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Extreme Ultraviolet Spectroscopy of Cu Cylindrical Wire Arrays On Zebra At UNR

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Abstract

Extreme ultraviolet (EUV) radiation from z-pinch plasma sources has been shown to play a substantial role in the evolution of z-pinches, contributing significant amounts of radiation in the wire ablation, stagnation, and plasma expansion phases. Recent studies of Cu z-pinch plasmas from cylindrical write arrays have also shown that temperatures (up to 450 eV) exist in the precursor plasmas, which have applications to inertial confinement fusion. The final expansion phase has shown that substantial EUV radiation continues even after the main x-ray bursts. In this work, EUV data were analyzed with the goal of understanding how the bulk cooler plasma might represent the main contribution to the total radiative output from z-pinch plasmas. In particular, a comparison and analysis of EUV data generated by two plasma sources is shown: the first set of experiments used Cu cylindrical wire arrays on the 1.0 MA Zebra generator at UNR. In addition to EUV data, x-ray data is also analyzed which shows dominant emission of Cu XX ions. The second set used Cu flat targets and was performed at the compact laser-plasma x-ray/EUV facility "Sparky" at UNR, which is used as a unique line calibration source. Moreover, spectral data generated by Sparky generally show better resolved lines. Cu L and M-shell lines in the range of 50-200 Å, specifically Cu VIII to Cu XIII ions, are identified. To help with identification of lines, a non-local thermodynamic equilibrium (non-LTE) kinetic model was utilized and was also used to determine plasma parameters, such as electron temperature and density. Future studies will focus on attaining time-gated EUV spectra in order to better understand its role in the evolution of z-pinch plasmas.

Cylindrical Wire Arrays (CWA): Distribution of EUV Energy Between Three Phases for the Examples With Different Mid-Atomic-Number Wire Materials

EUV: 8% | 77% | 15%

phase 1

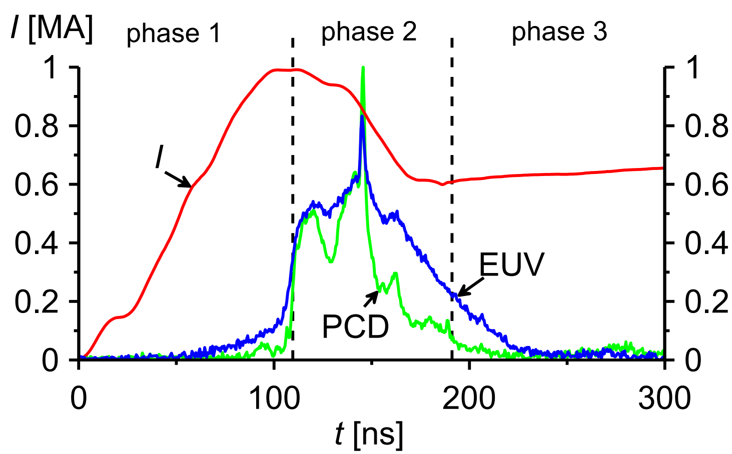
EUV: >17 eV

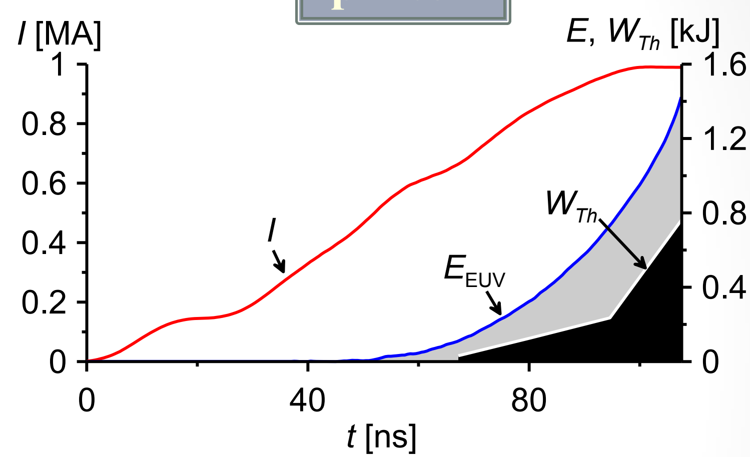
PCD: >0.75 keV

Cu CWA

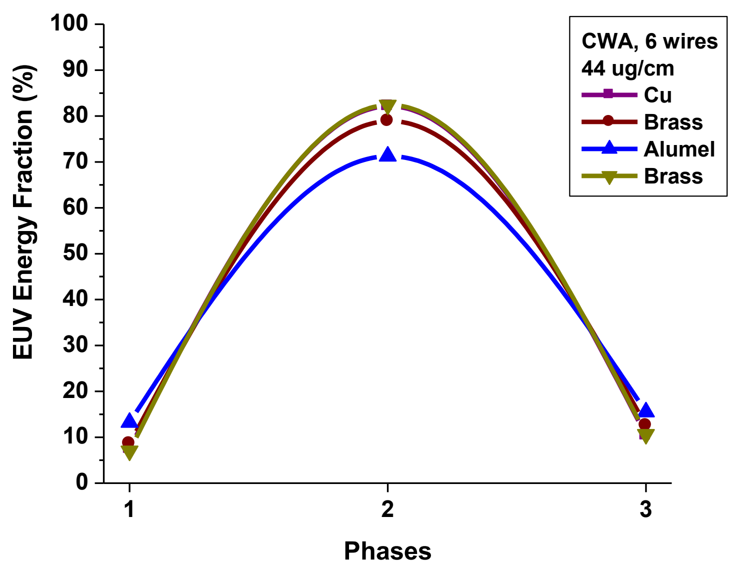
6 wires

44 ug/cm

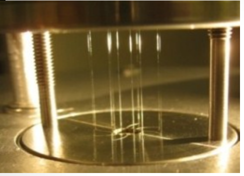




Small amounts of EUV energies in phases 1 and 3

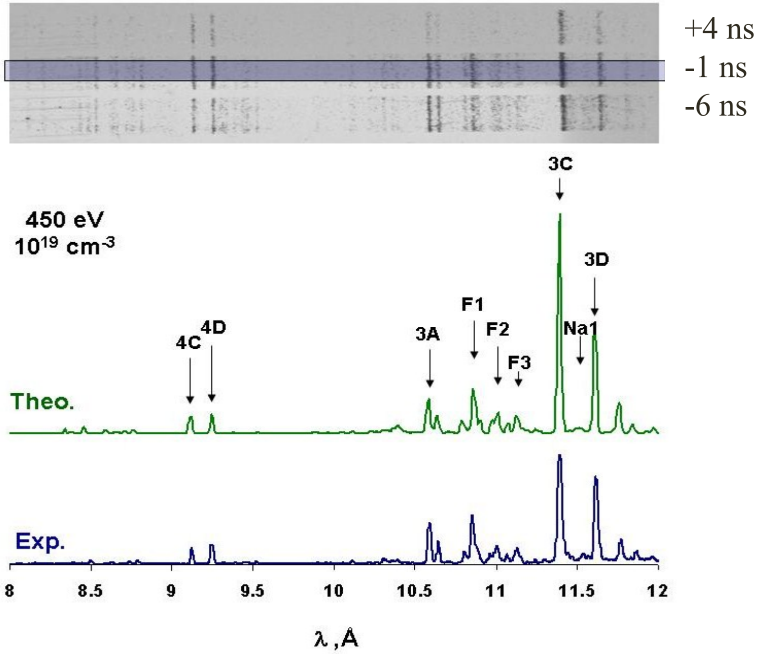


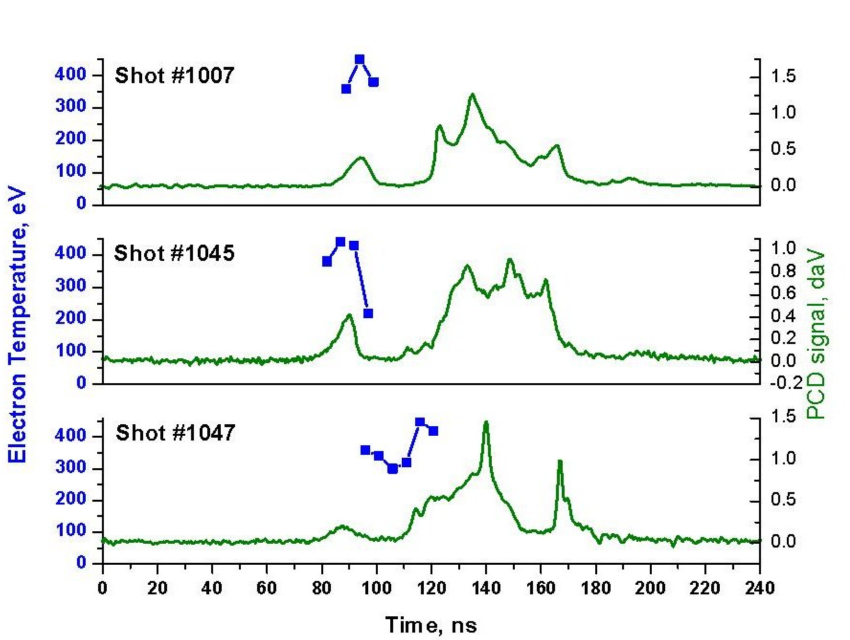
A.A. Esaulov, *et al.*, High Energy Density Phys. 5, 166, (2009).



Motivation to Study Radiation During All Phases of Evolution of Z- and X-Pinch Plasmas

- Precursor plasmas can be significantly hotter than previously observed (collaborative work with SNL)



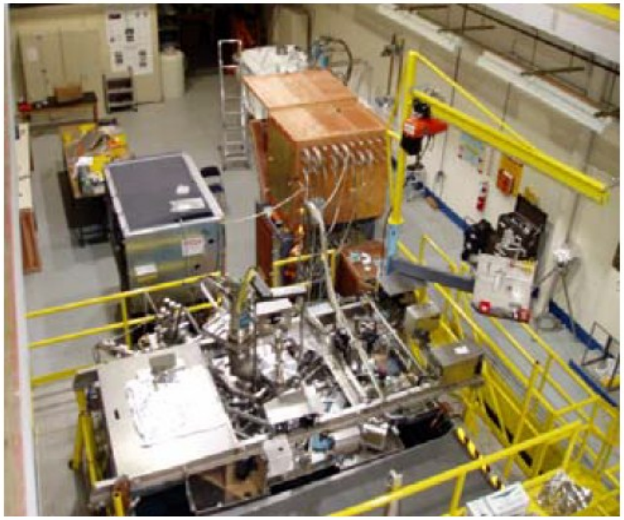


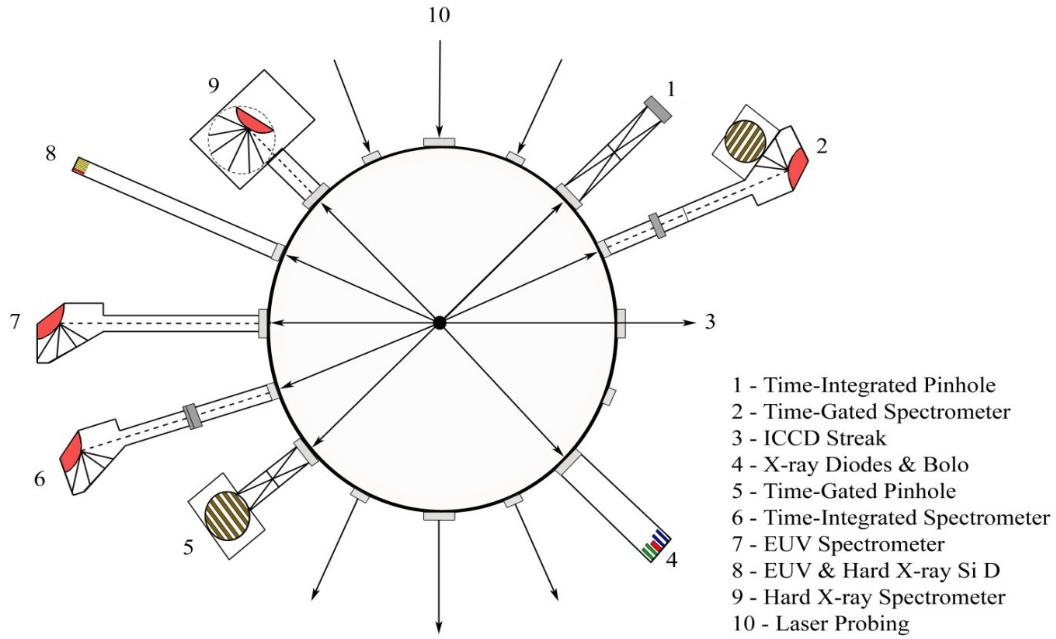
Phase 1. Precursor plasmas. Ni60 (96%Cu and 4% Ni) CWA.

Experiments with cylindrical copper wire arrays at the 1-MA Zebra facility show that high temperatures exist in the precursor plasmas formed when ablated wire array material accretes on the axis prior to the stagnation of a z pinch. In these experiments, the precursor radiated approximately 20% of the >1000 eV x-ray output, and time-resolved spectra show substantial emission from Cu L-shell lines. Modeling of the spectra shows an increase in temperature as the precursor forms, up to 450 eV, after which the temperature decreases to 220–320 eV until the main implosion.

C.A. Coverdale, A.S. Safronova, V.L. Kantsyrev, N.D. Ouart *et al*, PRL 102, 155006 (2009)

Diagnostic setup on Zebra at NTF



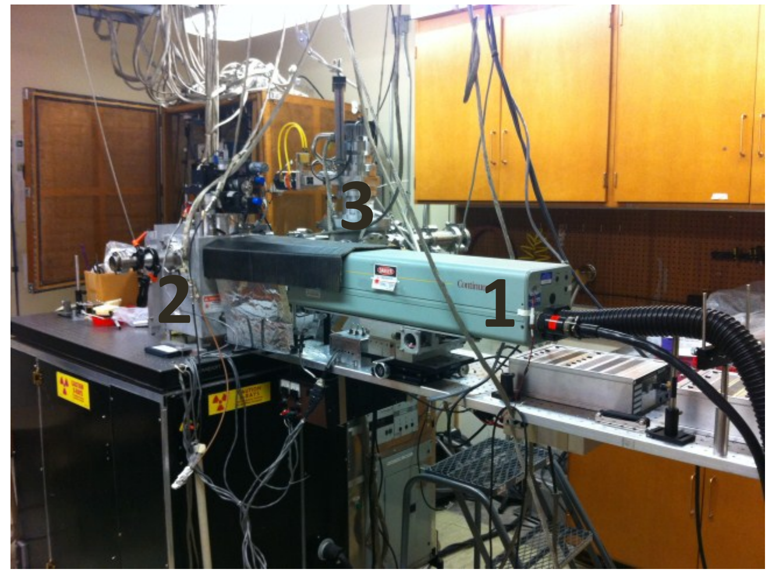


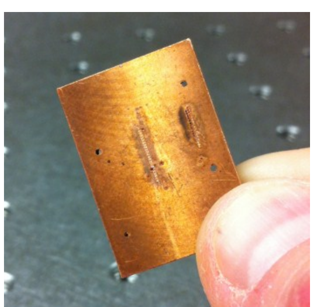
-1.7 MA Current
-100ns rise time
-1.9Ω Impedence

For more about experiments and diagnostics on Zebra: V. L. Kantsyrev *et al*, High Energy Density Physics, 5, 115 (2009).

Laser-plasma EUV/x-ray facility "Sparky"

- Developed partially to study EUV radiation from many different materials*.
- Laser specifications: 0.4 J, 3 ns, 10 Hz solid state laser.
- Flat slabs used as target (such as the Cu slab pictured below).
- EUV grazing incidence spectrometer implimented to capture 40 – 300 Å.





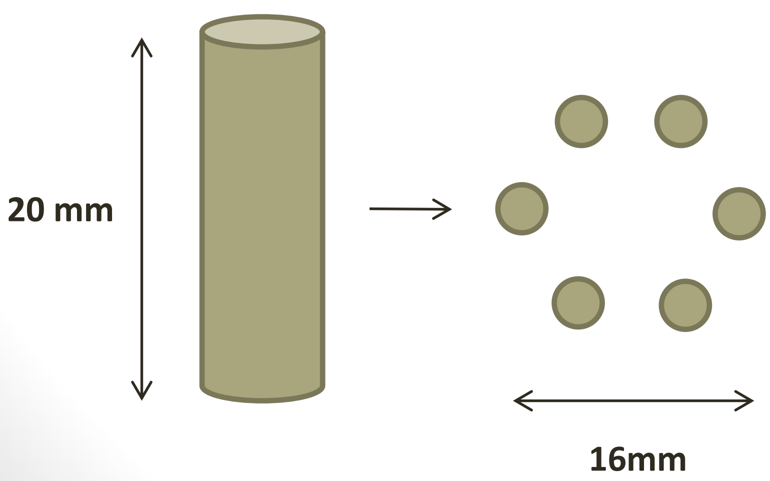
1. Laser.
2. Vacuum chamber for target.
3. Vacuum chamber for EUV grazing incidence spectrometer.

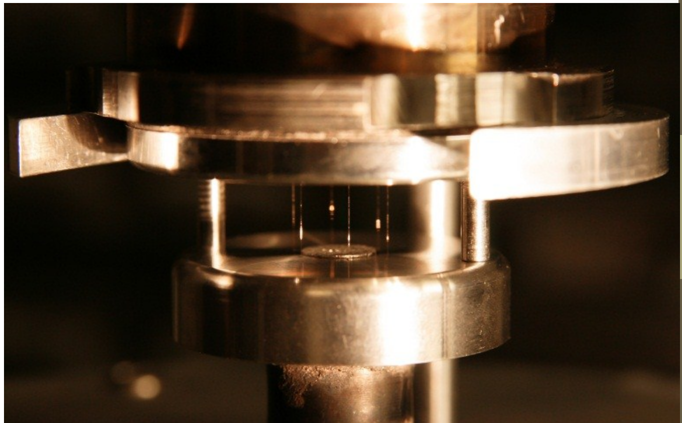
*V. L. Kantsyrev, A. S. Safronova, K. M. Williamson, P. G. Wilcox, N. D. Ouart, M. F. Yilmaz, K. W. Struve, D. L. Voronov, R. M. Feshchenko, I. A. Artyukov, and A. V. Vinogradov, Rev. Sci. Instrum. **79**, 10F542 (2008).

X-ray Radiation Analysis

Experimental Details For Cu Cylindrical Wire Array

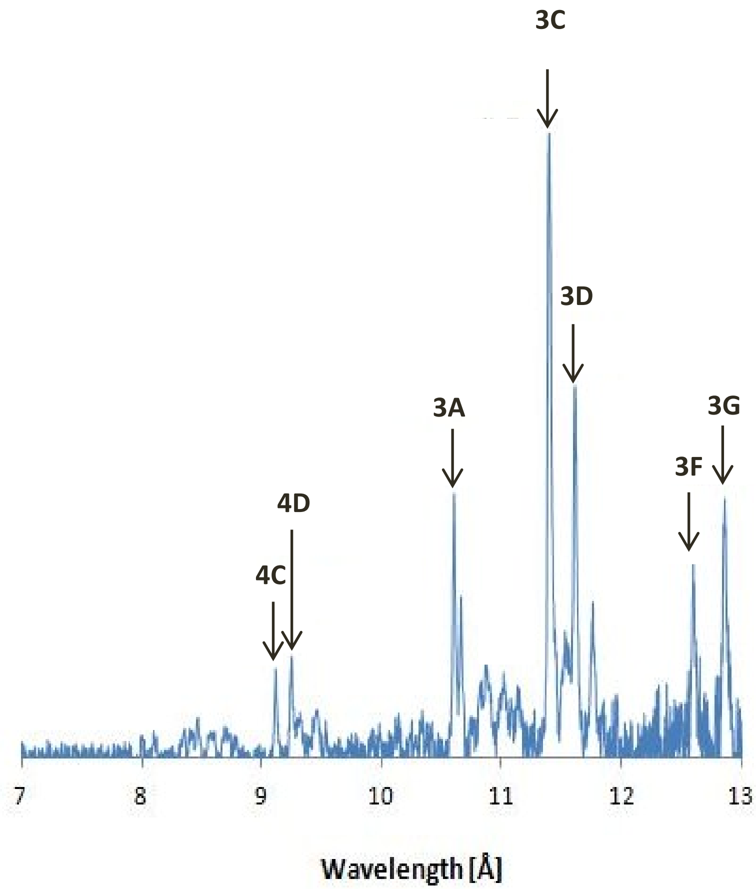
Shot #	N	Configuration	Material	D(μm)	Diameter (mm)	Energy (kJ)	Implosion Timing (ns)	Total Mass (μg/cm)
775	6	Cylindrical Array	Cu (Ni60 alloy)	10.16	16	15.8	127	87





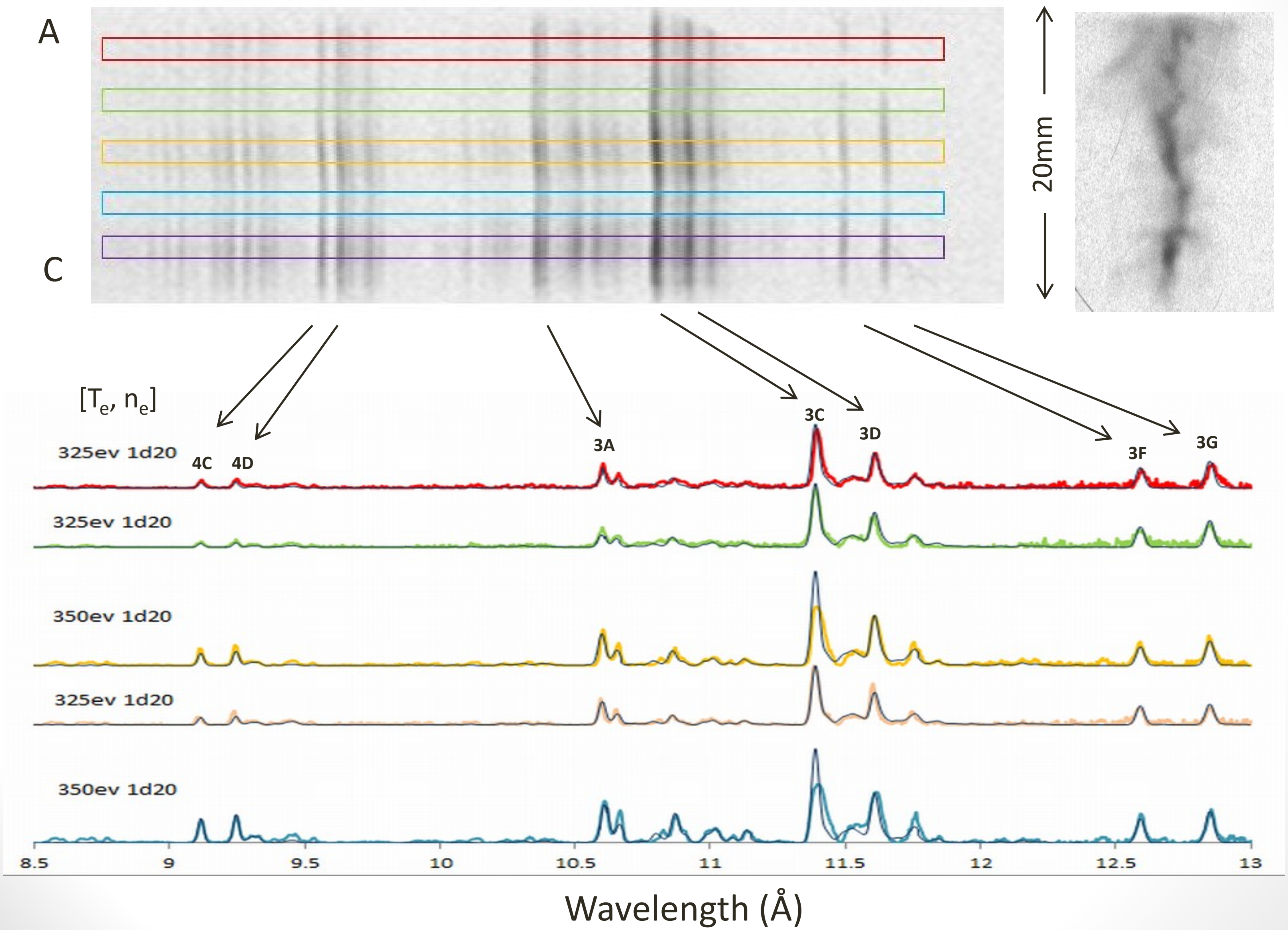
Diagnostically important Cu X-ray transitions

Ion Line	Transition (Upper → Lower)	Wavelength Å
4C	$1s^2 2s^2 2p_{1/2} 2p^4_{3/2} 4d_{3/2}$ J=1 → $1s^2 2s^2 2p^6$ J=0	9.115
4D	$1s^2 2s^2 2p^2_{1/2} 2p_3{}^3 4d_{5/2}$ J=1 → $1s^2 2s^2 2p^6$ J=0	9.245
3A	$1s^2 2s 2p^6 3p_{3/2}$ J=1 → $1s^2 2s^2 2p^6$ J=0	10.580
3C	$1s^2 2s^2 2p_{1/2} 2p_{3/2}{}^4 3d_{3/2}$ J=1 → $1s^2 2s^2 2p^6$ J=0	11.390
3D	$1s^2 2s^2 3p_{1/2}{}^2 2p_{3/2}{}^3 3d_{5/2}$ J=1 → $1s^2 2s^2 2p^6$ J=0	11.608
3F	$1s^2 2s^2 2p_{1/2} 2p_{3/2}{}^4 3s$ J=1 → $1s^2 2s^2 2p^6$ J=0	12.591
3G	$1s^2 2s^2 2p_{1/2}{}^2 2p_{3/2}{}^3 3s$ J=1 → $1s^2 2s^2 2p^6$ J=0	12.849



N.D. Ouart, PhD dissertation: "Radiative Properties of Z-pinch and Laser Produced Plasmas from mid-atomic-number materials". (UNR, 2010)

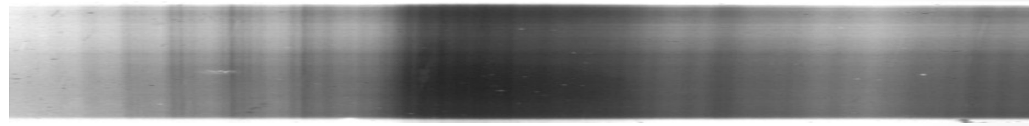
Analysis of Experimental Data and Diagnosis of Plasma Parameters
CWA – Ni 60 Alloy (96% Cu, 4% Ni)

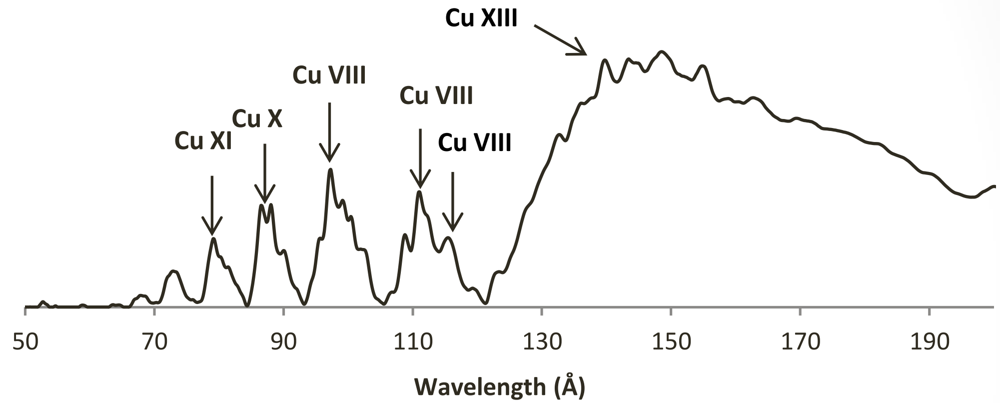


EUV Radiation: Experimental Results and Modeling

Comparison and Analysis of EUV Data Generated by Two Different Experiments

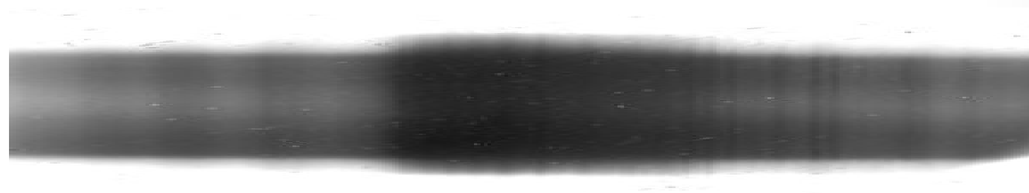
Sparky Laser Plasma Experimental Data:
500 Shots Cu flat target

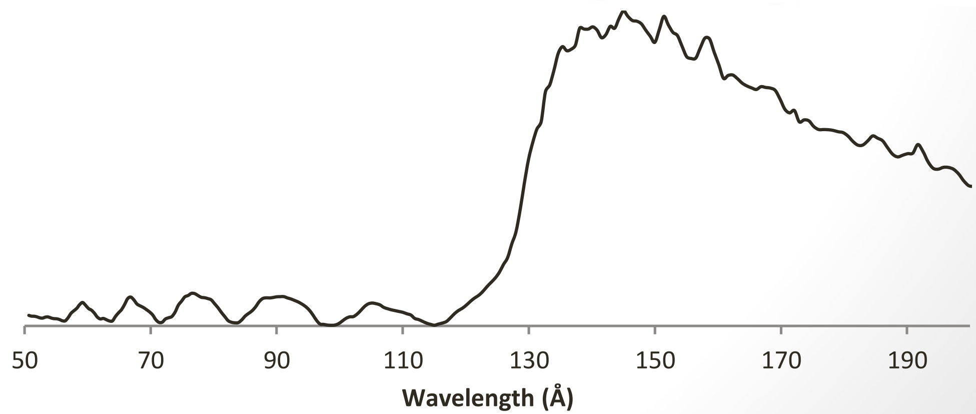




Sparky spectral data shows more and better resolved lines in comparison to Zebra spectra.

Zebra Z-pinch Experimental Data:
Shot 775 Cu Cylindrical Wire Array



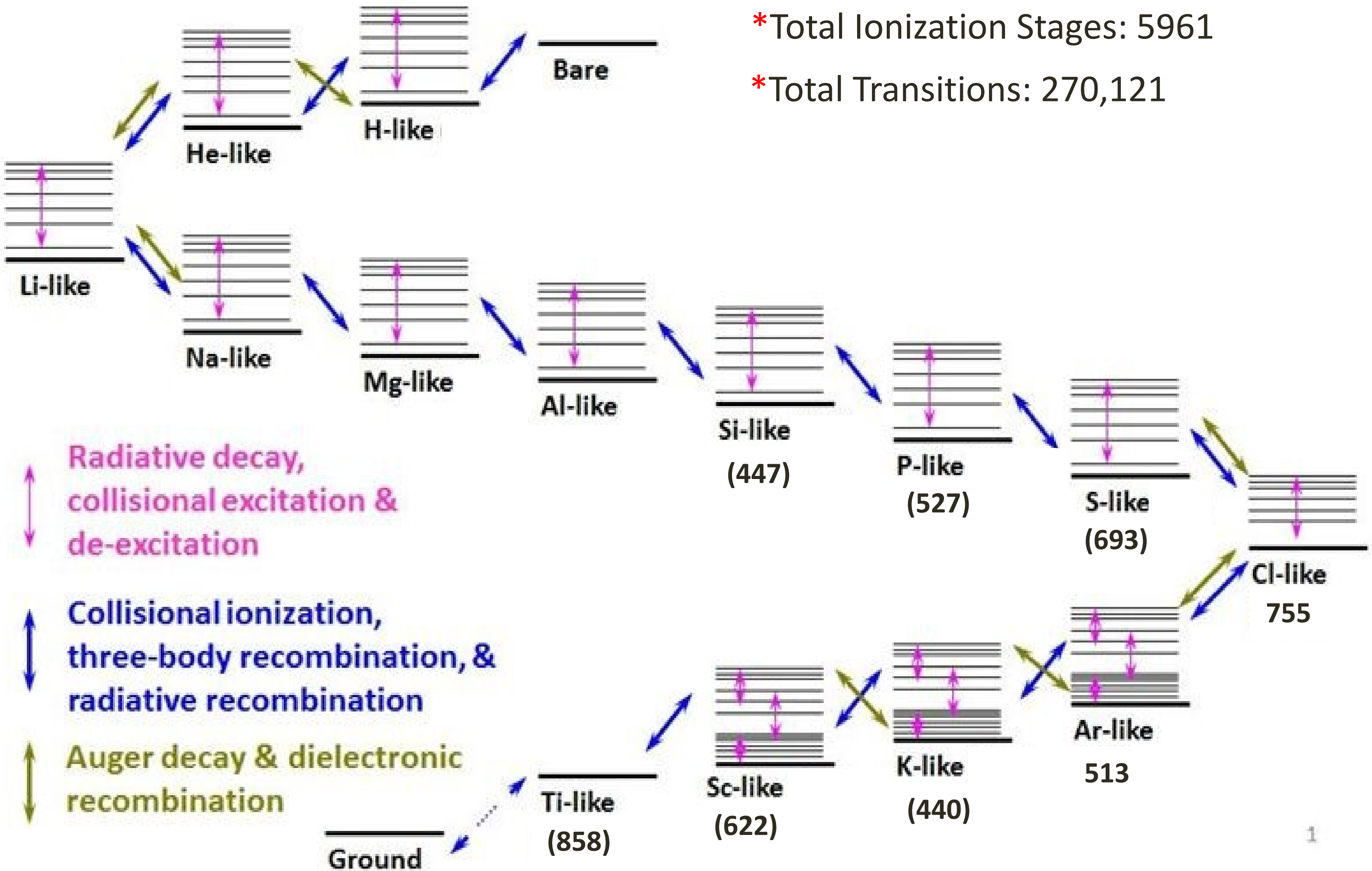


No low ionization stages from Zebra spectral data and different resolution. Doppler broadening of lines observed.

Copper Collisional Radiative Kinetics Model For EUV Spectra Based On Prism Data

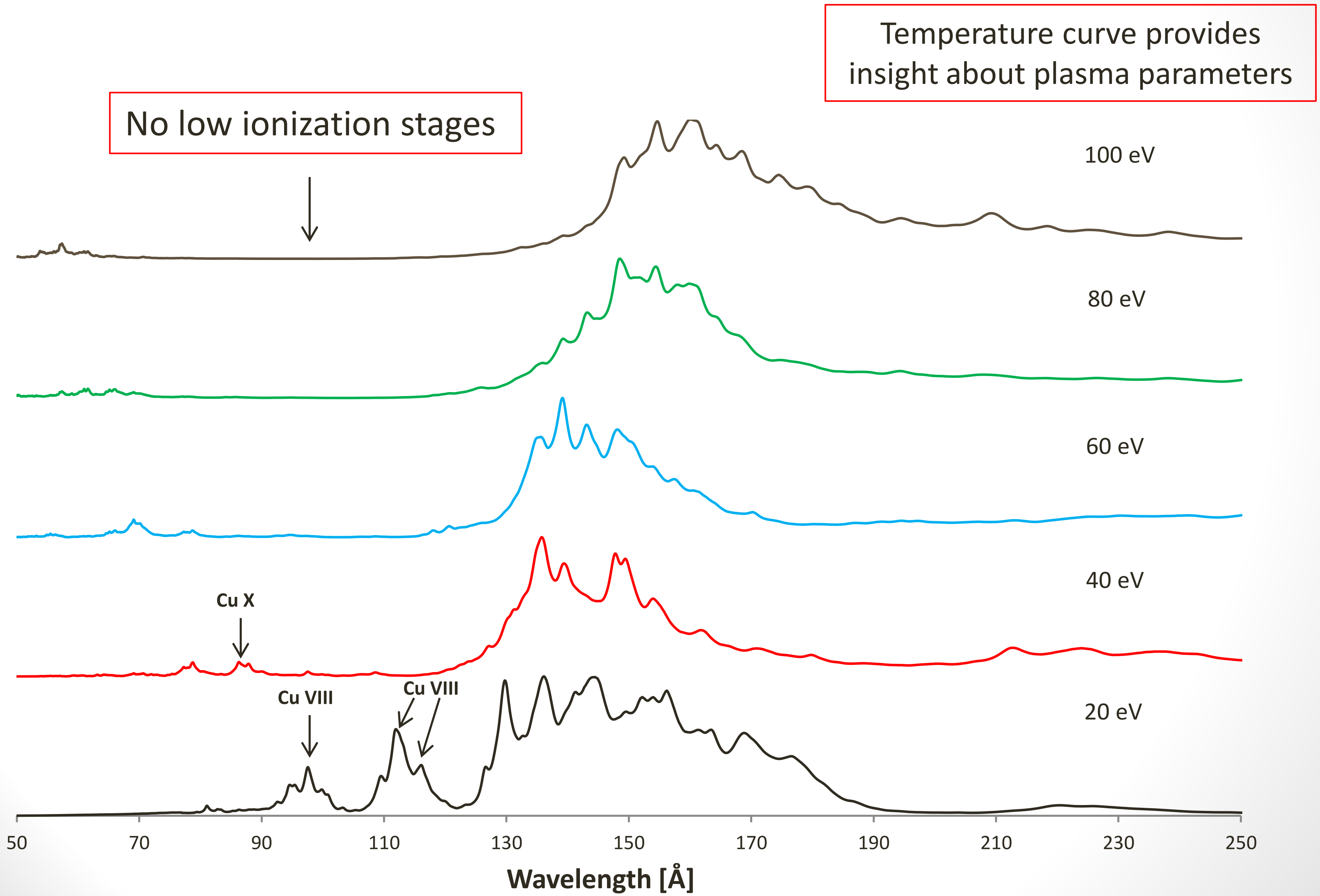
*Total Ionization Stages: 5961

*Total Transitions: 270,121



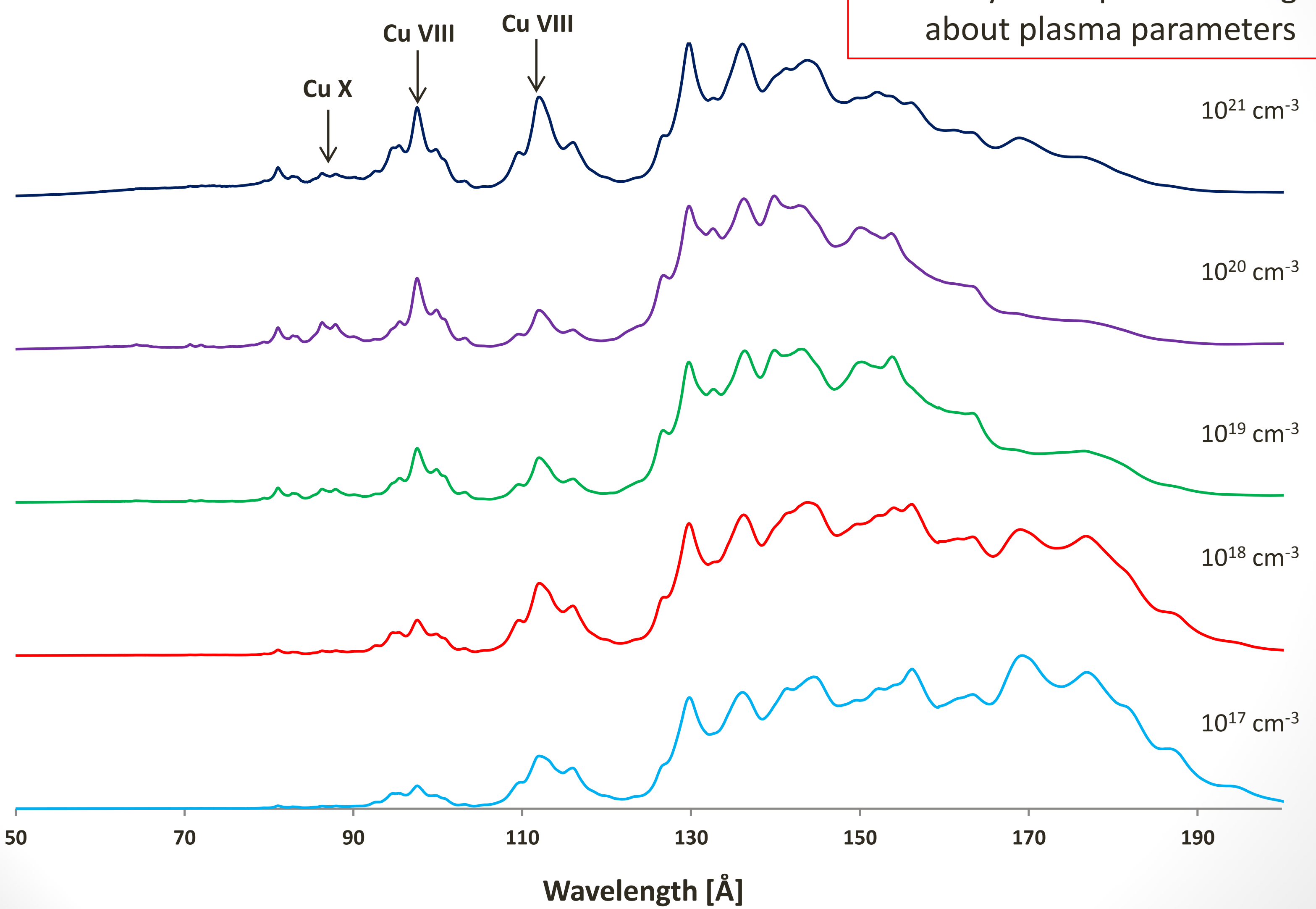
J. J. MacFarlane, I. E. Golovkin, P. Wang, P. R. Woodruff, and N. A. Pereyra, High Energy Den. Phys. 3, 181 (2007).

Temperature Dependence for non-LTE Model of Cu At Constant Density of $n_e=10^{19} cm^{-3}$

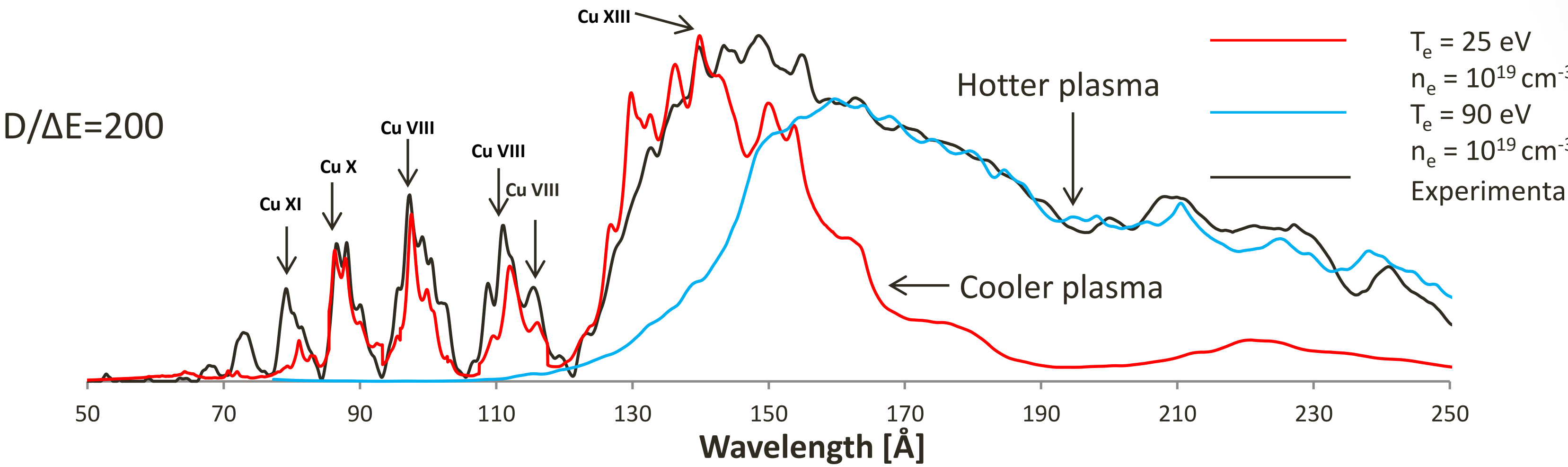


Density Dependence for non-LTE Model Of Cu at Constant Temperature of T_e=25 eV

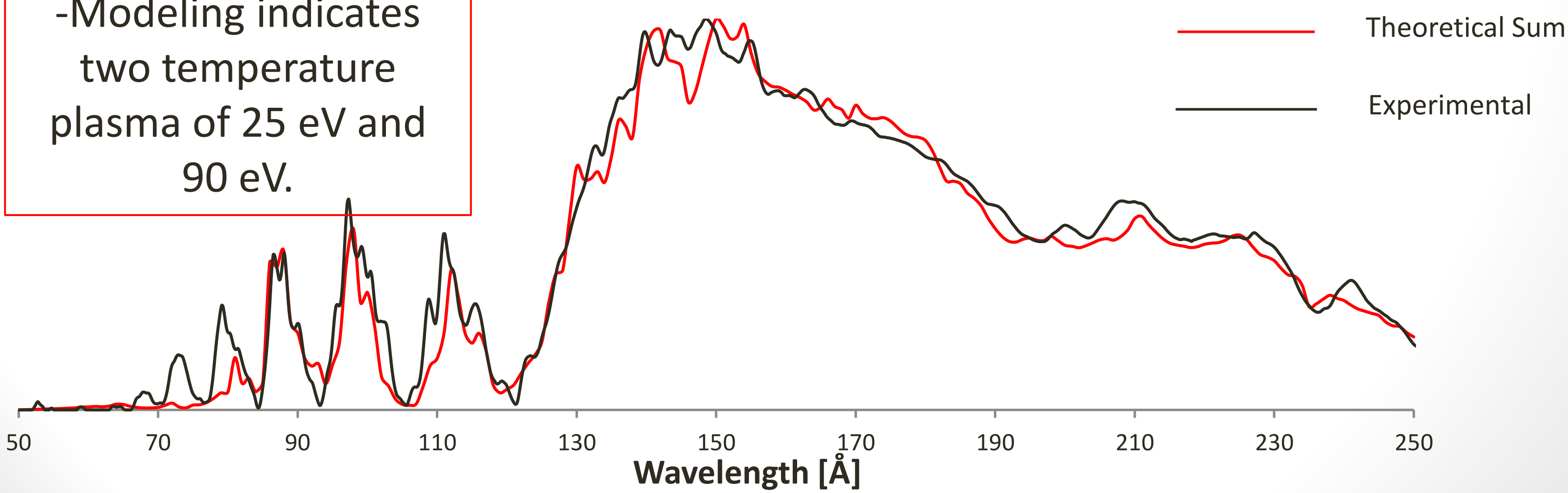
Density curve provides insight about plasma parameters



Modeling of Sparky EUV Data and Identification of Ionization Stages

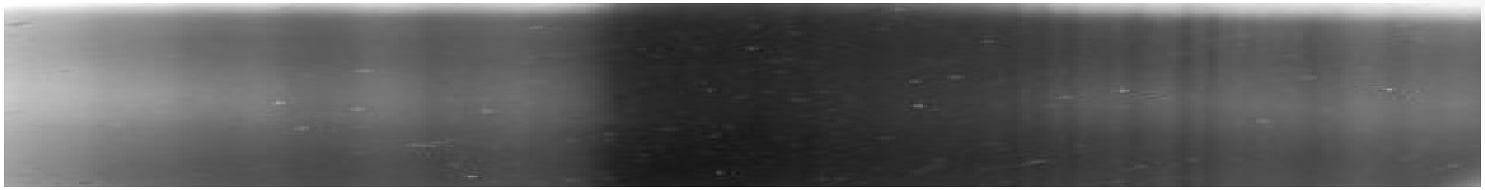


-Modeling indicates two temperature plasma of 25 eV and 90 eV.



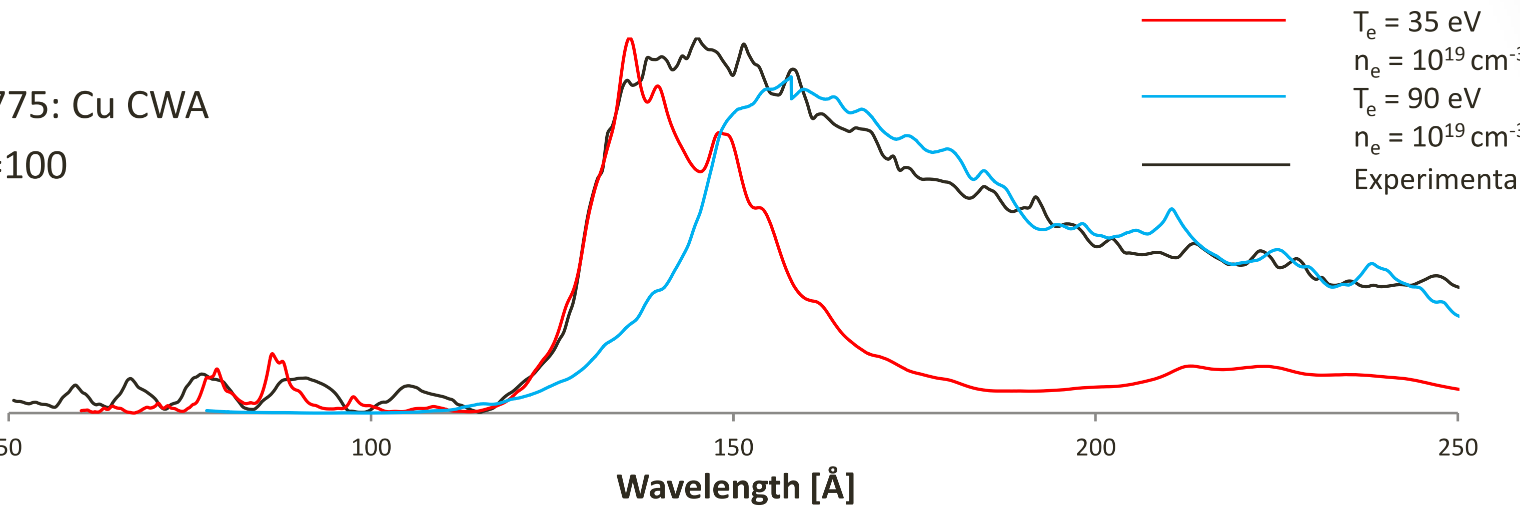
For more information, see: M.E. Weller, *et al* , Rev. Sci. Instrum. **83**, 10E101 (2012).

Modeling of Zebra EUV Data Indicates Reduced Intensity of Low Ionization Stages and Doppler Broadening of Lower Ionization Stages

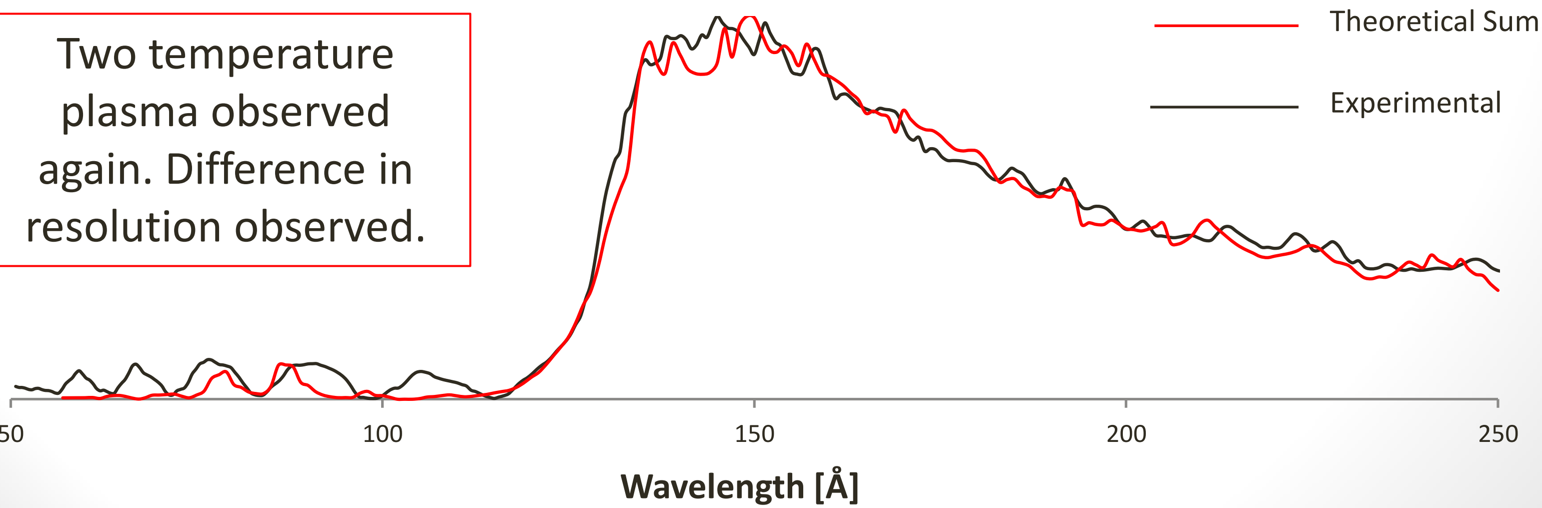


Shot 775: Cu CWA

D/ΔE=100



Two temperature plasma observed again. Difference in resolution observed.



A Comprehensive Analysis of Cu Radiation From CWA Has Been Completed

EUV: 8% | 77% | 15%

EUV: >17 eV

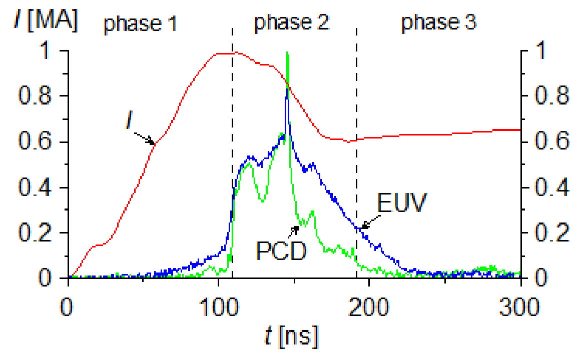
PCD: >0.75 keV

X-ray

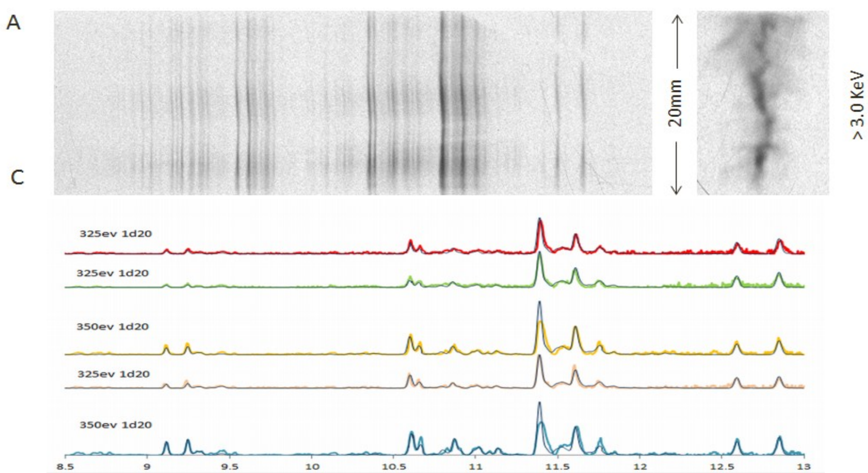
Cu CWA

6 wires

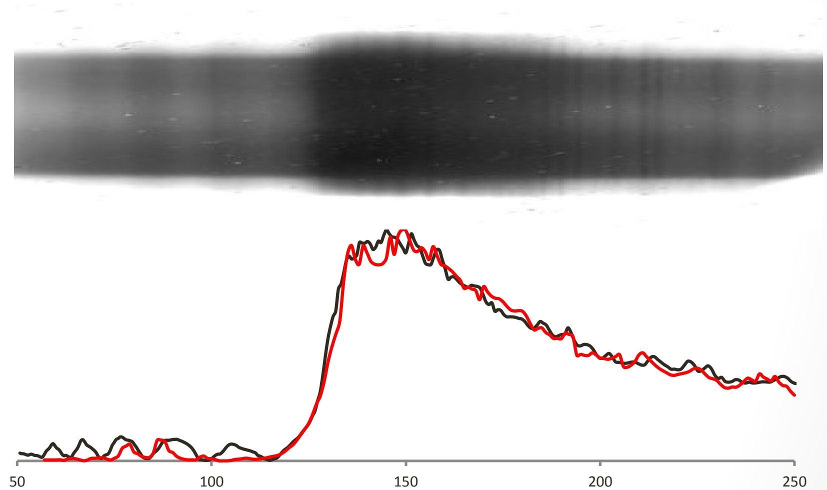
44 ug/cm



EUV



Wavelength [Å]



Wavelength [Å]

In addition to the of useful information gained by previous and current X-ray radiation analysis, further knowledge and insight has been gained by additionally exploring radiation in the EUV regime. We have shown a detailed analysis of X-ray radiation followed by an analysis of EUV radiation as well.

Conclusions

- X-ray Cu radiation from cylindrical wire arrays was analyzed and plasma conditions were diagnosed
- EUV Cu spectra have been studied from two different sets of experiments in the range between 50-200 Å
    - Z-pinch plasma on Zebra and laser-produced plasma on "Sparky"
    - Successfully modeled Cu EUV radiation from both experiments
    - Results indicated reduced intensity of low ionization stages on Z-pinch plasma and showed higher resolution in the laser-produced plasma.
- Attained approximate plasma conditions from both experiments indicating a non-uniform two-temperature plasma.
    - In the laser produced plasma, one with lower electron temperature of 25 eV emitting from the cooler outer shell and the other with higher electron temperature of 90 eV emitting from the hotter inner core, both with density of $10^{19}cm^{-3}$.
- Showed that EUV radiation plays an important role in the evolution of Z-pinch plasmas and contributes a significant amount of radiation.
- Future work will focus on attaining time-gated EUV spectra in order to better understand its role in the evolution of z-pinch plasmas and will also focus on detailed identification of ionization stages at higher wavelength.

Acknowledgements/References

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- M.E. Weller, *et al* , Rev. Sci. Instrum. **83**, 10E101 (2012).