LAWRENCE LIVERMORE NATIONAL LABORATORY

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Final Report on ORDER No. 5312-20110620-JOHNSON-01ITER: Core Imaging X-Ray Spectrometer Conceptual Design Review Support

P. Beiersdorfer

September 24, 2013

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ITER Core Imaging X-Ray Spectrometer Conceptual Design Review Support

Final Report on ORDER No. 5312-20110620-JOHNSON-01

P. Beiersdorfer

September 30, 2013

ABSTRACT

In the following we present the Final Report detailing our activities in support of the Conceptual Design Review (CDR) of the ITER Core Imaging X-ray Spectrometer that took place June 4-5, 2013, at the ITER Headquarters in Cadarache, France.

In support of the Conceptual Design Review (CDR) of the ITER Core Imaging X-ray Spectrometer that took place June 4-5, 2013, at the ITER Headquarters in Cadarache, France, we have prepared content for four documents. Some of this included performing some new studies of crystal choices and investigations on how to best diagnose the colder regions of the ITER plasma (r/a > 0.5) in anticipation of potential questions from the review committee.

The four documents, which we prepared or which we helped prepare, were entitled "Impurity Species and Crystal Choices," "Atomic Physics Issues," "Calibration activities for ITER high-resolution x-ray crystal imaging spectrometers," and "Thermal control of x-ray crystals and detectors for ITER CXIS." These documents have been submitted to ITER and were entered into their IDM system. Table 1 below summarizes the documents prepared under this contract and gives the respective IDM document numbers. The presentations were also sent in electronic form to PPPL, as attached.

Table 1. Overview of presentations prepared for the) of the ITER Core Imaging X-ray Spectrometer CDR.

#	Title	Presenter	IDM number
1	Impurity Species and Crystal Choices	Peter Beiersdorfer	ITER_D_HQZ4VJ v1.0
2	Atomic Physics Issues	Peter Beiersdorfer	ITER_D_HR2LCK v1.0
3	Calibration activities for ITER high-resolution x-ray crystal imaging spectrometers	Luis Delgado	ITER_D_HPZPZB v1.0
4	Thermal control of x-ray crystals and detectors for ITER CXIS	Luis Delgado	ITER_D_HPP24M v1.0

In fulfillment of this contract, Livermore scientist, Dr. Peter Beiersdorfer, also attended preparatory meetings that led up to the CDR in France and communicated with the PPPL team members on the project. In June, he attended the CDR at the ITER Headquarters in Cadarache and presented two of these documents (confer Table 1). In addition, he supported the presentations of the participants from PPPL and participated in the discussions during the meeting.

Impurity Species and Crystal Choices

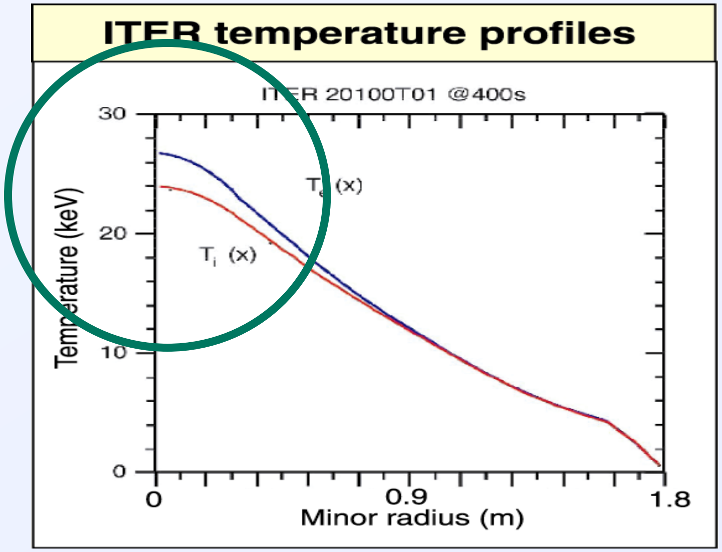
P. Beiersdorfer, G. Brown, H. Chen, J. Clementson, K. Morris, E. Wang
Lawrence Livermore National Laboratory, Livermore, CA
M. Bitter, R. Feder, D. Johnson, K. W. Hill
Princeton Plasma Physics Laboratory, Princeton, NJ
R. Barnsley
ITER International Organization, Cadarache

The high temperatures of ITER plasmas require line radiation from a high-Z ion

- X-ray crystal spectrometers on a variety of machines have been based on the K-shell emission lines of heliumlike ions; argon (Alcator, TFR), titanium (PLT, DIII-D), iron (TFTR), nickel (JET) have been used.

- EU crystal spectrometer design was based on the K-shell emission lines of krypton for diagnosing the plasma core given the presumed ITER electron temperatures

- We have conducted a thorough review of possible emission lines produced at the high-temperature conditions of ITER and have identified the L-shell lines from tungsten as the working radiation of the core imaging x-ray spectrometer



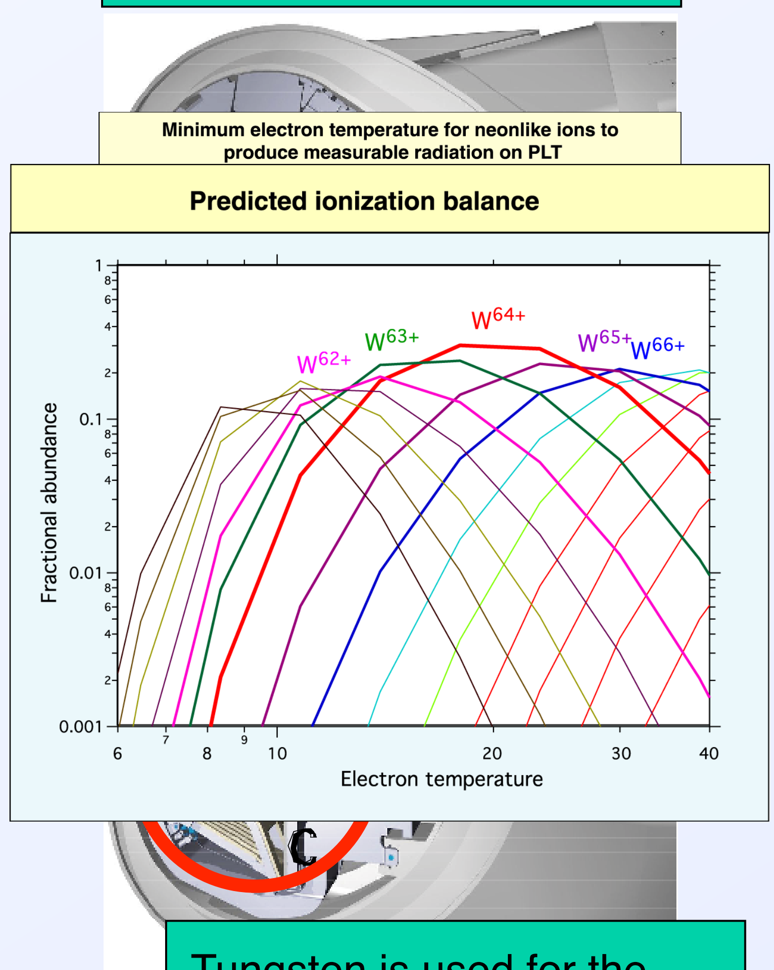
Radiation from the neonlike tungsten W^{64+} ion is a good choice for core temperature and velocity measurements

- **Tungsten is an intrinsic plasma impurity**
- **Measurements of neonlike ions on the Princeton Large Torus suggest neonlike tungsten will be detected at above 12 keV**
- **Ionization balance calculations predict neonlike tungsten will be abundant between 10 and 35 keV**

Wall materials of ITER

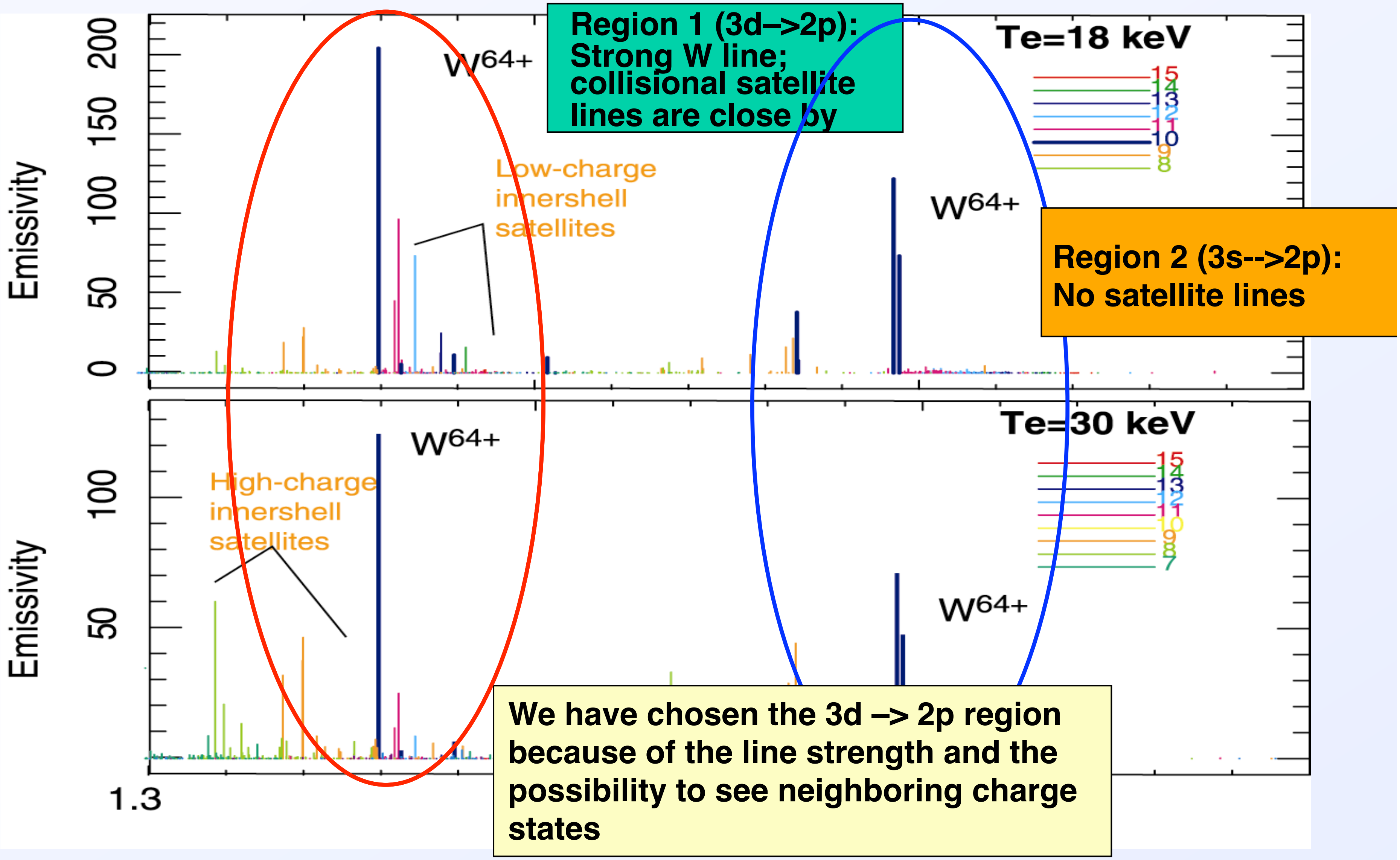
Minimum electron temperature for neonlike ions to produce measurable radiation on PLT

Predicted ionization balance



Tungsten is used for the baffle and dome
(Skinner, Can J. Phys. 86, 285 (2008))

Our predicted tungsten spectra reveal two regions for measurement



We have chosen the 3d –> 2p region because of the line strength and the possibility to see neighboring charge states

Comparison of L-shell W^{64+} and K-shell Kr^{34+} emission

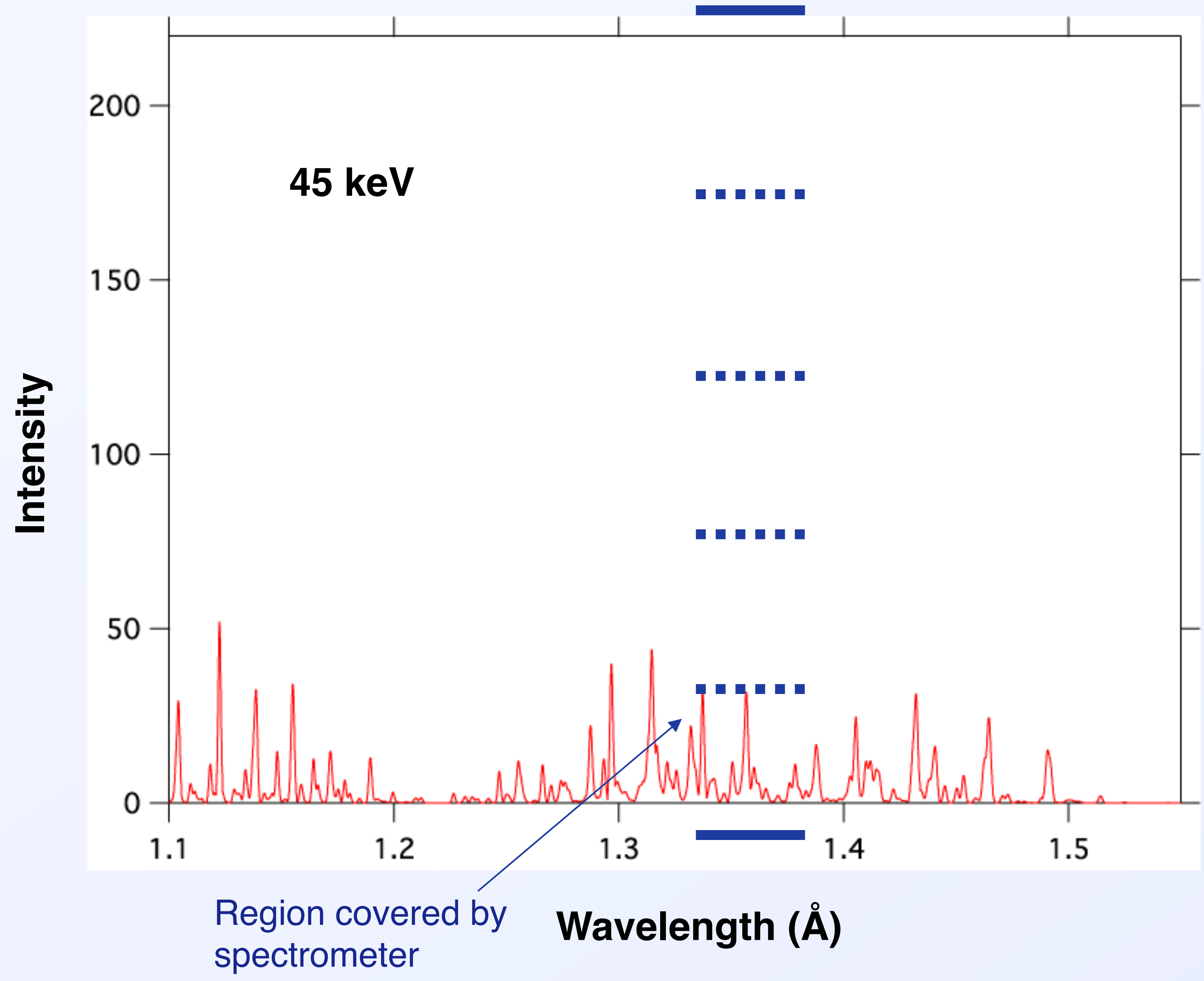
	Kr^{34+}	W^{64+}
T_e range	7–30 keV	10–35 keV
$E_{x\text{-ray}}$	13.1 keV	9.1 keV
Detector QE	70%	90%
1mm Be window	94%	87%
Quartz cut	(53-83)	(50-52)
Quartz θ_{Bragg}	55.3°	57.0
Quartz Reflect.	1.5 μrad	6.4 μrad
Ge cut	(808)	(444)
Ge θ_{Bragg}	56.5	56.3
Ge Reflect.	6.5 μrad	15.8 μrad
Emissivity @25keV, 10^{14}cm^{-3}	92 ph/sec/ion	730 ph/sec/ion

The main differences are:

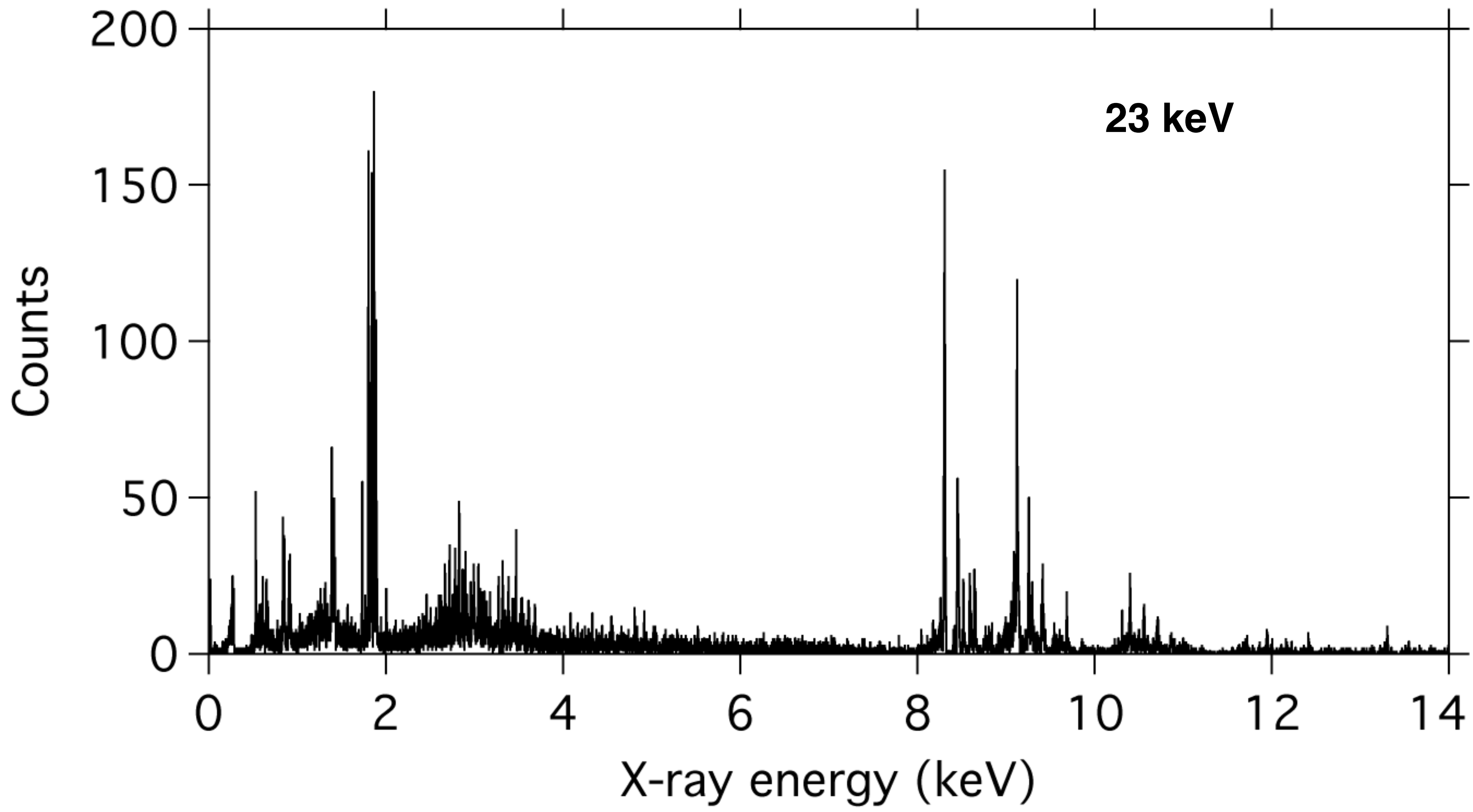
- W is indigenous in ITER
- About 3-4 times more signal collected with the crystal cuts used for W
- The W^{64+} lines are about 8x brighter than the Kr^{34+} lines
- About 25 times more Kr^{34+} than W^{64+} is needed to count the same number of photons in the detector

Beiersdorfer et al., J. Phys. B 43, 144008 (2010)

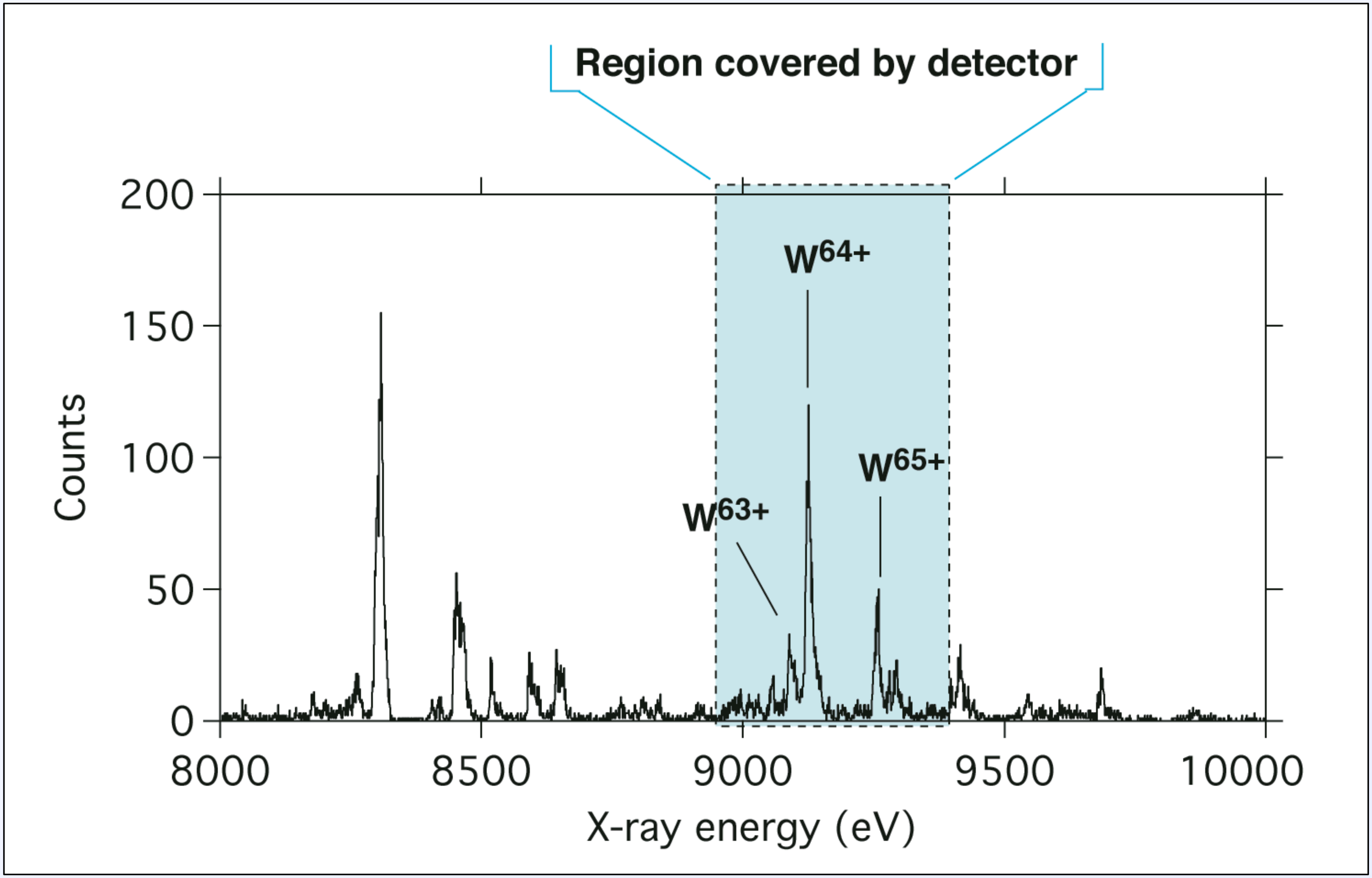
Calculated spectral emission as a function of electron temperature



The tungsten x-ray spectrum is well known from measurements on the Livermore electron beam ion trap



The detailed emission agrees reasonably well with the models



Radiation from other ions are needed to measure the temperature during startup and ohmic phases and near the edge

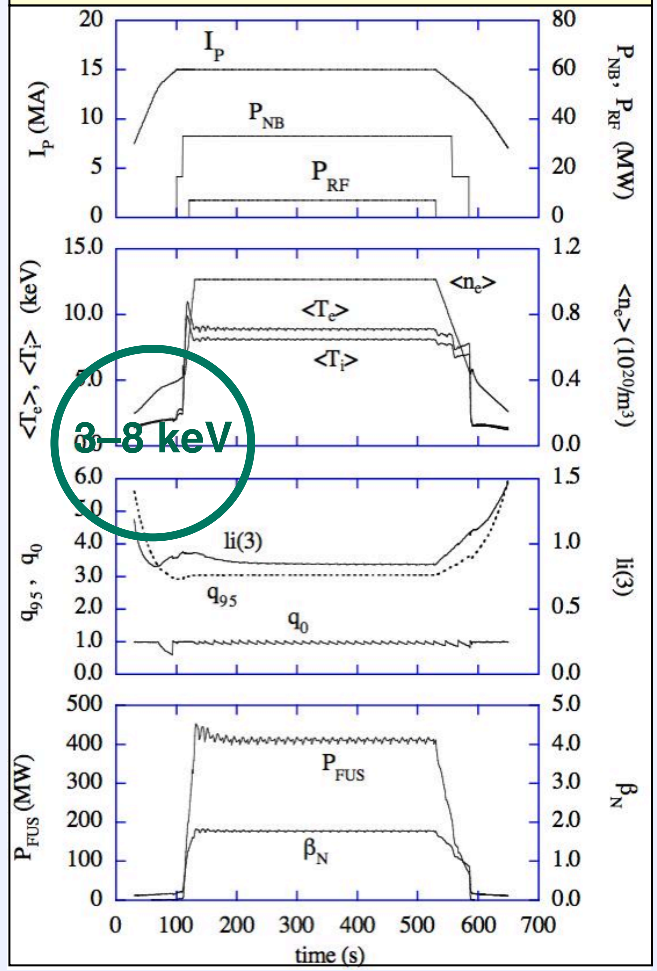
- **The start-up phase of ITER will not have high-power auxiliary heating available and the electron temperature will be below 10 keV**

- **The electron temperature will be below 10 keV for r/a > 0.6 even in high-power discharges**

- **For electron temperatures in the range from 2 to 10 keV we need radiation from lower-Z elements to provide us with the ion temperature**

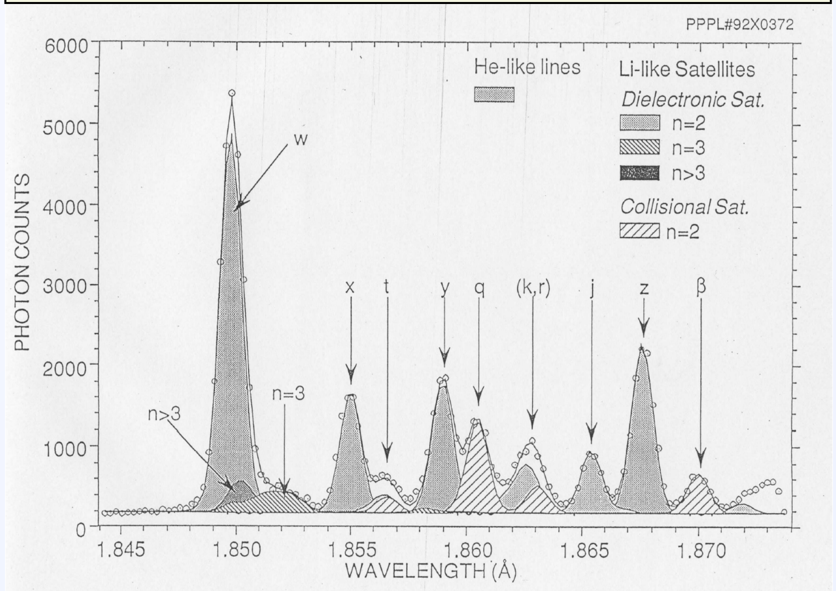
- **The K-shell emission from heliumlike (and possibly hydrogenlike) iron might be used**

Time traces of ITER parameters

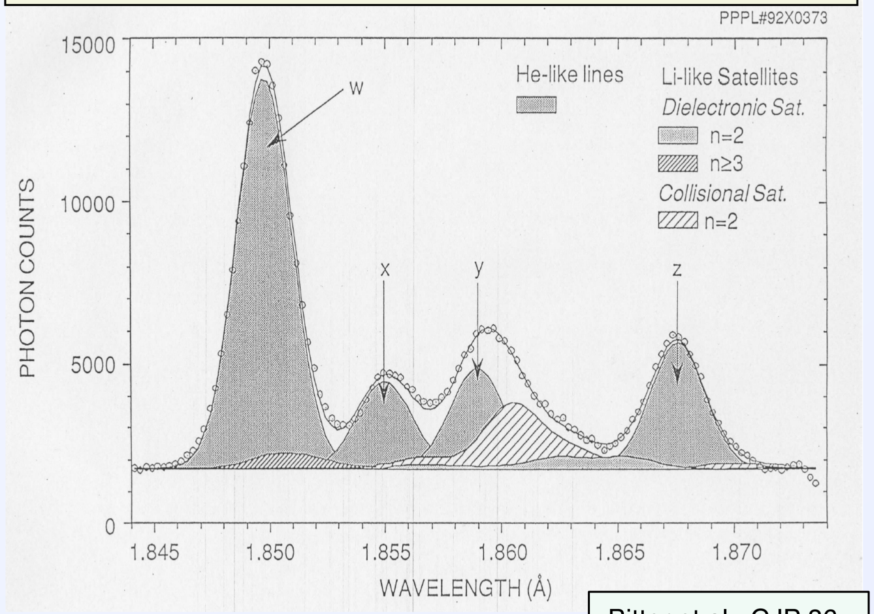


The K-shell spectrum of heliumlike iron has been used before for T_i and T_e measurements

Spectrum of heliumlike iron from TFTR; T_i = 3 keV



Spectrum of heliumlike iron from TFTR; T_i > 20 keV

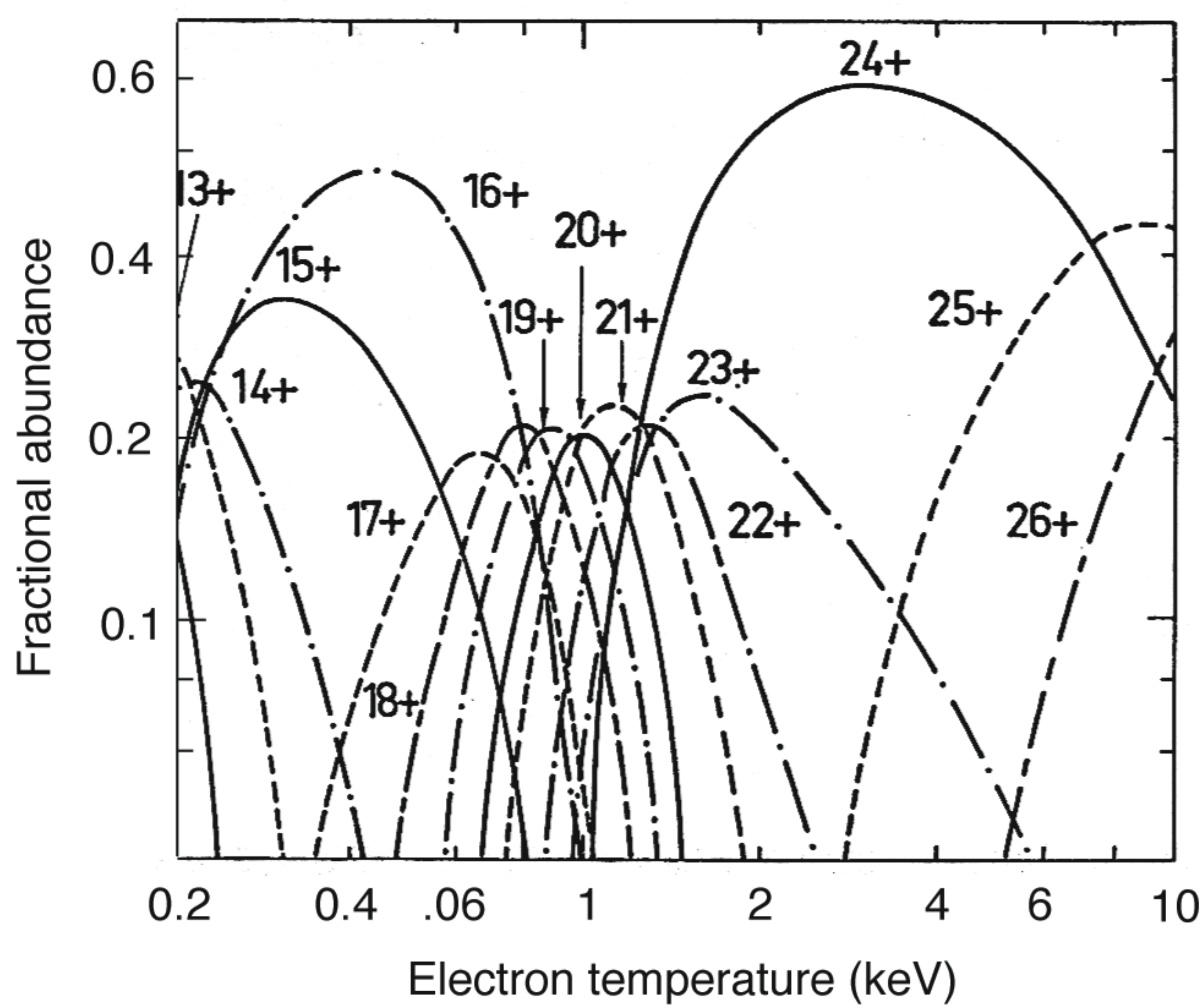


Bitter et al., CJP 86, 291 (2008)

Heliumlike iron provided the core ion temperature of TFTR (and PLT)

Fe^{24+} and Fe^{25+} ions are abundant in 2–10 keV plasmas

Predicted ionization balance (Breton & Michelis)



Comparison of heliumlike Fe^{24+} and hydrogenlike Fe^{25+} emission

	Fe^{24+}	Fe^{25+}
T_e range	1.5–8 keV	6–12 keV
$E_{x\text{-ray}}$	6.7 keV	7.0 keV
Detector QE	100%	100%
1mm Be window	72%	75%
Quartz cut	(4-13-1)	(4-13-2)
Quartz θ_{Bragg}	53.5°	55.5°
Quartz Reflect.	7.4 μrad	9.8 μrad
Ge cut	(422)	(511)
Ge θ_{Bragg}	53.3°	54.8°
Ge Reflect.	44.3 μrad	27.9 μrad
Emissivity @8 keV, 10^{14}cm^{-3}	217 ph/sec/ion	85 ph/sec/ion

The main results are:

- The Fe^{24+} emission is considerably stronger
- Excellent coincidences with W^{64+} Bragg angle exists both for Fe^{24+} and for Fe^{25+} (differences of 0.1° to 0.4°)

(Note that 1° difference in Bragg angle means a shift of about 35 mm of the detector or crystal)

Excellent Bragg angle coincidences are found

	Fe^{24+}	Fe^{25+}	W^{64+}
T_e range	1.5–8 keV	6–12 keV	10–35 keV
$E_{x\text{-}ray}$	6.7 keV	7.0 keV	9.1 keV
Detector QE	100%	100%	90%
1mm Be window	72%	75%	87%
Cut	Si(422)	SiO_2(4-40)	SiO_2(502
θ_{Bragg}	56.6°	56.9°	57.0°
Reflectivity	21.2 µrad	6.6 µrad	6.4 µrad
Cut	SiO_2(303)		Ge(444)
θ_{Bragg}	56.2°		56.3°
Reflectivity	5.0 µrad		15.8 µrad
Emissivity @8 keV, 10^{14}cm^{-3}	217 ph/sec/ion	85 ph/sec/ion	730 ph/se (@ 25 ke

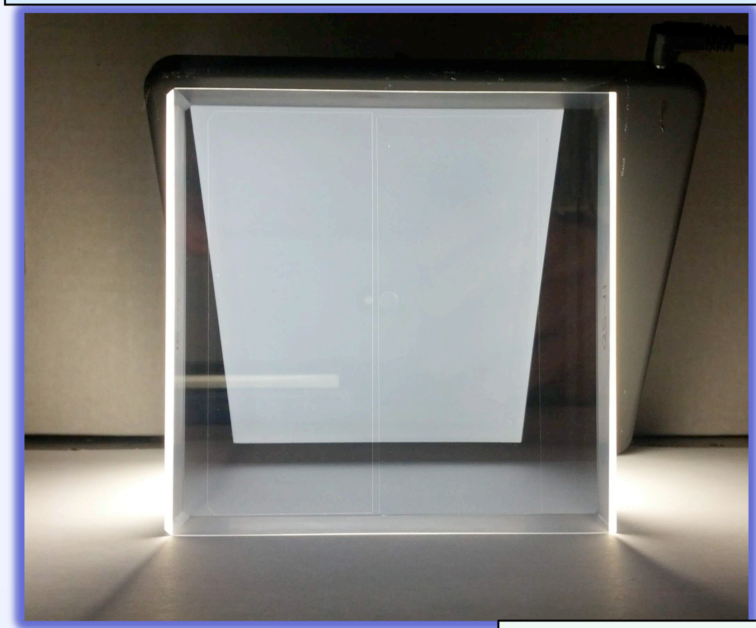
No design changes are needed to accommodate Fe^{24+} and W^{64+} or Fe^{25+} and W^{64+}.

This means both W and Fe can be measured simultaneously, if pulse-height discrimination is used to select Fe and W on the detector.

Simultaneous observation of Fe and W provides coverage for T_i ranges between about 0.7 to 45 keV

- The possibility of using two spherically bent crystals mounted side by side on the same substrate for ion temperature measurements has been demonstrated recently on the LHD (but using two detectors)
- Simultaneous measurement of Fe^{24+} and W^{64+} can be accomplished on ITER with a single detector
- We demonstrated that the signal from overlapping spectra can be separated using pulse height discrimination and an approach based on the so-called Shannon-Nyquist theorem [Wang et al., RSI 83, 10E139 (2012)]

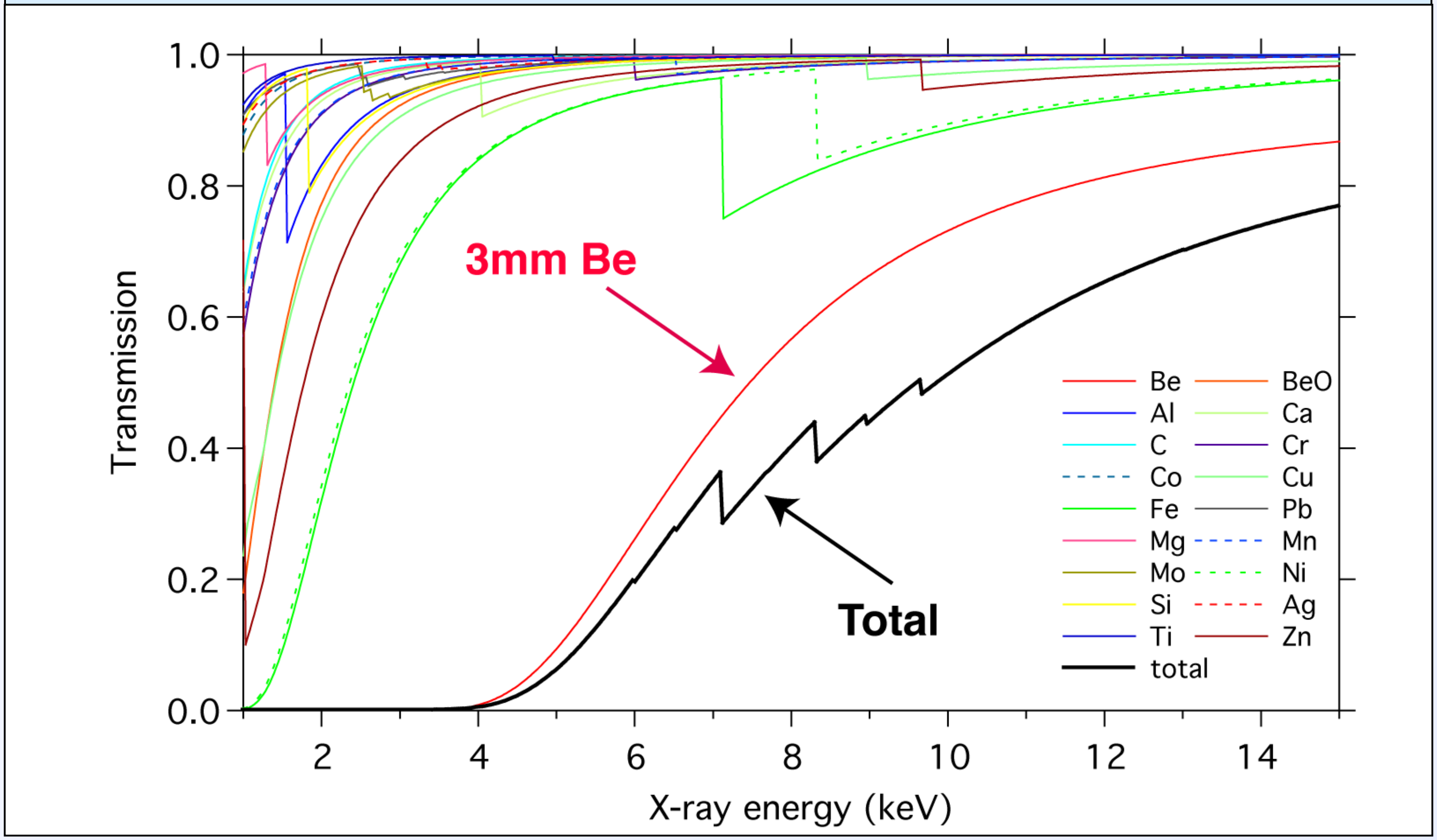
Double crystal on single substrate used on LHD



Lu et al., RSI 83, 10E130 (2013)

Using thick beryllium windows to prevent heat and tritium diffusion reduces the observed signal

Transmissivity of 3 mm beryllium – highest quality



X rays from argon cannot be used with the CIXS

Summary

• Core parameters (ion temperature, electron temperature, bulk ion motion) can be measured by observing the x-ray lines from neonlike W^{64+} and neighboring charge states when $T_e \geq 10$ keV and by observing heliumlike Fe^{24+} and neighboring charge states (or Fe^{25+}) when $T_e \leq 10$ keV

• Crystal choices are available to accommodate the *simultaneous observation* of the emission from W^{64+} and Fe^{24+} (or Fe^{25+})

• For equal impurity concentrations, the Fe^{24+} signal at 8 keV will be about 5x less than that of W^{64+} at 25 keV (depending on choice of crystal combination). A similar reduction is found for the Fe^{25+} signal level at 10 keV.

• For equal impurity concentrations, the Kr^{34+} signal at 25 keV will be about 25x less than that of W^{64+} at 25 keV.

Summary: Spectrometer performance characteristics

Spectrometer parameters:

- Crystal dimensions of 5 cm x 1.3 cm
- Germanium crystal
- Detector area 3 cm (spectral dimension) x 33 cm (spatial dimension)
- Demagnification of ~6:1

Plasma parameters:

- T_e = 25 keV, $n_e = 10^{14}$ cm^{-3}
- Tungsten concentration of 10^{-6}

Spectrometer performance:

- Each spatial resolution element is hit by 10^6 counts/s in the brightest line
  - 1000 counts/msec
- Spatial resolution about 5 cm
- Resolving power sufficient to measure ion temperatures as low as 1 keV

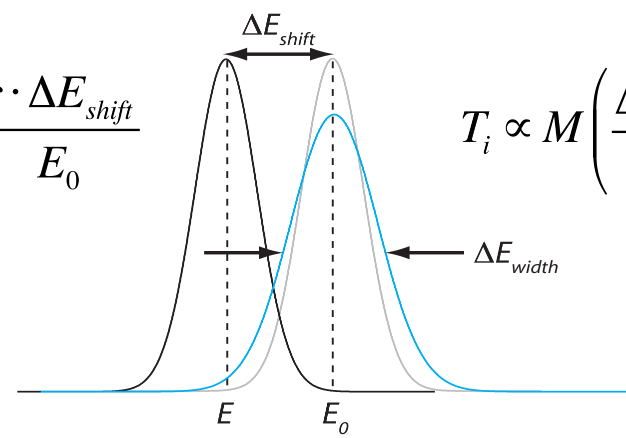
Atomic Physics Issues

P. Beiersdorfer, G. Brown, H. Chen, K. Widmann
Lawrence Livermore National Laboratory, Livermore, CA
M. Bitter, D. Johnson, K. W. Hill
Princeton Plasma Physics Laboratory, Princeton, NJ
R. Barnsley
ITER International Organization, Cadarache

Why is an understanding of the atomic physics necessary?

The ion temperature and bulk ion motion are derived from the width and shift of the line.

$$v = \frac{c \cdot \Delta E_{shift}}{E_0}$$



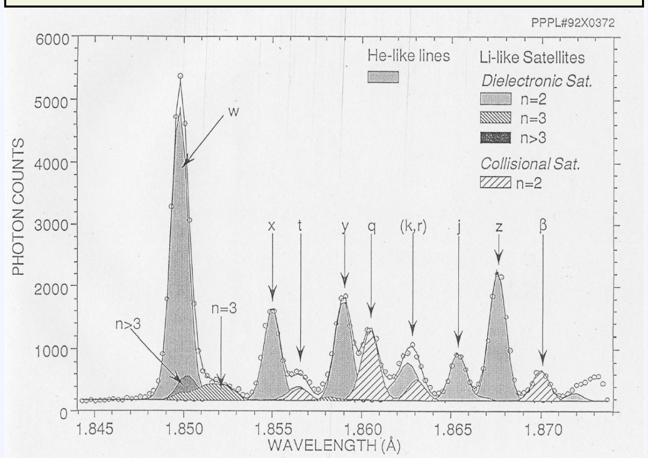
$$T_i \propto M \left(\frac{\Delta E_{width}}{E_0} \right)^2$$

- **At T_i=30 keV the line width is 9 eV.**
- **At a rotation velocity of 500 km/s the shift is ~10 eV.**
- **At a minimum everything that happens within ± 10 eV must be known**

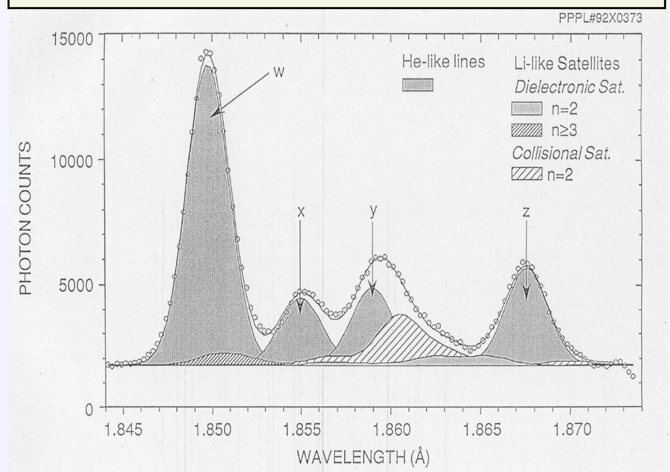
The atomic physics of the relevant spectral lines needs to be understood in order to maintain a high measurement reliability

Atomic physics that can shift or broaden the line of interest

Spectrum of heliumlike iron from TFTR; T_i = 3 keV



Spectrum of heliumlike iron from TFTR; T_i > 24 keV



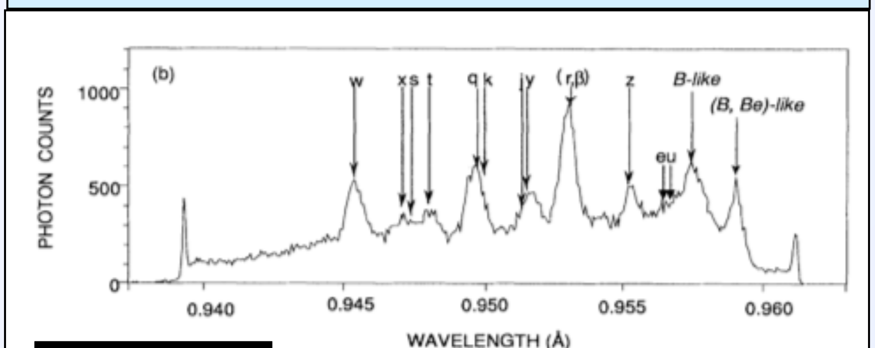
- **Blending with lines from other ions**
  - **Resultant broadening/shift depends on ionization balance, I.e., on the electron temperature and transport**
  - **Resultant broadening/shift depends on the presence of other impurity ions**
- **Dielectronic satellite lines**
  - **Resultant broadening/shift depends on the electron temperature**

Understanding the atomic physics behind these apparent broadening of shift mechanisms enhances the diagnostic value of the CIXS and provides a measure of transport and electron temperature

Blending with collisional (innershell) satellite lines has been investigated - heliumlike spectra

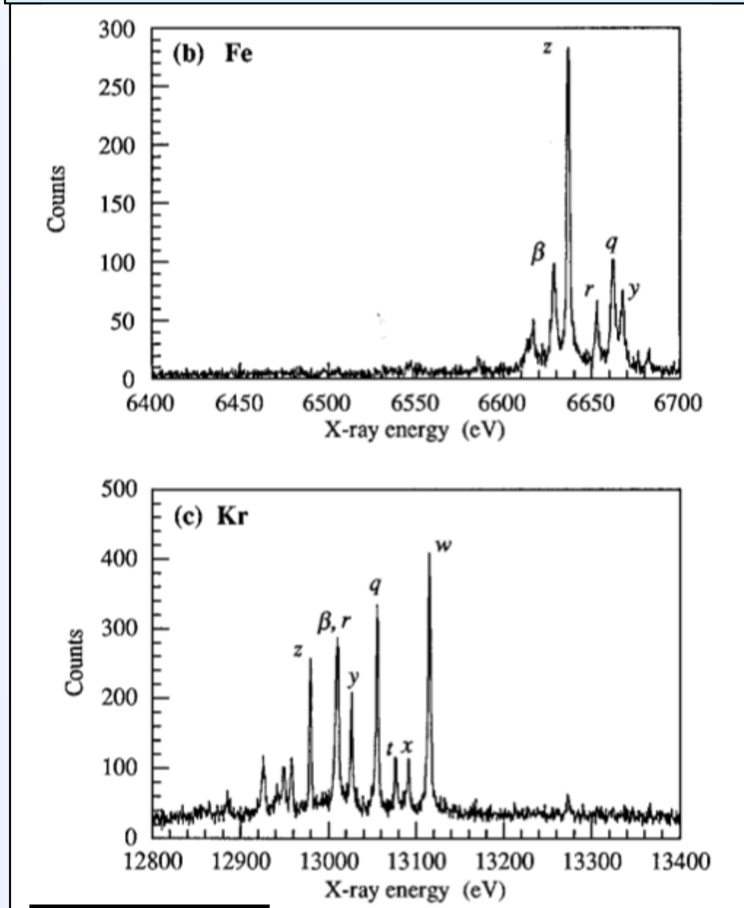
- Blending of lines from neighboring charge states is not a problem for heliumlike iron or krypton
- All lines are well known and are sufficiently far away

Krypton K-shell spectrum measured on TFTR



M. Bitter et al.
PRL 71, 1007 (1993)

Krypton and iron K-shell spectra measured on the Livermore EBIT

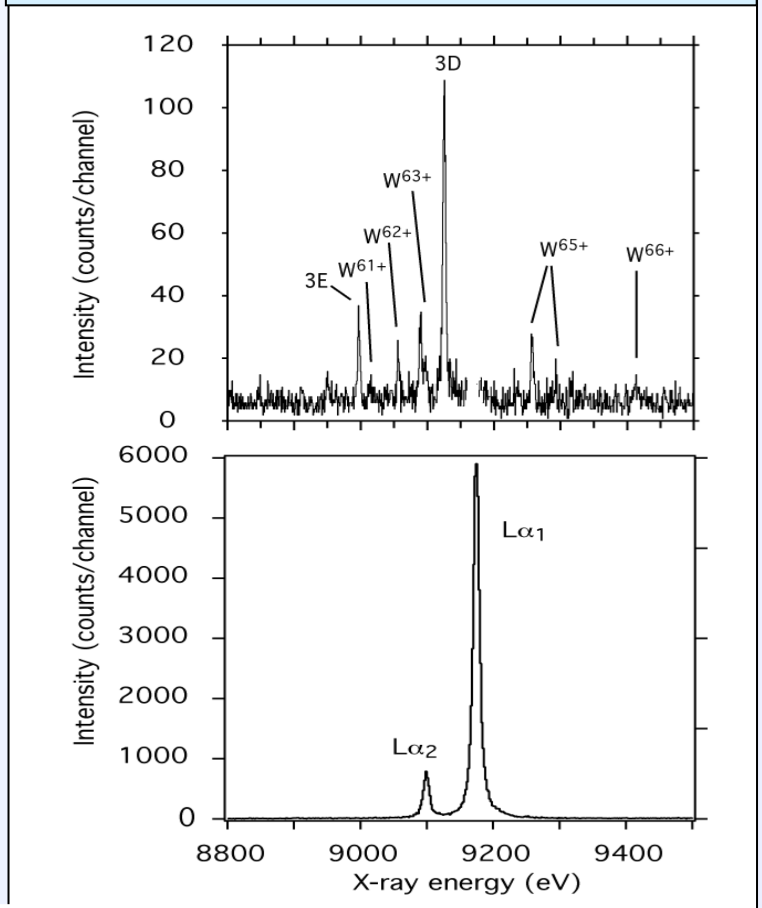


K. Widmann et al.
PRA 53, 2200 (1996)

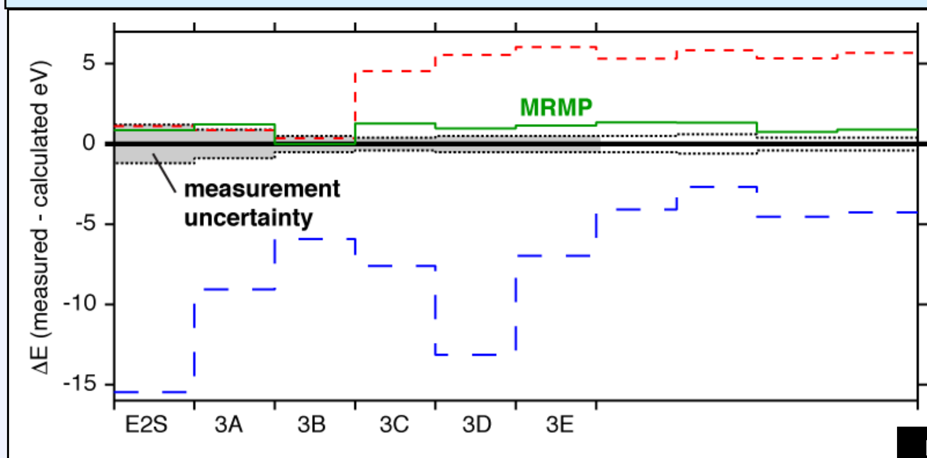
Blending with collisional (innershell) satellite lines has been investigated - neonlike spectra

- Collisional satellites lines of tungsten have recently been measured
- Closest lines are about 30 eV away and will not blend
- Theoretical values are off by up to 15 eV

Tungsten measured on EBIT and reference lines from Ir x-ray tube



Measured wavelengths compared to theory



P. Beiersdorfer et al.
PRA 86, 012509 (2012)

Collisional satellites provide a measure of plasma transport

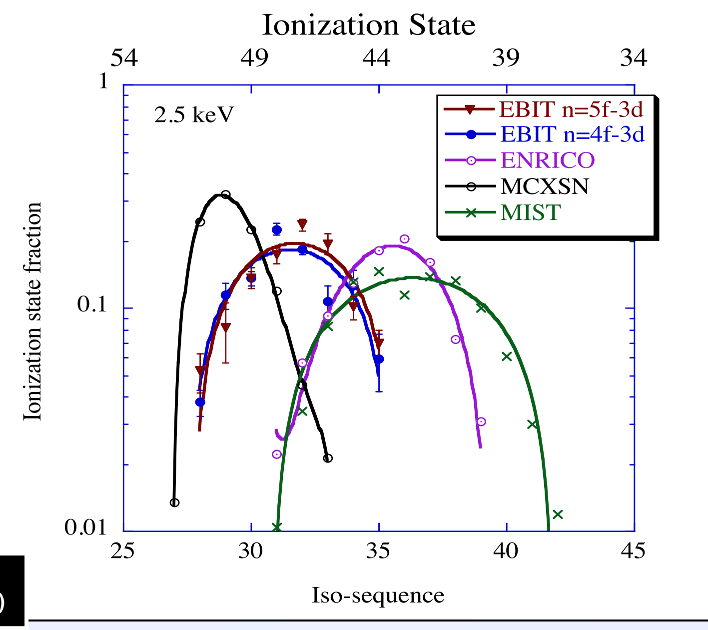
- Measurements of the collisional satellites provides a radial measure of the ionization balance and thus of plasma transport
  - For example, MIST predictions can be used to model spectra and infer transport

- Prerequisites for reliably inferring transport parameters from the spectra observed with CIXS are:

  (1) Accurate predictions of the ionization balance

  (2) Accurate excitation cross sections

Comparison of measured and calculated gold ionization balance at 2.5 keV



K. Wong et al.
PRL 90, 235001 (2003)

Dielectronic satellite lines are very prominent in high-Z heliumlike systems

- The strength of dielectronic satellite lines increases rapidly with Z and constitute a large fraction of the strongest heliumlike x-ray line
- They have been measured for heliumlike argon, titanium, chromium, iron, and nickel, for example, but not yet quantitatively for heliumlike krypton, and there are uncertainties in the iron spectrum
- The dielectronic satellites involving spectator electrons in levels with principal quantum number n=3 and larger blend with the heliumlike resonance line and must be fitted correctly when trying to infer a temperature or bulk ion motion
- Dielectronic satellite lines are temperature sensitive

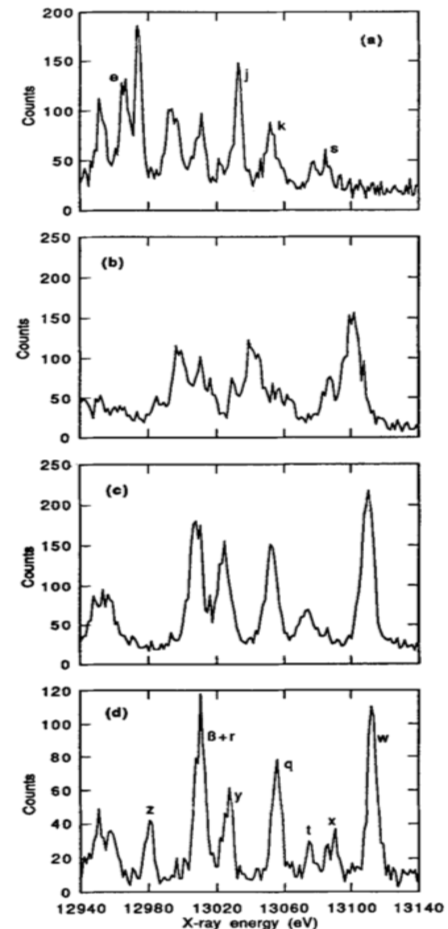
Dielectronic satellite spectra of Kr measured on EBIT at Livermore

DR satellites from n=2

DR satellites from n=3

DR satellites from n=4

Heliumlike Kr^{34+} plus collisional satellites



P. Beiersdorfer *et al.*
AIP Conf. Proc. 322, 129 (1995)

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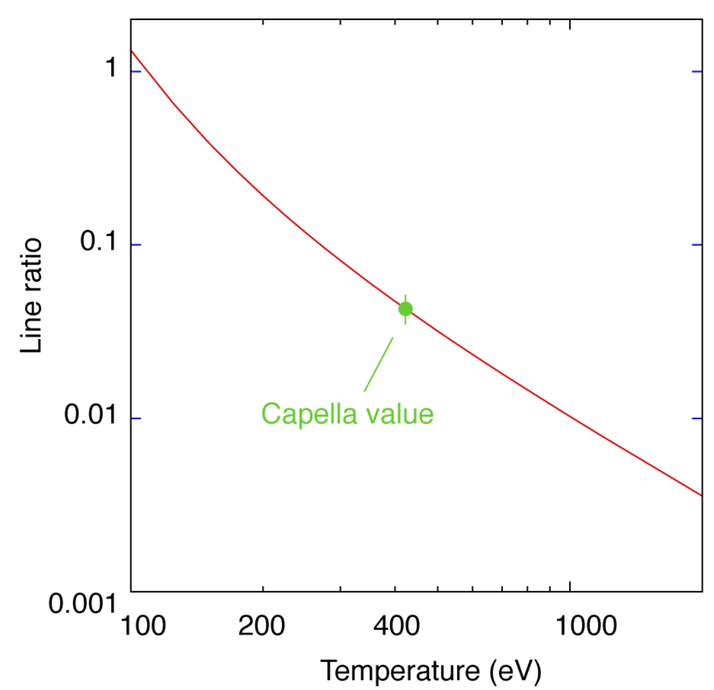
Temperature dependence of the dielectronic satellite lines of neonlike iron

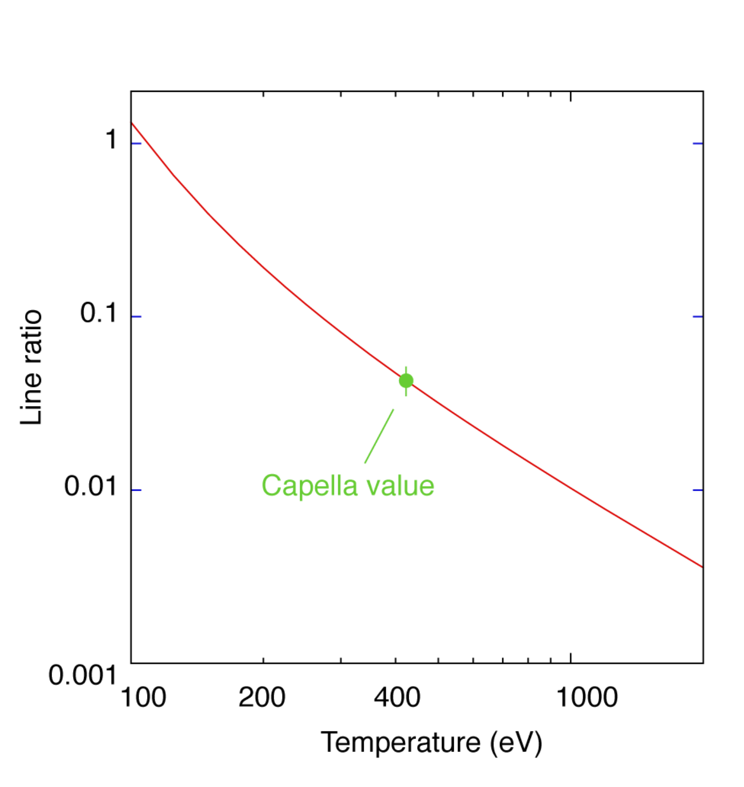


P. Beiersdorfer *et al.*
ASP Conf. Proc. 448, 787 (2011)

Dielectronic satellite lines are weak even in high-Z neonlike systems

- Dielectronic satellite lines are much weaker for neonlike ions
- They have been detected as faint contributions to the strongest lines of neonlike iron from stars and of neonlike xenon from the PLT tokamak
- No measurements of the wavelength or position of the tungsten dielectronic satellites exist as of today
- First calculations of the dielectronic satellite lines have been made

Temperature dependence of the dielectronic satellite lines of neonlike iron



P. Beiersdorfer *et al.*
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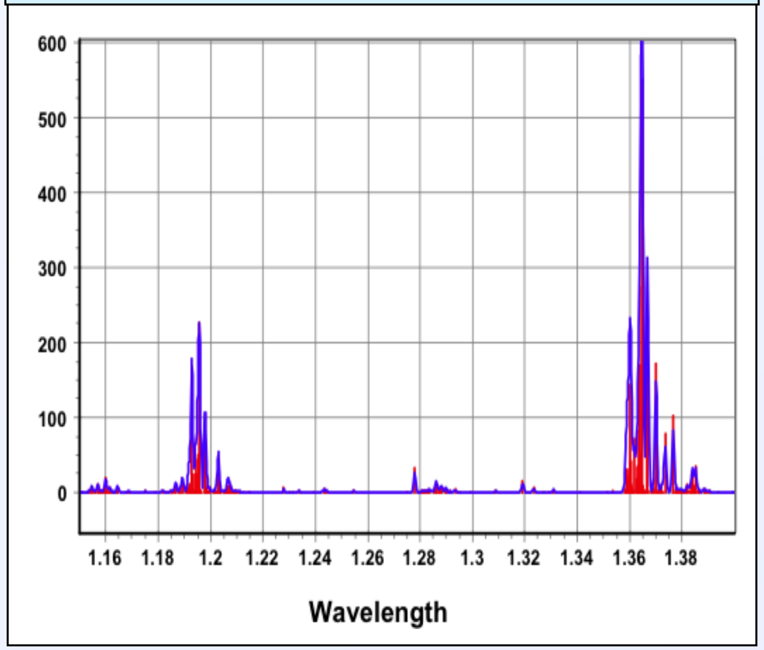
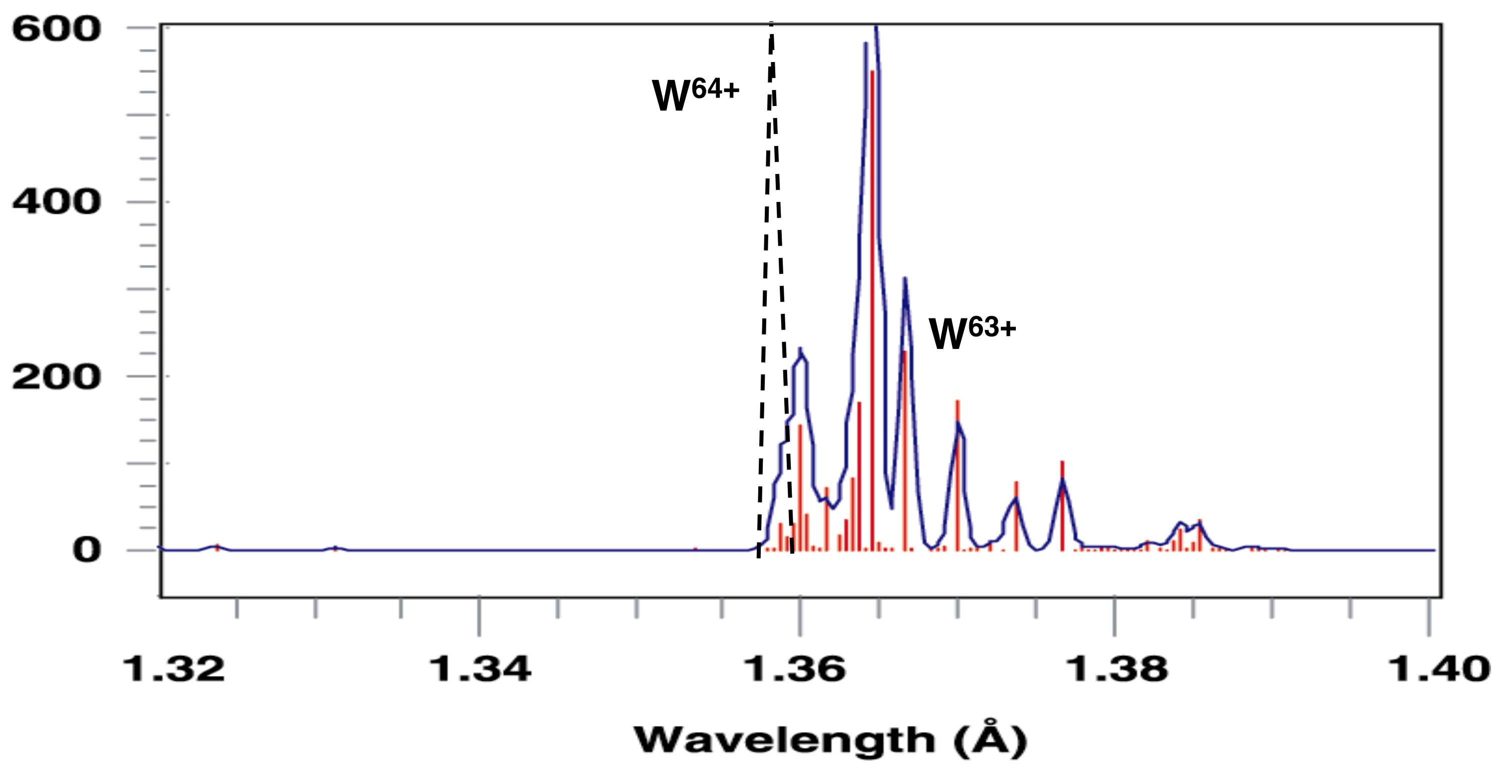
Theoretical predictions of the dielectronic satellite lines of neonlike tungsten W^{64+}



Safronova et al., At. Data Nucl. Data Tables **95**, 751 (2009)

Weak dielectronic satellite lines are predicted to exist next to the W^{64+} line

Theoretical location of the n≤7 dielectronic satellite lines relative to the measured position of the strong neonlike tungsten W^{64+} line



The wavelength of the satellite lines and their intensity must be measured to properly account for their effects on the apparent line width and shift

The CIXS provides a radial profile of the electron temperature

- The intensity of dielectronic satellites varies exponentially with the electron temperature
- The Fe^{24+} dielectronic satellites are a useful diagnostic for T_e between about 0.7 keV and 10 keV
- The W^{64+} dielectronic satellites are a useful diagnostic for T_e between about 10 keV and 20 keV

Fitting of Fe^{24+} spectra from TFTR give T_e=8.2 keV at T_i=20.7 keV

Parameters	Spectrum A	Spectrum B
Ti (keV)	3.2 $\pm$ 0.1	20.7 $\pm$ 0.3
Te (keV)	3.29$\pm$ 0.04	8.2 $\pm$ 0.04
N_{Li} / N_{He}	0.376$\pm$ 0.012	0.260$\pm$ 0.008
N_{Be} / N_{He}	0.144$\pm$ 0.013	0.018$\pm$ 0.005
xa *(multiplier)*	1.59$\pm$ 0.05	2.49$\pm$ 0.08
ya *(multiplier)*	1.61$\pm$ 0.04	1.80$\pm$ 0.04
za *(multiplier)*	1.65$\pm$ 0.04	2.29$\pm$ 0.06

Bitter et al., CJP 86, 291 (2008)

Measurements of the W^{64+} line

Wavelength:

- Currently wavelength of the W^{64+} line is known to ±0.50 eV
- The energy of the W^{64+} line should be known within 0.02 eV, if we want to measure an absolute velocity component of about 1 km/sec

Line width:

- The natural line width of the W^{64+} line is predicted to be 0.95 eV, which is assumed accurate to within about 10–15%
- The natural line width compares to a Doppler-broadened line width of 5.2 eV at T_i=10 keV and a Johann error of ~1.4 eV
- A measurement of the natural line width of the W^{64+} line is only needed, if we want to measure T_i with an accuracy better than about 300 eV, i.e., only in cold plasma

Measurements of the Fe^{24+} line

Wavelength:

- **Currently wavelength of the Fe^{24+} line is known to ±0.30 eV**
- **The energy of the Fe^{24+} line should be known within 0.02 eV, if we want to measure an absolute velocity component of about 1 km/sec**

Line width:

- **The natural line width of the Fe^{24+} line is predicted to be 0.30 eV, which is assumed accurate to within about 1%**
- **The natural line width compares to a Doppler-broadened line width of 4 eV at T_i=4 keV and a Johann error of ~1 eV**
- **The natural line width of the Fe^{24+} line does not need to be measured even when using the line to measure cold plasmas**

Summary

The atomic physics is sufficiently well understood for all relevant spectral lines to use the CIXS for ion temperature and bulk velocity measurements

- The reliability of the ion temperature and bulk velocity measurements will be improved if the position and intensity of the dielectronic satellite lines are known from independent measurements instead of theory
- Reliable knowledge of the dielectronic satellites will allow a determination of the electron temperature
- The absolute line positions of the W^{64+} and Fe^{24+} lines should be determined with higher accuracy than presently available so that the CIXS can make best use of fiducials from x-ray tubes for determining the toroidal rotation
- Better knowledge of ionization balance and excitation cross sections will allow a determination of transport paramters