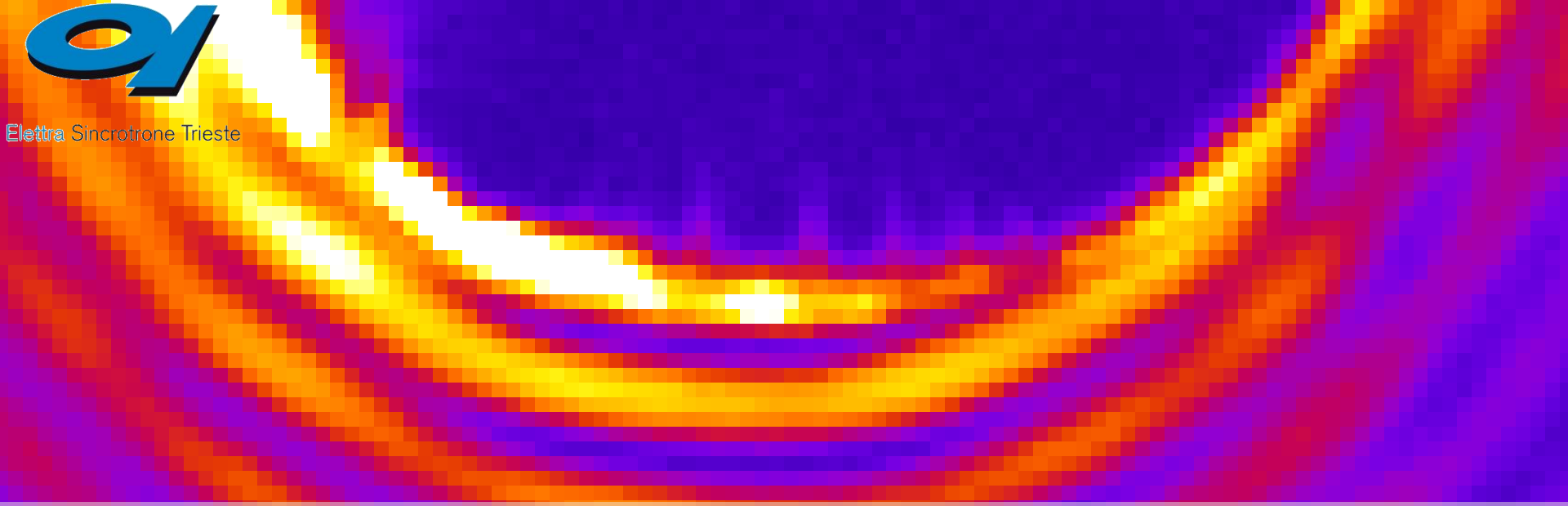


Elettra Sincrotrone Trieste

DiProI, the coherent diffraction imaging end-station at FERMI@Elettra FEL user facility: present status and future research opportunities.

Flavio Capotondi

(on behalf of DiProI team, collaborators and users)

Topics

- Introdution: FERMI FEL and core capabilities of DiProI end-station.
- Pump-Probe experiments with seeded FEL.
- Future upgrades and research opportunities.
- Conclusive remarks.

Topics

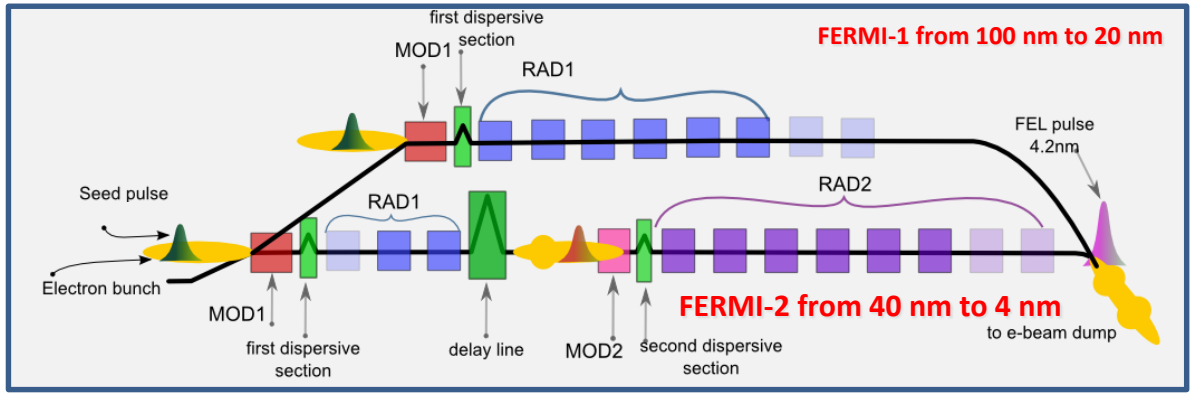
- ***Introduction: FERMI FEL and core capabilities of DiProI end-station.***
- Pump and Probe experiments with a seed FEL.
- Future upgrades, research opportunities.
- Conclusion remarks.

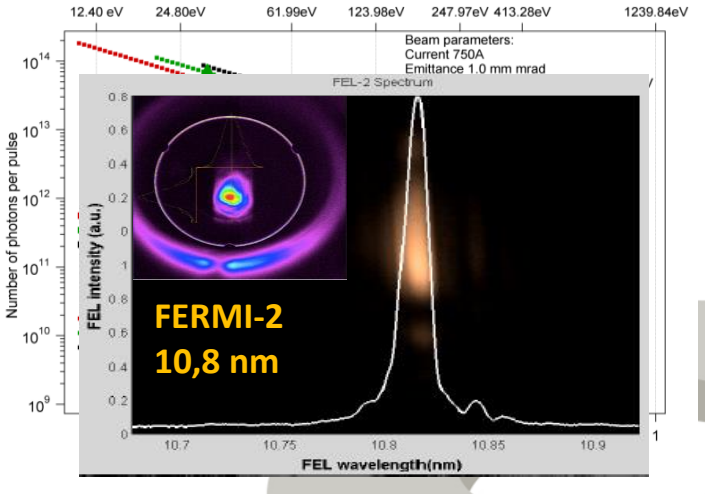
The FERMI FEL source

Elettra Sincrotrone Trieste

FERMI@Elettra is a single-pass seeded FEL user-facility.

- ✓ Two separate FEL amplifier cover the spectral range from 100 nm (12 eV) to 4 nm (320 eV).
- ✓ Based on the high gain harmonic generation scheme FERMI provides pulses of <100 fs with unique characteristics:
- ❑ ***high peak power***
- ❑ ***short temporal structure***
- ❑ ***tunable wavelength***
- ❑ ***variable polarization***





Refs: E. Allaria et al., Nature Photonics, **6**, 699 (2012)
W.M.Fawley, L. Giannessi et al., Nature Photonics, **7**,913 (2013)

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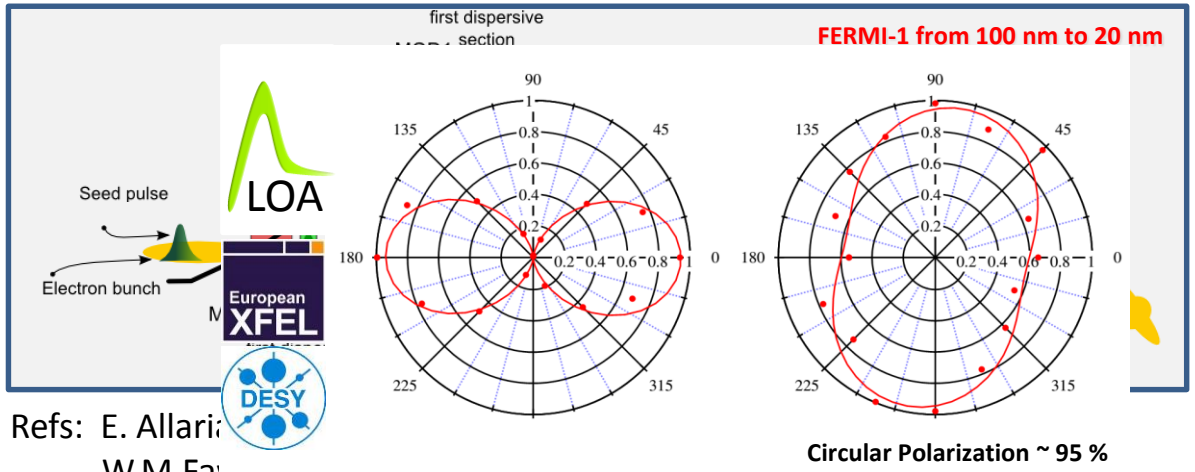
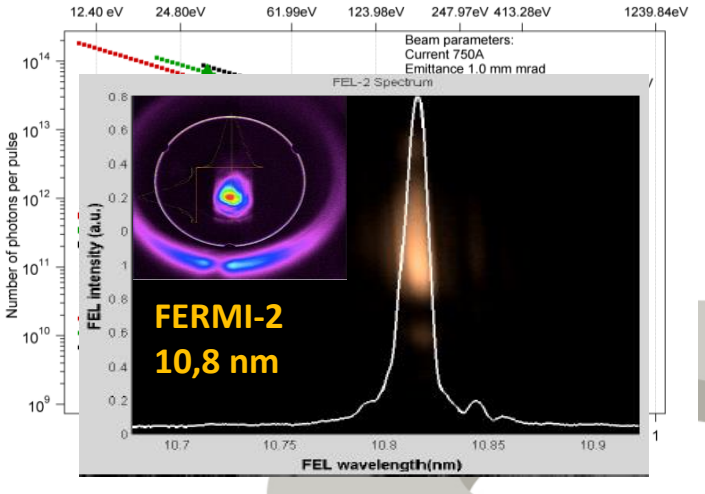


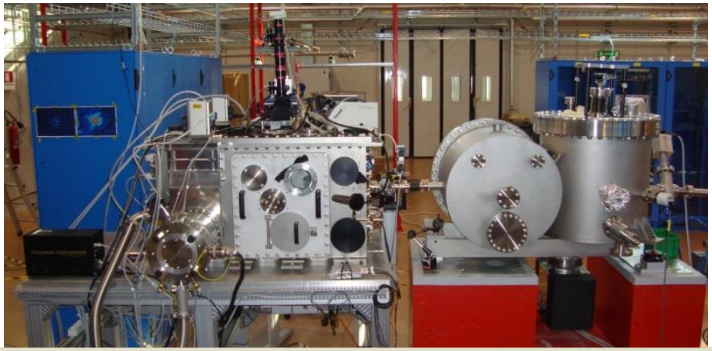
Refs: E. Allari
W.M.Fa

E. Allaria et al. Control of the polarization of a vacuum-ultraviolet, high-gain, free-electron laser PRX accepted.



DiProI – Core capabilities

Elettra Sincrotrone Trieste



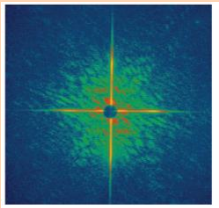
Installed on dedicated FERMI beamline: June 2011
Open to User Experiments: December 2012

Versatile modular construction allowing exchange and/or adding new components

Instrument design in collaboration with:
H.N. Chapman, S. Bajt, H. Fleckenstein, J. Schulz, J. Hajdu, M. Bogan

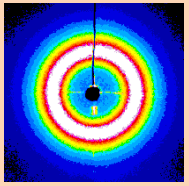
Forward scattering scheme

Single shot FEL pulse diffraction experiment and P&P experiment



H.N. Chapman et al. Nature Physic 2007

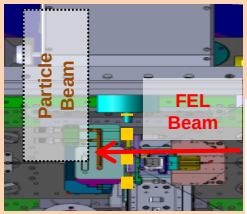
Magnetic Res-scattering



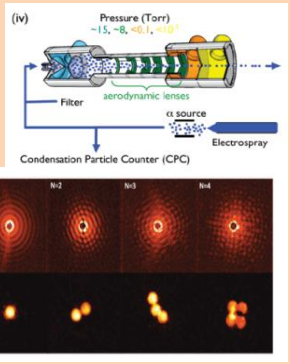
In collaboration with
G.Grübel (DESY)
S.Eisebitt (TU Berlin)
C. Gutt (Univ. Siegen)
J. Lüning (Univ.Paris)

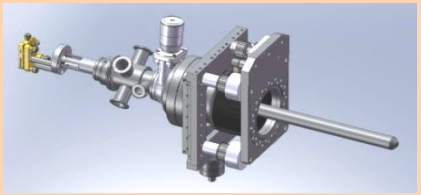
B. Pfau et al Nature Com. (2012)

Particle injector

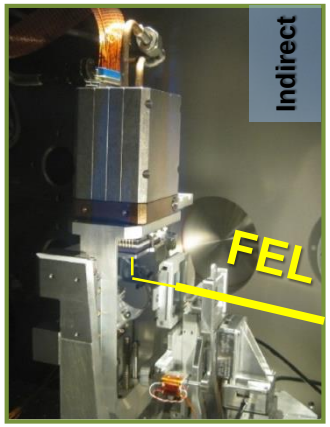


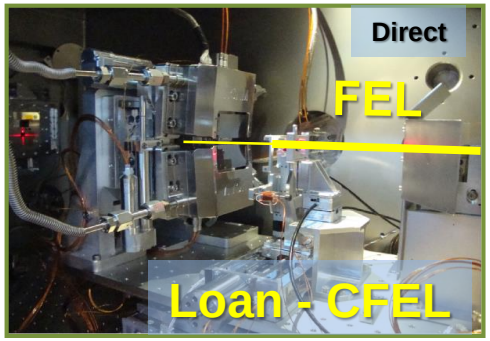
M, Bogan et al. NanoLett. 2009, AST 2010

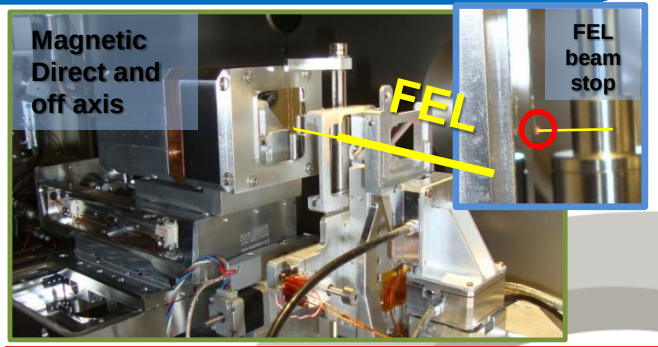




Aerosol particle injector coupled to i-TOF.
Developed by J. Hajdu et al. Univ. Uppsala



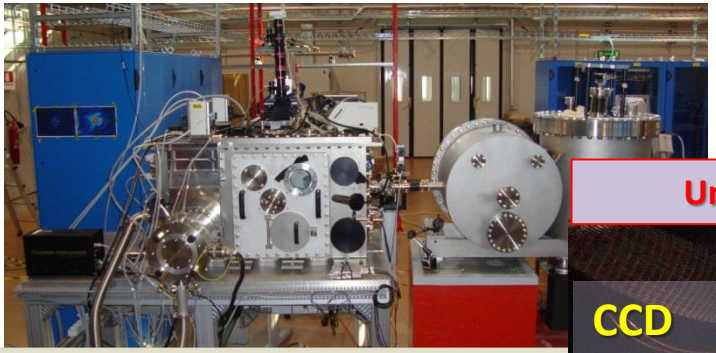




F.Capotondi et. al. *Rev. Sci. Instr. 84, 051301 (2013)*

DiProI – Core capabilities

Elettra Sincrotrone Trieste



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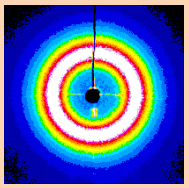

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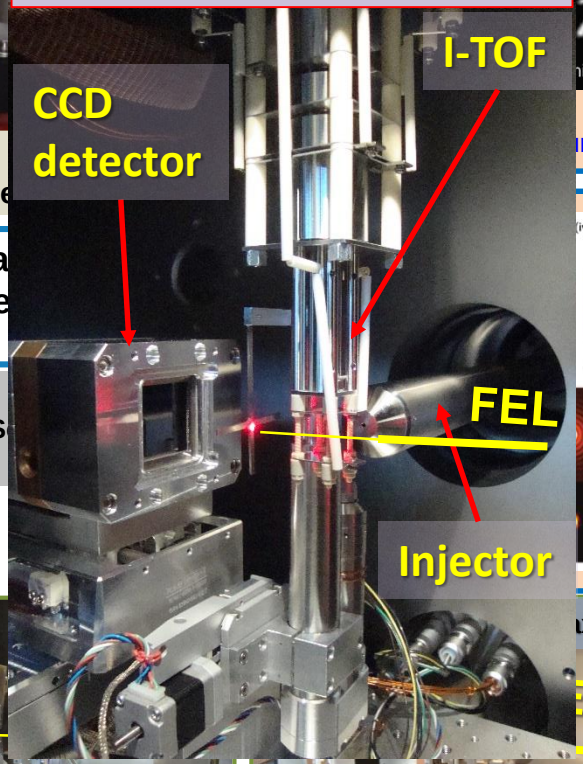
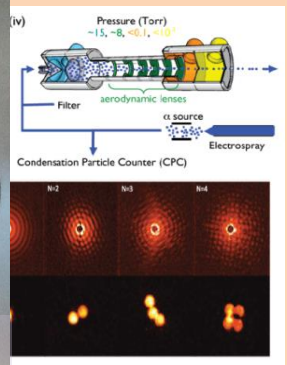
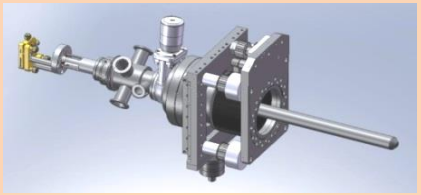
Under commissioning







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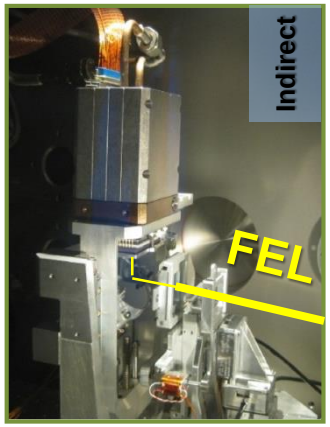
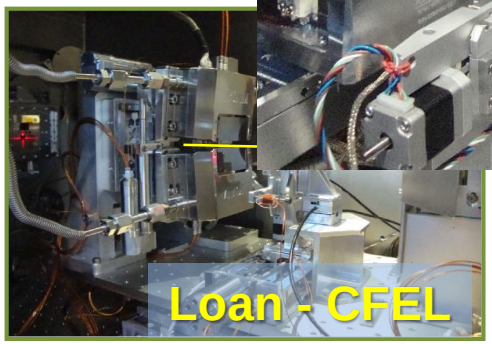
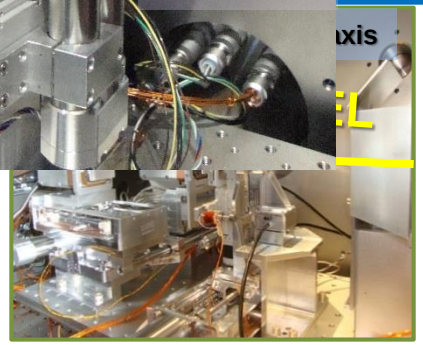
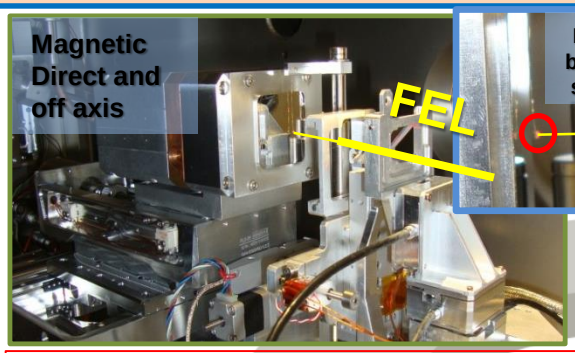




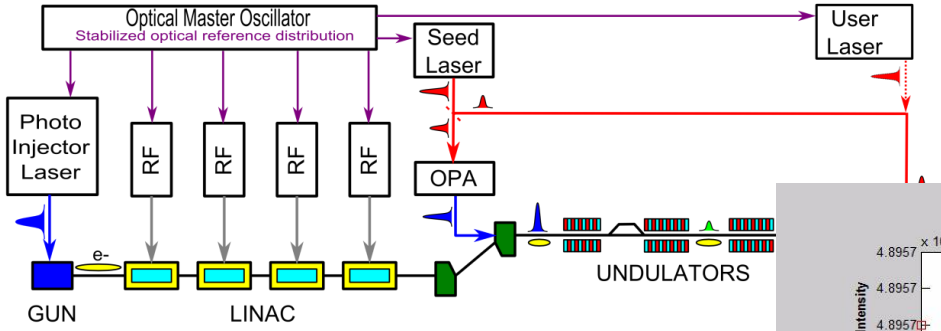




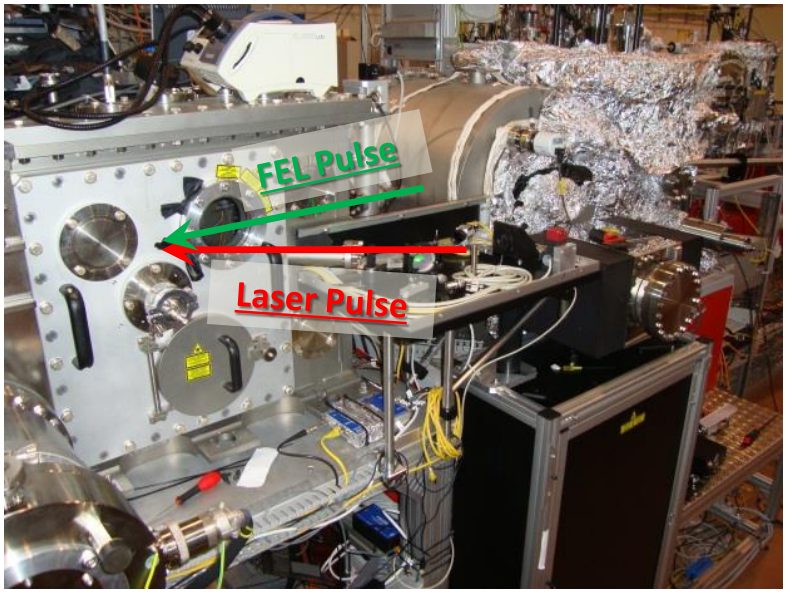
F.Capotondi et. al. *Rev. Sci. Instr. 84, 051301 (2013)*

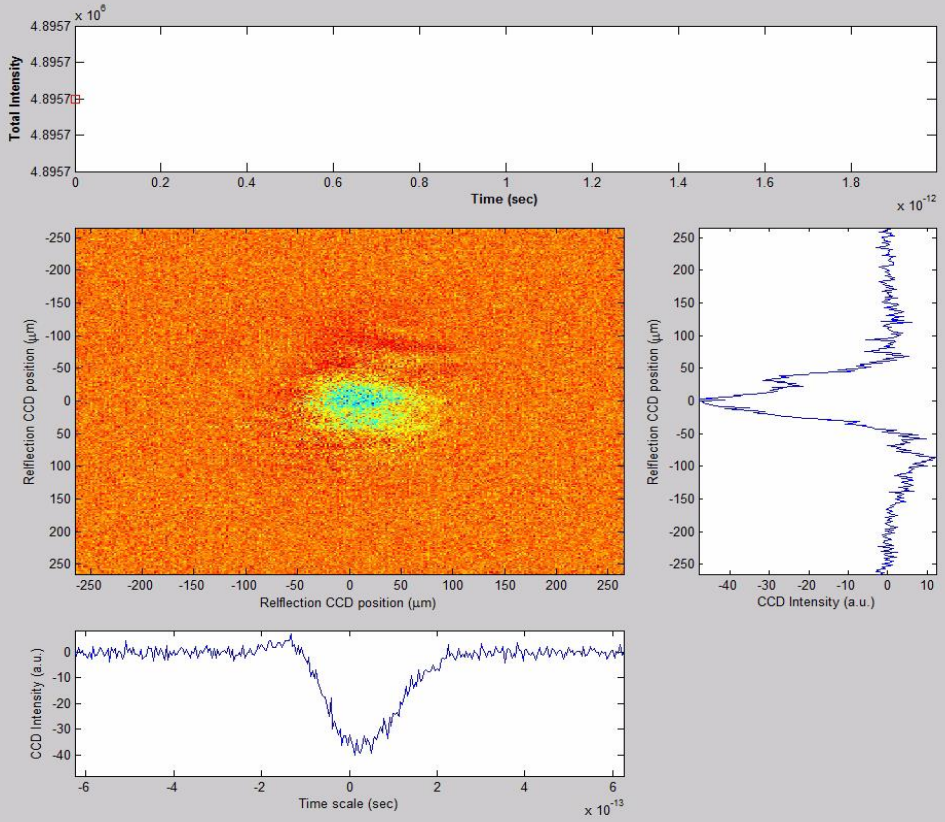
DiProI – user optical laser

Elettra Sincrotrone Trieste



P. Cinquegrana et al. Phys. Rev. STAB 17, 040702 (2014





Since Feb-2013 DiProI end station equipped with external user laser

In collaboration with: M.Danailov, A.Demidovich, K.Gabor, I.Nikolov, P.Cinquegrana, P.Sigalotti

DiProI – user optical laser

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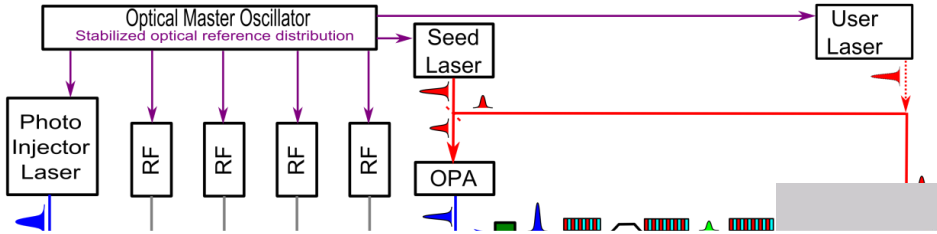

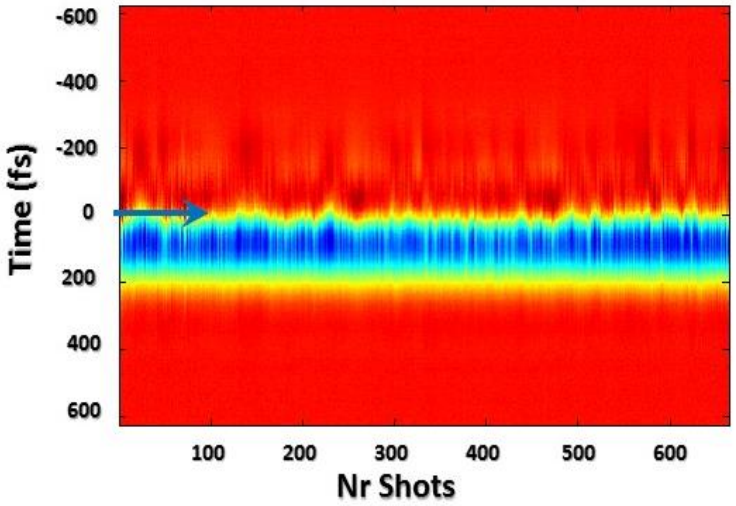

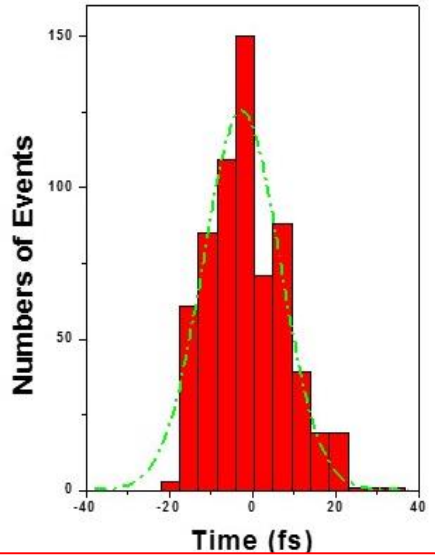

Arrival time jitter between FEL and IR laser ~ 10±2 fs (RMS), i.e. 3 μm difference paths length of two beams on 100 m !!!
Measured on at the ½ drop point of the reflectivity curve.

Long term (~ 1 day) stability time zero between FEL and IR laser ~ 70 – 60 fs.

M.Danailov et al. "Towards jitter-free pump-probe measurements at seeded free electron laser facilities" Optics Exp. 22, 12869-12879 (2014).

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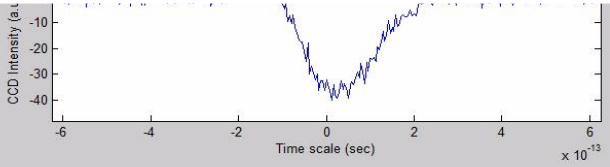

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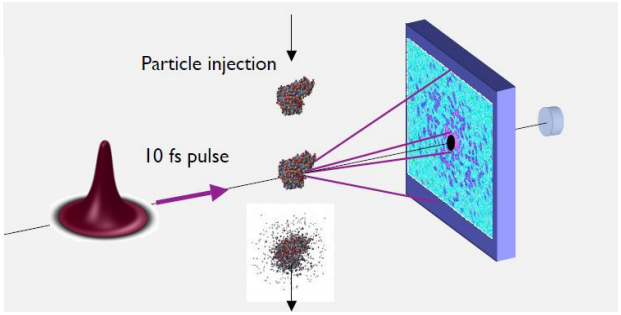
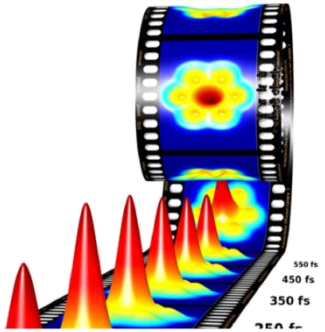
Elettra Sincrotrone Trieste

Towards *fs*-movie

Microscopists dream



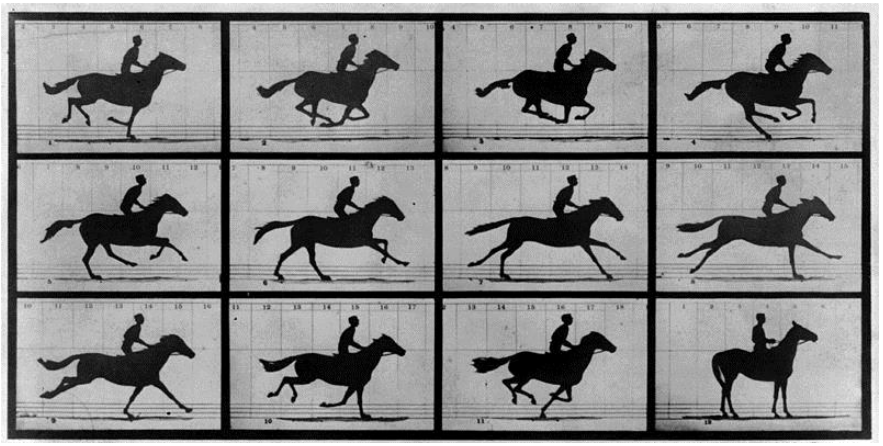


Challenging computational task:

a) Collection of a speckle pattern not a real space image. Phase retrieval algorithm.

b) Reconstruction algorithm has to catalog orientation and "recognize" the frames temporal evolution.

Proof of principle experiment



E. Muybridge (1872) had successfully photographed a horse at a trot.

Using a manifold algorithm, the conformational states sequence between the different frames can be inferred, monitoring the "similarity" among the diffraction patterns in the low q region.

C.H.Yoon et. al. "Conformation sequence recovery of a non-periodic object from a diffraction-before-destruction experiment" Optics. Exp. 22, 8085 (2014).

Elettra Sincrotrone Trieste

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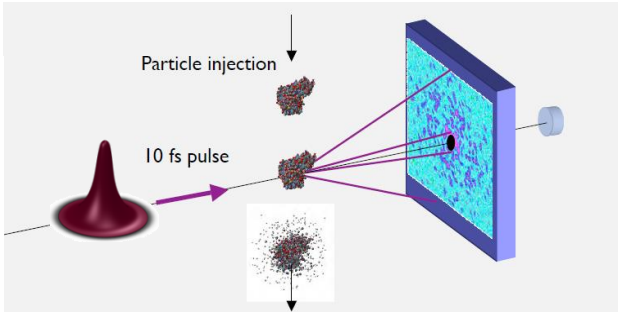

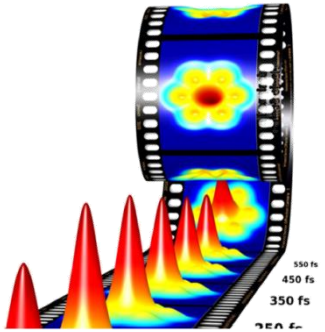

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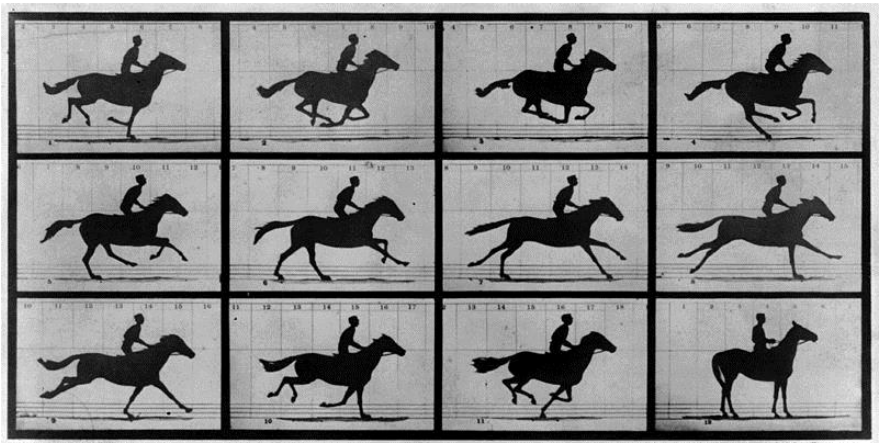

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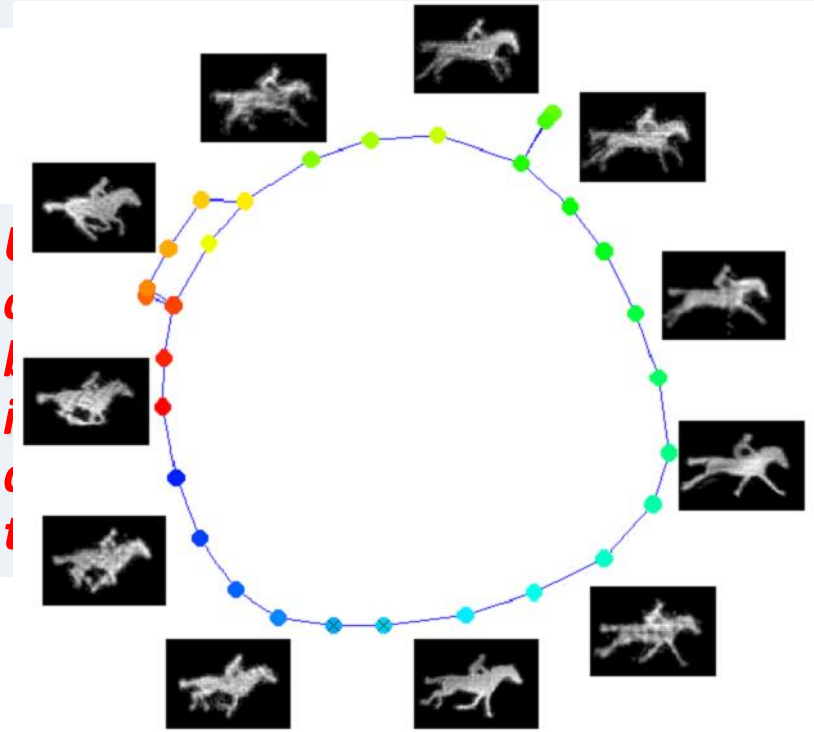

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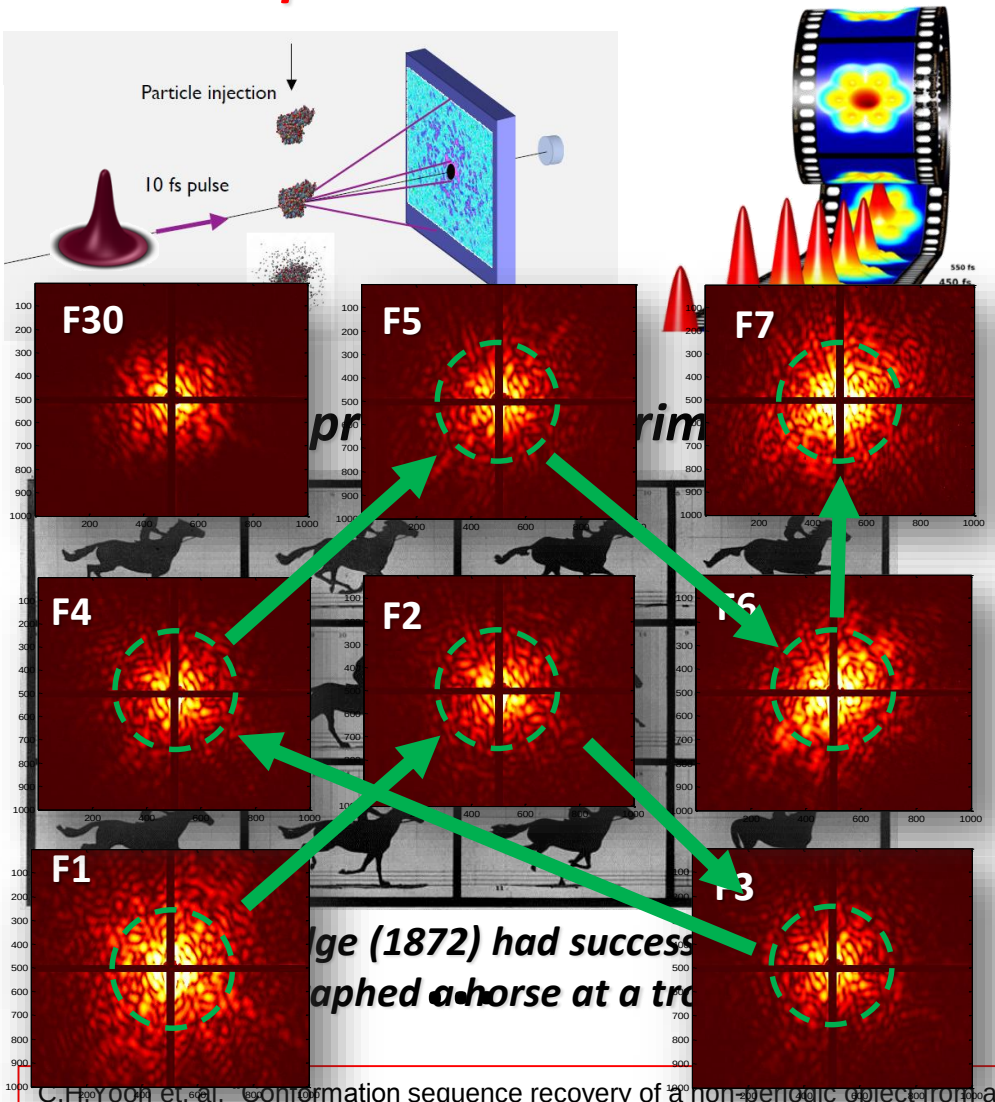

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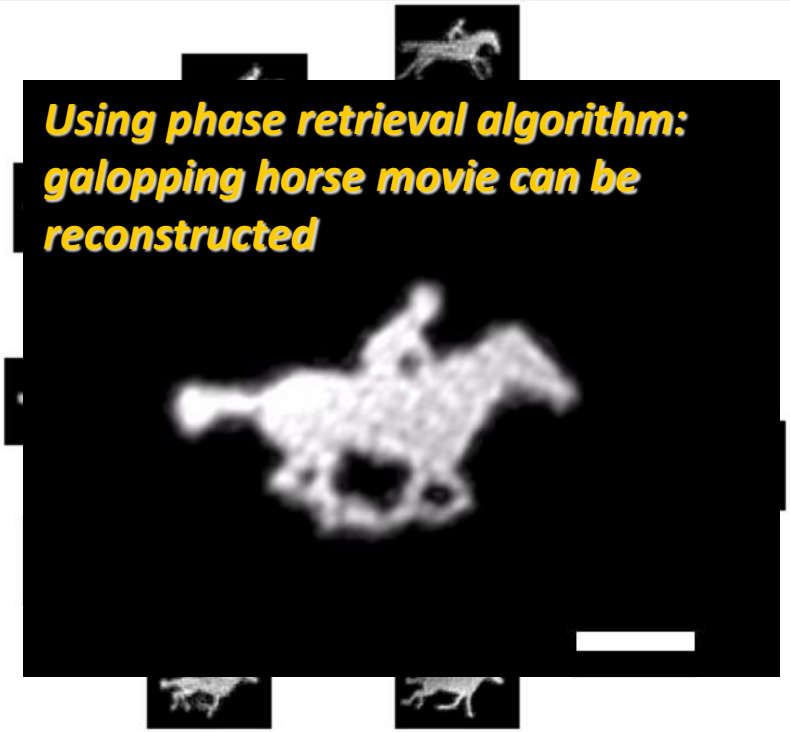
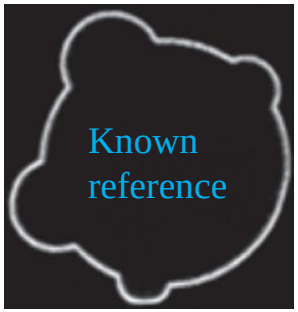


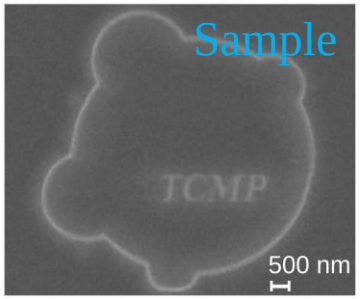
C.H. Yoon et.al. "Conformation sequence recovery of a non-periodic object from a diffraction-before-destruction experiment" Optics. Exp. 22, 8085 (2014).

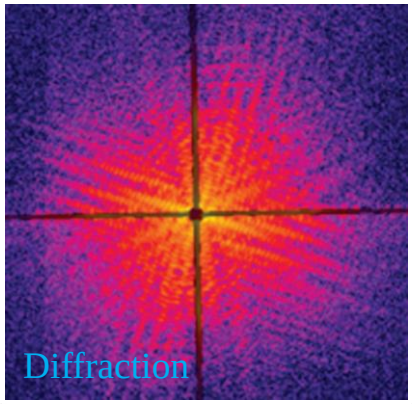
Elettra Sincrotrone Trieste

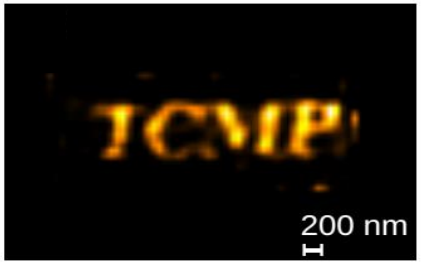
Extended reference holography

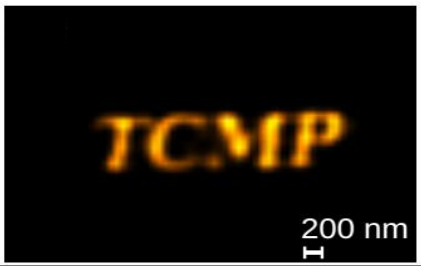
FTH ideal case is to optimize the experimental geometry without restriction due to the reference wave, permitting to optimize signal-to-noise and resolution.











Hologram obtained solving iteratively

$A_{data} - A_{ref} = C_{ref,obj}$

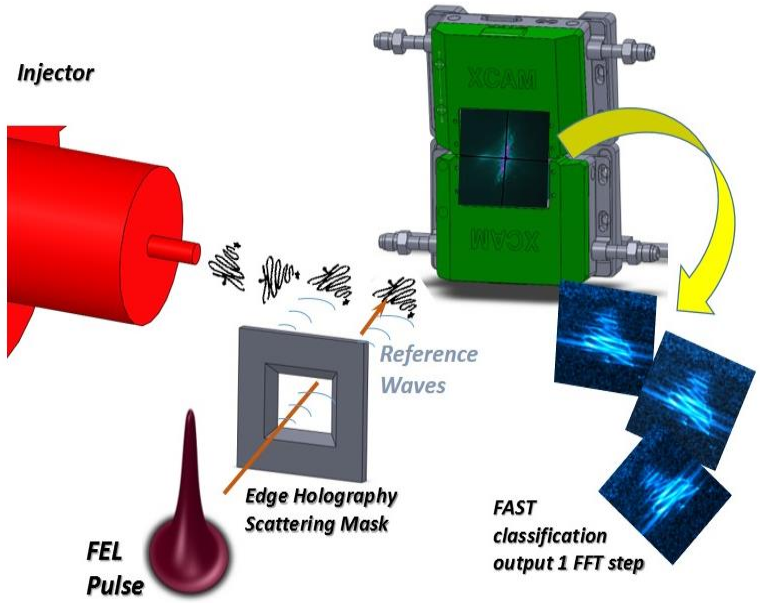
where $C_{ref,obj} = \Psi_{ref} * \Psi_{obj}$

Hologram refined with RAAR phase retrivial

Seed FEL pulse has an high degree of transversal and longitudinal coherence.

1. ***Transversal coherence is the key element in CDI.***
2. ***Longitudinal coherence is important in holography when mask is decoupled from the sample.***

Combining Extended Reference Holography with particle injector



A.V. Martin. et al. "X-ray holography with customizable reference" Nature Comm. 4, 2476 (2014).

Elettra Sincrotrone Trieste

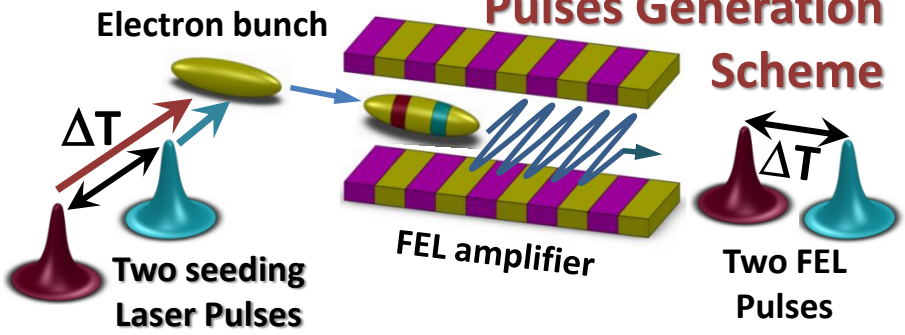
Topics

- Introduction:FERMI FEL and core capabilities of DiProI end-station.
- **Pump-Probe experiments with seeded FEL.**
- Future upgrades and research opportunities.
- Conclusive remarks.

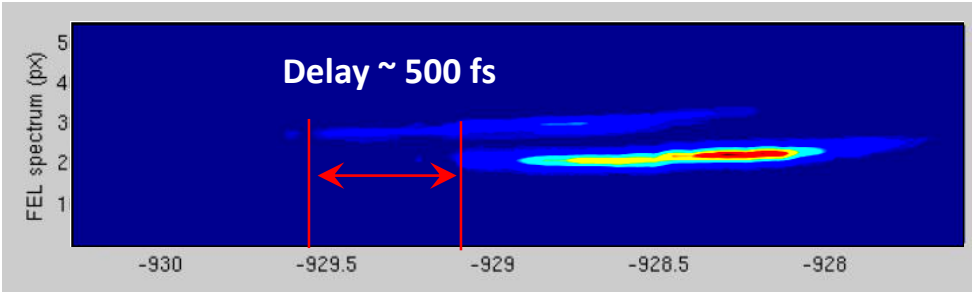
Two Color Pump and Probe

Elettra Sincrotrone Trieste

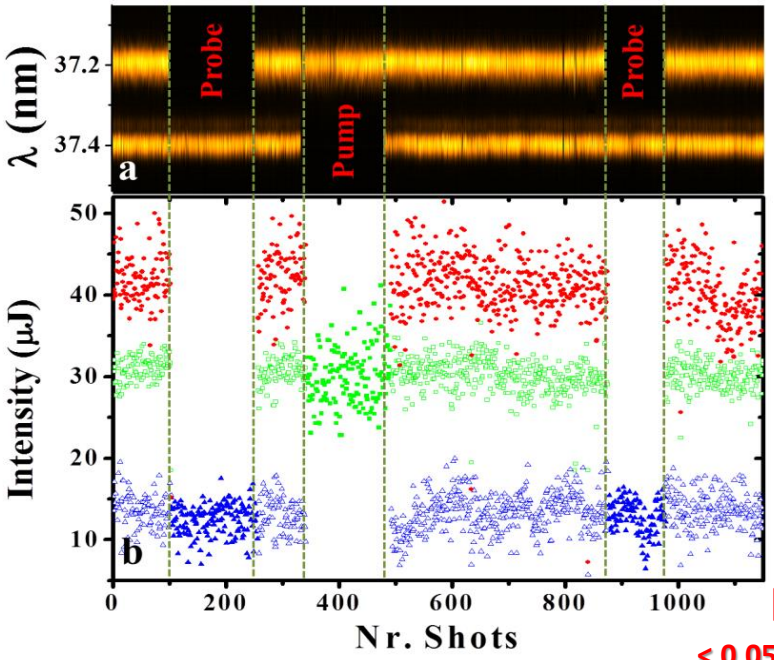
Pulses Generation Scheme

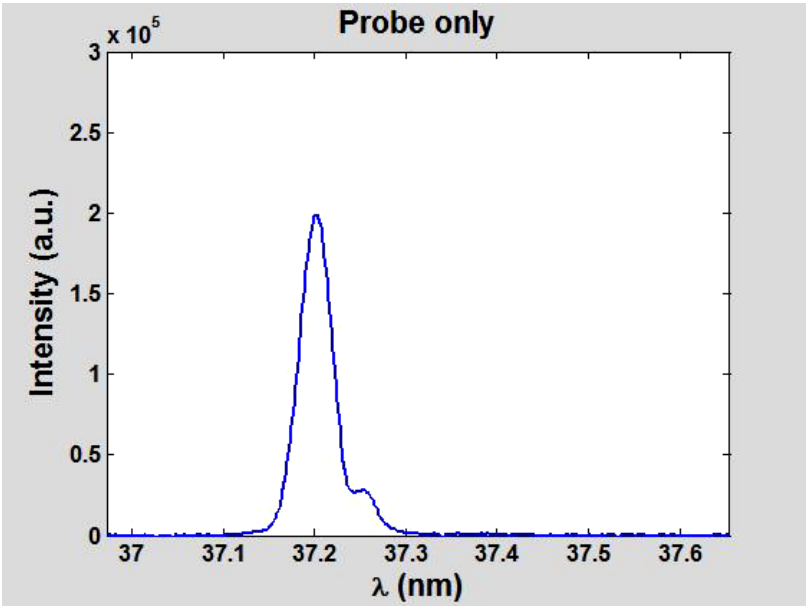


Pulses Delay



FEL stability





RMS - Jitter

< 0,05 % Shot-to-Shot spectral

< 15% Shot-to-Shot intensity

E. Allaria et al., Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser, Nature Communications. 4:2476 (2013).

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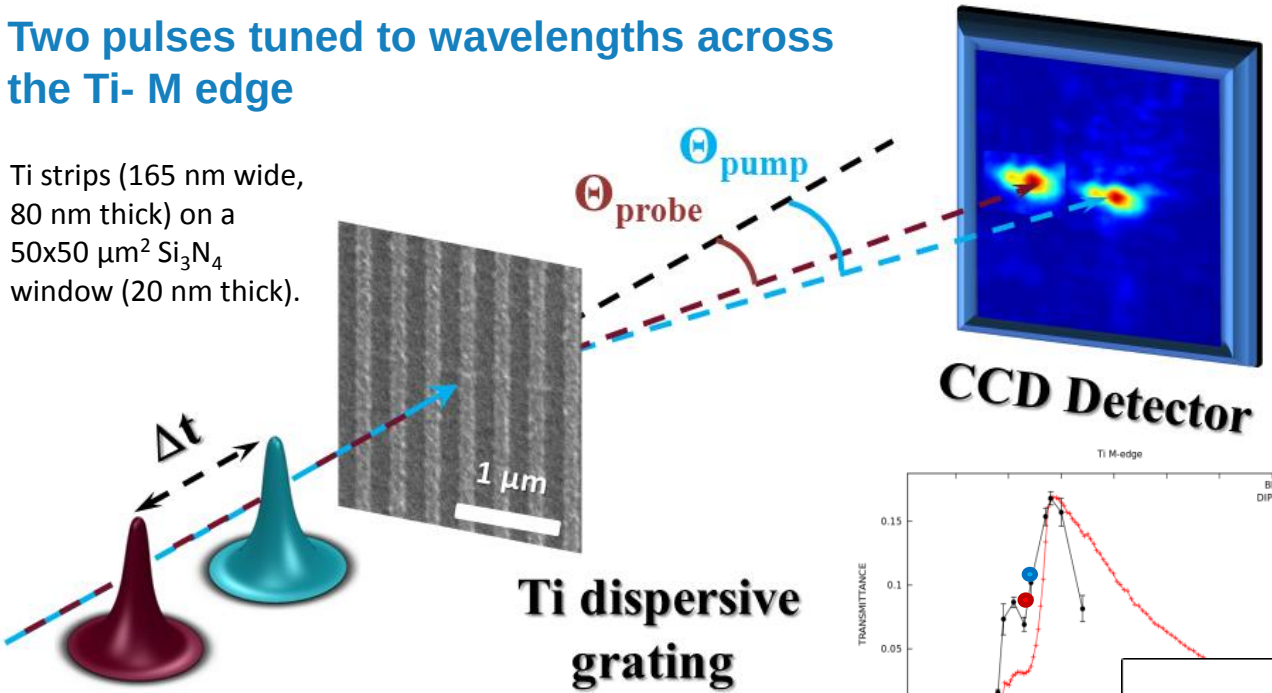
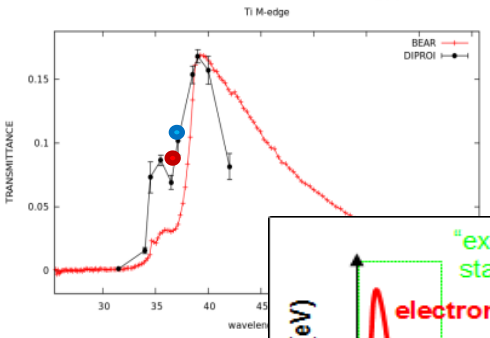
Two Color Pump and Probe *(Experiment)*

Two pulses tuned to wavelengths across the Ti- M edge

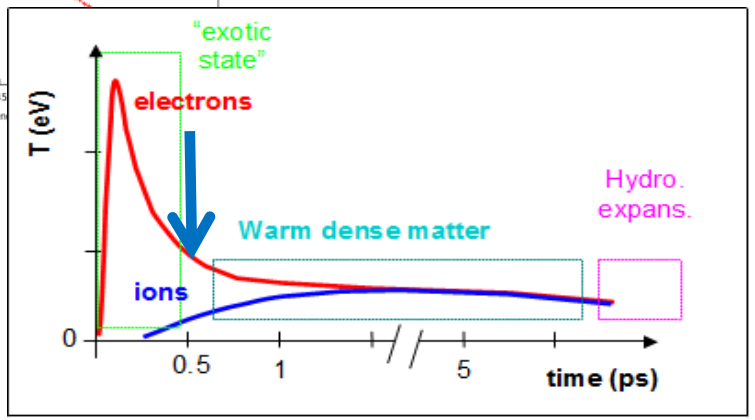
Ti strips (165 nm wide, 80 nm thick) on a 50x50 μm^2 Si_3N_4 window (20 nm thick).



Time delay 500 fs



Line grating expansion is negligible before a few ps => no change in sample morphology is expected before the arrival of the probe



E. Allaria et al., Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser, Nature Communications. 4:2476 (2013).

Two Color Pump and Probe *(Results)*

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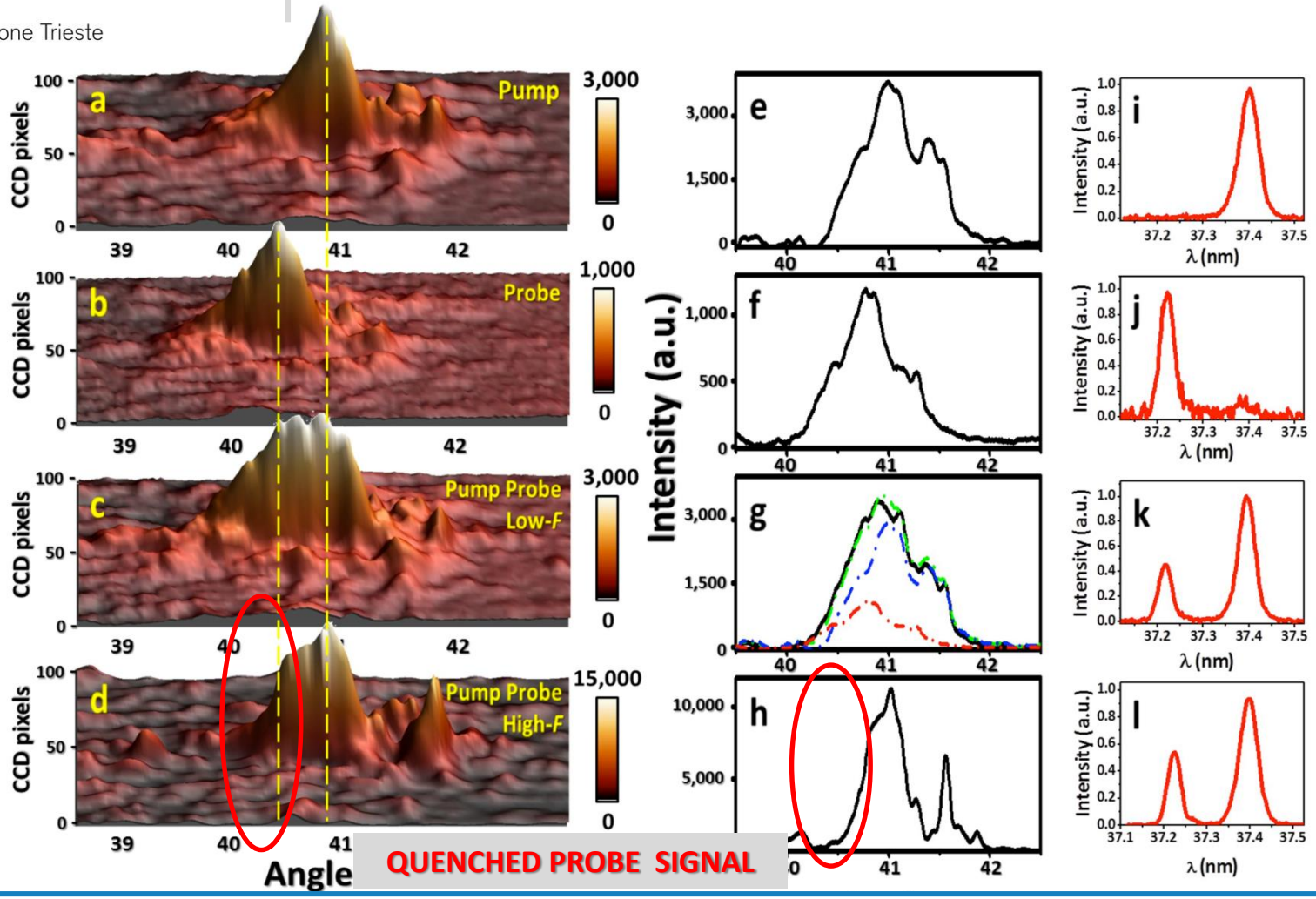


At high fluence => evidence for dramatic changes in the Ti electronic structure:
high degree of ionization that makes the grating 'transparent'.
The pulse length (~90 fs) and the delay (500 fs) are shorter than the time scales of hydrodynamic expansion 1 - 10 ps

E. Allaria et al., Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser, Nature Communications. 4:2476 (2013).

Two Color Pump and Probe *(Results)*

Elettra Sincrotrone Trieste

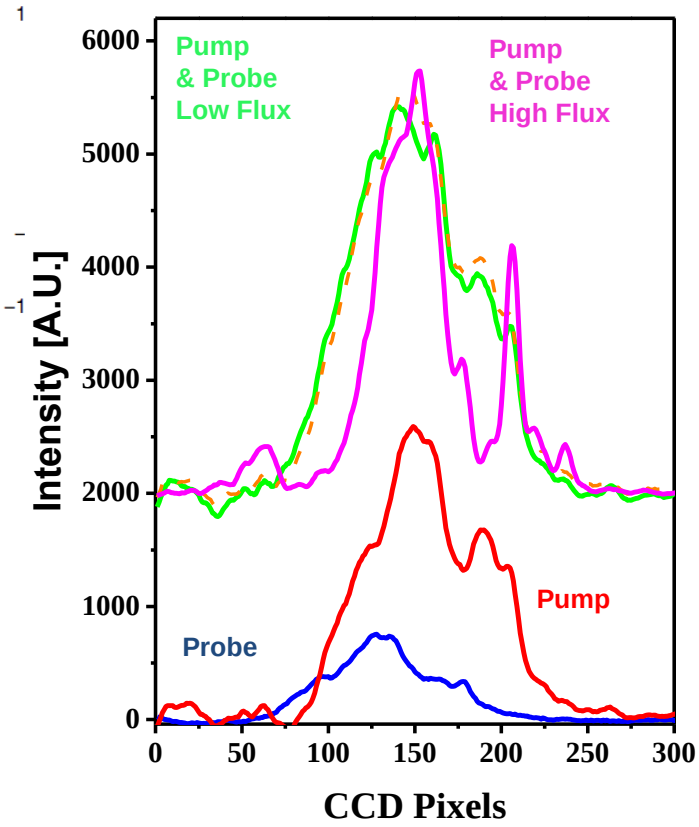
Multiwavelength Anomalous Diffraction at High X-Ray Intensity

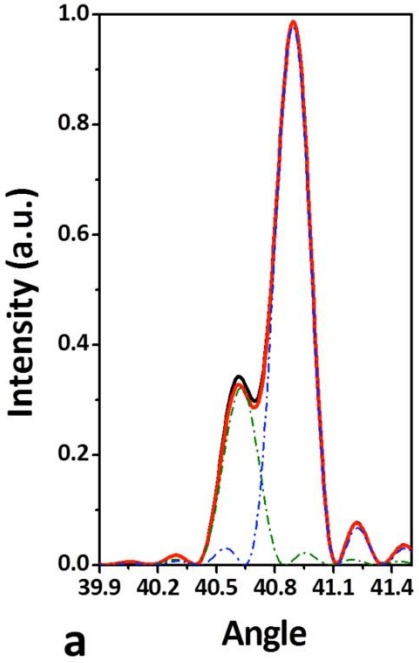
Sang-Kil Son (손상길),[1,*] Henry N. Chapman,[1,2,†] and Robin Santra[1,2,‡]
[1]*Center for Free-Electron Laser Science, DESY, Hamburg, Germany*

The wave propagates in the material as

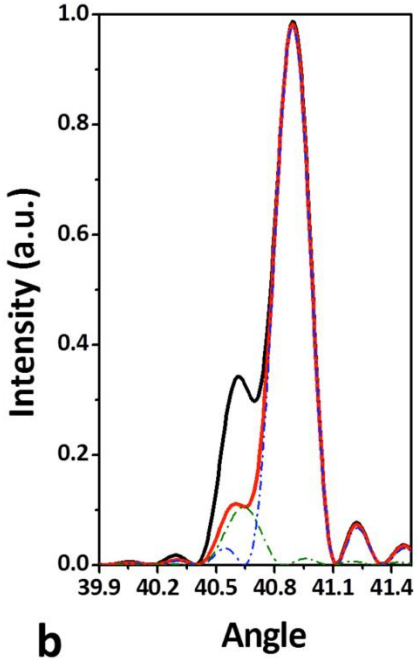
$$e^{i\cdot k_{mat}\cdot x} = e^{i\cdot\left(\frac{2\cdot\pi}{\lambda}\right)\cdot x\cdot(1-\delta)} \cdot e^{-\left(\frac{2\cdot\pi}{\lambda}\right)\cdot\beta\cdot x}$$

Phase term — Attenuation term





Assuming a 0.5 nm shift of probe optical constants.



Assuming a 2.5 nm shift of probe optical constants.

Beta

E. Allaria et al., Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser, Nature Communications. 4:2476 (2013).
F.Bencivenga et al., Multi-colour pulses from seeded free-electron-lasers: towards the development of non-linear core-level coherent spectroscopies, Faraday Discuss. (2014).

Two Color Pump and Probe *(Results)*

Elettra Sincrotrone Trieste

Multiwavelength Anomalous Diff

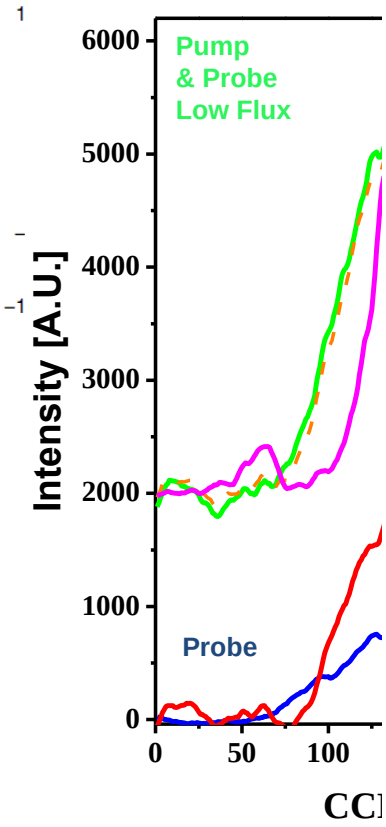
Sang-Kil Son (손상길),[1,*] Henry N.

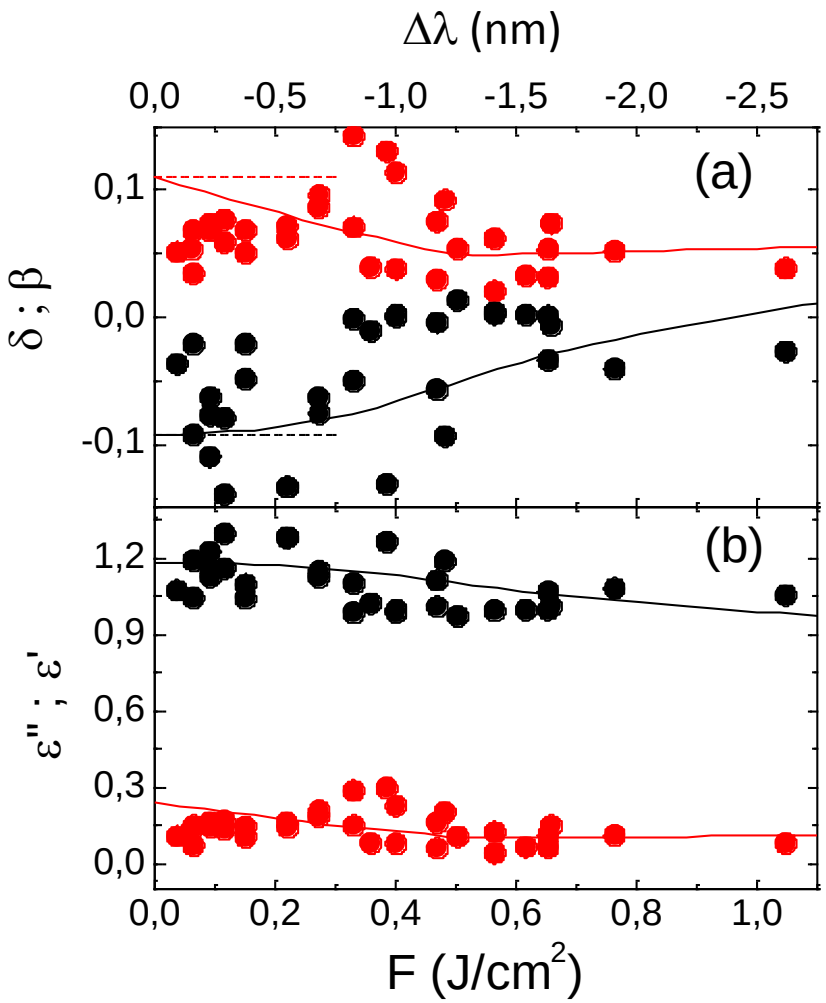
[1]*Center for Free-Electron Laser Sc*

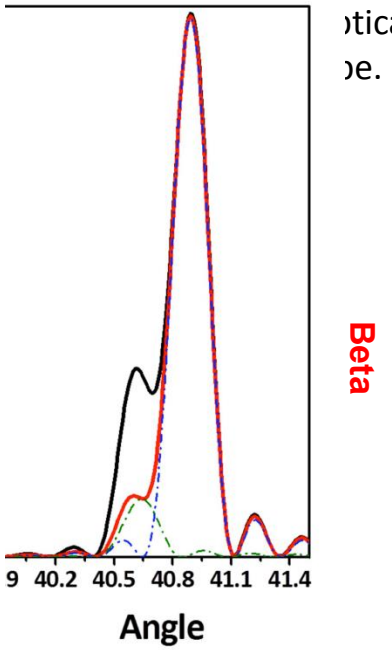
The wave propagates in the material as

$$\cdot(1-\delta) \cdot e^{-\left(\frac{2\cdot\pi}{\lambda}\right)\cdot\beta\cdot x}$$

term Attenuation term







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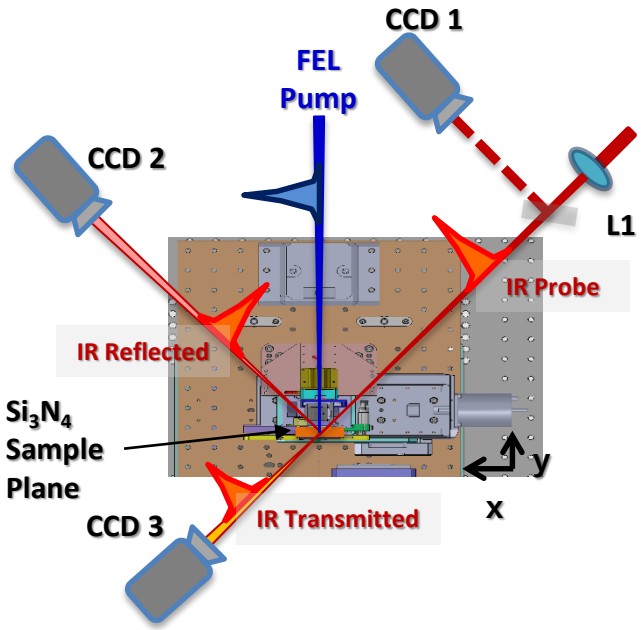
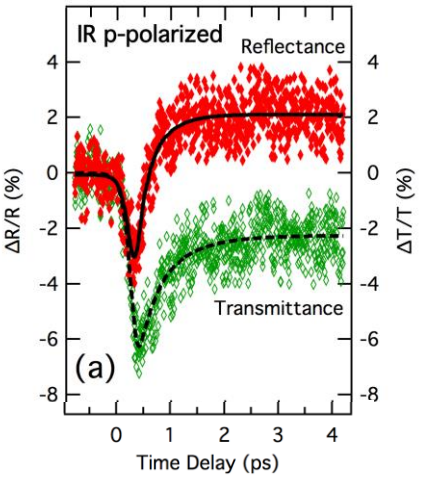
E. Allaria et al., Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser, Nature Communications. 4:2476 (2013).
F.Bencivenga et al., Multi-colour pulses from seeded free-electron-lasers: towards the development of non-linear core-level coherent spectroscopies, Faraday Discuss. (2014).

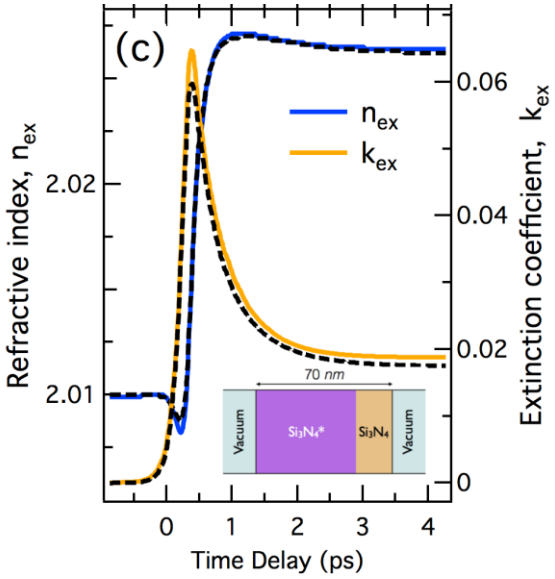
Elettra Sincrotrone Trieste

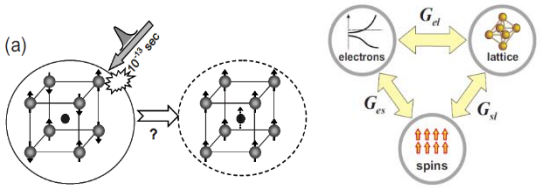
Role of interference effects on the Si_3N_4 optical response





Solving at each time delay *t*, the wave propagation equation for a stratified medium



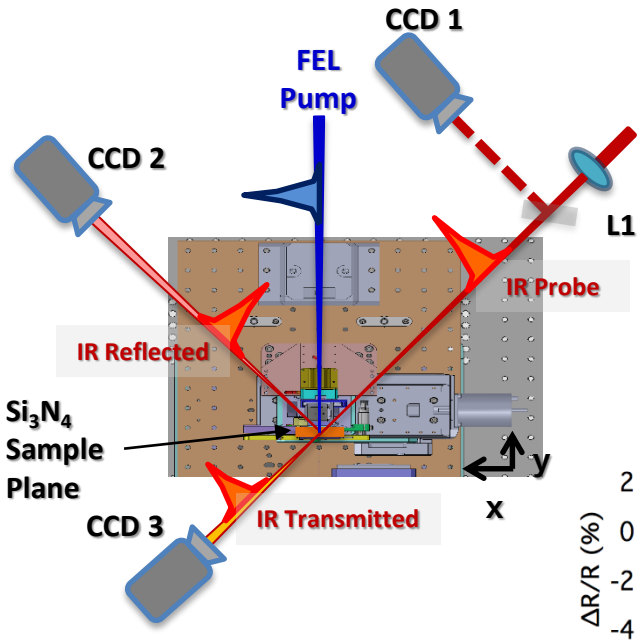


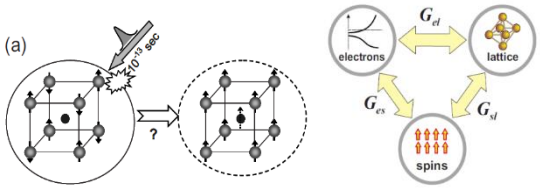
For energy density of 5-30 mJ/cm^2
During FEL pulse duration an electron density of > 10^{21} el/cm^3 is generated, close to the critical plasma density for IR radiation.

F. Casolari et al., Role of multilayer-like interference effects on the transient optical response of Si3N4 films pumped with free-electron laser pulses App. Phys. Lett. Appl. Phys. Lett. 104, 191104 (2014)

Role of interference effects on the Si_3N_4 optical response

Elettra Sincrotrone Trieste





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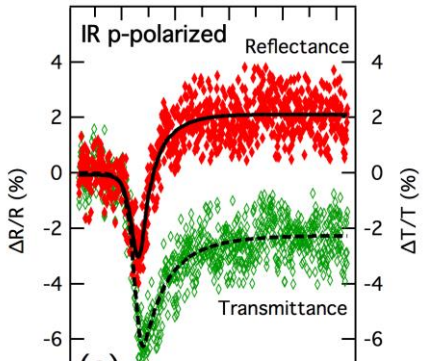

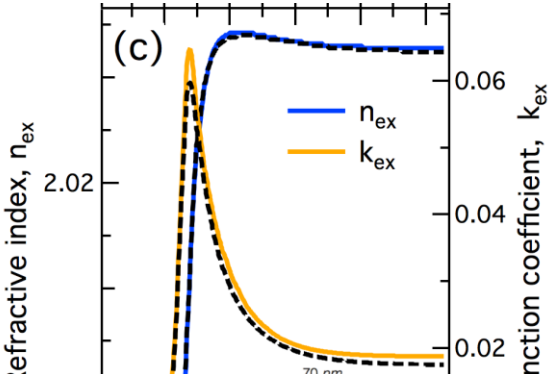

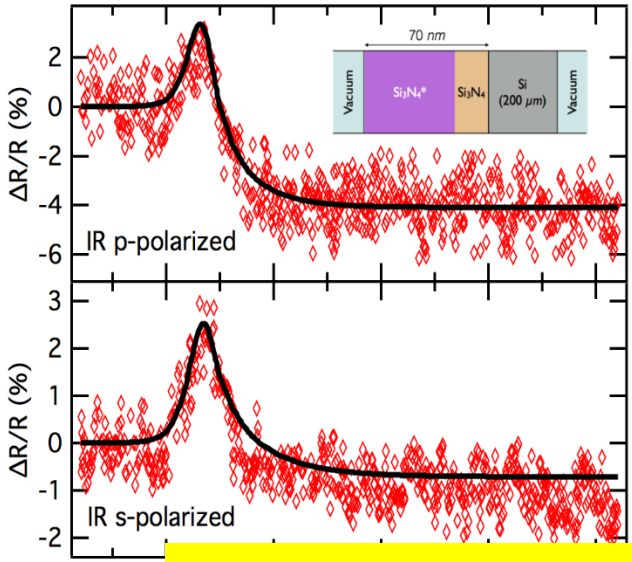

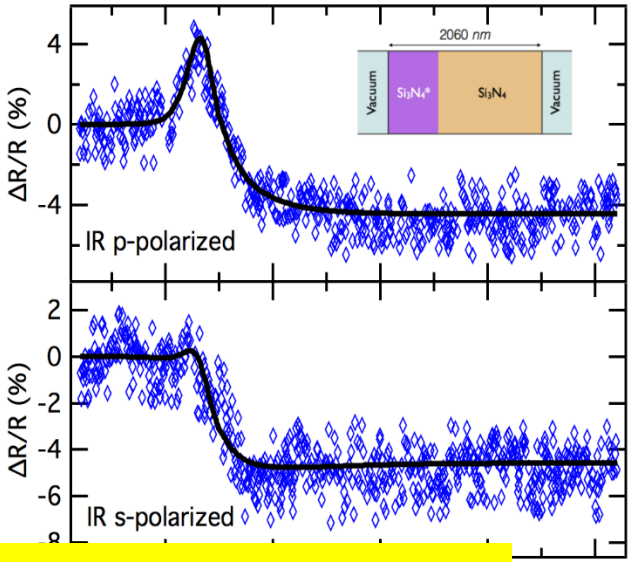

Poster NDP18 F.Casolari
Toward the tailoring of EUV-SXR/optical cross-correlator response: the role of interference effects

F. Casolari et al., Role of multilayer-like interference effects on t
films pumped with free-electron laser pulses App. Phys. Lett. Appl. Phys. Lett. 104, 191104 (2014)

Elettra Sincrotrone Trieste

Topics

- Introduction: FERMI FEL and core capabilities of DiProI end-station.
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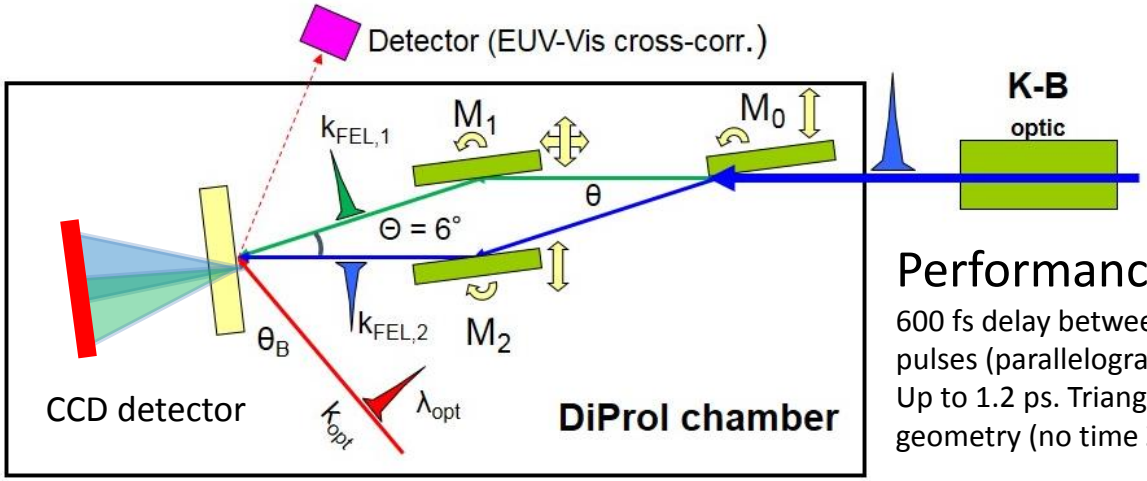
- Conclusive remarks.

Stroboscopic imaging

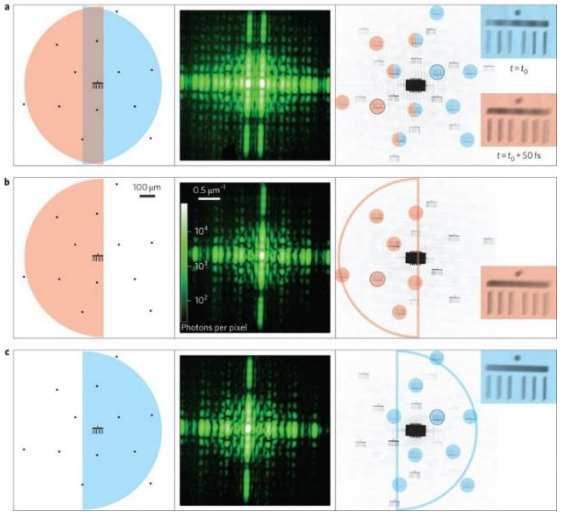
Elettra Sincrotrone Trieste

Compact mini-delay line

(in collaboration with F.Bencivenga C. Masciovecchio)



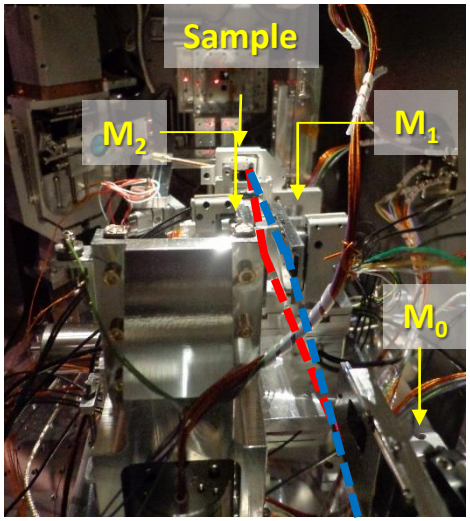
Ideal geometry for stroboscopic imaging

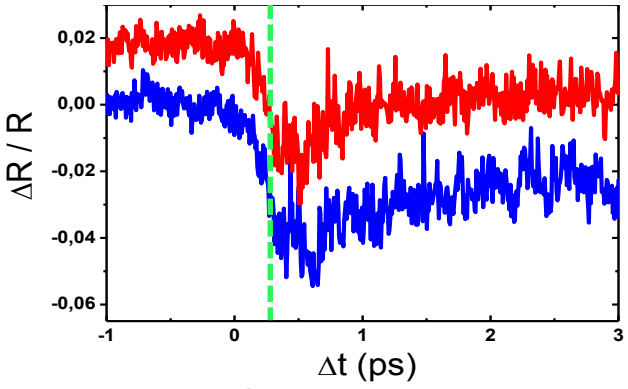


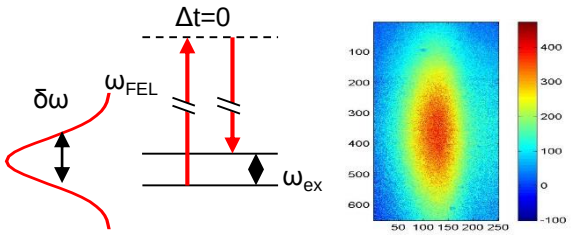
C.M. Gunther et al. Nat. Phot. 5 (2011)

Performances:

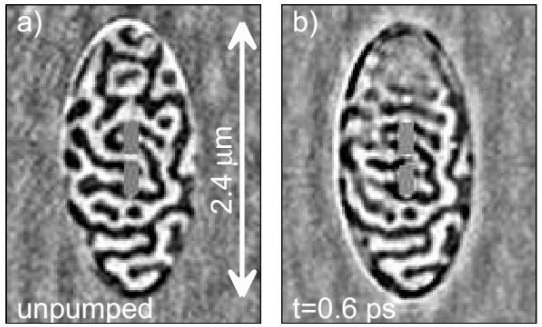
600 fs delay between 2 FEL pulses (parallelogram geometry)
Up to 1.2 ps. Triangular geometry (no time Zero)







Proof of principle FWM experiment:
F.Bencivenga talk Wednesday afternoon



C. von Korff Schmising et. al., Phys. Rev. Lett. 112, 217203 (2014).

Imaging fast demagnetization with after core level excitations instead of IR excitations

Elettra Sincrotrone Trieste

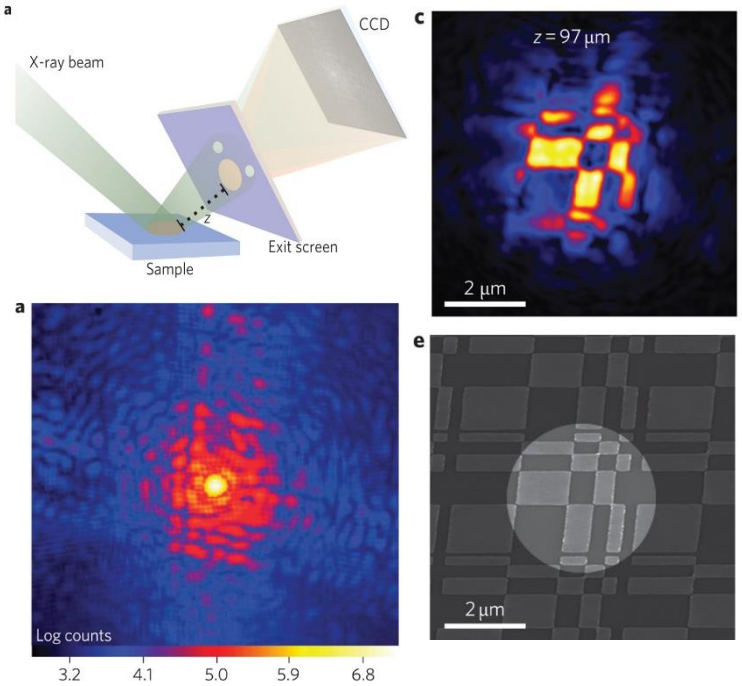
Reflection lensless set up

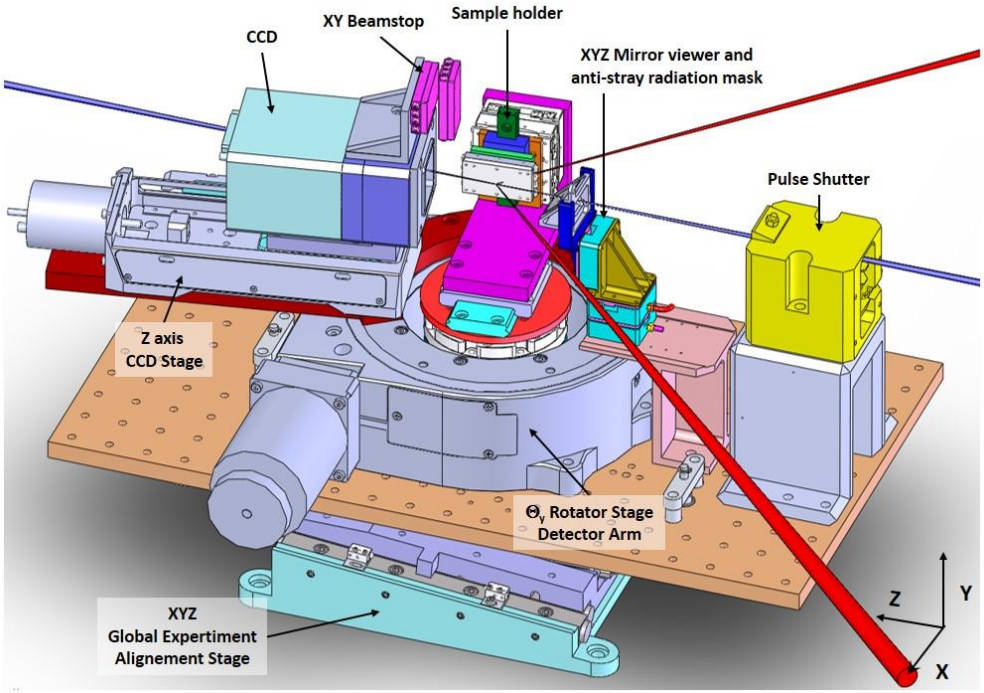
Forward scattering geometry is not applicable for opaque samples and in cases when the properties of the sample top layers are of interest, such as buried interfaces and thin films.

nature photonics LETTERS
PUBLISHED ONLINE: 20 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2011.11

Lensless X-ray imaging in reflection geometry

S. Roy[1]*, D. Parks[1,2], K. A. Seu[1,2], R. Su[1,2], J. J. Turner[3], W. Chao[4], E. H. Anderson[4], S. Cabrini[5] and S. D. Kevan[2]





In collaboration with C.Guth (Univ. Siegen)

Reflection geometry CDI can be appealing in the studies of magnetic proprerties are driven by the coexistence of different phase reflected by the sample morphology like MaAs (α and β phase) and FeRh (FM/AFM phase)

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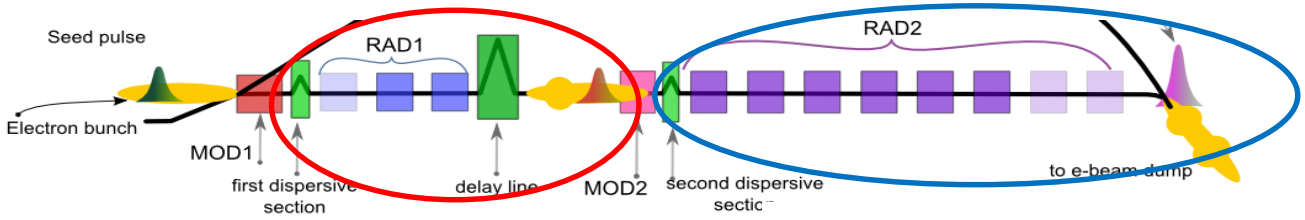
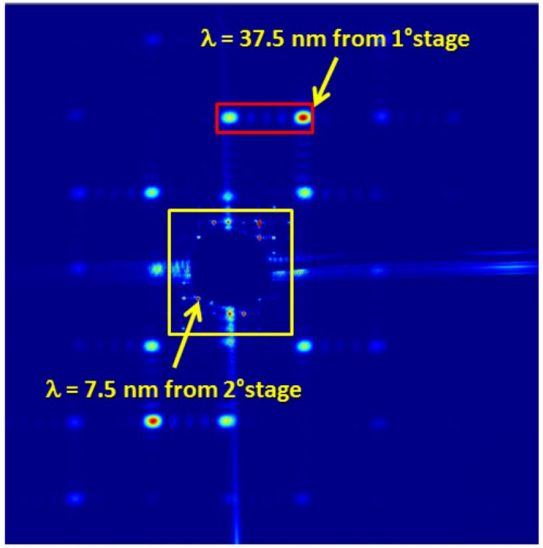
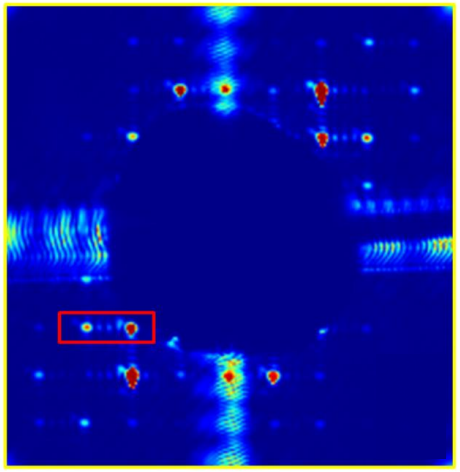
Multiwavelengths imaging with FERMI-FEL II



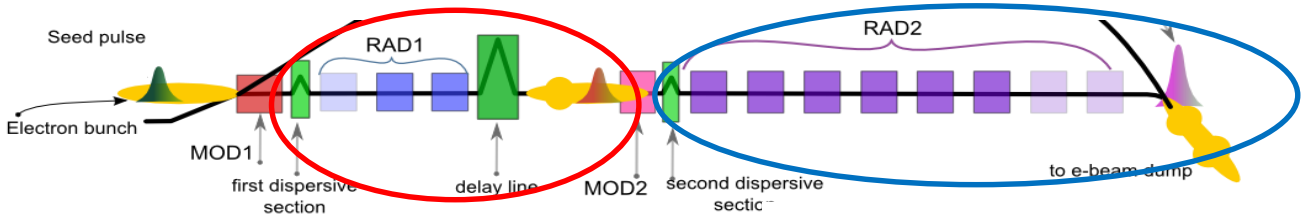
First stage emits at λ_1

Second stage emits at $\lambda_2 = \lambda_1/N^{arm}$





Multiwavelengths imaging with FERMI-FEL II



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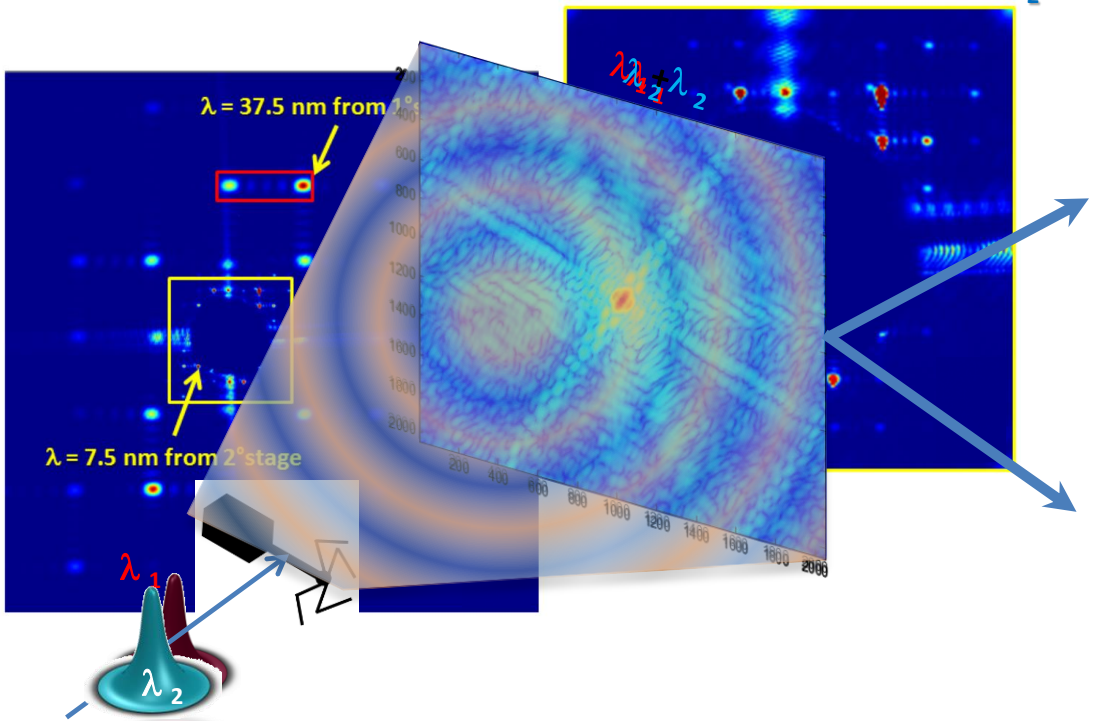
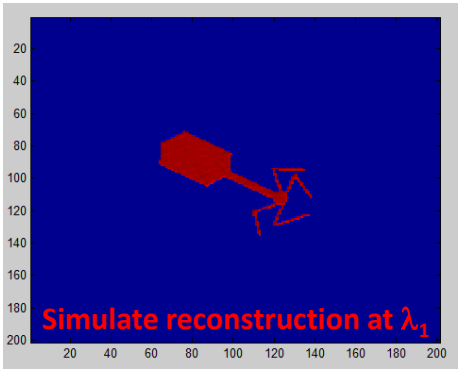
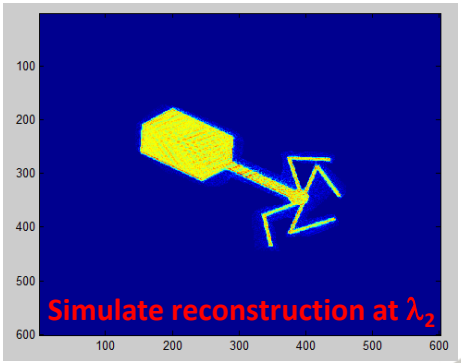


λ_1 and λ_2 arrive at the same time on the sample

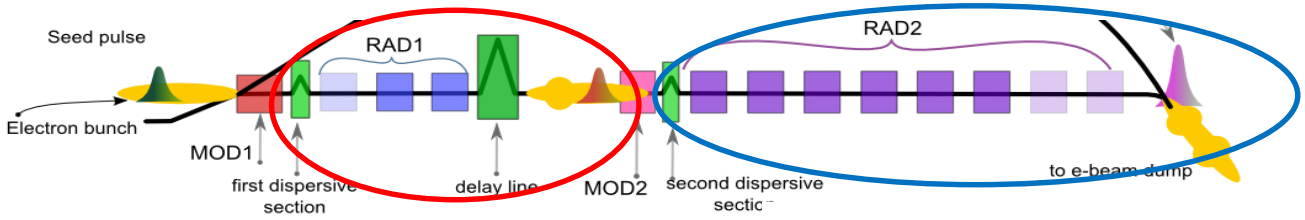


Low resolution image



High resolution image

Multiwavelengths imaging with FERMI-FEL II



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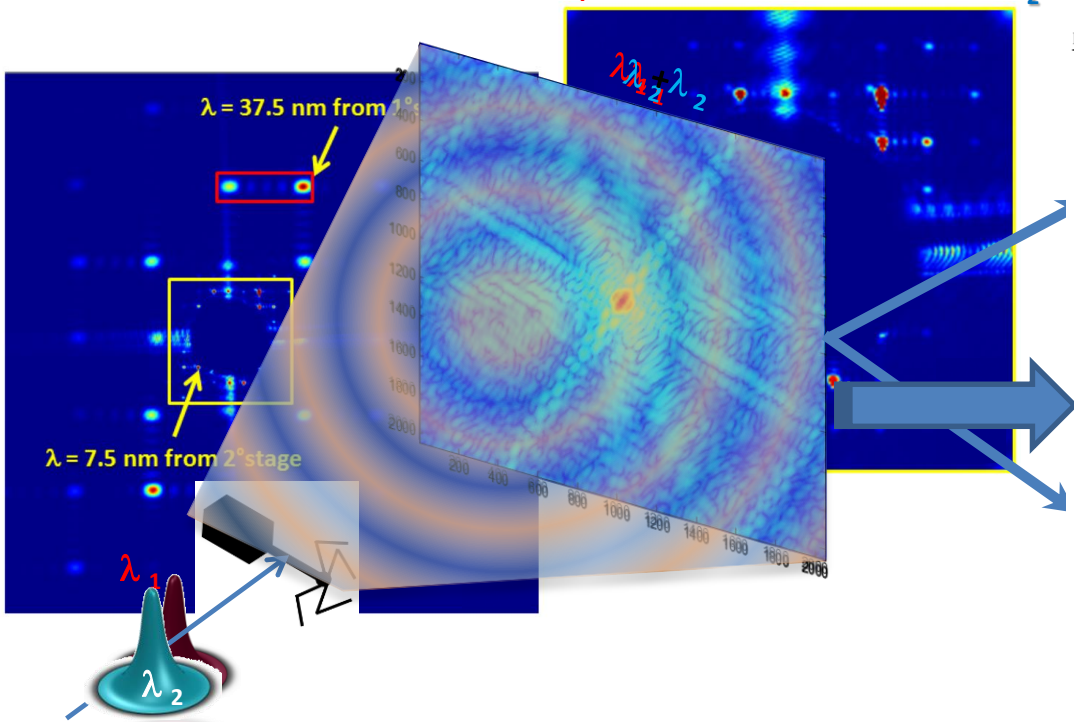

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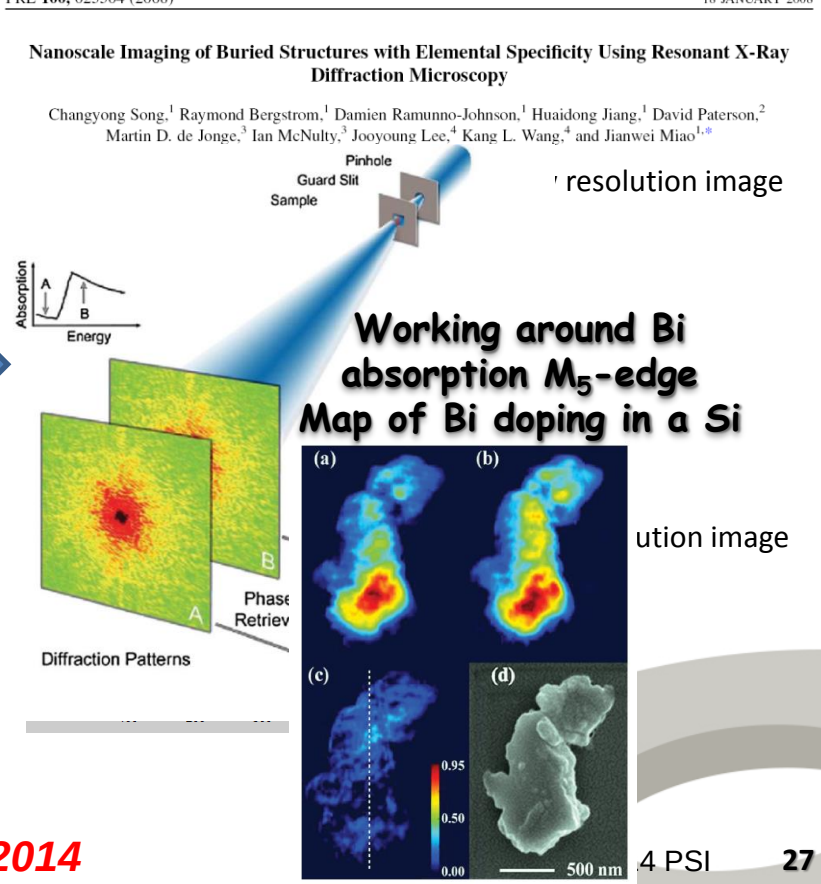

resolution image

Working around Bi absorption M_5-edge Map of Bi doping in a Si

ution image

Elettra Sincrotrone Trieste

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- ***Conclusive remarks.***

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Conclusions and Outlook

- ✓ **DiProI is a fully operative and user friendly multipurpose end-station dedicated to scattering experiments with FERMI-FEL**
- ✓ **Ongoing implementation and development of different pump - probe schemes (FEL/FEL, laser/FEL) with excellent temporal resolution.**
- ✓ **Novel schemes are under commissioning to extend the core capabilities of the instrument to particle injection, stroboscopic imaging and reflection-CDI. They open unique opportunities for novel experiments with both FERMI-FEL1 and FEL2.**

Trieste 11th – 12th Dec. 2014

wsimaging 2014

International Workshop on Advances in X-ray Imaging
ICTP, Trieste, Italy / 11-12 December 2014

Workshop topics
- **Phase-sensitive X-ray imaging**
- **X-ray tomography**
- **Coherent Diffraction Imaging**
- **Image reconstruction and phase-retrieval algorithms**
- **Applications**

USERS/COLLABORATORS

Internal and external

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DiProI: ***M. Kiskinova (coordinator)***,F. Capotondi (BL scientist), E. Pedersoli (post-doc), M. Manfredda (post-doc), F.Casolari (Phd student)

FEL physic: L. Giannessi, E.Allaria, C. Spezzani, and all the FERMI COMMISSIONING TEAM

Lasers: M. Danailov, A. Demidovich, I. Nikolov (pump&probe laser)

PADReS: M. Zangrando, N. Mahne, L. Raimondi (beamlines, optics)

Others: R.H. Menk (consulting for detectors), R. Borges (software), F. Bencivenga, C. Masciovecchio, D. Fausti (collaboration for instrumentation and experiments)

FEL SCIENCE

H. Chapman, S. Bajt, A. Barty, C.H. Yoon, A.V. Martin, M. Barthlmess, R.A. Kirian, H.Fleckenstein, F. Wang et al.

PULSE STANFORD **M. Bogan, N.D. Loh et al.**

UPPSALA UNIVERSITET **J. Hajdu, J.Andreasson et al.**

Lawrence Livermore National Laboratory **A. Nelson, M. Frank et al.**

berlin **S. Eisebitt, C. Von Korff Schmising, B. Pfau et al.**

DESY **G.Grübel, L. Müller, S Schleitzer, B. Keitel, K. Tiedtke,E. Plönjes-Palm et al.**

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THANK YOU FOR YOUR ATTENTION

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