System Design for Self-Seeding the LCLS at Soft X-ray Energies

Yiping Feng

SXRSS Collaboration Team

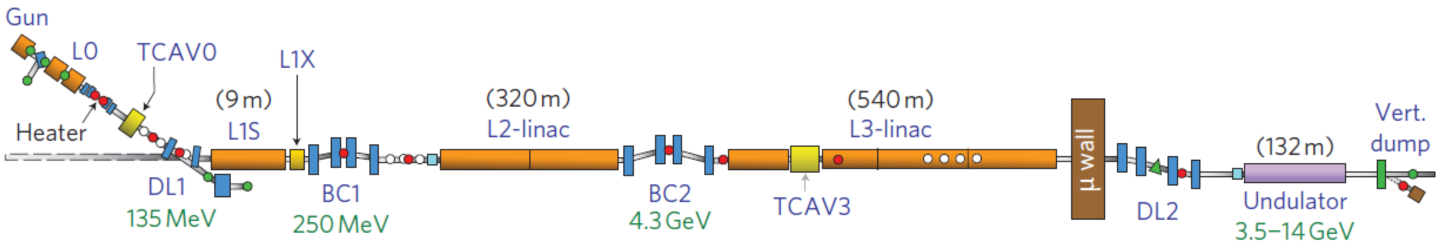
- LCLS, SLAC National Accelerator Laboratory
  - J. Amann, D. Cocco, Y. Feng, C. Field, J. Hastings, P. Heimann, Z. Huang, H. Loos, J. Welch, J. Wu
- ALS, Berkeley Lawrence National Laboratory
  - K. Chow, P. Emma, N. Rodes, R. Schoenlein

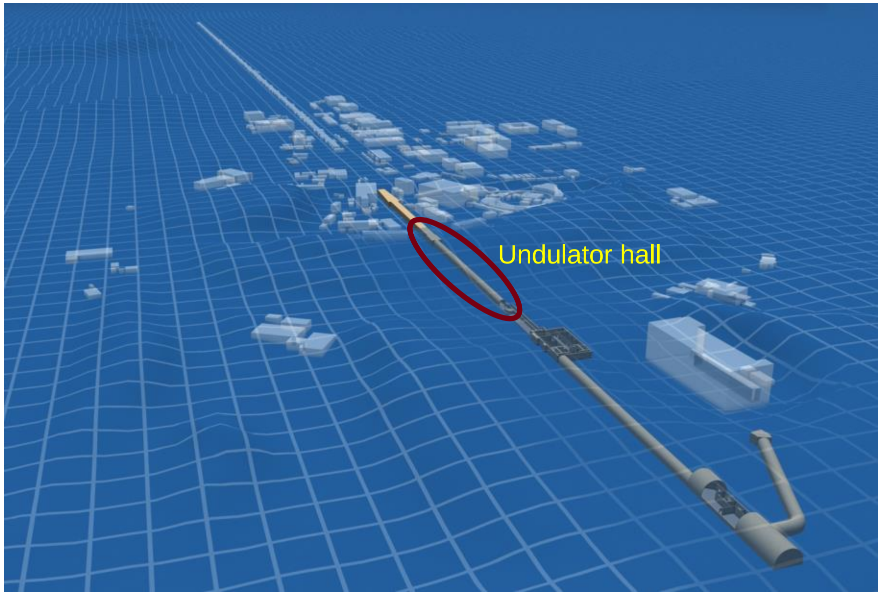
Outline

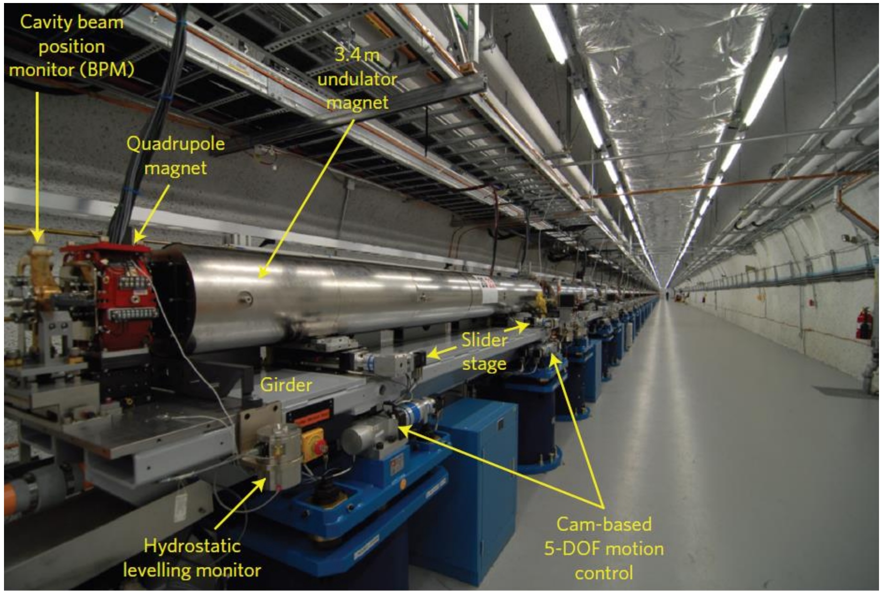
- Spectral fluctuations of LCLS-I SASE FEL
- Scientific drivers for seeded FEL
- System design of soft X-ray self-seeding at LCLS-I
  - Performance specifications
  - Hard X-ray self seeding at LCLS
  - X-ray optics
  - Electron optics
  - Alignment and diagnostic
- Simulations
- Mechanical design updates
- Summary

Linac Coherent Light Source

- LCLS-I is SASE based w/ 33 undulators
  - 500 eV to 10 keV, 5 – 50 fs, 5 mJ/pulse, lased in Apr. 2009*







* P. Emma *et al*, Nat. Photonics 4, 641 (2010).

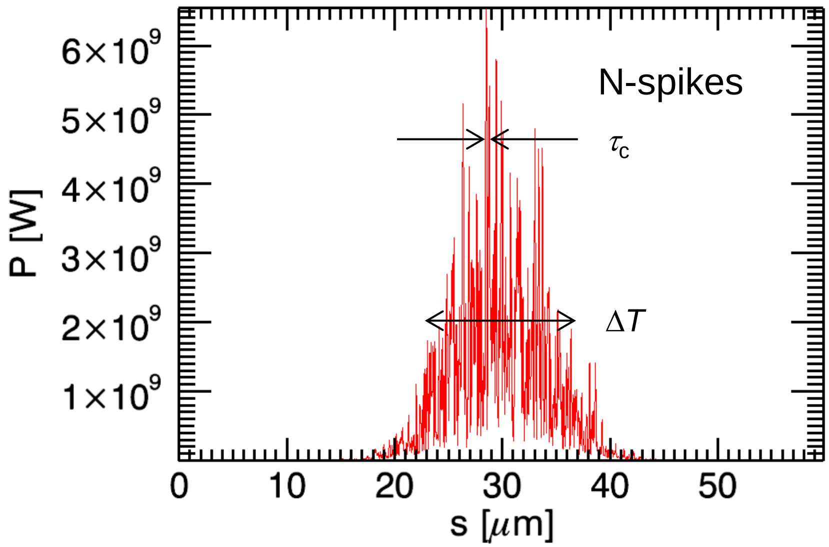
SASE FEL Characteristics

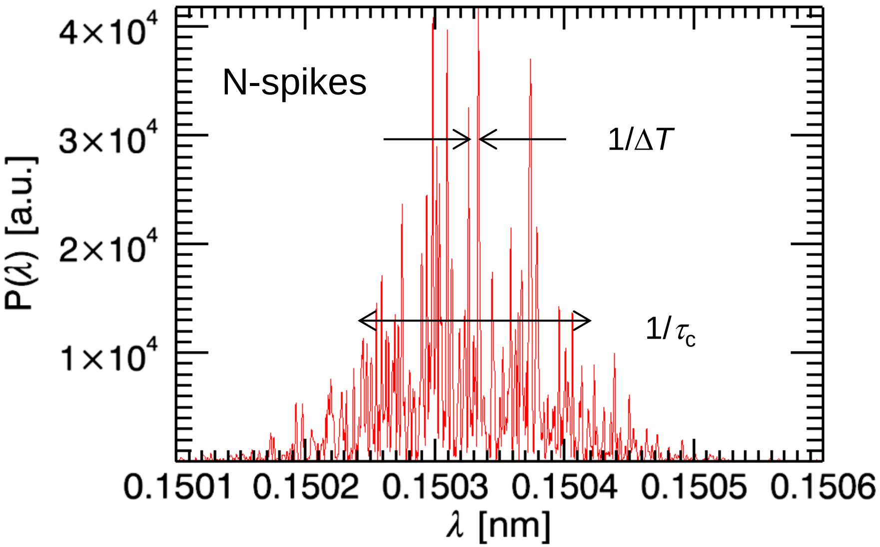
- SASE FEL starts from noise and is considered to be chaotic*

Temporal domain
(not easily measurable)

FEL simulation
Courtesy of J. Wu

Spectral domain
(readily measurable)





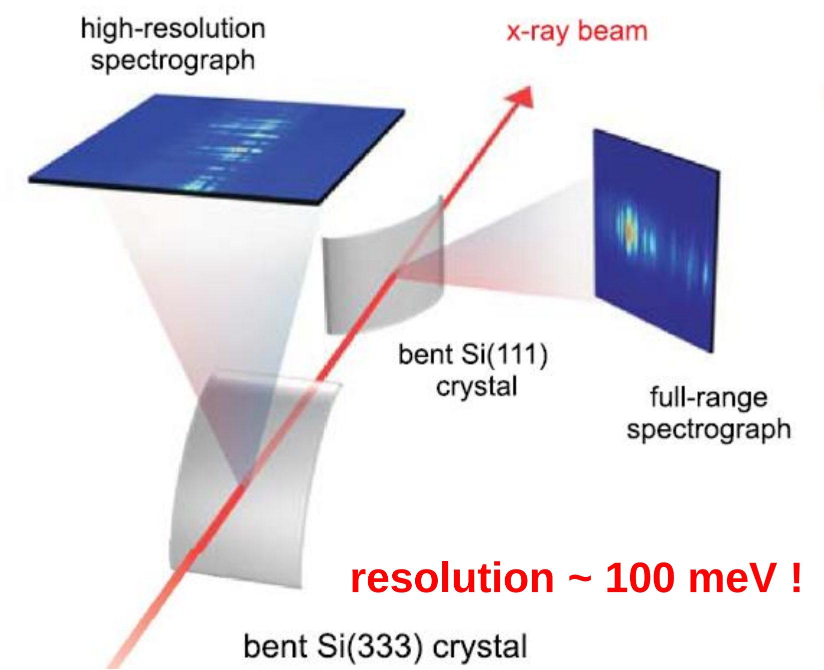
	Pulse duration	Coherence time	Spike width	Spectral range	# of spikes
Time domain	50 fs	200 as			250
Spectral domain			100 meV	25 eV	250

*for example, E. L. Saldin *et.al*. Opt. Comm. **148,** 383 (1998)

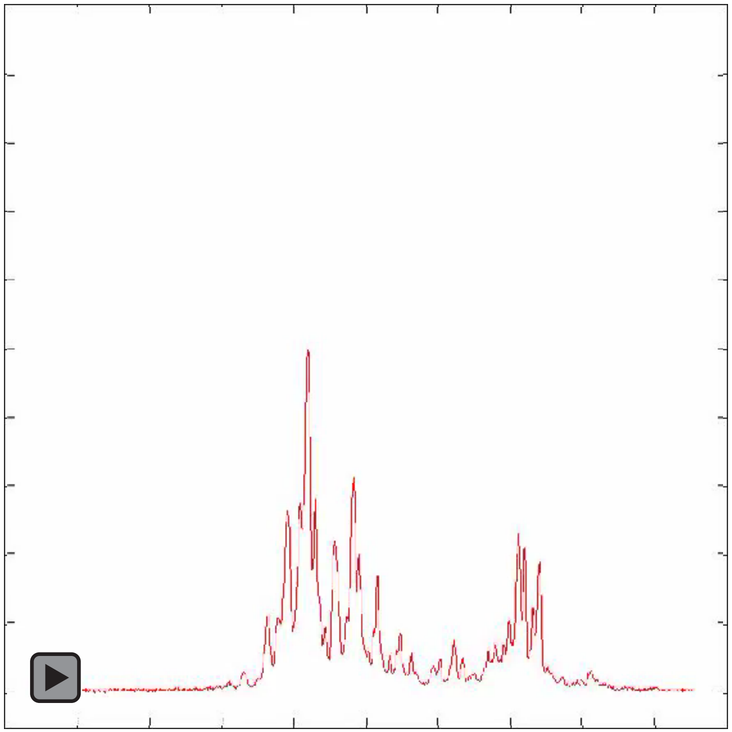
Single-shot Hard X-ray Spectrum

- “Every pulse is a new experiment!”

(a)



resolution ~ 100 meV !



APPLIED PHYSICS LETTERS **101**, 034103 (2012)

A single-shot transmissive spectrometer for hard x-ray free electron lasers

Diling Zhu,[a] Marco Cammarata,[b] Jan M. Feldkamp, David M. Fritz, Jerome B. Hastings, Sooheyong Lee,[c] Henrik T. Lemke, Aymeric Robert, James L. Turner, and Yiping Feng[a]

Linac Coherent Light Source, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA

SASE Stochastic behavior

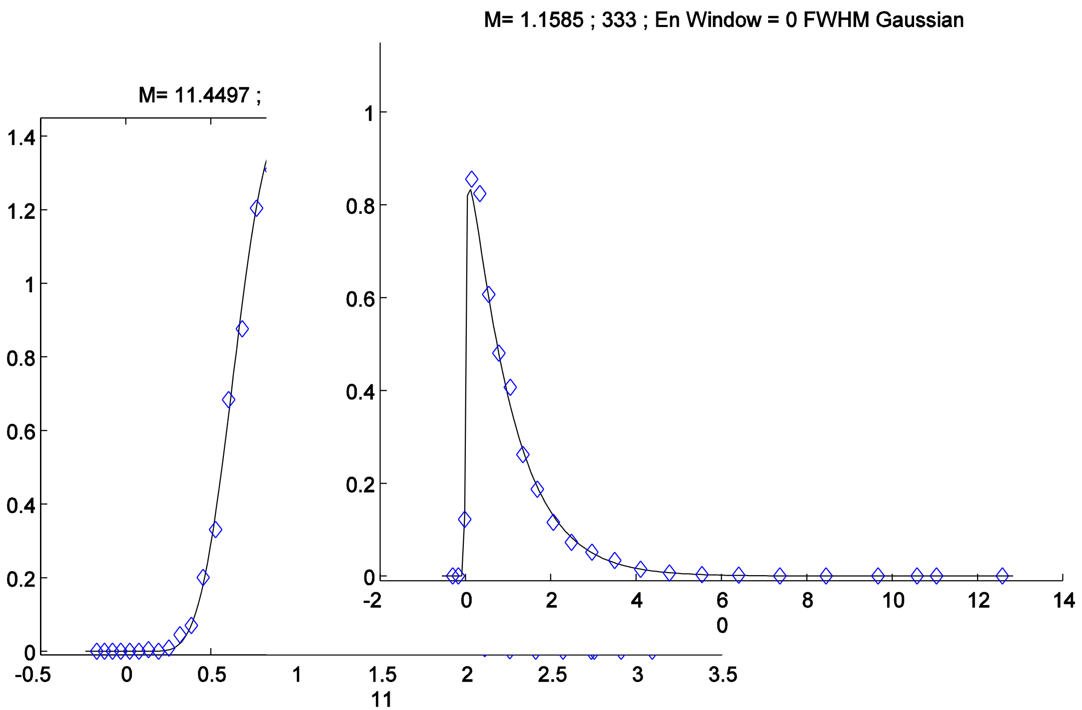
measured by high resolution spectrometer (100 meV @ 8.3 keV)

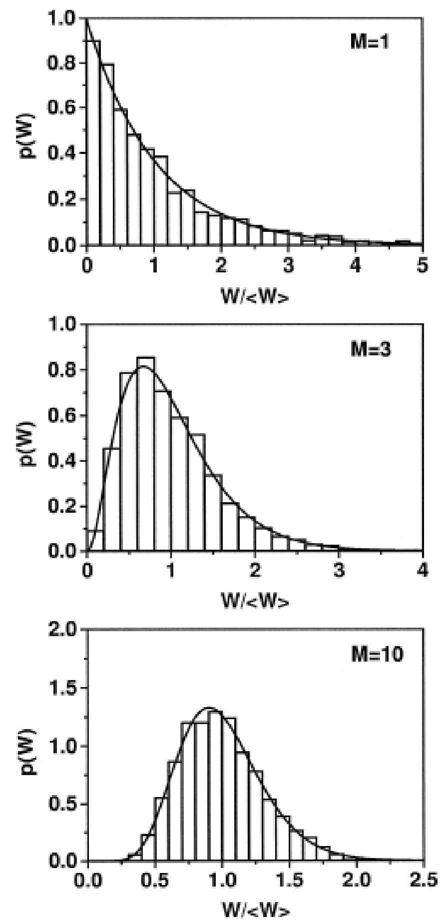
SLAC

- Intensity distribution in spectral domain

M = # of spikes in bandwidth

$$p(W) = \frac{M^M}{\Gamma(M)}\left(\frac{W}{\langle W\rangle}\right)^{M-1}\frac{1}{\langle W\rangle}\exp\left(-M\frac{W}{\langle W\rangle}\right),$$



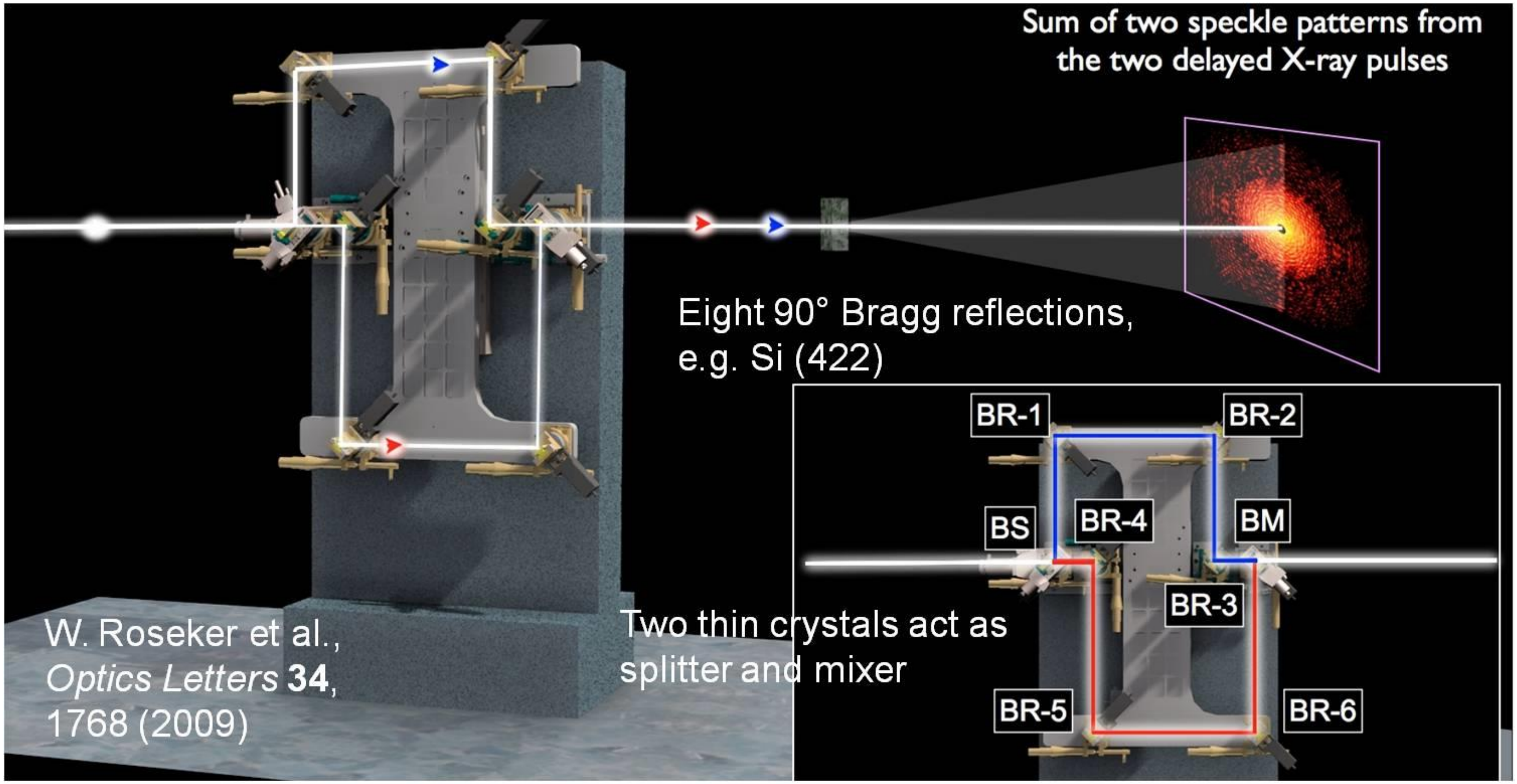


A. Lutman, Z. Huang, J. Krzywinski, J. Wu, and Y. Feng

*E. L. Saldin *et.al*. Opt. Comm. **148,** 383 (1998)

Experimental Challenges
when high resolution monochromator is required

X-ray Photon Correlation Spectroscopy w/ FEL and split-and-delay optics



90° diffraction angle gives fixed energy: 8.4 keV for Si (511), 7.9 keV for Si (422)

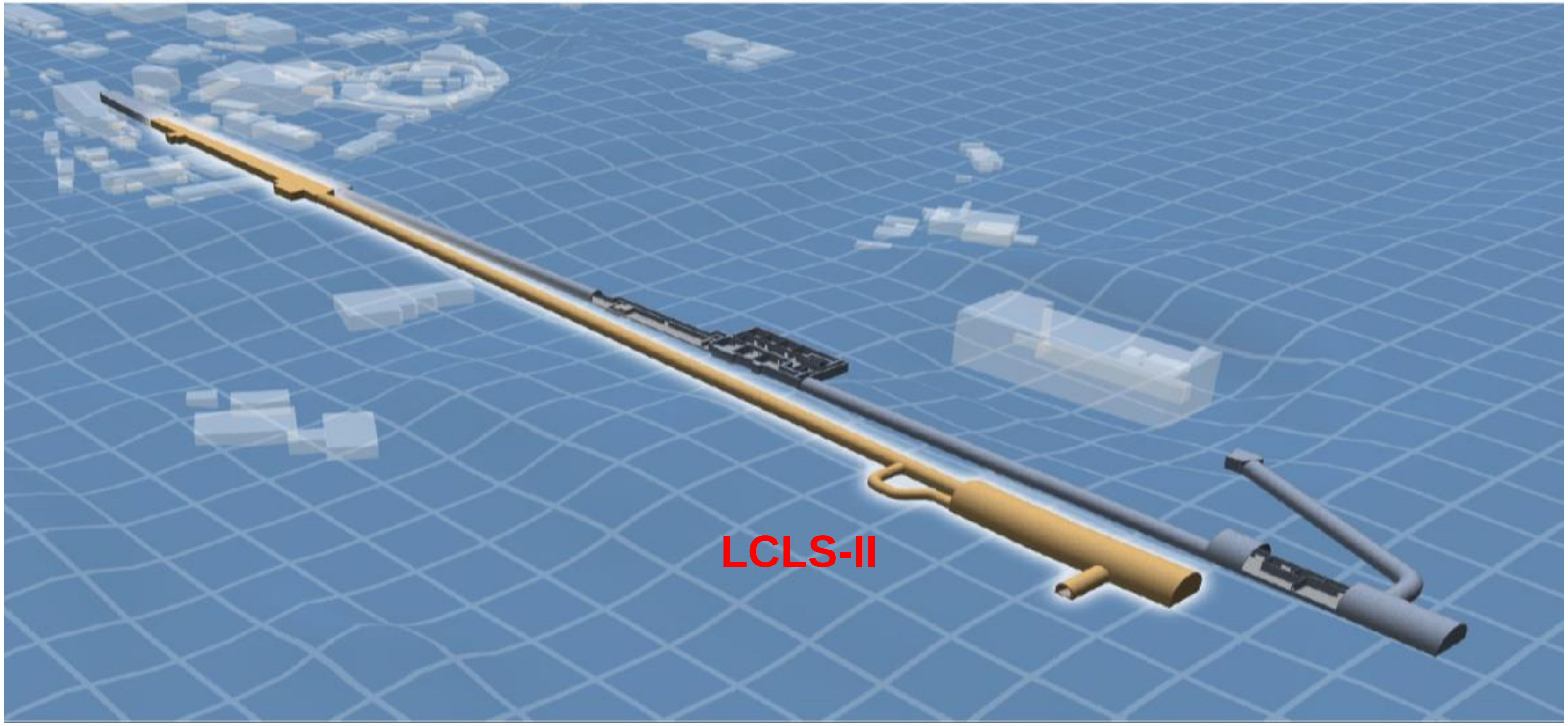
Courtesy of A. Robert and G. Gruebel

Scientific Drivers for Seeding

SLAC

LCLS-II NEW INSTRUMENTS WORKSHOPS REPORT

SLAC-R-993



Courtesy of P. Heimann & J. Hastings

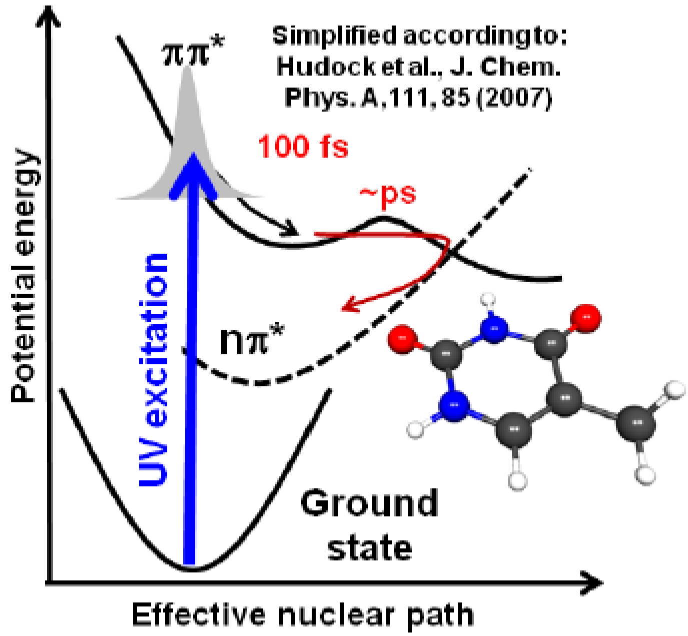
Key X-ray Parameters

Hard and soft x-ray self-seeding has the potential to dramatically narrow the bandwidth and enhance the peak power and temporal coherence.

Soft X-ray Science w/ Seeded FEL

- AMO science case-I
  - **Understanding electron-nuclear interaction in molecules by non-BOA* probing in the soft x-ray**

Non-adiabatic transition



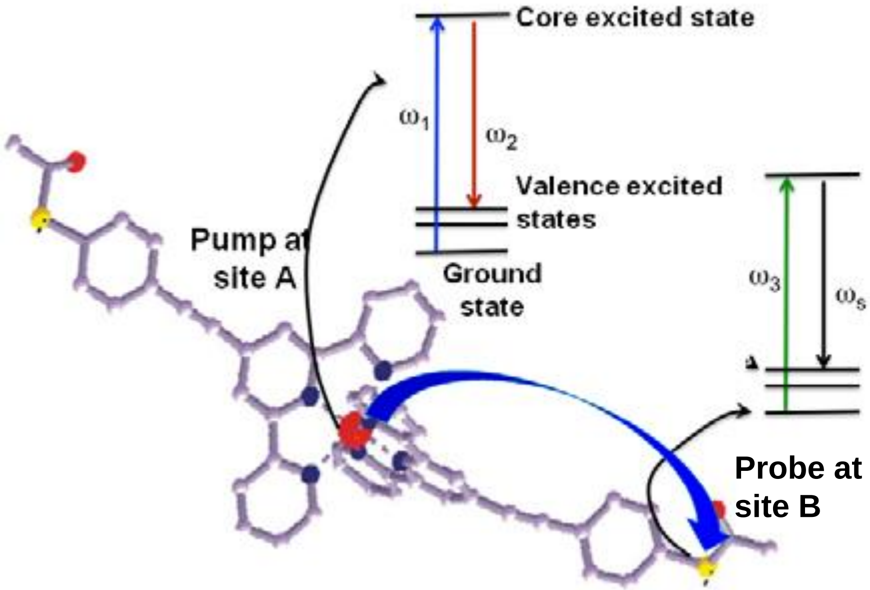
Simplified potential energy scheme for the nucleobase thymine
Excerpt from LCLS-II workshop

Requirements for LCLS-II
- Small bandwidth (5000 resolution) for absorption and emission studies, ideally with SXRSS
- Timing to VIS-UV laser on the order of 10 to 100 fs, either by active locking or by single shot timing tool
- X-ray fluorescence detectors, electron and ion time of flight spectrometers

*Born-Oppenheimer approximation

Soft X-ray Science w/ Seeded FEL

- AMO science case-II
  - **Understanding electron-electron interaction in molecules by studying Raman transitions**

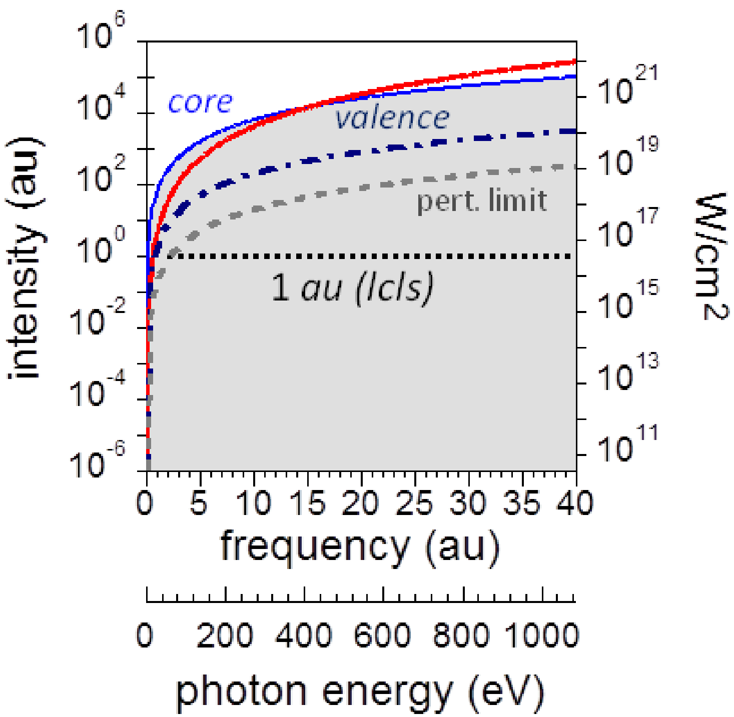


Requirements for LCLS-II
- Beams at different angles and different colors, time delays between multiple pulses
- Self seeding for tunable colors or shortest near Fourier limited pulses
- Intensities in the range 10^{17}-10^{18} W/cm^2
- X-ray fluorescence detectors

Excerpt from LCLS-II workshop

Soft X-ray Science w/ Seeded FEL

- AMO science case-III
  - **Understanding high intensity physics beyond the perturbation approximation**



Requirements for LCLS-II

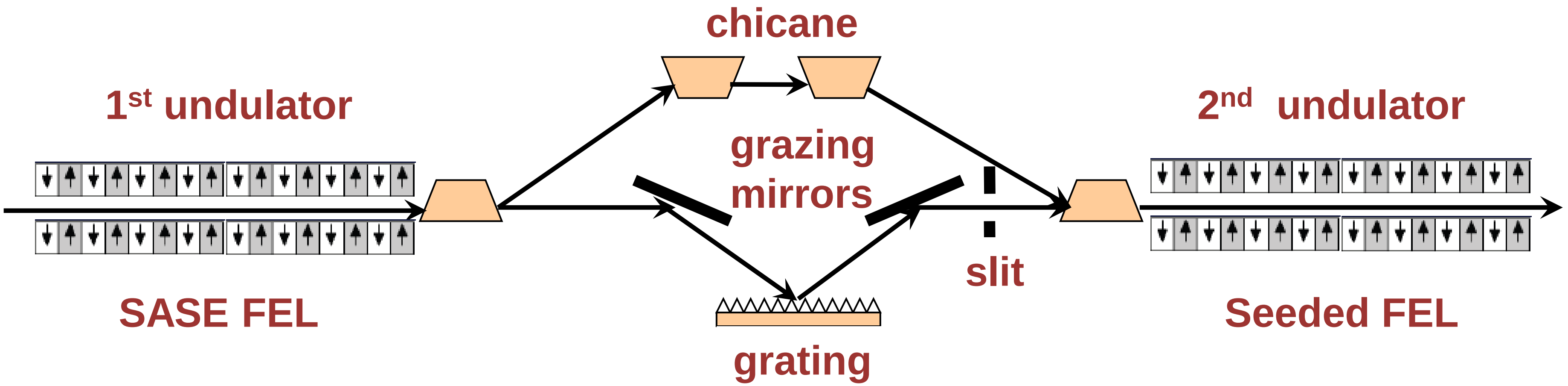
- Focusing system with minimal loss and intensities on the order of 10^{19} W/cm^2
- Time delay for x-ray pump-probe, 1st and 3rd harmonic
- Synchronized THz source
- Electron and ion detectors
- Scattering detector

TW capability
(implicitly requiring seeding)

Excerpt from LCLS-II workshop

SASE FEL Self-Seeding[1,2]

- First undulator generates SASE
- X-ray monochromator filters SASE and generates seed
- Chicane delays electrons and washes out SASE micro-bunching
- Second undulator amplifies seed to saturation



- Long x-ray path delay (~10 ps) requires large chicane that take space and may degrade beam quality
- Reduce chicane size by using two bunches[3] or single-crystal wake monochromator[4]

1. J. Feldhaus et al., NIMA, 1997.
2. E. Saldin et al., NIMA, 2001.
3. Y. Ding, Z. Huang, R. Ruth, PRSTAB, 2010.
4. G. Geloni, G. Kocharyan, E. Saldin, DESY 10-133, 2010.

Hard X-ray Self-Seeding @ LCLS-I

SLAC

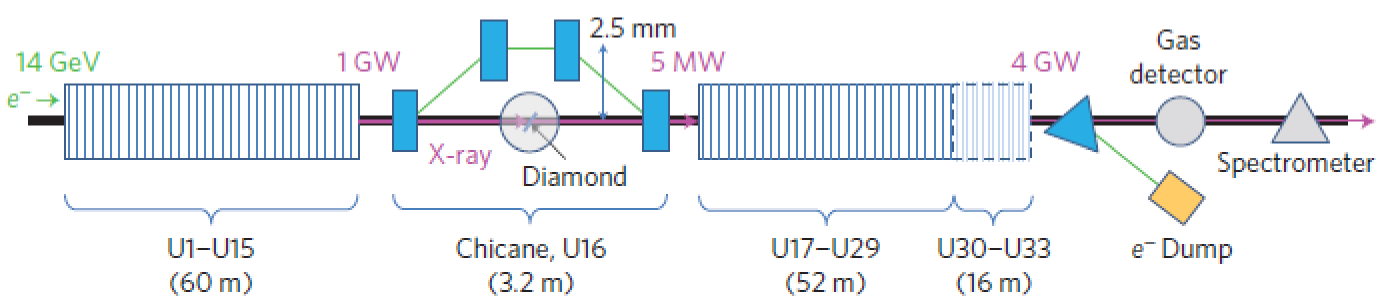
nature photonics

ARTICLES

PUBLISHED ONLINE: XX XX 2012 | DOI: 10.1038/NPHOTON.2012.180

Demonstration of self-seeding in a hard-X-ray free-electron laser

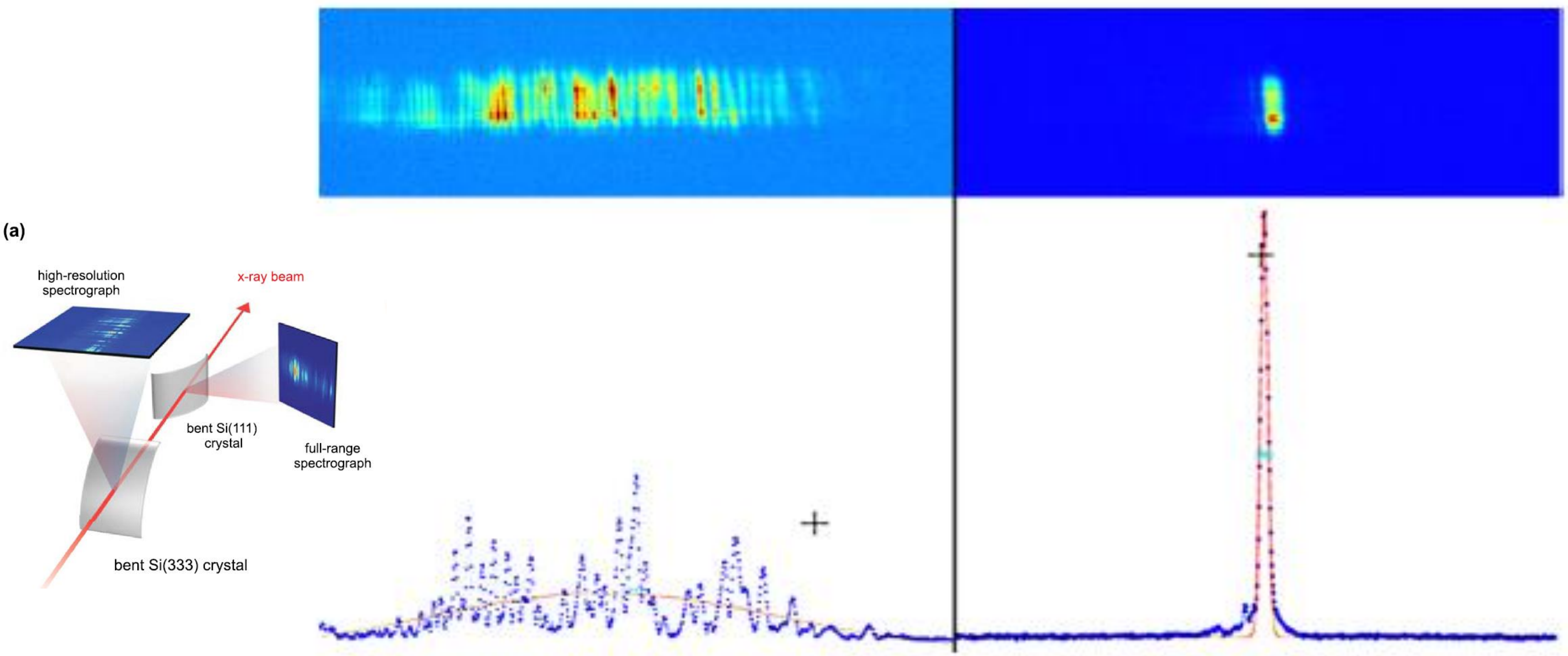
J. Amann[1], W. Berg[2], V. Blank[3], F.-J. Decker[1], Y. Ding[1], P. Emma[4*], Y. Feng[1], J. Frisch[1], D. Fritz[1], J. Hastings[1], Z. Huang[1], J. Krzywinski[1], R. Lindberg[2], H. Loos[1], A. Lutman[1], H.-D. Nuhn[1], D. Ratner[1], J. Rzepiela[1], D. Shu[2], Yu. Shvyd'ko[2], S. Spampinati[1], S. Stoupin[2], S. Terentyev[3], E. Trakhtenberg[2], D. Walz[1], J. Welch[1], J. Wu[1], A. Zholents[2] and D. Zhu[1]



Proposed by Geloni, Kocharyan, Saldin, *DESY 10-133, 2010*

Unequivocal signature of seeding

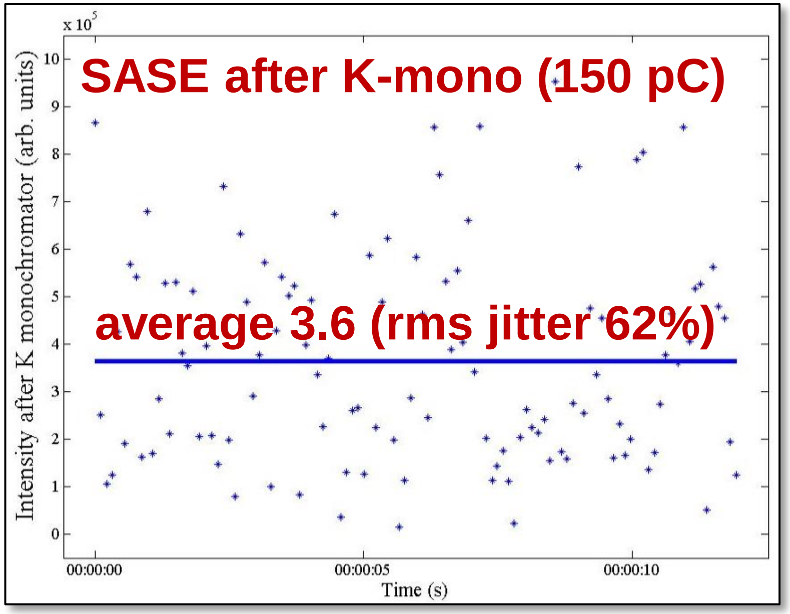
- Hard X-ray single-shot spectrometer
  - High resolution @ 100 meV



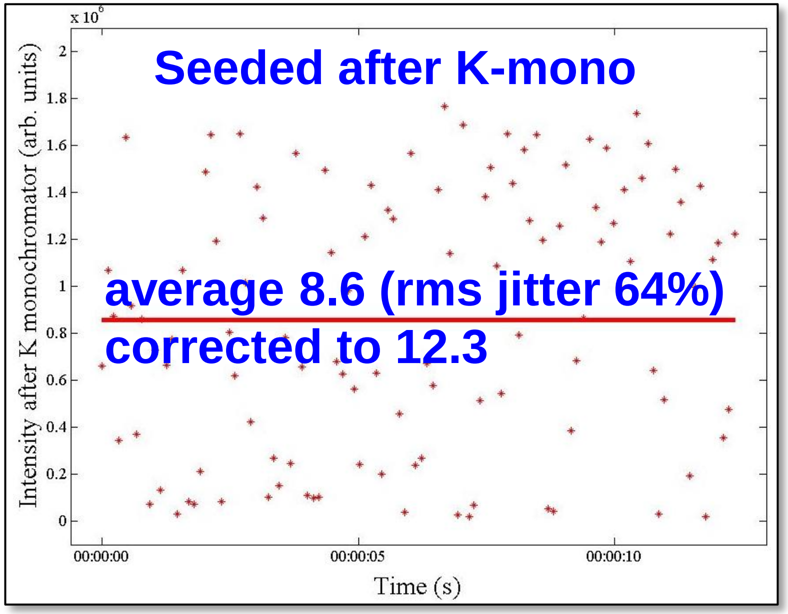
Most Important Performance Metric

- Intensity of best SASE after a mono w/ given $\Delta E/E$ vs. intensity of best SEEDED after a mono of $\Delta E/E$

SASE 2 mJ after K-mono (1eV BW @8 keV)
Solid attenuator 6, 8, 9 in



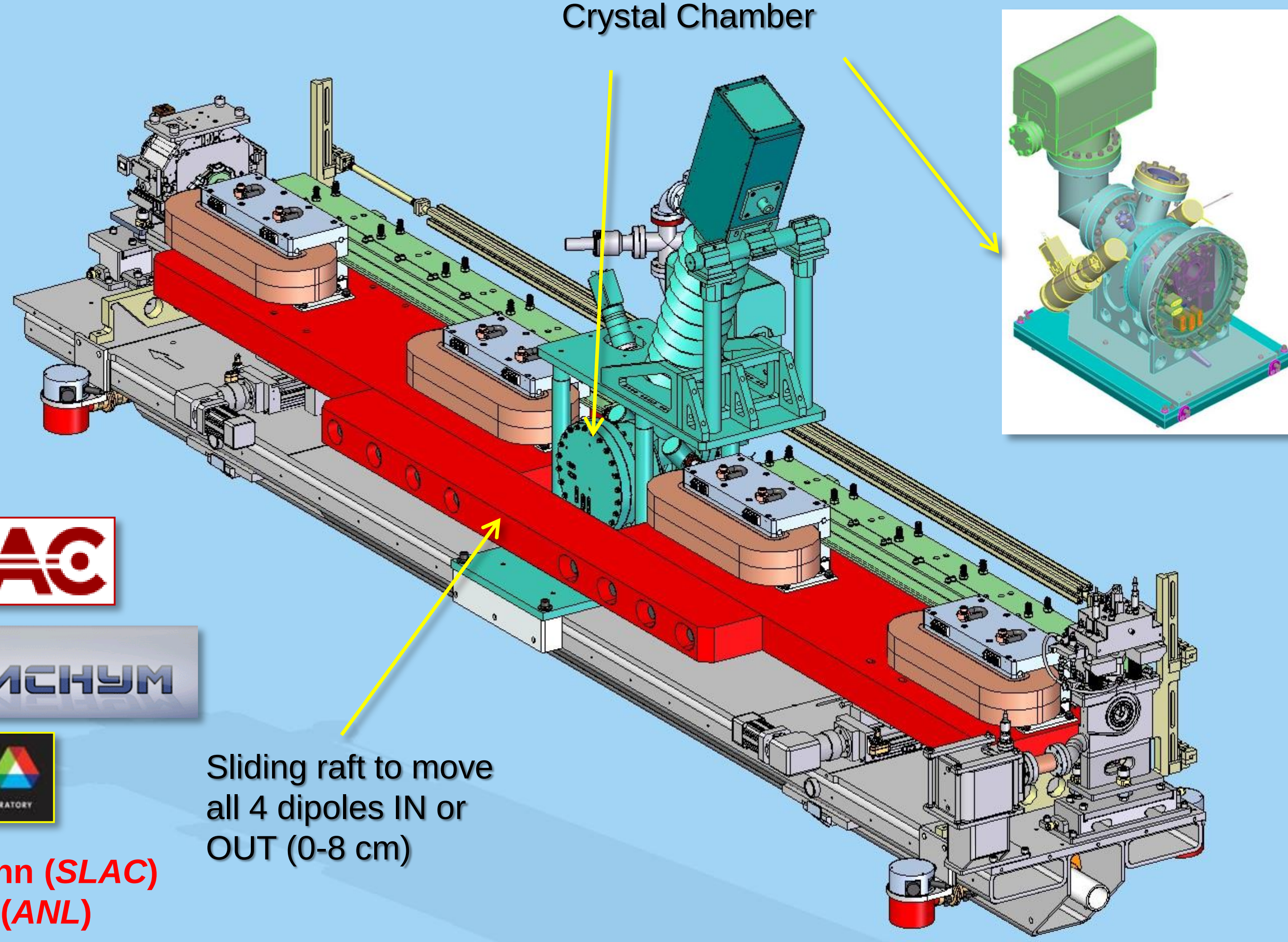
Seeded (U1-2 out) after K-mono
Solid attenuator 1-6, 8, 9 in



Spectral brightness increase = 12.3/3.6 = 3.5

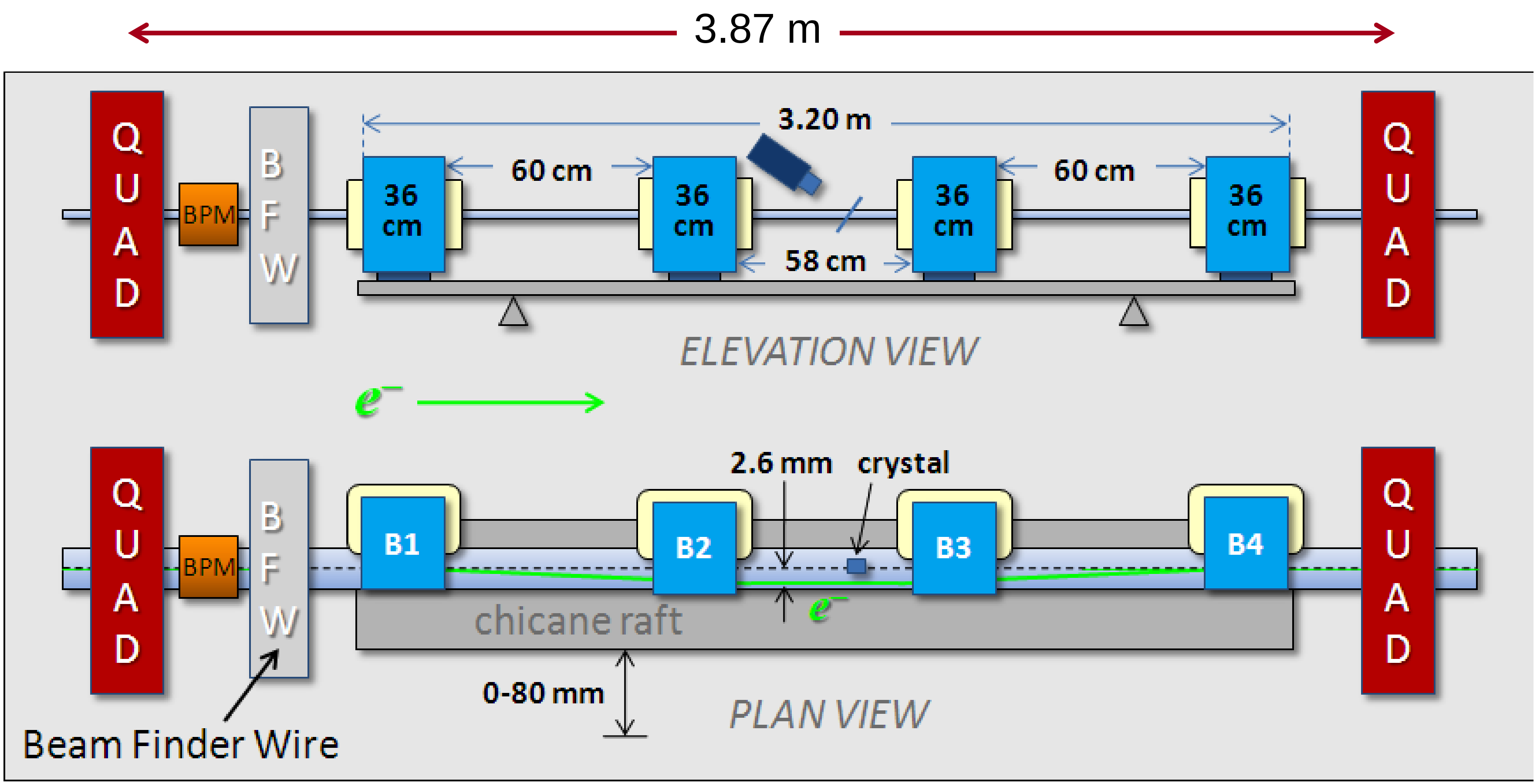
J. Welch et al., to be presented at FEL2012

HXRSS System @ LCLS-I



J. Amann (*SLAC*)
D. Shu (*ANL*)

HXRSS system @ LCLS-I



Original SXRSS Optical Design
for LCLS-II

- Primary performance specifications
  - (Grating Monochromator) resolving power to make pulse fully coherent, assuming flat-top profile
    - 200 eV, ΔT_{FWHM} =118 fs, R = 6400
    - 2000 eV ΔT_{FWHM} =41.6 fs, R = 22700
  - Seeding power (at start of 2nd undulator) required after all optics (from J. Wu)
    - 200 eV: > 10 kW
    - 2000 eV: > 20 kW
  - Seeding beam collinear w/ original beam
    - Transverse profile maintained if possible
  - Time delay
    - ~ 5 ps
    - Variable delay in tuning range is acceptable if within 10%

Y. Feng, J. Wu, *et al*., proceedings of 2010 FEL conference, Malmo, Sweden (2010).

Large Footprint of Original Design

- Cylindrical focusing mirror M1
- Plane pre-mirror M2
- Variable-line-spacing grating G
- Slit
- Spherical focusing mirror M3

15 m >> 3.87 m of LCLS-I inter-undulator space

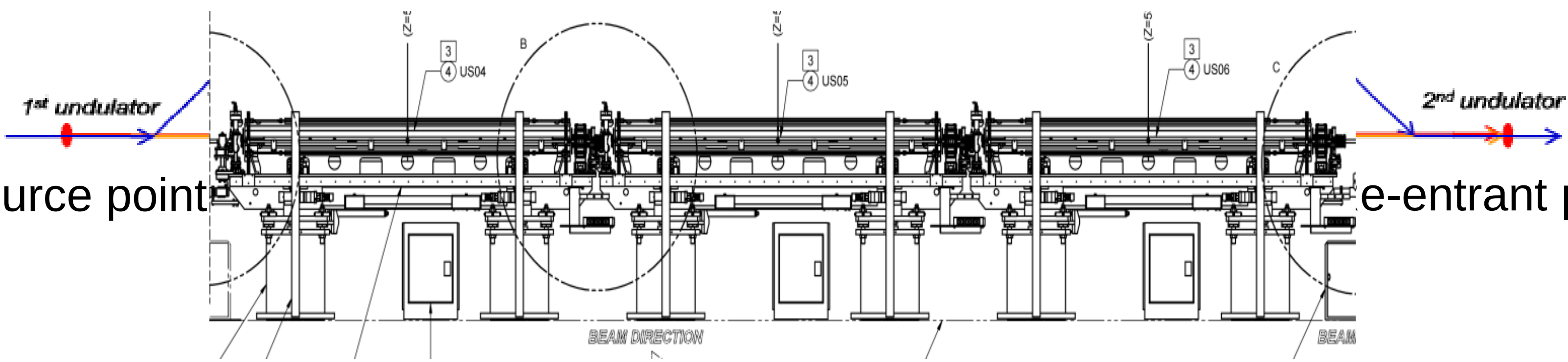
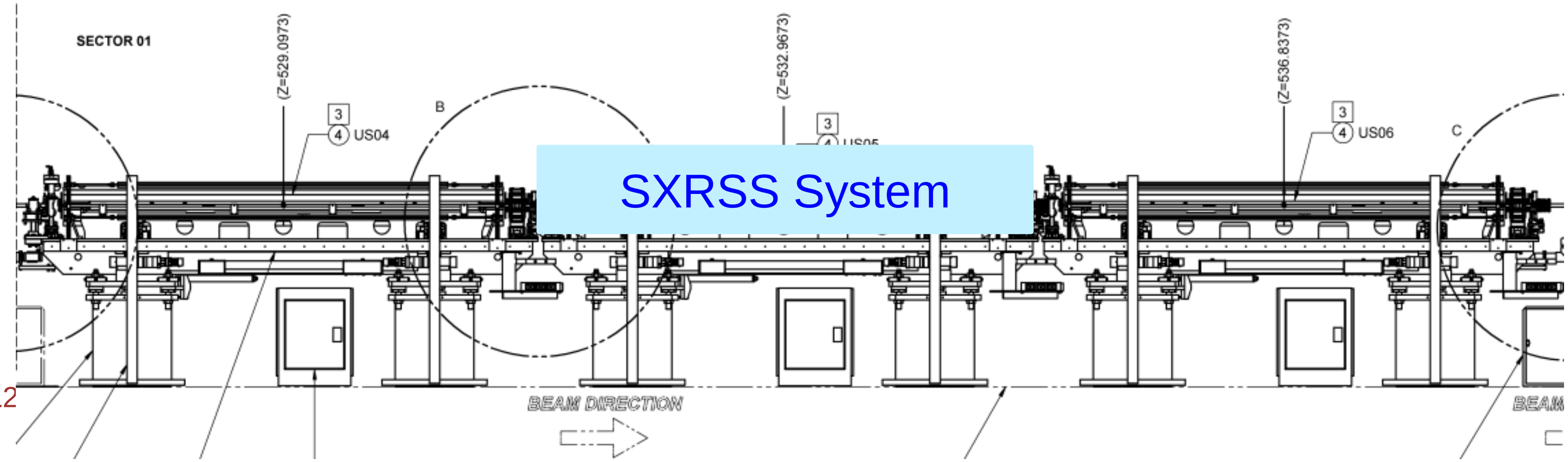


Figure 1: Schematics of the optics for soft X-ray self-seeding the LCLS-II.

Y. Feng, J. Wu, *et al.*, proceedings of 2010 FEL conference, Malmo, Sweden (2010).

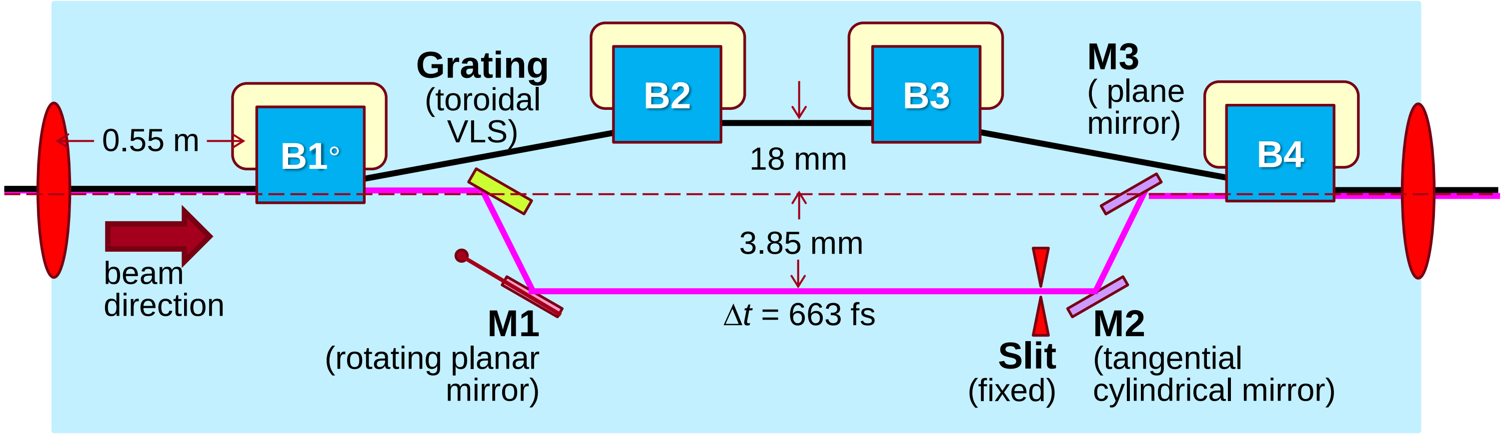
SXRSS for LCLS-I

- Physics requirements for X-ray optics
  - All optical components to fit a single undulator segment (3.87 m)
  - Resolving power > 5000
  - Energy range 500 to 1000 eV
  - Optical delay < 1 ps
  - Provide 1:1 imaging of source at equivalent point in seeding undulator
  - 20 kW seed power
  - Stay clear from e-beam by > 2.5 mm



Current X-ray Optics Design

- Toroidal variable-line-spacing grating G
  - Tangential radius of curvature R_t
  - Sagittal radius of curvature R_s
- Plane post-mirror M1
- Slit
- Cylindrical focusing mirror M2
- Plane mirror M3 for steering



SXRSS System

System Performance Specifications

Parameter	Nominal	Minimum	Maximum	Unit
Photon energy	500-1000	300	1200	eV
Electron energy	3.35-4.74	2.6	5.2	GeV
Repetition rate	120	1	120	Hz
Bunch charge	150	10	250	pC
e- bunch length	25	5	50	fs
γ bunch length	36-18	-	-	fs
Photon bandwidth	2×10^{-4}	-	-	-

Grating Specifications

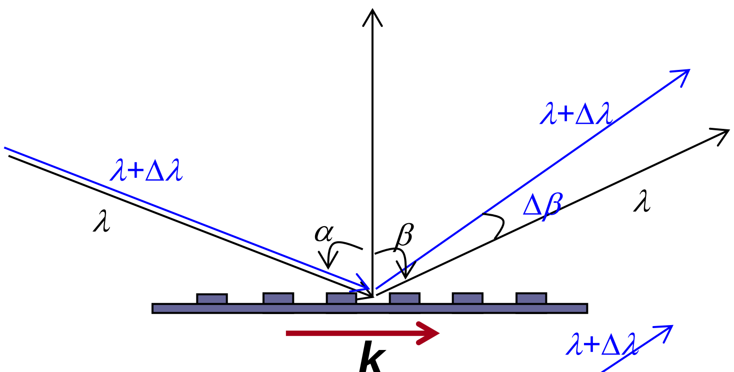
Parameter	Nominal	Minimum	Maximum	Unit
Line density (D_0)	1123	0.2%	0.1%	1/mm
Linear coeff. (D_1)	1.6	1%	0.2%	1/mm^2
Quad. coeff. (D_2)	0.002	100%	2%	1/mm^3
Groove profile	Blazed 1.2°	-	-	n/a
Tangential radius	195	1%	0.1%	m
Sagittal radius	18	5%	1%	cm
Diffraction order	+1	-	-	-
Incident angle	89.00	-	-	°
Exit angle	85.61-86.82			°

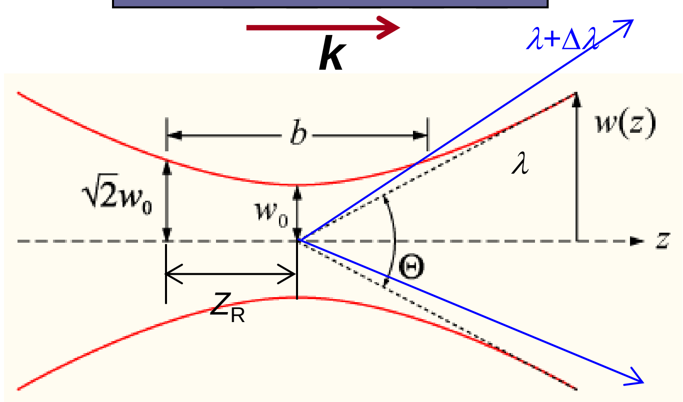
Dispersion

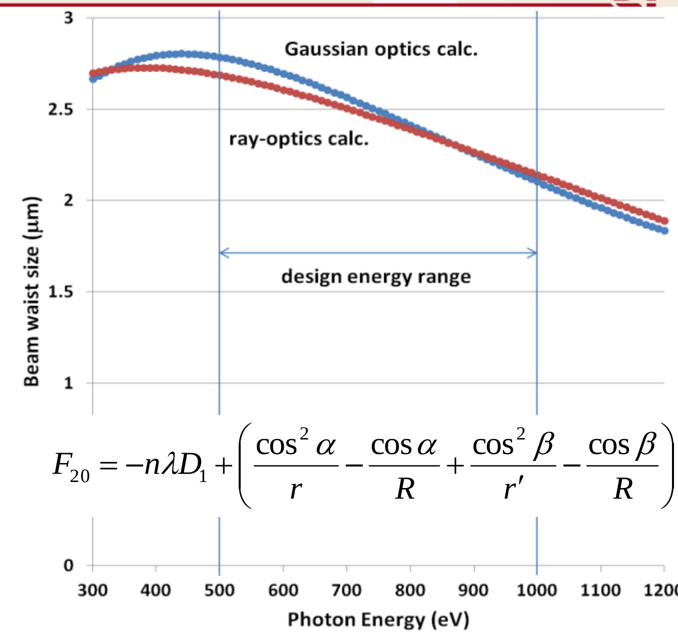
- Angular dispersion

$$\Delta\beta = -\frac{\lambda / R}{\sigma \cos\beta}$$

  - At required resolving power, much smaller than diffraction, requiring focusing for spatial separation







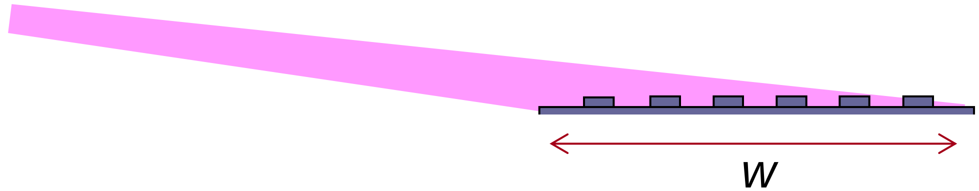
$$F_{20} = -n\lambda D_1 + \left(\frac{\cos^2\alpha}{r} - \frac{\cos\alpha}{R} + \frac{\cos^2\beta}{r'} - \frac{\cos\beta}{R} \right)$$

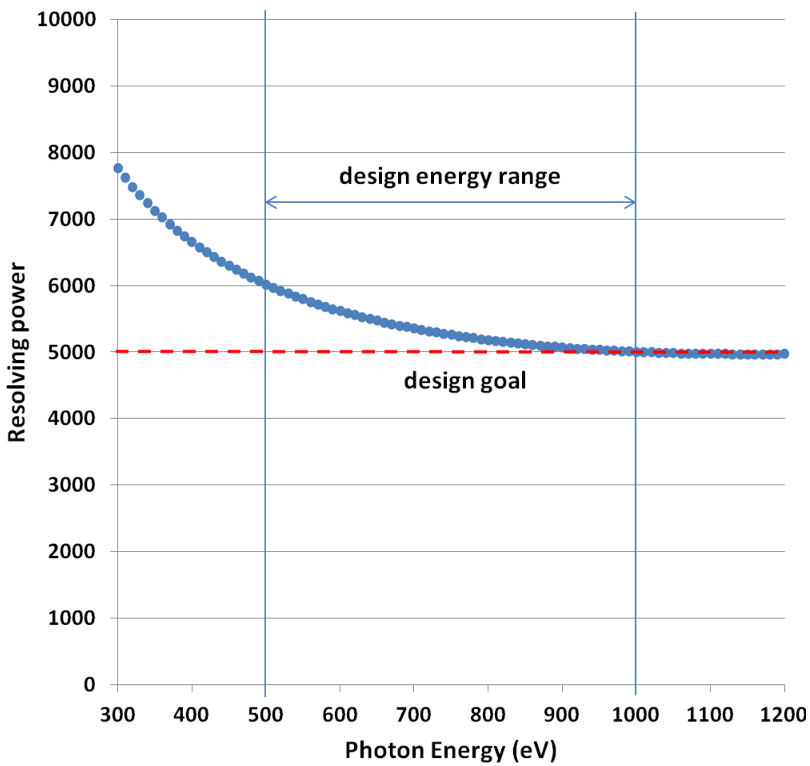
Source distance	**2972-4157**	**-**	**-**	**mm**
Source size	**30.6-24.7**	**-**	**-**	**µm**
Image distance	**1346.7-1348**	**-**		**mm**
Image size	**3-2.4**	**-**	**-**	**µm**
Exit slit location	**1348**	**0.1**	**0.1**	**mm**
Exit slit size	**3**	**5%**	**5%**	**µm**
Optical delay	**797.9-662.8**	**-**	**-**	**fs**

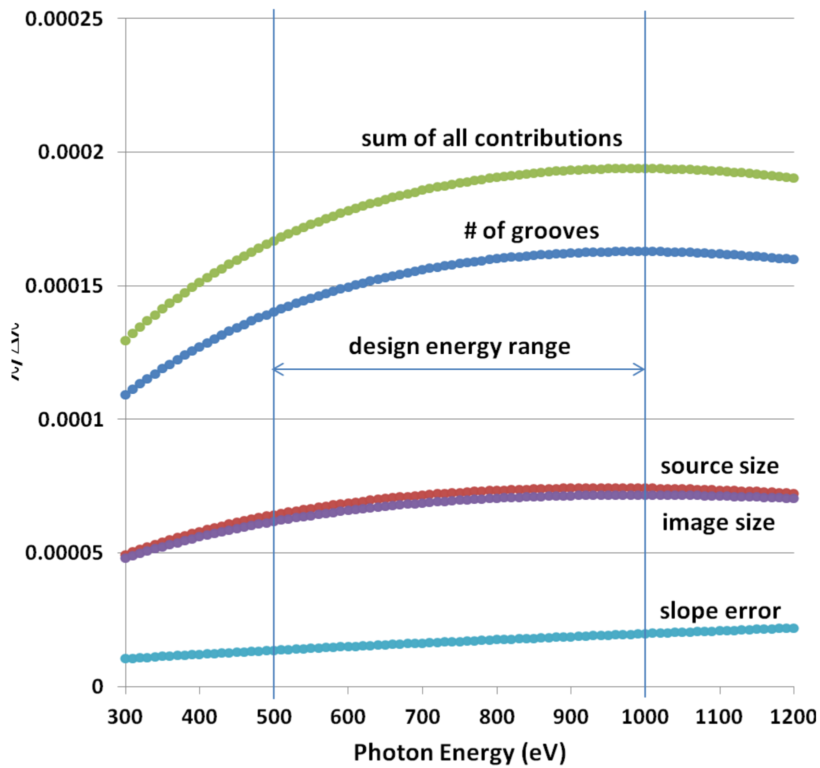
Resolving Power

- Resolving power is diffraction-limited

$$\frac{\Delta\lambda}{\lambda}=\frac{1}{N}=\frac{1}{D_0 w}$$

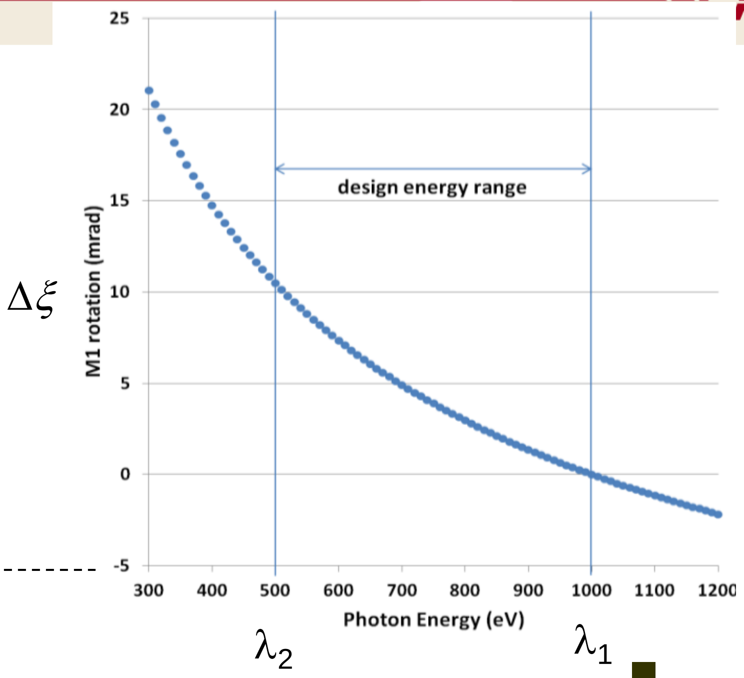


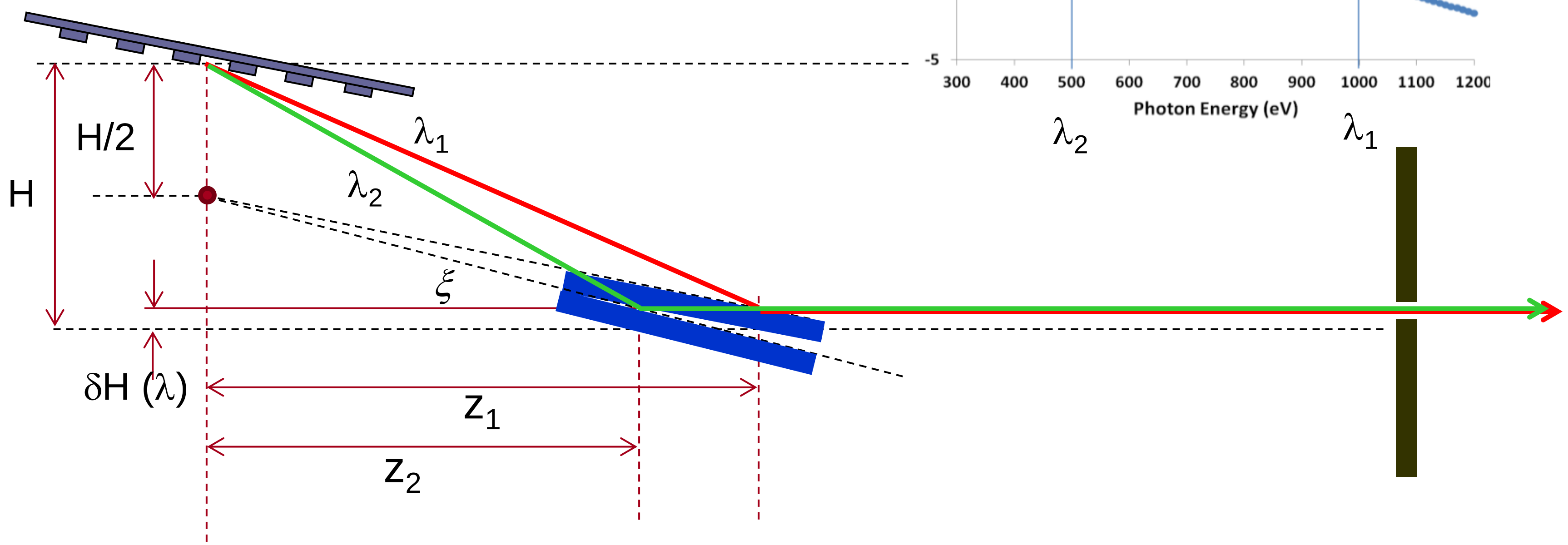




Energy Tuning

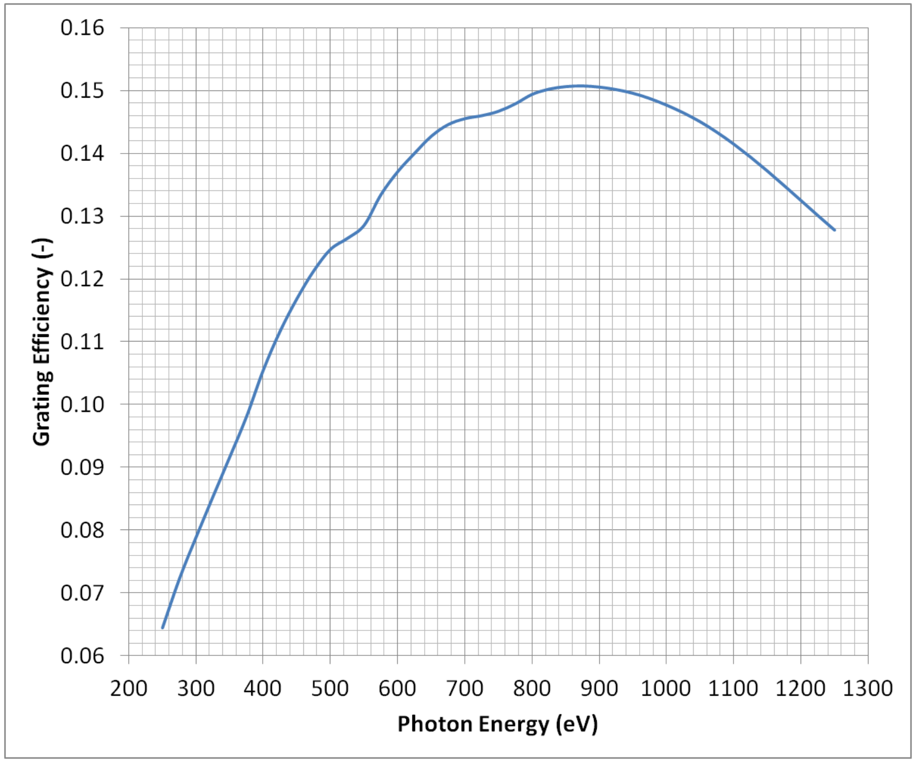
- Tuning achieved by a single rotation of M1
- Optical delay variable
  - 663 ➔ 798 fs (0.27 fs/eV)



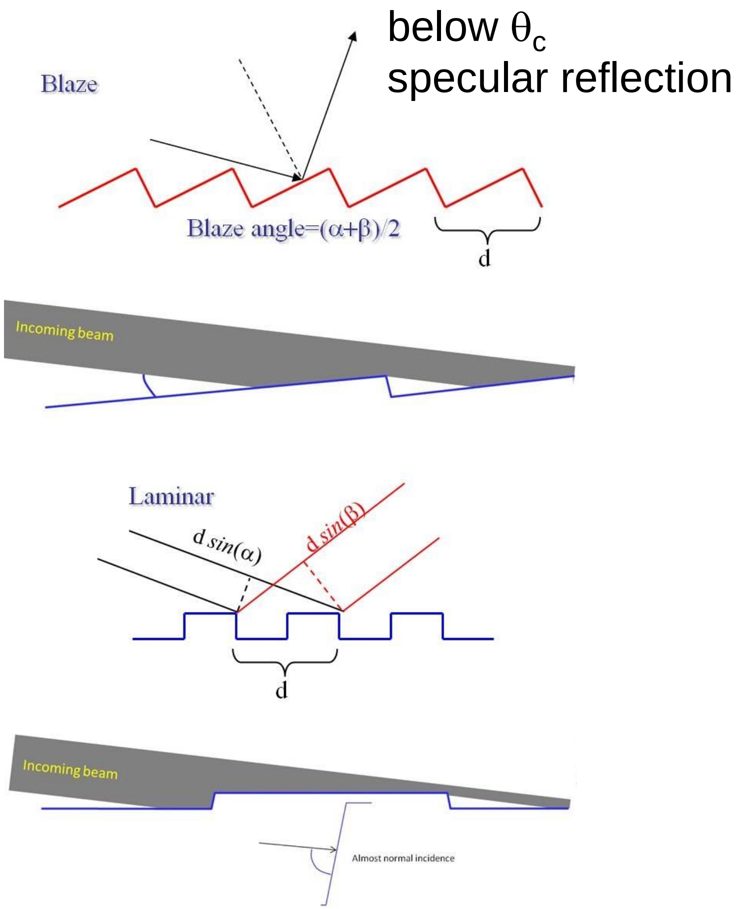


Grating Efficiency

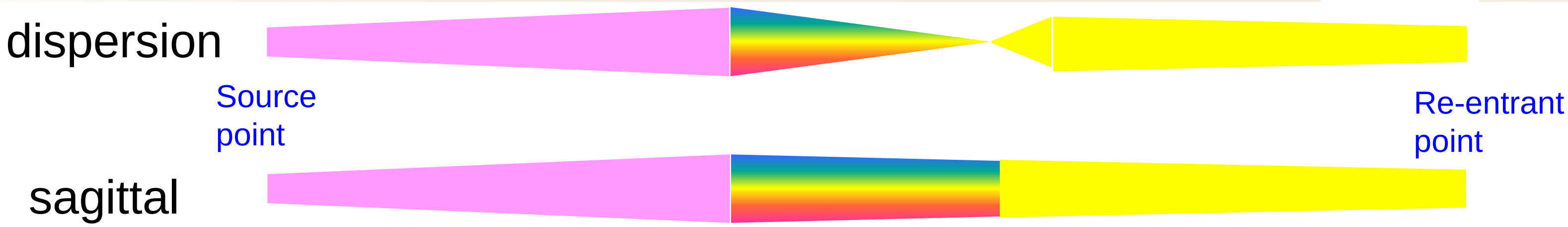
- Use blazed profile for greater efficiency & high damage threshold w/ Pt coating

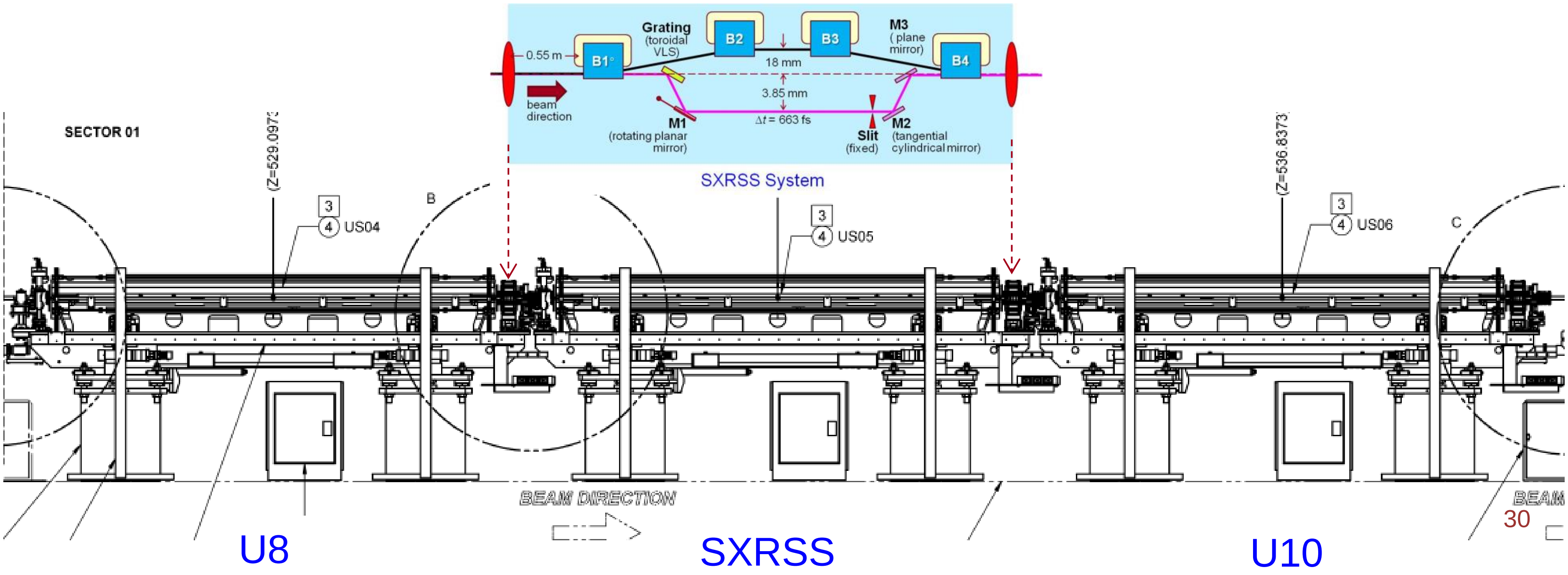


"Lumnab" code written by M. Neviere

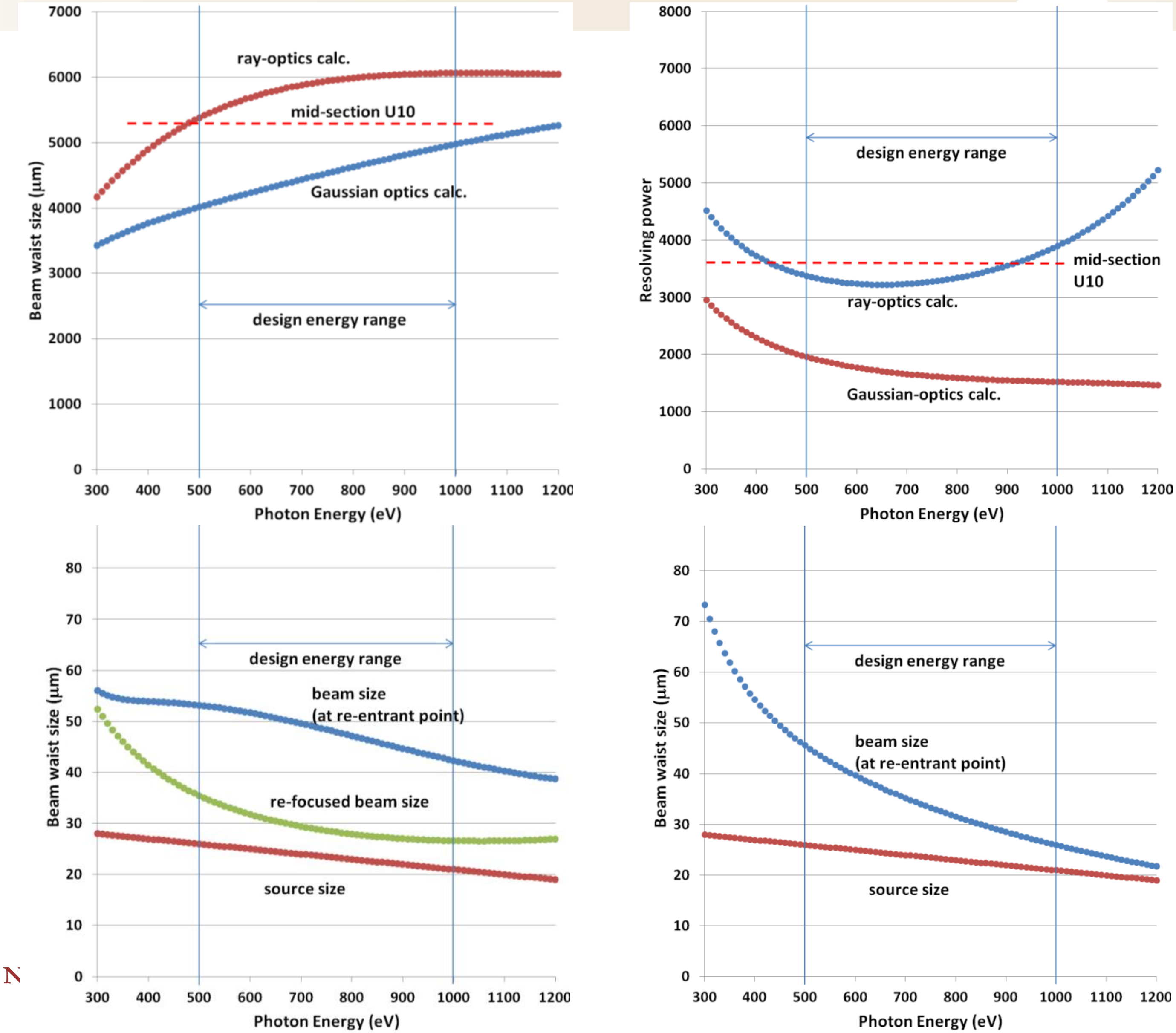


Imaging

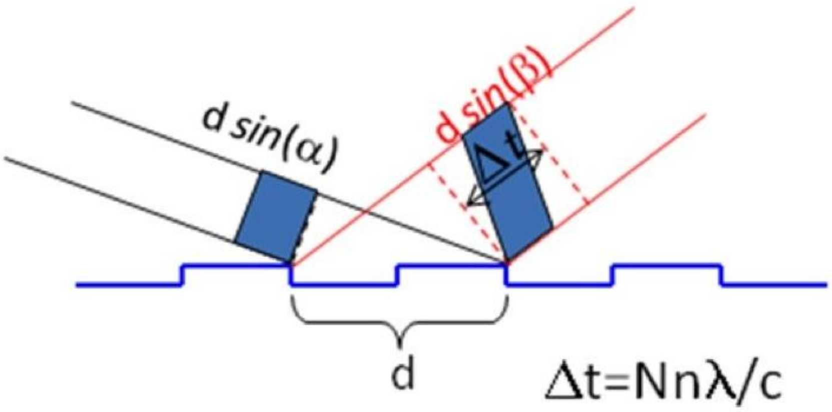

dispersion
Source point
Re-entrant point
sagittal

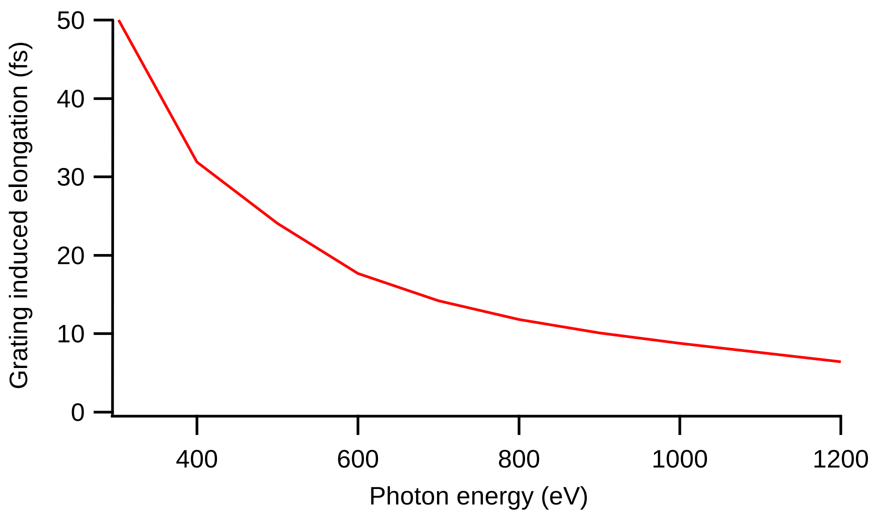

Grating (toroidal VLS)
B1
B2
B3
B4
M3 (plane mirror)
0.55 m
18 mm
3.85 mm
Δt = 663 fs
beam direction
M1 (rotating planar mirror)
Slit (fixed)
M2 (tangential cylindrical mirror)
SXRSS System
SECTOR 01
(Z=529.097
(Z=536.8373
US04
US05
US06
BEAM DIRECTION
U8
SXRSS
U10

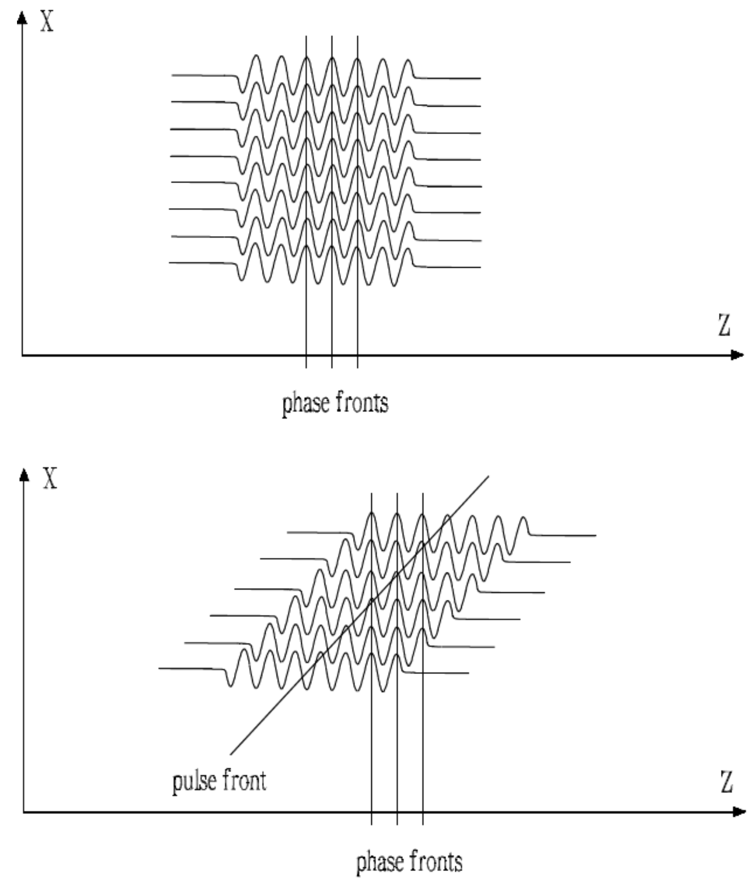
Imaging
(w/ Gaussian and Ray Optics)



Pulse-Front Tilt and Elongation



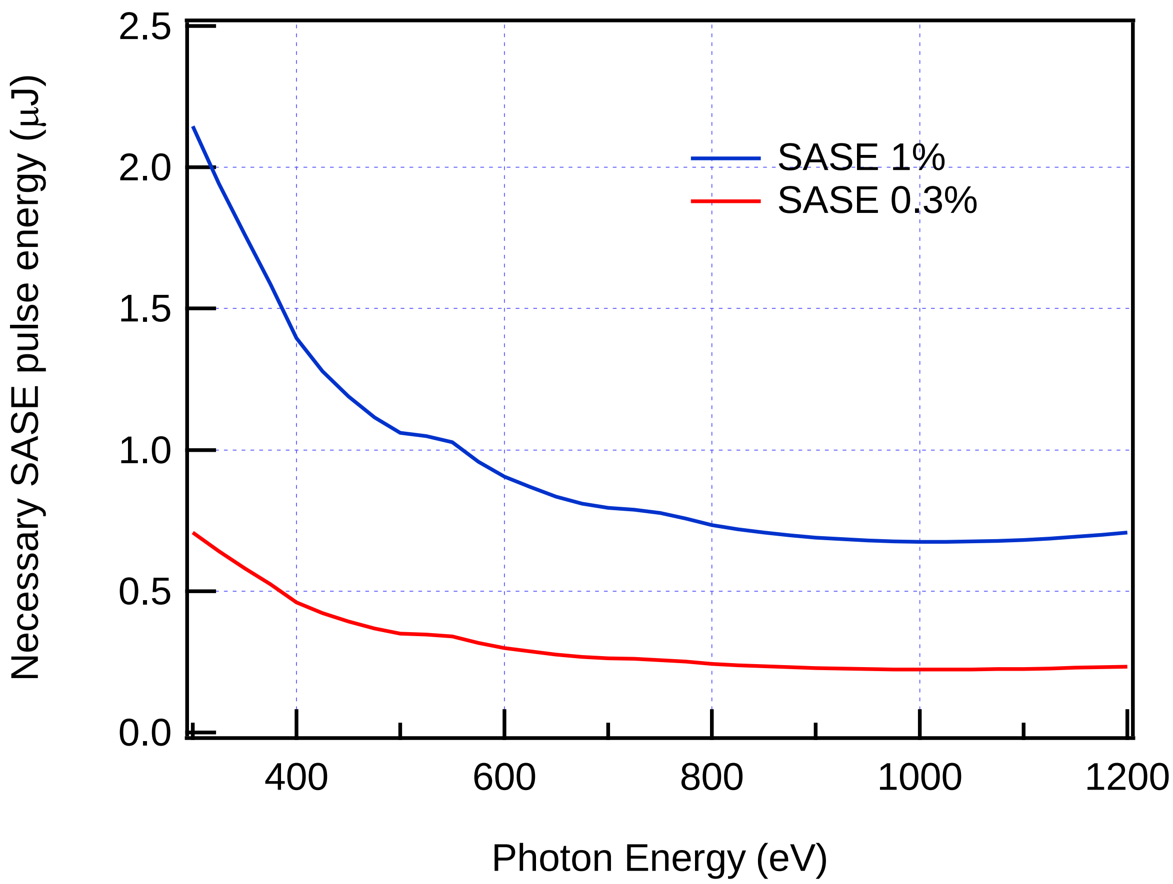




G. Geloni et al, DESY 12-051, 2012

Minimum Required Source Power

- Assuming 50 fs pulse length to produce 20 kW seed power



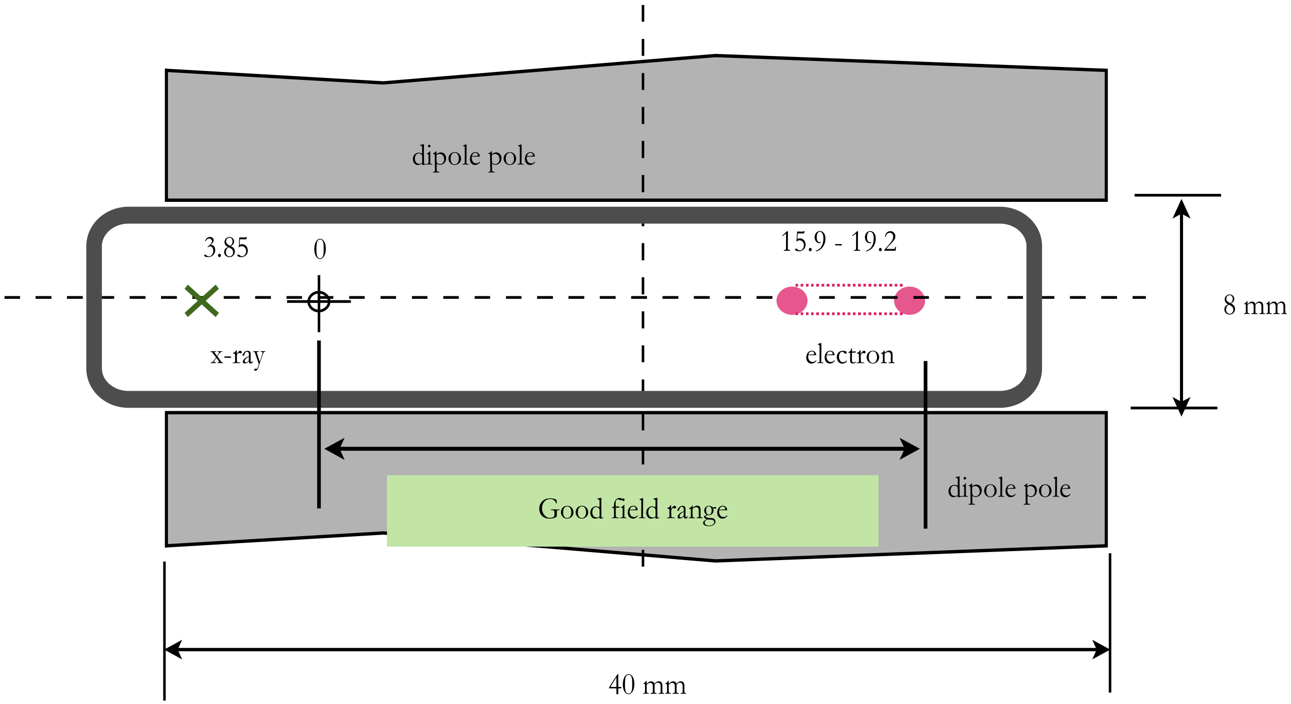
Technical Challenges

- Production and assembly of small optics
  - Grating's slope error < 1 μrad
  - Radius of curvature of M3 > |1 km|

- Alignment not trivial
  - System tolerances < those of SR monochromators
  - Tight space due to co-location w/ magnetic chicane
  - Only limited diagnostics available

Magnetic Chicane

- Four-dipole chicane system



Beam paths with horizontal displacements noted for the electron and X-ray beams are shown for the 1 keV case.

Magnetic Chicane

- Main parameters of the electron beam chicane

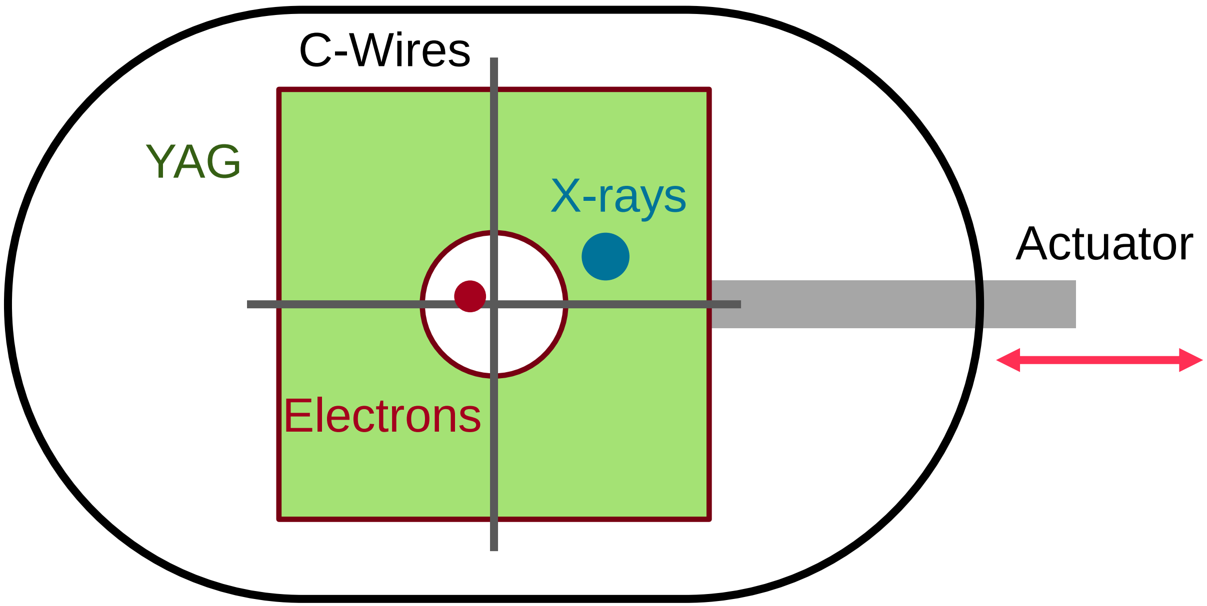
Parameter	Nominal	Minimum	Maximum	Unit
e- beam delay	633-930	300	1000	fs
Delay precision	0.1	0	1	fs
R_{56}	477-397	0	600	μm
Dipole bend angle	14.91-13.59	0	16.739	mrad
e- beam displ.	19.2-15.9	0	20	mm
H. separation	4.3-3.4	2	-	mm
Residual angle	0	0.0	0.1	μrad
Residual offset	0	0.0	3.0	μm

Diagnostics Design

- YAG:Ce crystal
  - Good sensitivity to both beams
  - Simultaneous observation of both beams
  - Radiation dose from e-beam exceeds undulator radiation damage tolerance
- Wire
  - Proven performance of undulator BFW meets e-beam requirement
  - X-ray position from secondary electrons induced in wire by x-rays and read out through charge amplifier
  - X-ray signal might be too weak, studies underway, but not conclusive yet if scheme might work

Possible Implementations

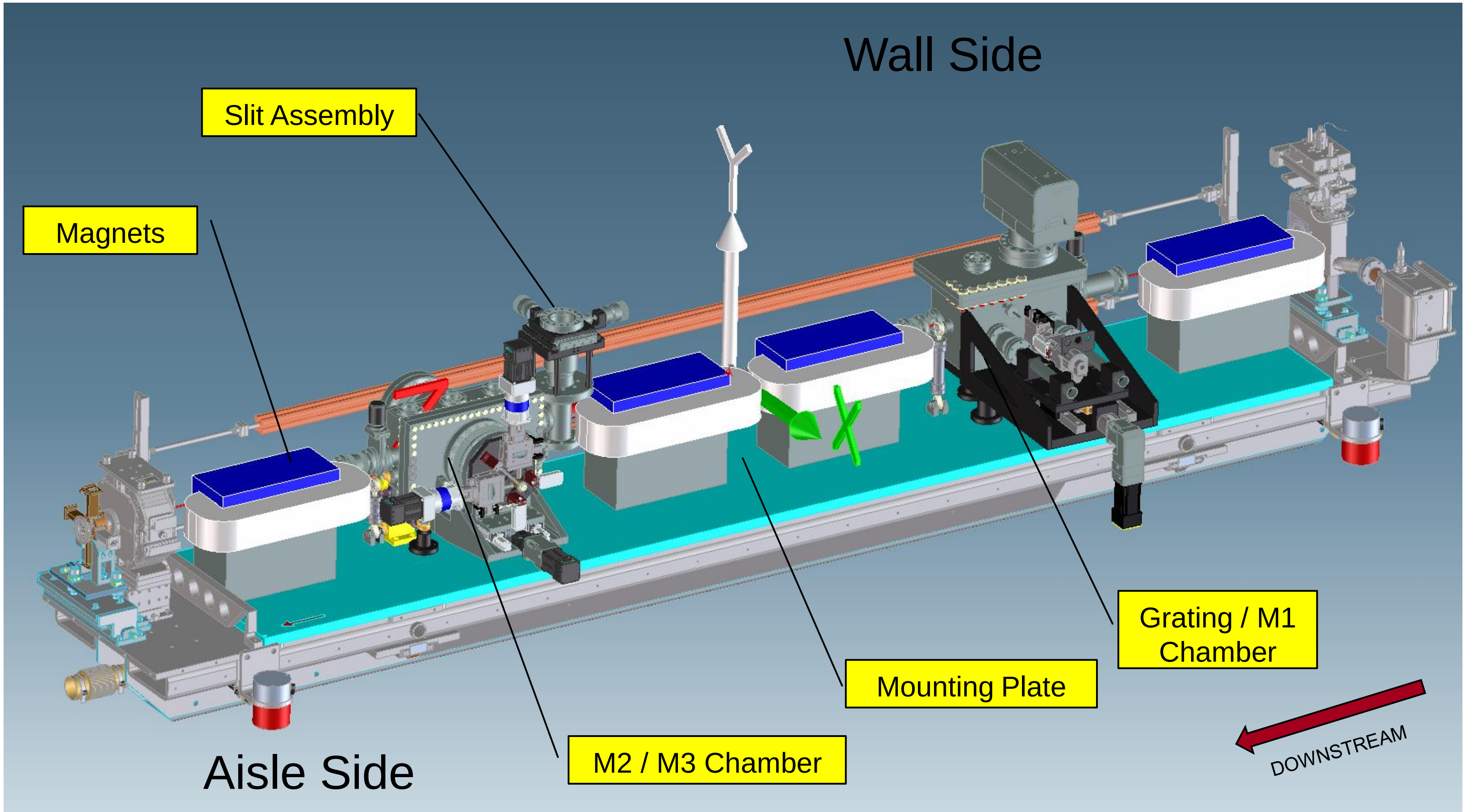
- Combination device
  - Wire for e-beam & YAG for x-rays on same actuator
  - Relative position of wire and x-ray beam image monitored by CCD



- Placed in long breaks between girders 9&10 and 12&13
- Scan position of whole assembly with upstream girder end

LBNL Current Design

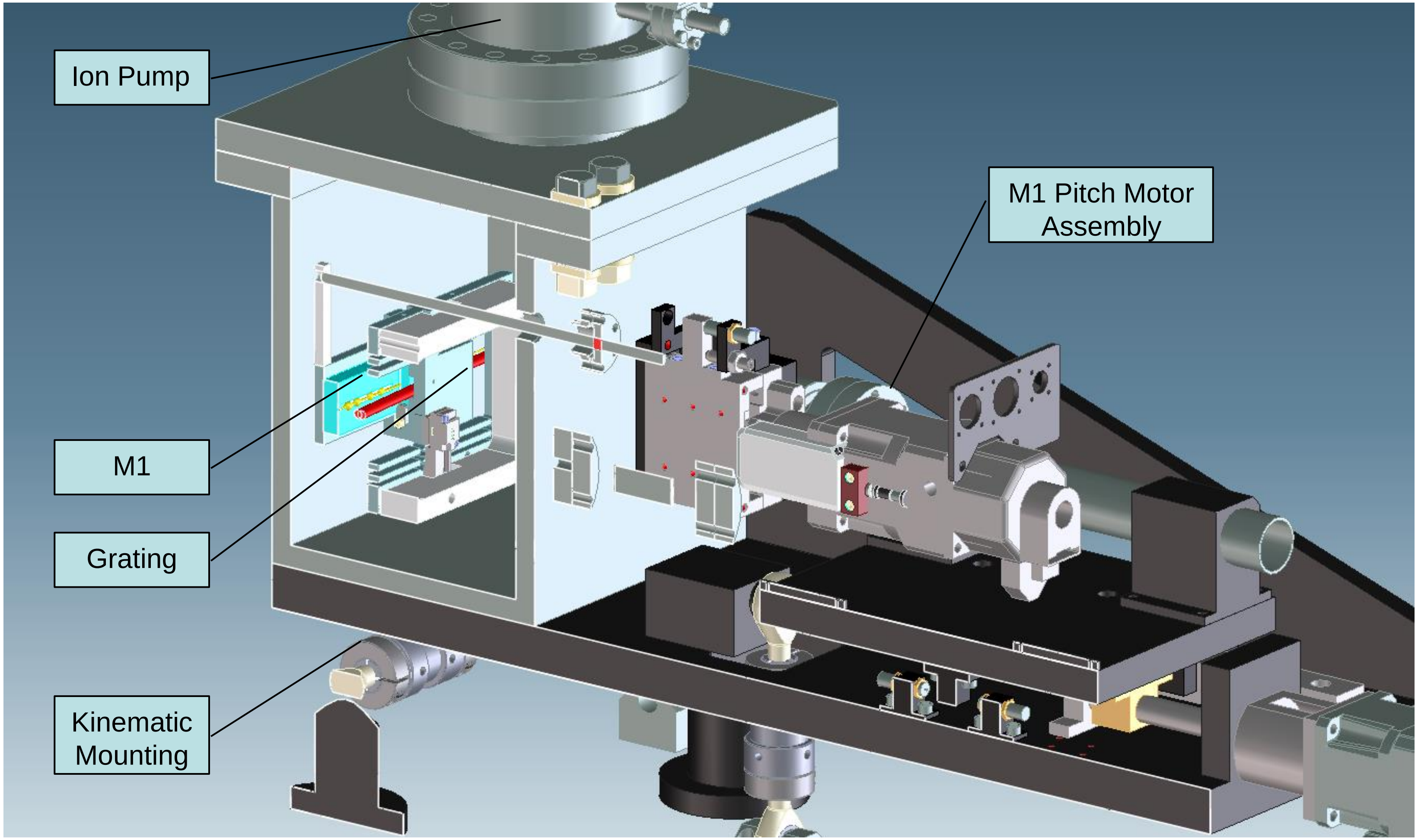
- Presented at conceptual design review



courtesy of LBNL SXRSS team

LBNL Current Design

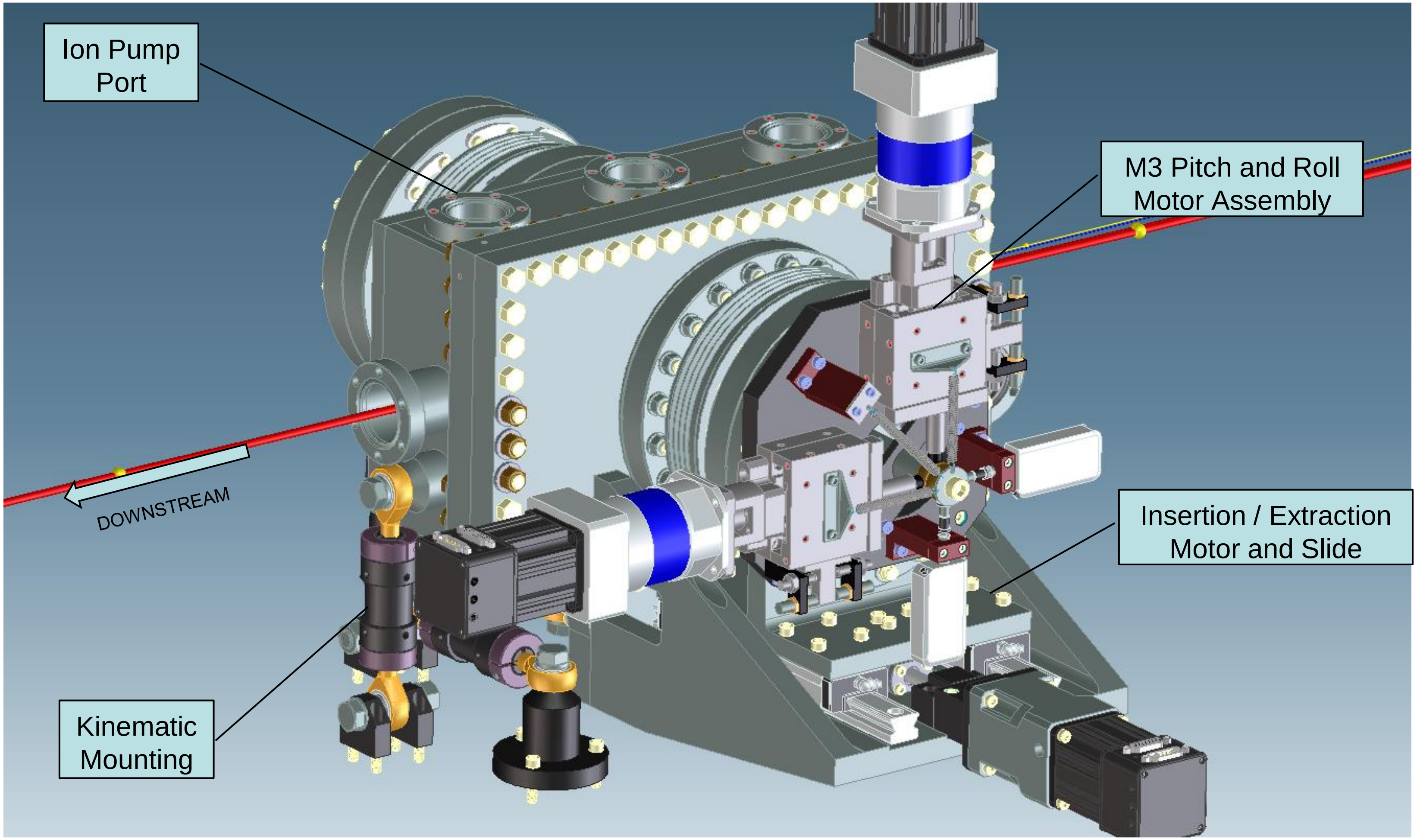
- Grating and M1 chamber



courtesy of LBNL SXRSS team

LBNL Current Design

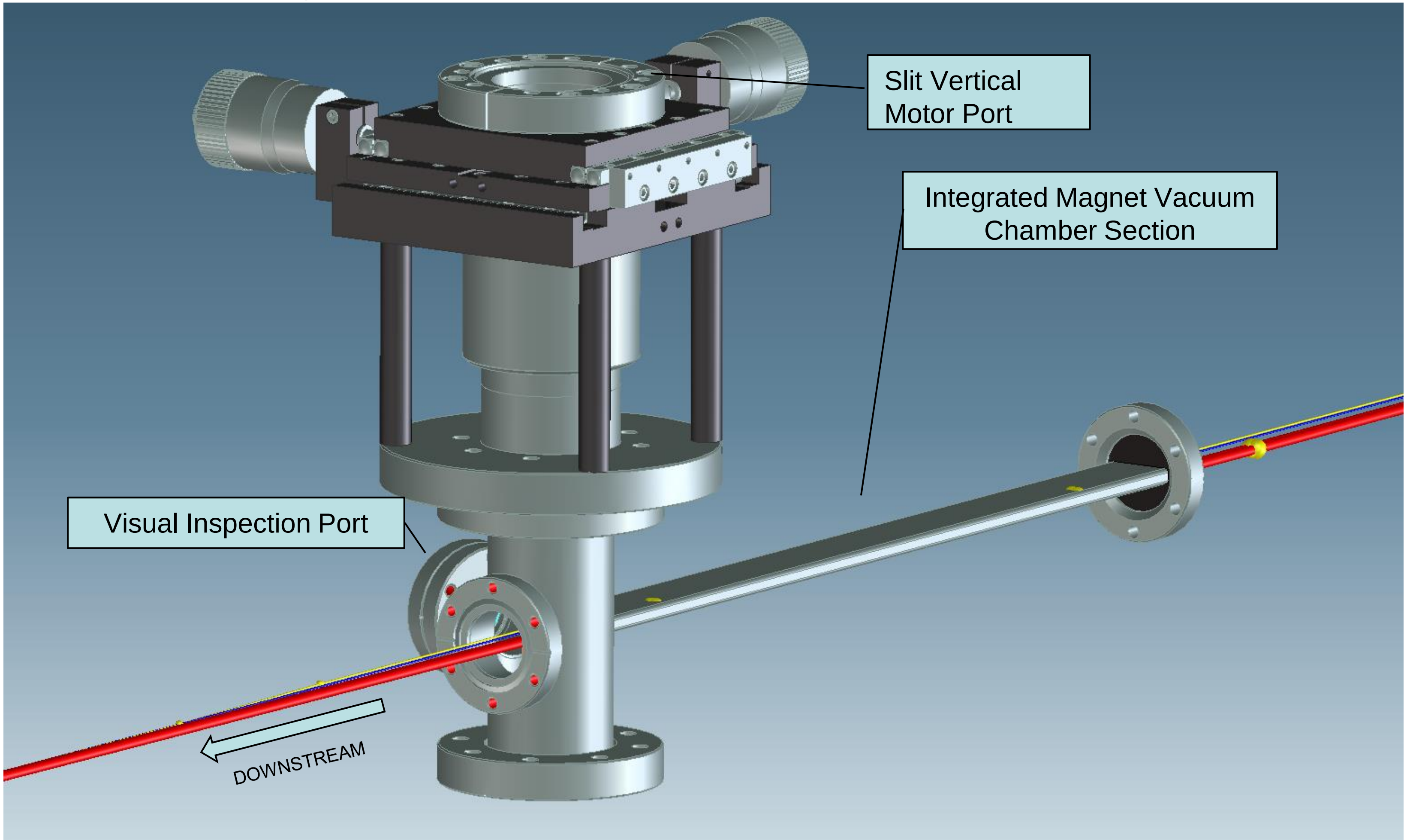
- M2 and M3 chamber



courtesy of LBNL SXRSS team

LBNL Current Design

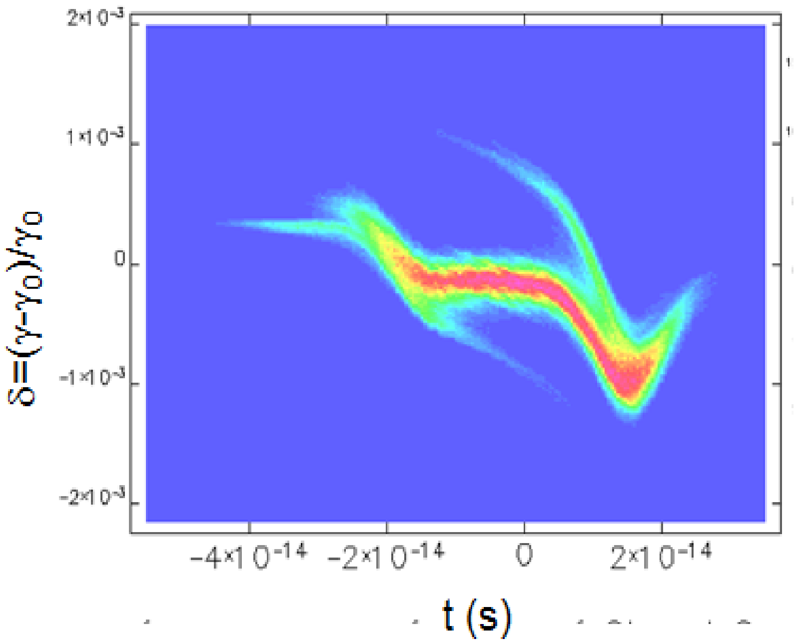
- Slit assembly



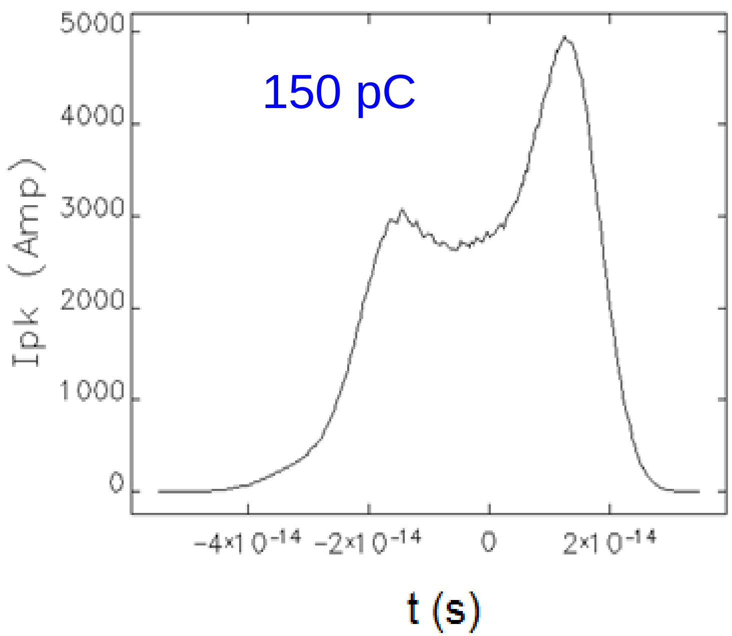
courtesy of LBNL SXRSS team

FEL simulations (J. Wu)

- Input e- beam at SASE undulator entrance



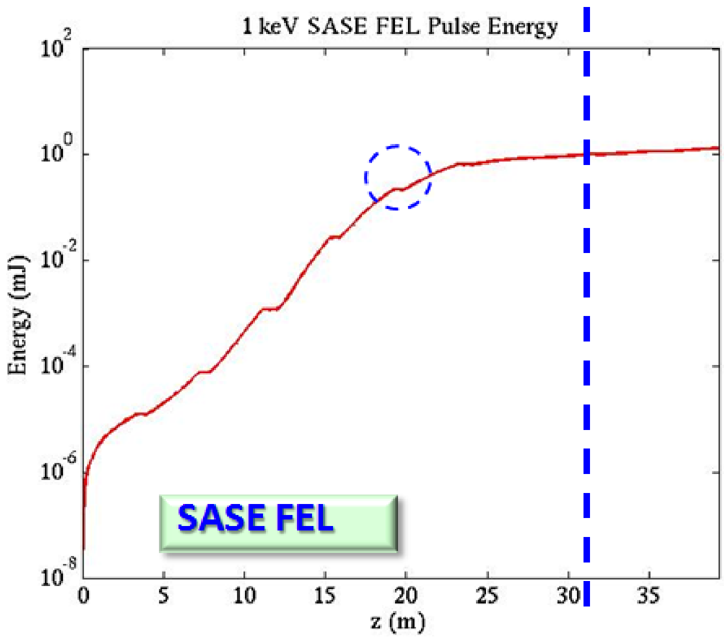
Longitudinal phase space of the electron bunch at the entrance of undulator system.



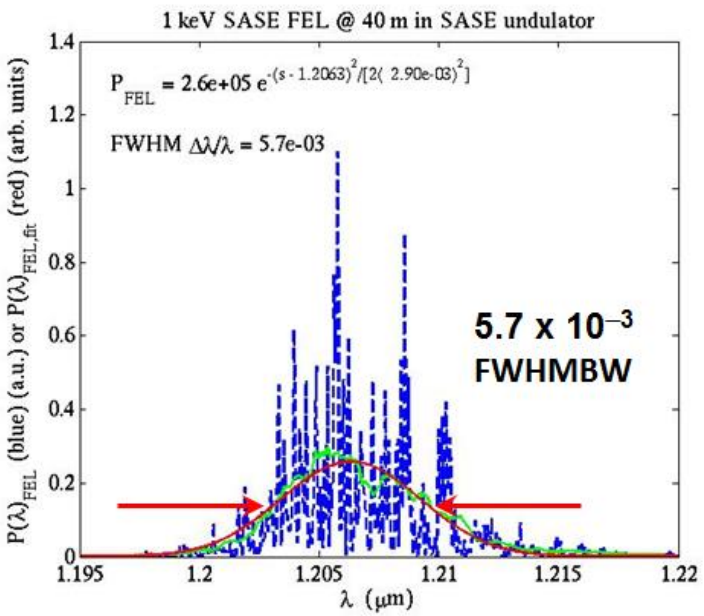
Double-horn profile of the electron bunch compressed to 3 kA peak current in the central part.

FEL simulations (J. Wu)

- SASE FEL at grating



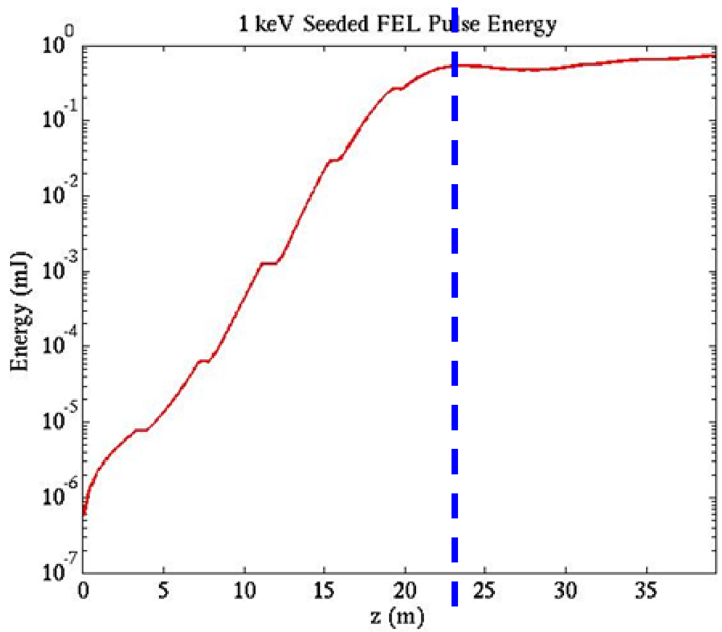
SASE FEL gain curve. The dashed vertical line stands for the end of U8; the dashed circle stands for the operation point.



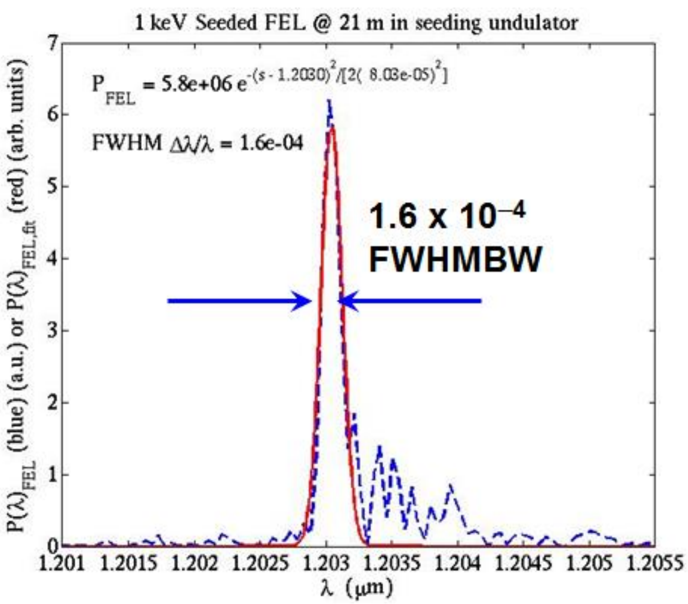
SASE FEL spectrum at 40 m in the SASE undulator.

FEL simulations (J. Wu)

- Seeded FEL reaching saturation



Seeded FEL gain curve. The dashed vertical line stands for the end of U15.



Seeded FEL spectrum at 21 m in the SASE undulator.

Summary

- There are strong scientific cases for soft X-ray seeding at LCLS
- Self-seeding seems to be the best choice for immediate implementation for LCLS-I
- System design near completion including X-ray optics, chicane, diagnostics, minor refinement continuing
- FEL simulation complete and looks extremely promising
- SXRSS Project is in full motion
- Mechanical design on-going and maturing
- Installation in FY13 summer shutdown on schedule