The importance of the EBIT data for Z-pinch plasmas diagnostics

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OUTLINE

I. **Introduction and Motivation**

II. **M-shell W radiation**

- **M-shell W model: atomic and plasma physics in the model**
- **Modeling of the spectra from LLNL EBIT**
- **Comparison of the M-shell W spectra from LLNL EBIT and UNR X-pinches and modeling of UNR X-pinch experiments**

III. **K-shell Ti radiation**

- **Modeling of spectra from LLNL EBIT and UNR X-pinch experiments**
- **Polarization of x-ray line radiation: calculations and applications to the LLNL EBIT and UNR X-pinch experiments**

IV. **Conclusion.** ***Why are the EBIT data so important for the HEDP diagnostics?***

INTRODUCTION: Previous work on M-shell Tungsten (selected papers)

- **The first x-ray spectra of M-shell W have been produced by high-density exploded–wire plasmas more than 25 years ago (Burkhalter *et al*. Phys. Rev. A 15, 700, 1977)**

- **The precision of the measurements of Ni-like W lines was improved in laser plasma experiments (Zigler *et al*. JOSA 70, 129, 1981)**

- **The extended analysis of Ni-like W spectra from laser plasma has included *nf*→*3d* (n=5-9), *nd*→ *3p* (n=4-6), and *np*→*3s* (n=4,5) transitions (Tragin *et al*. Phys. Scr. 37, 72, 1988)**

- **Despite the increasing number of papers about the implosions of the W arrays on the SNL-Z since 1998 (R.B. Spielman, C. Deeney, G.A. Chandler *et al*. *Tungsten wire-array experiments at 200 TW and 2 MJ*. Phys. Plasmas 5, pp. 2105-2111, 1998) and their recent applications to ICF, the M-shell diagnostic of W plasmas is not yet developed**

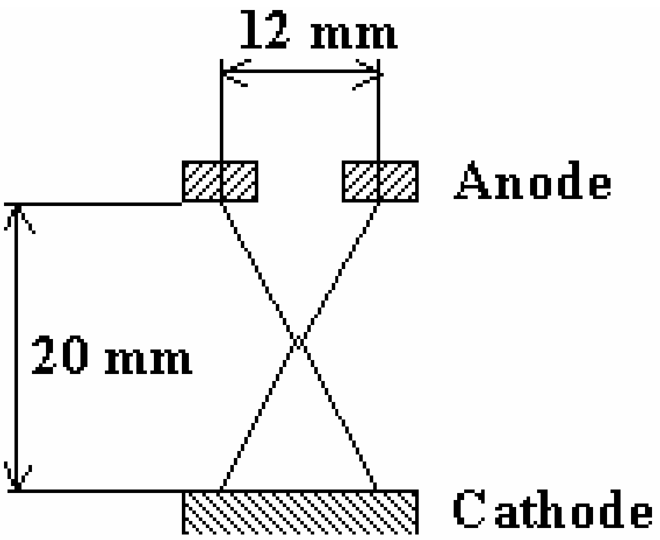
- **Recently, LLNL Electron-beam-ion-trap M-shell W spectra have been studied in a spectral region from 5 to 6 Å (P. Neill, C. Harris, A.S. Safronova, S.M. Hamasha, S.B.Hansen, P. Beiersdorfer, U.I. Safronova. *The study of x-ray M-shell spectra of W ions from the Livermore electron beam ion trap*. Can. J. Phys. 82, 931, 2004)**

Application of the model to experiments

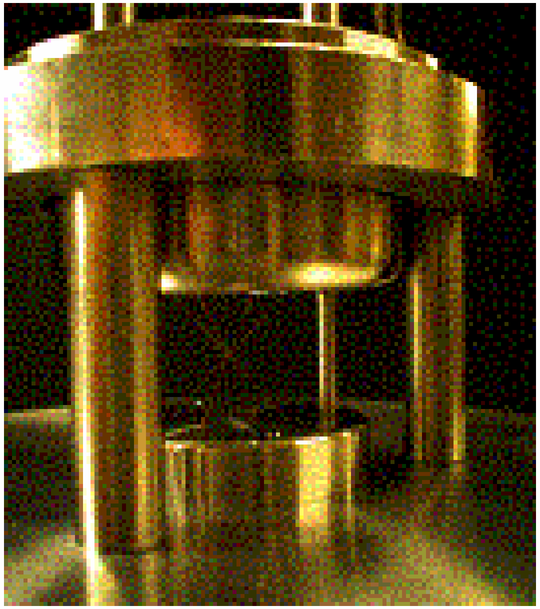
- LLNL EBIT experiments
- UNR pulsed power X-pinch experiments

What are X-Pinches?

- An x-pinch plasma is formed by touch-crossing two wires between the output electrodes of a high current pulsed power generator. The high current quickly vaporizes and strongly ionizes the wire material. The x-pinch yields short x-ray bursts from a small bright spot or spots at the intersection of the crossed wires.



- X-pinches are a good source for studying dynamics of z-pinch plasmas of very small sizes, high densities and temperatures, for developing 1-10keV x-ray backlighters, and can be used for testing x-ray spectropolarimetry (a powerful new tool for studying the anisotropy of high-temperature plasmas) and other applications.



- For more about X-pinch studies at UNR and experimental details see, for example,

V. L. Kantsyrev, A. S. Safronova, V.V. Ivanov *et al*
JQSRT 99, pp. 349-362 (2006)

M-shell W radiation

- M-shell W model: atomic and plasma physics in the model

- Modeling of the spectra from LLNL EBIT

- Comparison of the M-shell W spectra from LLNL EBIT and UNR X-pinches and modeling of UNR X-pinch experiments

Full Kinetic Model

- **The full kinetic model includes the ground states of all ions from neutral to bare W and a detailed structure for H- to Zn-like W ions (~4000 levels)**
- **The levels are linked through ionization, excitation, recombination, and radiative decays**
- **Atomic data were calculated using the FAC code by M. F. Gu**
- **The details and applications of this kinetic model for modeling of L-shell Mo Z-pinch spectra have been described in the references below.**

S.B. Hansen. PhD dissertation. University of Nevada, Reno (Dec. 2003)

A.S. Shlyaptseva, S.B. Hansen, V.L. Kantsyrev et al. *Advanced spectroscopic analysis of 0.8-1.0-MA Mo x-pinches and the influence of plasma electron beams on L-shell spectra of Mo ions.* Phys. Rev. E 67, 026409, 2003 .

RMBPT

Energies for excited states of 3l-4l', 3l-5l'', and 3l-6l ''' transitions in Ni-like ions and of 3l-4l' transitions in Cu-like ions are determined to second order in Relativistic Many Body Perturbation Theory (RMBPT). The calculations start from a closed-shell Dirac-Fock potential, and include second-order Coulomb and Breit-Coulomb interactions. Electric-dipole matrix elements are calculated in the second order for transitions from excited states to the ground state.

U.I. Safronova, W.R. Johnson, J.R. Albritton. *Phys. Rev. A* 62, 052505 (2000)

U.I. Safronova, W.R. Johnson, A. Shlyaptseva and S. Hamasha. *Phys. Rev. A* 67, 052507 (2003)

U.I. Safronova , A.S. Safronova, S.M. Hamasha, P. Beiersdorfer. *Atomic Data and Nuclear Data Tables* 96, pp. 47-104 (2006)

U.I. Safronova, A.S. Safronova, P. Beiersdorfer. *J. Phys. B* 39, pp. 4491-4513 (2006)

See also poster by Ulyana Safronova *et al* at this Conference

E1 and E2 transition rates (Ar in s^{-1}) and wavelengths (λ in Å) for transitions from excited states with J=1 and 2 into the ground state in Ni-like W (RMBPT)*

		RMBT		FAC	
N	LS	λ	Ar	λ	Ar
Ni1	3d6f $^1P_1$	3.803	5.30[13]	3.805	6.51[13]
Ni2	3d6f $^3D_1$	3.879	5.66[13]	3.880	7.25[13]
Ni3	3d5f $^1P_1$	4.308	1.16[14]	4.309	1.33[14]
NI4	3d5f $^3D_1$	4.403	9.07[13]	4.405	1.02[14]
Ni5	3p4d $^1P_1$	5.201	9.35[13]	5.195	9.54[13]
Ni6	3p4s $^1P_1$	5.689	3.72[14]	5.686	3.99[14]
Ni7	3d4f $^3D_1$	5.870	1.18[14]	5.872	1.24[14]
Ni8	3d4f $^3P_1$	6.154	2.21[13]	6.144	2.17[13]
Ni9	3d4p $^3D_1$	7.027	1.27[13]	7.028	1.21[13]
Ni10	3d4p $^3P_1$	7.174	6.67[12]	7.175	6.32[12]
Ni11	3d4s $^1D_2$	7.608	4.04[09]	7.610	4.55[09]
Ni12	3d4s $^2D_2$	7.929	5.32[09]	7.930	5.97[09]

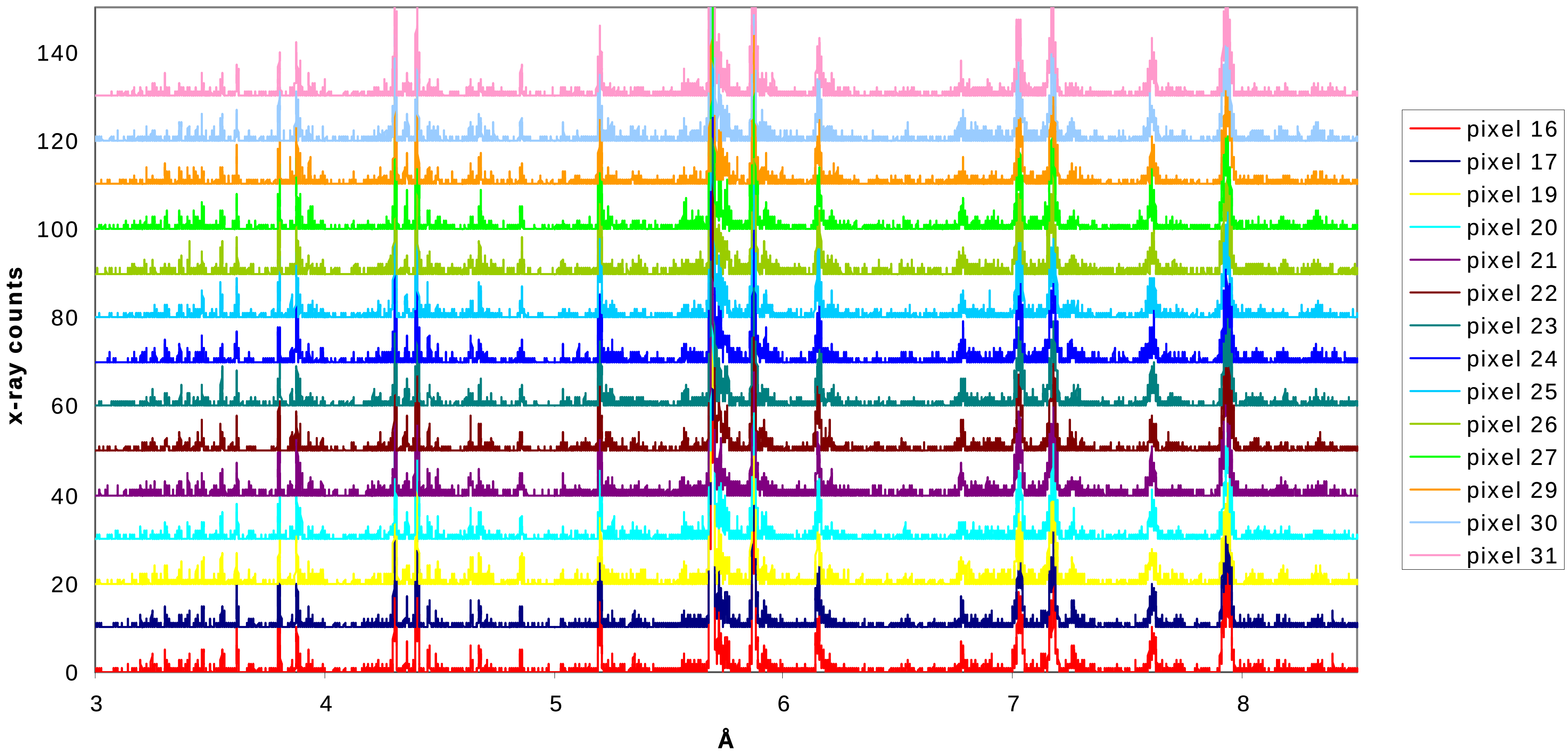
*U.I. Safronova , A.S. Safronova, S.M. Hamasha, P. Beiersdorfer. *Atomic Data and Nuclear Data Tables* 96, pp. 47-104 (2006)
U.I. Safronova, A.S. Safronova, P. Beiersdorfer. *J. Phys. B* 39, pp. 4491-4513 (2006)

For the detailed study of the X-ray M-shell spectra of W ions from the LLNL EBIT recorded by a crystal spectrometer at different electron beam energies see P. Neill, C. Harris, A.S. Safronova, S. Hamasha, S. Hansen, U.I. Safronova, P. Beiersdorfer, Can J. Phys. 82, pp. 931-942 (2004).

The data were collected and analyzed at 2.4, 2.8, and 3.6 keV, and for steps in energy of 100 eV over 3.9-4.6 keV range. The analysis of 11 W spectra in a spectral range from 5 to 6 Å has shown the presence of a wide variety of ionization stages from Se- to Cr-like W; the appearance of these ionization stages correlate well with the energy of their production.

- **Here we will present the recent study of the M-shell W spectra from LLNL EBIT recorded by the XRS microcalorimeter**

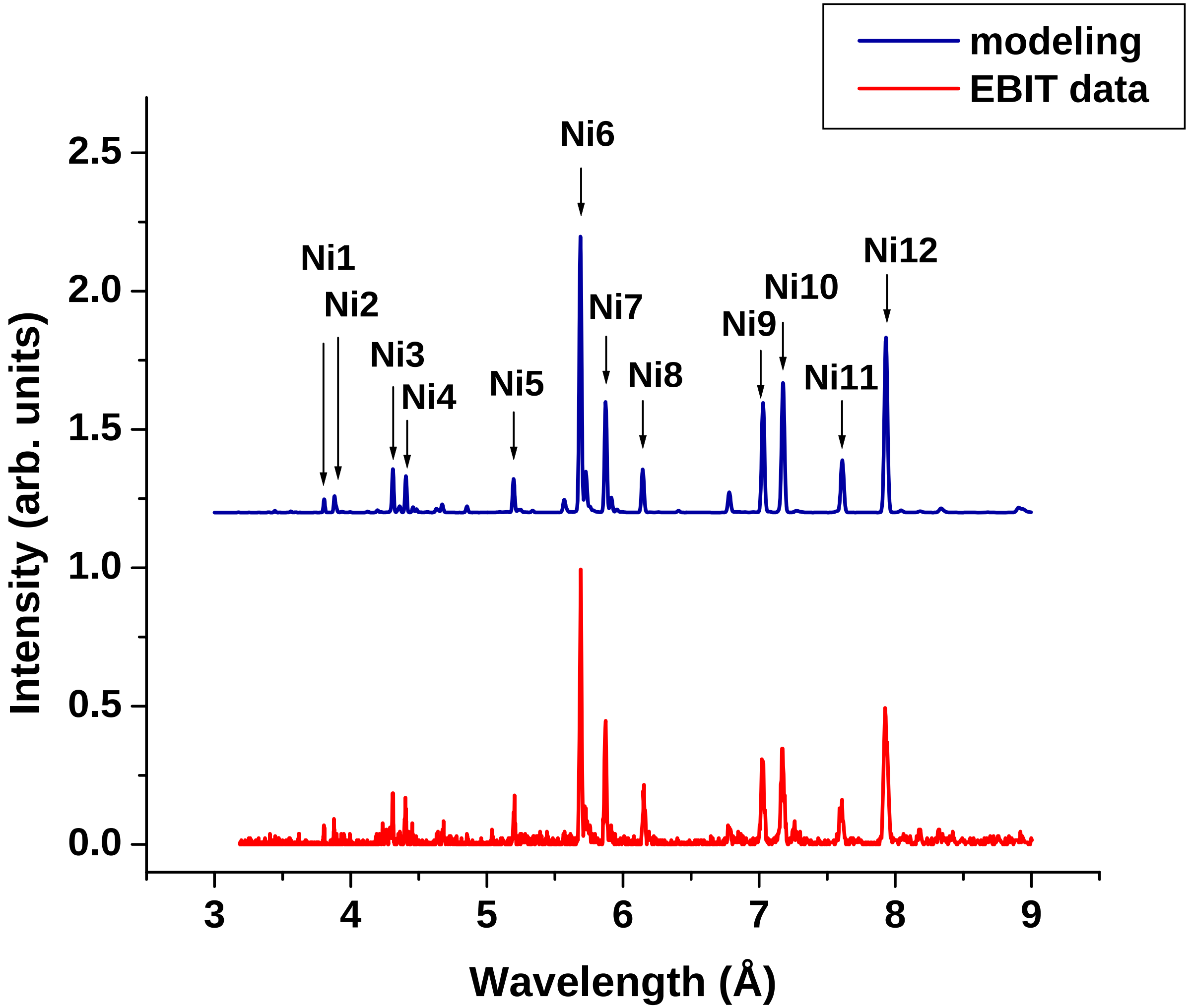
The XRS microcalorimeter is capable of acquiring, filtering, and characterizing x-ray events on 32 independent pixels*. In the present work, only 14 pixels were used to record spectra at Eb=3.9 keV



*F.S. Porter *et al*. *RSI* 75, pp. 3772-3774 (2004)

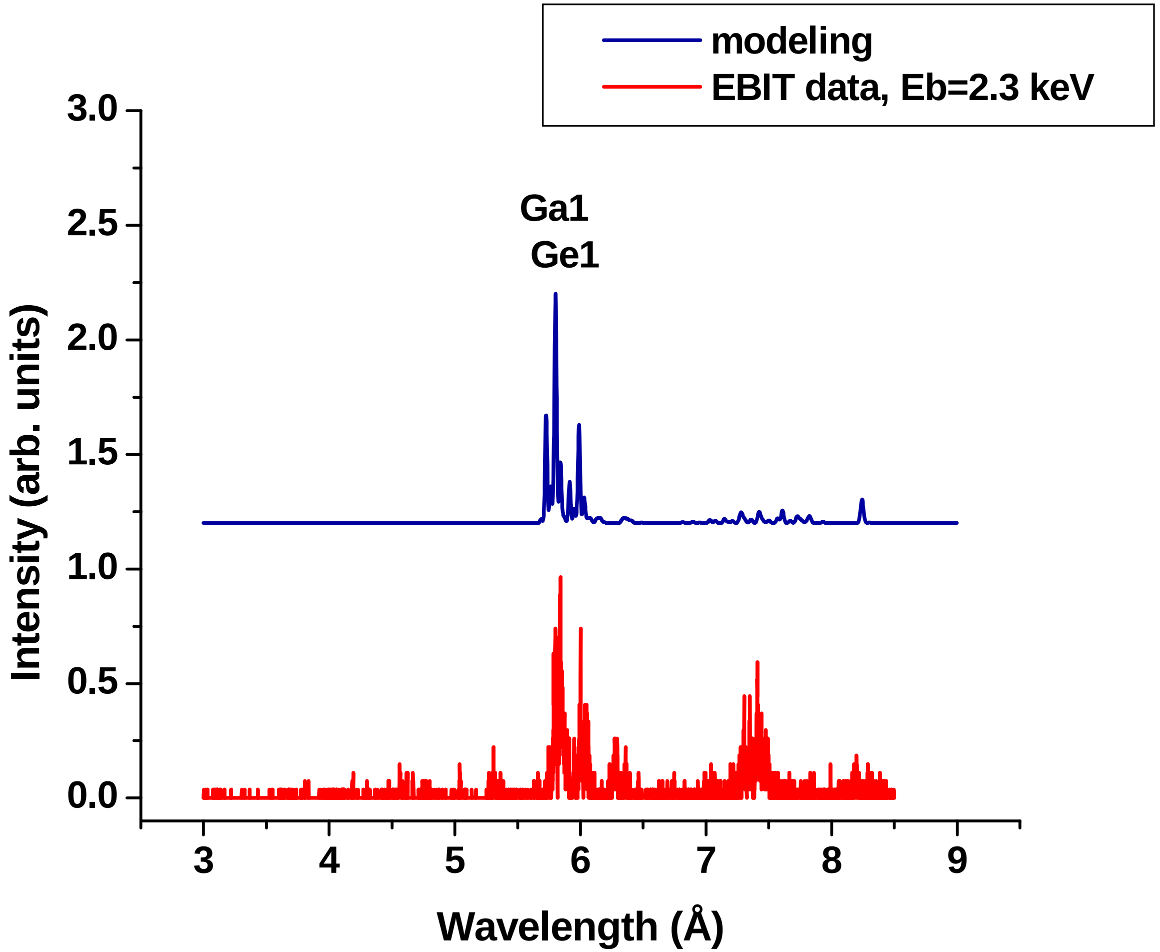
see also F.S. Porter *et al* at this workshop

Modeling reproduces well the LLNL EBIT data collected at E_b=3.9 keV and recorded with the XRS calorimeter



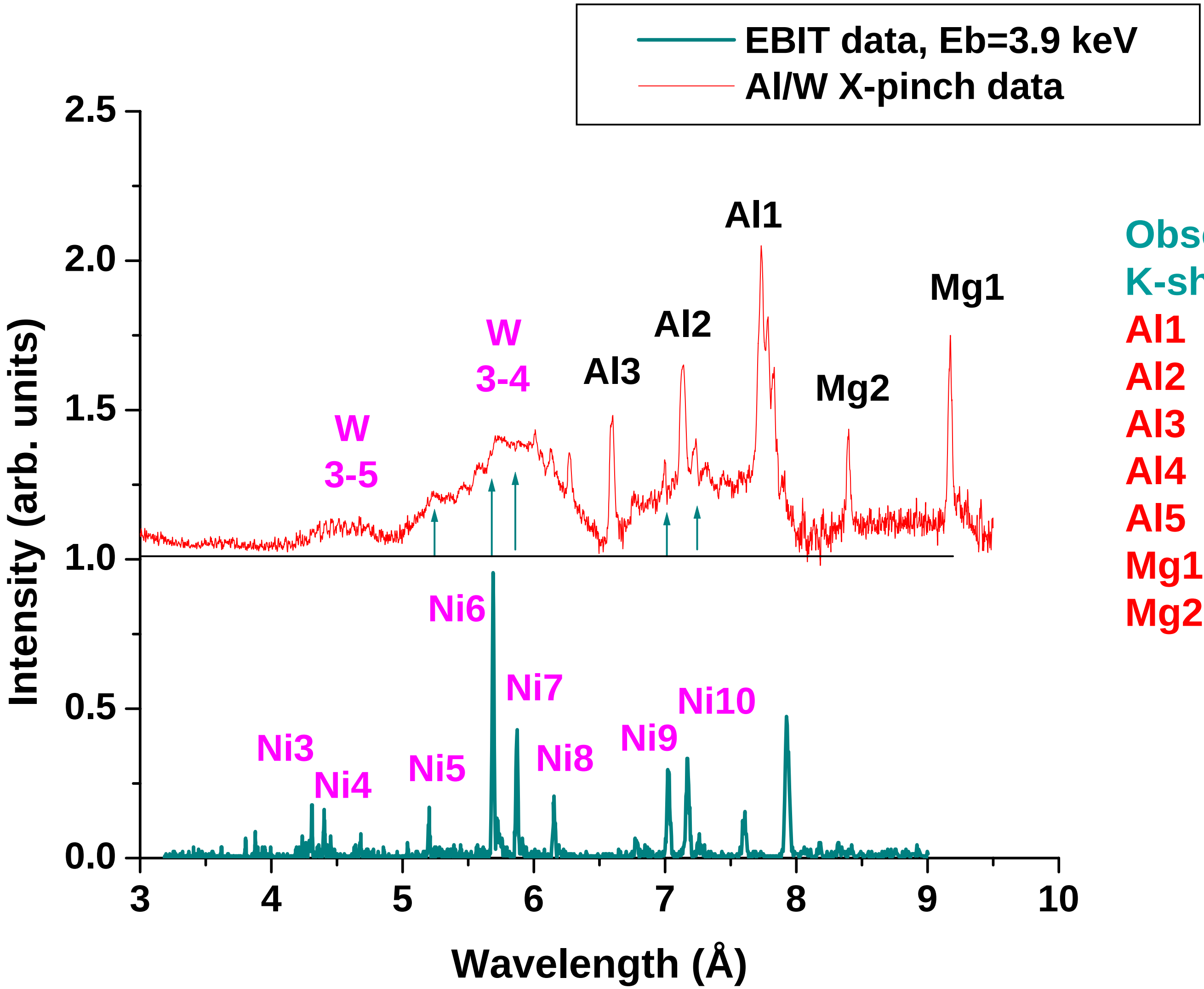
Note: at this energy of the electron beam Ni-like W lines dominate

Modeling of the LLNL EBIT data collected at E_b=2.3 keV recorded with the XRS calorimeter requires more work because of the limited number of transitions included in low ionization stages



Note: the most intense peak due to Ga- and Ge-like W is described well

Comparison of M-shell W spectra from combined UNR X-pinches and LLNL EBIT

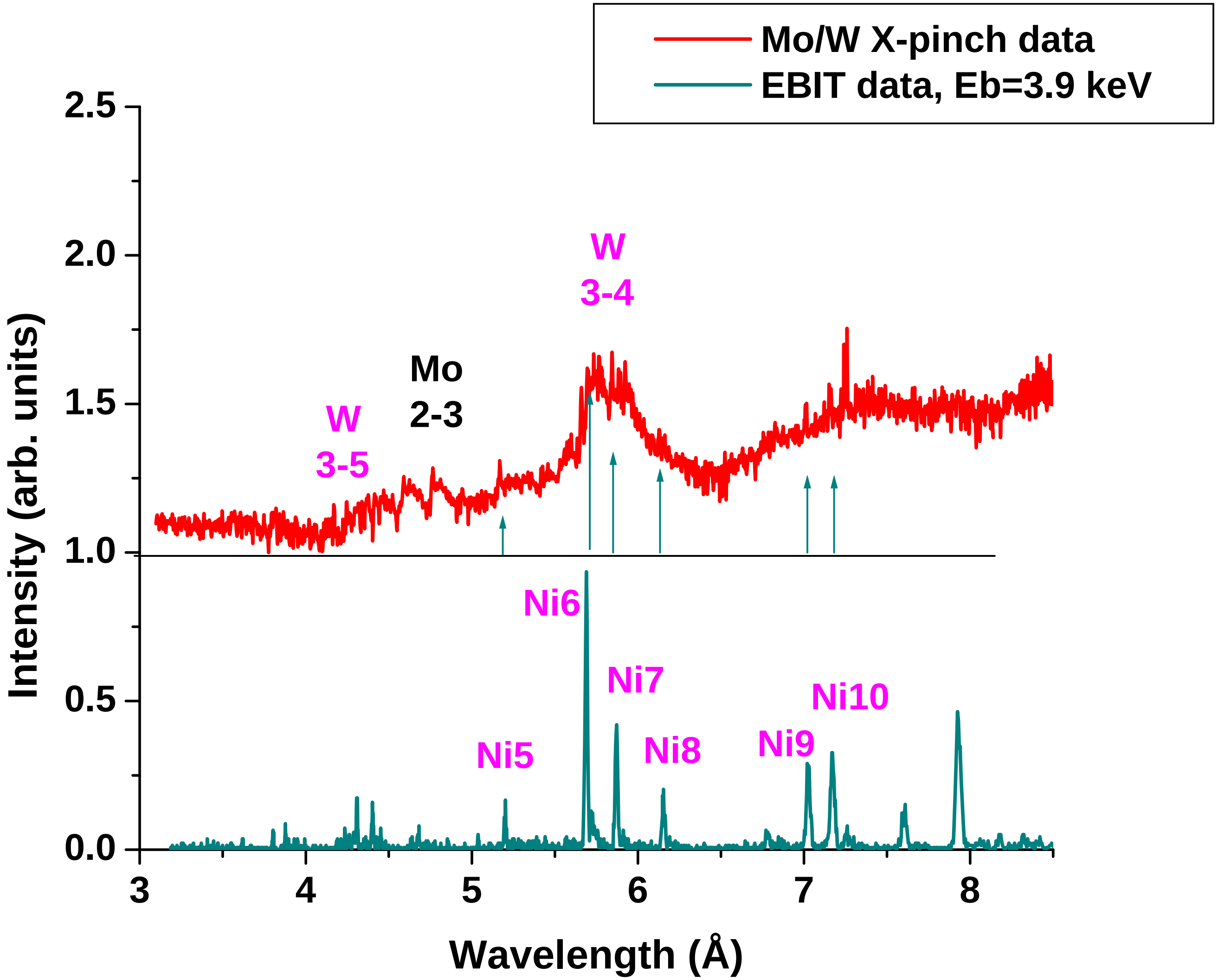


Observed K-shell lines:

Al1	Heα
Al2	Lyα
Al3	Heβ
Al4	Heγ
Al5	Lyβ
Mg1	Heα
Mg2	Lyα

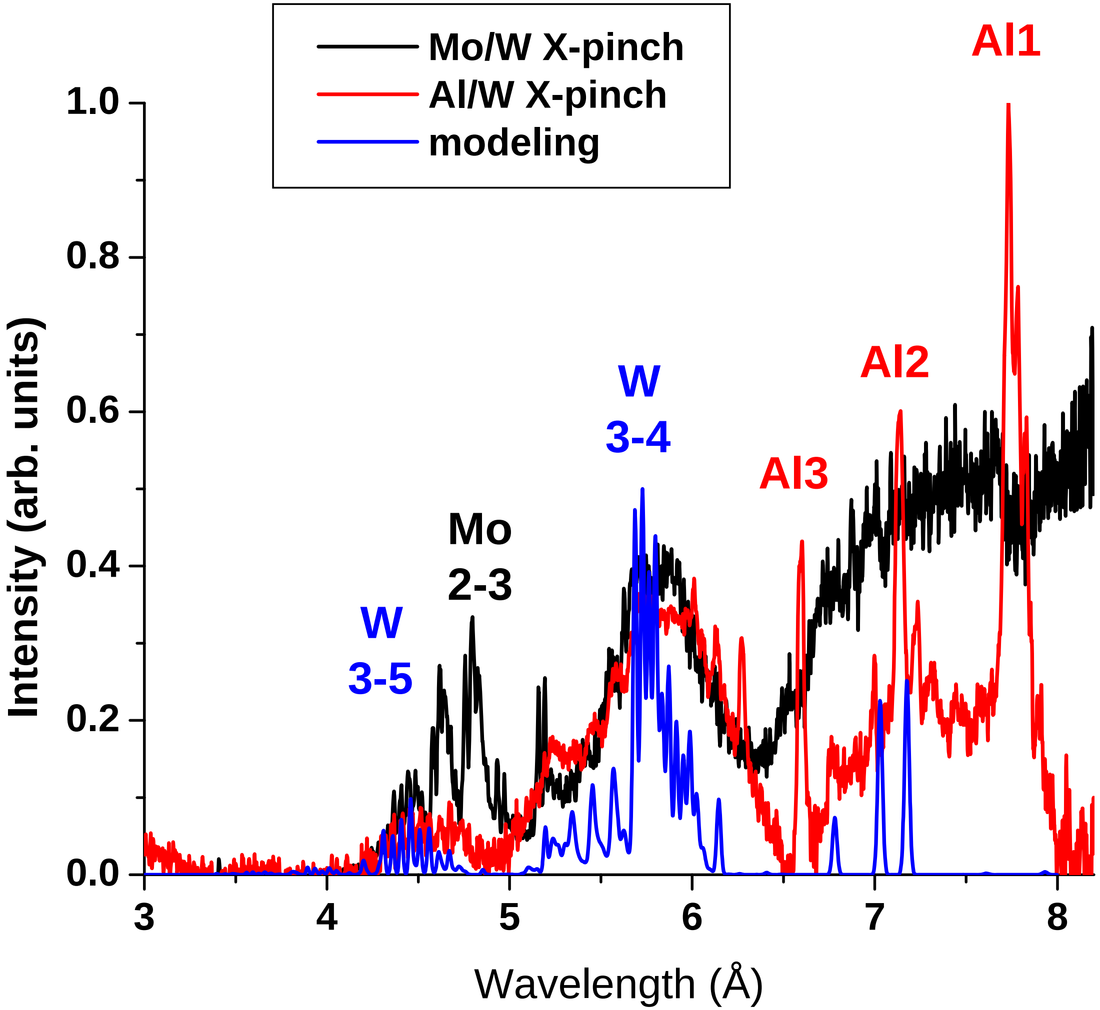
EBIT spectra are very useful in identification of M-shell W spectra from HEDP

Comparison of M-shell W spectra from combined UNR X-pinches and LLNL EBIT*



*For more details on the study of combined X-pinches at UNR see V. L. Kantsyrev, A. S. Safronova, D. A. Fedin *et al.* *IEEE Trans. Plasma Sci.*, v. 34, pp. 194-212 (2006)

Modeling of M-shell W spectra from X-pinches: Te=1 keV, Ne=10^{21} cm^{-3}, f=0.03 (blue line)



Modeling describes well the most intense peaks and the ratio between 3-5 and 3-4 transitions: more work is needed to match intensities of higher ionization stages

K-shell Ti radiation

- Modeling of spectra from LLNL EBIT and UNR X-pinch experiments

- Polarization of x-ray line radiation: calculations and applications to the LLNL EBIT and UNR X-pinch experiments

Previous work on the polarization of x-ray lines at LLNL EBIT (selected papers)

P. Beiersdorfer, D.A. Vogel, K.J. Reed, V. Decaux, J.H. Scofield, K. Widmann, G. Hölzer, E. Förster, O. Wehrhan, D.W. Savin, L. Schweikhard. *Measurement and interpretation of the x-ray line emission of heliumlike FeXXV excited by an electron beam*. Phys. Rev. A 53, pp. 3974-3981 (1996)

A.S. Shlyaptseva, R.C.Mancini, P. Neill, P. Beiersdorfer, J.R. Crespo-López-Urrutia, K. Widmann. *Polarization-depenedent spectra of x-ray dielectronic satellite lines of Be-like Fe*. Phys. Rev. A 57, pp. 888-898 (1998)

A.S. Shlyaptseva, R.C. Mancini, P. Neill, P. Beiersdorfer. *Polarization properties of dielectronic satellite lines in the K-shell x-ray spectra of B-like FeXXII*. J. Phys. B 32, pp. 1041-1051 (1999)

P. Beiersdorfer, G. Brown, S. Utter, P. Neill, A.J. Smith, R.S. Thoe. *Polarization of K-shell x-ray transitions of Ti^{19+} and Ti^{20+} excited by an electron beam*. Phys. Rev. A 60, pp. 4156-4159 (1999)

Diagnostically important K-shell Ti lines

Ion	Line	λ(Å)	Transition
He	w	2.6105	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$
He	x	2.6192	$1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$
He	y	2.6229	$1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$
Li	q	2.6277	$1s2s2p\ ^2P_{3/2} \rightarrow 1s^22s\ ^1S_0$
Li	r	2.6300	$1s2s2p\ ^2P_{1/2} \rightarrow 1s^22s\ ^1S_0$
He	z	2.6370	$1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$

Ratios of the line intensities from LLNL EBIT experiments produced by monoenergetic electron beam centered at 4.8 keV and Maxwellian electron beam at Te=2.3 keV at LLNL EBIT

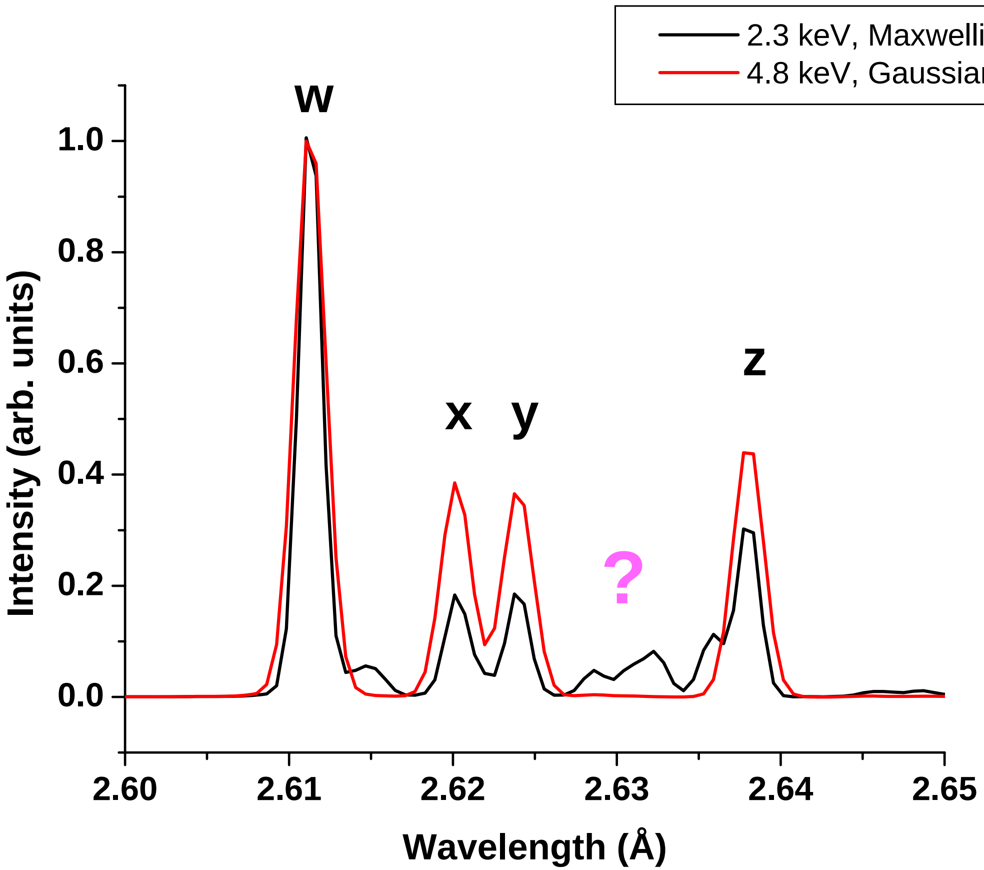
	Eb=4800 eV monoenergetic beam*		Tmax=2.3 keV quasi-Maxwellian beam**	
	Si(220)	Se(111)	Si(220)	Ge(111)
y/w	0.147	0.235	0.113	0.153
x/w	0.102	0.191	0.068	0.145
z/w	0.258	0.343	0.212	0.335
q/w	0.313	0.316	0.184	0.255

*P. Beiersdorfer, G. Brown, S. Utter, P. Neill, A.J. Smith, R.S. Thoe. *Phys. Rev. A* 60, pp. 4156-4159 (1999)

**A.S. Shlyapsteva, D.A. Fedin, S.M. Hamasha, S.B. Hansen, C. Harris, V.L. Kantsyrev, P. Neill, N. Ouart, P. Beiersdorfer, U.I. Safronova. *RSI* 74, pp. 1947-1950 (2003)

The almost pure parallel polarization states were recorded by Si (220) crystals in both experiments (blue columns) whereas the other spectrometers recorded the mixture of both polarization states

Comparison of theoretical spectra calculated for the monoenergetic electron beam centered at 4.8 keV and Maxwellian electron beam at Te=2.3 keV*

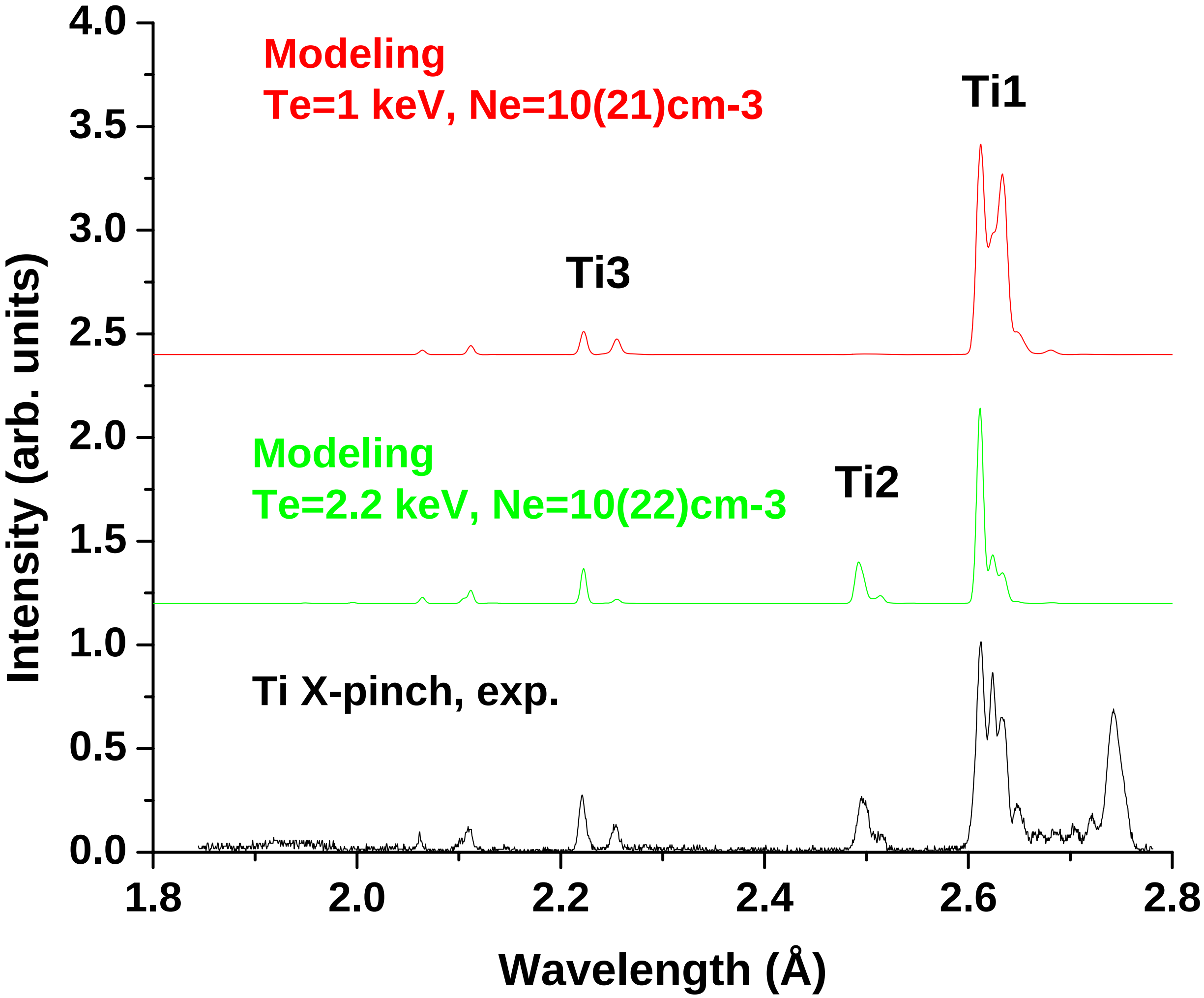


The theory describes well the ratios and difference in spectra between monoenergetic and quasi-Maxwellian beams

***For the details of the Ti model see S.B. Hansen and A.S. Shlyaptseva, *Phys. Rev. E* 70, 036402 (2004)**

Unsolved mystery: the modeling does not show any q line!

Modeling of the Ti X-pinch spectra indicates that the plasmas consists of at least two different regions: a hot dense region which radiates H-like and most of He-like lines and a cooler, and probably less dense region which radiates satellites



Why do we need to study polarization properties of X-ray lines?

- To correct crystal spectrometer data sensitive to line polarization

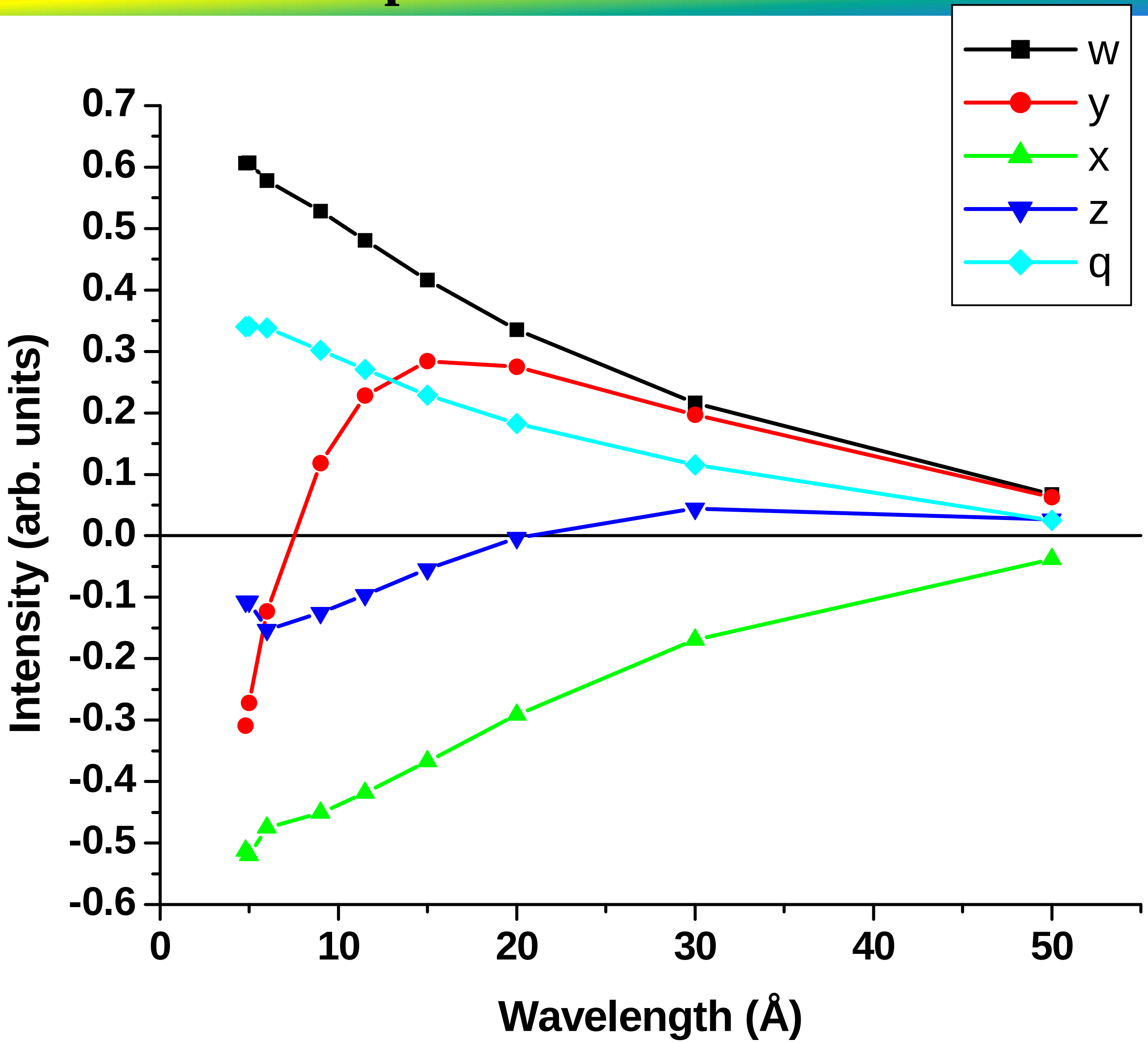
- To study plasma anisotropy and to develop diagnostics of electron beams in plasmas

Comparison of polarization degrees for the K-shell Ti lines

	4.8 keV			11.5 keV
	theory*	exp*	theory**	theory**
w	+0.608	+0.43	+0.607	+0.481
y	-0.339	-0.33	-0.309	+0.228
x	-0.519	-0.48	-0.513	-0.418
z	-0.106	-0.101	-0.106	-0.096
q	+0.341	+0.40	+0.340	+0.270

*P. Beiersdorfer, G. Brown, S. Utter, P. Neill, A.J. Smith, R.S. Thoe. *Phys. Rev. A* 60, pp. 4156-4159 (1999)
** present work, FAC code

Theoretical values of polarization for the K-shell Ti lines (FAC)



Note: the ratio y/w is very important in diagnostics of the energy of the electron beams

Ratios of the line intensities from LLNL EBIT experiments produced by monoenergetic electron beam centered at 4.8 keV and Maxwellian electron beam at Te=2.3 keV at LLNL EBIT

Experimental values of intensity ratios

	Tmax=2.3 keV quasi-Maxwellian beam	
	Si(220)	Ge(111)
y/w	0.113	0.153
x/w	0.068	0.145
z/w	0.212	0.335
q/w	0.184	0.255

Theoretical Line Polarization

Eb	4.8 keV	11.5 keV
w	+0.607	+0.481
y	-0.302	+0.228
x	-0.513	-0.418
z	-0.106	-0.096
q	+0.340	+0.270

Another mystery about q line! The value of polarization of the q line which can be derived from the intensities ratios using two-crystal technique (Table at the left) is negative instead of being positive.

X-ray spectropolarimetry in UNR Ti and Mo X-pinch experiments*

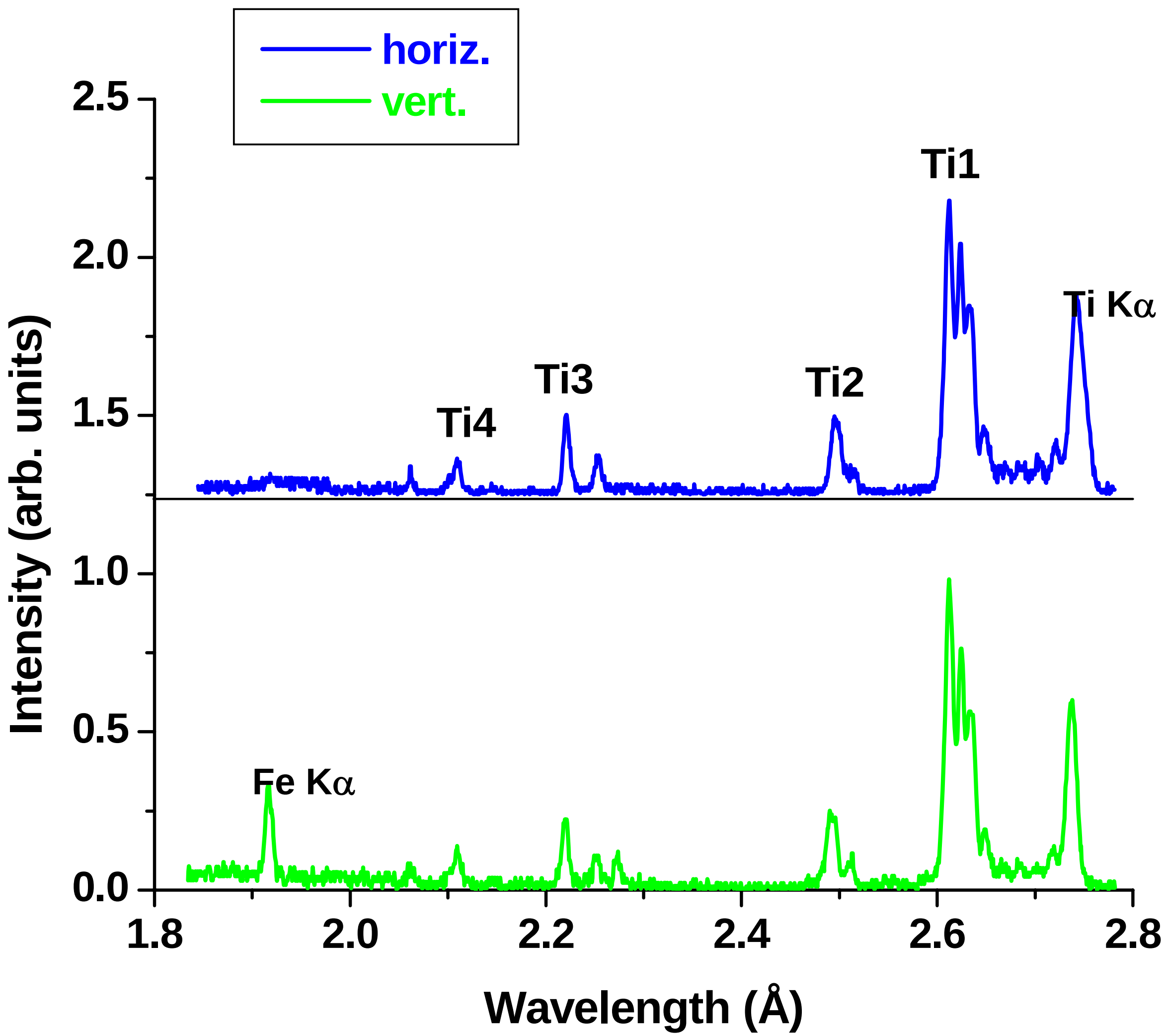
- **The crystals for Ti and Mo X-pinch measurements were selected to provide the value of a nominal Bragg angle close to 45°.**

- **For Ti X-pinches, LiF (2d=4.027Å) were used crystals with spacing corresponding to the nominal Bragg angle of 40° at the wavelength of 2.62 Å (Heα line).**

- **For Mo X-pinches, α-quartz (2d=6.687Å) crystals with spacing corresponding to the nominal Bragg angle of 46° at the wavelength of 4.8 Å (3D line).**

***A.S. Shlyaptseva, V.L. Kantsyrev, N.D. Ouart, D.A. Fedin, P. Neill, C. Harris, S.M. Hamasha, S.B. Hansen, U.I.Safronova, P. Beiersdorfer, A.G. Petrashen. *Proceedings of the PPS Workshop*. Eds. T. Fujimoto and P. Beiersdorfer, NIFS-PROC 57, 47 (2004)**

Typical experimental Ti X-pinch spectra recorded by horizontal (top, blue) and vertical (bottom, green) spectrometers



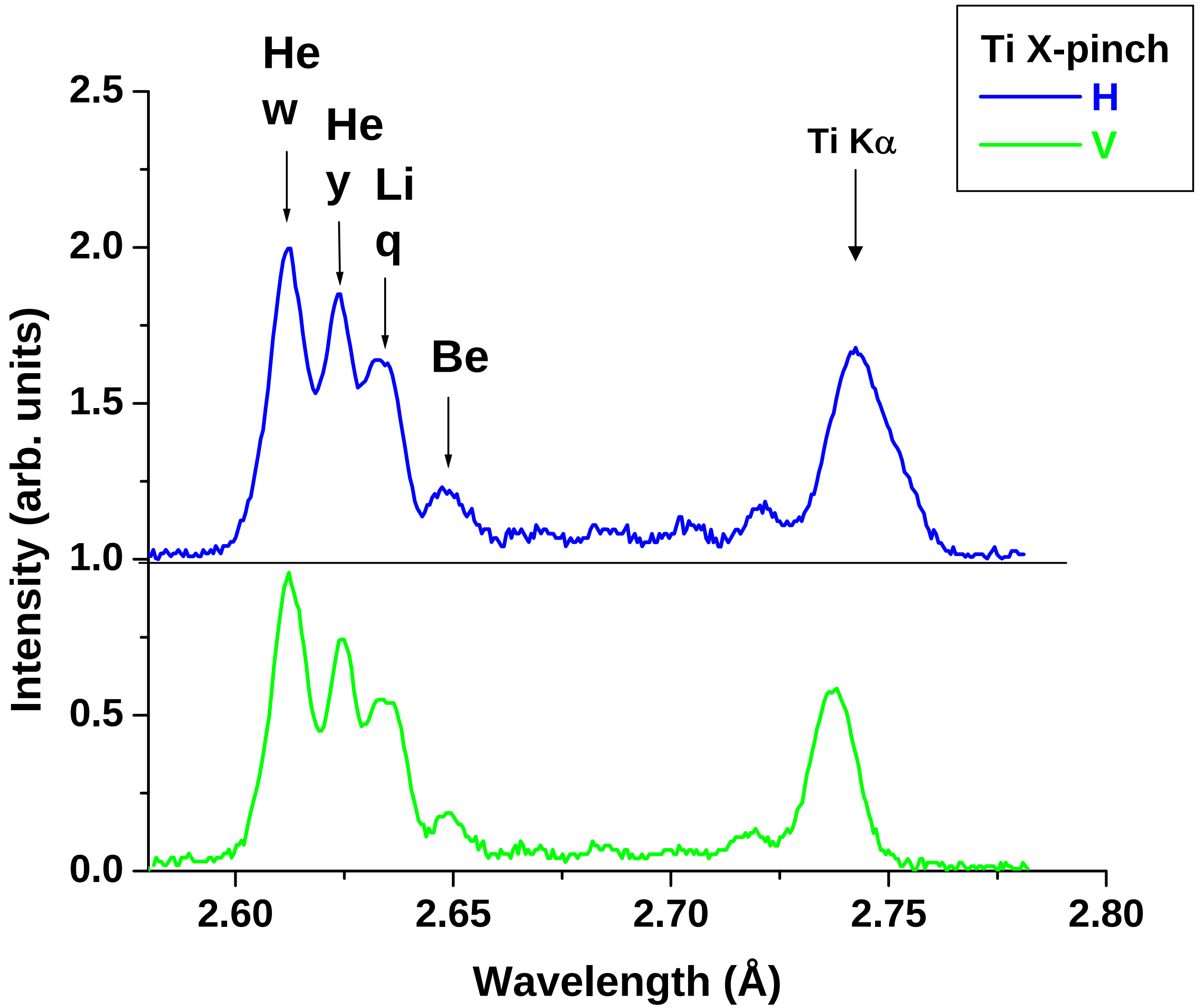
Ti1 Heα

Ti2 Lyα

Ti3 Heβ

Ti4 Heγ

Typical experimental Ti X-pinch spectra recorded by horizontal (top, blue) and vertical (bottom, green) spectrometers (enlarged spectral region from 2.6 to 2.8 Å)



Measured values of the intensities of lines recorded by a horizontal (H) and a vertical (V) spectrometers in Ti X-pinch experiments

Shot	36 H	36 V	36 H/V	37 H	37 V	37 H/V	39 H	39 V	39 H/V
Heα w	2.19[7]	1.90[7]	1.15	2.79[7]	2.68[7]	1.04	2.97[7]	3.66[7]	0.81
He y	1.98[7]	1.58[7]	1.15	2.38[7]	2.08[7]	1.14	2.62[7]	3.21[7]	0.82
Li q	1.69[7]	1.30[7]	1.30	1.79[7]	1.54[7]	1.16	2.36[7]	2.20[7]	1.07
Be	6.48[6]	5.23[6]	1.24	6.47[6]	5.22[6]	1.24	9.81[6]	7.34[6]	1.34
Kα	2.30[7]	2.24[7]	1.03	1.90[7]	1.64[7]	1.16	1.64[7]	1.43[7]	1.15
H Lyα	3.56[6]	3.56[6]	1.0	7.40[6]	6.84[6]	1.08	9.04[6]	6.84[6]	1.15
Heβ	5.49[6]	5.14[6]	1.07	7.57[6]	6.10[6]	1.24	8.74[6]	1.01[7]	0.86

- Seven shots from the polarization-sensitive Ti X-pinch experiments were analyzed
- Two out of seven indicate stronger the possible polarization of lines
- Ratio H/V for w and y lines was almost the same for all shots ⇒ $E_{\text{hot els}}$ > 25 keV

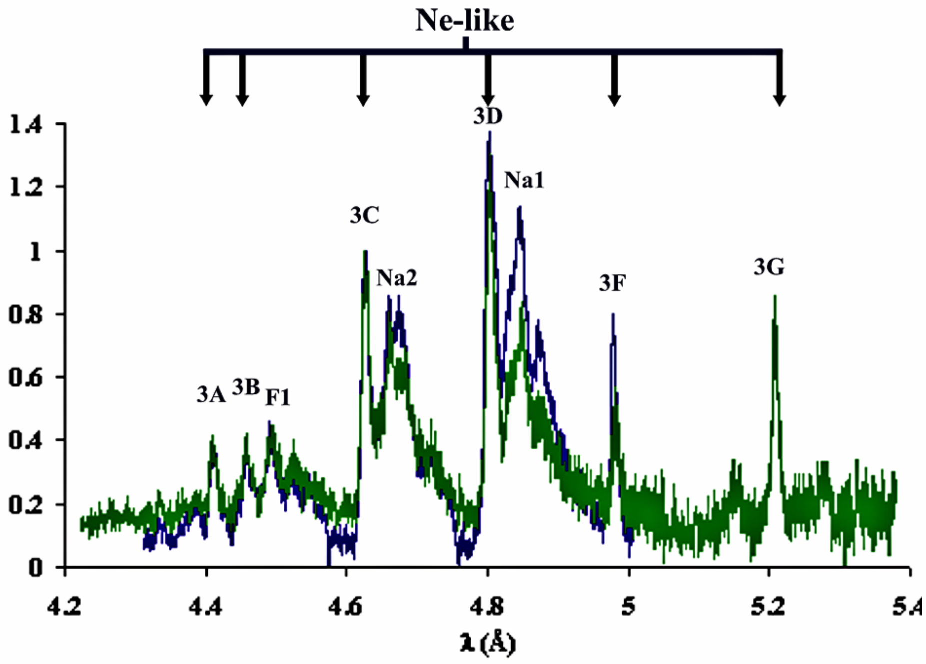
Measured values of the ratios of the intensities of lines recorded by a horizontal (H) and a vertical (V) spectrometers in Ti X-pinch experiments

Shot	36	36	36	37	37	37	39	39	39
	H	V	H/V	H	V	H/V	H	V	H/V
y/w	0.90	0.83	1.08	0.85	0.78	1.09	0.88	0.88	1.0
q/w	0.77	0.68	1.13	0.64	0.57	1.12	0.79	0.60	1.32
Be/w	0.30	0.27	1.11	0.23	0.20	1.15	0.33	0.20	1.65
Kα/w	1.03	1.18	0.87	0.68	0.61	1.11	0.55	0.19	2.89
Lyα/w	0.16	0.19	0.84	0.26	0.25	1.04	0.30	0.19	1.58
Heβ/w	0.25	0.27	0.93	0.27	0.23	1.17	0.29	0.28	1.03

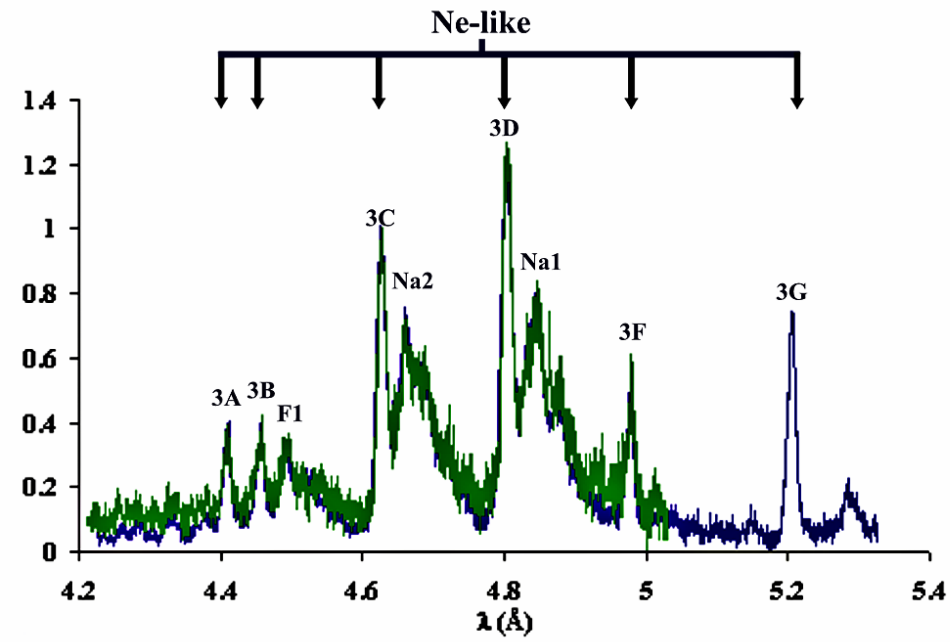
- **Though Kα line is about half of the w line for shot 39, it shows strong polarization ⇒ more experiments and analysis is needed to study polarization of the "cold" Kα line**

- **It seems that He-like lines (Heα (w), IC(y), and Heβ) are radiated from the same plasma region whereas H-like line (Ly α) from the another region: important question to answer whether the hot electron beams are different from these two regions**

More examples of polarization-sensitive X-pinch experiments at UNR (Mo X-Pinches)



Shot 91. Traces from H and V spectrometers are visibly different



Shot 97. Traces from H and V spectrometers are almost identical

Conclusion. *Why are the EBIT data so important for the HEDP diagnostics?*

Because they are extremely helpful in

- **Benchmarking the non-LTE kinetic codes (ionization balance calculations in particular)**

- **Verification of the atomic physics in the models (in very complex models such as the W model in particular), identification of lines**

- **Studying the X-ray line polarization (all electrons are non-Maxwellian)**

This research was supported by the DOE/NNSA under grant 52-06NA27588. Work at LLNL was performed under of auspices of the DOE under contract No. W-7405-Eng-48.

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Special thanks to M.F. Gu for sharing his FAC code with the community!