Modeling of the LCLS X-ray Beamline

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DESY Hamburg - 10/27/04

Spontaneous Radiation - General Properties

General Properties

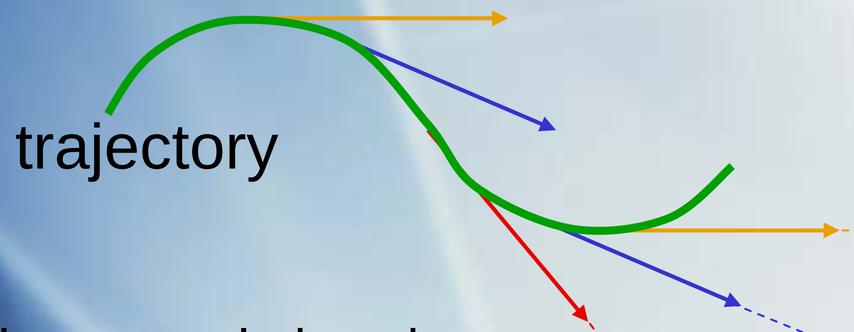
- Resonant wavelength:

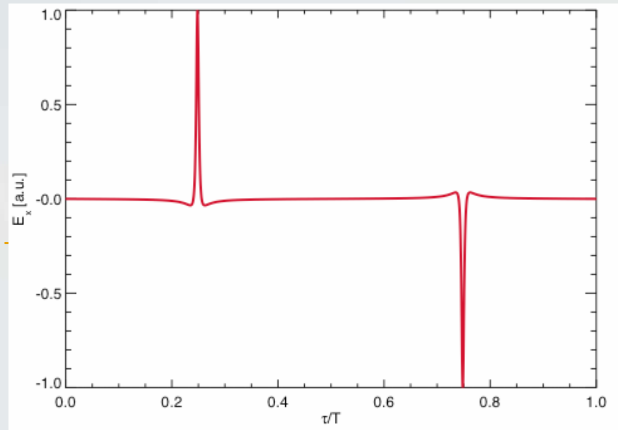
$$\lambda = \frac{\lambda_u}{\beta_0}(1 - \beta_0 \cos(\theta))$$

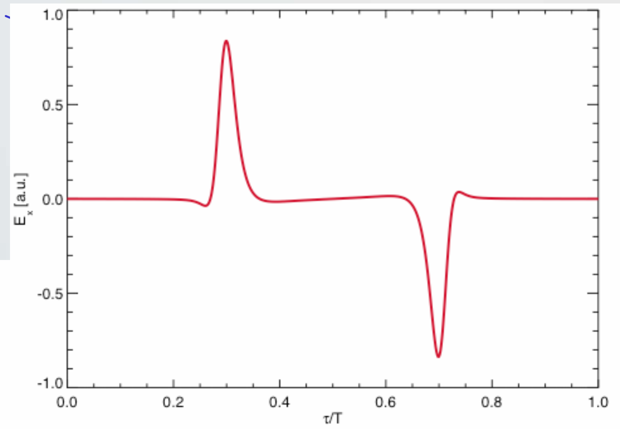
$$\approx \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

- Maximum signal when directions of observation and trajectory are parallel□□□□ a characteristic opening angle of $\Delta\theta = 1/\gamma$
- Maximum angle in electron trajectory is K/γ
- □□□□□□□□□solid angle of radiation is $\Omega = 1/\gamma \times K/\gamma$

The Signal in Time Domain

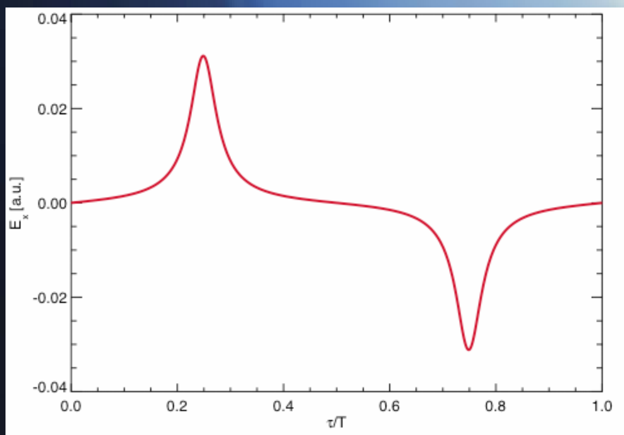


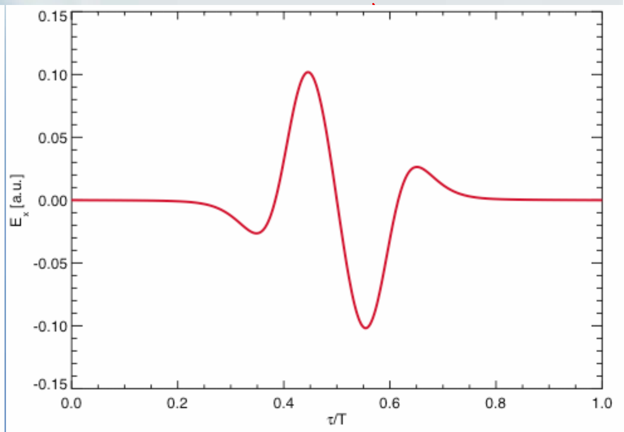




For larger angle in x the uni-polar signals move closer together, merging into a bi-polar signal for $\theta > K/\gamma$

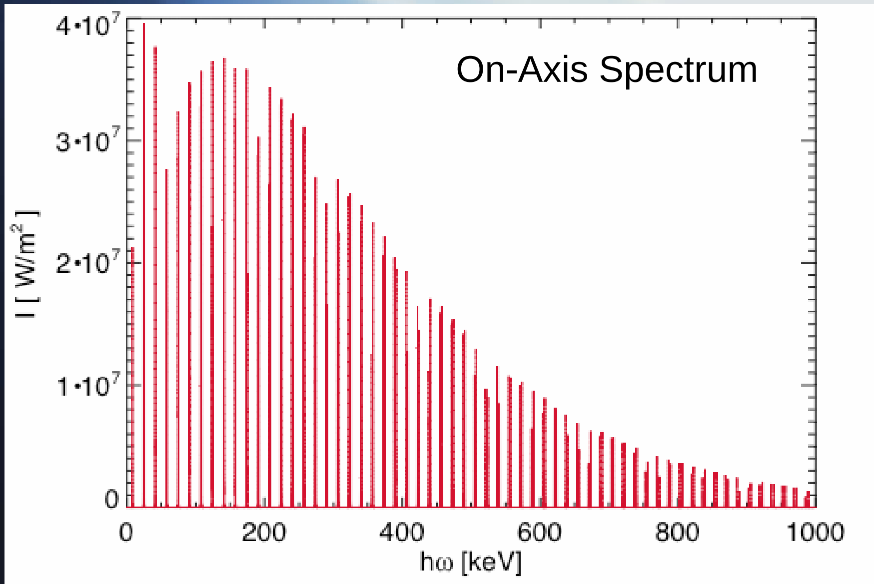
Above plane of oscillation

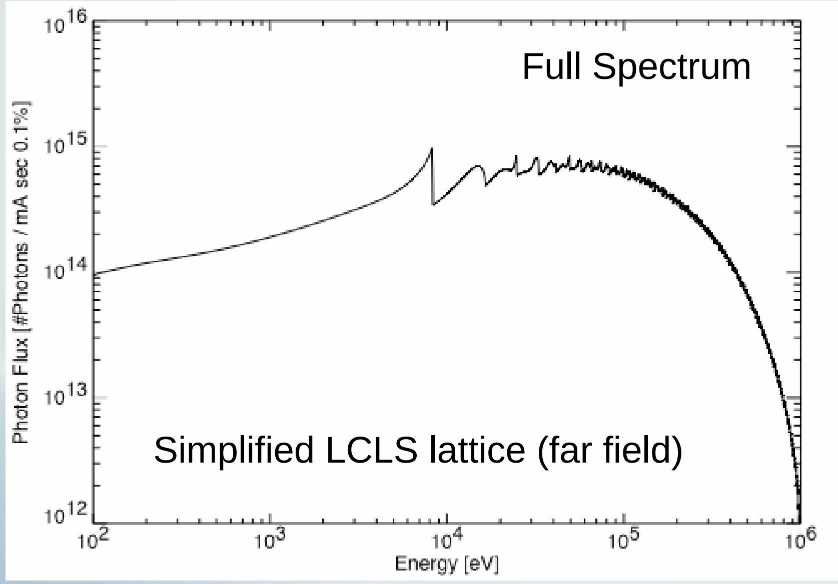




Spectrum

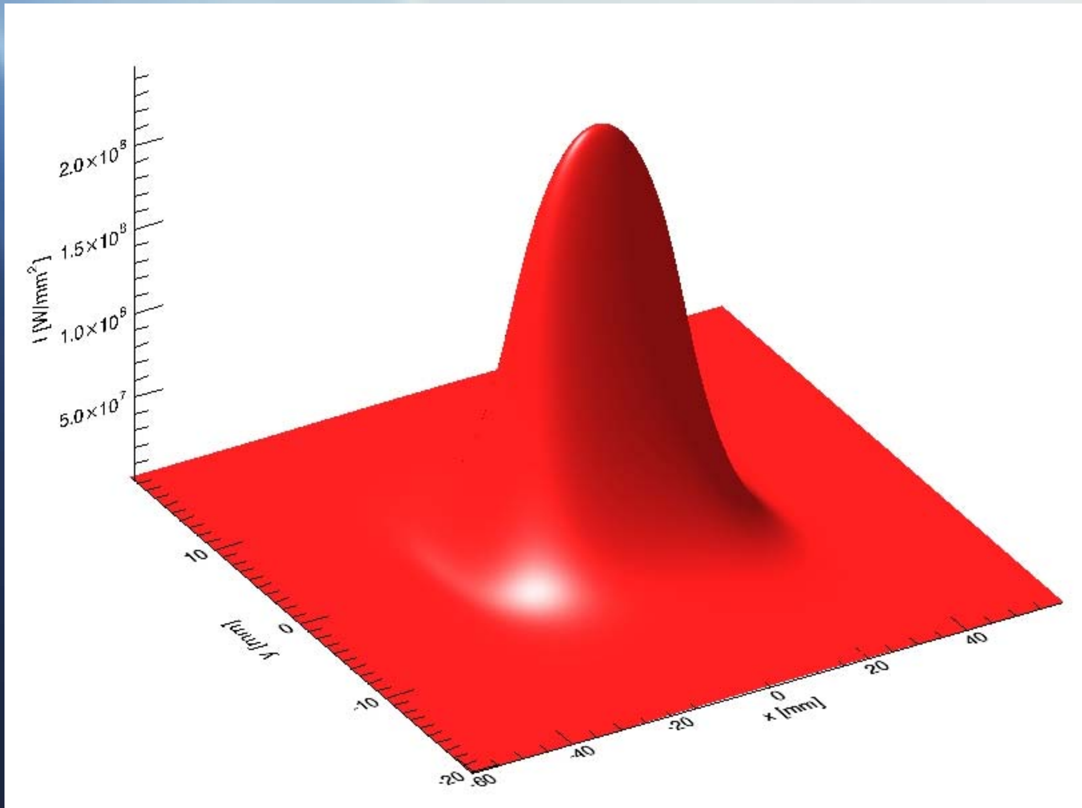
- LCLS-lattice with super period. Detector 113 behind exit of undulator.
- Rich harmonic content on-axis.
- Wider spikes for off-axis radiation due to red shift
- Reduced harmonic content for off-axis emission.





Intensity Distribution

- Angular distribution, 113 m behind undulator exit, using real LCLS lattice:



The peak intensity is 73 kW/mm^2

The distribution is almost like in the far field zone.

Total energy 75 GW

The intensity ratio to the FEL signal is 100:1

Spectral Power Cut

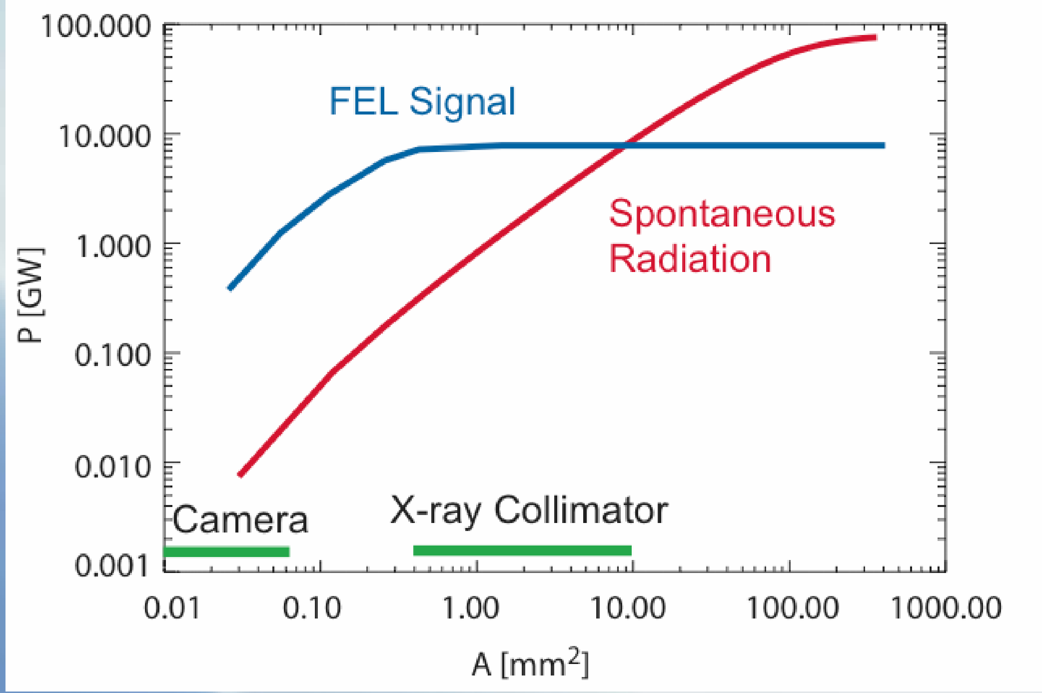
- The opening angle for a single frequency is:

$$\Delta\theta \approx \frac{K}{2\gamma}\sqrt{\frac{1}{N_u}}$$

- For LCLS the angle is $\Delta\theta = 1.5\ \mu$rad.
- The emitted power at the fundamental is about 1 MW per 0.1% bandwidth (the full FEL signal of about 10 GW falls within this bandwidth).
- Higher harmonics contribute less than 5% to the total background signal and are most likely filtered out by spatial apertures.

Spatial Power Cut

- Array detectors (e.g. X-ray CCD cameras) or spatial collimator improve the signal to noise ratio.
- For LCLS, any cut below 1 mm^2 at the first detector position (113 m behind undulator) would reduce also the FEL signal.

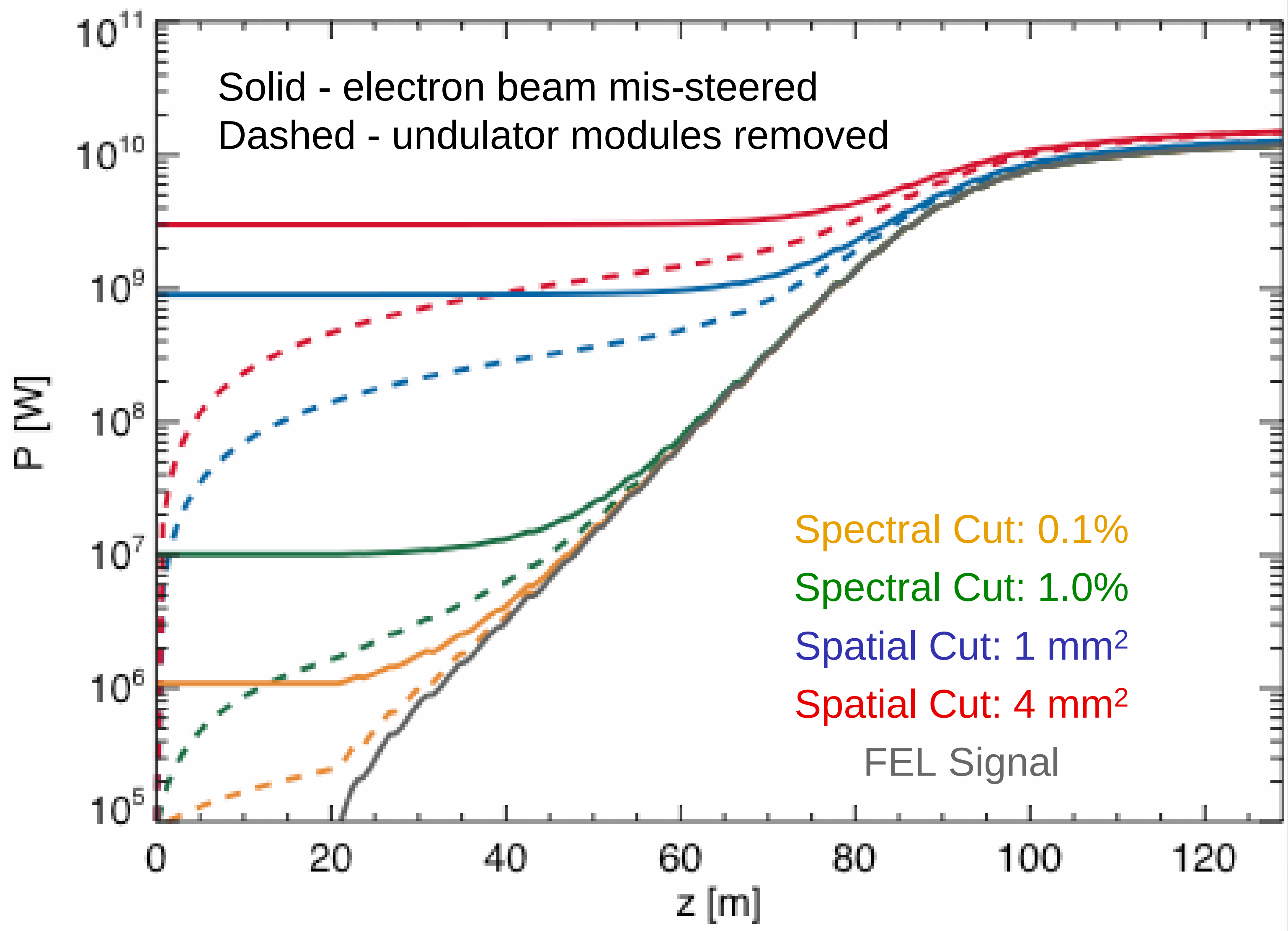


Signal-Noise (Full Undulator)

Case	1.5 Å	1.5 nm
FEL power	8 GW	4 GW
Spontaneous Radiation	75 GW	7.5 GW
Spectral Cut: 0.1%	1 MW	100 kW
Spectral Cut: 1.0%	10 MW	1 MW
Spatial Cut: 1 mm^2	0.9 GW	9 MW
Spatial Cut: 4 mm^2	3 GW	30 MW

The noise signal for spatial cuts can be lower, depending on the spectral response of the detector.

Detecting the FEL Signal

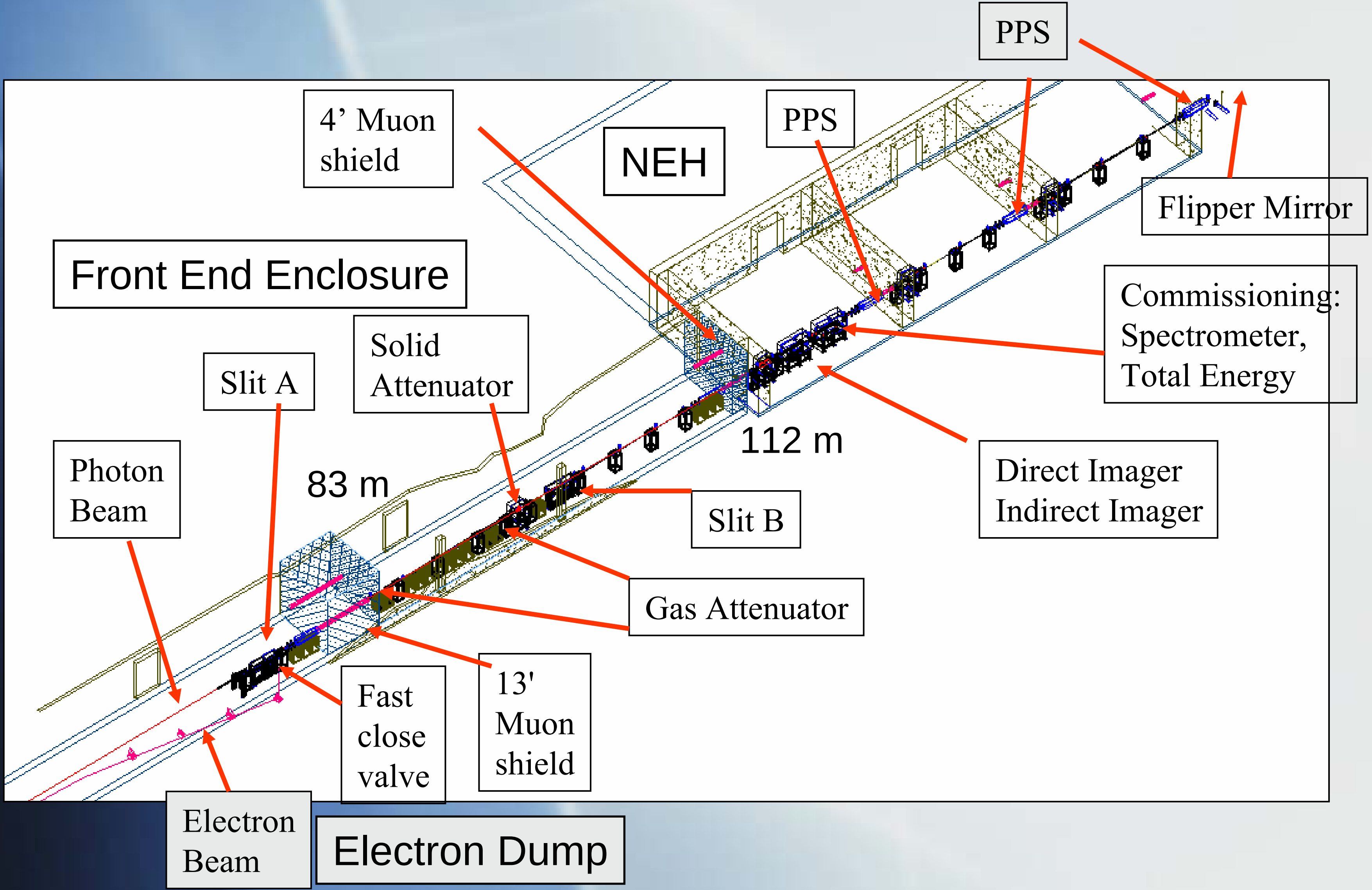


Detecting the FEL Signal

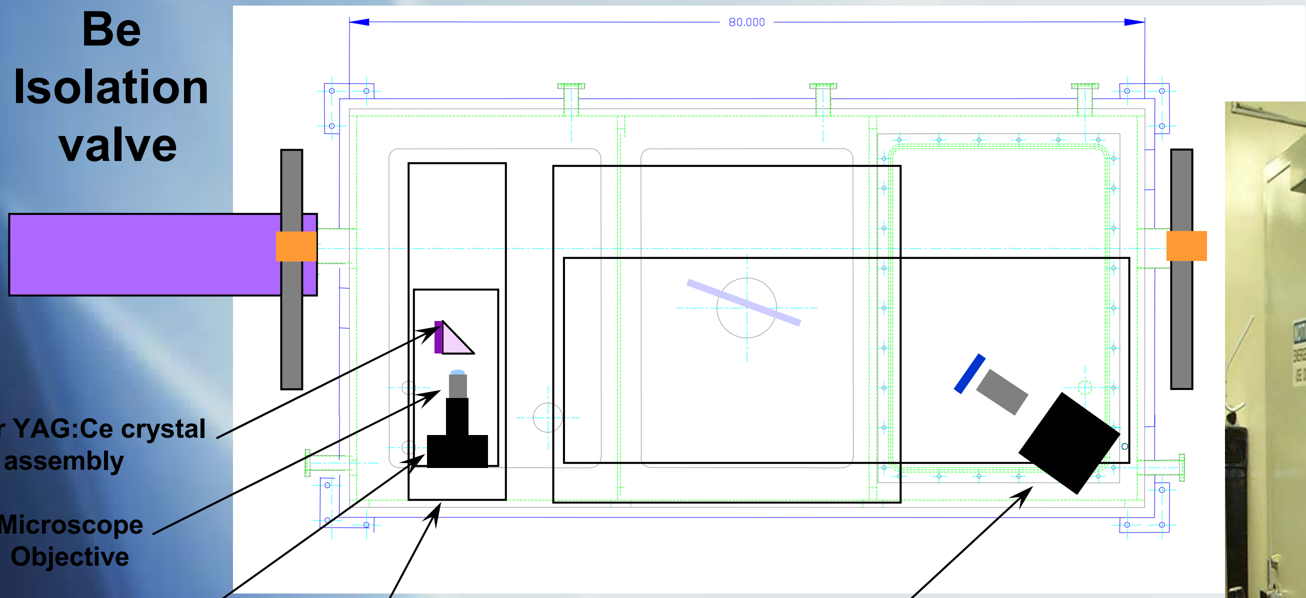
- For LCLS no information can be obtained from the FEL signal for the first 20 m with respect to undulator alignment and field quality.
- Operating at longer wavelength reduces the distance but makes the FEL signal less sensitive to the field quality.
- Short pulse operation of the FEL (e.g. two-stage pulse slicing or slit in dispersive section) reduces the signal-noise ration by 1-2 orders of magnitude.
- Information on undulator modules can be obtained by the spectrum of the spontaneous radiation.

Spontaneous Radiation at the LCLS Near Experimental Hall (NEH)

Near Experimental Hall



Imaging Detector Tank



Courtesy of R. Bionta

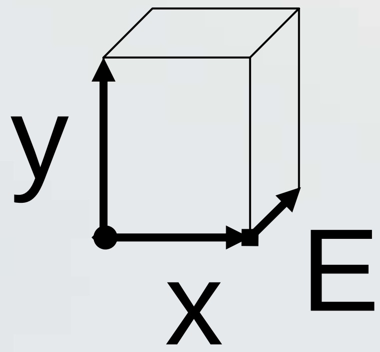
Spontaneous Data Chain

- UCLA Near-Field Calculator for Spontaneous Radiaiton
  - ~2 Gbyte HDF5
- Genesis 1.3 Postprocessor for FEL signal
  - ~1 Gbyte HDF5 (fine spectral resolution)

UCLA

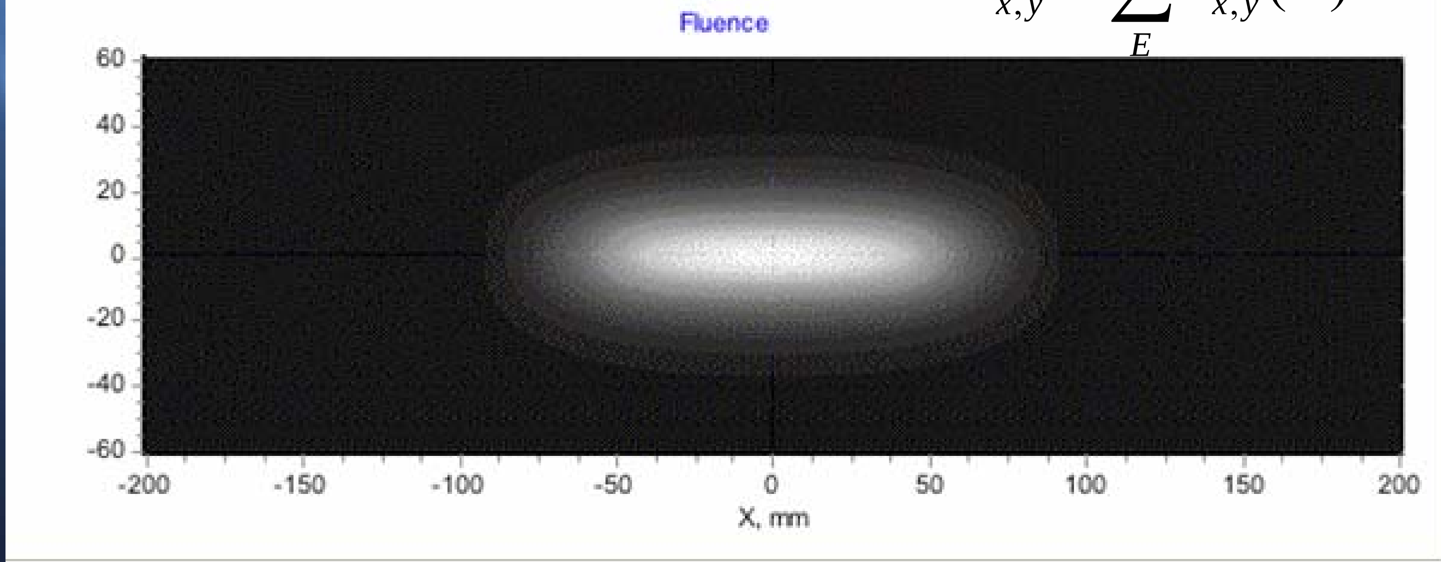
- HDF5 to Paradox Converter
  - (x,y,E,P) Paradox format, 4 X 1 GByte
- ReBinner – Coarser Energy Bins (159)
  - (x,y,E,P) Paradox format, 350 MByte
- Blob DB Converter – faster to read
  - (E,P[x,y]) Paradox, 50 MBytes
- Viewer

LLNL - R. Bionta

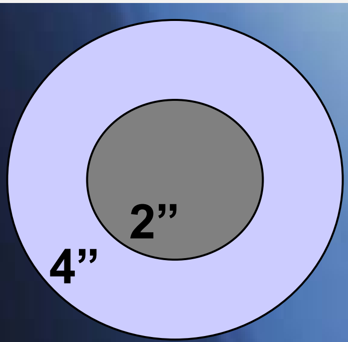


Spontaneous Fluence at NEH

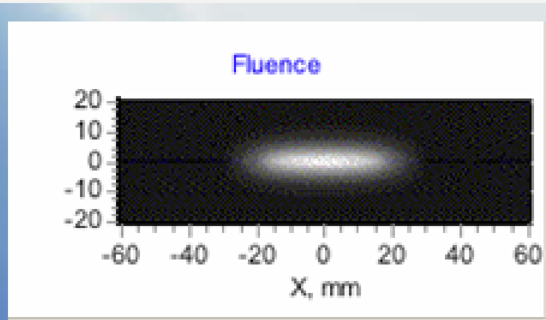
$$F_{x,y} = \sum_E P_{x,y}(E) \cdot E$$



Te = 4.5 GeV
Z = 243 m
Δ x = 1.0 mm
Δ y = 0.3 mm
1.85 mJ



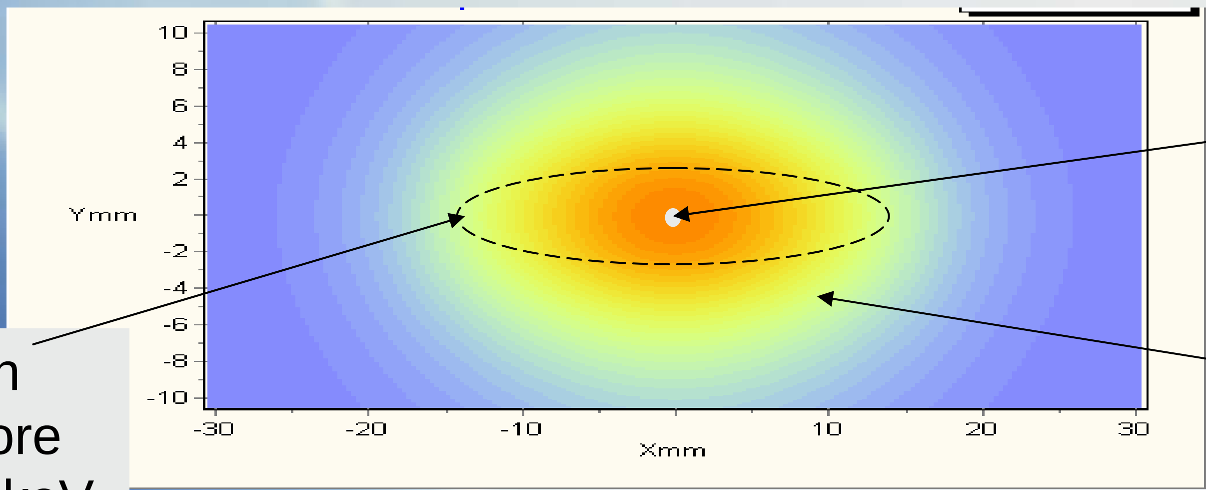
Beam Pipes



Te = 14.5 GeV
Z = 243 m
Δ x = 0.3 mm
Δ y = 0.1 mm
18.2 mJ

LCLS beam footprint

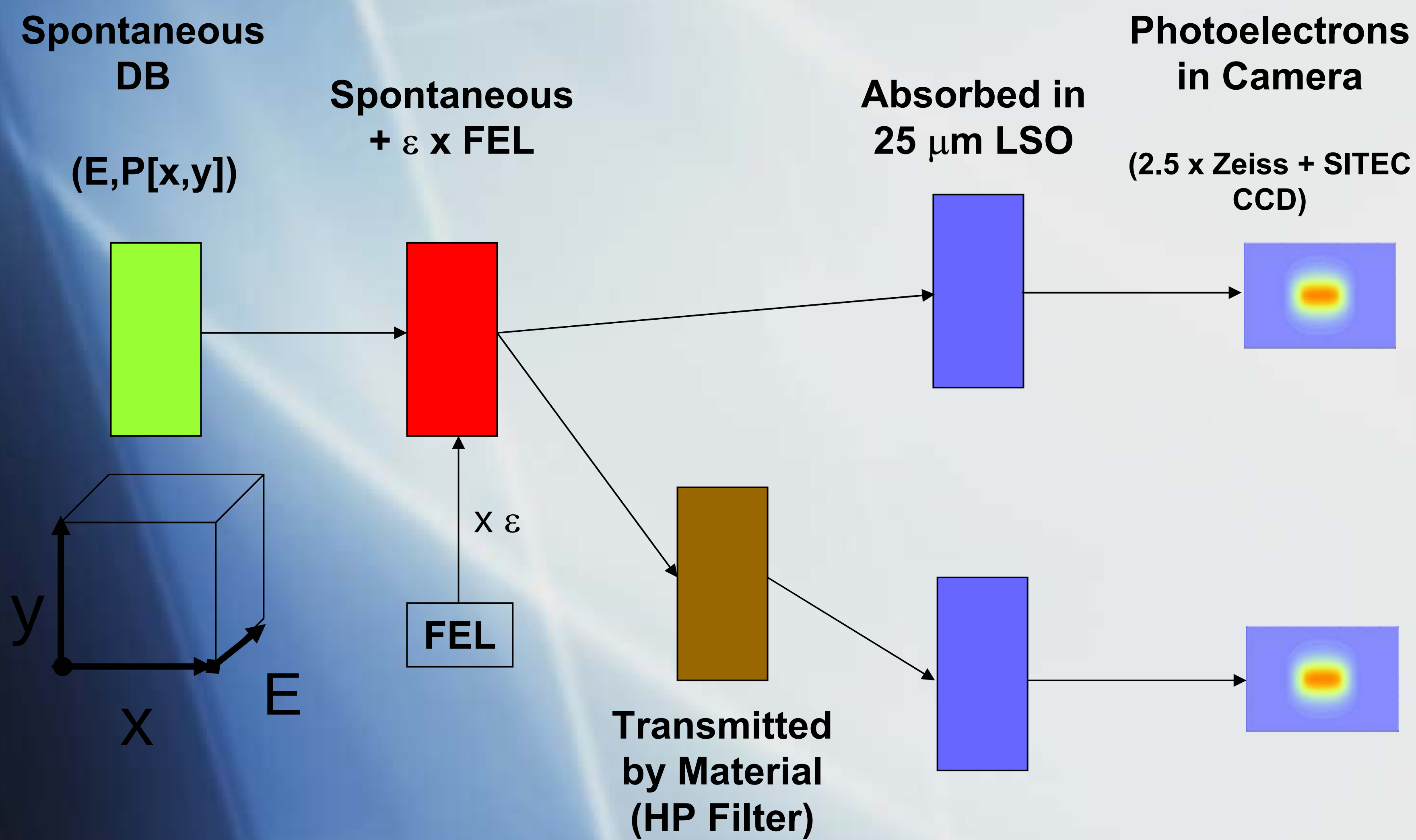
Expected LCLS beam profile contains FEL and Spontaneous halo



At entrance to NEH, FEL tuned to 8261 eV Fundamental

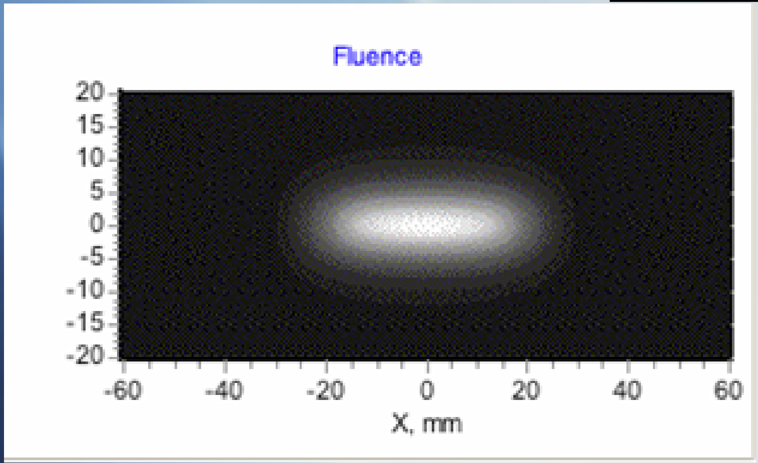
Spontaneous and FEL Signals in the Direct Imager Diagnostic

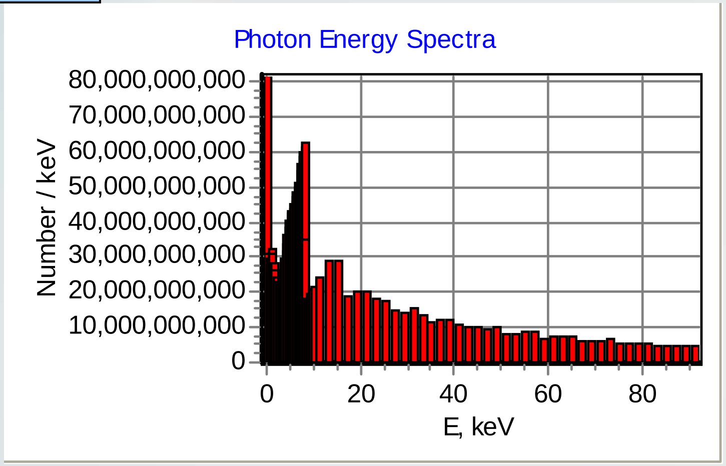
Camera Image Calculator Chain



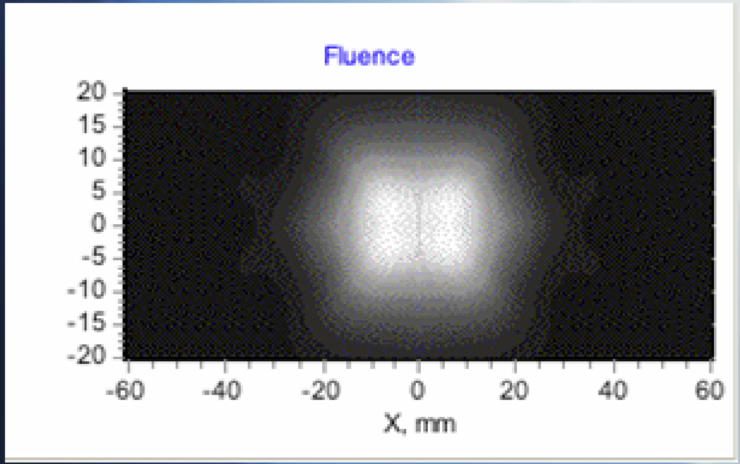
14.5 GeV Spontaneous, NEH H1

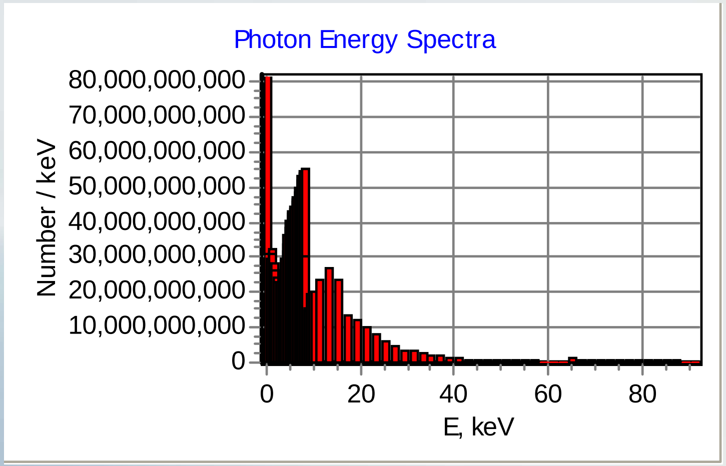
All photons





Stops in 25 μm LSO





14.5 GeV Spontaneous Direct Imager Signal

All photons

	Photons		Energy	
Total	1.661E+12		18.178	mJ
Peak	7.765E+07		0.002	mJ
Peak Density	2.588E+11	/cm2	5.728E-03	J/cm2

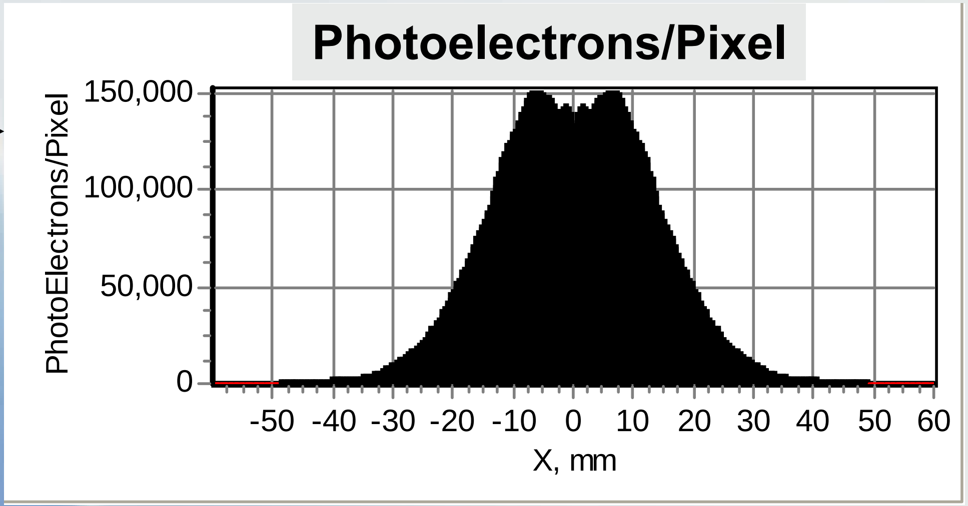
Stops in 25 μm LSO

	Photons		Energy	
Total	6.746E+11		1.576	mJ
Peak	1.688E+07		0.000	mJ
Peak Density	5.626E+10	/cm2	1.827E-04	J/cm2

CCD photoelectron levels < 150K e-

Full well (16 bit) 327K e- so this is ½ scale on CCD readout

(X-Ray resolution 300 x 100 μm)



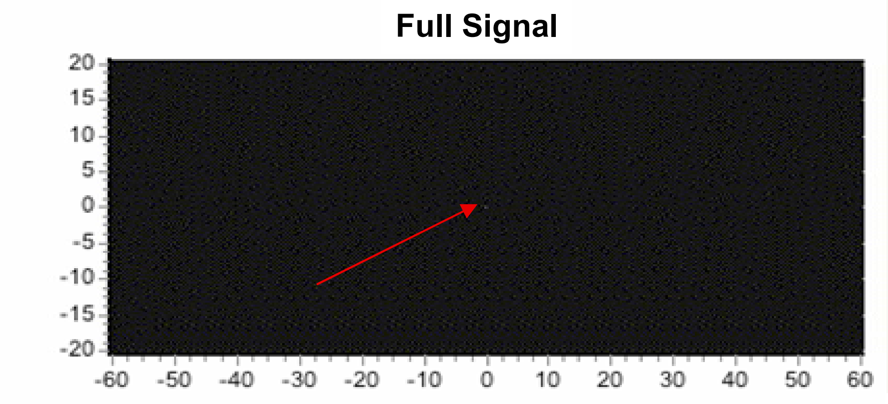
14.5 GeV Spontaneous + FEL

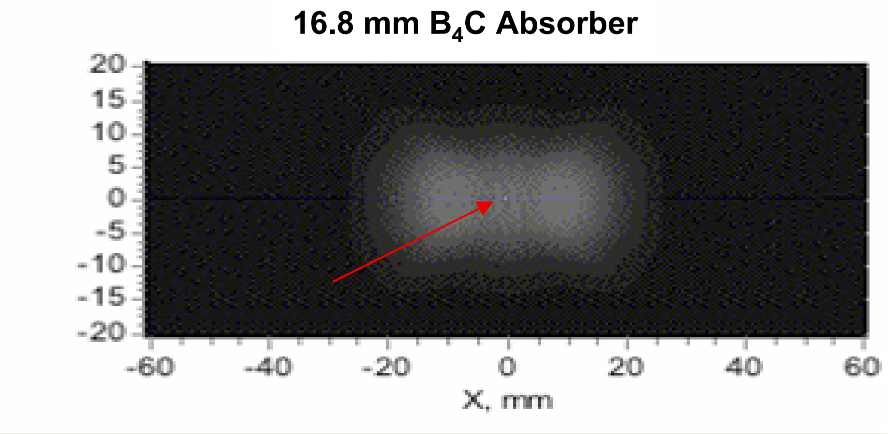
	Photons		Energy	
Total	2.133E+12		3.515	mJ
Peak	9.397E+11		1.249	mJ
Peak Density	3.132E+15	/cm2	4.165E+00	J/cm2

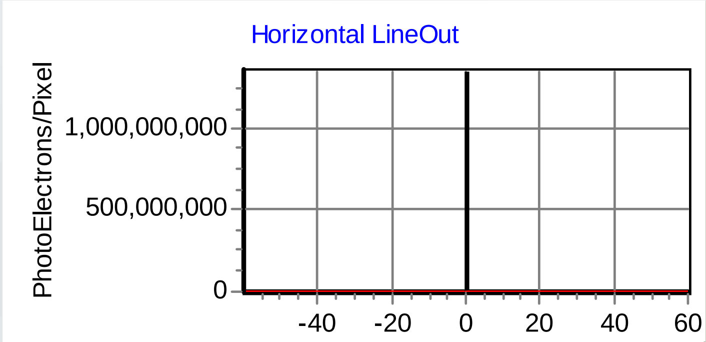
Stops in 25 μm LSO

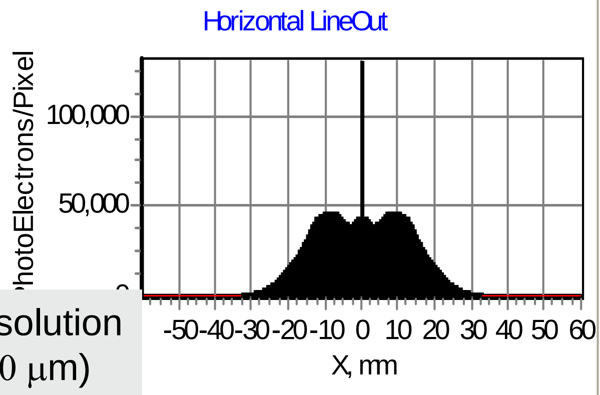
Need attenuation of 2.4 x 10^{-4} for CCD full well

Photoelectrons/Pixel







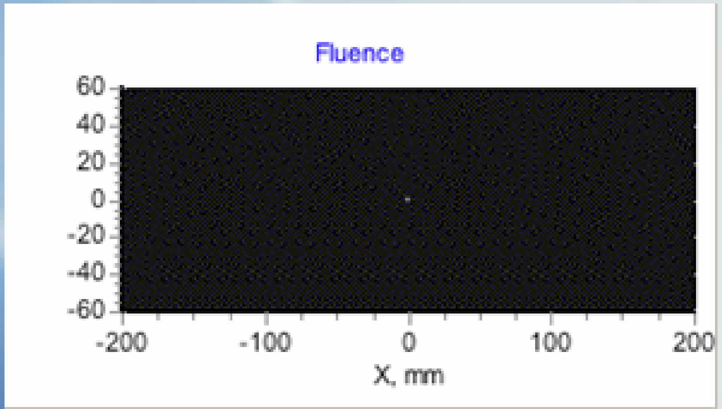


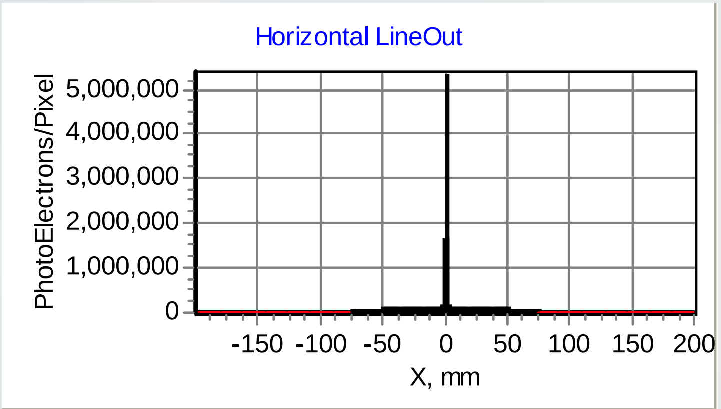
(X-Ray resolution 300 x 100 μm)

4.5 GeV Spontaneous + ε x FEL

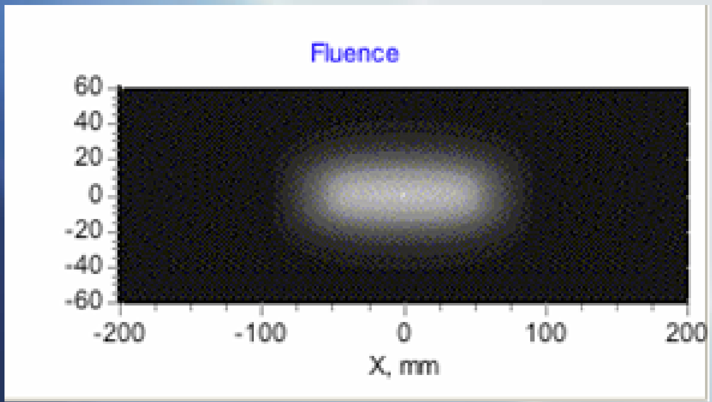
Direct Imager Image | **Direct Imager Photoelectrons**

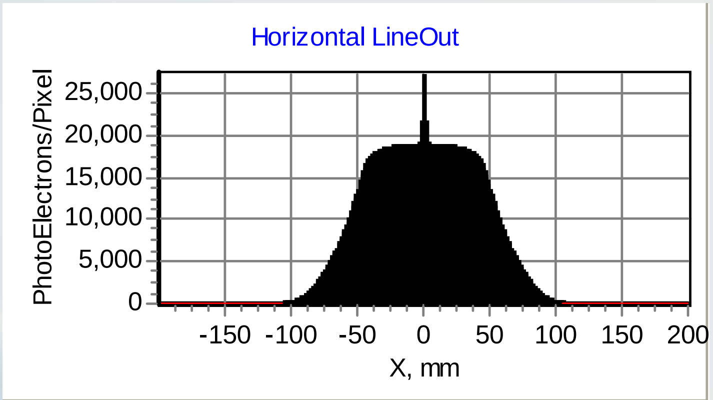
1 % FEL





0.01 % FEL



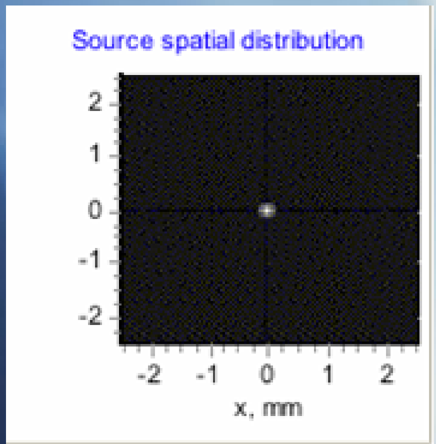


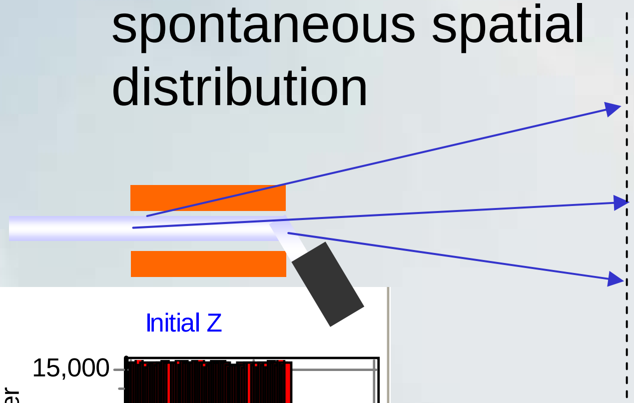
(X-Ray resolution
1000 x 300 μm)

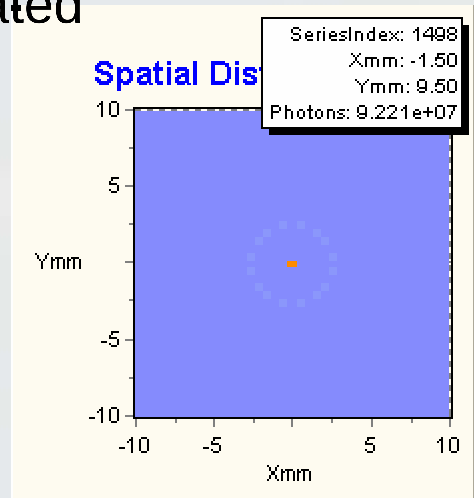
Impact of Aperture Limitation by Beam Pipe

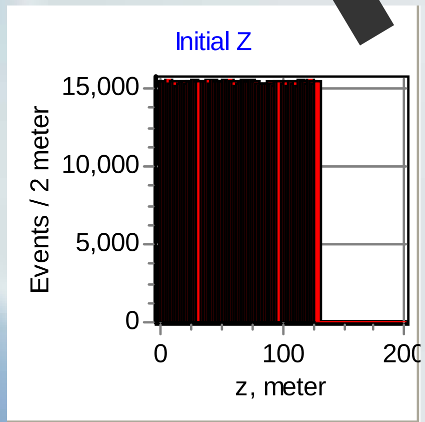
Spontaneous Monte Carlo Simulation

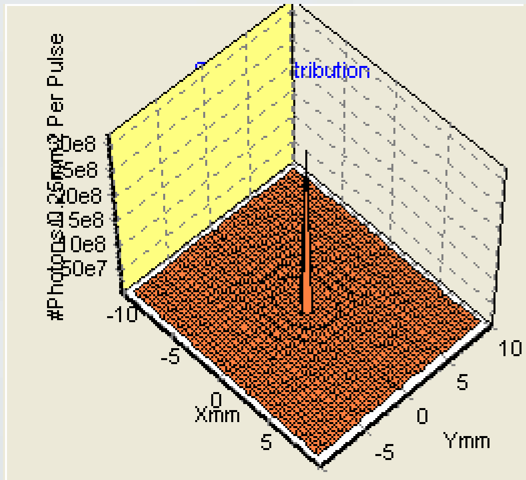
Photon starting angles generated to give calculated spontaneous spatial distribution







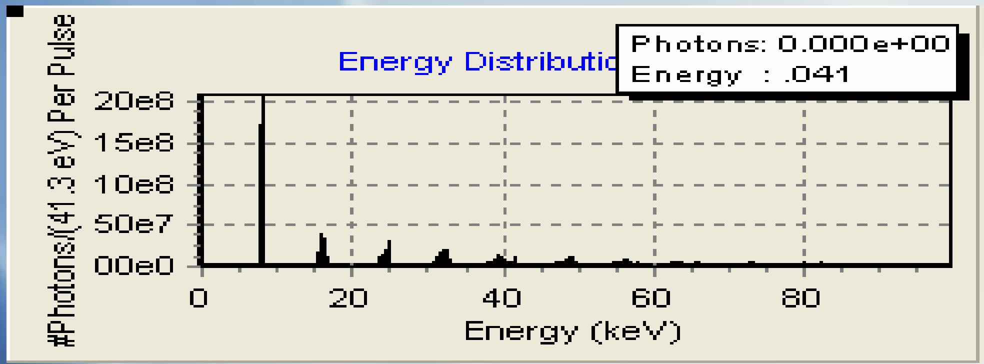




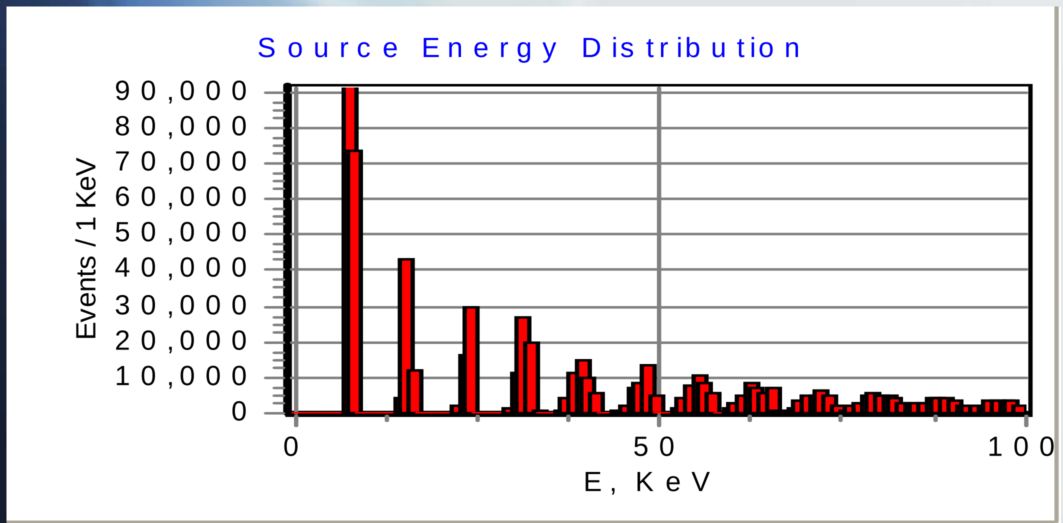
Photon starting x, y matches electron distribution, a Gaussian with $\sigma = 30\ \mu m$

Photon starting z is uniform along undulator (from $0 < z < 130$ m)

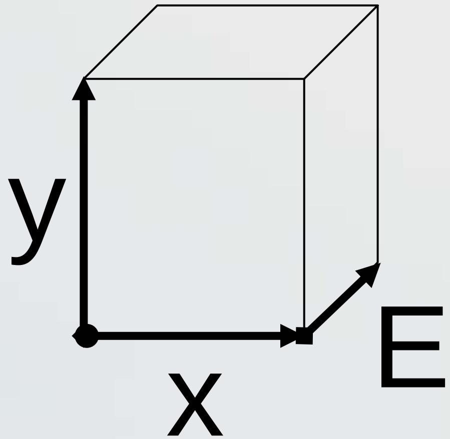
Each photon final x, y has its own cumulative energy distribution



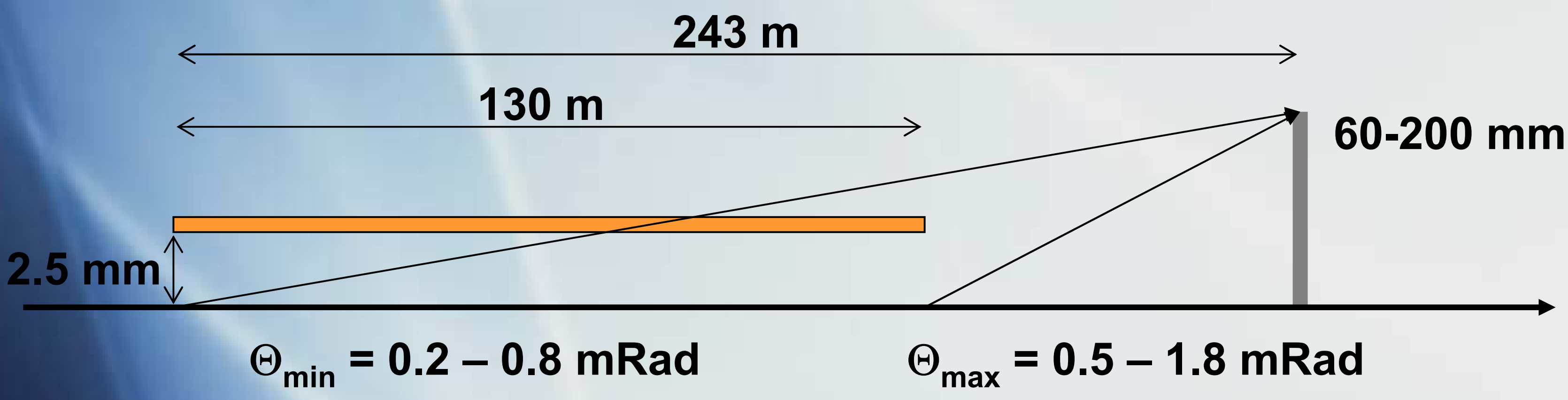
Calculated far-field energy spectrum

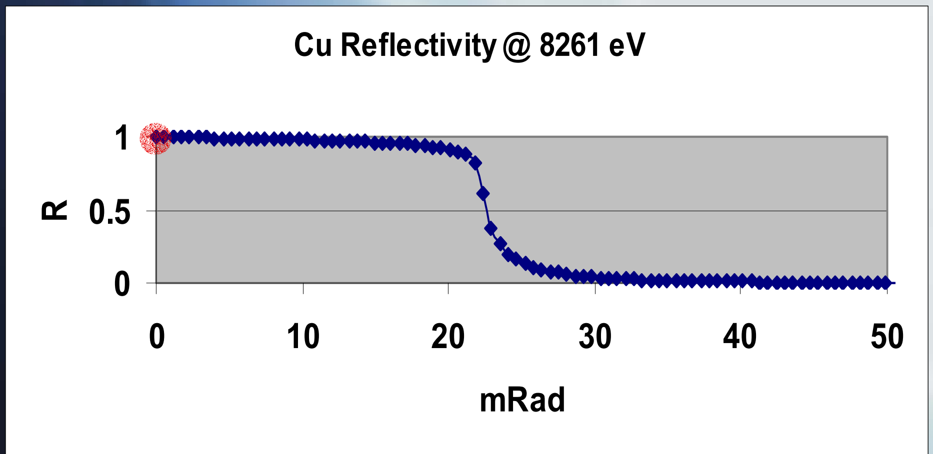


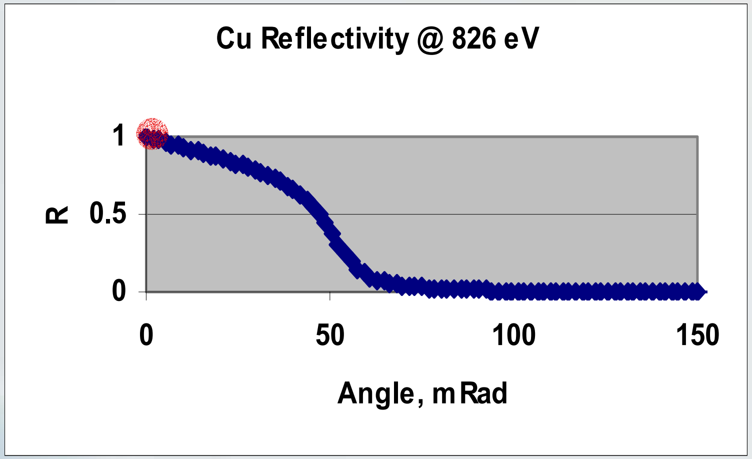
Monte Carlo Energy Distribution



Spontaneous Emission Angle Below Critical Angle

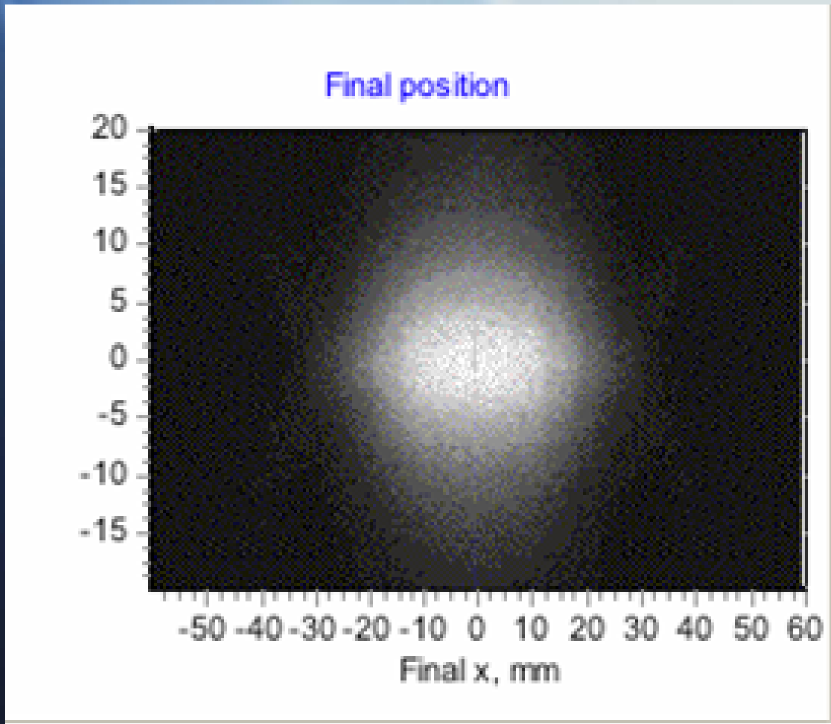




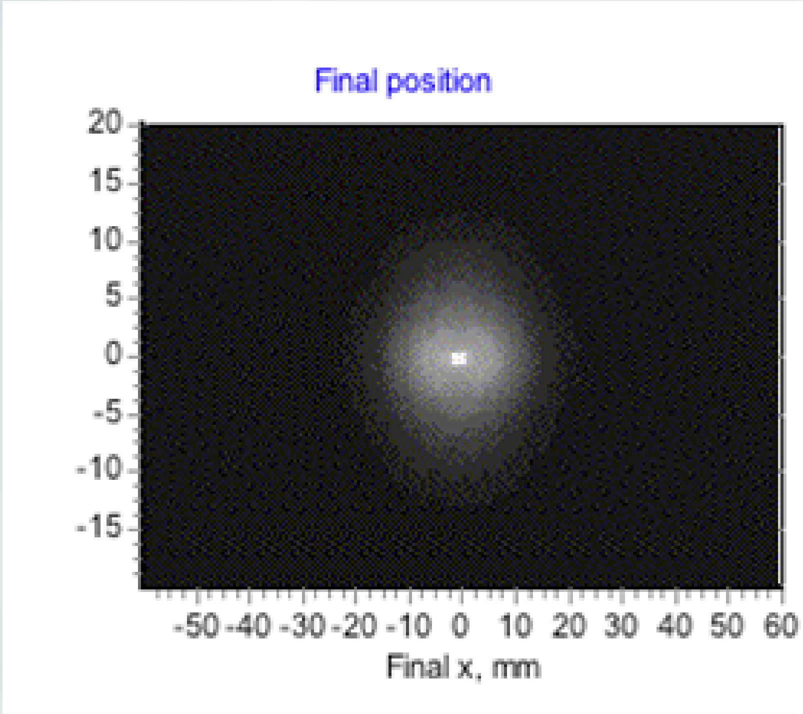


Vacuum Pipe Simulation 14.5 GeV

Without pipe

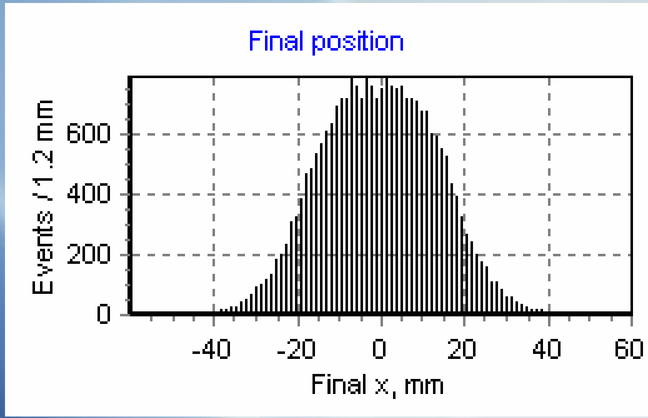


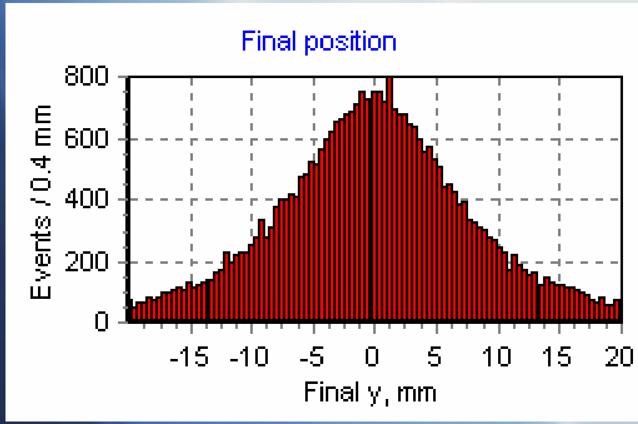
With pipe



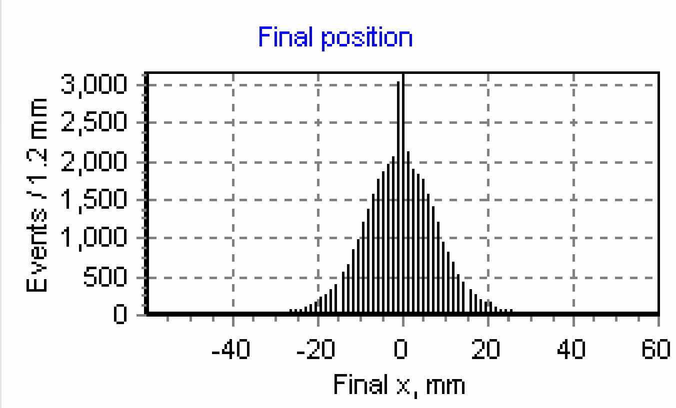
Line outs through center

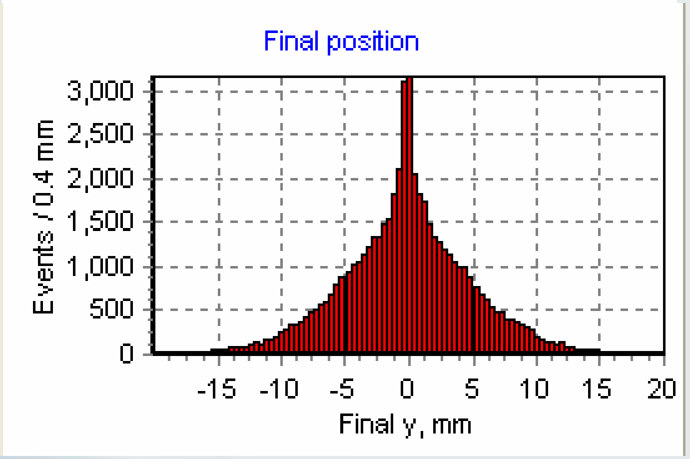
Without pipe





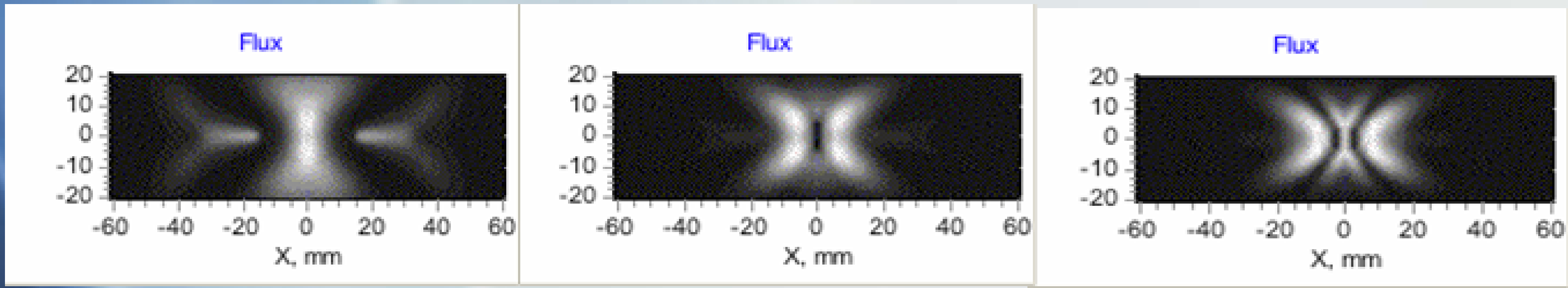
With pipe



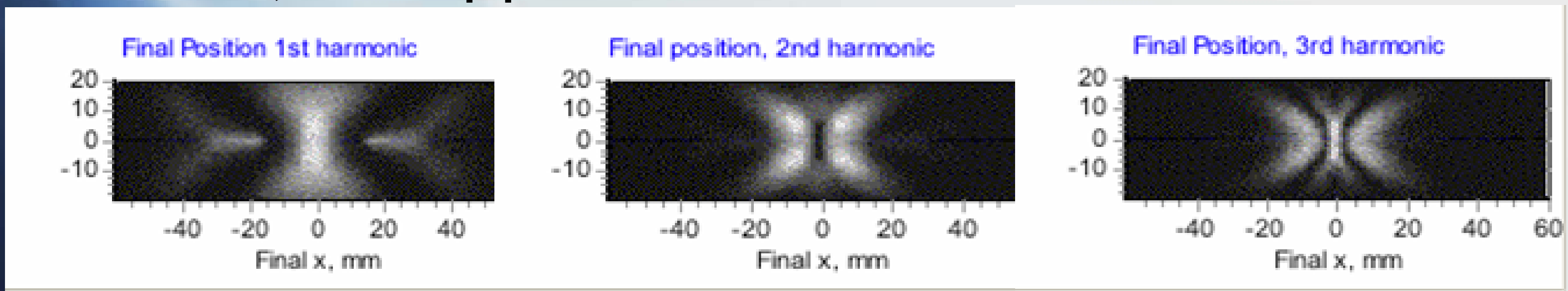


Reflection at higher orders

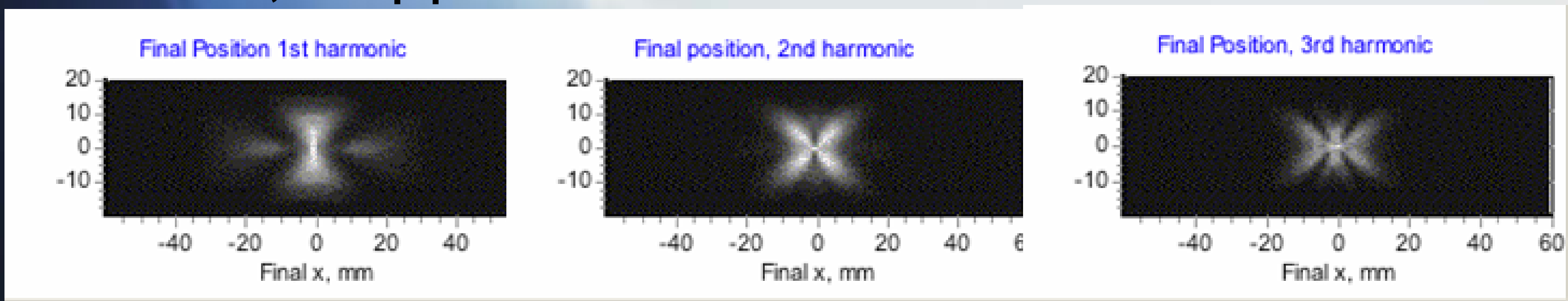
Lienard Wichert Calculation, without pipe



Monte Carlo, without pipe

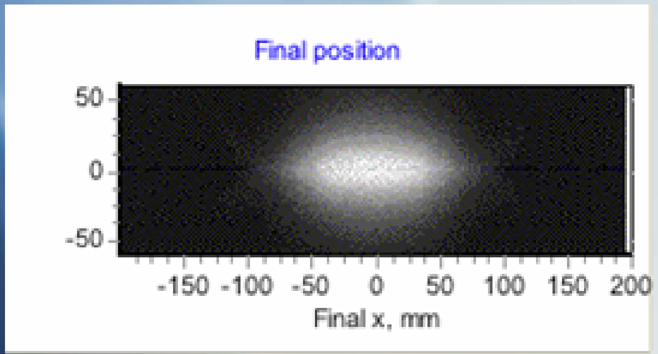


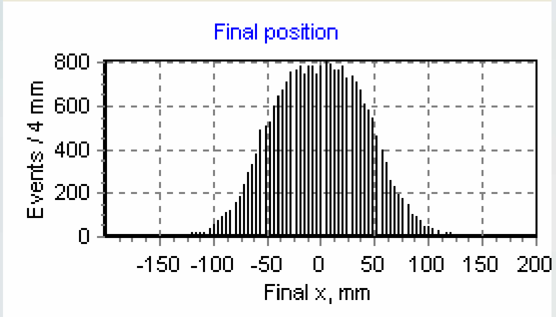
Monte Carlo, with pipe

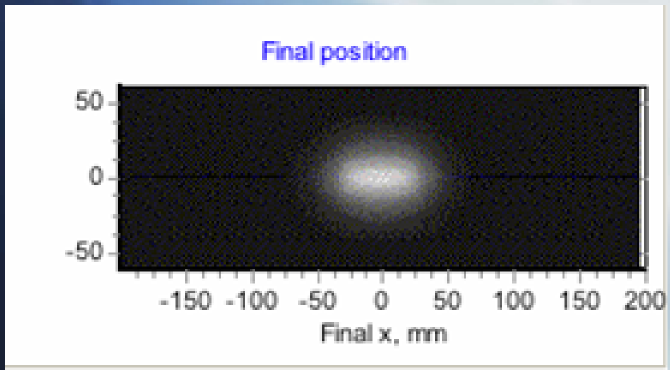


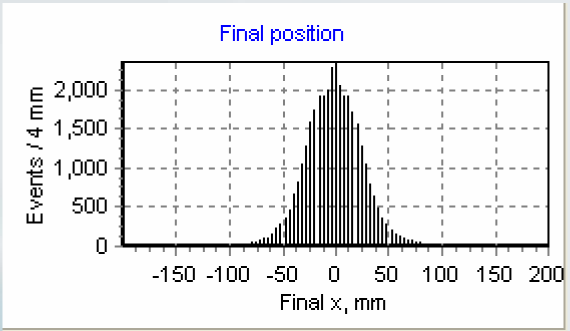
0 < E < 10 keV **10 < E < 20 keV** **20 < E < 30 keV**

Reflection in pipe at 4.5 GeV

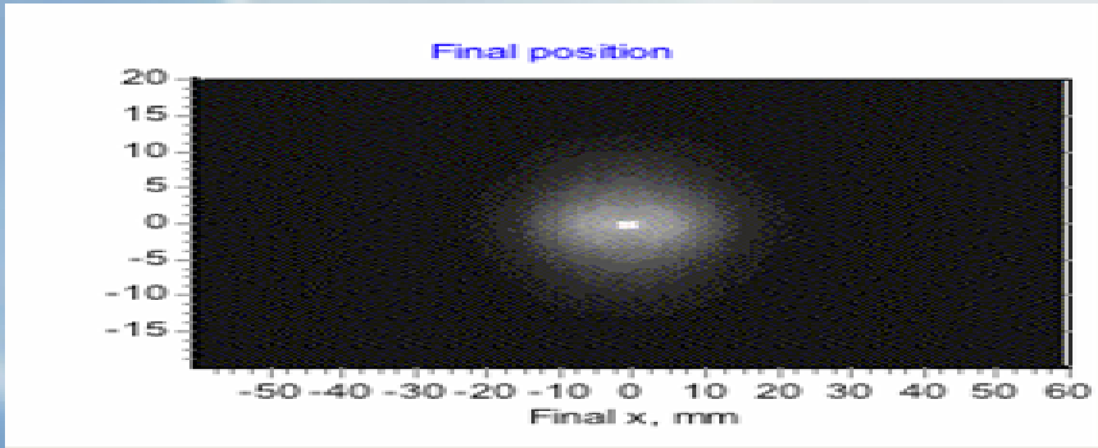




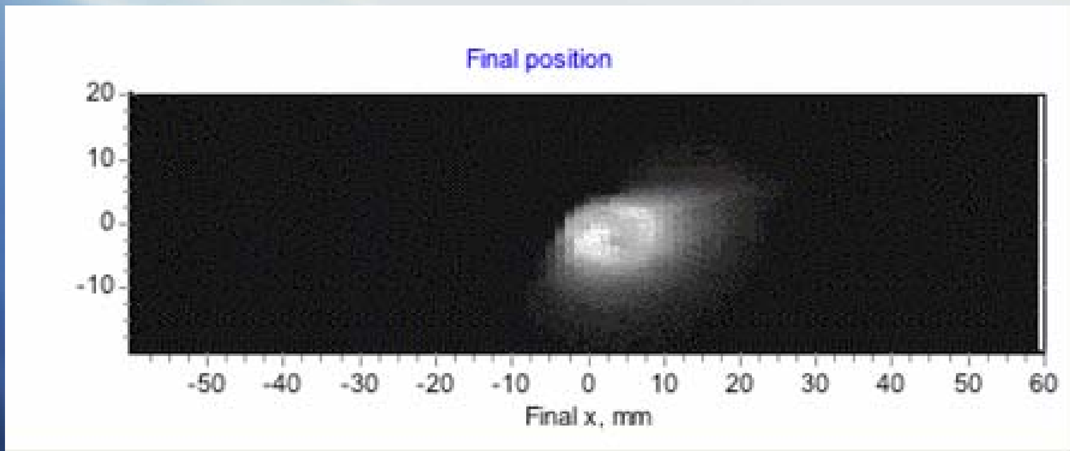




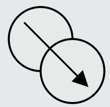
Tilted pipe at 14.5 GeV



Pipe parallel to beam



Pipe tilted 19 μR, raised 0.9 mm, and shifted to the right 0.9 mm

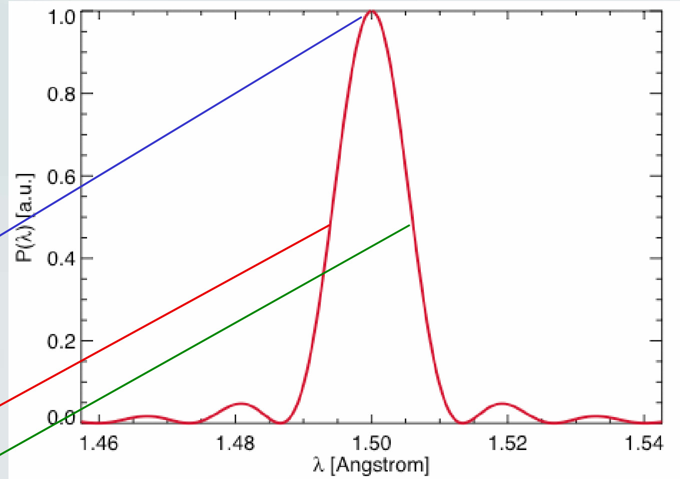


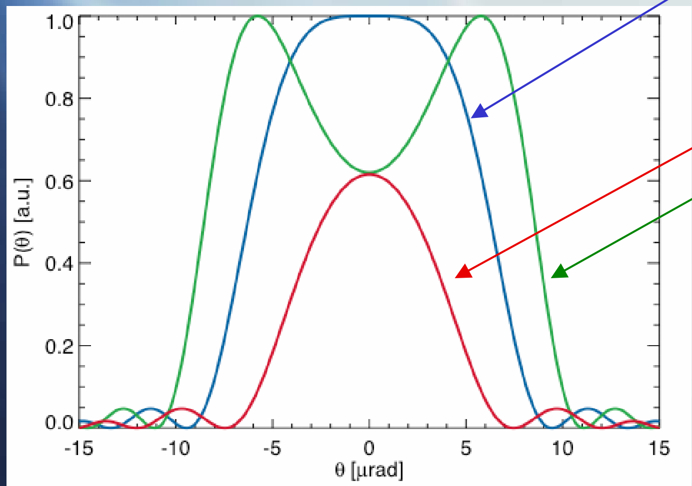
Conclusion

- Layout geometry is set
- Beam modeling codes in place
- Reflection of undulator vacuum chamber seriously distorts the spontaneous radiation pattern
- Direct imager model in progress to specify scintillator and attenuator thickness, and CCD gain parameters. Need similar model for Indirect Imager, and Calorimeter
- Excellent signal-noise ratio due to spectral and spatial cut of the direct imager model with CCD.

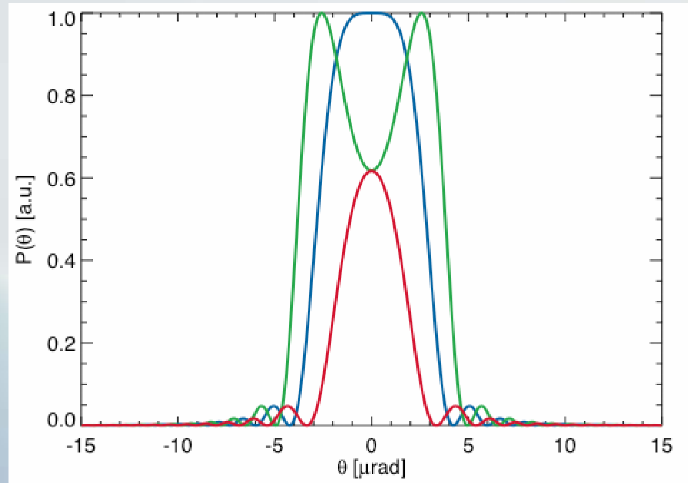
Single Module Spectrum

- Bandwidth of $1/N_u \sim 1\%$
- Angular distribution after monochromator





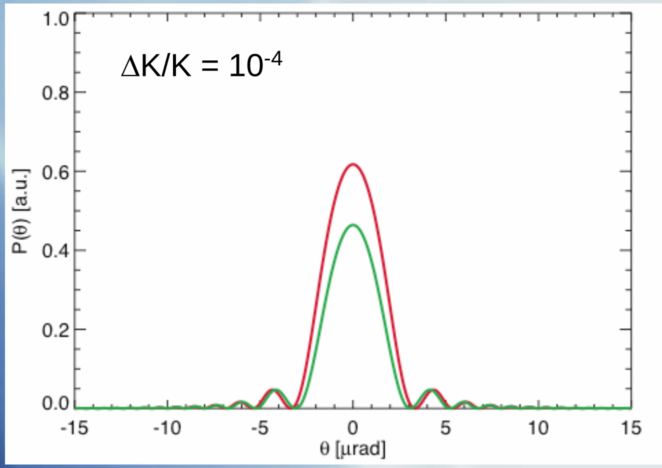
At 5th harmonic

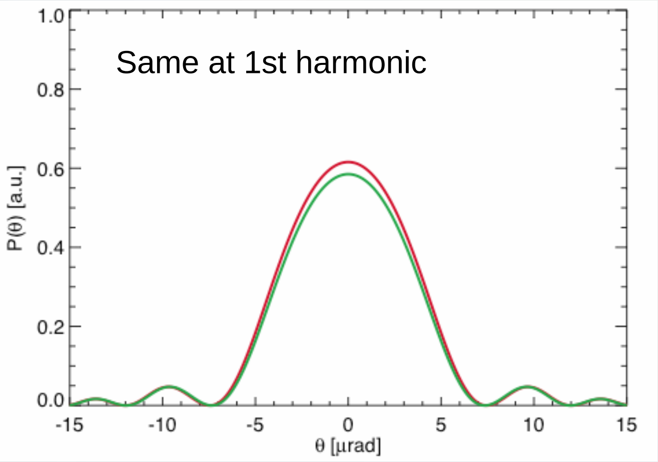


Ideal case of zero energy spread and emittance

Detuned Module

- Monochromator selects frequency slightly above 5th harmonic (shift of about $6 \cdot 10^{-4}$)

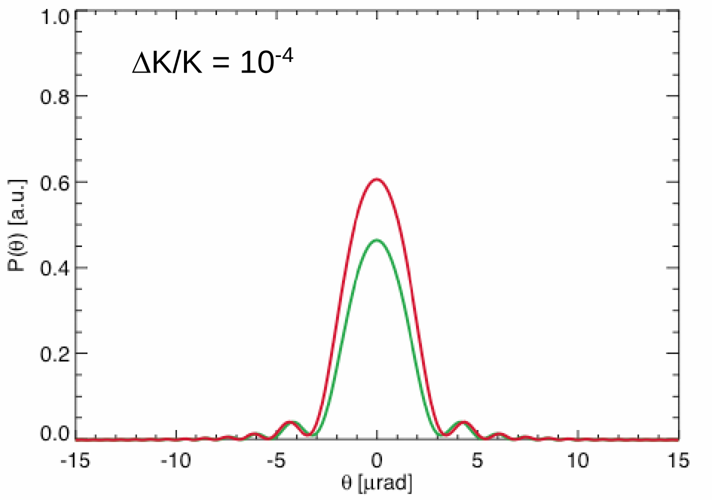


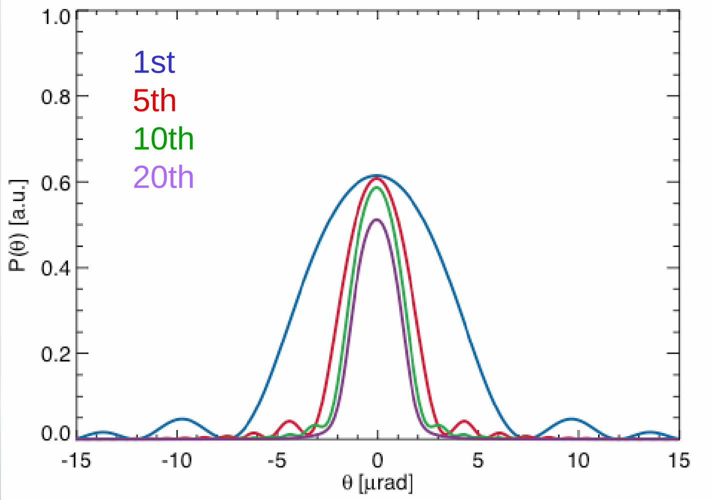


- Variation in detected power and width of distribution
- Works best for monochromator tuned to the half value point of the high-frequency side of the spectrum

Emittance and Energy Spread

- Line width and distribution size are dominated by emittance (energy spread is negligible) for the 10th or higher harmonics.
- At 5th harmonic no degradation by emittance and energy spread.
- No benefits by going to higher harmonics





Machine Jitter

- Energy jitter of 0.1% has same wavelength shift as detuning of $\Delta K/K=10^{-4}$, but can be eliminated by statistic
- Same argument applies to charge jitter
- Alternatively the radiation measurement can be binned by measuring charge and energy of the spent beam.
- Jitter in beam angle (0.12-0.24 μrad) is sufficiently small for the measurement. Transferred jitter on the radiation beam might be detectable if a X-ray BPM is installed.
- Other machine jitter not of relevance for tuning the modules.

Tuning the Undulator

- After BBA the orbit must be straight enough to have a beam divergence less than 1 μrad.
- X-ray BPM are complimentary measurement of the orbit straightness. Improvement in resolution when installed in far hall, but not necessary when BBA is successful.
- Tuning works only for one module per time. If tuned modules remain in beam line than line width and distribution are determined by emittance and change in signal is too weak.
- Emittance effects can be slightly suppressed by increasing the beta-function for tuning.