Synchrotron Radiation Instrumentation

Dr. Ray BARRETT (barrett@esrf.fr)
X-ray Optics Group Leader,
ESRF

PIONEERING SYNCHROTRON SCIENCE

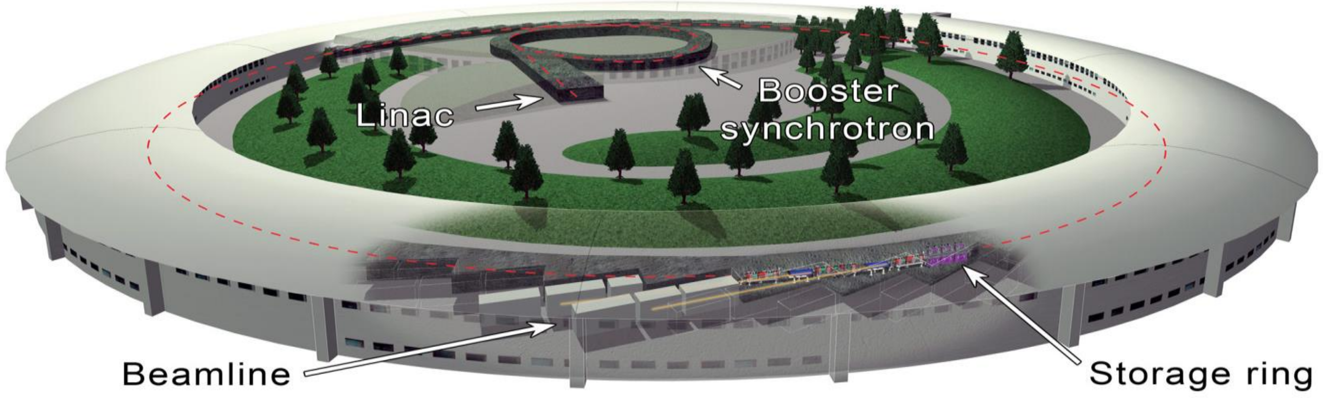
ESRF
The European Synchrotron

30 years of science

- What do we mean by instrumentation?

- Optics & Optomechanical Systems
- Sample Environments
- Thermal Management
- Detectors
- Integrated end-stations

Acknowledgements:
P. Fajardo, A. Goetz, P. Marion, J. Meyer & many colleagues from ESRF Instrument Support and Development Division (ISDD).



All the building blocks of a synchrotron beamline

- Source producing the X-rays
- Optics and optomechanics: conditioning and manipulating the X-ray beam
- Sample positioning and environments: placing the sample in the beam and subjecting to external stimuli
- Detectors
- Control software – and increasingly data analysis software

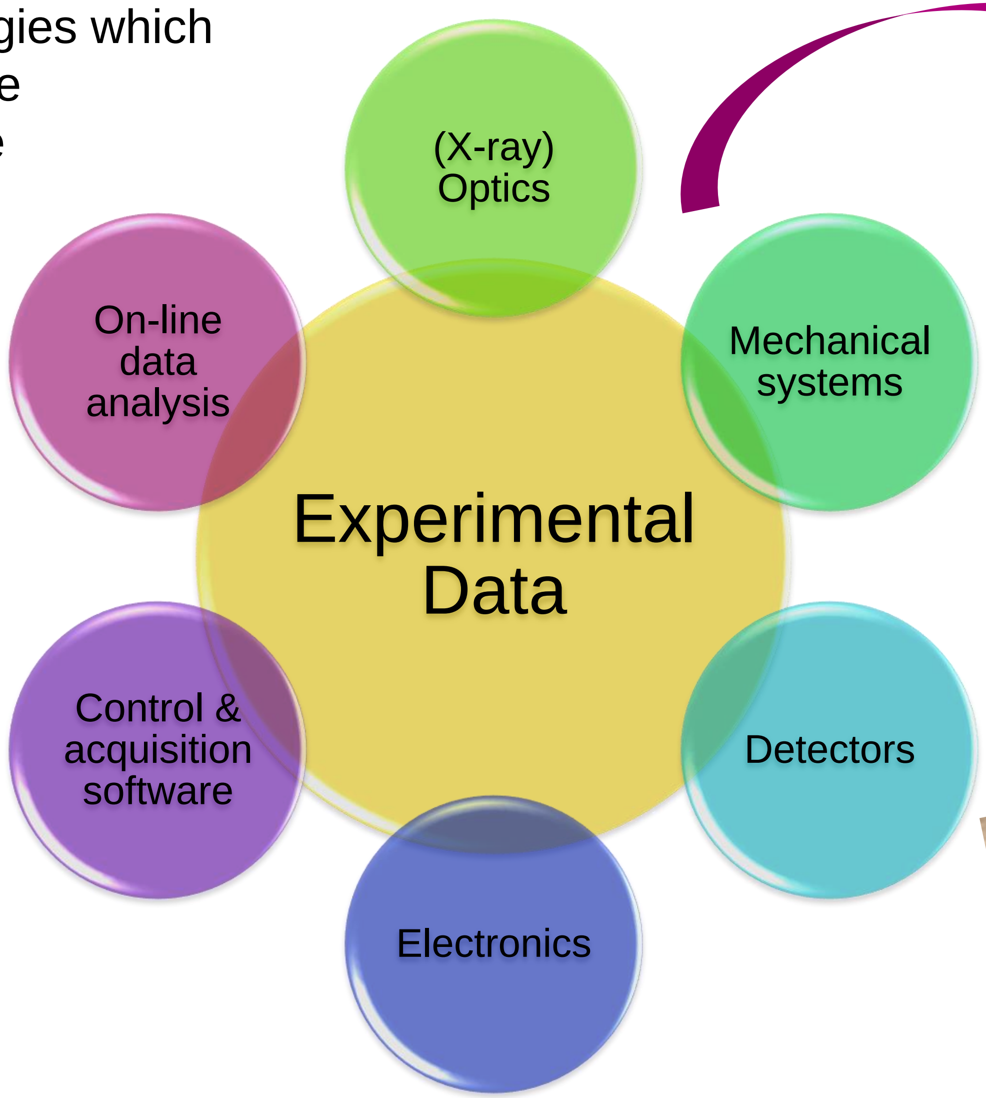
Synchrotron X-ray sources *cf* classical laboratory sources

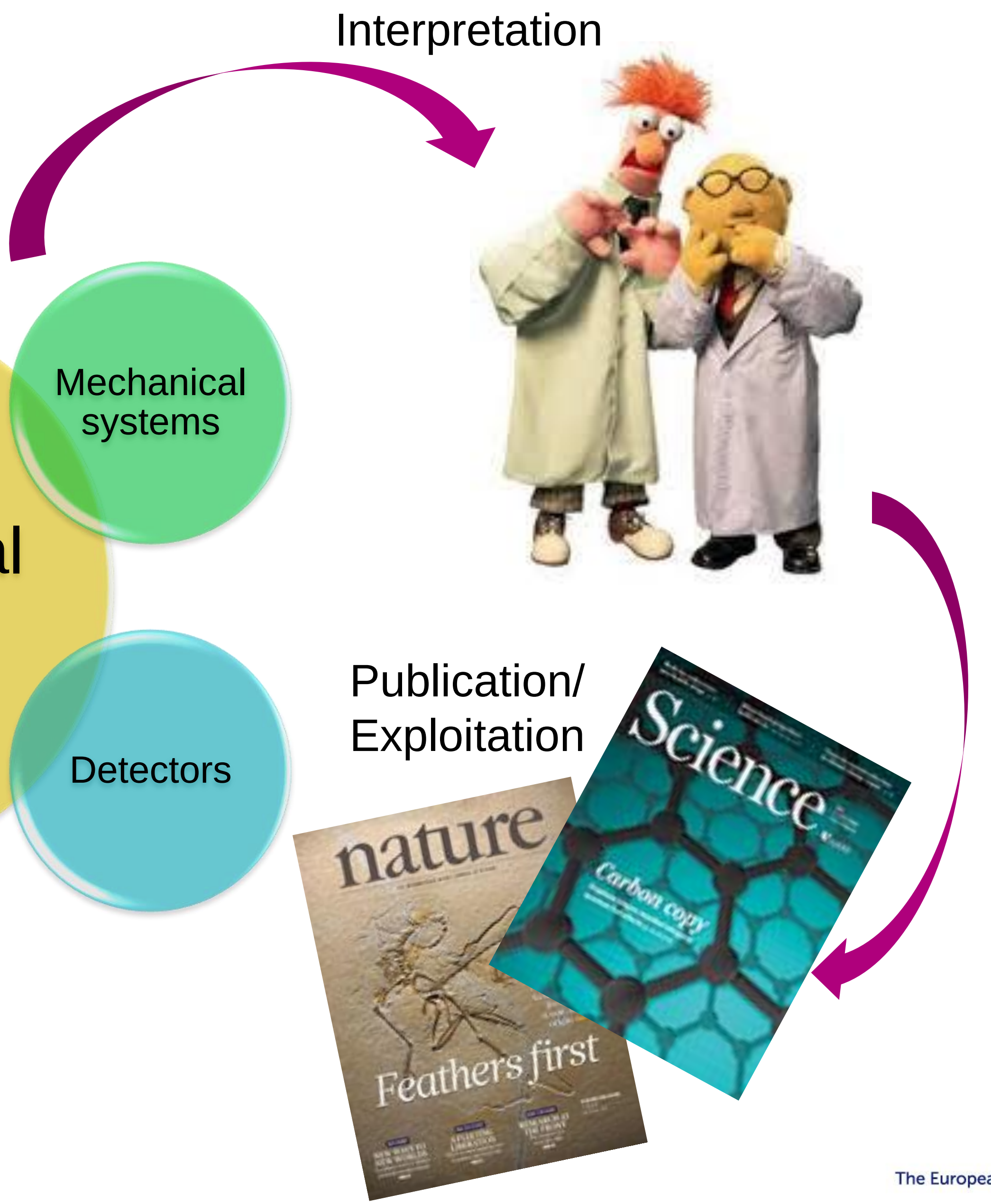
- Limited physical access (due to radiation shielding, vacuum)
- Flux orders of magnitude faster – dynamic experiments
- Pseudo-continuous spectrum – energy scanning
- Small beams
- Pulsed source
- Multiple users (often inexpert in the technique)
- Large instruments with high user demand – short beamtime with high data rates

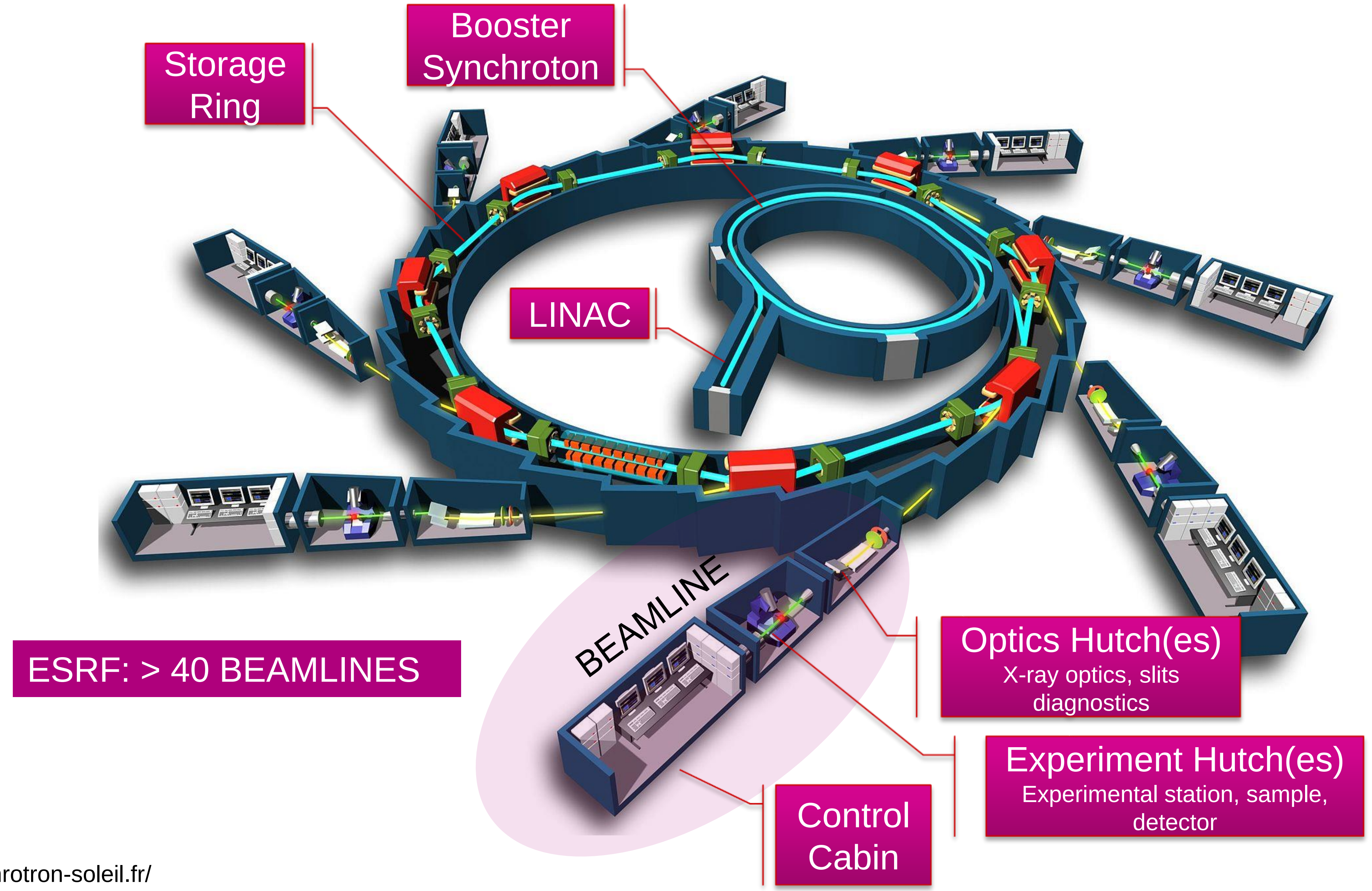
WHAT DO WE MEAN BY X-RAY INSTRUMENTATION AT A SR SOURCE?

Synchrotron Instrumentation:

- Enabling technologies which should optimize the experimental cycle







http://www.synchrotron-soleil.fr/

A TYPICAL BEAMLINE LAYOUT

Lead Radiation shielding

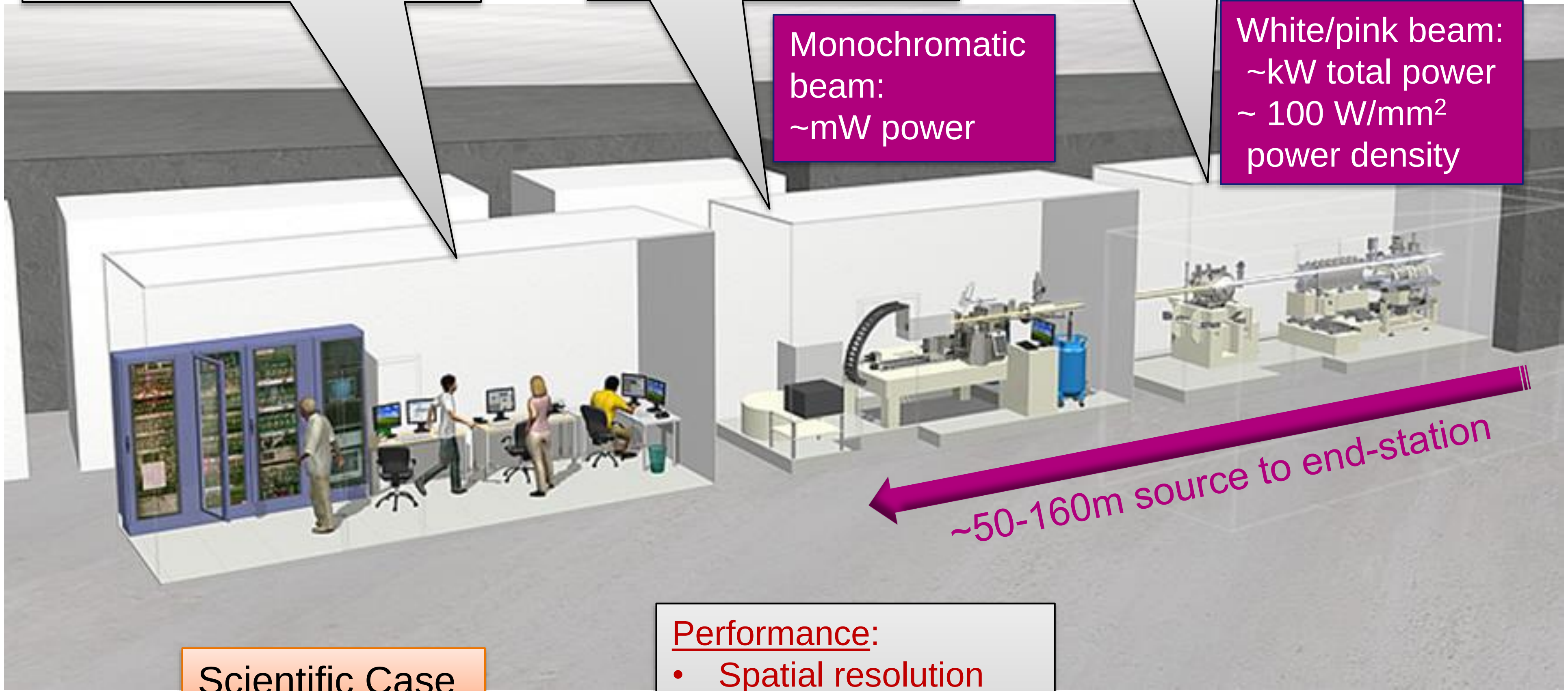
Data & control cabin

Experiment hutch

Optics hutch

Monochromatic beam:
~mW power

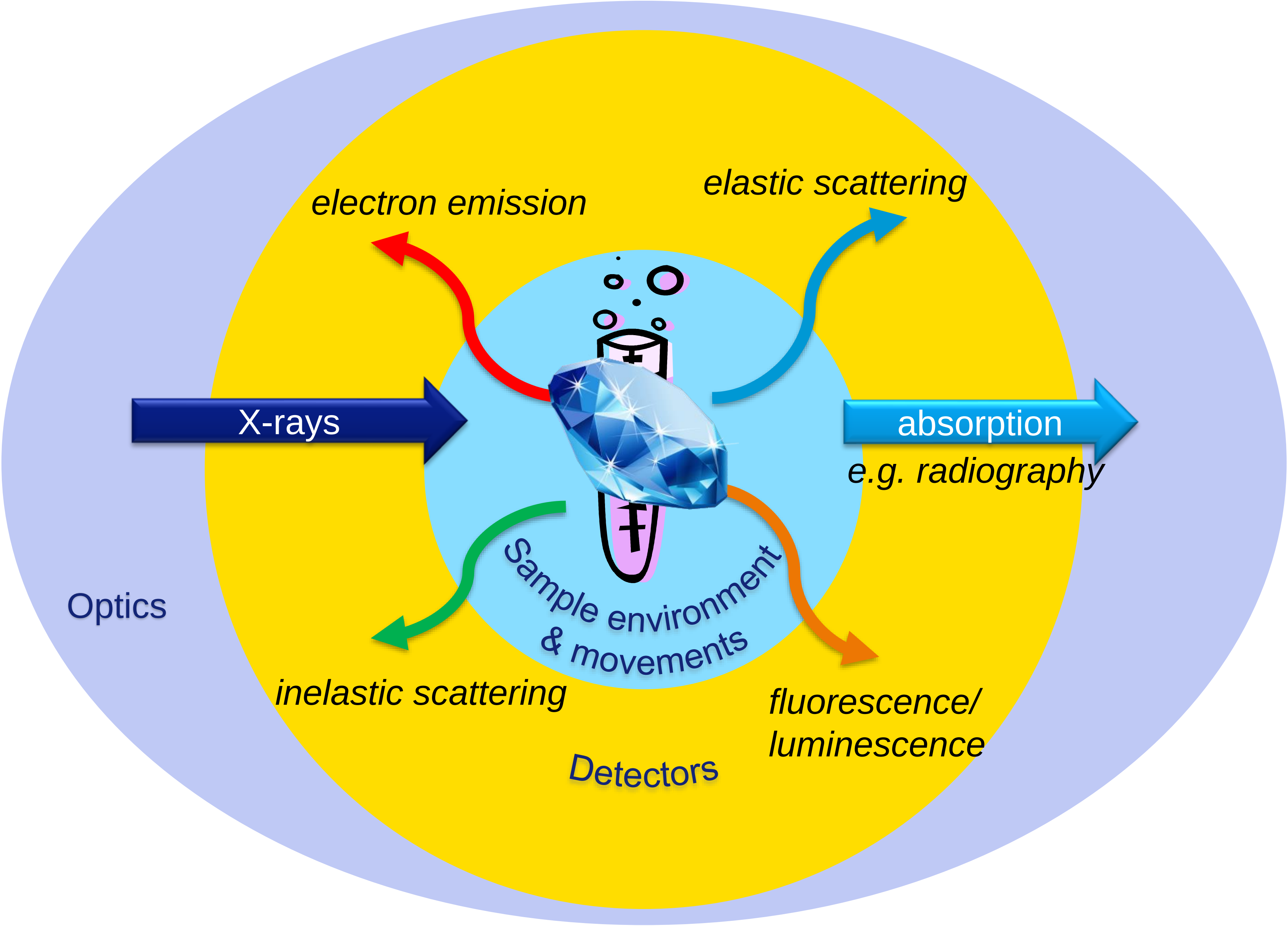
White/pink beam:
~kW total power
~ 100 W/mm^2
power density



Scientific Case

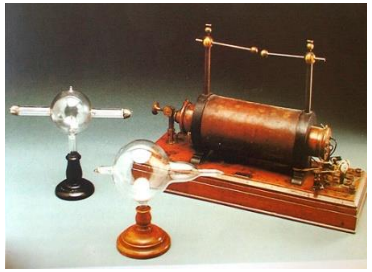
Performance:

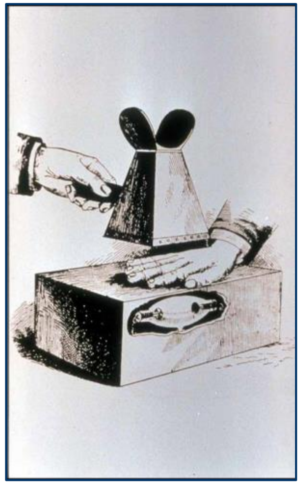
- Spatial resolution
- Spectral resolution
- Time resolution
- 1D→ 2D→ 3D → 4D
- High throughput


electron emission
elastic scattering
X-rays
absorption
e.g. radiography
Sample environment
& movements
Optics
inelastic scattering
fluorescence/
luminescence
Detectors

X-RAY INSTRUMENTATION: RÖNTGEN'S ORIGINAL WORK (1895)

after W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, 137, (1895)
English translation in Nature 53, (1996)





- "... The refractive index.... cannot be more than 1.05 at most.... X-rays cannot be concentrated by lenses…." — optics

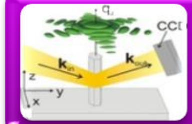
- "... Photographic plates and film are "susceptible to x-rays", providing a valuable means of recording the effects..." — detectors

- "... Detection of interference phenomena has been tried without success, perhaps only because of their feeble intensity..." — diffraction

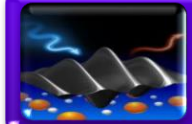
DIVERSITY OF APPLICATIONS ⇒ WIDE RANGE OF INSTRUMENTATION

The ESRF groups its 40+ beamlines according to scientific application:

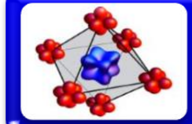
Structural biology



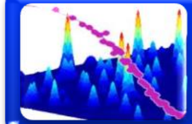
Structure of materials



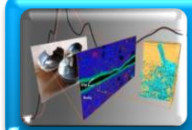
Electronic structure, magnetism & dynamics



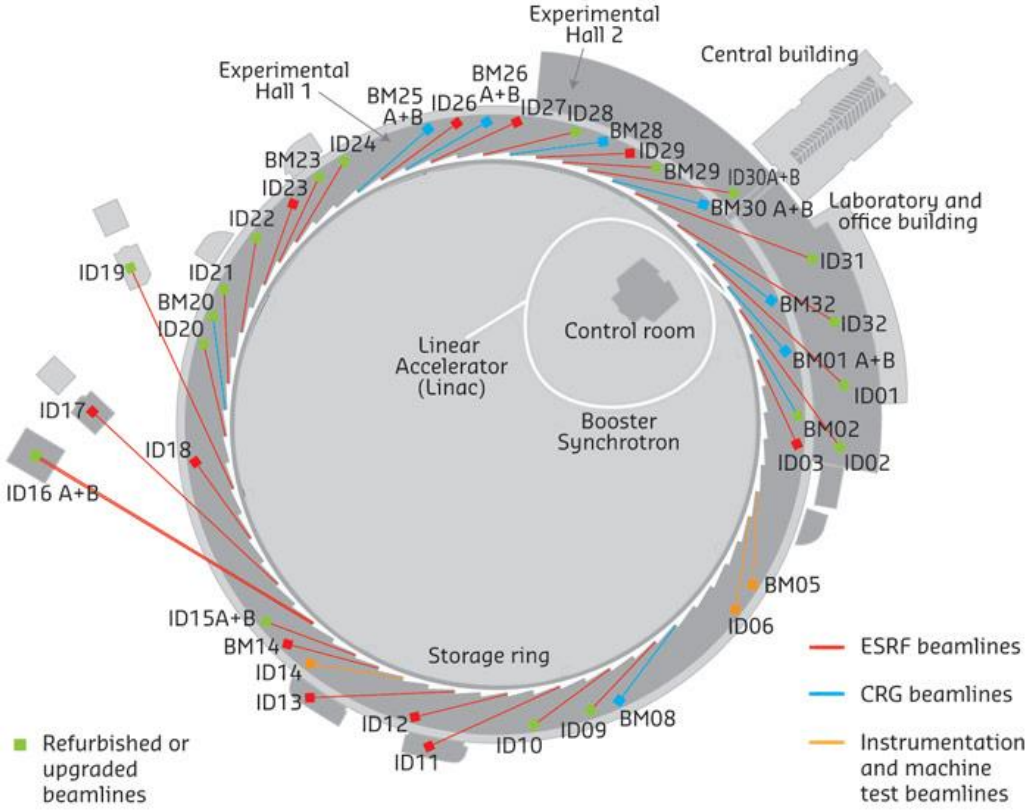
Matter at extremes



Complex systems & biomedical sciences



X-ray nanoprobes

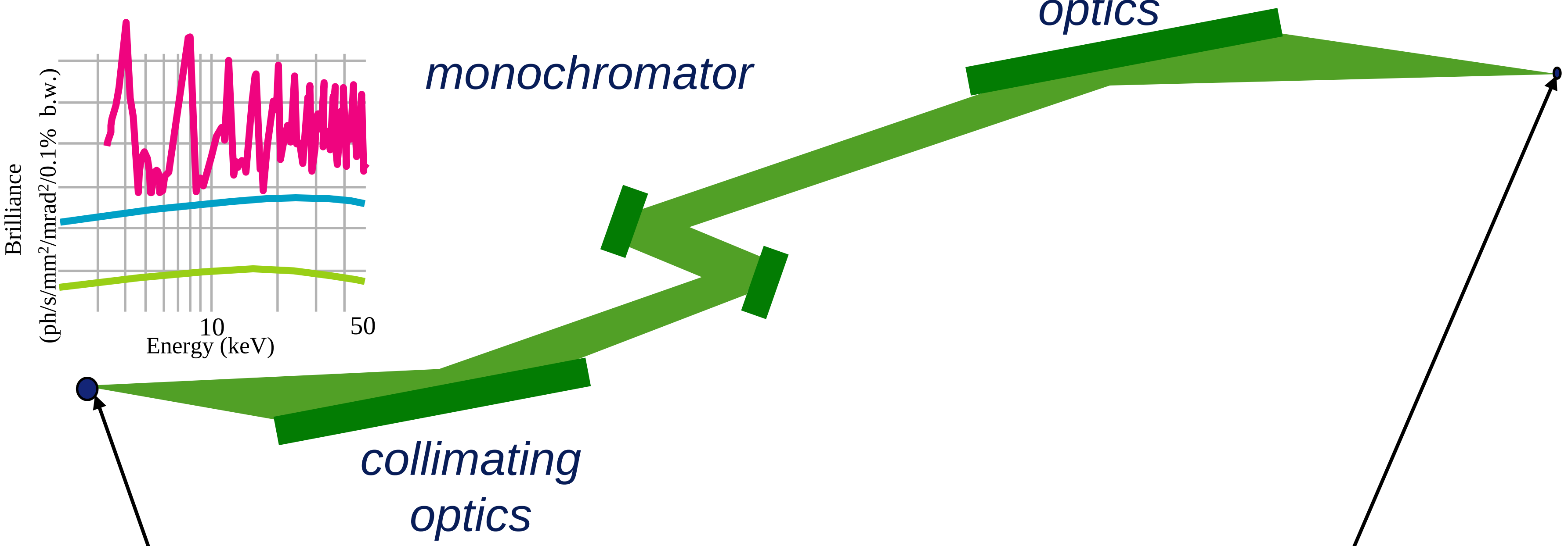


No 'standard' beamline design
– optimized for each application

X-RAY BEAMS AT 3RD AND 4TH GENERATION SR SOURCES

- Beam size
  - Unfocused: few mm to few cm (source is weakly divergent)
  - Focused beam: < 50 nm to ~10's μm
- Energy range/tunability
  - 0.1 eV < E < 0.5 MeV (at ESRF mostly 3-100 keV ≊ 4-0.125 Å)
- Energy bandwidth (ΔE/E):
  - 10^{-2} to 10^{-8} at sample, typically ΔE ~ few eV @ 20keV
- Polarized radiation
  - 100% linear or circular or elliptical
- Pulsed radiation
  - Typically 50 ps pulses every ns
- High degree of coherence
- Photon Flux
  - Brilliance: 10^{22} ph/sec/mrad^2/mm^2/0.1%bw (10^{11} higher than conventional sources) $\Rightarrow$ photon flux (@ ΔE/E = 10^{-4}): 10^9-10^{14} ph/s
  - Extremely variable photon rates on detectors (< 1 ph/s to full beam flux)
- Power
  - Several kW total power, several 100 W/mm^2 power density (white beam)

Typical optical geometry



Source
- spectrum (ΔE/E)
- emittance (size x divergence)
- degree of spatial coherence
- brilliance (ph/s/mm^2/mrad^2/0.1%bw)
- polarisation (linear, circular, elliptic)

OPTICS
?

Sample
- beam size (μm)
- beam divergence (μrad)
- flux (ph/s)
- temporal coherence: ΔE/E
- spatial coherence
- polarisation

X-RAY OPTICS: MANY POSSIBLE APPROACHES

"... The refractive index.... cannot be more than 1.05 at most....
....X-rays cannot be concentrated by lenses..."

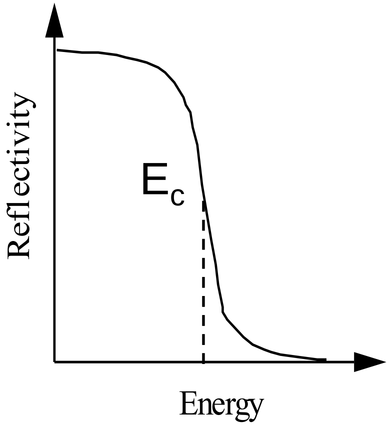
W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, **137**, p. 41, (1895)
*English translation in Nature **53**, p. 274*

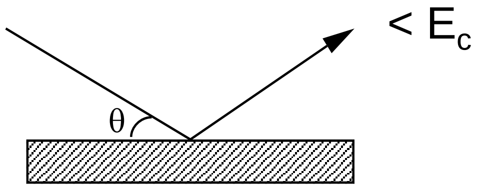
$n=1-\delta+i\beta$ with $\delta, \beta \lll 1$

δ (phase-shift), β (absorption), materials (and energy) dependent optical constants

- Very weak refraction
- Quite high absorption

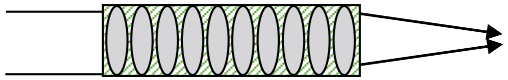
REFLECTION





- X-ray mirrors
- Capillaries
- Waveguides

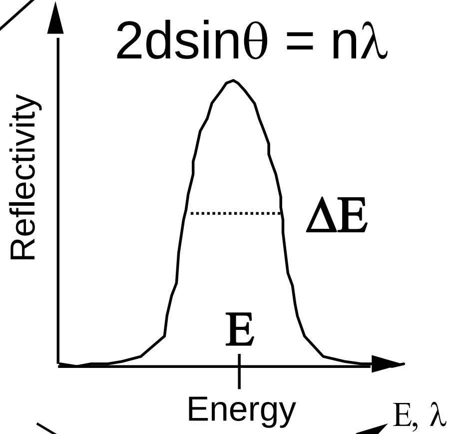
REFRACTION

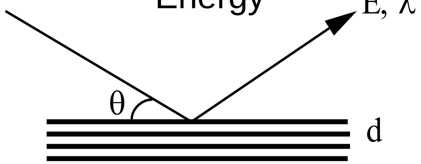


- Refractive lenses

DIFFRACTION

$2d\sin\theta = n\lambda$

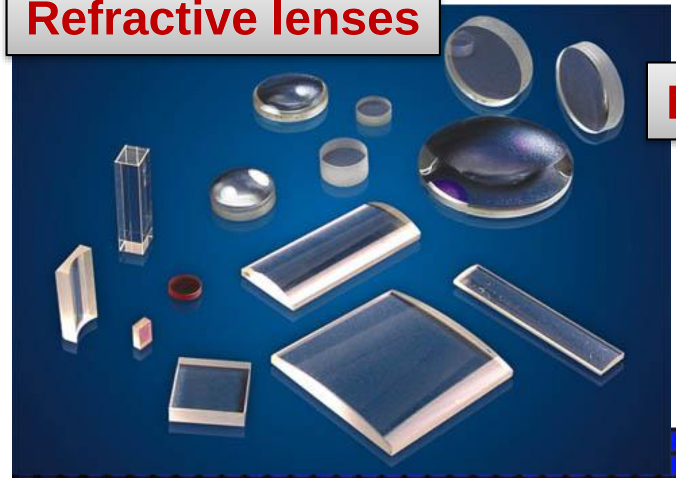




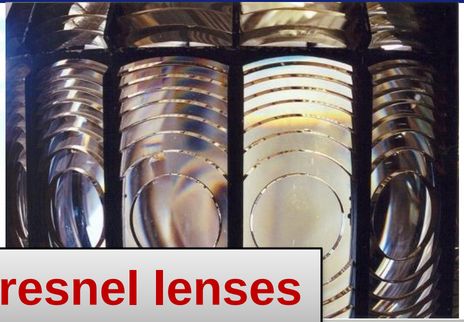
- Crystals & multilayers
- X-ray gratings
- Fresnel zone plates
- Bragg-Fresnel lens

VISIBLE LIGHT OPTICS

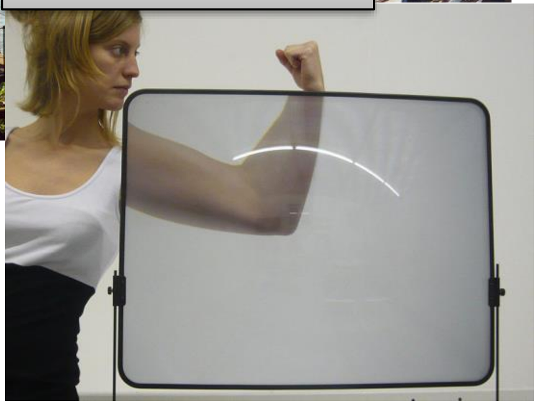
Refractive lenses



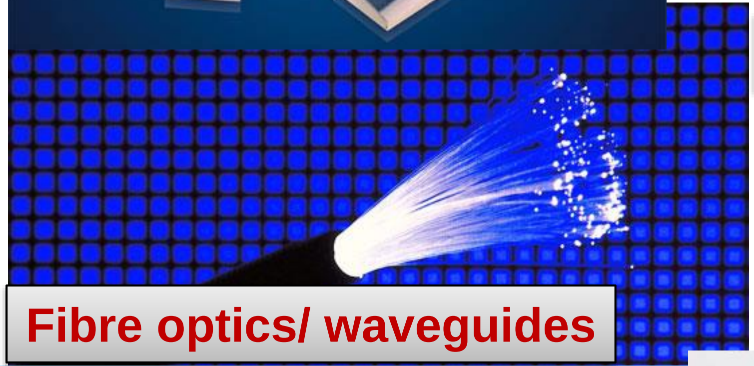
Polarising Optics



Fresnel lenses

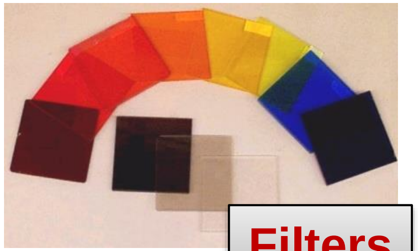


Diffractive optics



Fibre optics/ waveguides

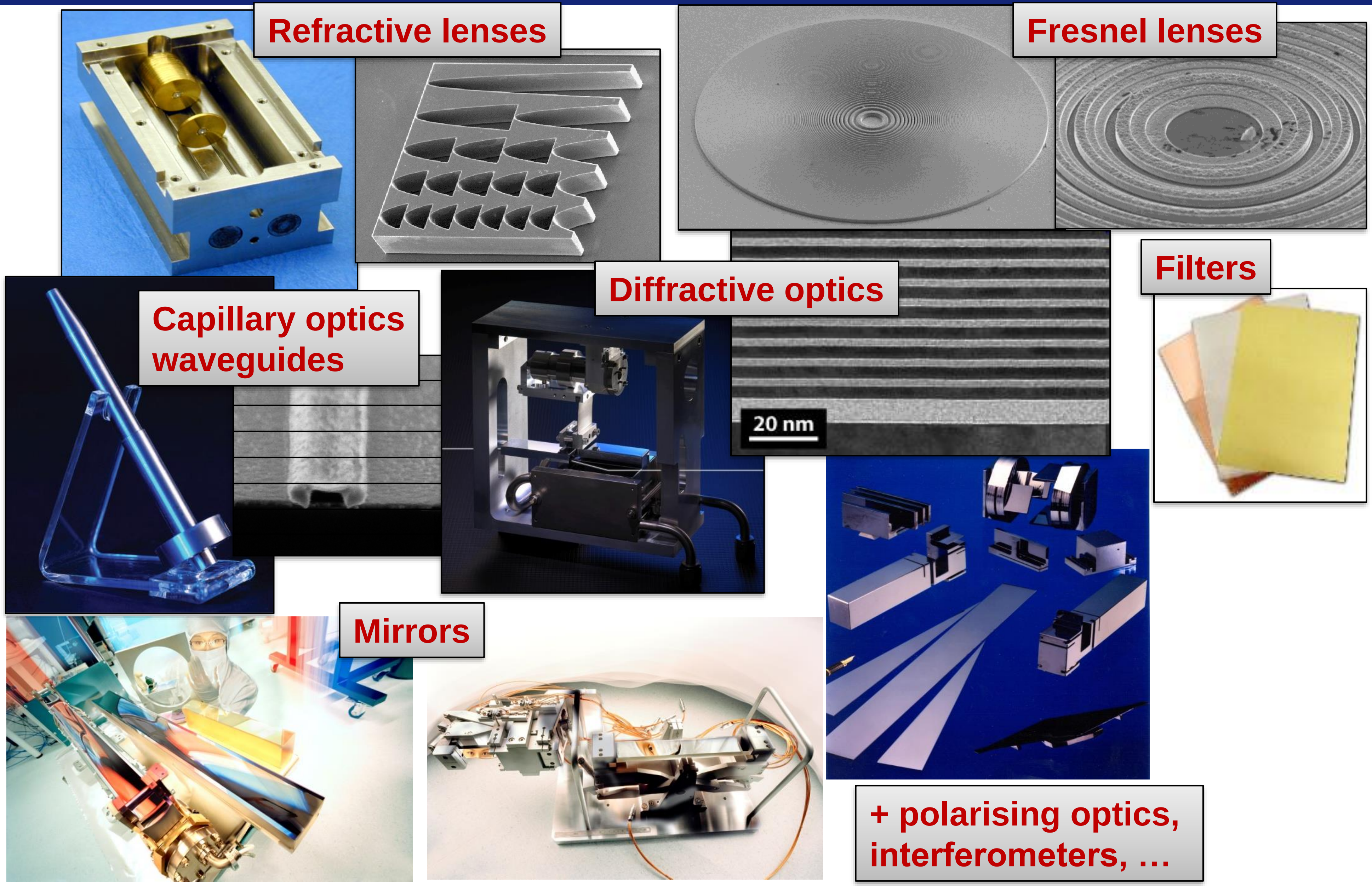
Mirrors

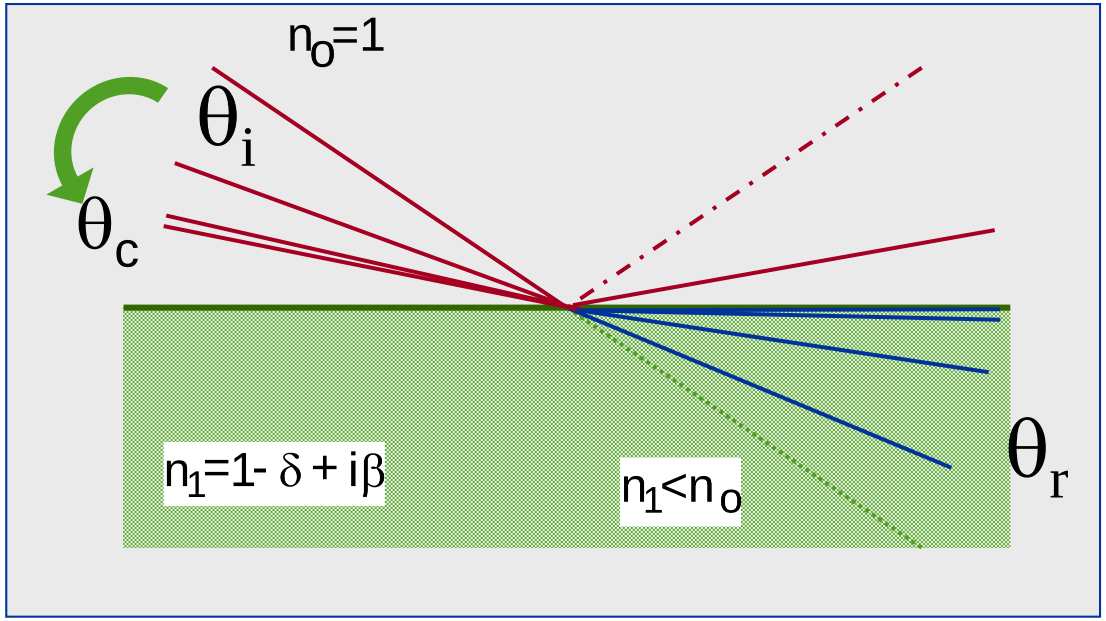


Filters

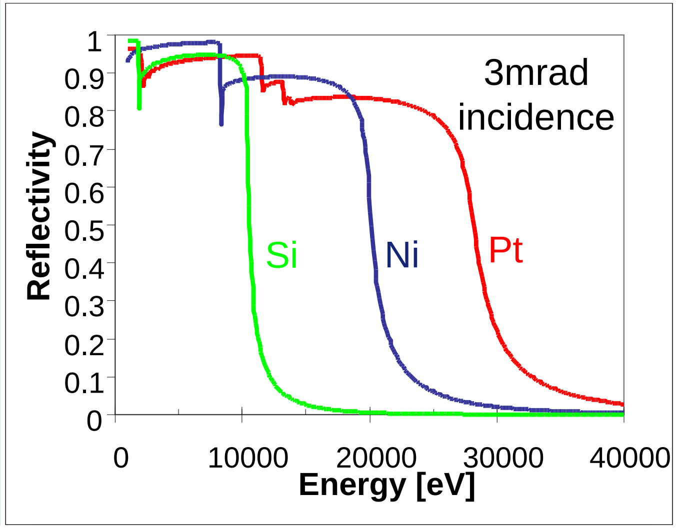
+ interferometers, …

X-RAY OPTICS


Refractive lenses
Fresnel lenses
Filters
Diffractive optics
Capillary optics
waveguides
20 nm
Mirrors
+ polarising optics,
interferometers, …



'real' materials



Snell's Law:

$$n_o \cos\theta_i = n_1 \cos\theta_r$$

for $\delta << 1$ and $\beta << \delta$

$$\theta_c \approx \sqrt{2\delta} \propto \lambda\sqrt{Z}$$

The critical angle for total external reflection.

$$\theta_{c_{[mrad]}} E_{c_{[keV]}} = 19.83\sqrt{\rho_{[g/cm^3]}}$$

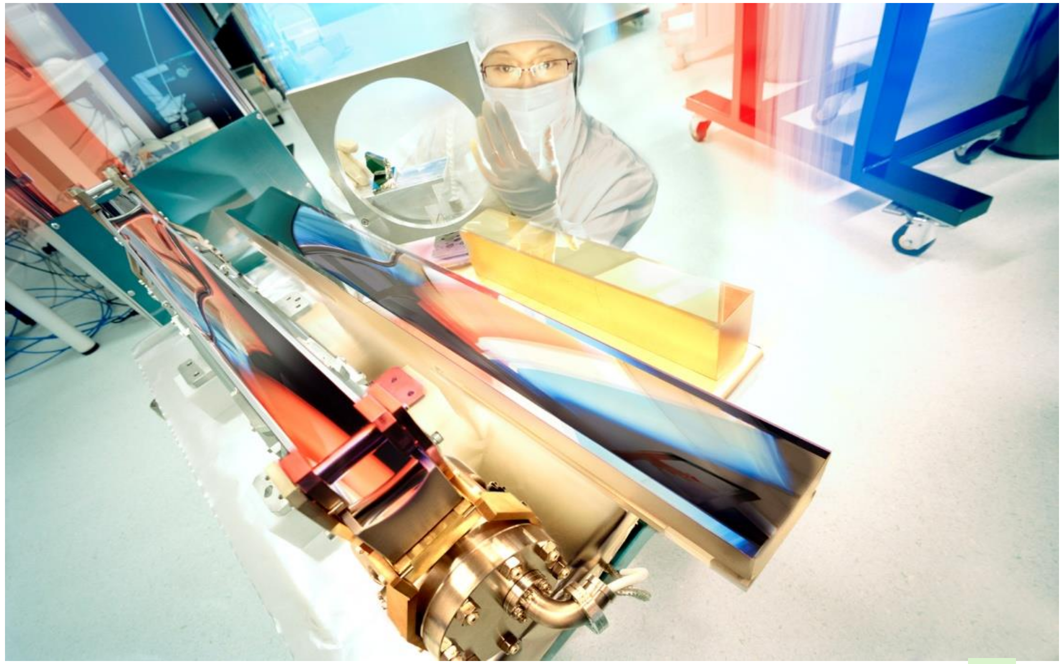
E=10keV

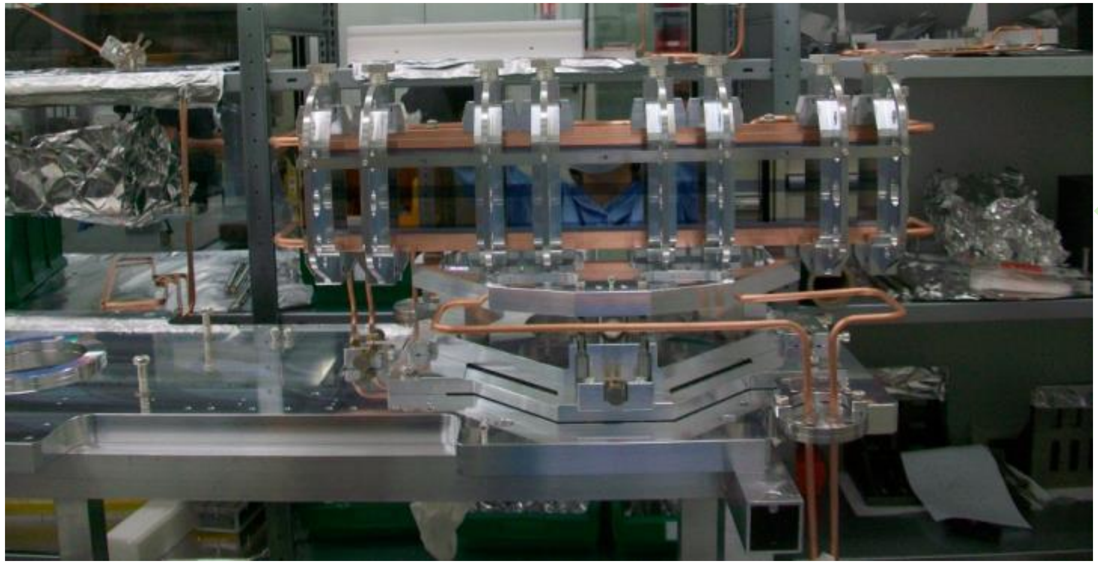
- Gold 9 mrad
- Nickel 6 mrad
- Silicon 3 mrad

- Grazing incidence ⇒ often long (gravity sag)
- Most SR mirrors manufactured from Si
- One or several coatings applied after polishing

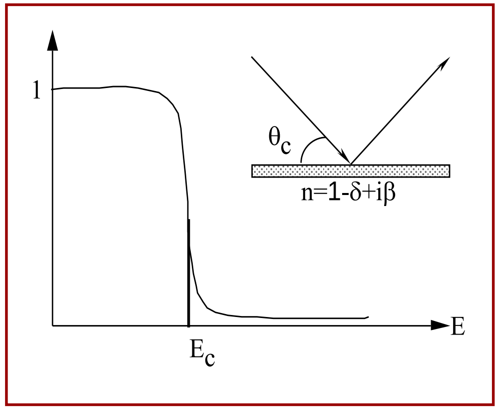
See also: http://www.coe.berkeley.edu/AST/sxreuv/

SILICON OPTICS – X-RAY MIRRORS





X-RAY MIRRORS : MAIN FUNCTIONS



•***Deflection***

beam steering (different experiments, Bremsstrahlung)

•***Power filter***

lower incident power on sensitive optical components

•***Spectral shaper***

energy low-pass filter (harmonic rejection)

mirror+filter = spectral window

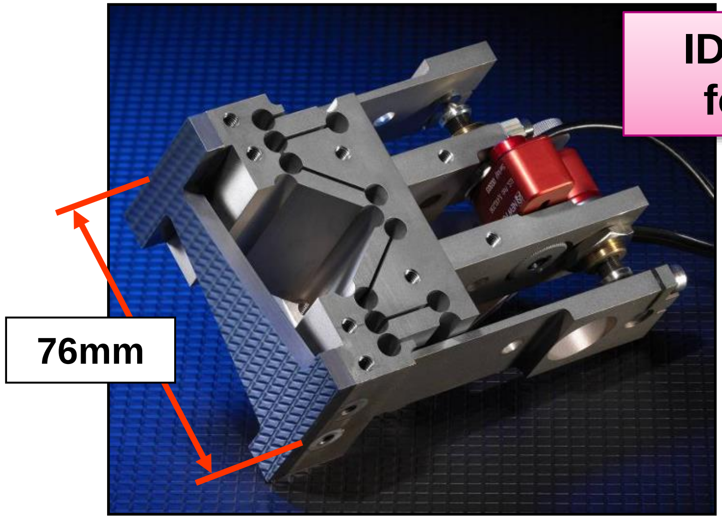
• ***Collimation or focusing – use of curved surfaces***

wiggler & bending magnet : spherical, cylindrical, and toroidal mirrors

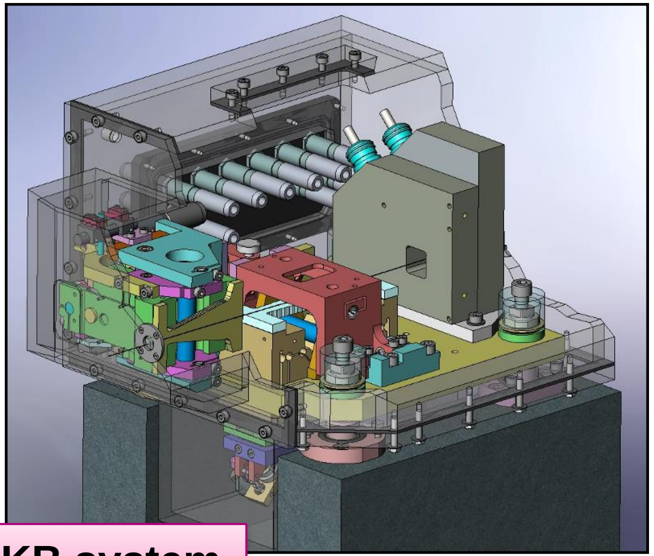
microscopy & microprobe : source demagnification (ellipsoidal mirror, Kirkpatrick-Baez mirrors…)

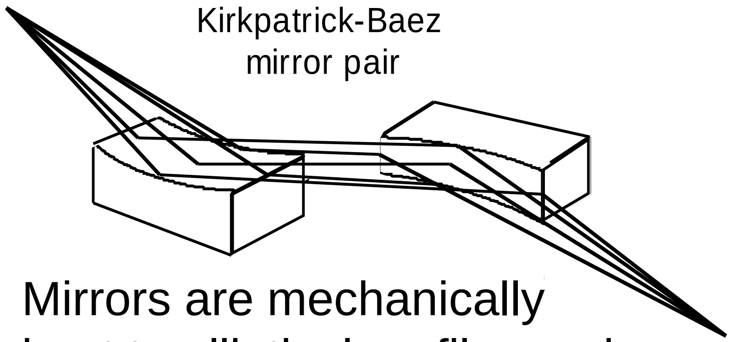
J. Susini, Optical Engineering, 34(2), (1995)

ESRF NANOFOCUSING ‘KIRKPATRICK-BAEZ’ MIRROR SYSTEM



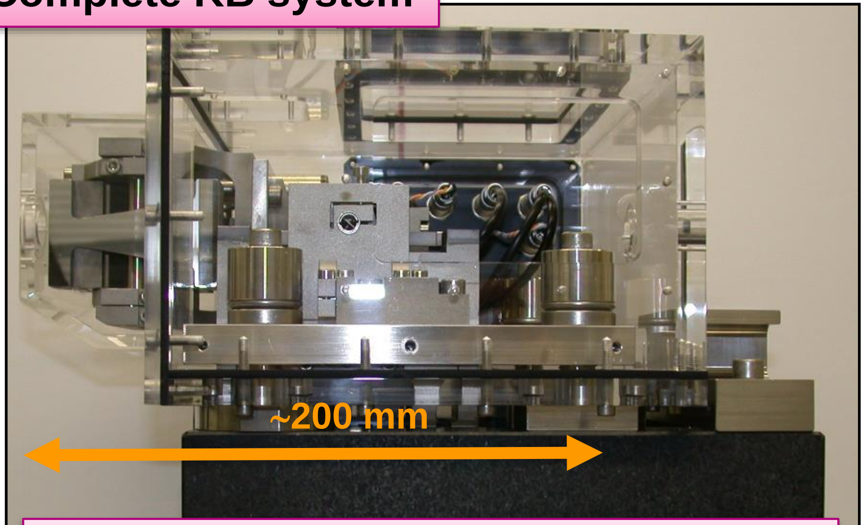
ID16B horizontally focusing bender





Mirrors are mechanically bent to elliptical profiles and focus X-rays

Complete KB system

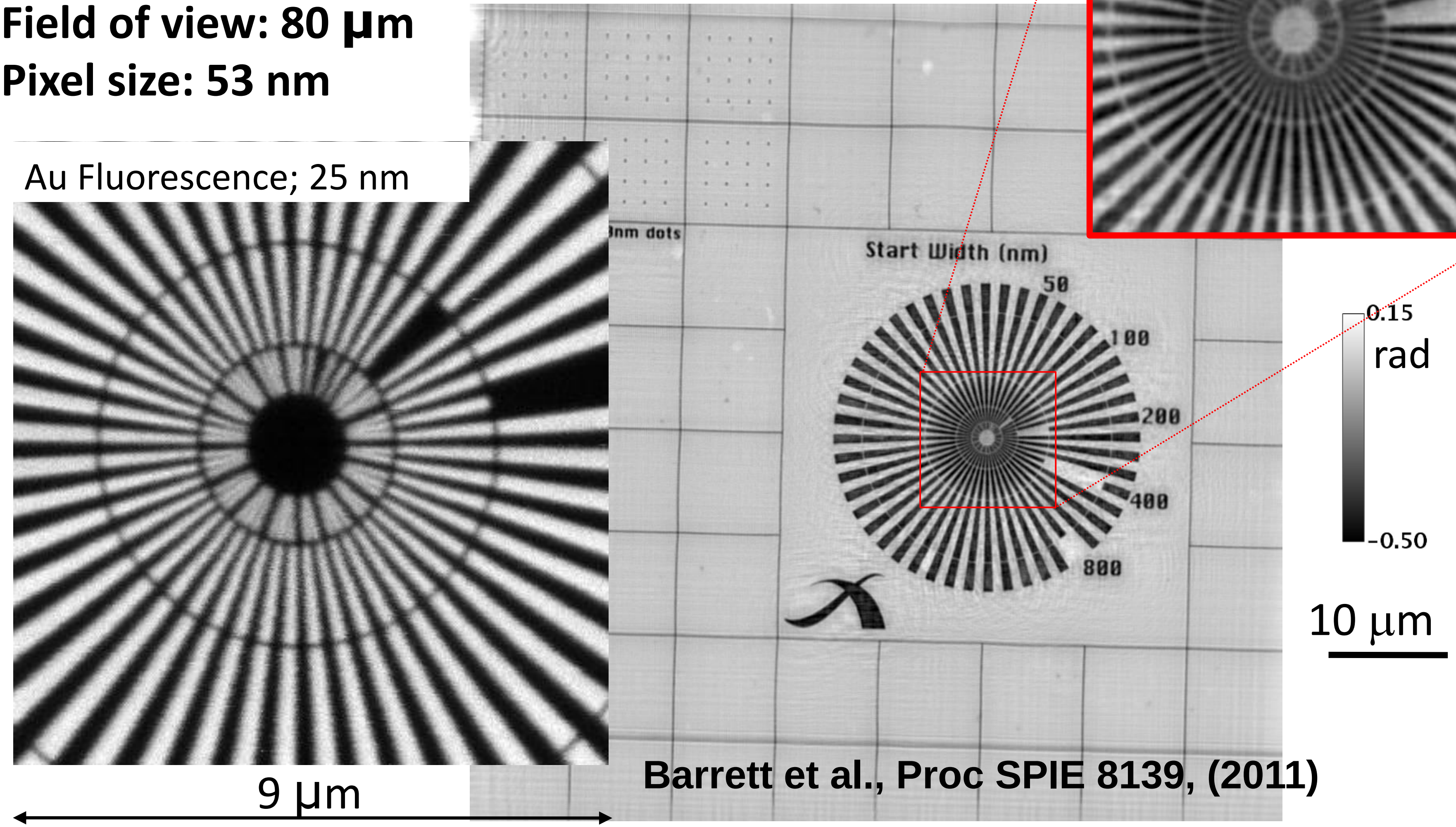


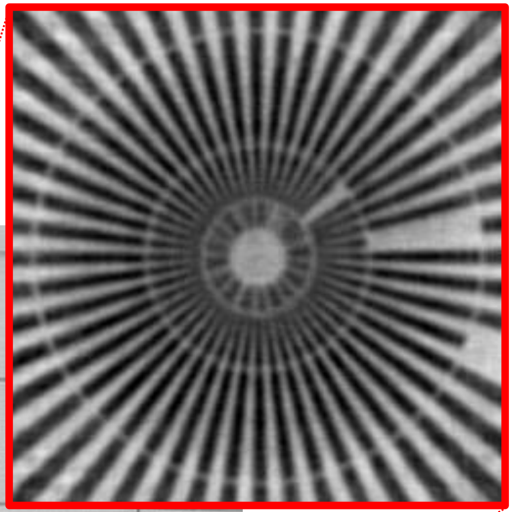
Sub 50 nm x 50 nm focus
Flux > 10^{12} ph/s (pink) on ID16B

PROJECTION MICROSCOPY USING KB OPTICS

Thin gold test pattern
Innermost line width: 50 nm
Energy = 17.3 keV
Field of view: 80 µm
Pixel size: 53 nm

Phase map

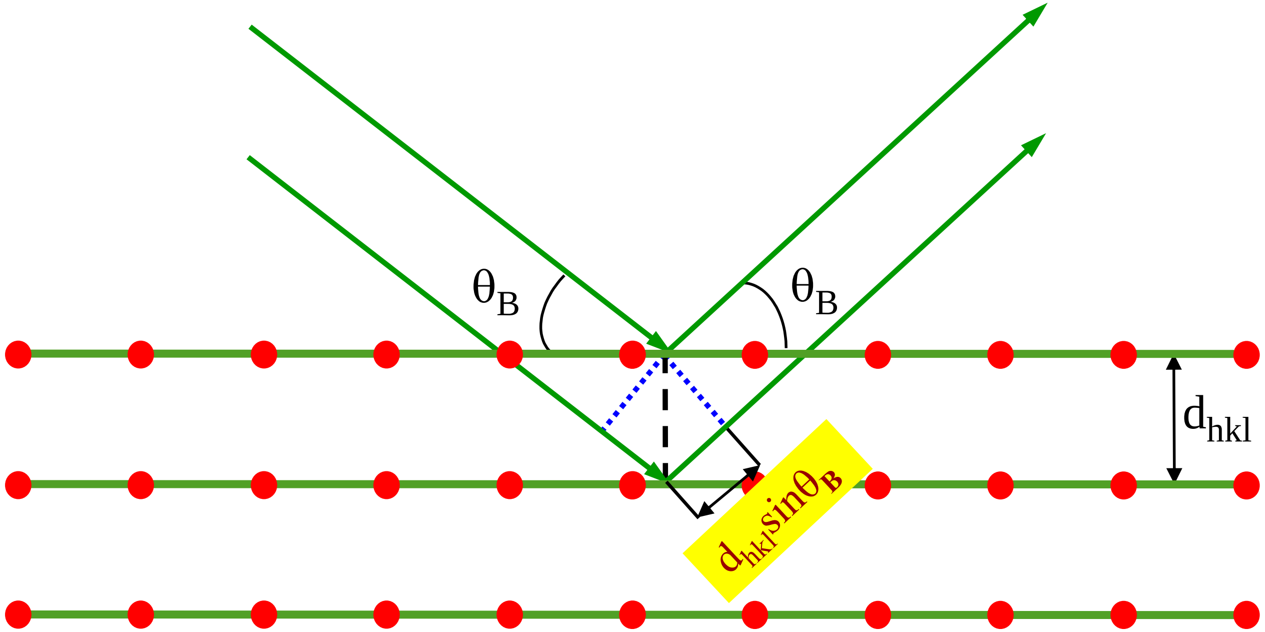




Barrett et al., Proc SPIE 8139, (2011)

X-RAY DIFFRACTION

X-ray diffraction results from elastic scattering of X-rays from structures with long-range order. For X-ray optics generally concerned with highly perfect single crystals *cf* neutron mosaic crystals



Bragg equation: $2d_{hkl}\sin\theta_B = n\lambda$

- Incident X-rays are “reflected” at atomic planes in the crystal lattice
- Path difference of the rays $2d_{hkl}\sin\theta_B$
- Constructive interference if the path difference amounts to λ (n λ?)

h k l are usually used, (e.g. 1 1 1, 3 3 3, 4 4 4), these are not Miller indices, but Laue indices, or “general Miller indices”.

CRYSTAL MONOCHROMATORS

A crystal monochromator slices out a narrow energy band by diffraction of a polychromatic incident beam.
Energy, E, determined by incidence angle, θ_B, of X-ray beam onto crystal planes according to Bragg equation:

$$E = \frac{hc}{\lambda} = \frac{hc}{2d_{hkl}\sin\theta_B}$$

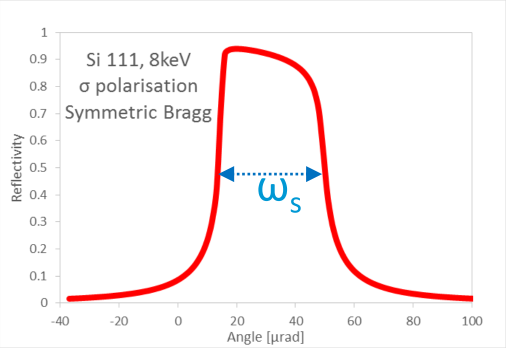
c = light velocity
h = Plancks constant

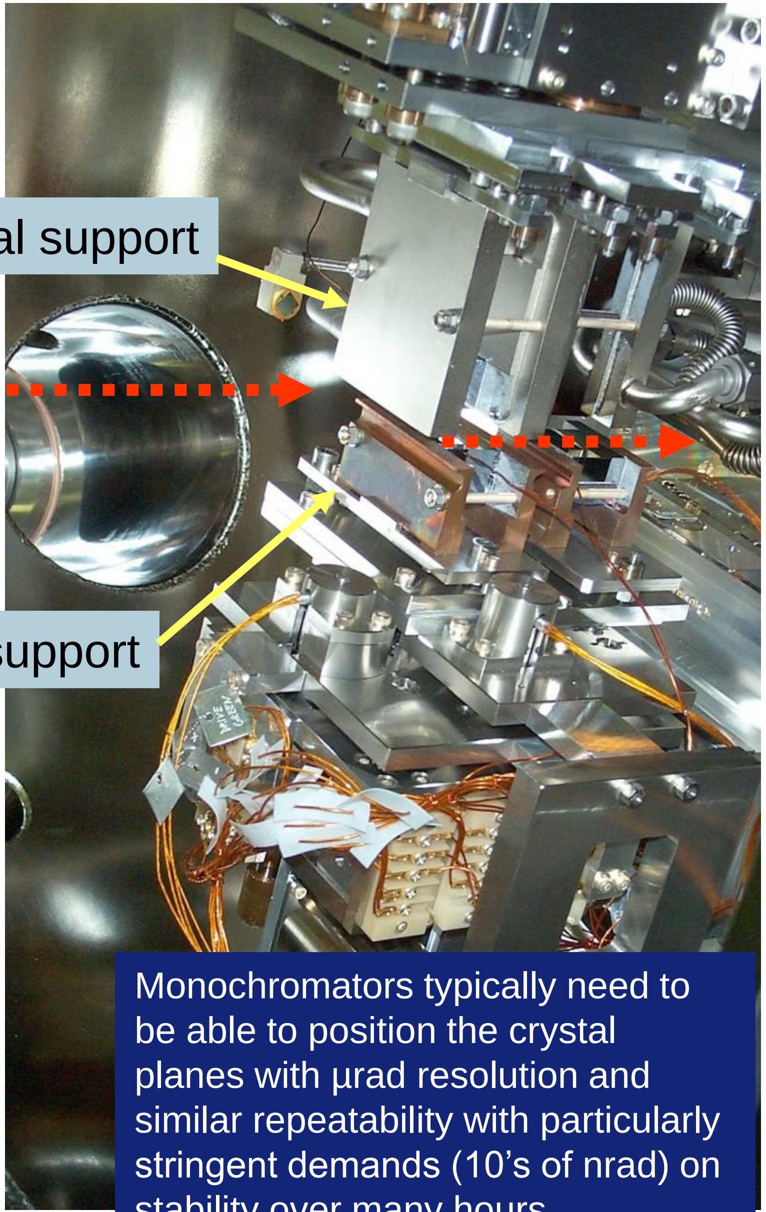
Energy width of beam depends upon type of crystal and reflecting planes used (determine Darwin width ω_s) & divergence of incident beam, ψ_0

$$\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \sqrt{\omega_s{}^2 + \psi_0{}^2}\cot\theta_B$$

e.g. **Si 111 reflexion**,
d_{hkl}= 3.1355Å
ω_s = 34 µrad (@ 8keV):

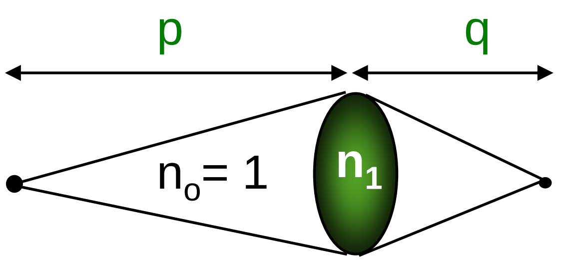
$\theta_B = 14°$
with a parallel incident beam:
$\Delta E/E = 1.4.10^{-4}$, ΔE=1.1eV





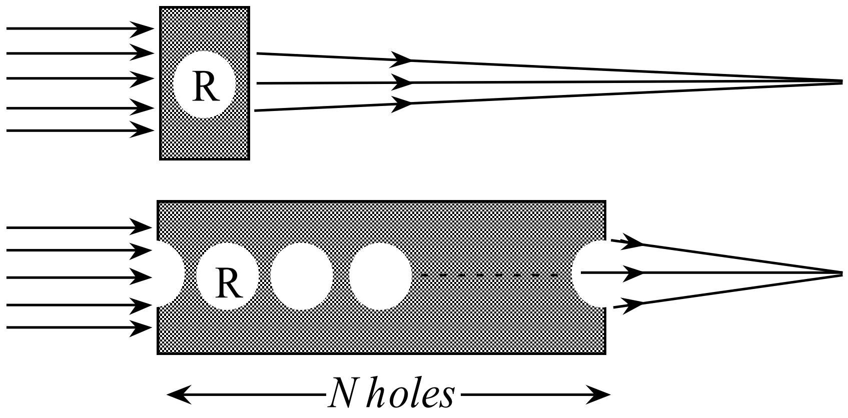
Monochromators typically need to be able to position the crystal planes with µrad resolution and similar repeatability with particularly stringent demands (10's of nrad) on stability over many hours

COMPOUND REFRACTIVE LENSES



Gaussian lens equation : $\frac{1}{f} = \frac{2(n_1 - 1)}{R}$

Thin lens equation : $\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$



$$\frac{1}{f} = \frac{2\delta}{R}$$

$$\frac{1}{f} = N\frac{2\delta}{R}$$

X-rays : $n = 1 - \delta + i\beta$

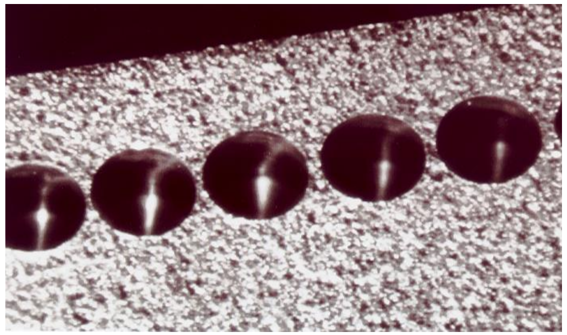
n_1< 1 : concave lens

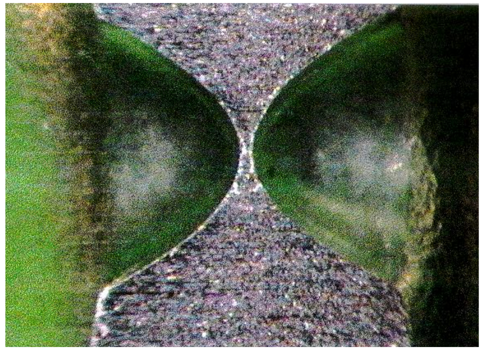
Typically Be or Al lenses – e.g.

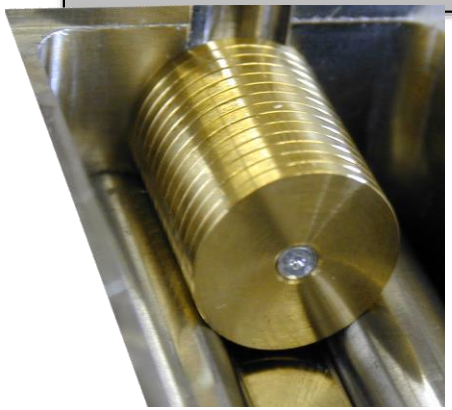
Aluminium @ 10keV $\delta = 5.5\ 10^{-6}$

1 hole 100 µm radius : f = 9 m

15 holes 100 µm radius: f = 60 cm

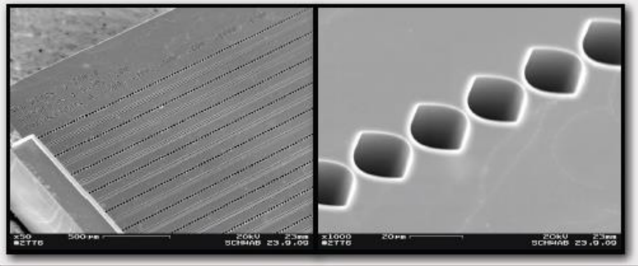






A. Snigirev et al. Nature, 384 (1996)

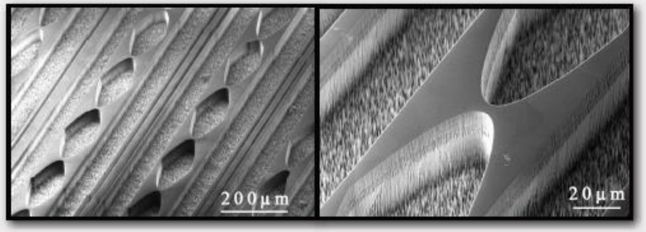
COMPOUND REFRACTIVE LENSES



new NFLs of highest quality

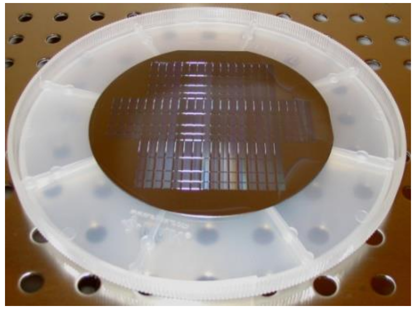
- new lens design ensures isotropic etching conditions
- reduced slope of sidewalls: <0.01 rad
- reduced roughness of surface: <20 nm rms

→ ready for AFL fabrication!

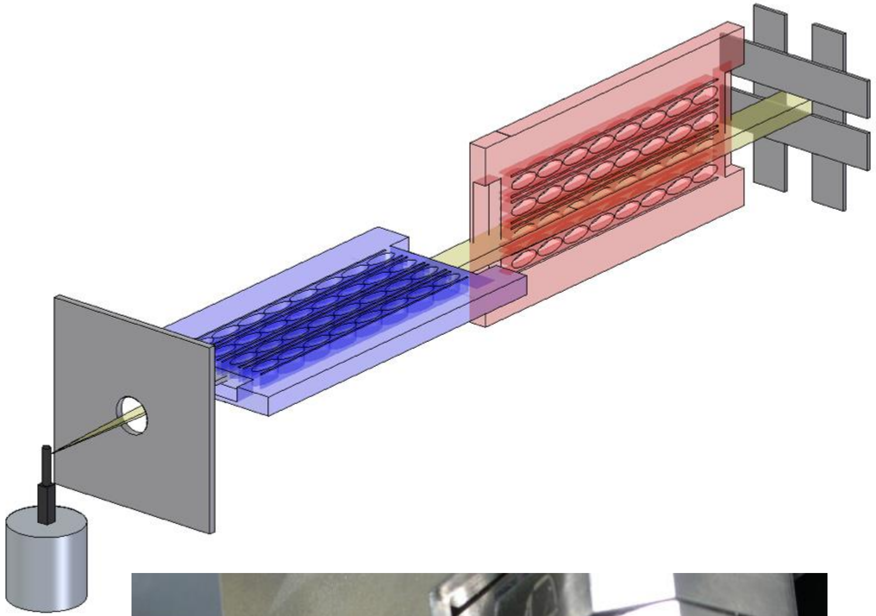


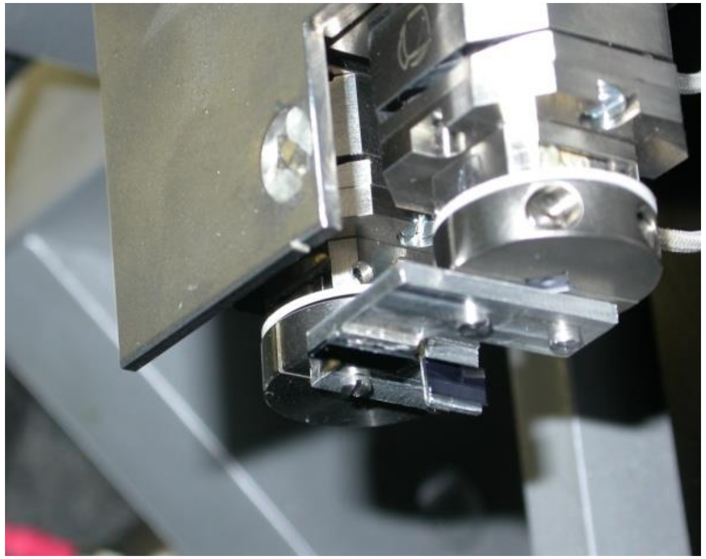
diamond lenses

- high lens shape precision
- improved deepness of structures (but still not deep enough)
- still a problem: roughness
- successfully tested in an experiment at the ESRF



3136 Silicon NFLs on wafer
about 600000 single lenses





PROGRESS IN HARD X-RAY FOCUSING

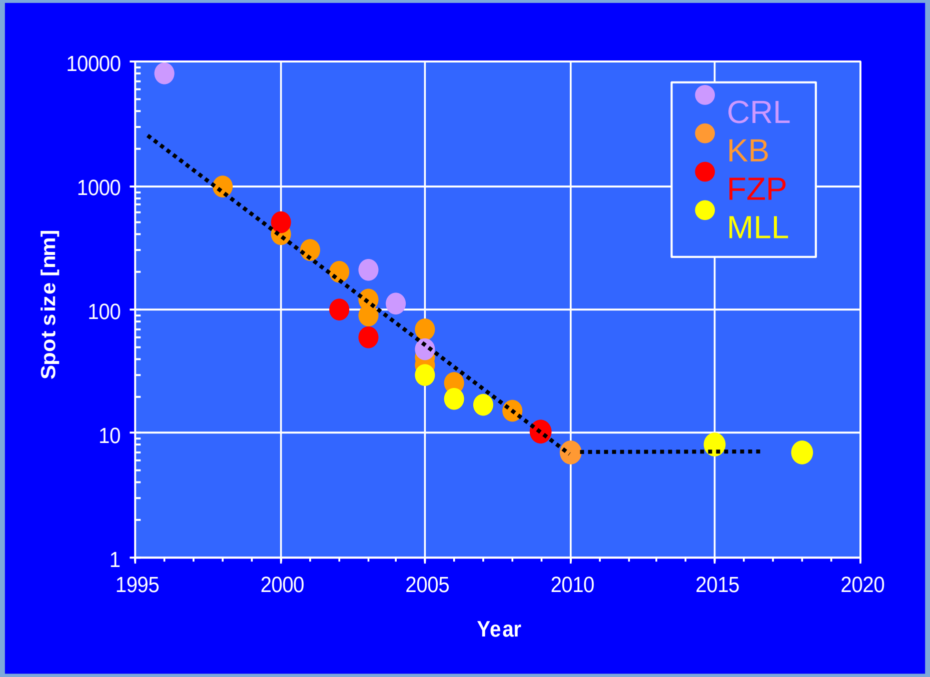
Moore's law adapted to the X-ray world:

ESRF Red Book (1987): very few beamline projects aiming even for 10 micron sized beams

Now optics exist for 10nm beams

Routine application of sub-micron beams still complicated

Also many engineering issues in implementing stable, reliable X-ray nanofocusing systems



Historical evolution of the measured spot size for different hard x-ray focusing elements *(courtesy C. Morawe)*

- A. Morgan et al. Scientific Reports, 5, 9892 (2015)
- H. Mimura *et al. Nature Physics*, **6**, 122-125 (2010).
- J. Vila-Comamala et al., Ultramicroscopy,**109**,1360–1364 (2009)
- H. Kang *et al., Physical Review Letters*, **96**:127401 (2006)
- C. Schroer *et al., Physical Review Letters*, **94**:054802 (2005)

Best focus Experiments

Ultimate resolution Theory

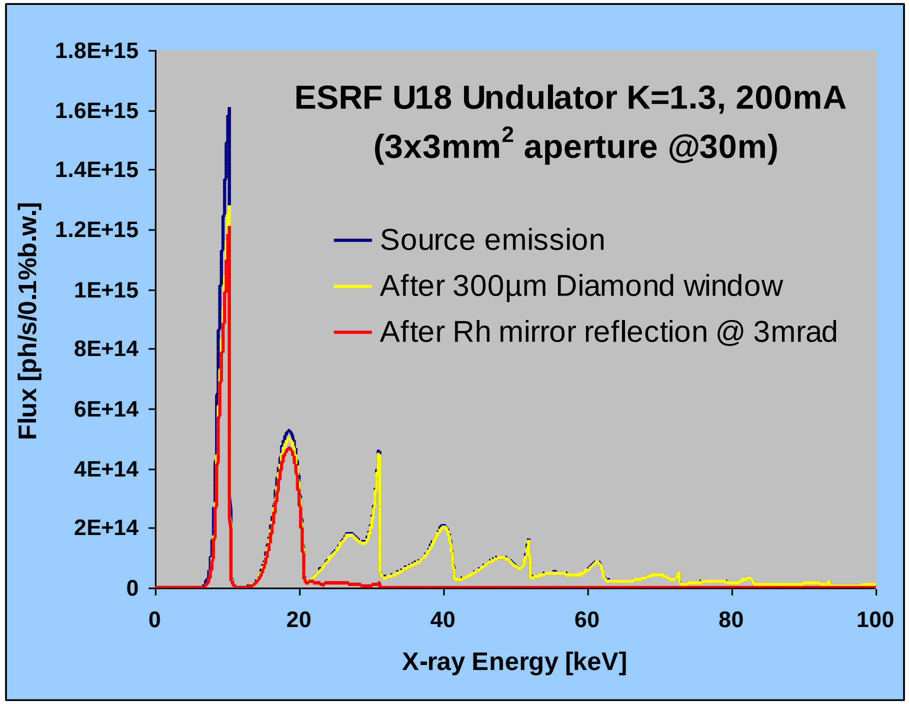
SYNCHROTRON BEAM POWER

ESRF U18 Undulator L=1.65m K=1.3, 90 periods, 200mA Storage Ring Current

Total Emitted Power = 4.5kW

Through 3x3mm aperture @ 30m = 1.4kW

On-axis Power density 210W/mm^2



- 300µm polished diamond absorber (high pass Energy filter) absorbs 135W
- Rh-coated mirror reflecting at 3mrad (low-pass energy filter) absorbs 700W
- Around 550W incident on monochromator crystal – essentially all absorbed

- efficient cooling to prevent from melting
- minimization of induced thermal deformation, drifts
- materials resistant to intense X-ray beams

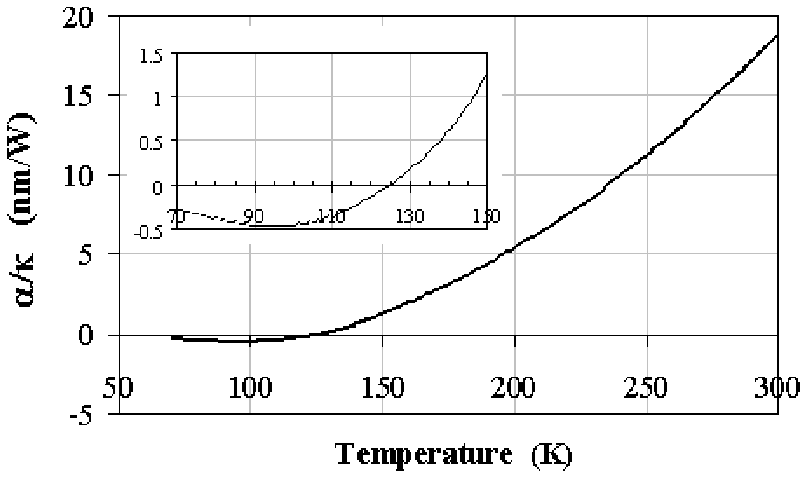
Demanding for optomechanical systems, especially with 4th gen sources

MONOCHROMATOR COOLING

Darwin widths of typical crystal reflexions are in the µrad range:

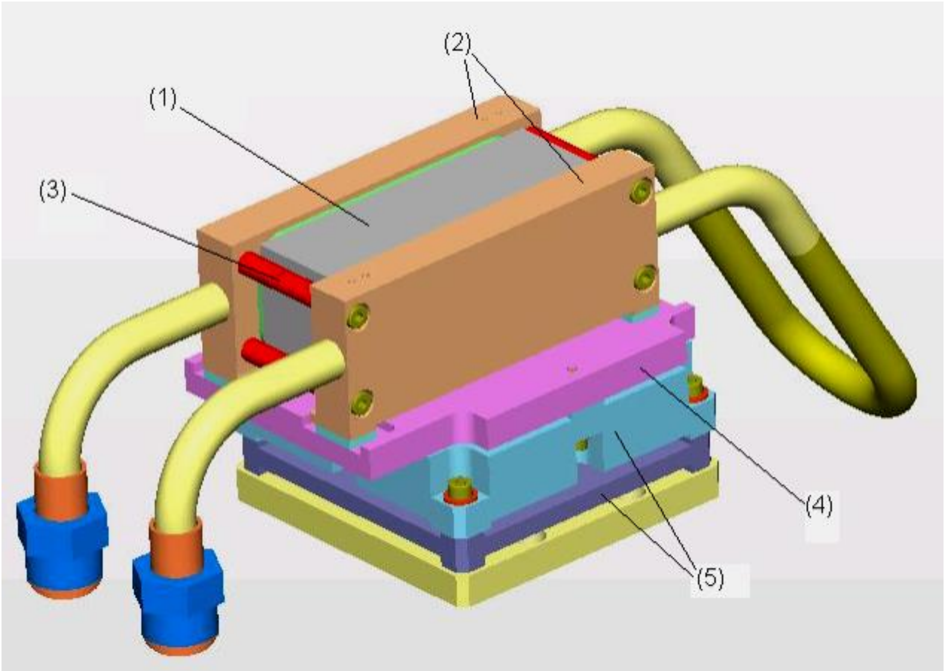
Monochromator performance is particularly sensitive to thermal deformations of diffracting crystals

By cooling Si to cryogenic temperatures (LN2 sufficient) – thermal deformations due to beam absorption can be minimised.



Ratio of thermal expansion and thermal conductivity of Si α/κ vs temperature

Example of ESRF first crystal assembly: (1) silicon crystal; (2) copper cooling blocks with internal fins; (3) invar clamping rods; (4) invar base plate; (5) ceramic insulating plates



- **Crystal is side cooled with cooling blocks clamped with pressures between 5-10bar**
- **Deformation of crystal planes due to clamping <1µrad**
- **Most ESRF beamlines using LN2 cooled monochromators**

SAMPLE ENVIRONMENT

High fluxes provide opportunities to perform in-situ experiments

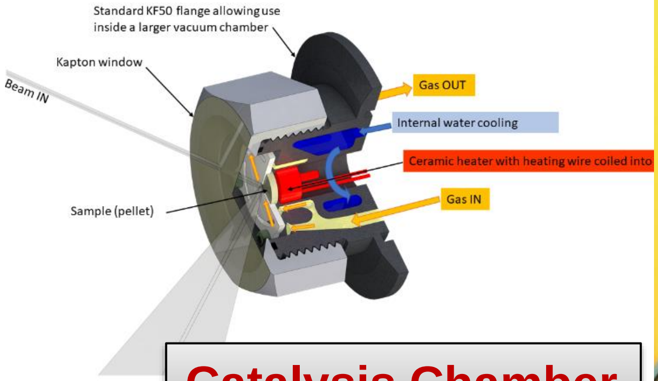
e.g. chemical reactions, phase transformations, crystal growth, material deformation

- **High temperature (furnaces)**
- **Low temperature (cryostat)**
- **Magnetic field**
- **Electric field**
- **Pressure application**
- **Controlled gas atmospheres**
- **Pump-probe experiments (laser excitation, …)**
- **Microfluidics**

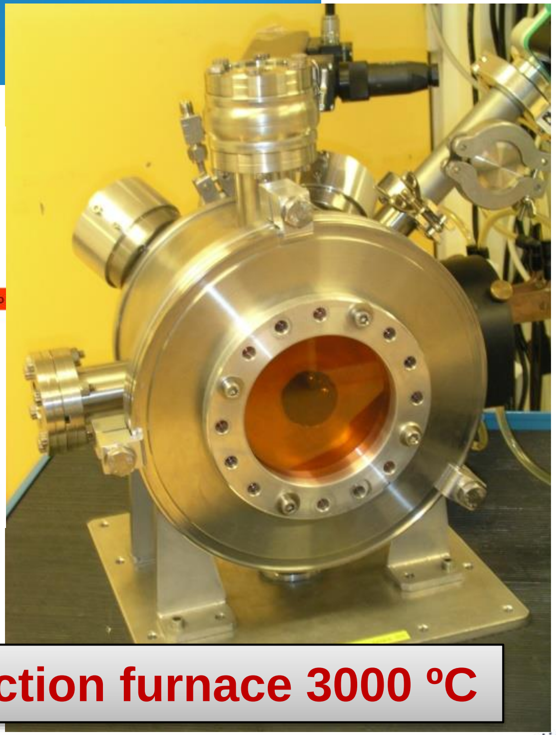
✓ **In-situ 3D printing, charge/discharge cycling of batteries, catalysis …**

Also use of cryogenic cooling to limit sample damage due to photon absorption (e.g. protein crystallography experiments) …

Mini flow cryostat: 2 Kelvin

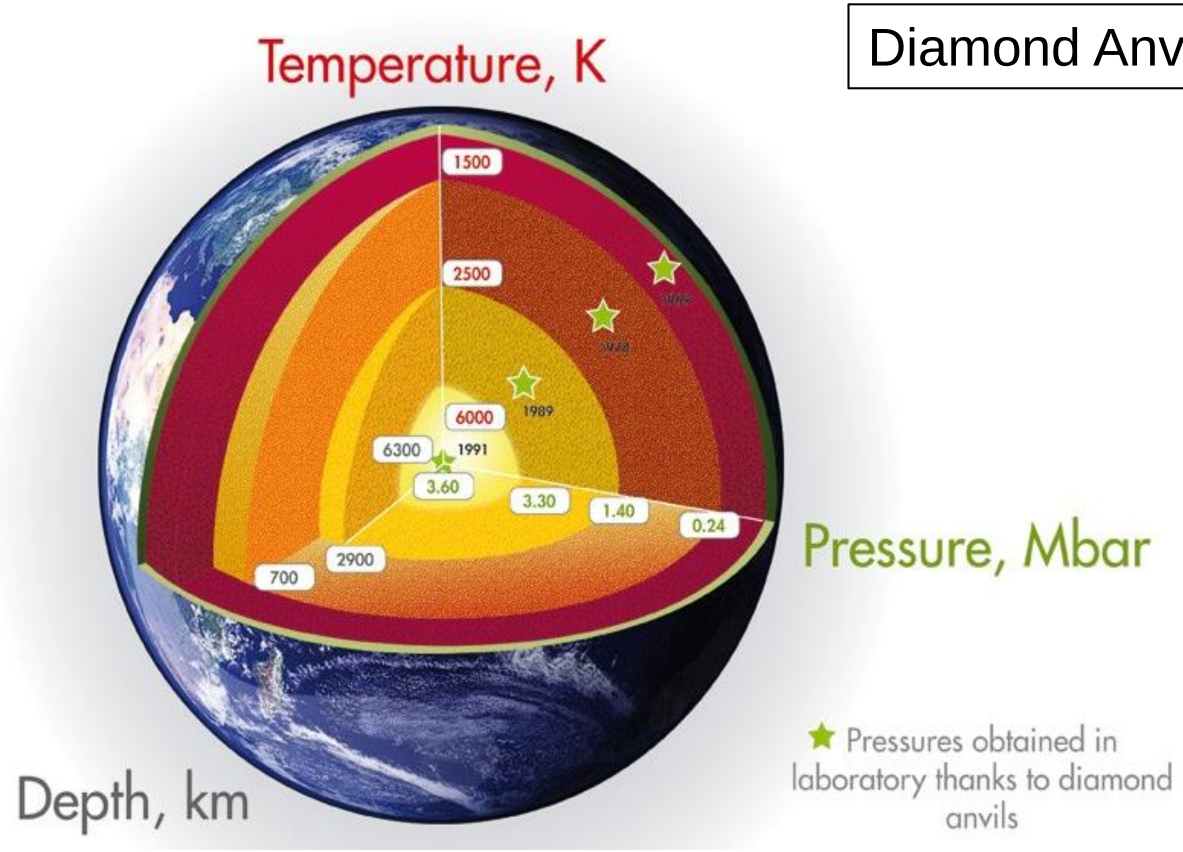


Catalysis Chamber

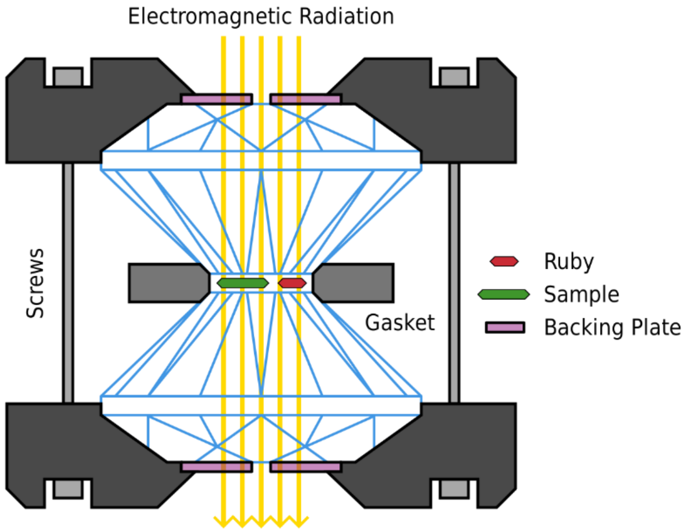


Induction furnace 3000 ºC

EXTREME CONDITIONS (T, P)



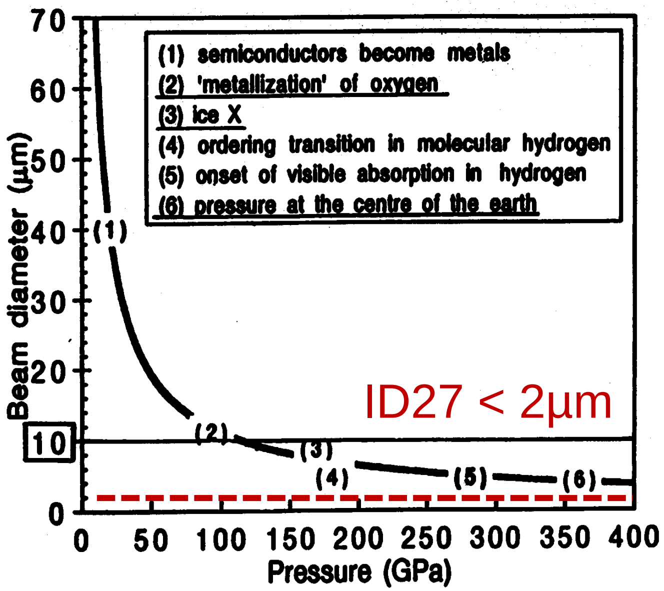
Diamond Anvil Cell (DAC)



Transparent diamonds allow simultaneous laser heating of sample

Record Pressure: 650 GPa (6.5 Mbar)

L. Dubrovinsky et al., Nature Commun. 3, 1163, 2012.



Need to be used with small beam focusing

Courtesy M. Mezouar (ESRF-ID27)

X-RAY DETECTORS

- **A few general considerations**
- **Detection principles used in SR detectors**
  - X-ray sensors and basic detection schemes
- **Main families and types of SR X-ray detectors**
  - Energy dispersive
  - X-ray imaging
  - Scattering/diffraction detectors

DETECTOR MEASUREMENTS

Quantities to measure:

intensity*:*

- photon flux integrated over a given time interval

photon energy

- energy dispersive detectors

- single photon processing

position

- intrinsic to 1D and 2D detectors

photon arrival time

- event timestamping, ultimate time resolution

Many technologies -
choice influenced by:

- Spatial, energy resolution
- Efficiency, dynamic range
- Signal intensity: photon counting, integrating – max count rate
- Robustness
- Price (most advanced detectors can cost >1M€)

X-RAY CONVERSION PROCESS/SENSORS

Sensors mostly used in SR X-ray detectors:

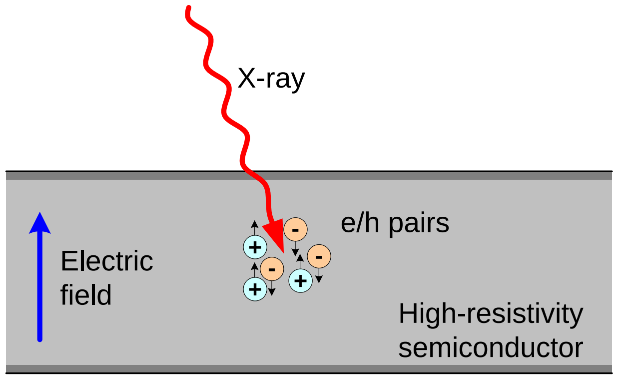
- ✓ ***semiconductors*** **X-ray → electron-hole pairs**
- ✓ ***scintillators*** **X-ray → visible light → light sensor**

Much less used in practice:

- ✓ ***gas*** **X-ray → ions**
  - Used primarily for diagnostics (ion chambers)
- ✓ ***photocathodes*** **X-ray → photoelectrons**
  - Certain soft X-ray applications or special cases (e.g. streak cameras)
- ✓ ***microbolometers*** **X-ray → phonons → precision thermometer (TES, MMC)**
- ✓ ***superconductors*** **X-ray → charged quasiparticles (STJ)**
  - Count rates too low for fluorescence measurements at synchrotrons
  - Energy resolution is insufficient for spectroscopy experiments
- ✓ ***film/image plates*** **X-ray → trapped electron states**

SEMICONDUCTORS (DIRECT DETECTION)

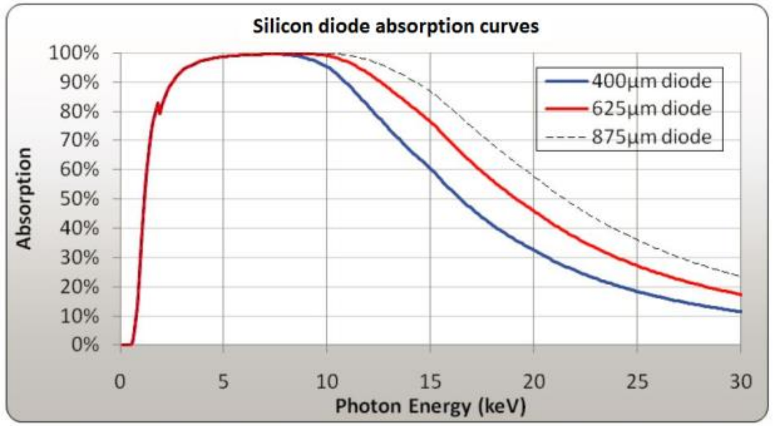
Direct detection: Absorbed X-rays directly generate electrical signal e.g. photodiodes, pixel-detectors, silicon drift-diodes



X-rays generate electron-hole pairs (photoelectric absorption)
e.g. PIN diode

Efficient charge collection requires high resistivity *semiconductors*:
- *Possibility of depleting the active volume*
- *Minimise dark current (may need cooling)*

Usable X-ray photon energy range :
- *lower limit: due 'entrance window' cut-off*
- *higher limit: sensor transmission*

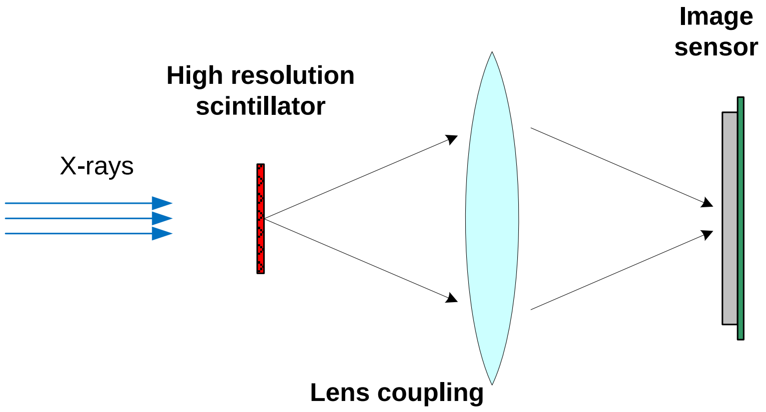


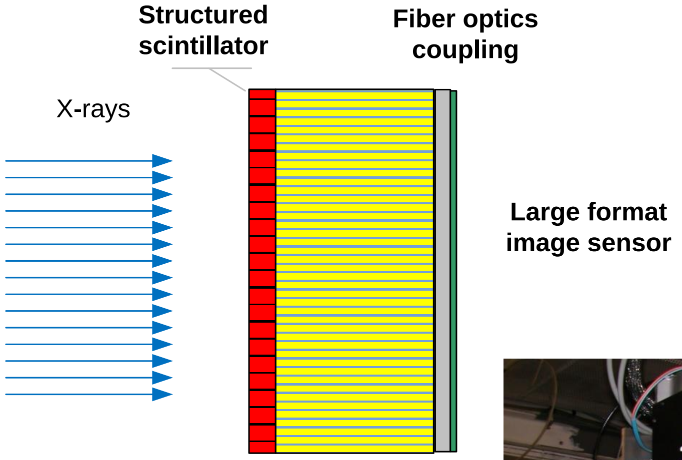
Silicon is the reference material, but:
- *limited energy range up to 15-20 keV*
- *not too radiation hard devices*

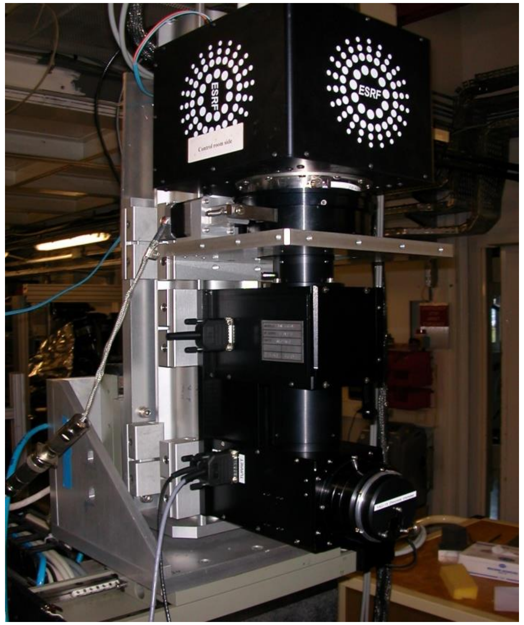
That is why other semiconductors are used or investigated (Ge, GaAs, Cd(Zn)Te, …)

SCINTILLATORS (INDIRECT DETECTION)

Indirect detection: X-rays absorbed by a conversion medium and secondary signal such as light, heat detected e.g. scintillator PMT, optically coupled CCD, bolometer, calorimeter







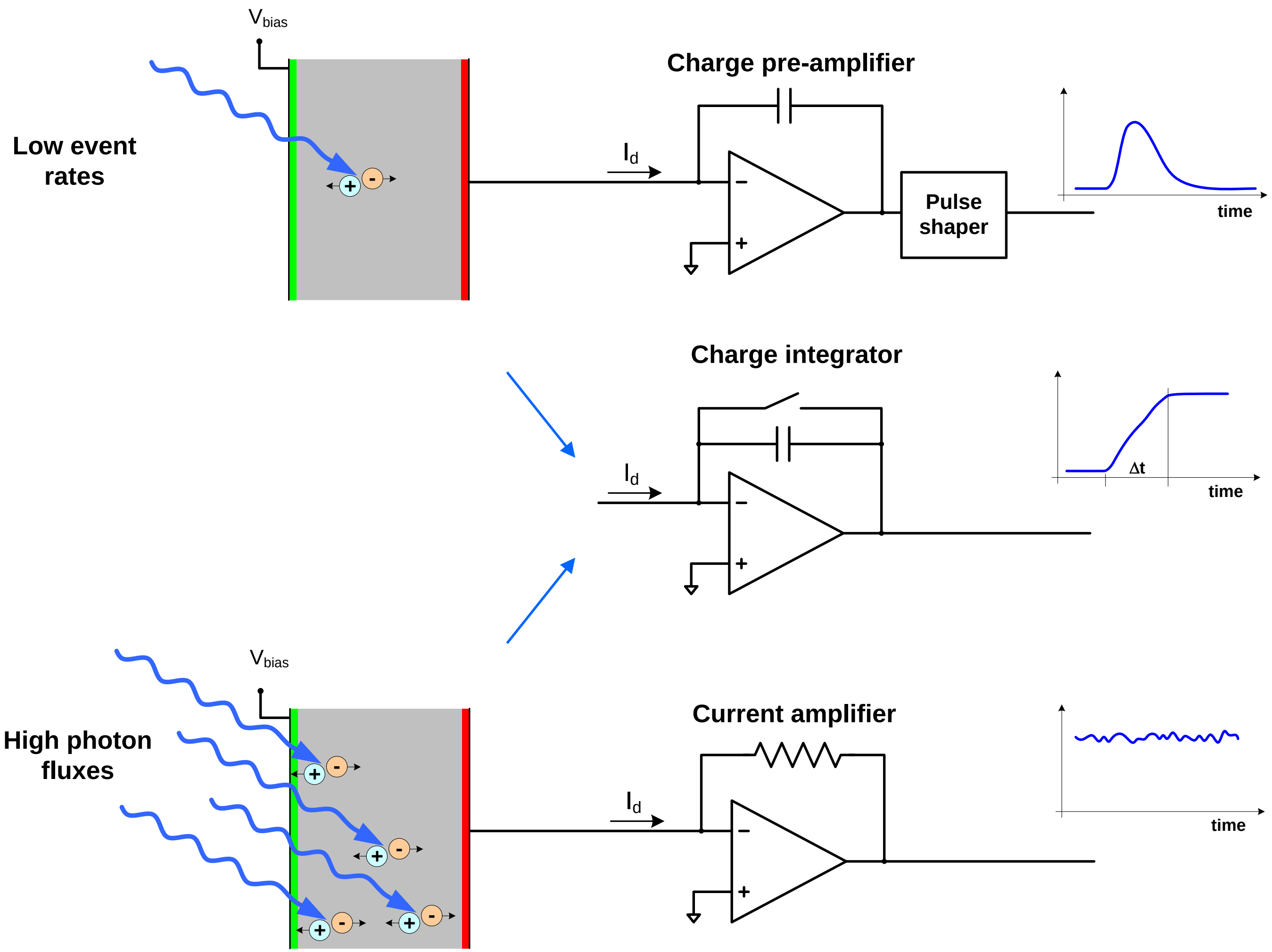
Main key points:

- Scintillators can be radiation hard (not always the optics)
  Convenient also for practical and cost reasons

- High spatial resolution is possible (optical magnification)

- Efficient for high energy photons.

BASIC READOUT PRINCIPLES



Charge integration can be partially or totally built in the sensor (i.e. CCDs)

Used for very high fluxes: i.e. beam intensity measurements

The X-ray intensity is measured by integrating the signal during an exposure time Δt

UNDESIRED EFFECTS

‘Undesired’ components of the measurement

- ***Noise**: random and unbiased*
- ***Systematic effects***

Correction of systematic errors in intensity measurements:

- **offset** *(dark signals, electronics offsets)*
- **flat field** *(efficiency or gain inhomogeneity)*
- **spatial distortion** *(construction defects, parallax errors, …)*
- **linearity corrections***:*
  - *charge integrating detectors: non-ideal electronics (INL correction)*
  - *photon counting detectors: photon pile-up (**deadtime correction**)*

DETECTOR NOISE

Noise ***cannot be corrected*** *(random nature) → must be minimised (development + usage)*

Noise is meaningful as a relative value:

Signal-to-Noise ratio: *(S / N)*

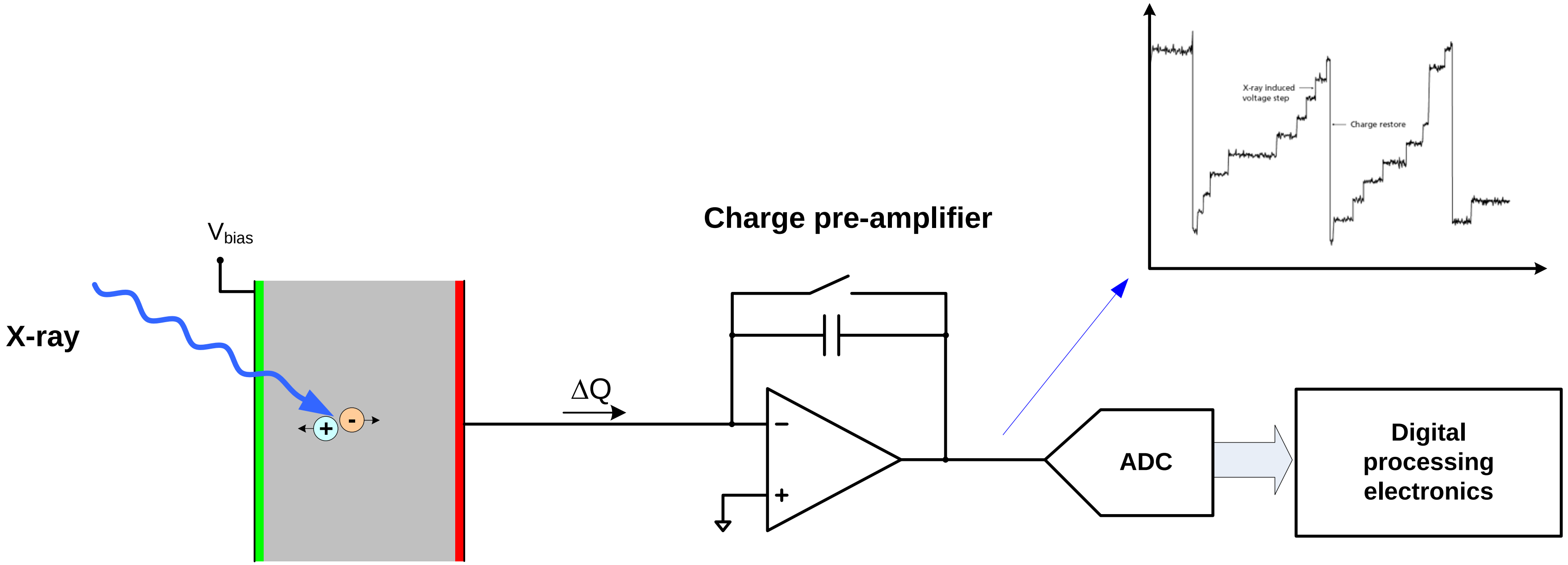
Dynamic Range: $DR = S_{max} / N$

Any effect that degrades the (S/N) ratio can be considered as an effective source of noise

'Effective noise' sources:

- *Photon fluctuations (input noise)* $\sigma_{N_{ph}} = \sqrt{N_{ph}}$ *(Poisson noise)*
- *Quantum efficiency (QE) of the sensor*
- *Fluctuations of the conversion process: X-ray → e-*
- *Dark current fluctuations*
- *Readout electronics:*
  - *- preamplifier noise (analogue)*
  - *- digitisation/quantisation noise (ADC resolution, V-to-F max. frequency, …)*
- *Interference/coupled noise (50Hz, pumps, motors, power supplies)*

ENERGY DISPERSIVE X-RAY DETECTORS (EDX)



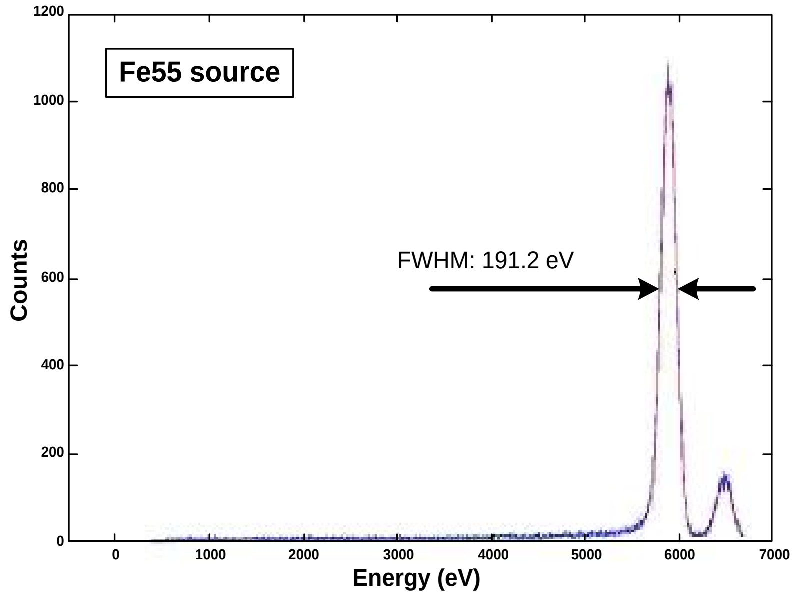
Evaluate the **photon energy** by measuring the charge generated in the sensor

Modern EDX detectors rely on very fast **digital pulse processors** (DPP) implementing rather sophisticated algorithms:

- Fast channel to identify photon events (hits)
- Slow channels to evaluate charge/energy content associated with each individual event

The resolution of the detector at a certain energy is usually defined as the full width at half-maximum (FWHM) of recorded spectra.

$$\text{FWHM} = 2.35\,\sigma_E$$



The *measured* spectral resolution is the quadratic-sum of various noise sources present in the detector:

$$\text{Resolution} = \sqrt{(\textit{conversion noise})^2 + (\textit{dark current noise})^2 + (\textit{preamplifier noise})^2}$$

Dominant terms

Can be reduced by proper sensor design and cooling

CHARGE GENERATION FLUCTUATIONS

The number of elementary charges generated by a single X-ray photon, N_Q , can be estimated as :

$$N_Q = \frac{E_{photon}}{\varepsilon_i}$$

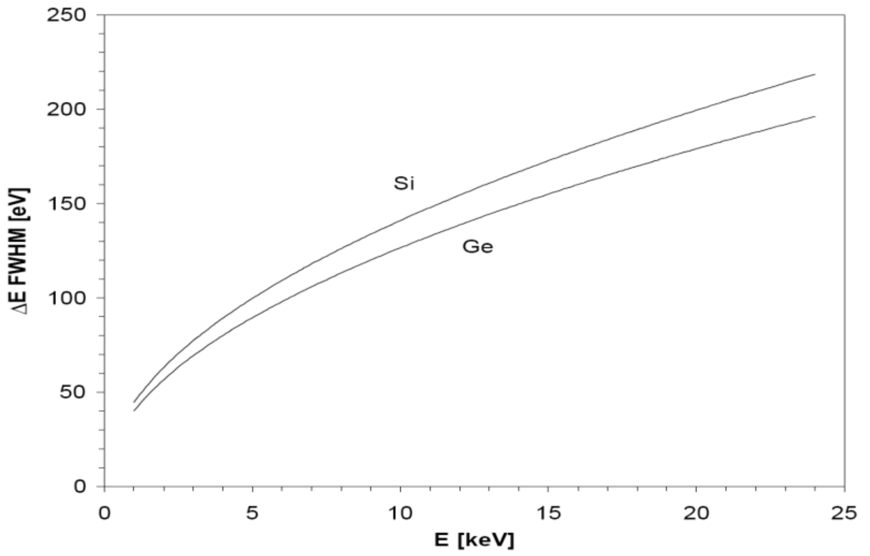
Where the ionisation energy ε_i is the average energy required to produce an elementary charge.

In silicon : ε_i = 3.6 eV , a 10 keV photon produces 2800 e/h pairs.

The RMS fluctuation (σ_E) associated with the charge generation

$$\left.\begin{array}{l}\sigma_{N_Q} \propto \sqrt{N_Q} \\ \sigma_E = \varepsilon_i \, \sigma_{N_Q}\end{array}\right\} \longrightarrow \sigma_E \propto \sqrt{E_{photon}\varepsilon_i}$$

Intrinsic resolution of Si and Ge detectors (Fano noise)



In semiconductors $\sigma_E = \sqrt{F\, E_{photon}\varepsilon_i}$ usually known as "*Fano noise*"

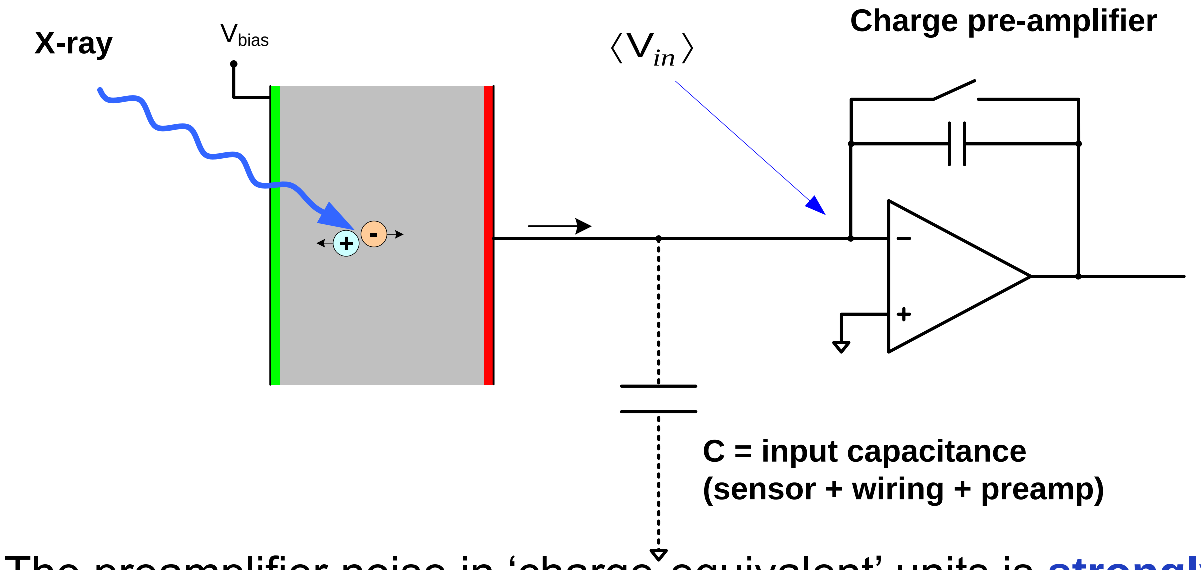
where F is the Fano factor ($F \approx$ 0.11 for Si and Ge) - less than Poisson noise due to interaction between ionization events

U. Fano, Phys. Rev. **72** (1947) 26

PREAMPLIFIER NOISE

Careful electronics design may reduce the noise contributions to the charge preamplifier noise as the main component.

The electrical capacitance seen at the input node plays a fundamental role through the “equivalent input voltage noise” $\langle V_{in} \rangle$ of the amplifier:



Contribution to charge noise (ENC):

$$\langle Q_{noise} \rangle = \mathbf{C} \times \langle V_{in} \rangle$$

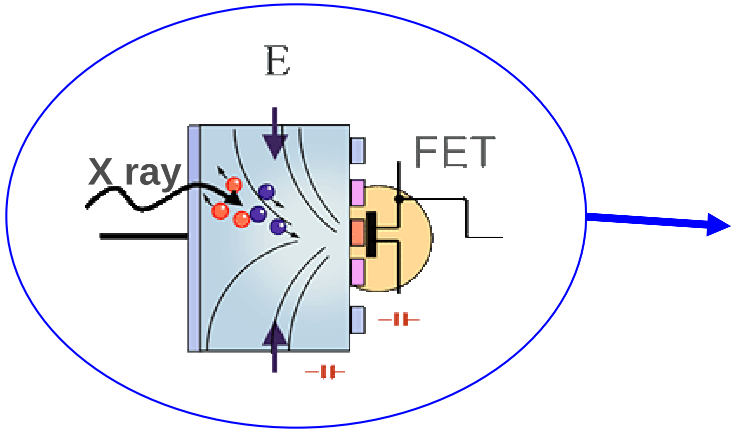
The preamplifier noise in ‘charge-equivalent’ units is **strongly dependent on the input capacitance**

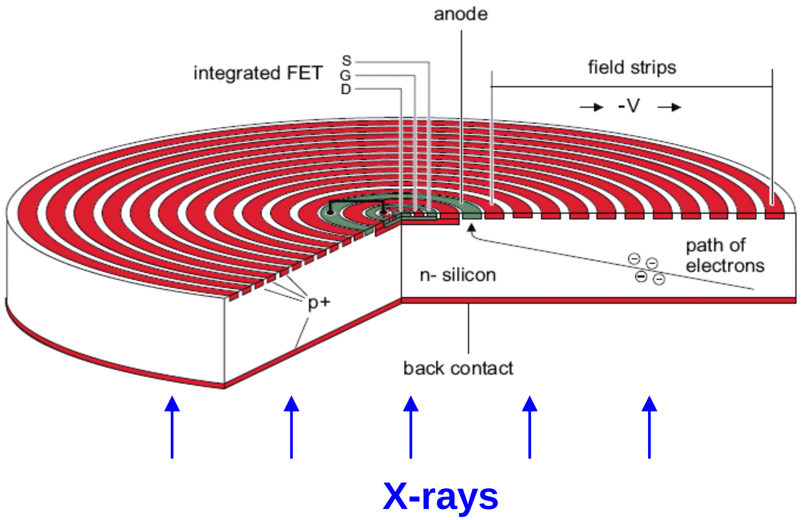
SILICON DRIFT DIODE (SDD)

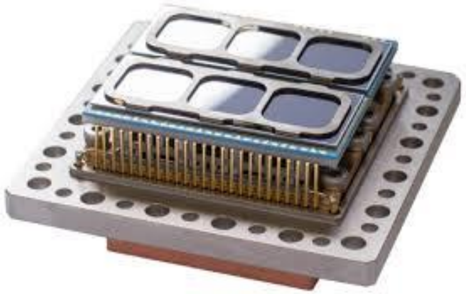
The **SDD** is an excellent example of ‘**capacitance reduction**’ techniques:

Multielectrodes create a *transverse drift field* that drives the charge to a small anode

Charge is collected over large surface area (up to 1cm^2) without increasing the anode capacitance







SDDs are now the most popular energy dispersive detectors for synchrotron applications.

But relatively thin (< 1 mm) detectors and limited to low energies (< 20 keV) (Ge used at higher energies)

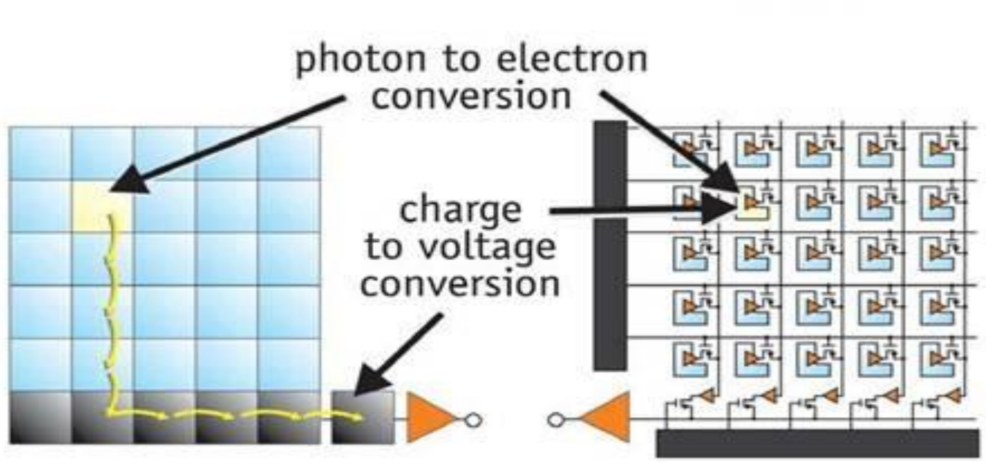
Can operate with moderate cooling (Peltier cooling -10ºC…-50ºC)

DETECTOR CHANNEL CONFIGURATION

a) ***Single element*** *(0D)*

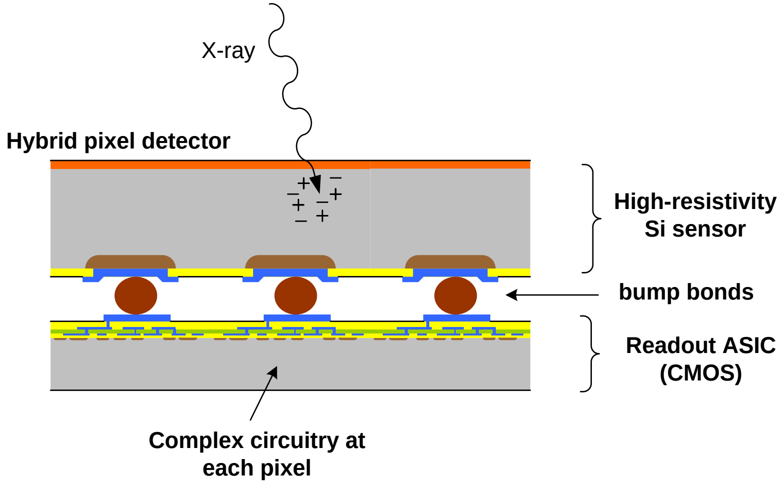
b) ***Multielement****: discrete or monolithic sensors*
readout: packaging of single element channels

c) ***Position sensitive*** *(large 1D or 2D detector arrays)*
from thousand to millions of channels (strips or pixels)
various technologies and readout mechanisms:



Charge coupled device (CCD)

CMOS image sensor (CIS)



Hybrid pixel detector
(e.g. Dectris, Maxipix/Medipix)

HYBRID PIXEL DETECTORS

1. **Detection Layer**

    Depleted, high resistivity semiconductor:

        Si, GaAs, CdTe…

    Individual 'pixels' formed lithographically

2. 'sandwich' construction **connecting bumps**

    Solder or indium lithographically deposited

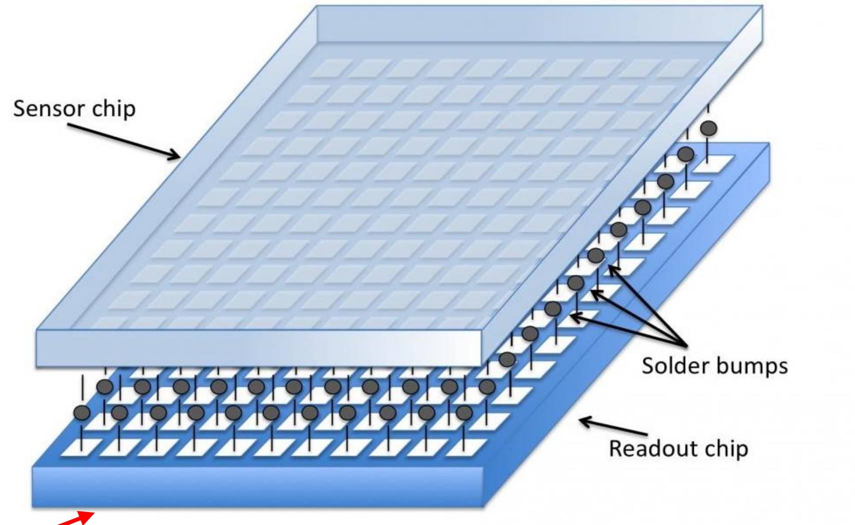
    ~ $10^{4 \ldots 5}$ pixels are individually connected

3. **Mixed analogue-digital ASIC readout** CMOS 'chip'

    pixel parallel signal processing: analogue preamp, shaper, thresholds, counter

    readout interface (serial-parallel)

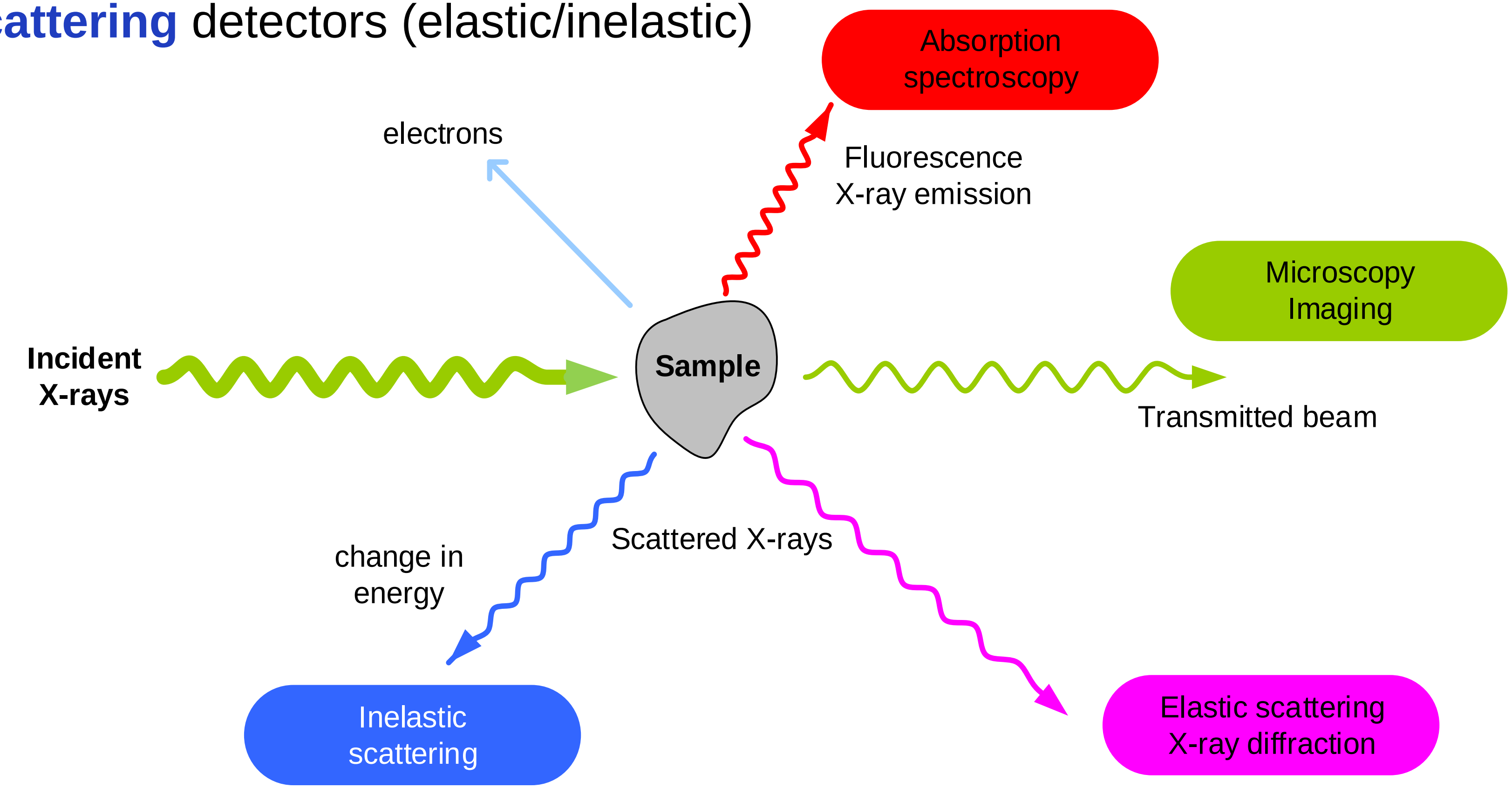
    wide range of possibilities for analogue input stage and digital readout architectures



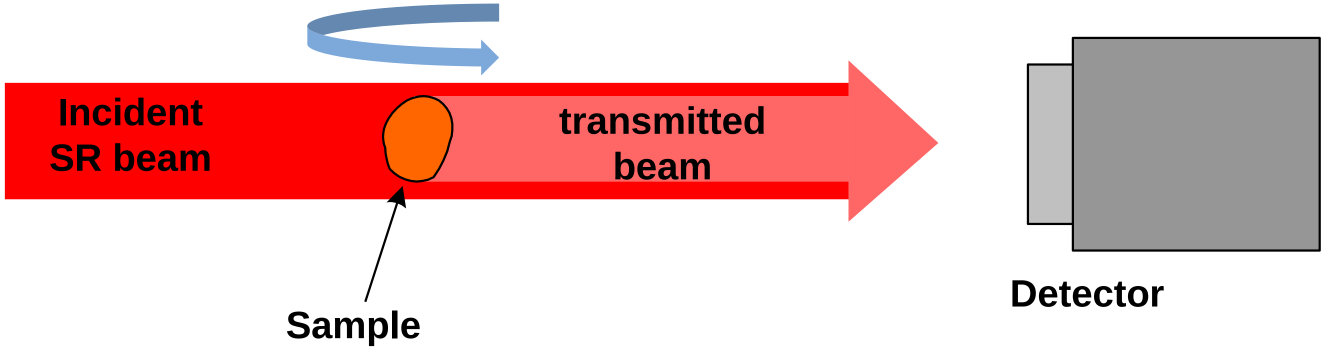
3 MAIN “FAMILIES” OF X-RAY DETECTORS FOR SR EXPERIMENTS

Simplified classification based on application (type of interaction):

- **X-ray imaging** (transmitted beam)
- **Energy dispersive** detectors (fluorescence)
- **Diffraction / scattering** detectors (elastic/inelastic)



X-RAY IMAGING



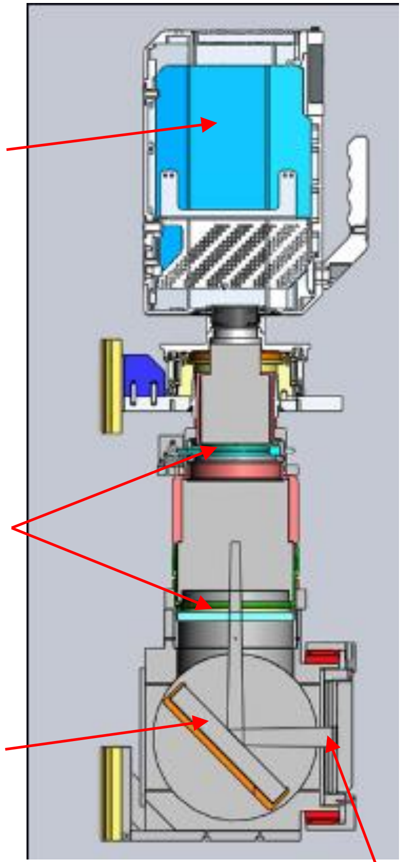
- The detector sees a projection image of the sample
  - absorption or phase contrast (beam is partially coherent)
- Very high flux on the detector (close to the full incident beam)
- Small pixels (0.5 to 50 µm)
- Indirect detection schemes are required
- 3D imaging is made by tomographic reconstruction from sets of 2D images acquired during sample rotation

EXAMPLE: LARGE FIELD-OF-VIEW IMAGING DETECTOR

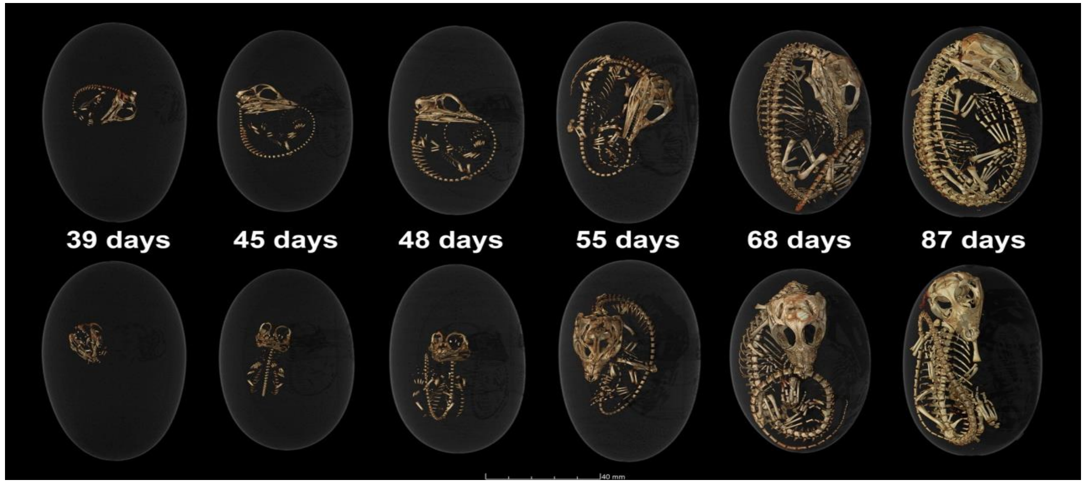
visible-light camera

(de)magnifying optics

folding mirror



scintillating screen
(X-ray to light conversion)



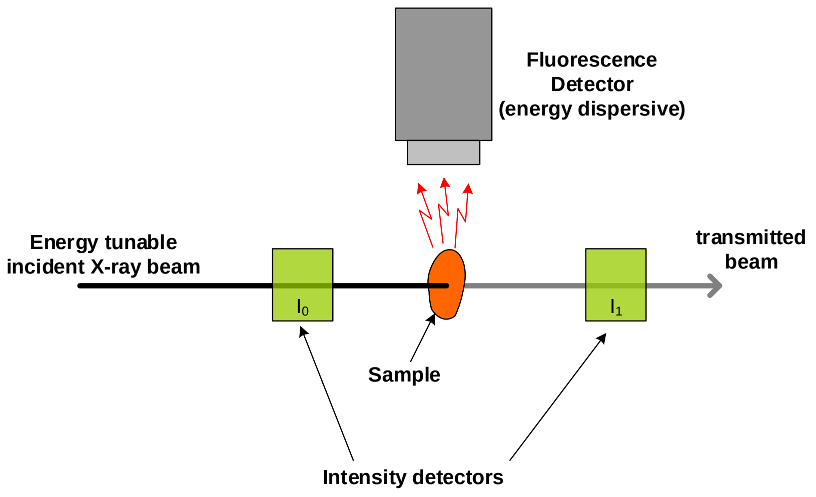
Development of an in-vivo crocodile
(Courtesy of P. Tafforeau, ID19)

Pixel size	49 µm
FOV	100×20 mm^2
QE @ 100 keV	**> 99%**

FLUORESCENCE DETECTION (ENERGY DISPERSIVE)

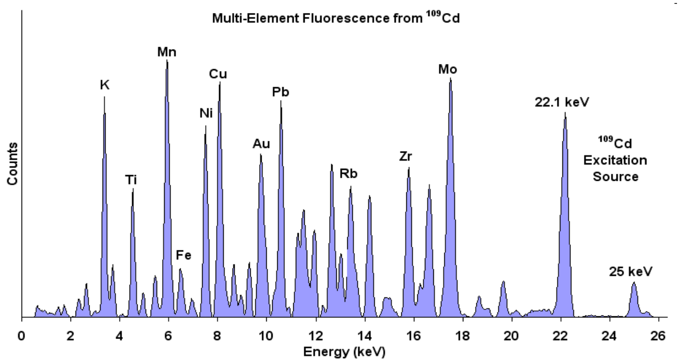
Absorption spectroscopy:

- Sample absorption (as a function of energy)
- Polarization dependence (dichroism)
- Measure either:
  Transmitted intensity (I_1/I_0)
  or
  Fluorescence yield
- Detectors:
  Intensity: ion chambers, photodiodes
  Fluorescence: semiconductor detectors



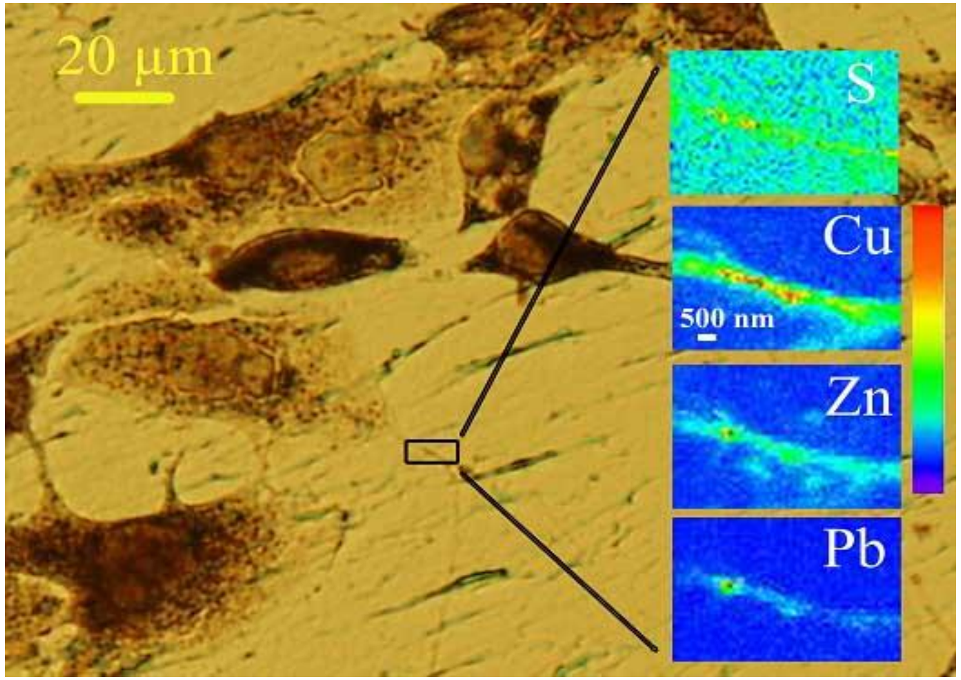
Fluorescence analysis:

- Measurement of fluorescence lines
  chemical analysis, mapping, ultra-dilute samples
- Detection: semiconductor detectors



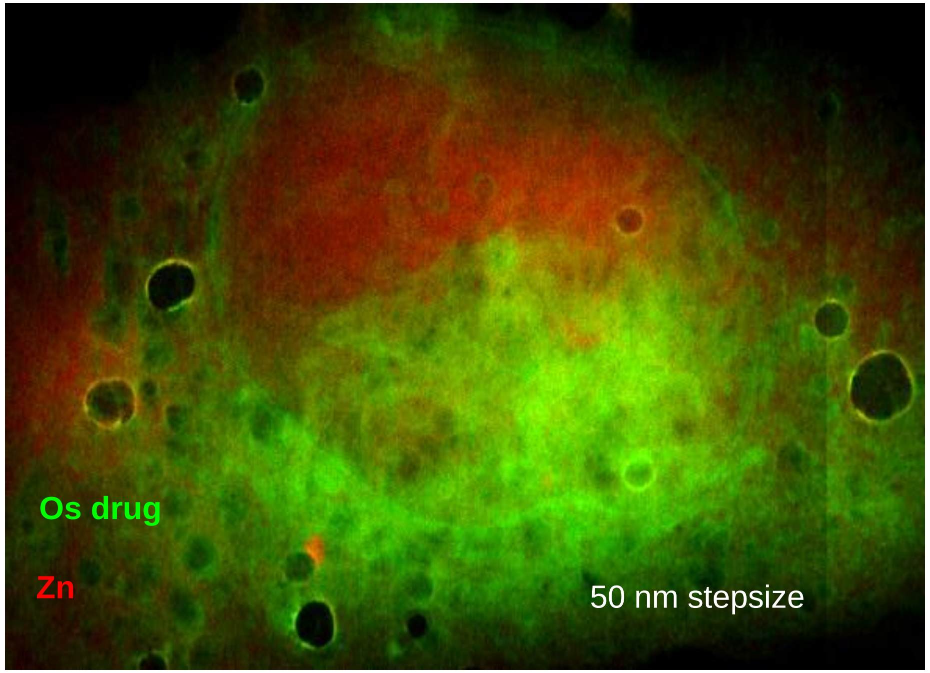
FLUORESCENCE 2D ENERGY RESOLVED 'IMAGING' OF SAMPLES

Neurite process



A Carmona et al. JAAS (2008)

Deciphering intracellular targets of new Anticancer Drugs in breast cancer cells



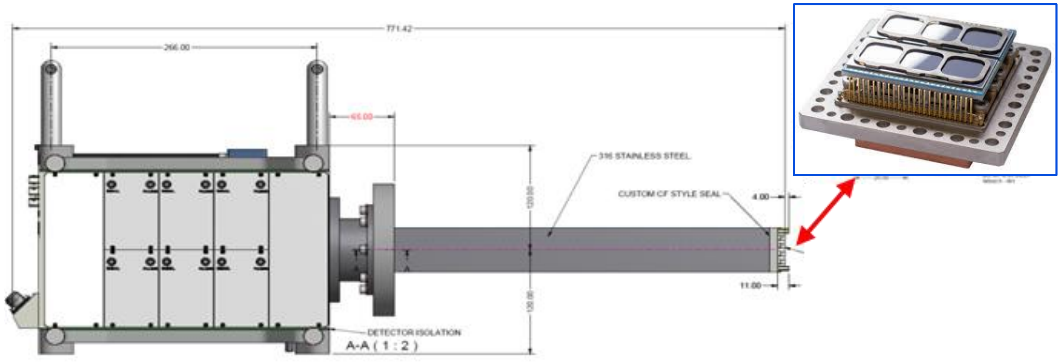
S. Bohic et al., Inserm U836, ESRF, Grenoble

ENERGY DISPERSIVE DETECTORS IN SR EXPERIMENTS

Off-the-shelf detectors (most used in practice in SR experiments):

- Silicon drift diodes (SDDs)
- High purity germanium detectors (HPGe)

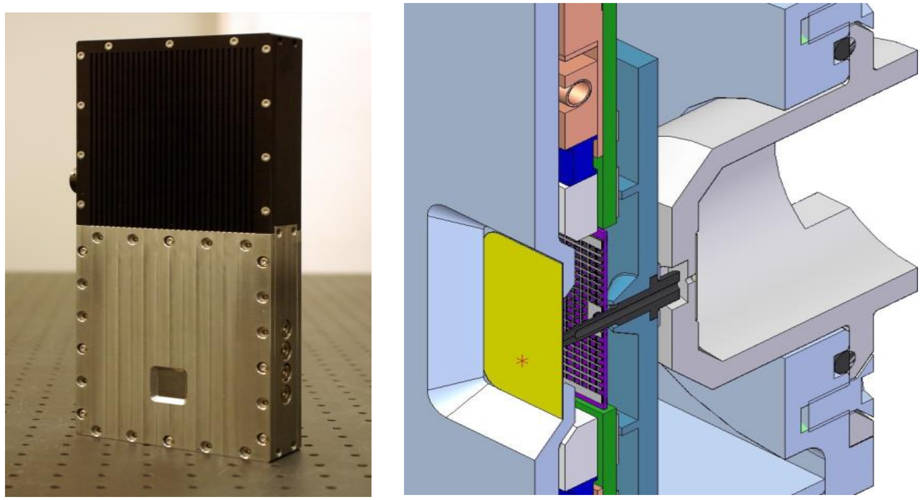
Customised instruments (multielement and special devices):



ESRF/ID16A

– SDD 6 element arrays = 2 x 540mm^2
– Energy range ~2…20keV
– Global *throughput* count rate to ~6Mcps
– 1kHz readout by XIA-XMAP pulse processors

Sensors from PNdetectors integrated by SGX Sensortech

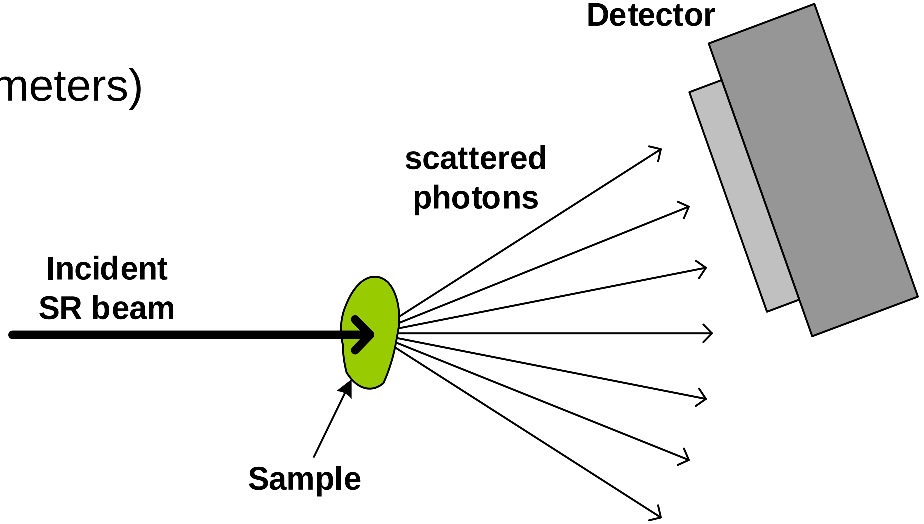


Maia *(CSIRO and BNL/NSLS)*

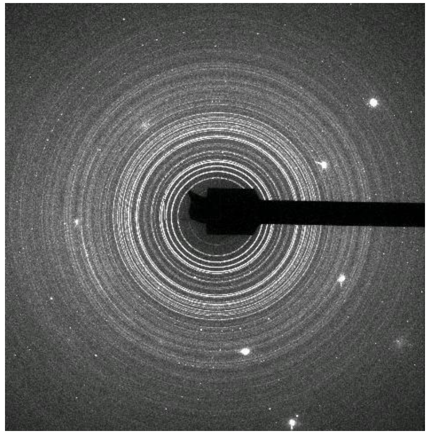
- Large solid-angle (1.2 sr)
- High-rate capability (384 Si PIN diodes)

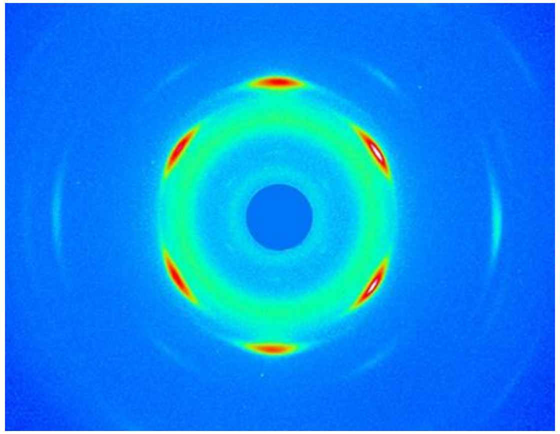
X-RAY SCATTERING (DIFFRACTION, SAXS, INELASTIC, …)

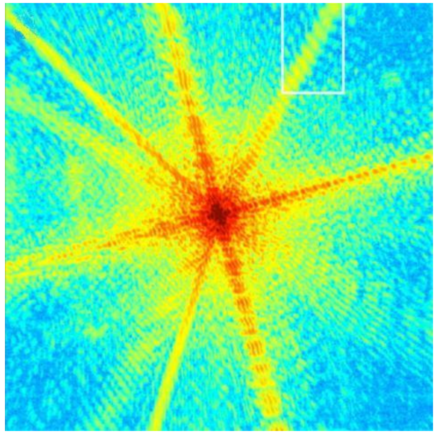
- Solid angle collection (0D (scanning), 1D or 2D)
- Spatial/angular resolution depends on detector-sample distance
- Large dynamic range requirements (many orders of magnitude)
- Inelastic scattering uses wavelength dispersive setups (spectrometers)



- detectors used:
  0D: scintillator-PMT; silicon-diode, APD using diffractometer
  1D: solid state semiconductors (1D strip or multielement array)
  2D: indirect or direct detection

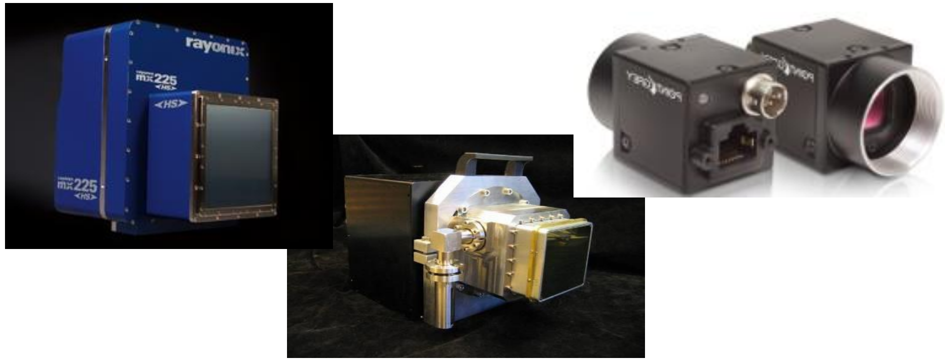






SCATTERING/DIFFRACTION DETECTORS

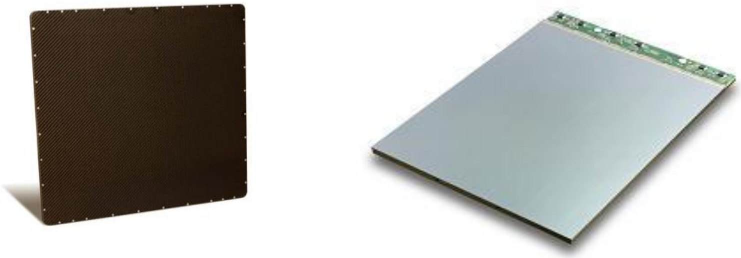
Main technologies for 2D detectors



- ❑ **CCD/CMOS based**

  Indirect (hard X-rays) or direct (soft X-rays) detection schemes

  Mature technology (little room for improvement)



- ❑ **Flat panels** (medical imaging) – losing ground

  a:Si (TFT technology)

  CMOS flat panels (tiling or CMOS image sensors)

- ❑ **Hybrid pixel detectors**

  At synchrotrons mostly photon counting devices

  Charge integrating detectors are starting to be deployed at 4th generation storage rings such as EBS due to increased flux

Fast, large array, 2D detectors are the principal source of data ‘avalanches’ – data rates up to 16 GB/s

HIGHLY SPECIALIZED EXPERIMENTAL STATIONS

adapted to one or more techniques…

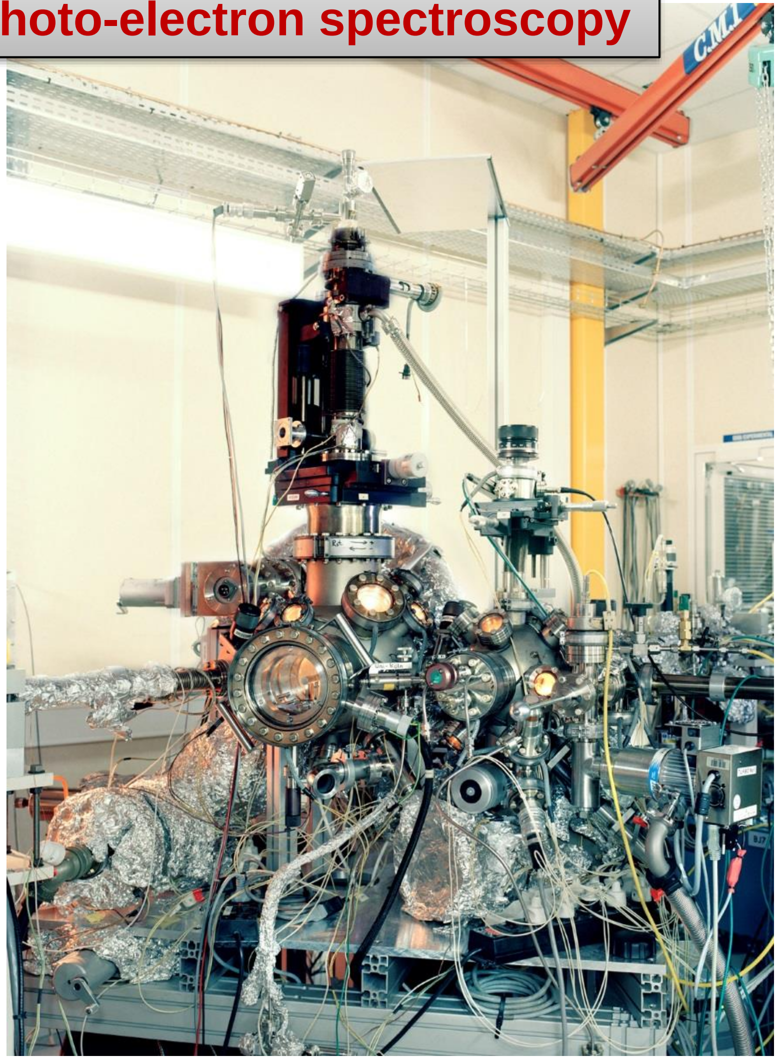
- X-ray Diffraction & Scattering
- X-ray Spectroscopy
- X-ray Fluorescence
- X-ray Imaging …

… on samples of varying types

- Inorganic/organic crystals
- Colloidal solutions
- Fossils
- Cells
- Industrial materials ...

… and different sample environments

ID32: experimental station - photo-electron spectroscopy

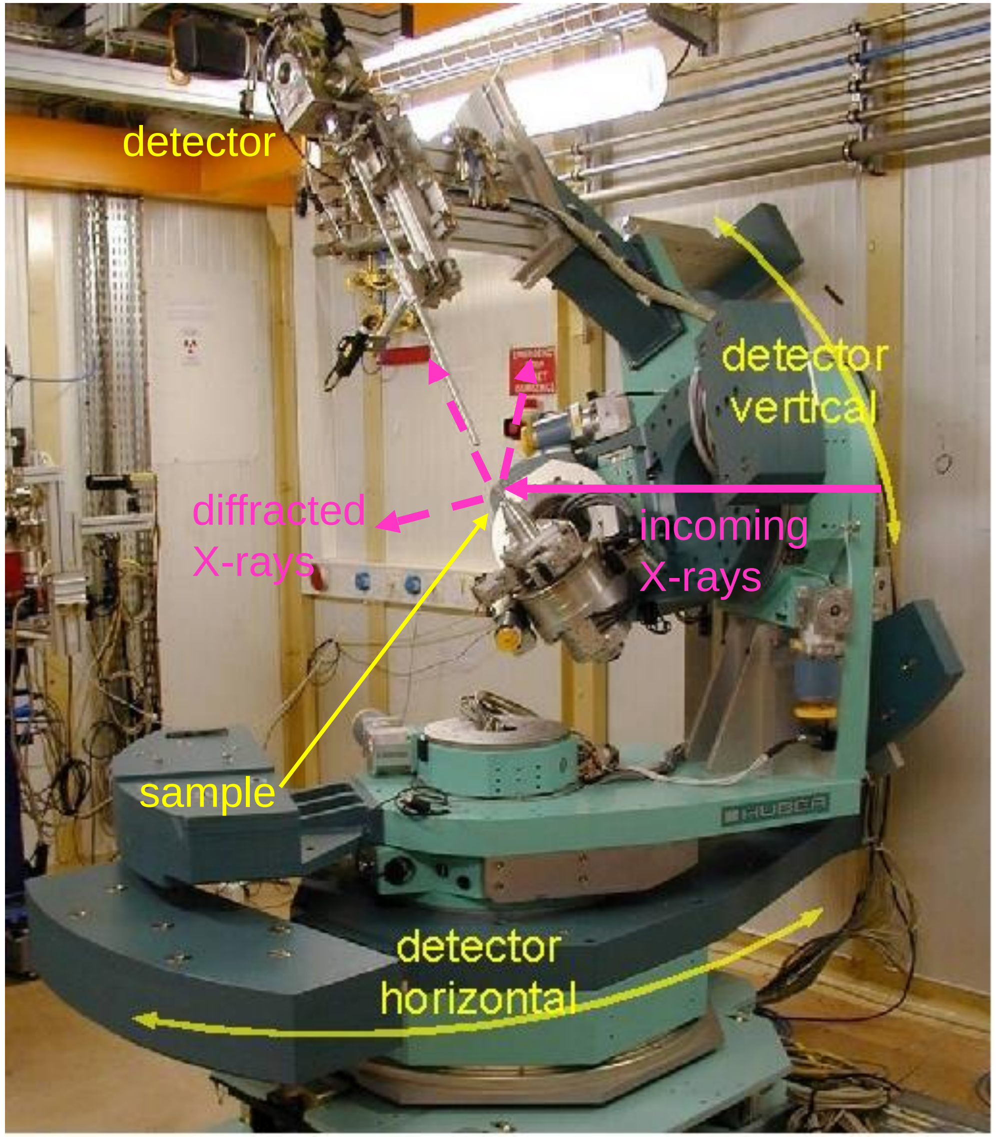


X-RAY DIFFRACTOMETER

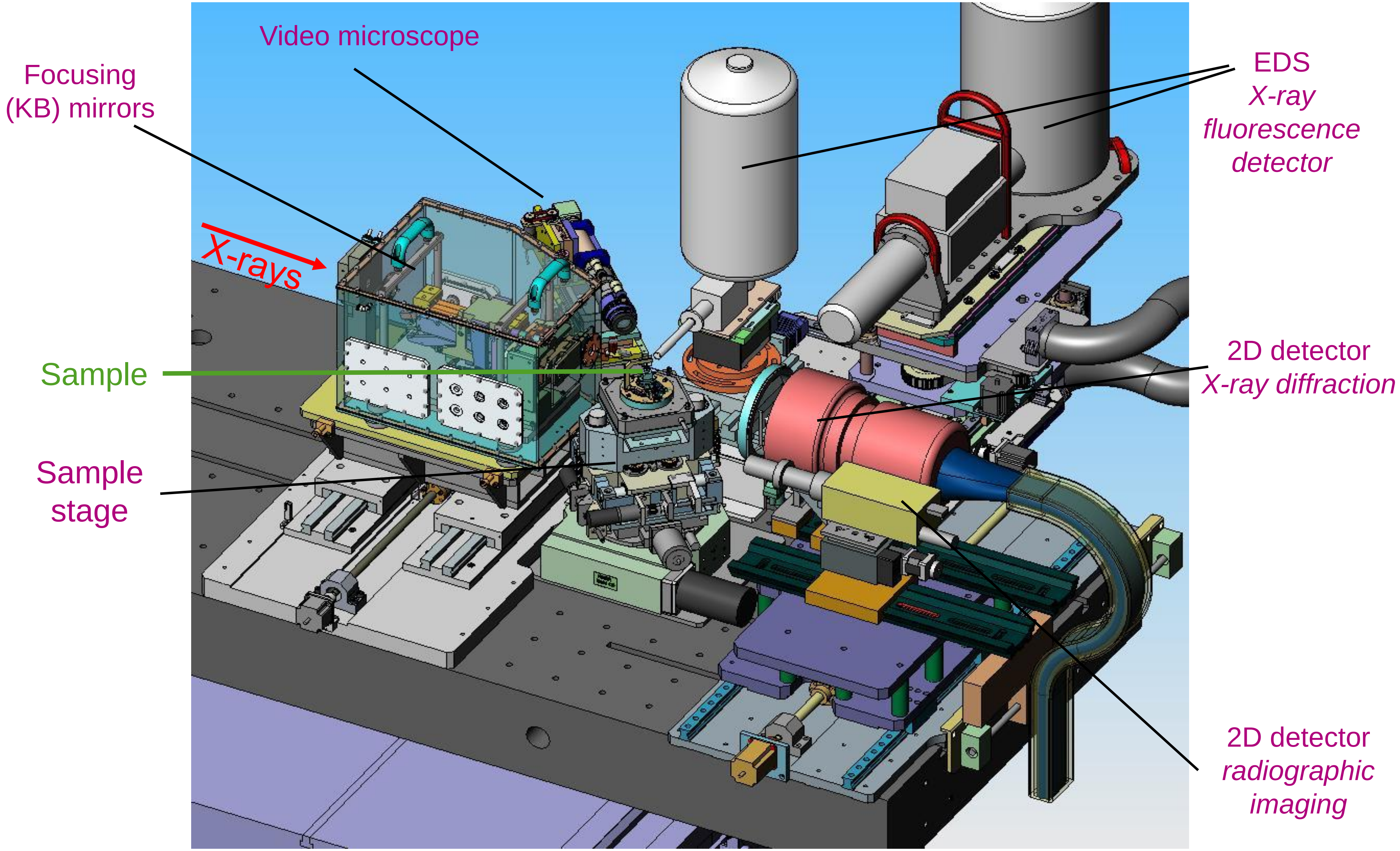
- X-ray diffraction experiments require precise positioning and orientation of the sample and detector relative to the X-ray beam

- Diffractometers provide versatile sample rotation around multiple axes intersecting at single point

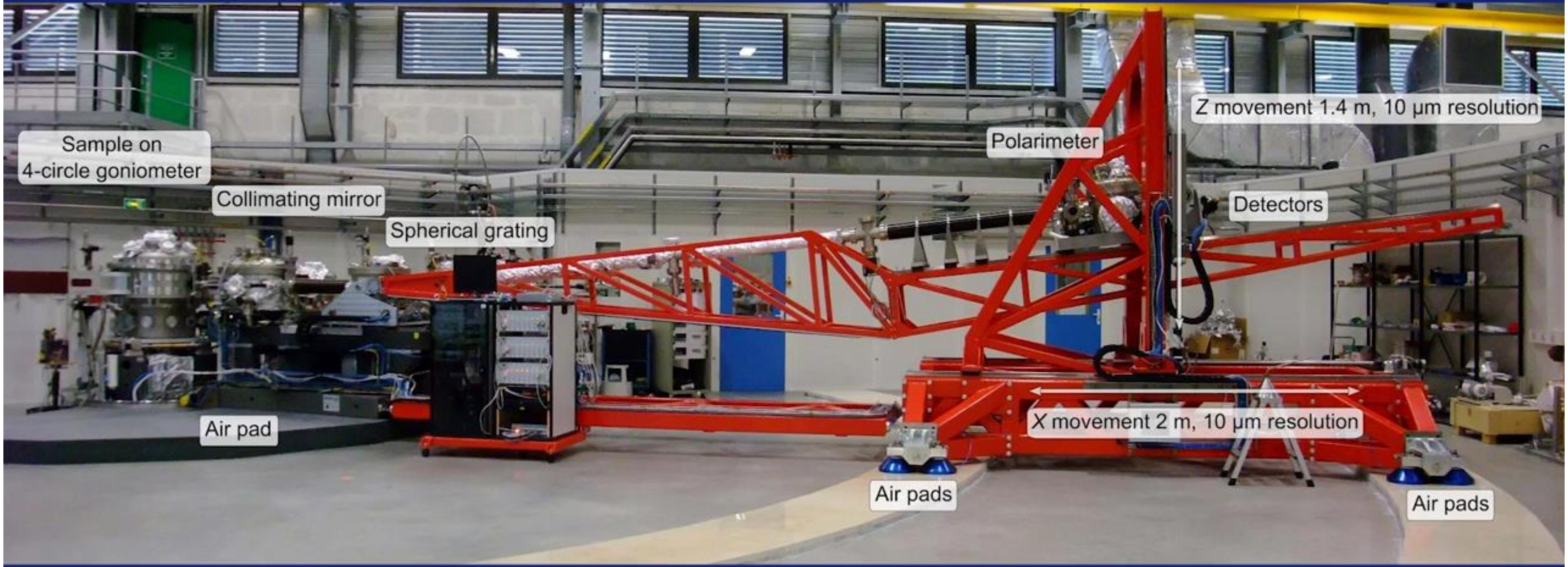
- Sample remains stable within a ‘Sphere of Confusion’ typically < 100 µm to minimise drifts relative to X-ray beam



HARD (5-70KEV) X-RAY MICROPROBE (EX-ESRF-ID22)

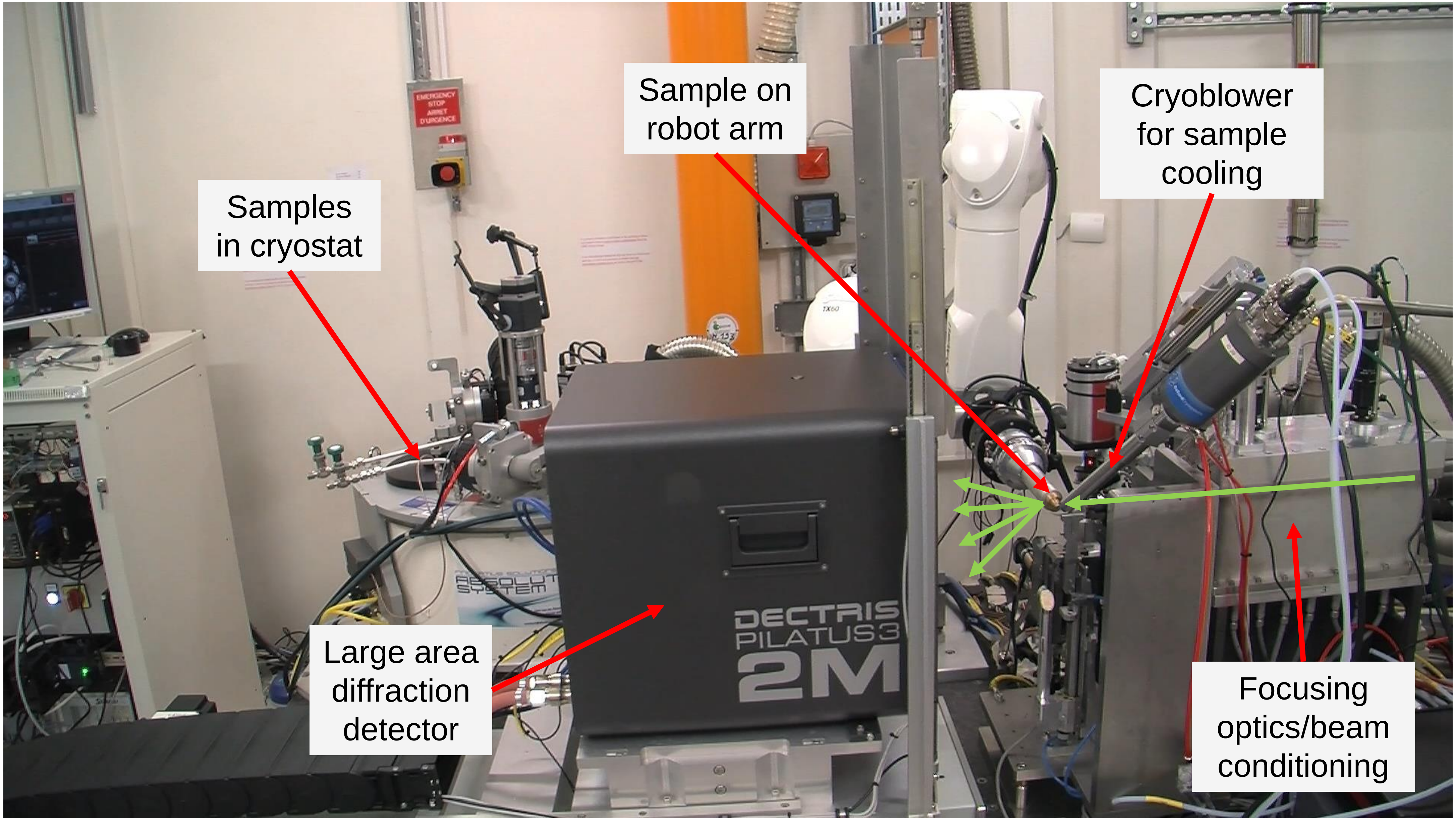


Soft X-Ray RIXS Spectrometer at ID32, ESRF



Its flexible sample and detector geometries make possible for the first time a 3D mapping of the energy and momentum dependences of charge and collective excitations (magnons, phonons…)

HIGHLY AUTOMATED DATA COLLECTION: MACROMOLECULAR CRYSTALLOGRAPHY (ESRF ID30A MASSIF)



SUMMARY

- Present day synchrotron radiation sources offer a unique tool for probing the interior of matter over length scales ranging from the few cm to sub-atomic dimensions

- The full potential of the continually improving sources can only be exploited by parallel developments in appropriate X-ray instrumentation
  - **X-ray optics/ optomechanics**
  - **Sample alignment systems**
  - **Sample environments**
  - **X-ray Detectors**

- The new capabilities of instrumentation in these fields mean that increasingly throughput is limited by:
  - **Sample exchange**
  - **Evaluation of data quality**
  - **Instrument control (optimised data collection)**
  - **Data handling and archiving**