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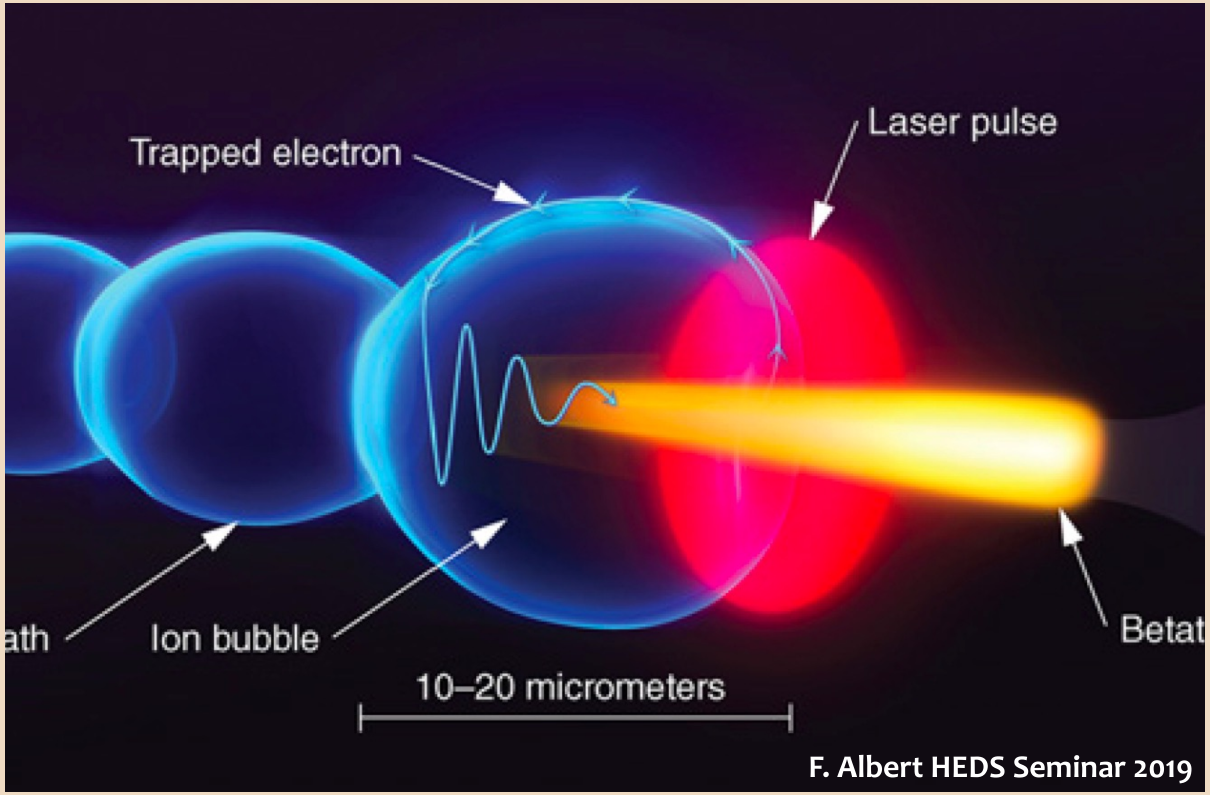
PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources

EuAPS:
User Perspectives



F. Albert HEDS Seminar 2019

A. Balerna

INFN-LNF DAΦNE-Light

EuAPS - EuPRAXIA Advanced Photon Sources
Kick-off meeting 28/02/2023

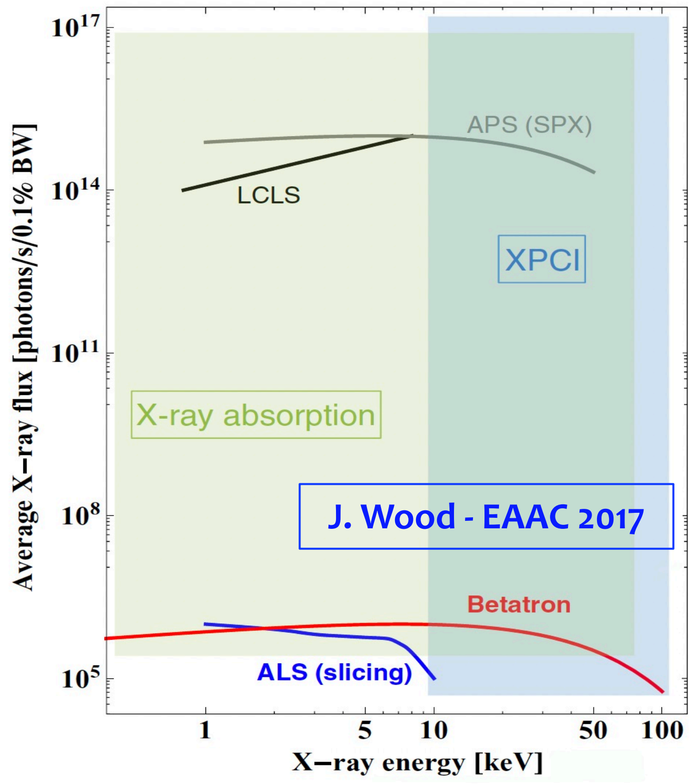
INFN Istituto Nazionale di Fisica Nucleare
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA
Consiglio Nazionale delle Ricerche

Users and a Betatron Radiation X-ray Source

Laser wakefield accelerator based light sources (LWFA) like **betatron radiation sources** have **many potential applications** in different fields like **X-ray phase contrast imaging (XPCI)** and **material science** using different **x-ray spectroscopies** (**XAS** and **XES**). **Improving the properties of betatron radiation sources** can **revolutionize energetic photon sources** in both size and capability, by providing **compact X-ray sources**.

Betatron Radiation can provide:

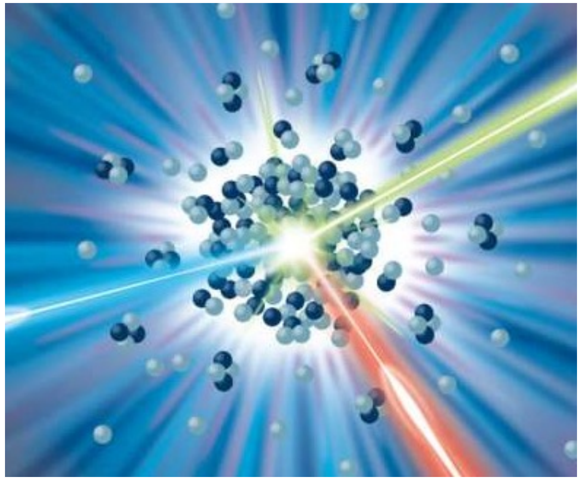
- **Laser pulse duration tens of fs** better **time resolution** compared to synchrotrons and useful for **time resolved experiments.**
- **Broad energy spectrum** very useful for **for material science measurements**.
- **Good average photon flux** useful for **high S/N ratios.**



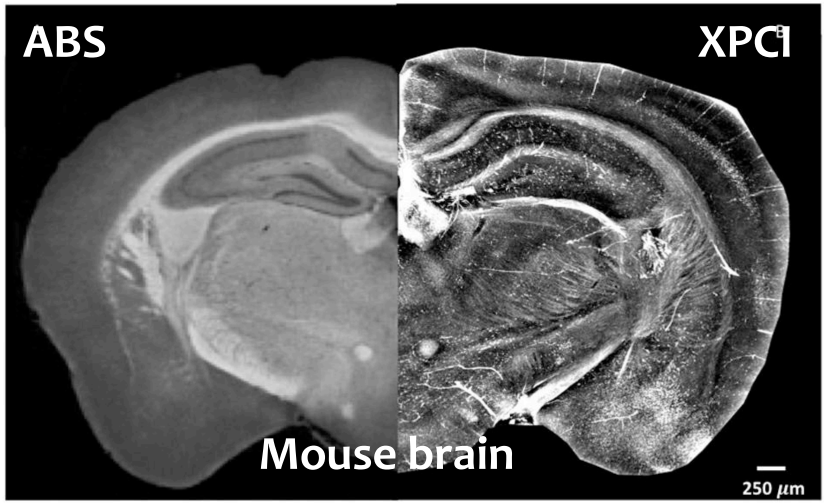
Large request - **50 synchrotron** light sources worldwide, **6 hard XFEL's** and **3 soft-ray** ones (**many accelerators operational and some under construction**).

Why LWFA-based X-ray light sources?

Time resolved X-ray Spectroscopy XAS and XES studies for material science studies at atomic scale.

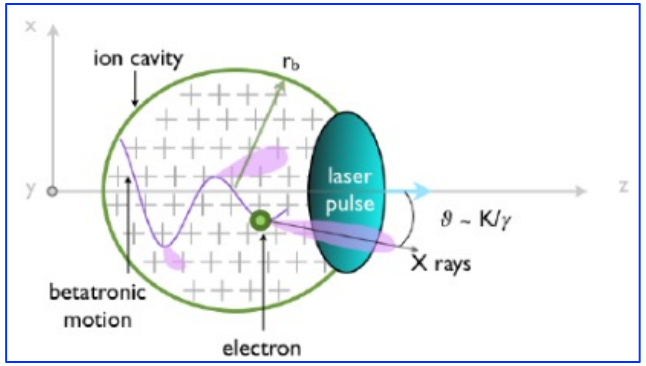


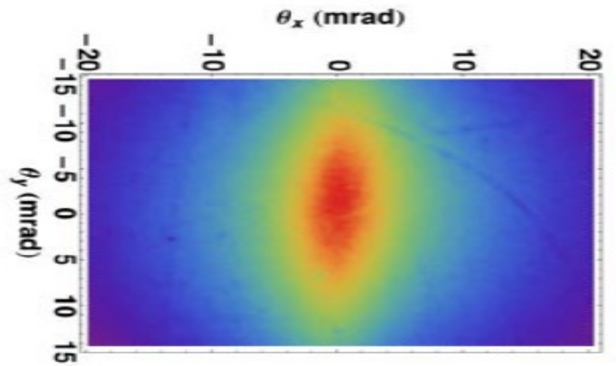
X-ray Phase Contrast Imaging - XPCI



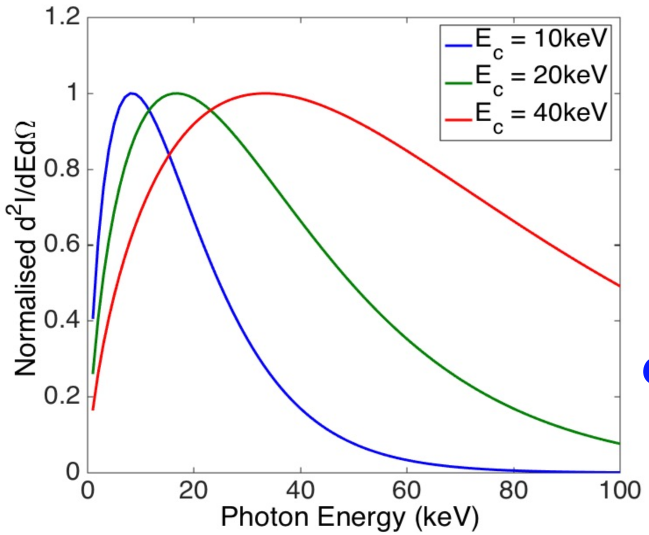
Improving the brightness in betatron experiments will give the possibility to **improve the S/N ratio of XAS measurements** needed (require >10^6 photons/eV) to probe matter and **single-shot image quality**.

Important information for users





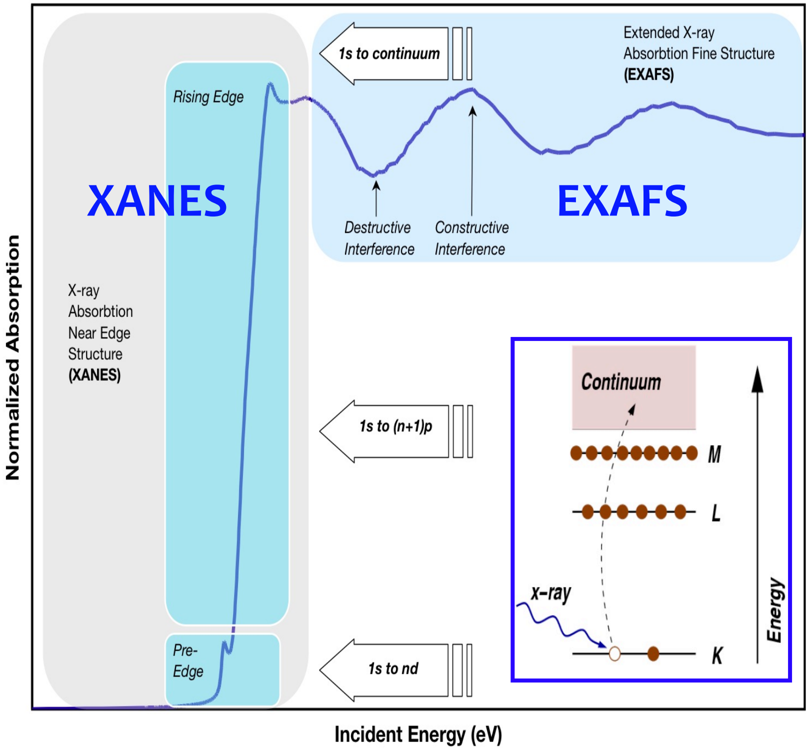
Come from the characterization of the X-ray source:
Source size, divergence, beam position stability and produced X-ray beam spectral-angular correlation.

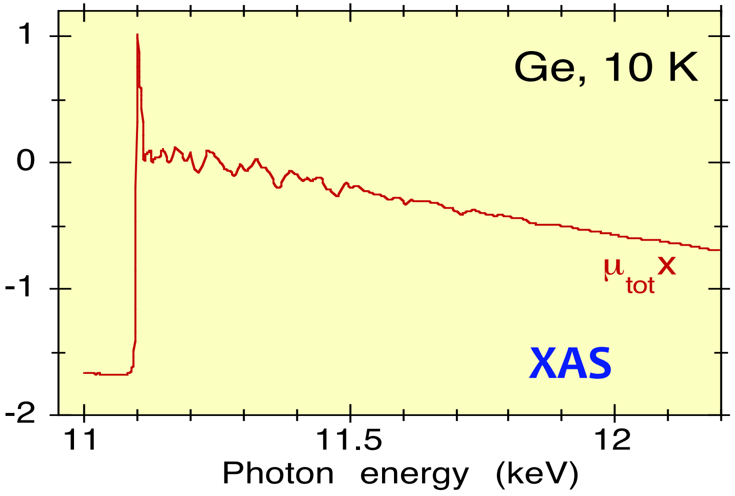


X-ray photons spectrum defined by critical energy

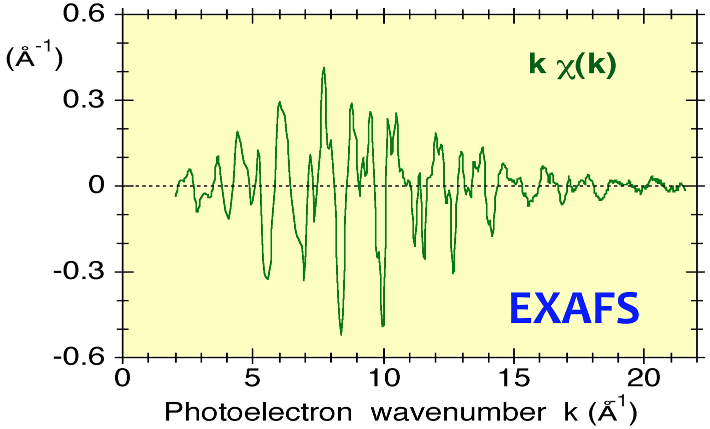
Material Science application
and
X-ray Absorption Spectroscopy (XAS)

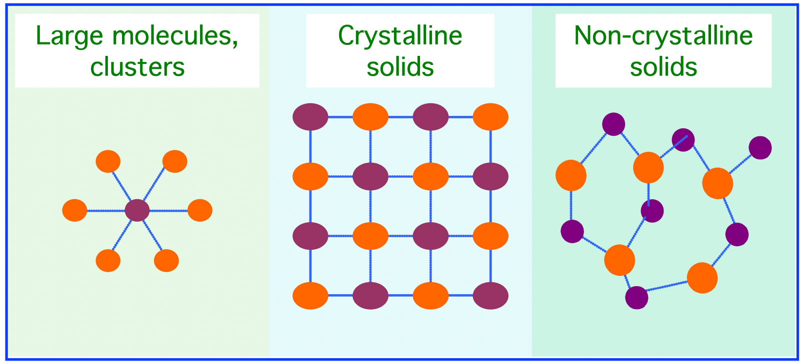
X-ray Absorption Spectroscopy - XAS



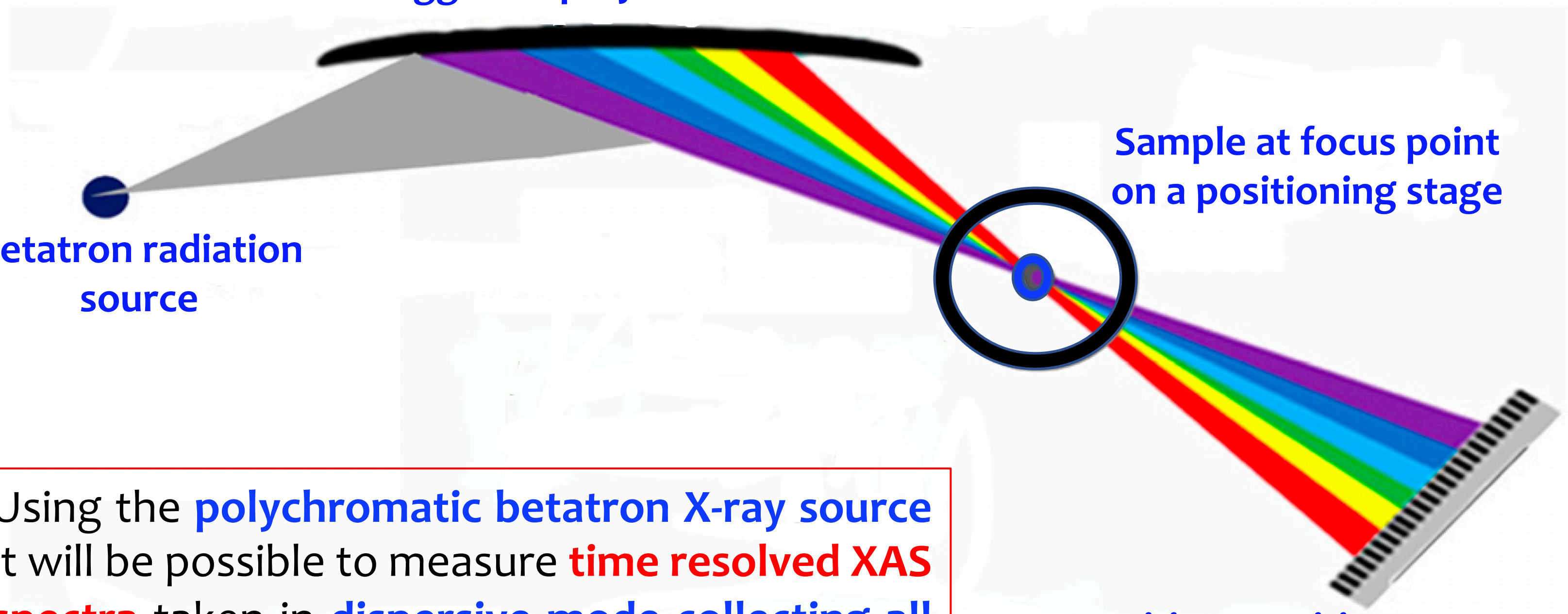


A **XAS spectrum is characterized by an absorption edge followed by oscillations** the **oscillation amplitude** or **EXAFS signal is of the order of a few % of the total absorption signal** (**the edge step**).

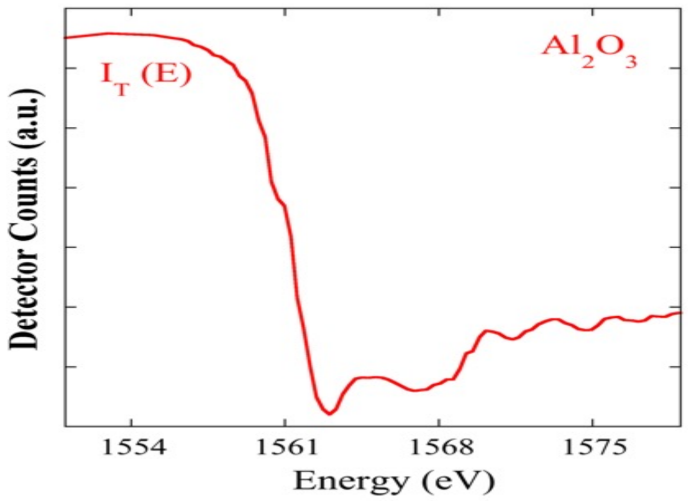




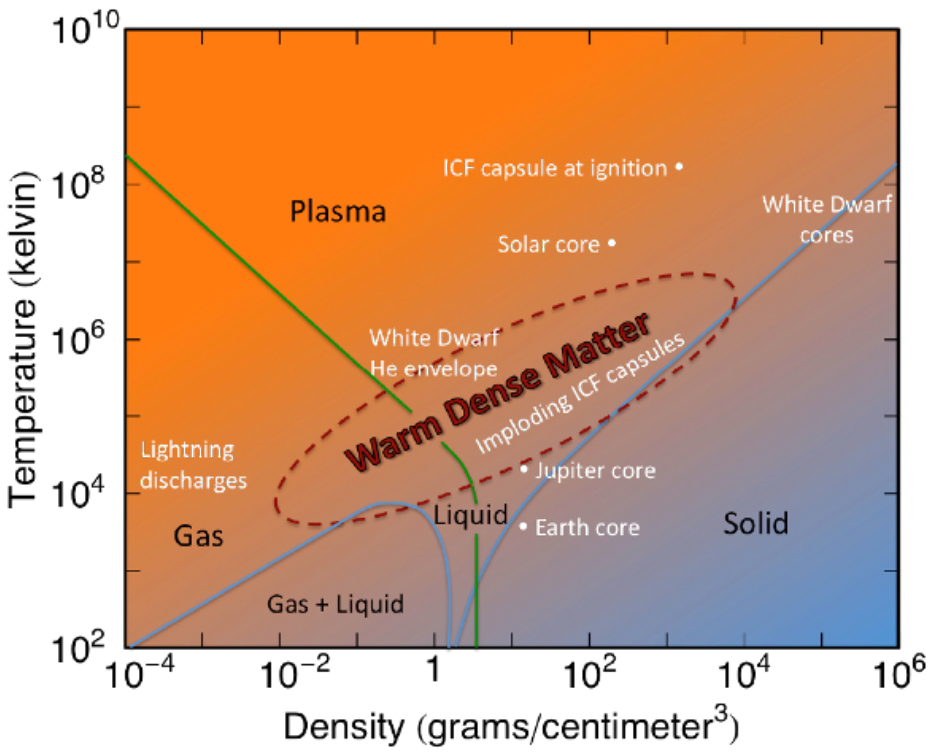
XAS spectra in dispersive mode



Using the **polychromatic betatron X-ray source** it will be possible to measure **time resolved XAS spectra** taken in **dispersive mode collecting all absorption spectra data at the same time**.



Material science application: Warm Dense Matter (WDM)



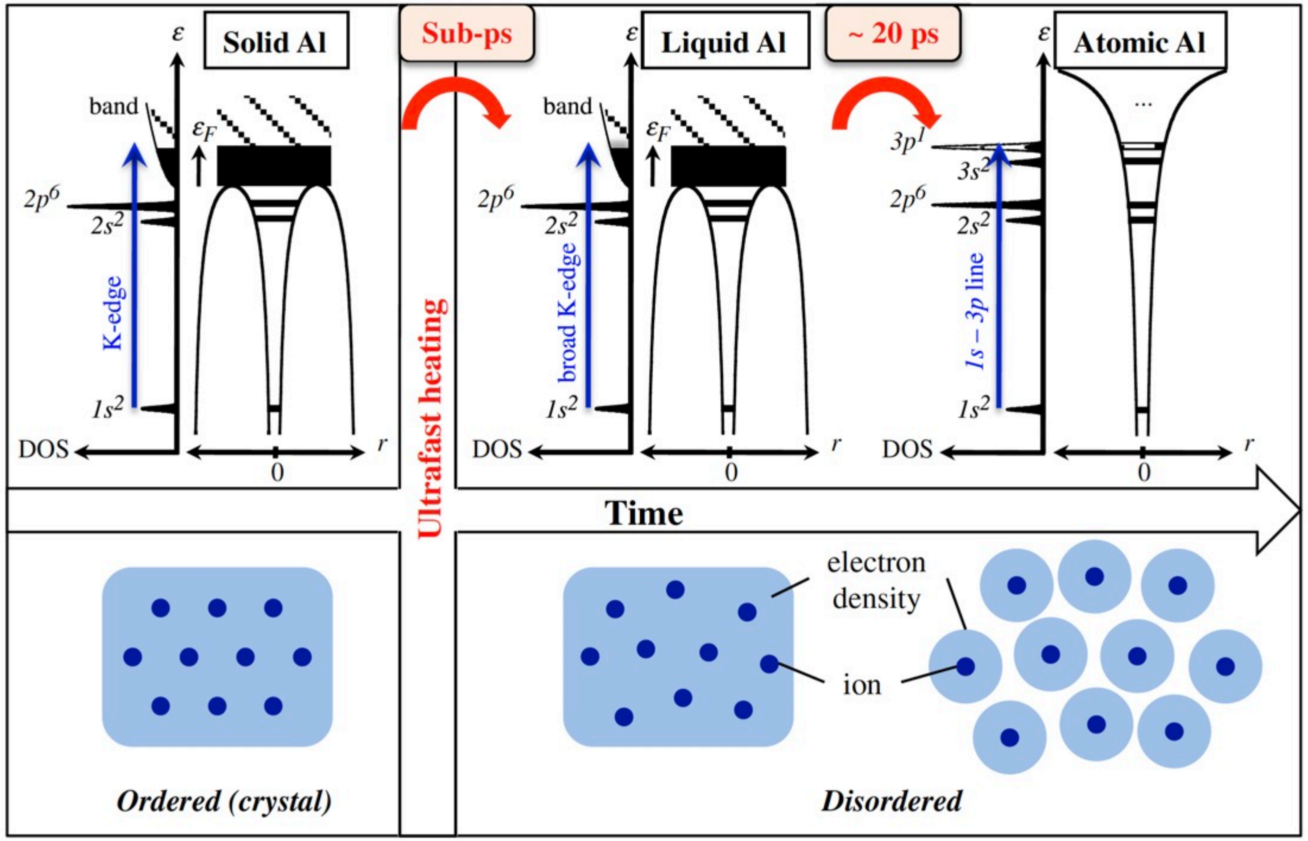
WDM occurs in:

- **Cores of large planets;**
- **Systems that start solid and end as a plasma;**
- **X-ray driven inertial fusion implosion (aspects of indirect-drive inertial fusion).**

The **investigation of such warm dense matter (WDM) is one of the great challenges of contemporary physics**.

Femtosecond lasers can rapidly heat matter, leading to ultrafast solid-liquid-WDM transitions, followed by a more complex **multiphase expansion at a picosecond time scale**. Highly nonequilibrium states of matter are expected, due to the finite rate of energy transfer from the excited electrons to the lattice.

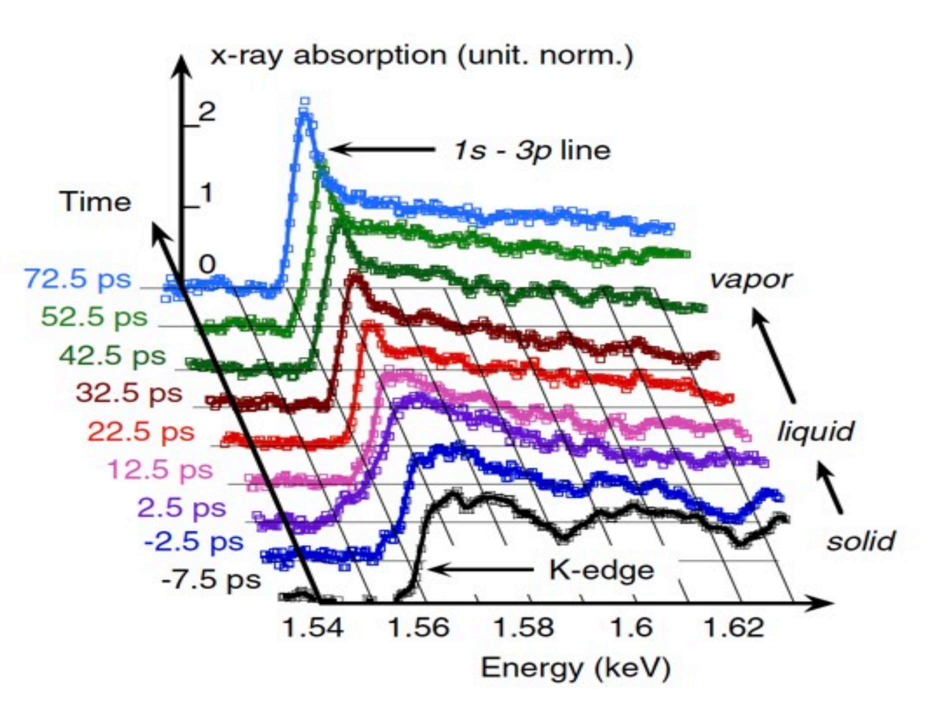
As the atomic structure modification is supposed to be driven by the photoexcited electrons, it is of primary importance to determine the respective time scales of the evolution of both electron and atomic structures.



Schematic of the aluminum solid-liquid-vapor transition dynamics at the atomic level.

- **Solid Al**: in the solid case, the **conduction band is partially occupied by valence electrons up to the Fermi energy EF**, leading to a **sharp x-ray absorption K edge**.
- **Liquid Al**: the laser deposits energy in the valence electrons and induces a **thermal broadening of the band occupation**, **leading to the K-edge broadening**. The **energy is transferred from electrons to the lattice, breaking the crystalline order.**
- **Atomic Al**: due to high thermal pressure, hydrodynamic expansion occurs driving the **transition to atomic vapor**. In **isolated atoms, the electrons are localized on the atomic orbitals**. As the **3p orbital is partially unoccupied, the 1s-3p line can be observed in the x-ray absorption spectrum**.

Double conical crystal x-ray spectrometer for high resolution ultrafast x-ray absorption near-edge spectroscopy of Al K edge



X-ray absorption for the study of warm dense matter Al K edge from 1.50 to 1.75 keV.

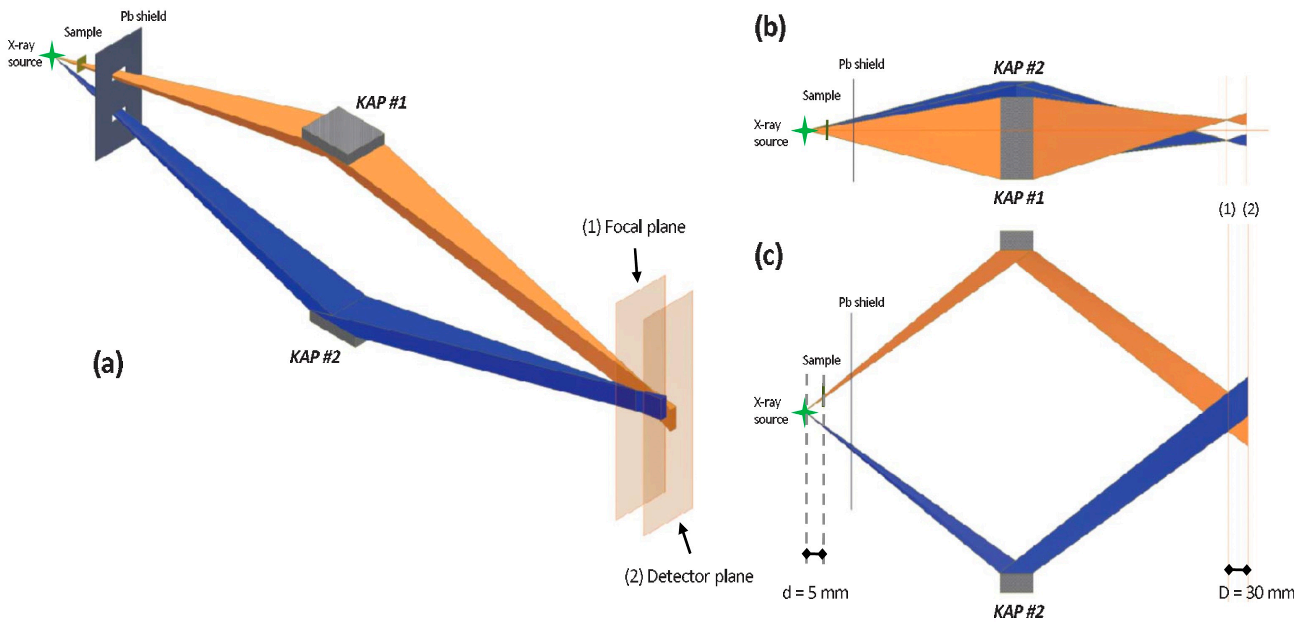
F. Dorchies et al. Phys. Rev. Lett. 107, 245006 (2011); https://doi.org/10.1103/PhysRevLett.107.245006

Double conical crystal x-ray spectrometer for high resolution ultrafast x-ray absorption near-edge spectroscopy of Al K edge

Pump-probe experiment- synchronization with heating laser.

Dispersive system using two conically bent KAP crystals. The main interest of this geometry is the focusing of the signal in a segment orthogonal to the detection axis.

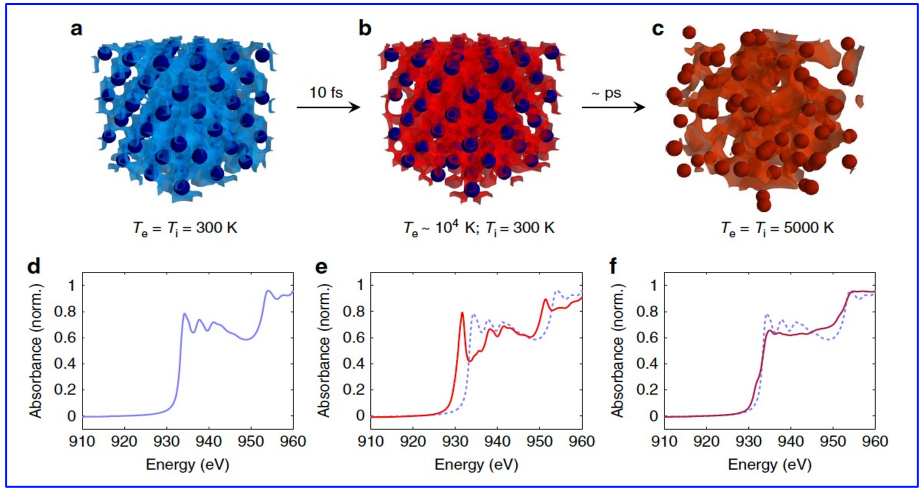
The crystals we used are characterized by the following parameters: a dimension of 50 x 30 mm², and the **upper and lower radii of curvature** are, respectively, **96.04 and 81.27 mm**.
The crystals are positioned at a distance **of 92.8 mm of the horizontal plane containing the x-ray source** and, in consequence, their alignment is optimized **to focus the signal in a plane at a distance** of **60 cm from the source**.



A slight **lateral translation is introduced between the 2 crystals** to **avoid the overlapping** of the two traces in the detection plane Using such spectrometer configuration **record simultaneously the direct emission of the x-ray source** KAP2 as well as **the transmitted spectrum through a sample** KAP1

A. Levy et al. Rev. Sci. Instrum. 81, 063107 (2010); https://doi.org/10.1063/1.3441983

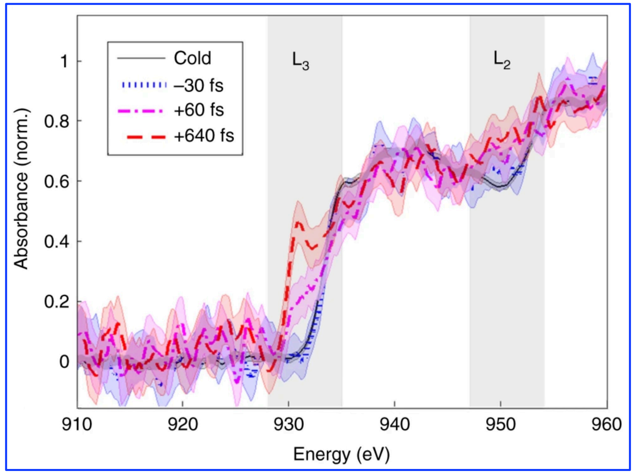
Probing warm dense matter using femtosecond X-ray absorption spectroscopy with a laser-produced betatron source

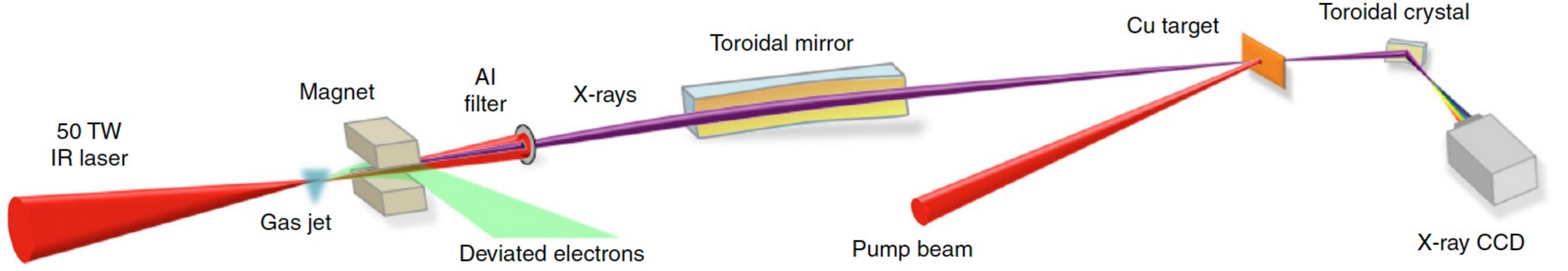


Theory

Cu L- edges

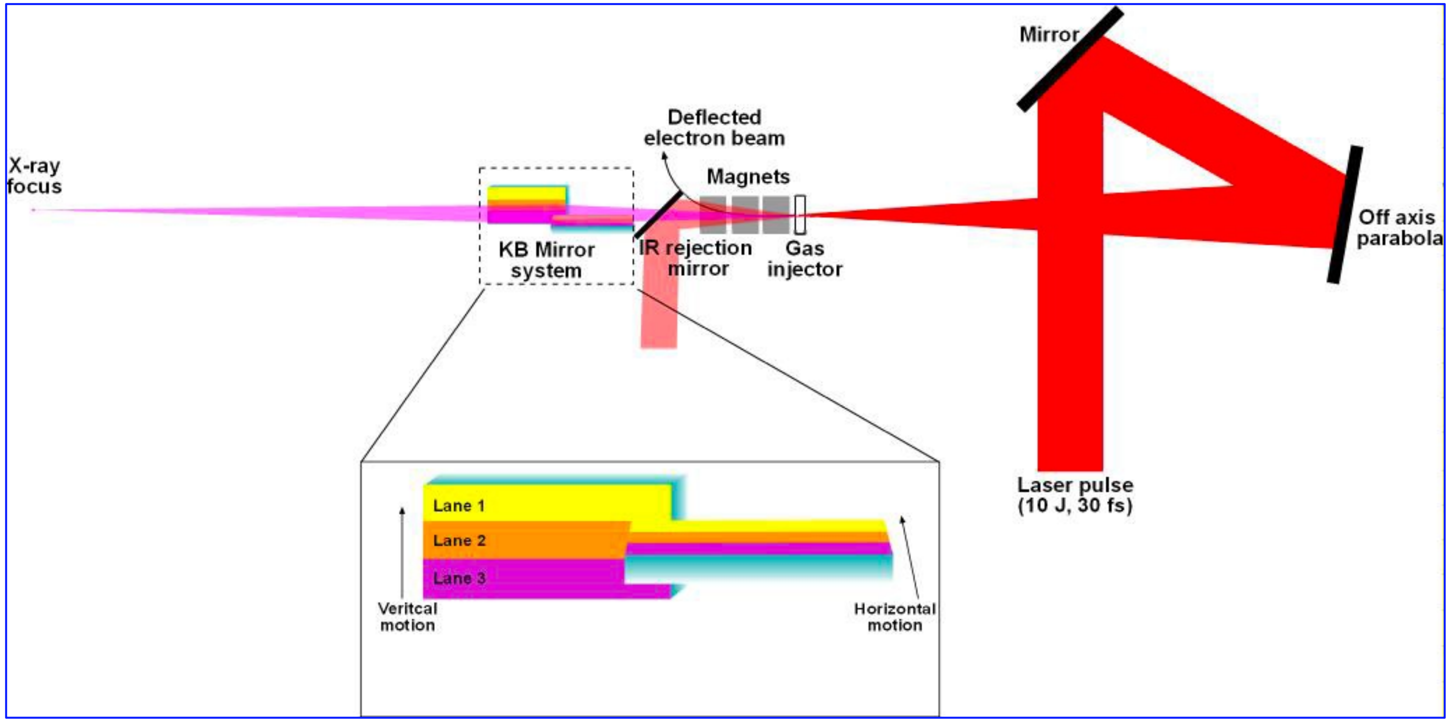
Experiments





B. Mahieu et al.,NATURE COMMUNICATIONS | (2018) 9:3276 | DOI: 10.1038/s41467-018-05791-4

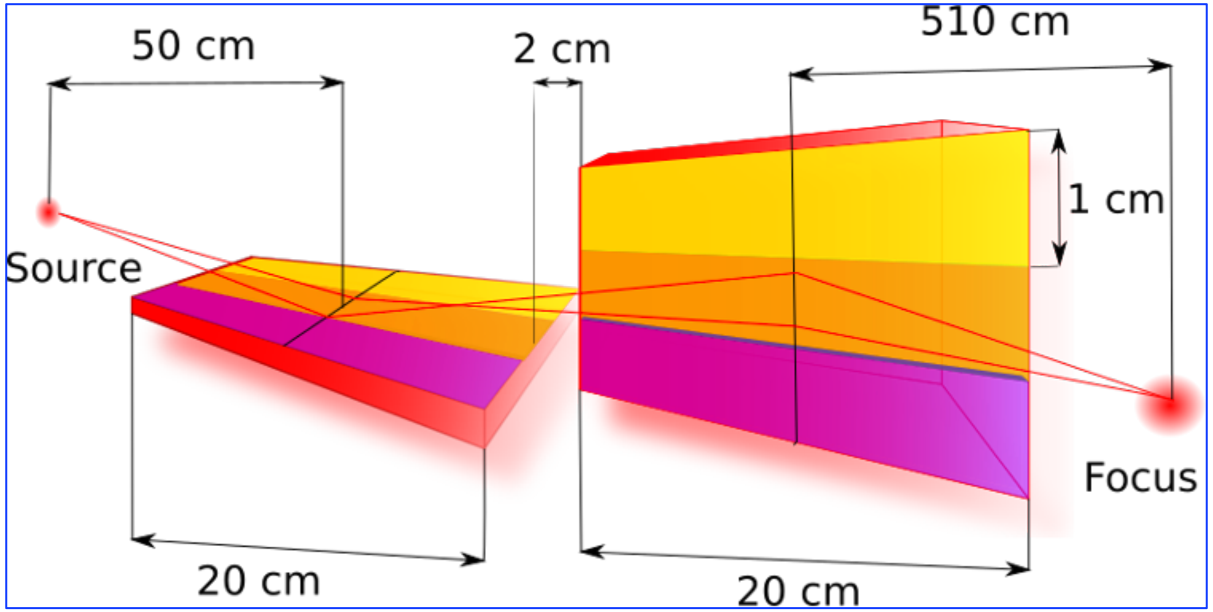
Multi-Lane Mirror for Broadband Applications of the Betatron X-ray Source



While the last decade **mainly focused on the optimization of the source properties**, the development of such sources into user-oriented beamlines in order to explore the potential applications has recently taken off and is expected to grow rapidly. An important aspect in the realization of such beamlines will be the implementation of proper X-ray optics. Here, we present the design of a multi-lane X-ray mirror as a versatile focusing device covering a wide spectral range of betatron X-rays.

M. Raclavský, et al., Photonics 2021, 8, 579. https://doi.org/10.3390/photonics8120579

Multi-Lane Mirror for Broadband Applications of the Betatron X-ray Source



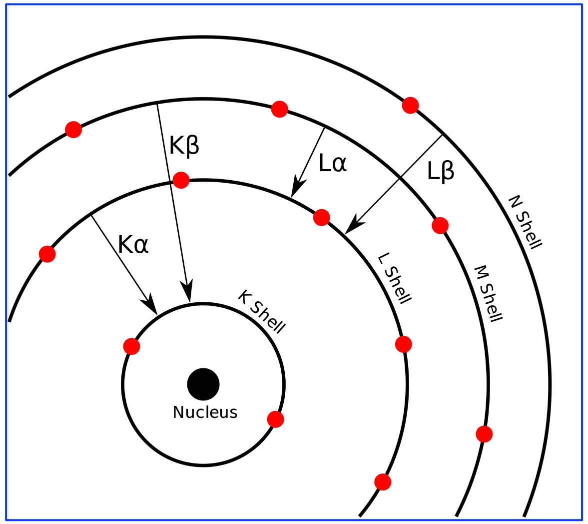
Kirkpatrick-Baez KB mirror system

Table 1. A summary of the coatings used for different lanes of the mirror and the corresponding reflectivity calculated at a grazing incidence angle of 5 mrad.

Lane	Transmission Efficiency (srad)	Layer Thickness Ir/Cr (nm)	Number of Periods	Energy Band (in keV) with Reflectivity > 0.6
1	9.6×10^{-3}	40/10	1	1–15
2	6.1×10^{-3}	5/5	5	15–18
3	6.8×10^{-3}	3.7/3.7	10	18–23

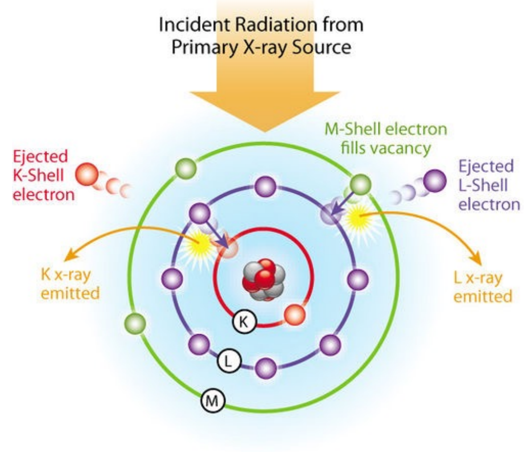
M. Raclavský, et al., Photonics 2021, 8, 579. https://doi.org/10.3390/photonics8120579

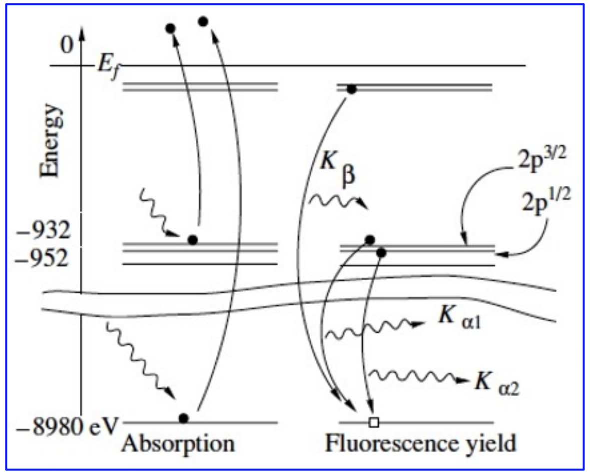
From XAS to XES



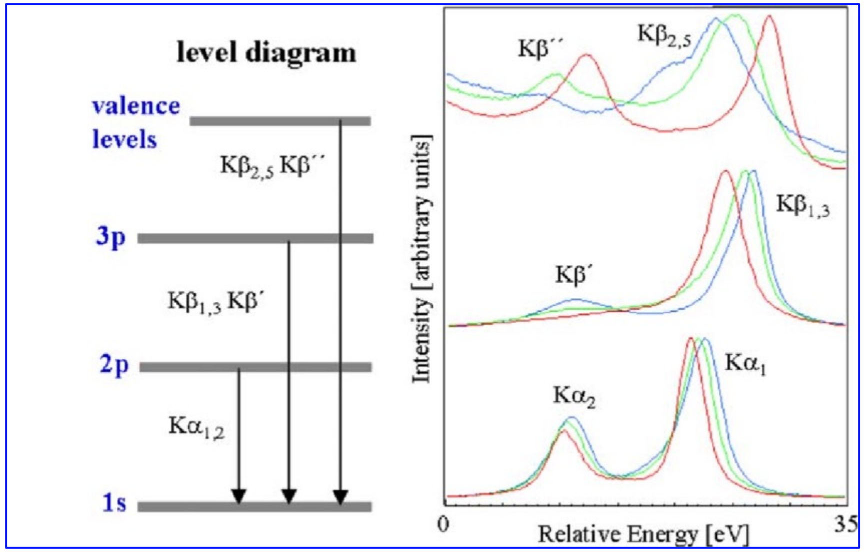
https://en.wikipedia.org/wiki/File:CharacteristicRadiation.svg

XES – X-ray Emission Spectroscopy





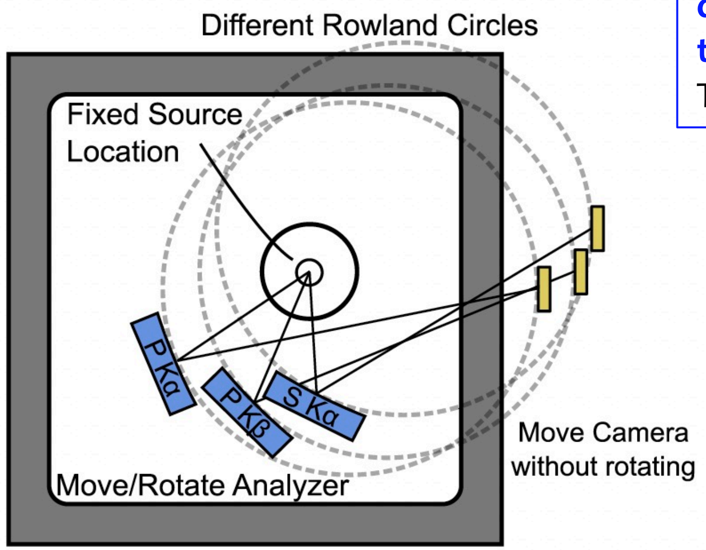
X-ray Emission Spectroscopy (XES) is an element-specific method to **probe the partially occupied electronic structure of materials complementary to XAS**. **X-ray fluorescence lines are measured with a spectral resolution needed to analyse the impact of the chemical environment on the X-ray line energy**. The emitted photon energy represents the energy difference between the electronic levels involved during the excitation. The XES analyses the energy dependence of the emitted X-ray photons by probing the decay process. **These X-ray emission spectra represent partial and local electron density of states due to the electric dipole selection rule**.



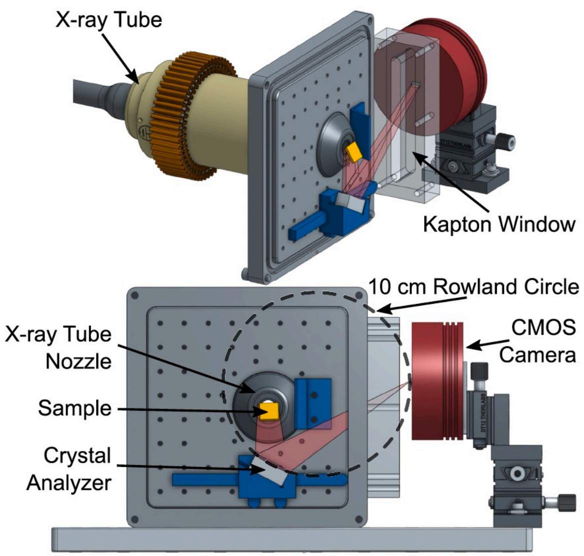
Peak energy position and shape depending on the oxidation state of the atom present in the material studied.

With **low spectral resolution normally K_α and K_β lines are measured** and these lines are only **element specific**. **Increasing the spectral resolution** and being able to **measure $K_{\alpha 1}$ lines and $K_{\beta 1}$ lines also information on the chemical environment** are gained.

A compact dispersive refocusing Rowland circle X-ray emission spectrometer for laboratory, synchrotron, and XFEL applications



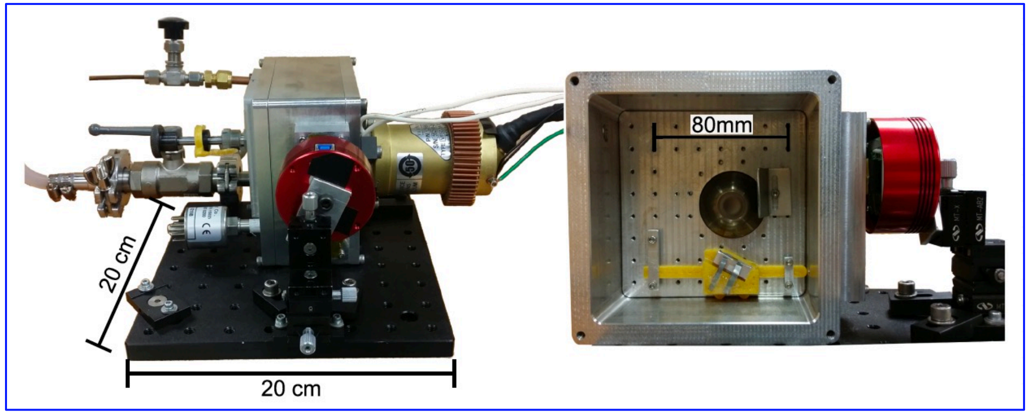
Design and performance of a **compact x-ray emission or XES spectrometer** that uses a **dispersive refocusing Rowland (DRR) circle geometry** to achieve excellent performance **for the 2–2.5 keV range**, i.e., especially for the **K-edge emission from sulphur and phosphorous**. The DRR approach allows **high energy resolution even for unfocused x-ray sources**.

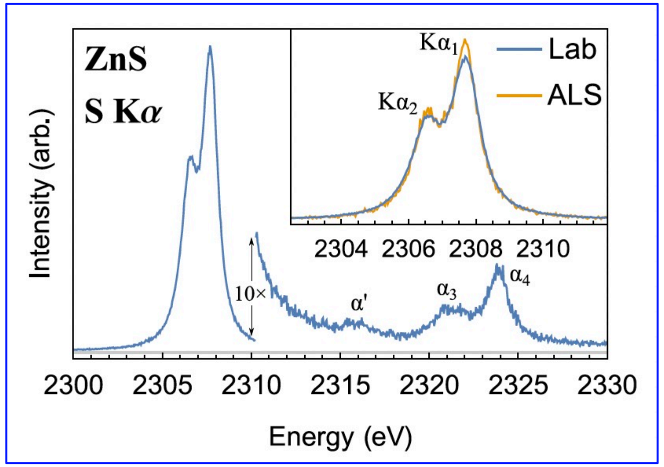


The spectrometer, whose overall scale is set by use of a **10-cm diameter Rowland circle** and a new small-pixel complementary **metal-oxide-semiconductor x-ray camera**, is easily **portable to synchrotron or x-ray free electron laser beamlines**.

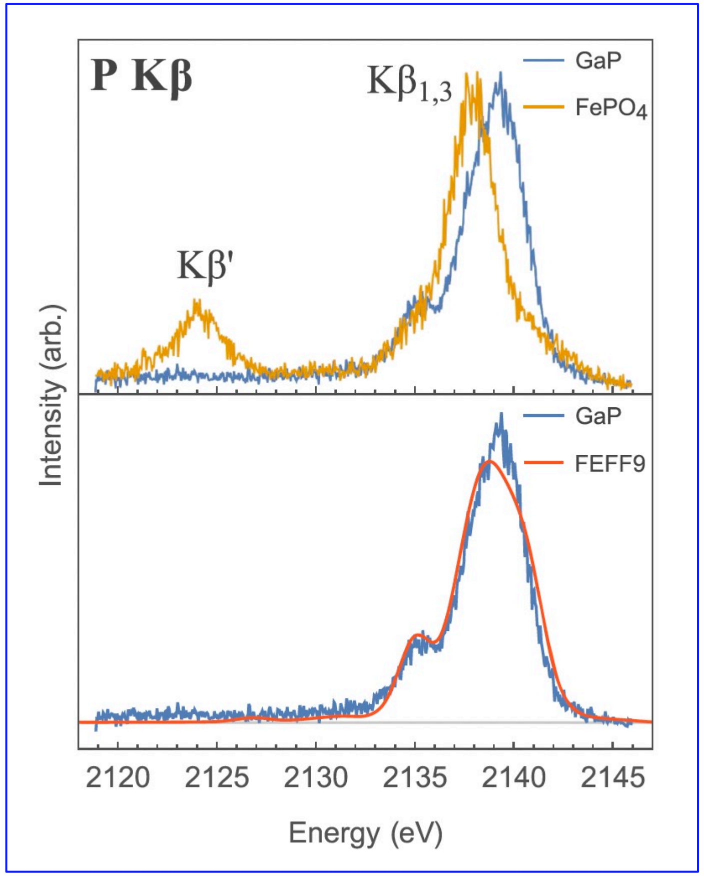
M. Holden Rev. Sci. Instrum. 88, 073904 (2017); https://doi.org/10.1063/1.499473

A compact dispersive refocusing Rowland circle X-ray emission spectrometer for laboratory, synchrotron, and XFEL applications





Sulphur $K_{\alpha 1}$ lines



M. Holden Rev. Sci. Instrum. 88, 073904 (2017);
https://doi.org/10.1063/1.499473

From X-ray spectroscopies to X-ray Imaging

Betatron Radiation and X-ray Imaging applications:
-Phase-Contrast Radiography
-Microcomputed Tomography

X-ray phase contrast imaging - XPCI

One particular area for XPCI with betatron radiation could be ultrafast x-ray imaging with femtosecond resolution.

Except XFEL sources, betatron radiation offers the best time resolution ever achieved for XPCI.

To generate a single-shot image, a large photon number is required. Therefore, for a low noise image the number of photons per shot should be $N >> 10^6$, assuming the x-rays uniformly fill the detector and are detected. In practice $N >> 10^8$ is more realistic, given non-uniformities, overfill and detection efficiency.

Phase contrast imaging is approximately a thousand times more sensitive than absorption contrast, but the advantage over absorption contrast will be more prominent in the hard x-ray region.

Although it is not monochromatic, betatron radiation already achieves performances sufficient for XPCI.

F. Albert et al. Plasma Phys. Control. Fusion 56 (2014) 084015

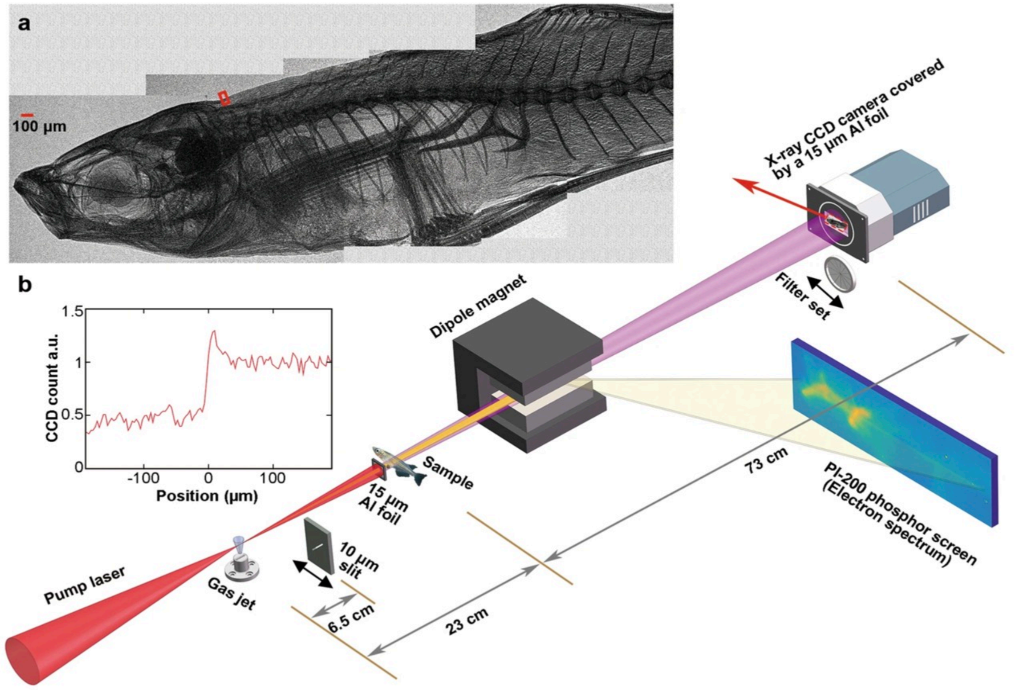
High-resolution phase-contrast imaging of biological specimens using a stable betatron X-ray source in the multiple-exposure mode

Highly stable multiple-exposure betatron source, with an **effective average source size of 5 µm**, photon number fluctuation better than 5% and spectral fluctuation better than 10%, can be obtained by utilizing ionization injection in pure nitrogen plasma using a 30–40 TW laser.

Using this source, **high quality phase-contrast images of biological specimens with a 5-µm resolution are obtained** for the first time.

High resolution phase-contrast imaging with stable betatron sources using modest power, high repetition-rate lasers.

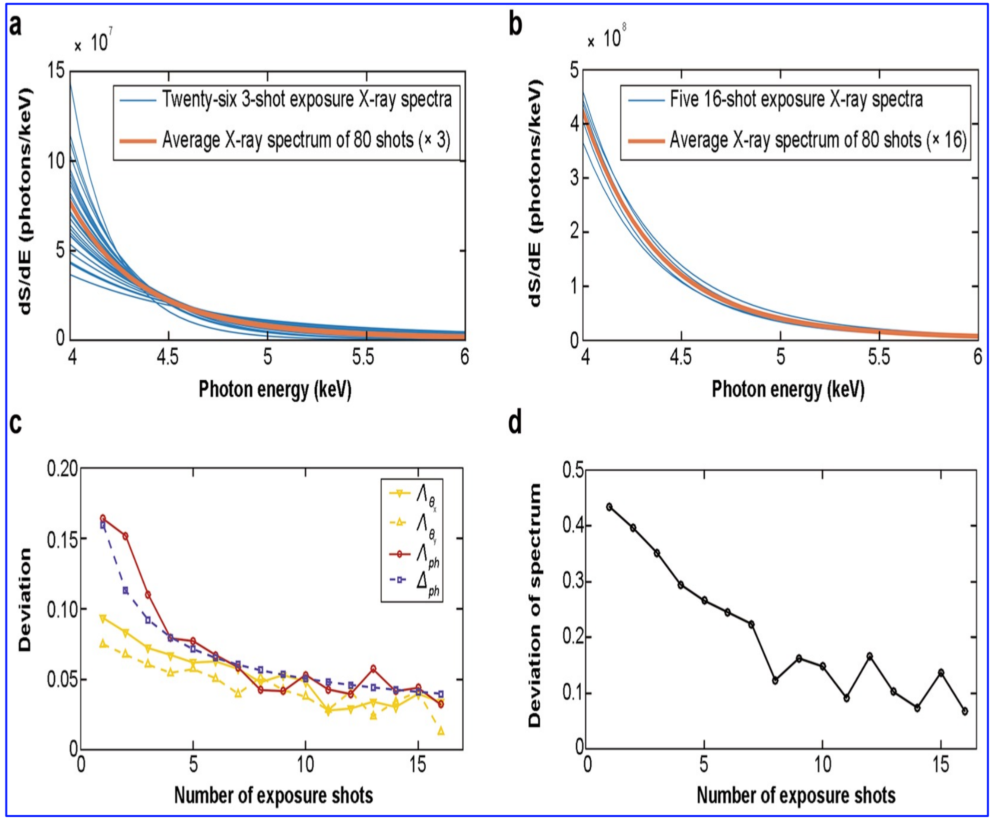
PCI image was obtained within 1 minute at a repetition rate of ~0.3 Hz (30 s for the butterfly, 60 s for the fish), **with a photon number of 1.1 x 10^7 per shot.** This **data acquisition time can be significantly reduced in future experiments** by a factor of 10–300, through **single shot photon number enhancement** (10 times enhancement under similar conditions has been recently demonstrated) and **repetition rate increasing to 1 Hz to 10 Hz.**

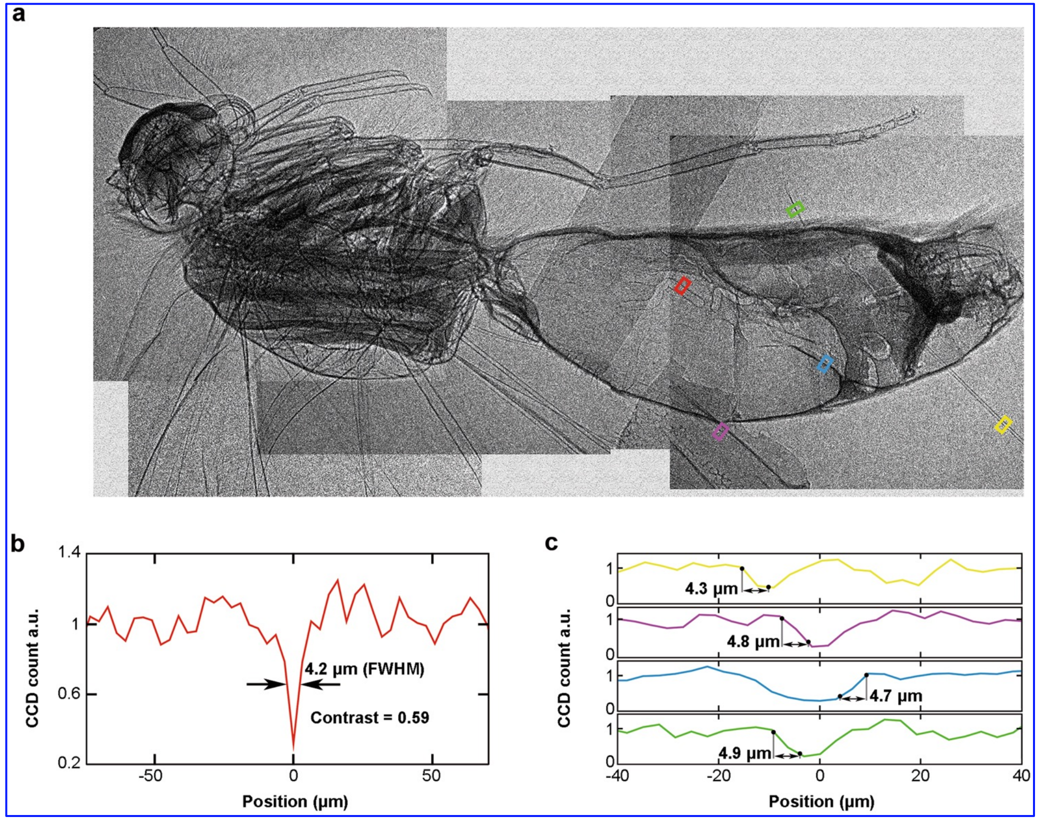


Schematic of the in-line phase-contrast imaging experimental layout. (**a**) A phase-contrast image of a small fish (1-cm long). The whole image was generated by 5 sub-images taken separately, and each sub-image was obtained by accumulation of 20 exposures. (**b**) Edge lineout for the back-fin marked by small red box in (**a**) showing a clear edge enhancement characteristic of PCI.

B. Guo et al., Sci. Rep. (2019) 9:7796 https://doi.org/10.1038/s41598-019-42834-2

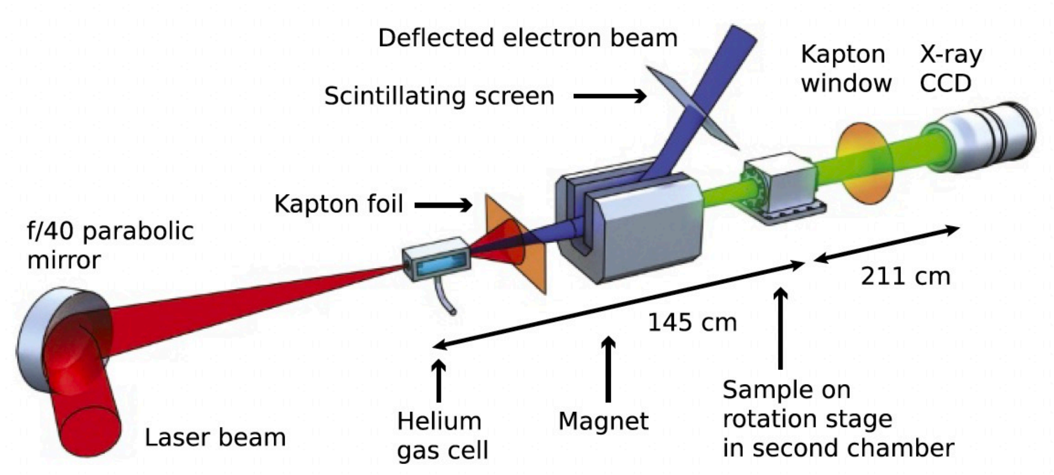
High-resolution phase-contrast imaging of biological specimens using a stable betatron X-ray source in the multiple-exposure mode





B. Guo et al., Sci. Rep. (2019) 9:7796 https://doi.org/10.1038/s41598-019-42834-2

High-resolution μCT of a mouse embryo using a compact laser-driven X-ray betatron source



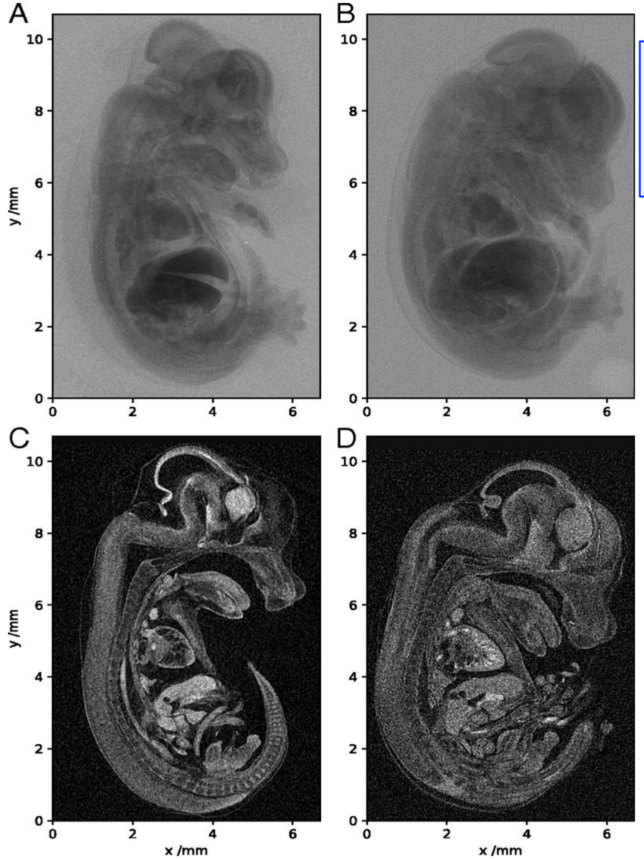
In the field of **X-ray microcomputed tomography** (μCT) there is a **growing need to reduce acquisition times at high spatial resolution** (approximate micrometres) to facilitate in vivo and **high-throughput operations**.

J. M. Cole et al., PNAS 2018

Significance

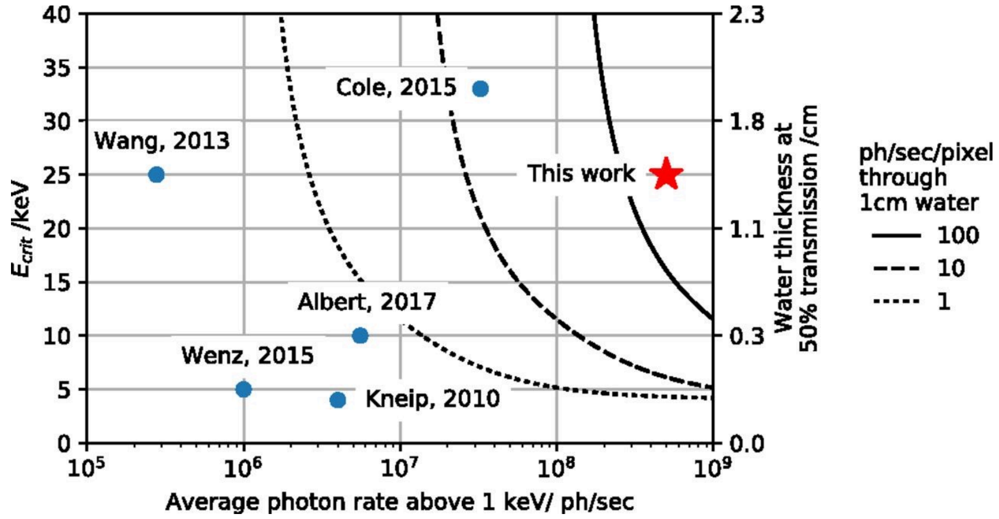
High-resolution microcomputed tomography with **benchtop X-ray sources requires long scan times because of the heat load limitation on the anode.** An alternative, **high brightness plasma-based X-ray sources that do not suffer from this restriction.** A demonstration of tomography of a centimetre-scale complex organism achieves equivalent quality to a commercial scanner. **Soon it will be possible to record such scans in minutes, rather than the hours required by conventional X-ray tubes**.

High-resolution μCT of a mouse embryo using a compact laser-driven X-ray betatron source



J. M. Cole et al. PNAS 2018

Single X-ray projections (**A and B**) and sagittal slices from 3D reconstruction (**C and D**). A and C were acquired with the laser-betatron source and B and D with a commercial microfocus scanner.



The average photon flux and characteristic energy of the X-ray source described here in comparison with previous results on laser-betatron X-ray sources giving and idea of the improvements.

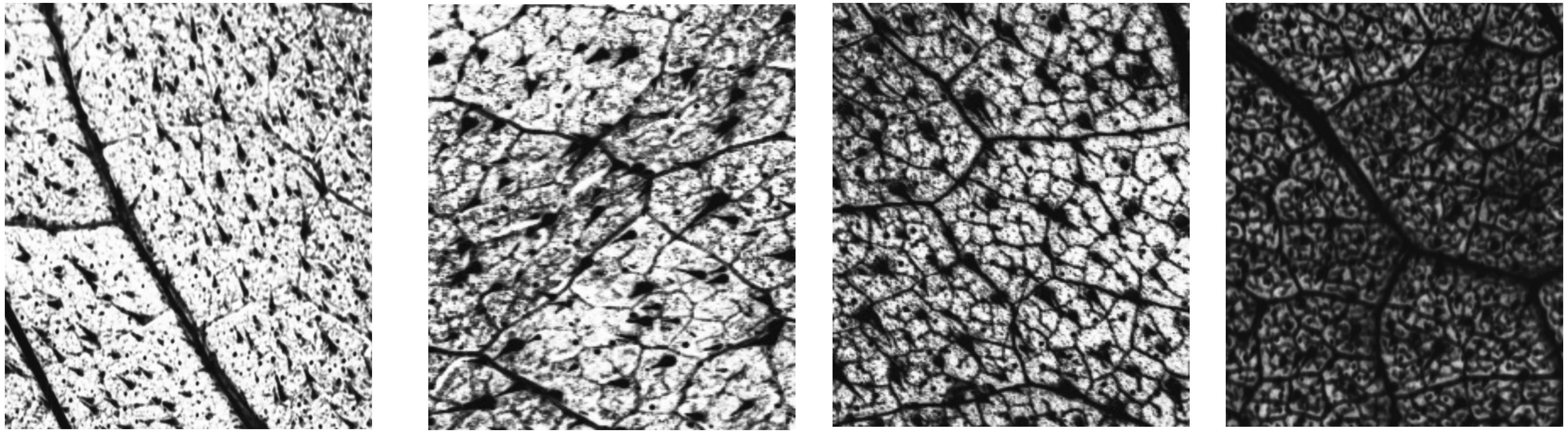
Applications using X-rays at EuAPS

Things to do in the near future

- Follow the characterization of the betatron X-ray source
- Define the first scientific case
- Define the elements (filters, focussing optics if needed, sample environment including movements, dispersive optics, detectors) needed for the X-ray beamline and the space requirements
- Go on following the presented roadmap (A. Cianchi).

Applications using X-rays at EuAPS

First ideas: Phase contrast imaging on leaves doped with metals as contaminants?



Images obtained for Cd doped leaves. The first image is the control sample (without treatment). The other represent the treatment with different concentrations of contaminants: 1 mM, 5 mM and 10 mM.

A. Reale et al. - MIDIX Soft X-rays microradiography

Thank you for your attention