Recent progress in scattering and imaging experiments at the DiProI CDI end-station of the FERMI seeded FEL

Elettra Sincrotrone Trieste

X-RAY SENSORS
ZÜRICH 12-16 JANUARY 2026

Flavio Capotondi
(on behalf of DiProI user community)

Topics

- Basic core capabilities of FERMI FEL and DiProI end-station.
- Examples of coherent-based imaging and scattering experiments.
- Perspectives of FERMI in soft X-ray Imaging.
- Conclusions.

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FERMI the first seeded FEL

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FERMI@Elettra is a single-pass seeded FEL user-facility in XUV/soft-X-ray. Two separate FEL amplifiers covering the spectral range from 100 to 4 nm (12-300 eV).

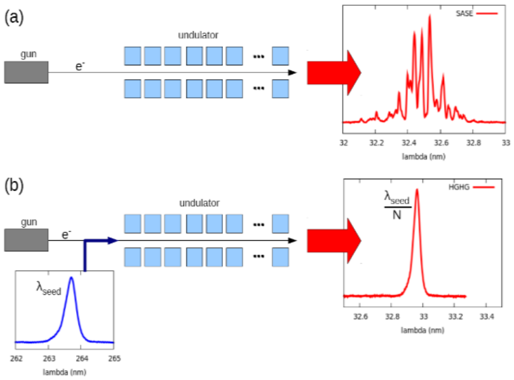
E. Allaria et al., Nature Photonics, **6**, 699 (2012).
E. Allaria et al., Nature Photonics, **7**, 913 (2013).

Unique source characteristics

High temporal coherence: pulses with defined Gaussian-like time–energy profiles - spectral purity ($\Delta\lambda/\lambda \sim 10^{-3}$)

⇓

Ultrafast events with chemical sensitivity, single shot resonant CDI - **mandatory for wave mixing and phase controlled experiments**

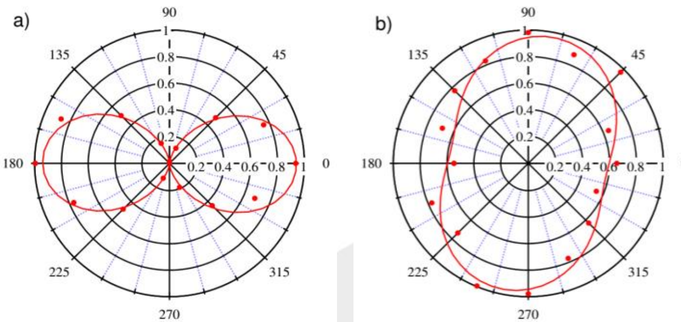


G. Penco et al. PRL (2014).

Fast energy tunability and variable polarization

⇓

Useful for near edge absorption for probing dichroic effects, such as resonant magnetic imaging



E. Allaria et al. PRX (2014).

Circular Polarization ~ 95 %

X-RAY SENSORS ZÜRICH 12-16 JANUARY 2026

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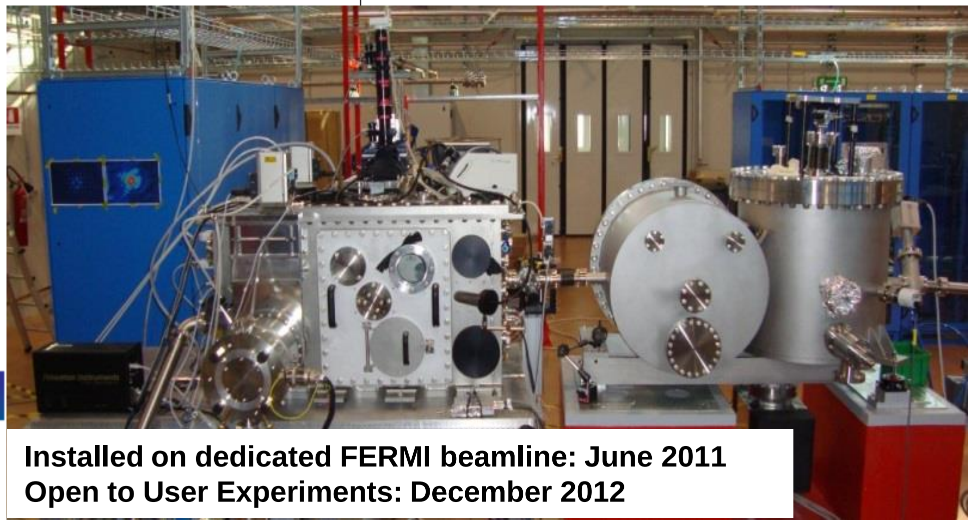
DiProI end-station



Installed on dedicated FERMI beamline: June 2011
Open to User Experiments: December 2012

Versatile modular construction allowing exchange and/or adding new components

Further info on DiProI end station:
F.Capotondi et al. RSI 84, 051301 (2013)
F. Capotondi et al. JSR 22, 544 (2015).

DiProI end-station

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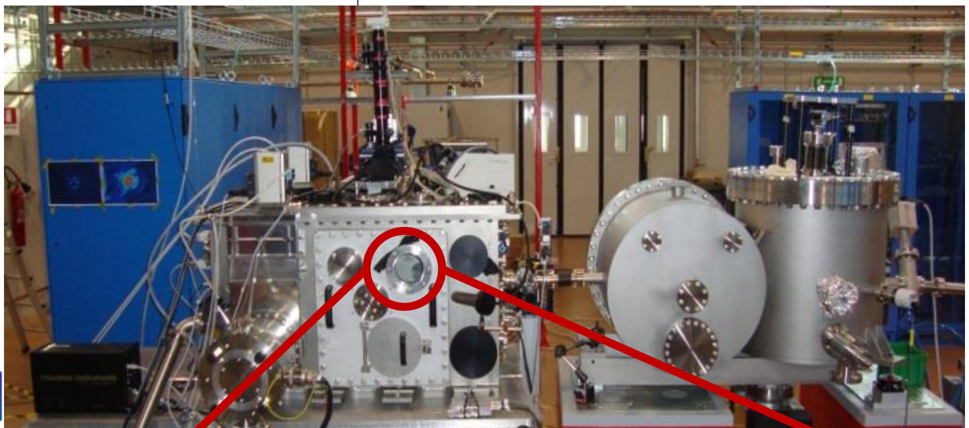

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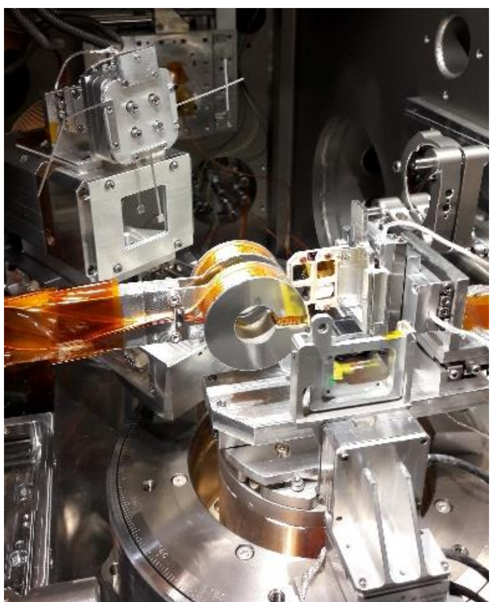

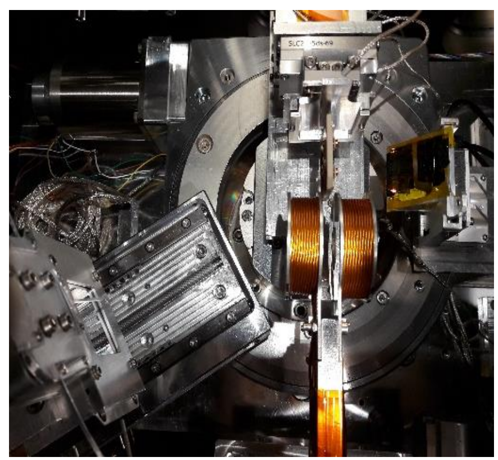

5-axis goniometer for scattering and imaging experiments in transmission and reflection geometry.
Commercial CCD or CMOS detector

C von Korff Schmising, et al
PRL 112 (21), 217203 (2014).
C Léveillé, et al. Nat. Comm. 13 (1), 1412 (2022).

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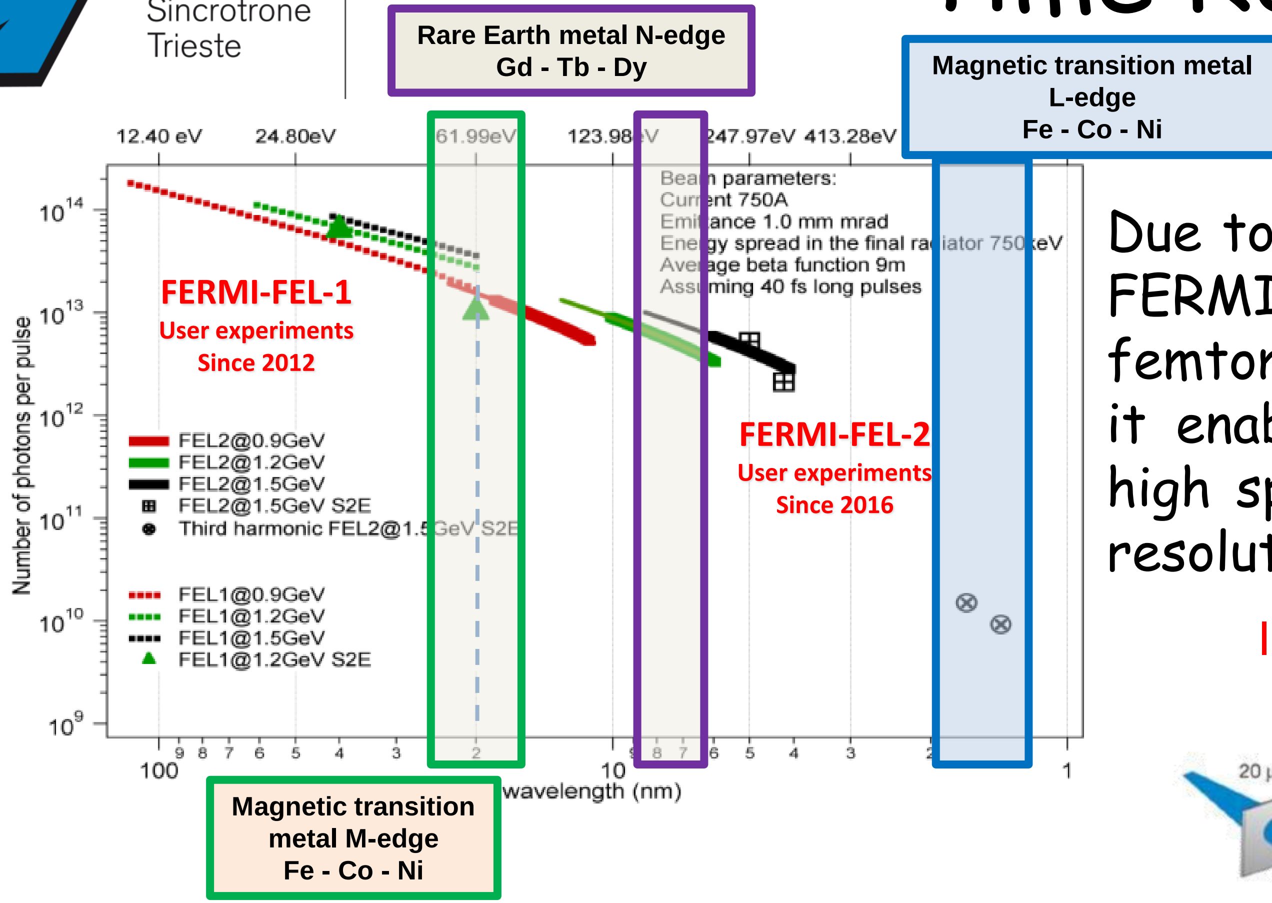
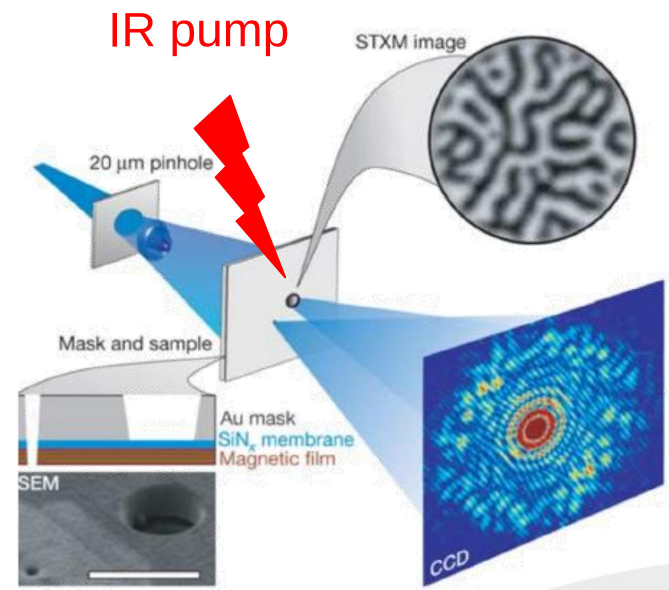
Time Resolved-FTH



Due to its polarization control, FERMI is appealing to the femtomagnetism community, as it enables the combination of high spatial and high temporal resolution.

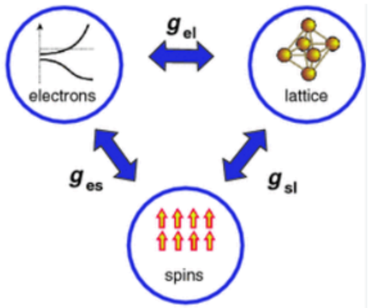


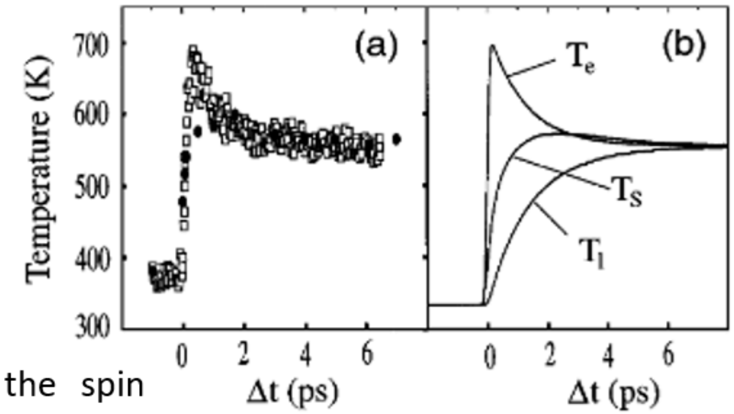
Eisebitt et al., *Nature*, Dec. 2004

C von Korff Schmising, et al. PRL 112 (21), 217203 (2014).
Willems F., et al. Structural Dynamics, 4 (1), 014301 (2017).

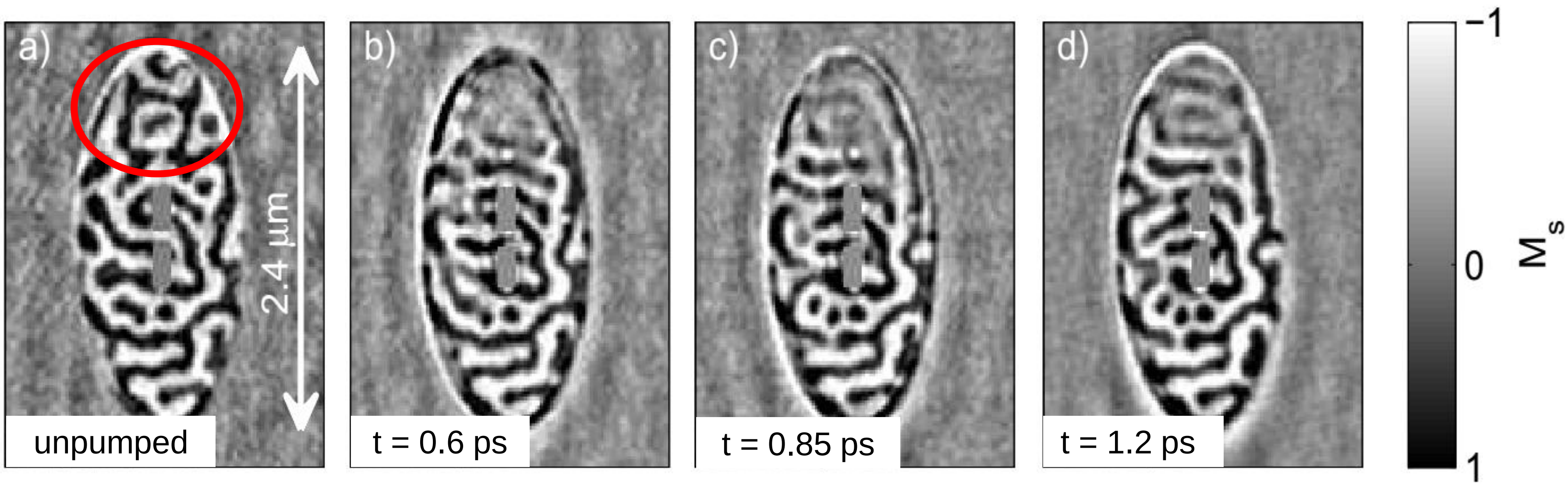
Time Resolved-FTH

Heuristic model





How fast one manipulates the spin moment is critical to the information technology industry: All-Optical Spin Switching.



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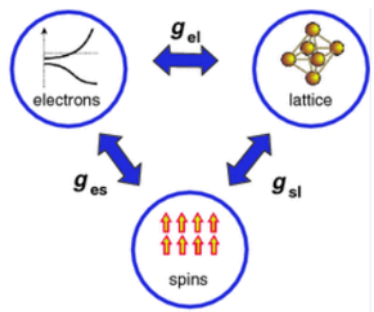

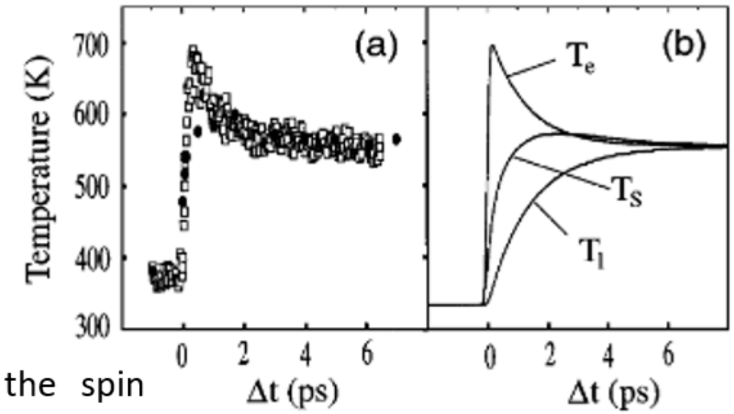

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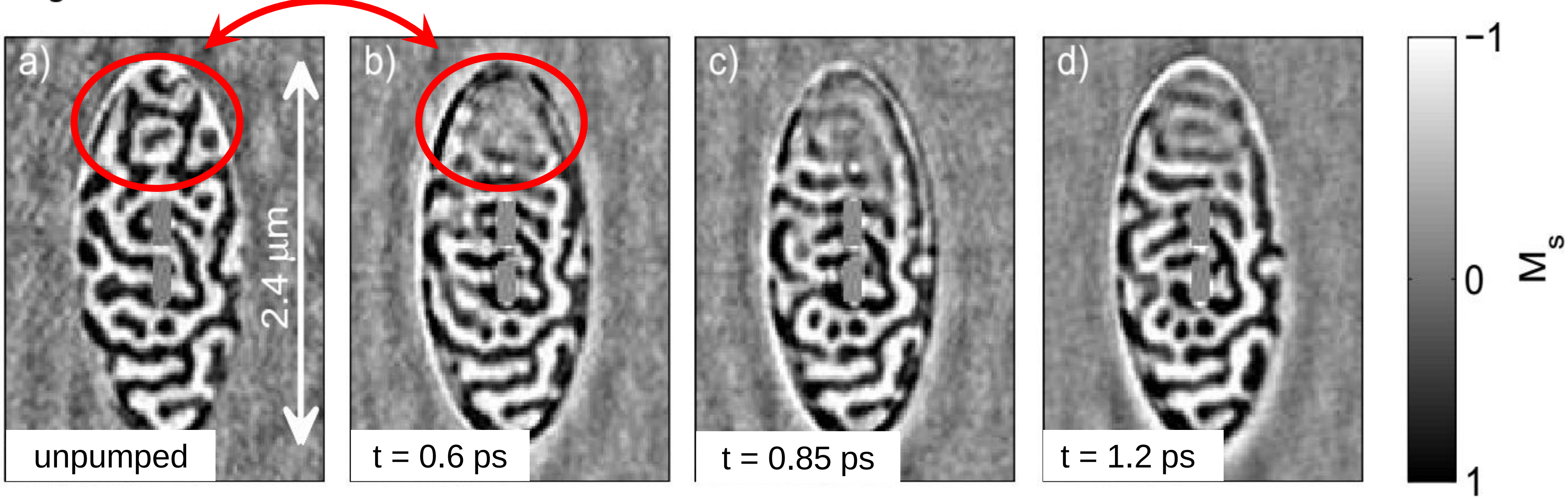

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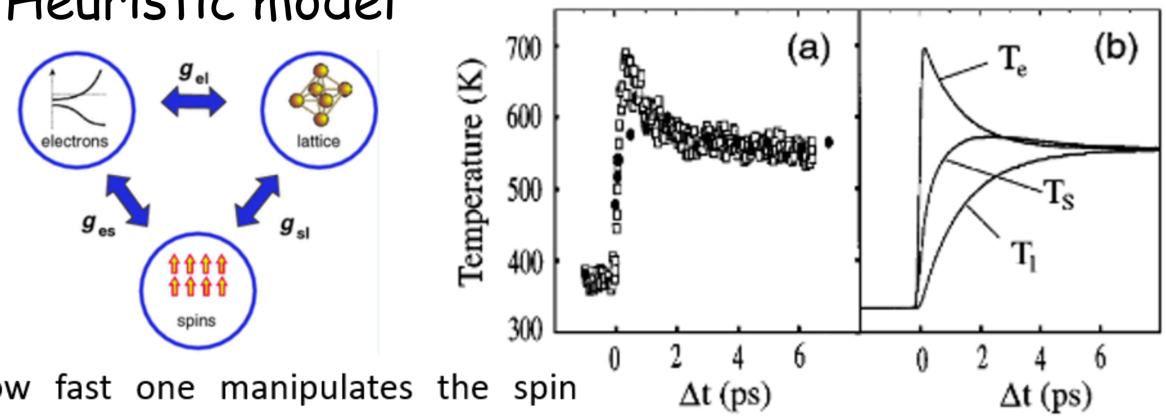

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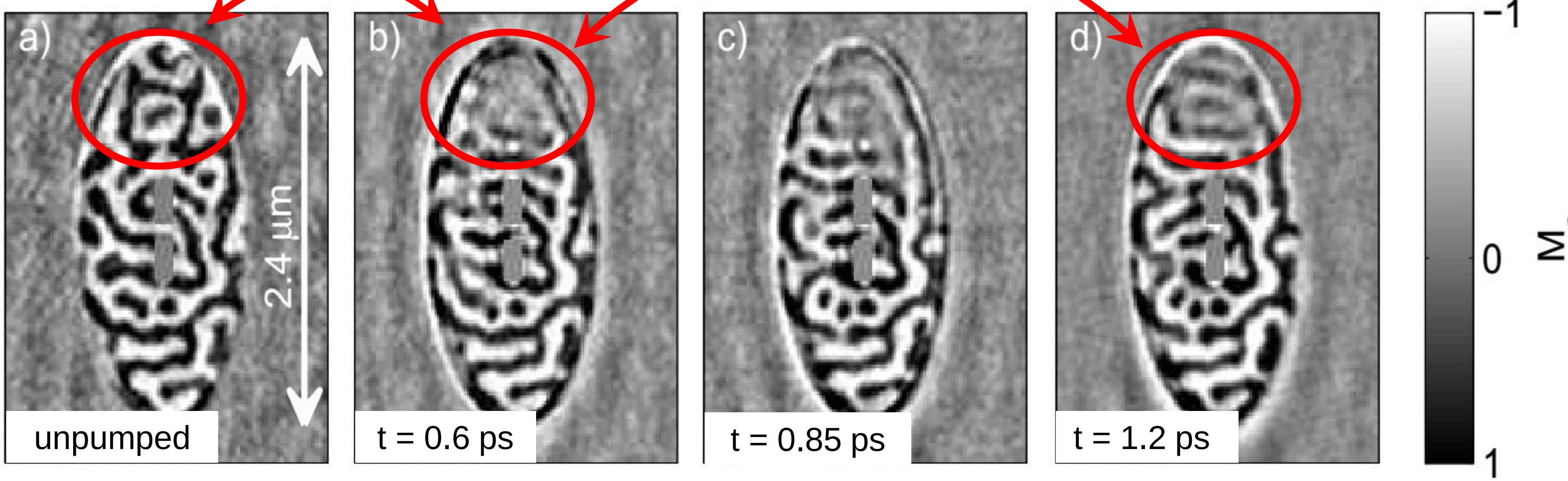

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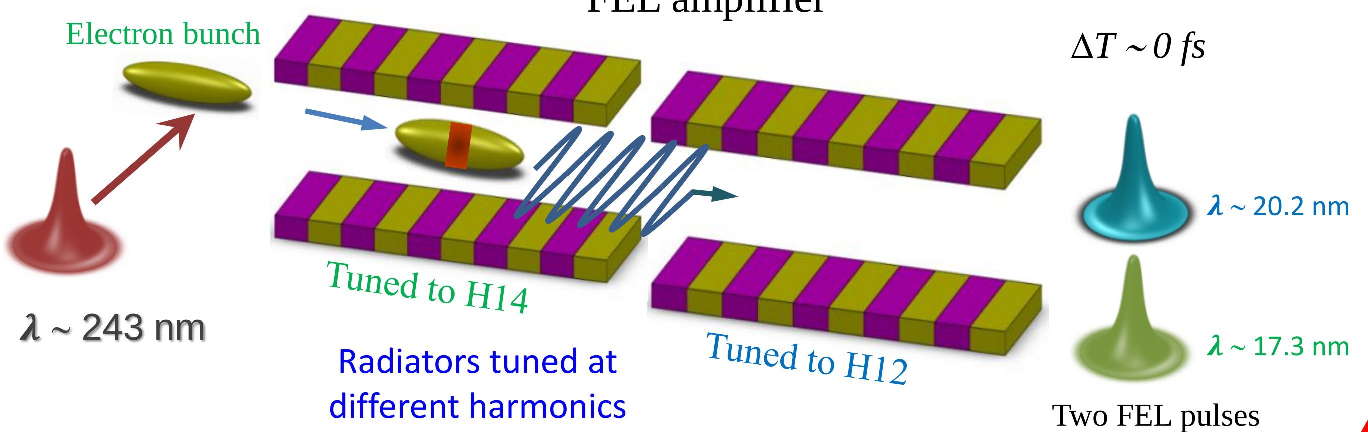
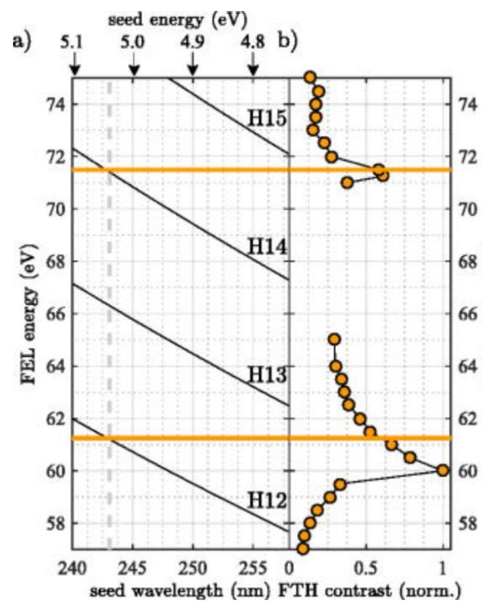
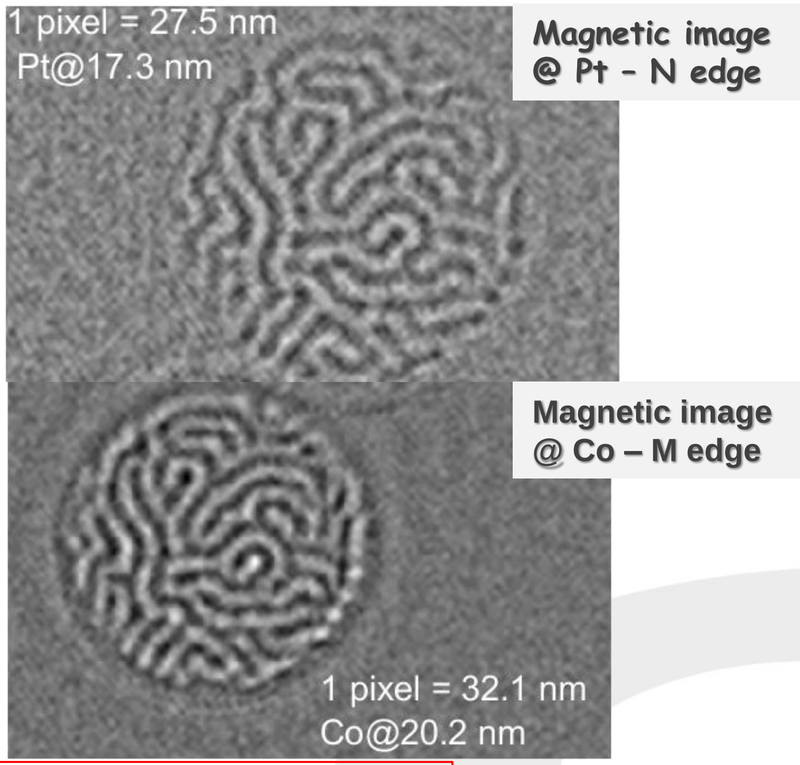


At the same time

Imaging CoPt domains around Co M-edge and Pt N-edge
Using FEL-1 and setting radiatiators to different harmonics





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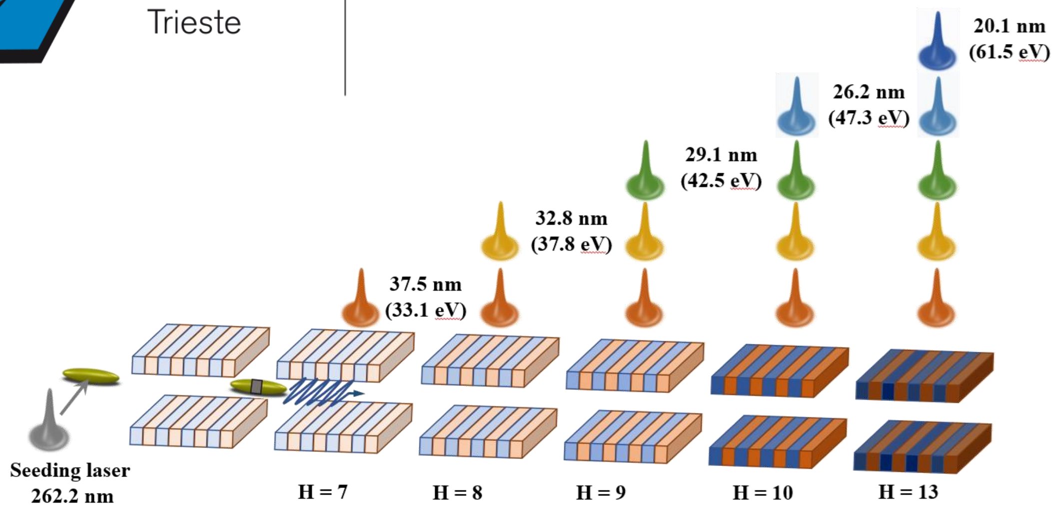
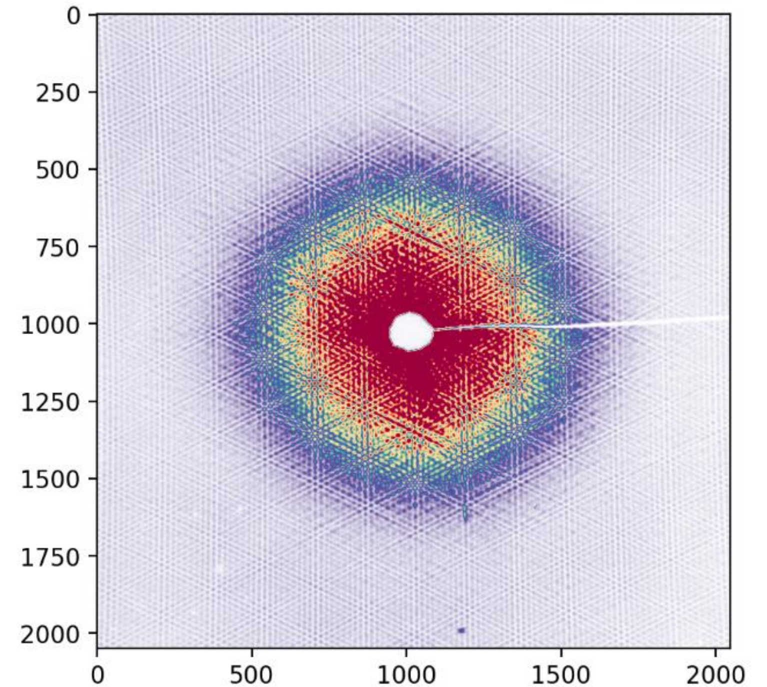
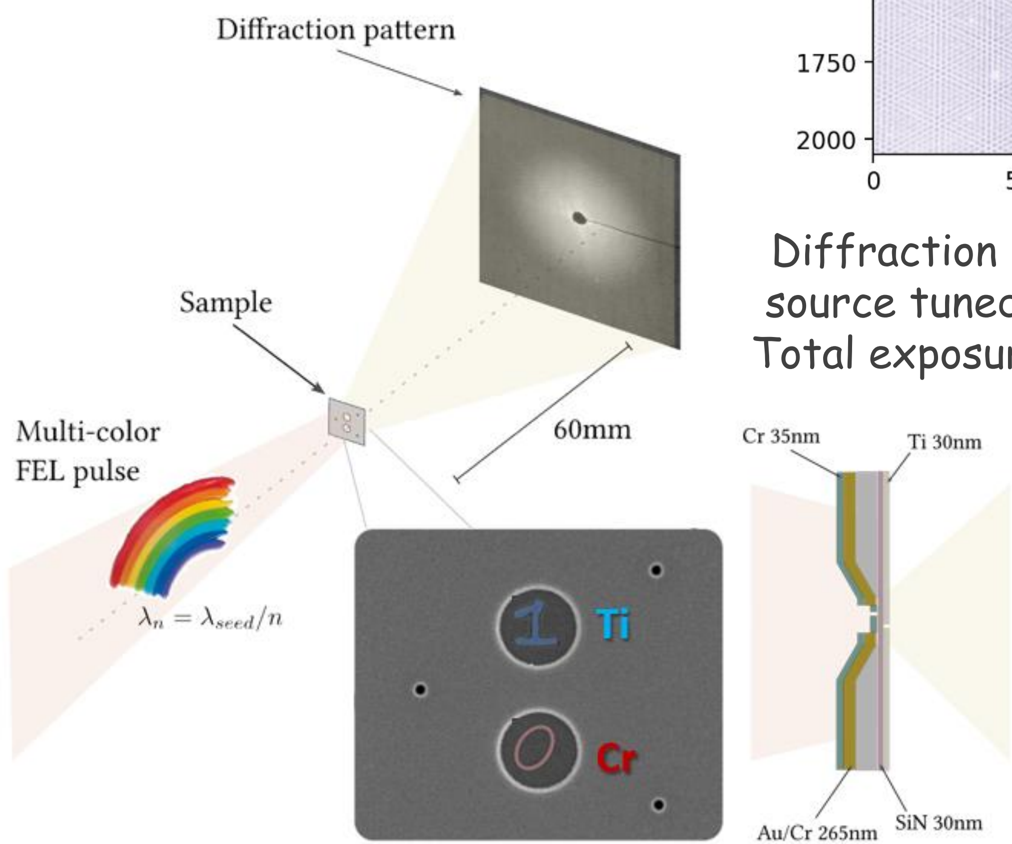
Multicolor rainbow imaging





Diffraction pattern collected with the source tuned at 5 different harmonics. Total exposure 1500 FEL shots @ 50 Hz



In collaboration with E.Malm and B.Pfau (in preparation)

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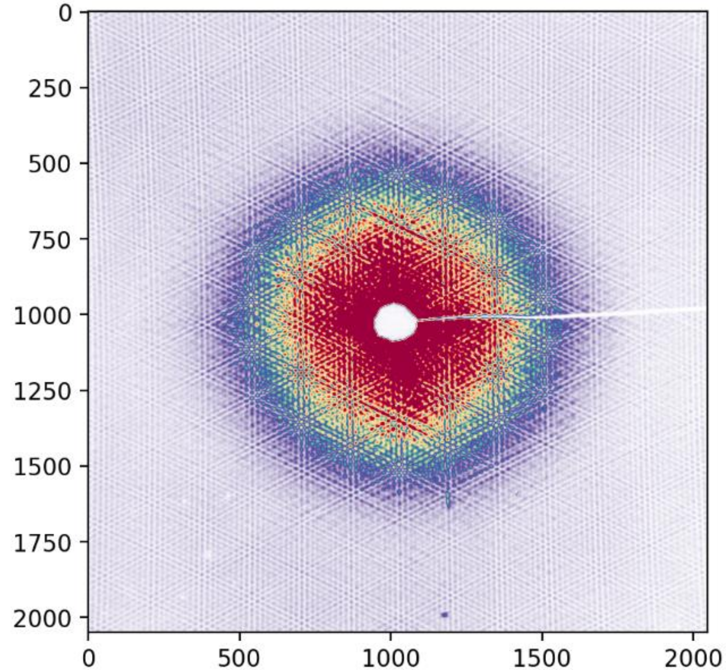
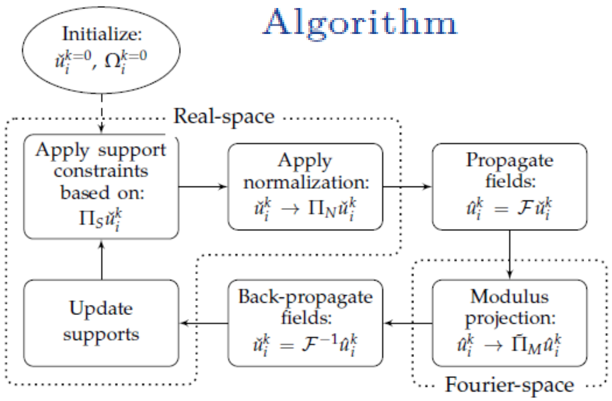


Multi-wavelength CDI

Algorithm



Multi-wavelength phase retrieval algorithm. Malm, Fohtung, and Mikkelsen, *Opt. Lett.*, 2021

- λ_i-dependent supports:

$$\Omega_i = \{x \in D : \varphi_i(x) \in \Omega_0\}$$
$$\varphi_i(x) = \frac{\lambda_i}{\lambda_0} x$$

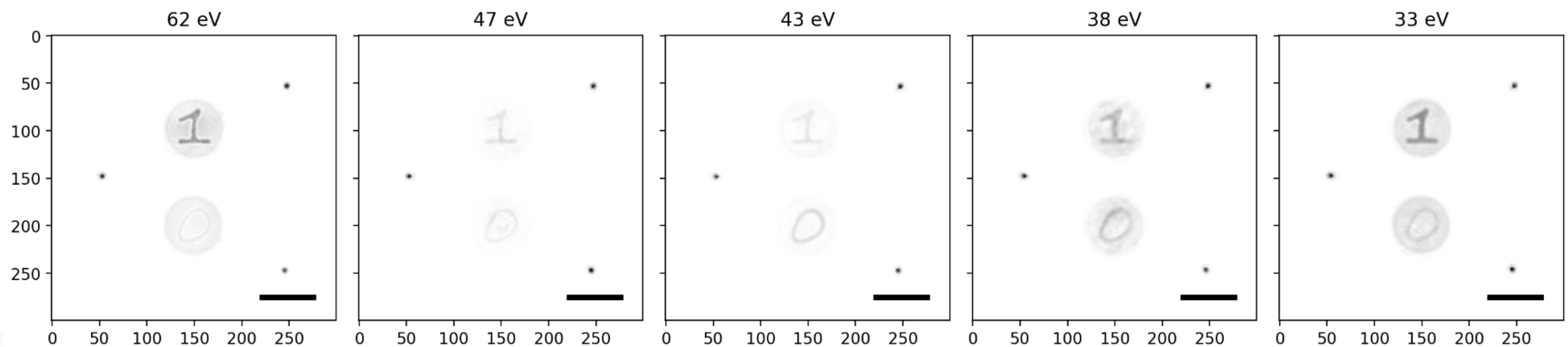
Modified projections:

- Support projection:

$$\Pi_S \check{u}_i(x) = \begin{cases} \check{u}_i(x) & x \in \Omega_i \\ 0 & x \notin \Omega_i \end{cases}$$

- Modulus projection:

$$\tilde{\Pi}_M \hat{u}_i(y) = \frac{\hat{u}_i(y)}{\sqrt{I(y)} + \epsilon} b(y)$$



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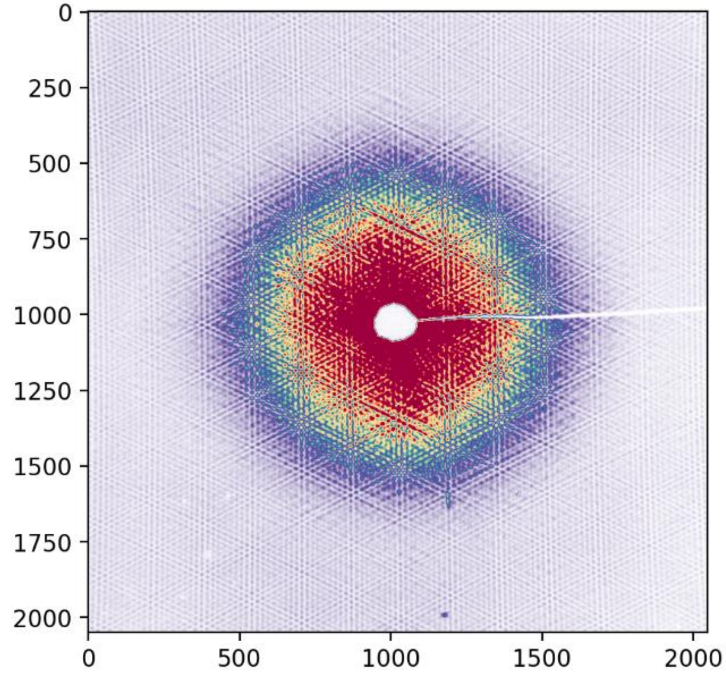

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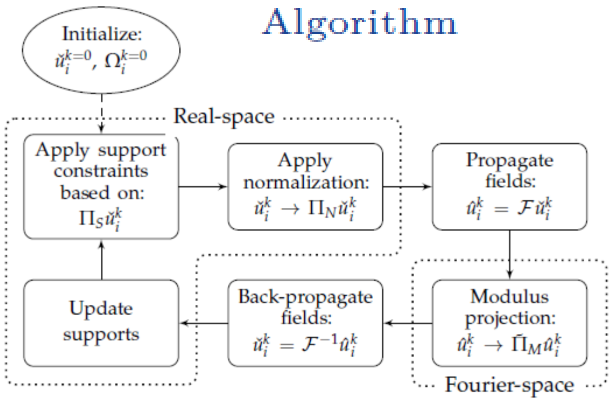

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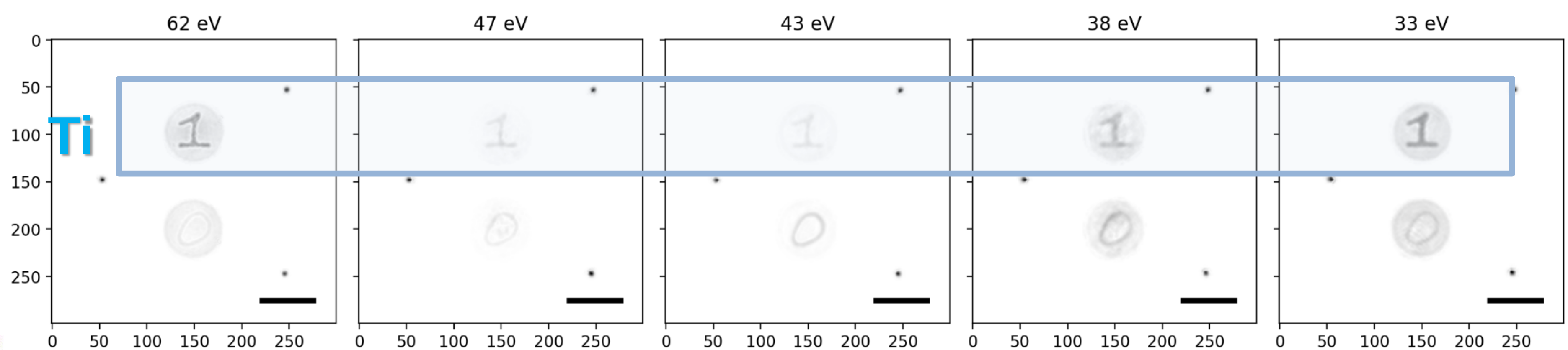

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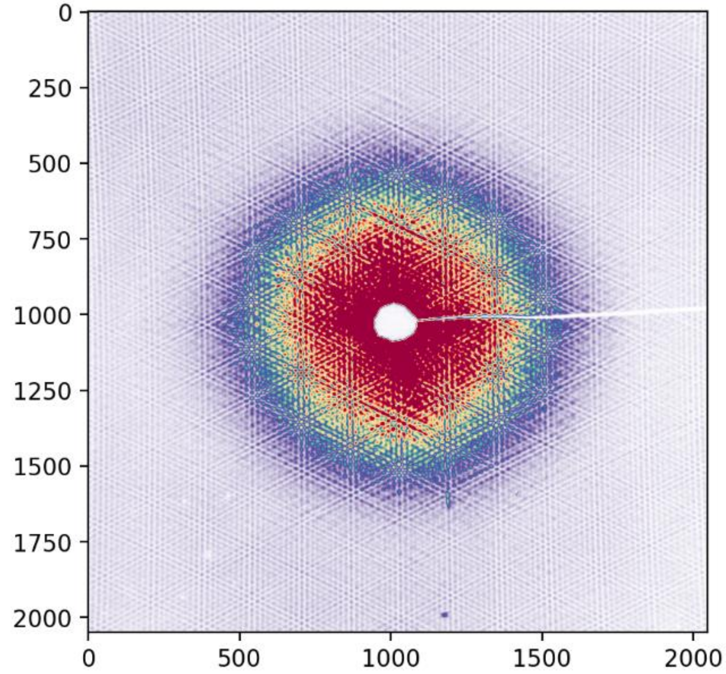

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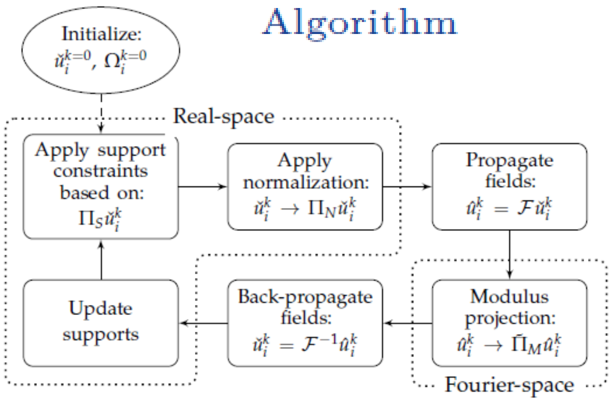

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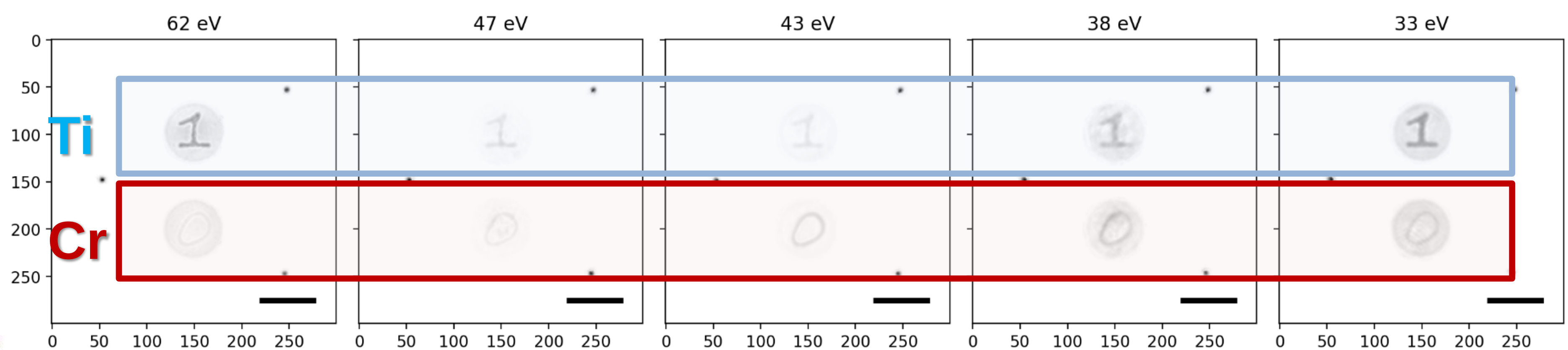

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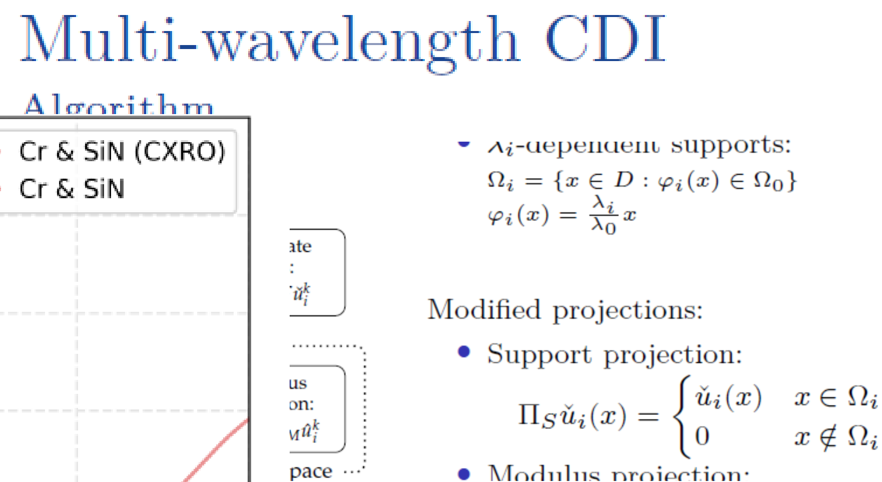


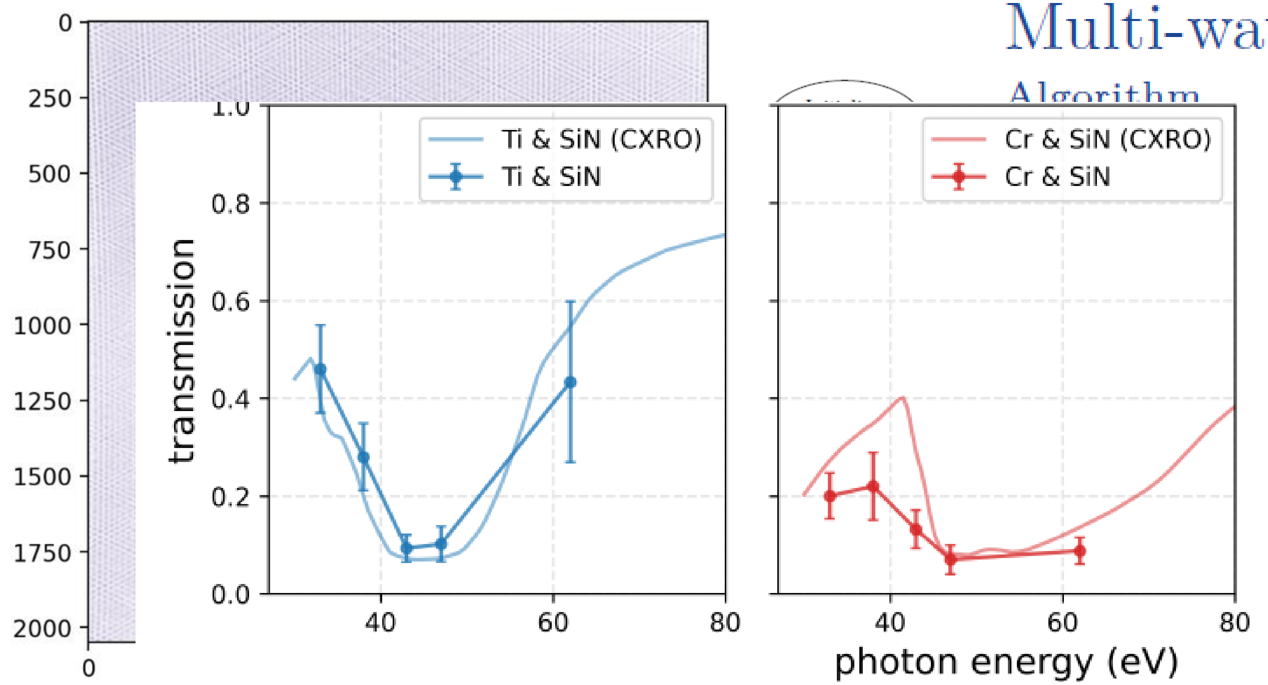
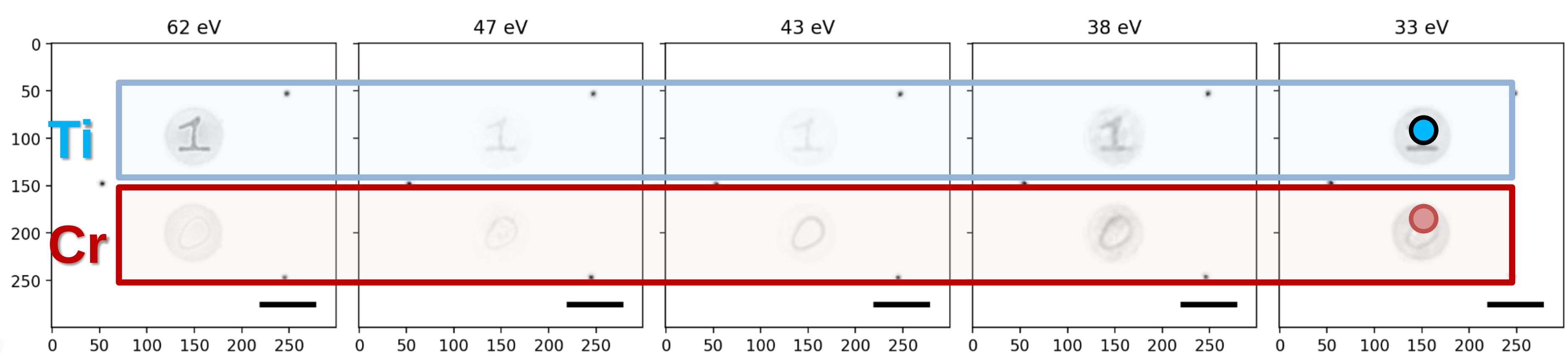


Image contrast well matches with XAS of two distinct elements



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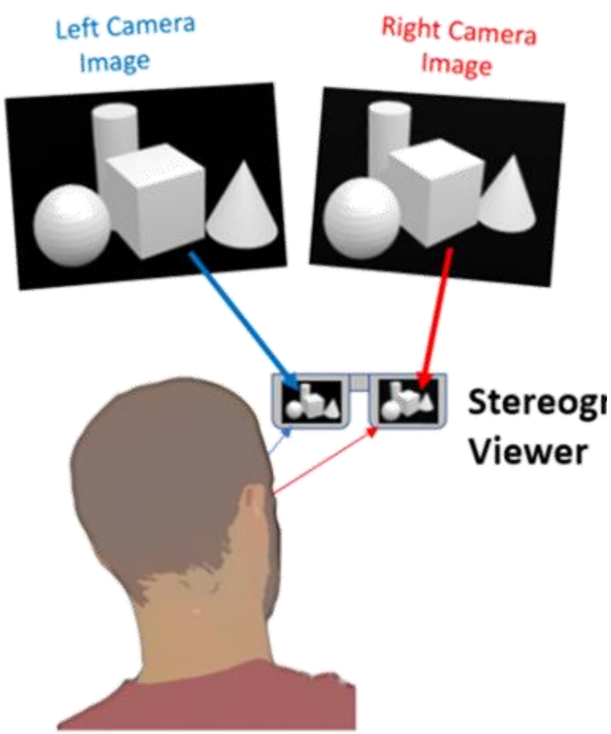
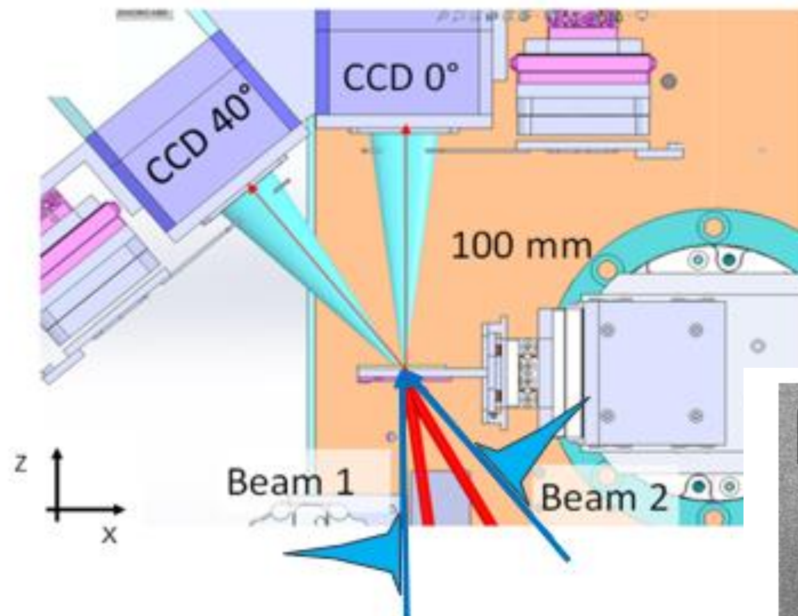
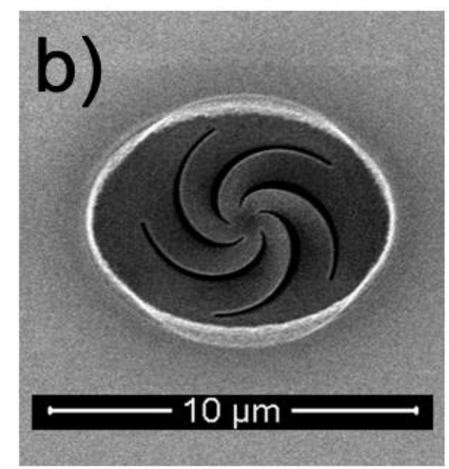
Stereo imaging

3D information is to simultaneously obtain multiple bidimensional visons of the same object. EUV stereoscopic imaging approach, similar to the natural process of binocular vision, provides sub-μm spatial resolution and single-shot capability.







D. Fainozzi et al. Three-dimensional coherent diffraction snapshot imaging using extreme-ultraviolet radiation from a free electron laser Optica 10, 1053-1058 (2023)
https://doi.org/10.1364/OPTICA.492730

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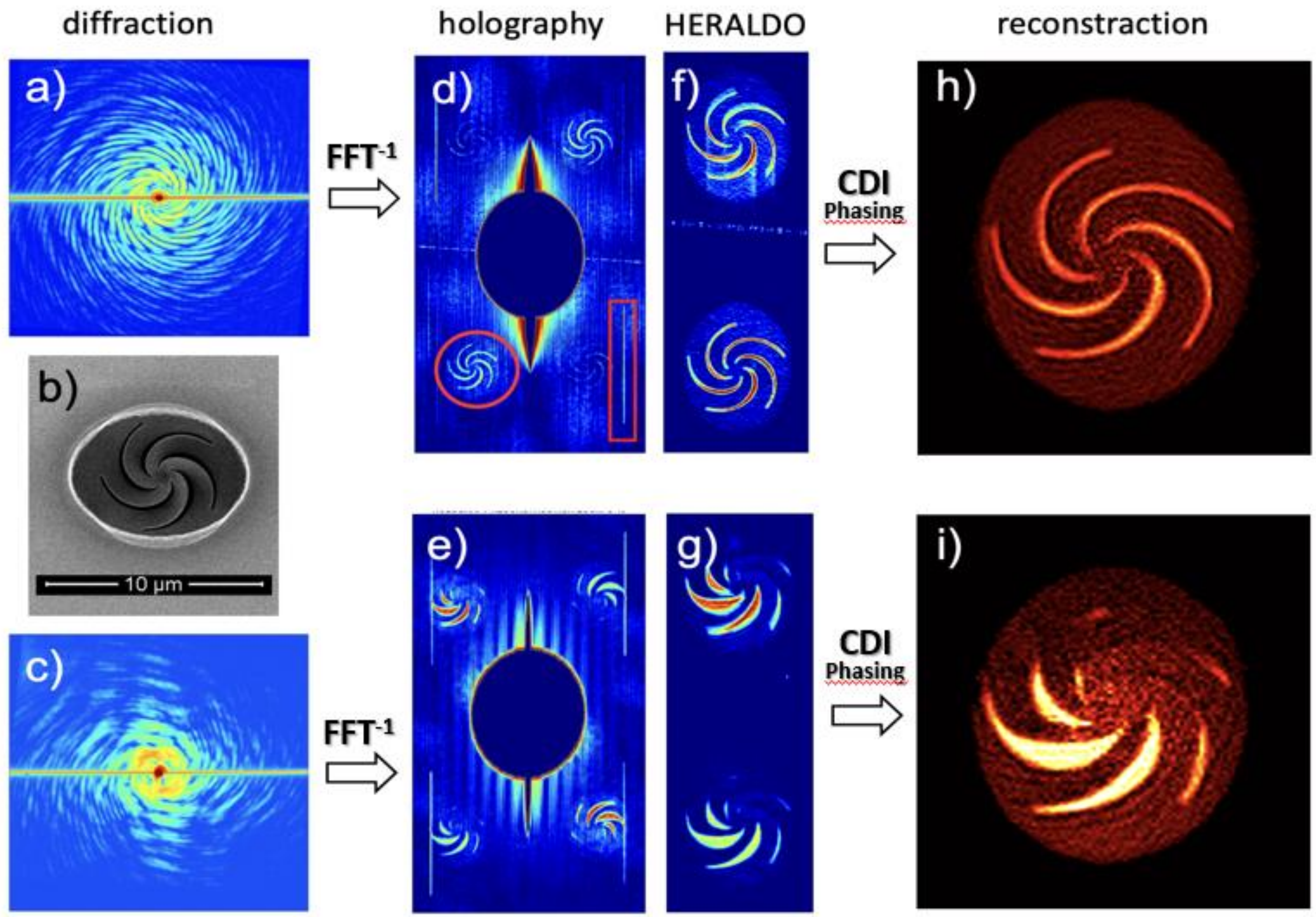

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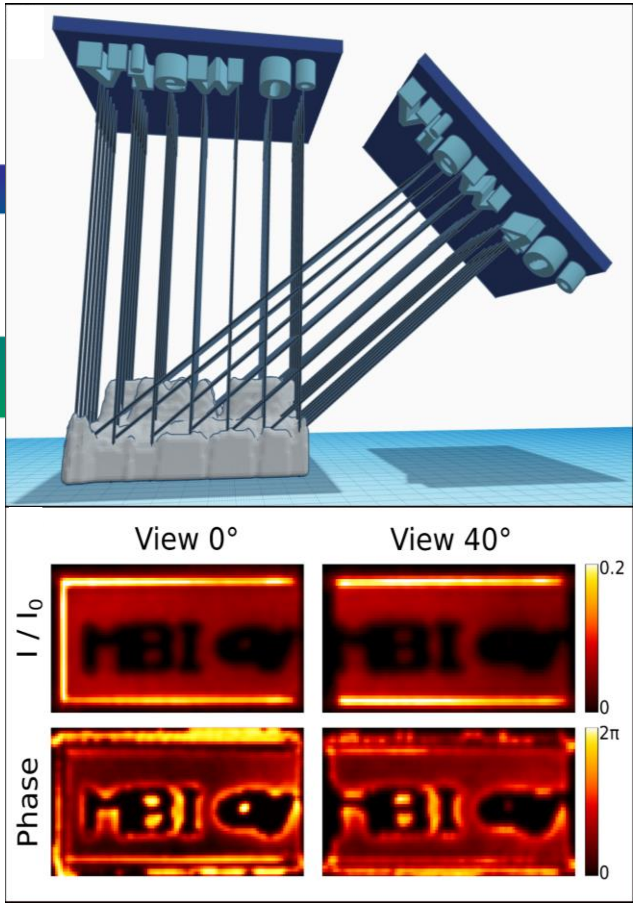

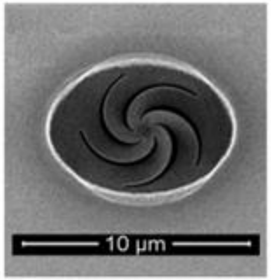

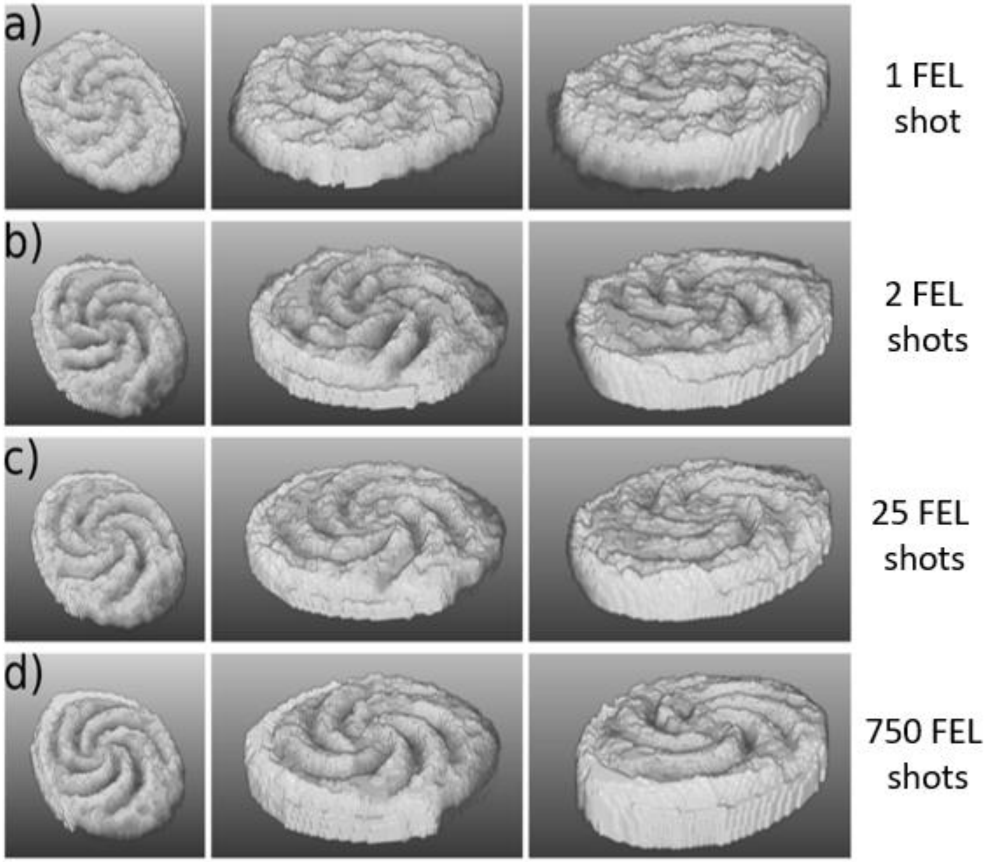

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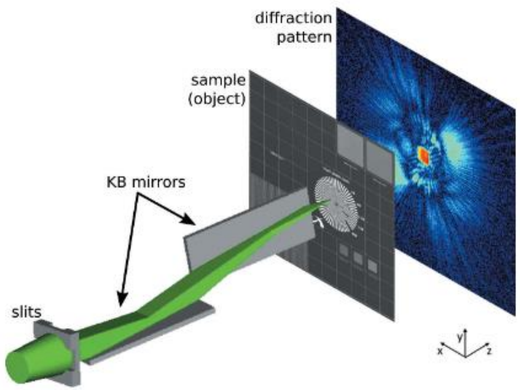
Ptychography with OAM

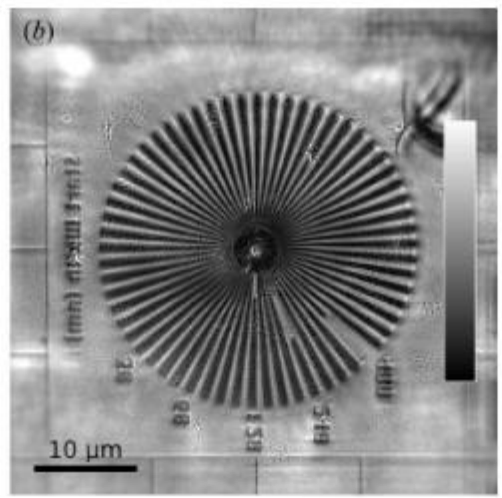
XUV ptychographic with structured illumination

Application of ptychographic @ FEL mostly as beam diagnostic tool but modest spatial resolution compared to SR microscopy due to high sensibility of reconstruction to beam intensity and pointing instability.

FEL beam focused by KB optics @ seeded FEL.

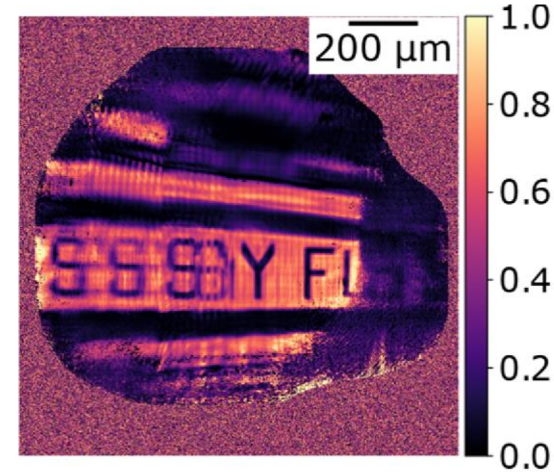


S. Sala et al.,
J. Appl. Cryst. (2020)



~ 500 nm resolution

FEL beam focused by KB optics @ SASE FEL.



K. Kharitonov et al.,
Opt. Exp. (2021)

~ 2.5 µm resolution

Ptychography with OAM

XUV ptychographic with structured illumination

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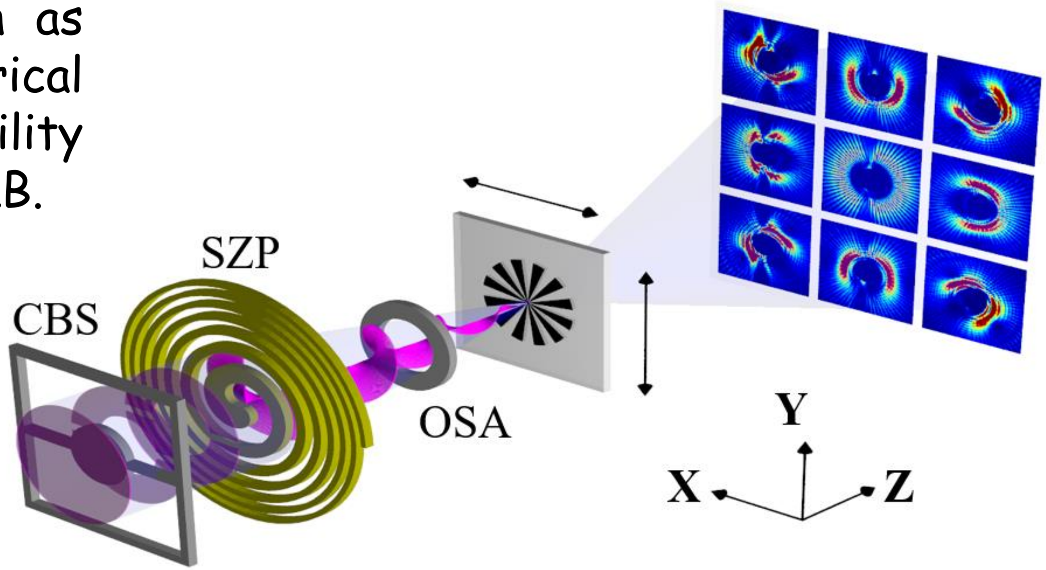
Diffractive optical elements, such as zone plates with a large numerical aperture, can enhance pointing stability compared to reflective optics like KB.



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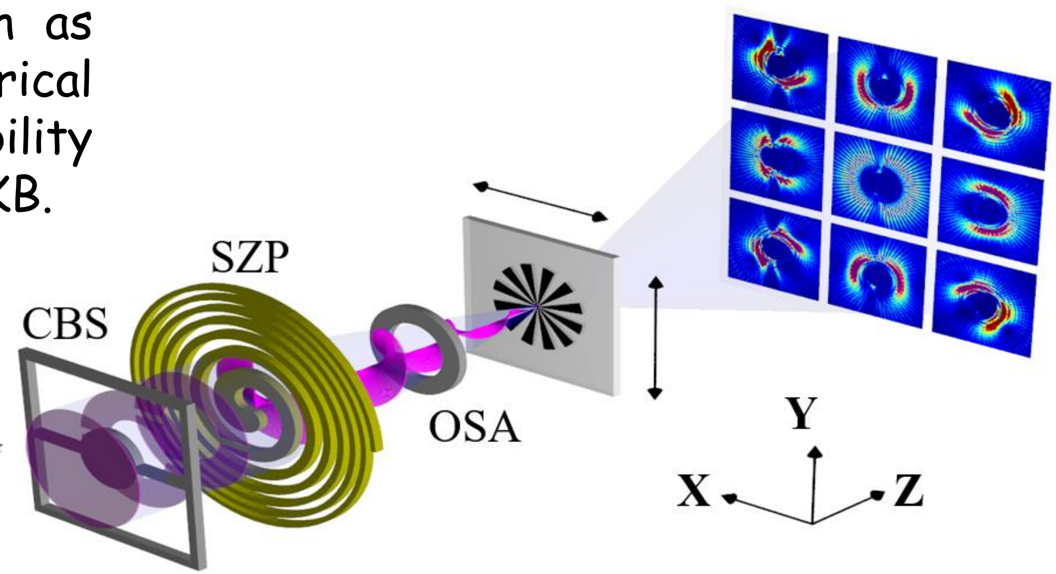
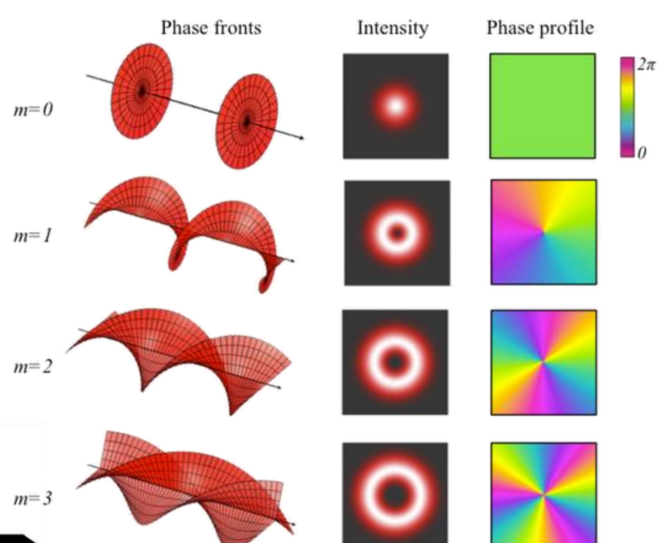
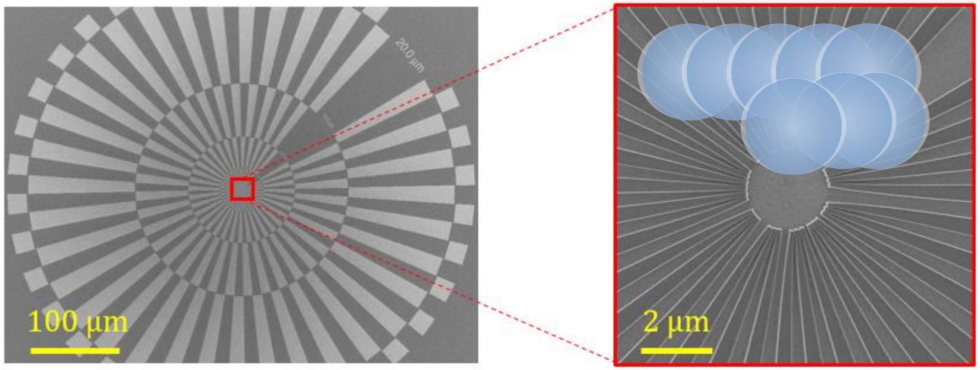




The use of structured illumination, such as the donut shape of an OAM beam, can improve spatial resolution.

F. Tamburini, et al. Phys. Rev. Lett. 97, 163903 (2006).
W. Eschen, et al. Opt. Express 32, 3480-3491 (2024)

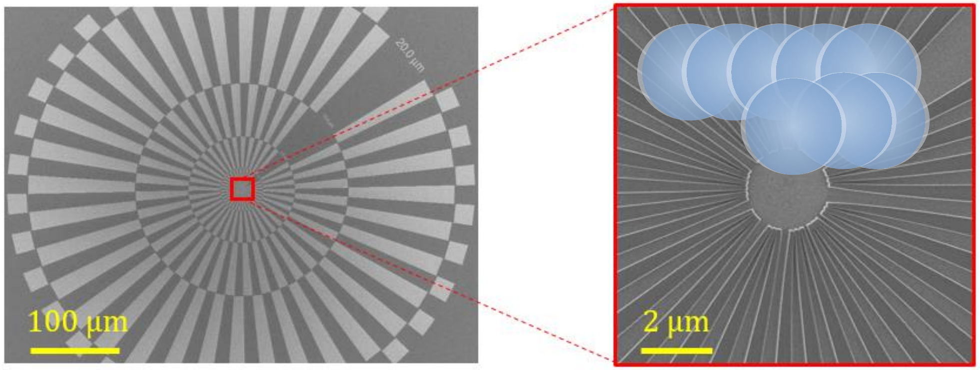
Ptychography with OAM



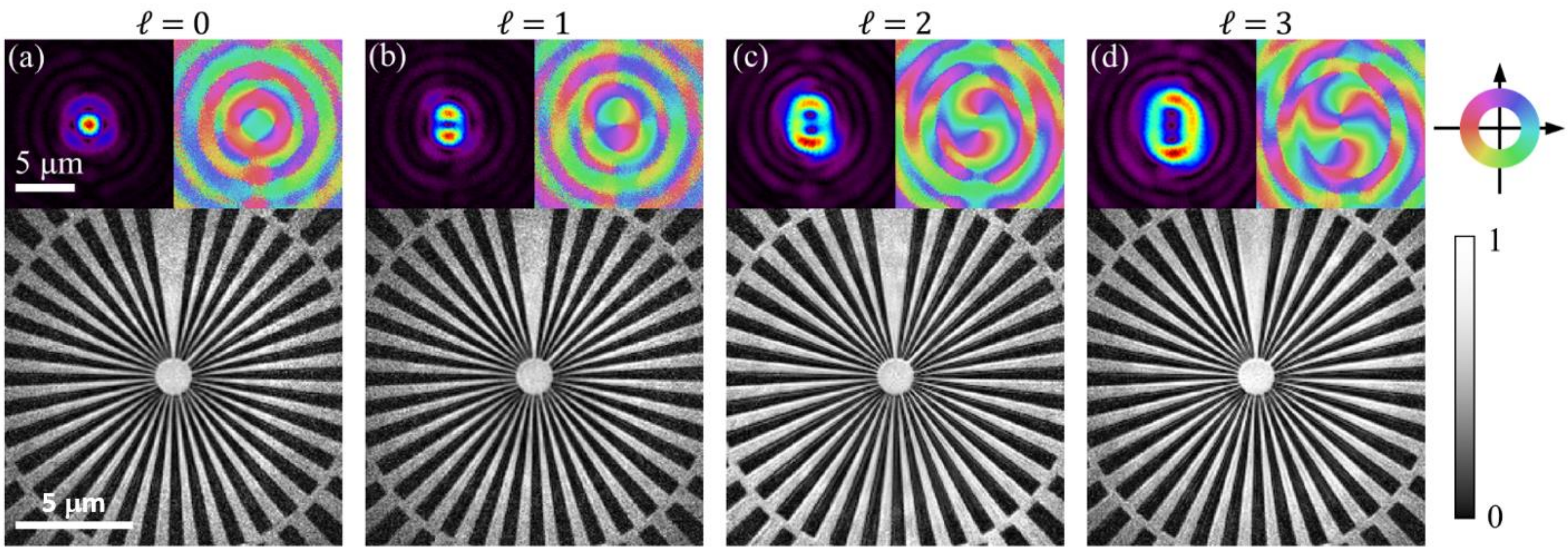
Single FEL shot per Ptychographic position

Pancaldi M. et al. High-resolution ptychographic imaging at a seeded free-electron laser source using OAM beams Optica 11, 403-411 (2024)
https://doi.org/10.1364/OPTICA.509745

Ptychography with OAM

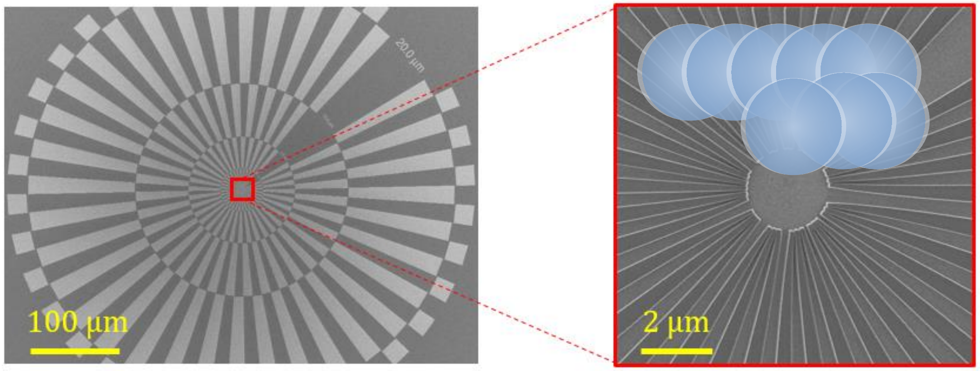


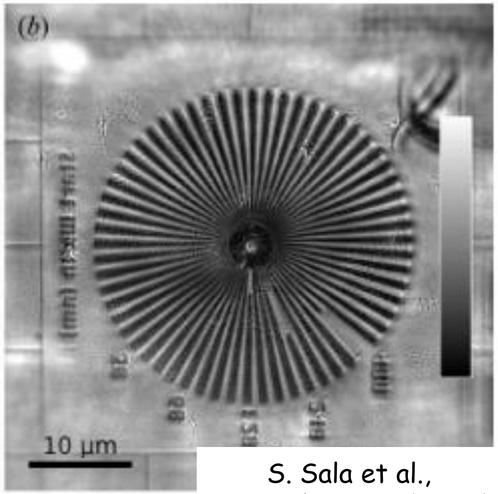
Single FEL shot per Ptychographic position



Pancaldi M. et al. High-resolution ptychographic imaging at a seeded free-electron laser source using OAM beams Optica 11, 403-411 (2024) https://doi.org/10.1364/OPTICA.509745

Ptychography with OAM





S. Sala et al.,
J. Appl. Cryst. (2020)

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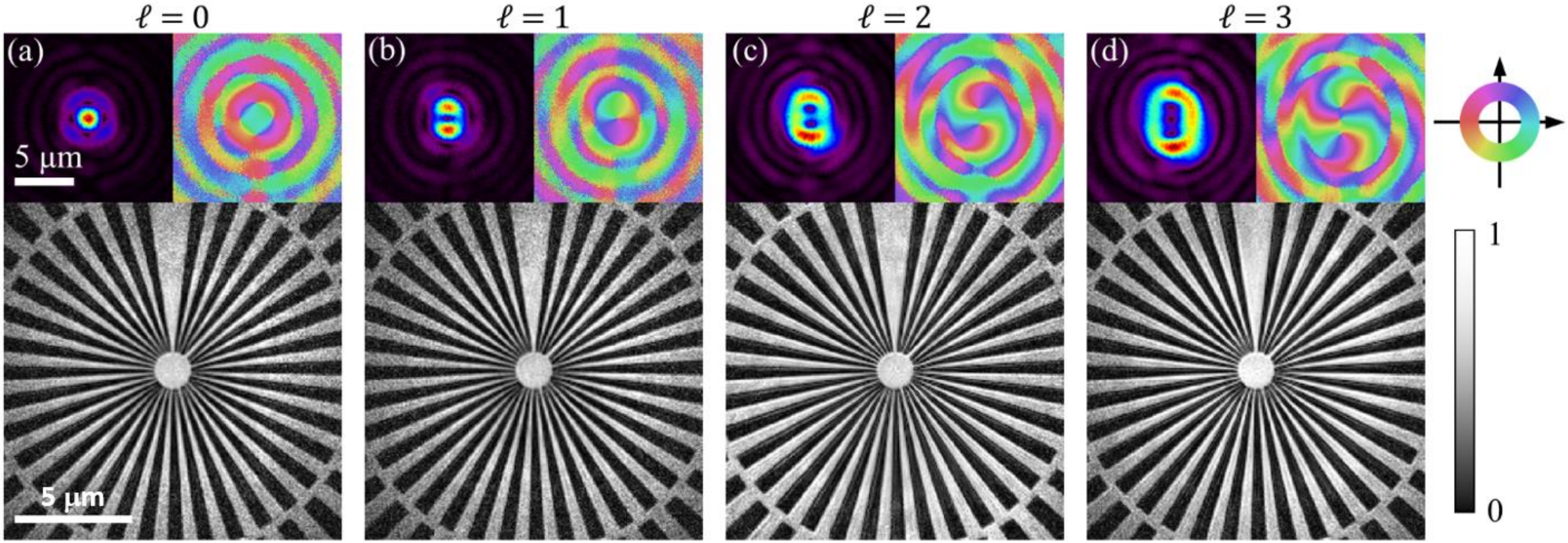

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Elettra Sincrotrone Trieste

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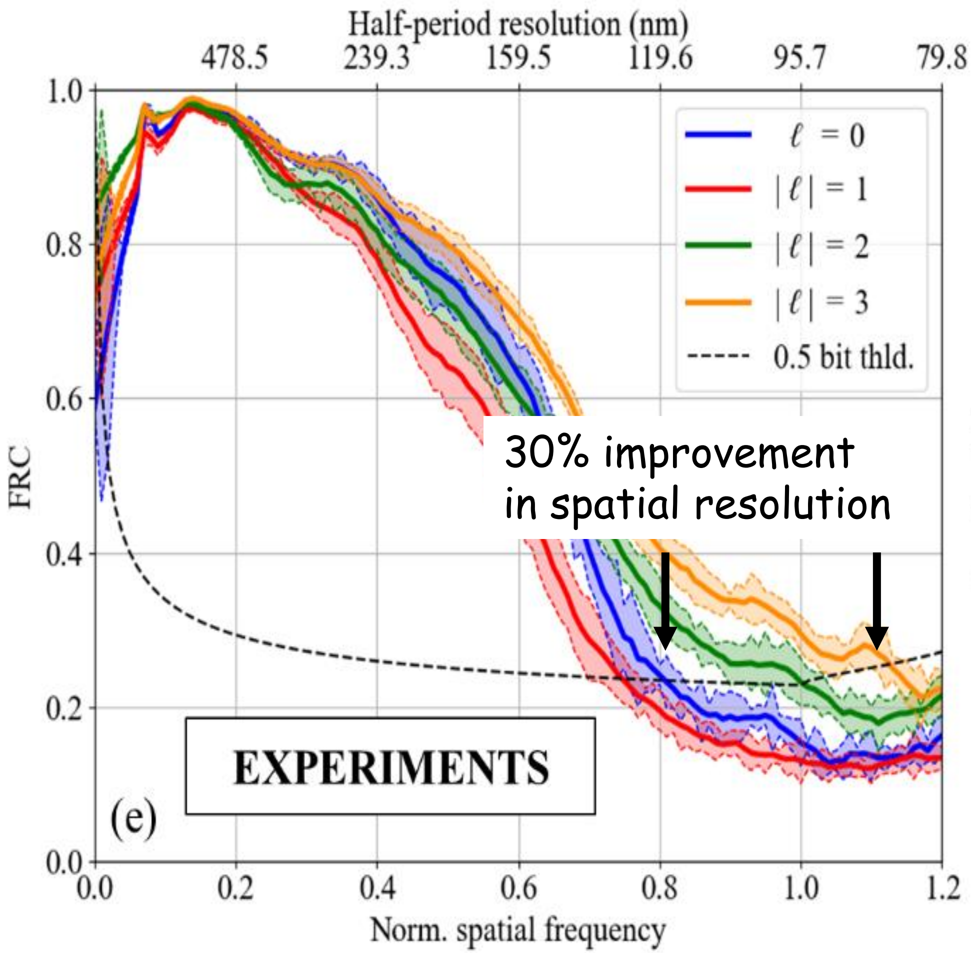
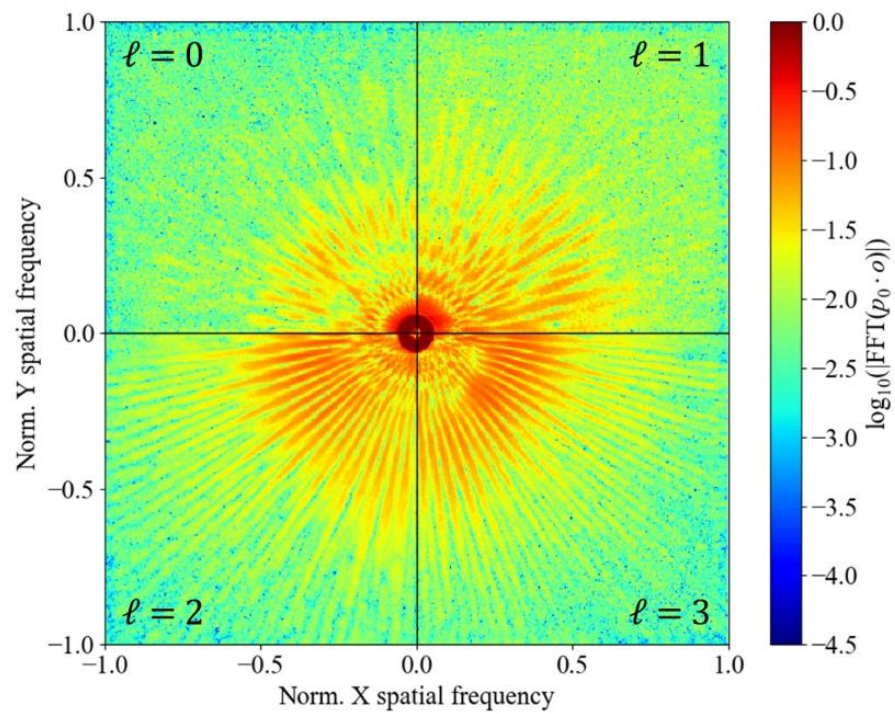


Fourier Ring Correlation



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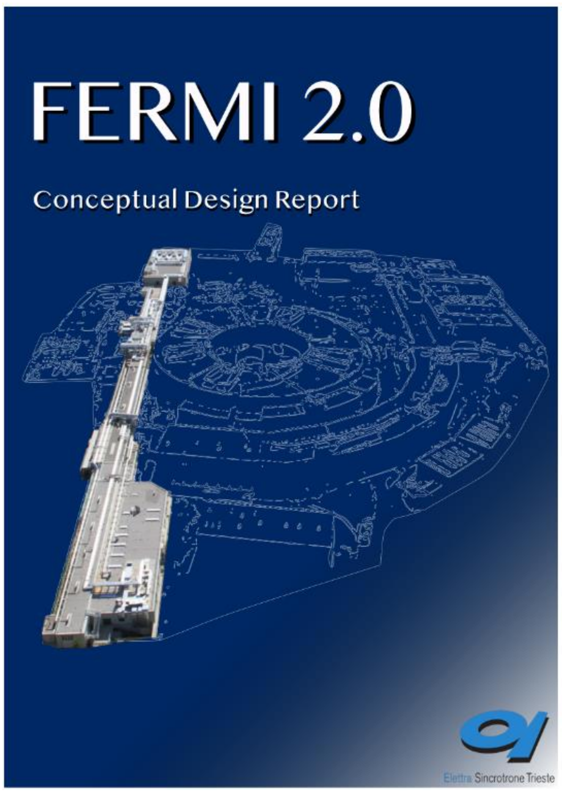
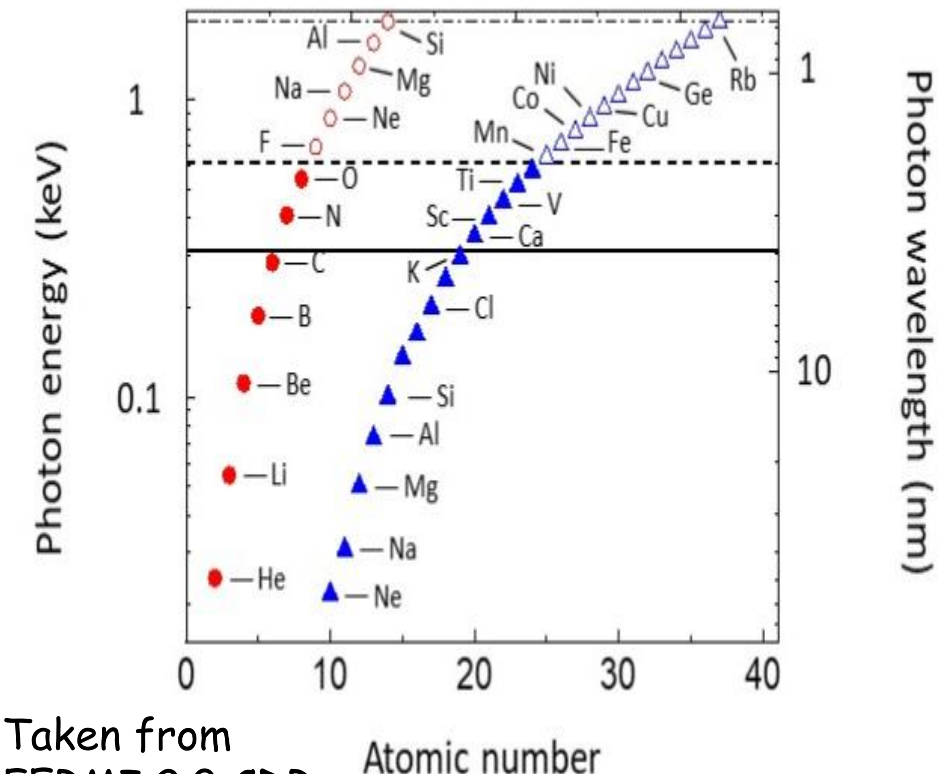
Topics

- Basic core capabilities of FERMI FEL and DiProI end-station.
    - Examples of coherent-based imaging and scattering experiments.
        - **Perspectives of FERMI in soft X-ray Imaging.**
            - Conclusions.

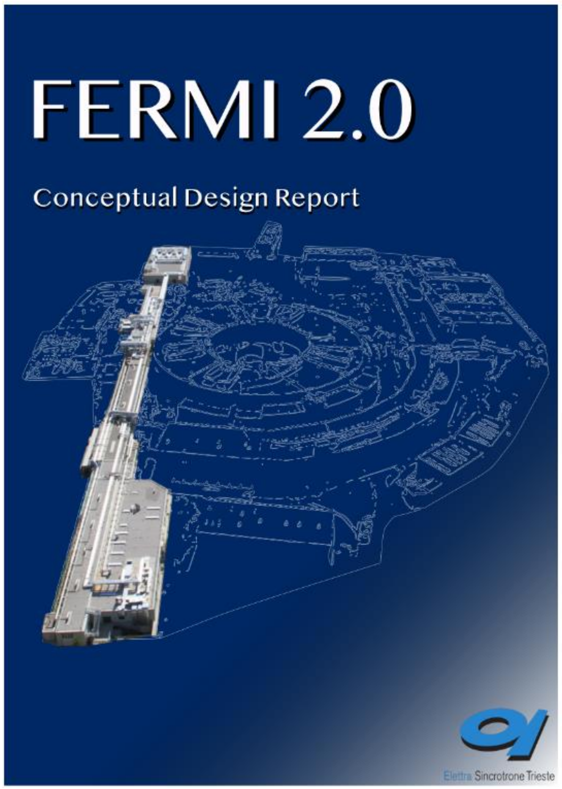
First steps toward soft X-ray



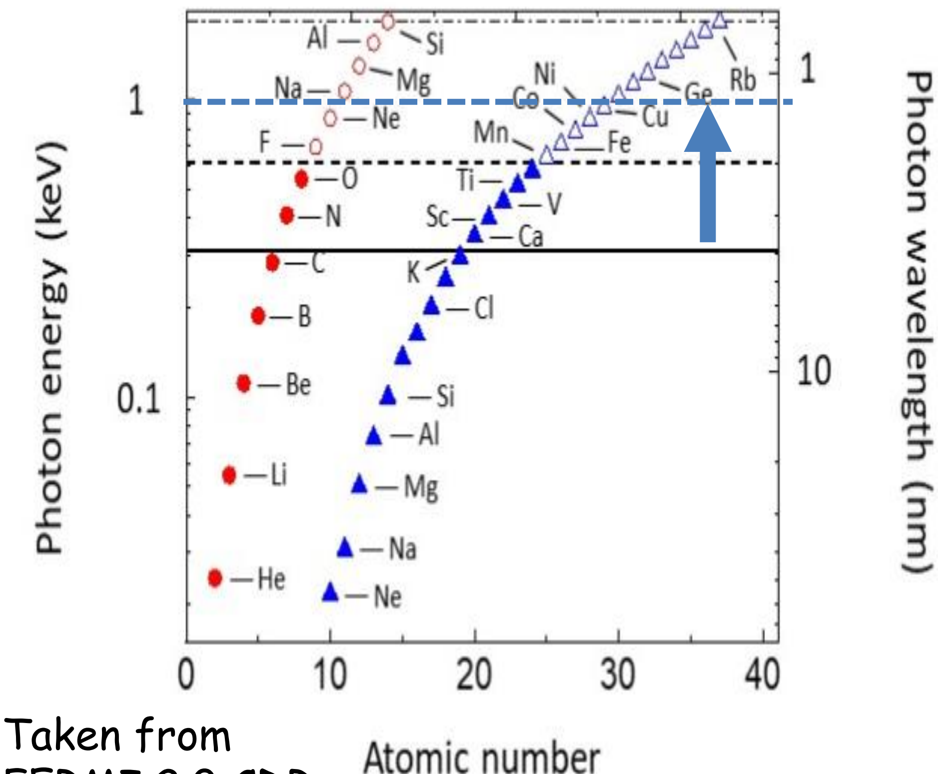


Taken from
FERMI 2.0 CDR

First steps toward soft X-ray



Extend the range of FERMI upto 1 KeV in fundamental emission with external seeding



Taken from FERMI 2.0 CDR

Flavio Capotondi

First steps toward soft X-ray

PHYSICAL REVIEW A 105, 053524 (2022)

Nonlinear harmonics of a seeded free-electron laser as a coherent and ultrafast probe to investigate matter at the water window and beyond

G. Penco,[1,*] G. Perosa,[2] E. Allaria,[1,3] L. Badano,[1] F. Bencivenga,[1] A. Brynes,[1] C. Callegari,[1] F. Capotondi,[1] A. Caretta,[1] P. Cinquegrana,[1] S. Dal Zilio,[4] M. B. Danailov,[1] D. De Angelis,[1] A. Demidovich,[1] S. Di Mitri,[1,2] L. Foglia,[1] G. Gaio,[1] A. Gessini,[1] L. Giannessi,[1,5] G. Kurdi,[1] M. Manfredda,[1] M. Malvestuto,[1] C. Masciovecchio,[1] R. Mincigrucci,[1] I. Nikolov,[1] E. Pedersoli,[1] S. Pelli Cresi,[1] E. Principi,[1] P. Rebernik,[1] A. Simoncig,[1] S. Spampinati,[1] C. Spezzani,[1] F. Sottocorona,[2] M. Trovó,[1] M. Zangrando,[1,4] V. Chardonnet,[6] M. Hennes,[6] J. Lüning,[6,†] B. Vodungbo,[6] P. Bougiatioti,[7] C. David,[7] B. Roesner,[7] M. Sacchi,[8] E. Roussel,[9] E. Jal,[6] and G. De Ninno[1,10,‡]

We estimate an average pulse energy at the sample plane of 3±2 nJ/shot ~ 2x10^7 ph/shots (@ 700/780 eV)

PHYSICAL REVIEW B 110, 174409 (2024)

Editors' Suggestion

Circular dichroism experiments at the *L* edge of magnetic transition metals enabled by elliptically polarized pulses from a seeded free-electron laser

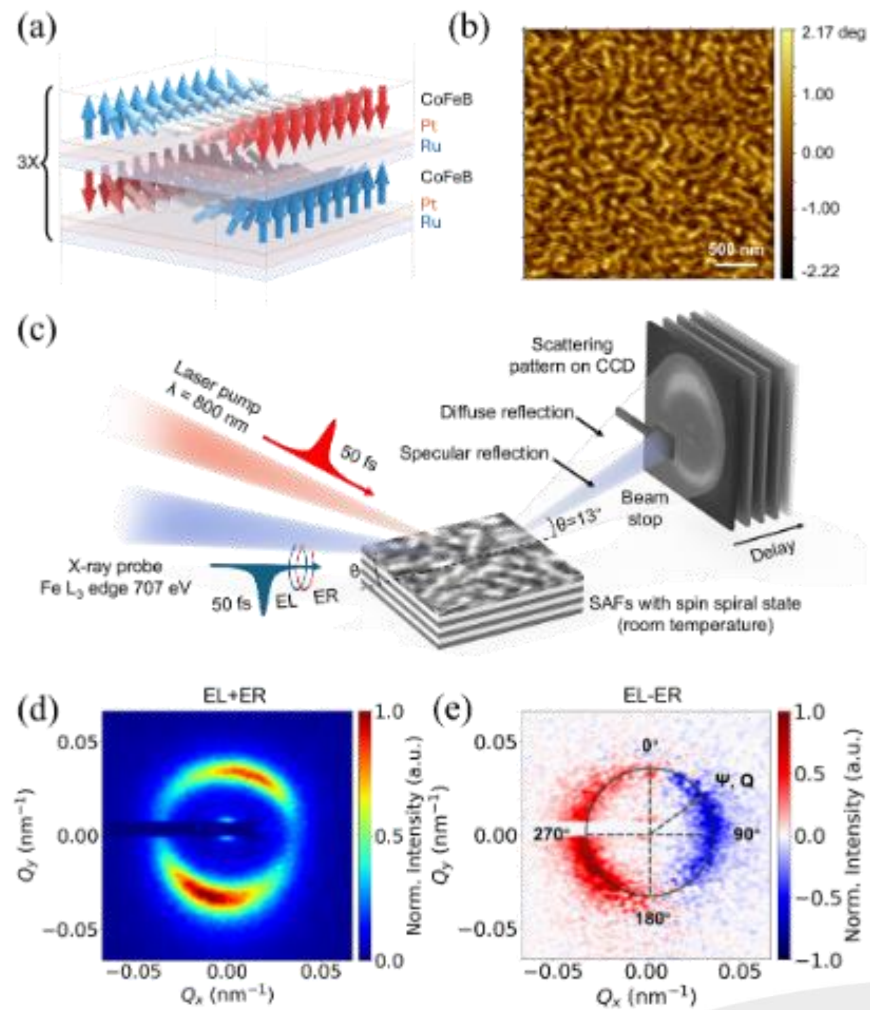
C. Spezzani,[1] A. Ravindran,[2] E. Allaria,[1] L. Badano,[1] R. Bhardwaj,[1] A. Brynes,[1] P. Capaldo,[2] A. Caretta,[1] P. Cinquegrana,[1] A. Contillo,[1] M. Danailov,[1] A. Demidovich,[1] S. Dal Zillo,[2] G. De Ninno,[1,2,*] B. Diviacco,[1] G. Kurdi,[1] D. Garzella,[1] G. Geloni,[3] L. Giannessi,[1,4] S. Laterza,[1] M. Manfredda,[1] I. Nikolov,[1] M. Pancaldi,[1,5] M. Pasqualetto,[1] E. Pedersoli,[1] G. Penco,[1] G. Perosa,[1,6] M. Prica,[1] L. Raimondi,[1] P. Rebernik Ribič,[1] C. Scafuri,[1] P. Sigalotti,[1] A. Simoncig,[1] F. Sottocorona,[1,6] S. Spampinati,[1] P. Susnjar,[1] F. Tripaldi,[1] M. Trovò,[1] M. Zangrando,[1,7] F. Capotondi,[1] N. Jaouen,[5,8] M. Malvestuto,[1] and M. Sacchi[8,9]

PHYSICAL REVIEW B 112, L020408 (2025)

Letter | Editors' Suggestion | Featured in Physics

Ultrafast dynamics of chiral spin structures in synthetic antiferromagnets

Zongxia Guo,[1,2] Raphael Gruber,[3] Dmitriy Ksenzov,[4] Cyril Léveillé,[1,2] Matteo Pancaldi,[5,6] Emanuele Pedersoli,[5] Carlo Spezzani,[5] Giovanni De Ninno,[5,7] Flavio Capotondi,[5] Christian Gutt,[4] Mathias Kläui,[3] Vincent Cros,[2] Nicolas Reyren,[2] and Nicolas Jaouen[1,6]

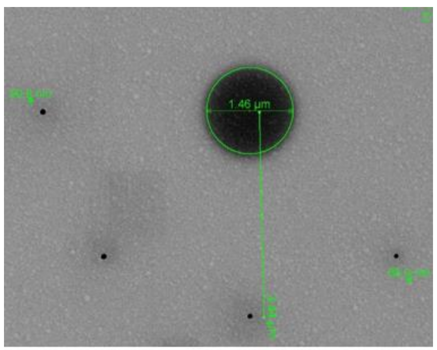


We estimate at least 40% of circular polarization @ 780 eV

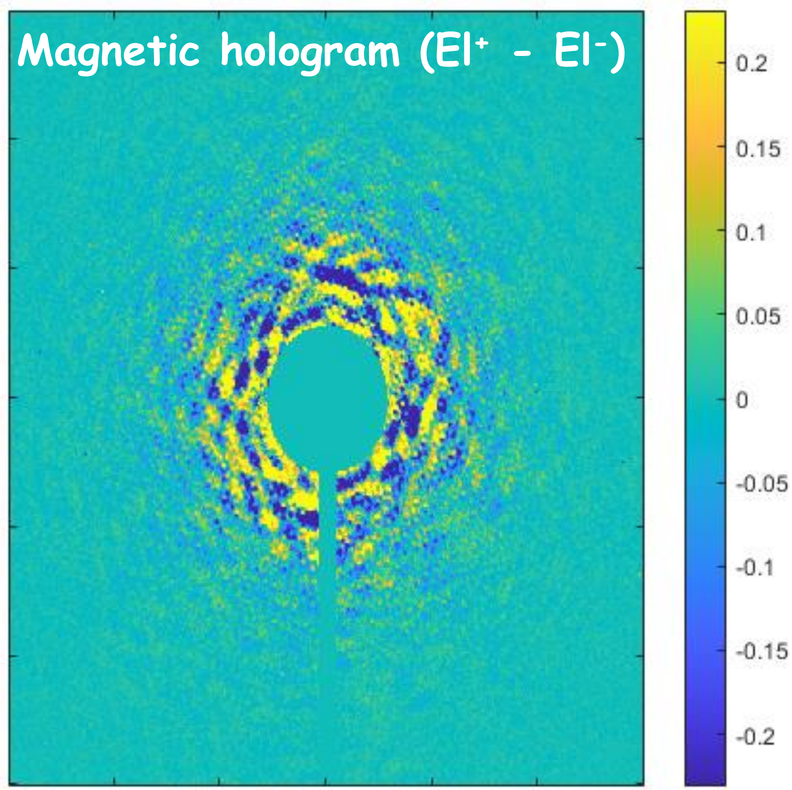
Elettra Sincrotrone Trieste

First steps toward soft X-ray

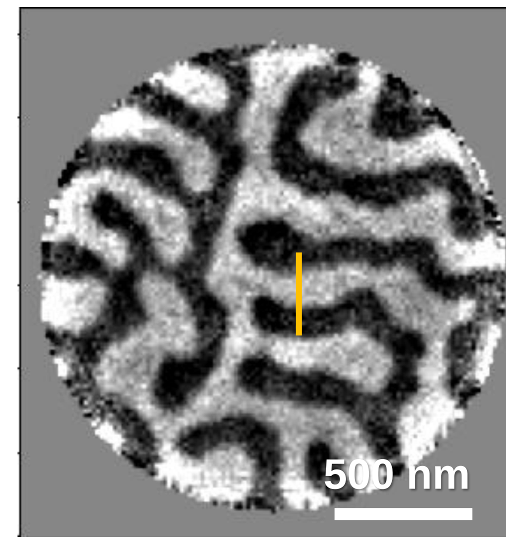
We use the recent demostrated polarization controll of high order nonlinear harmonic emitted by FERMI source to perform the first Fourier Transform Holography in Soft X-ray regime.

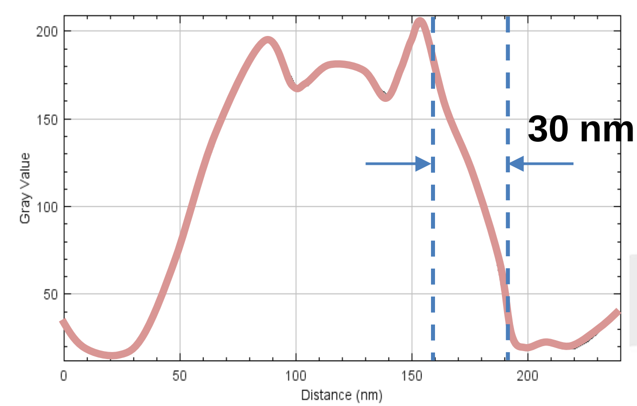


sample CoPt ML system
Ta(3 nm)/Pt(3 nm)/[Co(0.6)/Pt(0.8)]x20/Pt(3nm)



CDI REFINED





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Flavio Capotondi

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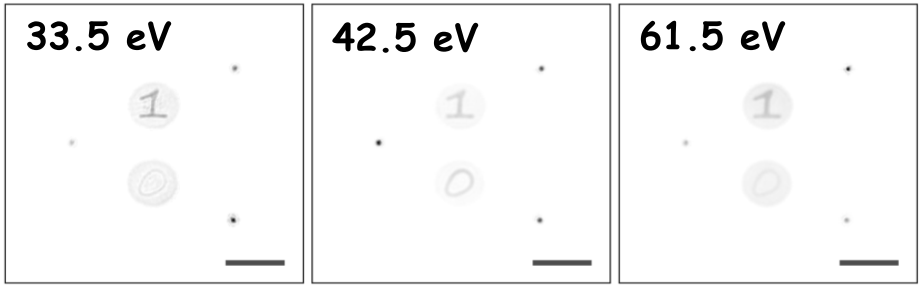

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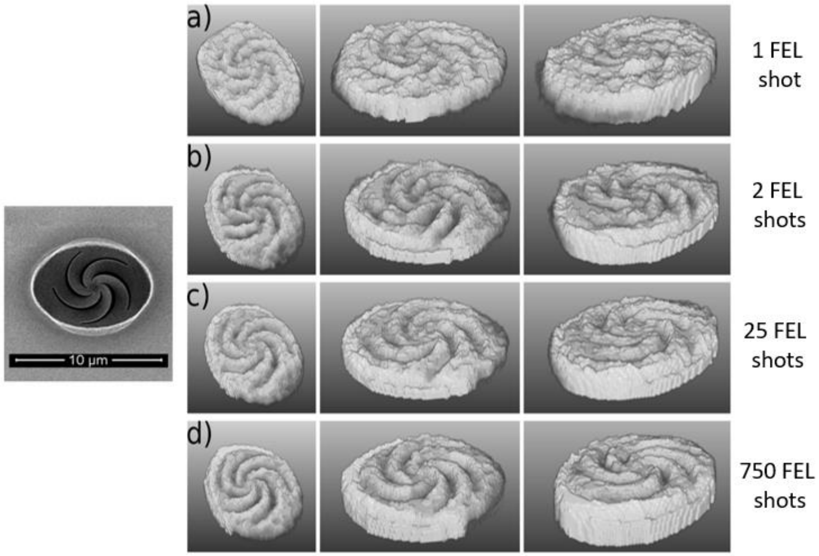

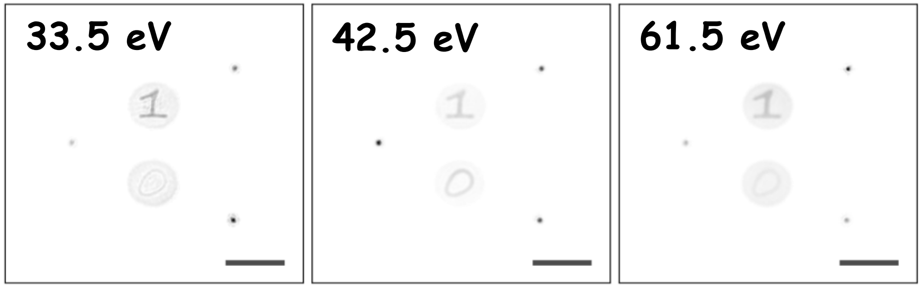

- **Sterographic imaging**

Elettra Sincrotrone Trieste

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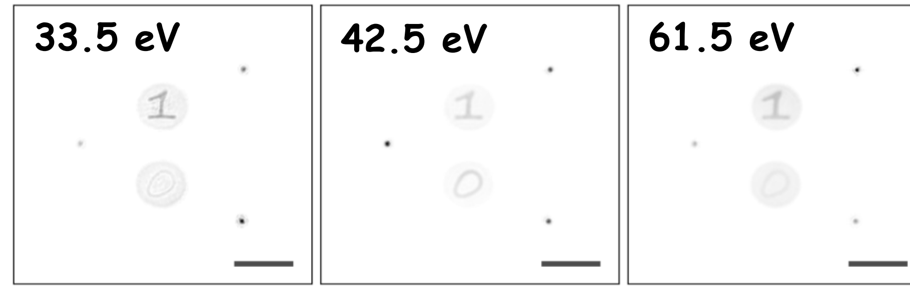

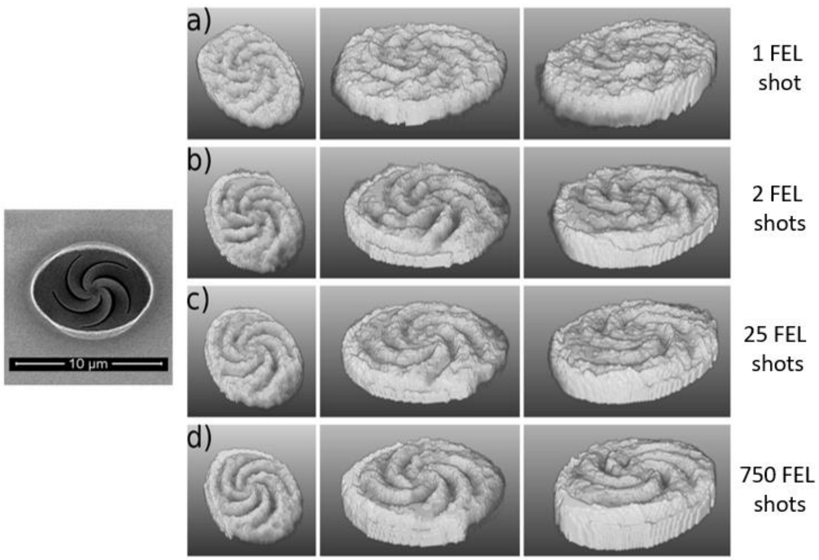

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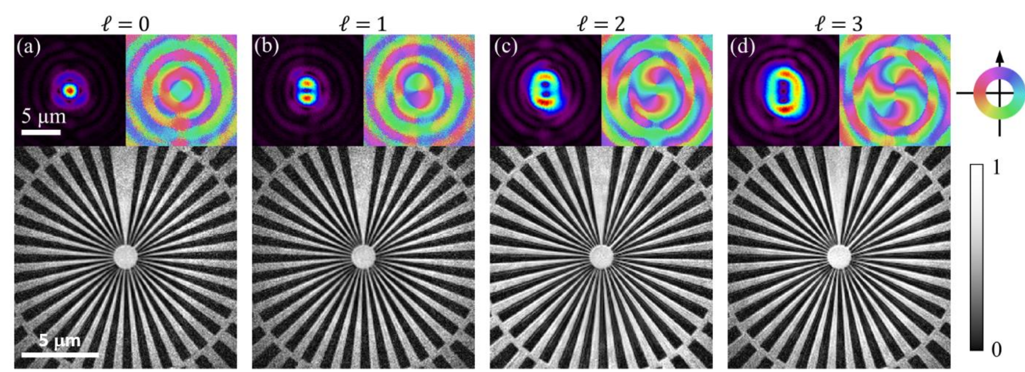

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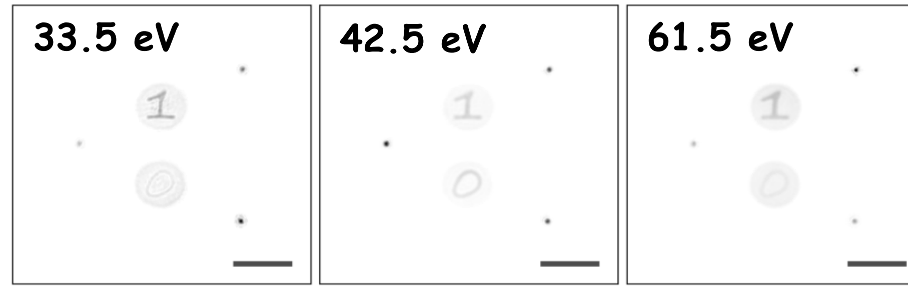

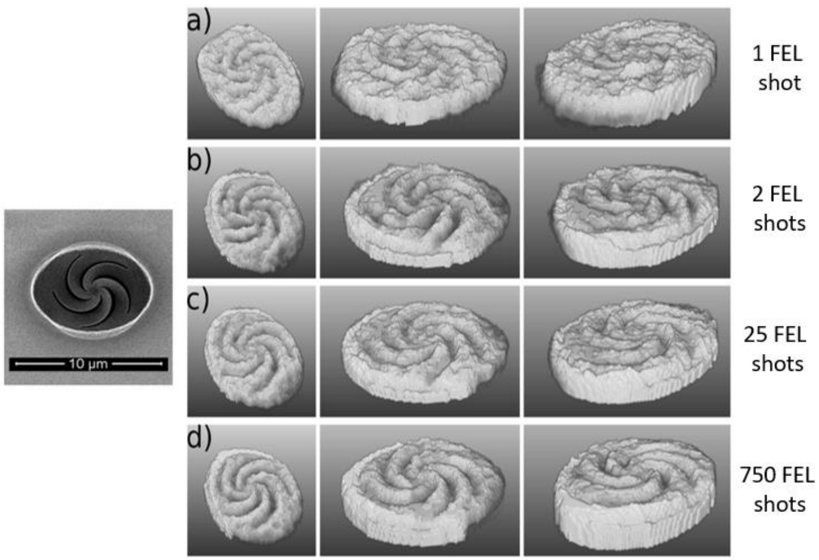

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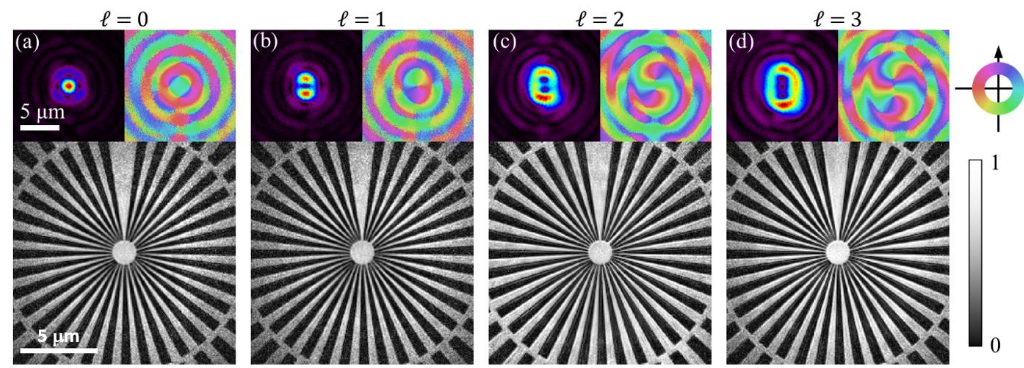

Both the future evolution of these approaches and their use by the user community demand the development of advanced detectors, especially for soft X-ray applications.

ACKNOWLEDGEMENTS

Elettra Sincrotrone Trieste

De Ninno – P. Rebernik Ribič – C. Spezzani – L.Gianessi (FEL source & Experiments)
M. Manfredda – A. Simoncig – M. Zangrando (Optics and WFS)
F. Guzzi – G. Kourousias (Phyco code development)
I.P. Nikolov (Laser)

Universität Siegen
D. Ksenzov
C. Gutt

Max-Born-Institut
S. Eisebitt
B. Pfau
C. Von Kroff

SOLEIL SYNCHROTRON
M. Sacchi
N. Jaouen

cea, université Paris-Saclay, cnrs, LIDYL
M. Fanciulli
T. Ruchon

PAUL SCHERRER INSTITUT PSI
C. David
I.Bykova
B. Rösner

UPMC Sorbonne Universités
E. Jal
J. Luning
B. Vodungbo, et al.

G. F. Mancini
C. Bevis
C. Grova

CIC nanoGUNE, Member of Basque Research & Technology Alliance
P. Vavassori

Elettra Sincrotrone Trieste

ACKNOWLEDGEMENTS

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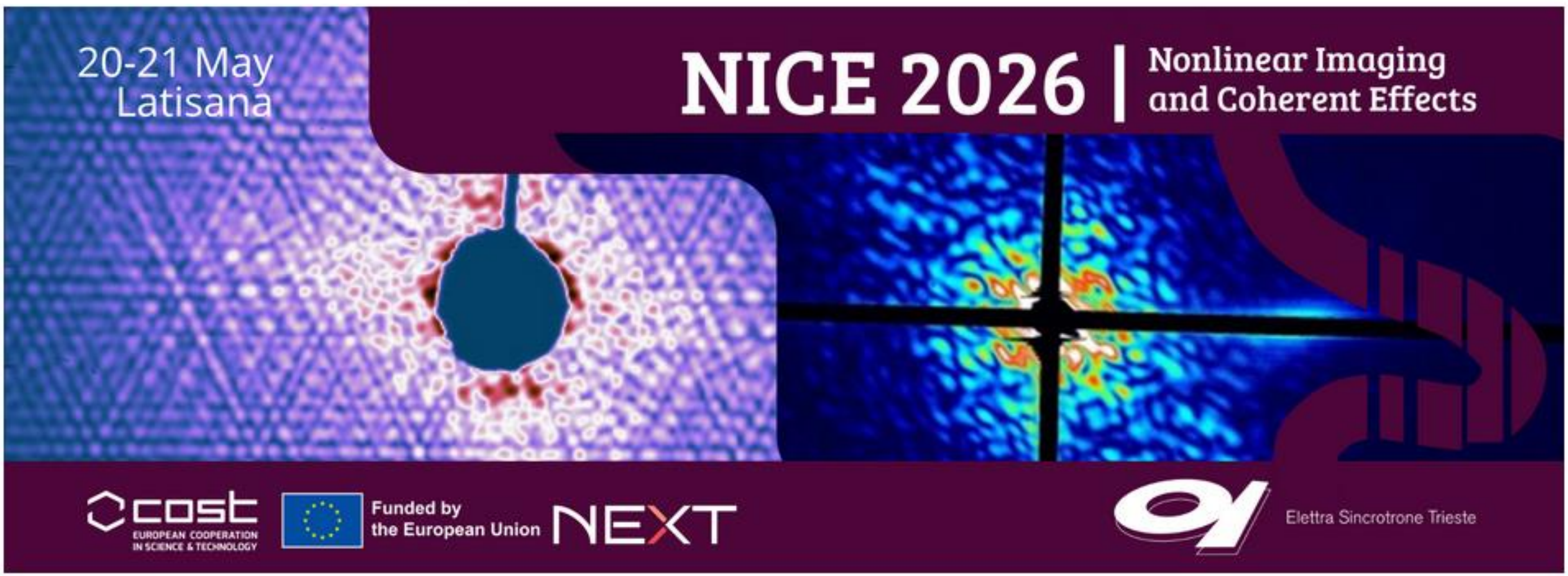
Last but not least



The workshop aims to bring together the linear and non-linear spectroscopy communities with the rapidly advancing field of coherent imaging.

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Flavio Capotondi

CIC nanoGUNE
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

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