The EuPRAXIA users' facilities

Francesco Stellato

University of Rome Tor Vergata & INFN

on behalf of the ***EuPRAXIA collaboration team***

(not only) photon sources @ EuPRAXIA

- **EuPRAXIA-PP**

  Photon and particle sources based on novel (plasma) acceleration techniques

- **Free Electron lasers: EuPRAXIA@SPARC_LAB**

  AQUA – water window FEL beamline

  ARIA - VUV FEL beamline

- **Betatron source**

(not only) photon sources @ EuPRAXIA

- **EuPRAXIA-PP**

  Photon and particle sources based on novel (plasma) acceleration techniques

- **Free Electron lasers: EuPRAXIA@SPARC_LAB**

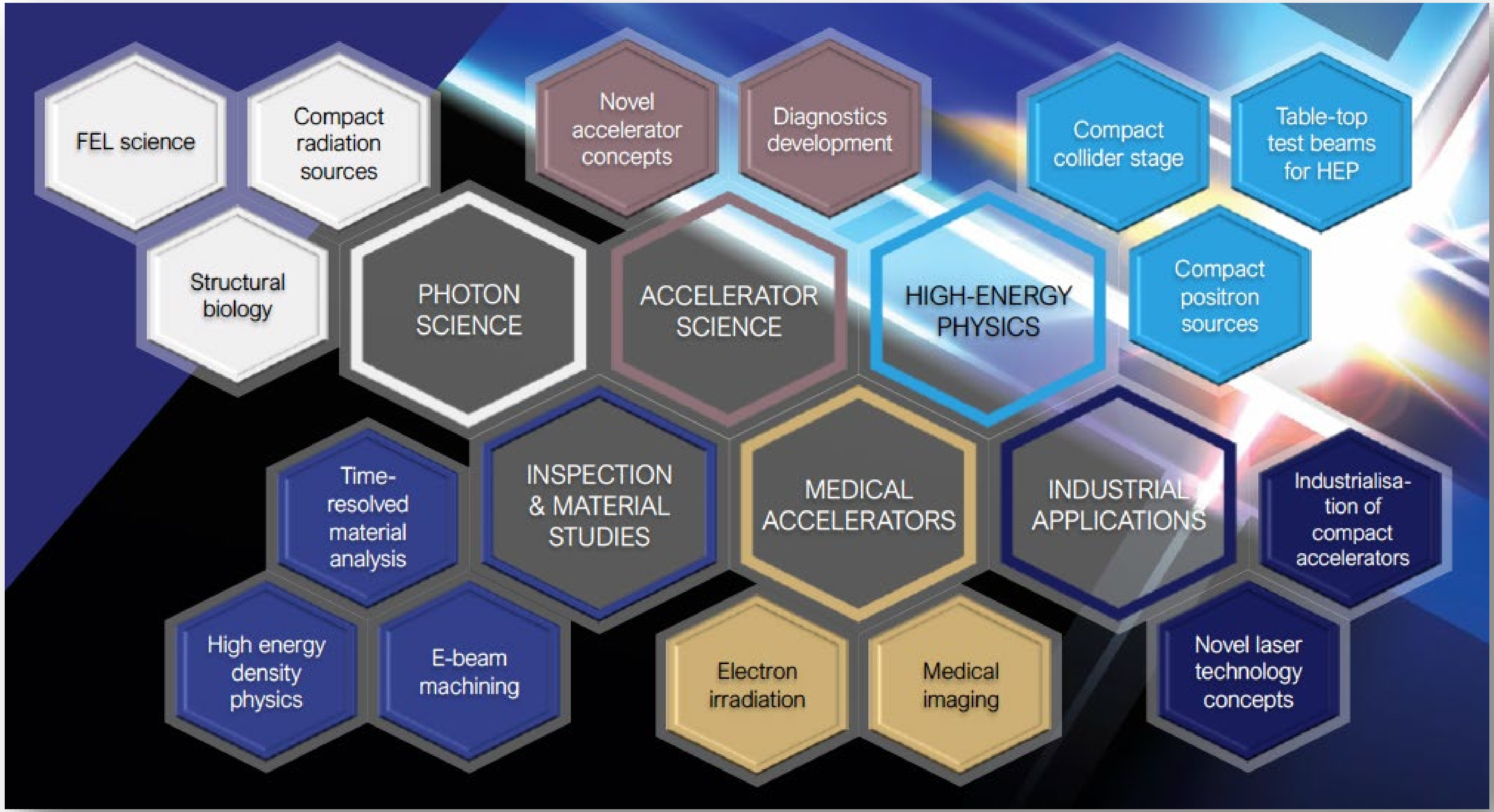
  AQUA – water window FEL beamline

  ARIA - VUV FEL beamline

- **Betatron source**

The EuPRAXIA users' program

- Electrons
  (0.1-5 GeV, 30 pC)
- Positrons
  (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers
  (100 J, 50 fs, 10-100 Hz)
- X-band RF Linac
  (60 MV/m , up to 400 Hz)
- Plasma Targets
- **Betatron X rays**
  (1-10 keV, 10^{10})
- **FEL light**
  (0.2-36 → 200 nm, 10^9-10^{13})

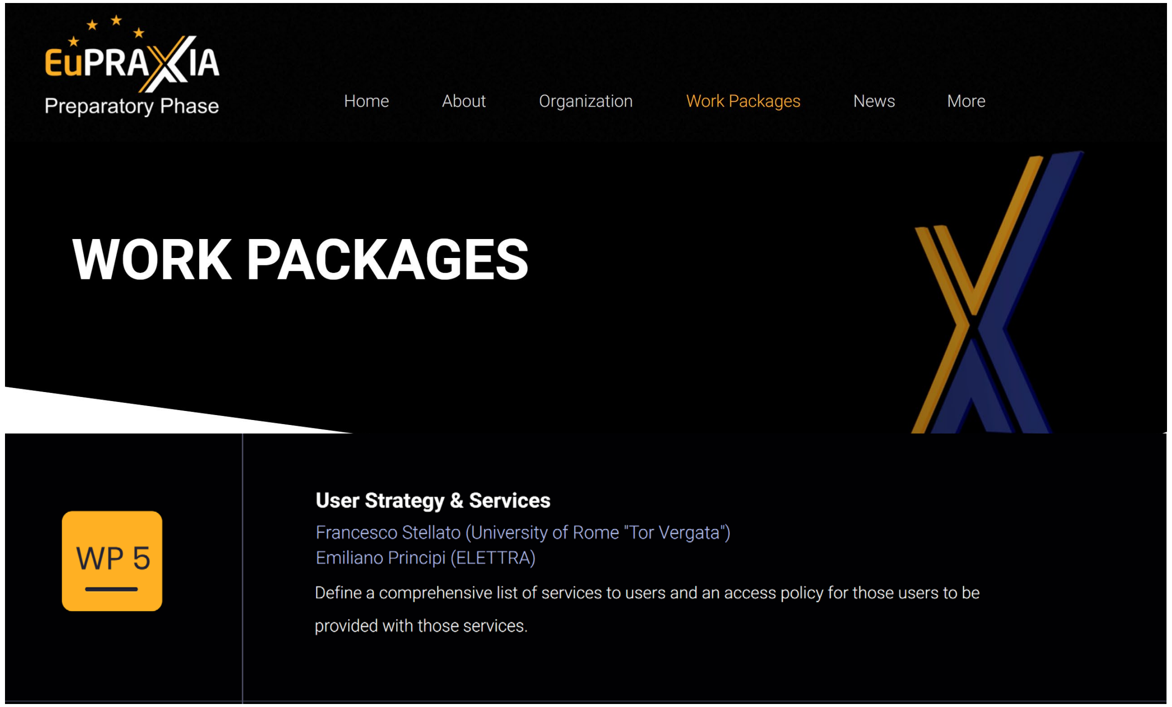


https://www.eupraxia-pp.org/

Courtesy M. Ferrario

Building up a users' community

Collecting needs of the future users' community
(both on the scientific and on the organization side)



Please do help us by filling **this survey**

https://surveys.infn.it/index.php/718177

(not only) photon sources @ EuPRAXIA

- EuPRAXIA-PP

  Photon and particle sources based on novel (plasma) acceleration techniques

- **Free Electron lasers: EuPRAXIA@SPARC_LAB**

  AQUA – water window FEL beamline

  ARIA - VUV FEL beamline

- Betatron source

FEL Photon beams parameters

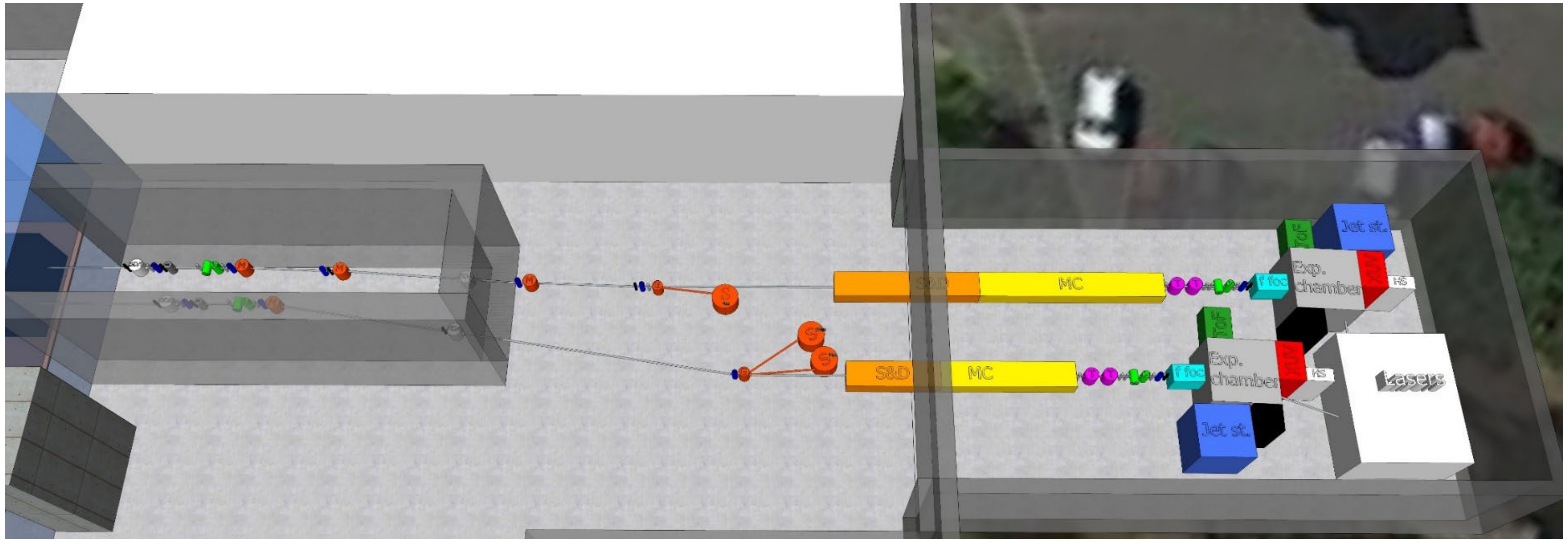
AQUA

Parameter	Value
Wavelength*	~4 nm
Photons/pulse	$10^{10} - 10^{11}$
Pulse duration	< 50 fs
Repetition rate**	10 Hz

ARIA

Parameter	Value
Wavelength	50-180 nm
Photons/pulse	$10^{13} - 10^{14}$
Pulse duration	20/200 fs
Repetition rate**	10 Hz

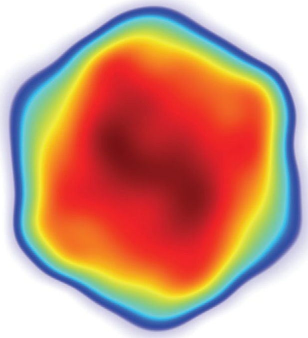
*Running at longer wavelength (~10 nm) is within the reach of the machine
** Options to run @ 400 Hz are being explored



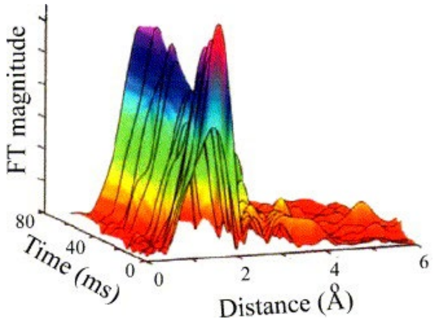
AQUA - Techniques & Samples in the water window

Experimental techniques and typology of samples

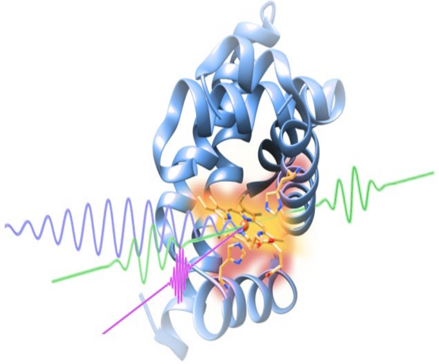
Coherent imaging
(advanced methods)



X-ray spectroscopy



Raman spectroscopy



Proteins
Viruses
Bacteria
Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules
Organometallic compounds

Ion Spectroscopy → **Destruction without diffraction** ???

Balerna *et al.* Cond. Mat. 2022

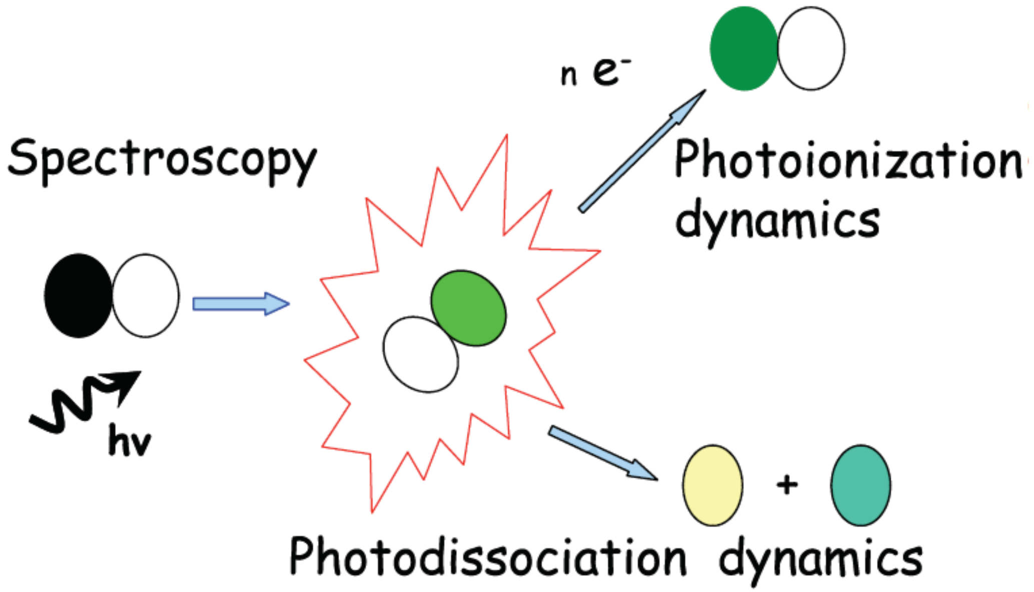
ARIA - Techniques & Samples @ 50-180 nm

Experimental techniques and typology of samples (and applications)

Photoemission Spectroscopy

Raman spectroscopy

Photo-fragmentation of molecules
Time of Flight Spectroscopy



Gas phase & Atmosphere
(Earth & Planets)
Aerosols
(Pollution, nanoparticles)
Molecules & gases
(spectroscopies, time-of-flight)
Proteins
(spectroscopies)
Surfaces
(ablation e deposition)

Villa *et al.* Cond. Mat. 2022

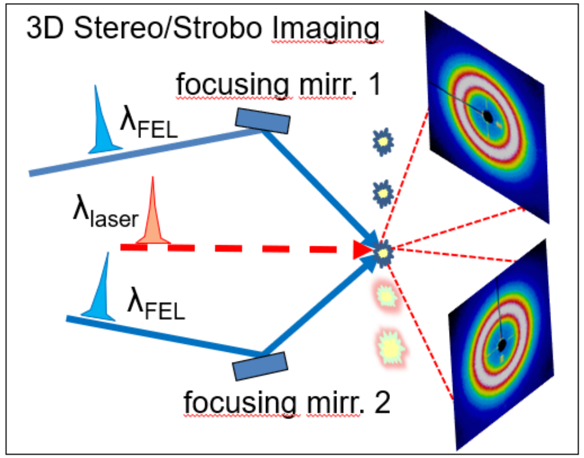
Experimental Techniques

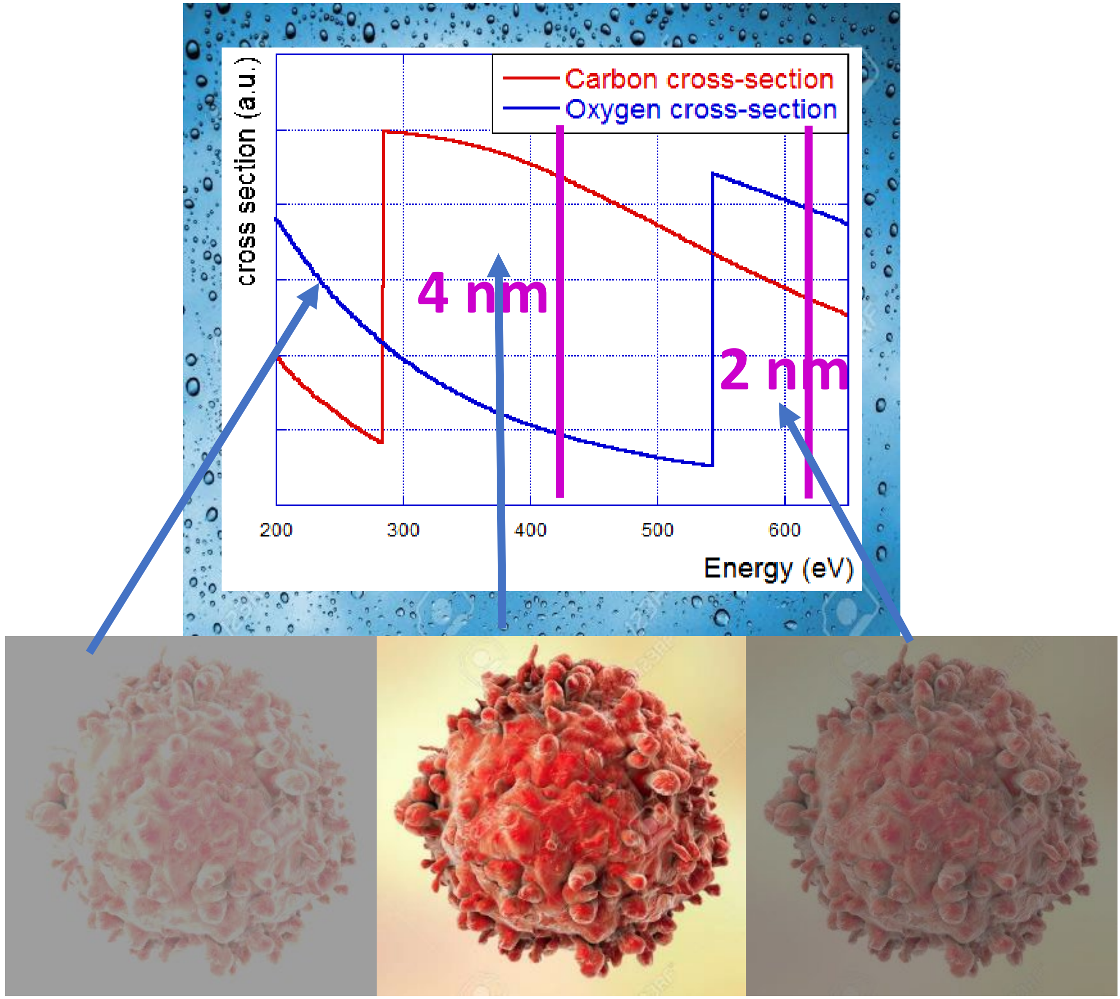
Experimental Techniques
Coherent imaging

The water window is a «sweet spot» for imaging of biological samples in their native environment.

The expected resolution is tens of nanometers
However, only room-temperature measurements of fully hydrated samples allow aquiring 2D images of **living cells** and of **organelles** in their native state

Single-shot 3D imaging of not-reproducible samples





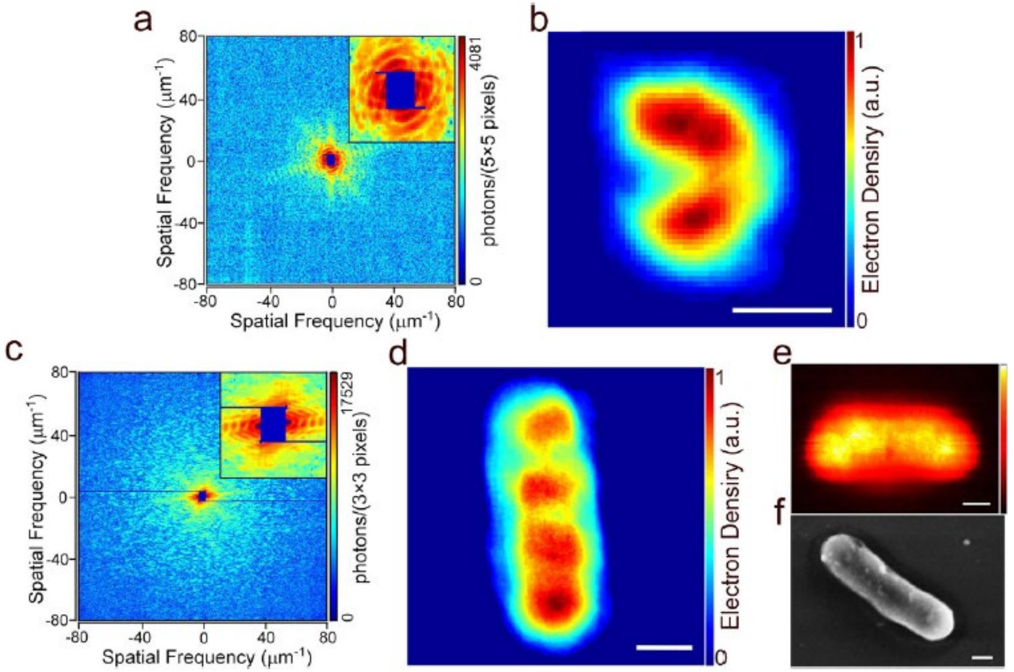
Experimental Techniques
Coherent imaging

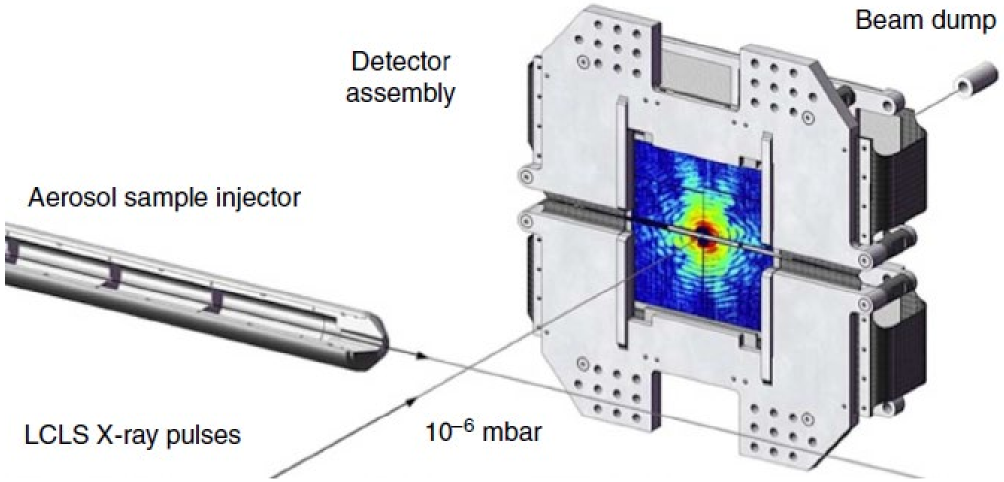
Images of living bacteria have been acquired at SACLA (*S. aureus*, 5.5 keV)

Fan, J., Sun, Z., Wang, Y., Park, J., Kim, S., Gallagher-Jones, M., ... & Jiang, H. (2016). Single-pulse enhanced coherent diffraction imaging of bacteria with an X-ray free-electron laser. *Scientific Reports*, *6*(1), 34008.

and LCLS (*C. gracile*, 517 eV)

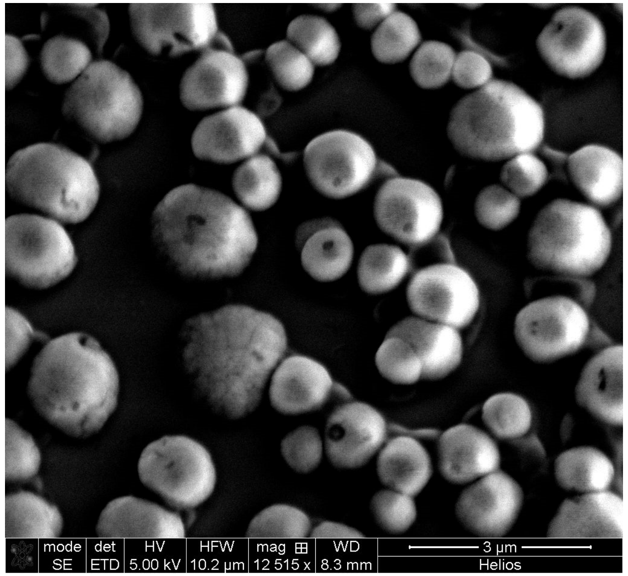
Van Der Schot, G., Svenda, M., Maia, F. R., Hantke, M., DePonte, D. P., Seibert, M. M., ... F. Stellato, ... & Ekeberg, T. (2015). Imaging single cells in a beam of live cyanobacteria with an X-ray laser. *Nature communications*, *6*(1), 5704.





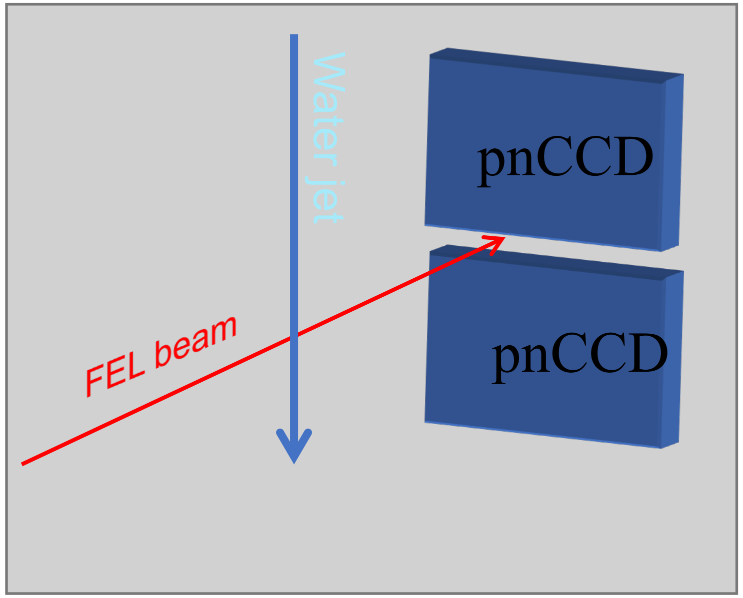
EuPRAXIA@SPARC_LAB

Experimental Techniques
Coherent imaging

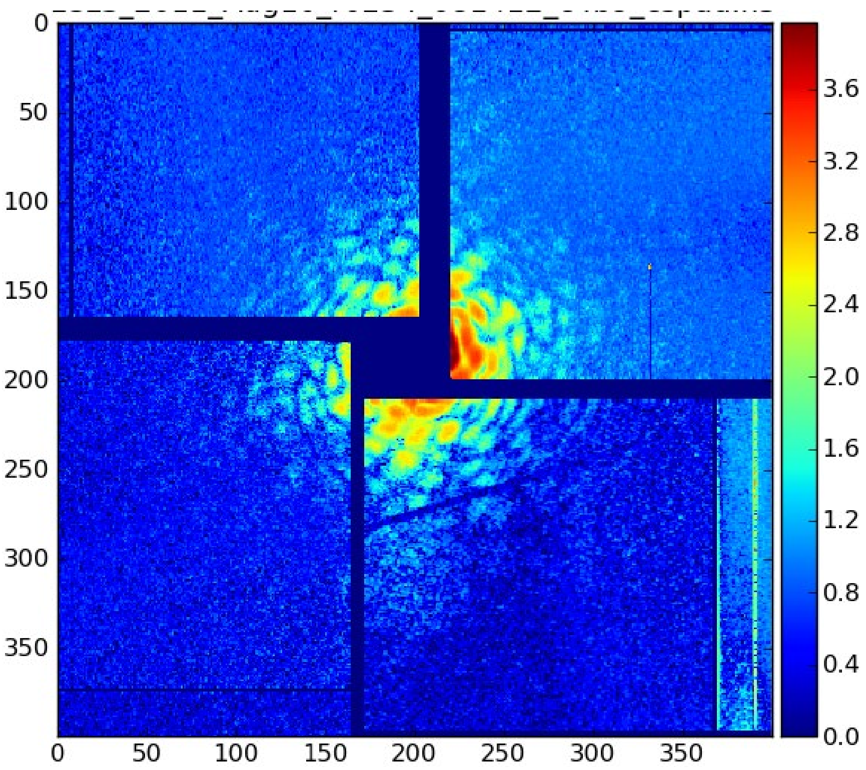


Yeast Nuclei
0.3 µm < diameter < 2 µm

Atomic Molecular and
Optical science beamline
CAMP Chamber
pnCCD



520 eV (2.4 nm) photons
3x2 µm² focus - 2 µJ

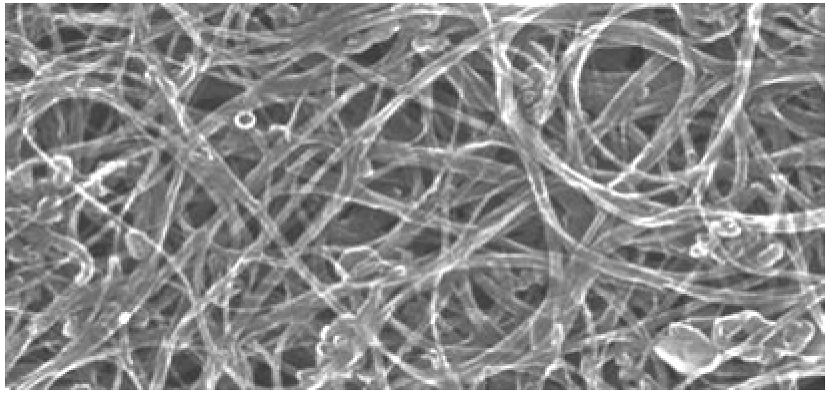


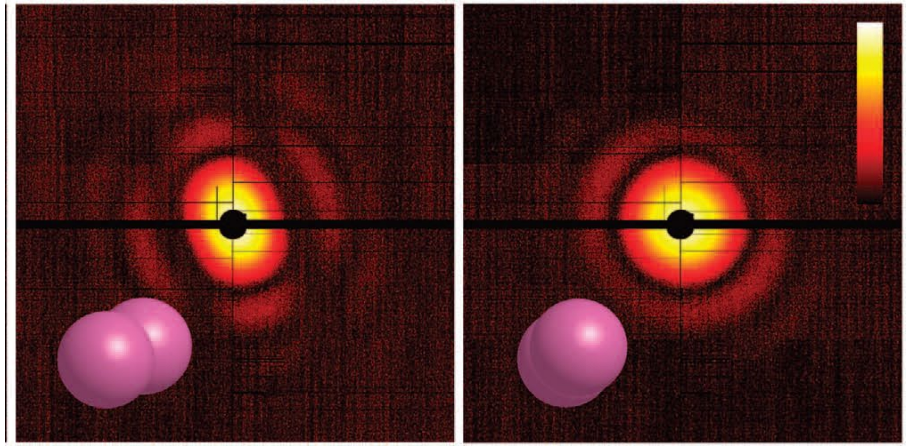
A yeast nucleus diffraction
pattern exhibiting clearly
visible speckles

LCLS experiments
(still) unpublished data

Experimental Techniques
Coherent imaging

Imaging can be also performed on inorganic samples.





Nanotubes, nanoparticles, combustion products (soot)

Again, high time-resolution pump-probe studies are the target.

Experimental Techniques
X-ray spectroscopy: absorption (and emission)

AQUA

No **monochromator** in phase one (but space for a monochromator foreseen)

SASE w/o monochromator (ghost-spectroscopy) scheme

Klein, Y., Tripathi, A. K., Strizhevsky, E., Capotondi, F., De Angelis, D., Giannessi, L., ... & Shwartz, S. (2023). High-spectral-resolution absorption measurements with free-electron lasers using ghost spectroscopy. *Physical Review A*, *107*(5), 053503.

Downstream **spectrometer** for X-ray emission measurements

ARIA

Seeded w/o monochromator scheme with short (20 fs) pulses for VUV spectroscopy

Seeded with monochromator scheme with long (200 fs, 10^{14} photons/pulse) pulses for VUV spectroscopy

Experimental Techniques
X-ray spectroscopy

C K-edge

Hydrocarbons, aminoacids

Al to K L-edges

Alloys, warm-dense matter (pump-probe)

Cu to Ru M-edges

Samples: cuprates, porphyrins, metalloproteins

Sb to Ne L-edges

Lanthanides superconductors, catalysts

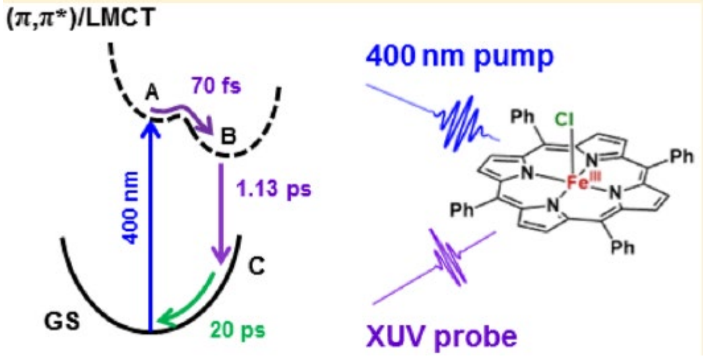
J Synchrotron Radiat. 2013 Jul 1; 20(Pt 4): 614–619.
Published online 2013 May 30. doi: 10.1107/S0909049513003142
PMCID: PMC3682637
PMID: 23765304

Soft X-ray absorption spectroscopy and resonant inelastic X-ray scattering spectroscopy below 100 eV: probing first-row transition-metal *M*-edges in chemical complexes

Hongxin Wang,[a,b,*] Anthony T. Young,[c] Jinghua Guo,[c] Stephen P. Cramer,[a,b] Stephan Friedrich,[d] Artur Braun,[e] and Weiwei Gu[b]

JACS Journal of the American Chemical Society
Article
Cite This: J. Am. Chem. Soc. 2018, 140, 4691−4696
pubs.acs.org/JACS

Tabletop Femtosecond M-edge X-ray Absorption Near-Edge Structure of FeTPPCl: Metalloporphyrin Photophysics from the Perspective of the Metal



Experimental Techniques
X-ray spectroscopy

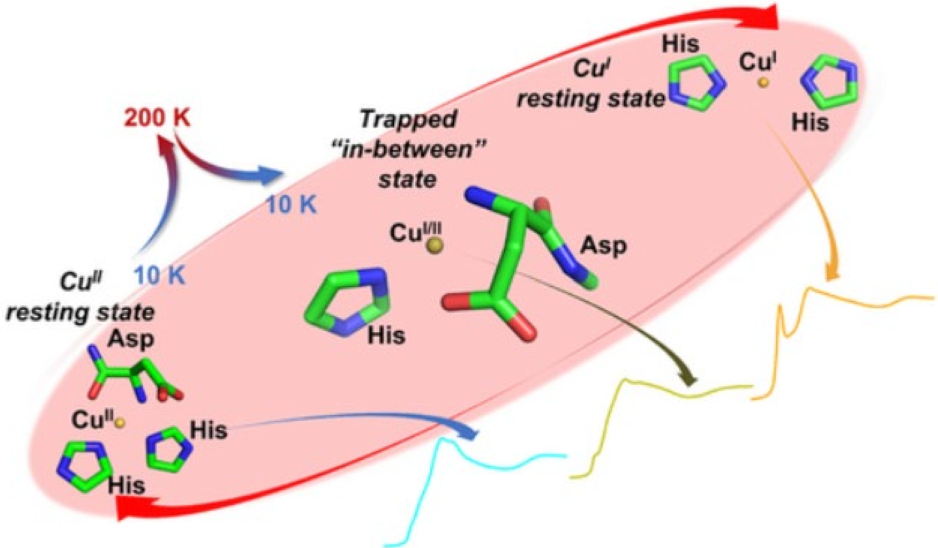
Angewandte Chemie International Edition — GDCh — A Journal of the German Chemical Society

Communication | Open Access

Chasing the Elusive “In-Between” State of the Copper-Amyloid β Complex by X-ray Absorption through Partial Thermal Relaxation after Photoreduction

Enrico Falcone, Germano Nobili, Michael Okafor, Olivier Proux, Giancarlo Rossi, Silvia Morante, Peter Faller, Francesco Stellato

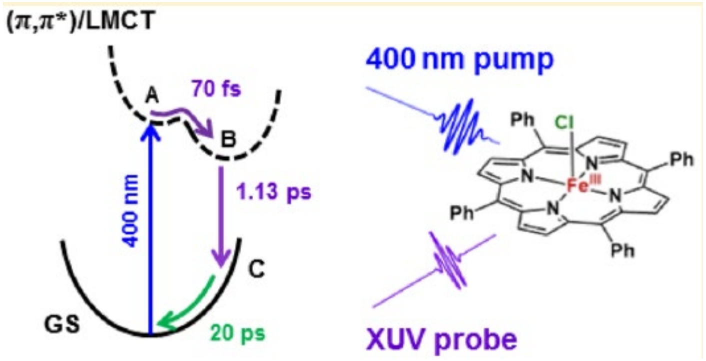
First published: 03 March 2023 | https://doi.org/10.1002/anie.202217791



Cu to Ru M-edges

Samples: cuprates, porphyrins, metalloproteins

Structure of FeTPPCl: Metalloporphyrin Photophysics from the Perspective of the Metal



Sb to Ne L-edges

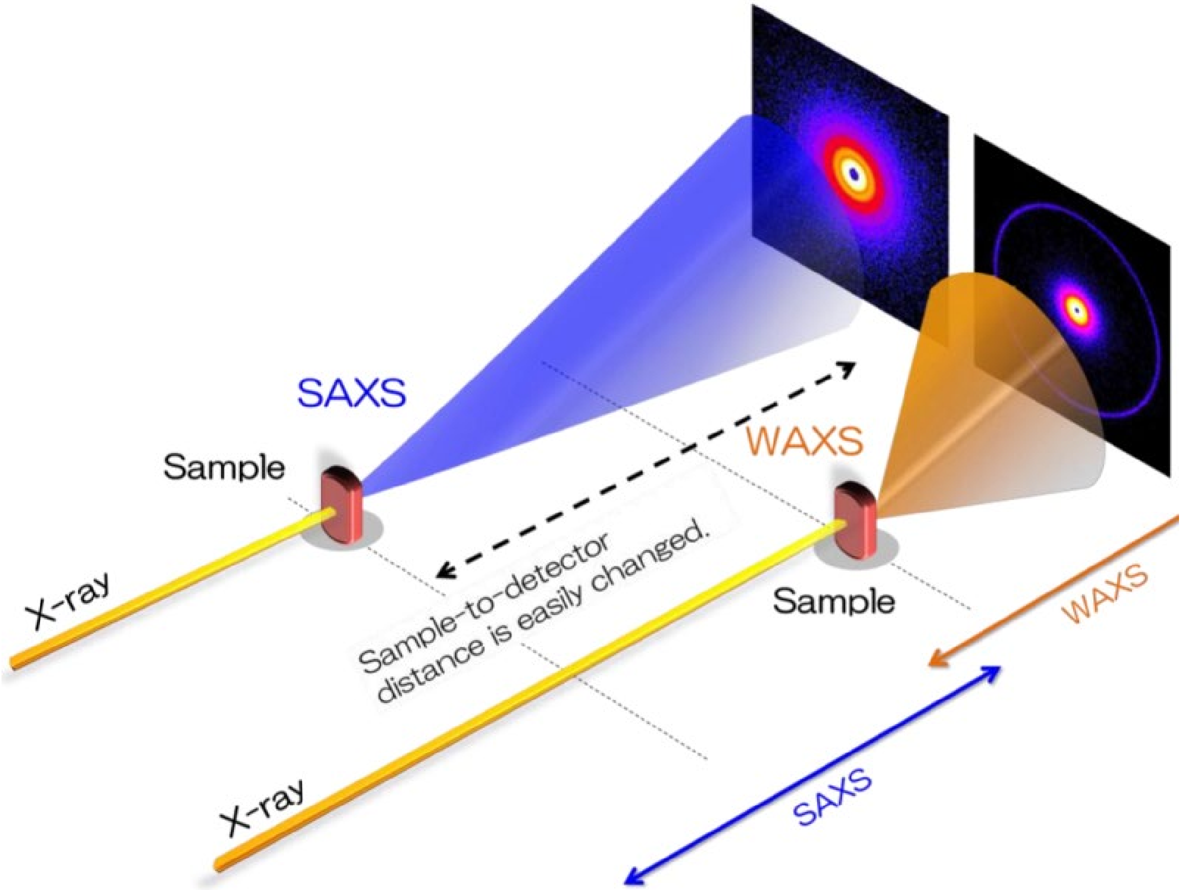
Lanthanides superconductors, catalysts

Experimental Techniques
Small (and wide) Angle X-ray Scattering

Small angle scattering measurements provide low-resolution structural information

The ultra-short FELs allows time-resolved pump-probe measurements

At both **AQUA** and **ARIA**, these measurements are @ reachable camera lengths



Experimental Techniques
Small (and wide) Angle X-ray Scattering

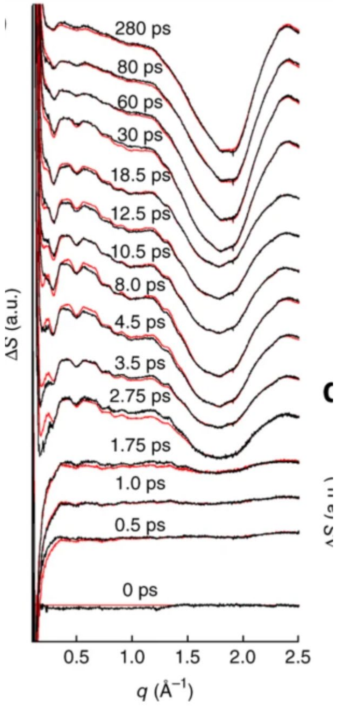
Pump-probe schemes allow to exploit SAXS (and WAXS) to track fast structural changes in catalysts, superconductors, photo-sensitive biological molecules, …

J|A|C|S
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

pubs.acs.org/JACS Communication

Operando Resonant Soft X-ray Scattering Studies of Chemical Environment and Interparticle Dynamics of Cu Nanocatalysts for CO_2 Electroreduction

Yao Yang, Inwhan Roh, Sheena Louisia, Chubai Chen, Jianbo Jin, Sunmoon Yu, Miquel B. Salmeron, Cheng Wang,* and Peidong Yang*



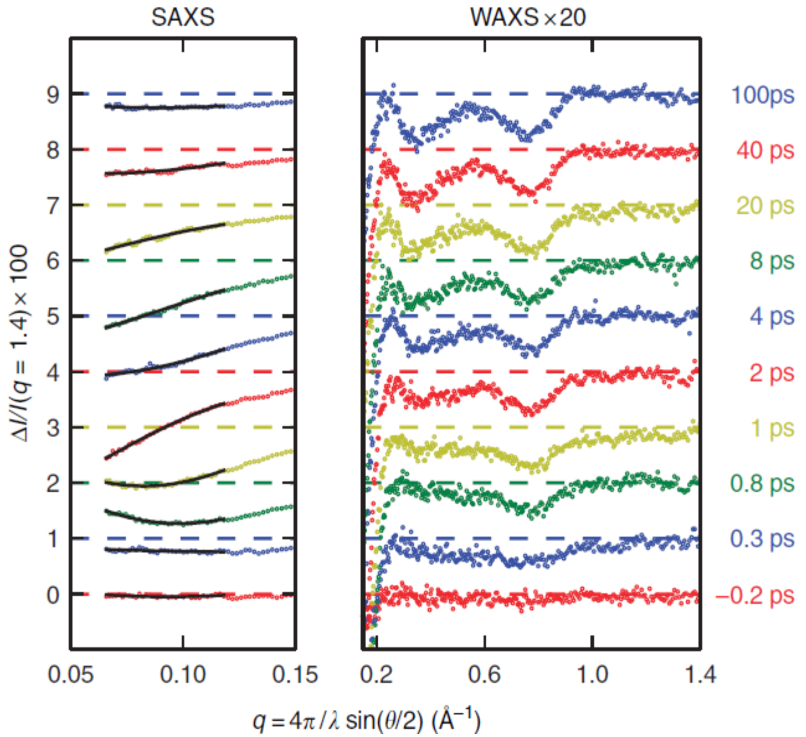
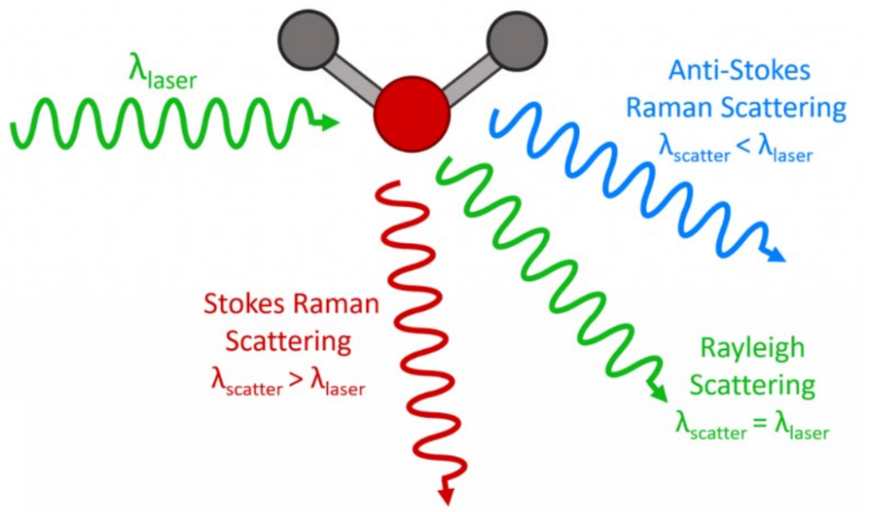


Photo-excitation of proteins monitored by SAXS & WAXS
Arnlund *et al.*, Nat Methods 2014
Levantino *et al.*, Nat Comm 2014

Experimental Techniques
Raman Spectroscopy

FEL pulses can be exploited as pump pulse for stimulating chemical reactions or for generating coherent excitations, and, on the other hand, they can be used as selective probe to monitor the evolution from reactant to photoproduct.

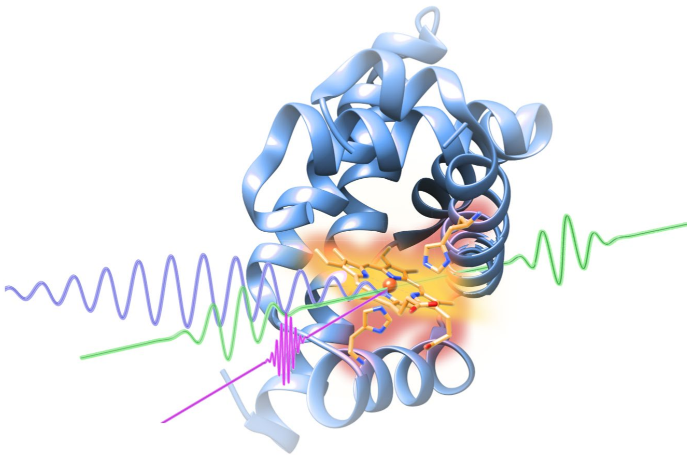


ARIA

Electronic transitions for **cluster materials** such as nanocarbons and potential gap dielectrics from **metal oxides**, **nano structure**, wide band-gap materials.

AQUA

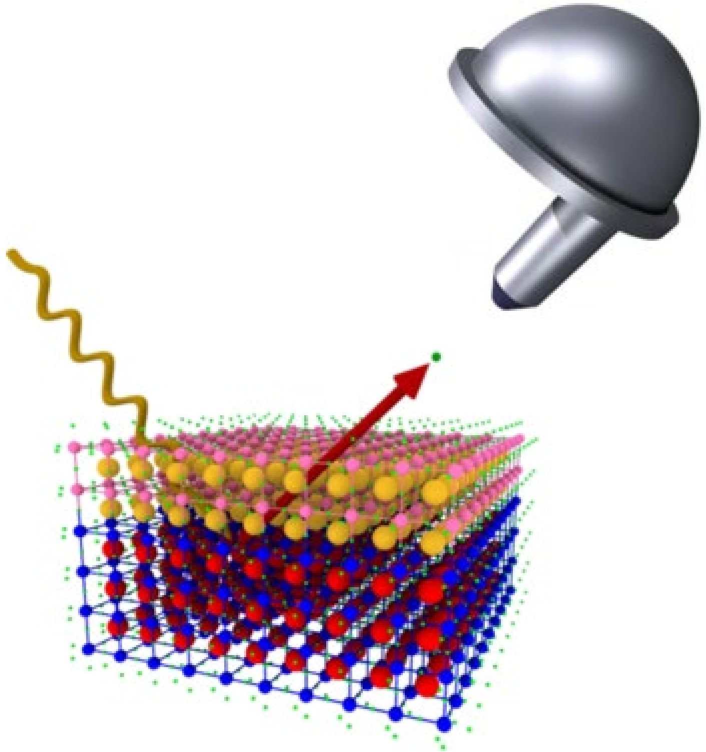
Electronic information on materials such as Silicon carbide SiC, boron nitride BN, Zinc sulfide ZnS, energy transfer in TiO_2/Ln^{+3} doped glass).
Photocatalytic reactions CO_2 and N_2 reduction and H_2O oxidation



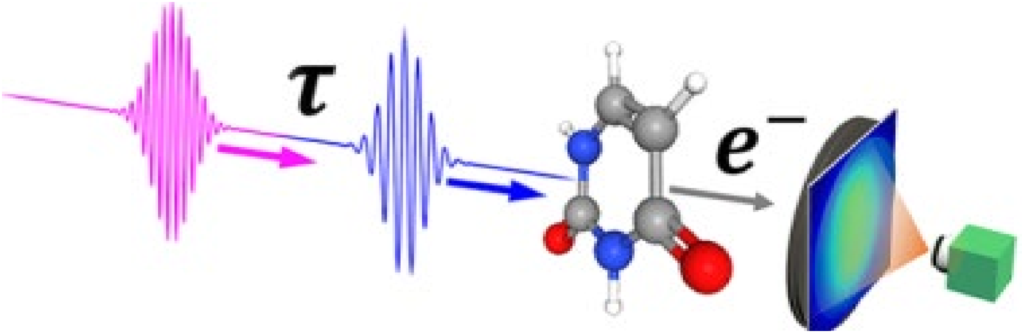
Courtesy of Zeinab Ebrahimpour

Experimental Techniques
Photoemission Spectroscopy

The **AQUA** and **ARIA** energy ranges are also suitable to perform Photoemission Spectroscopy (**PES**) experiments, in which the energy spectrum of the emitted photoelecton is measured.
This provides information on the electronic structure of the samples.

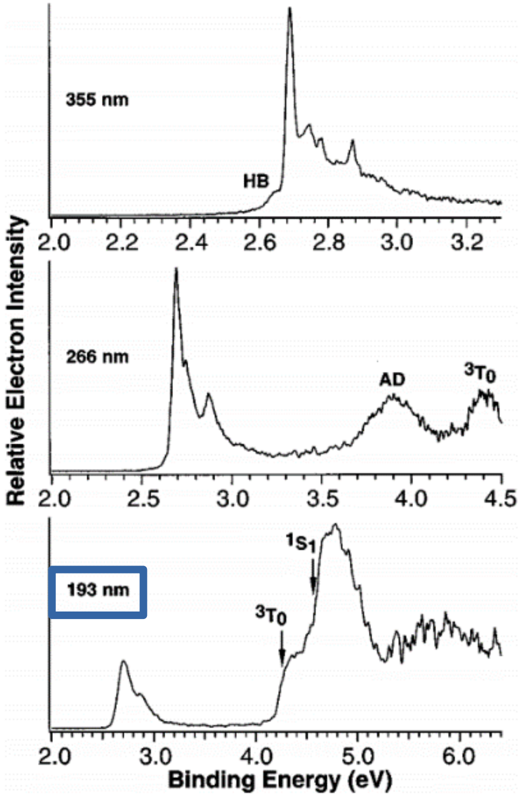


PES can be performed in different schemes and it will benefit from the ultrafast structure of the FEL radiation for pump-probe measurements.



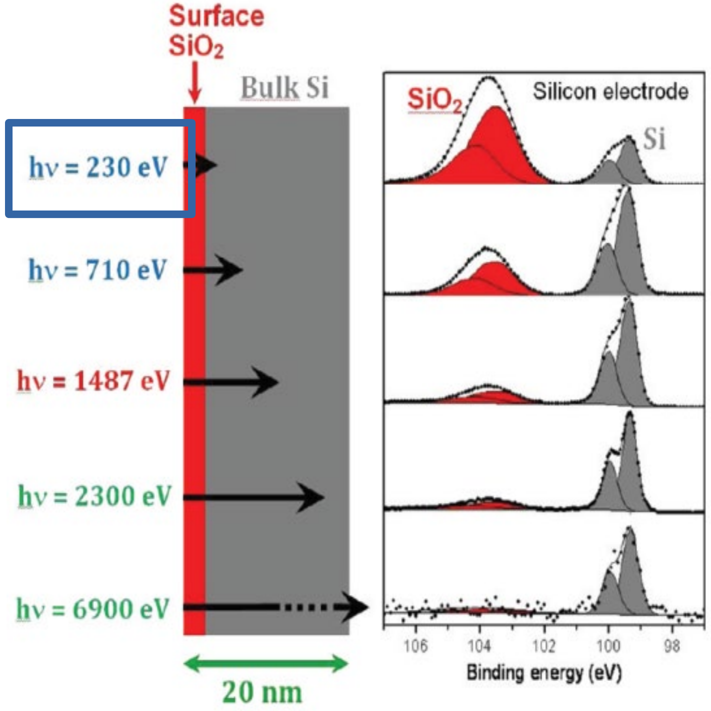
Experimental Techniques
Photoemission Spectroscopy

X-ray Photon Spectroscopy C^{-}_{60}



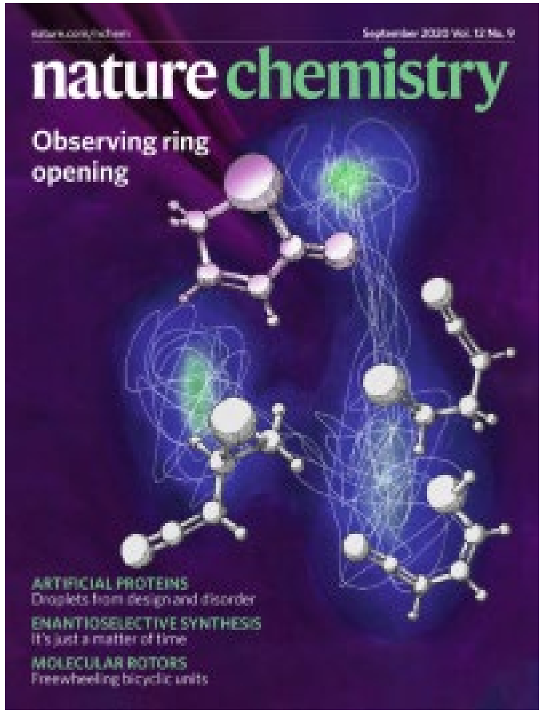
Photoelectron spectra of C60 2 at 355, 266, and 193 nm with photon fluxes of 5, 1.5, and 0.7 mJ/cm2, respectively. (Xue-Bin Wang, 1999)

Lithium Battery interface during charge/discharge



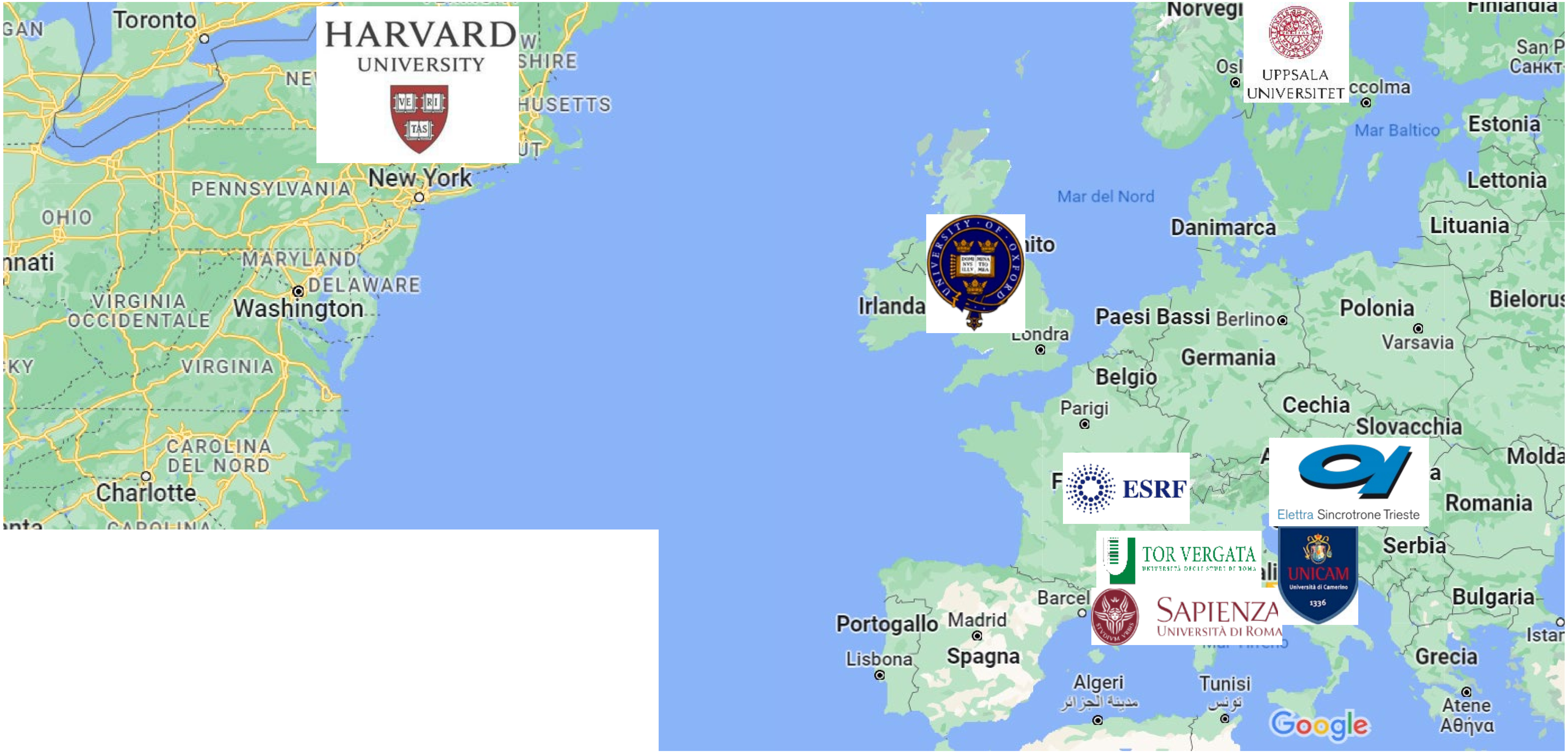
Si 2p spectrum of the pristine silicon electrode (Bertrand Philippe, 2016)

PES measuements of organic rings opening



Courtesy of Federico Galdenzi

Users’ community



Users’ community

EuPRAXIA@SPARC_LAB user workshop

14-15 October 2021
Europe/Rome timezone

- Overview
- Timetable
- Registration
- Participant List

Participant List
147 participants

Last Name	First Name	Affiliation

The first EuPRAXIA@SPARC_LAB user workshop

More than 140 registrants from 9 countries and ~30 institutions

https://agenda.infn.it/event/27926/overview

Users' community - Feedback

Pros

Energy ranges (both **AQUA** and **ARIA**) not primary for many FEL sources

Flexibility in pulse duration

Beamtime availability for long-term projects

Presence of two beamlines at very different energies

Presence of the **EuAPS** betatron source

Cons (limitations)

Limited photon flux

Limited repetition rate (mitigated if 400 Hz are reached)

Limited wavelength range (not reaching the O K-edge)

What else?

Input from potential users still more than welcome

(not only) photon sources @ EuPRAXIA

- EuPRAXIA-PP

  Photon and particle sources based on novel (plasma) acceleration techniques

- Free Electron lasers: EuPRAXIA@SPARC_LAB

  AQUA – water window FEL beamline

  ARIA - VUV FEL beamline

- **Betatron source**

EuAPS – Betatron radiation source

Parameter	Value	unit
Photon Critical Energy	1 -10	keV
Photons/pulse	10^6-10^9	
Repetition rate	1-5	Hz
Beam divergence	3-20	mrad

Expected parameters of the EuAPS betatron radiation source

Photon science case

Plasma-Generated X-ray Pulses: Betatron Radiation Opportunities at EuPRAXIA@SPARC_LAB

Francesco Stellato [1,2,*], Maria Pia Anania [3], Antonella Balerna [3], Simone Botticelli [2], Marcello Coreno [3,4], Gemma Costa [3], Mario Galletti [1,2], Massimo Ferrario [3], Augusto Marcelli [3,5,6], Velia Minicozzi [1,2], Silvia Morante [1,2], Riccardo Pompili [3], Giancarlo Rossi [1,2,7], Vladimir Shpakov [3], Fabio Villa [3] and Alessandro Cianchi [1,2]

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

EuAPS – Betatron radiation source

What are betatron pulses good for?

Betatron radiation covers a broad energy range

Spectroscopic techniques

Betatron pulses are short (femtoseconds)

Pump-probe, time-resolved experiments

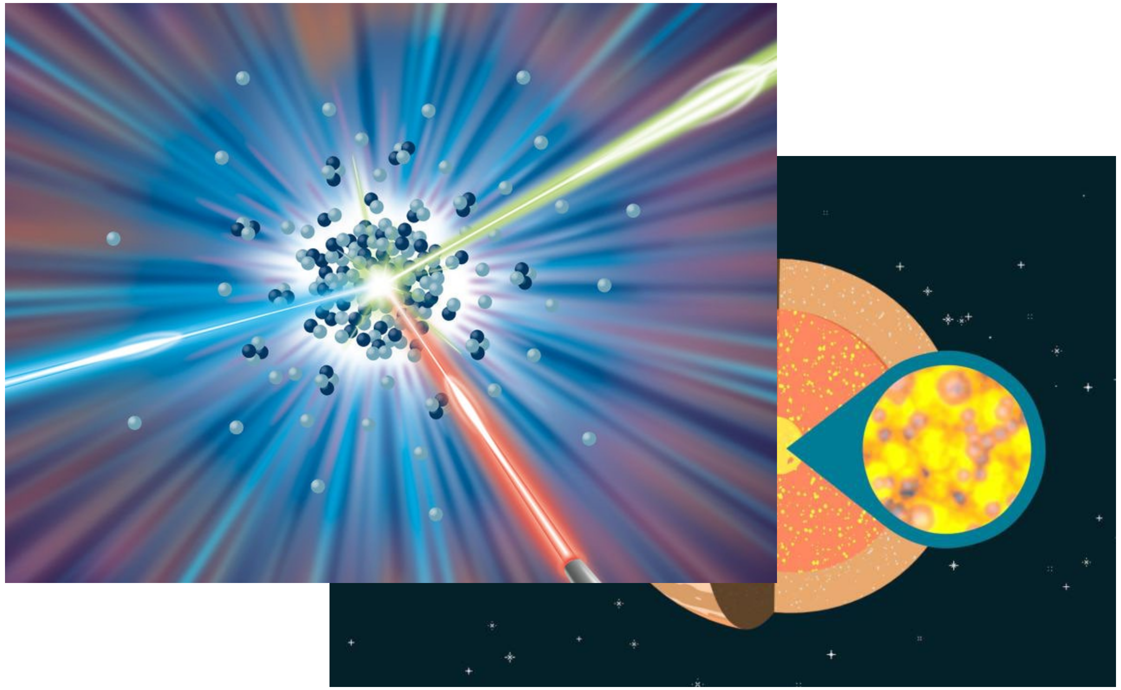
Betatron radiation is partially (spatially) coherent

Phase-contrast imaging

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

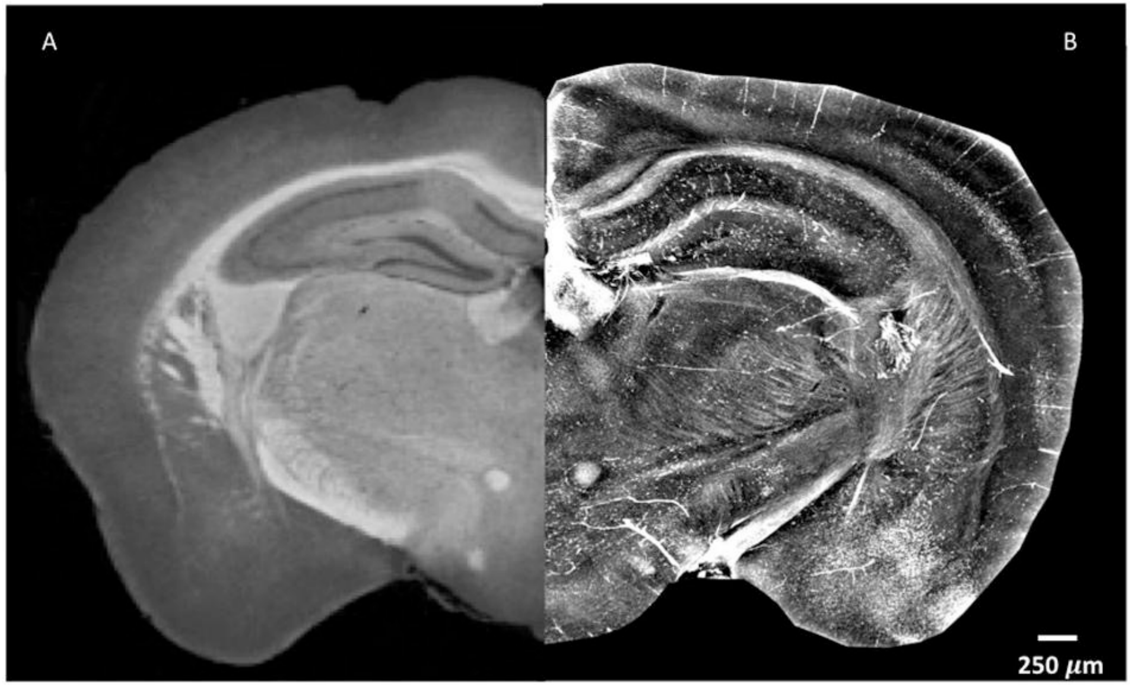
Photon Science @ EuAPS

Ultra-fast, pump-probe time-resolved X-ray Spectroscopy



Physics of warm-dense matter
Femtochemistry of organometallic complexes

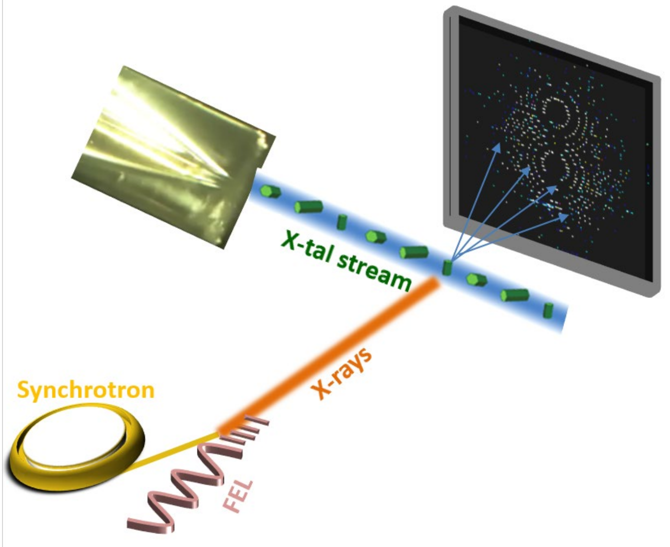
Imaging at a small-scale source



Tissues
Plants
Cultural Heritage

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

Photon Science @ EuAPS



- **Imaging of biological (and cultural heritage) samples**

  Exploits the brilliance and coherence of betatron radiation, requires small divergence and good focusing

- **Static X-ray Spectroscopy**

  Relatively easy, but does not exploit the radiation time structure

- **Ultra-fast X-ray spectroscopies** exploiting **ultra-short betatron pulses**

  More complicated, requires timing between pump and probe pulses, but fully exploits the fs pulse duration

- **Time-resolved diffraction**

  Depending on the samples, likely exploiting a white beam in a Laue scheme

  → **Serial crystallography**

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

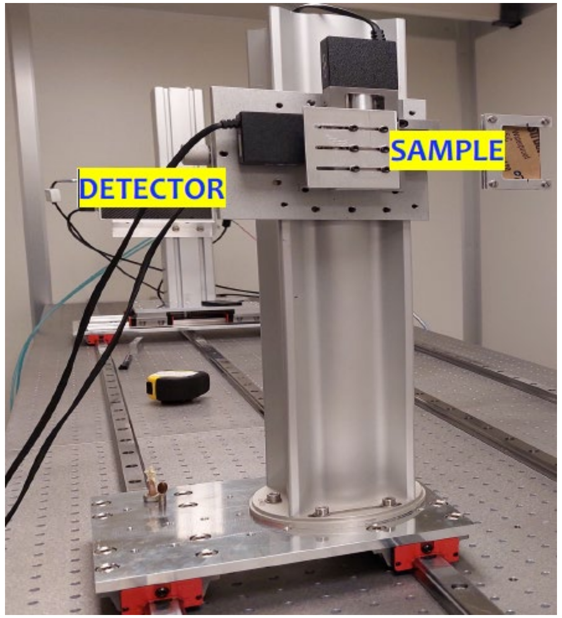
Imaging setup

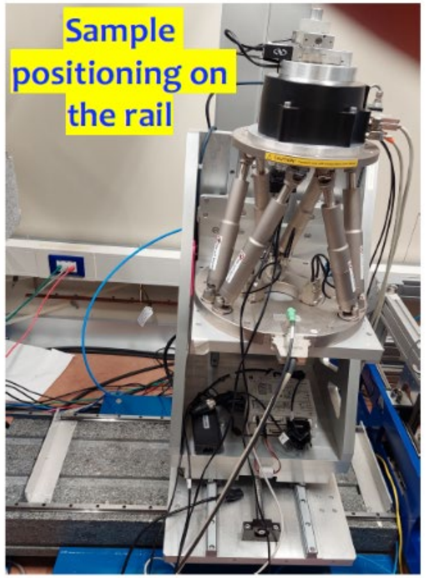
Variable sample-detector distance

Accurate sample positioning and rotation

Small pixel, 2D X-ray detector

CCD or CMOS





Courtesy A. Balerna

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

Imaging – The pilot experiment

Green science

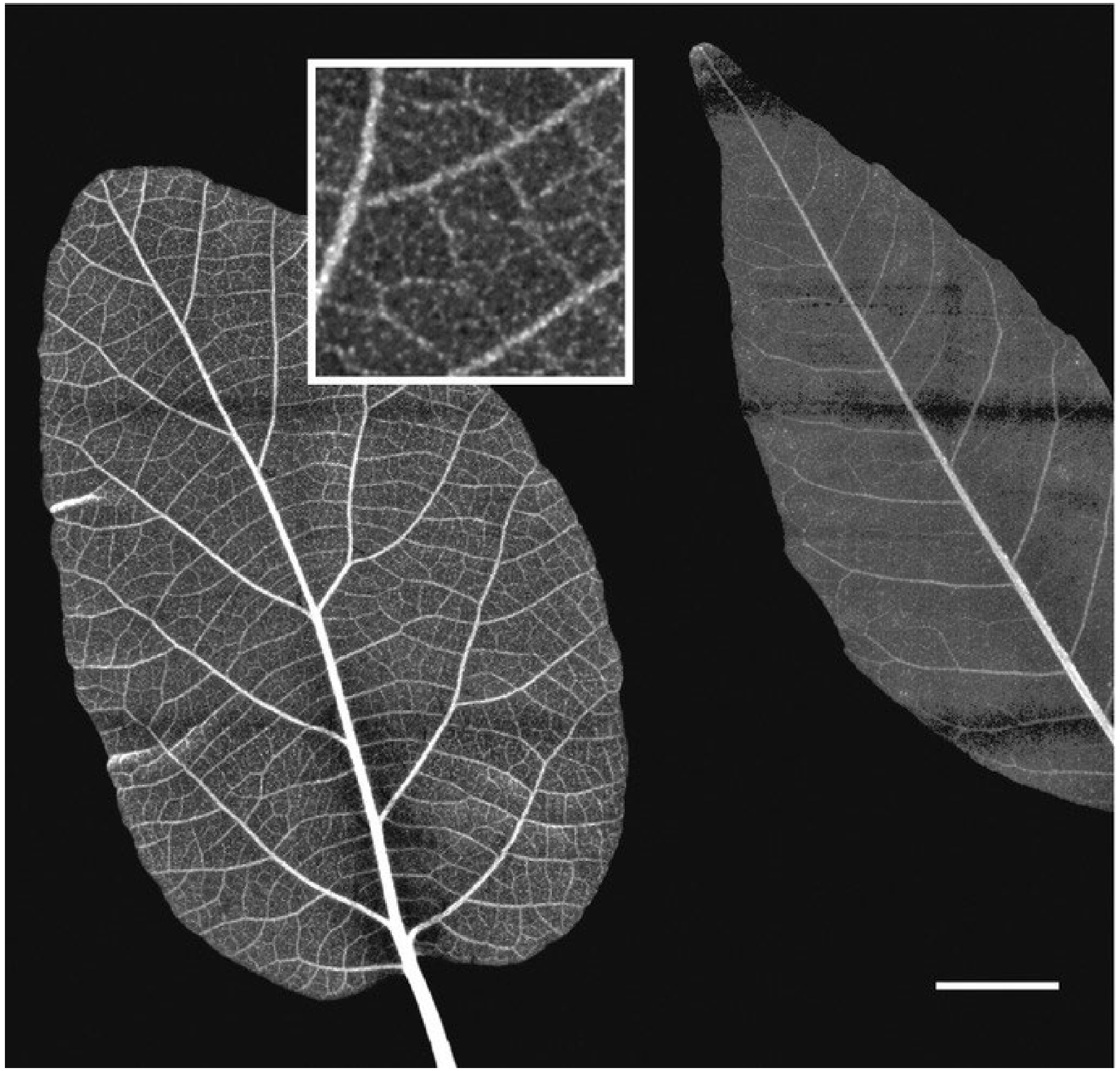
X-ray imaging of **leaves** (and **wood → connection with Swedish researchers**)

aiming at the (tens of) microns resolution

Living plants, different hydration stares

Experiments performed with the broad radiation spectrum **filtered** by different materials to obtain **difference maps** emphasizing the presence of heavy metal contaminants → **pollution control**

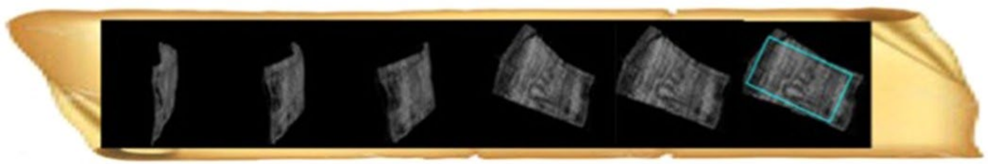
Reale et al. - MIDIX Soft X-rays microradiography



Imaging – Cultural Heritage

Imaging of ancient paper documents

A



B

Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography

I. Bukreeva, A. Mittone, A. Bravin, G. Festa, M. Alessandrelli, P. Coan, V. Formoso, R. G. Agostino, M. Giocondo, F. Ciuchi, M. Fratini, L. Massimi, A. Lamarra, C. Andreani, R. Bartolino, G. Gigli, G. Ranocchia & A. Cedola

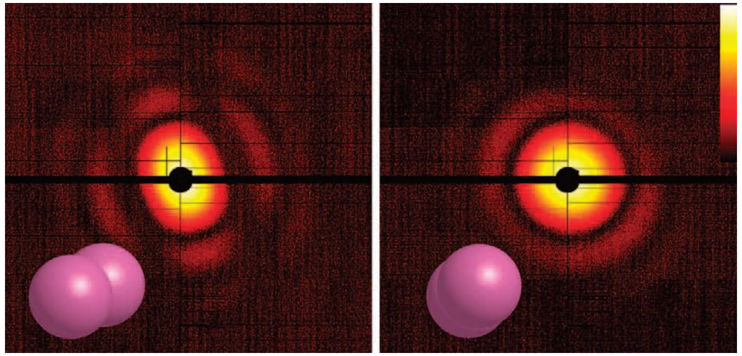
Scientific Reports **6**, Article number: 27227 (2016) | Cite this article

Characterization of **inks**
(chemical sensitivity thanks to filters)

with Dr. Giulia Festa, Centro Studi e Ricerche Enrico Fermi

Time-resolved Imaging

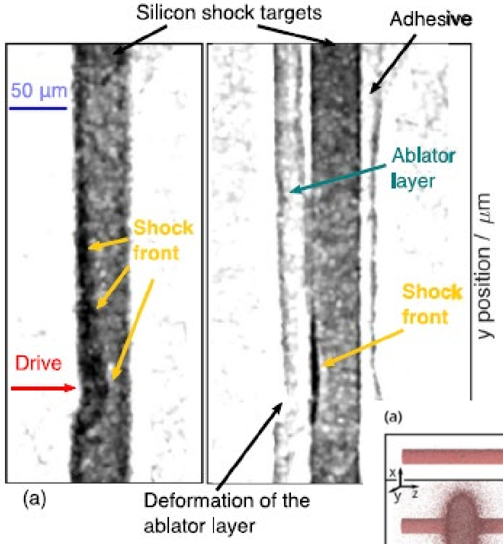
Nanoparticles dynamics

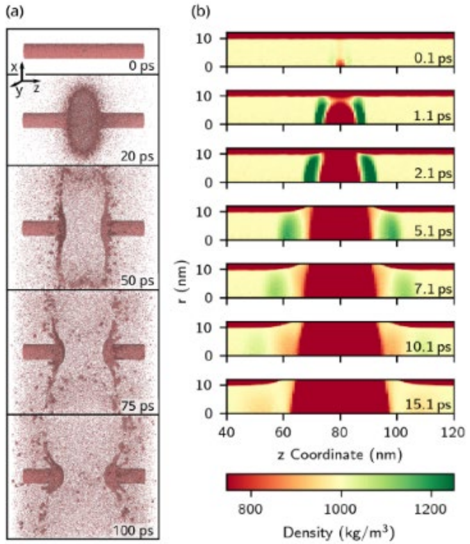


Shock-waves in materials

Ultrafast Imaging of Laser Driven Shock Waves using Betatron X-rays from a Laser Wakefield Accelerator

J. C. Wood[1], D. J. Chapman[2], K. Poder[1], N. C. Lopes[1,3], M. E. Rutherford[2,4], T. G. White[5], F. Albert[6], K. T. Behm[7], N. Booth[8], J. S. J. Bryant[1], P. S. Foster[8], S. Glenzer[9], E. Hill[10], K. Krushelnick[7], Z. Najmudin[1], B. B. Pollock[6], S. Rose[10], W. Schumaker[9], R. H. H. Scott[8], M. Sherlock[10], A. G. R. Thomas[7], Z. Zhao[7], D. E. Eakins[2,4] & S. P. D. Mangles[1]





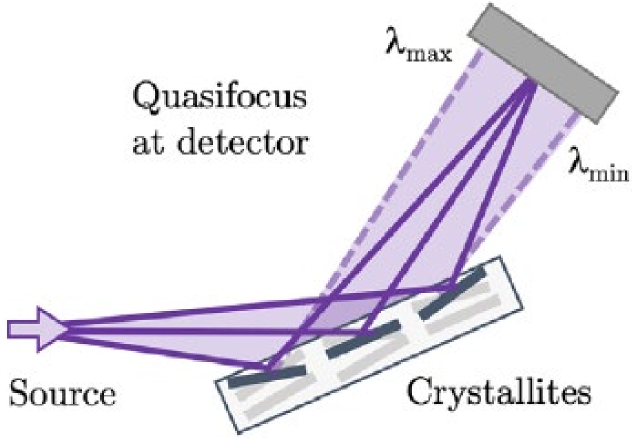
Liquid jet explosion

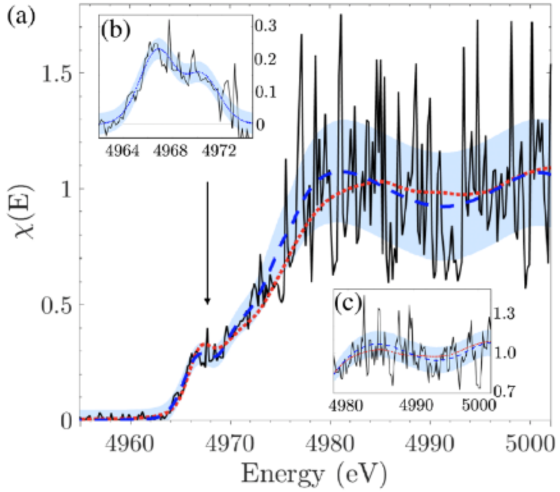
under X-ray beams

EuAPS

Absorption Spectroscopy

Single-shot **XANES** spectrum at the Ti K-edge





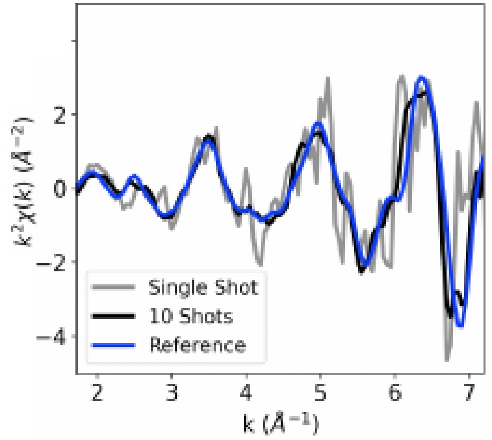
Mosaic crystal analyzer

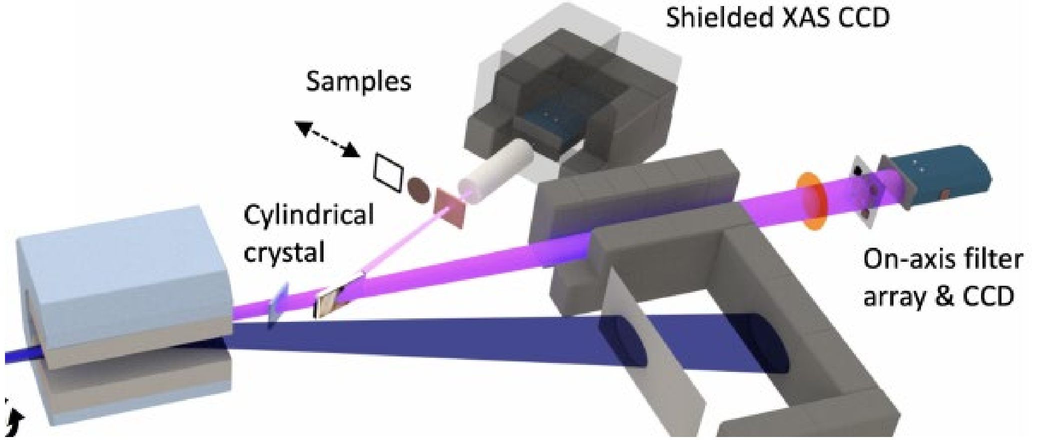
Kettle *et al.* Phys. Rev. Lett. 2021

Single-shot **EXAFS** spectrum at the Cu K-edge

Kettle *et al.* arxiv 2023

Cylindrical crystal



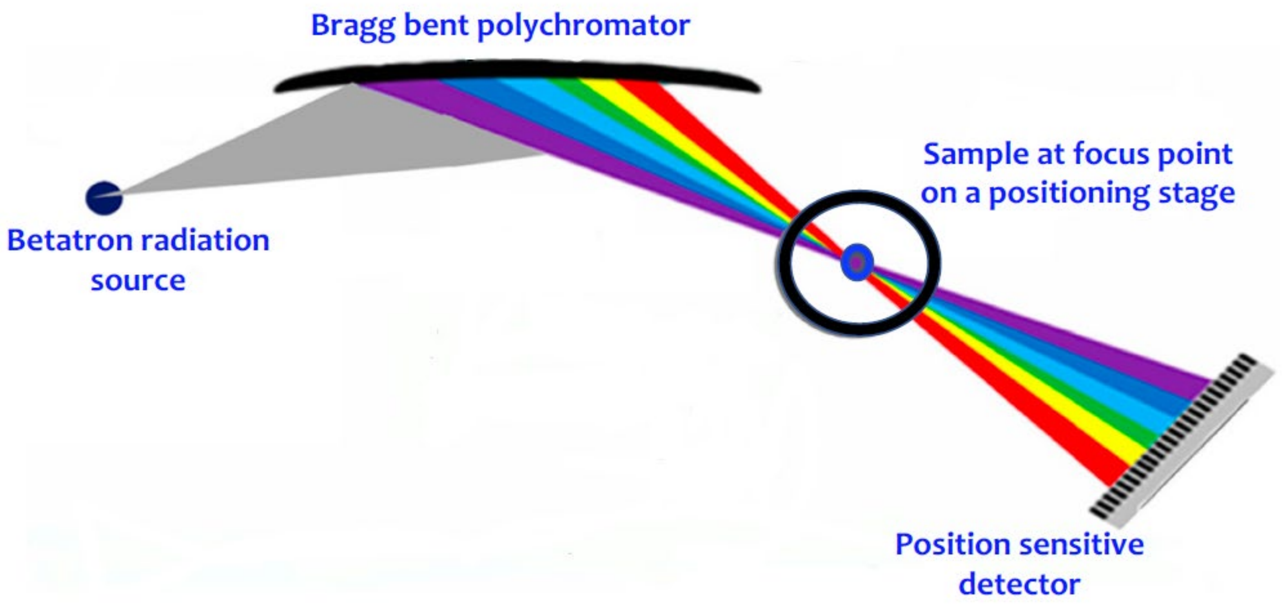


Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

Spectroscopy Setup

X-ray Absorption Spectroscopy
in **dispersive mode**

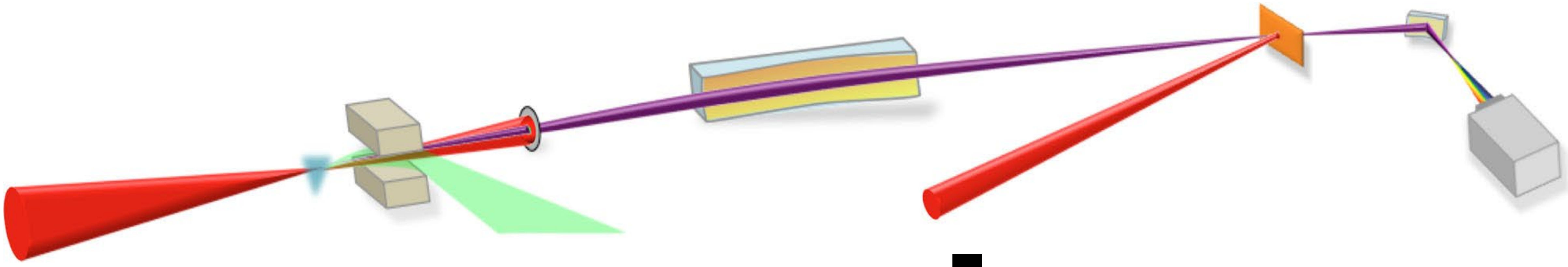
Curved or mosaic crystal analyzers
+
Position sensitive detector
+
High-power femtosecond laser for pump-probe measurements



No **monochromator** to maximize the photon flux on the sample

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources
INFN Istituto Nazionale di Fisica Nucleare
EuPRAXIA

Ultra-fast Spectroscopy

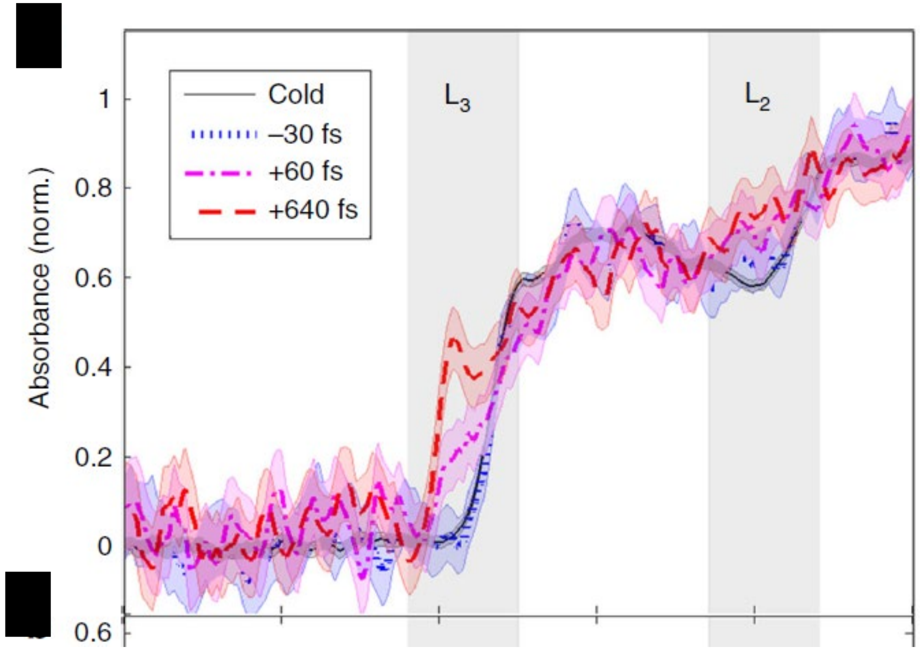


Optical laser pump / betatron probe experiments can follow the non-equilibrium dynamics of the copper heating process via XAS on fs timescale

Mahieu *et al.* Nature Comm 2015

Measurements of Ionization States in Warm Dense Aluminum with Betatron Radiation

Mo *et al.* 2017



Outlook

- Building up the scientific case and the users' community for
  plasma-based pulsed sources: from X-rays to VUV

- EuPRAXIA@SPARC_LAB Technical Design Report
  Detailed definition of spaces and experimental requirements

- EuAPS
  Final design of experimental chamber, getting ready for pilot experiments

- R&D: optics, sample delivery, detection schemes