Stark broadening of Kr He-β lines for electron-density measurement on NIF

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Summary

• Kr He$\beta$, 15.43 keV, $\Delta E=400$ eV or 1.4 keV, Ge (220), $\theta_B=11.6^\circ$, $\Delta \theta_{RC} \sim 41 \mu$rad, $\Delta E_{RC}=3$ eV

• Cylindrical
  – Rays from 2-cm high crystal ($\Omega \sim 1.3 \times 10^{-6}$ sr) fit within a 400-\textmu m slit
  – Energy spread over 100-\textmu m detector “pixel”: 5.5 eV (-> 6.25 eV total)
  – High quality concave cylindrical lenses are available as substrates

• Conical
  – Rays from 2-cm high crystal fit within a 200-\textmu m slit
  – Narrow spatial peak will provide better time resolution with DISC
  – Energy spread over 100-\textmu m detector “pixel”: 7.5-9 eV for 100-\textmu m or 500-\textmu m slit
  – Substrate requires special fabrication

• Cone length 23.5 mm, angle: 23.545°, $r_{\min} : 95.447$ mm, $r_{\max} : 100.14$ mm

• We plan to obtain both a cylindrical and a conical crystal for evaluation
• Layout drawings to confirm clearances relative to other systems in progress
R&D progress has been made on DIM-based high resolution x-ray spectrometer

- Physics parameters to measure
  - $T_e$ from dielectronic satellites
  - $n_e$ from Stark broadening of He-β lines
  - K or L₃ absorption edge spectra with high resolution
  - Doppler $T_i$

- Focused on two experiments
  - Time resolved measurement of Kr Heβ in symcap
    - $n_e$ from Stark broadening
    - $T_e$ from dielectronic satellites
  - XAFS of Cu K or Ta L_{III} edge

- Estimated performance metrics
  - X-ray intensities
  - Spectrometer throughputs
  - Signal levels at detector
  - Optimization of S/N
  - Resolution expected

- R&D performed
  - Analytically evaluated six spectrometer geometries
  - Experimentally evaluated four spectrometer geometries
We have developed analytical optical tools and experimentally studied several spectrometer geometries

- **Spatially focusing** – best for streak camera
  - Optimal S/N
  - Sagittally focusing Johann ($\theta>45^\circ$) (TITAN, ORION) – excellent spectral res. & sagittal focusing
  - Spherical crystal von-Hamos-like geometry ($\theta<45^\circ$) – *ditto* but low throughput in DIM geometry (small Bragg angle)
  - von Hamos (cylindrical) – $\Omega \sim 2 \times 10^{-6}$ sr
  - Conical crystal von Hamos

- **Spatially diverging** – for area detectors
  - Suitable for framing camera or image plate
  - Modified Johann (source inside Rowland circle)
  - Flat crystal
  - Convex spherical crystal
  - 2D logarithmic spiral

- **Advanced concepts**
  - 2D and 3D Logarithmic spiral
  - Spherical crystal with detector near Rowland circle
Electron-density measurement by Stark broadening of Cl He-β lines was demonstrated on ORION

Fit of the chlorine He-β line with ALICE

- Ion dynamics changes the line shape by filling in the central dip
- ALICE treats the three species in PyD (C₈H₆Cl₂) self-consistently
- The calculations assume a temperature of Tₑ = 550 eV and a density of 3.0 e²³ cm⁻³

Beiersdorfer et al.
Photonics were estimated for two experiments

- Time resolved measurement of Kr He$\beta$ in a symcap
  - $T_e$ = 3 keV
  - $n_e$ = 2x10$^{24}$ cm$^{-3}$
  - 0.01% Kr
  - 50 $\mu$m symcap
  - Spectrometer solid angle = 10$^{-6}$ sr
  - -> 7x10$^4$ photons in 30 ps
Simulation of ray paths for cylindrical and conical von Hamos spectrometers
For cylindrical von Hamos the image from a 2-cm high crystal fits within a 400 µm slit (blue curves)

- The x-ray intensity is distributed spatially (Z detector) uniformly within the bowtie limit lines
- For a conical crystal the intensity is highly concentrated in the center of the slit
- Calculations for 400-eV bandwidth

Boundaries of spectral-spatial image on detector
The “bowtie” effect broadening, however, is large if the full 25-mm photocathode is illuminated.

- Cylindrical von Hamos
- 15.2 – 16.67 keV
- 10-cm high crystal fills a 1-mm wide slit (red lines)
X-ray intensities from equal areas of crystal are concentrated toward center of detector in the conical crystal geometry.

All x rays from a 20-mm high crystal are concentrated inside a 200 µm detector slit.
Most of the intensity is concentrated in a narrow line (conical crystal)

98% of intensity falls within 100 μm slit
The spatial width of the spectrum increases with crystal height.
The energy spread falling on a 100-µm detector “pixel” within 100 and 500-µm wide slits is 7.5-9 eV versus 5.5 eV for a flat or cylindrical crystal.
For $L=1280$ mm a 25-mm photocathode just barely includes the Kr He-$\delta$ line.

The inverse dispersion ranges from 55 to 66 eV/mm.
Mechanical layouts
An NXS drawing was used to estimate clearance of a conical crystal HiRes relative to the polar beams and TIM envelope.

- For L=1280 mm from TCC to DISC photocathode, the front end of the crystal clears the polar beam by 29 mm.
- More accurate CAD layouts are being done.

K. Hill 10/6/2015
Graphing the x-ray paths in our IDL program allows study of the crystal clearance for different values of $L$.

Note: Drawing is not isotropic!

$\alpha = 11.3$, $L = 1280$, $\det = 244$

- $\text{Ge <220>}$
- $\text{polar beam}$
- $\text{DIM axis}$
- $\text{y clearance}$

Values:
- $E_{\text{min}} = 15.22$
- $E_{\text{max}} = 16.67$
- $\text{lxtal} = 75.64$
- $\text{ldet} = 24.4$
- $x_{\text{clear}} = 83.6$
- $y_{\text{clear}} = 28.8$
- $y_{\text{xtal}} = 125.8$
- $\text{rhomn} = 115.6$
- $\text{rhomx} = 130.2$
Larger L (TCC-to-detector) clears polar beams better but may violate TIM stay-in radius requirement

All distances in mm (Ge <220>)

<table>
<thead>
<tr>
<th>L</th>
<th>x clearance</th>
<th>y clearance</th>
<th>detector length</th>
<th>y-crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>31.1</td>
<td>10.7</td>
<td>19.1</td>
<td>108.1</td>
</tr>
<tr>
<td>1100</td>
<td>49.8</td>
<td>17.2</td>
<td>21.0</td>
<td>117.9</td>
</tr>
<tr>
<td>1280</td>
<td>83.6</td>
<td>28.8</td>
<td>24.4</td>
<td>125.8</td>
</tr>
<tr>
<td>1350</td>
<td>96.7</td>
<td>33.3</td>
<td>25.8</td>
<td>132.7</td>
</tr>
</tbody>
</table>

- y-crystal is distance from axis to front surface of crystal; add thicknesses
- x,y clearances are x,y distances of left front edge of crystal from polar beam
- Need to add thicknesses of crystal/substrate, crystal holder, cassette wall
- Detector lengths for E from 15.22 to 16.67 keV

K. Hill 10/6/2015
A Ge $<111>$ crystal fits inside a smaller cassette, but the spectral resolution is poorer.
The quartz $<102>$ and Ge $<111>$ crystals allow better clearance

All distances in mm

<table>
<thead>
<tr>
<th>L</th>
<th>x clearance</th>
<th>y clearance</th>
<th>detector length</th>
<th>y-crystal length</th>
<th>Crystal</th>
<th>Bragg angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1280</td>
<td>83.6</td>
<td>28.8</td>
<td>24.4</td>
<td>125.8</td>
<td>Ge $&lt;220&gt;$</td>
<td>11.59°</td>
</tr>
<tr>
<td>1280</td>
<td>128</td>
<td>44.2</td>
<td>22.6</td>
<td>110.4</td>
<td>quartz $&lt;102&gt;$</td>
<td>10.16°</td>
</tr>
<tr>
<td>1280</td>
<td>215</td>
<td>74.4</td>
<td>22.0</td>
<td>77.0</td>
<td>Ge $&lt;111&gt;$</td>
<td>7.06°</td>
</tr>
</tbody>
</table>

- But reflectivity of quartz $<102>$ is one fifth that of Ge $<220>$
- Resolution of Ge $<111>$ is poorer than that of Ge $<220>$
Clearance from polar beams and cassette boundary requirement have been studied.
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EXTRAS
Energy increases with x position on crystal and y position on detector

Martinolli, RSI (2004)
Z is the spatial coordinate in the image plane (detector)

Martinolli, RSI (2004)
Geometry used for the PPPL conical von Hamos calculations

M. Bitter
For detectors perpendicular to the spectrometer axis the “bowtie” effect occurs for cylindrical or spherical crystals.

- Sagittal focusing greatly improves S/N; may saturate detector
- Image plate for EXAFS can be on SFL
- “Bowtie” effect can affect performance for streak camera
- Consider putting GXD electronics to side of MCP, instead of behind

Doeppner et al. RSI 2014
We have been focusing on cylindrical and conical von Hamos configurations

- Kr He$\beta$, 15.43 keV, Ge (220), 11.6° Bragg angle, $\Delta\theta \sim 41$ μrad
- Solid angle $\Omega \sim 2 \times 10^{-6}$ sr for crystal height $h_c = 3$ cm and source-to-detector distance $L = 128$ cm
- Dispersion along slit $\sim 55$ eV/mm and on axis $\sim 11$ eV/mm
- For comparison, NXS with a flat Ge (220) crystal and 500 μm slit has $\Omega \sim 1.7 \times 10^{-8}$ sr ($\phi = 0.04/97 \sim 4.2 \times 10^{-4}$)
The bowtie is 370 µm high at the tungsten $L\alpha_1$ line

But the OMEGA EP streak-camera slit can be placed on the sagittal focal line

- Line separation is ~ 62 eV and 2.98 mm on CCD
- Si 220, $\theta=23^\circ$, $R=35$ cm, 8 cm x 2.5 cm, crystal-detector distance=20 cm
Photonics were estimated for two experiments

- **Time integrated XAFS of Cu K or Ta L₃ edge**
  - Backlighter: $4 \times 10^{18}$ eV/eV at 10 keV
  - Spectrometer solid angle $10^{-6}$ sr
  - 10% detector efficiency
  - 30% transmission through target
  - $\rightarrow 10^6$ counts/eV
  - Note: spectrometer dispersion is about 50 eV/mm for detector perpendicular to DIM axis or 11 eV/mm for detector surface along axis (von Hamos)
We need a silicon or germanium cylindrical crystal to continue lab evaluations

Jim Emig provided us with KAP and mica crystals, but the spatial-spectral images are poor, and it is hard to find a single sagittal focus. We work in 4\textsuperscript{th} and 3\textsuperscript{rd} orders with these crystals, whereas we would have first order reflection with Si or Ge (111), and probably much better quality images.
Our conical crystal analysis code predictions are similar to those of Martinolli et al. RSI (2004)

PPPL 0.8 Å, Kr Heβ

Martinolli, 8 Å
We have looked at concepts for a dual von Hamos spectrometer for time integrated and time resolved spectra.