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

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Summary

- Kr Heβ, 15.43 keV, ΔE=400 eV or 1.4 keV, Ge (220), θ_B=11.6°, $\Delta\theta_{RC}$ ~ 41 μrad, ΔE_{RC}=3 eV
- Cylindrical
  - Rays from 2-cm high crystal (Ω ~ 1.3 x 10^{-6} sr) fit within a 400-μm slit
  - Energy spread over 100-μm 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-μm slit
  - Narrow spatial peak will provide better time resolution with DISC
  - Energy spread over 100-μm detector "pixel": 7.5-9 eV for 100-μm or 500-μm 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 L_3 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

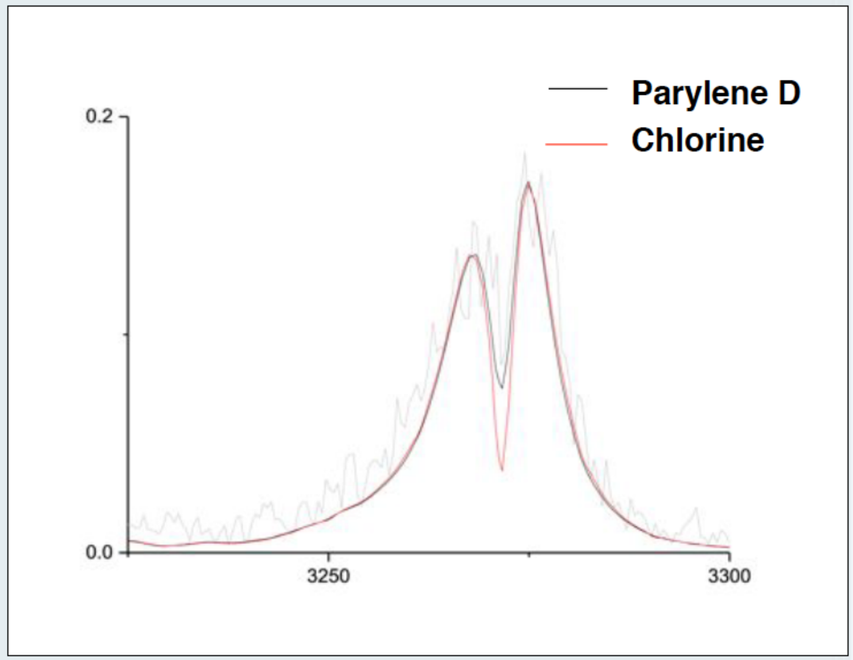
We have developed analytical optical tools and experimentally studied several spectrometer geometries

- **Spatially focusing – best for streak camera**
  - Optimal S/N
  - Sagittally focusing Johann (θ>45°) (TITAN, ORION) – excellent spectral res. & sagittal focusing
  - Spherical crystal von-Hamos-like geometry (θ<45°) – *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 ($C_8H_6Cl_2$) self-consistently**
- **The calculations assume a temperature of T_e = 550 eV and a density of 3.0 e^{23} cm^{-3}**



Beiersdorfer *et al.*

Physics Division

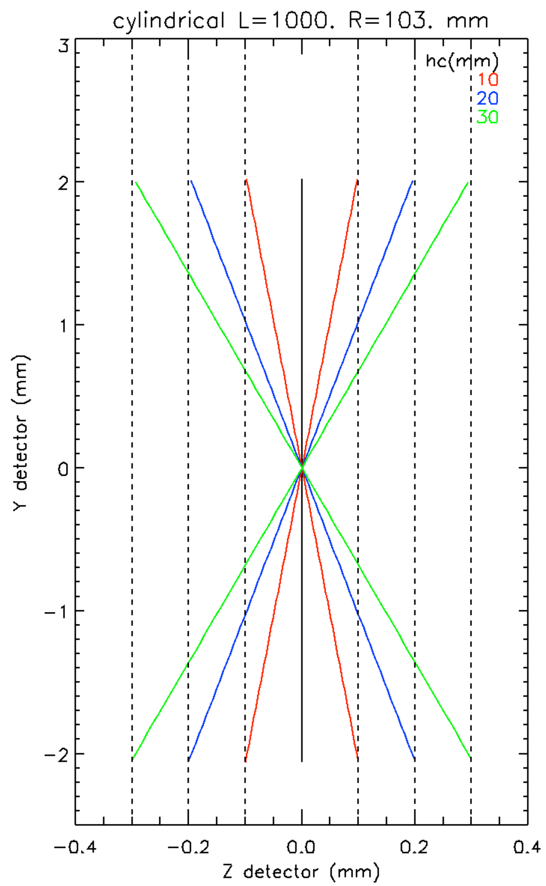
Photonics were estimated for two experiments

- Time resolved measurement of Kr Heβ in a symcap
  - T_e=3 keV
  - n_e=2x10^{24} cm^{-3}
  - 0.01% Kr
  - 50 μm symcap
  - Spectrometer solid angle = 10^{-6} sr
  - -> 7x10^4 photons in 30 ps

Simulation of ray paths for cylindrical and conical von Hamos spectrometers

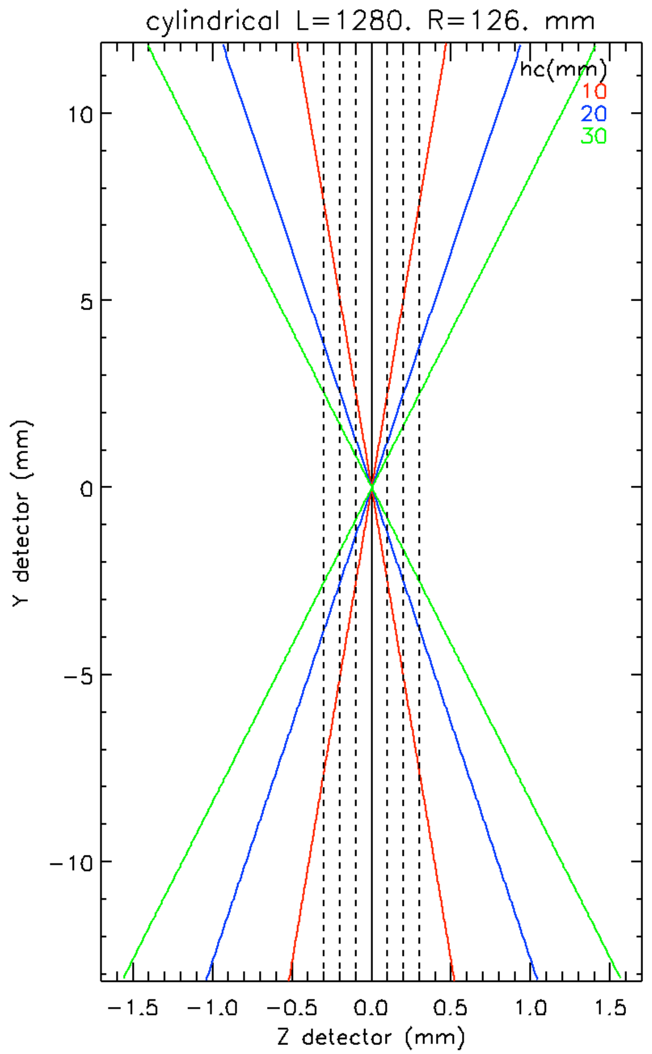
For cylindrical von Hamos the image from a 2-cm high crystal fits within a 400 μm slit (blue curves)

Boundaries of spectral-spatial image on detector



- 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

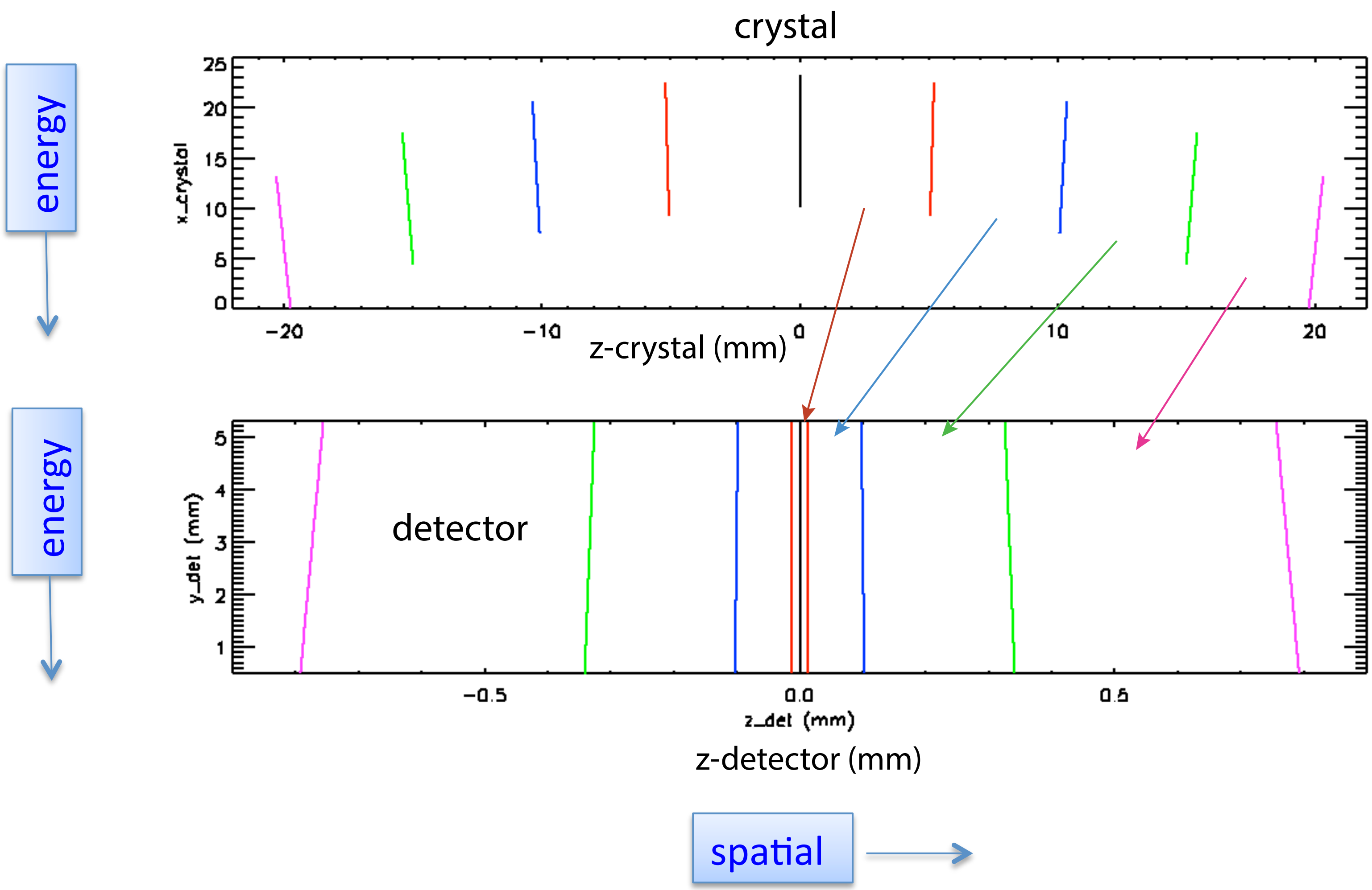
The "bowtie" effect broadening, however, is large if the full 25-mm photocathode is illuminated



- Cylindrical von Hamos
- 15.2 – 16.67 keV
- 10-cm high crystal fills a 1-mm wide slit (red lines)

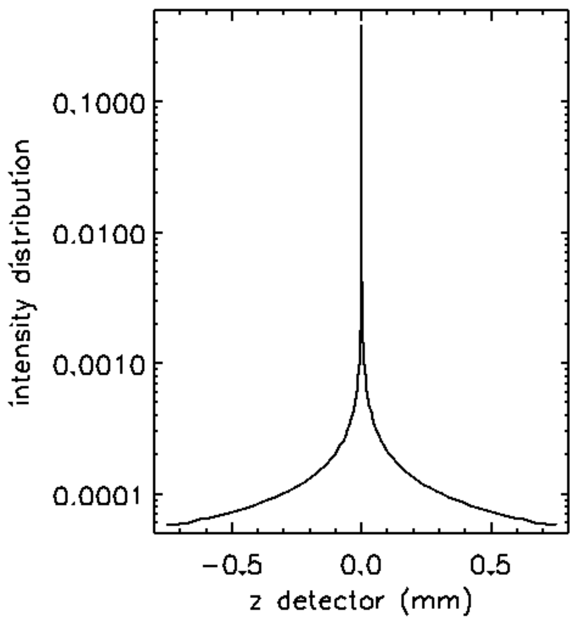
X-ray intensities from equal areas of crystal are concentrated toward center of detector in the conical crystal geometry

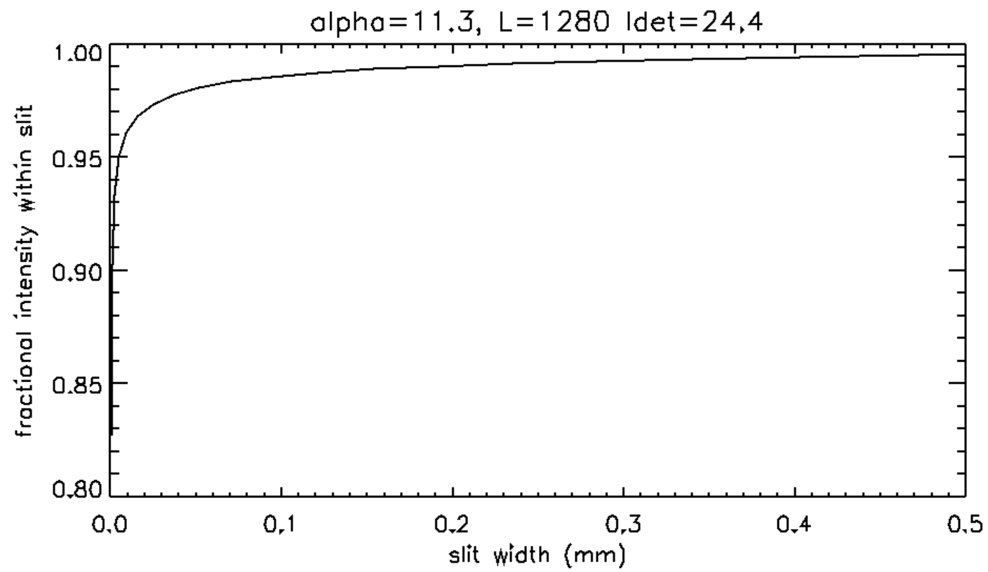
All x rays from a 20-mm high crystal are concentrated inside a 200 μm detector slit



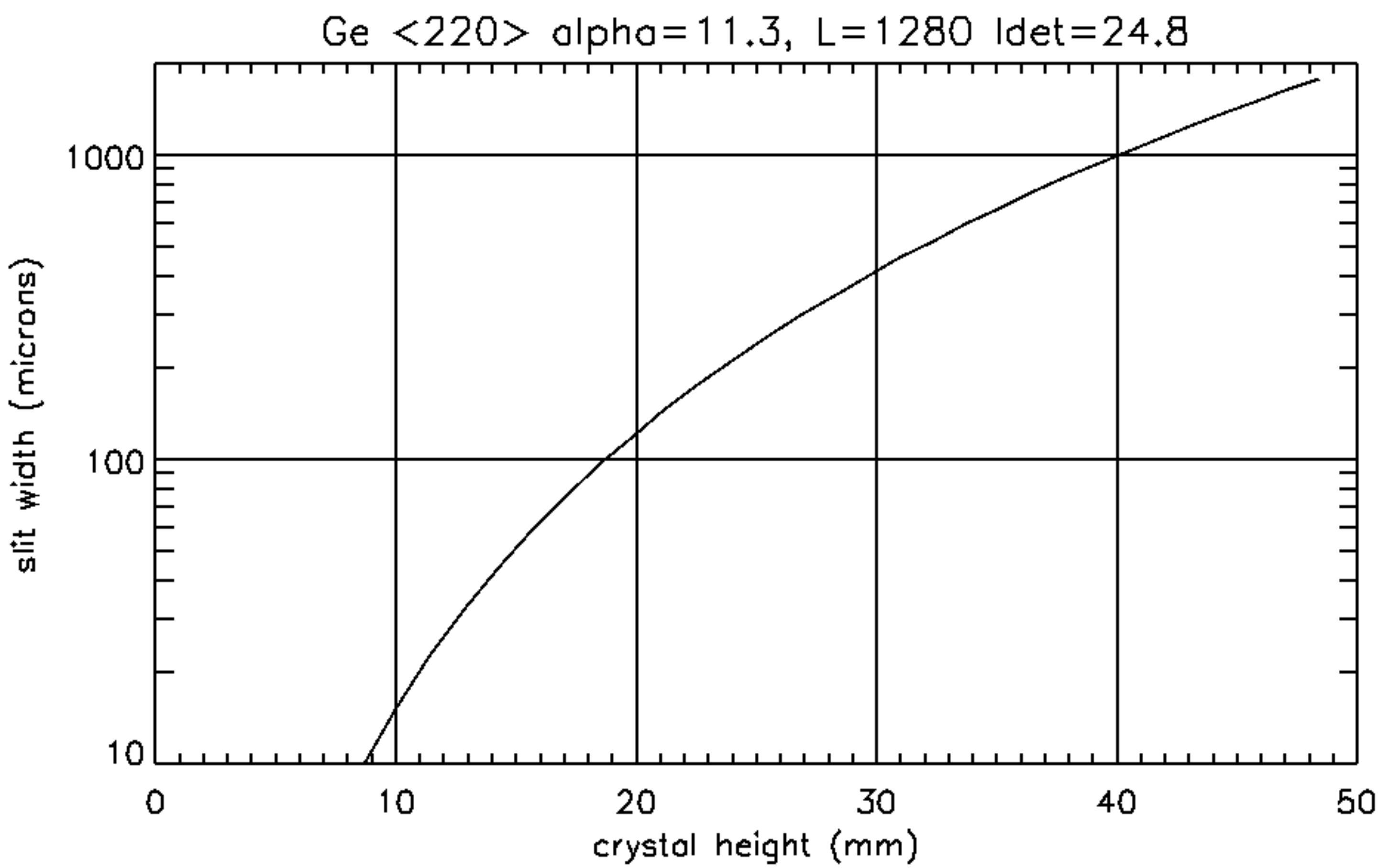
Most of the intensity is concentrated in a narrow line (conical crystal)

98% of intensity falls within 100 μm slit

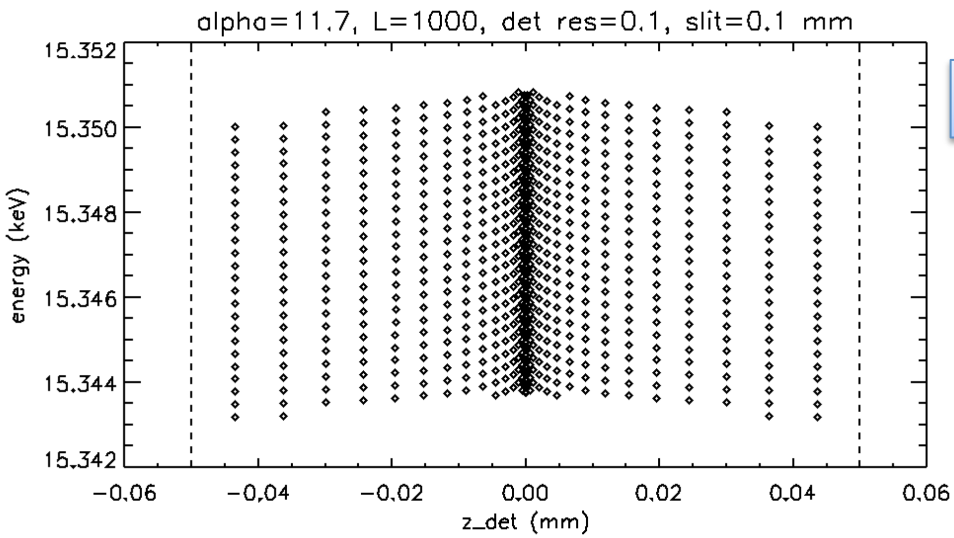




The spatial width of the spectrum increases with crystal height



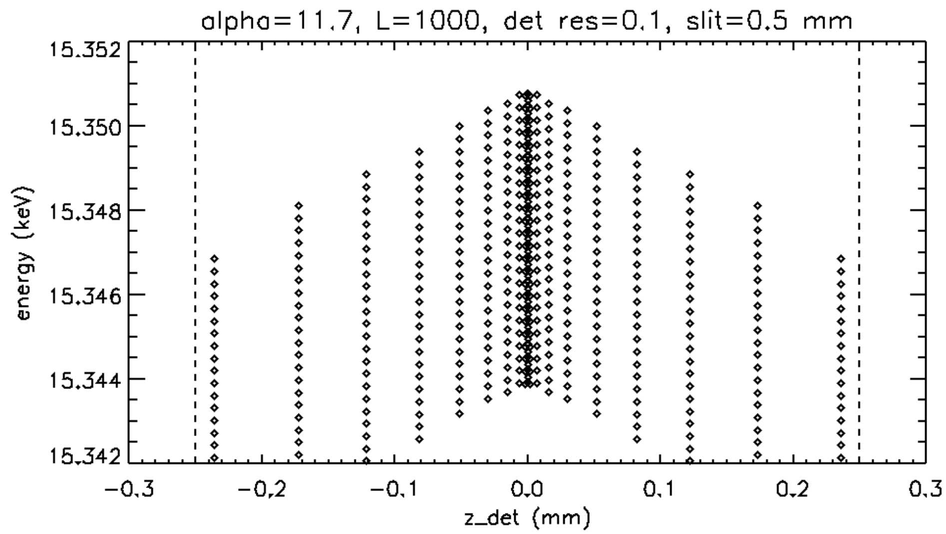
The energy spread falling on a 100-μm detector "pixel" within 100 and 500-μm wide slits is 7.5-9 eV



100-μm slit

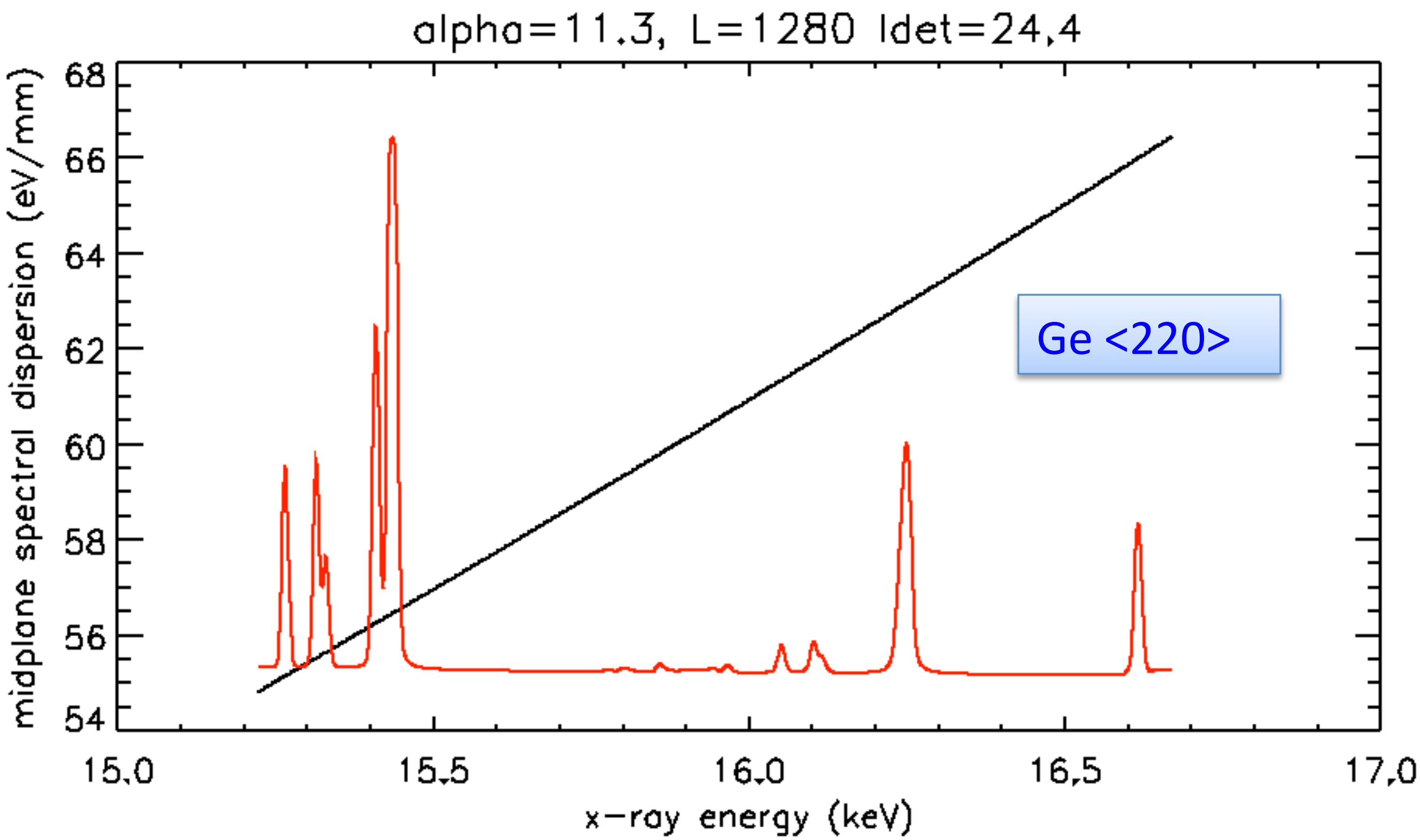
500-μm slit

conical



versus 5.5 eV for a flat or cylindrical crystal

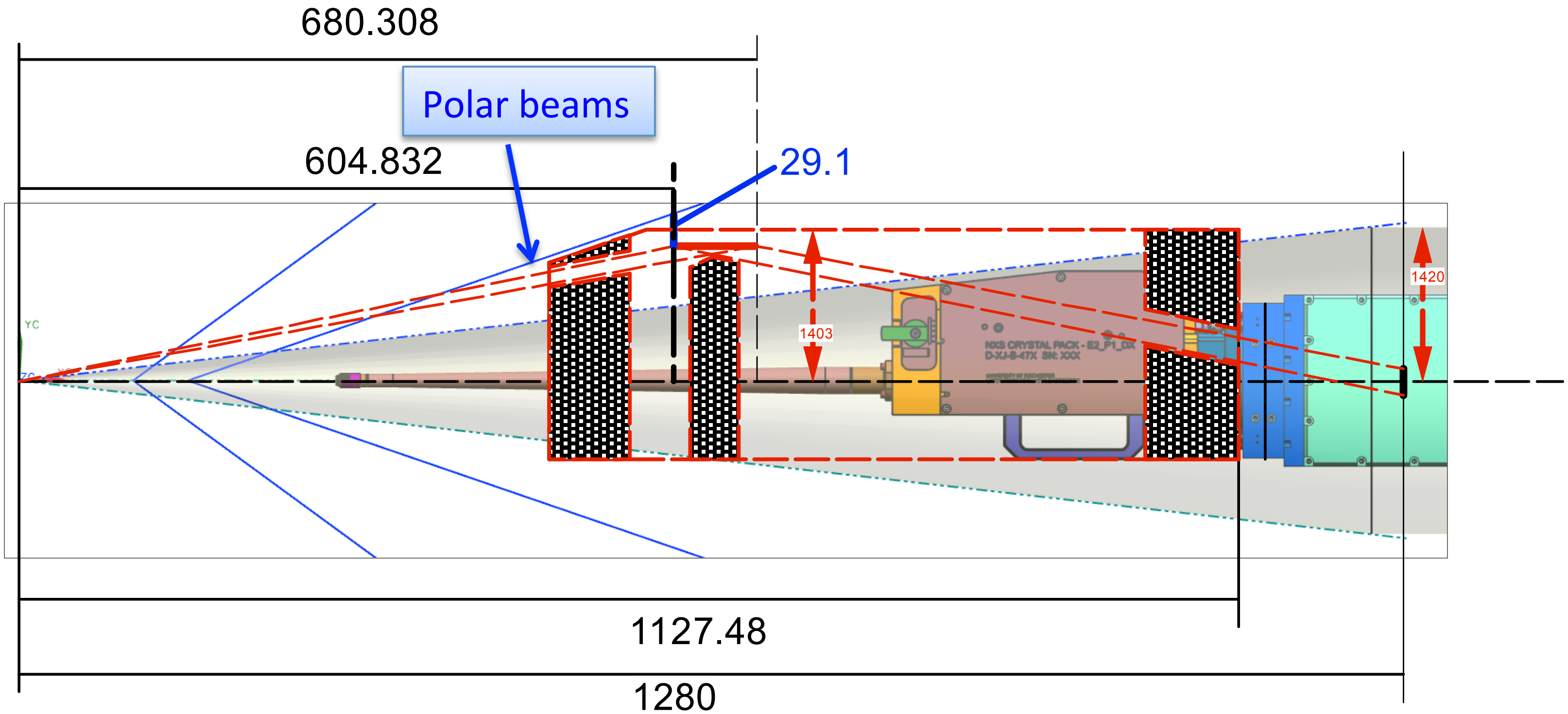
For L=1280 mm a 25-mm photocathode just barely includes the Kr He-δ line



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

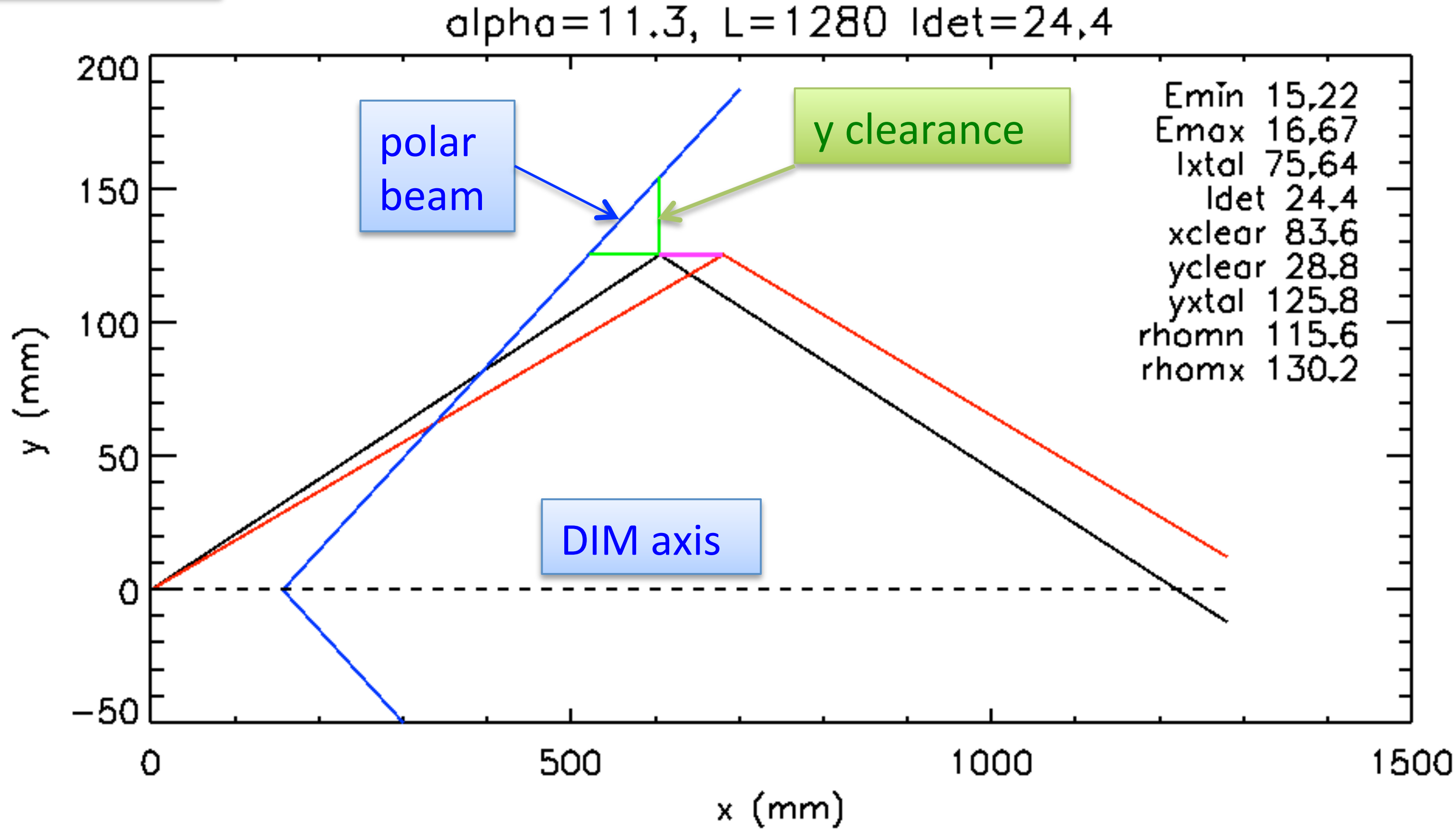


- For L=1280 mm from TCC to DISC photocathode, the front end of the crystal clears the polar beam by 29 mm
- More accurate CAD layouts are being done

Graphing the x-ray paths in our IDL program allows study of the crystal clearance for different values of L

Ge <220>

Note: Drawing is not isotropic!



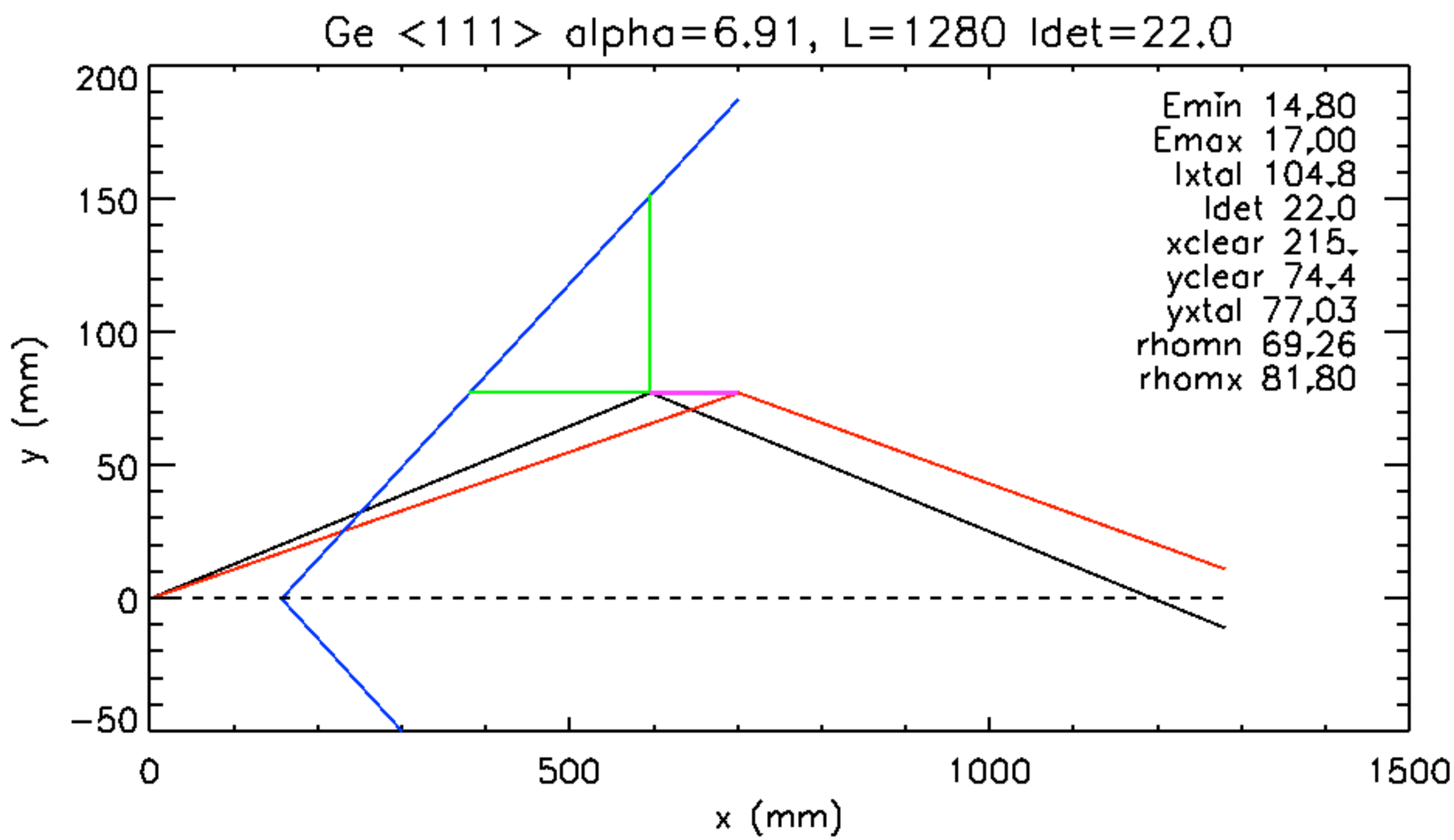
Larger L (TCC-to-detector) clears polar beams better but may violate TIM stay-in radius requirement

All distances in mm (Ge <220>)

L	x clearance	y clearance	detector length	y-crystal
1000	31.1	10.7	19.1	108.1
1100	49.8	17.2	21.0	117.9
1280	83.6	28.8	24.4	125.8
1350	96.7	33.3	25.8	132.7

- 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

A Ge <111> crystal fits inside a smaller cassette, but the spectral resolution is poorer



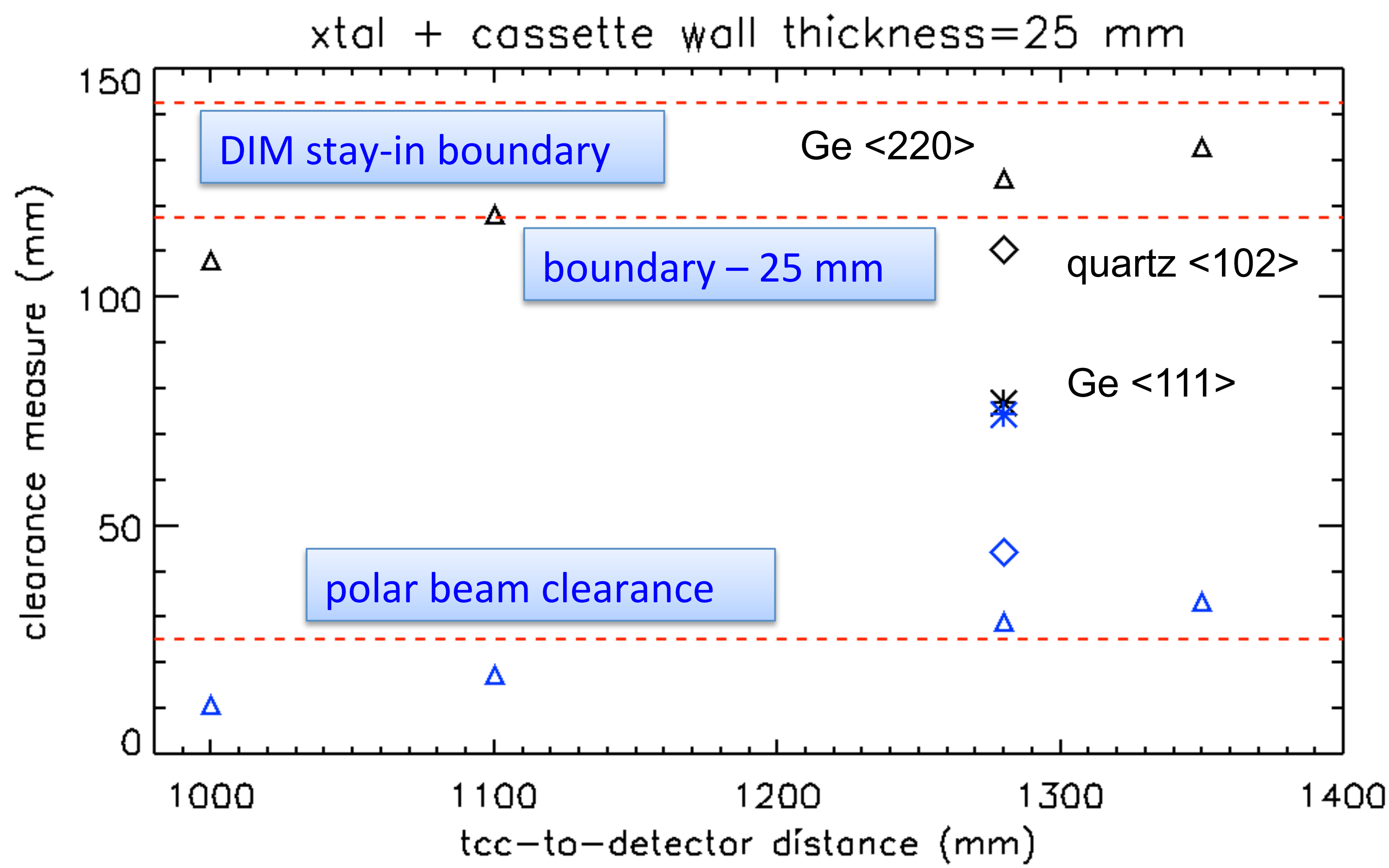
The quartz <102> and Ge <111> crystals allow better clearance

All distances in mm

L	x clearance	y clearance	detector length	y-crystal	Crystal	Bragg angle
1280	83.6	28.8	24.4	125.8	Ge <220>	11.59°
1280	128	44.2	22.6	110.4	quartz <102>	10.16°
1280	215	74.4	22.0	77.0	Ge <111>	7.06°

- 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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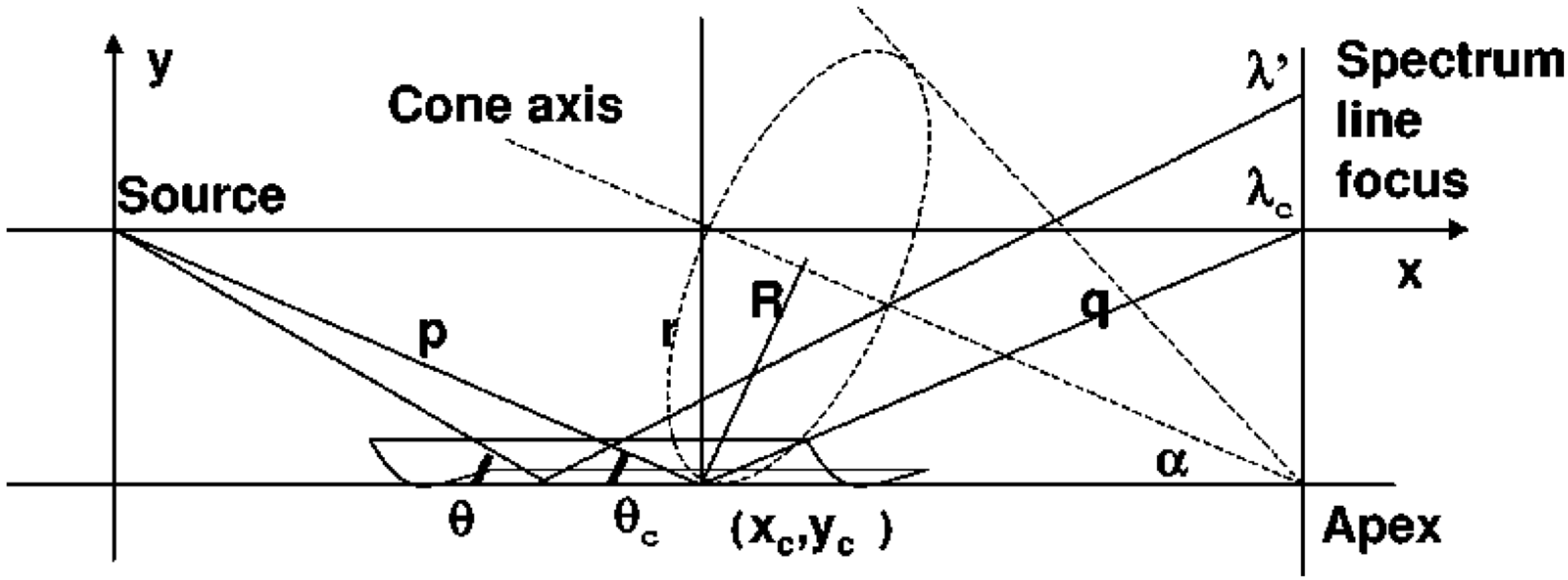
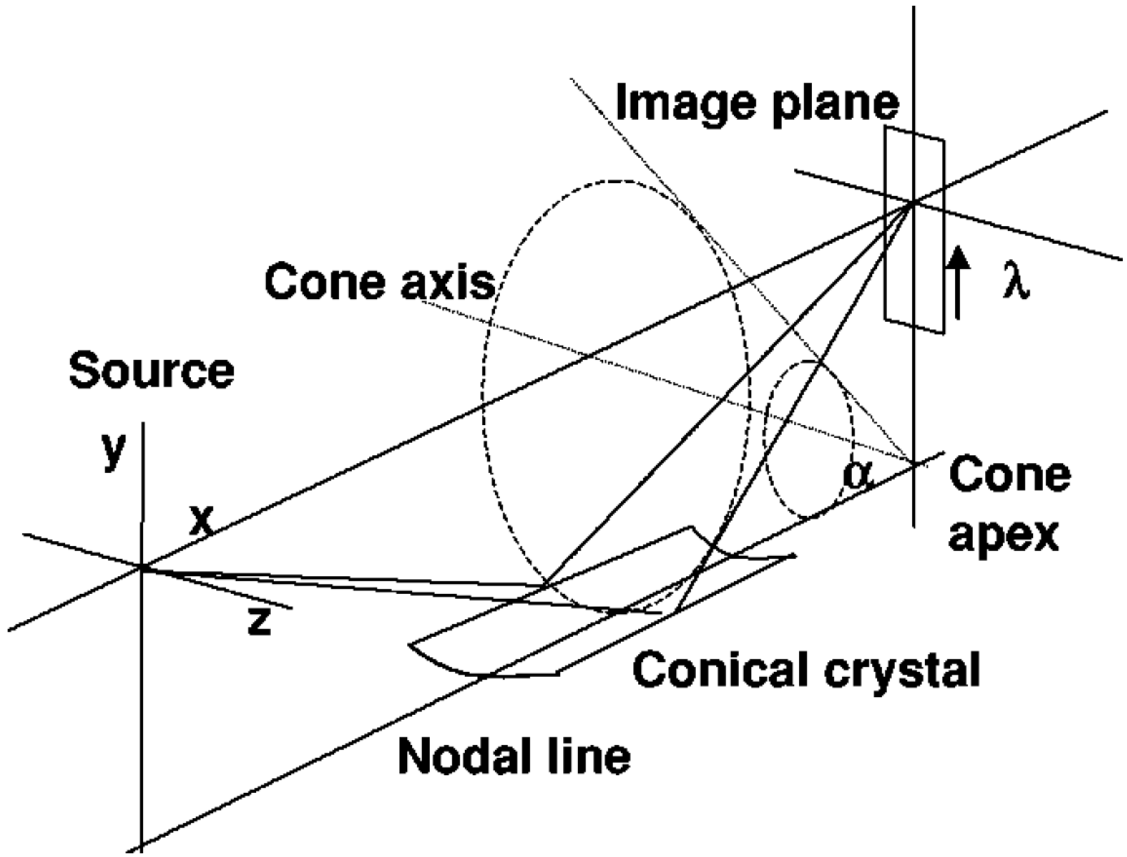
EXTRAS

Energy increases with x position on crystal and y position on detector



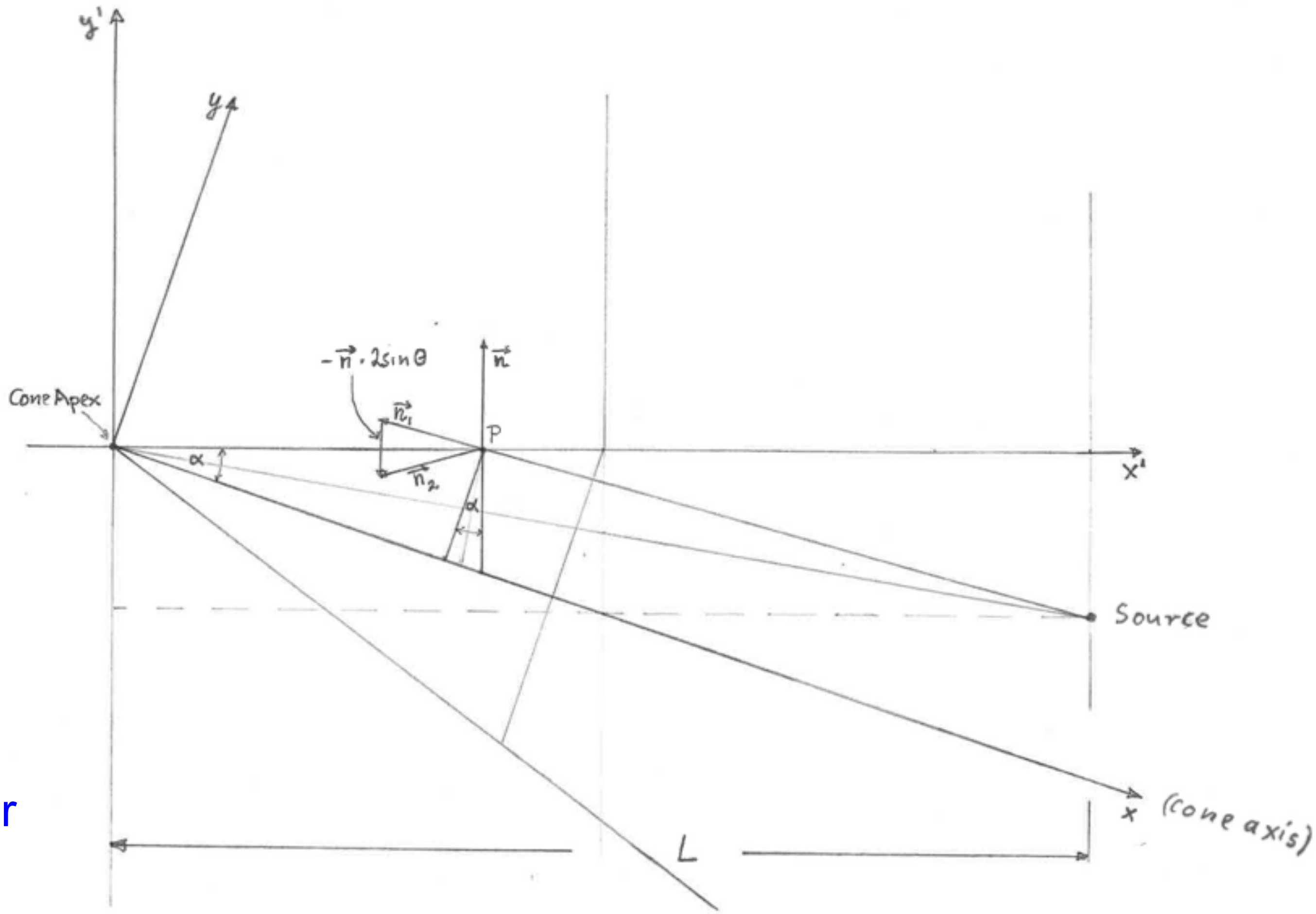
Martinolli, RSI (2004)

Z is the spatial coordinate in the image plane (detector)



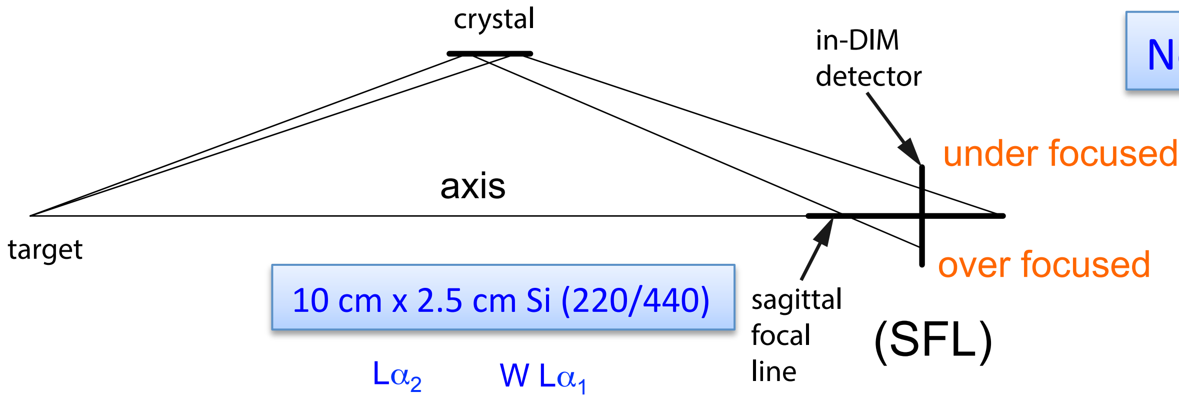
Martinolli, RSI (2004)

Geometry used for the PPPL conical von Hamos calculations

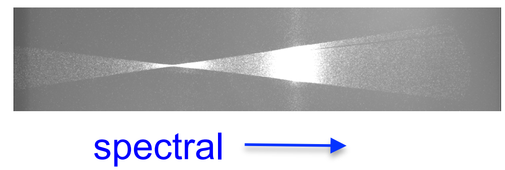


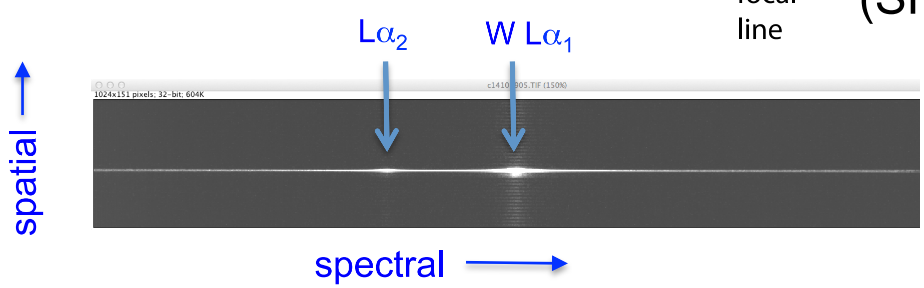
M. Bitter

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

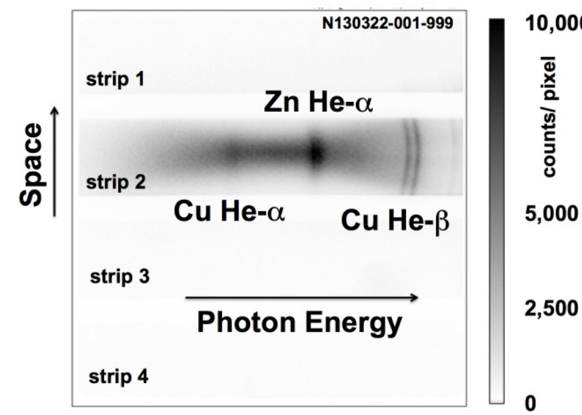


Not on SFL => “bowtie” effect





Det. on sagittal focal line (SFL) – 10 μm width



Doeppner et al. RSI 2014

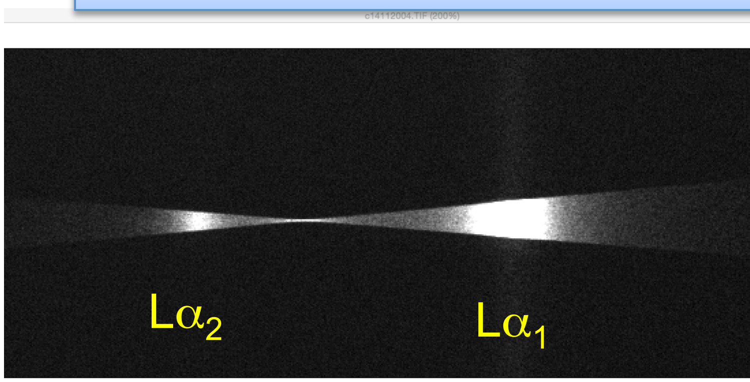
- Sagittal focusing greatly improves S/N ; may saturate detector
- Image plate for EXAFS can be on SFL
- “Bowtie” effect can affect performance for streak camera
- Consider putting GXD electronics to side of MCP, instead of behind

We have been focusing on cylindrical and conical von Hamos configurations

- Kr Heβ, 15.43 keV, Ge (220), 11.6° Bragg angle, $\Delta\theta$ ~ 41 μrad
- Solid angle **Ω ~ 2 x 10^{-6} sr** for crystal height h_c=3 cm and source-to-detector distance L=128 cm
- Dispersion along slit ~ 55 eV/mm and on axis ~ 11 eV/mm
- For comparison, NXS with a flat Ge (220) crystal and 500 μm slit has **Ω ~ 1.7 x 10^{-8} sr** (ϕ=0.04/97 ~ 4.2 x 10^{-4})

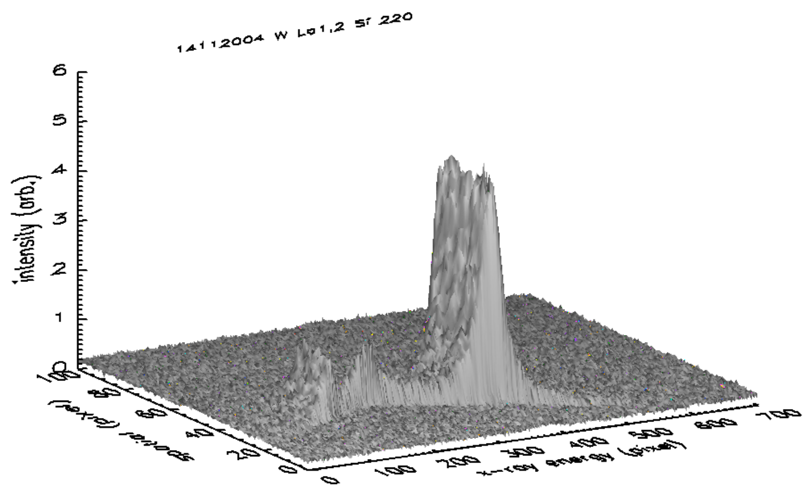
The bowtie is 370 μm high at the tungsten $L\alpha_1$ line

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



spectral →

- Line separation is ~ 62 eV and 2.98 mm on CCD
- Si 220, θ=23°, R=35 cm, 8 cm x 2.5 cm, crystal-detector distance=20 cm



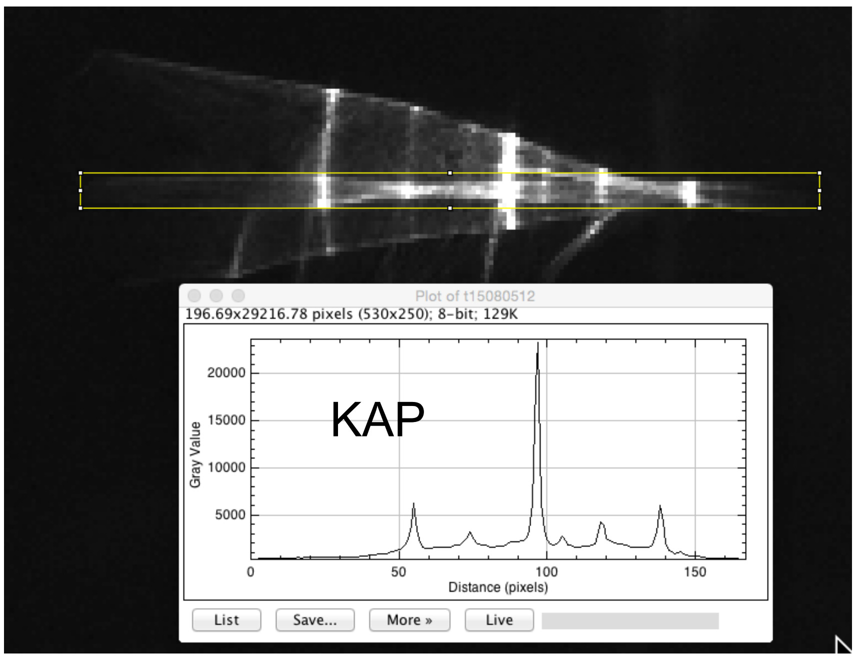
spectral →

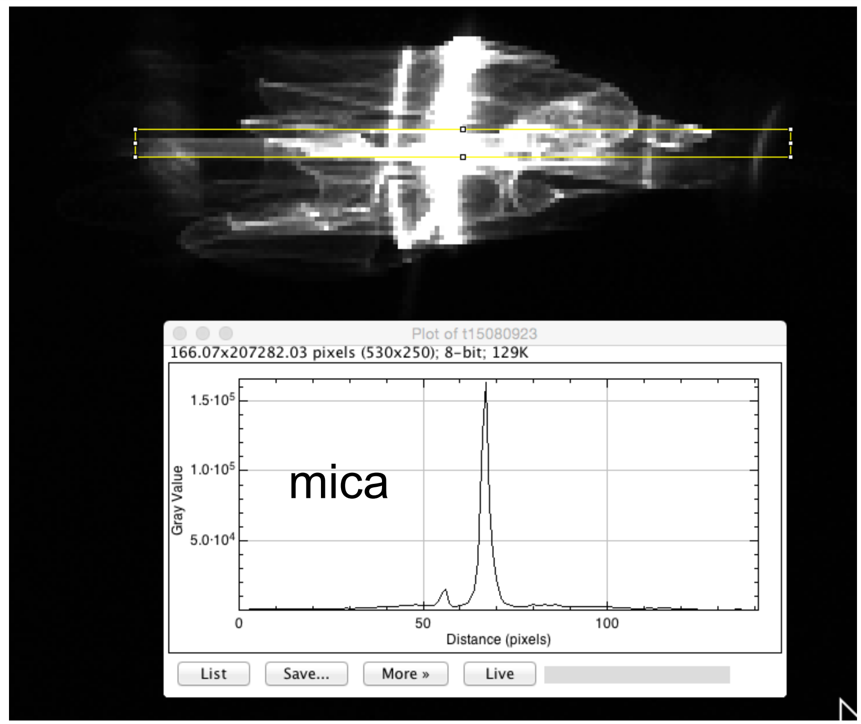
Photonics were estimated for two experiments

- Time integrated XAFS of Cu K or Ta L_3 edge
  - Backlighter: 4 x 10^{18} eV/eV at 10 keV
  - Spectrometer solid angle 10^{-6} sr
  - 10% detector efficiency
  - 30% transmission through target
  - -> 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

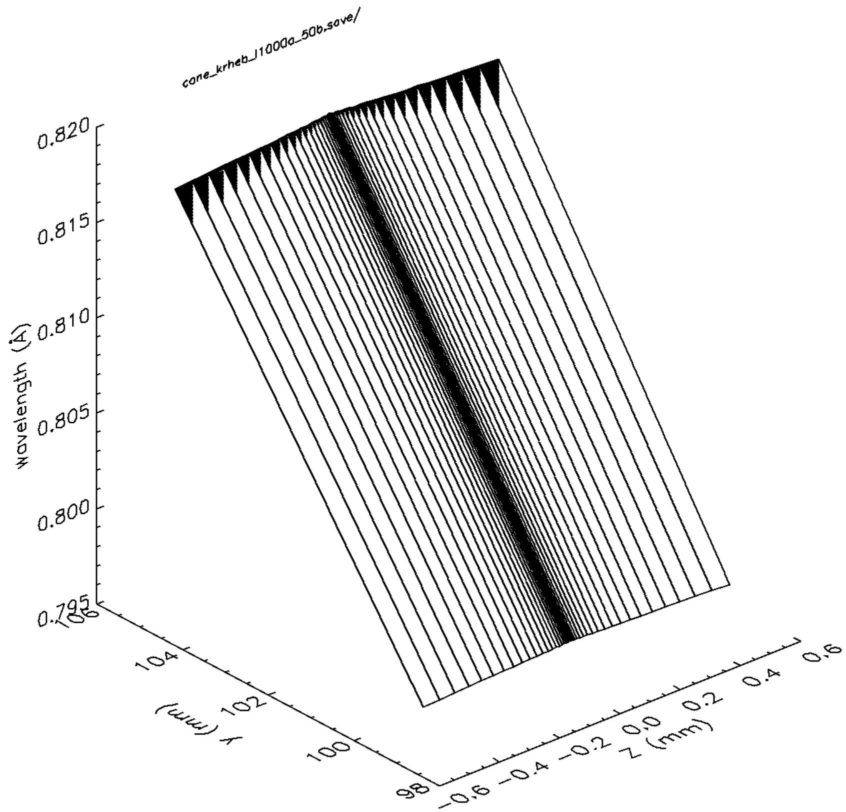
Jim Emig provided us with KAP and mica crystals, but the spatial-spectral images are poor, and it is hard to find a single sagittal focus. We work in 4th and 3rd orders with these crystals, whereas we would have first order reflection with Si or Ge (111), and probably much better quality images.



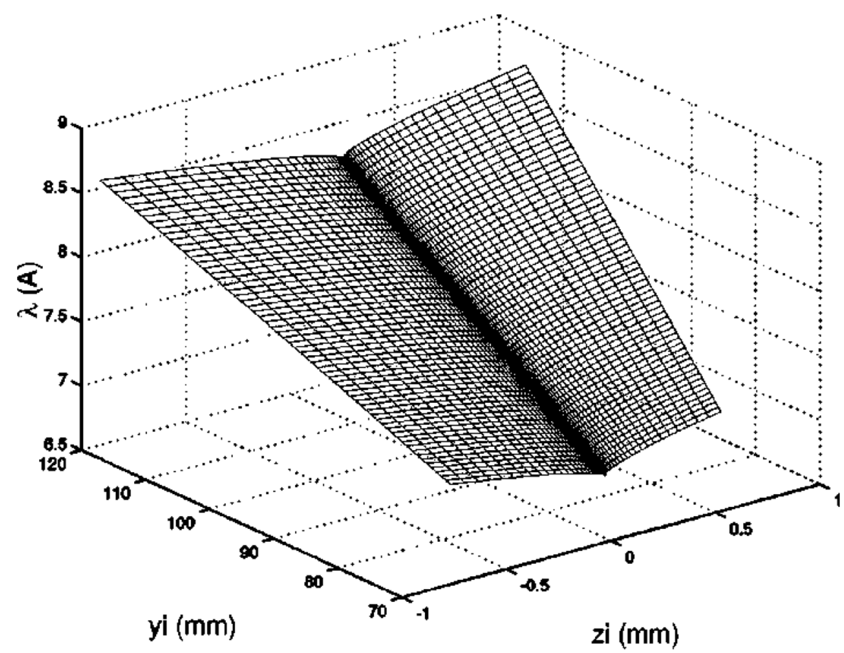


Our conical crystal analysis code predictions are similar to those of Martinolli et al. RSI (2004)

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