Soft X-ray beamline design and optics consideration

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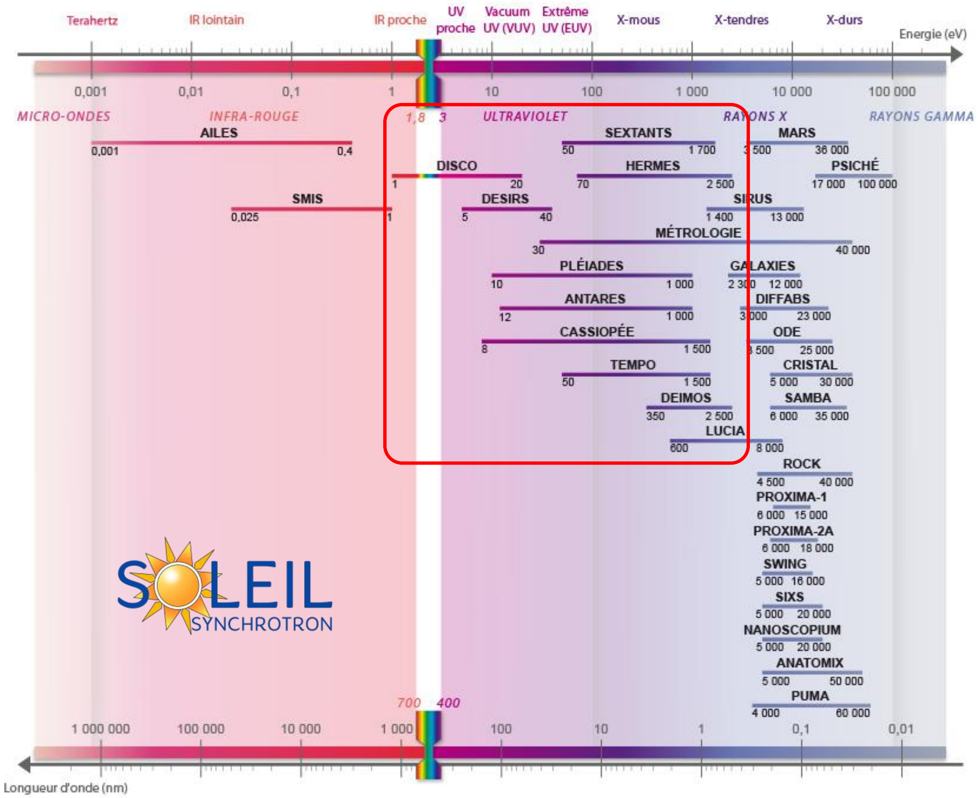
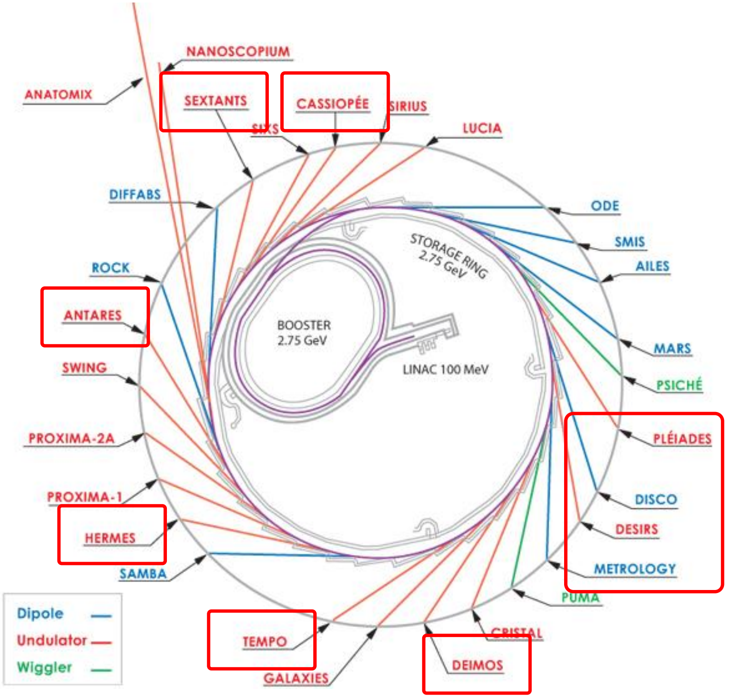
Soft X-ray beamline design and optics consideration

Outline:

- Similar patterns everywhere
- Soft x-ray beamline topology
  - Source
  - Chicane
  - Monochromator
  - Refocusing
  - Experimental station
- Where to learn more?

Soft x-ray beamlines: a "heliocentric" view of optical design





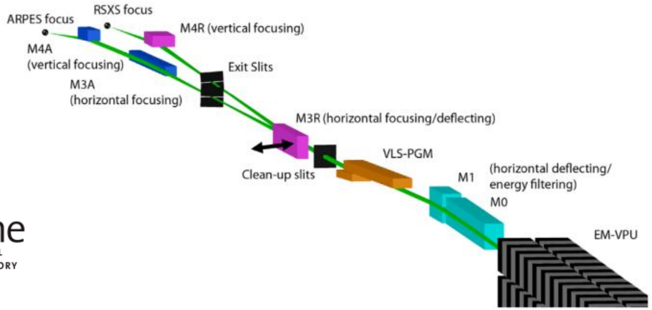
SOLEIL beamlines, their energy ranges together with their position along the storage ring. This talk is based on gathered experience from SOLEIL and SOLEIL-II optical design.

Soft x-ray beamlines: similar patterns everywhere

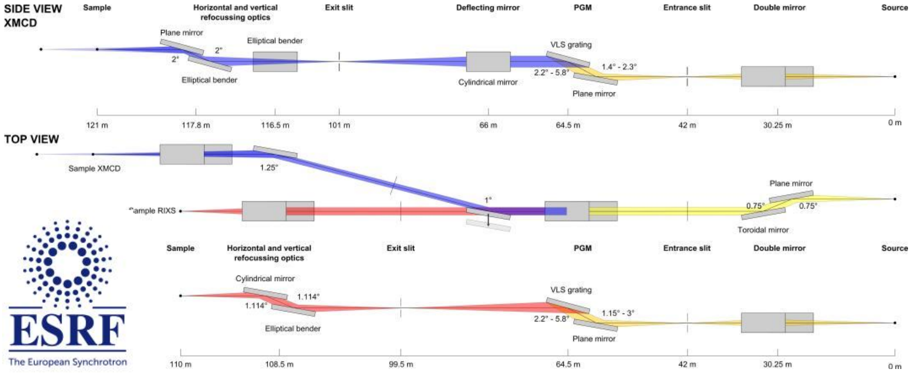
Same patterns are found within **low-** and **mid- energy storage rings** (the usual suspects: $\mathcal{E}$<3 GeV).

Soft x-ray beamlines: similar patterns everywhere

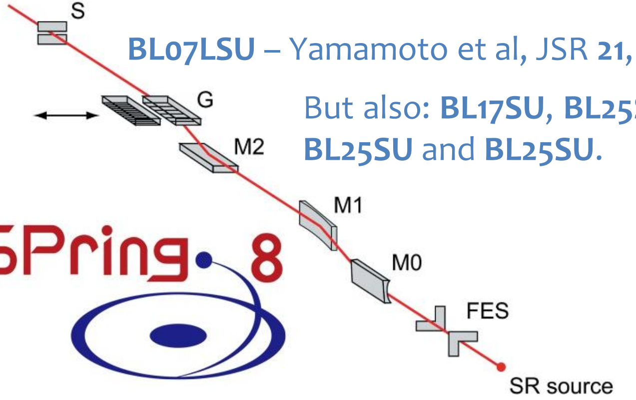
But also at **high energy** facilities ($\mathcal{E}$>3 GeV):



29ID – McChesney et al, NIMA **746**, 98–105 (2014)

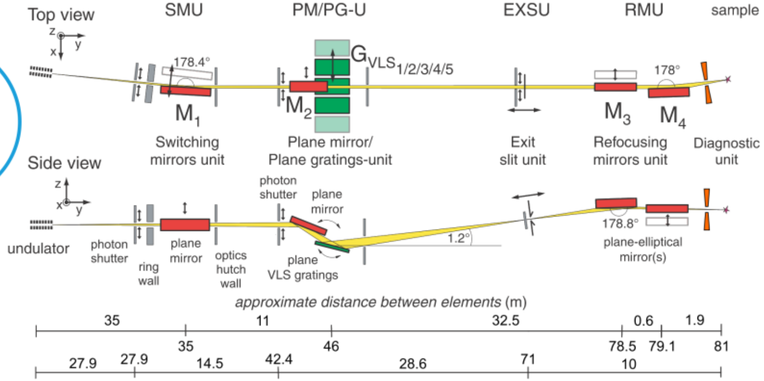


ID32 – Brookes et al, NIMA **903**, 175–192 (2018)



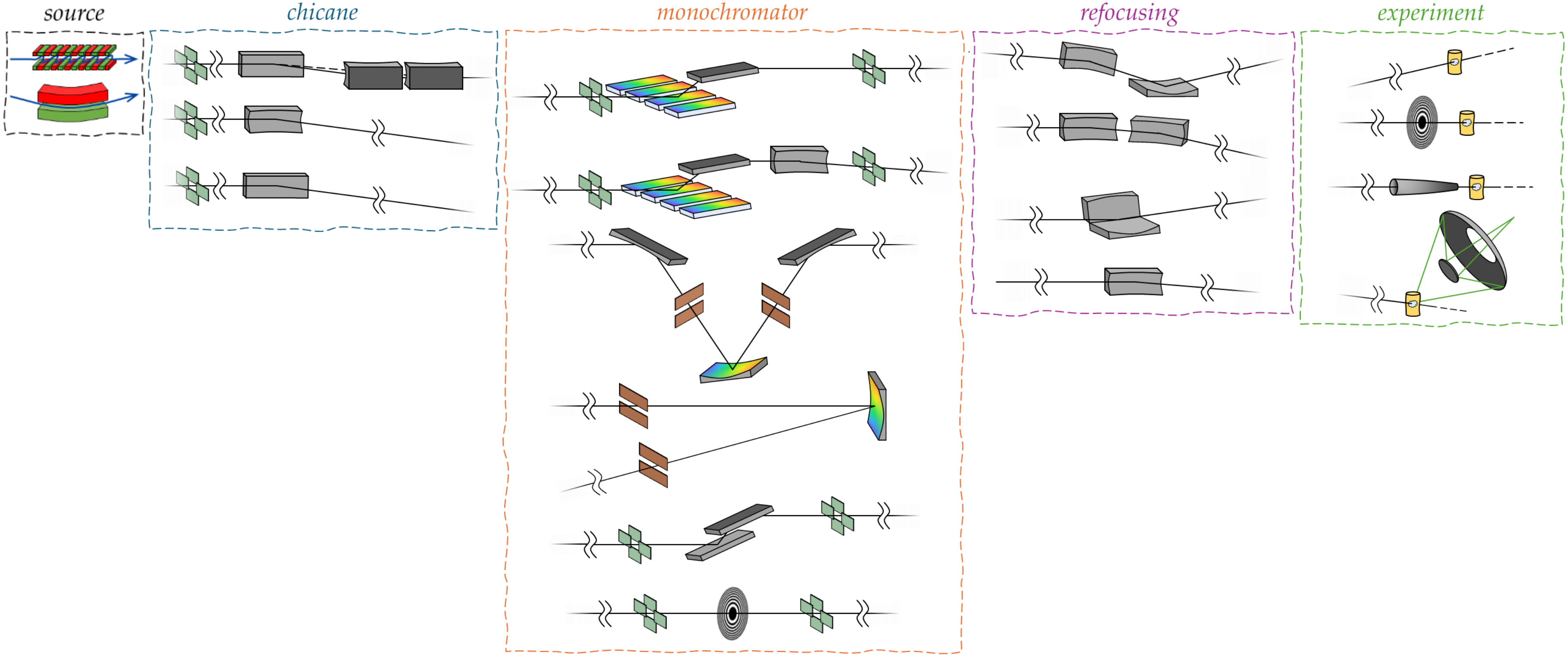
BL07LSU – Yamamoto et al, JSR **21**, 352–365 (2014)

But also: **BL17SU**, **BL25SU**, **BL25SU** and **BL25SU**.



P04 – Viefhaus et al, NIMA **710**, 151–154 (2013)

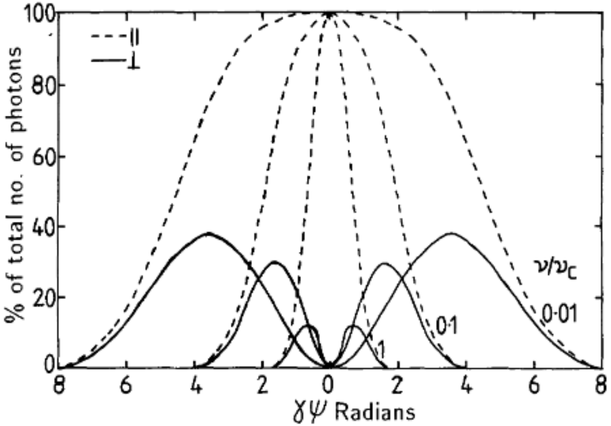
Soft x-ray beamline topology



topology of a generic soft x-ray beamline. The beamline is responsible for **photon transport** from **source** to the **experimental station.** It **shapes** (collimates, focuses...) the **beam** and **selects** an **energy** (band) for the experiment.

Soft x-ray beamline: the source

Often associated with **SXR sources** is the necessity of polarisation **tunability/control** and **purity** over a **wide energy range.**



reproduction from Fig. 1.7 from “*Optical systems for soft x-rays*” by A. Michette (1986) representing the angular distribution of the polarised components of BM emission.

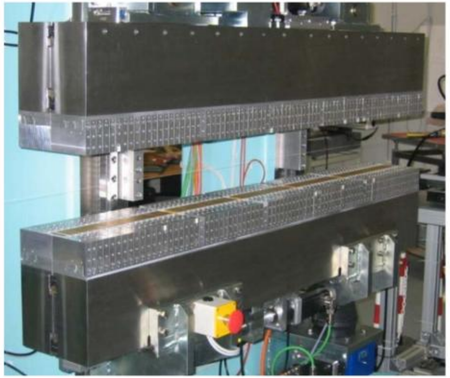


Figure 2: The assembled HU80 undulator

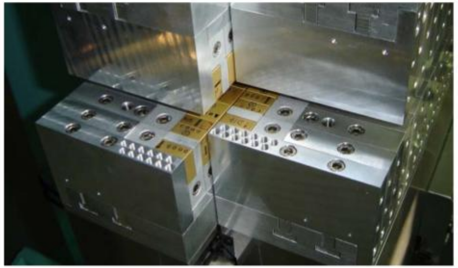
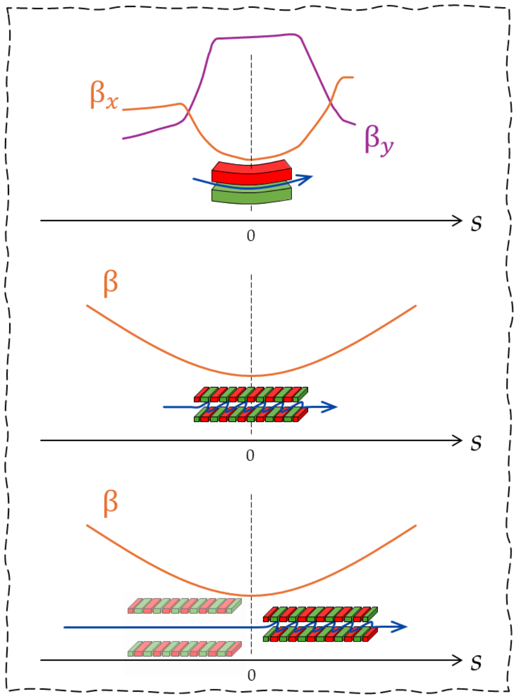


Figure 5: Undulator end-section showing the holder for the small correcting permanent magnet pieces.

Diviacco et al, Proc. PAC (2005)

source



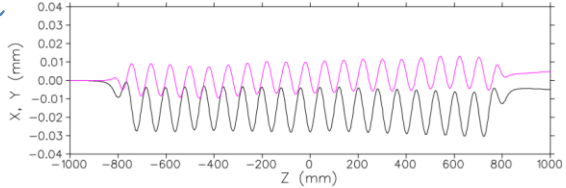
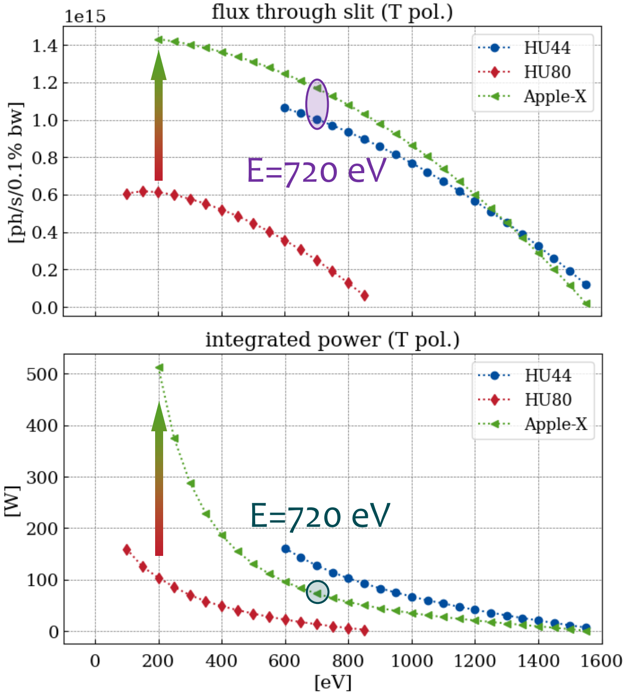
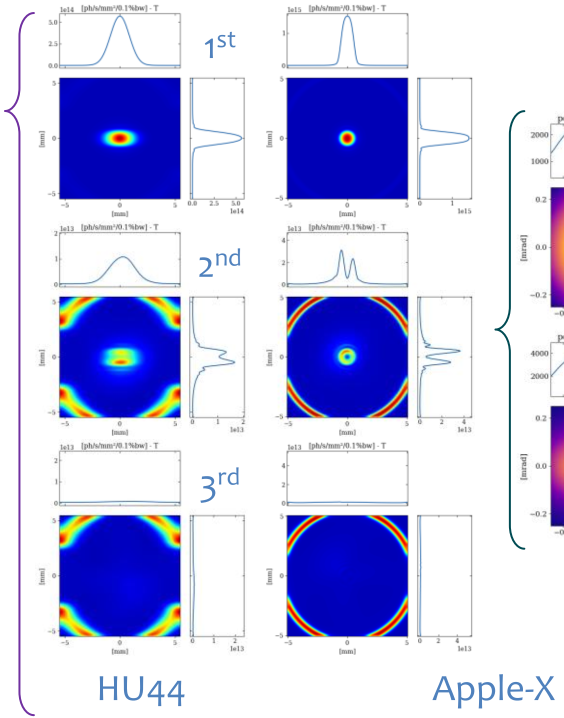


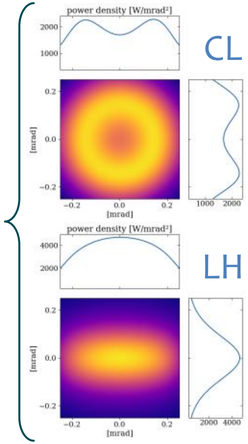
Figure 8: Horizontal (black) and vertical (magenta) trajectory in elliptical polarization mode.

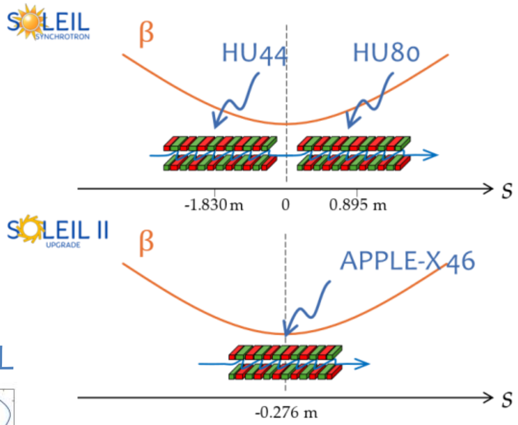
Soft x-ray beamline: the source

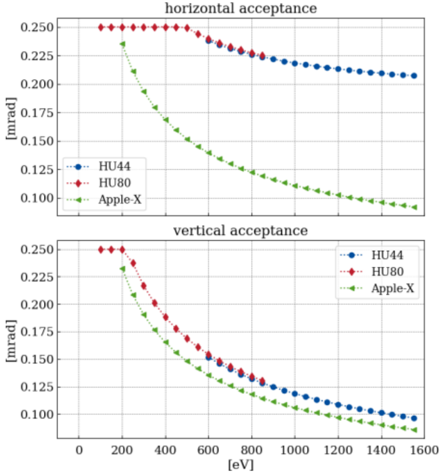
Accurate source modelling: **flux** and **power** and **coherent fraction**.





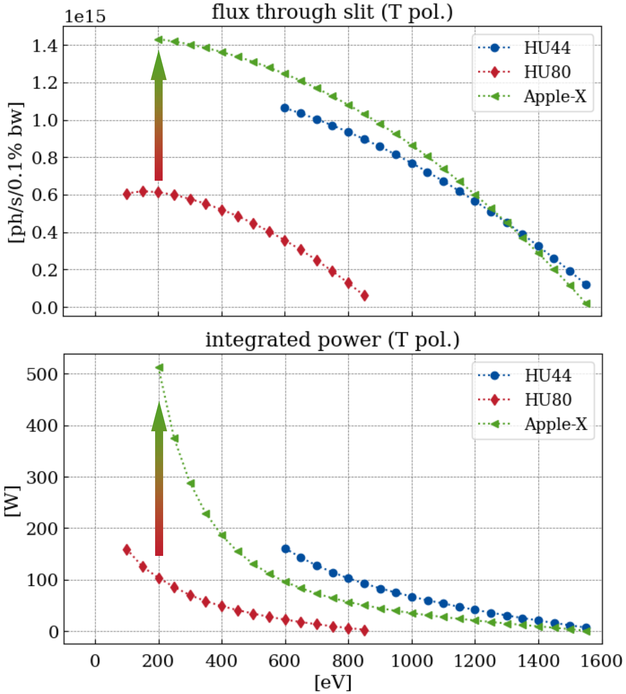


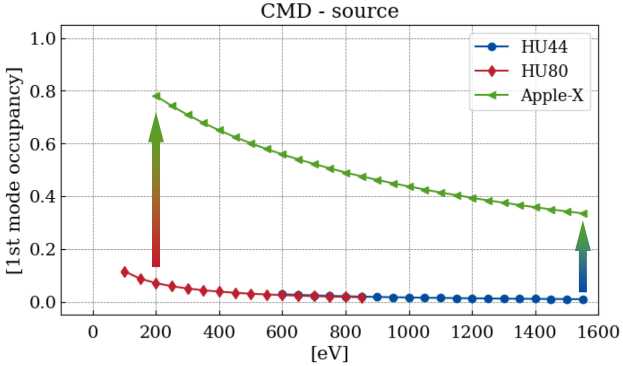




Soft x-ray beamline: the source

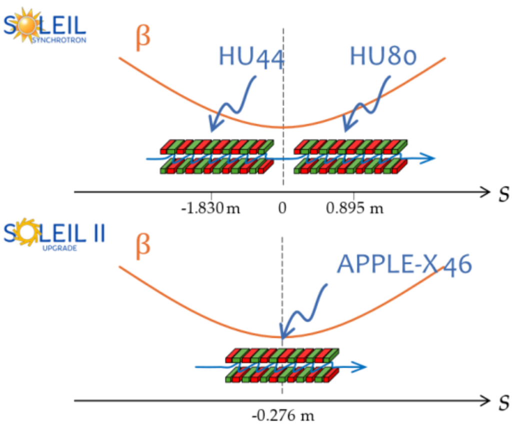
Accurate source modelling: **flux** and **power** and **coherent fraction**.

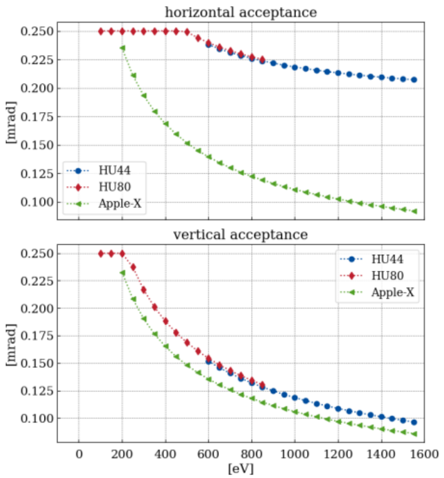




Increased coherent fraction means that **diffraction effects** may not be neglected! Choosing an **appropriate optical theory** is important.

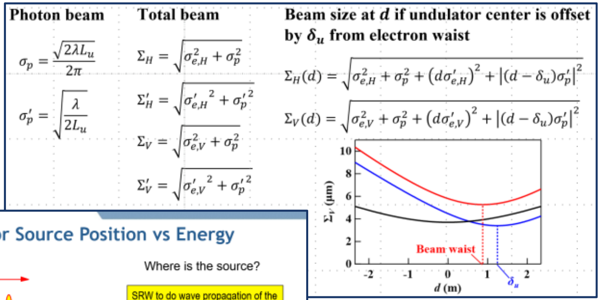
Talk: *Methods for beamline simulations (Ray tracing/Wave optics/HYBRID)* by Rebuffi and Shi



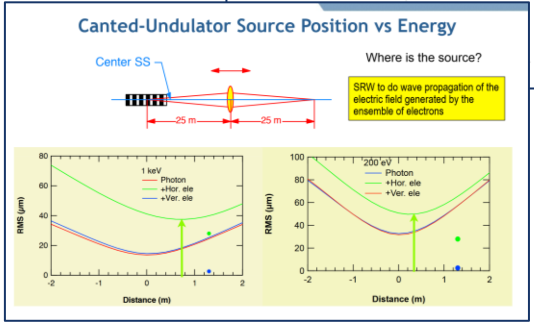


Soft x-ray beamline: the source

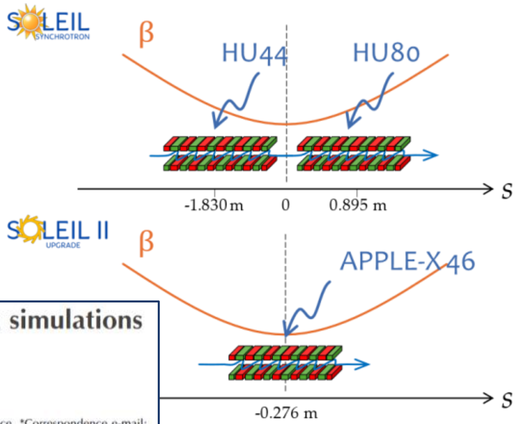
Accurate source modelling: **position, shape, size** and **divergence**.



Photon beam	Total beam	Beam size at d if undulator center is offset by δ_u from electron waist
$\sigma_p = \frac{\sqrt{2\lambda L_u}}{2\pi}$	$\Sigma_H = \sqrt{\sigma_{e,H}^2 + \sigma_p^2}$	$\Sigma_H(d) = \sqrt{\sigma_{e,H}^2 + \sigma_p^2 + (d\sigma'_{e,H})^2 + \lvert(d-\delta_u)\sigma'_p\rvert^2}$
$\sigma'_p = \sqrt{\frac{\lambda}{2L_u}}$	$\Sigma'_H = \sqrt{\sigma'^2_{e,H} + \sigma'^2_p}$	$\Sigma_V(d) = \sqrt{\sigma_{e,V}^2 + \sigma_p^2 + (d\sigma'_{e,V})^2 + \lvert(d-\delta_u)\sigma'_p\rvert^2}$
	$\Sigma_V = \sqrt{\sigma_{e,V}^2 + \sigma_p^2}$	
	$\Sigma'_V = \sqrt{\sigma'^2_{e,V} + \sigma'^2_p}$	



(top): reproduction from Shi et al, Proc SPIE **10388**C (2017).
(bottom): slide taken from Reininger "X-Ray optics simulations and current developments on software packages – II" SyncLight 2015 (2015).



Modelling undulators in ray tracing simulations

Manuel Sanchez del Rio* and Juan Reyes-Herrera

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J. Synchrotron Rad. (2025). **32**, 340–354

Undulator radiation brightness calculations in the Sirepo GUI for SRW

B. Nash, O. Chubar, D. L. Bruhwiler, M. Rakitin, P. Moeller, R. Nagler, N. Goldring

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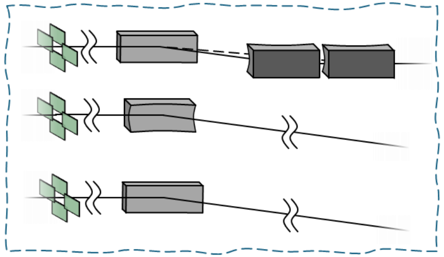
Proceedings Volume 11110, Advances in Laboratory-based X-Ray Sources, Optics, and Applications VII; 111100K (2019) https://doi.org/10.1117/12.2530663
Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

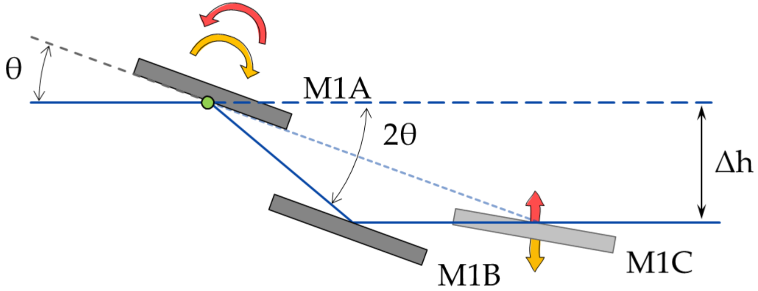
selected publications (and references therein) dealing with accurate photon beam shape, size and divergence from a finite-emittance electron beam considering energy spread effects.

Soft x-ray beamline: the chicane



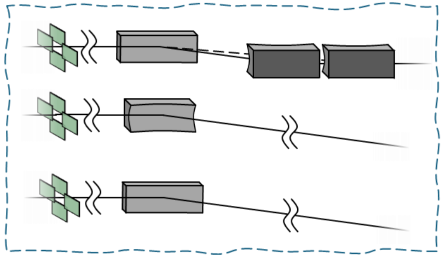
The functions of the chicane are manifold:

- **Radio protection**: the first mirror **cuts** the **line of sight** between the **accelerator** and the rest of the **beamline.** Associated with it, is a high Z material for blocking (very high) energy photons;
    - a second mirror (pair) can be used for making the outgoing beam parallel to the incoming beam.



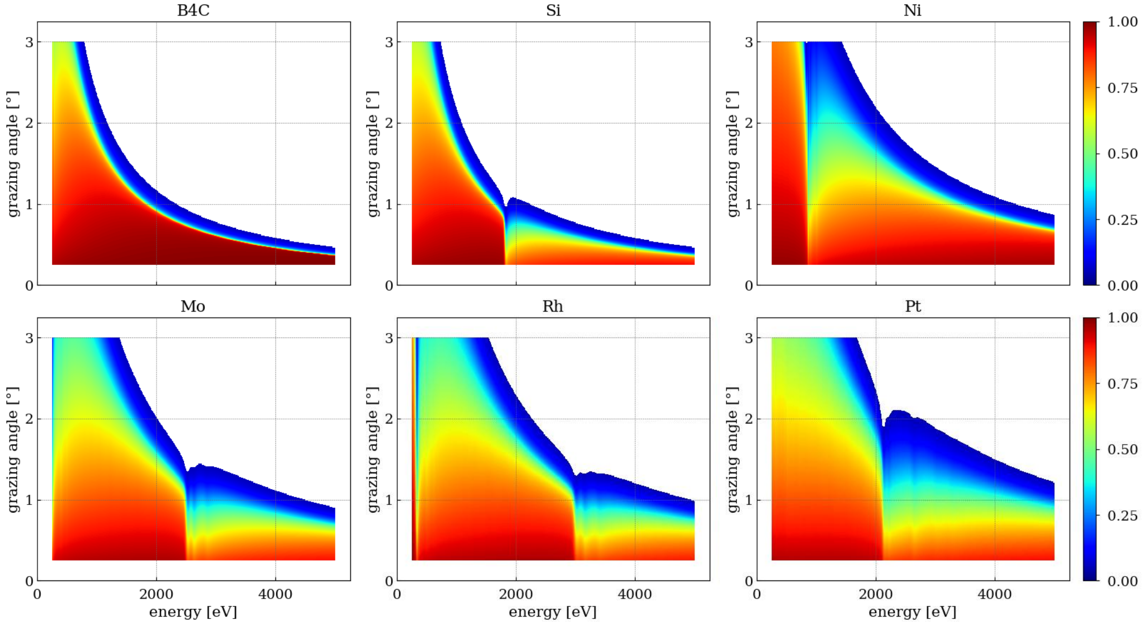
sketch of a typical M1 chicane used at SOLEIL

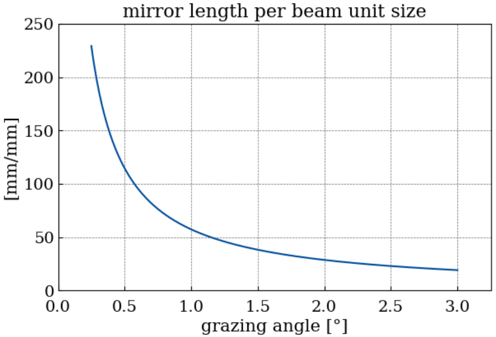
Soft x-ray beamline: the chicane



The functions of the chicane are manifold:

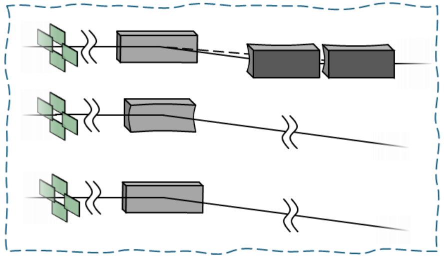
- **Energy filtrering:** mirrors (and their coatings) act as a low pass filter (true for all BL mirrors).





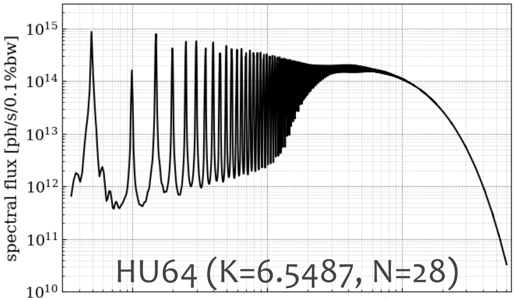
reflectivity for commonly used materials in x-ray mirrors. The M1 system is compromise between grazing angle/total mirror length and overall transmission for the specified energy range.

Soft x-ray beamline: the chicane

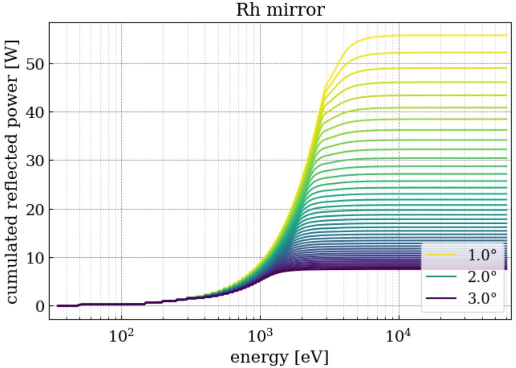


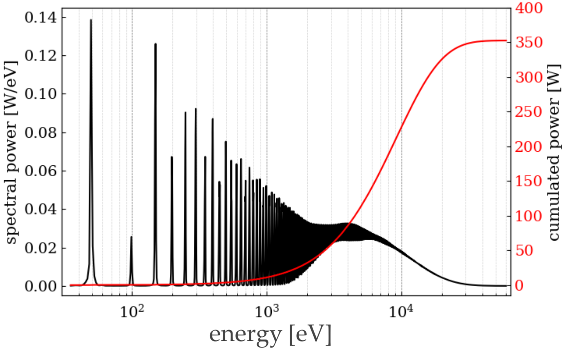
The functions of the chicane are manifold:

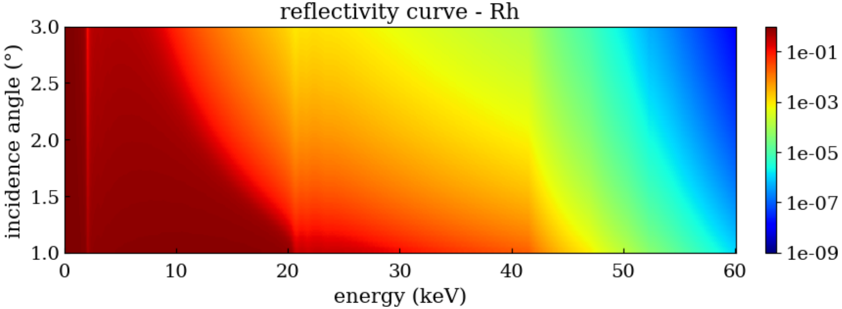
- **Power absorption:** the high energy content filtered out by the M1 is absorbed by it.



0.2 x 0.2 mrad



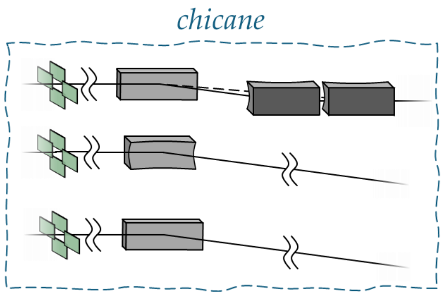




Talk: *Power transport calculation, SRCalc, XOPPY* by Sanchez del Rio

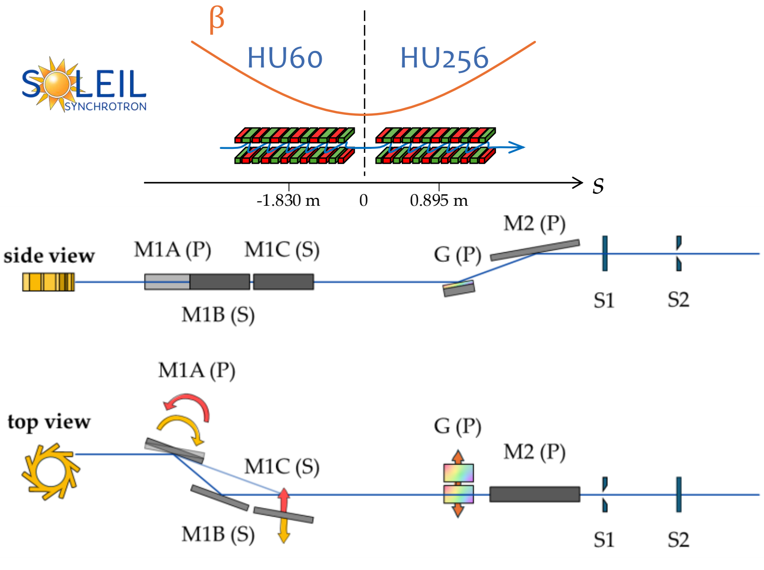
Talk: *Thermal load calculation through beamline* by Rebuffi

Soft x-ray beamline: the chicane

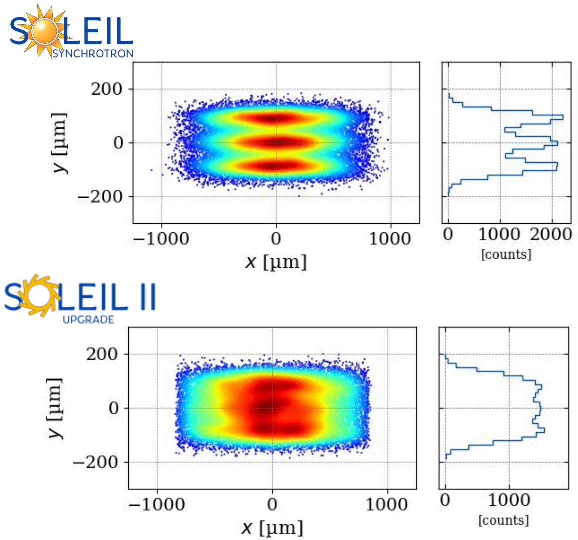


The functions of the chicane are manifold:

- **Condensation or collimation:** if **curved mirrors** used to **condition** the **beam** prior to the monochromator, they **impact** the beamline **energy resolution.**



source and truncated beamline (Antares)



$E_0 = 101\text{eV}$
(E/ΔE = 20k)

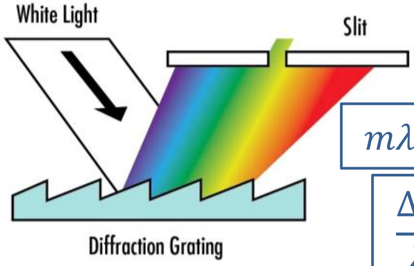
effect moving 0.895 m upstream the HU256 on the energy resolution of the G600l/mm grating monochromator.

Soft x-ray beamline: the monochromator

Monochromators in SXR beamlines are usually built with **gratings** (in normal or grazing incidence) for the lower energies, **multilayer gratings** or **high-d spacing crystals** for the higher energies.

Grating-based systems are more preponderant for SXR beamlines:

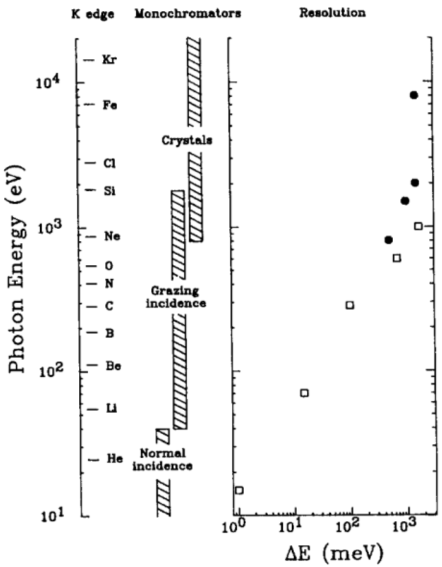
- energy selection is done by **spatially filtering** polychromatic **SR** with an **exit slit** where the beam is focused onto
- always **compromise** between **flux** and **energy resolution** (slit size)



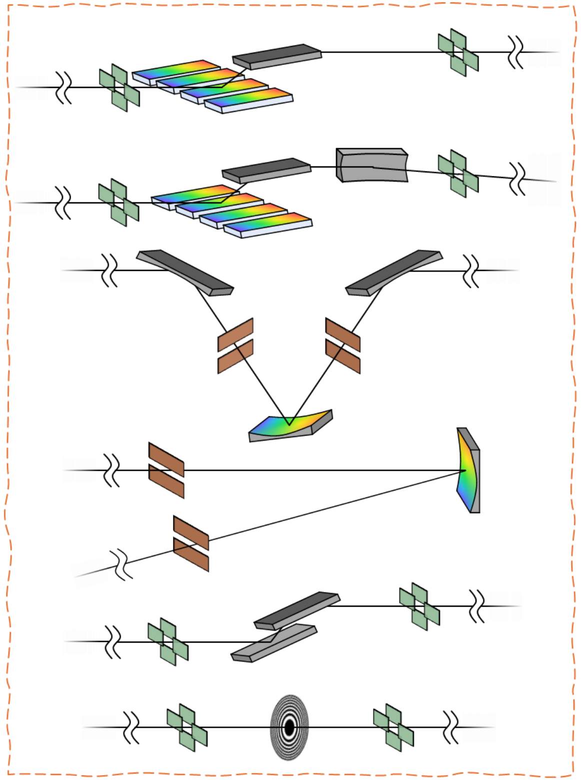
$$m\lambda = D_0(\sin\alpha + \sin\beta)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta E}{E} = \frac{s\cos\beta}{\lambda m D_0 r'}$$

Grating cartoon taken from Edmund Optics website

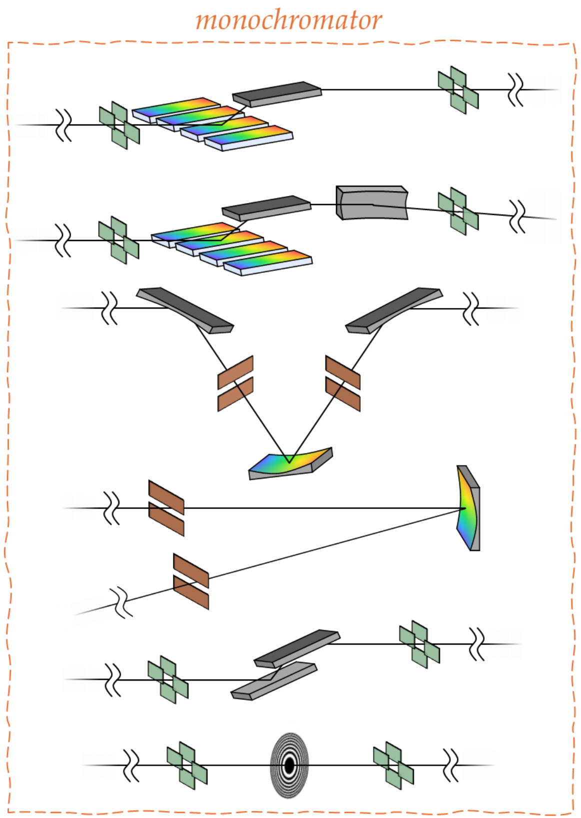


monochromator



Reininger, "Monochromators and associated optical equipment", CAS: SR and FELs 1990.

Soft x-ray beamline: the monochromator



Special topic: Grating monochromators

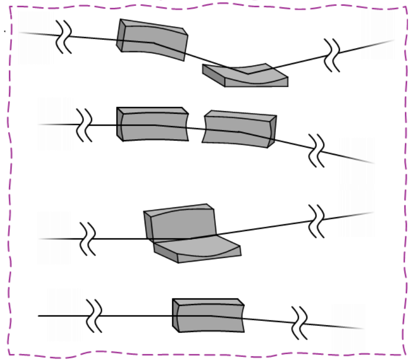
Talk: *Grating design* by Sanchez del Rio

Talk: *Grating simulations* by Sanchez del Rio

You can **learn more** about grating & monochromators here:

- Reininger, "*Monochromators and associated optical equipment*," CERN Accelerator School : Synchrotron Radiation and Free-electron Lasers, pp.401-426 (1990).
- Hulbert, "Grating-based monochromators," International Tables for Crystallography 302–314 (2022).
- Koike, "*1. Normal-Incidence Monochromators and Spectrometers*," Experimental Methods in the Physical Sciences 1–20 (1998).
- Padmore, Howells, and McKinney, "*2. Grazing-Incidence Monochromators for Third-Generation Synchrotron Radiation Sources*," Experimental Methods in the Physical Sciences 21–54 (1998).
- Underwood, "*3. Spectrographs and Monochromators Using Varied Line Spacing Gratings*," Experimental Methods in the Physical Sciences 55–72 (1998).
- Thorne and Howells, "*4. Interferometric Spectrometers*," Experimental Methods in the Physical Sciences 73–106 (1998).

Soft x-ray beamline: refocusing

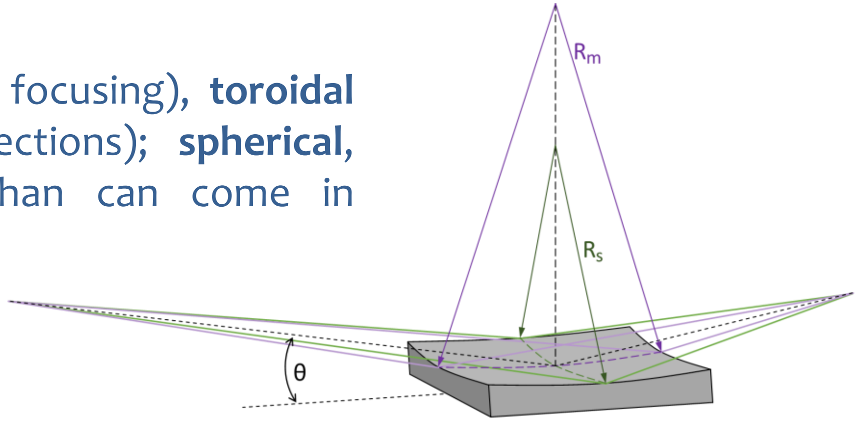


This part of the beamline is responsible for **focusing** the **beam** leaving the monochromator **into the sample** or to a **secondary source** for further demagnification downstream in the experimental station.

- mirrors **reflect** efficiently for **grazing angles** smaller than $\theta_c < \sqrt{2\delta}$
- **paraxial design** is done using the **Coddington equations**

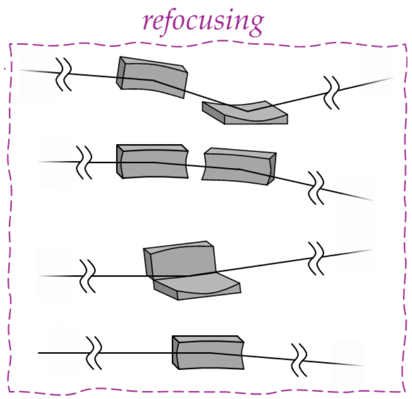
$$f_m = \frac{\mathrm{R_m} \cdot \sin(\theta)}{2} \qquad f_s = \frac{\mathrm{R_s}}{2\sin(\theta)}$$

- typical shapes used for x-ray mirrors: **plane** (no focusing), **toroidal** (focusing in both sagittal and meridional directions); **spherical, parabolic, ellipsoidal** and **hyperbolic** shape than can come in **cylindrical** variations.
- **spherical** and **coma aberrations** are present!



Talk: *X-ray mirror system design and specification* by Shi

Soft x-ray beamline: refocusing



Commonly used **crossed two mirror** systems:

- Kirkpatrick-Baez (KB)
- Hildenbrand-Montel (or confocal KB)

These systems **do not obey the Abbe sine condition,** and the focused beam will present coma aberration for large angular collection.

Commonly used **coaxial two mirror** systems:

- Wolter (types I, II, III)
- Wolter-Schwarzschild
- Namioka-Conjugate Spheres

These systems **obey the Abbe sine condition!**

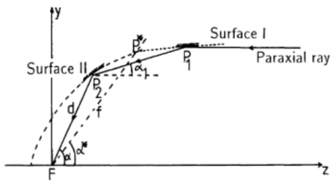


Figure 2.20. Wolter–Schwarzschild type I optical system.

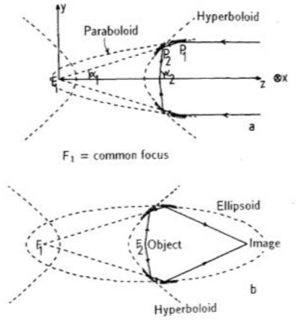


Figure 2.17. Wolter type I optics: (a) telescope; (b) microscope.

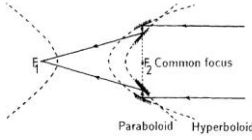


Figure 2.18. Wolter type II telescope.

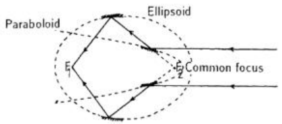


Figure 2.19. Wolter type III telescope.

reproduction from "*Optical systems for soft x-rays*" by A. Michette (1986)

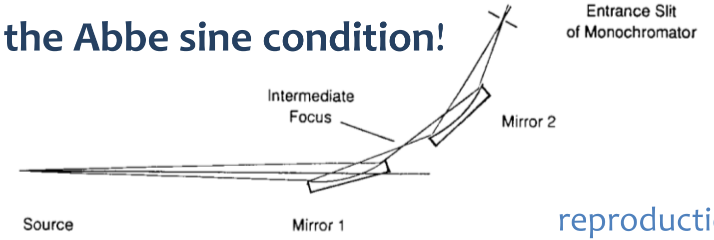
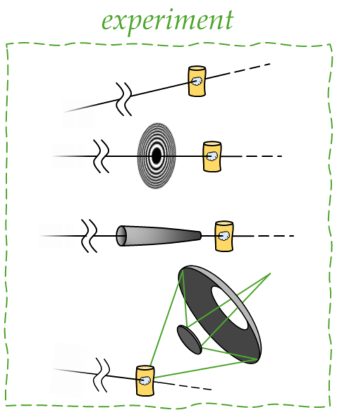


Figure 5.3.2: The Namioka Conjugate Sphere System [5.3]

reproduction from "*Gratings, mirrors and slits*" by W. Peatman (1997)

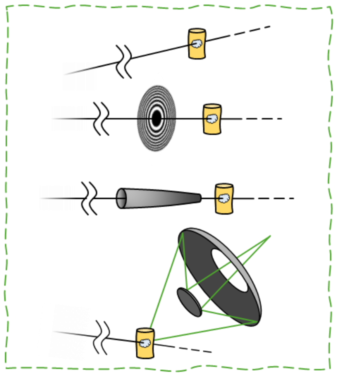
Soft x-ray beamline: optics in the experimental station



The optics in the experimental hutch are **not** often **included** in the **beamline design** and are **subjected** to a **separate calculation.** Their **choice** is directly **related** to the experimental **technique**:

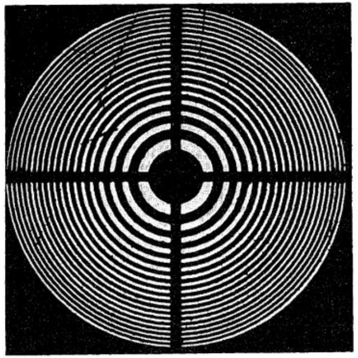
- x-ray focusing (or condensing) into the sample;
- collection of x-rays from the sample;
- as both a condenser and objective lenses.

Soft x-ray beamline: optics in the experimental station



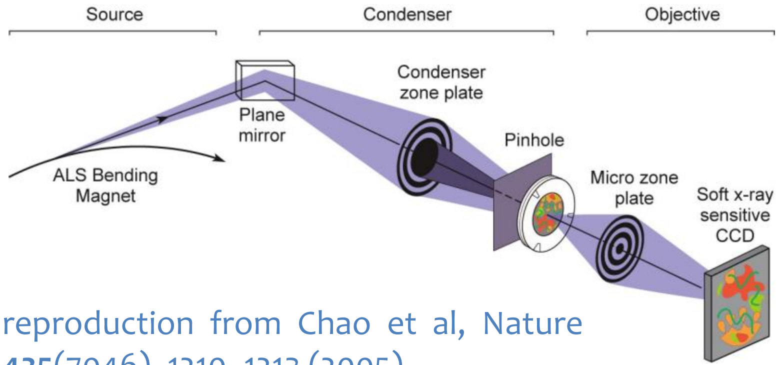
The optics in the experimental hutch are **not** often **included** in the **beamline design** and are **subjected** to a **separate calculation**. Their **choice** is directly **related** to the experimental **technique**:

- Fresnel **zone plates** (diffractive)



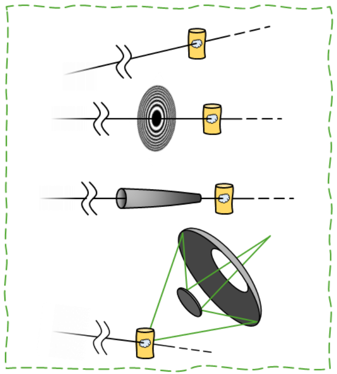
Baez, J. Opt. Soc. Am. **51**(4), 405 (1961)

reproduction from "*x-ray-optics.de*" by Last (2025) based on Jefimovs et al, J Synchrotron Rad **15**(1), 106–108 (2007).



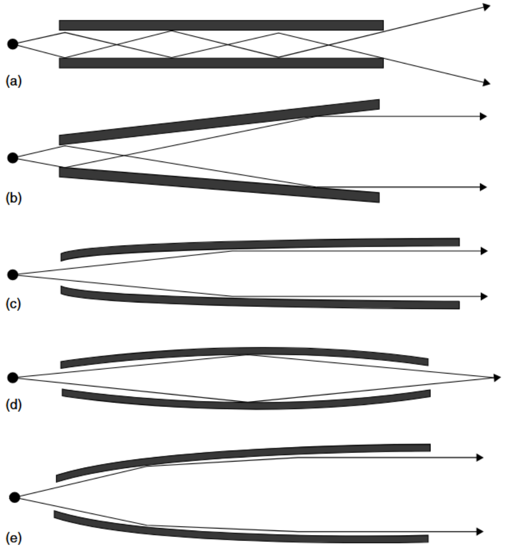
reproduction from Chao et al, Nature **435**(7046), 1210–1213 (2005).

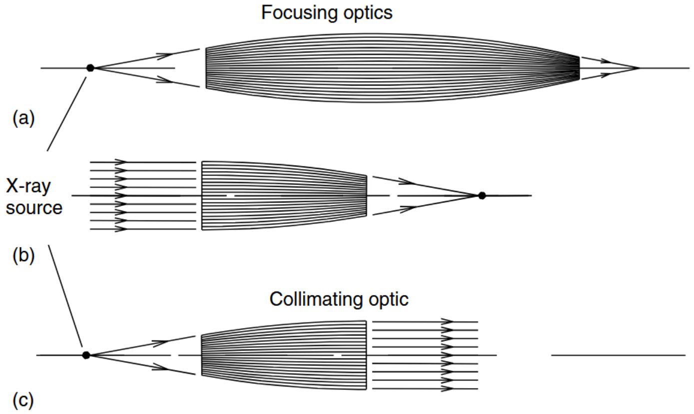
Soft x-ray beamline: optics in the experimental station



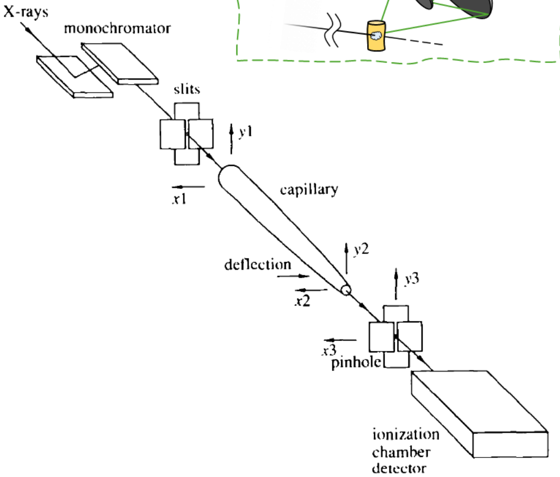
The optics in the experimental hutch are **not** often **included** in the **beamline design** and are **subjected** to a **separate calculation**. Their **choice** is directly **related** to the experimental **technique**:

- (mono/poli) **capillary** optics (reflective)



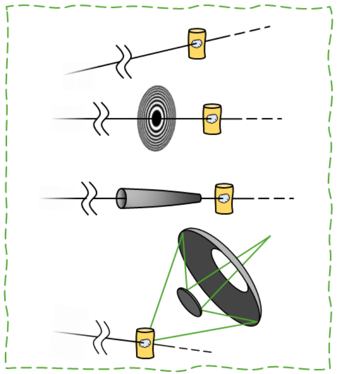


Yanagihara et al, "X-Ray Optics," X-Ray Spectrometry: Recent Technological Advances 63–131 (2004).



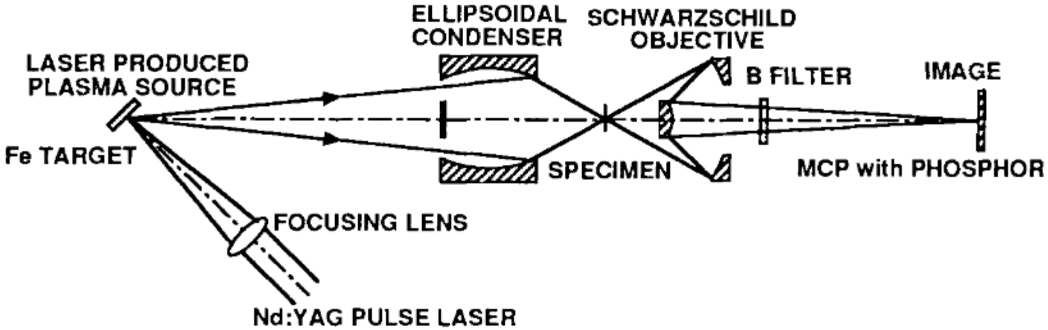
Balaic et al, J Synchrotron Rad **2**(6), 296–299 (1995).

Soft x-ray beamline: optics in the experimental station

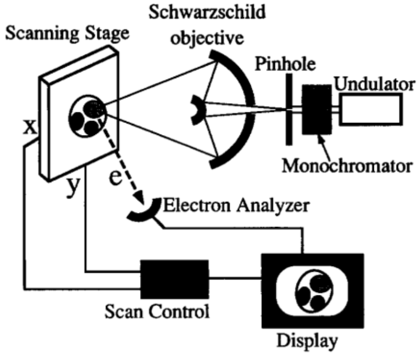


The optics in the experimental hutch are **not** often **included** in the **beamline design** and are **subjected** to a **separate calculation**. Their **choice** is directly **related** to the experimental **technique**:

- Schwarzschild/Cassegrain (reflective)

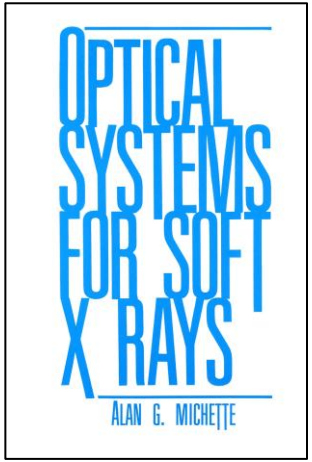


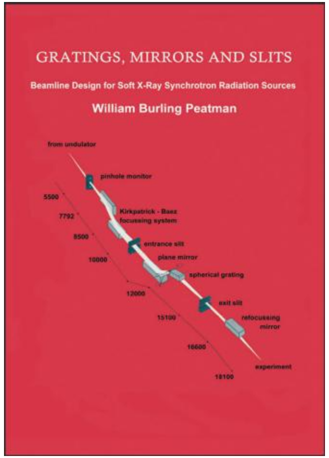
Horikawa et al, Journal of Microscopy **172**(3), 189–194 (1993).

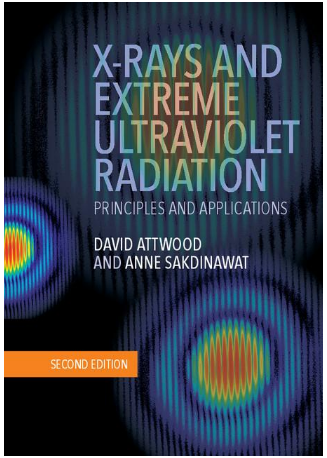


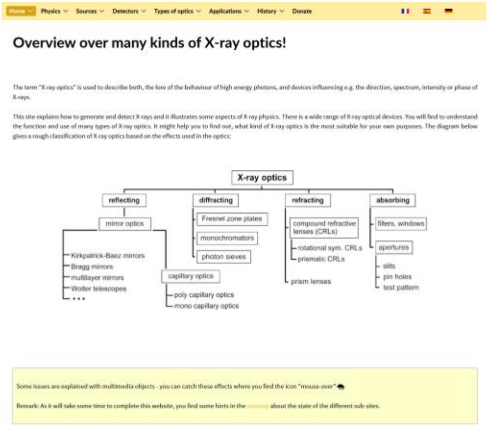
Capasso et al, Surface Science **287–288**, 1046–1050 (1993).

Where to learn more?









http://www.x-ray-optics.de

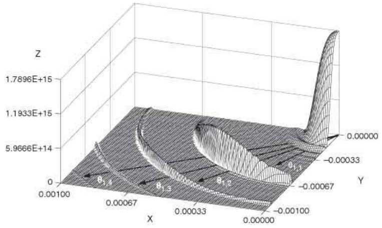
RESEARCH ARTICLE | APRIL 01 1989

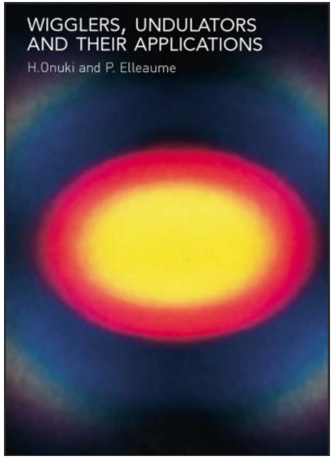
Characteristics of synchrotron radiation

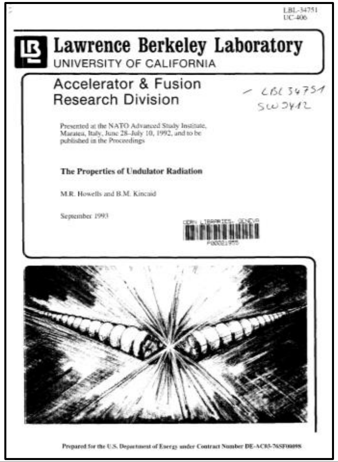
Kwang-Je Kim

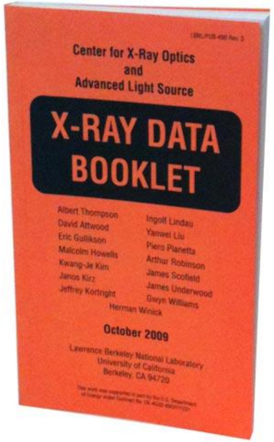
AIP Conf. Proc. 184, 565–632 (1989)

https://doi.org/10.1063/1.38046









Thank you!