Development and Calibration of EUV and Soft X-Ray Optics and Detectors
for NRL/NASA/NOAA Solar, Astrophysical, and Laboratory Instrumentation

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X24C research focus:
Scientific research and development related to the optical properties of materials, multilayer reflective coatings, diffraction gratings and zone plates, transmissive filters, electronic detectors, and material interface science in the extreme ultraviolet and soft x-ray regions.

NRL is interested in transferring these capabilities at NSLS II.
# X24C Key Personnel

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spokesperson</td>
<td>Jack Rife</td>
<td>NRL</td>
</tr>
<tr>
<td>PRT management, scheduling</td>
<td>John Seely</td>
<td>NRL</td>
</tr>
<tr>
<td>Beamline Scientist, Safety, Training, Local Contact</td>
<td>Benjawan Kjornrattanawanich</td>
<td>USRA</td>
</tr>
<tr>
<td>Technical Staff, Local Contact</td>
<td>Johnny Kirkland</td>
<td>SFA Inc.</td>
</tr>
<tr>
<td>Technical Staff</td>
<td>Glenn Holland</td>
<td>SFA Inc.</td>
</tr>
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</table>

## Key PRT Members

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mike Kowalski</td>
<td>NRL</td>
</tr>
<tr>
<td>Bill Hunter</td>
<td>NRL</td>
</tr>
<tr>
<td>Jim Long</td>
<td>NRL</td>
</tr>
<tr>
<td>Charlie Brown</td>
<td>NRL</td>
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</table>
NRL Commitment to NSLS

• NRL originally designed and built X24C and has operated it continuously since the beginning (> 20 years).

• NRL Space Science Division periodically invests capital equipment funds for X24C improvements:
  • Recently upgraded the monochromator and reflectometer motors and the computer control system from the original CAMAC to Mac.
  • $188K is budgeted in FY08 for replacement valves, ion pumps, and ion gauges.
• Two elements (e.g. grating and mirror) are precisely translated and rotated by computer control while maintaining fixed entrance and exit slits.

• Gratings are selected without breaking vacuum and cover from 1 keV through the visible.

• 2° grazing mirrors M1 and M2 were upgraded in 1999 with NRL capital equipment funds.

• $10^8$ to $10^{12}$ photons/sec/0.1% bandpass peaking at ~ 100 eV, resolution up to 1000.

The radiation is 90% polarized with the electric field vector in the plane of the storage ring. This permits the study of the polarization properties of EUV/x-ray optics. The polarization properties impact the science that can be accomplished with solar and astrophysical spaceflight instruments. X24C is the world’s leading beamline for these studies.
X24C Sample Chambers

• UHV reflectometer is used for small sample measurements:
  • Can be rotated about the incident beam for S and P polarization studies.
  • High reflectance multilayer interference coatings on mirror/grating substrates.
  • High efficiency diffraction gratings (reflection and transmission gratings).
• Photodiode chamber for detector sensitivity and radiation damage studies.
• Large calibration chamber for large optics and spaceflight instrument components.
Research, development, and calibration of spaceflight optics and detectors:

• Large (up to 1 m long) optics, detectors, instrument components can be calibrated.

• Clean vacuum conditions (RGA and TQCM monitors).

• Isolated from the UHV reflectometer and beamline by differentially pumped filters.

• Sample and detector mounts/goniometers with computer-controlled, precision translational and angular motions.
Projects and Collaborations

• NRL/ONR: High efficiency multilayer-coated EUV gratings
  ISAS/Japan, Mullard Space Lab/England; Reflective X-Ray Optics
  Normal-incidence multilayer grating covering 17-30 nm wavelengths.

• NASA: High-resolution EUV spectrometer for the Solar-B mission
  Reflective X-Ray Optics (David Windt)

• NASA: λ<3 nm multilayers and interface engineering <0.1 nm
  Reflective X-Ray Optics, Lebedev Institute/Russia

• NASA/Goddard: Multilayer telescope/grating absolute calibrations
  Goddard Space Flight Center
  Boeing Aerospace/Seattle, Assurance Technology Corp/Boston,
  International Radiation Detectors Inc/Los Angeles

• NOAA: Solar spectrometer calibrations for the GOES N/O/P/Q satellites
  MIT Lincoln Lab, Mullard Space Lab/England, NASA

• DOE: Time-resolved soft x-ray flux from laser-produced plasmas
  Silicon photodiode sensors, absolute calibrations, subnanosec time response.
  NRL Plasma Physics Division, NIKE laser
First satellite spectrometer with a multilayer grating:

- Multilayer coatings cover 17-21 nm and 23-29 nm.
- Designed for the study of solar regions: corona, active regions, flares.
- Measurement of temperatures, densities, emission measure, Doppler shifts.
Characterization of Xradia Zone Plate (1)

- Fresnel zone plate is composed of open and opaque circular zones designed to focus the +1 diffraction order on the axis with focal length $f \approx 1/\lambda$.
- The $-N$ orders are diverging, and the $N=\text{even}$ orders ideally have zero efficiency.
Characterization of Xradia Zone Plate (2)

Important experimental parameters:

- 2 mm OD, 180 nm thick gold.
- 1 mm central stop, 0.5 mm thick ss.
- Si$_3$N$_4$ support membrane, 2.5x2.5 mm$^2$ area, 100 nm thick.
- $f = \text{OD } \frac{\Delta R_n}{N \lambda} = 300 \text{ mm/N} \lambda [\text{nm}]$ where N=order number.

### Zone Plate Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>2000 (um)</td>
</tr>
<tr>
<td>Inner Diameter (no zones)</td>
<td>1000 (um)</td>
</tr>
<tr>
<td>Outermost Zone Width</td>
<td>150 (nm)</td>
</tr>
<tr>
<td>Zone Material</td>
<td>Electroplated Gold</td>
</tr>
<tr>
<td>Zone Height</td>
<td>180 +/- 10%</td>
</tr>
<tr>
<td>Number Of Zones$^2$</td>
<td>3330</td>
</tr>
<tr>
<td>Suggested Energy Range$^3$</td>
<td>0.13-1.4 keV</td>
</tr>
<tr>
<td>Theoretical Max. Diffraction Efficiency$^1$</td>
<td>15 (@ 1.1 keV)</td>
</tr>
<tr>
<td>Support Membrane Material</td>
<td>Si$_3$N$_4$</td>
</tr>
<tr>
<td>Support Membrane Thickness</td>
<td>0.1 (um)</td>
</tr>
<tr>
<td>Support Membrane Size</td>
<td>2.5 x 2.5</td>
</tr>
<tr>
<td>Support Silicon Frame Size</td>
<td>6 x 6</td>
</tr>
<tr>
<td>Central Stop Diameter$^4$</td>
<td>1000 (um)</td>
</tr>
<tr>
<td>Central Stop Height / Material</td>
<td>500/stainless steel</td>
</tr>
</tbody>
</table>

$^1$ The guaranteed focusing efficiency for condenser zone plates is 50% of the theoretically calculated value.
$^2$ Number of fabricated rings calculated for a full zone plate (no missing inner zones).
$^3$ Energy range for which the theoretical efficiency is greater 10%.
$^4$ The stop for the condenser is a EDM-cut stainless steel plate.
Characterization of Xradia Zone Plate (3)

Front view of the CMOS imager:

Back view of the diode mount:

Motions controlled from outside
- Calibration chamber x-y-yaw plate:
  - Center ZP or surrogate in beam.
  - Rotate ZP off-axis.
- Huber x-z relative to x-y-yaw plate:
  - Change ZP-detector distance.
  - Move ZP or surrogate into beam.
- Detector x-y relative to ZP:
  - Center detector behind ZP.
Characterization of Xradia Zone Plate (4)

- Apertures upstream of the ZP define the radiation beam diameter/divergence.
- The beam divergence was ±5 mrad (small, resulting in sharp shadows).
- The beam through the 2 mm aperture overfilled the ZP and revealed features.
- Image has 100x100 pixels (48 μm), 4.8x4.8 mm² size (13.5 nm wavelength):

  - 3 mm ID hole
  - 2 mm OD ZP
  - 1 mm OD occulter
  - 0.3 mm wide supports
  - 2.5x2.5 mm² Si₃N₄ membrane
  - Residual sensor artifact

Undiffracted
-1 order (diverging)
0 order (undeflected)
+1 order (converging)
Optical models for the responsivities of EUV/x-ray photodiodes (Si, SiC).

- Multiple-layer coatings provide EUV bandpasses, polarization sensitivity, and visible light blocking.

- Adopted for GOES EUV spectrometers and for NRL laboratory x-ray measurements.

- Calibration model for an uncoated Si photodiode:
Radiation damaged is modeled by reduced charge collection efficiency in the topmost Si layer.
### Pulsed Photodiode Responsivity

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Area (mm²)</th>
<th>Aperture Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AXUV-HS5</td>
<td>1 x 1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>AXUV-HS5</td>
<td>1 x 1</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>AXUV-HS1</td>
<td>0.22 x 0.22</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>AXUV-100G</td>
<td>10 x 10</td>
<td>0.8</td>
</tr>
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</table>

**HS5: 700 ps NSLS single bunch**

- Input Pulses: 88 V, 66 V, 44 V

**68 ps laser**

- Input Pulses: 88 V, 66 V, 44 V, 22 V

**Inferred Capacitance**

- Pulsed Laser Illumination
  - 0.4 mm aperture
  - 0.8 mm aperture
- Pulsed X-Ray Illumination
  - 0.8 mm aperture

- No Illumination