Undulator Performance Characteristics for the MBA Lattice

R. Dejus on behalf of the APS Upgrade Team
October 18, 2013

Outline

- Details on how the MBA lattice will effect the on-axis brilliance (brightness), flux, and power of the x-ray photon beam
  - Large increase in brightness and coherent flux (> 100x)
  - A more modest increase in flux (2 – 3x)
  - Optimization of undulator period length for user program energies of interest
  - Undulator bandwidths

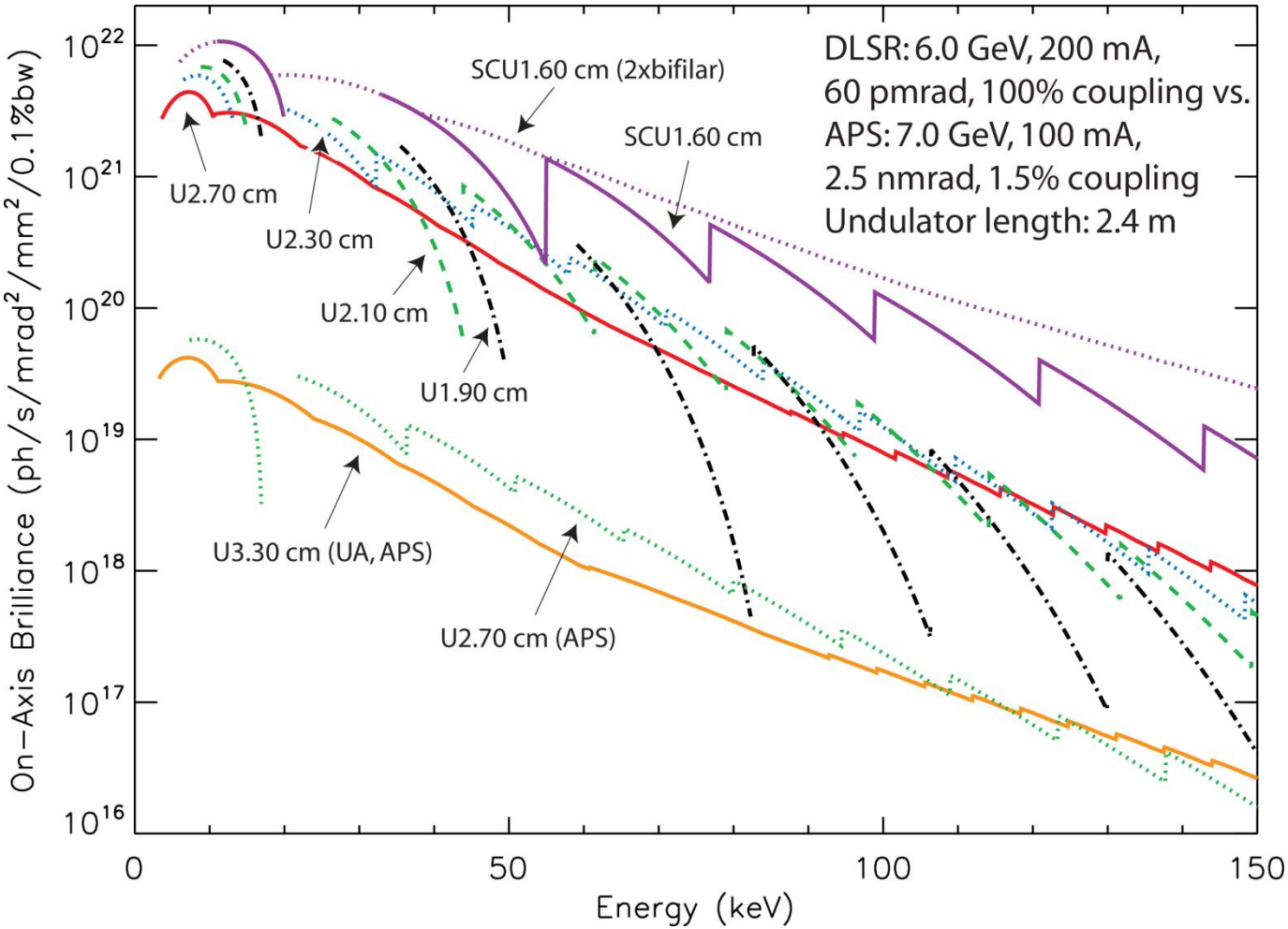
- Other issues
  - Undulator phasing
  - Undulator gap control
  - Radiation damage

DLSR Source Parameters from LS Note #337, Rev. 1.28, Oct. 1, 2013

Table 7: Parameters for ID source points for H7BA-TwoSector-60pm-nux105-nuy34

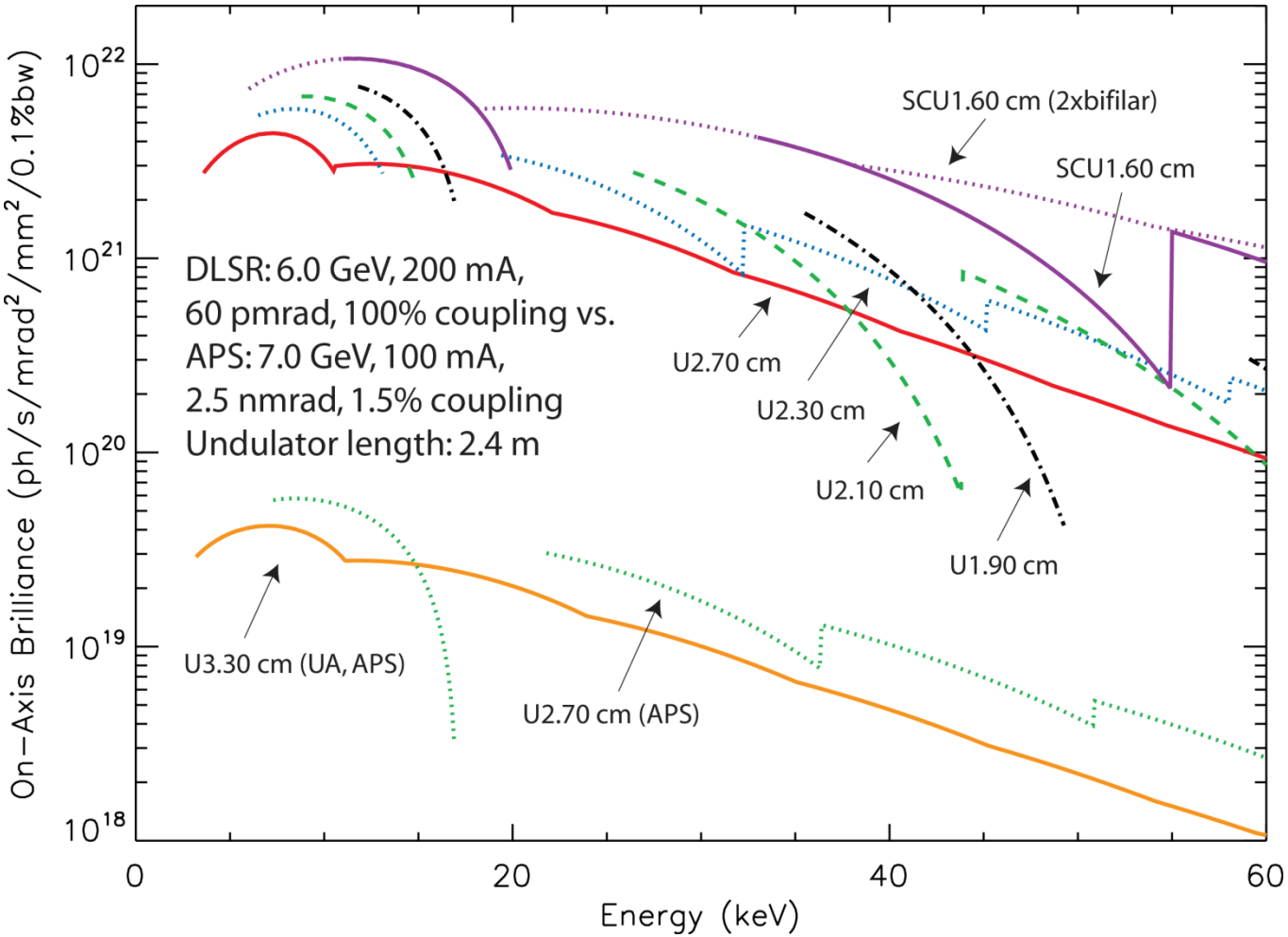
κ	σ_t ps	ϵ_x pm	ϵ_y pm	β_x m	β_y m	σ_x μm	σ'_x μrad	σ_y μm	σ'_y μrad	σ_δ 10^{-4}	$\tau_{10^{th}}$ hour	$\Delta T_{\rm inj}$ s
					$N_b = 48$		$f_b = 13.0$MHz					
1.00	70	41.7	41.7	1.3	2.9	7.4	5.7	10.9	3.8	9.95	1.38	10.4
					$N_b = 81$		$f_b = 22.0$MHz					
1.00	35	42.5	42.5	1.3	2.9	7.4	5.7	11.0	3.9	1.00×10^1	1.19	5.3
1.00	69	39.6	39.6	1.3	2.9	7.2	5.5	10.6	3.7	9.77	2.23	9.9
					$N_b = 162$		$f_b = 44.0$MHz					
1.00	21	41.6	41.6	1.3	2.9	7.3	5.7	10.9	3.8	9.95	1.41	3.1
1.00	35	39.6	39.6	1.3	2.9	7.2	5.5	10.6	3.7	9.77	2.23	5.0
0.24	68	56.1	13.3	1.3	2.9	8.5	6.6	6.2	2.2	9.74	3.00	6.7
					$N_b = 216$		$f_b = 58.7$MHz					
1.00	20	40.7	40.7	1.3	2.9	7.3	5.6	10.8	3.8	9.86	1.72	2.9
1.00	34	38.8	38.8	1.3	2.9	7.1	5.5	10.5	3.7	9.70	2.91	4.9
0.11	68	61.4	6.5	1.3	2.9	8.9	6.9	4.3	1.5	9.79	3.00	5.0
					$N_b = 324$		$f_b = 88.0$MHz					
1.00	18	39.5	39.5	1.3	2.9	7.2	5.5	10.6	3.7	9.76	2.32	2.6
0.22	35	56.6	12.6	1.3	2.9	8.6	6.6	6.0	2.1	9.74	3.00	3.3
0.10	68	59.8	5.9	1.3	2.9	8.8	6.8	4.1	1.4	9.69	4.31	4.8

On-Axis Brilliance Tuning Curves of HPMs and SCUs: The Big Picture



- Calculated odd harmonic brightness tuning curves of hybrid permanent magnet undulators (HPMs) and superconducting undulators (SCUs) for today's APS lattice and the proposed DLSR lattice. The magnetic length is 2.4 m for all devices. The shorter the period length the higher the brightness (and flux) for any given harmonic energy. The minimum gap is 8.5 mm for the DLSR (11.0 mm APS).
- Reductions due to magnetic field error were applied to all undulators (estimated from one measured undulator A at the APS).
- The brightness gain for the DLSR SCUs approaches three orders of magnitude for photon energies above 100 keV!

On-Axis Brilliance Tuning Curves of HPMs and SCUs: 0 – 60 keV



- Close-up 0 – 60 keV of previous figure.
- For the DLSR the optimum period length becomes shorter than today. The U2.7 cm (maybe U2.8 cm) becomes the new "Undulator A" for continuous energy coverage.

Universal Helical Undulator – Original Idea

The idea of a universal helical structure is described in the paper by D. Alferov, Yu. Bashamkov, and E. Bessonov "Generation of circularly polarized electromagnetic radiation," Zh. Tekh. Fiz **46**, 2392-2397, November 1976.

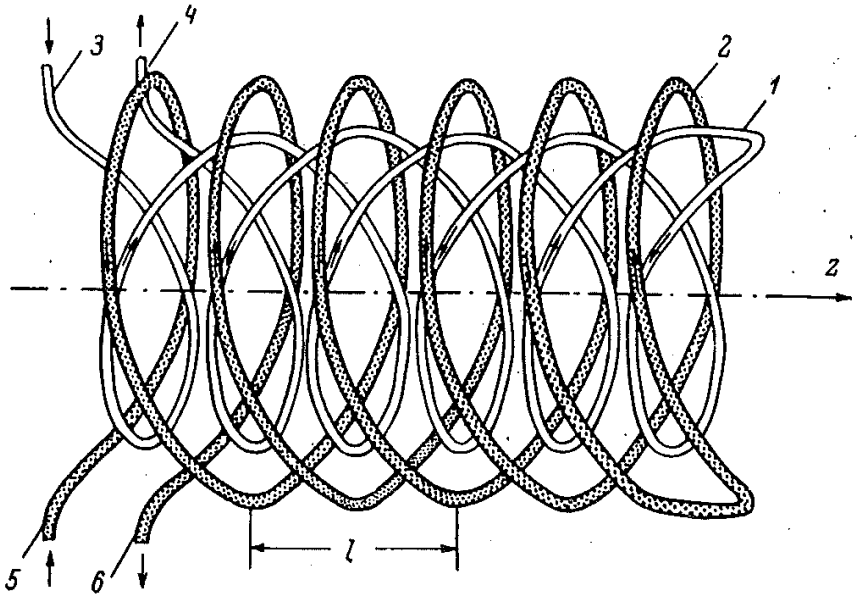
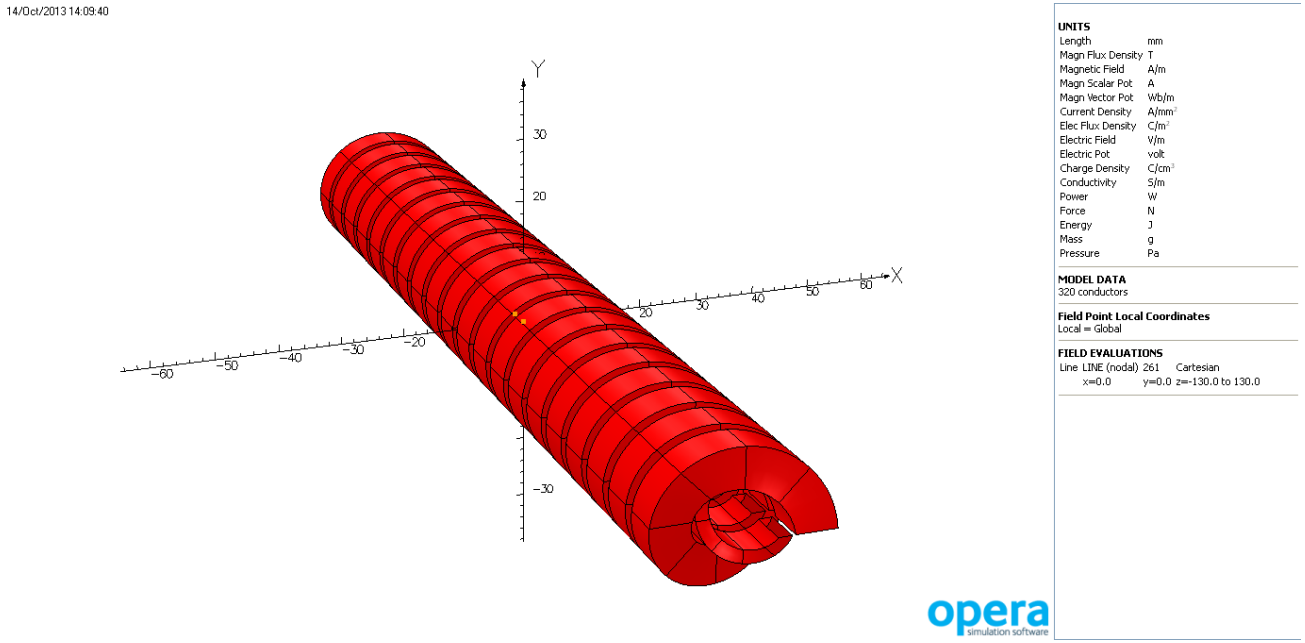


FIG. 2. Schematic diagram of a helical undulator.

The structure suggested by the authors as a universal helical undulator capable of generating both helical and planar undulator magnetic fields.

Realistic Model



Inner bifilar coil:

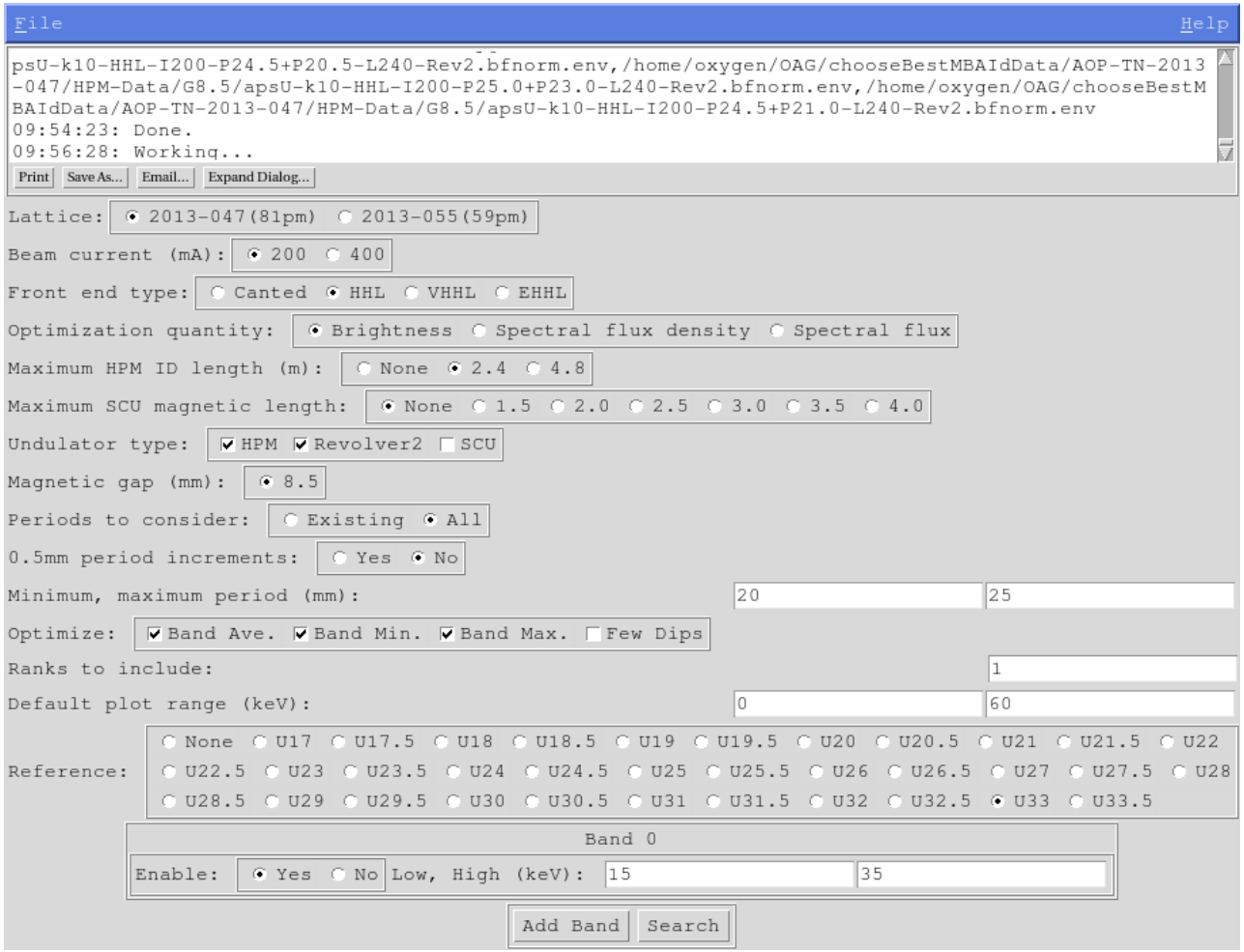
Period: 16 mm
Winding bore: 6 mm
Winding: 6 mm (W) x 2mm (H)
Current density: 0 A/mm^2
or ±940.3 A/mm^2

Outer bifilar coil:

Period: 16 mm
Winding bore: 11 mm
Winding: 6 mm x 6 mm
Current density: 0 A/mm^2
or 1400 A/mm^2

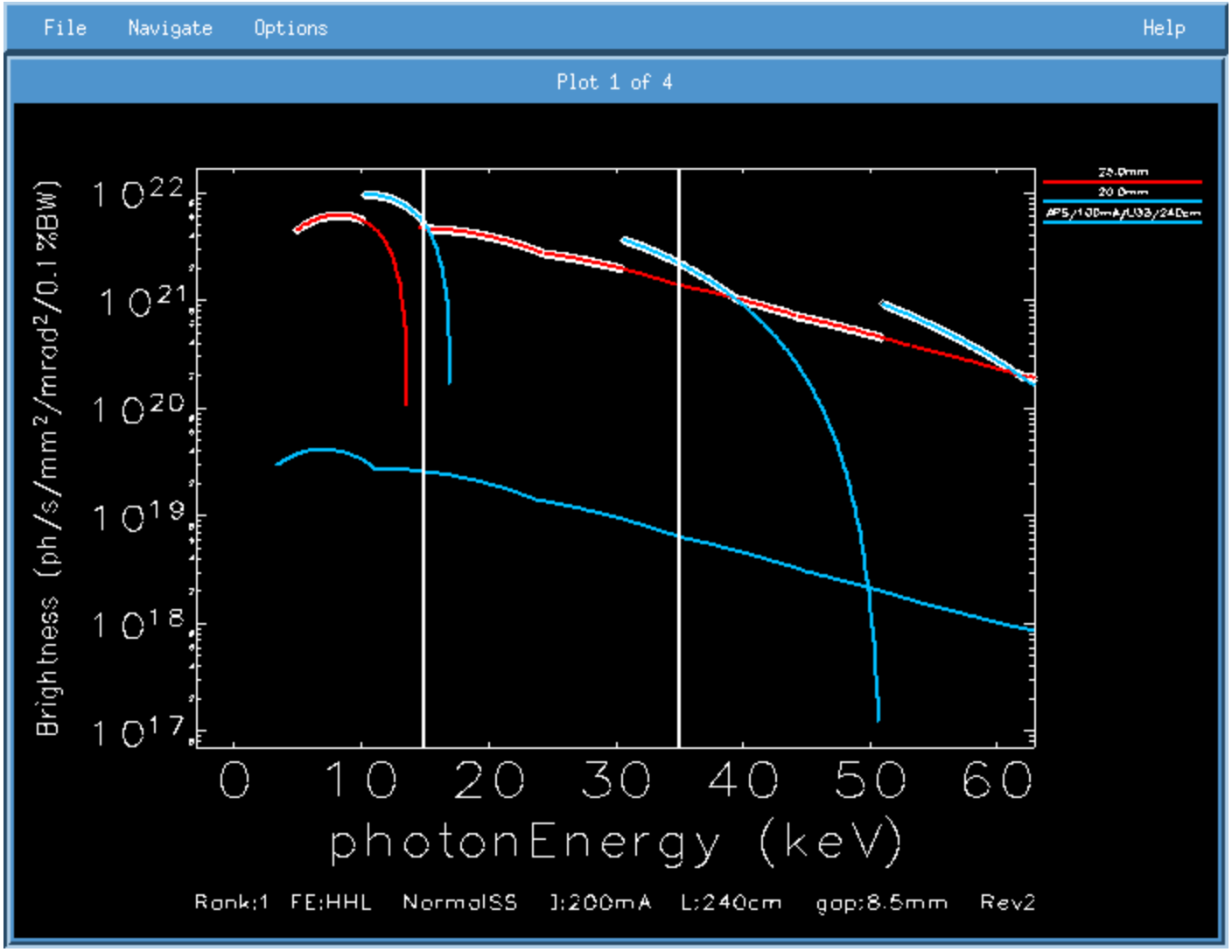
Inner Coil	Outer Coil	Field Configuration
J = 940.3 A/mm^2	0	Helical B_y =0.8022 T, B_x = 0.8022 T
0	J = 1400 A/mm^2	Helical (opposite helicity) B_y =0.8022 T, B_x = 0.8022 T
J = 940.3 A/mm^2	J = 1400 A/mm^2	Vertical B_y = 1.6041 T, B_x = 0
J = - 940.3 A/mm^2	J = 1400 A/mm^2	Horizontal B_y = 0, B_x = 1.6041 T

On-Axis Brilliance Tuning Curves of HPMs: Revolver ChooseBestMBAID

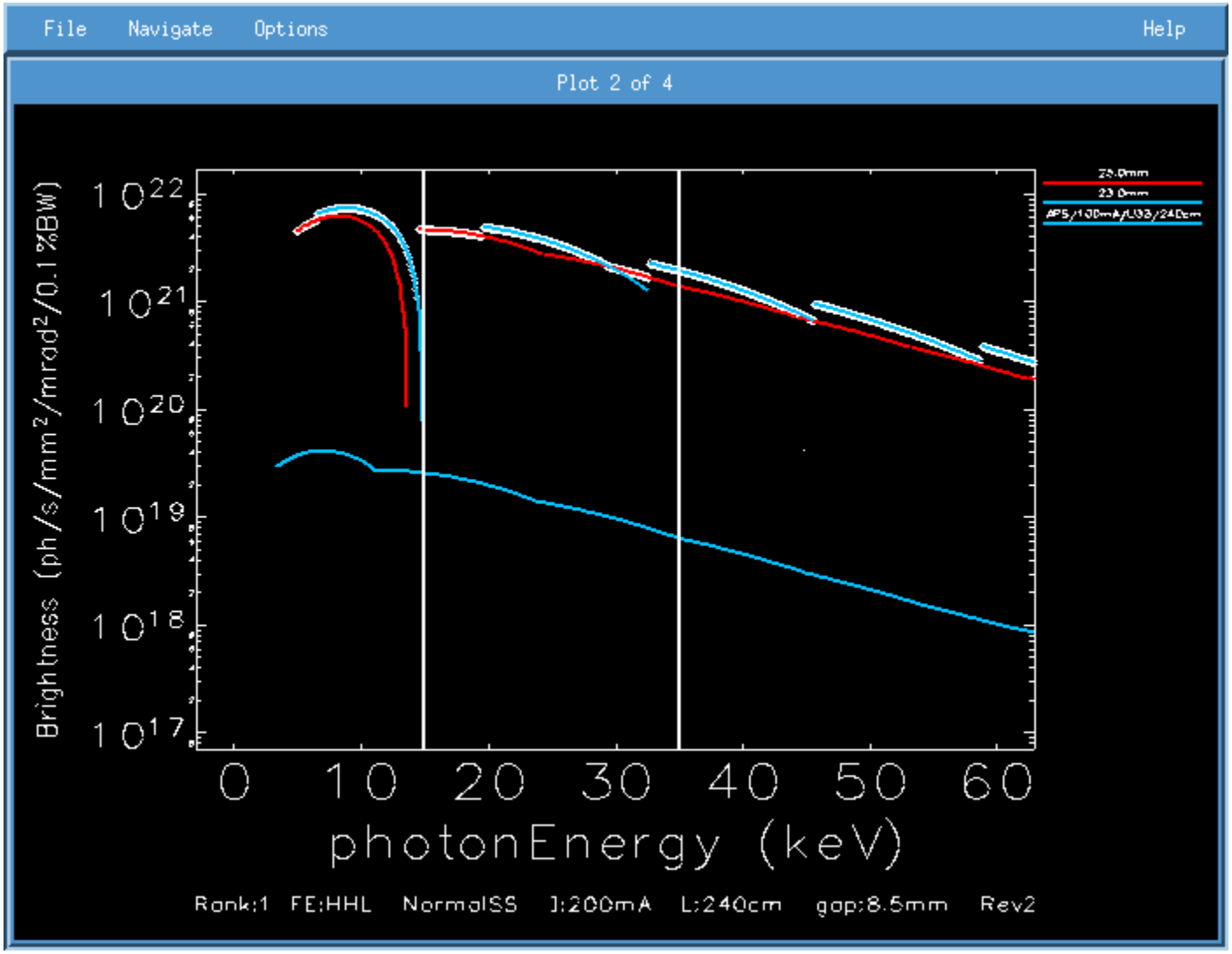


- Use M. Borland's ChooseBestMBAID. On the Linux workstation: /usr/local/oag/apps/bin/linux-x86_64/chooseBestMBAID
- Web App: http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/cgi-bin/chooseBestMBAID.cgi
- Example: Revolver with 2 IDs, search periods in the range 20 – 25 mm only, and optimize for the energy range 15 – 35 keV.

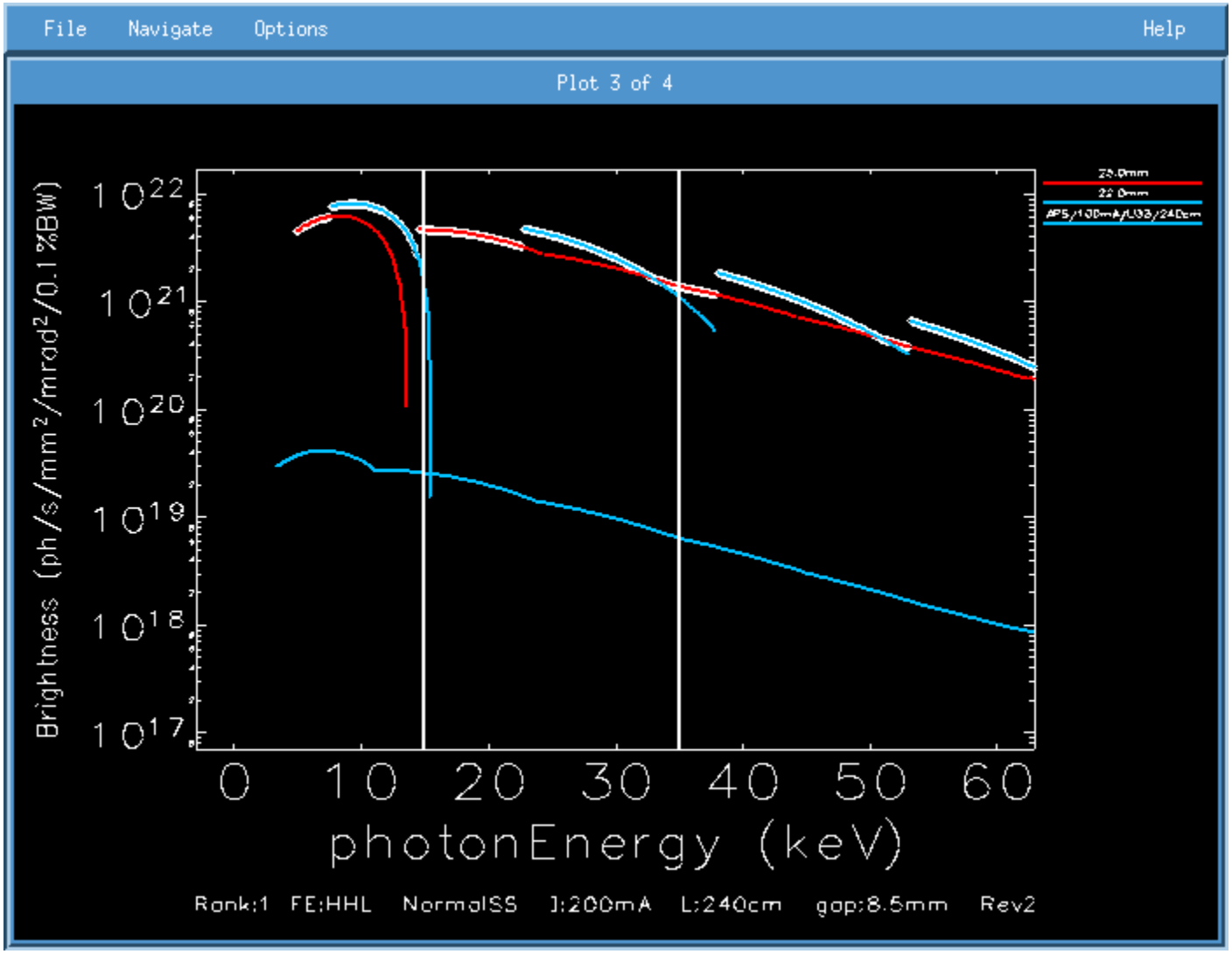
ChooseBestMBAID (Revolver) Plot 1: U2.50 cm & U2.00 cm



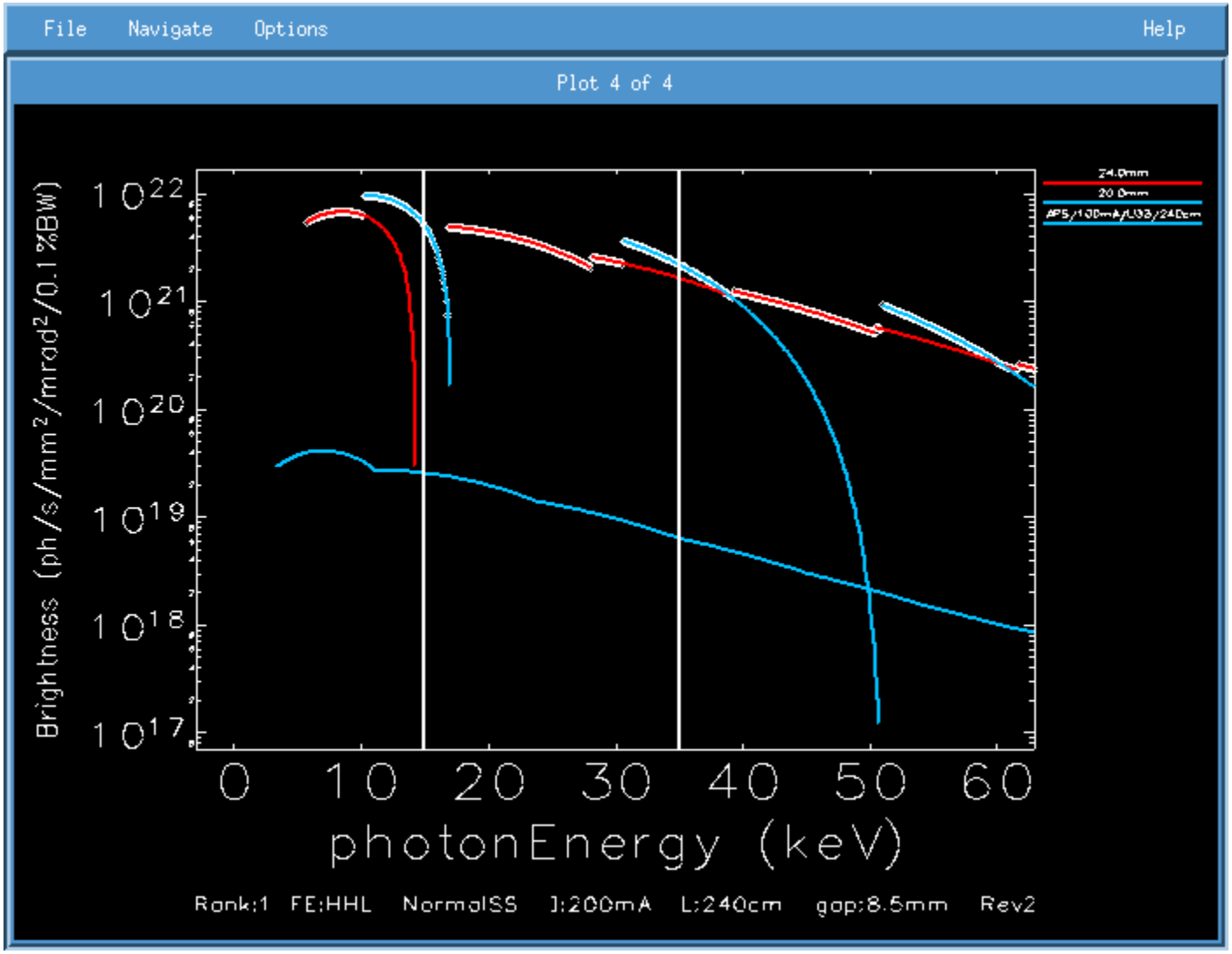
ChooseBestMBAID (Revolver) Plot 2: U2.50 cm & U2.30 cm



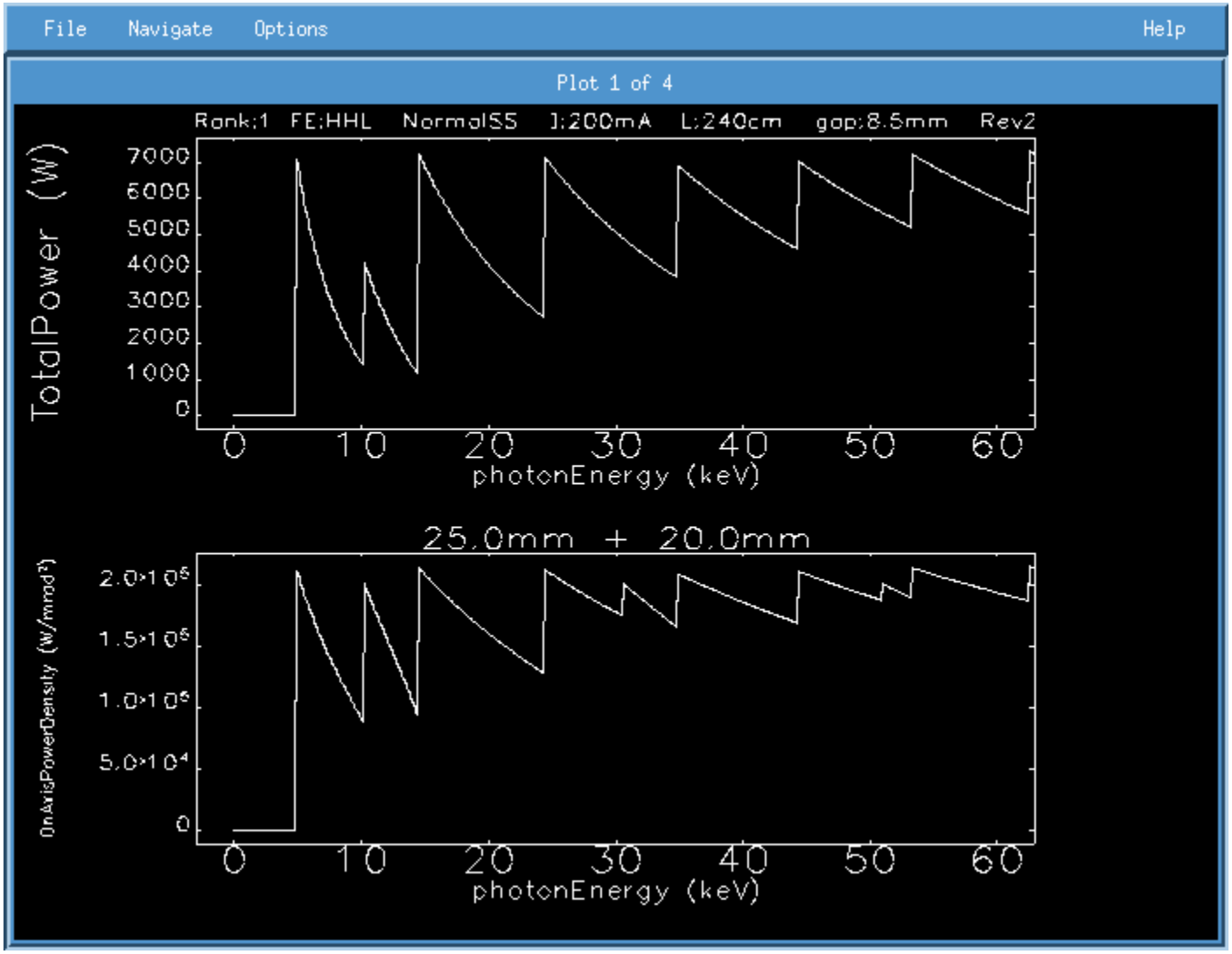
ChooseBestMBAID (Revolver) Plot 3: U2.50 cm & U2.20 cm



ChooseBestMBAID (Revolver) Plot 4: U2.40 cm & U2.00 cm



ChooseBestMBAID (Revolver) Powers/Power Density: U2.50 & U2.00 cm



Other combinations similar.

ChooseBestMBAID Revolver Logfile

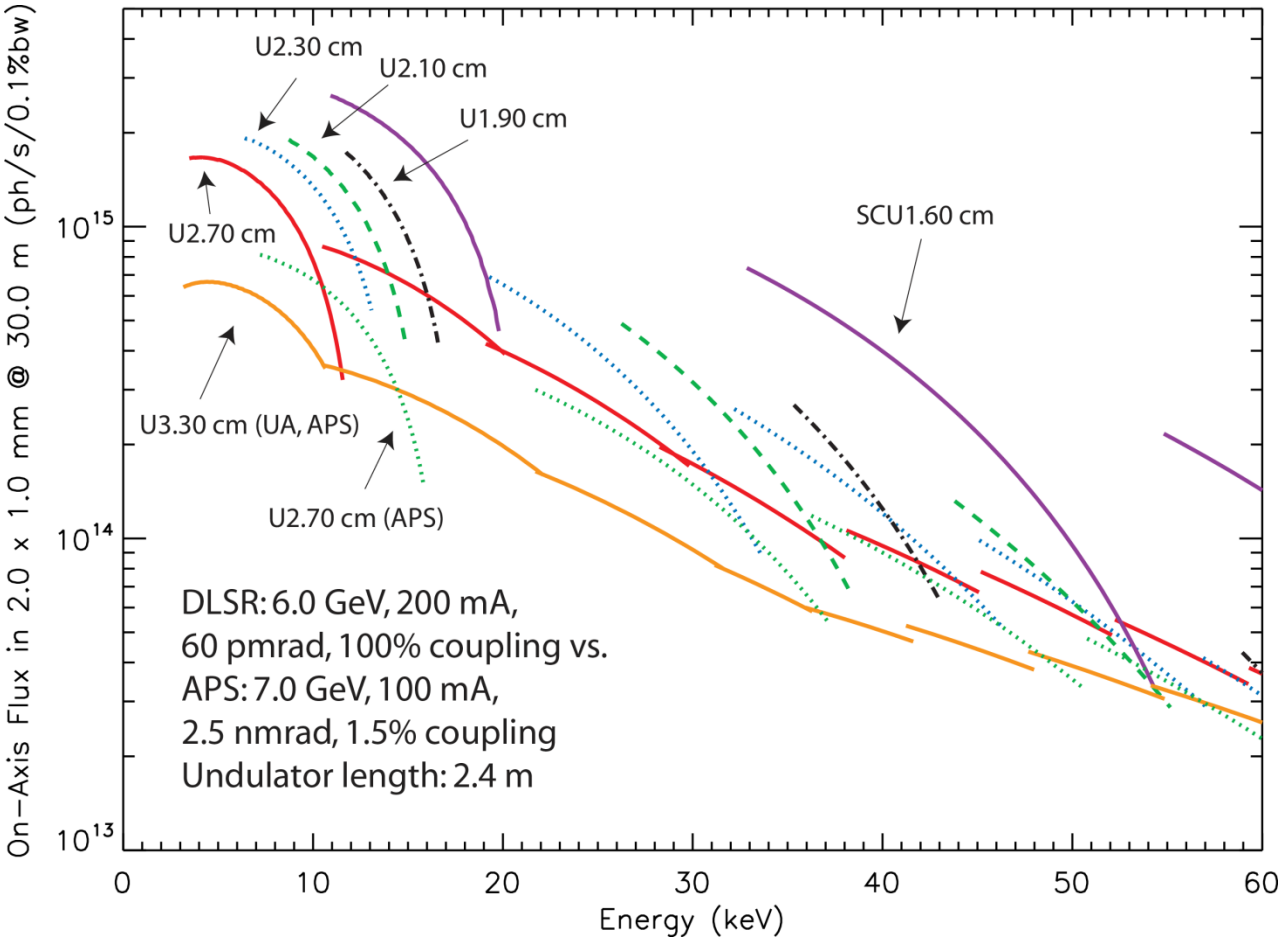
```
Printout for SDDS file /tmp/131017-095628-12902dejus52.best

                  Tag0                      Rank     TotalPowerMax  OnAxisPowerDensityMax  photonEnergyMin
                                                                                                  keV
-----------------------------------------------------------------------------------------------------------
    k10-HHL-I200-P25.0+P20.0-L240-Rev2          1   7.148119e+03          2.125504e+05     4.900000e+00
    k10-HHL-I200-P25.0+P23.0-L240-Rev2          1   7.148119e+03          2.125504e+05     4.900000e+00
    k10-HHL-I200-P25.0+P22.0-L240-Rev2          1   7.148119e+03          2.125504e+05     4.900000e+00
    k10-HHL-I200-P24.0+P20.0-L240-Rev2          1   6.673058e+03          2.144052e+05     5.700000e+00
Printout for SDDS file /tmp/131017-095628-12902dejus52.best

                  Tag0                      BandRange0     BrightnessGap0  BrightnessMax0  BrightnessMin0  BrightnessAve0  BrightnessDips0
                                                                                  SBU             SBU             SBU
-----------------------------------------------------------------------------------------------------------------------------------------
    k10-HHL-I200-P25.0+P20.0-L240-Rev2         15-35keV        0.00e+00        5.04e+21        1.96e+21        3.20e+21         0.00e+00
    k10-HHL-I200-P25.0+P23.0-L240-Rev2         15-35keV        0.00e+00        4.89e+21        1.68e+21        3.34e+21         0.00e+00
    k10-HHL-I200-P25.0+P22.0-L240-Rev2         15-35keV        0.00e+00        4.71e+21        1.37e+21        3.36e+21         0.00e+00
    k10-HHL-I200-P24.0+P20.0-L240-Rev2         15-35keV        0.00e+00        5.04e+21        7.38e+20        3.29e+21         1.00e+00
```

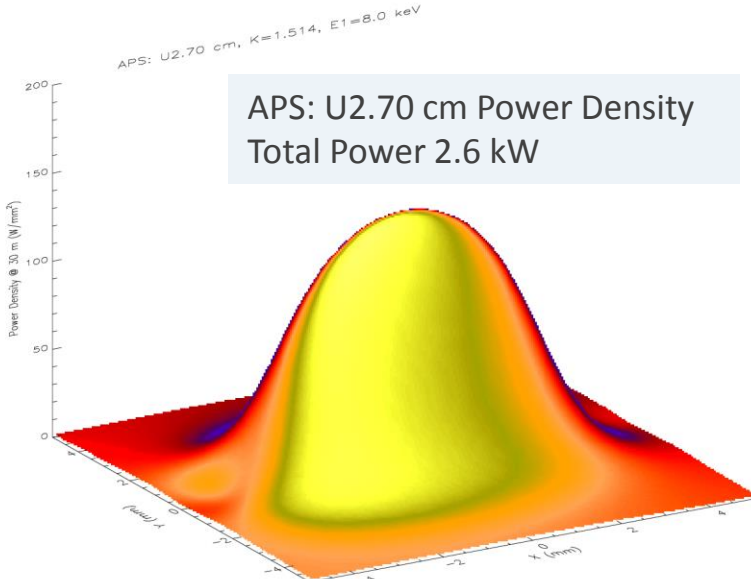
Close | Print | Print... | Export text... | Email... | Replot | Save Plots

On-Axis Flux Tuning Curves of HPMs and SCUs: 0 - 60 keV

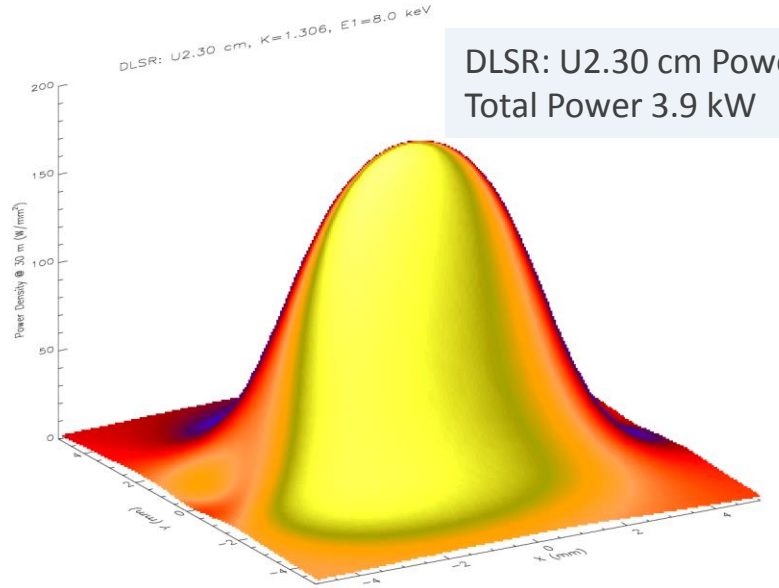


- Calculated odd harmonic flux tuning curves of hybrid permanent magnet undulators (HPMs) and one superconducting undulator (SCU) for today's APS lattice and the proposed DLSR lattice. The magnetic length is 2.4 m for all devices. The minimum gap is 8.5 mm for the DLSR (11.0 mm APS).
- Reductions due to magnetic field error were applied to all undulators (estimated from one measured undulator A at the APS).
- The flux gain for the DLSR undulators is in range 2 – 3x. (A factor of 2 comes from the higher operating current of the DLSR).

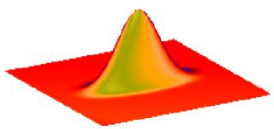
Power Density and Flux in the Central Cone at 8.0 keV at 30 m



APS: U2.70 cm Power Density
Total Power 2.6 kW

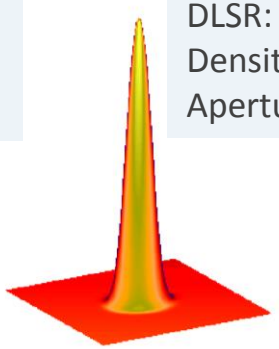


DLSR: U2.30 cm Power Density
Total Power 3.9 kW



APS: U2.70 cm Spatial Flux
Density at 8.0 keV (first harm)
Aperture Power =280 W; K=1.51

Full size ~ 2 x 1 mm

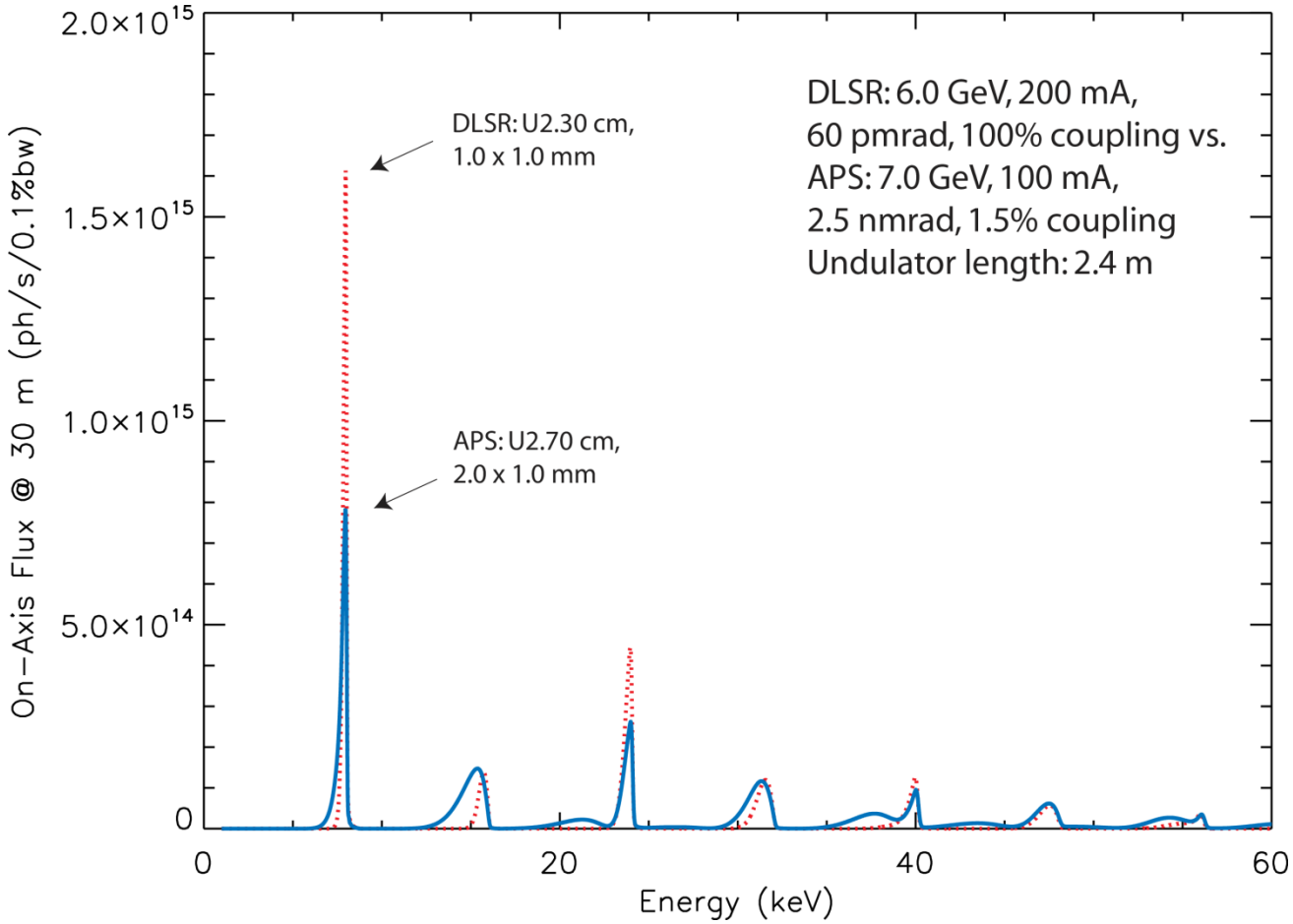


DLSR: U2.30 cm Spatial Flux
Density at 8.0 keV (first harm)
Aperture power=180 W; K=1.31

Full size ~ 1 x 1 mm

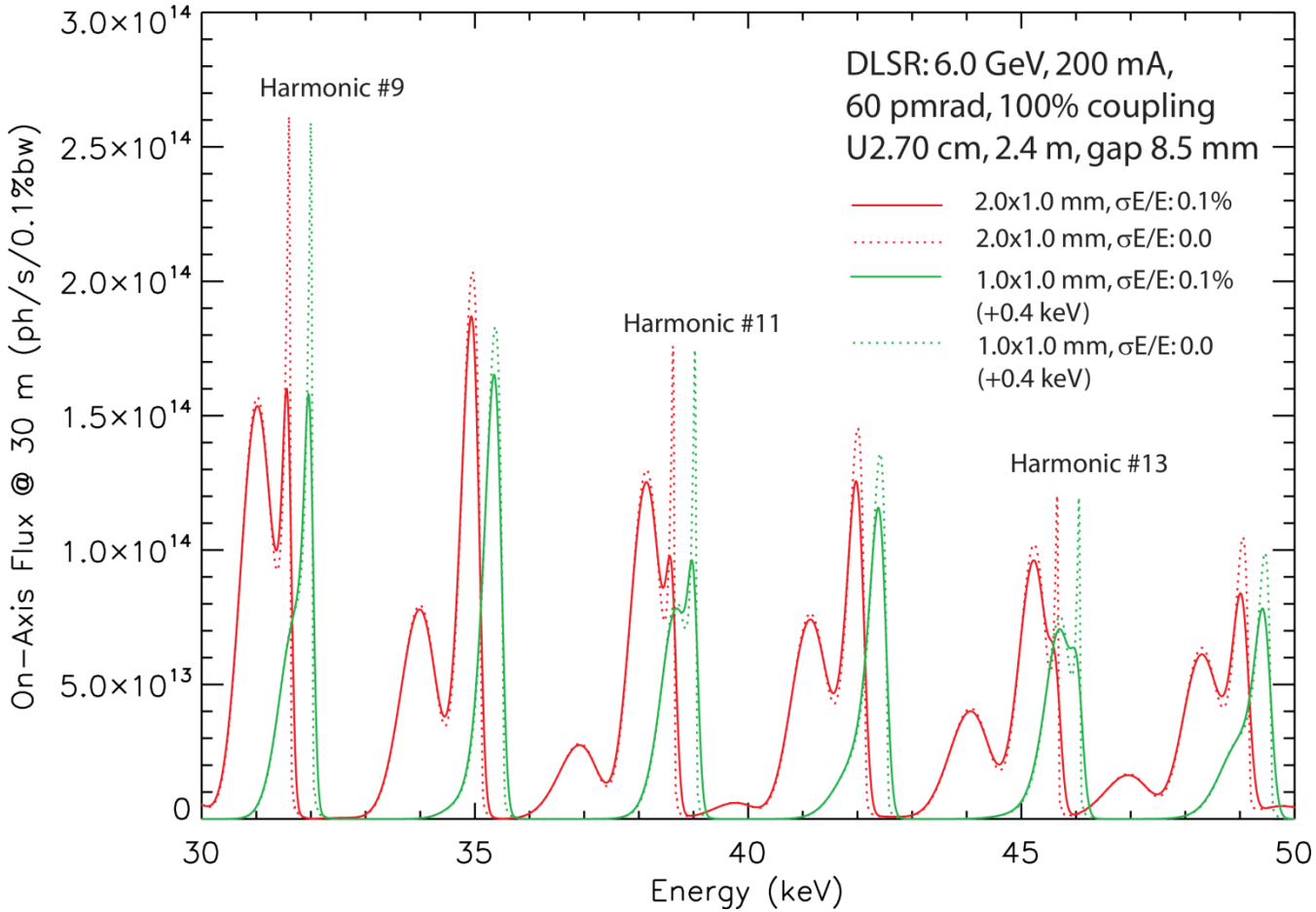
- Important: Notice that the size of the power distribution is essentially unchanged whereas the size of the central cone is reduced by a factor of ~ 2 in the horizontal plane (lower order odd harmonics).

Flux Spectra of U2.30 cm (DLSR) vs. U2.70 cm (APS)



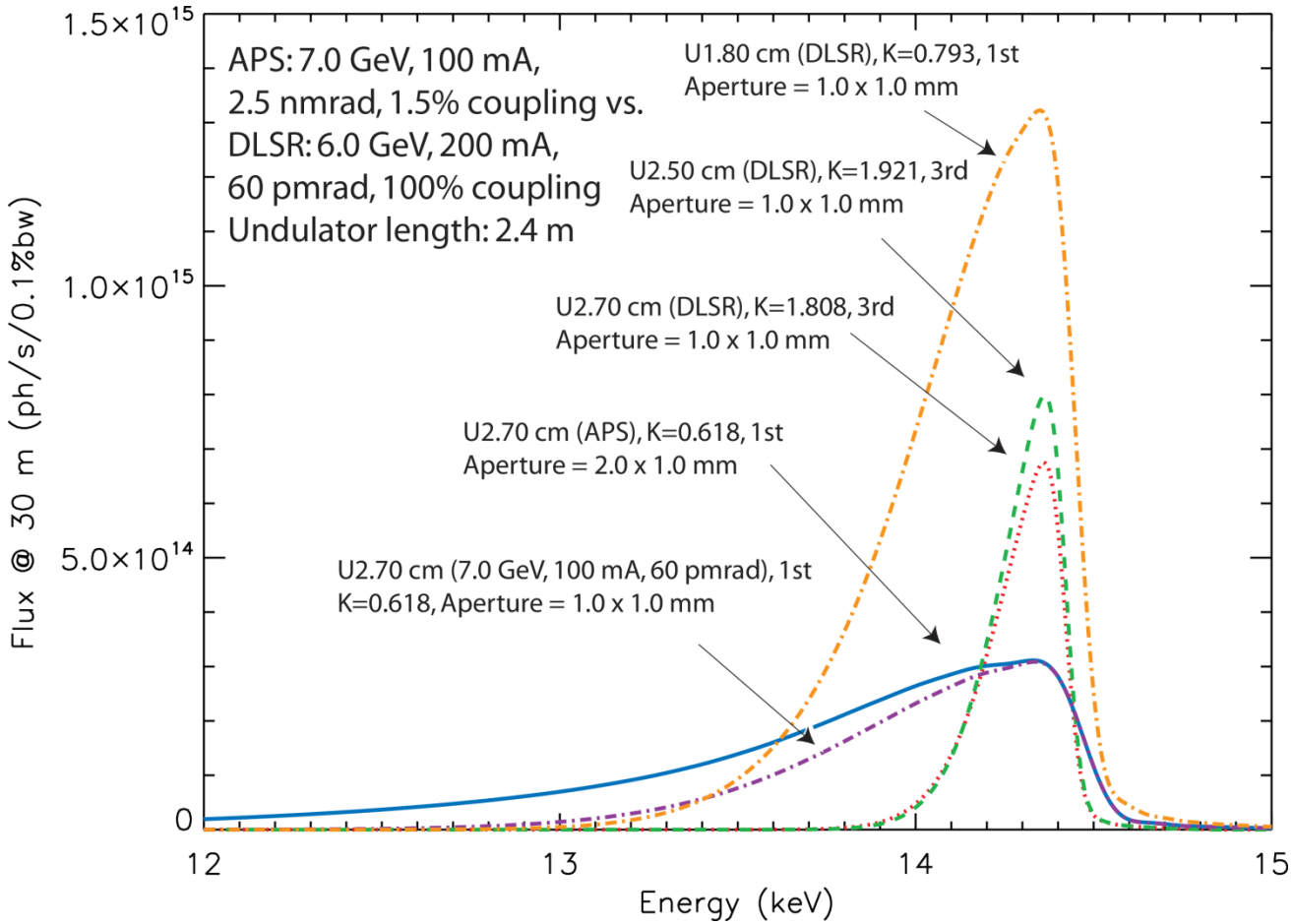
First harmonic energy at 8.0 keV.

Optimum Flux Depends on Aperture Size and Harmonic Number (comparison of 1x1 mm aperture vs. 2x1 mm aperture)



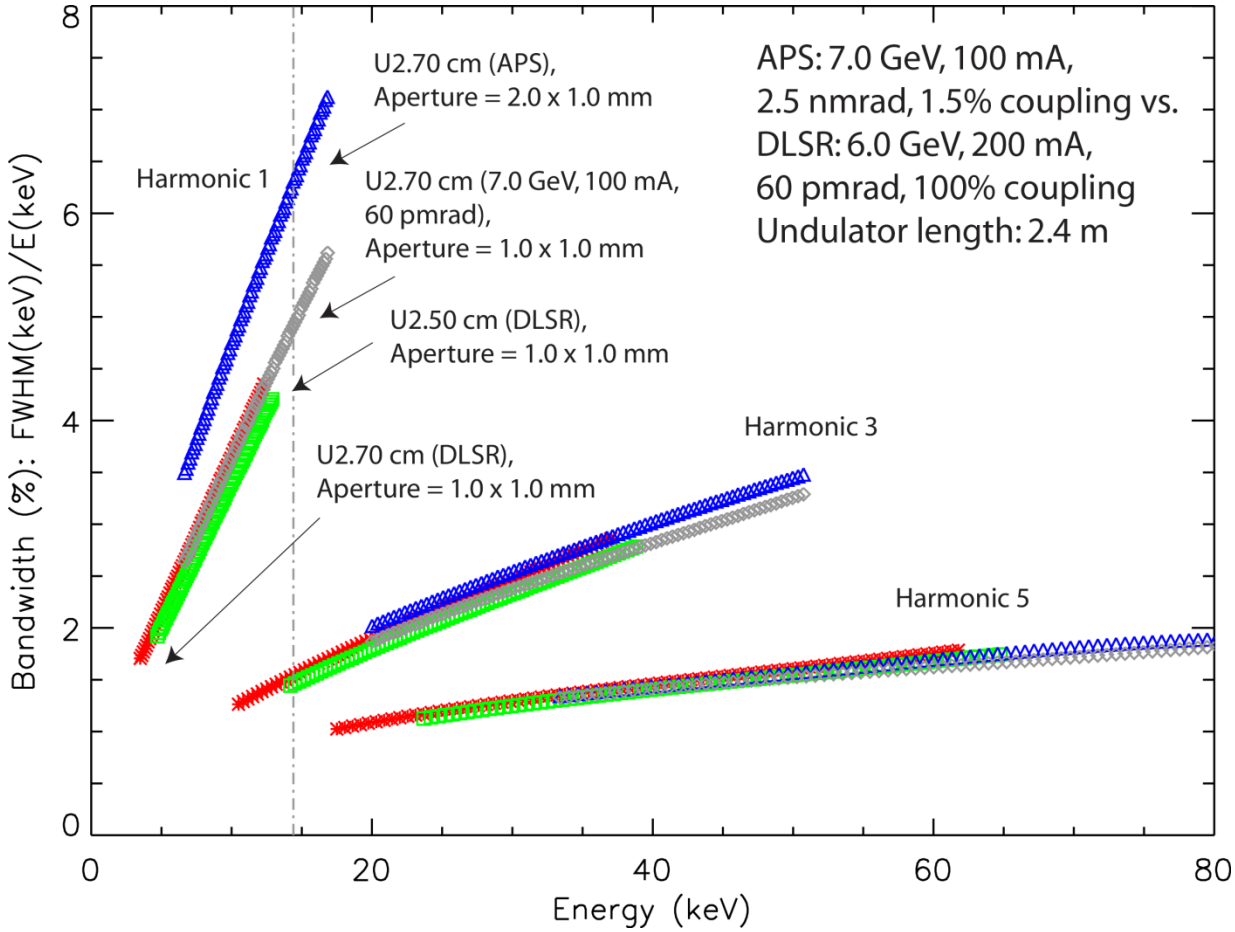
- The flux for a 2.0 x 1.0 mm aperture is noticeably higher for odd harmonics above 9. (First harmonic is at 3.5 keV.)

Example: Optimized Flux at 14.4 keV



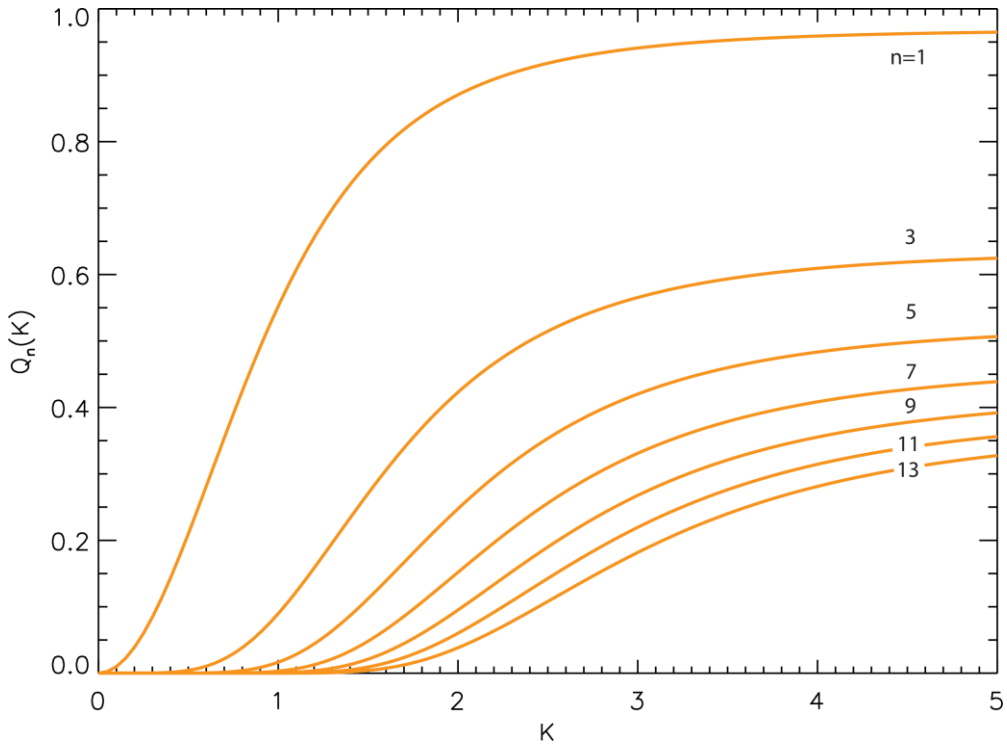
- Flux gain is 4x for this beamline. Best choice is a period length of 1.80 cm with modest power and power density while operating in the first harmonic.

Undulator Harmonic Bandwidths



- The first bandwidth becomes smaller. For example at 8 keV it is smaller by ~ 25% (red vs. blue markers)

Flux in the Central Cone



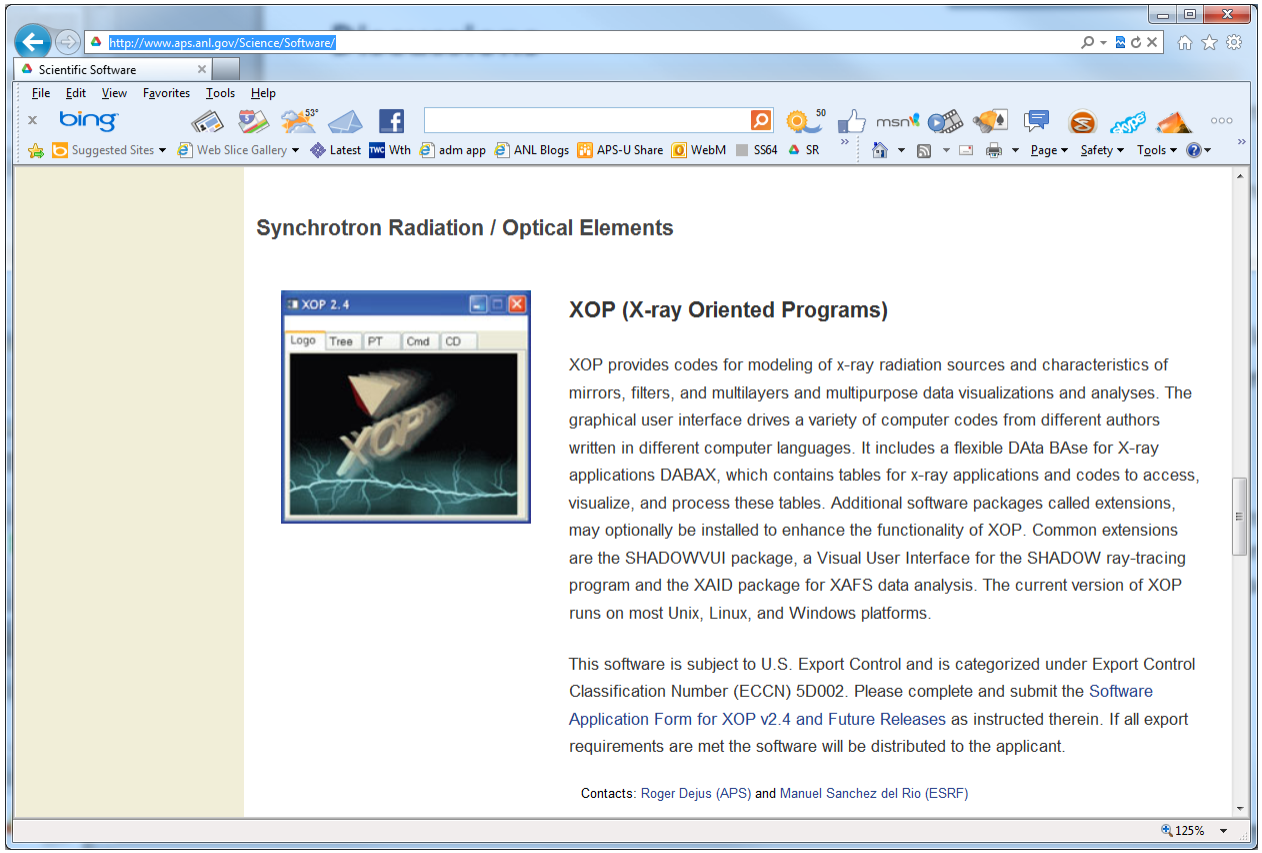
The flux in the central cone with harmonic number n is

$$F^n \propto NQ_n(K)I$$

where *N* is the number of undulator periods and *I* is the ring current.
The coherent flux is directly related to the brightness

$$F^n_{coh} = F^n x\ fcoh = F^n\ x \frac{(\lambda/2)^2}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} = B^n\ x(\lambda/2)^2$$

Software: Use ChooseBestMBAID and XOP



Contact MD-Group (R. Dejus) and ASD Operations (M. Borland)

- XOP (X-ray Optics); new version 2.4 to be released October 2013: http://www.aps.anl.gov/Science/Software/
- Use M. Borland's ChooseBestMBAID. On the Linux workstation: /usr/local/oag/apps/bin/linux-x86_64/chooseBestMBAID
- Web App: http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/cgi-bin/chooseBestMBAID.cgi

Discussions/Summary

- The issue of undulator phasing becomes important for the DLSR lattice. Remedies:
  - make one 4.8-m-long undulator instead of 2 x 2.4 m, however,
  - long undulators and a smaller minimum gap (8.5 mm instead of 10.5 mm) increase the attractive magnetic forces, but
  - we may make the magnets narrower in the horizontal direction (good field region 3 mm instead of 5 mm), and
  - use undulator with shorter periods (< 2.8 cm), so forces are expected to be less than for the Undulator A.
- Undulator gap precision is typically about 10 μm for the Undulator A and better for shorter period lengths (~ 5 μm). It may need to be set tighter for certain applications for the DLSR due to a smaller bandwidth.
- The power and on-axis power density for the DLSR undulators are typically higher by 30 – 50%. The power scales with E^2 and the power density with E^4 but we are operating at smaller gap with larger K value. For example, the Undulator A (3.3 cm) at 10.5 mm gap generates 6 kW power and 170 kW/mrad^2 power density and the U2.7 cm at 8.5 mm gap on the DLSR generates 9 kW power and 225 kW/mrad^2.
- Radiation damage may become increasingly important because of the smaller minimum gap. Need tighter beam-loss control and to consider SmCo magnet material, which has higher radiation resistance than NdFeB. (The tuning ranges would become somewhat smaller). All results presented here used NdFeB magnets.

Discussions/Summary

- Helical devices may be more prominent for the DLSR due to the round beam pipe. The brightness/flux is higher than for the planar devices (first harmonic only). Higher harmonics are strongly suppressed on-axis. The on-axis power density is also considerably lower for reasonably large K values.
- A remarkable increase in brightness and coherent flux is expected (> 100 x) for the DLSR. A more modest increase in flux is expected (2 – 3x).
- Use the software presented to explore options for your own beamlines. May set front end heat load limits too in the optimization code ChooseBestMBAID.