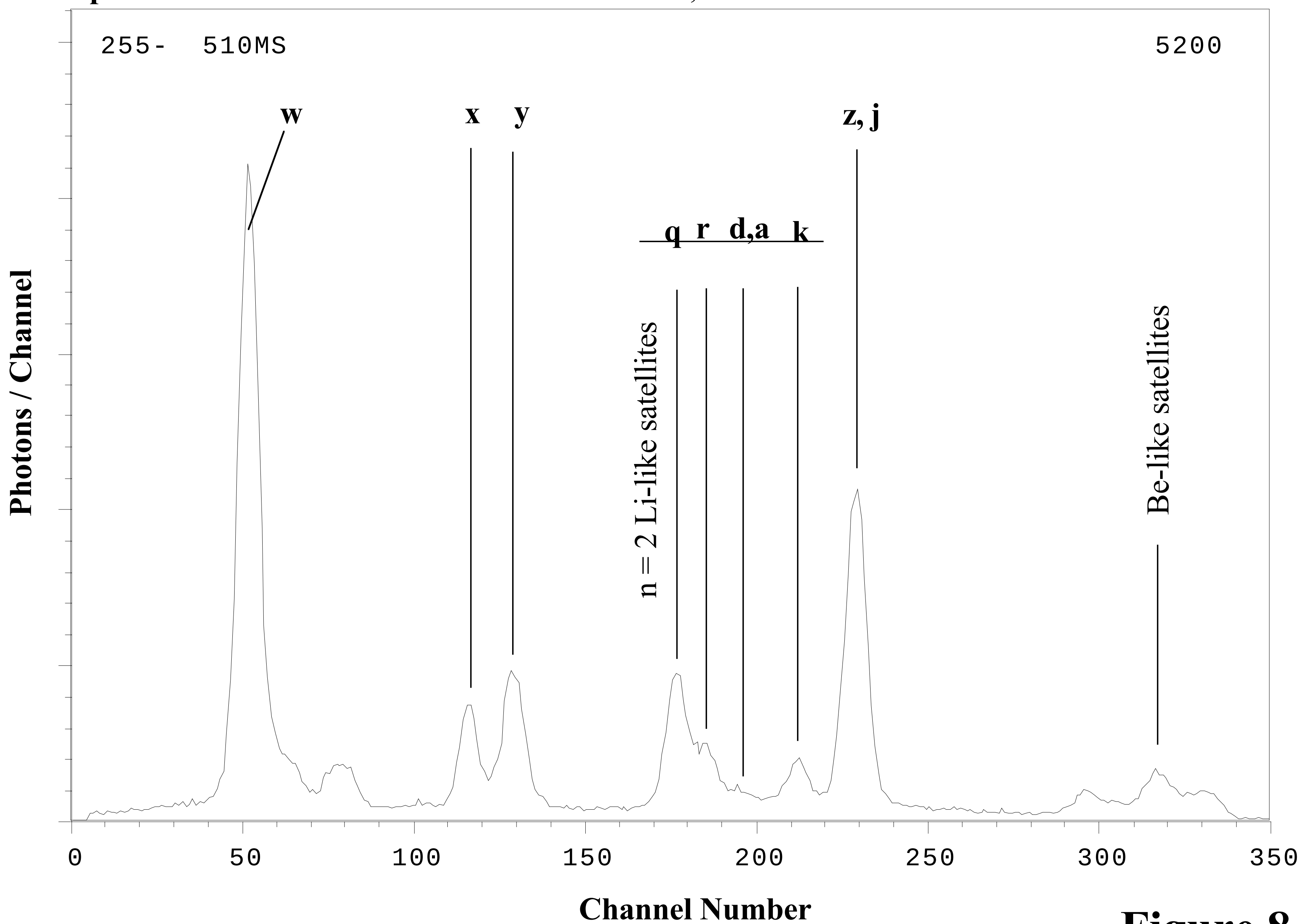


Figure 8

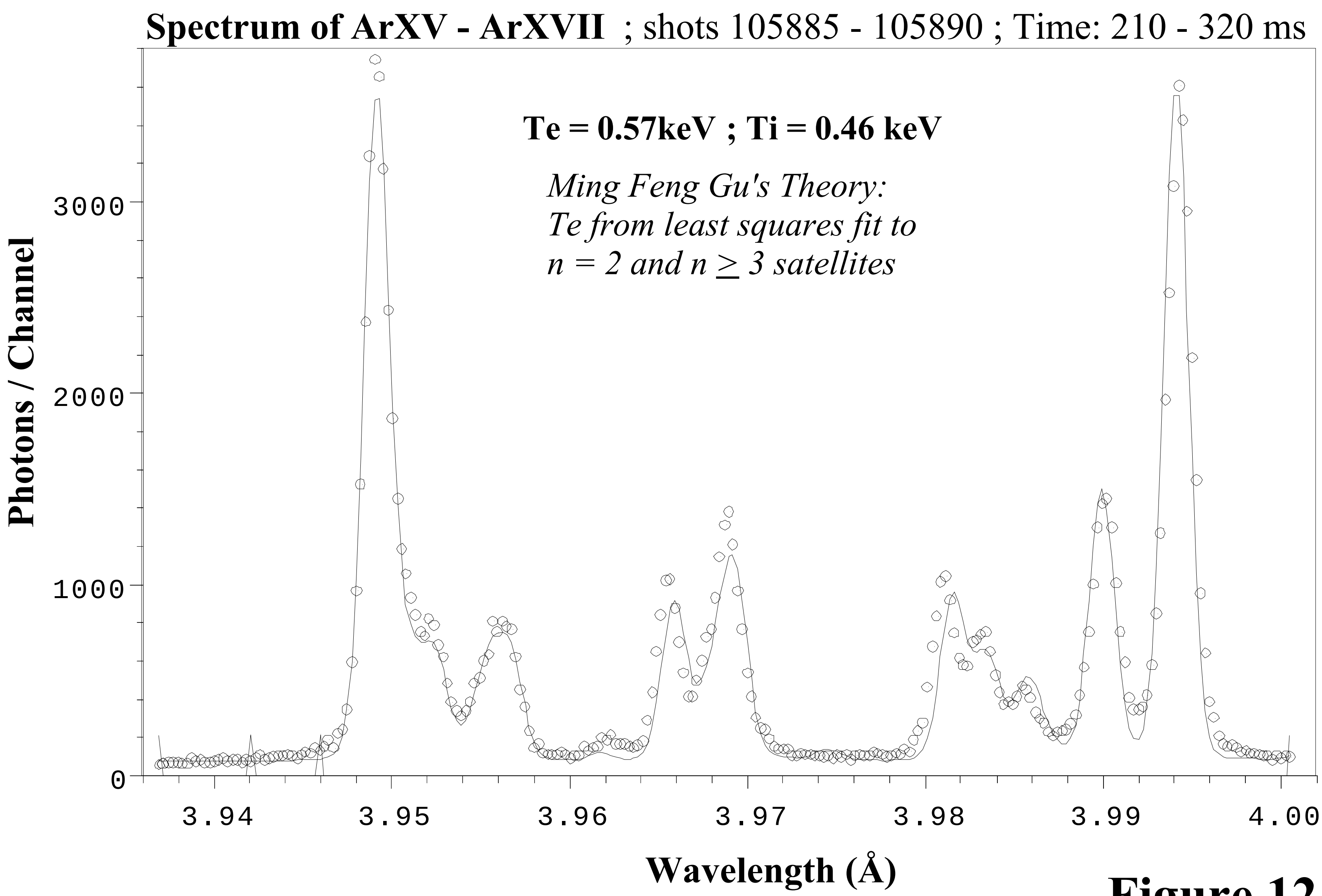

Spectrum of ArXV - ArXVII ; shots 105885 - 105890 ; Time: 210 - 320 ms
Te = 0.57keV ; Ti = 0.46 keV
Ming Feng Gu's Theory:
Te from least squares fit to
n = 2 and n ≥ 3 satellites
Photons / Channel
0
1000
2000
3000
3.94
3.95
3.96
3.97
3.98
3.99
4.00
Wavelength (Å)

Figure 12

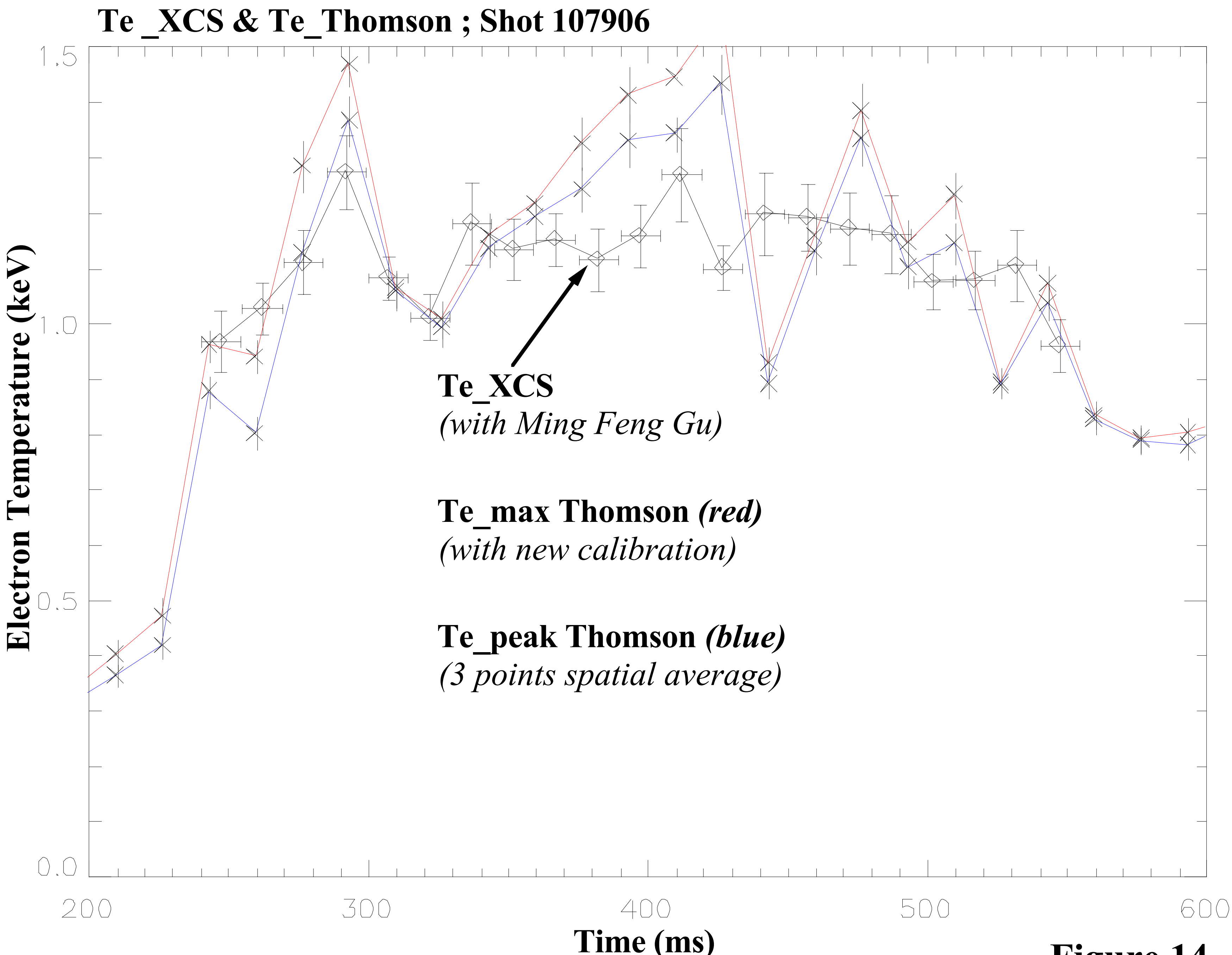

Te _XCS & Te_Thomson ; Shot 107906
1.5
1.0
0.5
0.0
200
300
400
500
600
Electron Temperature (keV)
Time (ms)
Te_XCS
(with Ming Feng Gu)
Te_max Thomson (red)
(with new calibration)
Te_peak Thomson (blue)
(3 points spatial average)

Figure 14

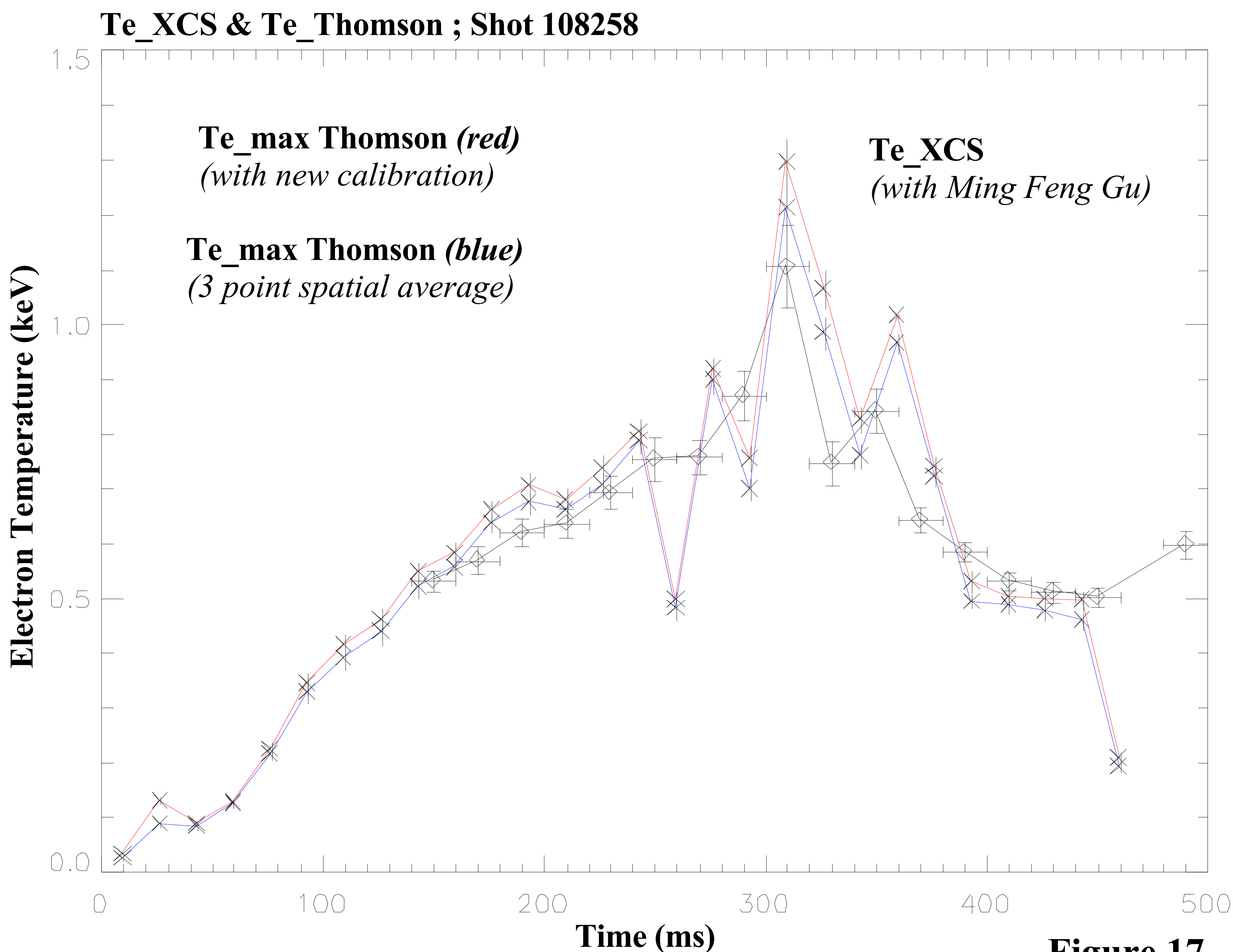

Te_XCS & Te_Thomson ; Shot 108258
Te_max Thomson (red)
(with new calibration)
Te_max Thomson (blue)
(3 point spatial average)
Te_XCS
(with Ming Feng Gu)
Electron Temperature (keV)
Time (ms)
0.0
0.5
1.0
1.5
0
100
200
300
400
500

Figure 17

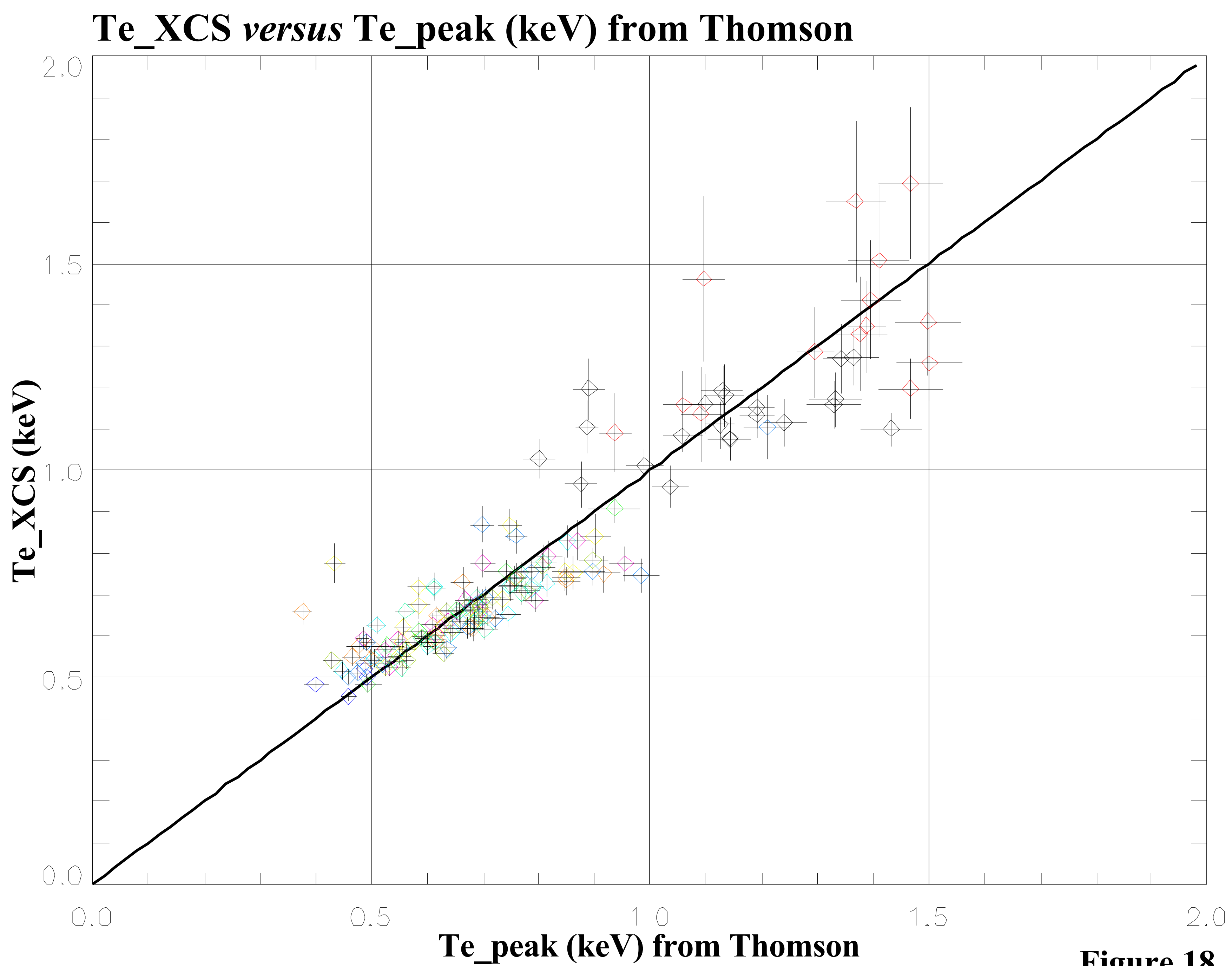
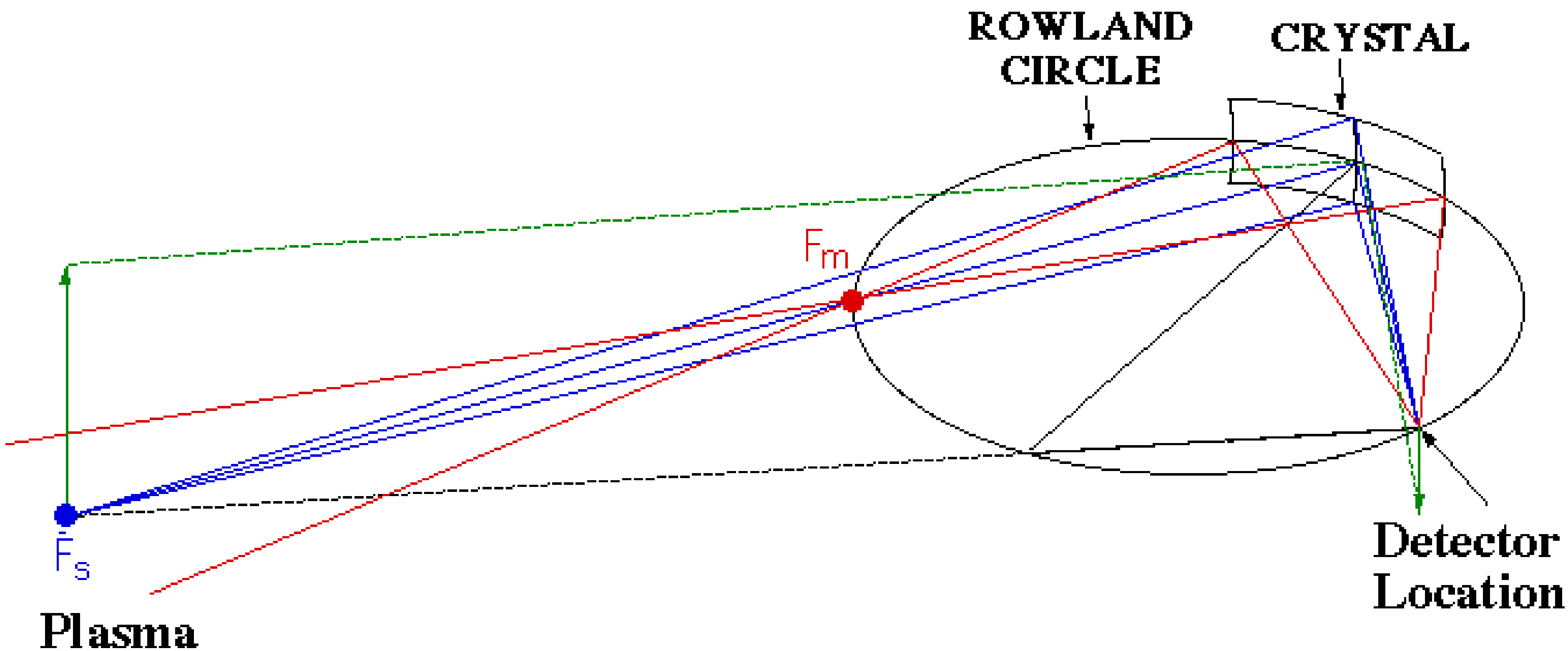

Te_XCS versus Te_peak (keV) from Thomson
Te_XCS (keV)
Te_peak (keV) from Thomson
0.0
0.5
1.0
1.5
2.0

Figure 18

III. Imaging Properties *(Astigmatism)* of a Spherical Crystal.



Due to the astigmatism of a spherical crystal two images, $\mathbf{F_m}$ and $\mathbf{F_s}$, of a point source *located on the Rowland circle at the position of the detector* are formed by the meridional and sagittal rays. For a Bragg angle of 45°, $\mathbf{F_s}$ is at infinity, so that, if the rays are reversed, a parallel bundle of X-rays emerging from the plasma is focused to a point on the detector. Parallel bundles, which are oblique to the main (horizontal) diffraction plane, are focused to points above or below the horizontal plane. These imaging properties are still approximately fulfilled for Bragg angles somewhat larger than 45°, e.g. a Bragg angle of 54°, which is used for the NSTX spectrometer.

Parameters of the upgraded X-ray Imaging Crystal Spectrometer

- **Crystal:**
  spherically bent circular 110-quartz crystal: 2d = 4.913 Å
  radius of curvature $\mathbf{R_c}$ = 375 cm
  crystal disc diameter d = 8 cm

- **Bragg angles for Lines of ArXVII:** 53.5 < θ < 54.5 degrees

Distance crystal-detector:	R_c* sin(θ) = 303 cm
Distance of meridional image $\boldsymbol{F_m}$ *from crystal:*	R_c* sin(θ) = 303 cm
Distance of sagittal image image $\boldsymbol{F_s}$ *from crystal:*	981cm
Spatial Resolution in Plasma Center	3 cm
Distance crystal-NSTX Center Stack:	733 cm
Diameter of NSTX Center Stack:	33 cm
Distance between lines **w** and **z** on detector:	4.7 cm
Distance between lines **w** and **z** on Center Stack:	13 cm

- The sightlines for the entire spectrum end at the NSTX Center Stack. ***This is important for measurements of line ratios.***

V. Developments of large 2D detectors

(1) **Multiwire Proportional Counters** can be built in any size. They have a high signal-to noise ratio but are count rate limited to 500 kHZ. They will be used first and provide guidance for the development of other detectors.

(2) **GEM detectors** provide count rates of several MHz and a spatial resolution comparable to that of multi-wire proportional counters. Large 2D GEM detectors with delay line readout are developed by O. Siegmund in a joint SBIR project with PPPL.

(3) **Hamamatsu Imaging tubes** are appropriate detectors for krypton lines at X-ray energies of 13 keV. They could be used for ITER. - Experiments to test the performance of these detectors are planned at JET.

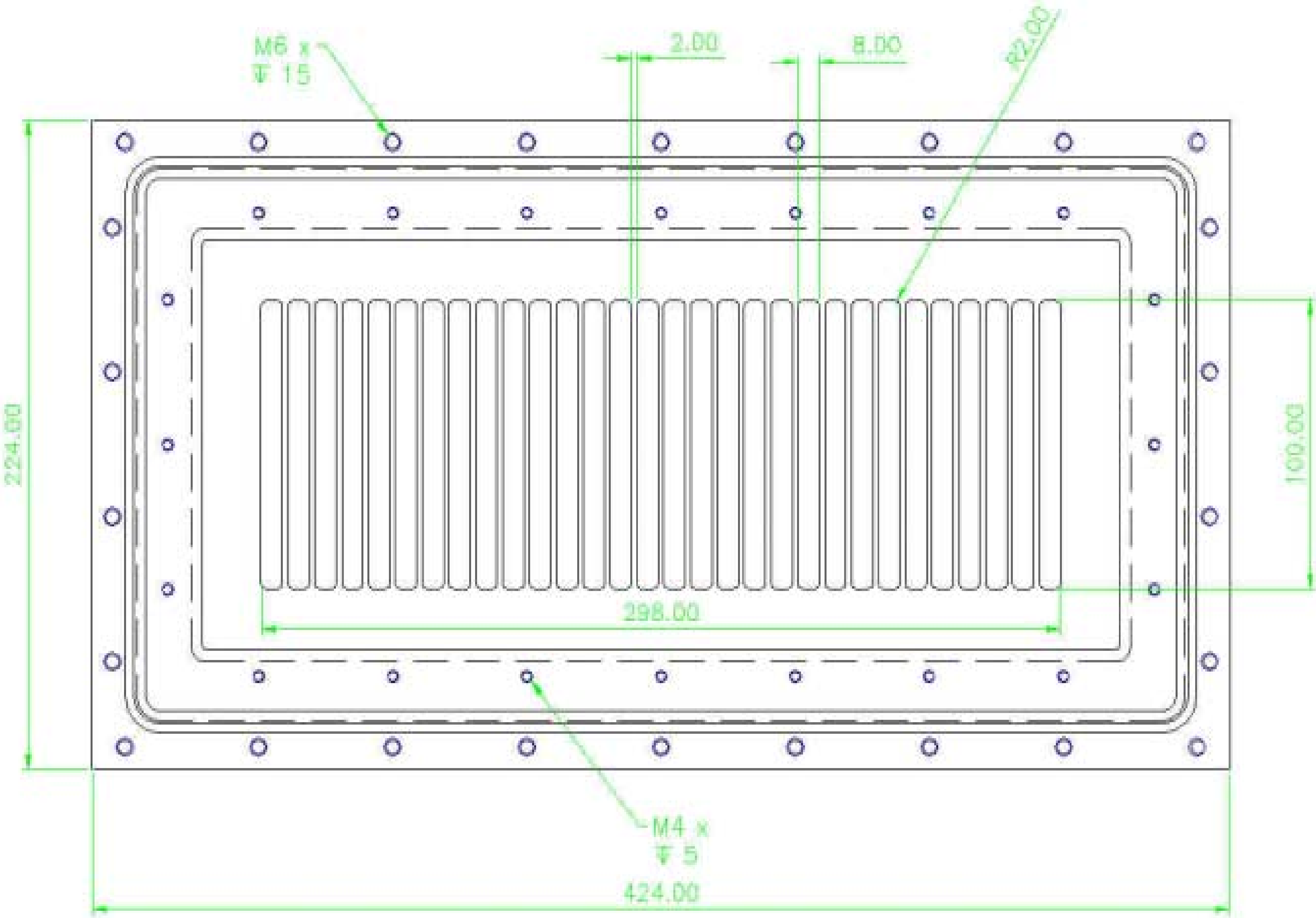
The following figures show:

- **A 10 cm x 30 cm large 2D position-sensitive multi-wire proportional counter built by Dr. S. G. Lee at the Korean Basic Science Institute**. The detector has a spatial resolution of 0.1 mm and a count rate capability of 500 kHZ. It will be tested at the NSTX X-ray crystal spectrometer in January 2003 and later be installed at an X-ray imaging crystal spectrometer at KSTAR.

- **Principle of the GEM** (**G**as **E**lectron **M**ultiplication) **detector from F. Sauli at CERN and Delay line readout developed by O. Siegmund.**

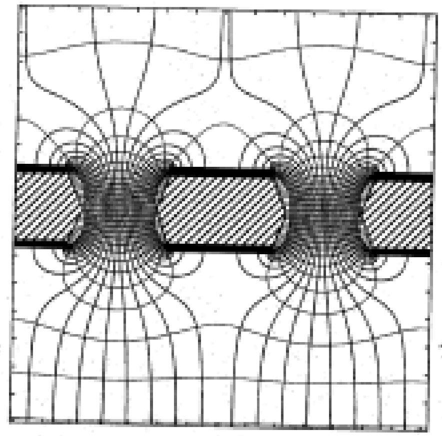
- **A Hamamatsu X-ray imaging tube from the high-speed soft x-ray camera at TEXTOR**. The tube was temporarily used for test purposes with the high-resolution X-ray crystal spectrometer at TEXTOR for the detection of argon, ArXVI-XVII, spectra at 3 keV. The TEXTOR spectrometer uses a conventional, cylindrically bent, quartz crystal. The obtained spatially resolved spectra are shown. The signal-to-noise ratio of the Hamamatsu tube for these low-energy photons of 3 keV is, however, less than that of multi-wire proportional counters.

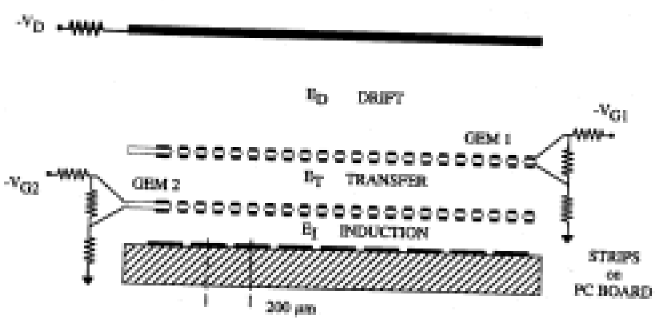
- **A large aperture *(250 mm diameter)* X-ray imaging tube developed by Hamamatsu** for the European Synchrotron Radiation Facility in Grenoble. Such a tube could be used for krypton experiments at JET.


M6 x
∓ 15
2.00
8.00
R2.00
224.00
100.00
298.00
M4 x
∓ 5
424.00

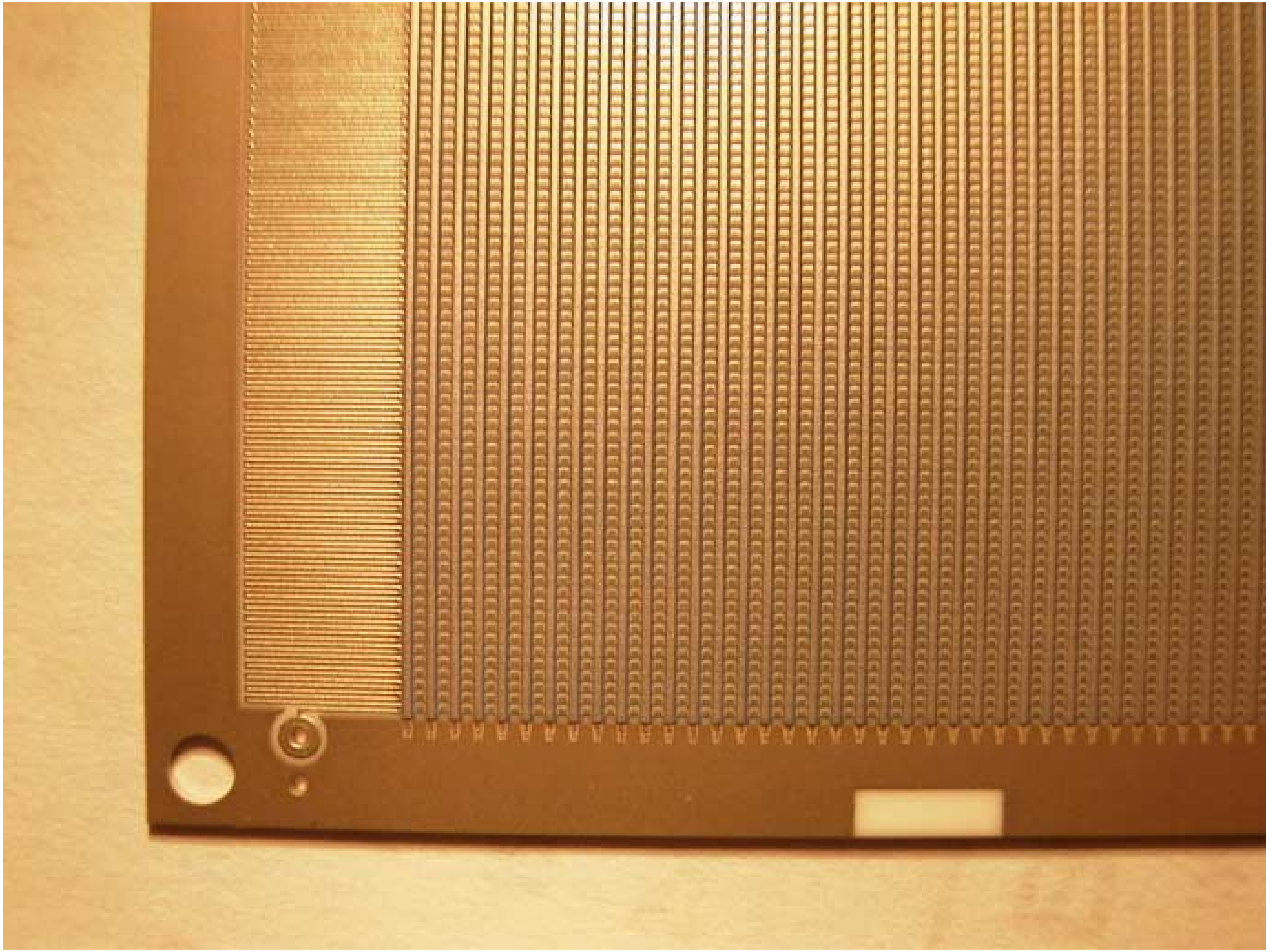
Gas Electron Multiplication (GEM) Detectors

developed by F. Sauli at CERN





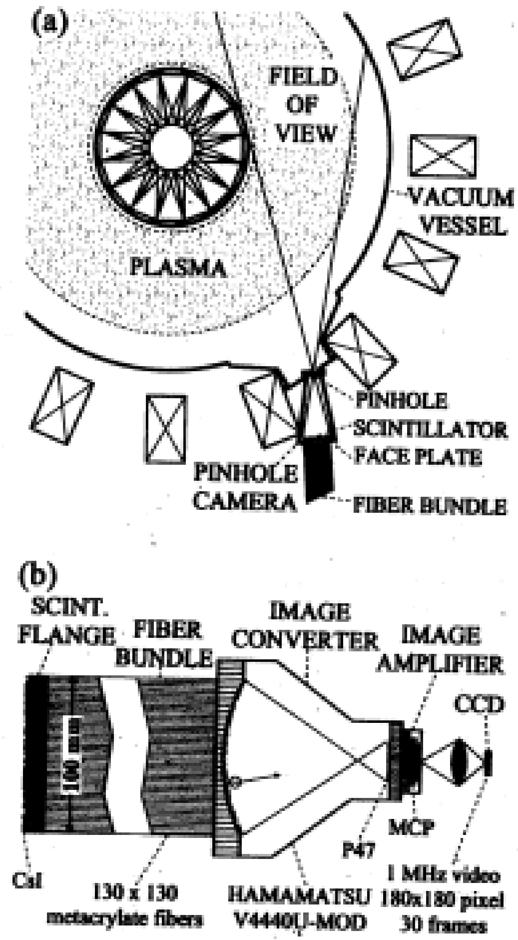
Can be combined with a fast delay line read-out system
by O. Siegmund University of Berkeley California



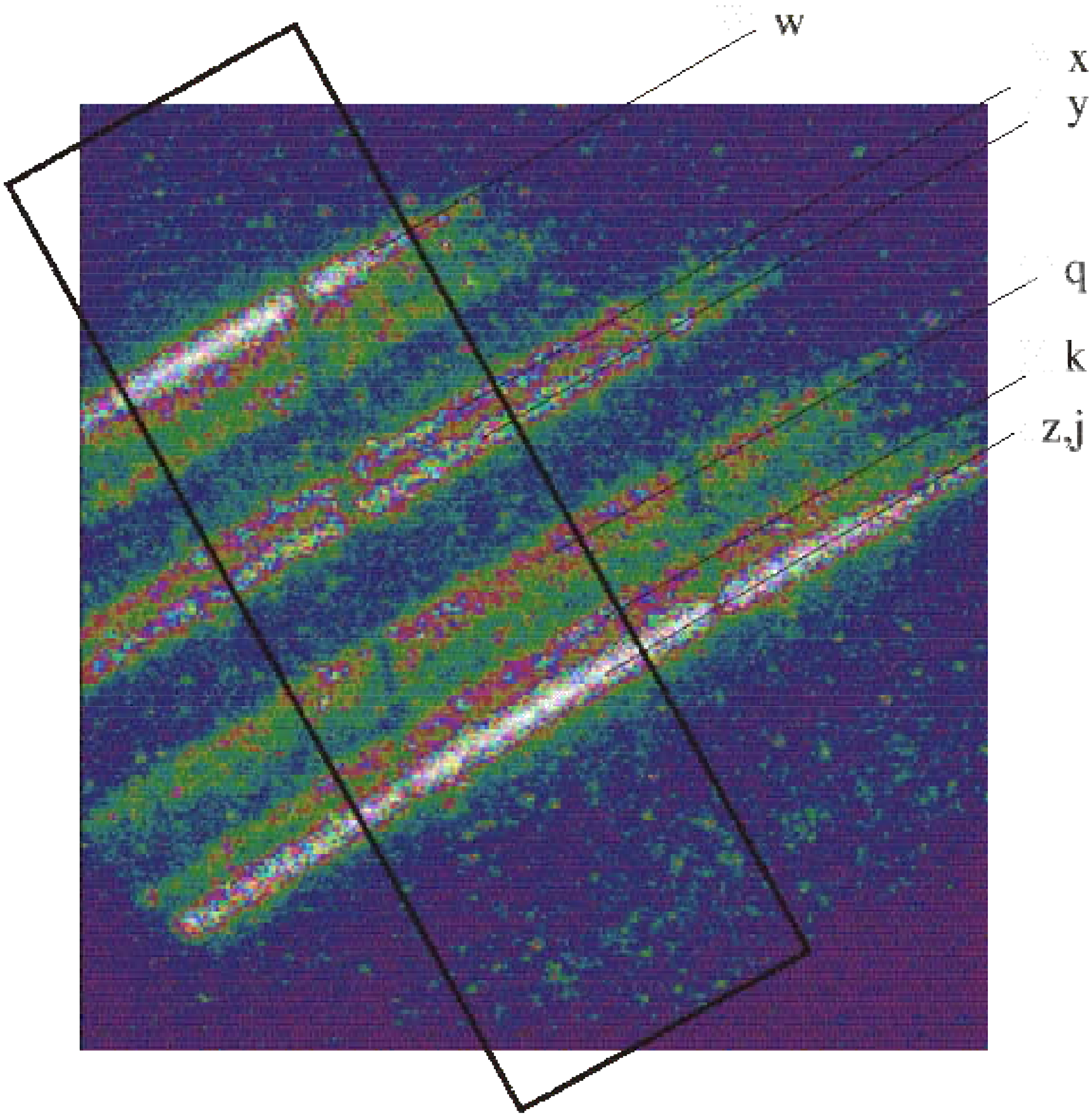
High speed tangential Soft X-ray Camera for MHD instability studies at TEXTOR

S. von Goeler et al., Rev. Sci. Instrum. **70**, 599 (1999)

Hamamatsu Tube 444OU-MOD (100 mm diameter)

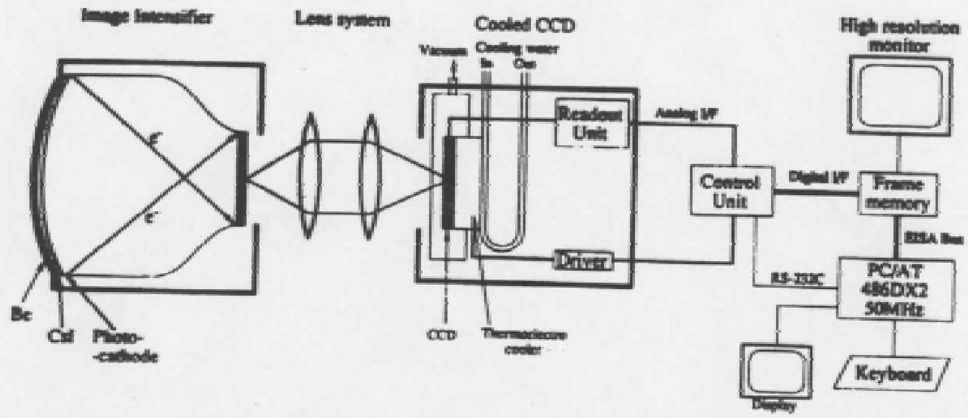


Spatially resolved ArXVI - XVII spectra obtained with a Hamamatsu V440U-Mod Imaging Tube from the X-ray Crystal Spectrometer TEXTOR, M. Bitter, et al., *26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, 14 – 18, June 1999 – ECA Vol. 23 J (1999) 1689 – 1692 (P4.084)*



Large-aperture TV detector with beryllium-windowed image intensifier for x-ray diffraction

Y. Amemiya, K. Ito, N. Yagi et al. , Rev. Sci Instrum. **66**, 2290 (1995)



Entrance window:	1 mm thick beryllium, diameter = 150 mm or 230 mm
CCD:	1000(H) x 1018(V) pixels of 12μm x 12μm. The CCD is either a cooled frame-transfer or a TV-rate (30 frames/s) interline-transfer CCD.

The TV detector was developed at the ESRF in Grnoble/France in collaboration with Hamamatsu.

V. ITER-relevant experiments at JET

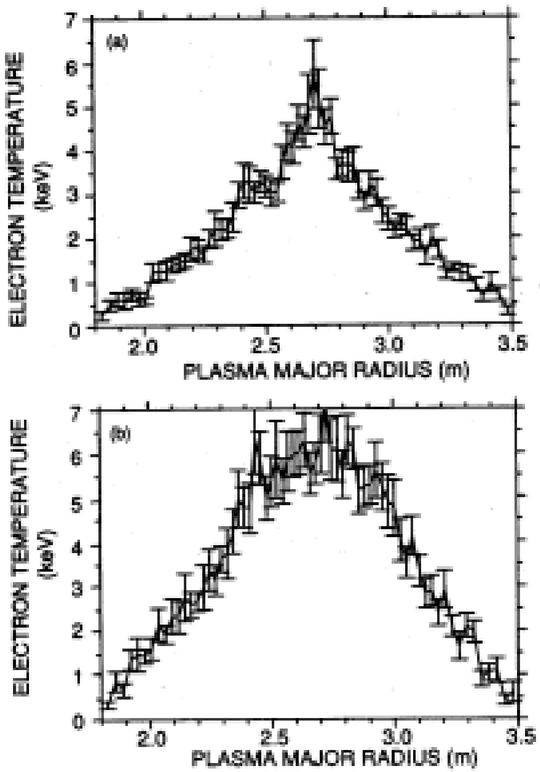
- **The X-ray imaging crystal spectrometer** could be used for **non-perturbing measurements of Ti profiles at ITER** using krypton, which will be in the helium-like state for central electron temperatures of 10 keV. ITER relevant performance tests of an X-ray imaging crystal spectrometer could be performed at JET by measuring the total radiated power, instrumental throughput, and Z_{eff}, as a function of the krypton gas puffs for different discharges.

- **Some preliminary experiments with krypton have been performed at TFTR in ohmic discharges** with different plasma currents. These discharges had a central electron temperature of 6 keV and either peaked or broad electron temperature profiles. The radiated power and krypton charge state distribution were dependent on the shape of the electron temperature profile. **Helium-like krypton was only observed with broad Te profiles –** ***see below.***

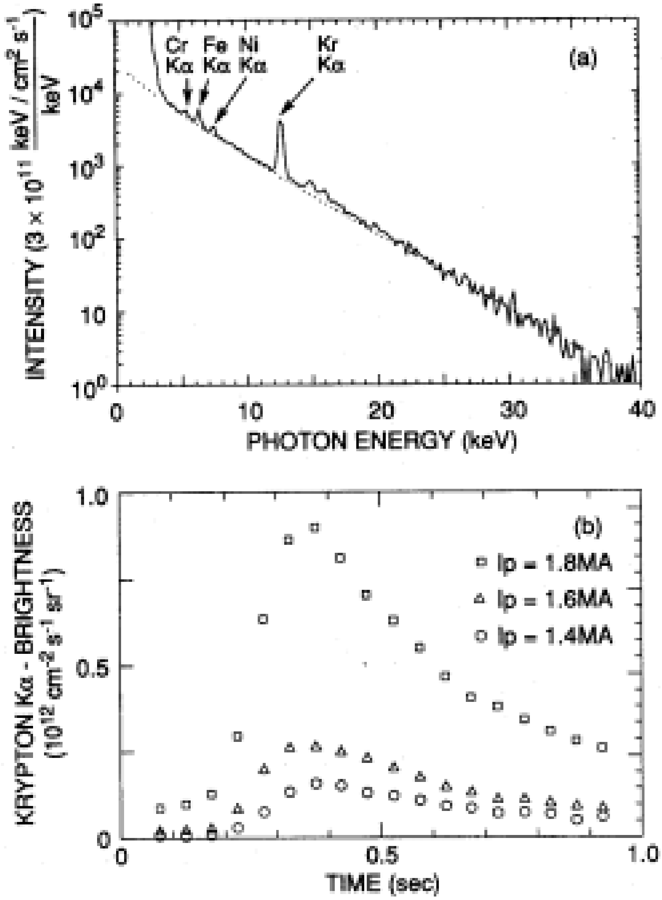
- **The existing** ***(Italian)*** **X-ray crystal spectrometer at JET** ***shown below*** could - after some modifications - be used for these experiments.

Spectra of helium-like Krypton from TFTR

M. Bitter et al., Phys. Rev. Lett. **71**, 1007 (1993)



(a) Te-profile for $I_p = 1.4$ MA
(b) Te-profile for $I_p = 1.8$ MA



(a) PHA Spectrum
(b) Krypton Kα Brightness for $I_p = 1.4$ MA, 1.6 MA, and 1.8 MA

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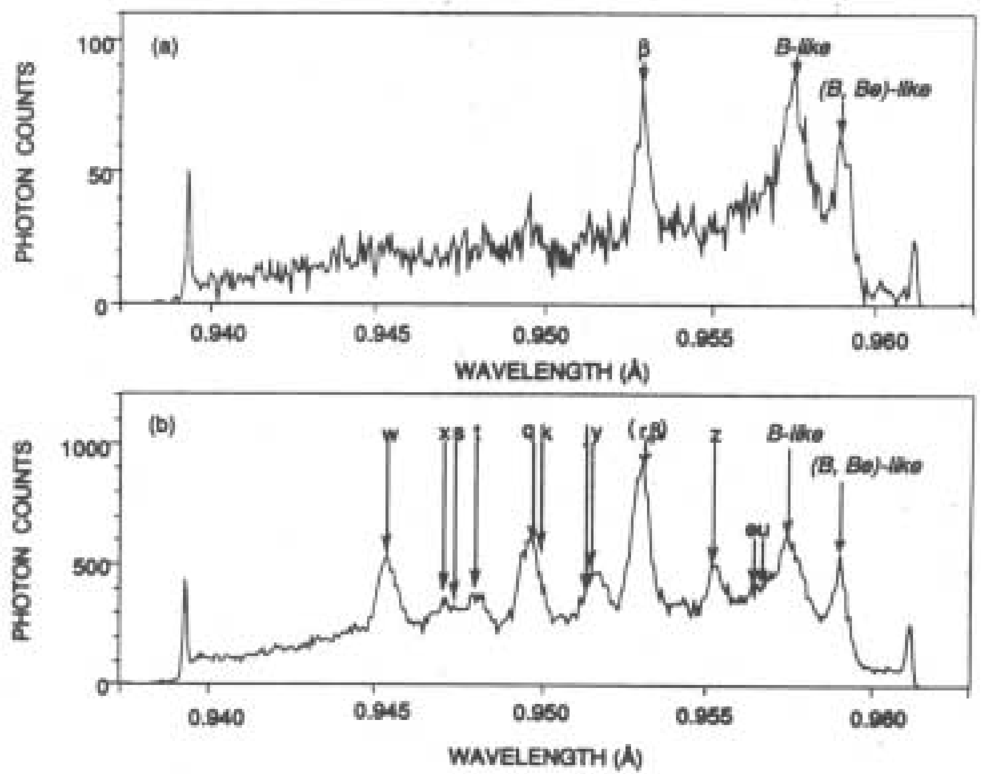
Spectra of helium-like Krypton from TFTR

M. Bitter et al., Phys. Rev. Lett. **71**, 1007 (1993)



(a) Spectrum for $I_p = 1.4$ MA
(b) Spectrum for $I_p = 1.8$ MA

The spectra were obtained with a 203-quartz crystal (2d = 2.7497 A) in 2nd order. The detector was covered with Al-foils to attenuate the bremsstrahlung at 6.5 keV, which was Bragg reflected in 1st order.

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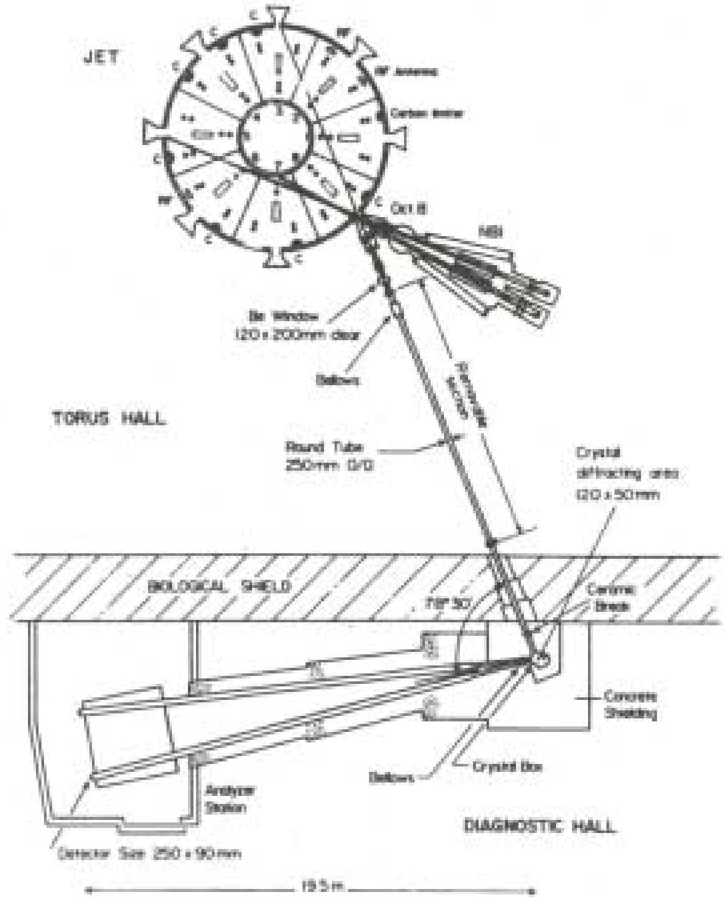
JET X-ray Crystal Spectrometer

F. Bombarda et al., Phys. Rev. A **37**, 504 (1988)



Can the JET spectrometer be upgraded to an imaging X-ray crystal spectrometer to test its performance for ITER relevant Ti-measurements from helium-like krypton?

VI. Conclusions

- **The new X-ray imaging crystal spectrometer at NSTX** will allow **measurements of Ti and Te profiles** & **ionization equilibrium** with **only one spherically bent crystal and a 2D position-sensitive detector**.

- **The spectrometer is very well suited for measurements of Ti profiles in plasmas with pure ohmic and RF heating, in the absence of a neutral beam.**

- Another important application are **profile measurements of the toroidal rotation for the study of transport barriers in RF heated plasmas** - see, J. Rice et al., **LP1 10,** APS2002. **For this purpose, a second instrument with a vertical view should be installed at NSTX.**

- **ITER relevant experiments with krypton at JET** are proposed to explore the potential of the new spectrometer for Ti-measurements at ITER.