# Synchrotron based methods for materials characterization 2: **Looking at the ring and the beamlines**

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Most of these viewgraphs are from an NSLS2 course:
https://www.bnl.gov/ps/userguide/lectures/
I recommend you go to this site for more details
Other sources, I leave source information on the “borrowed” slide
Some slides are from Jim Clarke, Daresbury Laboratory
Some material is from David Attwood of UC Berkeley

# Outline

**Looking behind the shield wall: the ring**

- Source Brilliance plots
- Relativisitic radiation section
  - Nonrelativisitic
  - Brief reminder of relativistic
  - Relativistic radiation folding approximately
- Different sources, bending, wiggler, undulator
  - Motion of electron in a B field
  - Bending magnet radiation(power)
  - Bandwidth/spectra of BM
  - Wiggler
  - Undulator
- Matching source to experiment
- Emittance
- A real source size
- RF source and bunches

**Outside the shield wall: the beamlines**

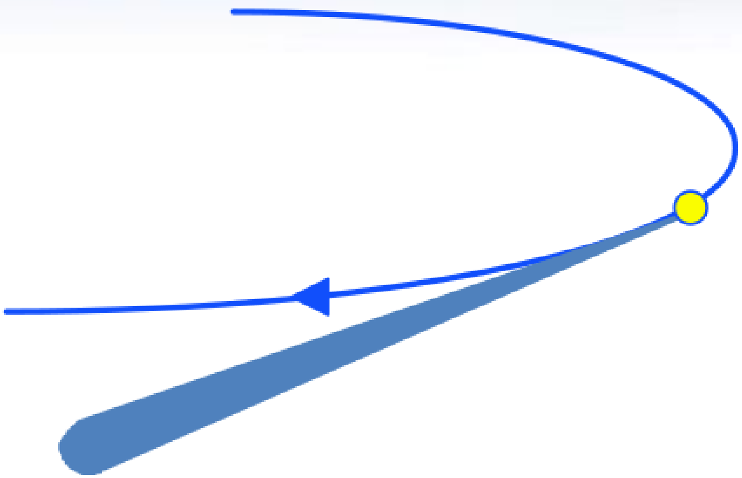
- How to build a beamline in N easy viewgraphs
- Choose the beast: Undulator or Wiggler or ..
- Taming the beast: Ways to reduce heatload , filters(types), first mirror, soft vs. hard.
- Mono-chromators Energy selection, gratings, LN2 cooling, diamond vs. silicon
- Re-focusing mirrors
- Stability
- Secondary focusing

**My personal work**

- Beamline quick walk down ours.
- Optics
- In-situ growth

# Synchrotron Light Source

*T. Shaftan's Lecture 9/16/2015*



- Particles called electrons are accelerated to extremely high speeds, injected in the synchrotron ring to move in a large circle.
- As the electrons pass through magnets around the ring, they loose energy in the form of light, emitted as a narrow pencil directed forward.

- This light is channeled out of the ring into beamlines, where it is tailored to accommodate specific needs of the research conducted
- All beamlines operate simultaneously
- Each beamline is designed for use for a specific type of research
- Experiments run 24 hours a day

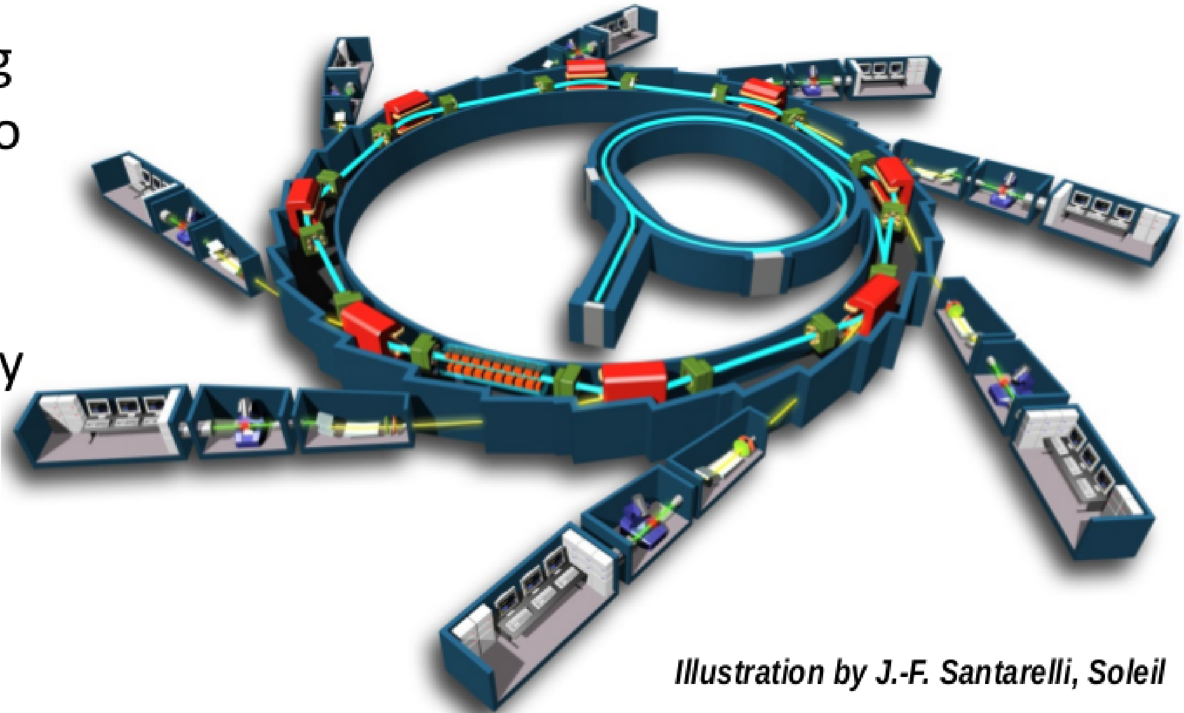
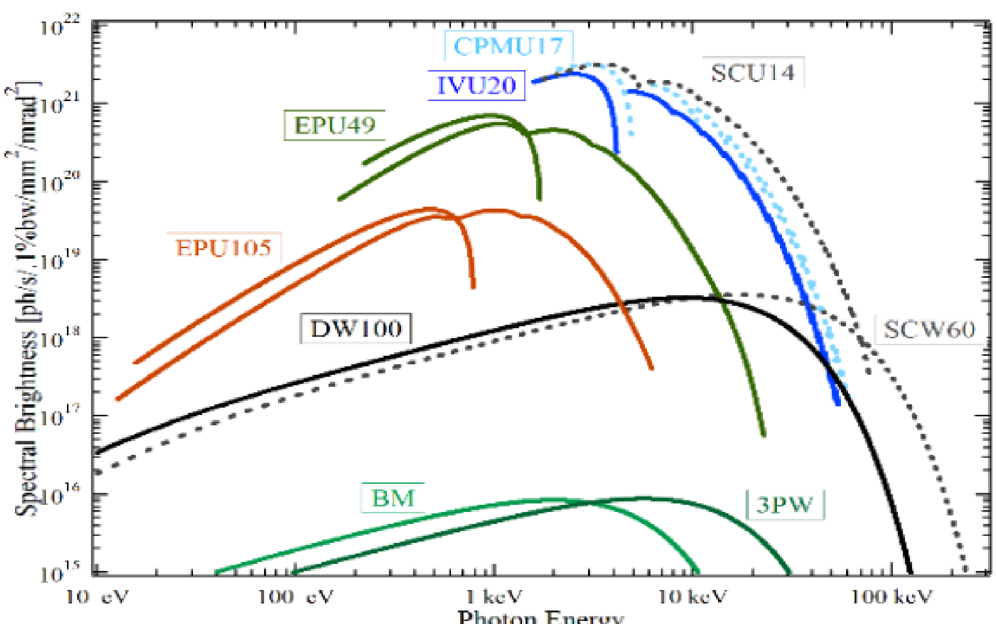


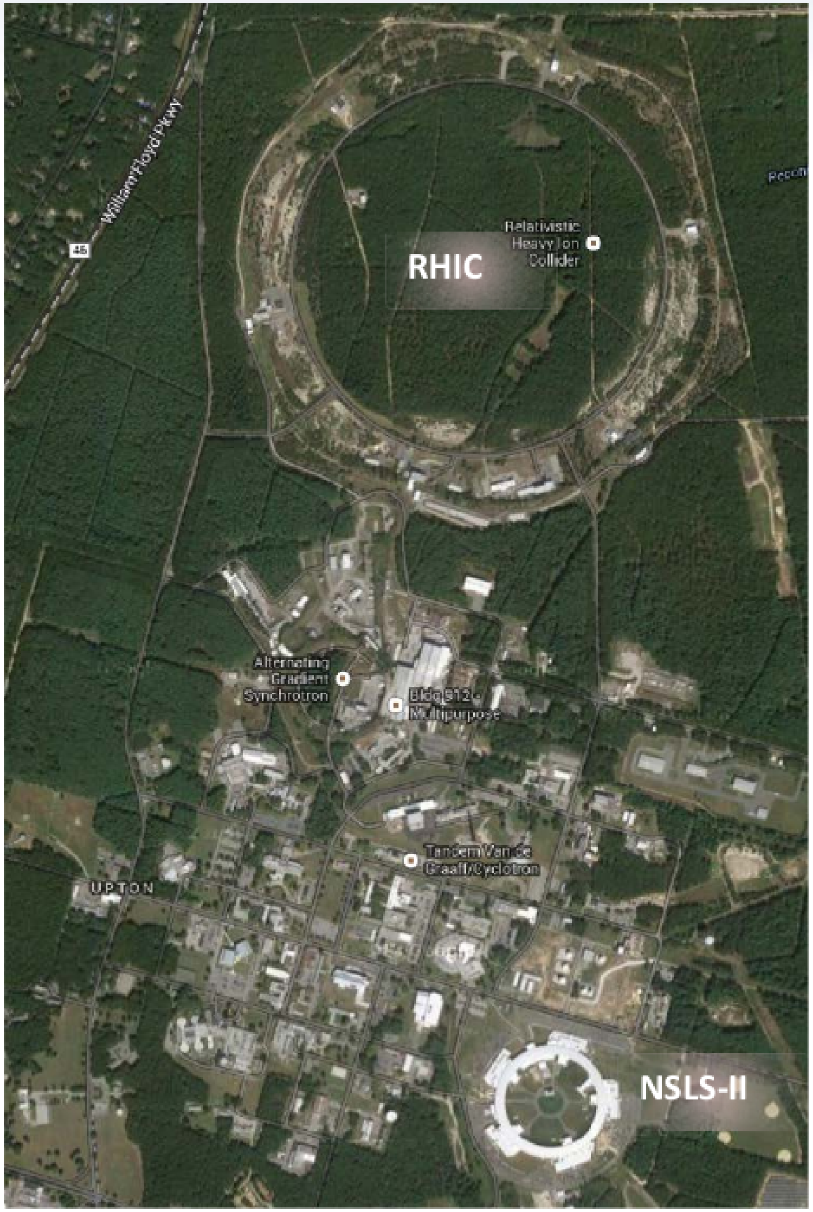
***Illustration by J.-F. Santarelli, Soleil***

# National Synchrotron Light Source II

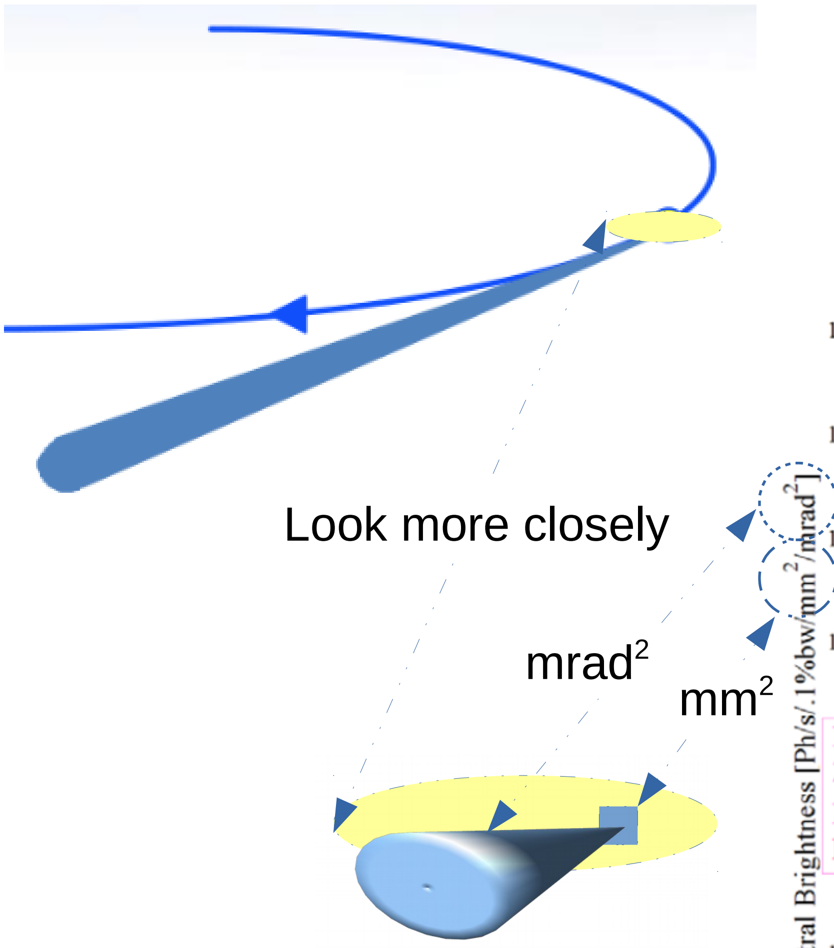
## NSLS-II At-A-Glance

Storage ring circumference: 792 meters
Electron energy: $3 \times 10^9$ electron volt
Electron current: 0.5 amperes
Photon energy: from IR to hard X-rays
Capacity: >70 simultaneous experiments
Visiting users: > 4000 per year



# Understanding a Brightness plot




Defined at the source, in the ring
Photons
Per second
Per mm$^2$ (area)
Per mrad$^2$ (angular spread)
Per .1% bandwidth

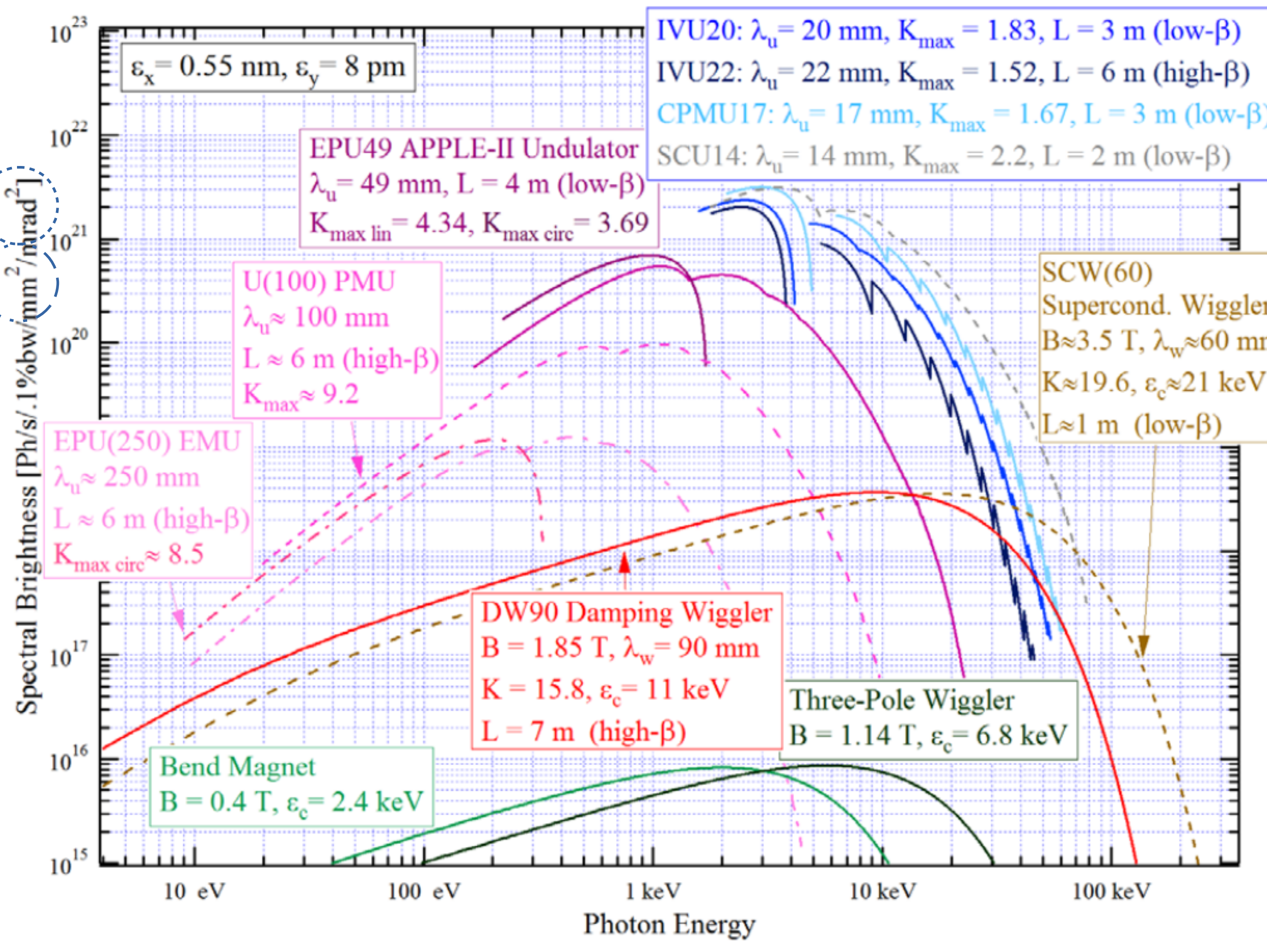



**Figure 1. Brightness versus photon energy for a number of different NSLS-II radiation sources, at 3 GeV and 500 mA.**

# Radiation non-relativistic, v<<c

$$\frac{E_\perp}{E_r} = \frac{\Delta v\, t\ \sin\theta}{c\Delta t}$$

Substituting for $E_r$

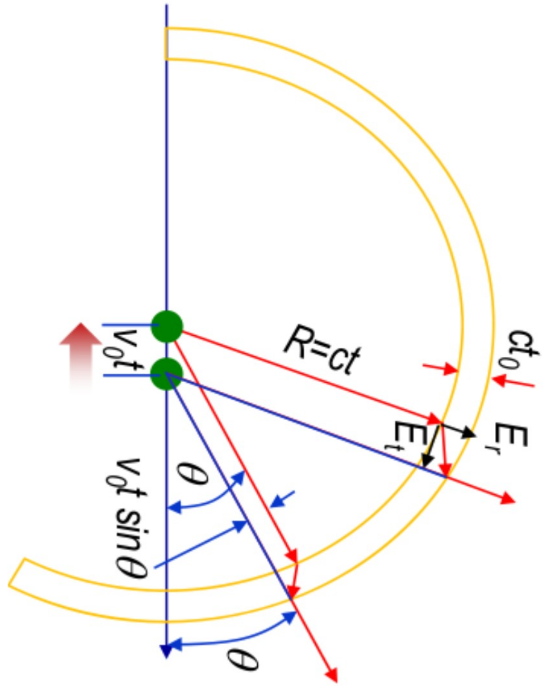
$$\boxed{E_r = \frac{q}{r^2}}$$

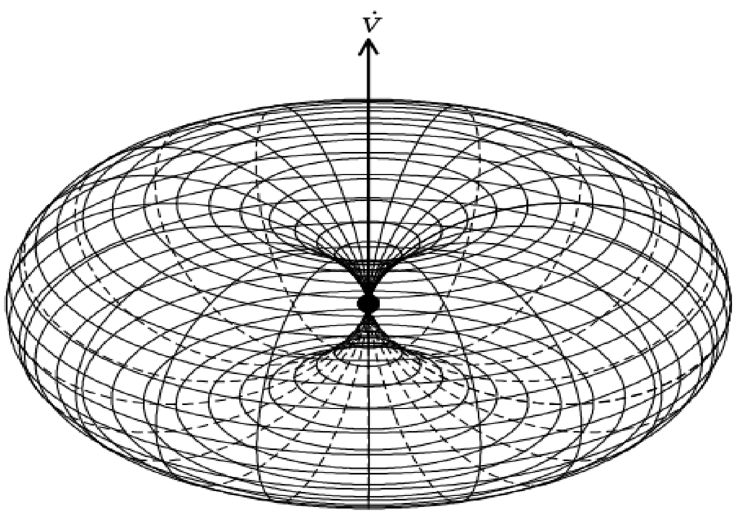
And for t = r/c, you get

$$E_\perp = \frac{q}{r^2}\left(\frac{\Delta v}{\Delta t}\right)\frac{r\sin\theta}{c^2}$$

And this is the form you get if you did it the hard way

$$E_\perp = \frac{q\dot{v}\sin\theta}{rc^2}$$



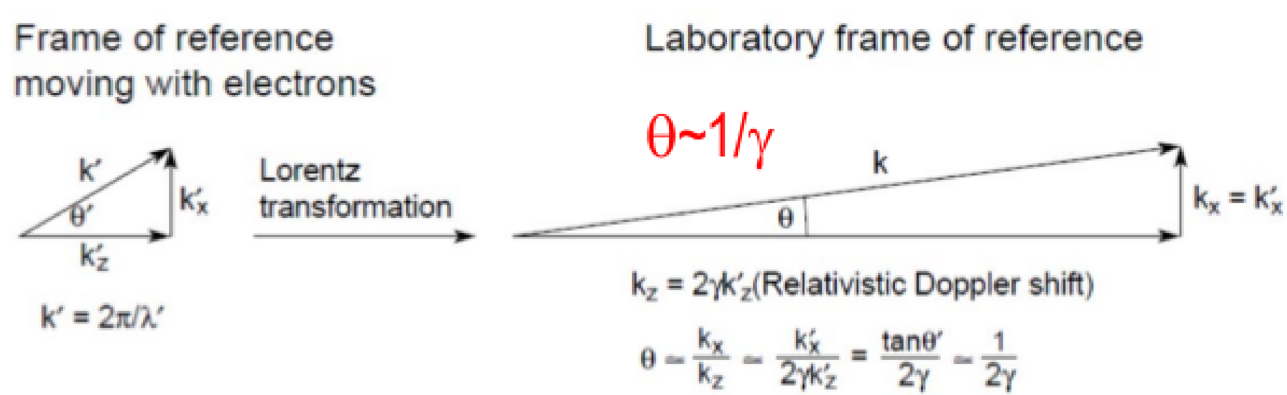




By the way if you integrate $E_\perp$ , to get the total power radiated you get the familiar

$$P = \frac{2}{3}\frac{q^2\dot{v}^2}{c^3}$$

# Radiation in the relativistic limit

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$




$\beta = 0$ $\qquad$ $\beta = 0.5$ $\qquad$ $\beta = 0.85$

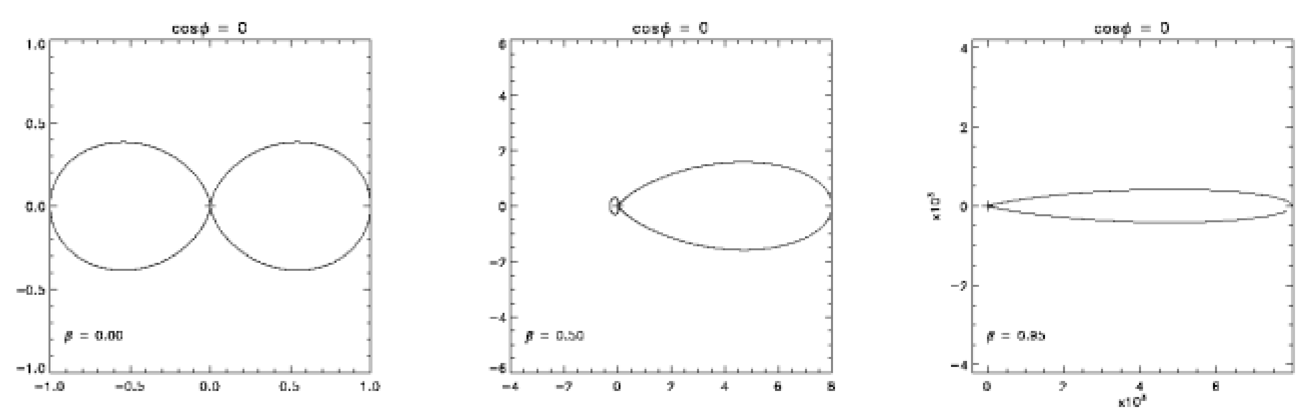



Figure 4.9: Polar plots of the radiation intensity as a function of direction, with acceleration perpendicular to $\mathbf{v}$, for the case where $\hat{\mathbf{R}}$ lies in the plane of $\mathbf{v}$ and $\dot{\mathbf{v}} \wedge \mathbf{v}$.

# Synchrotron radiation angular distribution

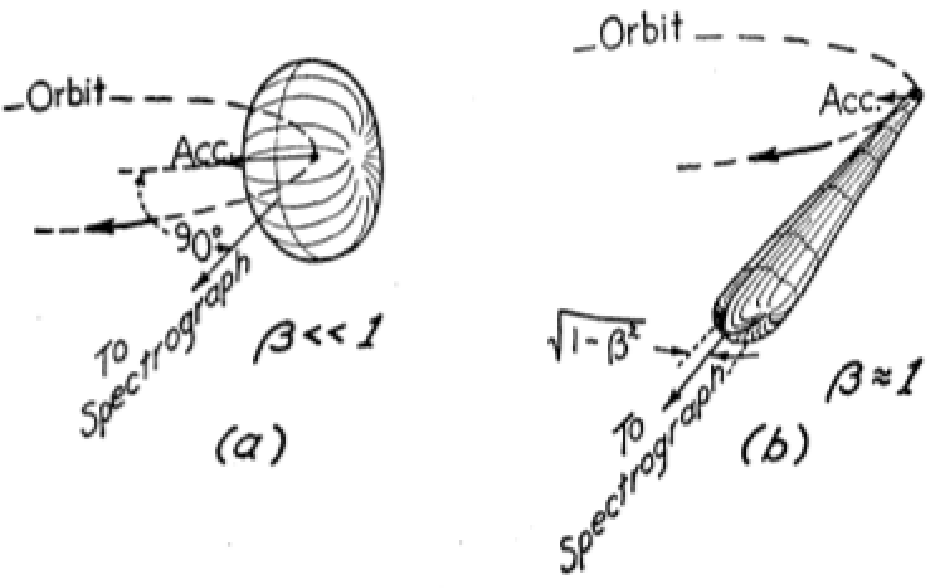
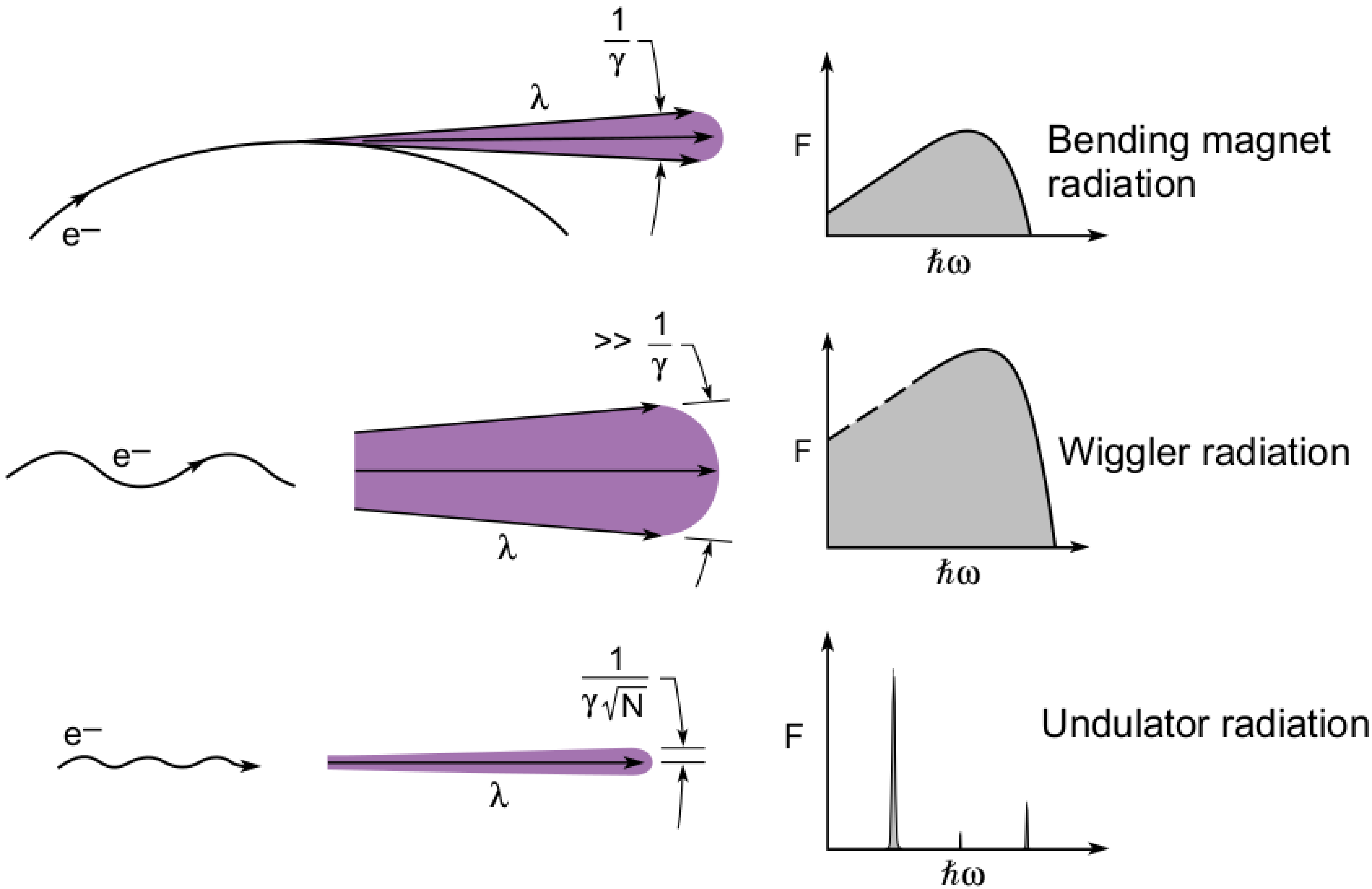



FIG. 1. Qualitative radiation patterns to be expected from electrons in a circular orbit (a) at low energy and (b) as distorted by relativistic transformation at high energy. [See also discussion in W. K. H. Panofsky and M. Phillips, *Classical Electricity and Magnetism* (Addison-Wesley Press, Cambridge, 1955), pp. 301–307.]

From: D. H. Tomboulian and P. L. Hartman, Phys. Rev., 102, 1423 (1956).

# Three Forms of Synchrotron Radiation



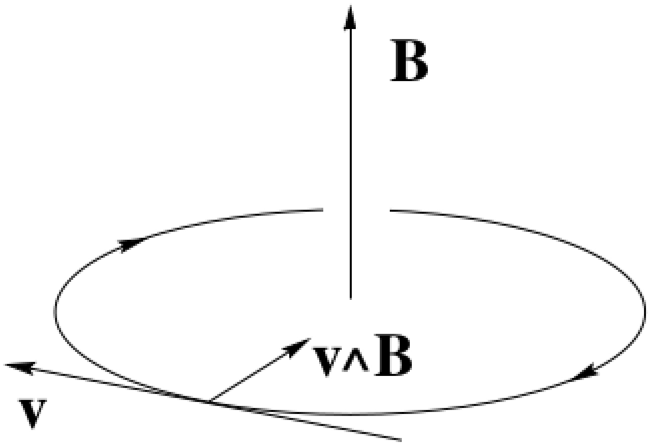
# Electron motion in a magnetic Field

First the more familiar non relativistic case

$$\vec{F} = q\left(\vec{v} \otimes \vec{B}\right)$$

$$\vec{F} = m\left(\frac{v^2}{R}\right)$$

$$\Rightarrow R = \frac{mv}{qB}$$




Luckily the relativistic case is simple because v is perpendicular to acceleration

$$\Rightarrow R = \frac{\gamma\, mv}{qB}$$

Reminders on some over-simplified relativity that will be helpful to understand synchrotron sources

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\boxed{\text{Energy} = \gamma\, m\, c^2}$$

$$\boxed{\gamma = \frac{\text{Ring Energy}}{511\,\text{keV}} = 1957\left(\text{Ring Energy}\left(\text{GeV}\right)\right)}$$

For NSLS2 , $\gamma = 5871$

# Bending Magnet Radiation

$$2\,\Delta\tau = \tau_e - \tau_r$$

$$2\,\Delta\tau = \frac{\text{arc length}}{\text{v}} - \frac{\text{radiation path}}{c}$$

$$2\,\Delta\tau \simeq \frac{R \cdot 2\theta}{\text{v}} - \frac{2R\sin\theta}{c}$$

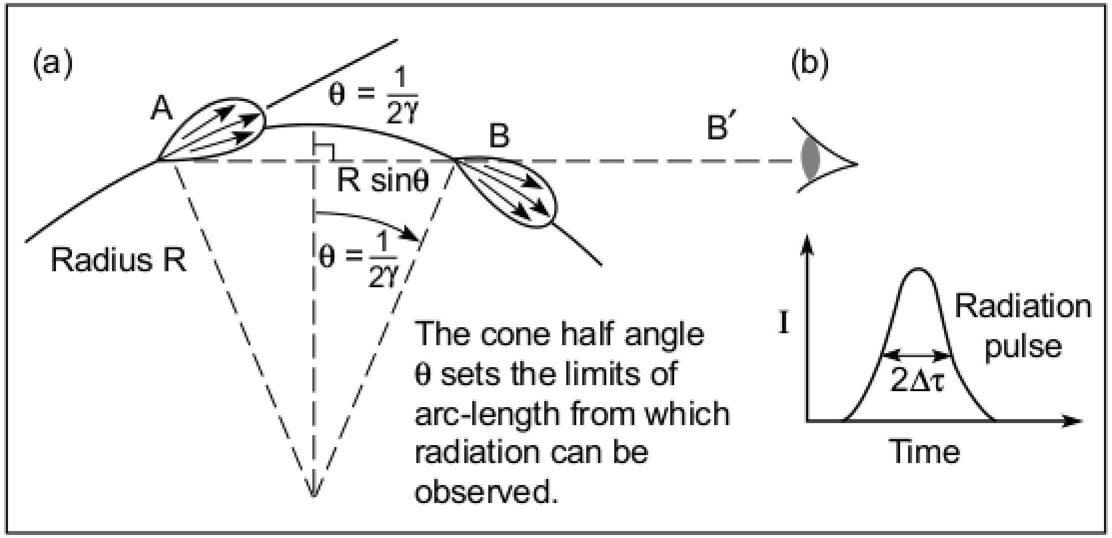
With $\theta \simeq 1/2\gamma$, $\sin\theta \simeq \theta$

$$2\,\Delta\tau \simeq \frac{R}{\gamma \text{v}} - \frac{R}{\gamma c} = \frac{R}{\gamma}\left(\frac{1}{\text{v}} - \frac{1}{c}\right)$$

With $\text{v} = \beta c$

$$2\,\Delta\tau \simeq \frac{R}{\gamma\beta c}(1-\beta) \quad \text{but} \quad (1-\beta) \simeq \frac{1}{2\gamma^2} \quad \text{and} \quad R \simeq \frac{\gamma mc}{eB}$$

$$\therefore \; 2\Delta\tau = \frac{m}{2eB\gamma^2}$$

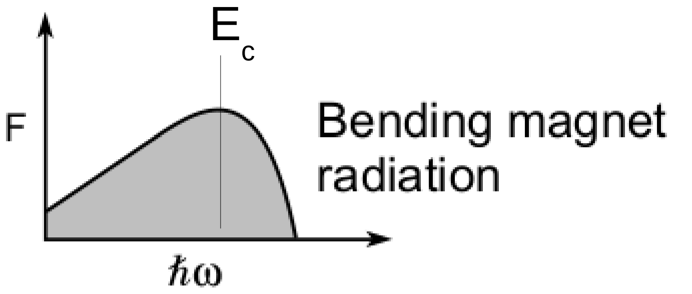


# Bending Magnet Critical Energy

From Heisenberg's Uncertainty Principle for rms pulse duration and photon energy (Fourier transforms strike again):

$$\Delta E \cdot \Delta \tau \geq \frac{\hbar}{2}$$

$$\Delta E \geq \frac{\hbar 2 e B \gamma^2}{m}$$



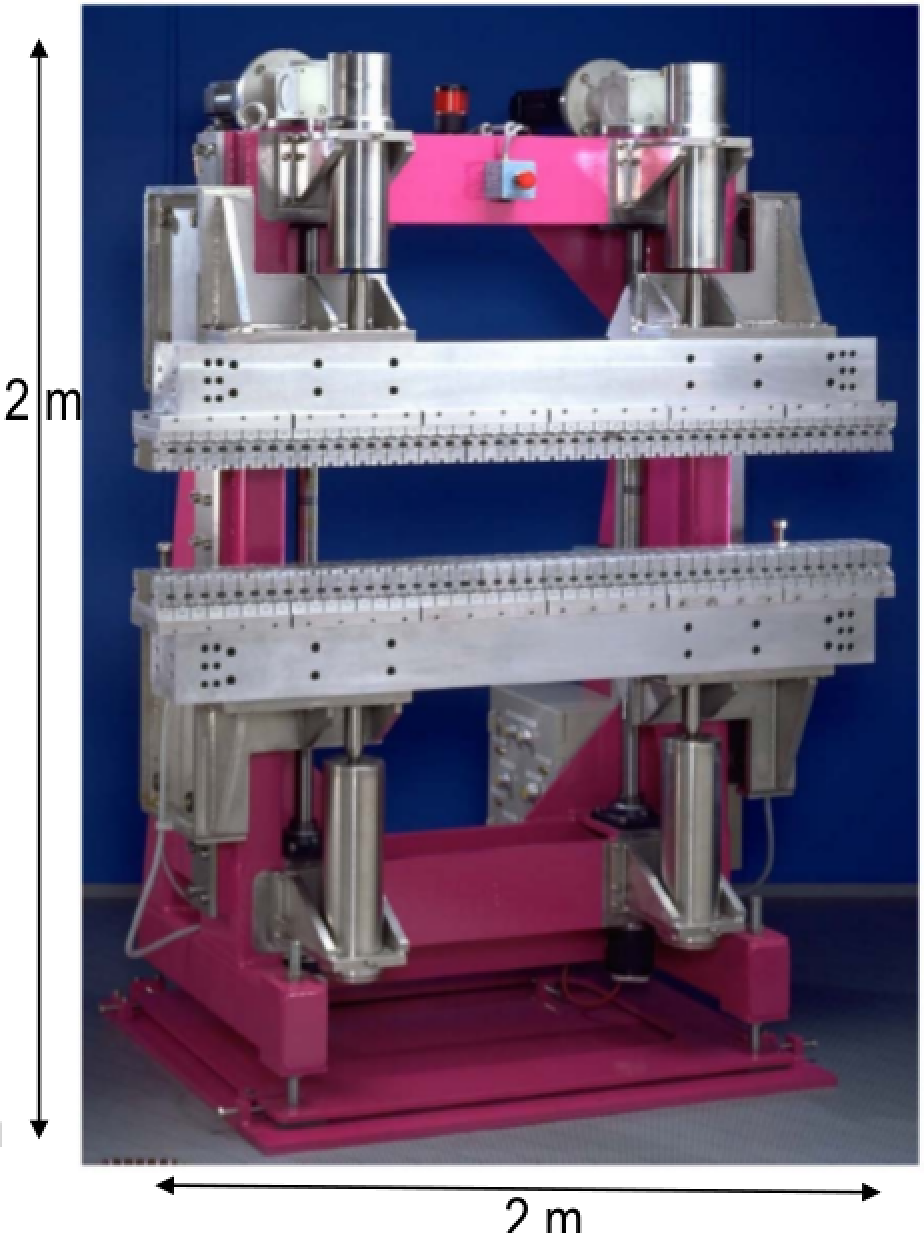

Critical Energy $E_c$ is the energy with half the power below and half the power above

A useful re-writing gives:

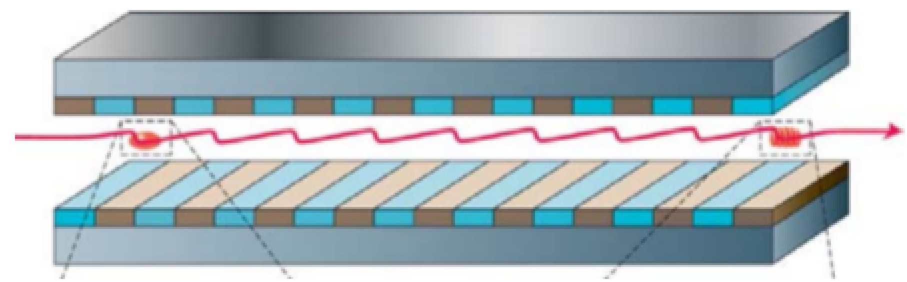
$E_c$(keV)= 0.6650 $E_{ring}$(GeV)B(T) = 0.6650(Ring energy in GeV)(Magnetic Field in Tesla)

Main point: **to get harder x-rays, increase ring energy, bend magnet field or both**

# Wigglers and Undulators




Instead of just a uniform magnetic field, send the electrons into a magnet array



$$\vec{B} = \left(0, B_0 \cdot \sin\left(2\pi \frac{s}{\lambda_0}\right), 0\right)$$

$$m\,\ddot{x} = q\left(\vec{v} \otimes \vec{B}\right)$$

## Angular Deflection

The B field is assumed to be **sinusoidal** with period $\lambda_u$

$$B_y(s) = -B_0 \sin\left(\frac{2\pi s}{\lambda_u}\right)$$

Integrate once to find $\dot{x}$ which is the horizontal angular deflection from the s axis

$$\dot{x}(s) = \frac{B_0 e}{\gamma m_0 c}\frac{\lambda_u}{2\pi}\cos\left(\frac{2\pi s}{\lambda_u}\right)$$

Therefore, the peak angular deflection is $\frac{B_0 e}{\gamma m_0 c}\frac{\lambda_u}{2\pi}$

Define the **deflection parameter**

$$\boxed{K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0 \lambda_u}$$

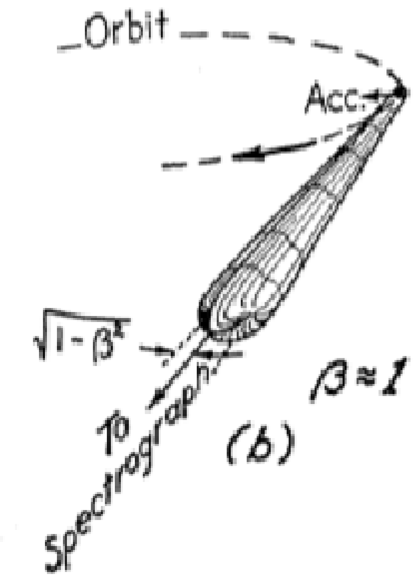
($B_0$ in T, $\lambda_u$ in m)

# Distinction between a wiggler and undulator

K gives the scale of electron motion in the magnet array.

The peak angular deflection is ~ $K/\gamma$ .

But remember that the radiation fan is $1/\gamma$




This sets up two limits

1) K >> 1, or the wiggler limit. Each oscillation is independent.

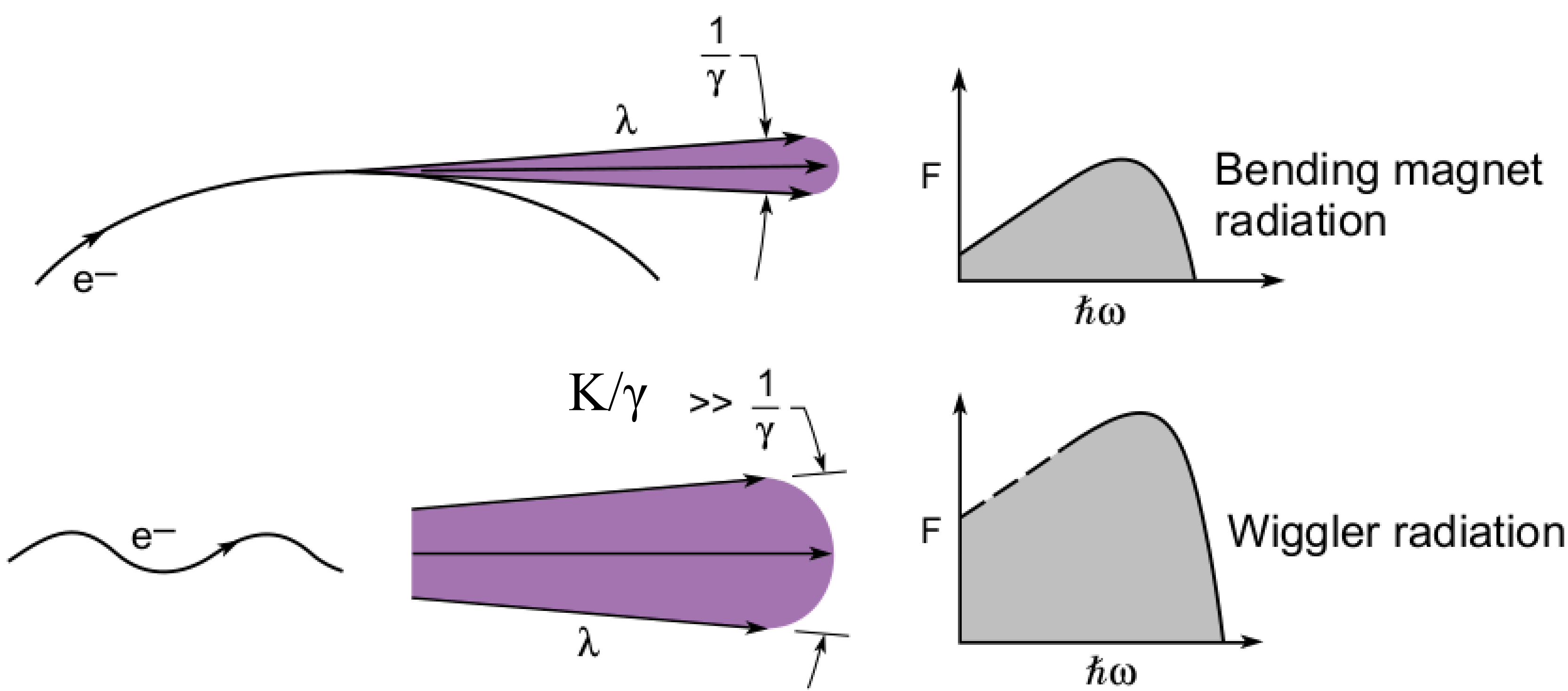
2) K ~< 1, undulator limit. The radiation from each oscillation can interfere coherently.

# Wiggler

Maximum deflection angle is K/γ.
So horizontal angular divergence σ’ is ~ K/γ

It behaves like many bend magnets together so more flux than a single bend magnet

2N times the flux.



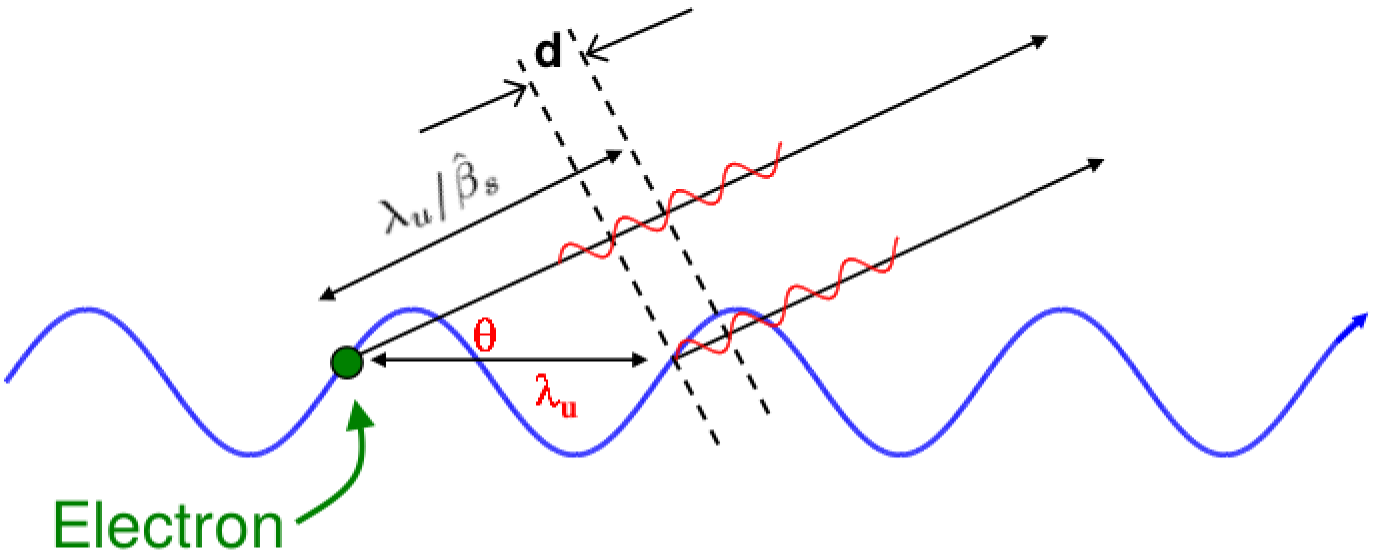
# Undulator

For the undulator a little more work is needed.

The overlapping radiation field is not enough; you need phase matching also.

# The Condition for Interference

For constructive interference between wavefronts emitted by the same electron **the electron must slip back by a whole number of wavelengths** over one period




Speed = distance/time = c

The time for the electron to travel one period is $\lambda_u / c\hat{\beta}_s$

In this time the first wavefront will travel the distance $\lambda_u / \hat{\beta}_s$

# Skipping some algebra

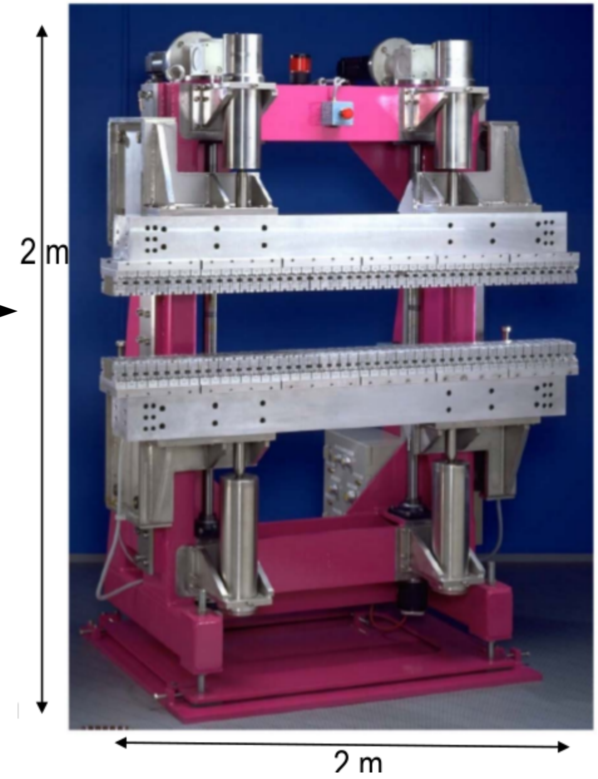
## And the undulator equation

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

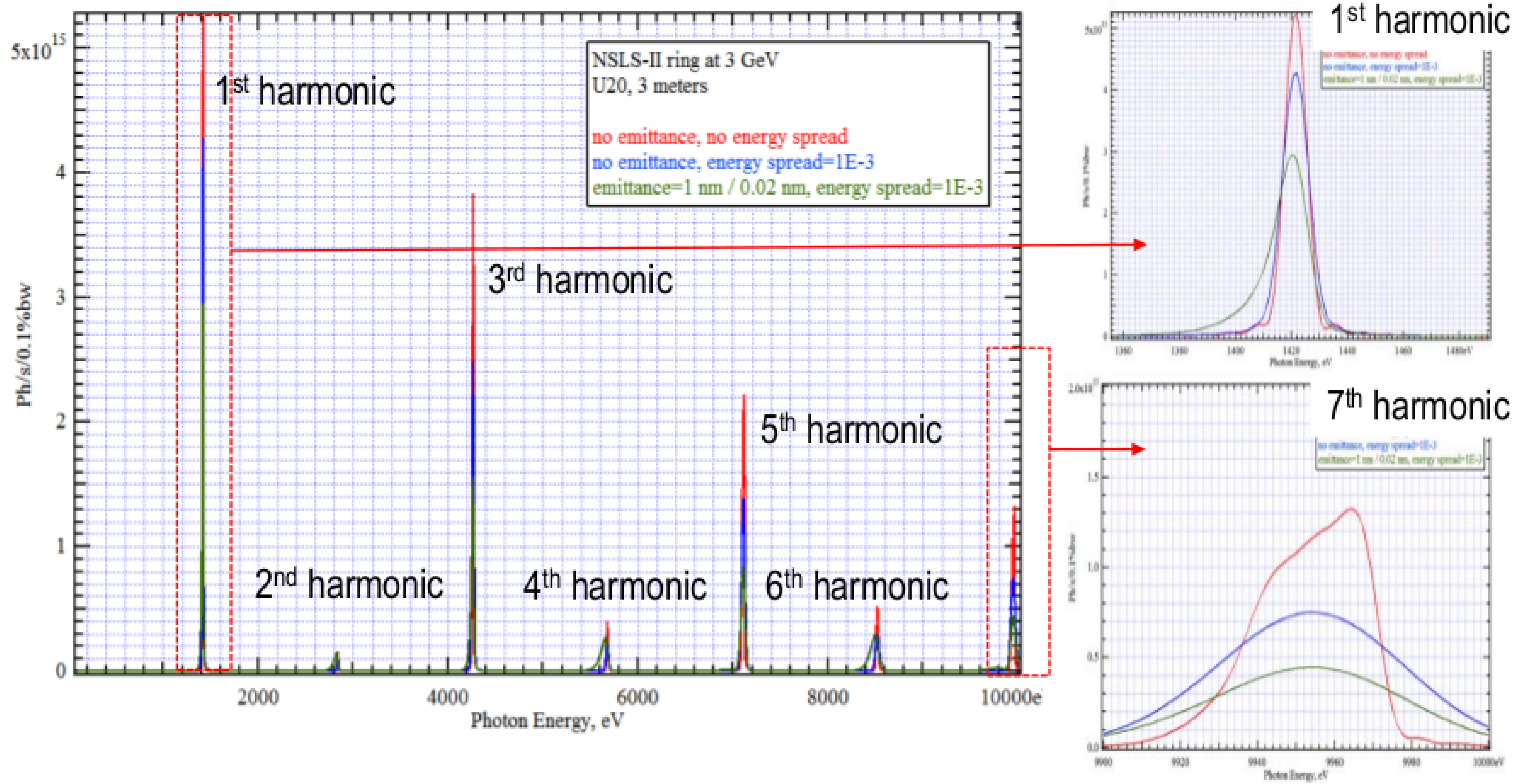
Remember that K: $$\boxed{K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0\lambda_u}$$

So by changing the magnitude of the B field , or the magnet lattice period you can change the wavelength of emitted radiation!

Thats why you have this



# Spectrum: Impact from the finite source size




- Two contributions to the source size: emittance and energy spread
- Distortion of lineshape; reduction of peak flux

# Some undulator properties

The angular divergence of the undulator

$$\Delta\theta = \sqrt{\frac{2\lambda}{N\lambda_u}}$$

Note that $N\lambda_u$ is the length of the magnet array , typically ~3meters

Also $\Delta\theta \sim 10^{-5}$ rads, which is less than $1/\gamma \sim 1.7\times10^{-4}$

**Bandwidth** (width of harmonic line):

$$\boxed{\frac{\Delta\lambda}{\lambda} \sim \frac{1}{Nn}}$$

# Combining electron and photon source properties

Undulator brightness is the flux divided by the phase space volume given by these **effective** values

$$B = \frac{\dot{N}}{4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}}$$

Source sizes

$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_r^2}$$

$$\Sigma_y = \sqrt{\sigma_y^2 + \sigma_r^2}$$

Source divergence

$$\Sigma_{x'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}$$

$$\Sigma_{y'} = \sqrt{\sigma_{y'}^2 + \sigma_{r'}^2}$$

Electron beam size

Effective radiation (photon) beam size, derived from known divergence

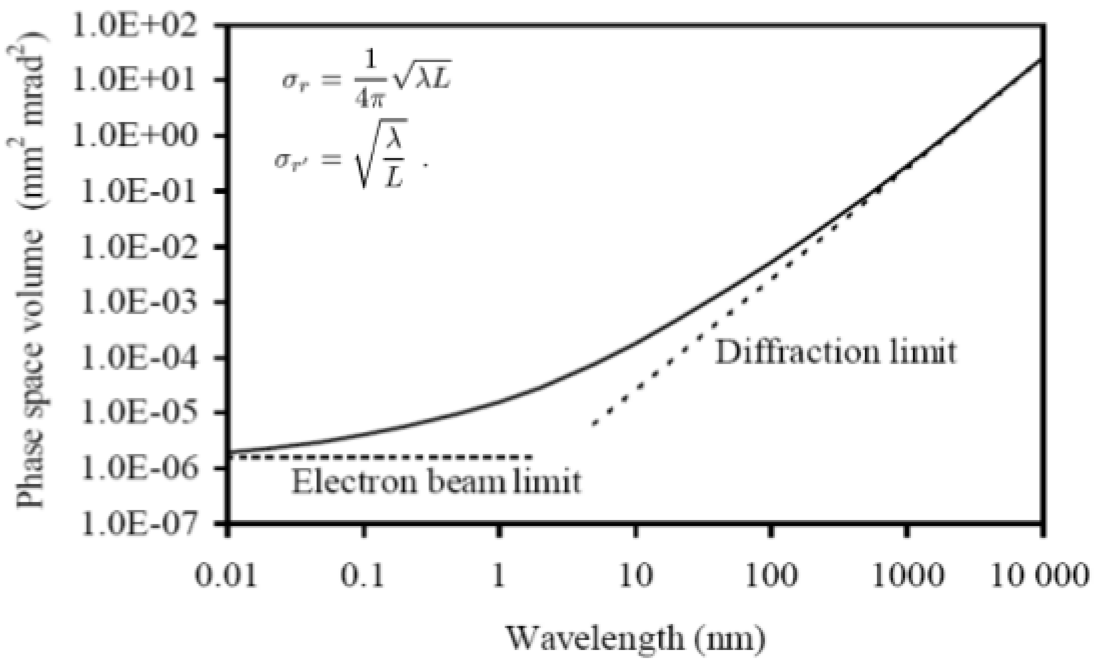
The goal for ring designers is to make the source diffraction limited, which means the electron beam size and divergence is sufficiently smaller than the photon size and divergence; you cannot improve beyond that.

# Diffraction Limited Sources

Light source designers strive to reduce the electron beam size and divergences to maximise the brightness (minimise emittance & coupling)

But when $\sigma_r \gg \sigma_{x,y}$ and $\sigma_{r'} \gg \sigma_{x',y'}$ then there is nothing more to be gained

In this case, the source is said to be **diffraction limited**




Example **phase space volume** of a light source

$$4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}$$

Using the same electron parameters as before

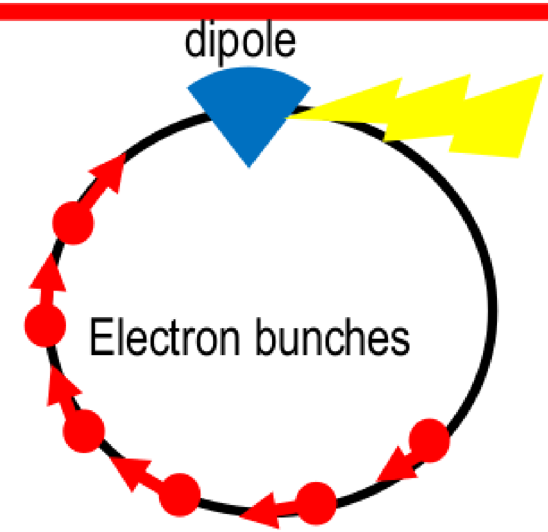
In this example, for wavelengths of >100nm, the electron beam has virtually no impact on the undulator brightness

# Time structure

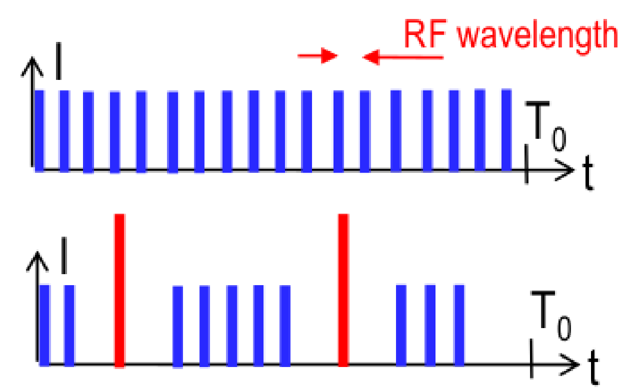
- Storage ring gets filled with several (many) bunches
- Bunches circulate around the ring arriving to the source point once per revolution

- Bunch length can vary between ns and ps as required by an application
- There are techniques to select ~100 fs long portion of radiation pulse
- Free Electron Lasers radiate short pulses down to 6-fs RMS

- Detectors of synchrotron radiation react on either average intensity or on harmonic of revolution frequency




Intensity time patterns




$T_0$ = time of 1 revolution

# 1. Choose your beast: Undulator or Wiggler

If you are looking at small samples (i.e. you need high brightness) you will want an undulator.

If are doing spectrosopy ( scanning energy) you are better off with a wiggler. Heatload does not change much as you change photon energies on sample.

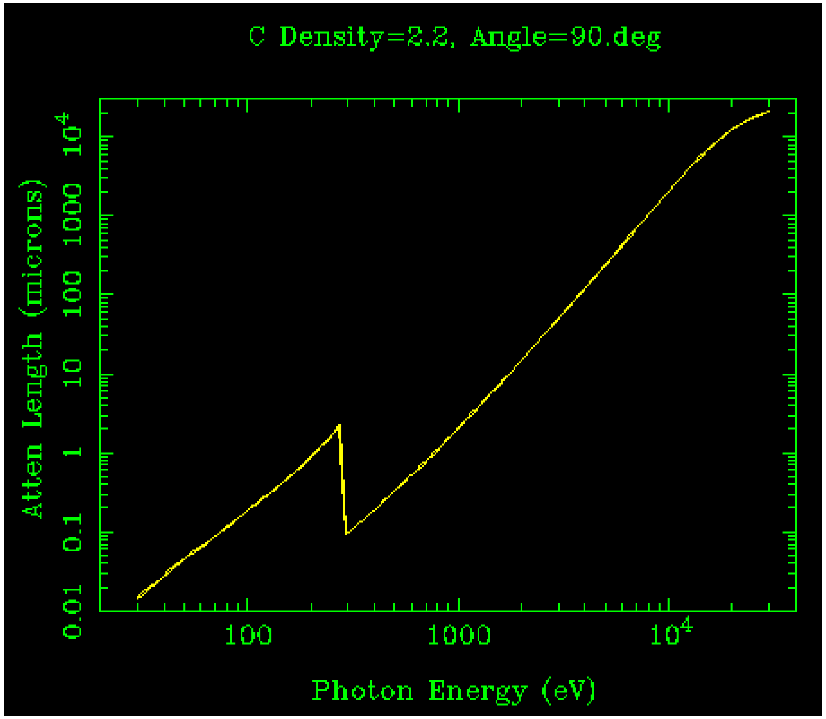
# 2a. Tame the beast

Kilowatts of power come down the pipe. How can you control it.

Some choices:

- Filters. Thin pieces of material that can absorb energy.

Plot of Attenuation Length as a function of Photon Energy




$$Transmission = \exp\left(-\frac{Filter\ Thickness}{Attenuation\ Length}\right)$$

Filter energy is energy for Filter Thickness equal to Attenuation Length.

Energies << Filter energy are attenuated

Energies >> Filter energy pass through

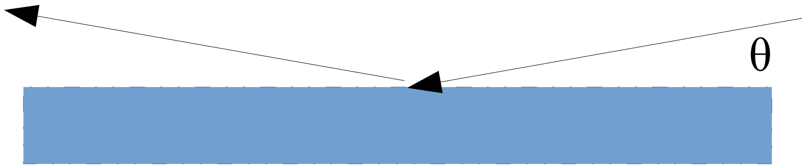
**This is a High Pass Filter.**

# 2b. Tame the beast

Kilowatts of power come down the pipe. How can you control it.

Some choices:

- Water cooled mirror




$$Critical\ angle = \sqrt{2\delta} \propto \frac{1}{(Photon\ Energy)}$$

If photon energy is less than critical energy it gets reflected.
If photon energy is above critical energy it gets absorbed by the mirror.

**=> Low pass filter**

# Wavelength Selectors/Monochromators

Considerations.

- Energy ranges

  Above about 2.5 keV crystal monochromators

  Below that typically gratings.

- Bandwidth

  $\Delta E/E$

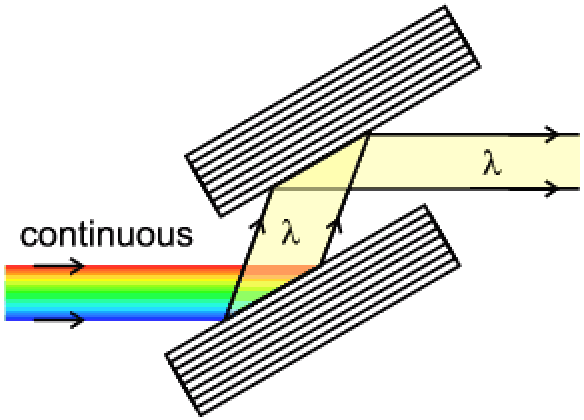
- Efficiency/Transmission

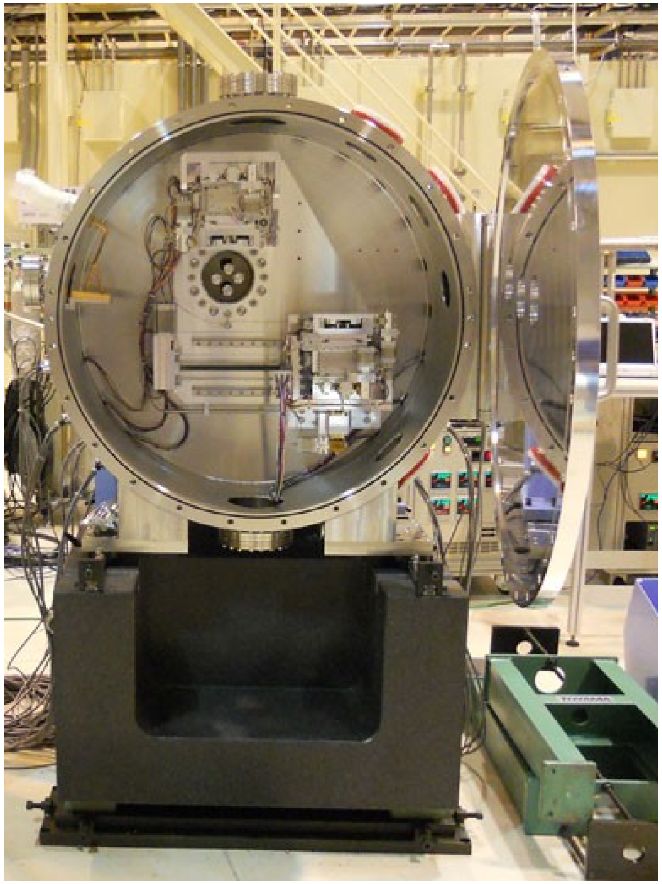
  Better to be efficient

# Double Bounce Monochromotars

Most often two crystals are used to keep the beam in the same direction.

Beam from Synchrotron

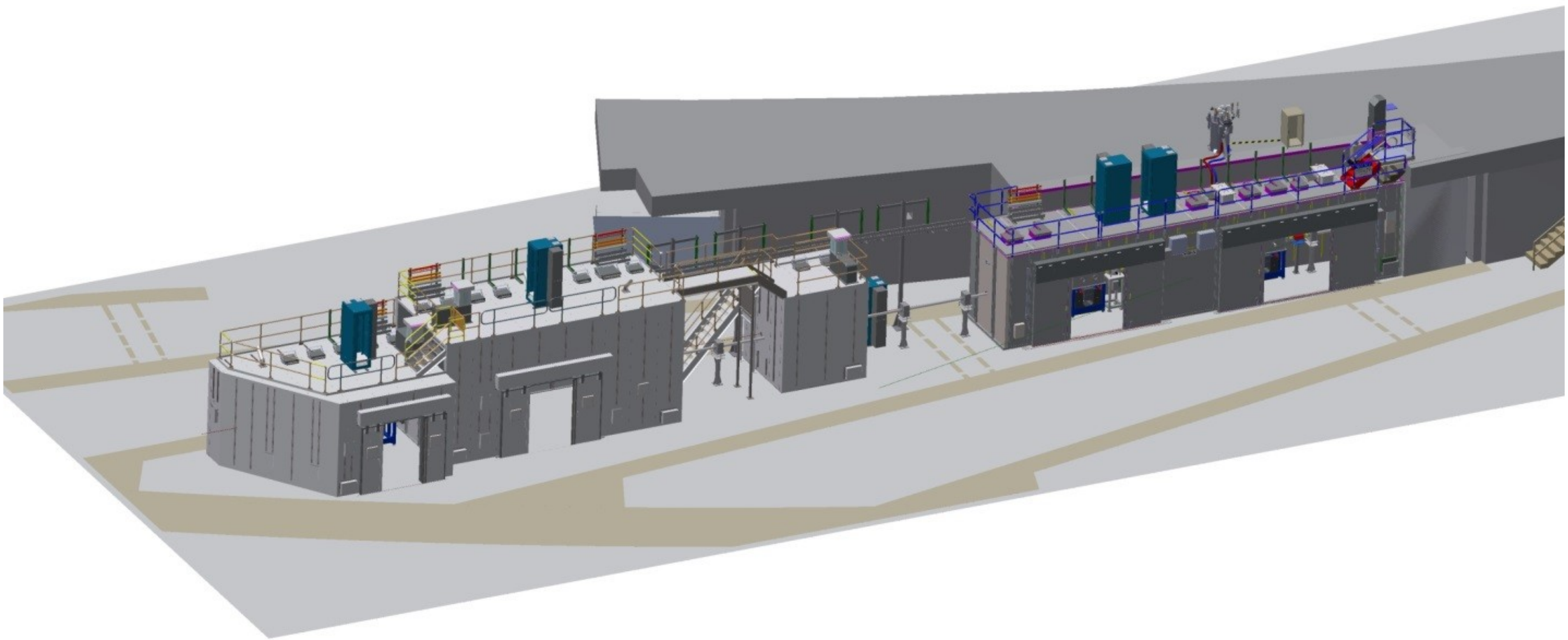


Obviously there is a physical limit to angles.
From $\lambda = 2d\sin\theta$, with d=3.1356 (Silicon 111) we get a max of 6.26, which translates to an energy of 12.39/6.26 = 1.98 keV
So a minimum energy for a Si(111) crystal mono is 1.98 keV

Bandwidth $= \Delta\lambda/\lambda$ is determined by the choice of crystals.
Si crystals have a narrower bandwidth than Ge crystals

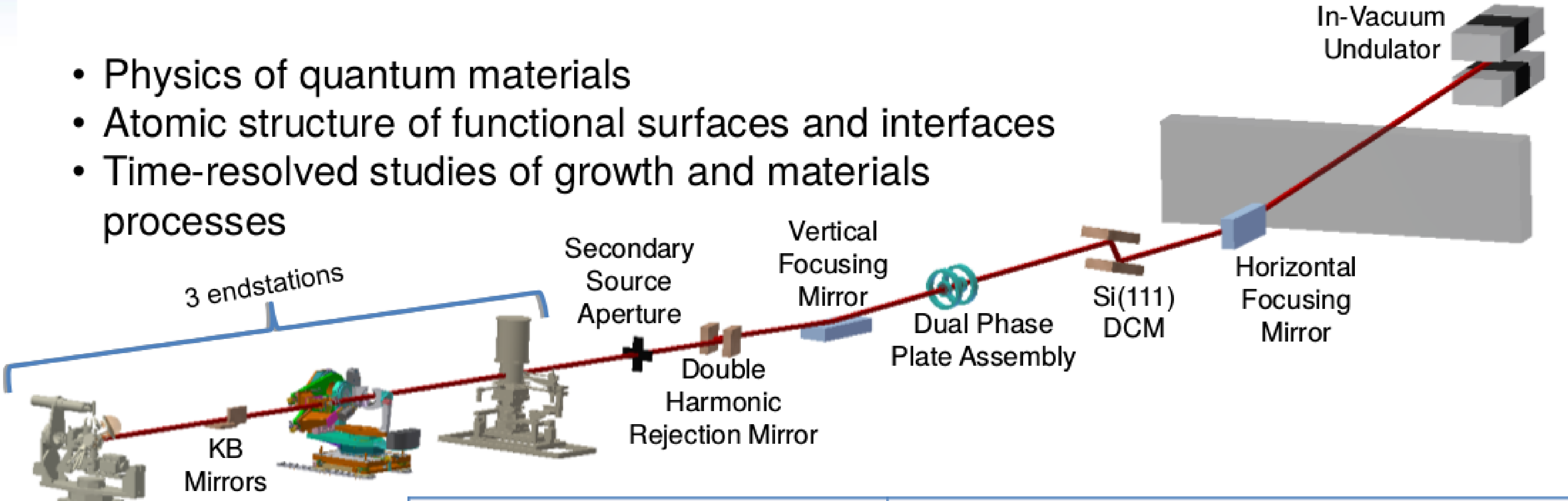
# The ISR beamline



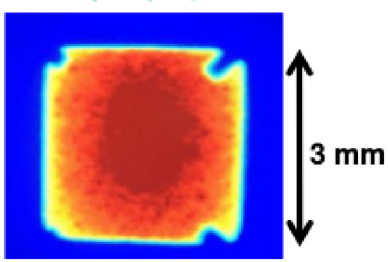
# NSLS-II Beamline 4-ID: *In-Situ* and Resonant X-ray Studies

## Science focus areas:

- Physics of quantum materials
- Atomic structure of functional surfaces and interfaces
- Time-resolved studies of growth and materials processes

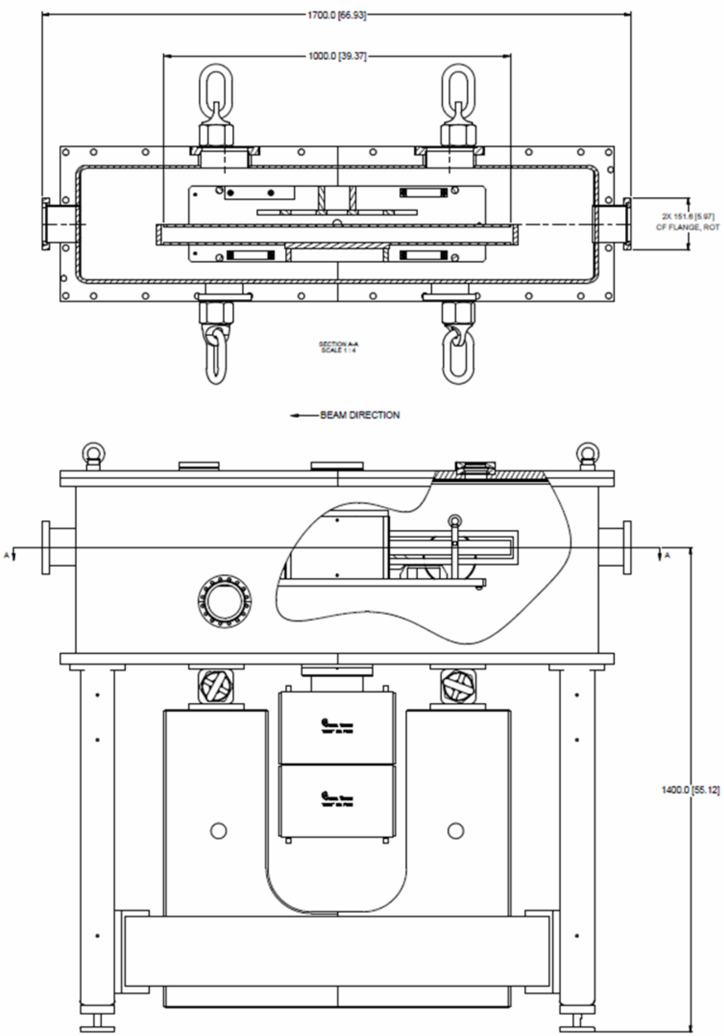


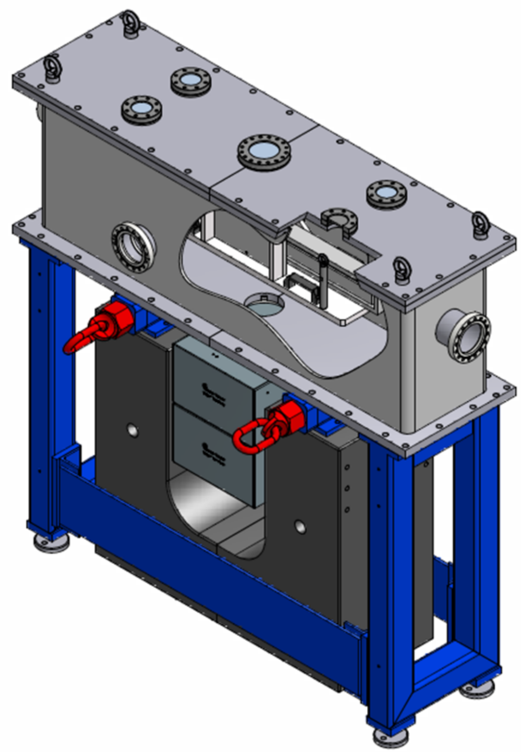

**1st Light on 7/11/16!**




| | |
|---|---|
| Insertion device: | 2.8 m long, 23 mm period, in-vacuum undulator |
| Energy range: | 2.4 – 23 keV with 1.4 x $10^{-4}$ $\Delta E/E$ |
| Beam size at sample (FWHM): | tunable down to 20 (H) x 2 (V) $\mu m^2$ |
| Flux at sample (500 mA ring current): | ~$10^{13}$ photons/s |
| Harmonic suppression: | ~$10^{-5}$ for third harmonic with fundamental at 3 keV |
| Polarization control: | $P_{L,C} \geq 0.9$ for 2.4 keV $\leq E \leq$ 14 keV |
| Three custom endstations: | base diffractometer for high magnetic field studies; instrumented 6-circle diffractometer; base diffractometer for *in-situ* studies of growth and materials processes, with gas handling system infrastructure |

# Horizontal Focusing Mirror

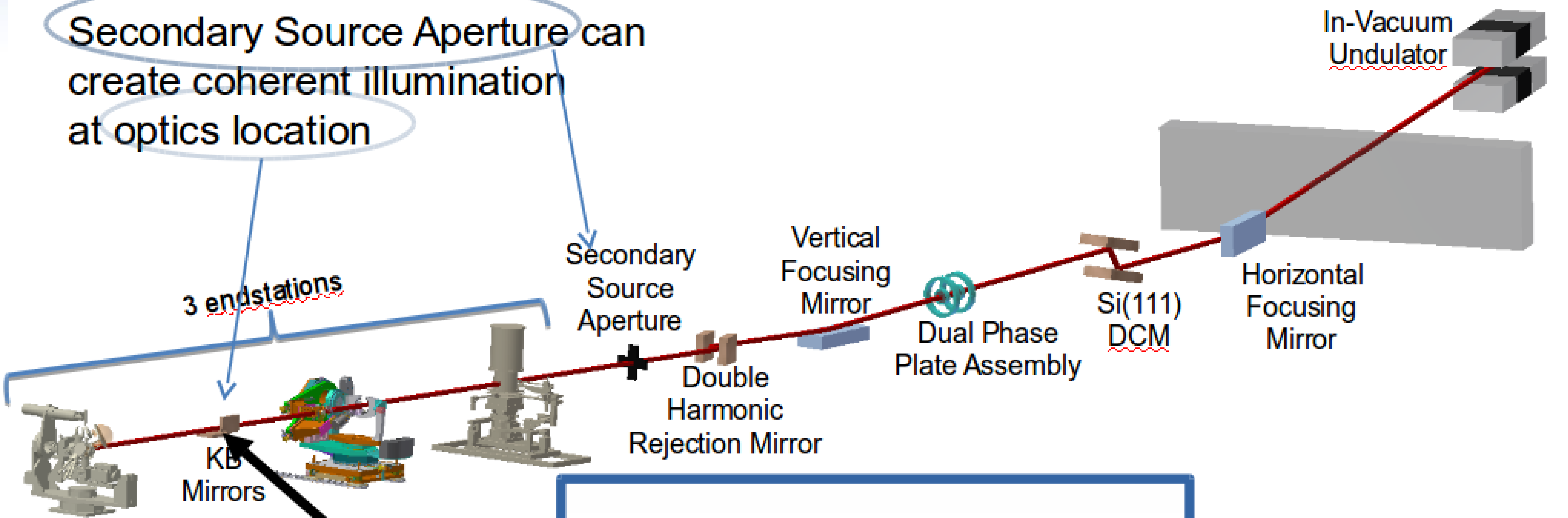


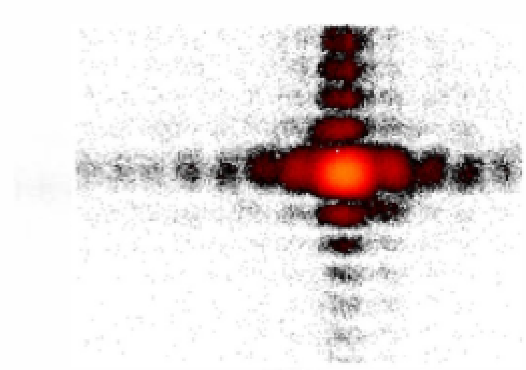
- Indirect water cooling with a closed-loop system
- Design to include:
  - cooled disaster mask
  - cooled Compton shield
  - flanged viewport with a manual shutter
  - vibration sensors
  - capacitive sensors for measuring stability of incidence angle
  - thermal sensors
  - limit switch on bender

# NSLS-II Beamline 4-ID: Creating coherent illuminaton

Secondary Source Aperture can create coherent illumination at optics location



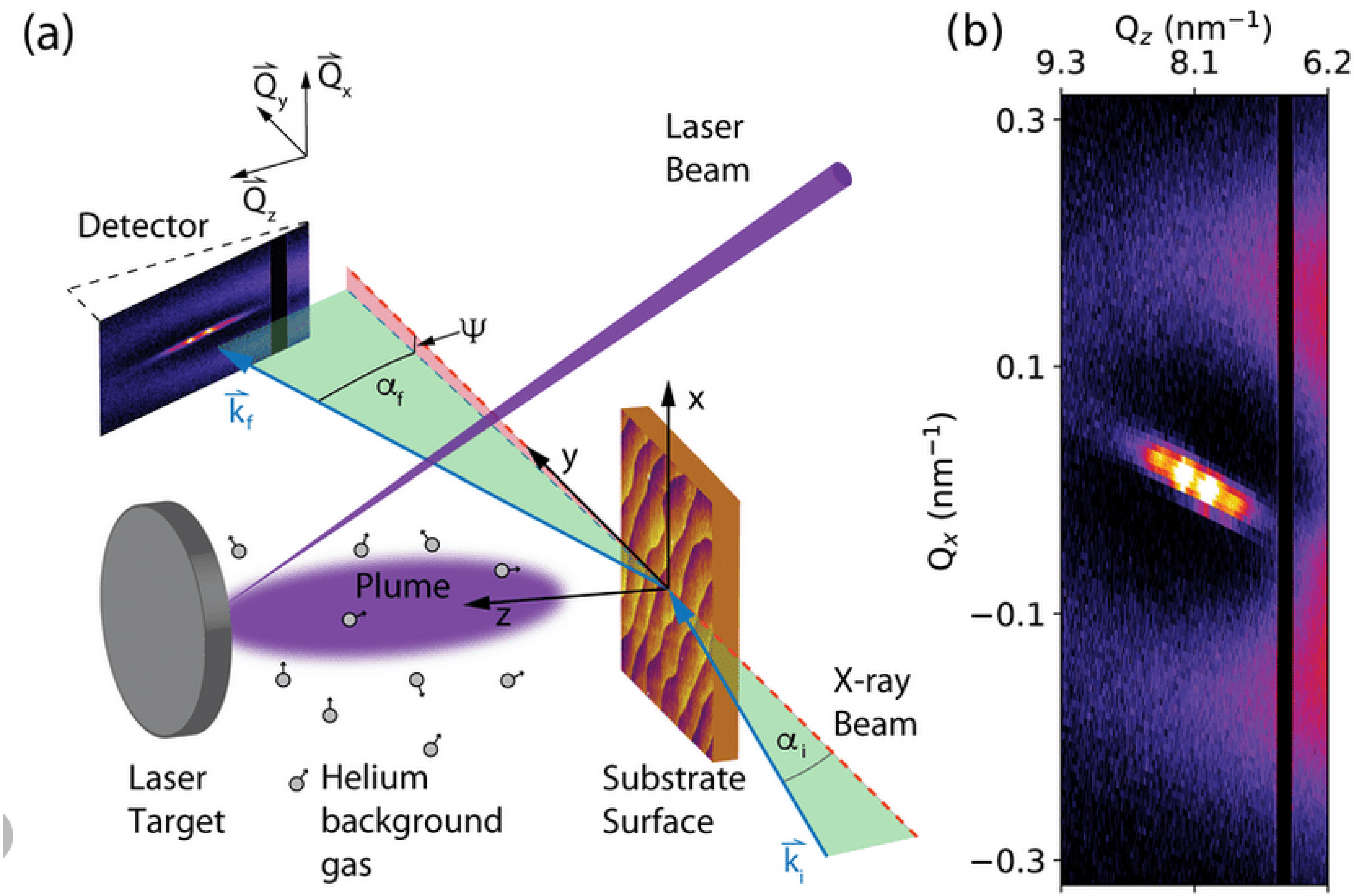

Eiger 1M fringes at 17meters



Analysis indicates fringes correspond to SSA opening of 1.5 microns

# Examples of some in-situ work @ ISR

from Phys. Rev. B 101, 241406 (2020)



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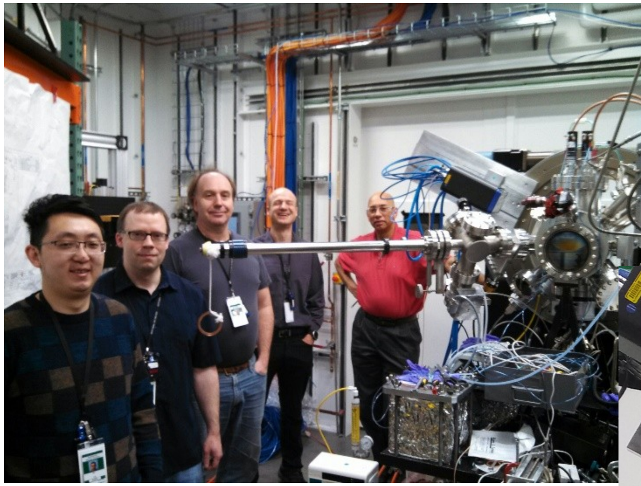
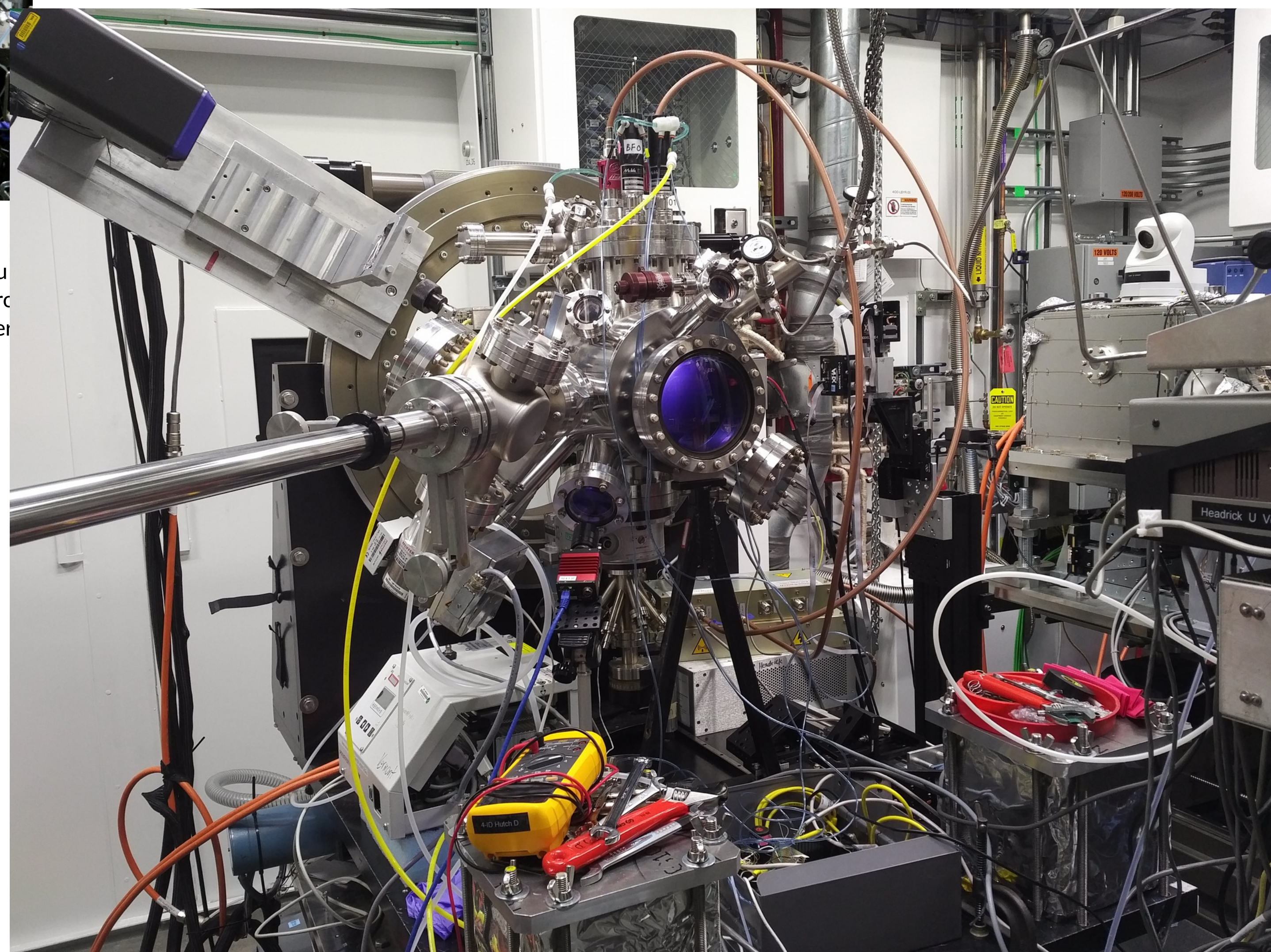


From left to right: graduate students Rui Liu Brook) and Jeffrey Ulbrandt (Vermont), Pro Randall Headrick (Vermont) and Matthew Dawber Brook), and Kenneth Evans-Lutterodt (NSLS-II).



# Kinoform Optics at High Photon Energies

*Kenneth Evans-Lutterodt, NSLS-II*

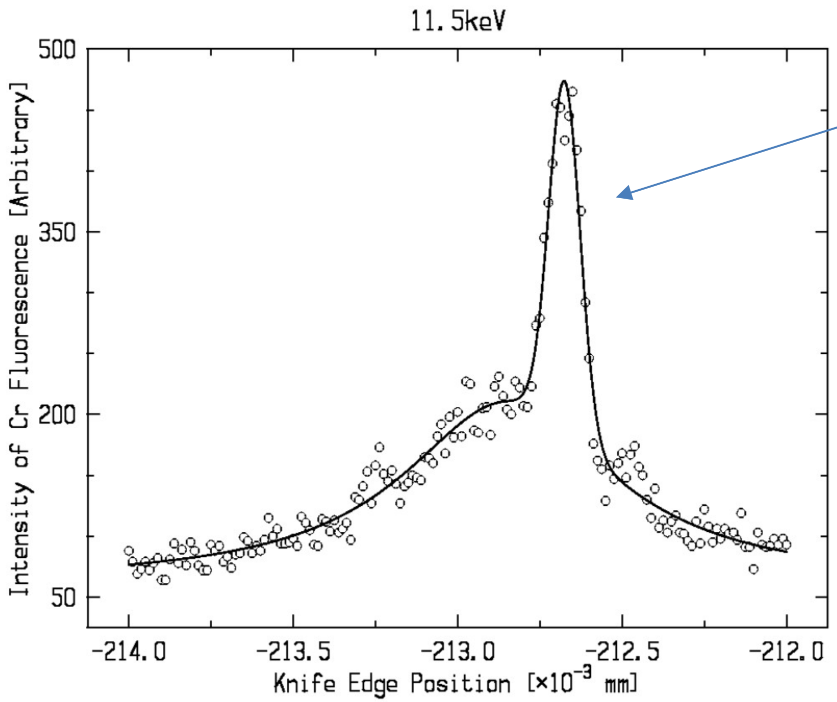
# Collaborators

- **Sarvjit Shastri ( 1-ID, ANL )**
- Aaron Stein (CFN,BNL)
- Rich Sheffield (LANL)
- Ming Lu (CFN,BNL)
- Meredith Metzler (CNF, now at Penn State)
- Abdiel Quetz (Southern Illinois Univ.)
- V. Stanic (LNLS)
- Wenge Yang ( HP Sync)
- Craig McGray
- Evgeny Nazaretski
- Christie Nelson


# Funding

- Eliane Lessner (DOE)
- Rich Sheffield (LANL)

# Recent results: 113nm FWHM @ 11.53 keV



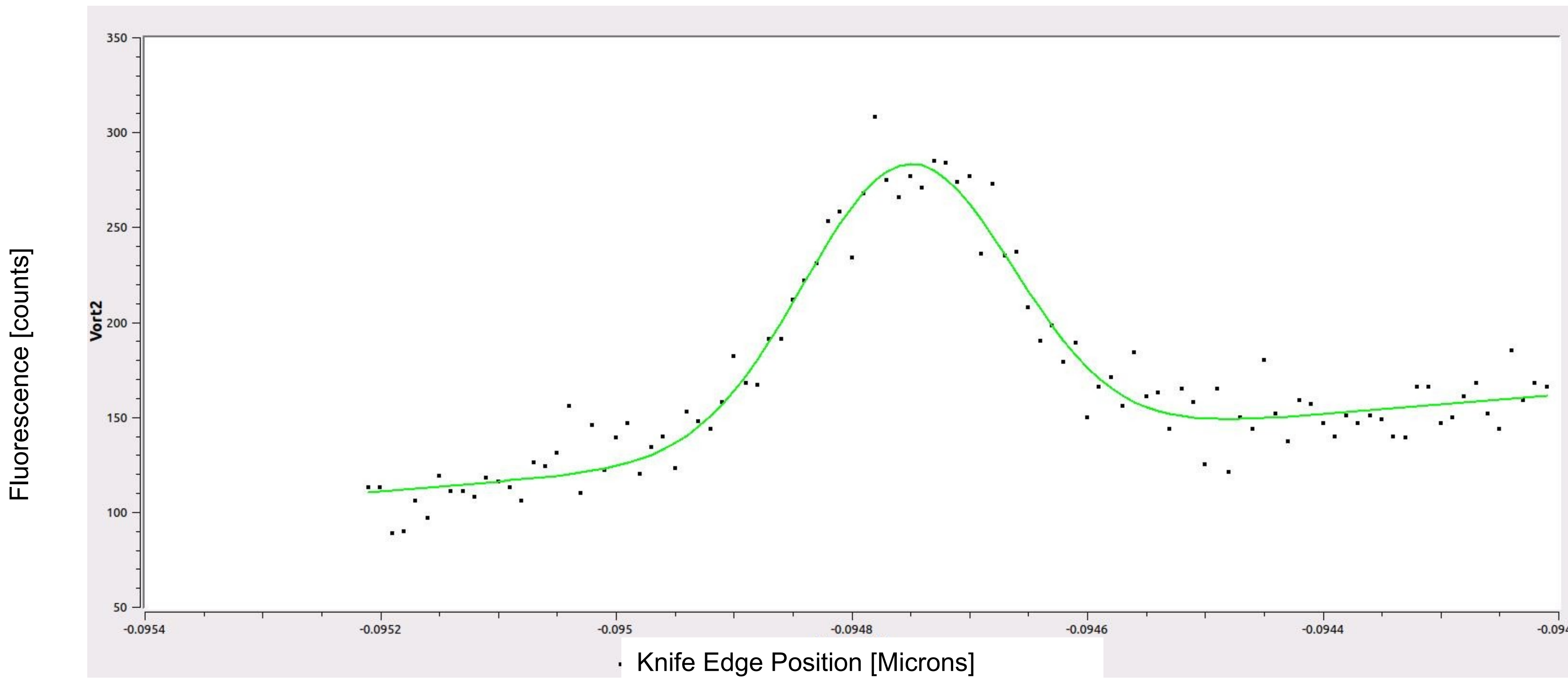

113nm +-10nm

Each step is $\frac{2\text{ microns}}{160\text{ steps}} = 12.5\text{ nanometers}$

Each step is

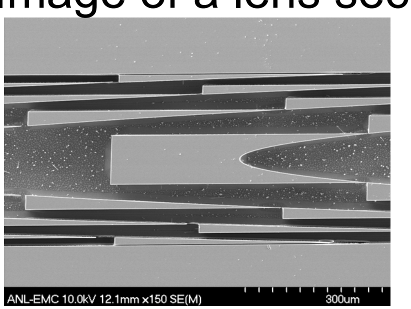
Thanks ADR, for the funding that made this possible.

# Recent results: 209 nm FWHM @ 77 keV




200 nm

Image of a lens section




APS 1-ID with Shastri

Focal length = 0.16m

Number of lens elements = 180

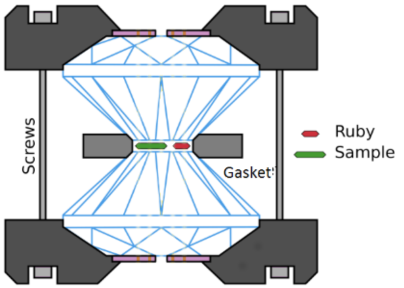
Sort of works, BUT : Background is high. Probably due to sidewall roughness.

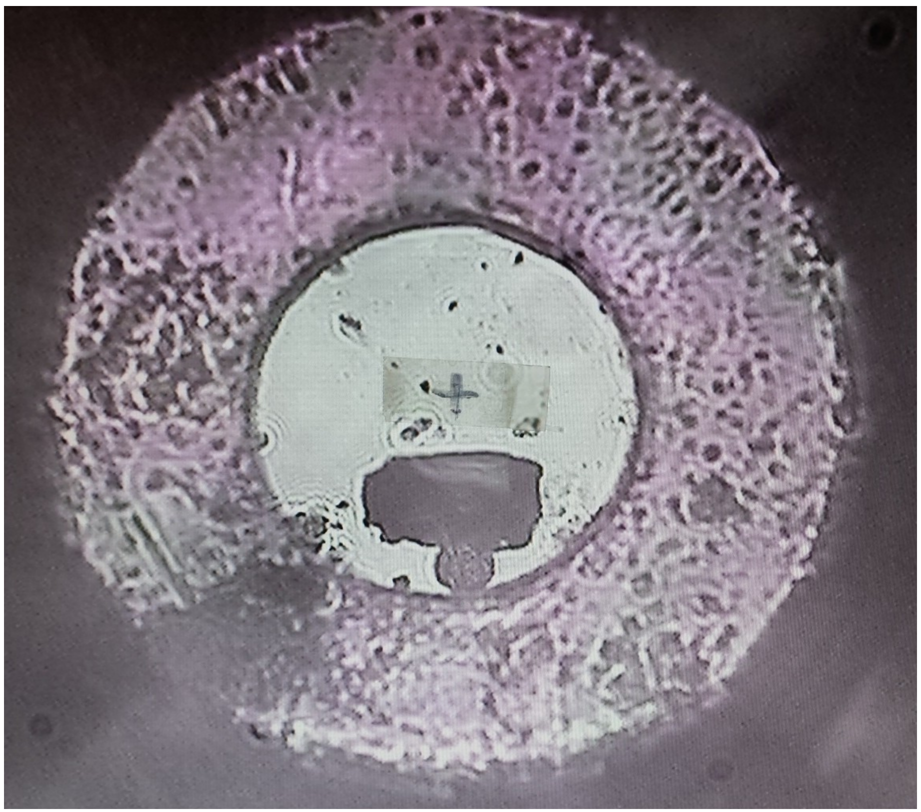
# One Science example that motivates this work: PDF at 1GPa in a DAC in ID11 at 107 keV

Pair Distribution Function

Gigapascal

Diamond Anvil Cell



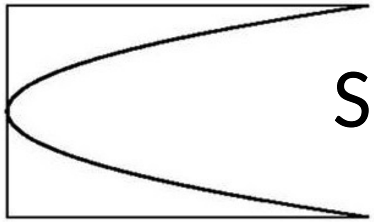
Microscope view of diamond anvil cell
Rhenium gasket
Inner diameter of gasket ~150 microns
Sample is ~ 40 microns by 25 microns

Source Brightness matters
High Photon Energy (107 keV) matters

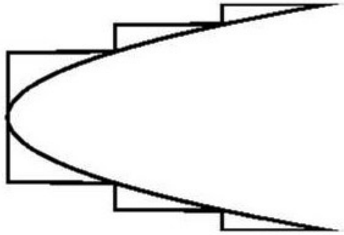
Optics requirement:
Spotsize ~< 5 microns at about 0.75 m

# Refractive Optic Types and Materials

Rely on refractive index and shape of material



Solid Refractive



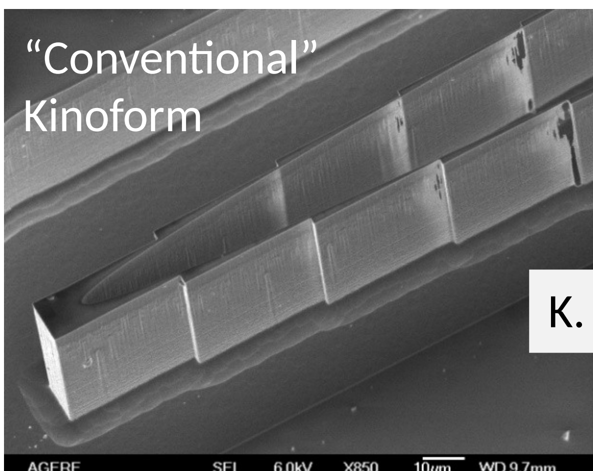
Kinoform

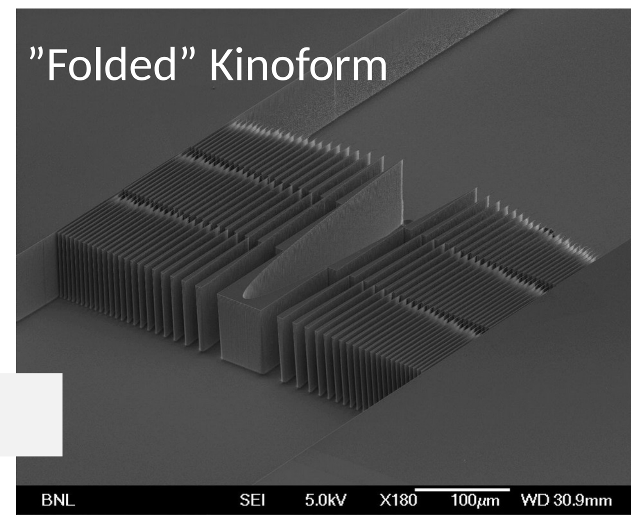
Typical Materials: Beryllium, Diamond, **Silicon**

NSLS2 R&D : ~~Beryllium~~, Diamond, **Silicon**

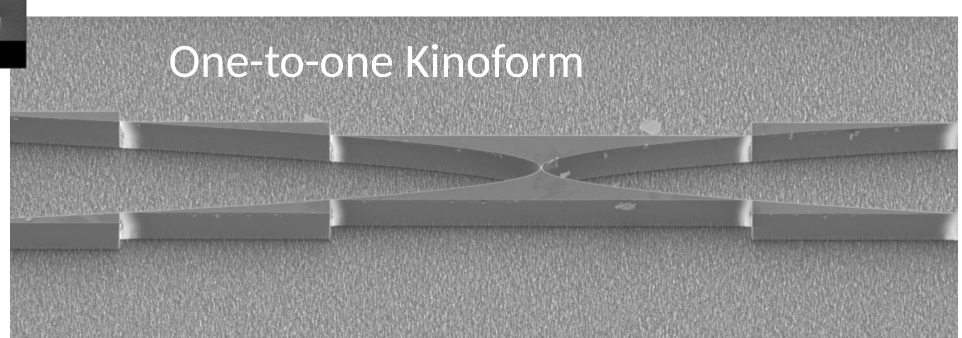
# A sampling of some of our existing kinoforms:

| Focal Length | Energy | Measured FWHM | Comments |
| --- | --- | --- | --- |
| 0.1m | 12.1 keV | 130 nm | |
| 0.9m | 7.35 keV | 1.1 µm | 8-ID Standard equipment<br>Diffraction limited |
| 3.5m | 10 keV | 4 µm | For NSLS2 XPCS |
| 34m | 21.7 keV | 64µm | |
| 0.25m | 51.2 keV | 225nm | |
| 1m | 102.4 keV | 1.3 µm | |

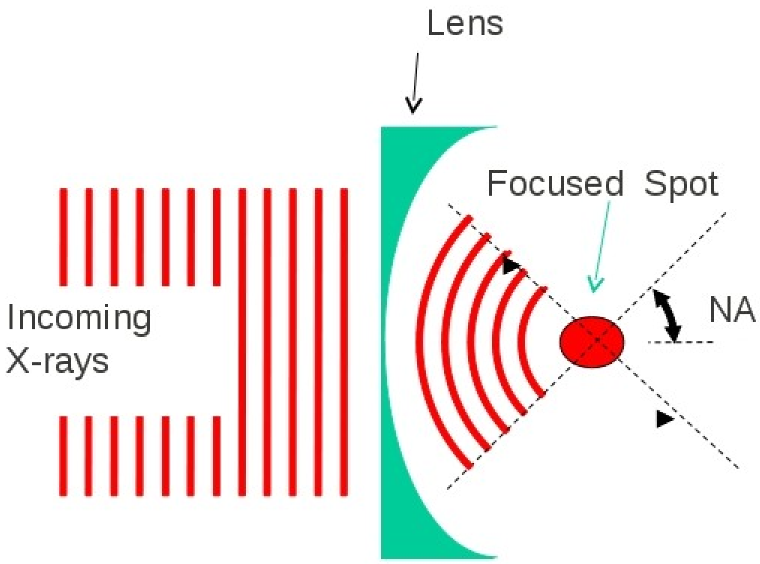



K. E-L et. al., Optics Express, 11, 919, 2003



# Relevant Basics of Optics




$$\Delta_t = \frac{0.61\lambda}{NA}$$

$$\Delta_l = \frac{\lambda}{(NA)^2}$$

- n=1- $\delta + i\beta$, where $\delta$ is of order $10^{-6}$
- Real part of refractive index is < 1
- Imaginary part (absorption) limits the Numerical Aperture (NA) of a solid refractive
- Need the right shape for the optic (Elliptical, for a single lens)
- Decreasing focal length reduces source size contribution

# Electron Beam Lithography is done at CFN


Aaron Stein
CFN

Important Characteristics:
Laser interferometer => Placement accuracy (4nm/500$\mu$m)
Flexible

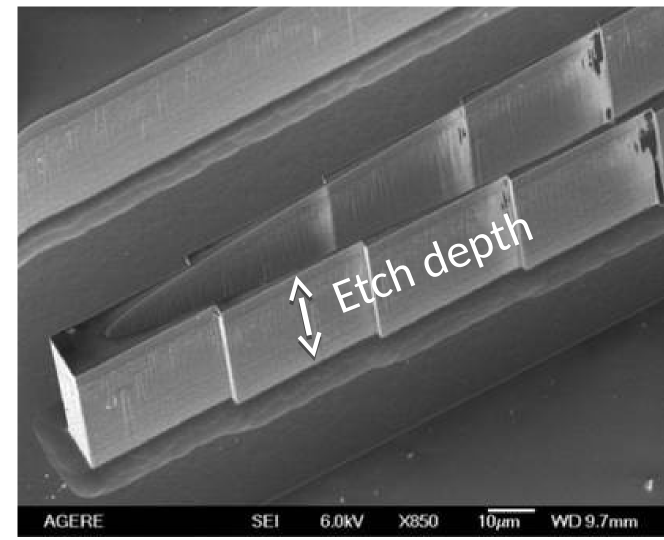
400 nm UV3 chemically amplified resist (CAR) – negative type

30 nm Cr

4” Si wafer

(at BNL)

expose with e-beam lithography/write, post exposure bake (PEB), & chemically develop

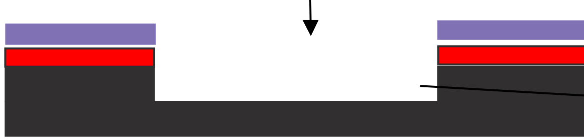



(at BNL)

dry etch of Cr using $O_2$ and Cl

(at BNL)

deep Si etch – Bosch process (gas phase, reactive ion)



Up to 100 µm depth in Si (currently).
~~Effort underway towards 150 µm~~.

Currently180 microns