

Road to Technology



A State-of-the-Art (Pakistani) Beamline at SESAME

"how and why?"

Zahid Hussain

Scientific Support Group, Leader
Advanced Light Source

Lawrence Berkeley National Laboratory

Synchrotron Radiation

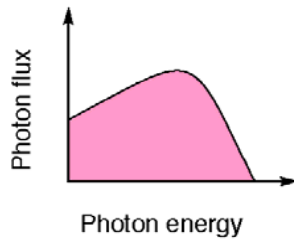
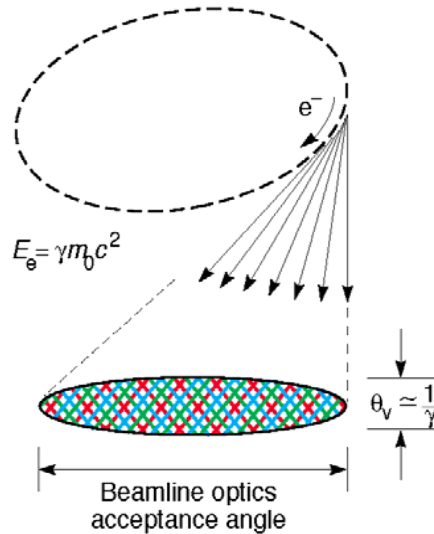
- Important Characteristics



ALS Radiation is Produced by Bend Magnets and Undulators

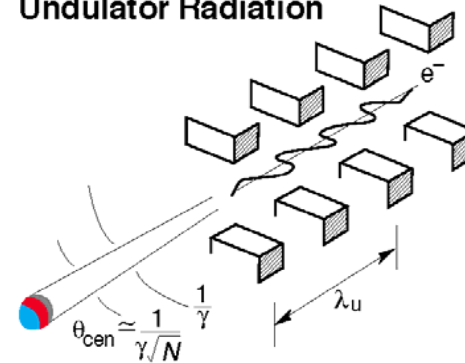
ALS

Bend-Magnet Radiation



meV to 50 keV
- high brightness

Undulator Radiation

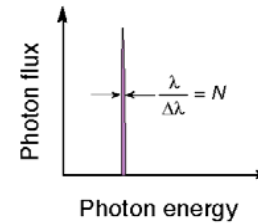


$$\lambda_x = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)$$

In the central radiation cone:

$$\frac{\Delta\omega}{\omega} \approx \frac{1}{N}$$

$$\theta_{cen} \approx \frac{1}{\gamma N}$$

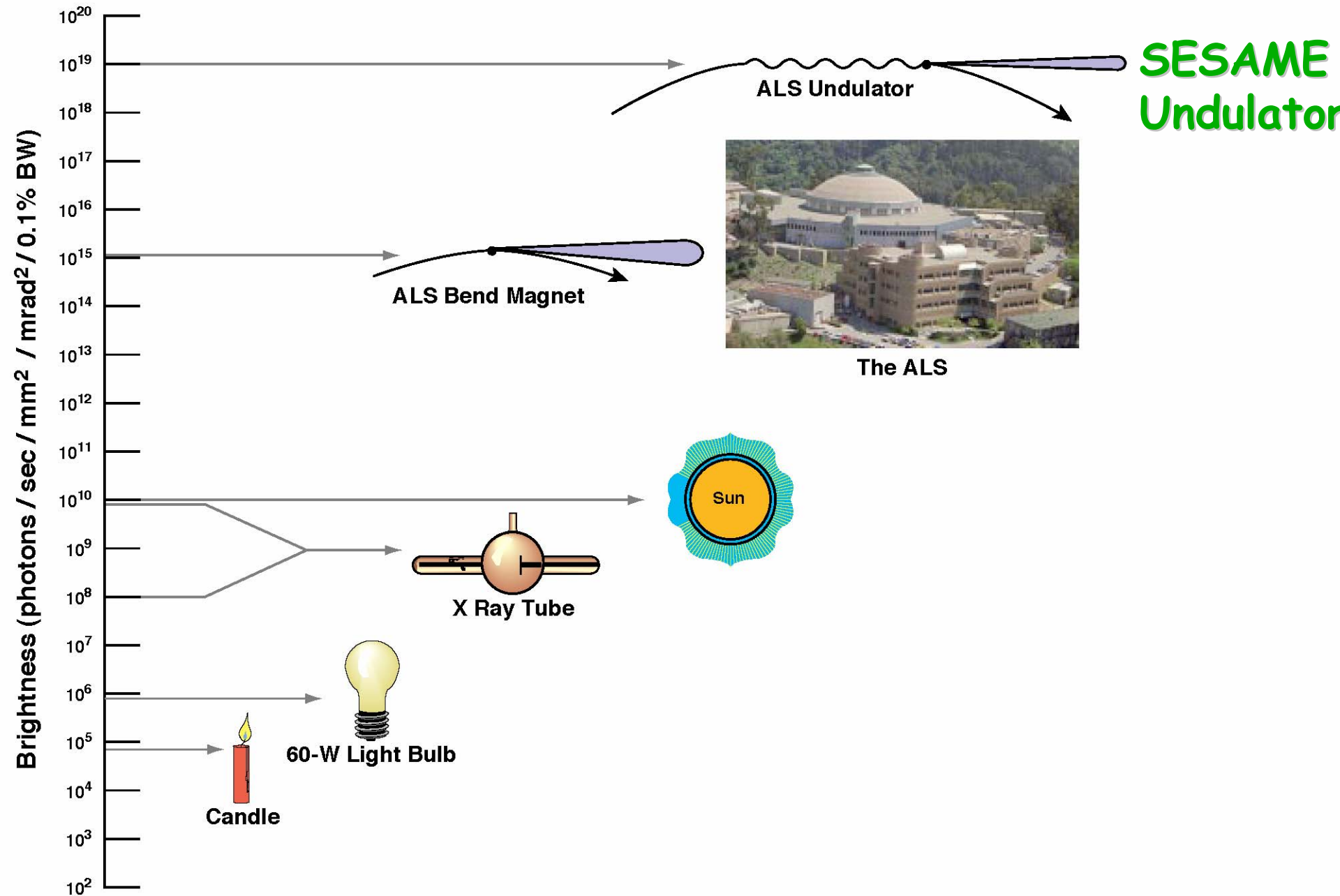


5eV to 2keV
- extreme brightness

jc.fs/bend&und/12-95

How Bright Is the Advanced Light Source?

ALS

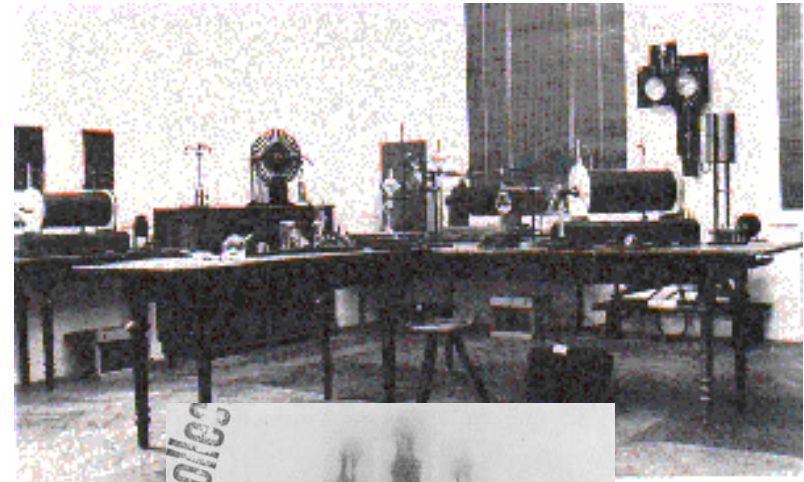


Production of the First X-Rays

Wilhelm Conrad Roentgen
1845-1923

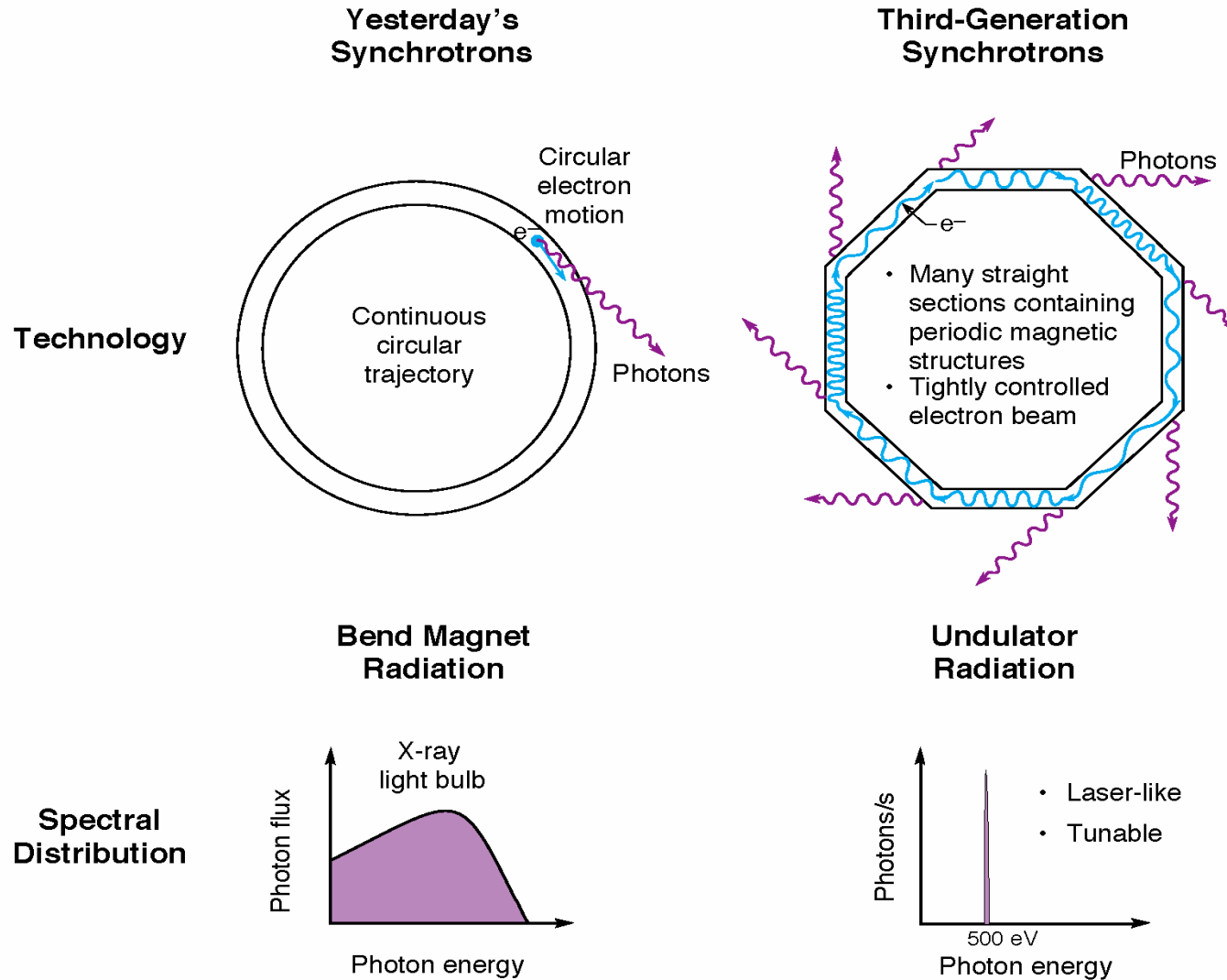


An X-ray lab – circa 1895



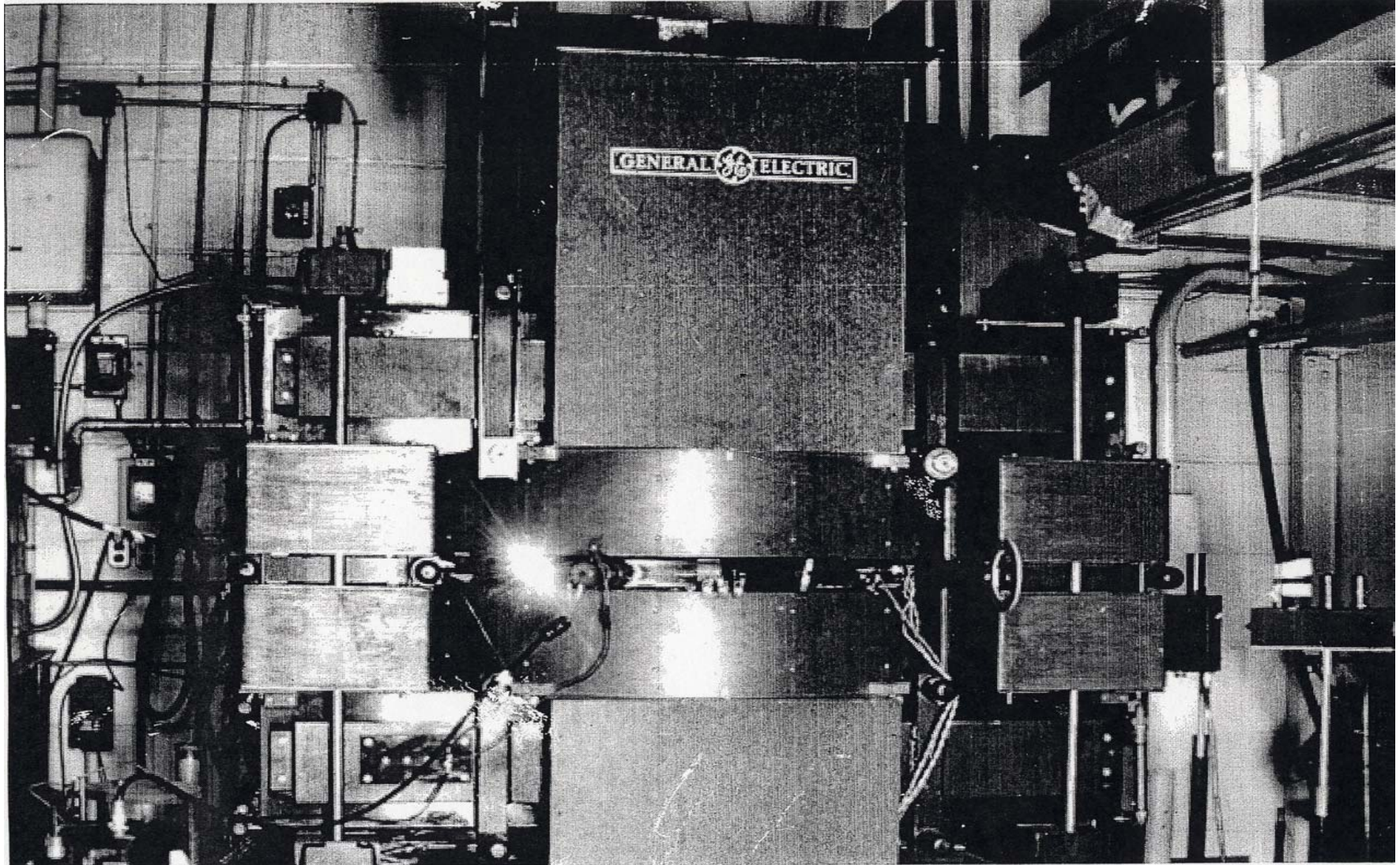
Evolution of Synchrotron Radiation

ALS

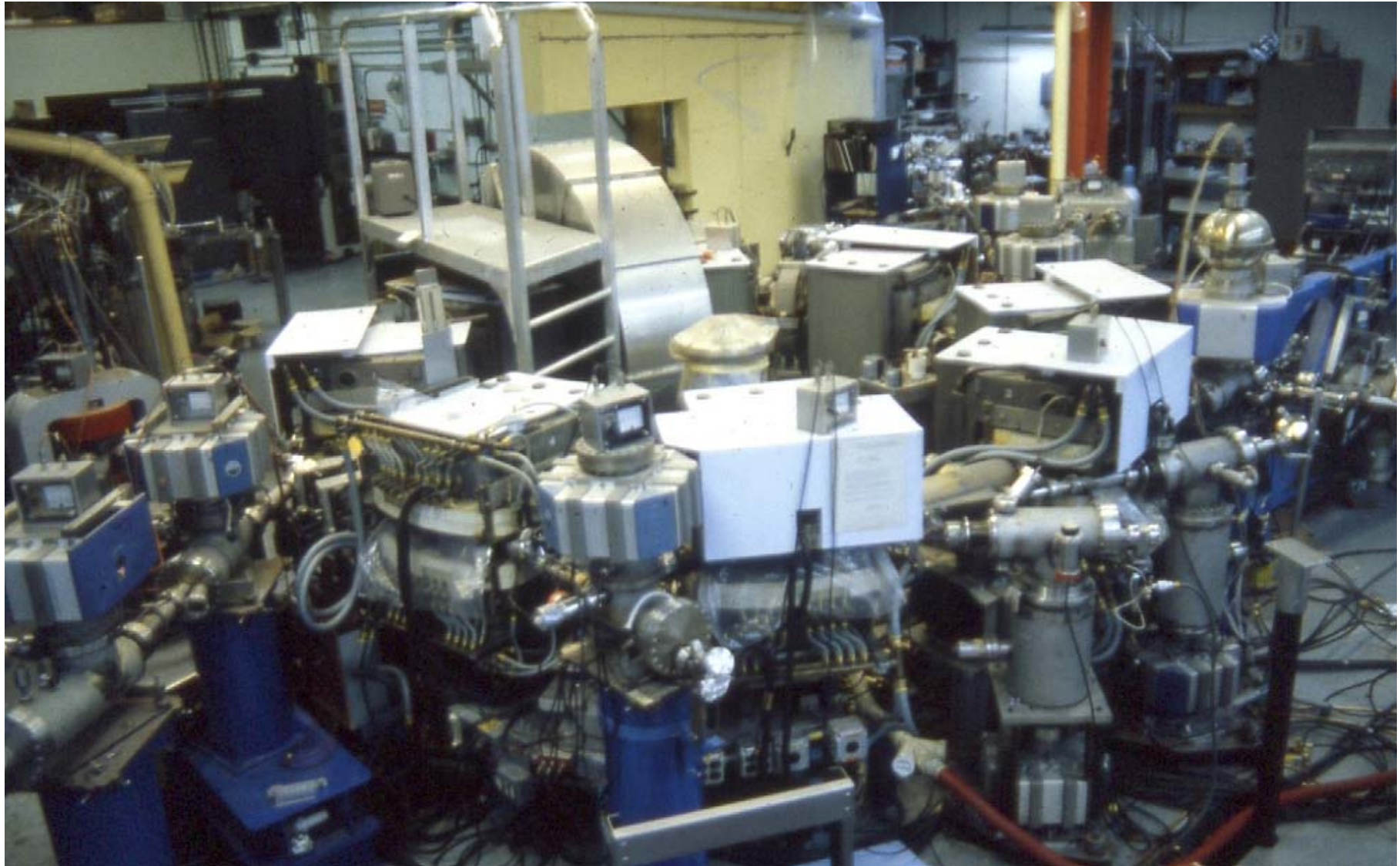


jc.fs/evolution/6-95
XBD9506-02543.PGM

First visual observation of synchrotron light at the General Electric 70 MeV synchrotron in 1947



SR in the early days: Tantalus at Univ. Wisconsin



LAWRENCE BERKELEY NATIONAL LABORATORY

European Synchrotron Radiation Facility - France



7 GeV

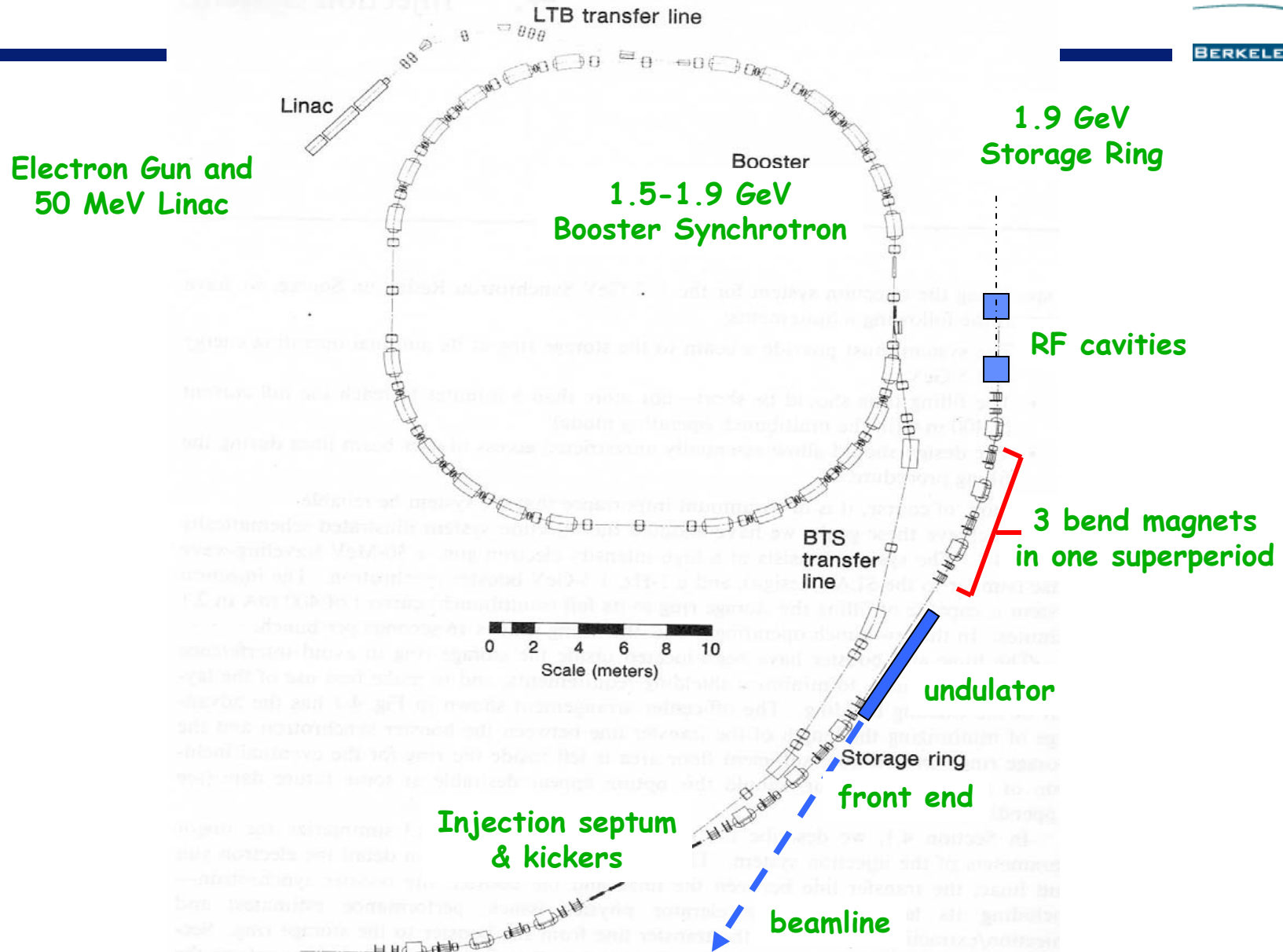
ESRF - France

APS - USA

Spring8 - Japan

Over 50 SR facilities
in the world

ALS: From the Booster to the Beamlines



Bunchers and Acceleration Section

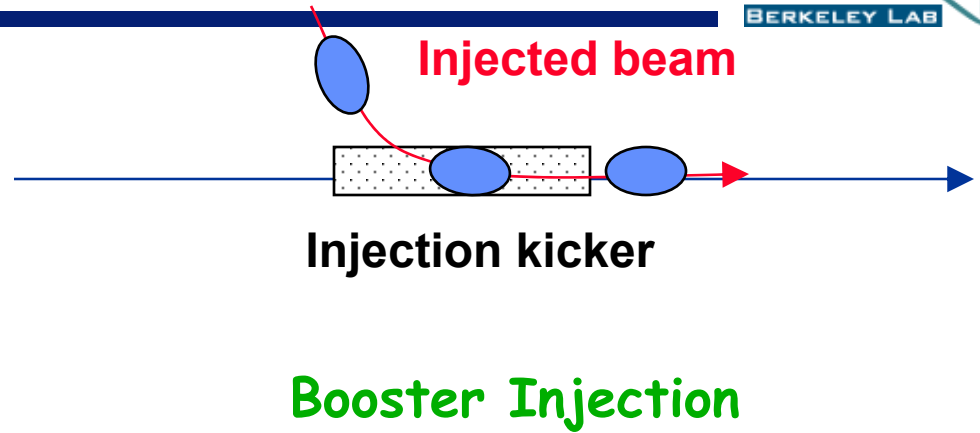


Linac
50MeV

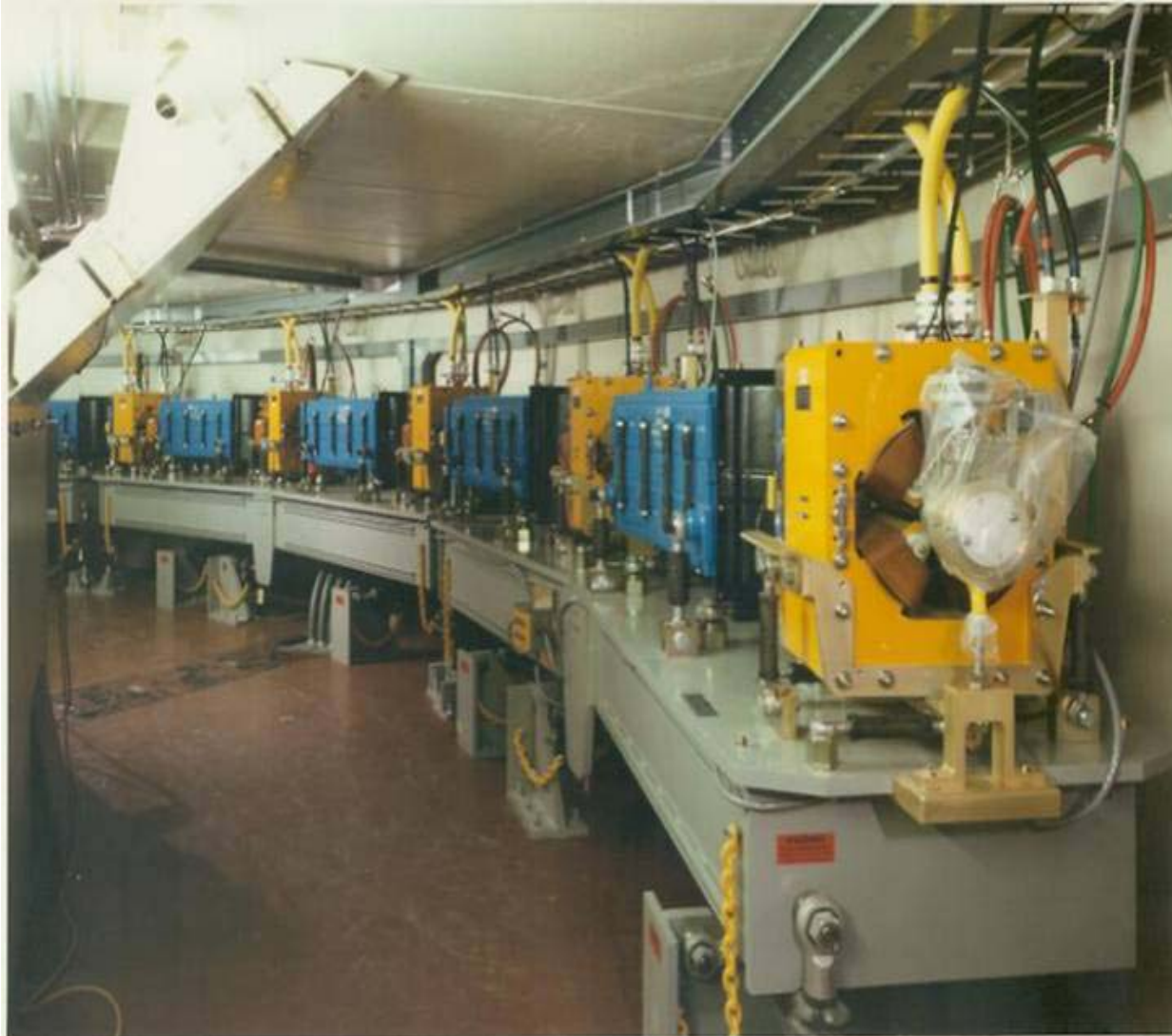
Linac to Booster



Transfer line



Booster Synchrotron



Ramps up the
energy to
1.9 GeV (ALS)

Electron Storage Ring



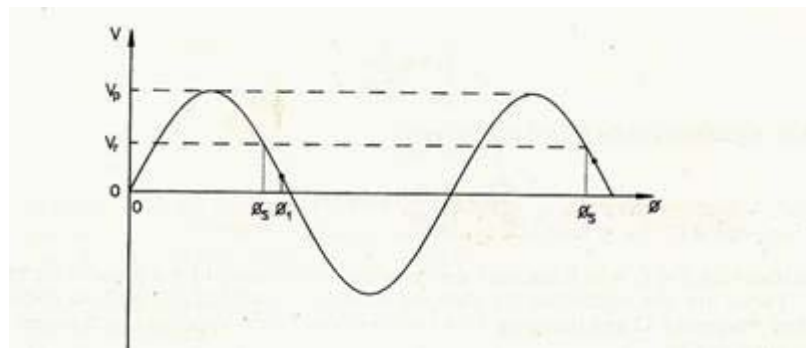
Various magnets allow:

- Change of direction
- Focusing of electrons
- Shaping of electron beam

RF (500 MHz) Cavities



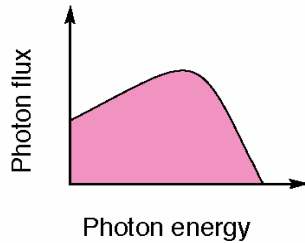
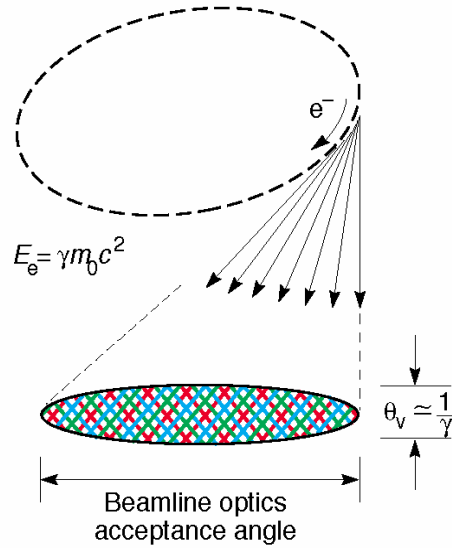
- Restores synchrotron radiation losses
- Provides longitudinal bunching



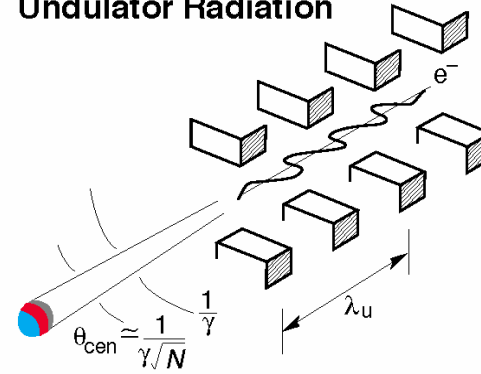
ALS Radiation is Produced by Bend Magnets and Undulators

ALS

Bend-Magnet Radiation



Undulator Radiation

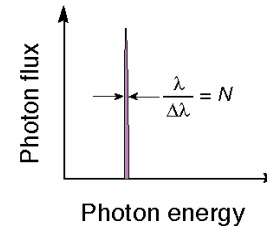


$$\lambda_x = \frac{\lambda_u}{2\gamma^2} (1 + \frac{K^2}{2} + \gamma^2 \theta^2)$$

In the central radiation cone:

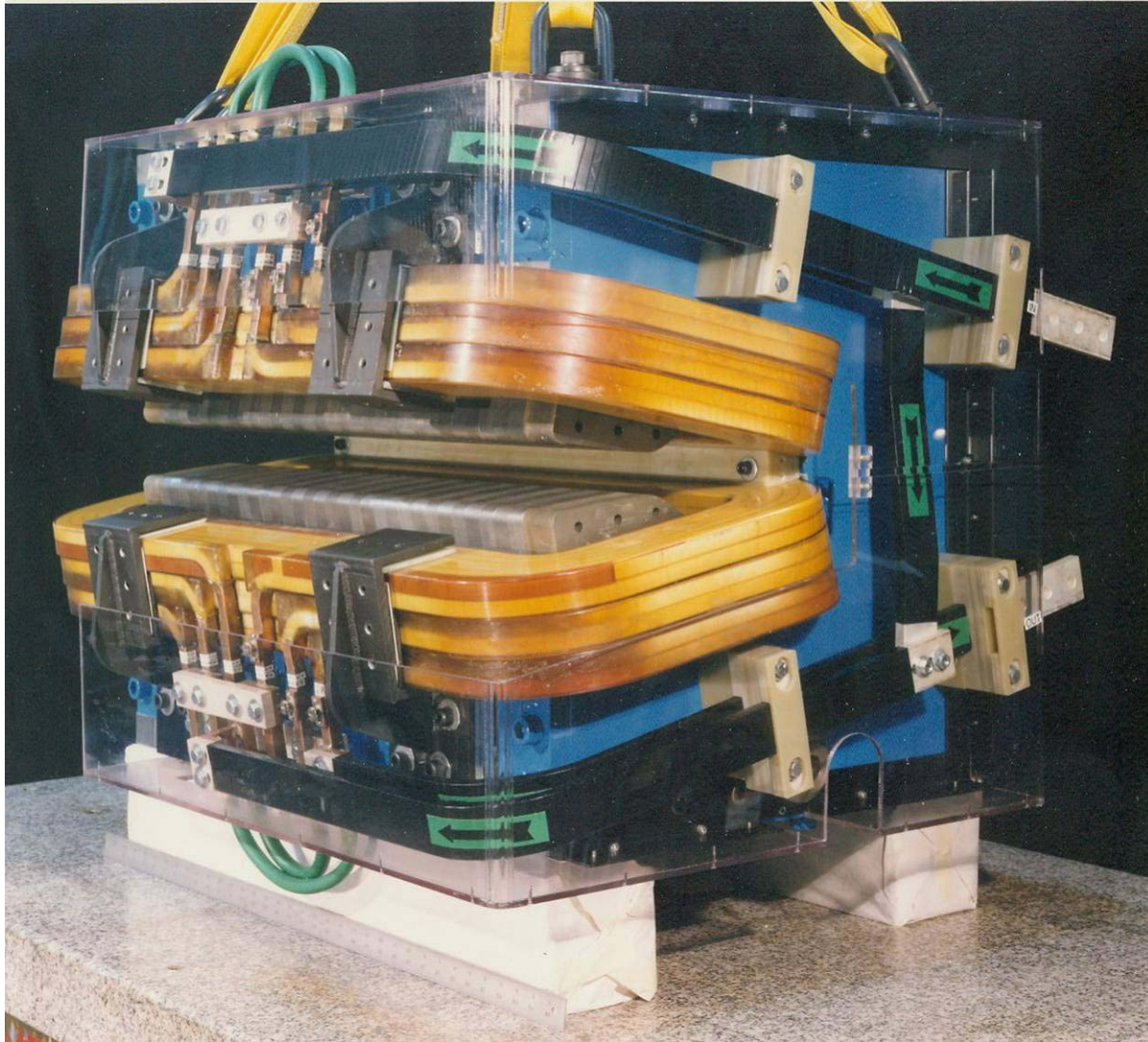
$$\frac{\Delta\omega}{\omega} \approx \frac{1}{N}$$

$$\theta_{cen} \approx \frac{1}{\gamma N}$$



jc.fs/bend&und/12-95

Normal conducting bending magnet: $E < 16$ keV



Superconducting bending magnets: $E < 60$ keV



Three of the existing thirty six **1.3 Tesla** dipoles have been replaced with three **5 Tesla** superconducting dipoles

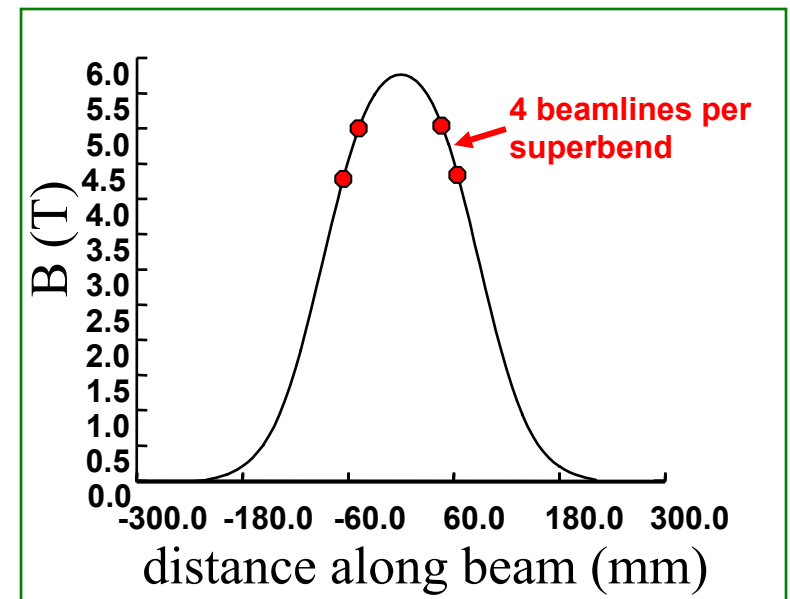
Superbend
with cryostat



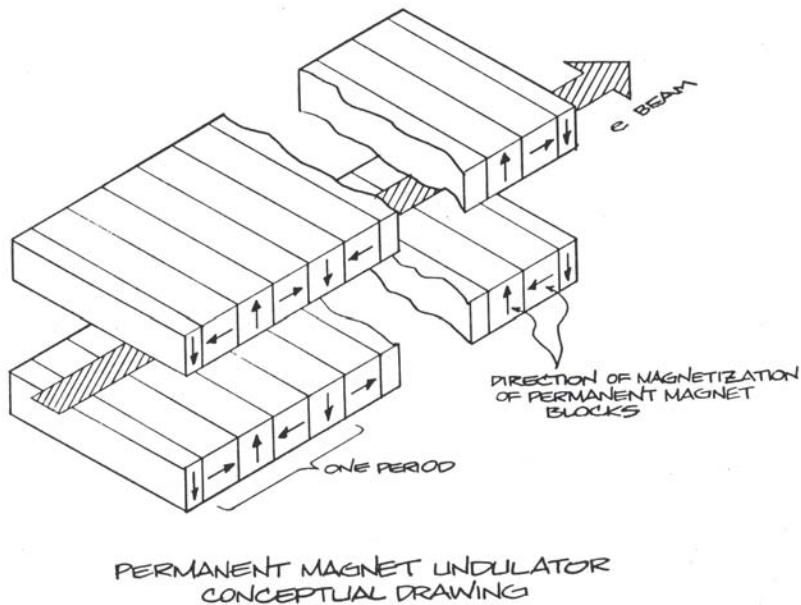
Superbend
without cryostat



Superbend
magnetic field

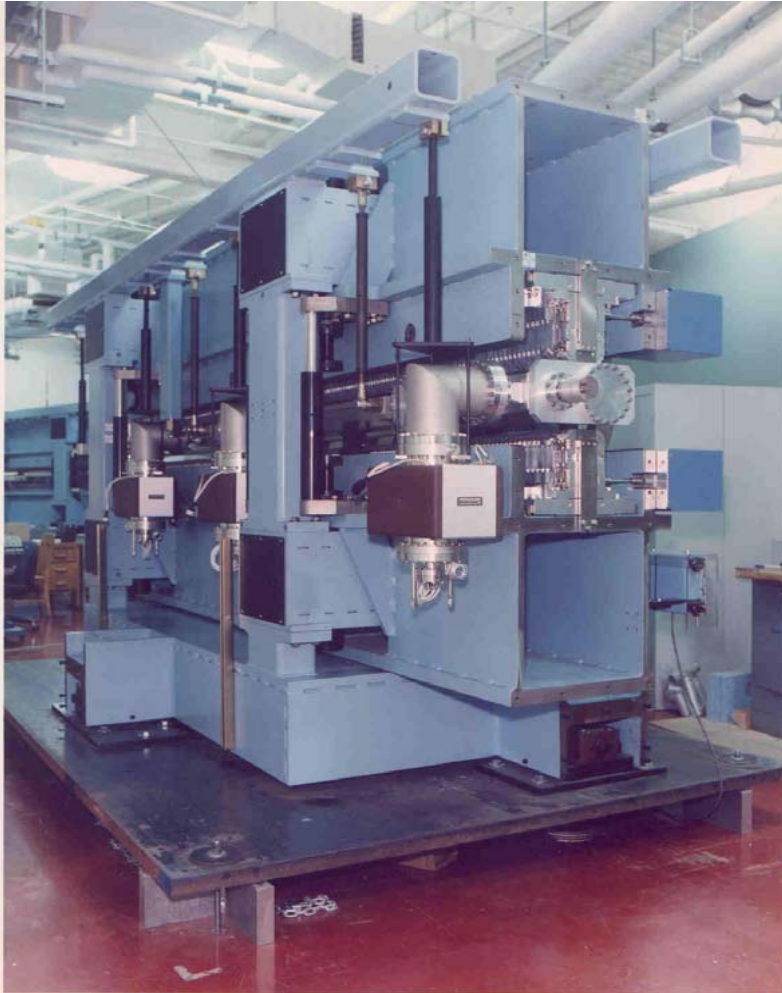


The First Permanent Magnet Undulator



- invented by Klaus Halbach
- built at LBNL
- installed at SSRL in 1980

Undulators at the ALS

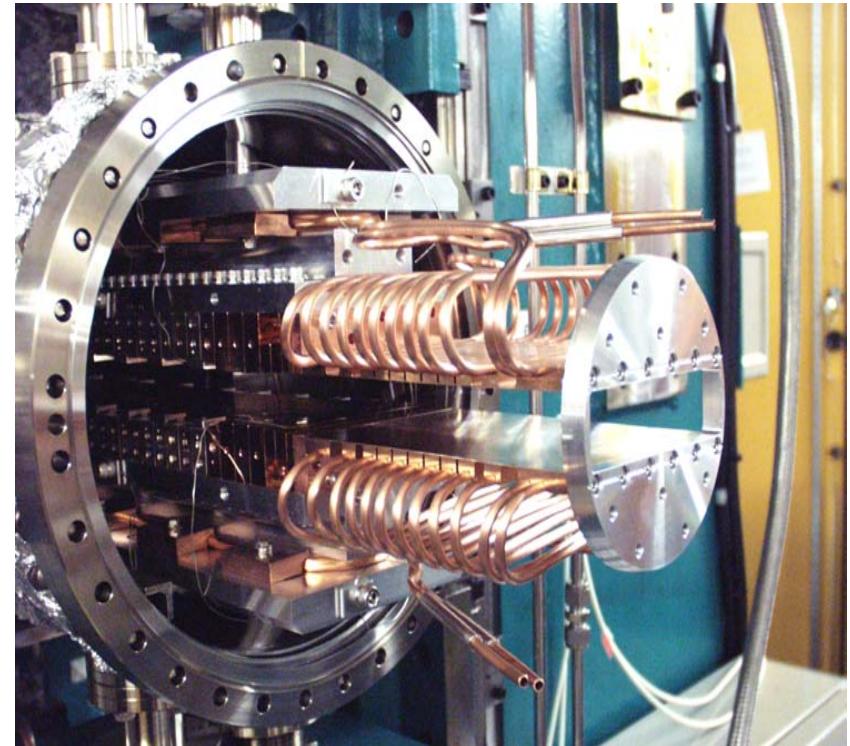


ALS U50 (1993)
Hybrid permanent magnet technology



ALS EPU50 (1998)
Pure permanent magnet technology, elliptically polarizing capability

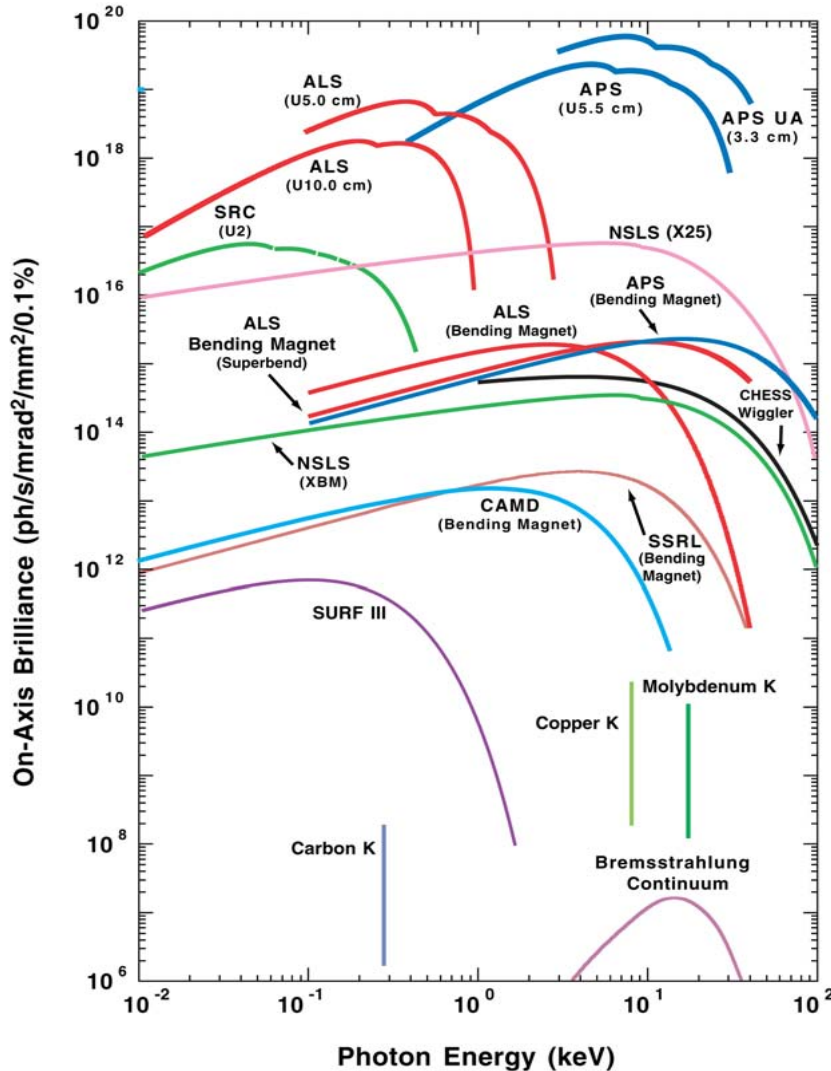
Undulators at the ALS



30 mm period, 1.5T wiggler / undulator (2005)

- in-vacuum magnets
- commercial device

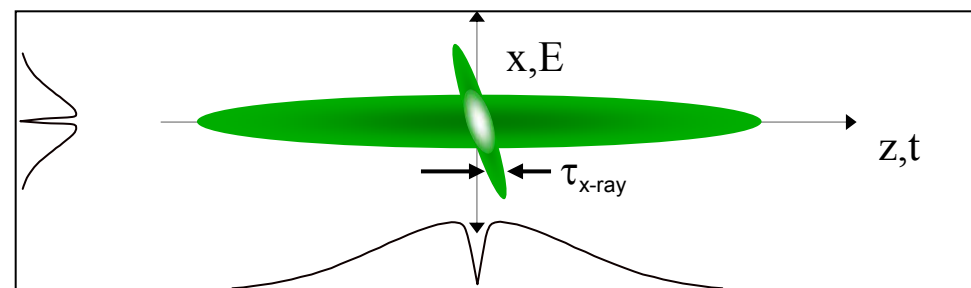
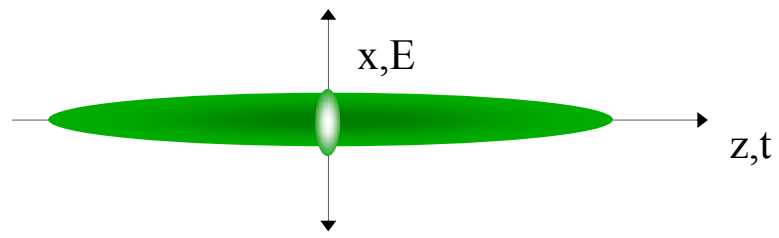
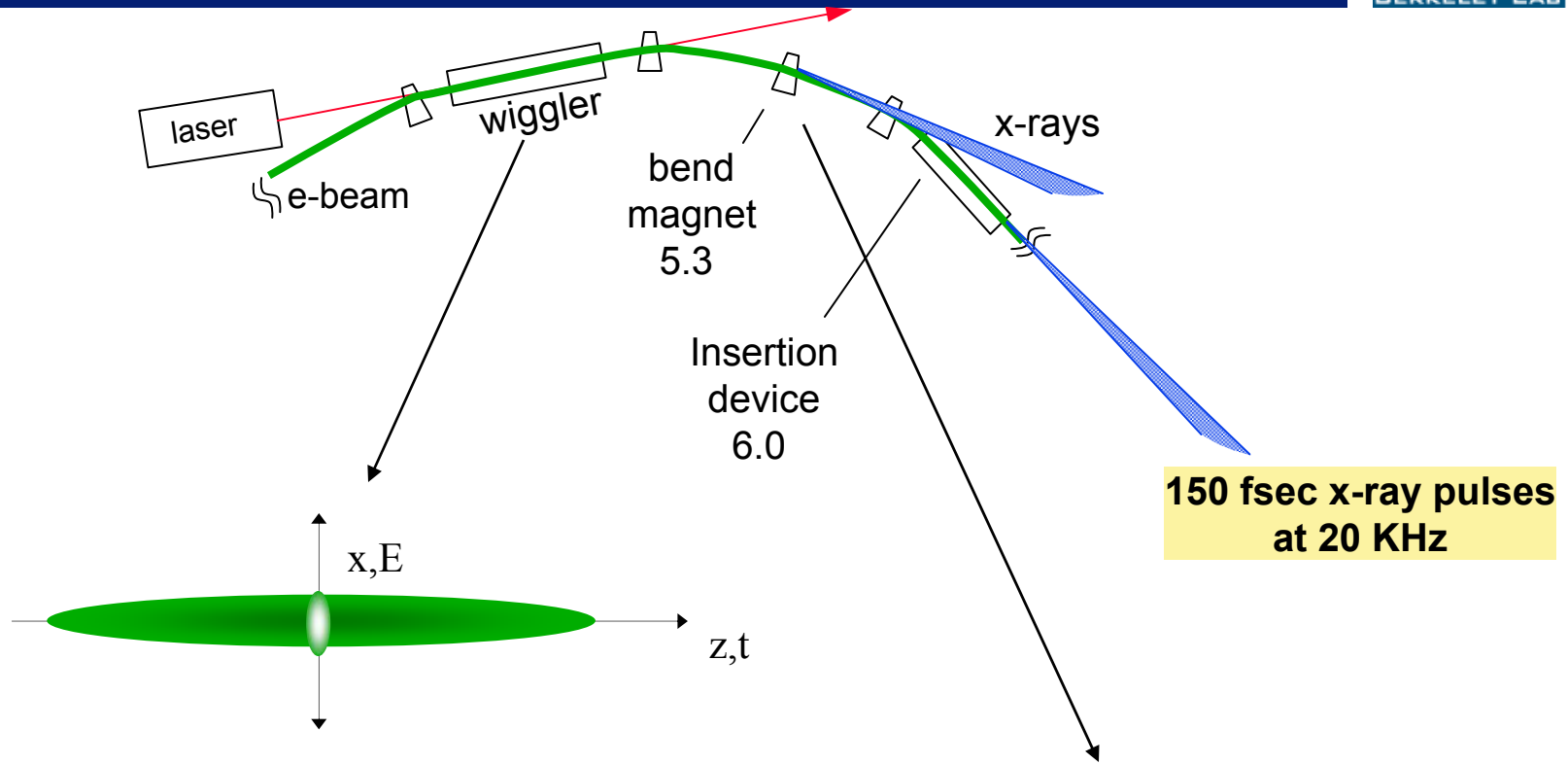
On-Axis Brightness of SR Sources



New devices:

- in-vacuum permanent magnet
- in-vacuum cryo permanent magnet
- superconducting

Slicing the electron beam for ultrashort pulses



ALS Beamlines



~ 40 beamlines
Operate simultaneously

How a beamline is constructed ?

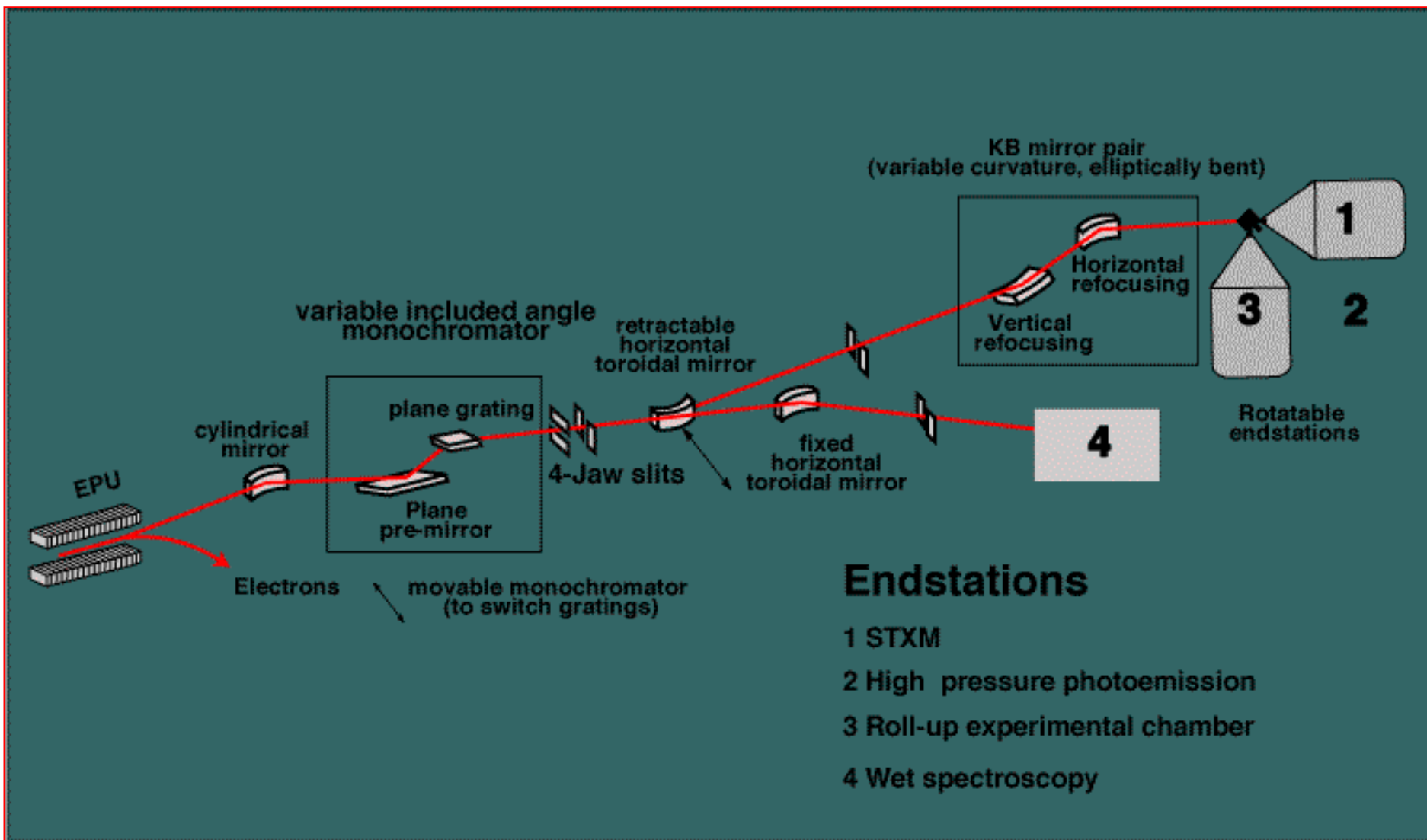


Story of a soft x-ray

MES beamline at the ALS

- How does a beamline look like?
- What are its essential components?

Beamline 11.0.2 Schematic



ALS-MES Beamline 11.0.2.1-2

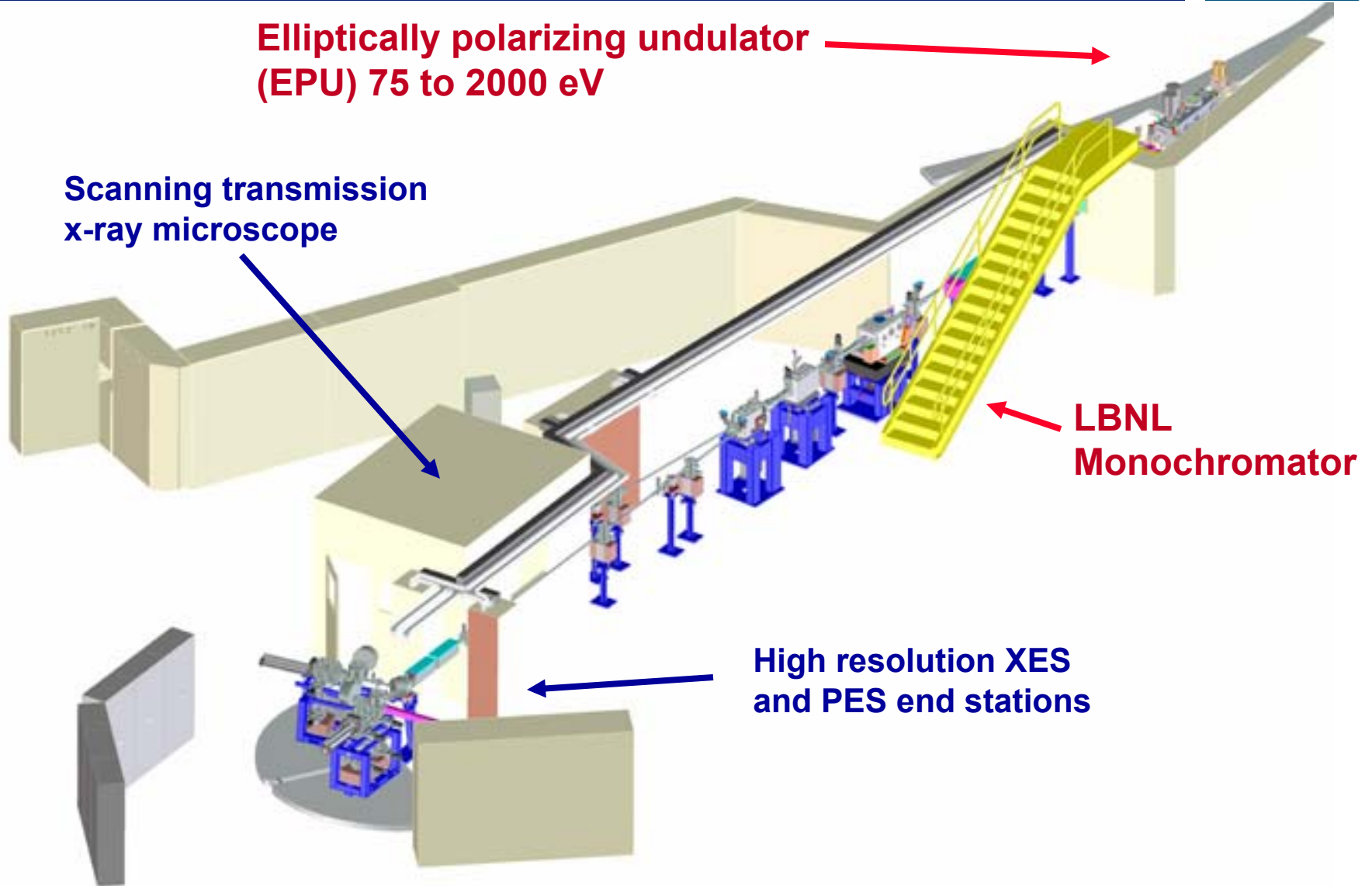


Elliptically polarizing undulator
(EPU) 75 to 2000 eV

Scanning transmission
x-ray microscope

LBL
Monochromator

High resolution XES
and PES end stations



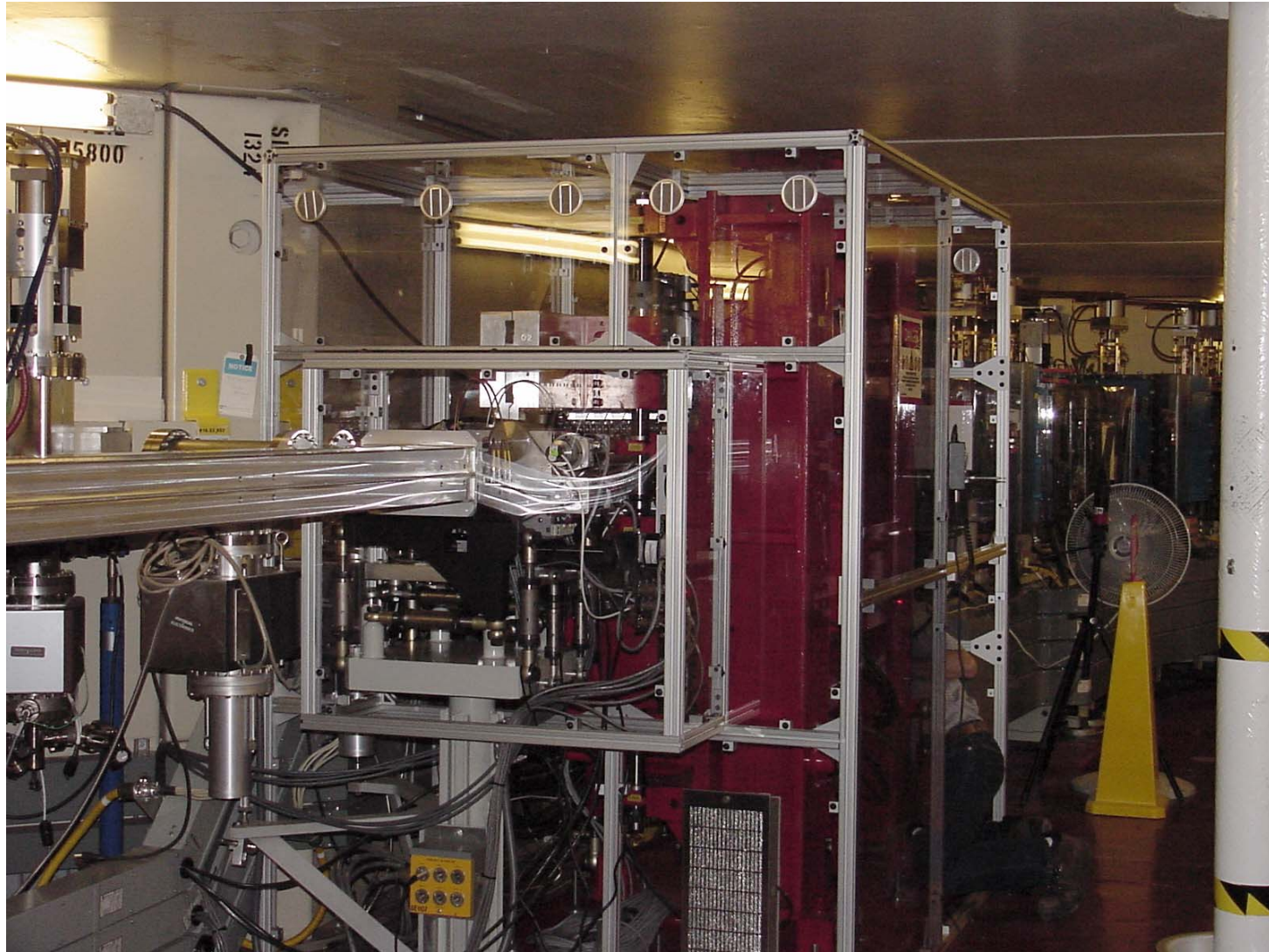
Panoramic view of the ALS-Molecular Environmental Science Beamline 11.0.2



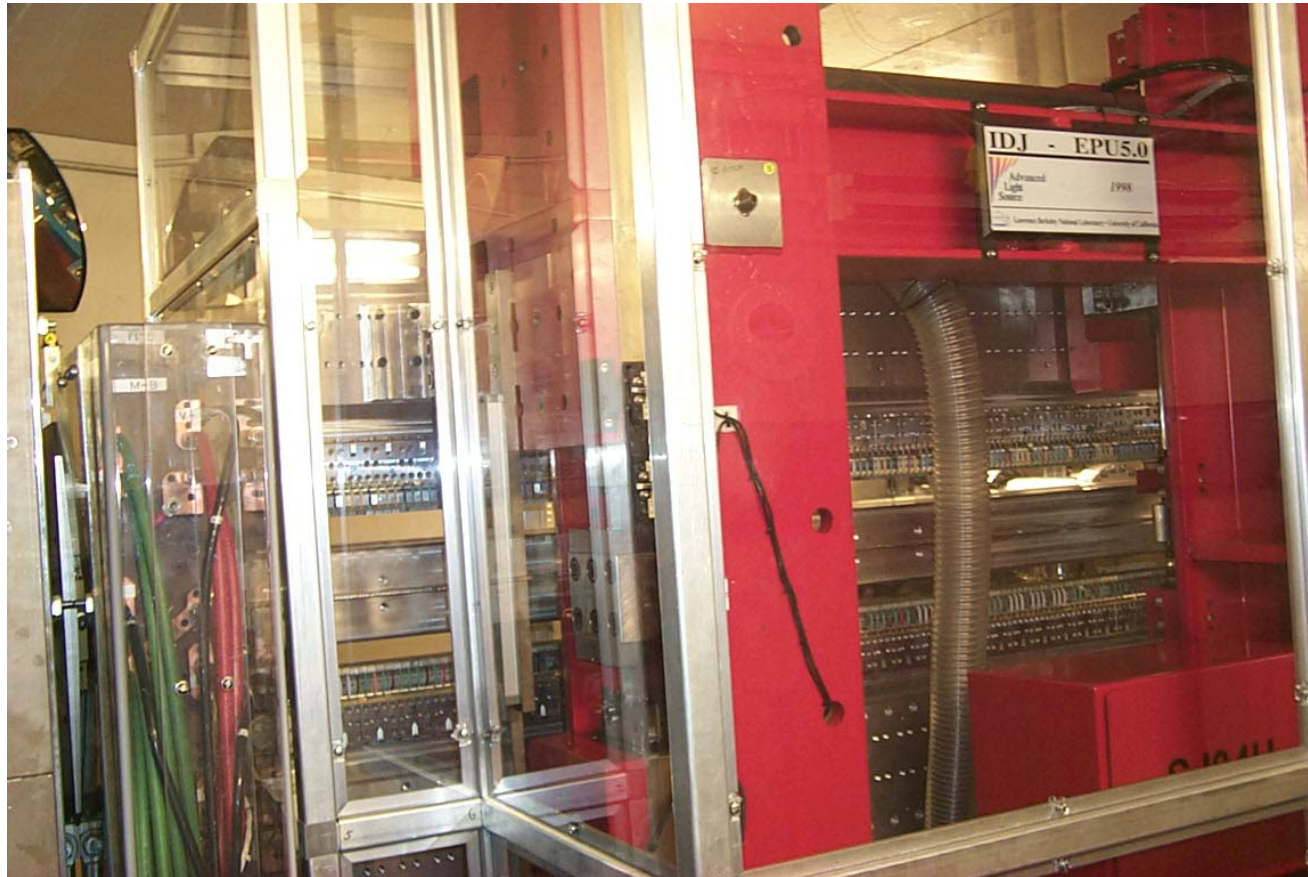
Storage ring chambers ready for installation



EPU In the ALS Storage Ring



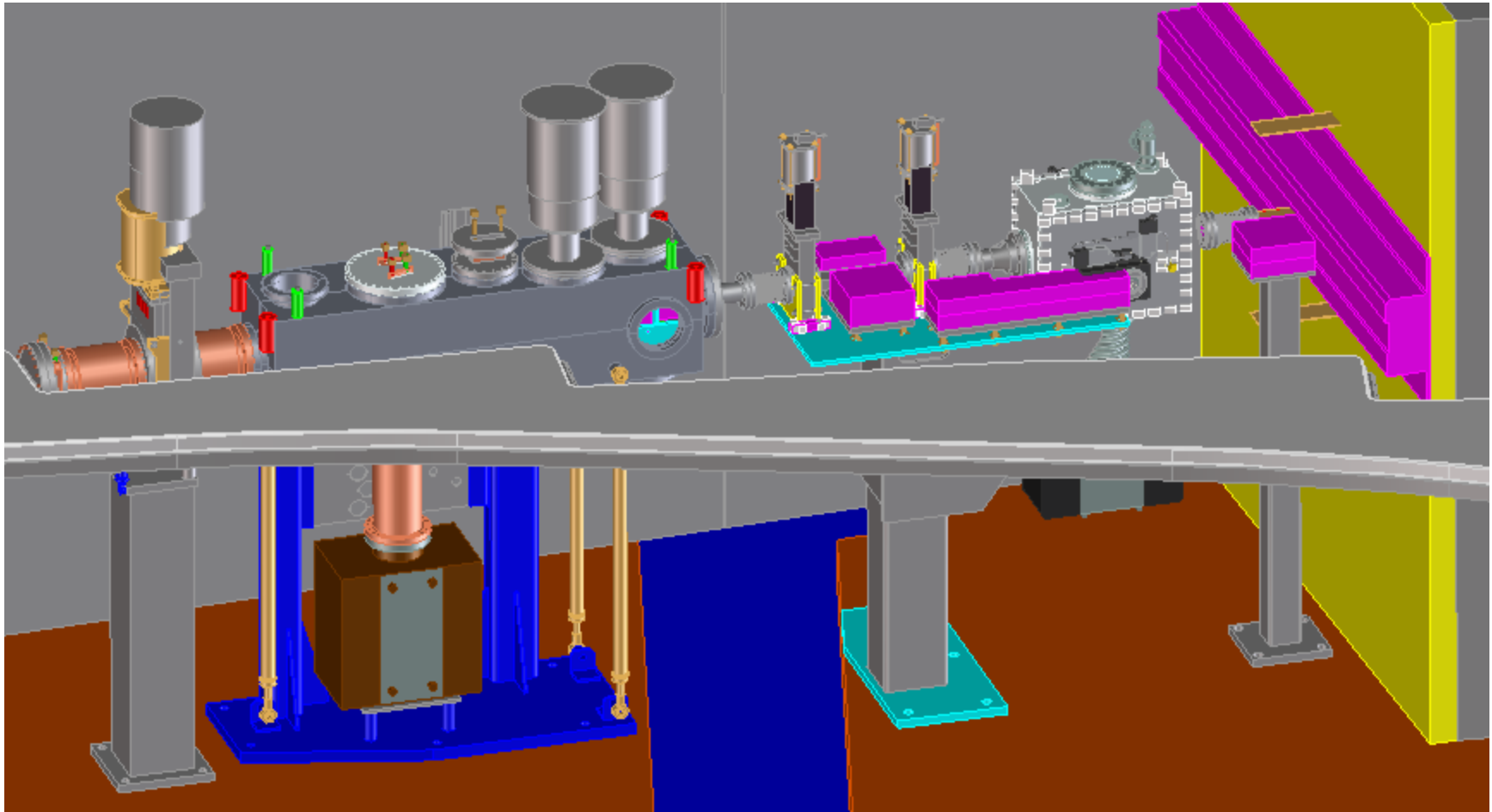
Elliptically polarizing undulator



MES Beam Line 11.0.2 October 2002



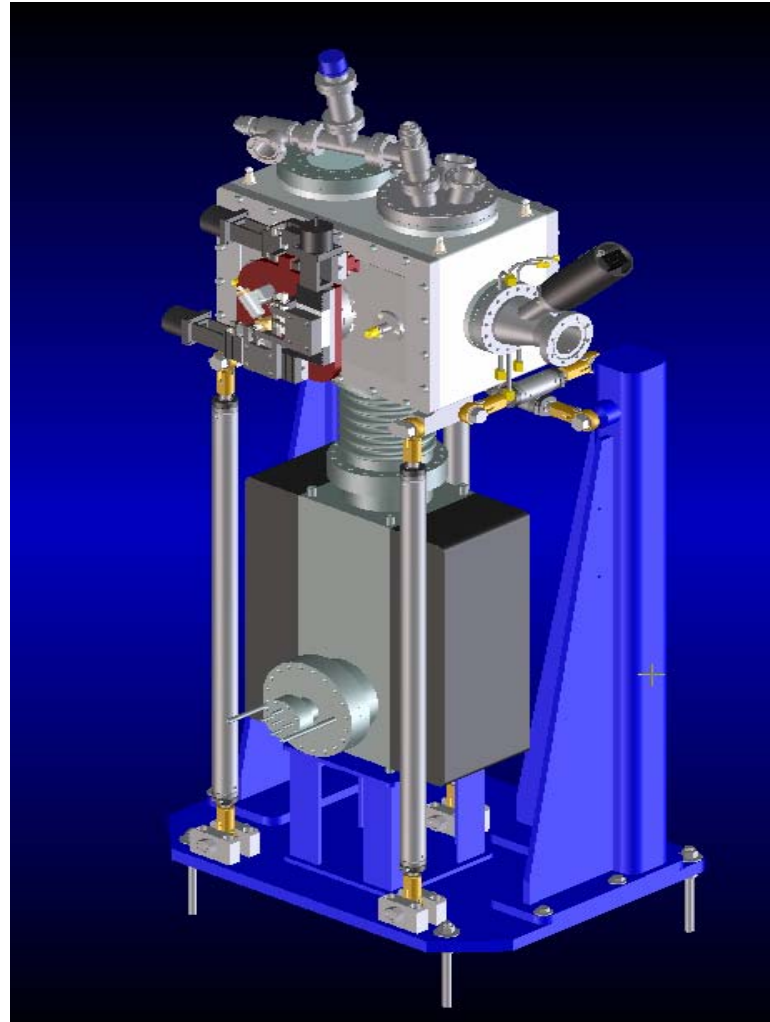
Double Front-End



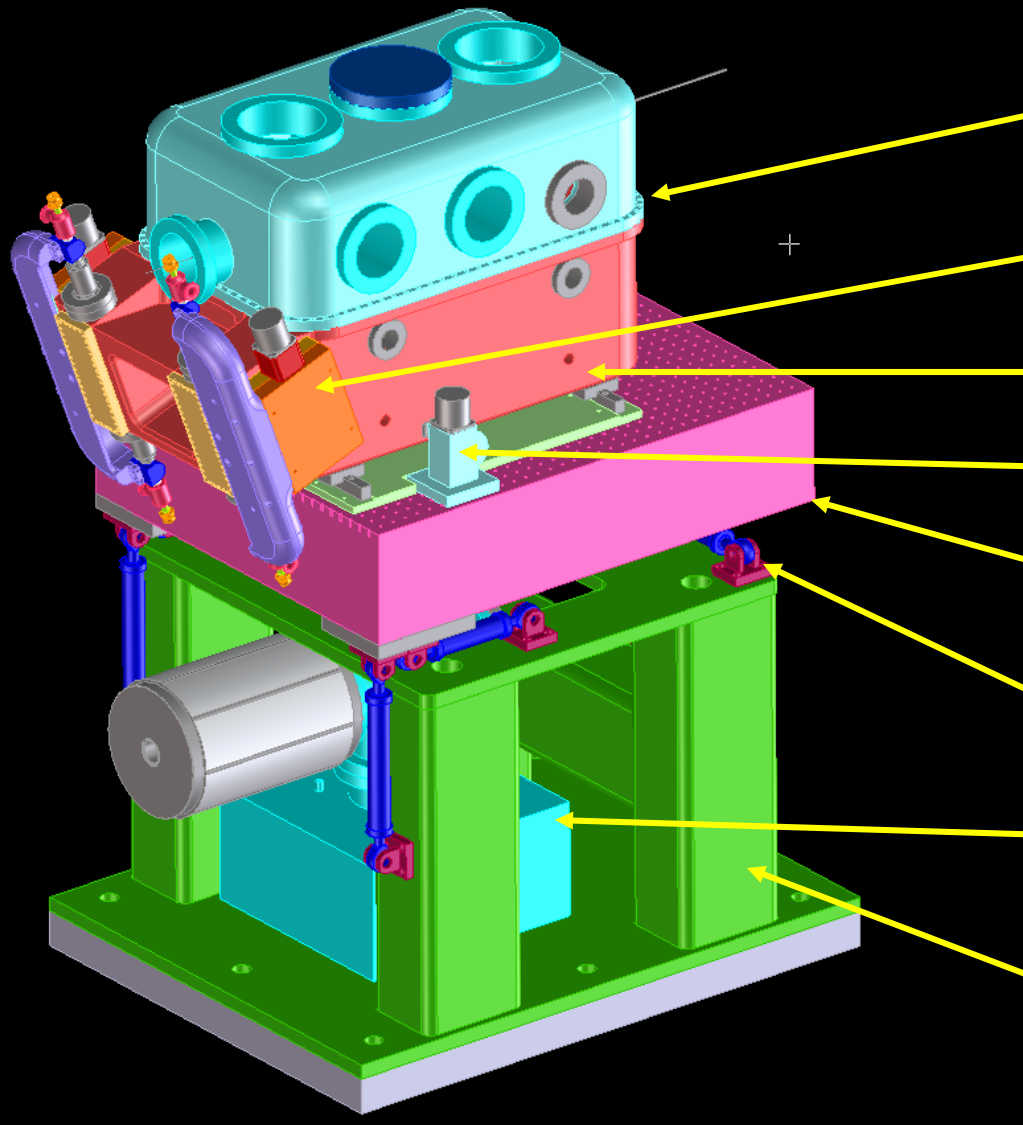
Front end stands installed



First mirror tank inside shield wall



New implementation of SX700 monochromator



Seal joint below beam height for alignment access

External sine-bar drives and linear encoders

Aluminum structural vessel

External grating changer

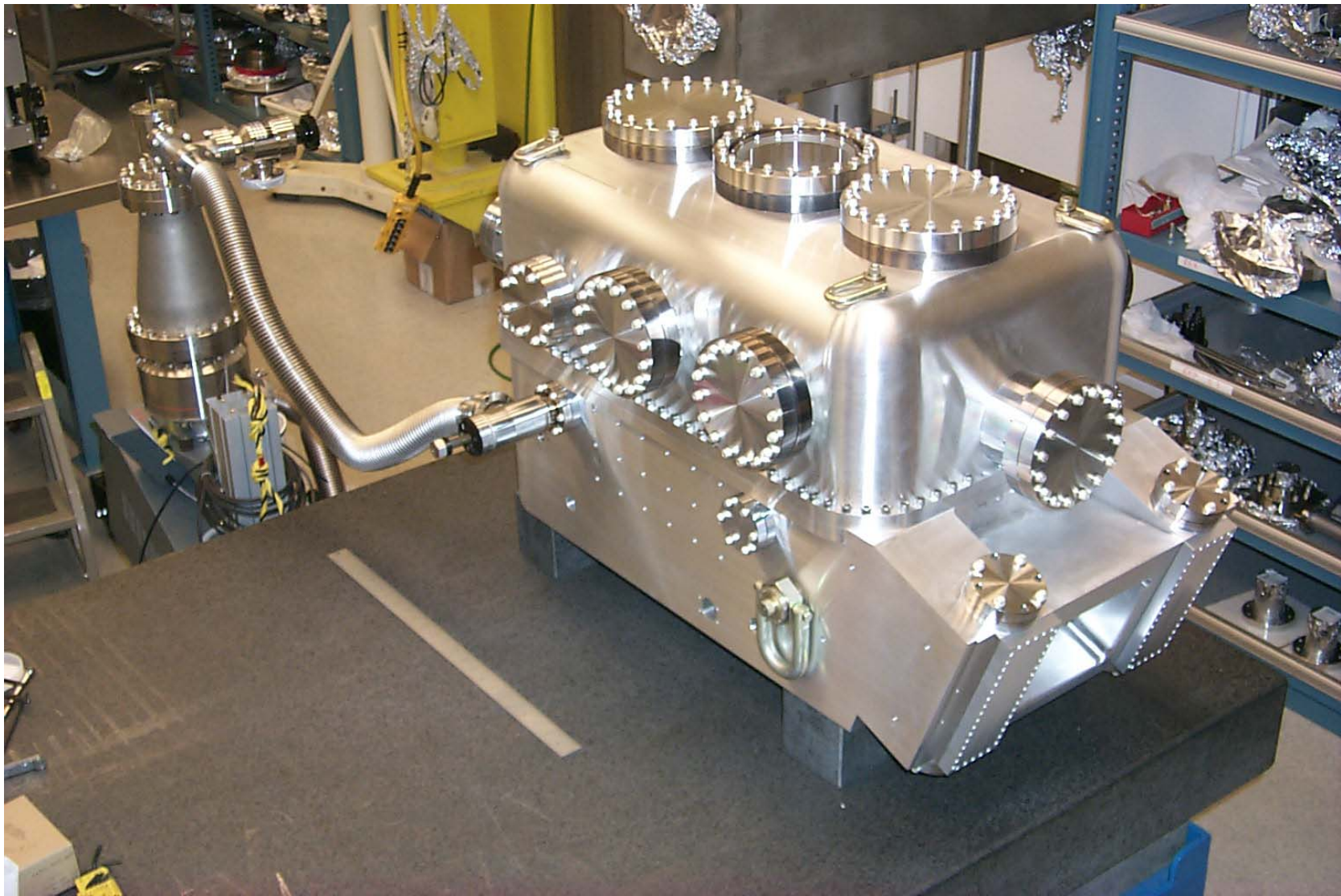
Lightweight rigid honeycomb table

6-strut alignment

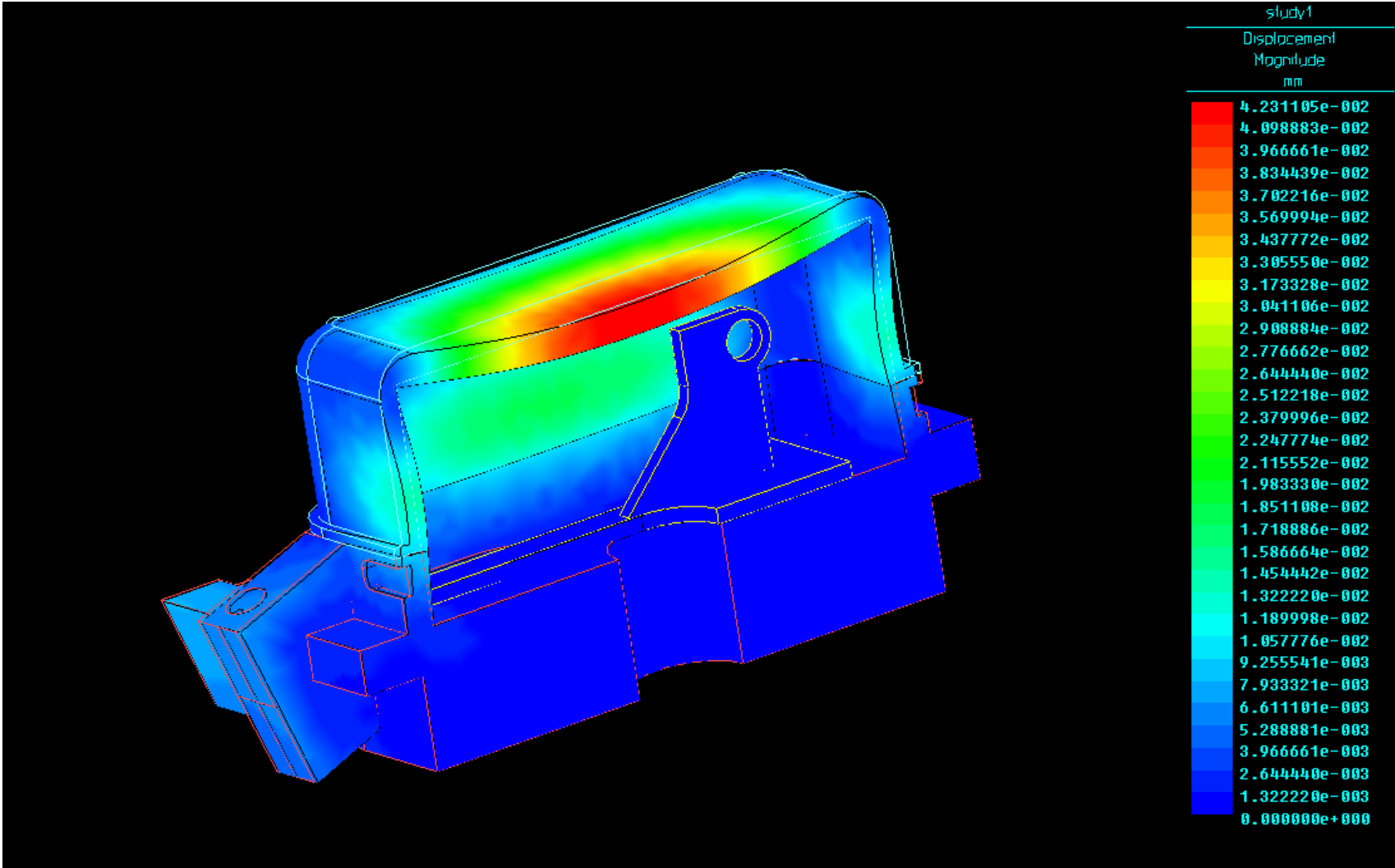
Heavy pump below bellows on separate support

Legs filled with epoxy granite

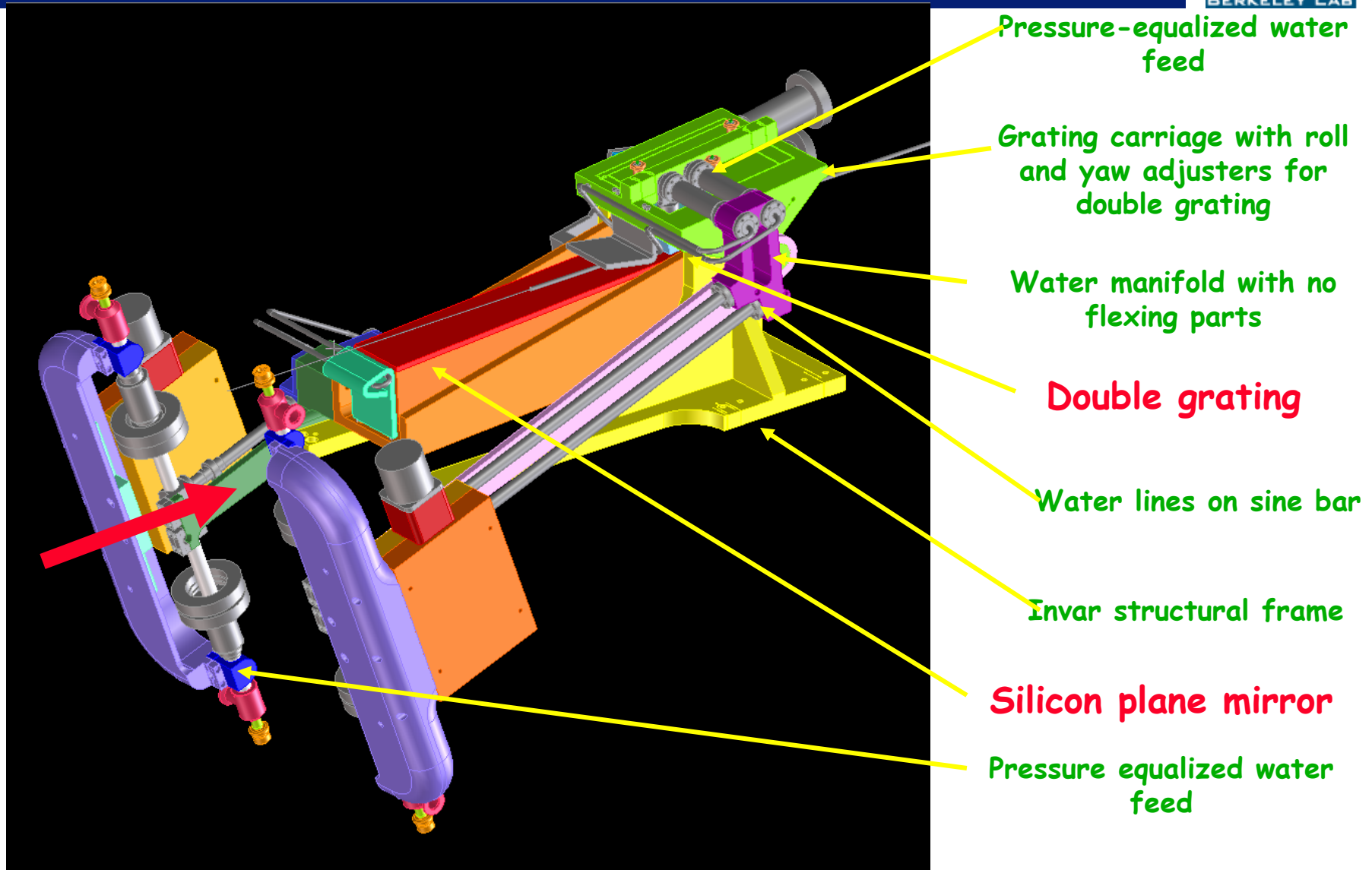
Monochromator chamber, vacuum test Oct 2001



Chamber deformation under vacuum



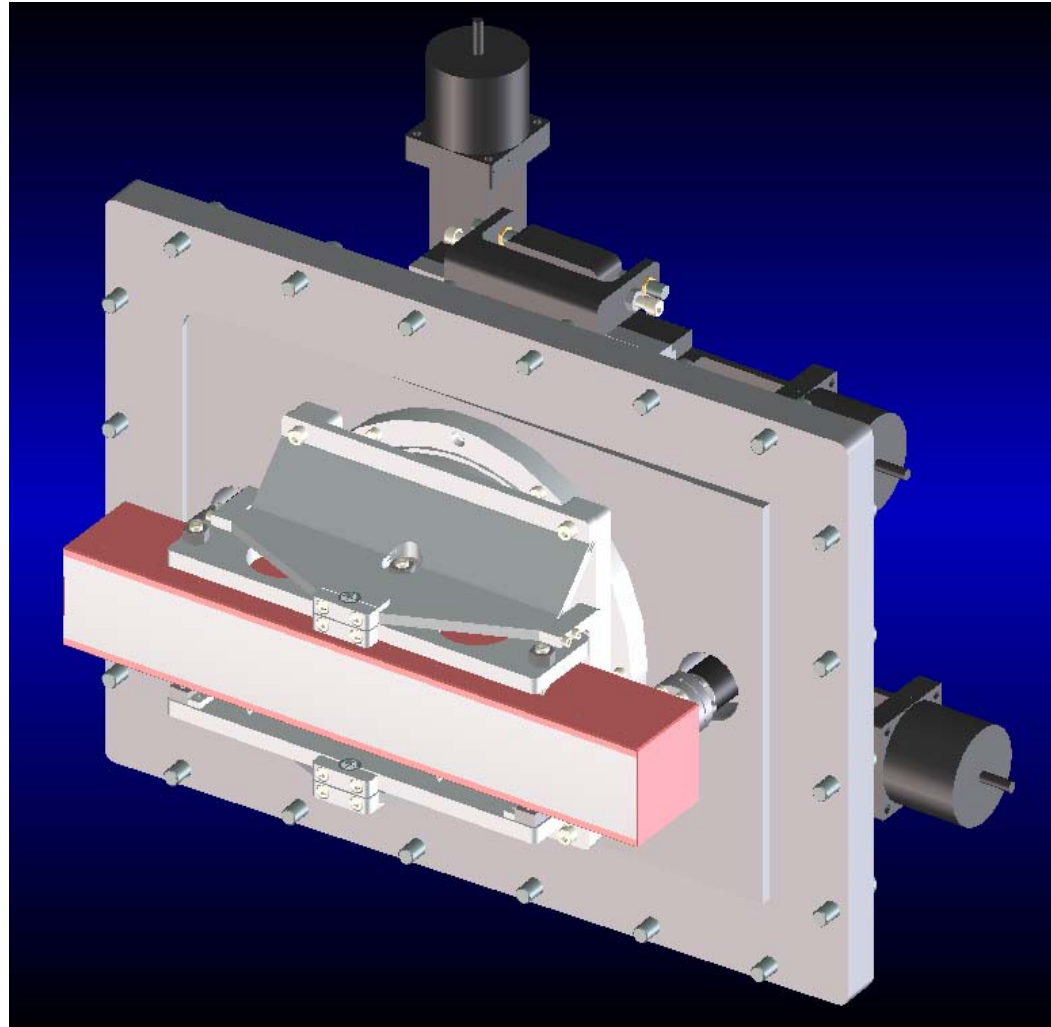
Scanning mechanism with integral cooling



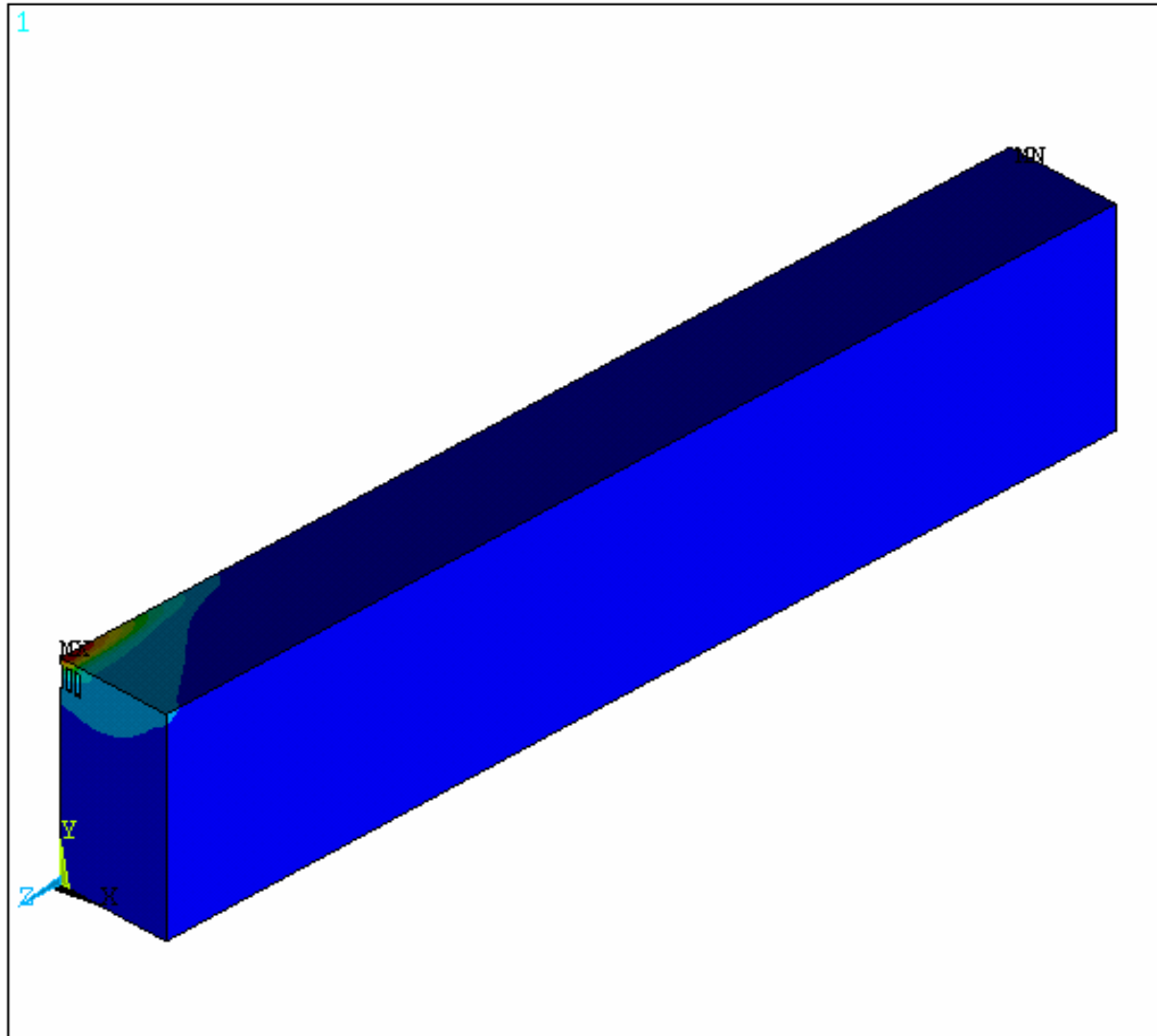
Grating substrates ready for polishing and ruling



Actuation Mechanism



Plane pre-mirror heating (ANSYS Analysis)



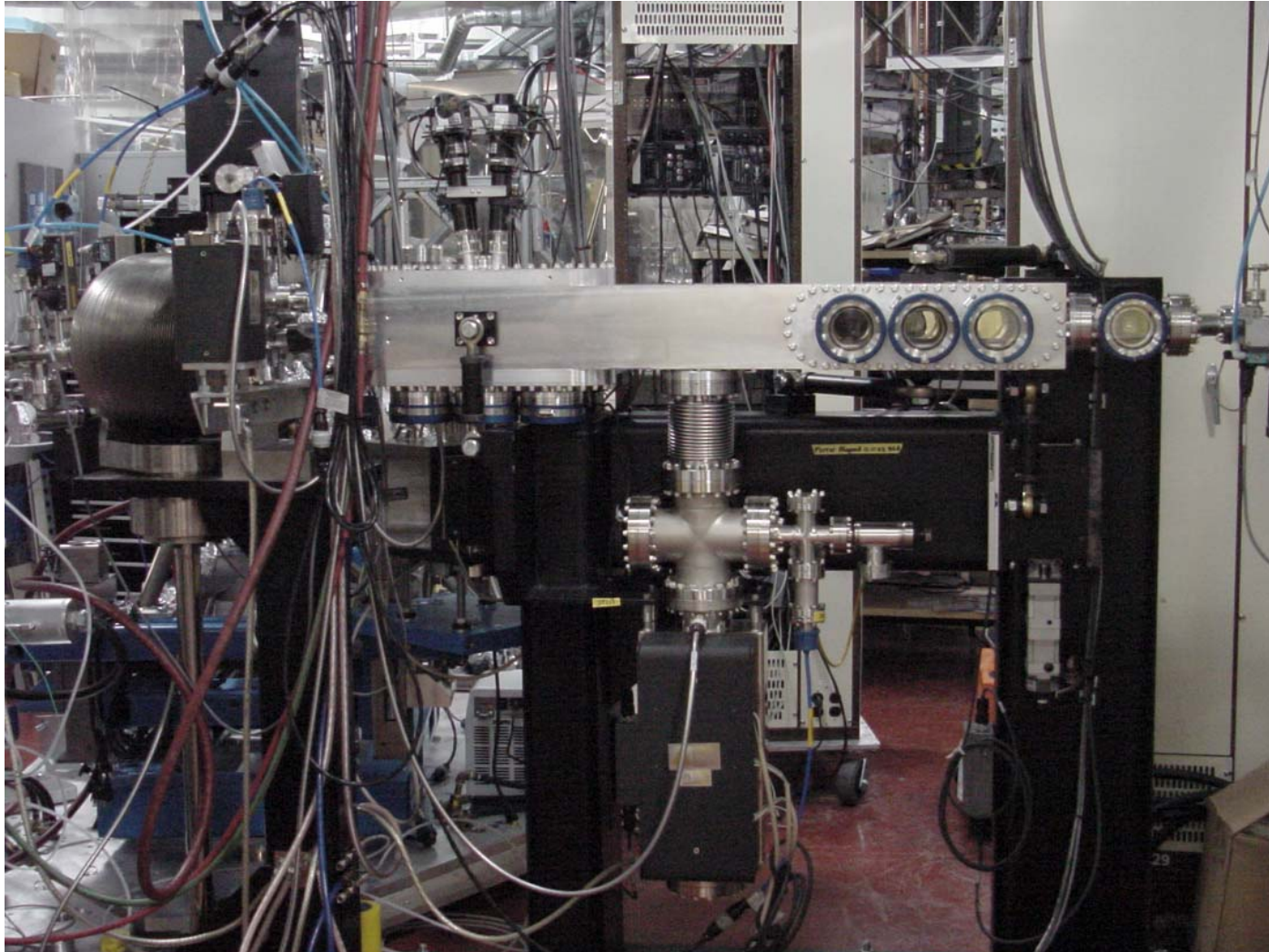
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ANSYS 5.6.1
OCT 10 2000
15:25:23
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP      (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN  =.001639
SMX  =7.199
.001639
.801399
1.601
2.401
3.201
4
4.8
5.6
6.4
7.199
```

Toroidal Mirror (Protein Crystallography M2)

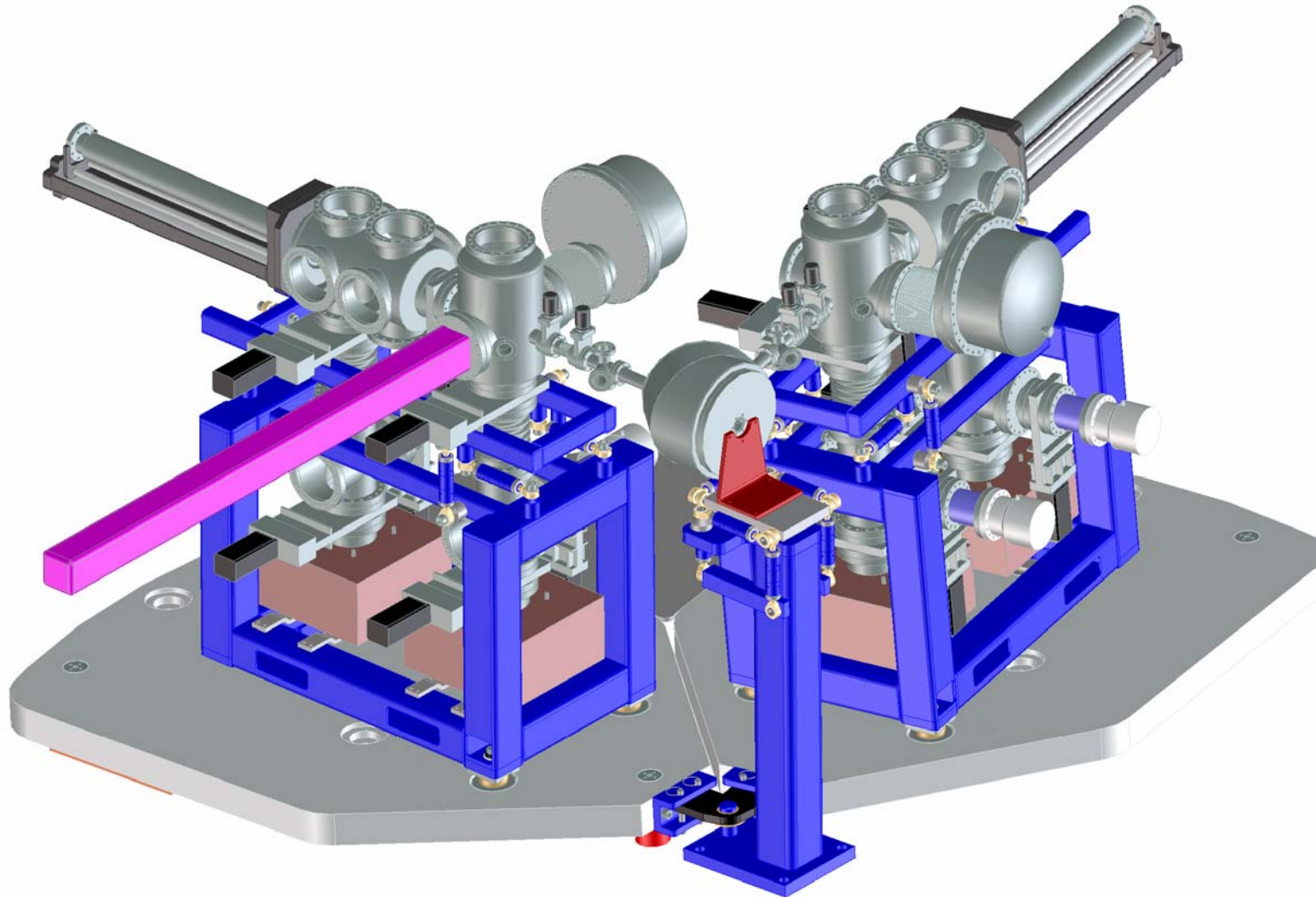


- sagittal cylinder bend into a toroidal shape ($R \sim 2 \text{ km}$, $r_0 \sim 10 \text{ cm}$)
- figure testing in progress on LTP (micro radian figure error;
< 5 Angstrom roughness)

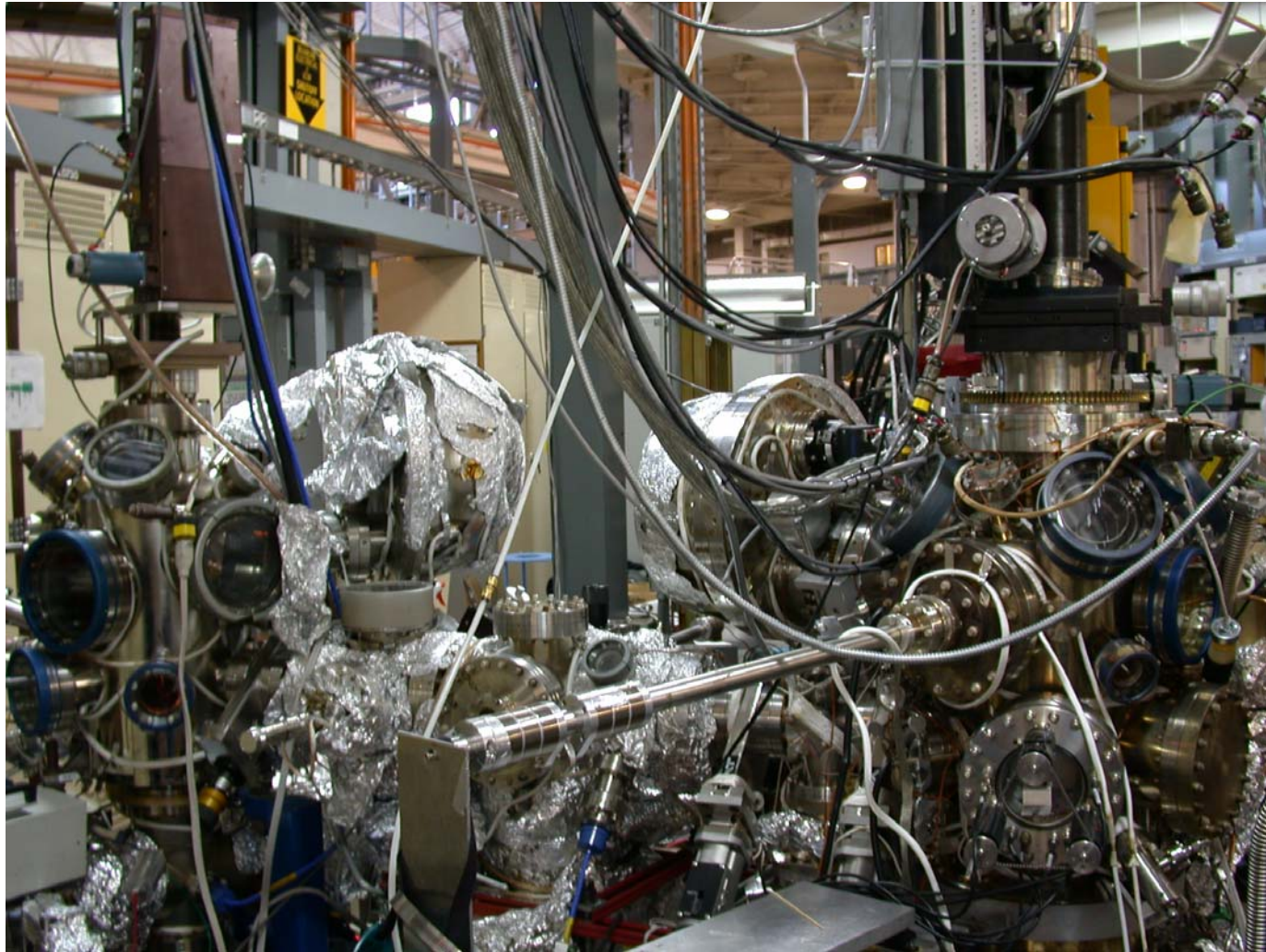
K-B Mirrors



Two Wet Spectroscopy End Stations



Angle Resolved Photo-Electron Spectroscopy (ARPES)



Eli Rotenberg et al, BL 7.0

Design of a Pakistani Beamline at SESAME

- What is the cost?
- What are the benefits for Pakistan to build a beamline at SESAME ?
- How could we build it ?

Requirements (Pakistani Beamline @ SESAME)



- Photon Energy Range = 50 to 2000eV
- Resolving Power = 10,000 - 25000 (High Resolution and moderate resolution with high flux modes)
- Control of linear polarization and circular polarization
- KB focus to 5 μ m vertically for XES (spectroscopy)
- Full power, high resolution at \approx 50-100eV for high resolution band structure mapping (spectroscopy)
- Fully optimized endstation with Scienta electron energy analyzer, emission spectrograph and sample transfer system
- Roll-up port with pathway for future development
- User friendly (advanced designing but easy in use)

THE GRATING EQUATION

- Sign convention: α , β have opposite signs if they are on opposite sides of the normal
- $m\lambda = d(\sin \alpha + \sin \beta)$
- Given m , λ and d , there are still an infinite number of α , β pairs that satisfy this equation
- Therefore we can impose a relationship between α and β as follows:

• **FIXED IN-OUT DIRECTIONS (SGM):**

$$\alpha - \beta = 2\theta$$

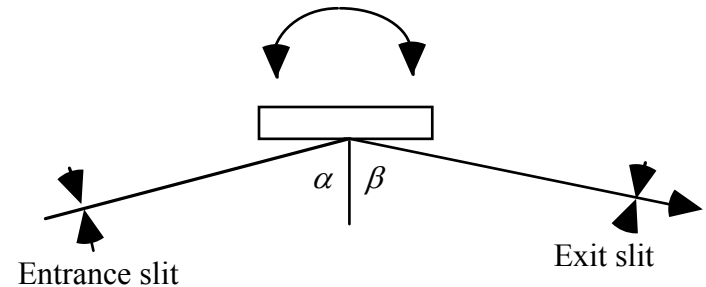
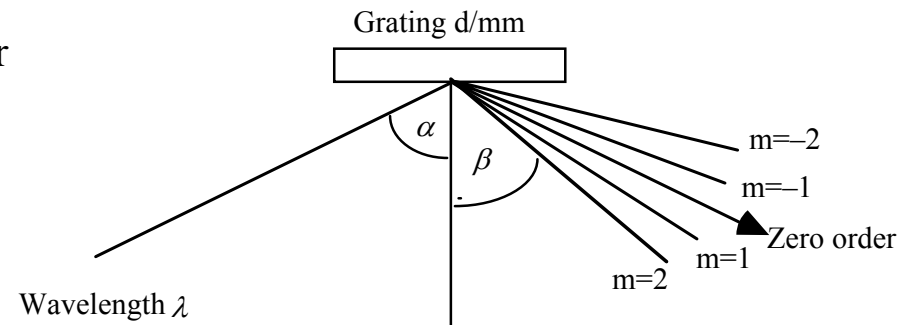
$$m\lambda = 2d \cos \theta \sin(\beta + \theta)$$

- **In this case there is a “horizon” wavelength:** If α or β becomes 90° , the acceptance falls to zero which happens at wavelength $\lambda_H = 2d \cos^2 \theta$

- **CONSTANT VALUE OF** $c_{ff} = \frac{\cos \beta}{\cos \alpha}$ **(SX700)**

$$\left(\frac{m\lambda}{d} - \sin \beta \right)^2 = 1 - (1 - \sin^2 \beta) c_{ff}^2$$

General reference:
Howells, X-ray Data Booklet, 2001



RESOLUTION OF A GRATING SYSTEM



$$m\lambda = d(\sin \alpha + \sin \beta)$$

$$\left[\frac{\partial \lambda}{\partial \beta} \right]_{\alpha} = \frac{d \cos \beta}{m}$$

$$\frac{d\lambda}{dq} = \frac{d\lambda}{d\beta} \frac{d\beta}{dq} = \frac{d \cos \beta}{mr'} \equiv \frac{10^{-3} d(\text{\AA}) \cos \beta}{mr'(\text{m})} \text{\AA}/\text{mm}$$

From this we get the exit- and entrance-slit-width-limited resolutions

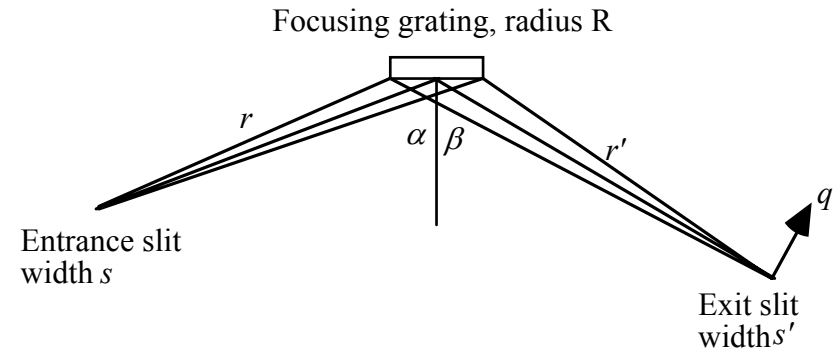
$$\Delta \lambda_s = \frac{d \cos \alpha s}{mr} \quad \Delta \lambda_{s'} = \frac{d \cos \beta s'}{mr'}$$

Taking the derivative of the grating equation at constant λ gives the magnification $M(\lambda)$

$$0 = d(\cos \alpha d\alpha + \cos \beta d\beta)$$

$$M(\lambda) = \frac{s'}{s} = \frac{r' d\beta}{r d\alpha} = -\frac{r' \cos \alpha}{r \cos \beta}$$

$$\text{If } r = R \cos \alpha, \quad r' = R \cos \beta \quad (\text{Rowland circle}) \rightarrow M(\lambda) \equiv -1$$



Diffraction-limited resolution = $1/N$

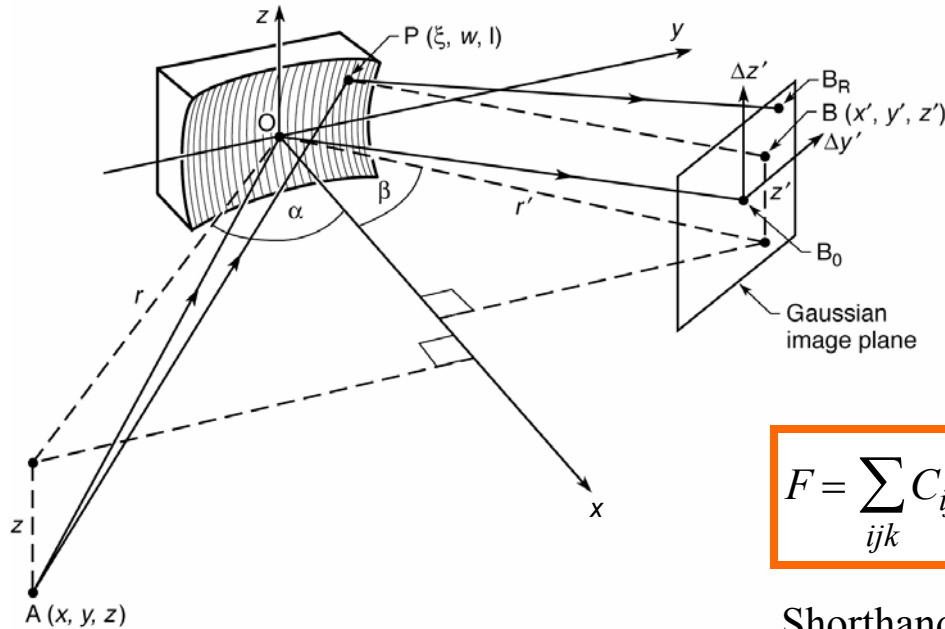
BUT

Provided the grating is big enough, the number of illuminated grooves is always sufficient to achieve the slit-width-limited resolution because of diffraction at the entrance slit

GRATING THEORY

Noda et al 1974

Padmore, Howells & McKinney 2000



OPTICAL PATH FUNCTION THEORY FOR A ROWLAND GRATING

$$F = \langle AP \rangle + \langle PB \rangle + mn\lambda = \langle AP \rangle + \langle PB \rangle + \frac{m\lambda}{d_0} w$$

where P lies on the surface $\xi = \sum_{ij} a_{ij} w^i l^j$

From standard geometry:

$$\langle AP \rangle = \sqrt{(r \cos \alpha - \xi)^2 + (r \sin \alpha - w)^2 + (z - l)^2}$$

similarly for $\langle BP \rangle$, expanding by Mathematica™

$$F = \sum_{ijk} C_{ijk}(\alpha, r) w^i l^j z^k + \sum_{ijk} C_{ijk}(\beta, r') w^i l^j z'^k + \frac{m\lambda}{d_0} w$$

Shorthand notation:

$$T = \frac{\cos^2 \alpha}{r} - 2a_{20} \cos \alpha, \quad S = \frac{1}{r} - 2a_{02} \cos \alpha,$$

$$T' = \frac{\cos^2 \beta}{r'} - 2a_{20} \cos \beta, \quad S' = \frac{1}{r'} - 2a_{02} \cos \beta$$

THE GOAL IS TO KNOW WHERE THE RAYS GO IN THE ABERRATED IMAGE AND WHY



Padmore, Howells and McKinney 2000 for an explanation

$$\Delta y' = \frac{r'_0}{\cos \beta_0} \frac{\partial F}{\partial w}, \quad \Delta z' = r'_0 \frac{\partial F}{\partial a}$$

Recall that $\Delta y'$ and $\Delta z'$ are the coordinates of the ray arrival point relative to the Gaussian image point. F behaves like a potential and allows them to be calculated by taking the derivative. Because F is composed of a sum of terms, we can calculate the contributions of each aberration type separately

$$\Delta y'_{ijk} = \frac{r'_0}{\cos \beta_0} \frac{\partial}{\partial w} \{F_{ijk} w^i l^j\} \quad \Delta z'_{ijk} = r'_0 \frac{\partial}{\partial a} \{F_{ijk} w^i l^j\}$$

$$\Delta y' = \sum_{ijk} \Delta y'_{ijk}, \quad \Delta z' = \sum_{ijk} \Delta z'_{ijk}$$

So aberrations can reinforce or cancel each other

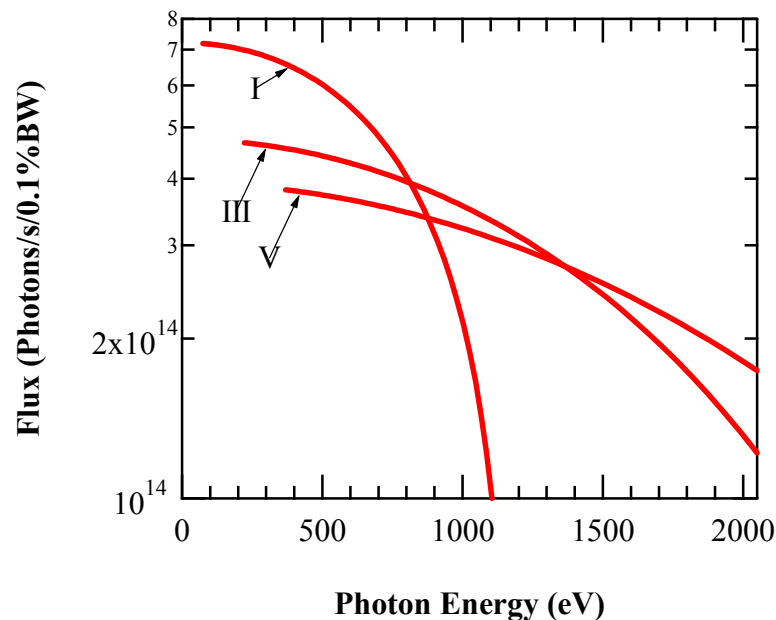
Standard practice is to calculate ray positions this way and independently check them against **SHADOW** ray-traces done with a point source and few rays. When this works and the result looks good, SHADOW can be run with a realistic source and thousands of rays to fully evaluate the design

SESAME Source Parameters

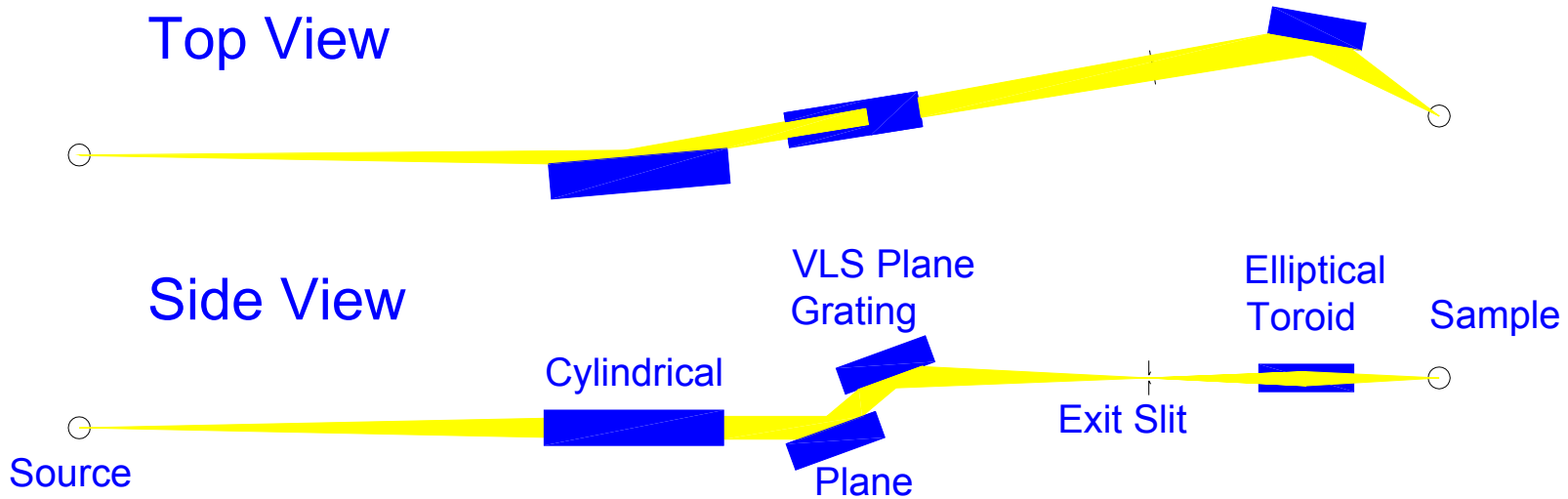


Energy	2.5 GeV
Current	200 mA
σ_x	0.8 mm
σ_y	0.028 mm
σ'_x	45 μrad
σ'_y	9 μrad
ID length	2.6 m
λ_u	50 mm
k_{\max}	5.5

Central Cone Flux



Pakistani Beamline Layout



* Minimum # (4) of Advanced Optics

* High resolution with no translation of slits or grating Tank

Element	Distance from Source (m)	Angle of Incidence	Coating	Deflection
Cylindrical	15.0	88.0°	Au	Hor.
Plane	15.71-15.96	78.9°-88.6°	Au	Vert.
Gratings	16.0	84.0°-89.5°	Au	Vert.
Slit	24.0			
Ellip. Toroid	26.0	88.0°	Au	Hor.
Sample	27.04			

VLS Plane Gratings



line density = $k(1 + 2b_2 w + 3b_3 w^2 + \dots)$

$$f_{20}(\lambda, c) = \frac{\cos^2 \alpha(\lambda, c)}{dSoGr} + \frac{\cos^2 \beta(\lambda, c)}{dGrEx} + 2b_2 m k \lambda$$

$$f_{30}(\lambda, c) = \sin \alpha(\lambda, c) \frac{\cos^2 \alpha(\lambda, c)}{dSoGr^2} + \sin \beta(\lambda, c) \frac{\cos^2 \beta(\lambda, c)}{dGrEx^2} + 2b_3 m k \lambda$$

f_{20} and f_{30} can be zeroed at one λ each

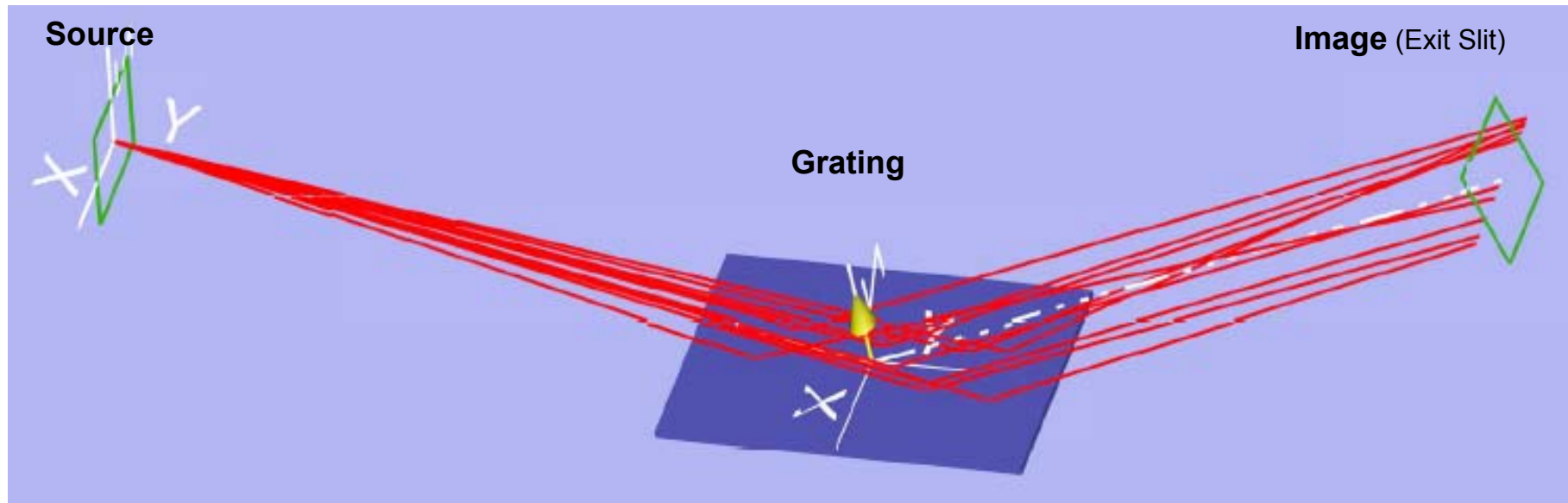
By varying c one can zero f_{20} for all λ .

	k (mm ⁻¹)	b_2 (mm ⁻²)	b_3 (mm ⁻³)
LEG	800	1.574×10⁻⁴	1.96×10⁻⁸
HEG	1800	1.300×10⁻⁴	1.62×10⁻⁸

The goal is to know where the rays go in the aberrated image and why



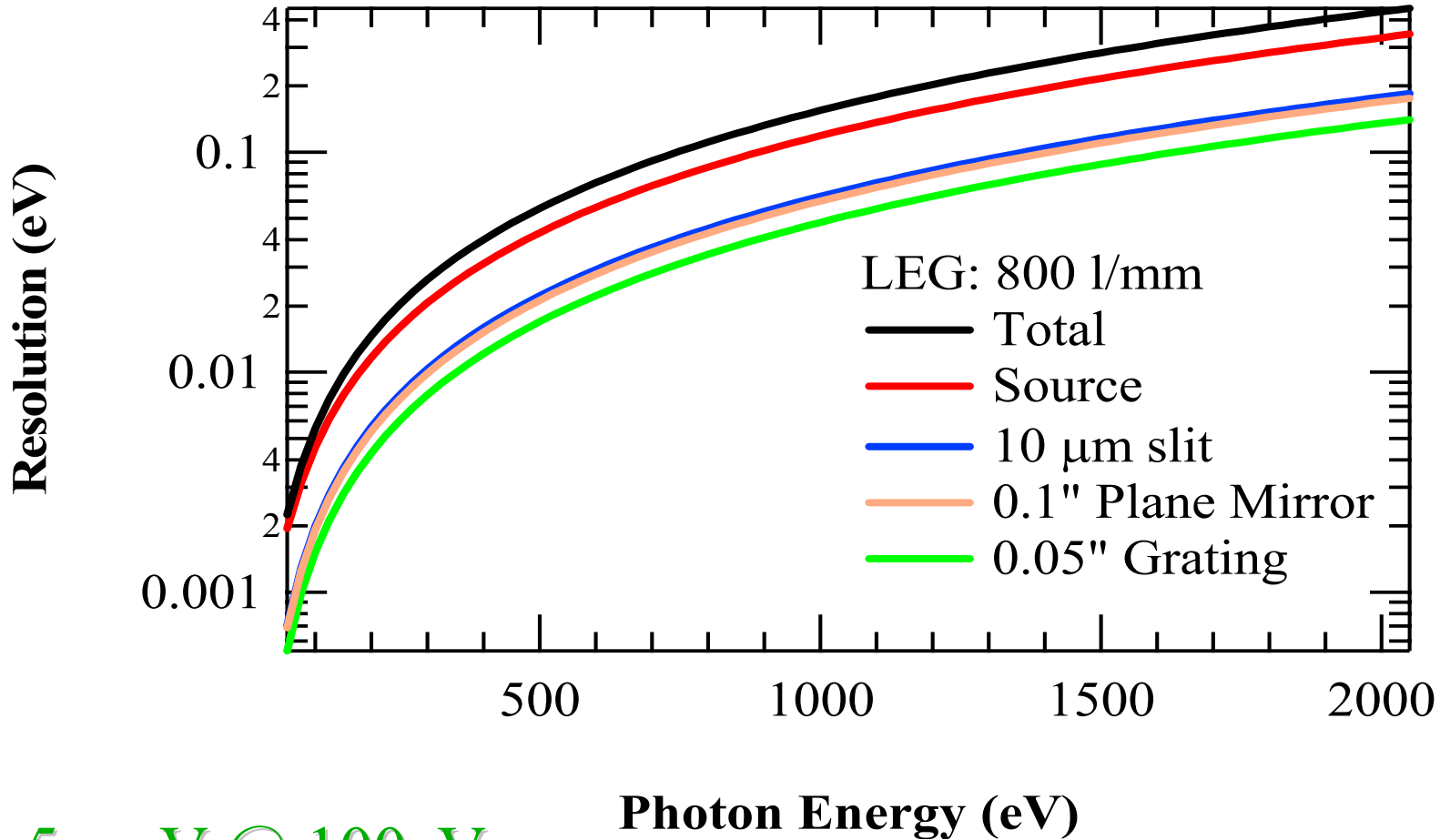
Ray Tracing (Shadow)



- Variable line spacing gratings with pre-mirrors
- Real SESAME Source in space and angular distribution

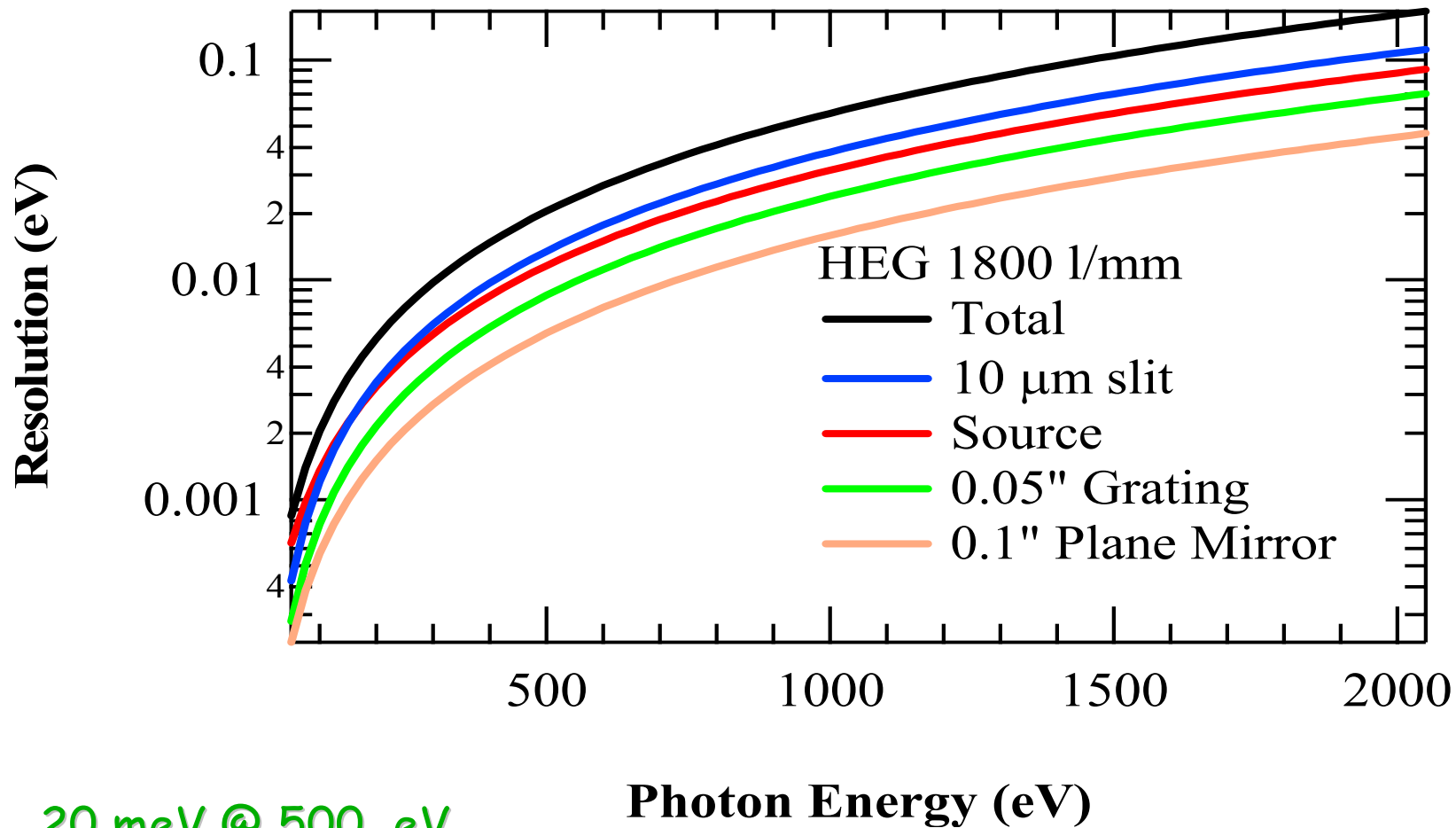
Ruben Reninger

Resolution Low Energy Grating (LEG)



5 meV @ 100eV

Resolution High Energy Grating HEG



Resolution at 100 eV (LEG)



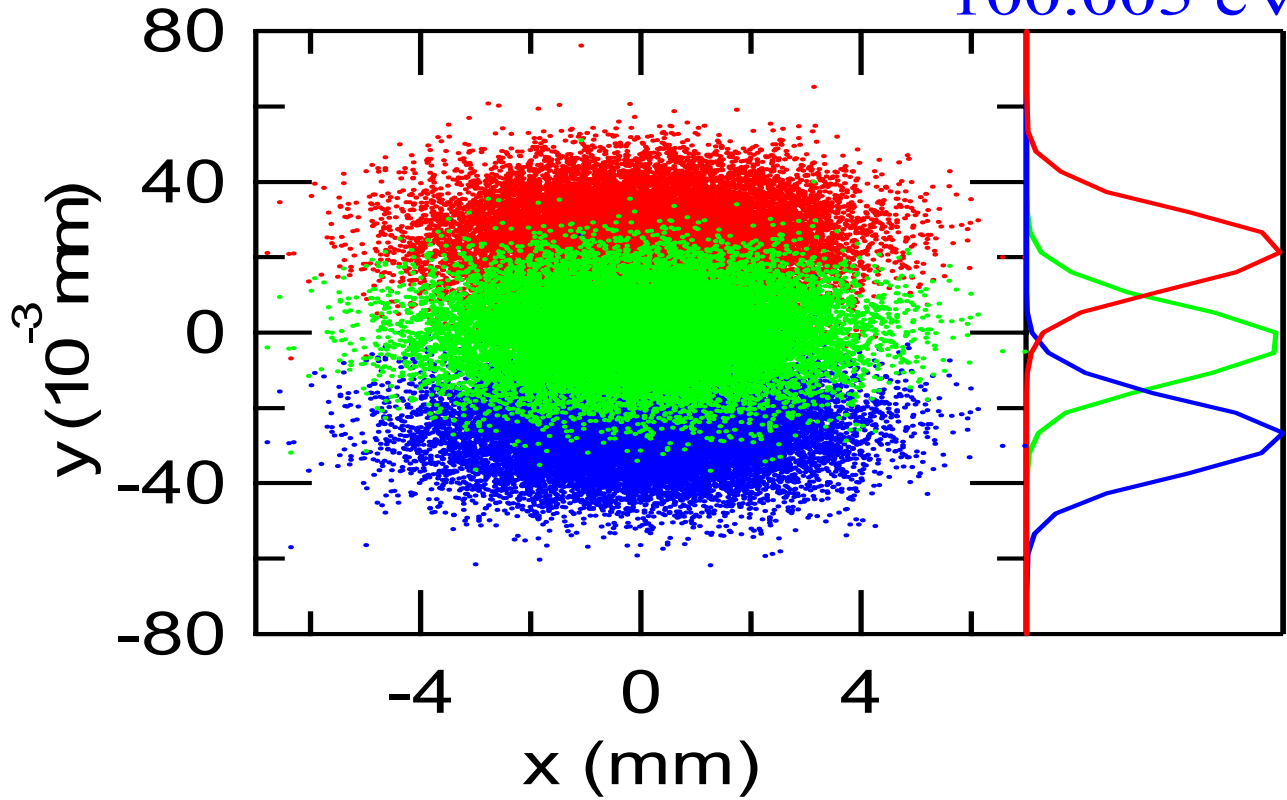
$\sigma_x: 1.8 \text{ mm}$ $\sigma_y: 0.01 \text{ mm}$

99.995 eV

100.000 eV

100.005 eV

h ν ~ 100eV



Sigmas are for the central λ

Resolution at 400 eV (HEG)



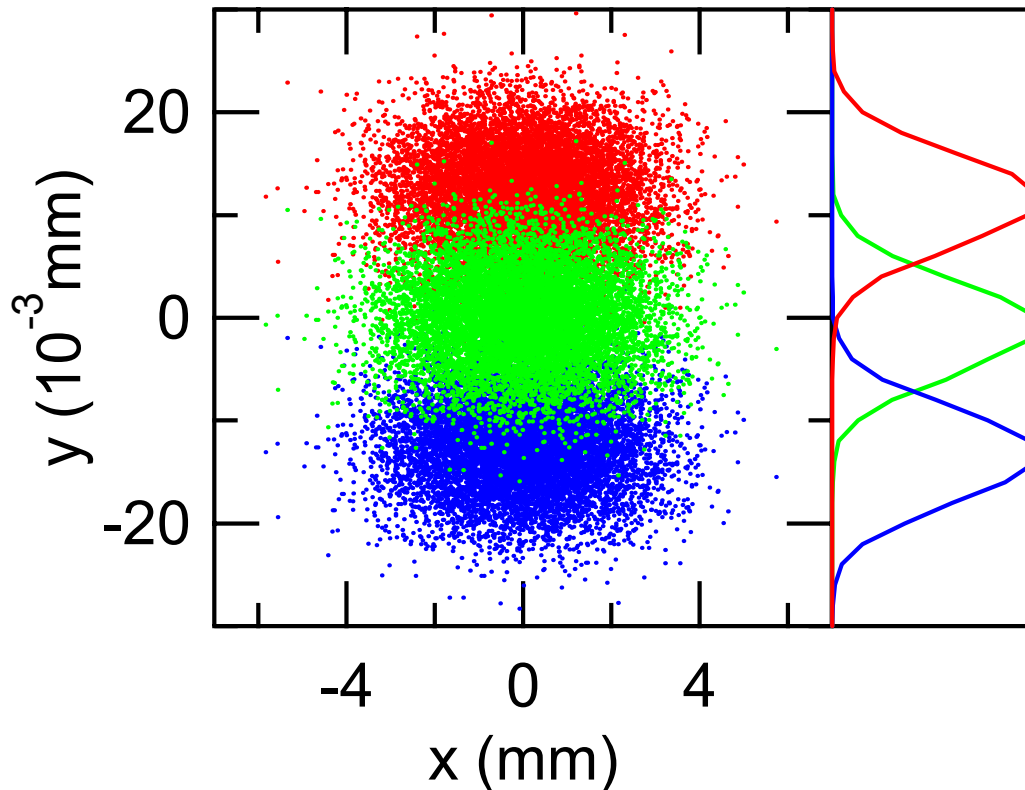
$\sigma_x: 1.5 \text{ mm}$ $\sigma_y: 0.0043 \text{ mm}$

399.988 eV

400.000 eV

400.012 eV

h ν ~ 400eV



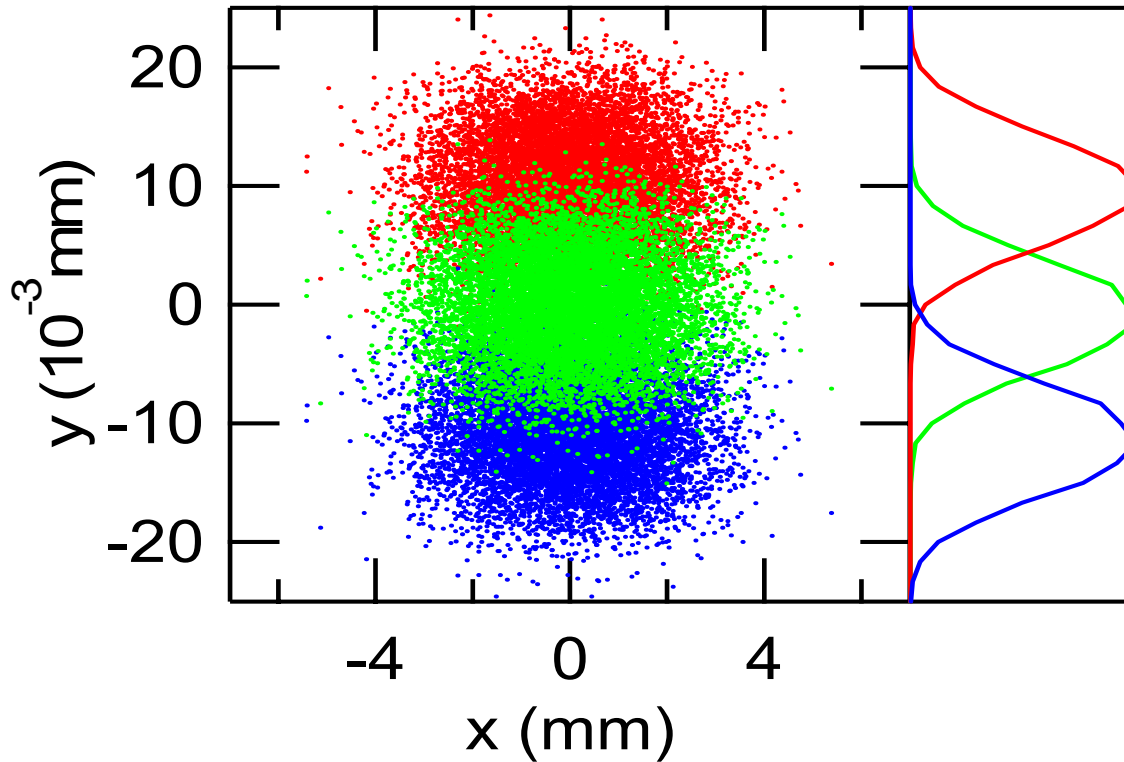
Resolution at 1000 eV (HEG)



σ_x :1.4mm σ_y :0.0042 mm

999.96 eV
1000.00 eV
1000.04 eV

h ν ~ 1000eV



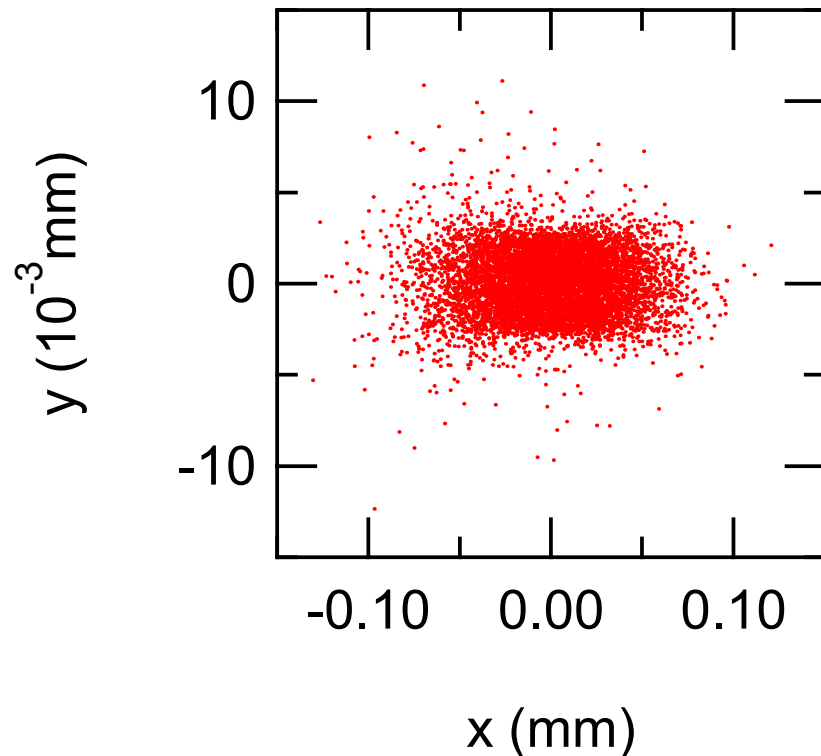
Spot at Sample



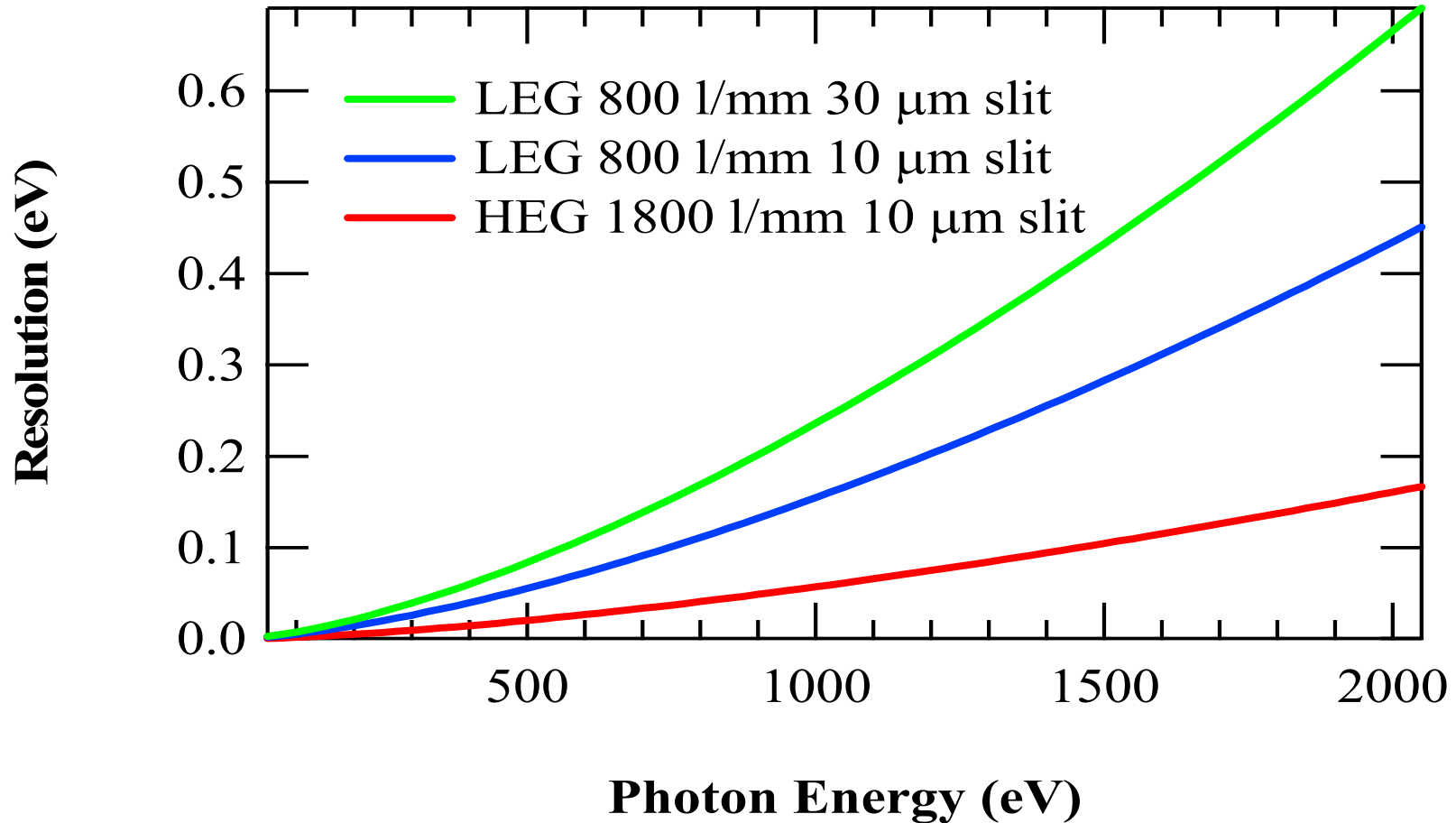
Vertical FWHM: $\sim 5 \mu\text{m}$

Horizontal FWHM: $\sim 7 \mu\text{m}$

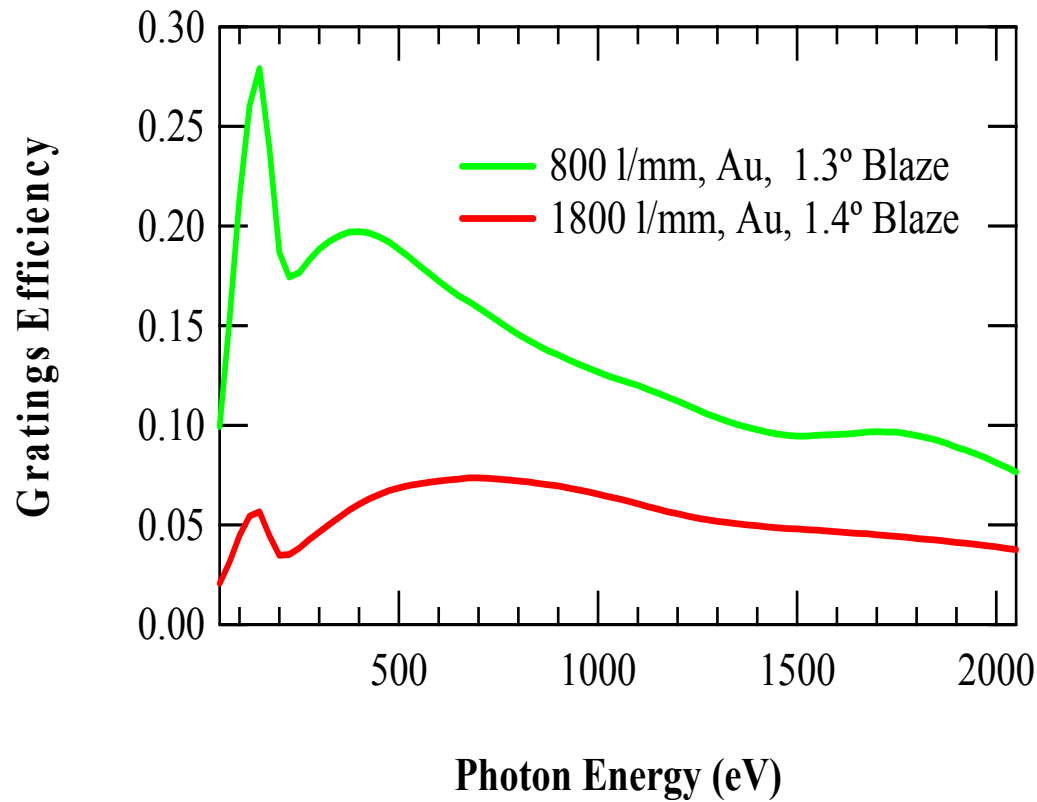
Sample 100 eV, 10 μm slit
 $\sigma_x: 0.032\text{mm}$ $\sigma_y: 0.0018\text{mm}$



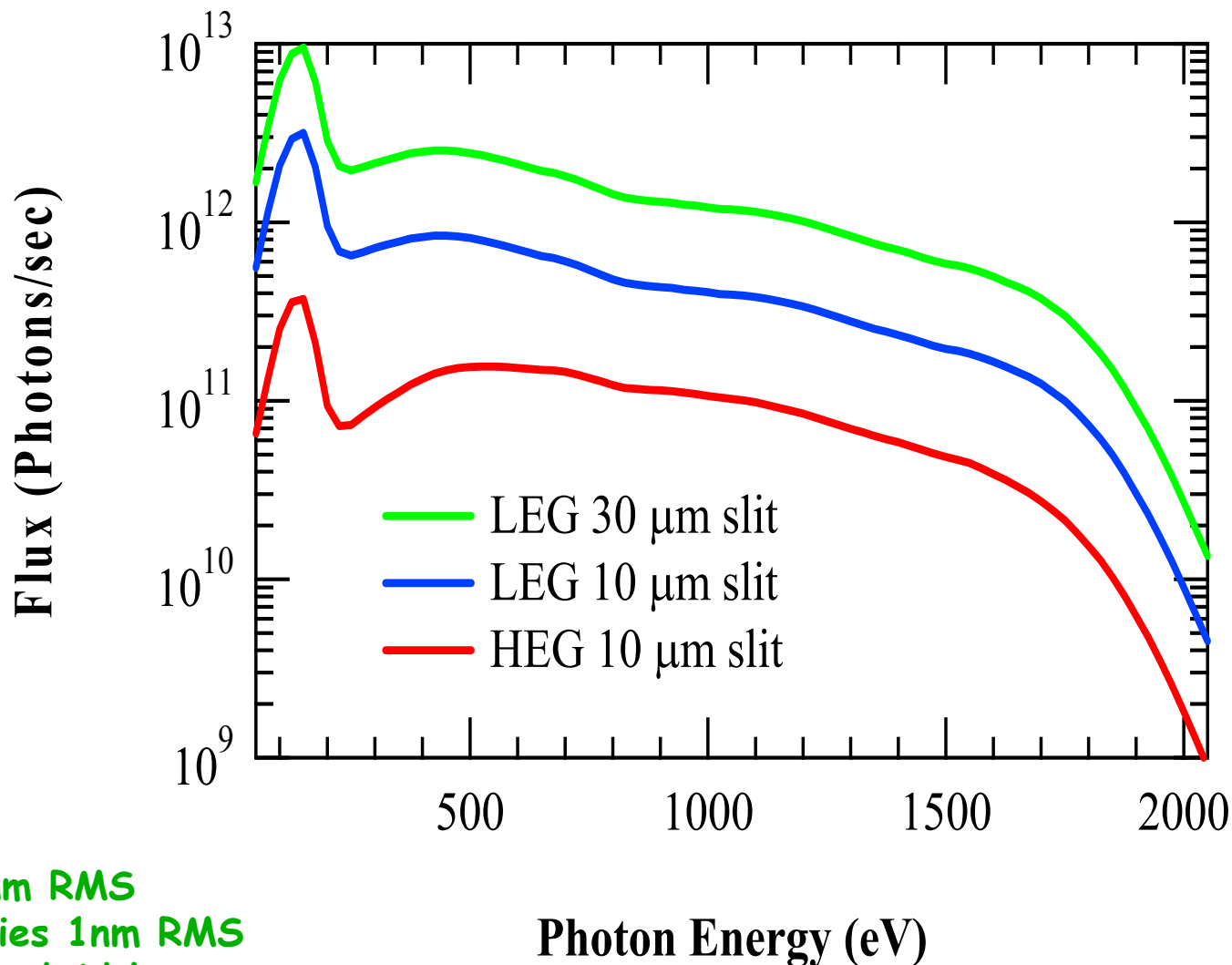
Total Resolution (varous gratings and slit settings)



Grating efficiencies

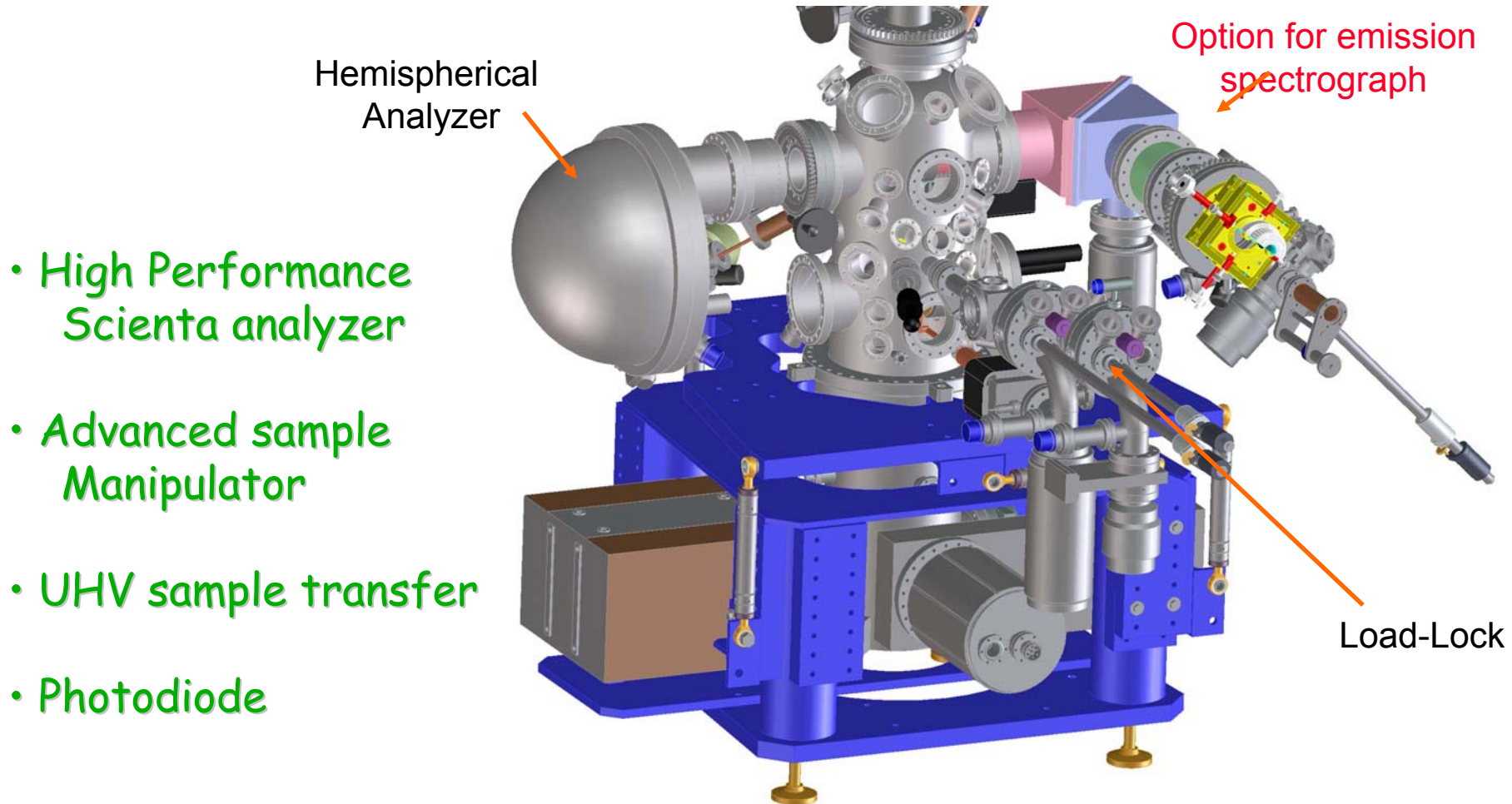


Total Flux at sample

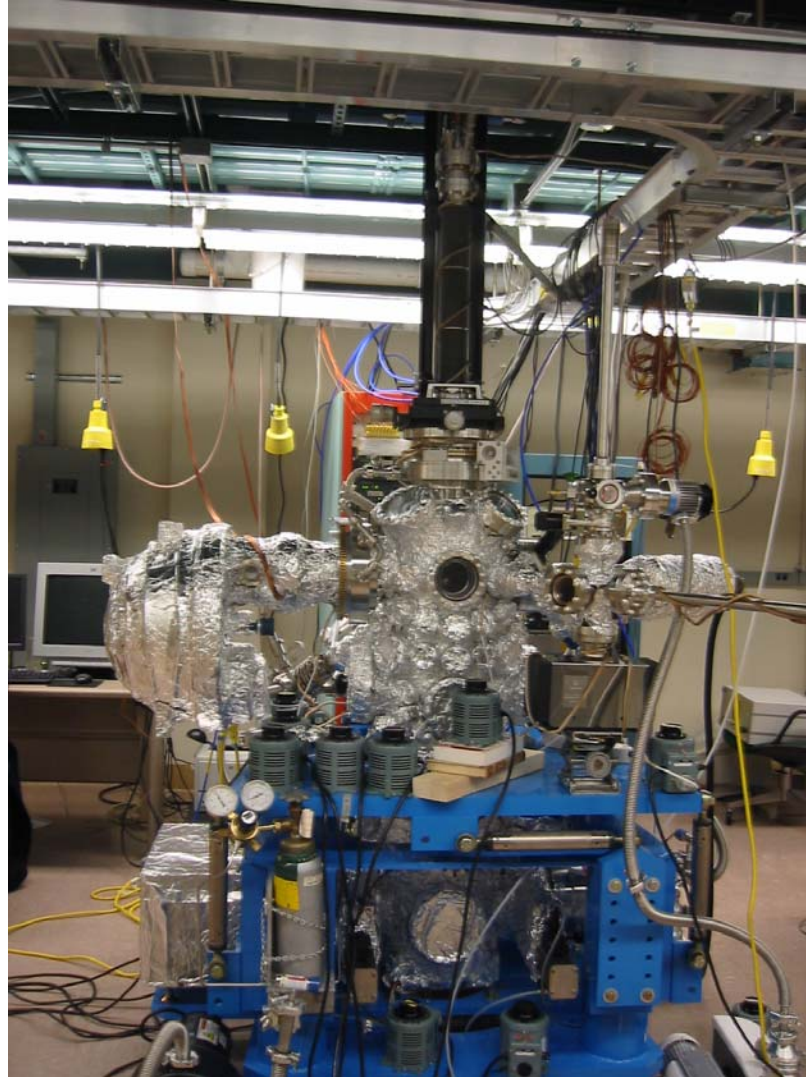


Undulator Flux
Reflectivities 1 nm RMS
Grating Efficiencies 1nm RMS
Correction for bandwidth

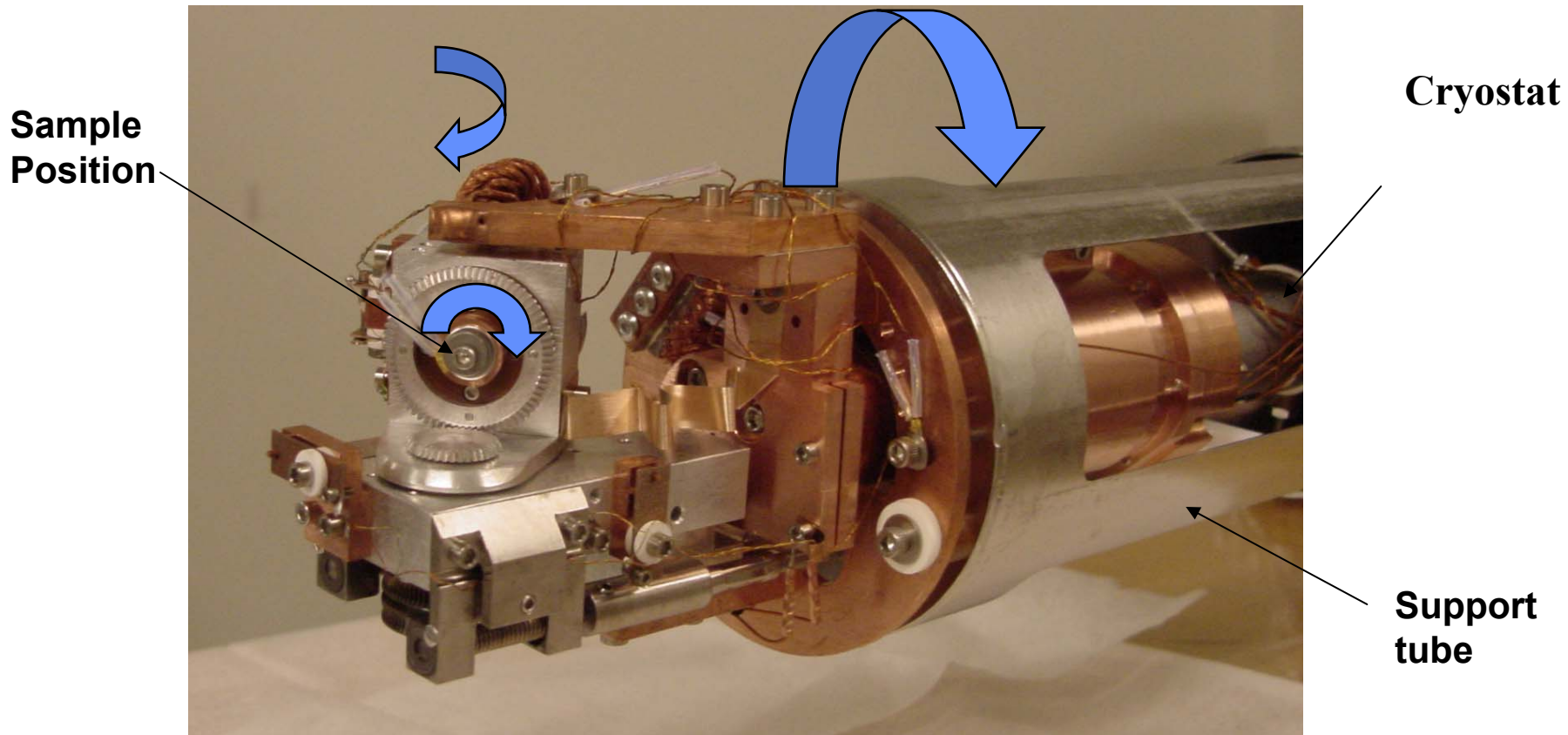
Endstation - SESAME



Experimental Chamber - day 1



Low-Temperature Goniometer with Six Degrees of Freedom



- (1). **Six degrees of freedom:** 3 rotational and 3 translational;
- (2). Samp temperature **~10 K** (no radiation shield);
- (3). Stability of sample against temperature change

Designed and fabricated by John Pepper (BL 10.0)

Design of a Pakistani Beamline at SESAME

- What is the cost?
- What are the benefits for Pakistan to build a beamline at SESAME ?
- How could we build it ?

Cost of the beamline



1. Optics (mirrors and 2 gratings) = \$ 600k
2. Mirror tanks and controllers = \$ 200k
3. Monochromator tank and controller = \$400k
4. Vacuum Hardware, stands and pumps etc = \$400k
5. Control system, wireways = \$ 200k
6. Project management (3months) = \$ 60k
7. Experimental Station = \$ 750k
8. Contingency (10%) = \$ 260k

Grand Total = \$2,870k

Undulator and the front end provided by SESAME

Requires training of ~3 scientists and ~2 engineers @ ALS (urgent)

Design of a Pakistani Beamline at SESAME

- What is the cost?
- What are the benefits for Pakistan to build a beamline at SESAME ?
- How could we build it ?

What are the benefits for Pakistan to build a beamline at SESAME ?



- Education; an experimental facility for students and researchers to carry out advanced research, practical training of technicians (electrical, mechanical, computer control, instrument automation)
- Transfer of technology for construction of advanced instrumentation
-make use of the existing infra-structure
(time is right: SESAME under UNESCO)
- Catch up with developing countries (India, Singapore, Thailand, Korea, Spain, Brazil, Taiwan)
- Provide easy access for R & D research (specific to our own needs: if and when needed)
 - nano science; solar energy, environmental problems, catalysis, health,

THE ADVANCED LIGHT SOURCE

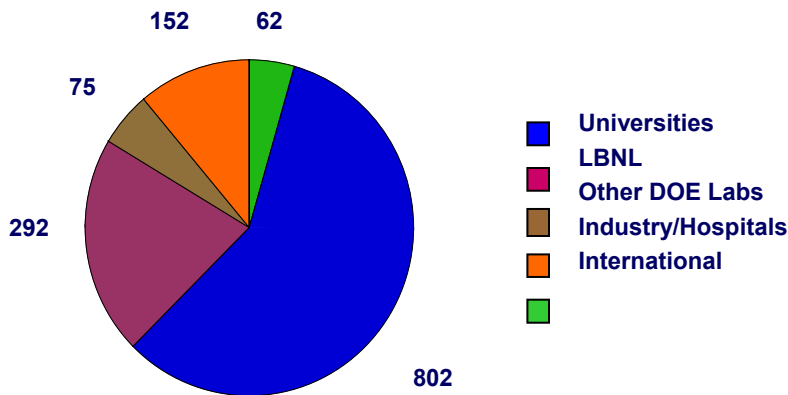


THE MISSION OF THE ALS IS TO SUPPORT USERS IN DOING OUTSTANDING SCIENCE

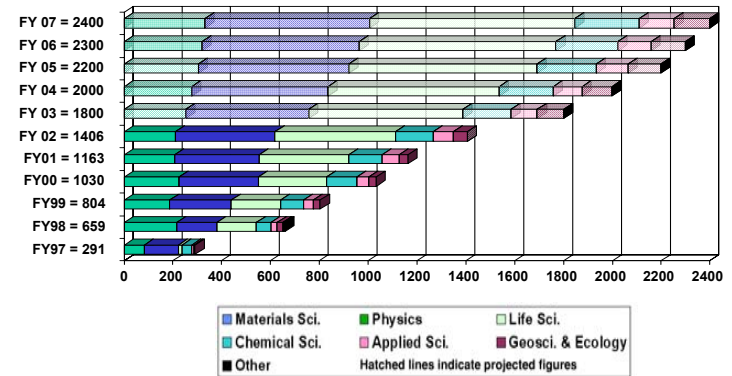
- The Advanced Light Source is one of the world's brightest sources of soft x rays
- The ALS began operations in 1993, and in the first ten years 38 beam lines were added
- The ALS serves the national research, education and high tech industrial communities

ALS Construction \$150 million

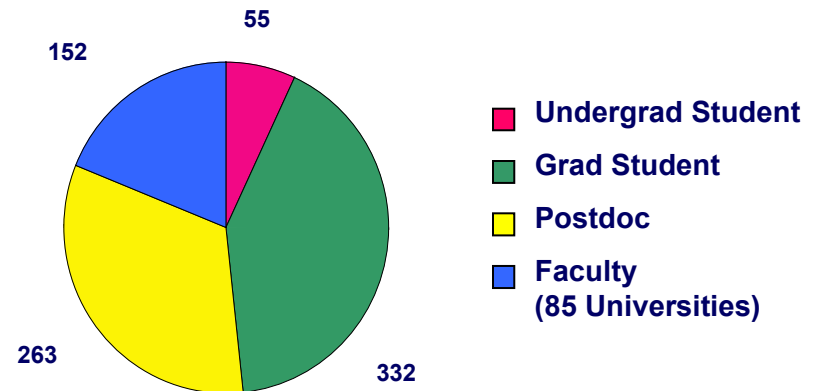
ALS Users by Home Institution



ALS User Population Projected to 2007



ALS Academic Users



UHV Component Development

ULTRA HIGH VACUUM SPUTTER ION PUMPS DEVELOPED AT CAT



In order to construct such accelerators, one requires many frontline technologies. These include ultra high vacuum technology, magnet technology, high power precision power supplies, control electronics, etc.? The centre has taken up development of most of these technologies.

Most of the ultra high vacuum hardware required for Indus-1, Indus-2, linac, beamlines, etc. are developed in-house? These components include sputter ion pumps of capacities ranging from 35l/sec to 500 l/sec, turbo molecular pumps, titanium sublimation Pumps, fast acting valves, gate valves and gauges.???

All UHV components are chemically cleaned and electro polished in a chemical treatment facility set up at the centre.

Design of a Pakistani Beamline at SESAME

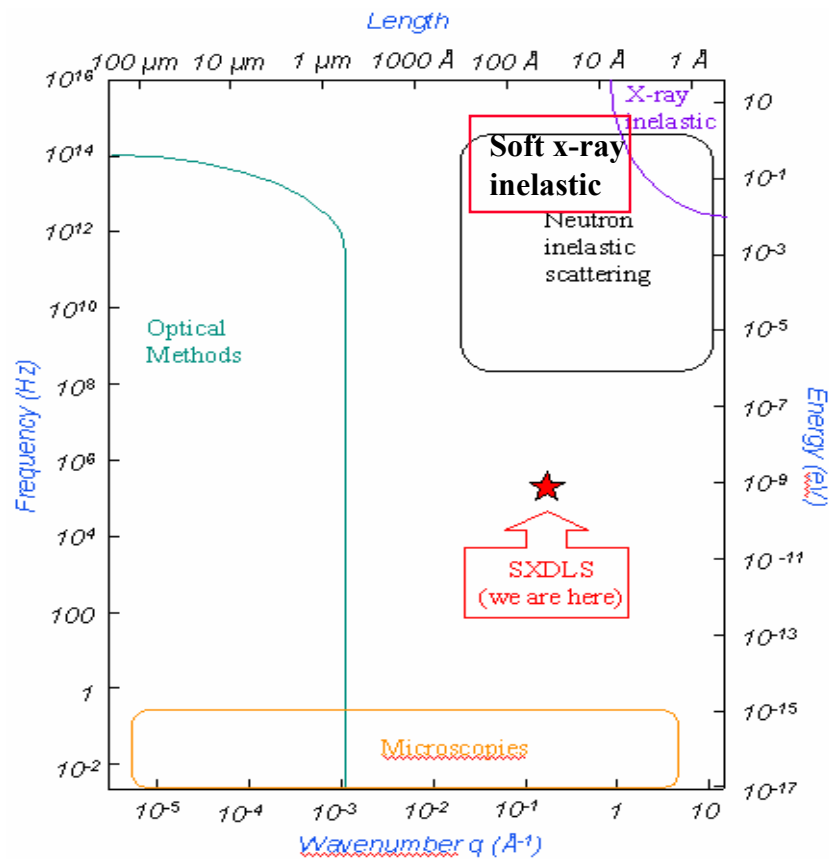
- What is the cost?
- What are the benefits for Pakistan to build a beamline at SESAME ?
- **How could we build it ?**

How could we build it ?

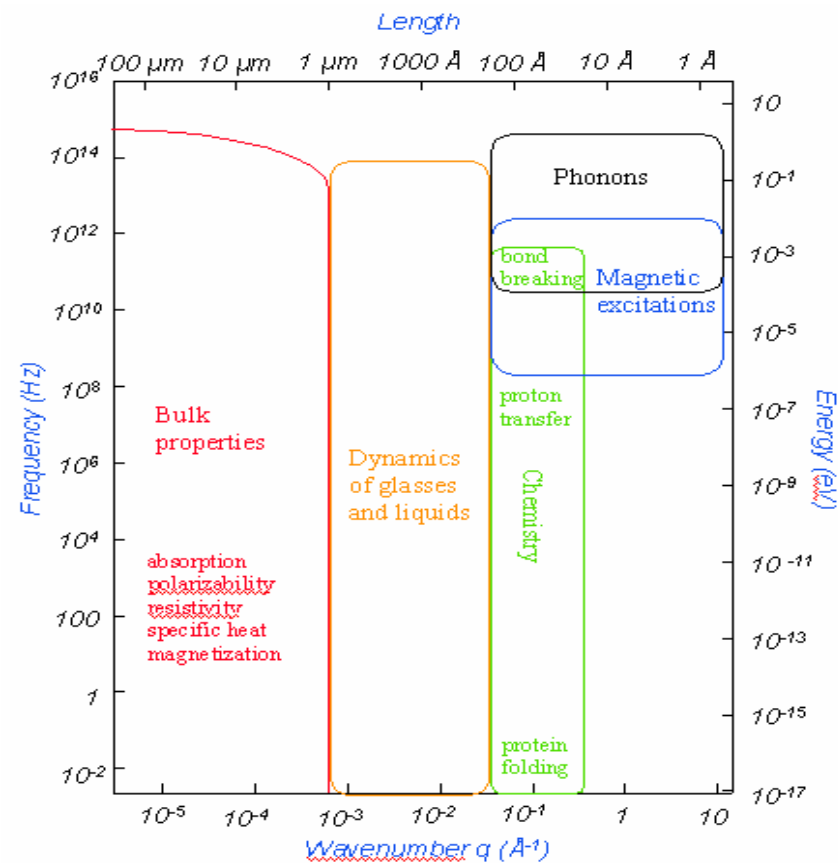


- Preliminary design is complete
(performance >100 times better than the best Indian beamline in Indus II)
- Train scientists and engineers at the ALS (1-2 years hands on training)
- Use existing engineering drawings (blue prints) and knowledge from the ALS;
design optimized according to SESAME parameter
- Plan for building SR facility in Pakistan during the next 5-10 years (cost \$50M - \$80M)

Spatial and temporal frequency sensitivities of various techniques and physical phenomena



Spatial and temporal frequency sensitivities of various techniques



Relevant spatial and temporal frequency scales for various physical phenomena

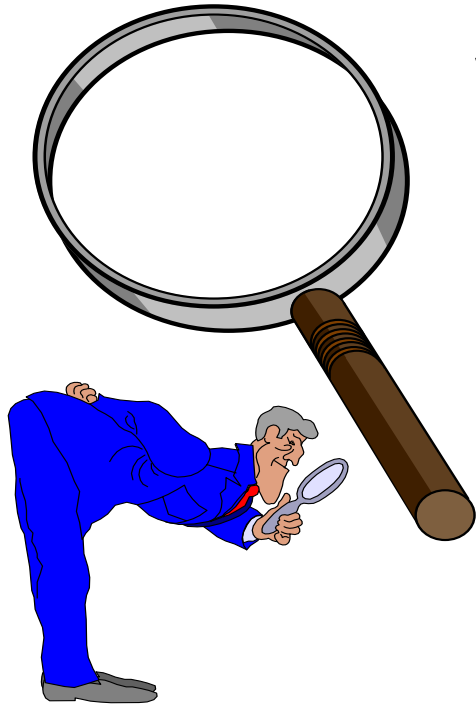
Acknowledgement



o Beamline:
Ruben Reninger (independent consultant)
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Howard Padmore,
Tony Warwick
David Shuh

o Science:
Zahid Hasan, Princeton University
ZX Shen, Stanford University
Eli Rotenberg
Lou Terminello, LLNL
Steve Kevan, univ of Oregon

Conclusions



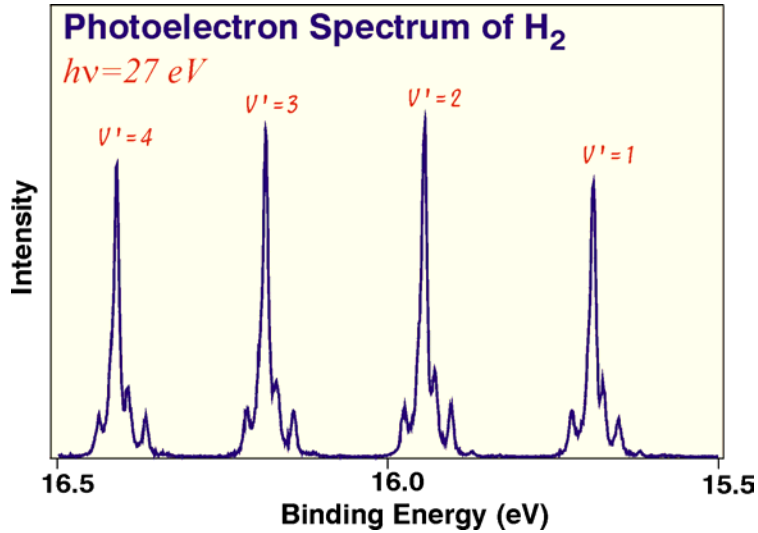
We may need to look harder but
a lot of new physics still to come!!



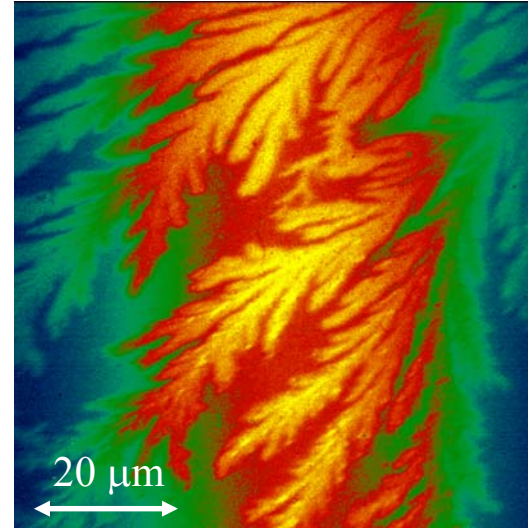
Science with Synchrotron Radiation

- Techniques ?
 - 100 years of Physics :
 - Story of Einsteins' Photoelectric effect
- Applications in the field of:
 - Nano science
 - Strongly correlated systems (high T_c , CMR)
 - Magnetism
 - Energy (combustion dynamics, solar energy, electrochemical cell,
 - Hydrogen strorage)
 - Environment
 - Catalysis, corossion

WHAT DOES SR BRIGHTNESS BUY YOU?



Very High Energy Resolution



Magnetic structure of LaFeO₃ layer on surface oxide.

Submicron Spatial Resolution



Coherence

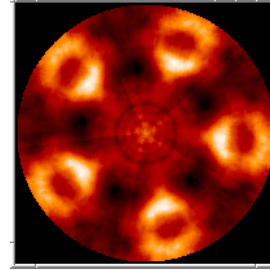
IMPORTANCE FOR MATERIALS AND CHEMICAL SCIENCES



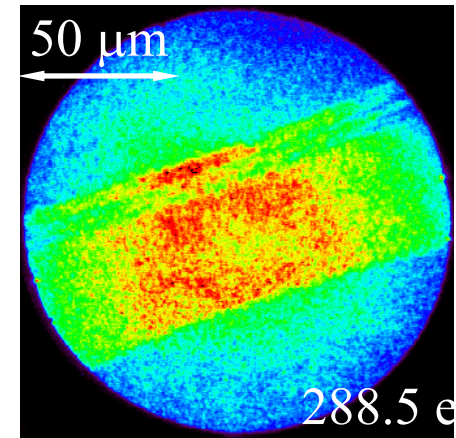
Ultimately, the

electronic,

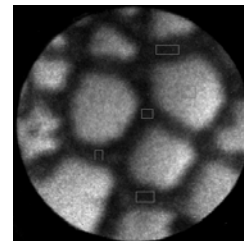
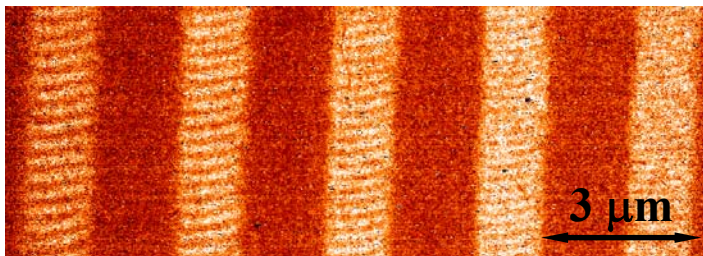
magnetic,



chemical,



mechanical,



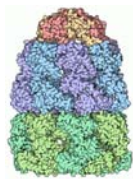
optical, thermal, and structural properties of matter depend on the behavior of electrons.

Imaging of Biological Systems

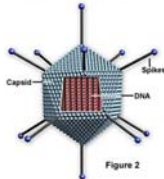
Size (m) 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1



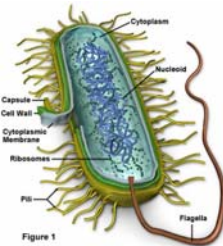
Molecules



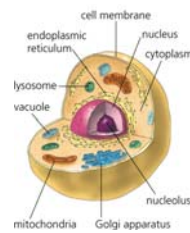
Complexes



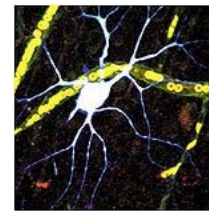
Viruses



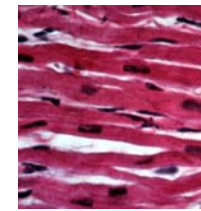
Bacteria



Cellular compartments



Cells



Tissues



Whole organisms

Cryo-electron microscopy

Light microscopy

X-ray crystallography

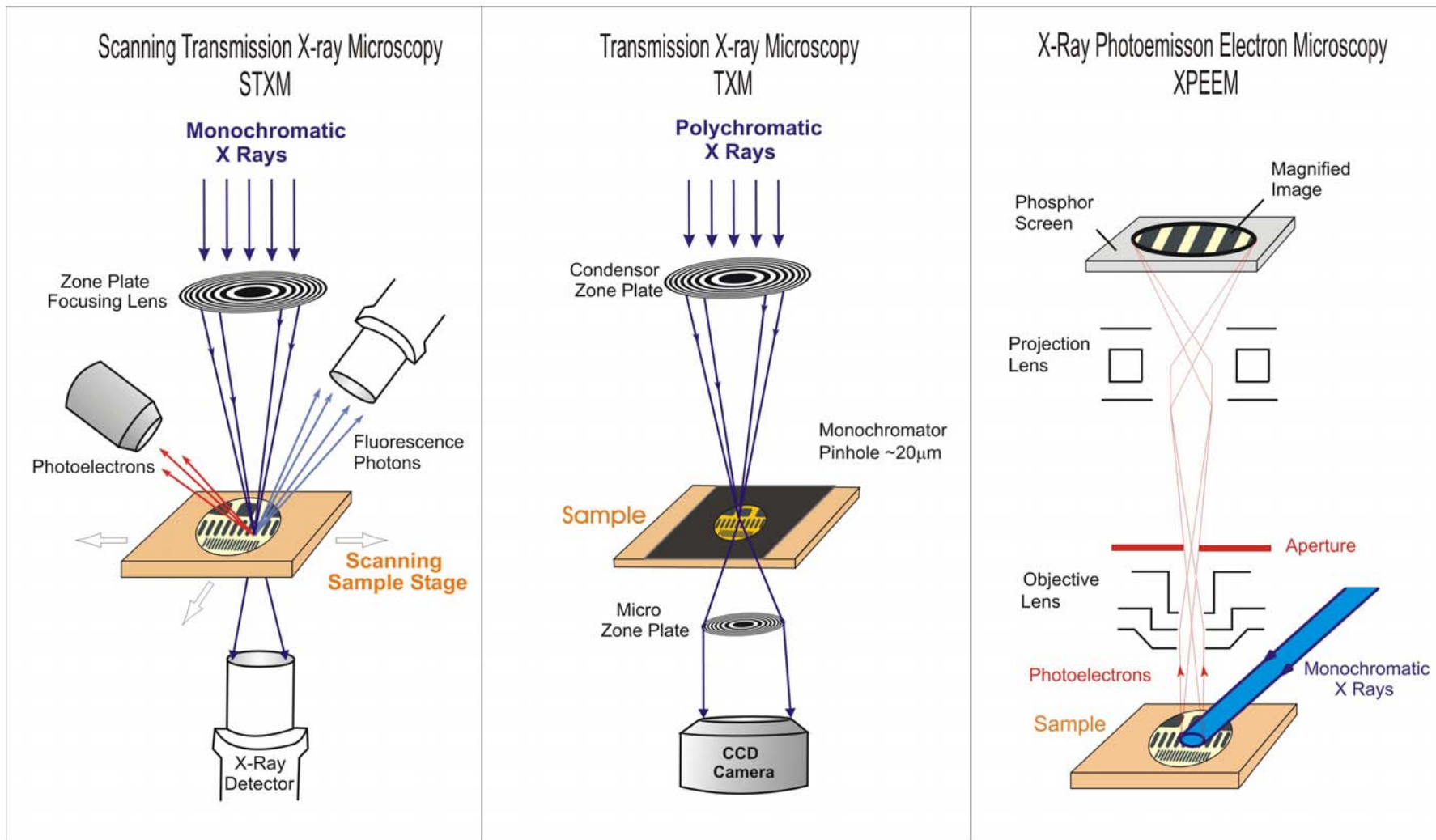
- atomic resolution
- needs protein crystals

MRI

X-ray microscopy

- 20 nm resolution
- thick objects (compared to EM)

X-ray Microscopes



ABERRATION NAMES



$C_{000} = r$	Constant term
$C_{100} = -\sin \alpha$	Grating equation
$C_{011} = -\frac{1}{r}$	Law of reflection in the sagittal plane
$C_{111} = -\frac{\sin \alpha}{r^2}$	Line curvature
$C_{102} = \frac{\sin \alpha}{r^2}$	Line curvature
$C_{200} = \frac{T}{2}$	Tangential-plane defocus
$C_{020} = \frac{S}{2}$	Sagittal-plane defocus (astigmatism)
$C_{120} = \frac{S \sin \alpha}{2r} - a_{12} \cos \alpha$	
$C_{300} = \frac{T \sin \alpha}{2r} - a_{30} \cos \alpha$	Aperture defect (also called primary coma)
$C_{400} = \frac{T \sin^2 \alpha}{2r^2} - \frac{T^2}{8r} + \frac{a_{20}^2}{2r} - \frac{a_{30} \sin 2\alpha}{2r} - a_{40} \cos \alpha$	Spherical aberration
$C_{220} = \frac{S \sin^2 \alpha}{2r^2} - \frac{TS}{4r} + \frac{a_{20} a_{02}}{r} - \frac{a_{12} \sin 2\alpha}{2r} - a_{22} \cos \alpha$	F_{220} aberration

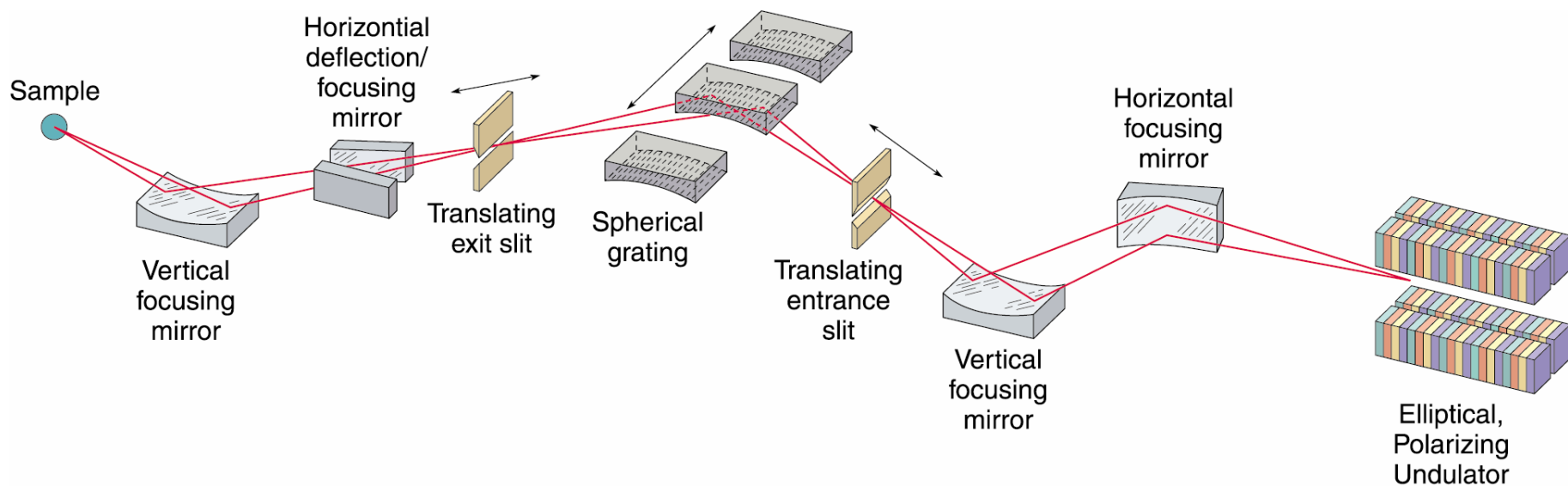
meV Resolution Spectroscopy Beamline



Specifications:

- Resolving power: $E/\Delta E = 100,000$ with $5\mu\text{m}$ slits
i.e. better than 1 meV when photon energy is below 100eV
- Photon energy range: 15eV to 100eV, fully optimized
maximum achievable photon energy $\sim 140\text{eV}$
- Elliptically Polarized Undulator (EPU): full polarization selection (linear and/or circular)
- Photon Flux: $\sim 5 \times 10^{11}$ photons/s/meV

Optical Layout (SGM)



Ray Tracing (Shadow)



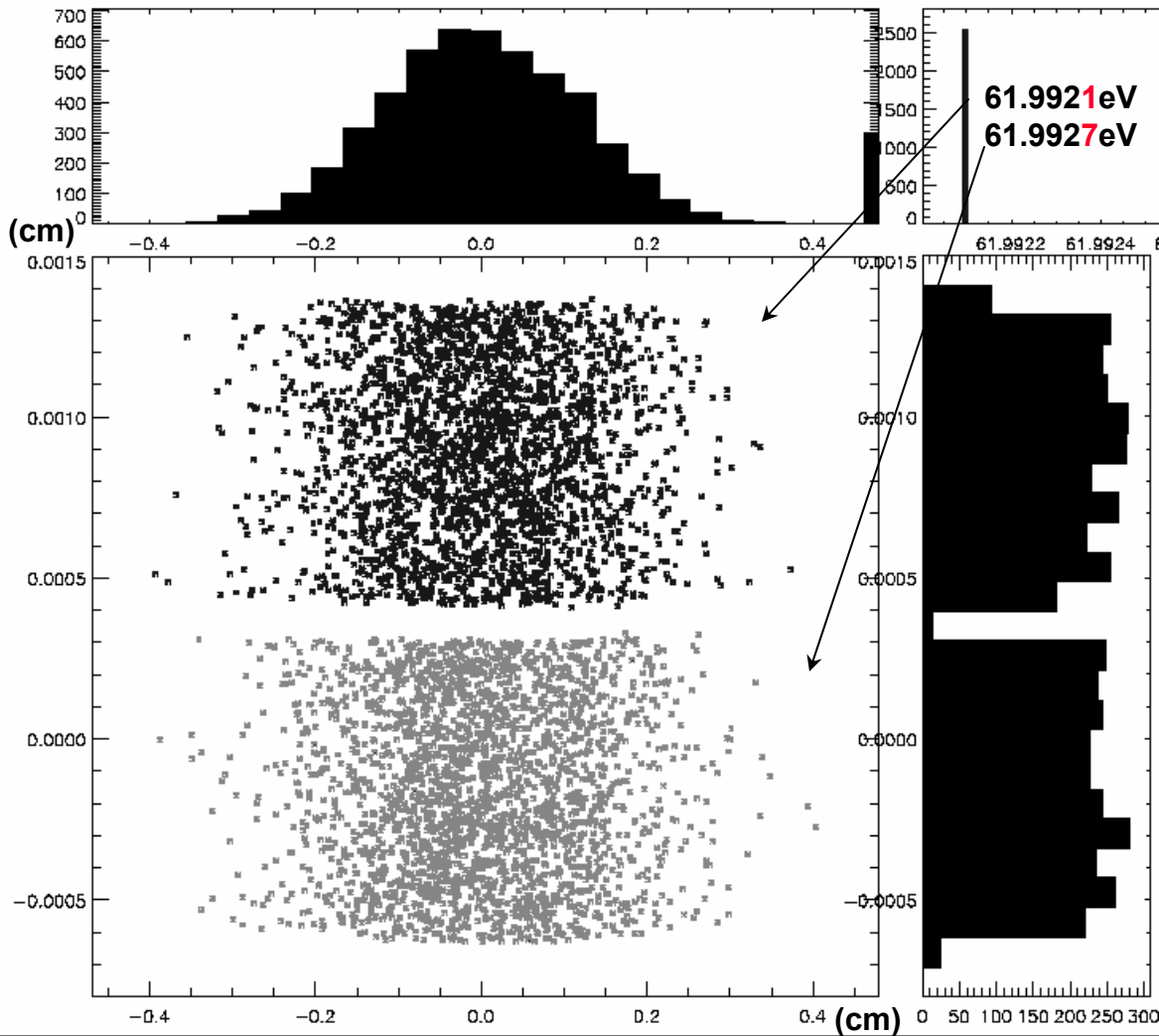
hν ~ 60eV

Groove density=3,600 l/mm

$\Delta E_{\text{slit}} = 0.057 \text{ meV}/\mu\text{m}$
 $\Delta E_{\text{slope}} = 0.44 \text{ meV}/\mu\text{rad}$

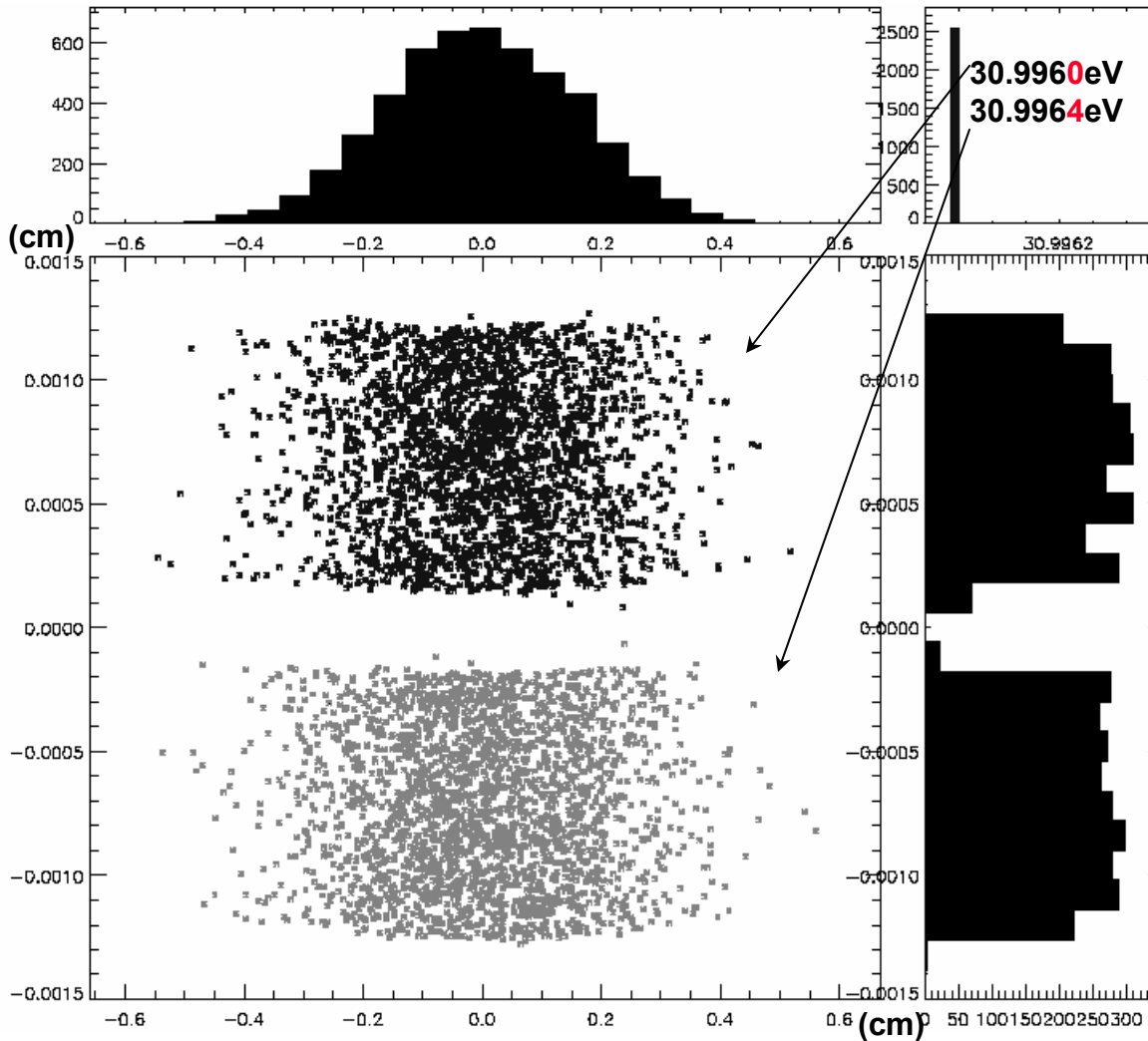
$\Delta E_{\text{slit}} = 0.29 \text{ meV @ } 5 \mu\text{m slit}$

slope error (μrad)	0.25	0.50
ΔE_{slope} (meV)	0.11	0.22
$\Delta E_{\text{tot}} = (\Delta E_{\text{slit}}^2 + \Delta E_{\text{slope}}^2)^{1/2}$	0.31	0.36



Yi-De Chuang

Ray Tracing (Shadow)



hν ~ 30eV

Groove density=1,800 l/mm

$$\Delta E_{\text{slit}} = 0.029 \text{ meV}/\mu\text{m}$$

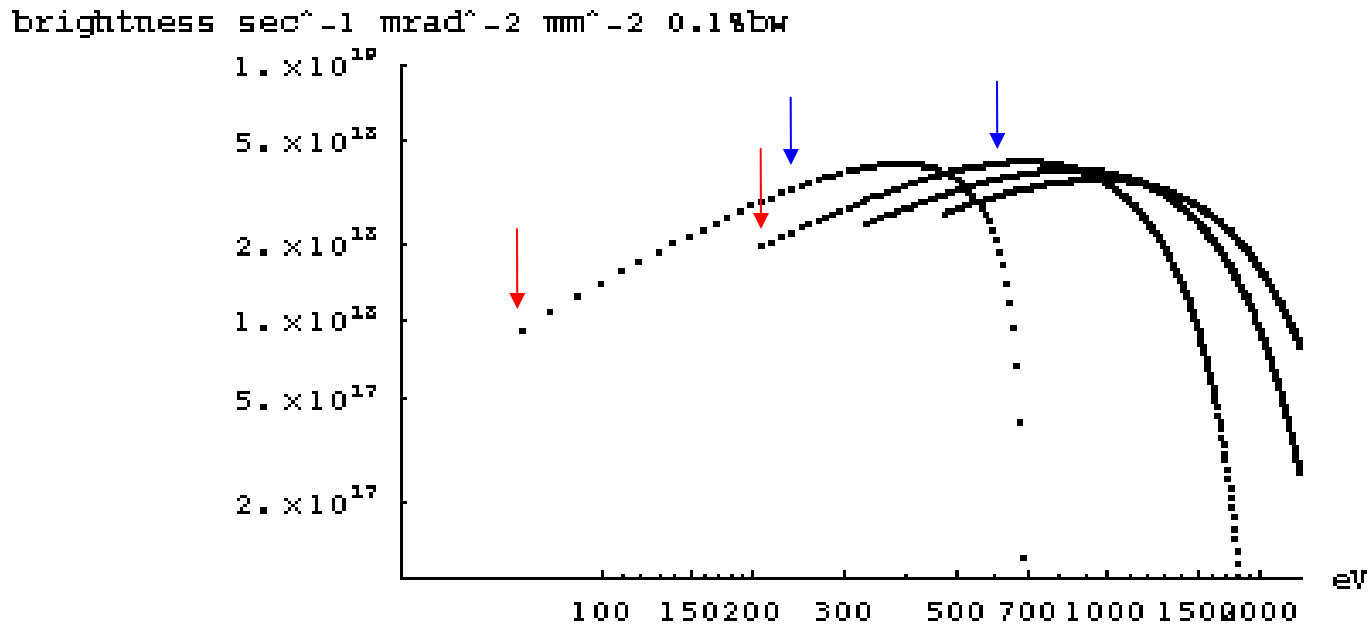
$$\Delta E_{\text{slope}} = 0.22 \text{ meV}/\mu\text{rad}$$

$\Delta E_{\text{slit}} = 0.14 \text{ meV @ } 5 \mu\text{m slit}$

slope error (μrad)	0.25	0.50
ΔE_{slope} (meV)	0.055	0.11
$\Delta E_{\text{tot}} = (\Delta E_{\text{slit}}^2 + \Delta E_{\text{slope}}^2)^{1/2}$	0.15	0.18

Yi-De Chuang

Undulator brightness



Undulator brightness, harmonics 1 through 7, linear polarization.
5.0cm period, 37 periods, 400mA, 1.9GeV, 1×10^{-4} dE/E

horizontal polarization:

13.0mm gap $k_y=4.307$, lowest energy=66.753eV

vertical polarization:

13mm gap $k_x \approx 2.0$, lowest energy=228.633eV

Note, the higher harmonics lose brightness if the energy spread increases.