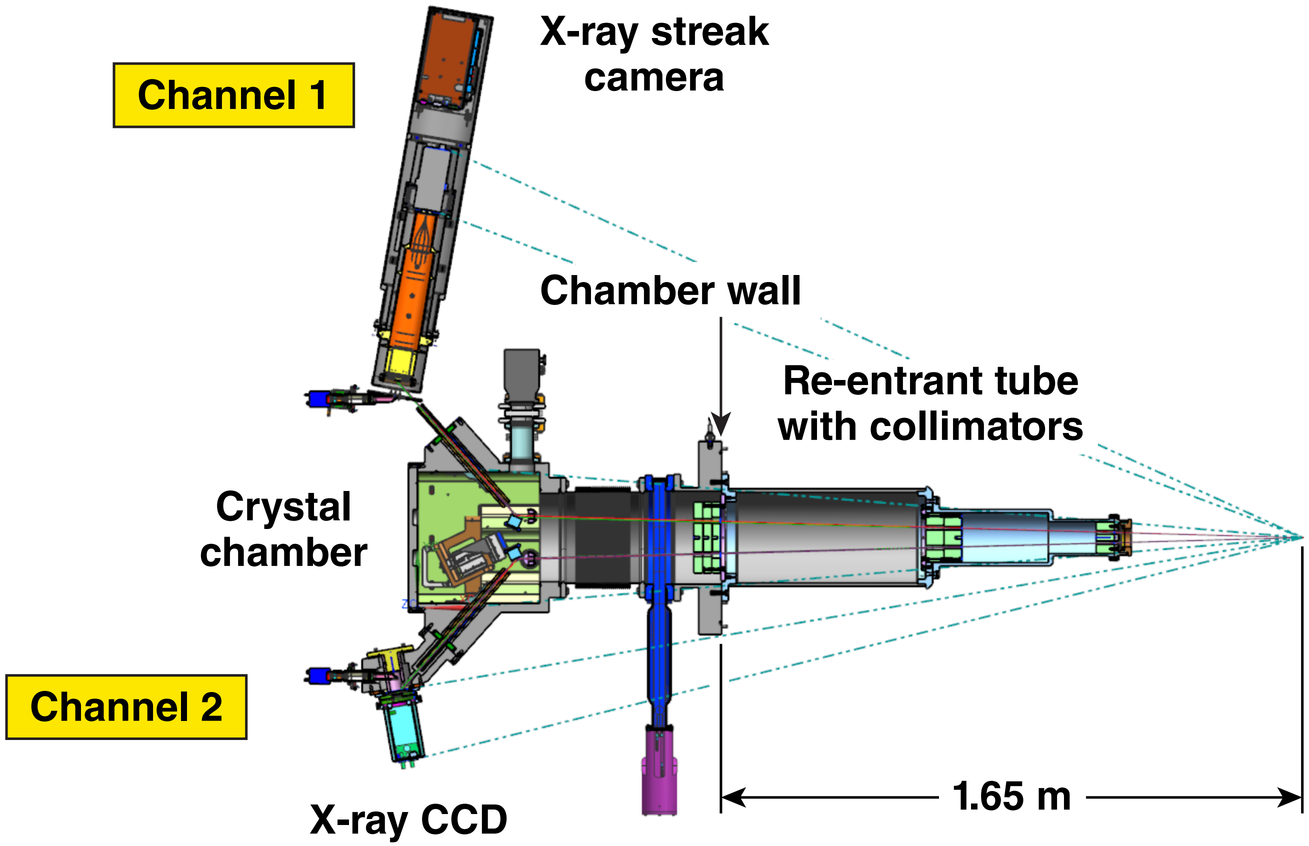
High-Resolving-Power, Ultrafast Streaked X-Ray Spectroscopy on OMEGA EP



P. M. Nilson
University of Rochester
Laboratory for Laser Energetics

Omega Laser Facility
Users Group Workshop
Rochester, NY
27–29 April 2016

Summary

A high-resolving-power, streaked x-ray spectrometer is being developed and tested on OMEGA EP

- The goal is to achieve resolving power of several thousand and 2-ps temporal resolution
- Temporal spectral shifts on the Cu K_{α} line in isochorically heated solid targets provide a fairly simple system where the spectrometer performance will be validated
- The instrument will be used to measure temperature-relaxation dynamics and material response to ultrafast heating at depth

Development is underway to deploy the instrument on OMEGA EP by Q2FY17.

Collaborators

F. Ehrne, C. Mileham, D. Mastrosimone, R. K. Jungquist,
C. Taylor, R. Boni, J. Hassett, D. J. Lonobile, R. W. Kidder,
M. J. Shoup III, A. A. Solodov, C. Stoeckl, and D. H. Froula*

University of Rochester
Laboratory for Laser Energetics
*also Department of Physics

K. M. Hill, L. Gao, M. Bitter, and P. Efthimion

Princeton Plasma Physics Laboratory

D. D. Meyerhofer

Los Alamos National Laboratory

Outline

- Motivation
  - temperature-equilibration dynamics
  - material response to ultrafast heating at depth
- Conceptual design
  - high-resolution spectrometer (HiResSpec)
- Phase I
  - time-integrating x-ray spectrometer
- Phase II
  - time-resolved x-ray spectrometer
- Summary and conclusions

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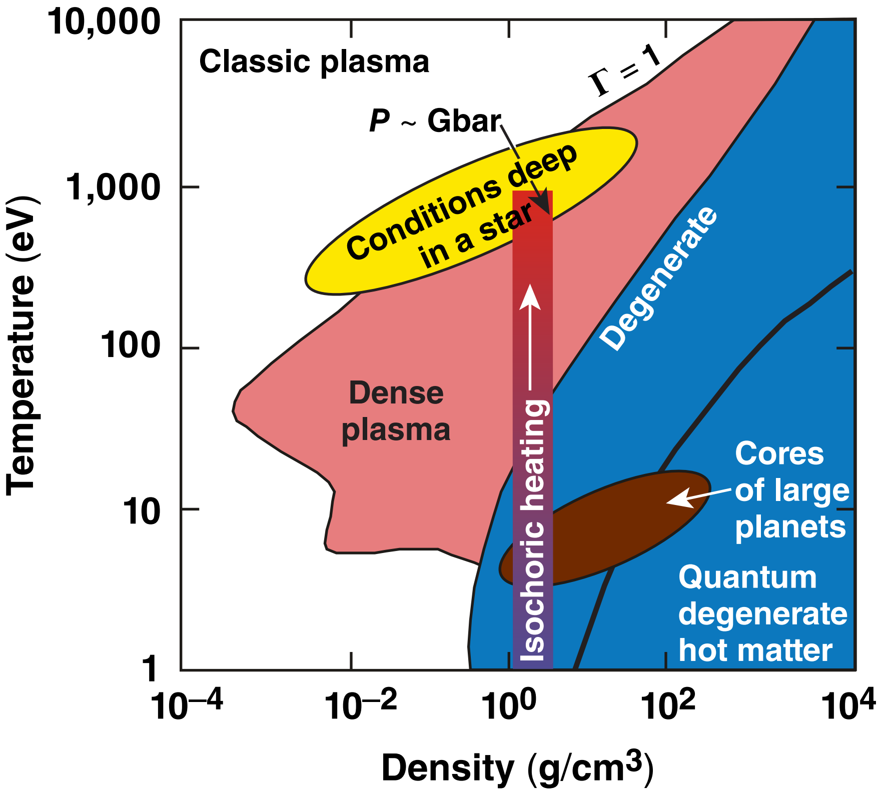
Motivation

A high-energy ultrafast laser can heat solid-density material on a time scale much faster than the material expands

- Heating at high density produces exotic states of matter in extreme thermodynamic conditions
  - matter in these states is normally found only in the interiors of planets or dense stars[1]
- The possible extremes in temperature enables novel material and radiative properties experiments[2]
  - e.g., mean opacity of solar interior matter[3]
- New diagnostic techniques are sought for testing
  - plasma-dependent atomic processes[4]
  - plasma opacity[5] and equation-of-state models[6]



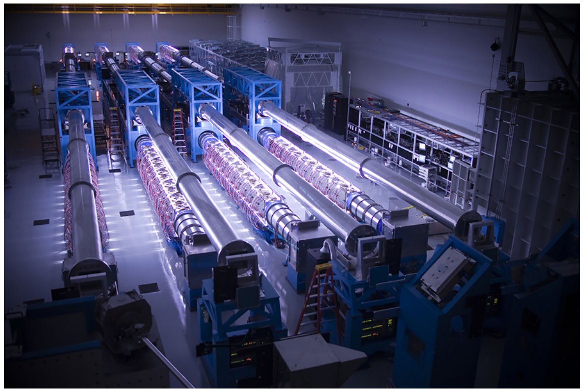
These studies require dense, high-temperature plasmas that are well characterized.

1 A Report on the SAUUL Workshop, Washington, DC (17–19 June 2002).
2 K. Nazir *et al*., Appl. Phys. Lett. 69, 3686 (1996).
3 J. E. Bailey *et al*., Nature 517, 56 (2015).
4 D. J. Hoarty *et al*., Phys. Rev. Lett. 110, 265003 (2013).
5 R. A. London and J. I. Castor, High Energy Density Phys. 9, 725 (2013).
6 M. E. Foord, D. B. Reisman, and P. T. Springer, Rev. Sci. Instrum. 75, 2586 (2004).

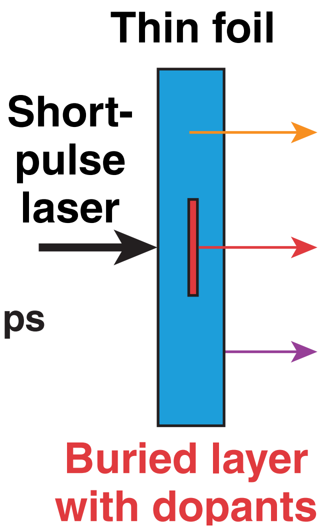
E21173e

An experimental platform is being developed to study heating of dense matter by laser-generated hot electrons

Multi-Terawatt (MTW) Laser: 10 J, 1 ps
Frequency: 1ω or 2ω
Intensity: >10^{18} W/cm^2



OMEGA EP Laser System: 2.6 kJ, 10 ps
Frequency: 1ω
Intensity: >10^{18} W/cm^2



- **Source and coupling: K-line emission**
  PI's—P. Nilson (LLE)/K. Hill (PPPL)
  - laser-to-electron coupling[1] $\eta_{L\text{-}e}$
  - mean hot-electron energy[2] $\langle E \rangle$
  - relaxation rate[3] τ_e
  - ionization distribution $\langle Z \rangle$
- **Bulk response: thermal emission**
  PI—C. Stillman (Ph.D. student, DOE SSGF)
  - Al, Fe, and Mg spectroscopy
  - density and temperature: n_e, T_e
- **Surface response: XUV emission**
  PI—S. Ivancic (Postdoc, DOE/FES Grant)
  - heat flow and pressure relaxation
  - density and temperature: n_e, T_e

PI: Principal Investigator
DOE SSGF: Department of Energy Stewardship Science Graduate Fellowship
DOE/FES: Department of Energy/Fusion Energy Science
PPPL: Princeton Plasma Physics Laboratory
XUV: extreme ultraviolet

[1] P. M. Nilson *et al.*, Phys. Rev. Lett. 105, 235001 (2010).
[2] P. M. Nilson *et al.*, Phys. Rev. Lett. 108, 085002 (2012).
[3] P. M. Nilson *et al.*, J. Phys. B 48, 224001 (2015).

E25090

Uncertainties exist in the hot-electron equilibration dynamics and material response to ultrafast heating at depth

UR LLE

- The plasma conditions are inferred from x-ray spectroscopic measurements
- Data interpretation[1] implies accurate modeling of
  - the early-time heating dynamics
  - the radiative properties of the heated sample
- To produce synthetic spectra, one must describe the major physical processes
  - hot-electron generation and relaxation phases
  - radiative–hydrodynamic evolution of the target
- Time-resolved measurements are required to test energy-partition and temperature-equilibration model predictions for different materials and heating profiles

In these conditions, measuring the ionization distribution is of fundamental importance for understanding plasma production and radiation conditions.[2]

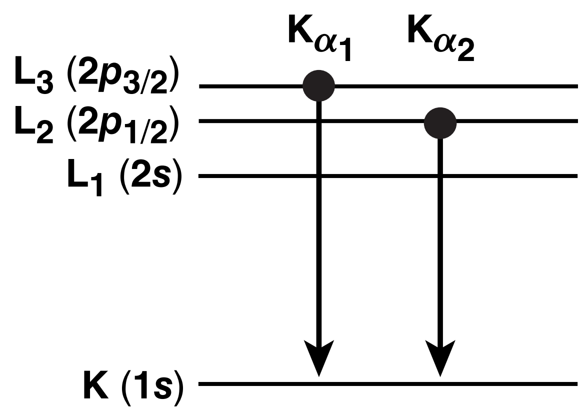
[1] V. Dervieux *et al.*, High Energy Density Phys. 16, 12 (2015).
[2] J. F. Seely *et al.*, High Energy Density Phys. 9, 354 (2013).

Motivation

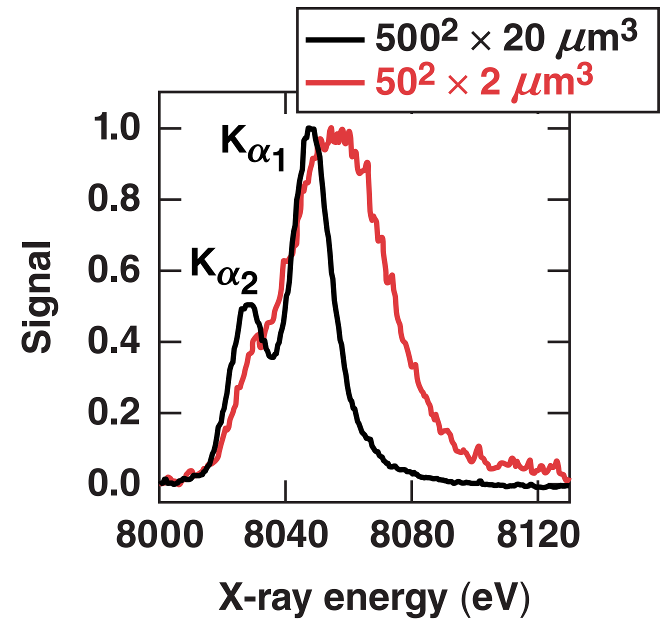
Outer shell ionization affects the energy and shape of the characteristic K_α line in a partially ionized plasma

- Hot electrons create K-shell vacancies when colliding with ions
- Ionization by thermal electrons removes electrons from the ions outer shells
- As the ionization progresses, the $K_{\alpha_{1,2}}$ lines increase their energy[1–4]

Fine structure of the characteristic K_α line



MTW laser: 5×10^{18} W/cm^2
Target: Cu foil



The transition energies are sensitive to the configuration of bound electrons.

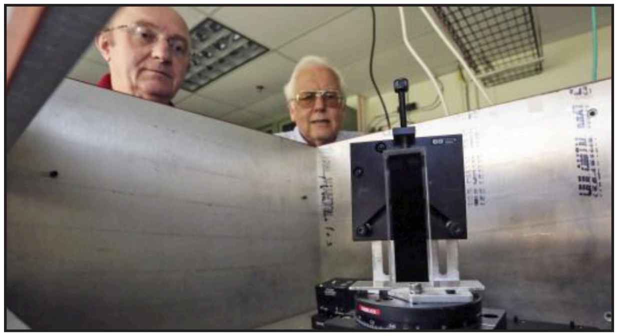
[1] K. Słabkowska *et al.*, High Energy Density Phys. 15, 8 (2015).
[2] K. Słabkowska *et al.*, High Energy Density Phys. 14, 30 (2015).
[3] G. Gregori *et al.*, Contrib. Plasma Physics 45, 284 (2005).
[4] P. M. Nilson *et al.*, Phys. Plasmas 18, 042702 (2011).

Motivation

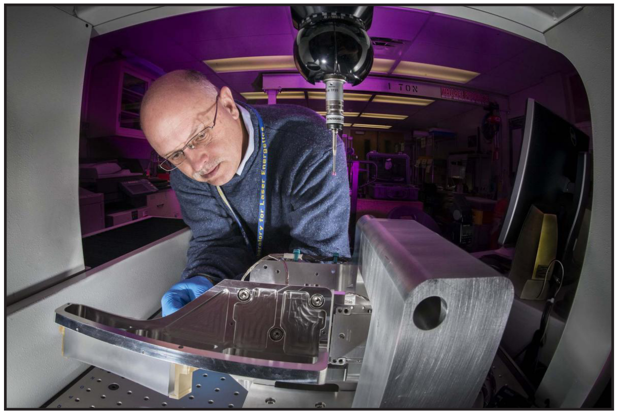
OLUG played an important role in fostering the collaboration between LLE and PPPL on high-resolution x-ray spectroscopy

- The National Diagnostic Plan recognizes the transformational impact of high-resolving-power x-ray spectroscopy
  - inertial confinement fusion (ICF) physics
  - high-energy-density (HED) physics
- Better measurements are needed
  - coupling to picosecond resolution x-ray detectors provides crucial insight on equilibration dynamics
- In 2012, initial MTW experiments were being carried out on resolving K-line shifts with an ultrafast x-ray streak camera
- At the OLUG Workshop that year, K. Hill presented various concepts for high-resolving-power x-ray spectrometers

An OMEGA EP platform was proposed to combine these efforts, which became the HiResSpec Project.



K. Hill and M. Bitter (PPPL)
Initial Si220 crystal tests



F. Ehrne (LLE)
Si220 crystal alignment for OMEGA EP shots

E25108

Outline

- Motivation
  - temperature-equilibration dynamics
  - material response to ultrafast heating at depth
- Conceptual design
  - high-resolution spectrometer (HiResSpec)
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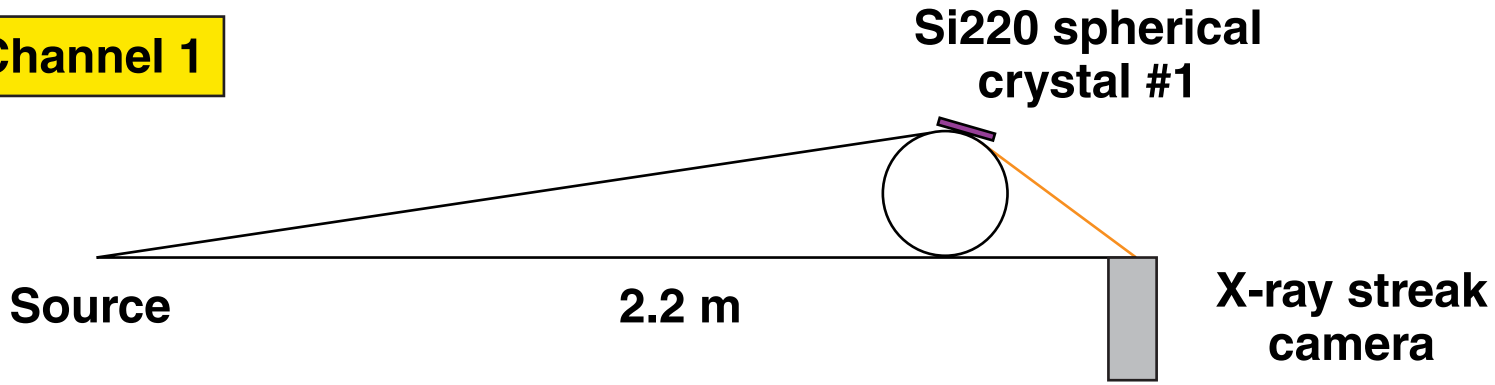
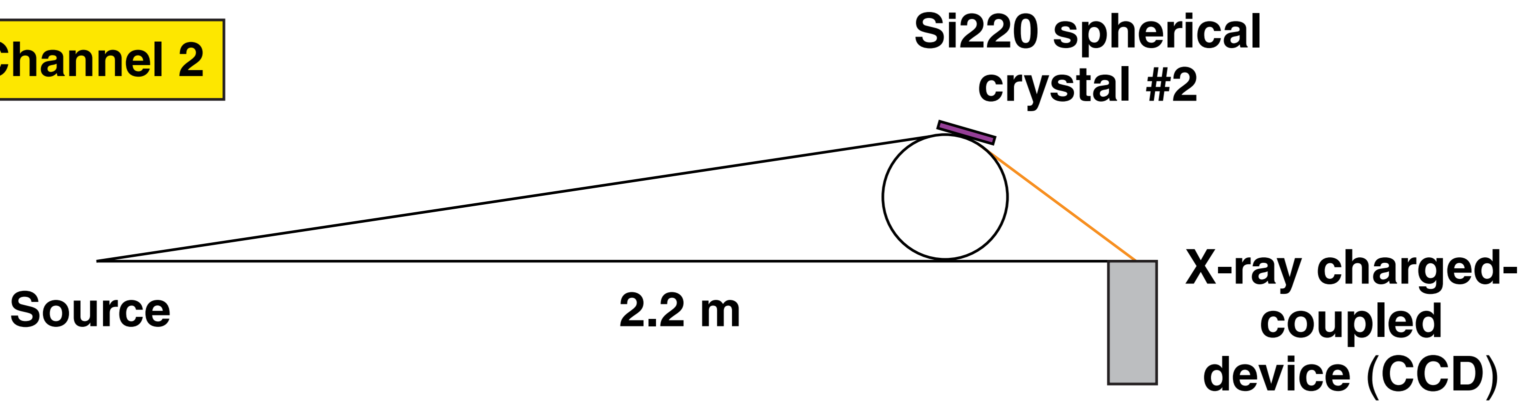
E25089b

The instrument is based on two diagnostic channels, each with a spherical Bragg crystal

Channel 1



Channel 2



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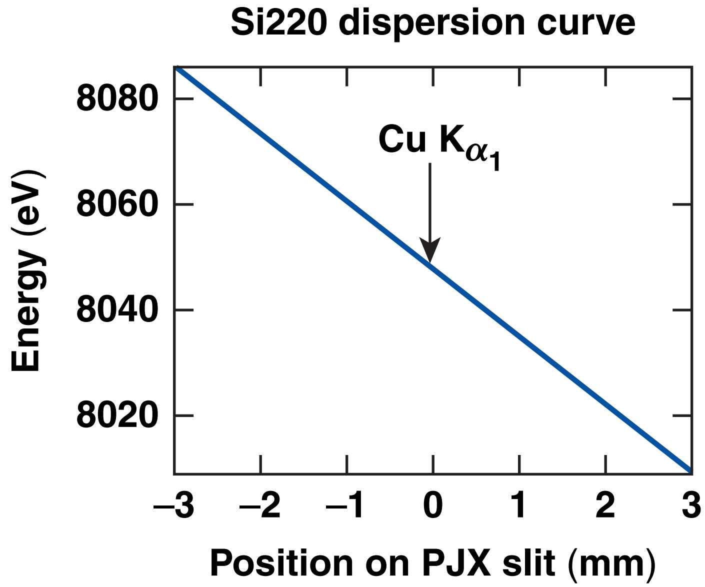
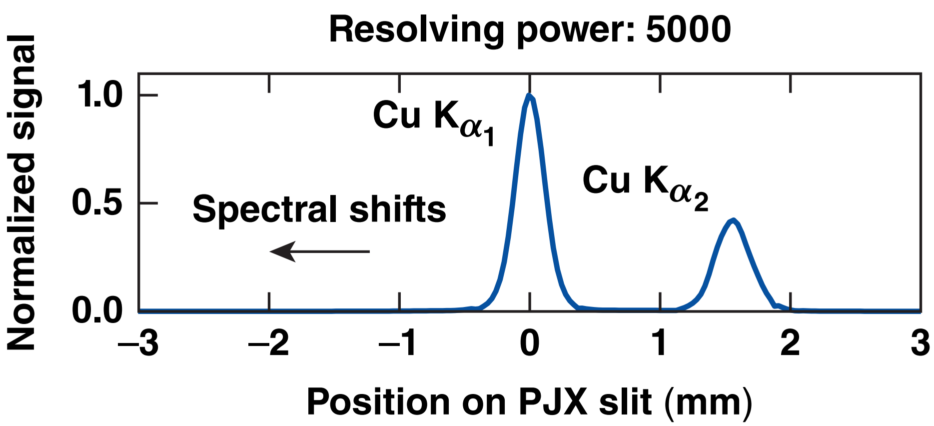
The instrument parameters are set by the expected Cu K_α line shifts

- X-ray source size:
  ~100 μm^2
- Spectral range:
  7.97 to 8.11 keV
- Resolving power:
  ~5000 (streak-camera limited)
- Spectral shifts:
  few eV to 20-eV line shifts
- K_α flash time:
  few picoseconds to 20 ps
- Streak-camera temporal resolution: ~2 ps





E23449a

Temporal spectral shifts on the Cu K_{α} line in rapidly heated solid matter will validate the spectrometer performance

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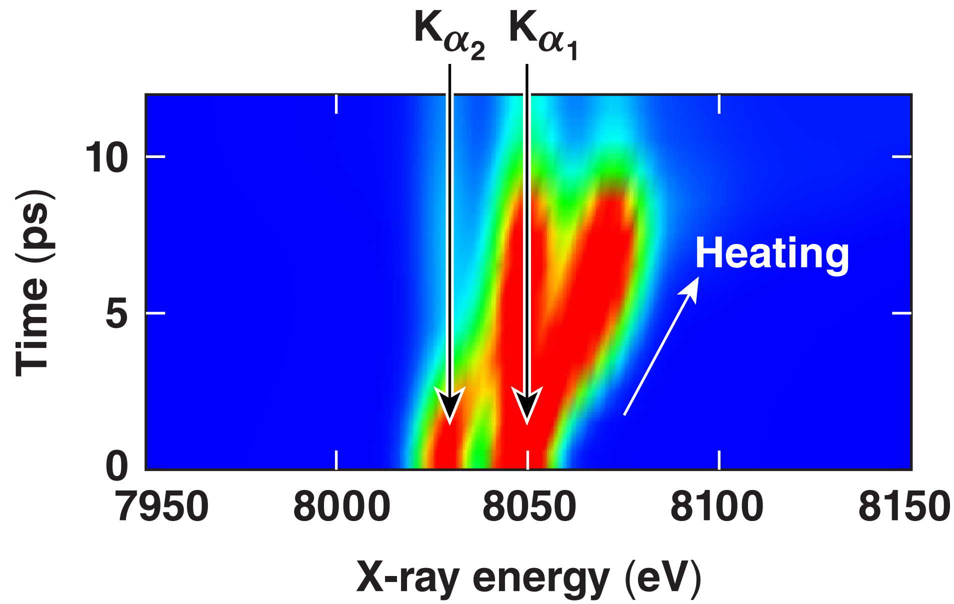
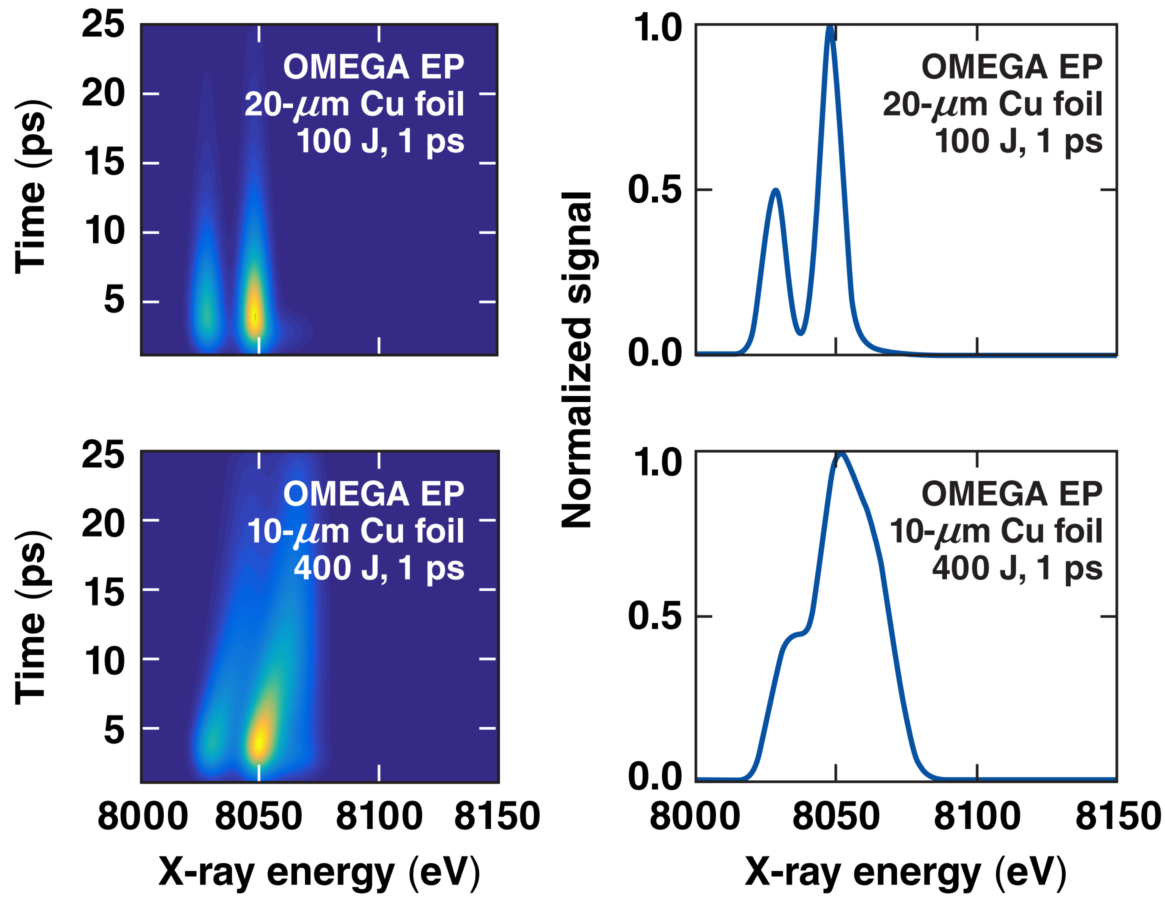
- *PlasmaGEN* and *PrismSPECT* collisional–radiative model calculations*
- 2-μm Cu foil
- Linear heating gradient from 1 to 350 eV over 10 ps
- Synthetic detector parameters
  - resolving power $\lambda/\Delta\lambda$: 1000
  - temporal resolution: 2 ps



*Prism Computational Sciences Inc., Madison, WI 53711.

Synthetic spectra are calculated by post processing *LSP* output with tabulated collisional-radiative model predictions

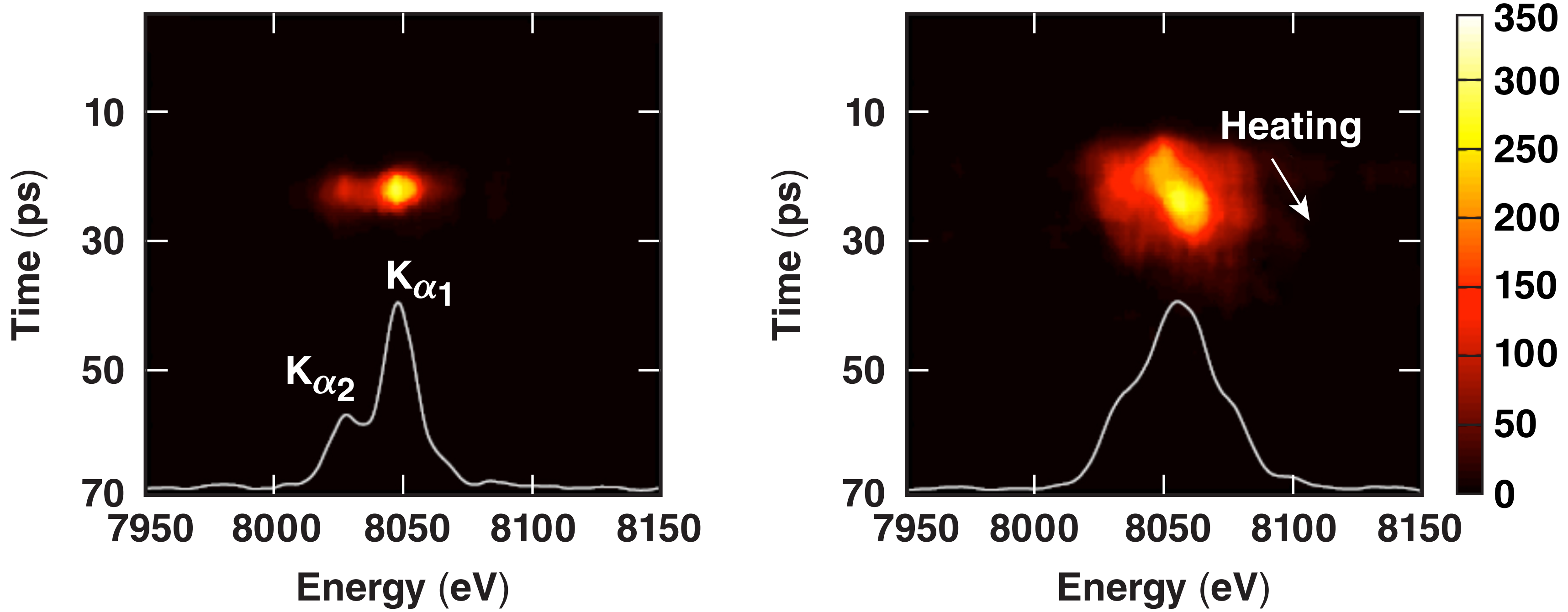
- Synthetic spectra from hot, dense matter are required
  - energy-transport physics
  - *LSP* calculates cold K-line emission
- Post process *LSP* output in *MATLAB* using tabulated collisional-radiative data from *PrismSPECT**
  - uses the local density and temperature at the time of emission
  - includes line-of-sight and high-T_e opacity effects



E25130

*Prism Computational Sciences, Inc. Madison, WI 53711

Survey experiments on the MTW laser have demonstrated temporal spectral shifts on the Cu K_α line



Shot 5708: 1 J, 0.8 ps
500 × 500 × 20 μm Cu

Shot 5698: 10 J, 7 ps
60 × 60 × 2 μm Cu

As the plasma heats, higher ionization and excited states are populated.

Project Structure

To understand system performance and mitigate risk, HiResSpec is being implemented in two phases

UR LLE

Project requirements

Spherical crystal
- Spectral range
- Radius of curvature
- Integrated reflectivity
- Resolving power

Crystal spectrometer
- Chamber interface to OMEGA EP
- Vacuum system
- Shielding
- Crystal mount/control
- System stability
- Spectrometer alignment

Detectors

PJX-3
- Deployment
- Shielding
- Stability
- Alignment
- Control systems
- Data acquisition

CCD
- Shielding
- Stability
- Control systems
- Data acquisition

High-Risk Issues
- Crystal manufacturing
- Crystal performance on high-power shots
- Streak-camera build, characterization, and calibration
- Streak-camera deployment and shielding requirements
- Signal alignment to the streak camera

E25131

To understand system performance and mitigate risk, HiResSpec is being implemented in two phases

UR LLE

Project requirements

Spherical crystal
- Spectral range
- Radius of curvature
- Integrated reflectivity
- Resolving power

Crystal spectrometer
- Chamber interface to OMEGA EP
- Vacuum system
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- Crystal mount/control
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- Spectrometer alignment

Detectors

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- Deployment
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CCD
- Shielding
- Stability
- Control systems
- Data acquisition

High-Risk Issues: Phase I
- Crystal manufacturing
- Crystal performance on high-power shots

High-Risk Issues: Phase II
- Streak-camera build, characterization, and calibration
- Streak-camera deployment and shielding requirements
- Signal alignment to the streak camera

Phase I

Phase II

E25093

Outline

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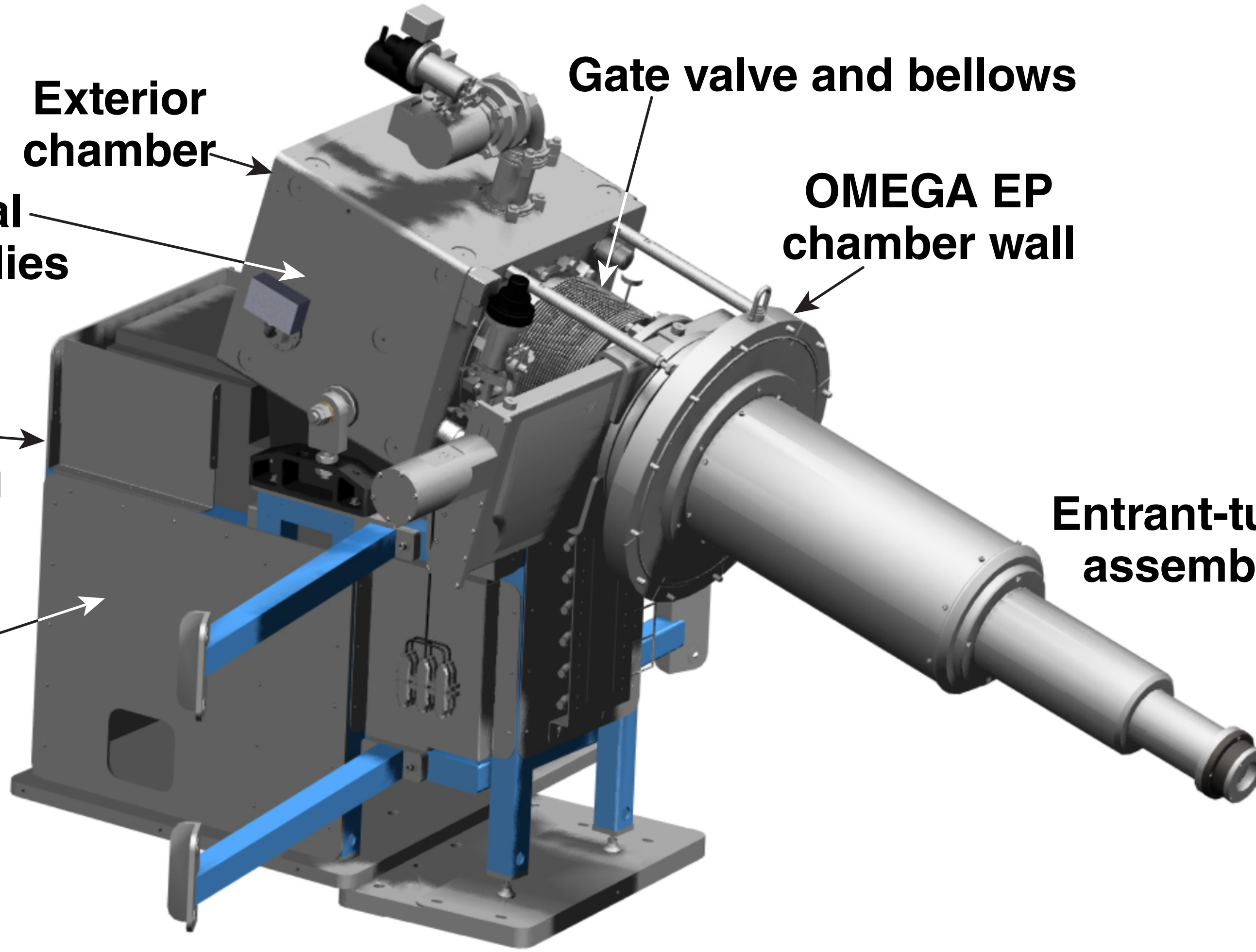
E25089c

The Phase I spectrometer was deployed on OMEGA EP for experiments and diagnostic development in January 2016

UR LLE

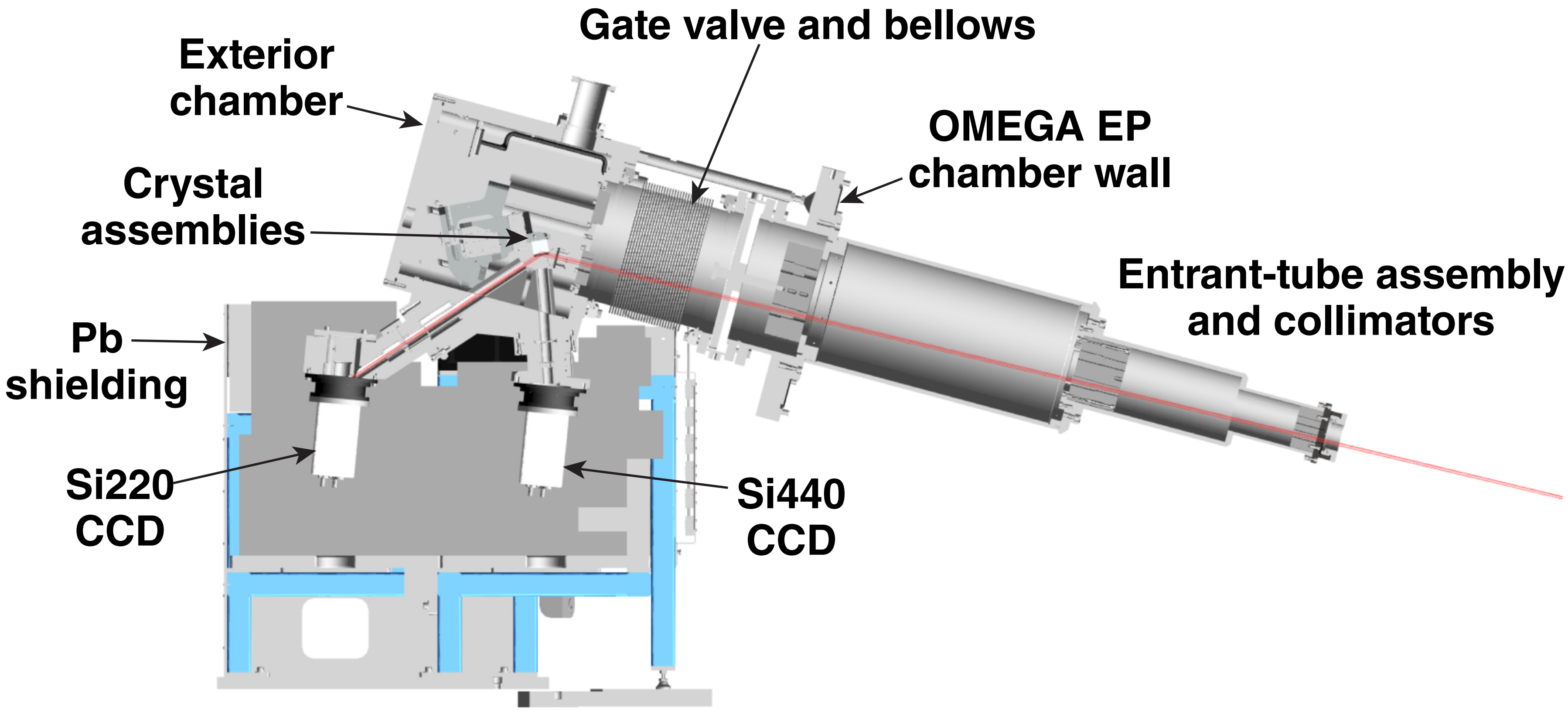


Deck 2 modifications

E25094

The Phase I spectrometer was deployed on OMEGA EP for experiments and diagnostic development in January 2016

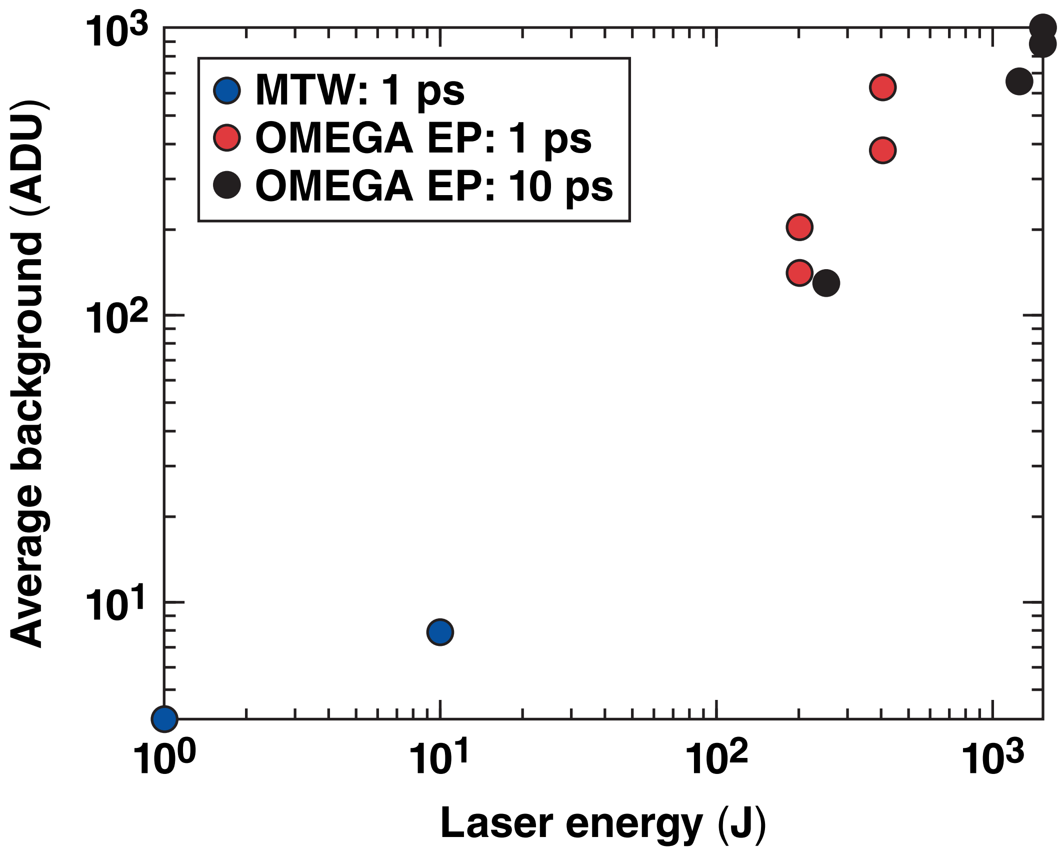
UR LLE

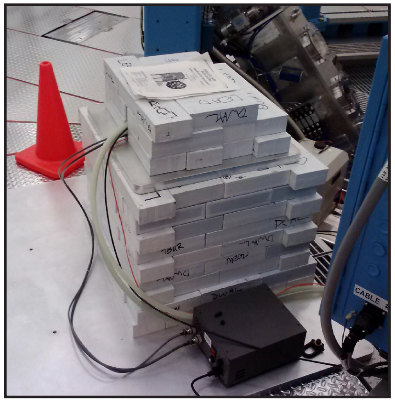


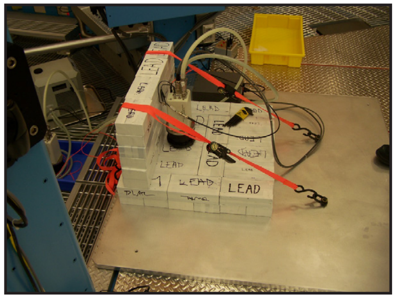
E25095

Shielding Tests

OMEGA EP data show average background signals per pixel of up to 1000 ADU at 1.65 m from the source



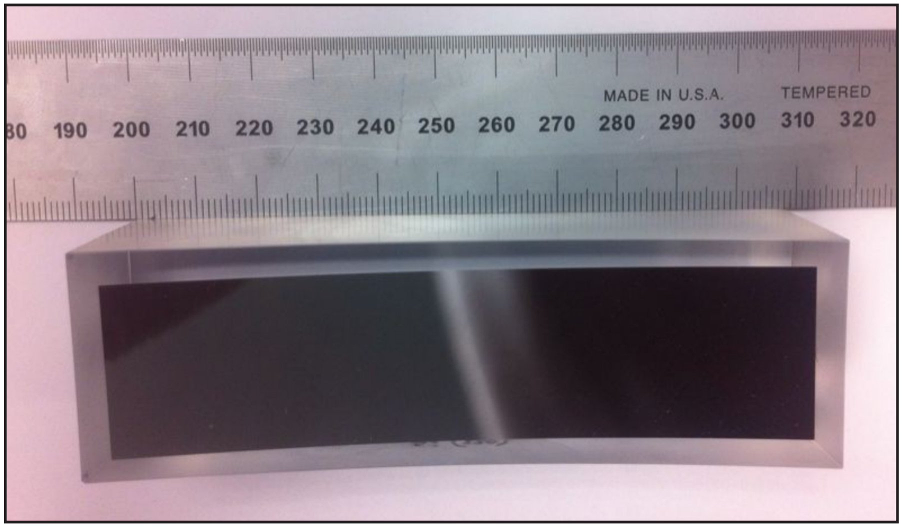




A 5-cm direct line-of-sight lead shielding reduced the background to ~50 ADU.

E23454

Inrad Optics manufactured the crystal assemblies

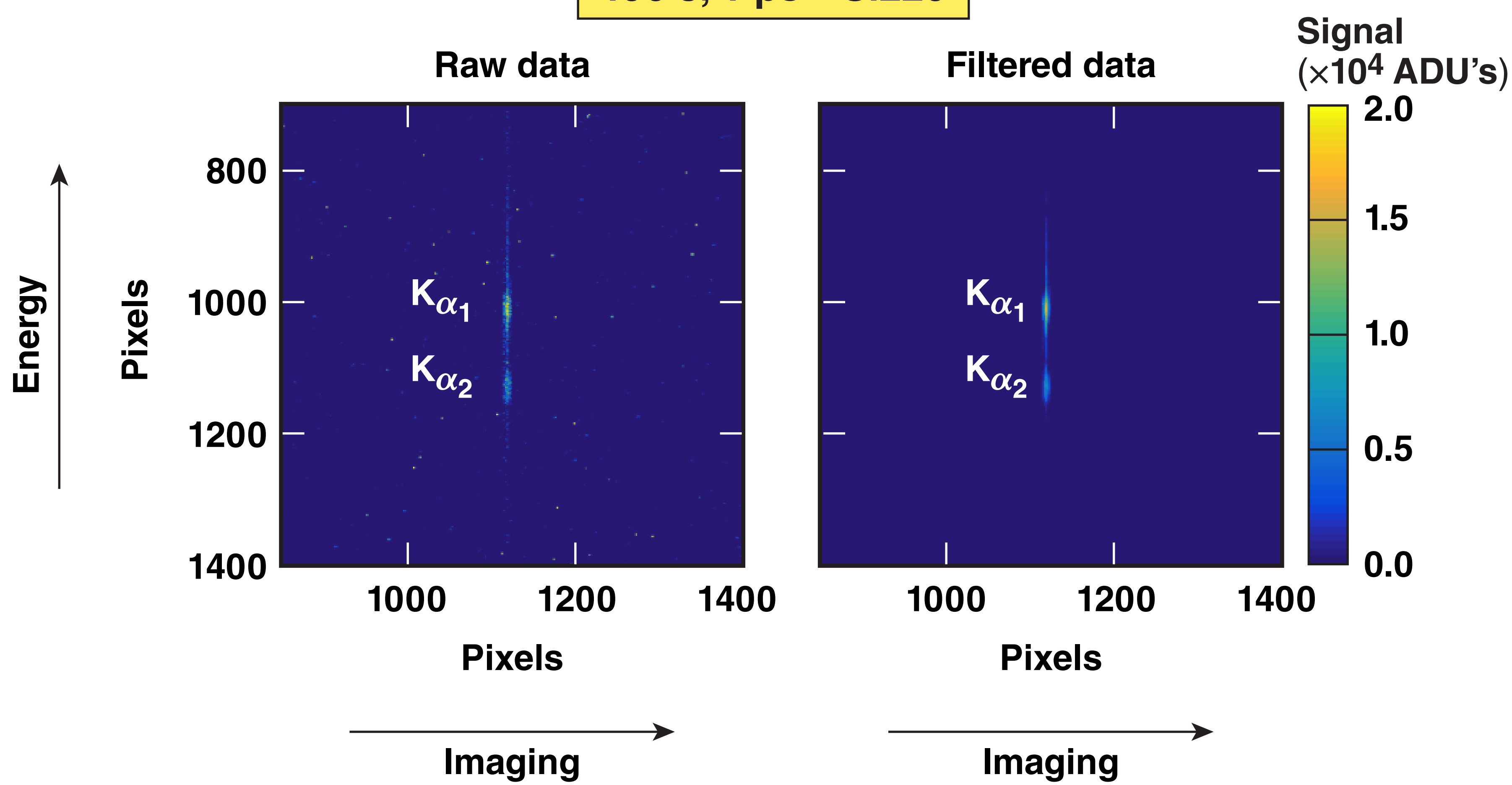


- The silicon crystal is 100 μm thick and 25 mm × 100 mm in size
- The crystal is optically bound to a glass substrate that is shaped to a radius of $R = 330$ mm

High-power experiments show excellent focusing fidelity, resolving power, and throughput

UR LLE

Shot 22854
100 J, 1 ps—Si220

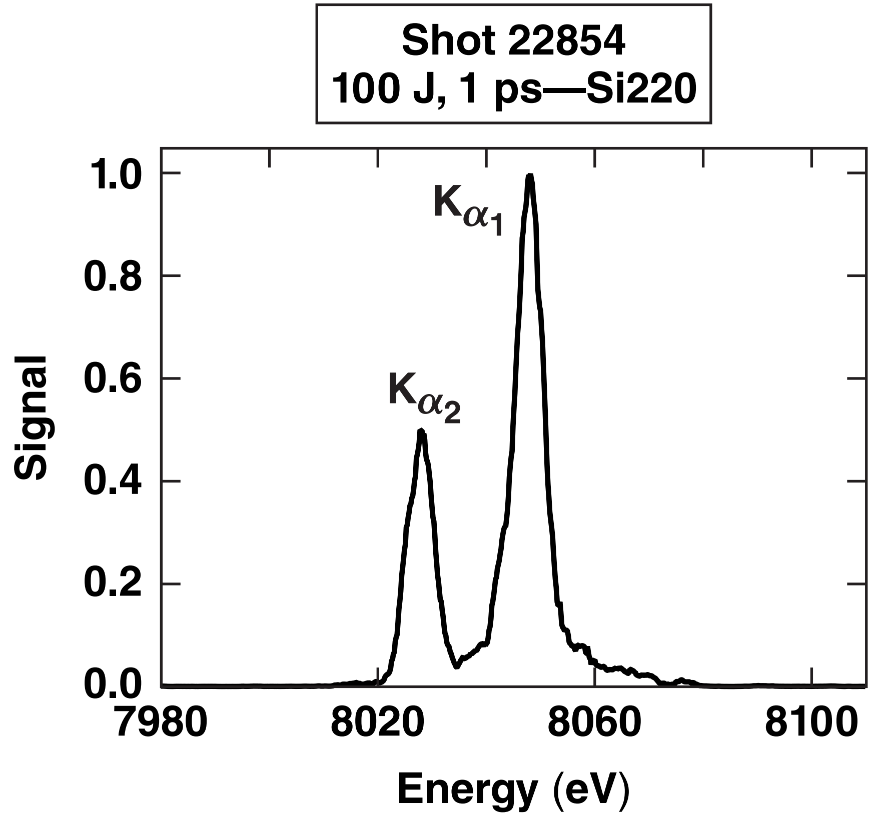


E25096

Photometrics

The Si220 throughput will provide a measurable signal on the PJX-3 streak camera

- The measured throughput is 1.4×10^{-7} ph/ph
- The photometric estimates are based on
  - laser energy: 100 J
  - x-ray flash duration: 10 ps
- The predicted signal at the streak camera are
  - 1700 ADU's per pixel for K_{α_1}
  - 860 ADU's per pixel for K_{α_2}



Phase I has provided the foundation for designing and implementing the time-resolved instrument.

E25097

Outline

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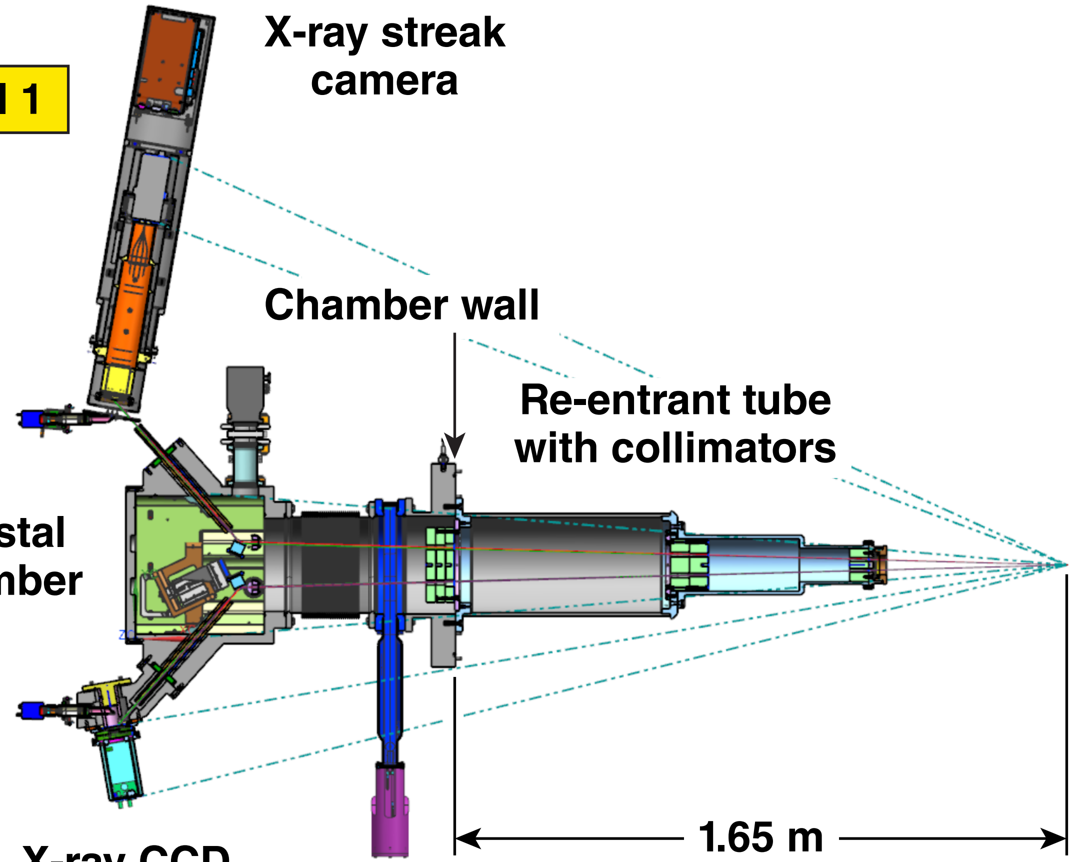
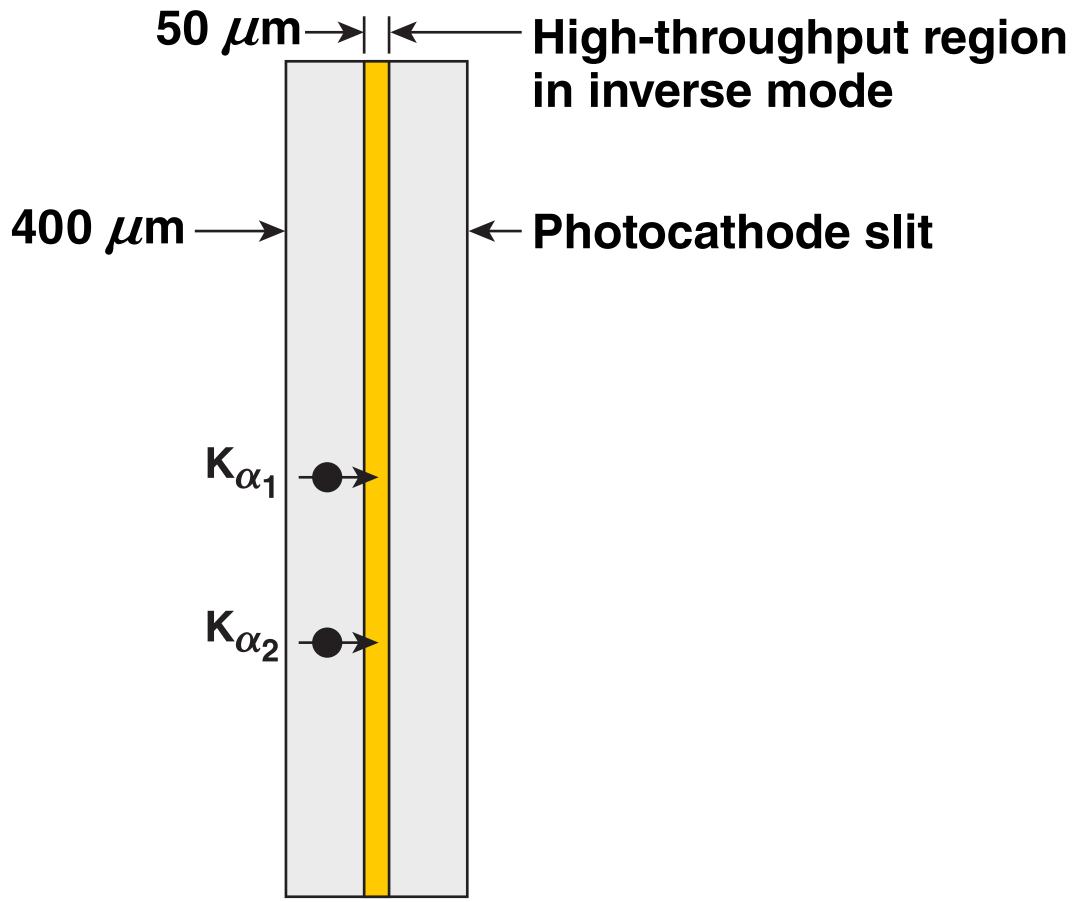
- Conceptual design
  - high-resolution spectrometer (HiResSpec)
- Phase I
  - time-integrating x-ray spectrometer
- **Phase II**
  - **time-resolved x-ray spectrometer**
- Summary and conclusions

The Phase II instrument adds a second crystal assembly and the PJX-3 x-ray streak camera for time-resolved measurements



E23455b

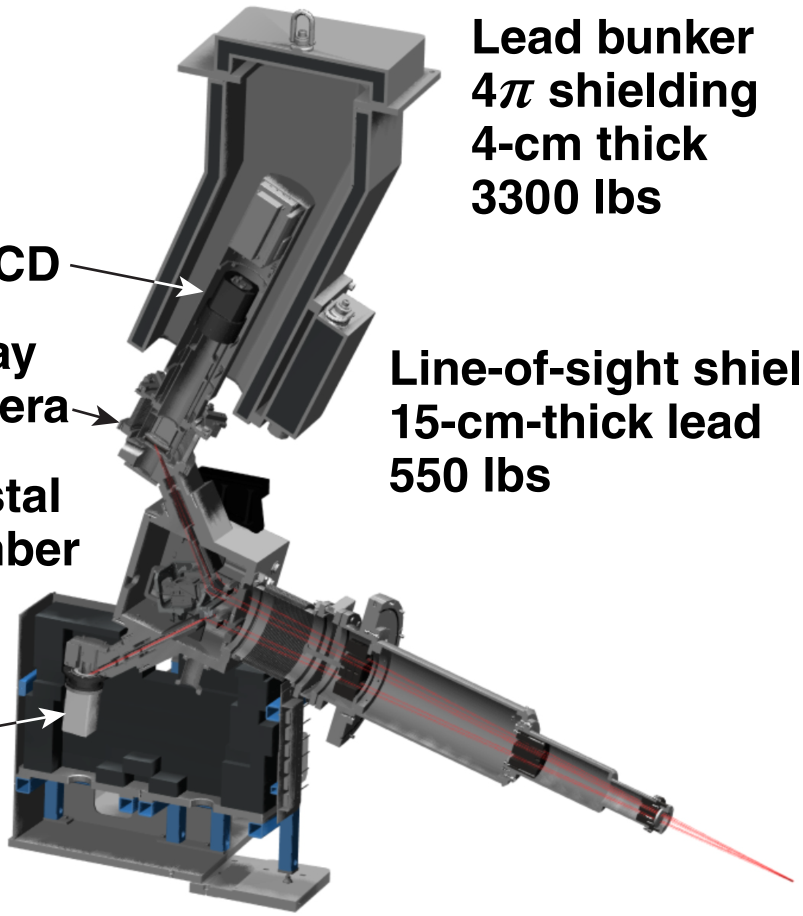
The x-ray signal must be aligned to a 50-μm-wide high-throughput region on the photocathode

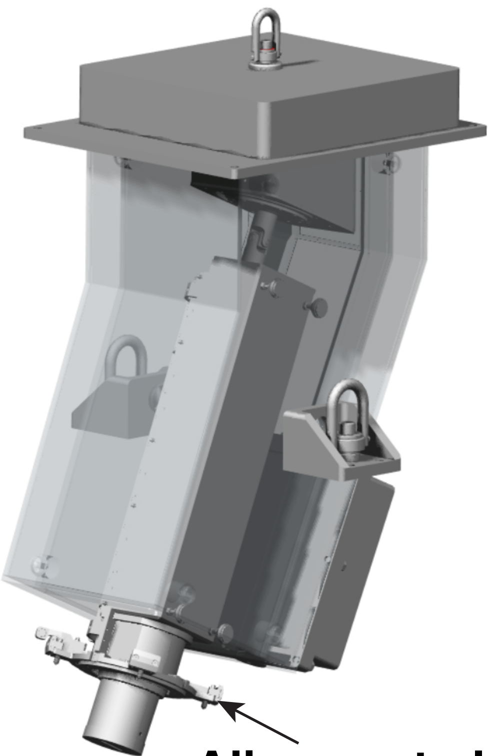


The alignment plate is the crucial component for transferring alignment from an x-ray CCD to the photocathode.

E25099

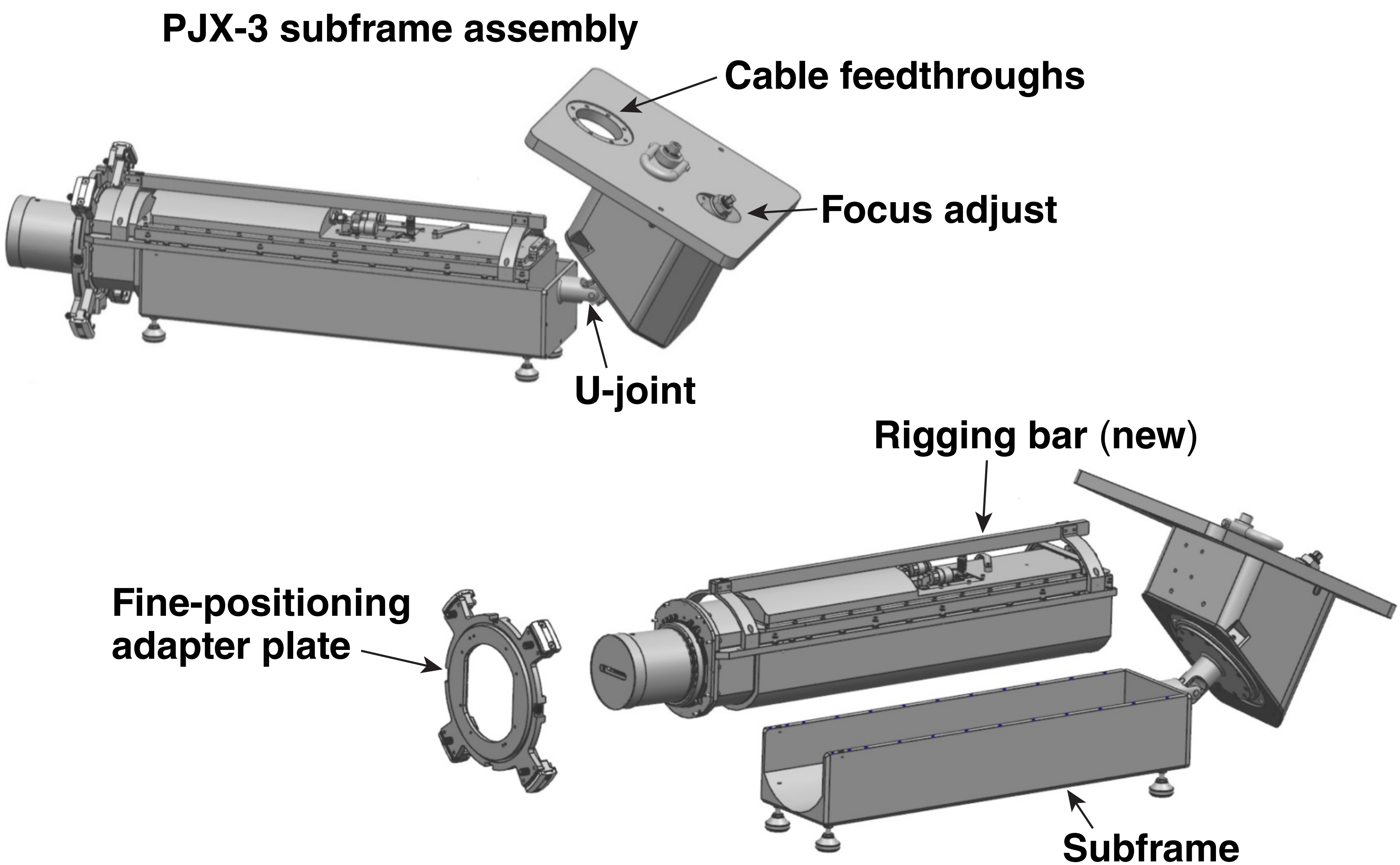
Significant shielding assemblies are required for the x-ray streak camera





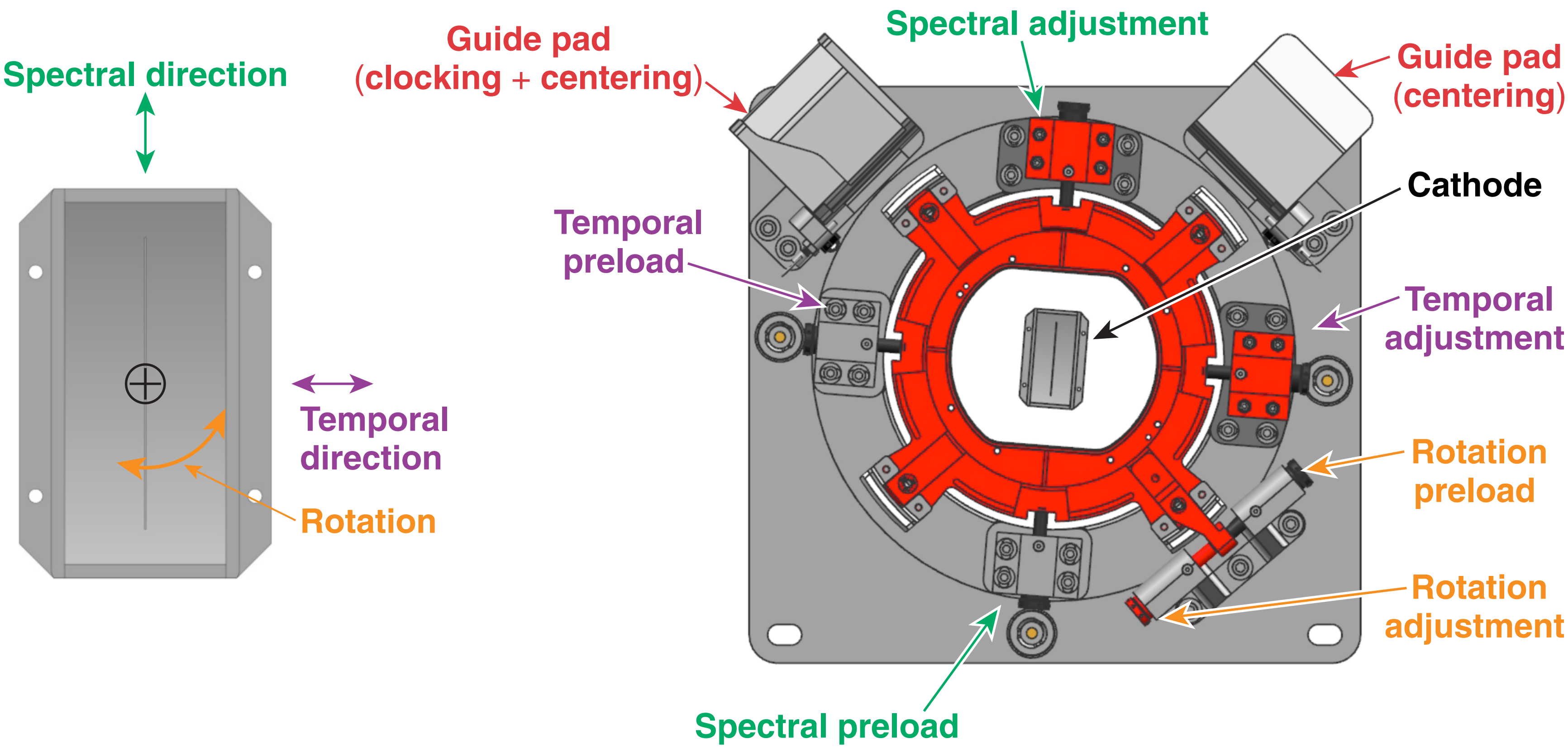
E25098

The PJX-3 camera subframe assembly accommodates the required orientations for deployment and alignment



E25100

Fine adjust along four degrees of freedom is provided near the PJX-3 cathode*



*For detailed tolerance analysis, see D-HS-R-121 Rev A (March 2015).

E25101

Schedule

HiResSpec will be deployed for commissioning and first high-power shots in Q2FY17

- Phase II implementation includes six support activities
  - build the PJX-3 streak camera – complete
  - PJX-3 impulse-response measurements – in progress
  - PJX-3 sweep-speed calibration with 4ω pulses – in progress
  - test new photocathode plates – in progress
  - calibrate PJX-3's 2-D imaging mode – in progress
  - complete PJX-3 shielding tests on OMEGA EP – in progress
- The final design review (FDR) is scheduled for 27 June 2016
- Following instrument fabrication, the system will be deployed and integrated into OMEGA EP during November and December 2016

Operational Readiness Review (ORR)—4 January 2017.

E25102

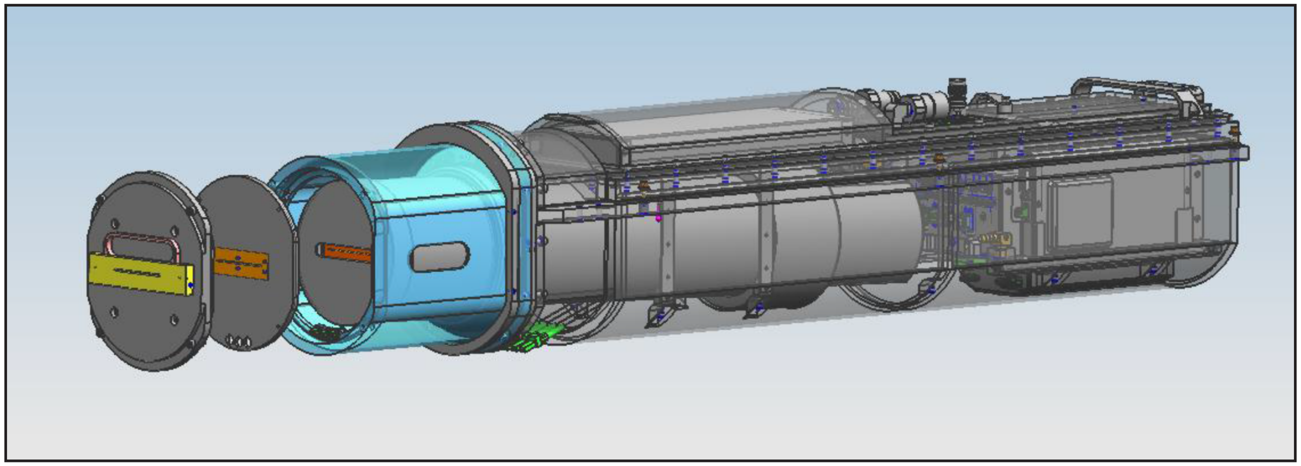
Summary/Conclusions

A high-resolving-power, streaked x-ray spectrometer is being developed and tested on OMEGA EP

- The goal is to achieve resolving power of several thousand and 2-ps temporal resolution
- Temporal spectral shifts on the Cu K_{α} line in isochorically heated solid targets provide a fairly simple system where the spectrometer performance will be validated
- The instrument will be used to measure temperature-relaxation dynamics and material response to ultrafast heating at depth

Development is underway to deploy the instrument on OMEGA EP by Q2FY17.

The high-resolution spectrometer uses the PJX3 streak camera; streak-camera calibration is underway on the MTW laser



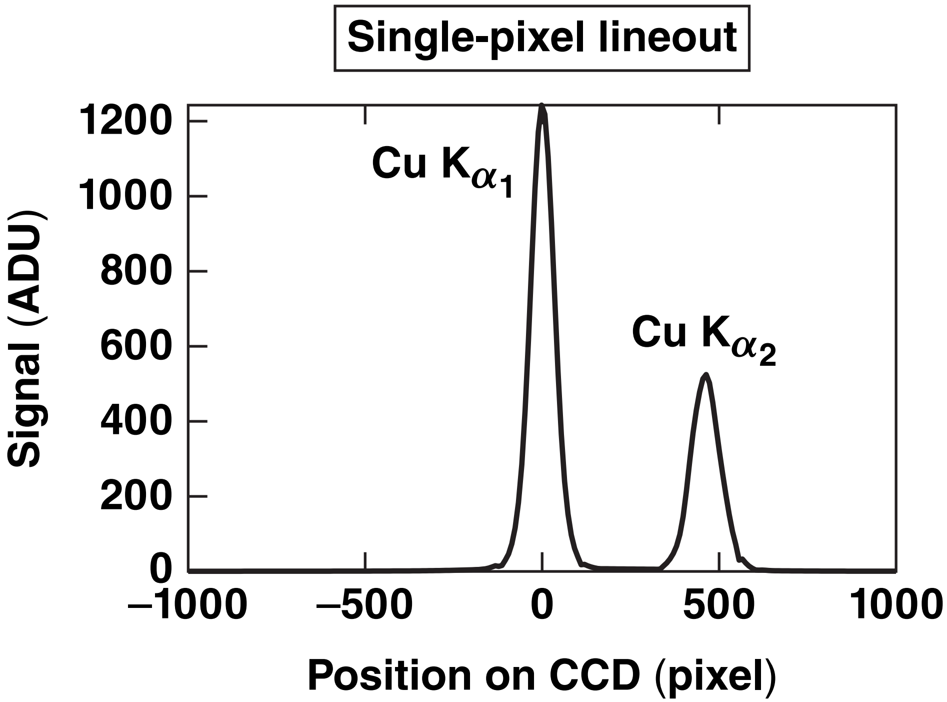
Streak camera	Temporal window (ns)	Temporal resolution (ps)	Dynamic range	Spatial resolution at x-ray photocathode (mm)	X-ray photocathode length (mm)	Number of spatial-resolution elements
PJX3* inverse mode	2 (0.5)	2	30:1**	0.018	6	330

*P. A. Jaanimagi: Photonis model P853 streak tube
**Space-charge–broadening limited

E23448a

The shielding requirements are based on photometric calculations and high-power background measurements

- Throughput: 1.4×10^{-8} ph/ph
- Laser energy: 1000 J
- K_{α} conversion efficiency: 1×10^{-3}
- Photocathode: two secondary electrons per absorbed K_{α} photon
- Internal magnification: 4×
- Number of analog-digital units (ADU's) per electron: 100
- Sweep: 0.5 ns
- Binning: 1 × 1
- Flash time: 15 ps



These system parameters are based on prudent estimates.