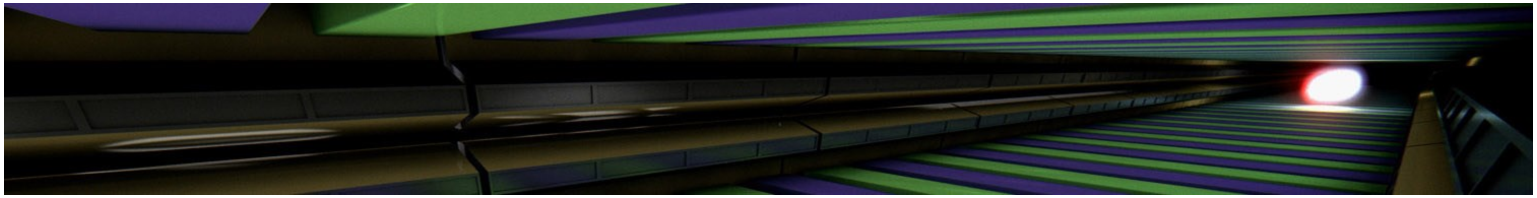

Coherent Diffraction Imaging (CDI) with X-Rays

School on Synchrotron and Free-Electron-Laser Based Methods:
Multidisciplinary Applications and Perspectives

ICTP Trieste,
April 15 - 2016

Anders Madsen
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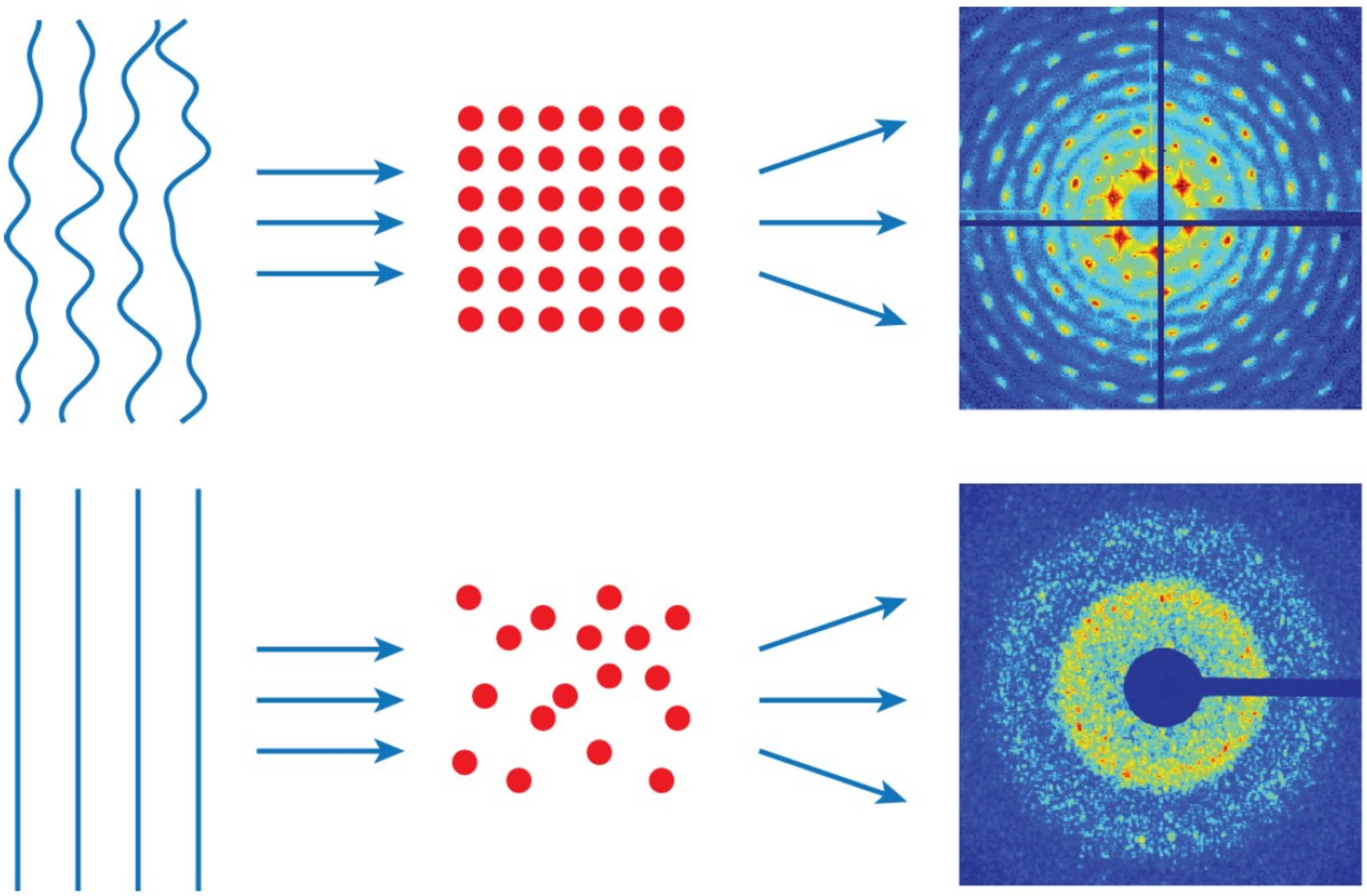
Outline

- Motivation
- X-ray Imaging
- X-ray Coherence
- All the tricks of CDI
- Image reconstruction
- Related methods
- Applications

- BREAK -

- Sources of Coherent X-rays
- The European XFEL project
- CDI science at XFELs
- Summary

Coherent scattering. Motivation

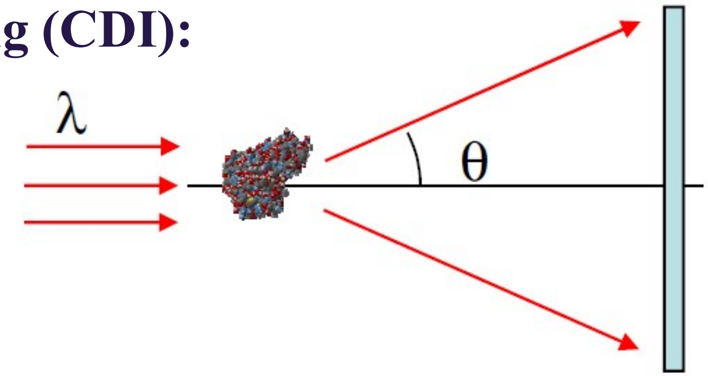


Slide courtesy of I. Vartaniants (DESY)

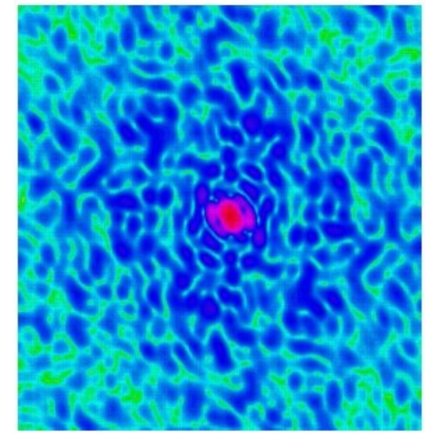
Coherent scattering. Motivation

Isolated object

Coherent Diffraction Imaging (CDI):



Static scattering

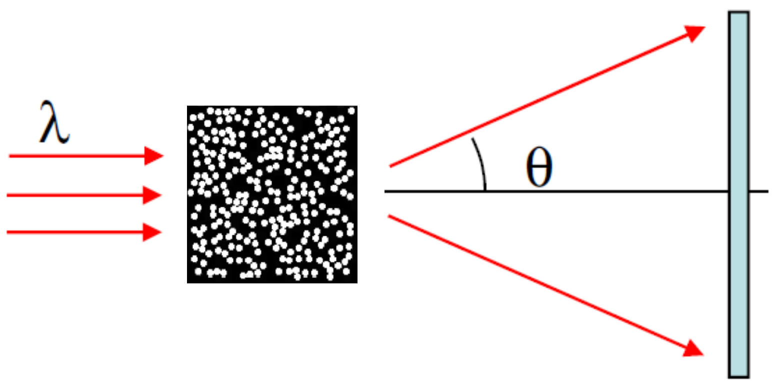


Ensemble of objects

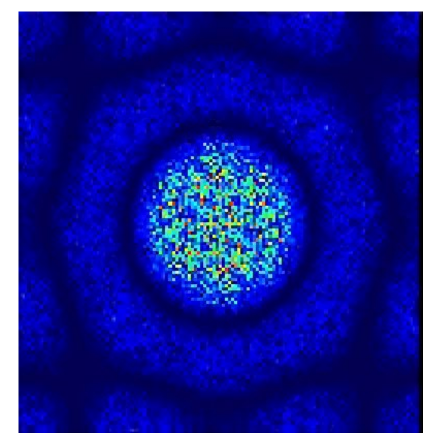
Correlation spectroscopy:

Temporal: XPCS

Spatial: XCCA



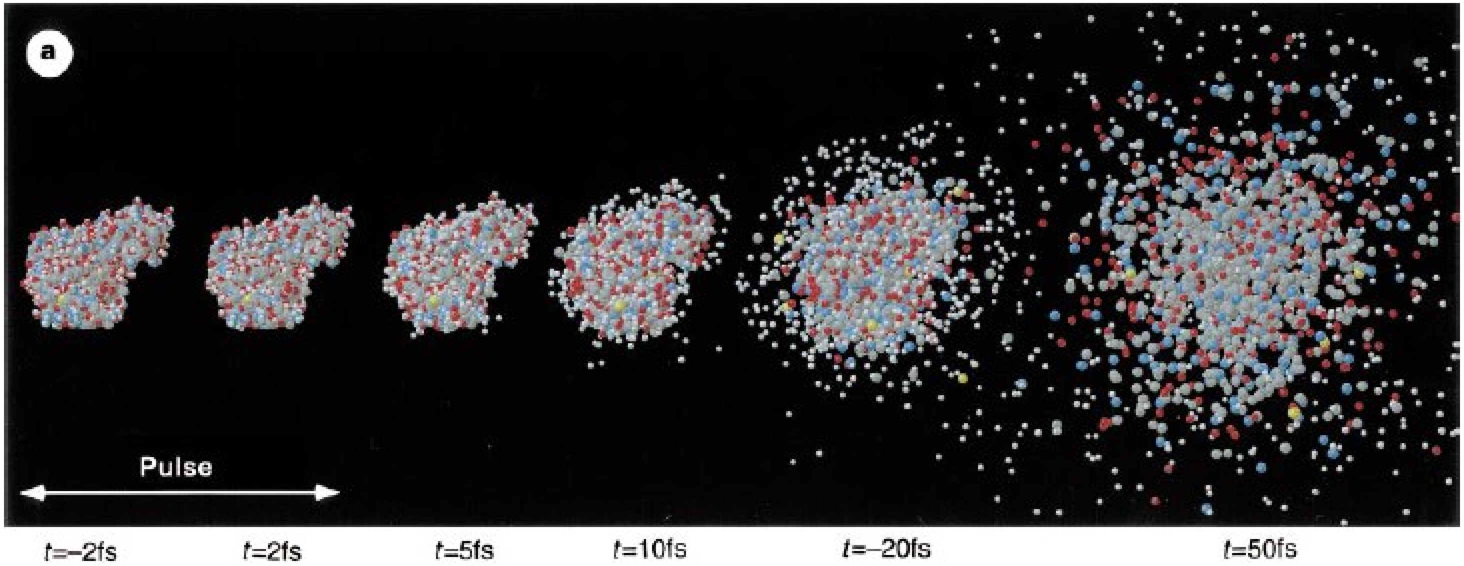
Dynamic scattering



Coherent scattering. Motivation

Diffraction imaging of biomolecules with coherent femtosecond X-FEL pulses

Very much excitement, now for >15 years:

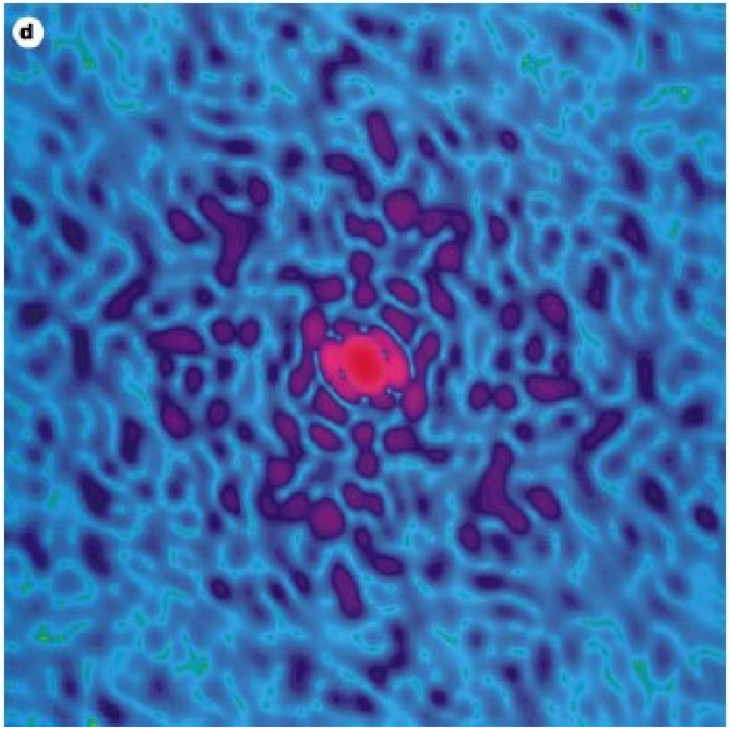


Coulomb explosion of T4 lysozyme

R. Neutze *et al.*, Nature **406**, 752 (2000)

Coherent scattering. Motivation

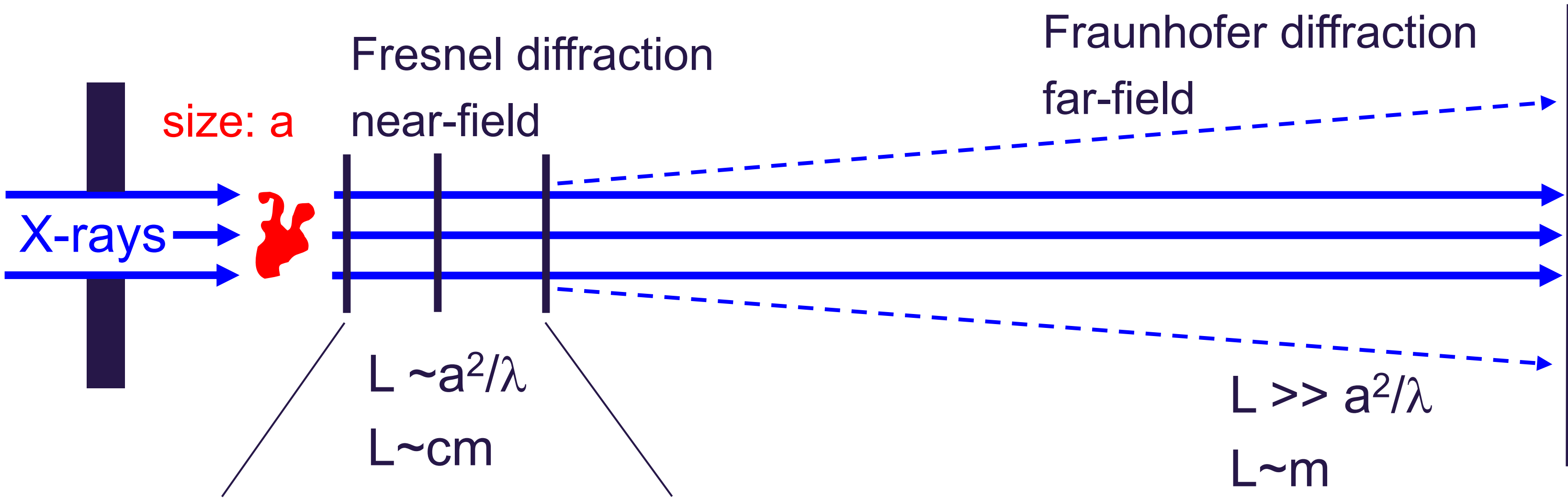
Diffraction imaging of biomolecules with coherent femtosecond X-FEL pulses



Simulated coherent scattering image **(speckle)** of a T4 lysozyme molecule

R. Neutze *et al.*, Nature **406**, 752 (2000)

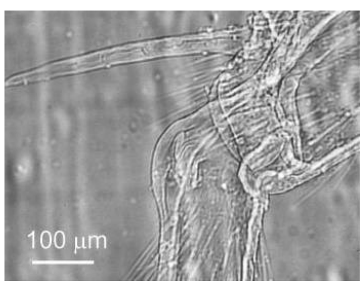
Different regimes of lensless X-ray imaging



Absorption

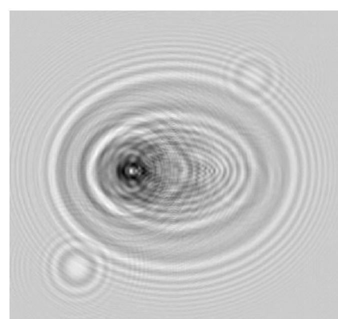
Röntgen (1895)

Phase contrast



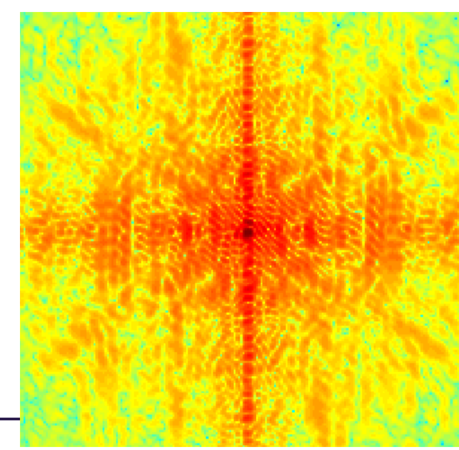
Koch *et al.* (1998)

In-line holography



Zhang (2003)

Coherent Diffraction Imaging (CDI)



Different regimes of lensless X-ray imaging

Absorption regime

Easy reconstruction based on attenuation

3D tomographic reconstruction, inverse Radon transformation

Phase contrast regime

Edge enhanced contrast

Transport-of-intensity (TIE) equation

Holotomographic reconstruction (Talbot effect)

In-line holographic regime

Holographic reconstuction (detector dependent resolution)

Twin image problem

Coherent diffraction imaging

Tricky data treatment

Resolution like in scattering, i.e. $\Delta_{min} = 2\pi/Q_{max}$

….

Coherence

Quantum mechanics → probability amplitudes (waves)

Optics → Young's double slit experiment, interference

X-ray (and neutron) scattering

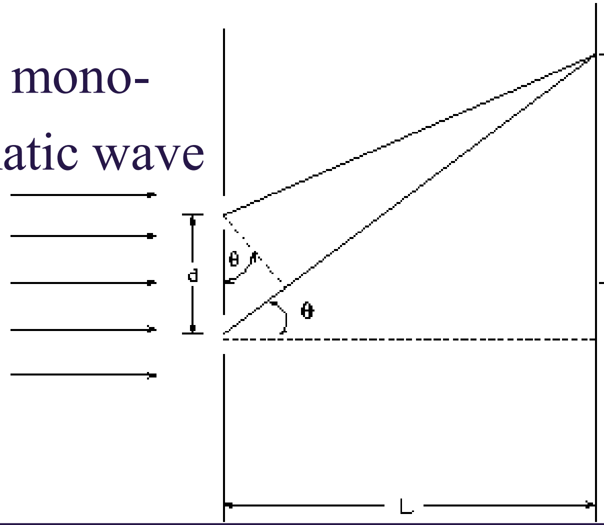
It's all about probability amplitudes and interference !!!

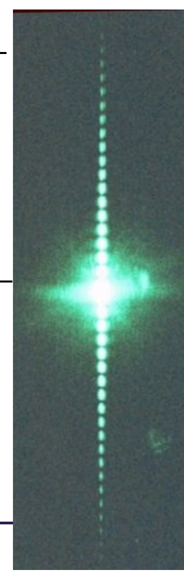
Example: Young's double slit experiment (Thomas Young, 1801)

[wave-character of quantum mechanical particles (photons)]

Plane, mono-chromatic wave

Laser beam





$P=|\Sigma_j \Phi_j|^2$

Φ: probability amplitude

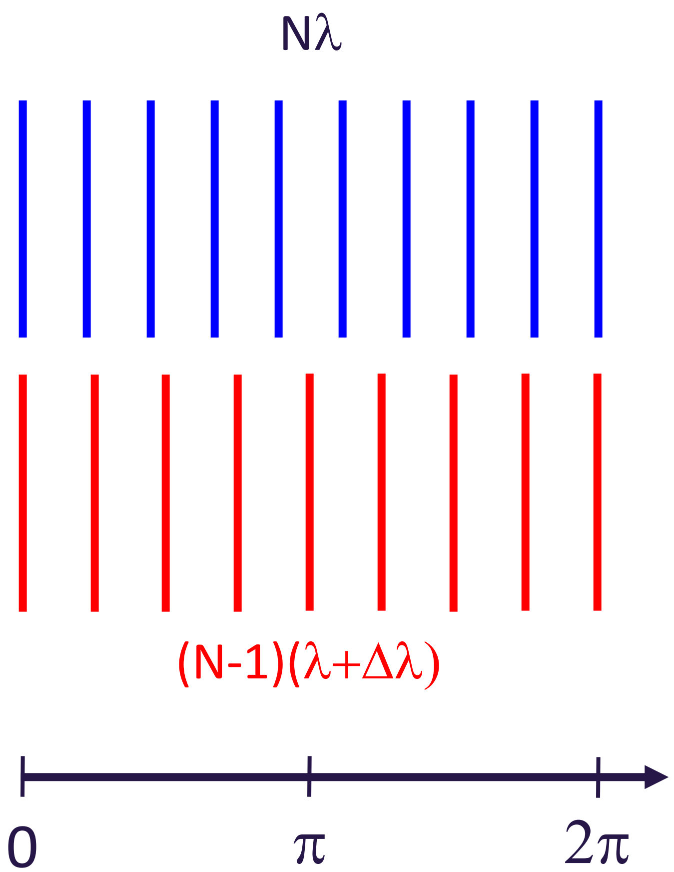
$\Phi_j \sim \exp[-i(\omega t - k l_j)]$

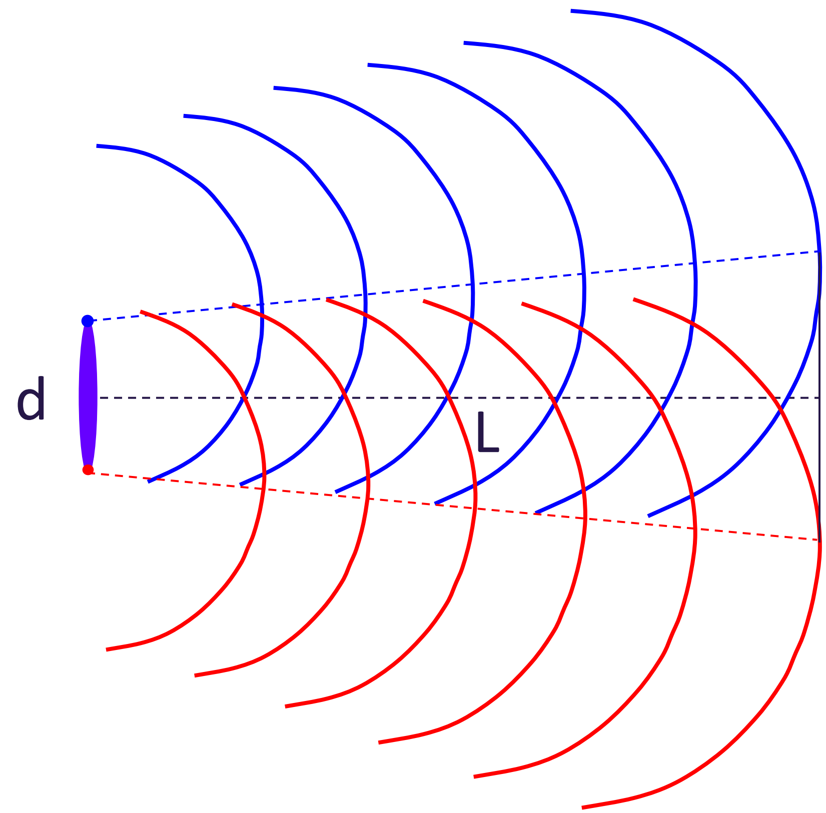
$\omega = ck$, $k = 2\pi/\lambda$, $l_j(L,y)$

$P(y) \sim \cos^2(\pi y d/\lambda L)$

$\Delta y = \lambda L/d$

Coherence lengths

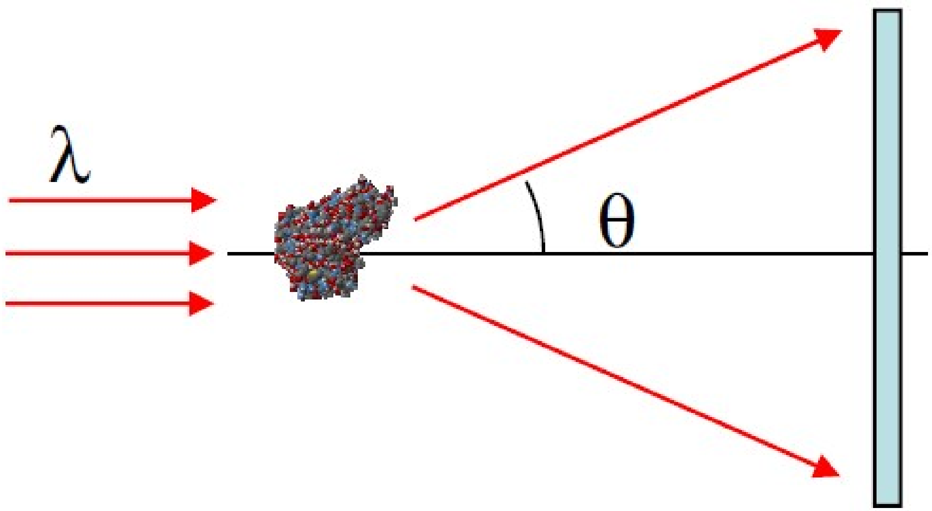


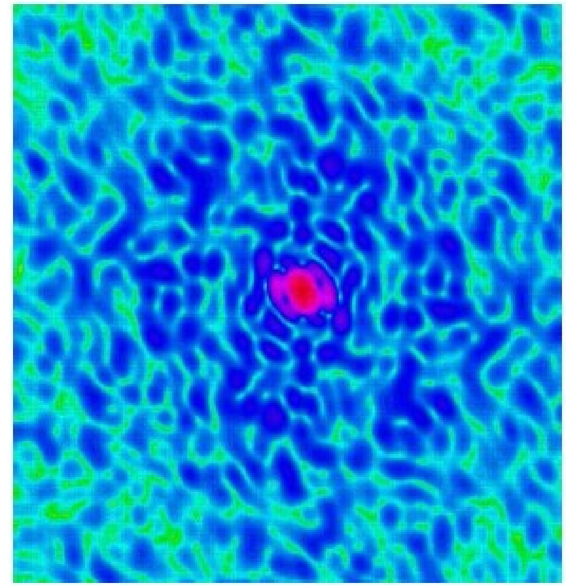


Longitudinal coherence length $l_l = \lambda / 2(\Delta\lambda/\lambda)$

Transverse coherence length $l_t = \lambda L / 2d$

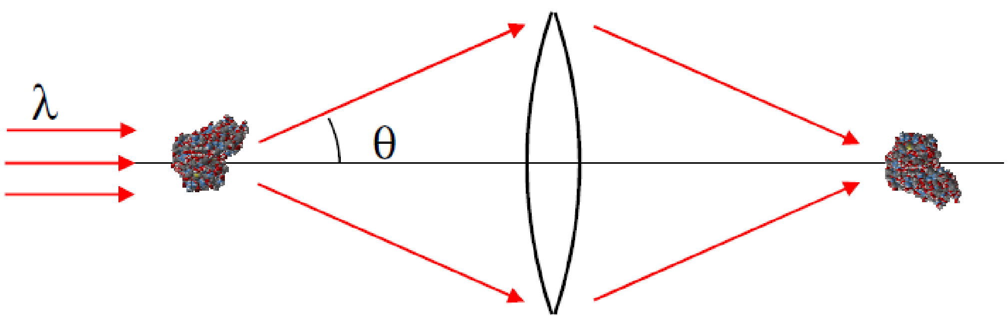
The CDI Challenge





I(q)

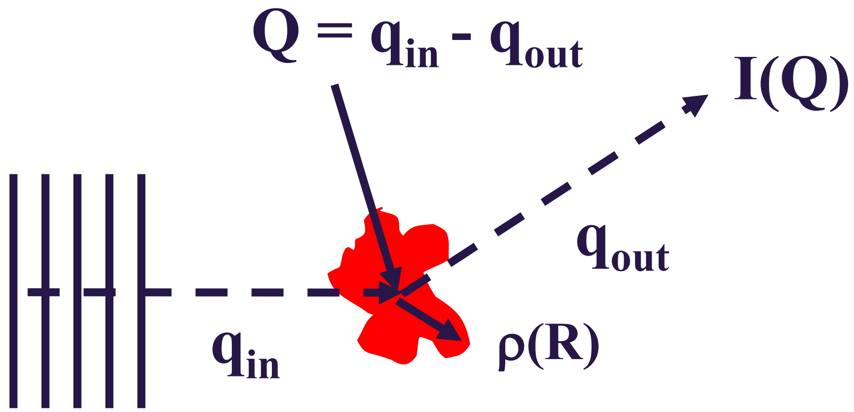
Using a lens to form the image



Question

Speckle pattern does not look like sample. How to determine the sample from I(q) ?

The phase problem in scattering



$|\mathbf{q}| = 2\pi/\lambda$

$|\mathbf{Q}| = 4\pi \sin(\theta)/\lambda$

$$E(\mathbf{Q}) \sim \int \rho(\mathbf{R}) \exp[i\mathbf{Q}\cdot\mathbf{R}]\, d\mathbf{R}$$

Reciprocal space E(**Q**) ←←← FT →→→ ρ(**R**) Real space

But… $I(\mathbf{Q}) = E(\mathbf{Q})E^{*}(\mathbf{Q}) = |E(\mathbf{Q})|^2$

The phase problem in scattering

Aim: To find $E(Q)$ from measurements of $I(Q) = |E(Q)|^2$

But $E(Q)$ is a complex number with both phase and amplitude

$E(Q) = A \exp(i\phi)$

Measurement: $I(Q) = |E(Q)|^2 = A^2$

No direct access to phase….

Exercise

FT of XFEL logo → $E(Q)$

$I(Q) = |E(Q)|^2$ (simulation of coherent scattering)

Construct $E(Q)$:

$A = \mathrm{sqrt}(I(Q))$

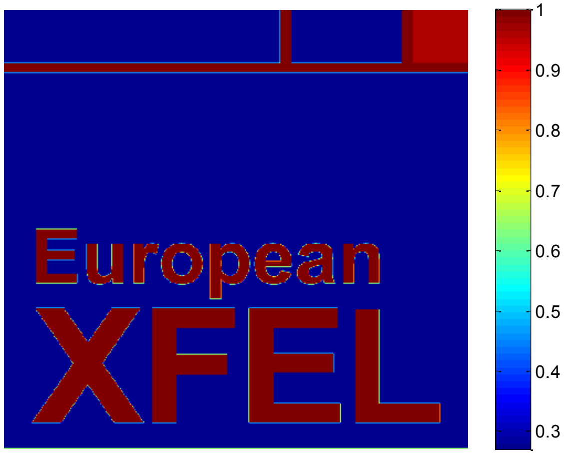
Take random phases ϕ

Inverse FT transform of $A \exp(i\phi)$

Phase matters!

$\rho(R)$

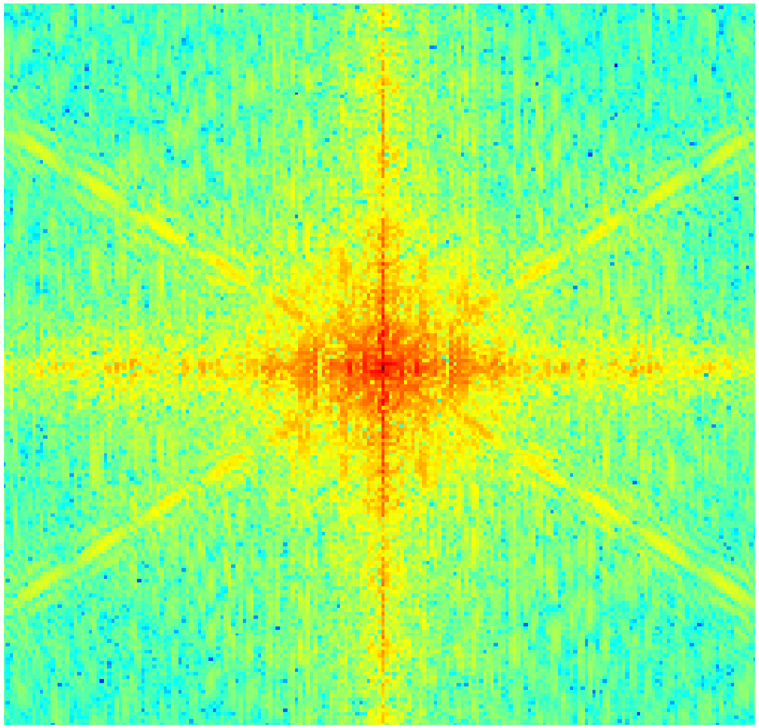
ampl
A



phase
ϕ

FT

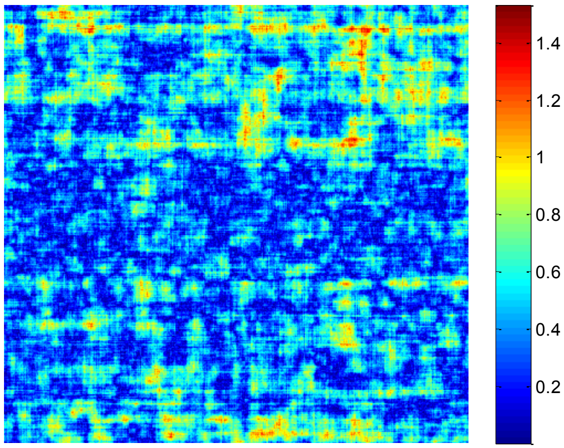
$$|FT\{\rho(R)\}|^2 = |E(Q)|^2 = I(Q)$$



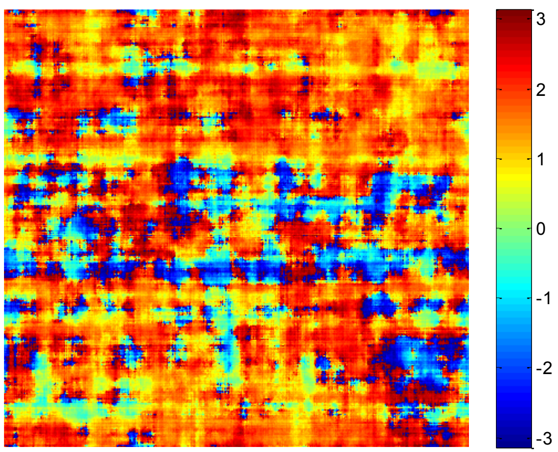
Phase matters!

ρ(R)

ampl

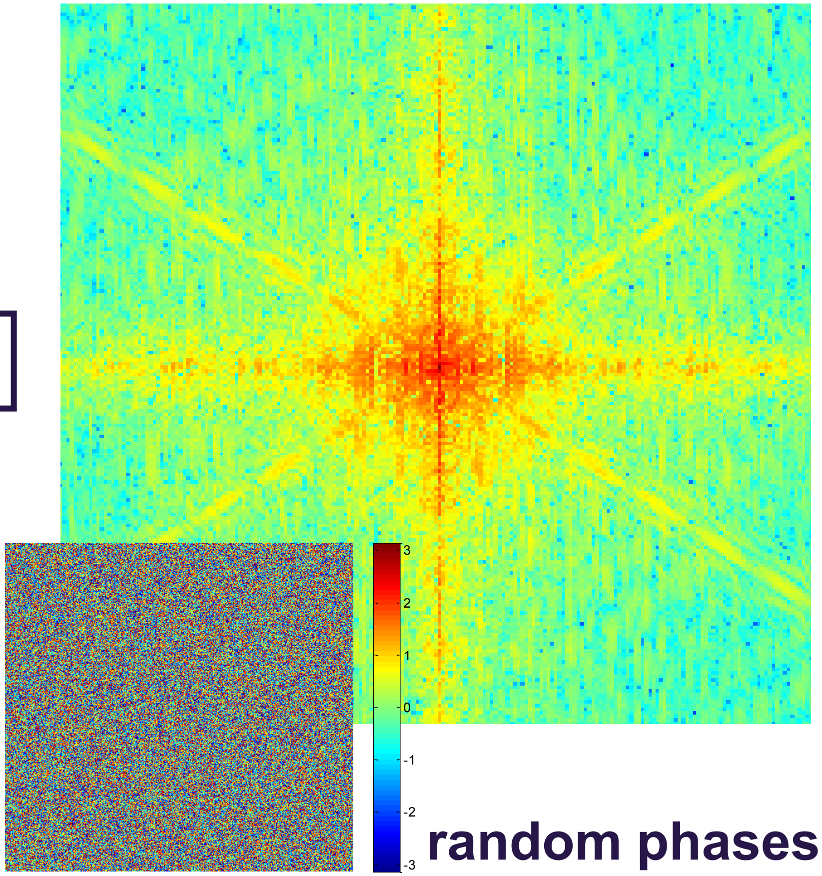


phase



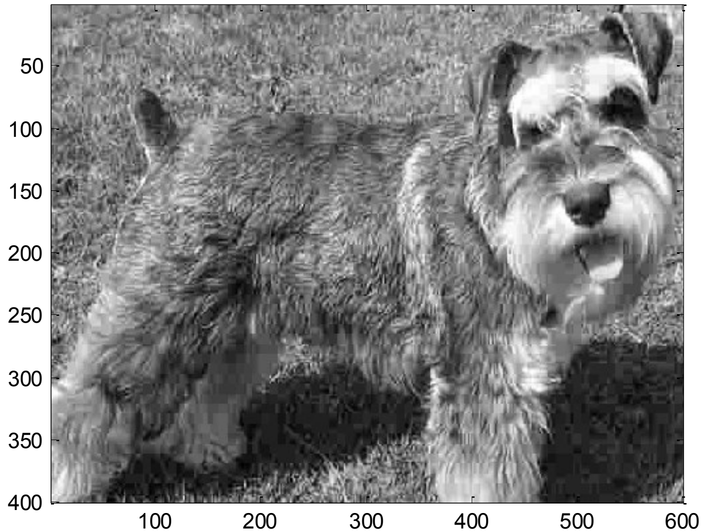
$FT^{-1}\{E(Q)\}$

√I(Q) as amplitude



random phases

Phase is more important than amplitude



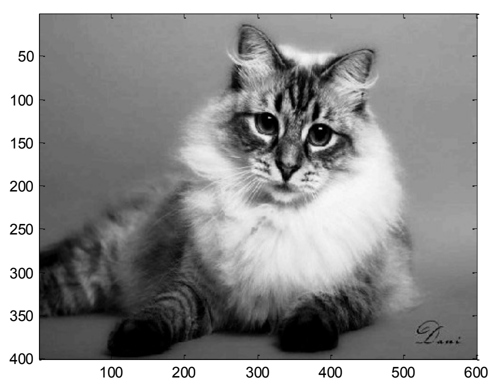
Fourier transform my dog → $A\,e^{i\phi}$

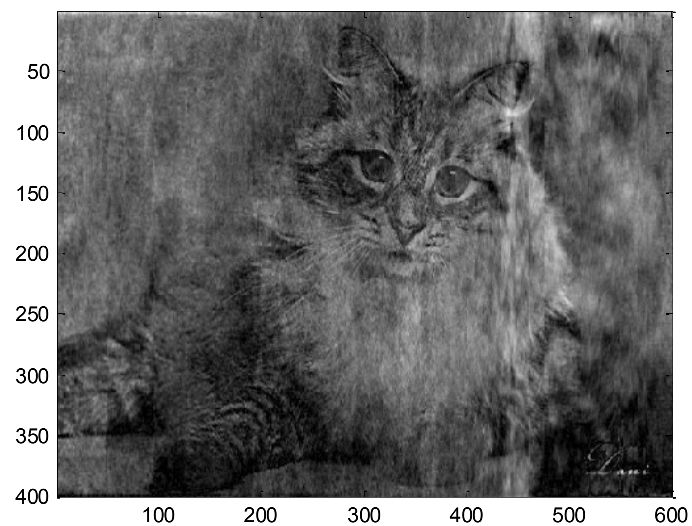
Keep amplitudes A

Substitute with another image's phases ϕ

Inverse Fourier transform

The phases came from a cat…





How can the phase be determined?

ρ

N^2 pixels

$2N^2$ unknowns

→

$\mathbf{I}$

N^2 pixels

N^2 equations

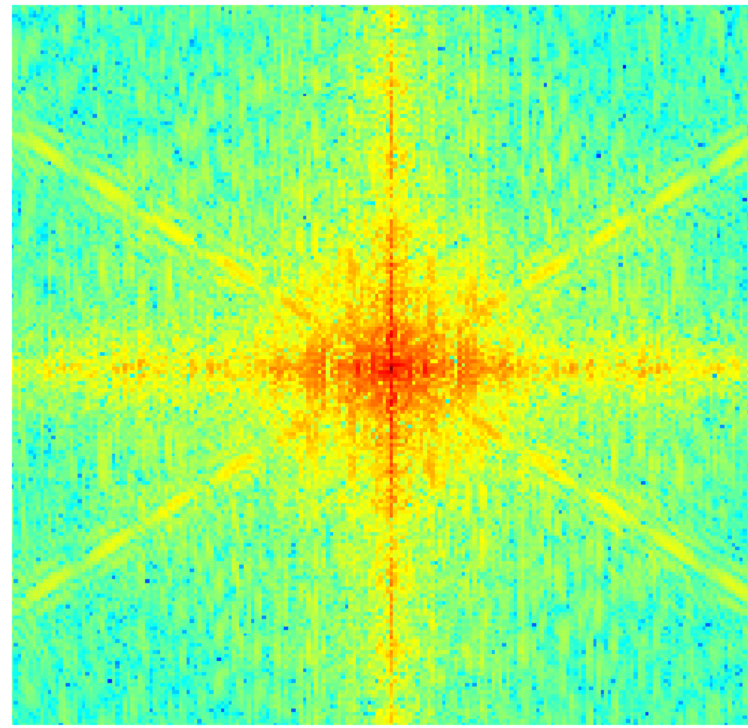
Question

How can we make this solvable?

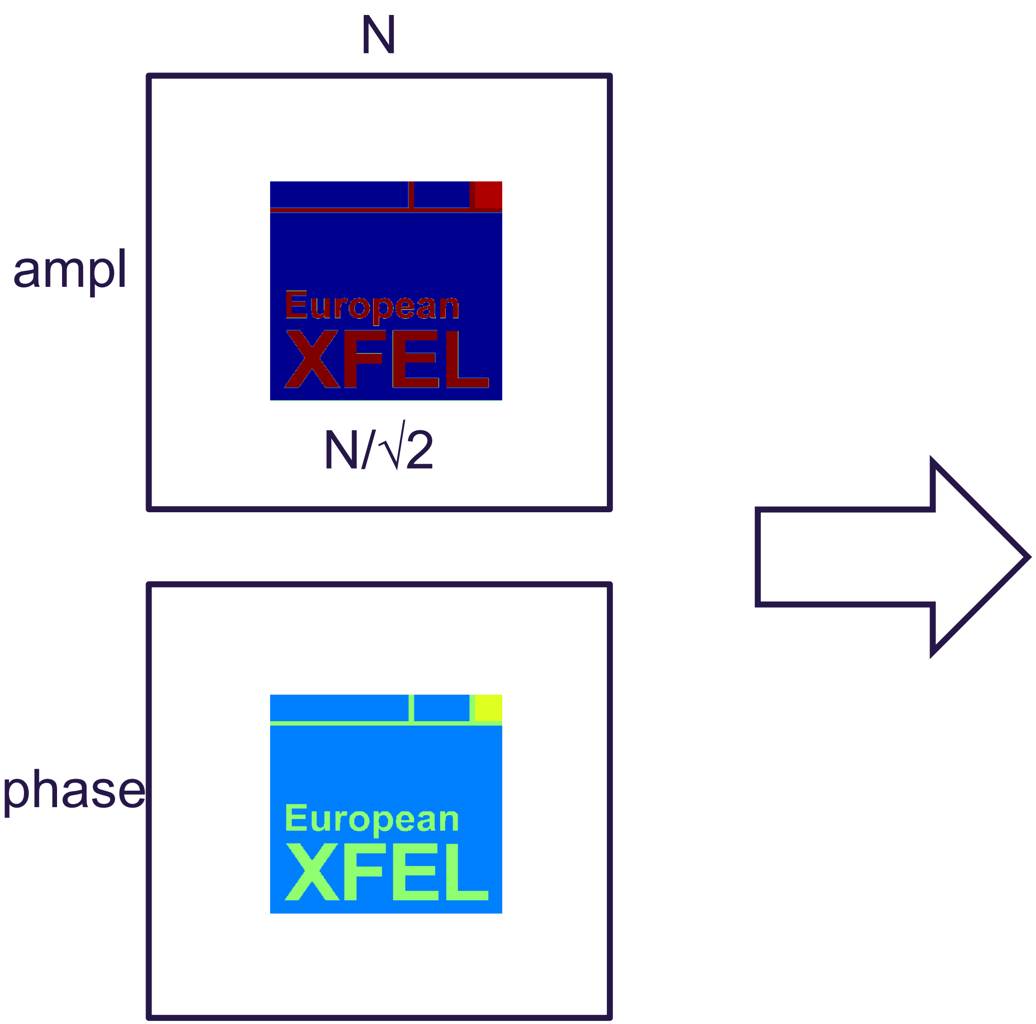
ampl

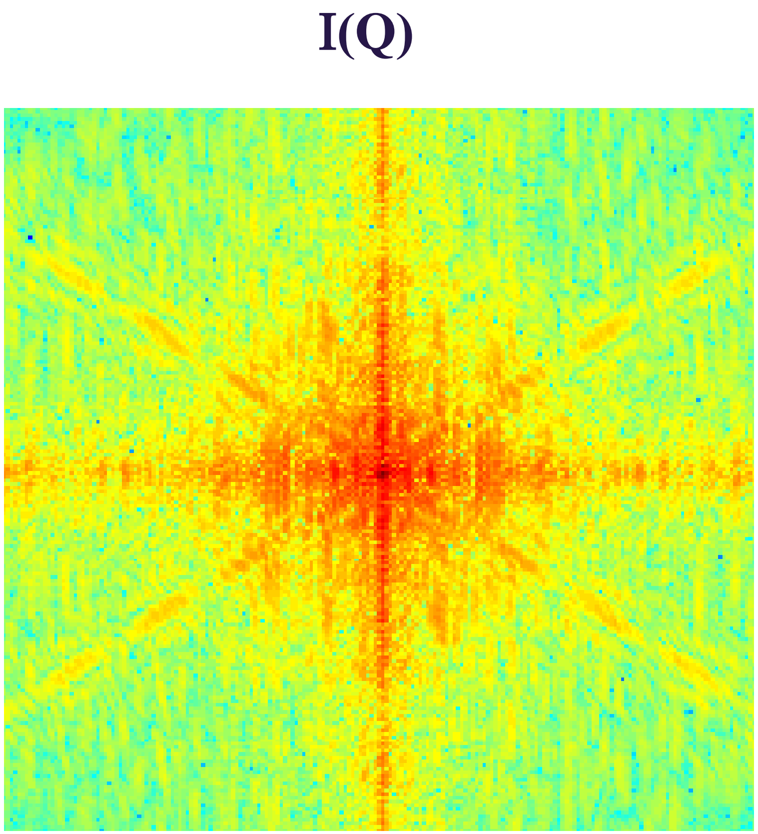
phase

I(Q)

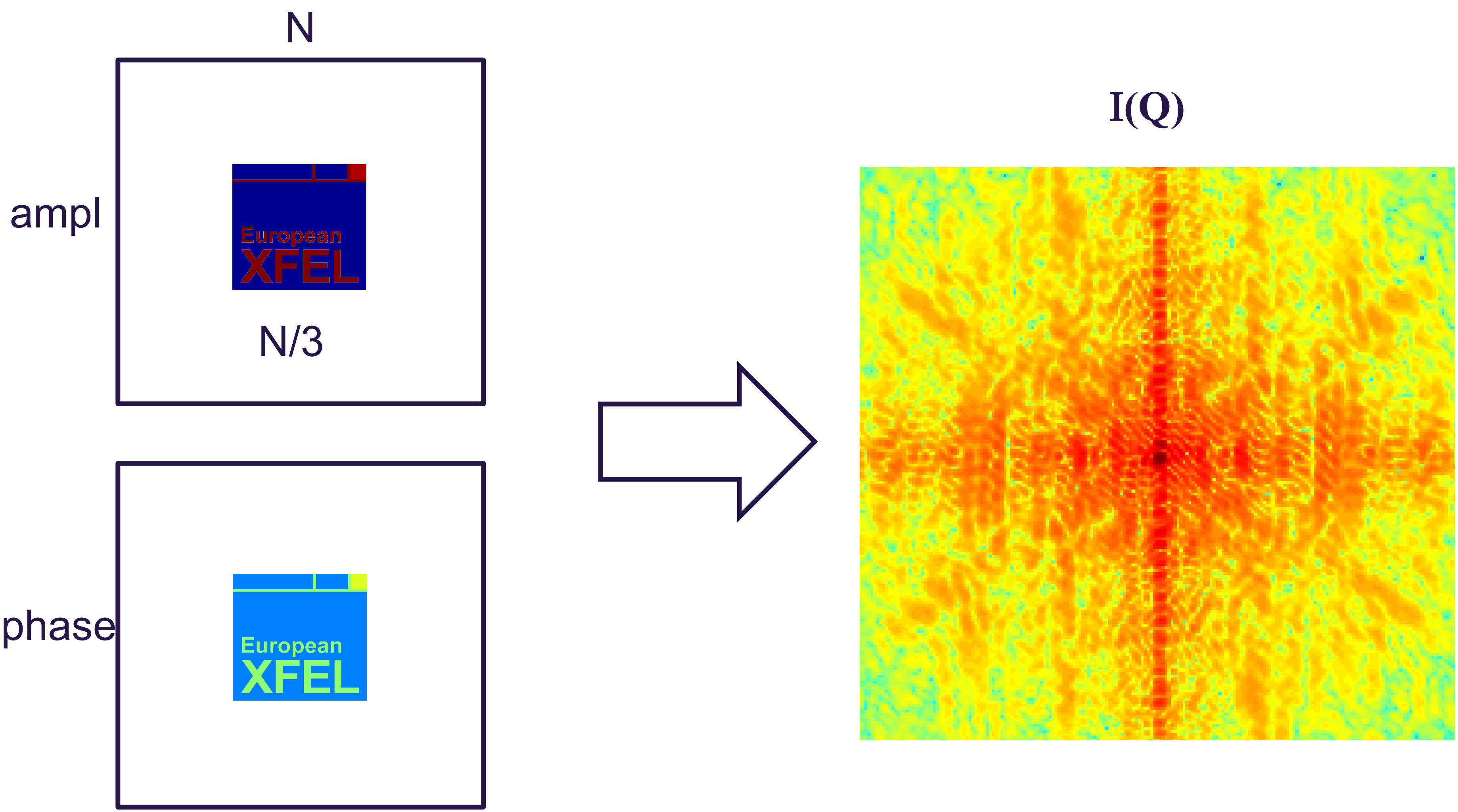


Finite support constraint

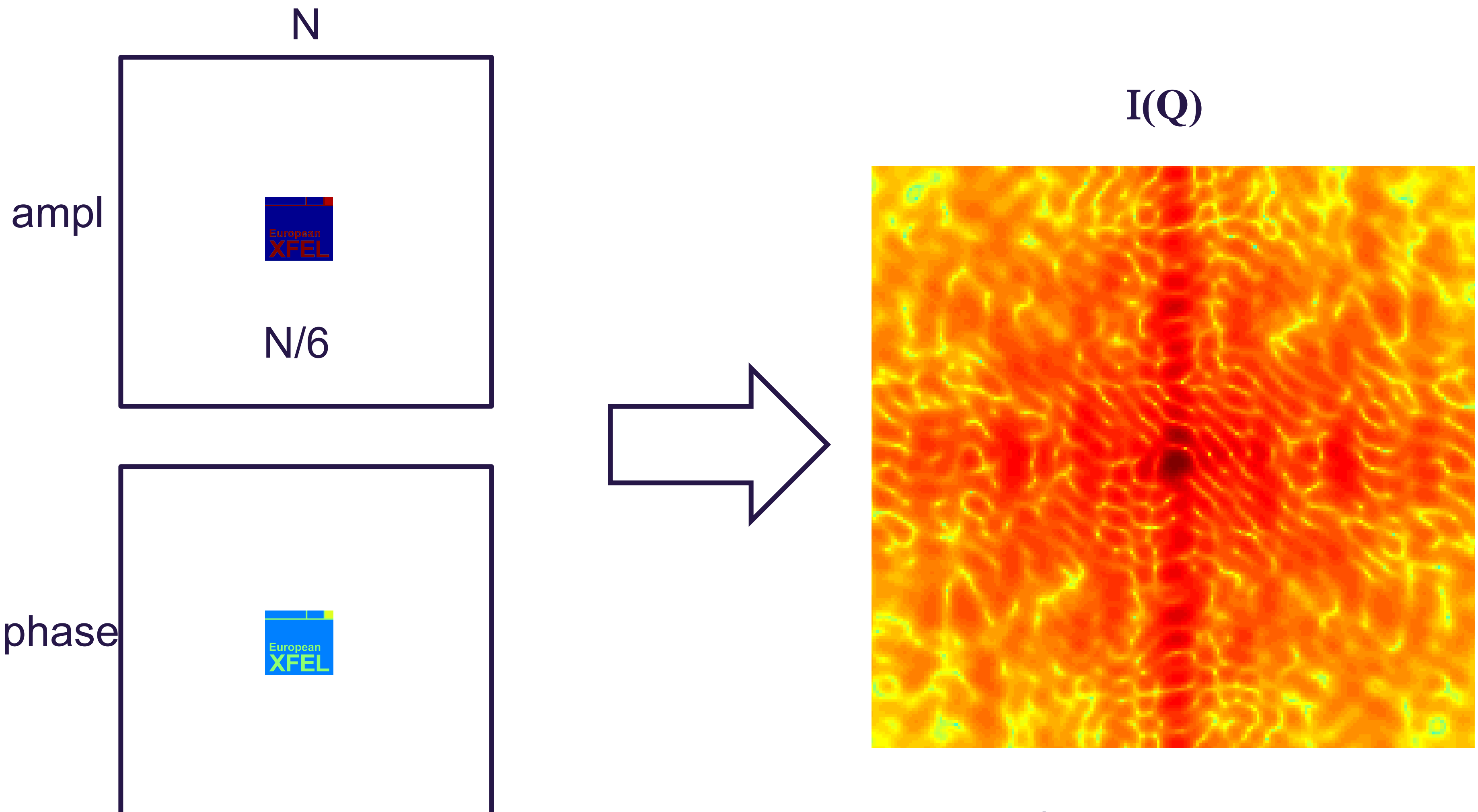




Finite support constraint



Finite support constraint



Angular speckle size ~ λ/sample size

Oversampling

David Sayre (1952)

Acta Cryst. (1952). **5**, 843

Some implications of a theorem due to Shannon. By D. Sayre, *Johnson Foundation for Medical Physics, University of Pennsylvania, Philadelphia 4, Pennsylvania, U. S. A.*

(*Received* 3 *July* 1952)

Shannon (1949), in the field of communication theory, has given the following theorem: If a function $d(x)$ is known to vanish outside the points $x = \pm a/2$, then its Fourier transform $F(X)$ is completely specified by the values which it assumes at the points $X = 0, \pm 1/a, \pm 2/a, \ldots$. In fact, the continuous $F(X)$ may be filled in merely by laying down the function $\sin \pi aX/\pi aX$ at each of the above points, with weight equal to the value of $F(X)$ at that point, and adding.

Now the electron-density function $d(x)$ describing a single unit cell of a crystal vanishes outside the points $x = \pm a/2$, where a is the length of the cell. The reciprocal-lattice points are at $X = 0, \pm 1/a, \pm 2/a, \ldots$, and hence the experimentally observable values of $F(X)$ would suffice, by the theorem, to determine $F(X)$ everywhere, if the phases were known. (In principle, the necessary points extend indefinitely in reciprocal space, but by using, say, Gaussian atoms both $d(x)$ and $F(X)$ can be effectively confined to the unit cell and the observable region, respectively.)

For centrosymmetrical structures, to be able to fill in the $|F|^2$ function would suffice to yield the structure, for sign changes could occur only at the points where $|F|^2$ vanishes. The structure corresponding to the $|F|^2$ function is the Patterson of a single unit cell. This has twice the width of the unit cell, and hence to fill in the $|F|^2$ function would require knowledge of $|F|^2$ at the half-integral, as well as the integral h's. This is equivalent to a statement made by Gay (1951).

I think the conclusions which may be stated at this point are:

1. Direct structure determination, for centrosymmetric structures, could be accomplished as well by finding the sizes of the $|F|^2$ at half-integral h as by the usual procedure of finding the signs of the F's at integral h.

2. In work like that of Boyes-Watson, Davidson & Perutz (1947) on haemoglobin, where $|F|^2$ was observed at non-integral h, it would suffice to have only the values at half-integral h.

The extension to three dimensions is obvious.

References

Boyes-Watson, J., Davidson, E. & Perutz, M. F. (1947). *Proc. Roy. Soc.* A, **191**, 83.

Gay, R. (1951). Paper presented at the Second International Congress of Crystallography, Stockholm.

Shannon, C. E. (1949). *Proc. Inst. Radio Engrs., N.Y.* **37**, 10.

Basic experimental requirements for CDI

In 2D:

- Need that sample size a is √2 smaller than beam size D: $a < D/\sqrt{2}$ **(reduce number of unknowns)**

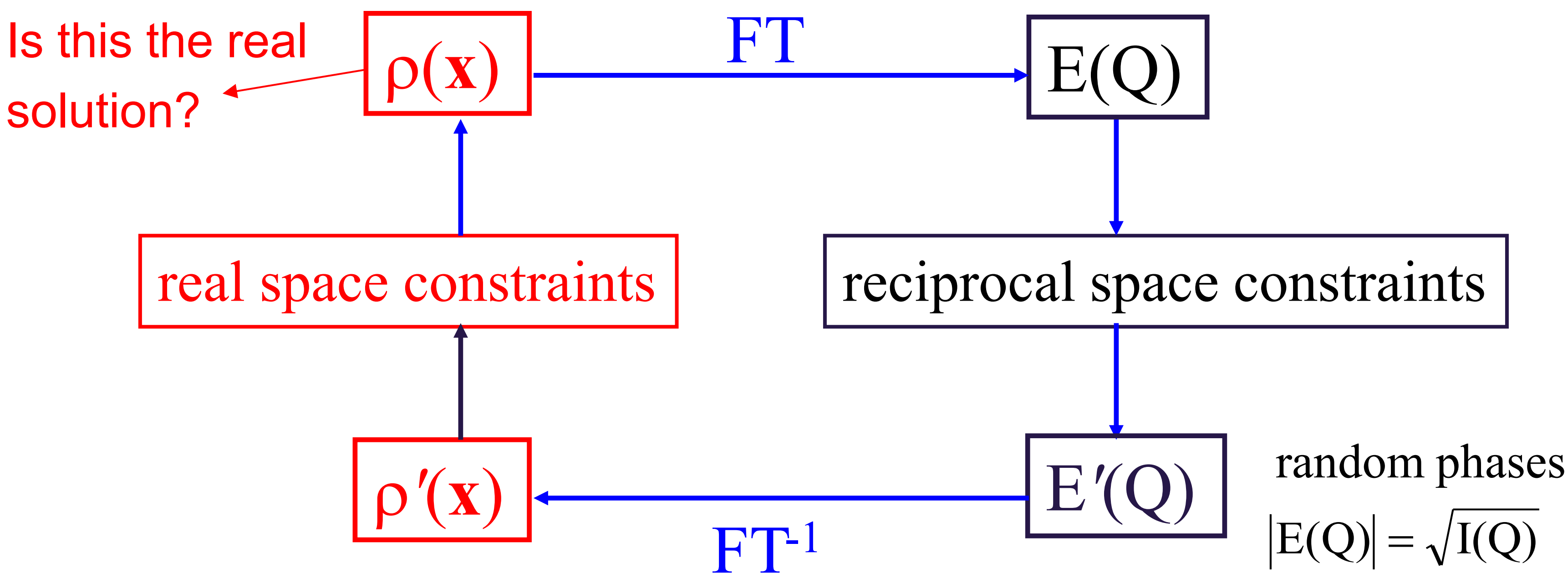
- Need to measure the speckle pattern with a resolution that is at least √2 finer that speckle size in both dimensions. Therefore, the pixel size Δp must fulfil: $\Delta p < L\lambda/(a\sqrt{2})$, where L is the sample-detector distance **(increase number of equations)**

- Beam must be coherent over the sample size a, **otherwise the FT relationship does not hold**

Question

How to solve the non-linear system of N^2 equations and M unknowns ($M < N^2$) to find $\rho(R)$?

Iterative Phase Retrieval Algorithm



Real space constraints:

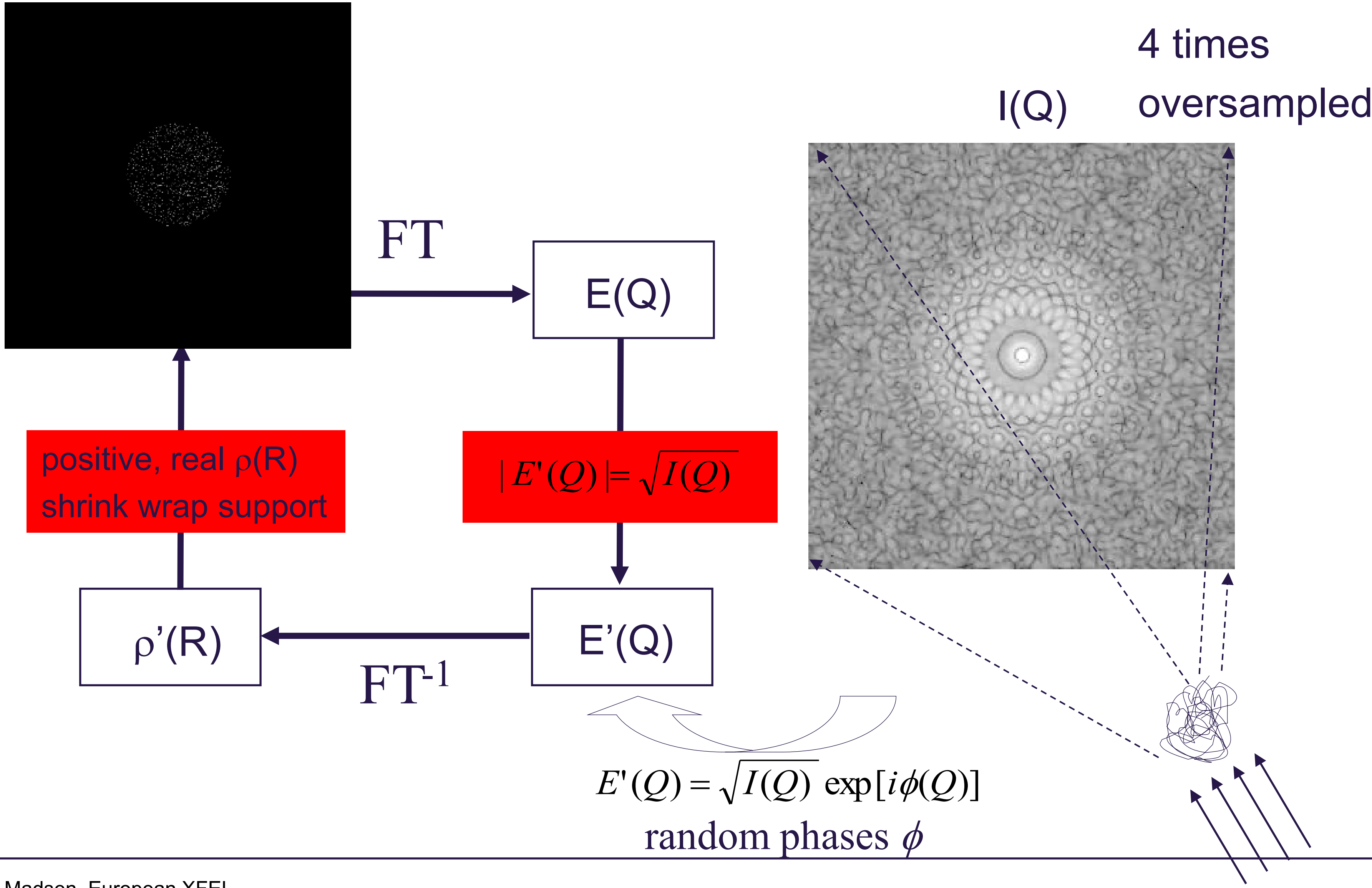
finite support ($\rho=0$ outside sample)

real ρ ? positive ρ ? other?

Reciprocal space constraints

$$|E(Q)| \rightarrow \sqrt{I(Q)}$$

Computer simulation



Iterative Phase Retrieval Algorithm

R. W. Gerchberg and W. O. Saxton, Optik **35,** 237 (1972)

J.R. Fienup, Appl. Opt. **21**, 2758 (1982)

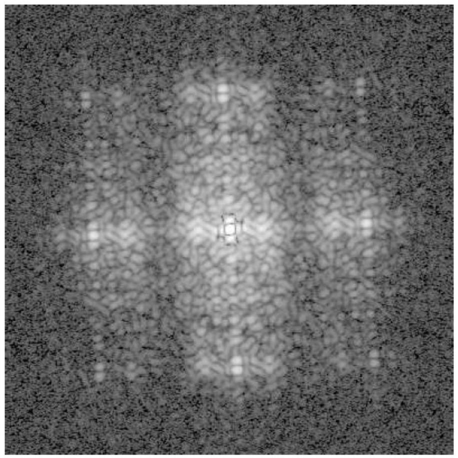
Review: R. Millane *et al*., J. Opt. Soc. Am. **A14**, 568 (1997)

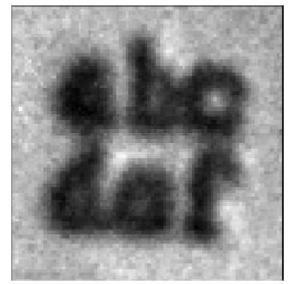
Difference map: V. Elser, J. Opt. Soc. Am. **A20**, 40 (2003)

1st Experimental demonstration with X-rays

Data collected at NSLS beamline X1B

λ=1.8 nm soft x-ray diffraction pattern





Low angle data From optical micrograph

Scanning electron micrograph of object

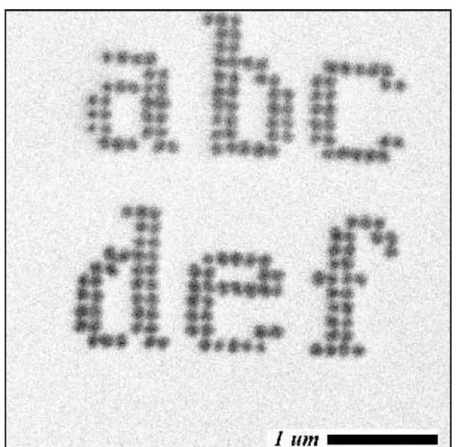
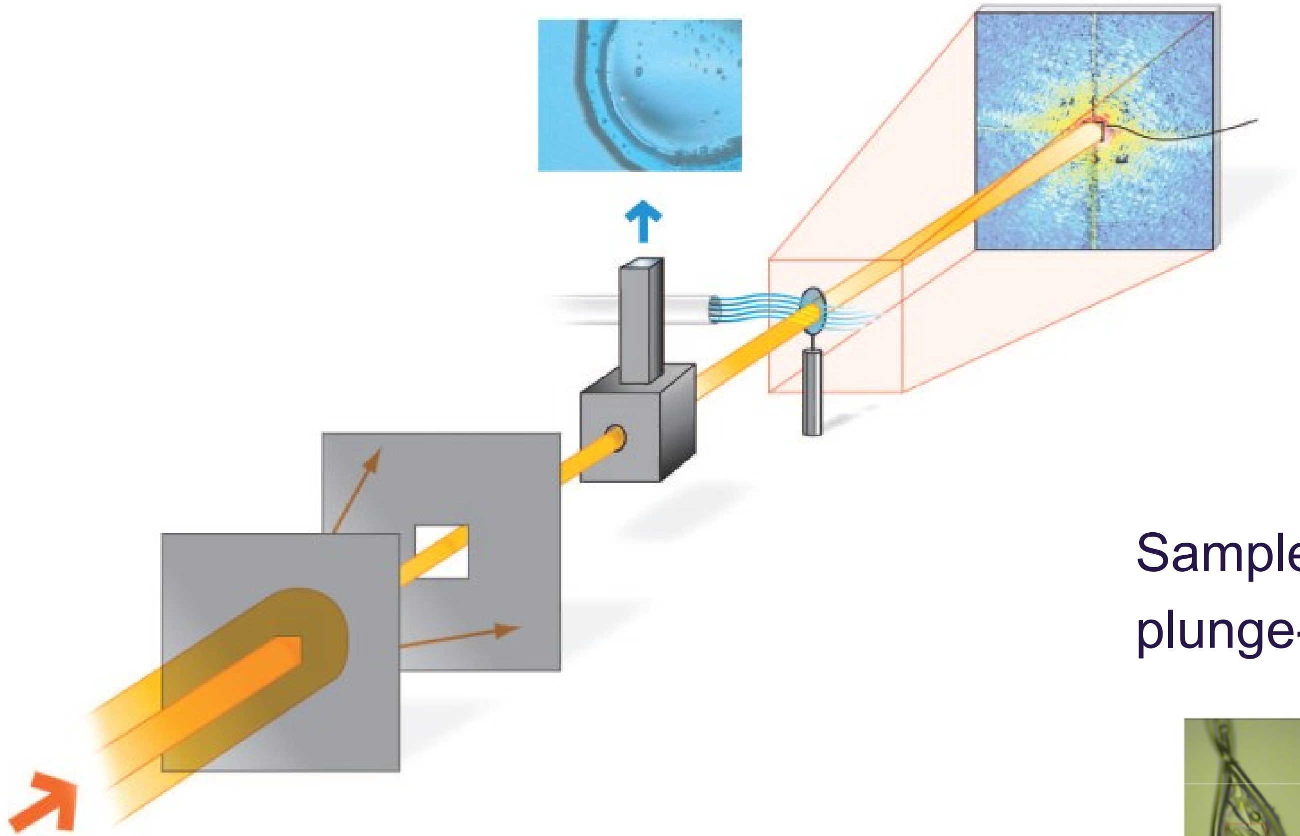


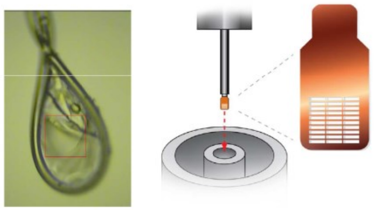
Image reconstructed from diffraction pattern (θ_{max} corresponds to 80 nm). Assumed positivity

J. Miao *et al*, Nature **400**, 342 (1999)

Setup for Biological CDI

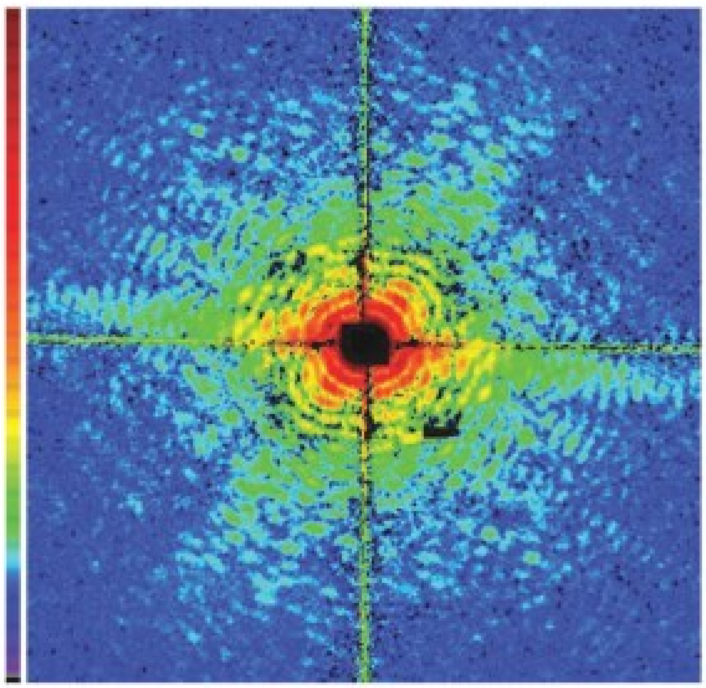


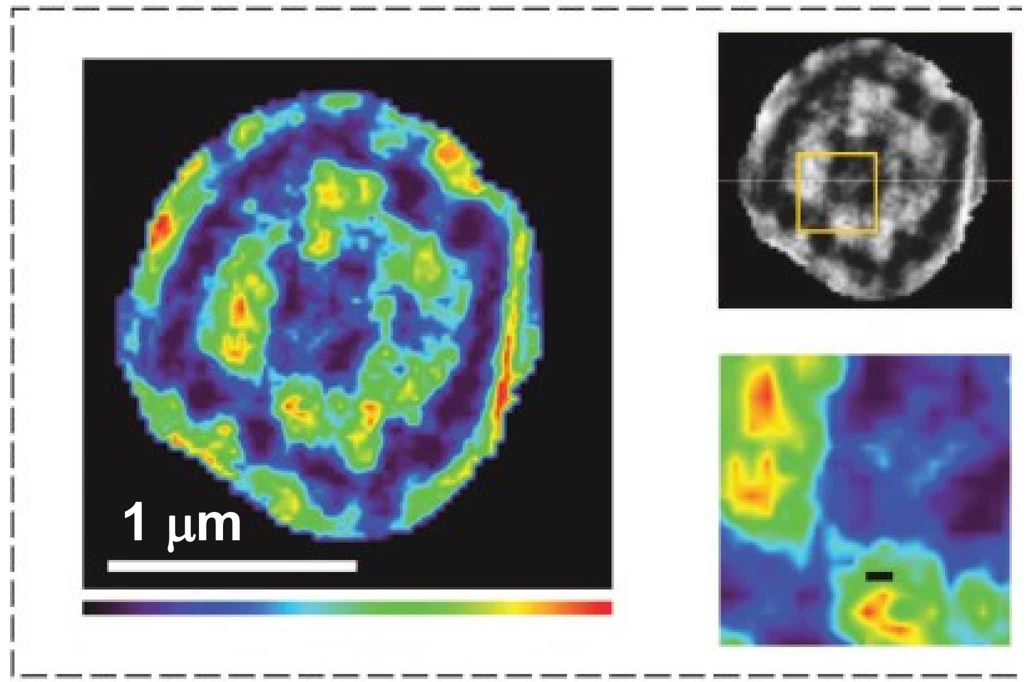
Sample preparation
plunge-freezing



Bio-CDI with hard X-rays

D. Radiodurans cell





Resolution about 30 nm

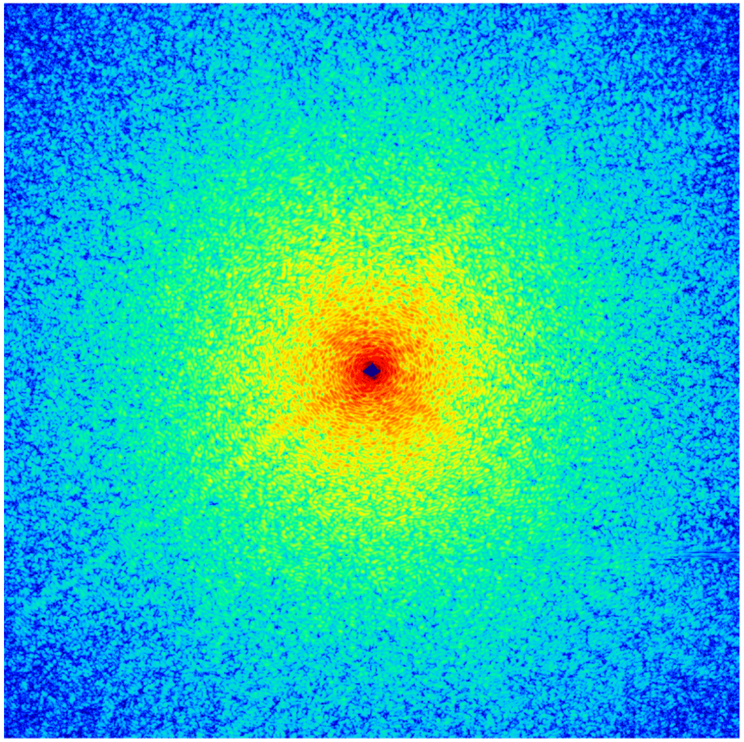
Goal: ~10 nm

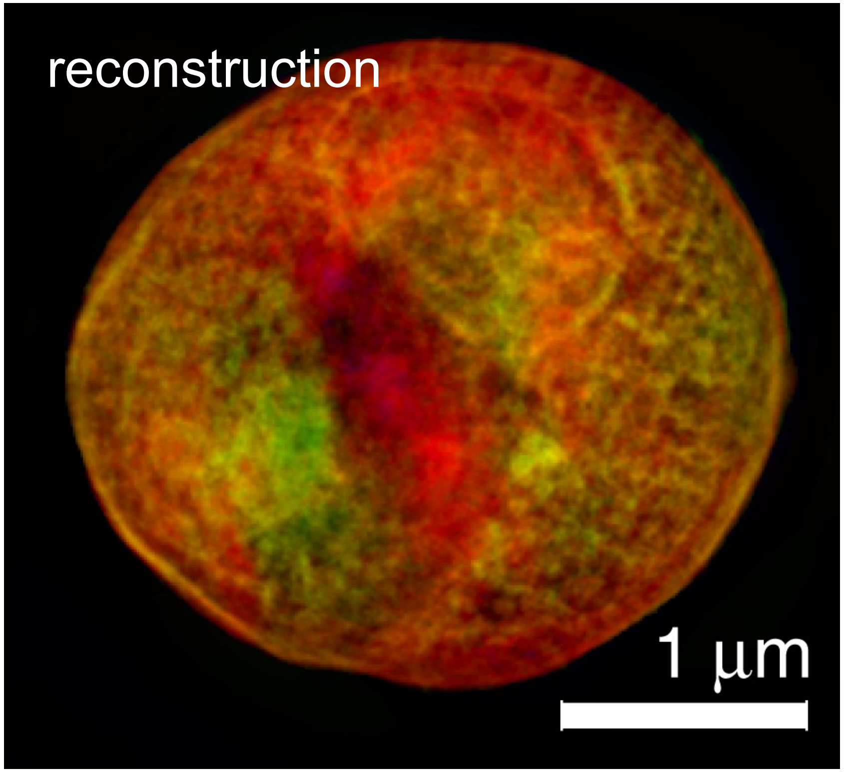
E. Lima *et al*, PRL **103**, 198102 (2009)

Bio-CDI with soft X-rays

CDI from a yeast cell.

Speckle pattern, λ=16.5 Å (ALS)





No shrink warp, “hand drawn” support

Difference map algorithm

Averaging iterates (Elser & Thibault)

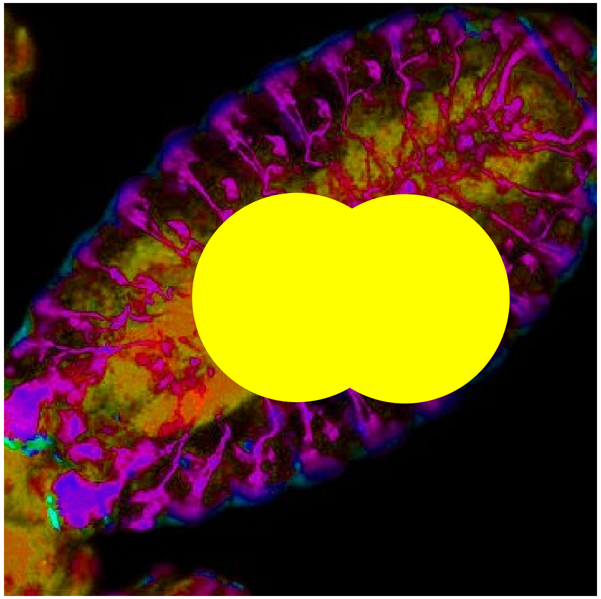
Resolution ~ 30 nm

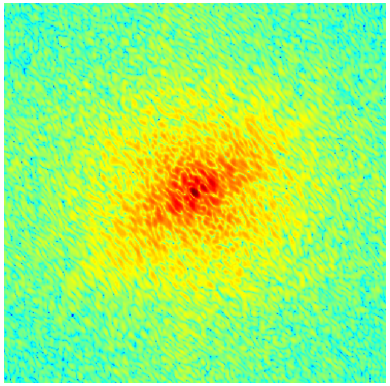
D. Shapiro *et al*, PNAS **102**, 15343 (2005)

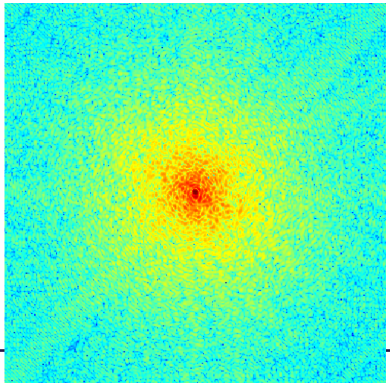
Ptychography

- The requirement that sample < beam is a limitation for many practical purposes
- Can we find another constraint so the $2N^2$ unknowns can be determined?
- The answer is : Ptychography!

Ptych- :
(to) fold (from Greek)







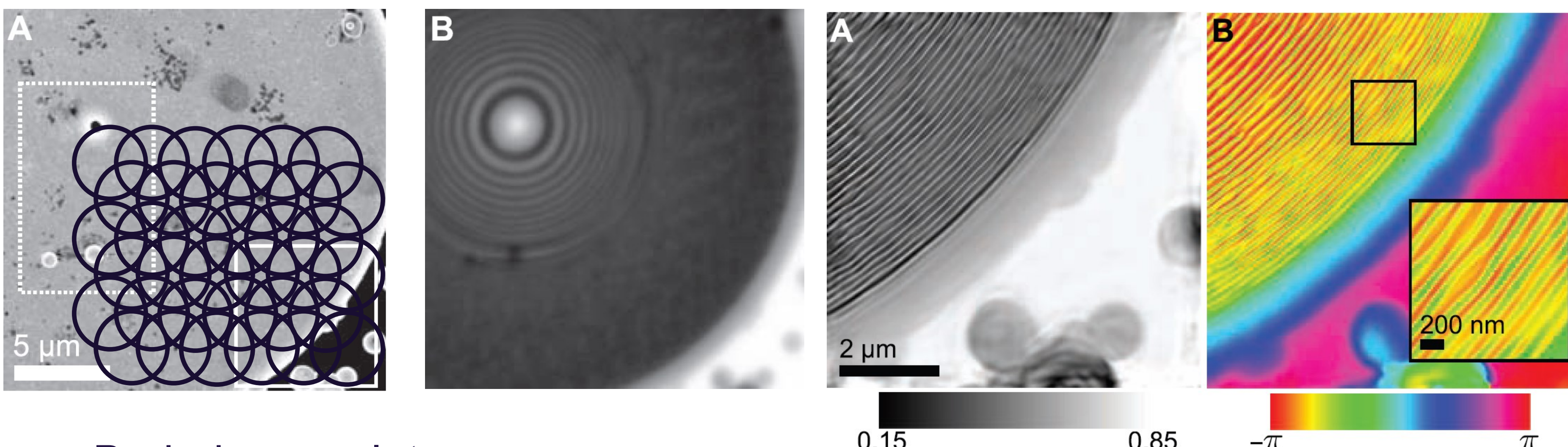
High-Resolution Scanning X-ray Diffraction Microscopy

Pierre Thibault,[1*] Martin Dierolf,[1] Andreas Menzel,[1] Oliver Bunk,[1] Christian David,[1] Franz Pfeiffer[1,2]

Science, **321,** 379-382 (2008)

SEM

absorption



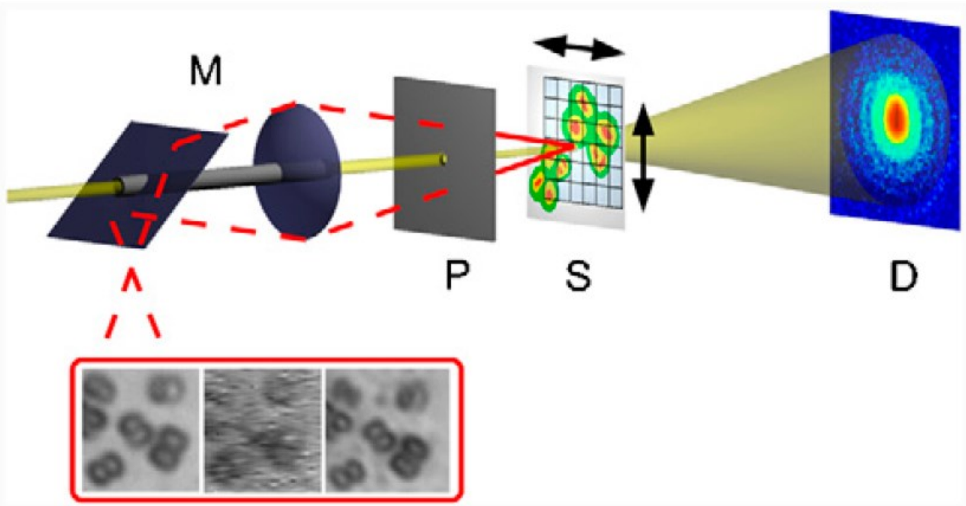
Buried zone plate

Quantitative biological imaging by ptychographic x-ray diffraction microscopy

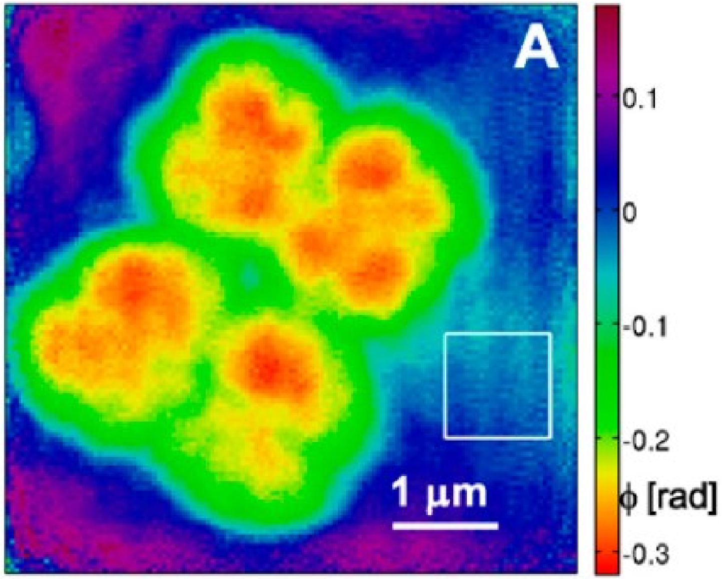
Klaus Giewekemeyer[a,1], Pierre Thibault[b], Sebastian Kalbfleisch[a], André Beerlink[a], Cameron M. Kewish[c], Martin Dierolf[b], Franz Pfeiffer[b], and Tim Salditt[a,1]

Proc. Natl. Acad. Sci. USA 107, p. 529-534 (2010)

Setup at cSAXS beamline, SLS



D. Radiodurans



Question

Do you know another method where the phases are encoded, i.e. easy reconstruction?

Holography

Famous method to encode the phases in the intensity pattern

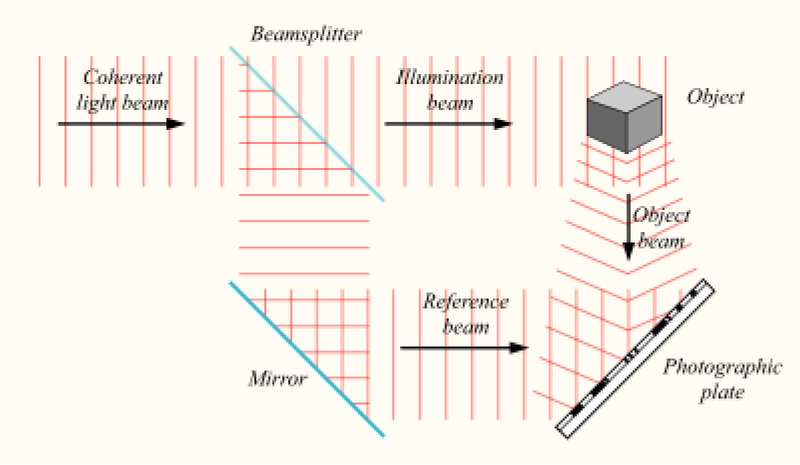
Dennis Gabor

Nobel prize 1971

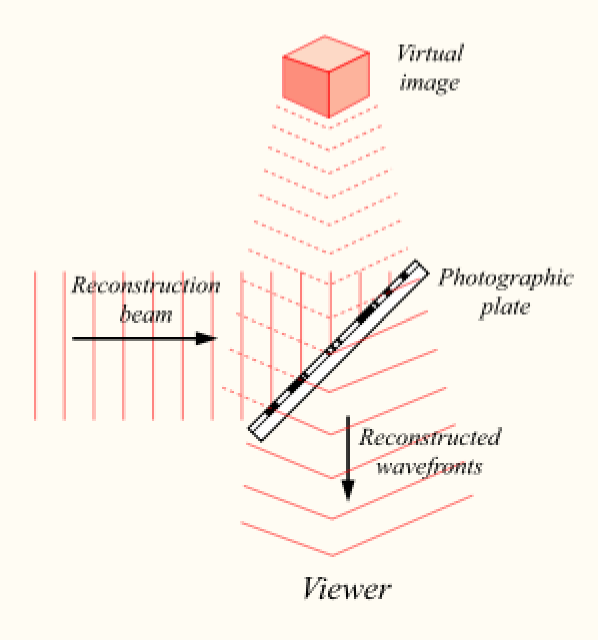
In-line holography (electrons, Gabor 1947);

Laser (1960), 1st optical hologram ~1962

Recording



Holographic reconstruction



First SR hologram:

Aoki et al. Jap. J. Appl. Phy 11, 1857 (1972)

Fourier Transform Holography

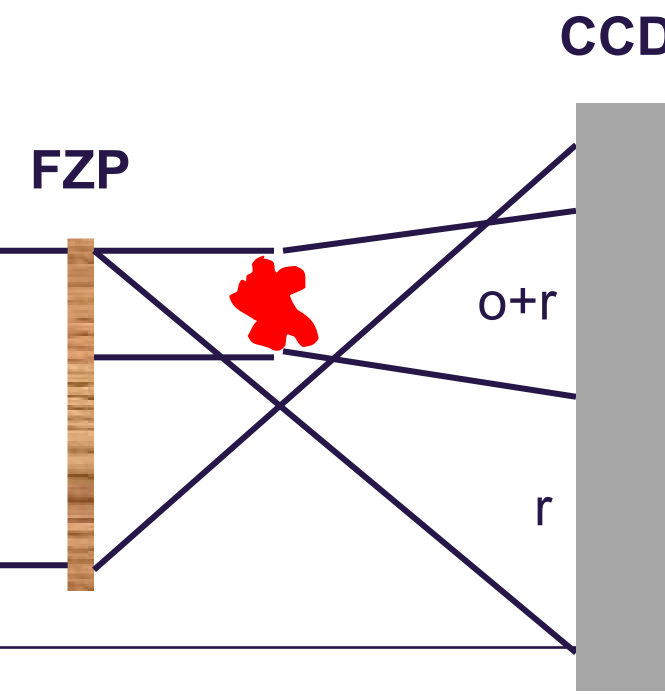
Fourier transform holography

- Spherical reference wave (r) spreads speckles and encodes phases of object wave (o)
- Simple reconstruction by FT:

$$I_{holo} = |FT\{o+r\}|^2 = |FT\{o\} + FT\{r\}|^2 = |O + R|^2 = |O|^2+|R|^2+OR^*+RO^*$$

$$FT\{I_{holo}\} = o \otimes o + r \otimes r + o \otimes r + r \otimes o$$

- How to get a spherical reference wave?

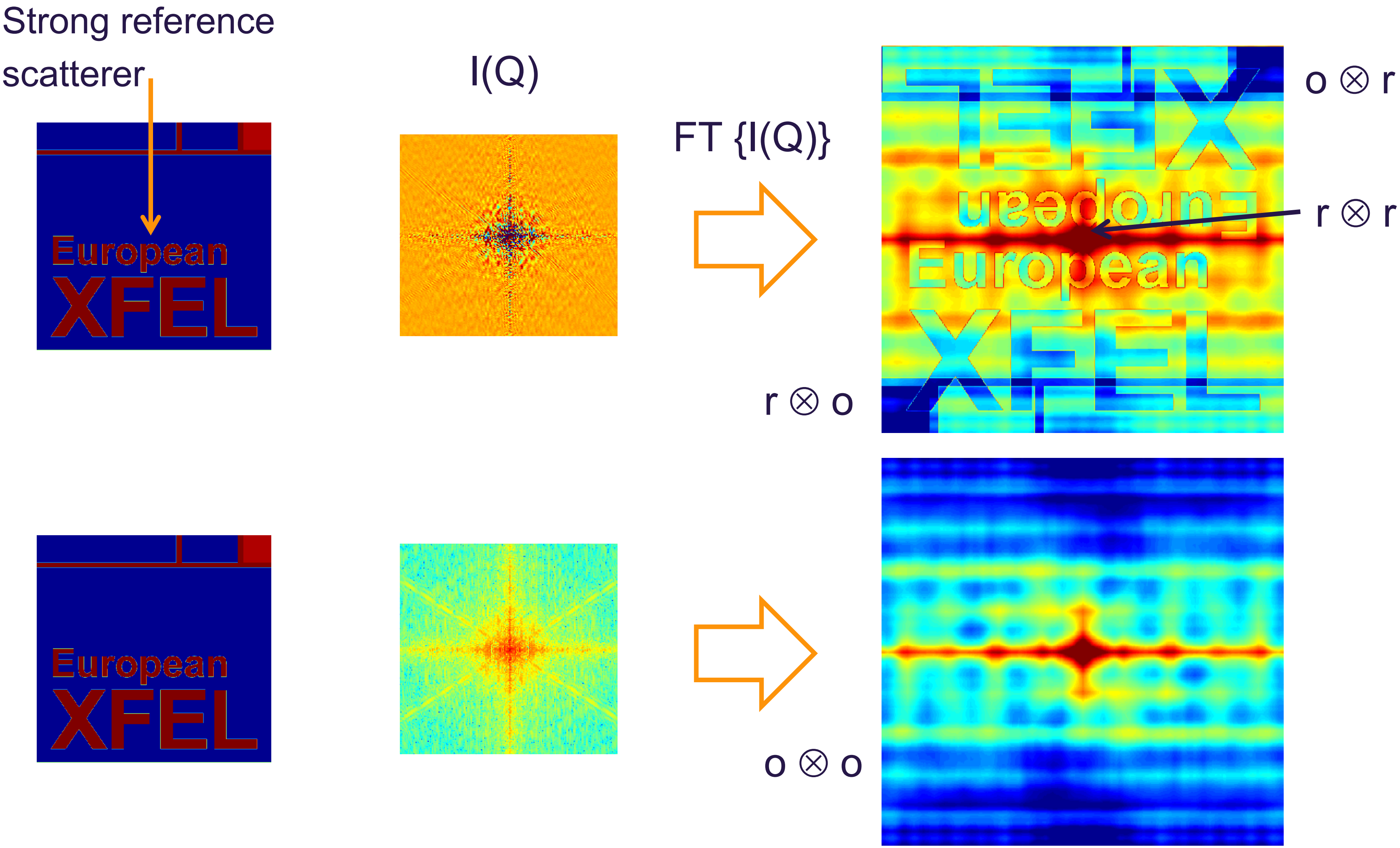


1st order from a FZP, sample in 0th order beam

McNulty et al,

Science **256**, 1009 (1992)

Fourier Transform Holography

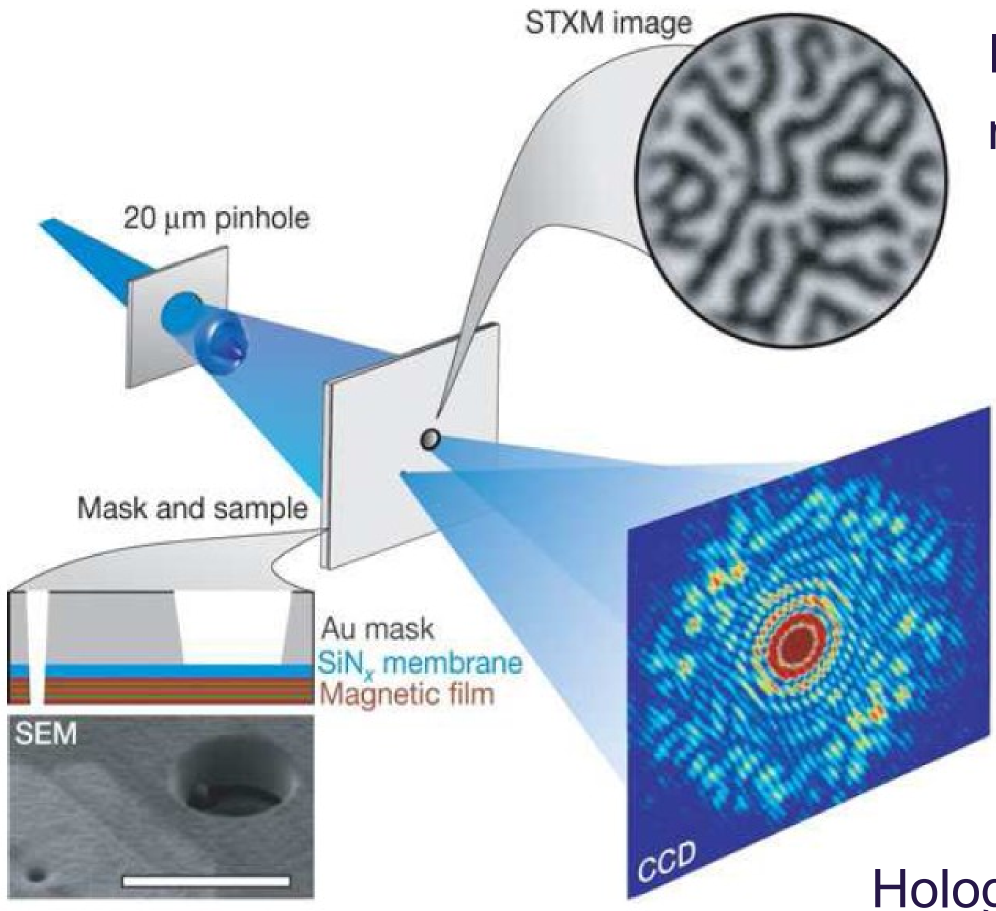


FT Holography with soft X-rays

S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt and J. Stöhr Nature 432, 885-888(2004)

Imaging of magnetic domains

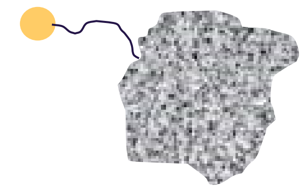
Soft X-rays



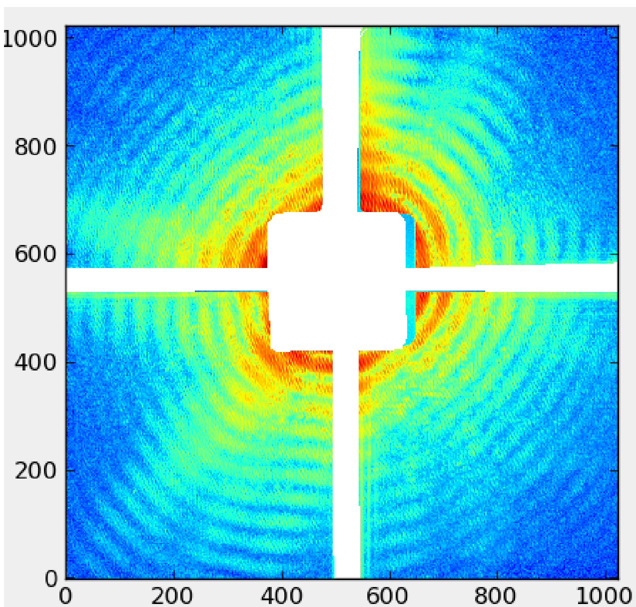
Holography at BESSY

Biological FT Holography

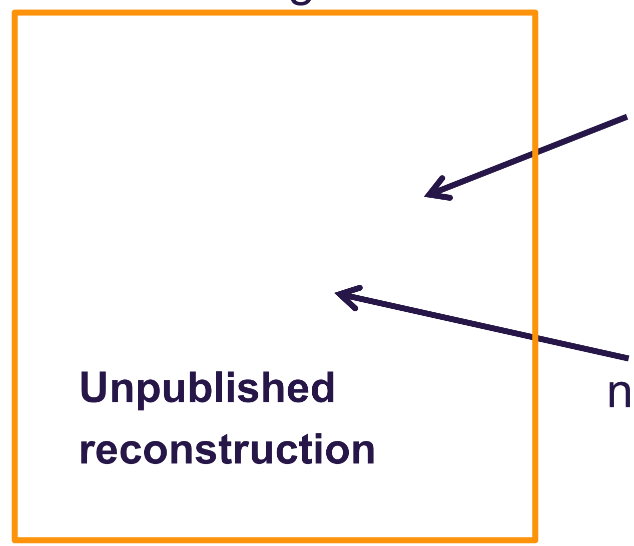
Holography of Pichia Pastoris (yeast) cell + 250 nm Au particle



1st results from ID10, ESRF @ 8 keV



hologram



Stadler, Büldt, Madsen *et al. (unpublished)*

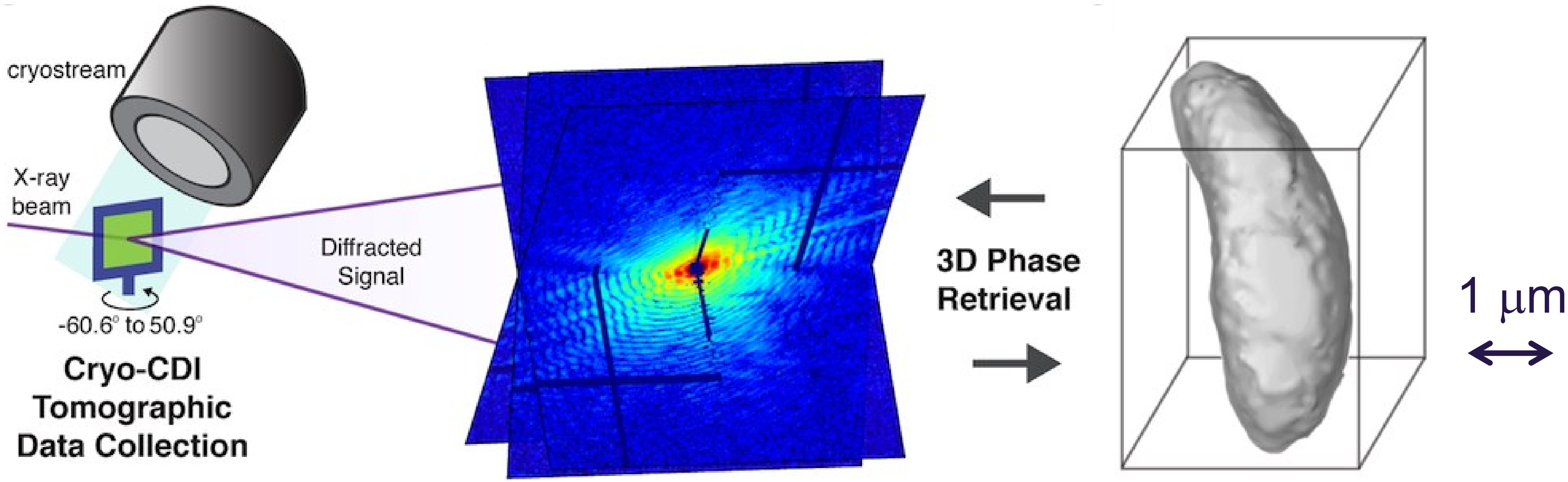
3D resolution is required

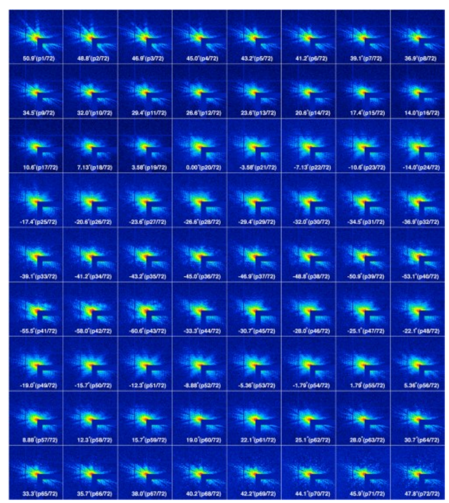
Shadow sculptures, Tim Noble and Sue Webster

http://www.thisismarvelous.com/amazing-shadow-sculptures-by-tim-noble-and-sue-webster/

Tomography: 3D Bio-CDI

ESRF



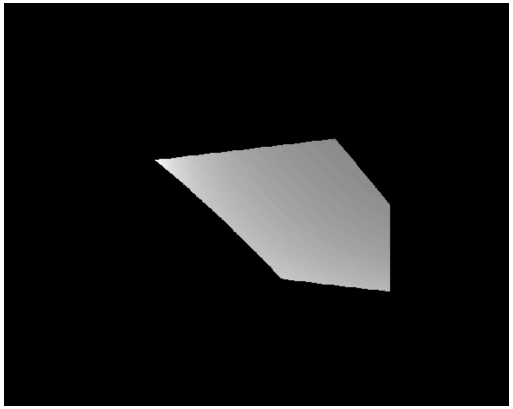


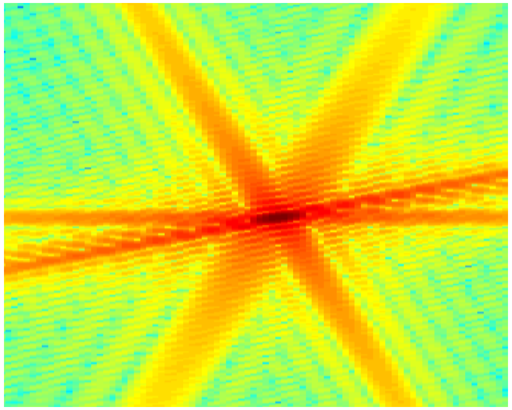
More than 100 different 2D projections necessary for 3D phase retrieval

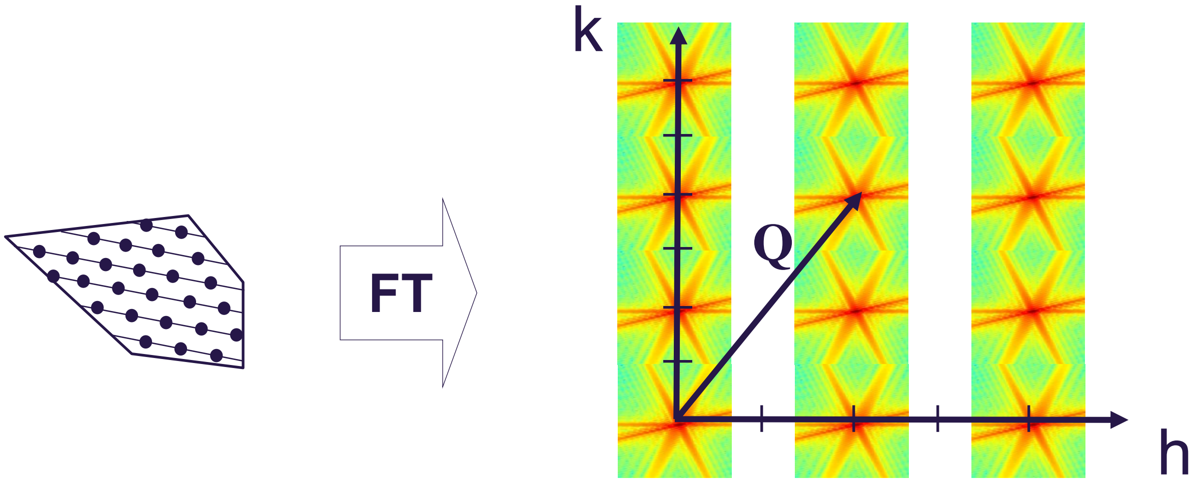
Rodriguez *et al*. (2015)
IUCrJ **2**, 575

Neospora caninum parasite

Tomography: 3D Bragg CDI

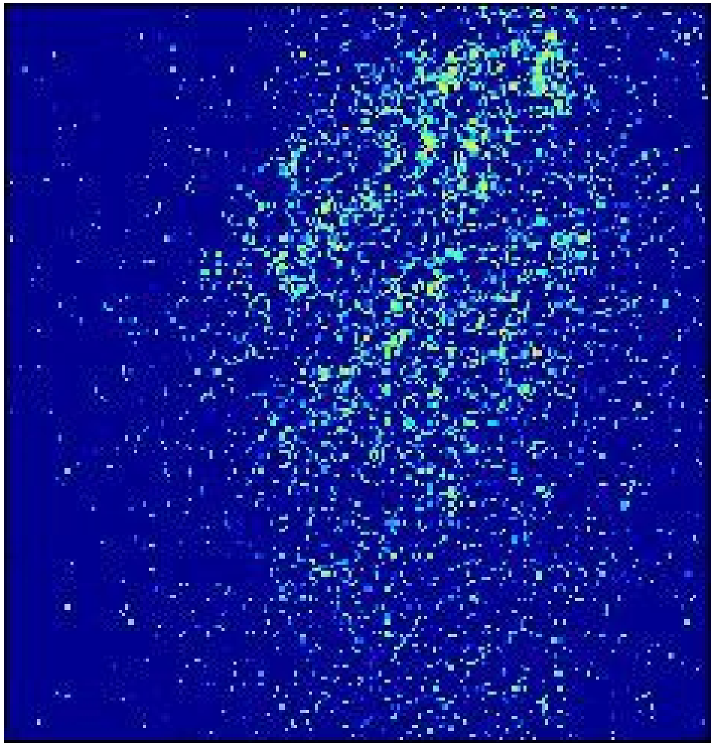


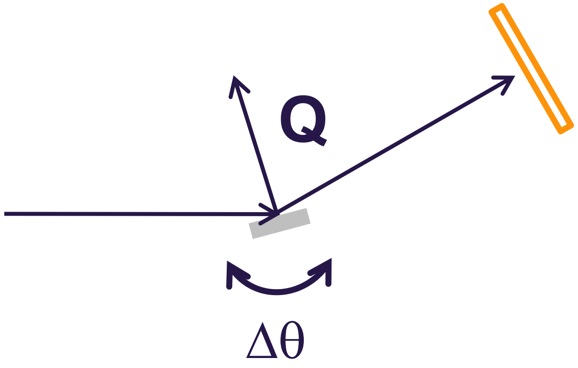




Tomography: 3D Bragg CDI

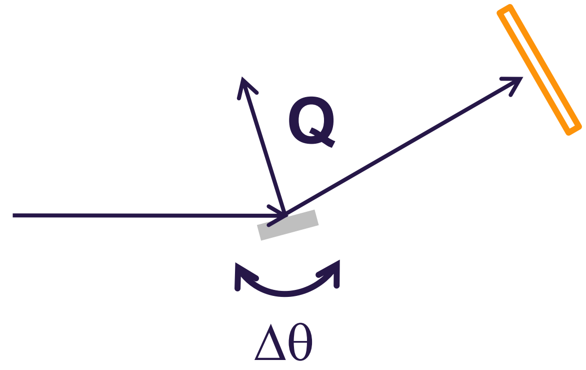
Rocking scan (Δθ) sweeps the detector-plane through reciprocal space



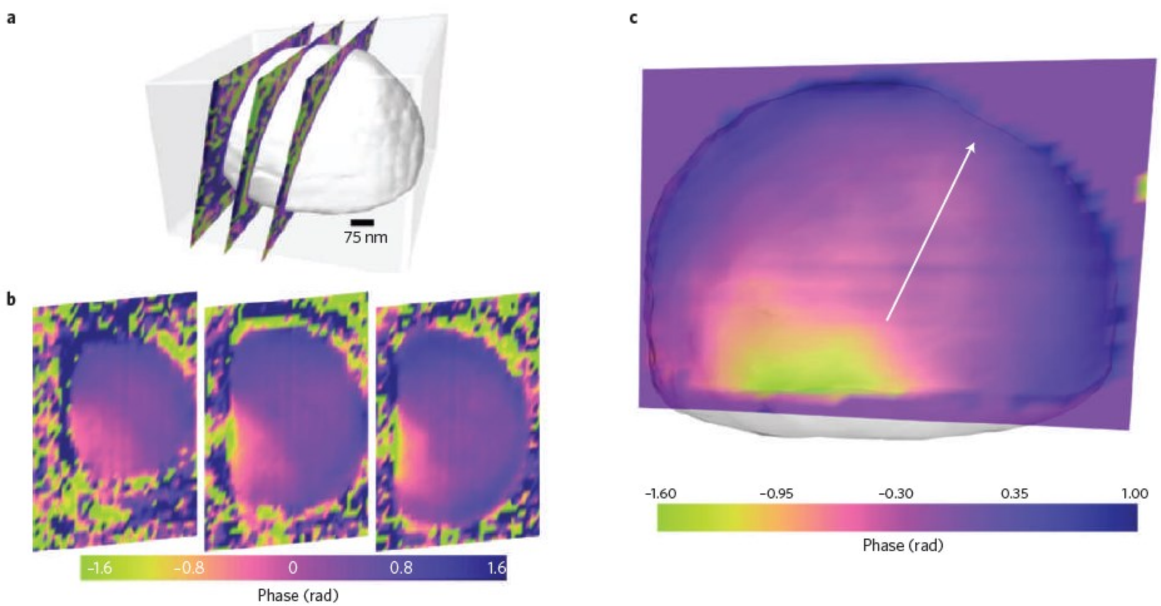


Tomography: 3D Bragg CDI

Rocking scan ($\Delta\theta$) sweeps the detector-plane through reciprocal space



Study of Pb nanocrystals



I. K. Robinson & R. Harder
Nature Materials **8**, 291 (2009)

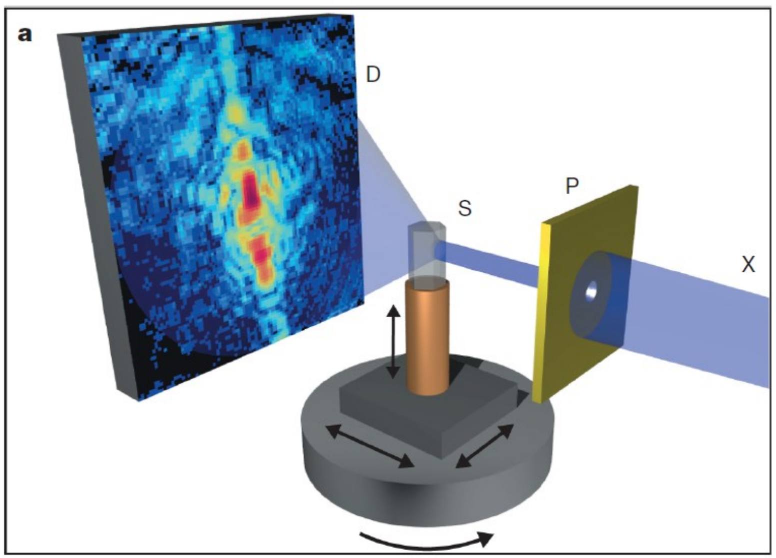
Work from APS, sector 34

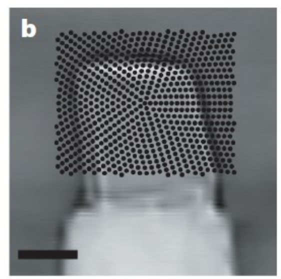
Tomography: 3D ptychography

Ptychographic X-ray computed tomography at the nanoscale

Martin Dierolf[1], Andreas Menzel[2], Pierre Thibault[1], Philipp Schneider[3], Cameron M. Kewish[2]†, Roger Wepf[4], Oliver Bunk[2] & Franz Pfeiffer[1]

Nature **467**, p. 436 (2010)





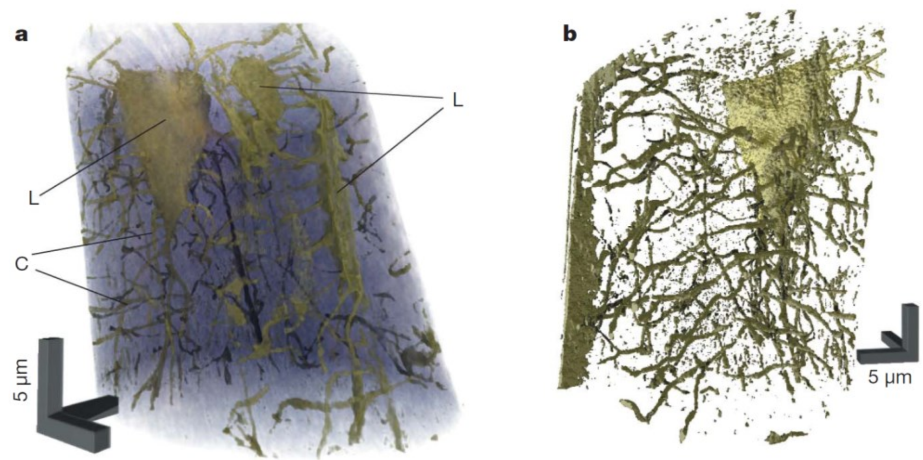


Figure 3 | 3D rendering of the tomographic reconstruction. a, Volume rendering with the bone matrix in translucent colours to show osteocyte lacunae (L) and the connecting canaliculi (C). **b**, Isosurface rendering of the lacuno-canalicular network obtained by segmenting the corresponding peak in the density on histogram shown in Fig. 4c. Morphological analysis of tomographic reconstructions is most often based on this type of segmentation, which is independent of the absolute scale of the density. Long edges of 3D scale bars, 5 μm.

Recap

- Why is phase important
- How does phase retrieval work in coherent diffraction imaging
- How does phase retrieval work in ptychography
- How does phase retrieval work in holography
- Examples of published work
- 3D resolution is needed!

Next: X-ray sources, new opportunities with Free-electron lasers

The European X-ray Free-Electron Laser in Hamburg

Coherent Intensity

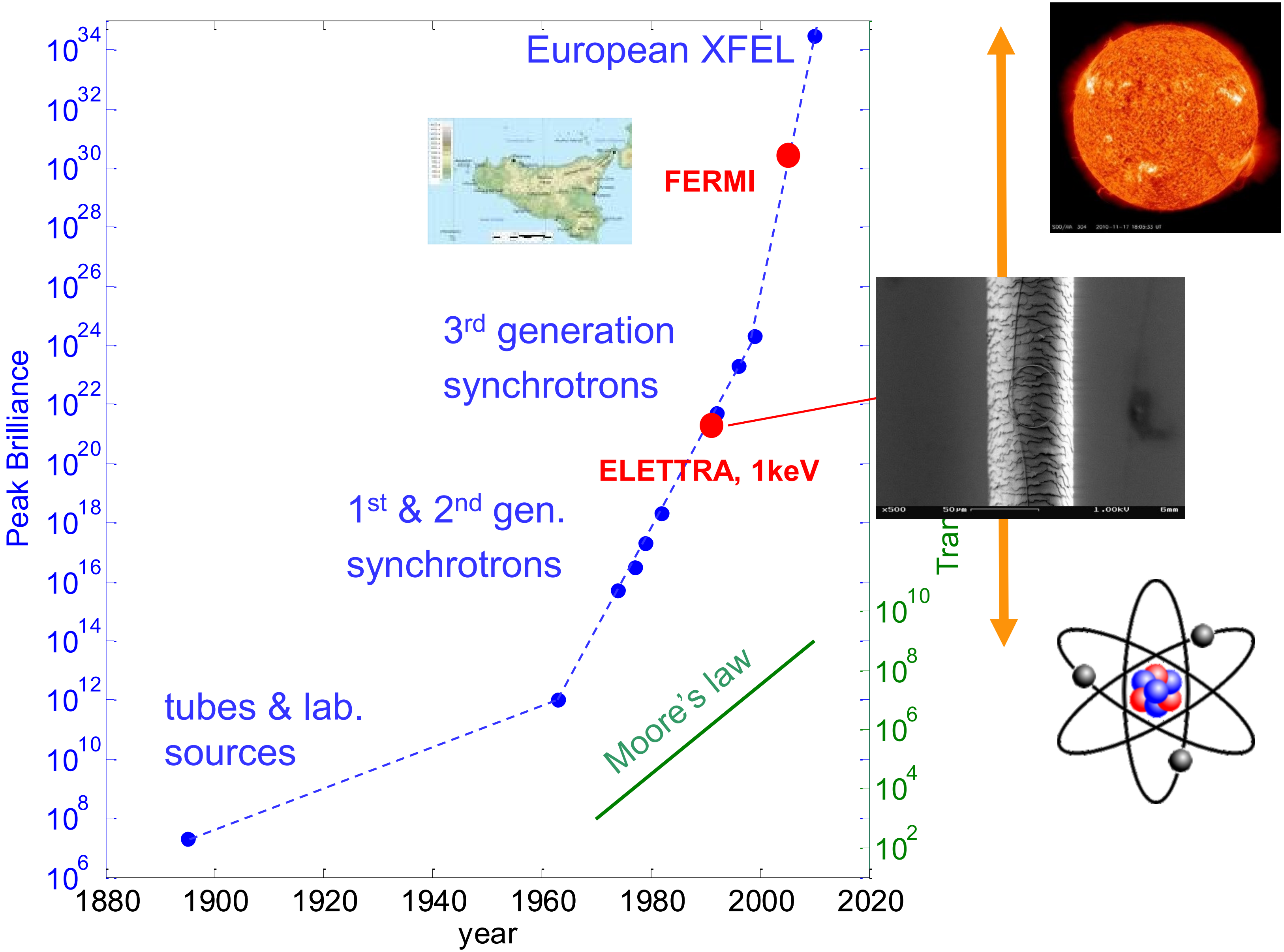
$$I_C = \lambda^2 B/4 \quad ^{(*)}$$

B: Brilliance (spectral brightness) of source

$$B: \frac{ph/s}{mm^2\, mrad^2\, 0.1\% BW}$$

(∗) only strictly valid for chaotic sources

Development of X-ray sources



Free-Electron Lasers Around the World

Soft X-Rays:

FLASH (Hamburg, Germany) [first x-ray laser]
FERMI (Trieste, Italy) [first seeded x-ray laser]
…

Hard X-Rays:

LCLS (Stanford, USA) [first hard x-ray laser]
SACLA (Sayo, Japan)

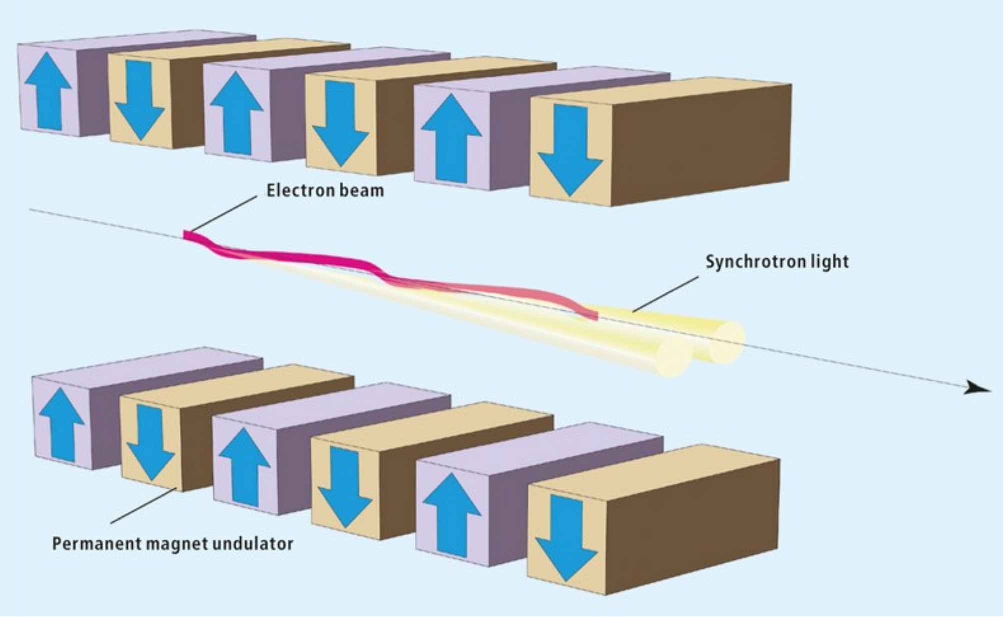
PAL-XFEL (Pohang, Korea), first beam ~2016
SwissFEL (Villingen, Switzerland), first beam ~2016
European XFEL (Hamburg, Germany), first beam ~2017
…

Undulator radiation

Undulator: Magnetic device installed in the straight sections of the synchrotron

N ~100 magnetic poles

$\mathbf{F} = e(\mathbf{v} \times \mathbf{B})$



1st, 2nd and 3rd generation

$I \propto N_e$ (Bending magnet)

$I \propto N_e \cdot N$ (Wiggler)

$\mathbf{I \propto N_e \cdot N^2}$ **(Undulator)**

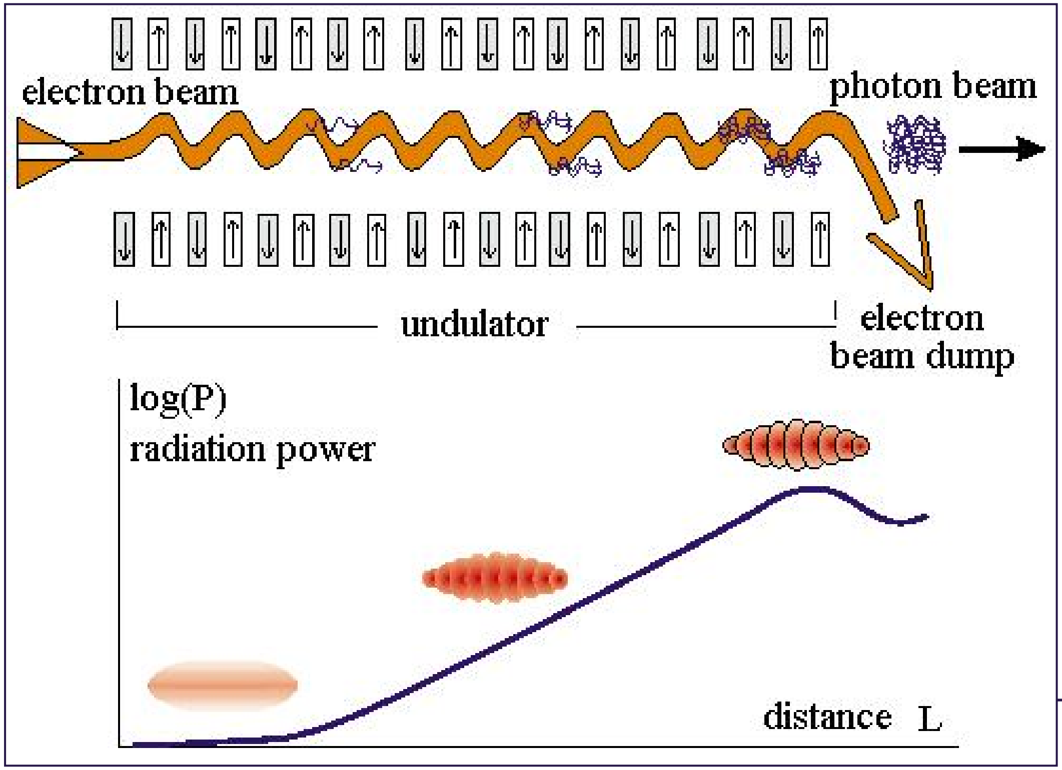
X-Ray Free-Electron Lasers

SASE: Self-Amplified Spontaneous Emission

SR undulator: **2 - 5 m**

SASE undulator at European XFEL: **175 m**

Operates with a linac feeding short (<100 fs) electron bunches into a long undulator



Interaction between intense EM-field and electrons leads to e-beam instability and micro-bunching of the electrons.

Micro-bunching gives lasing & saturation:

Coherent sum of emitted fields from all electrons

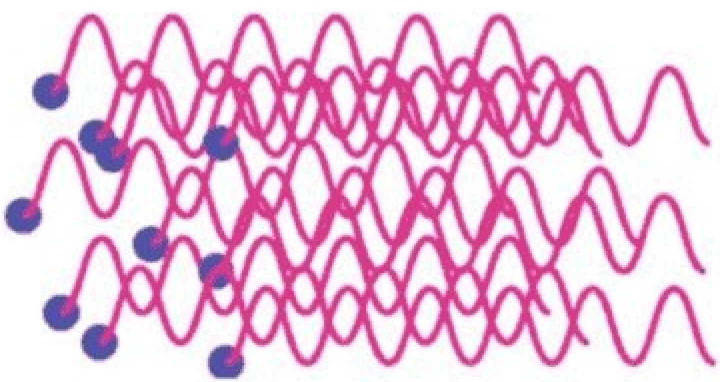
$I \propto N_e^2$ for SASE

Self-Amplified Spontaneous Emission (SASE)

The “trick” of Free-Electron Lasers:

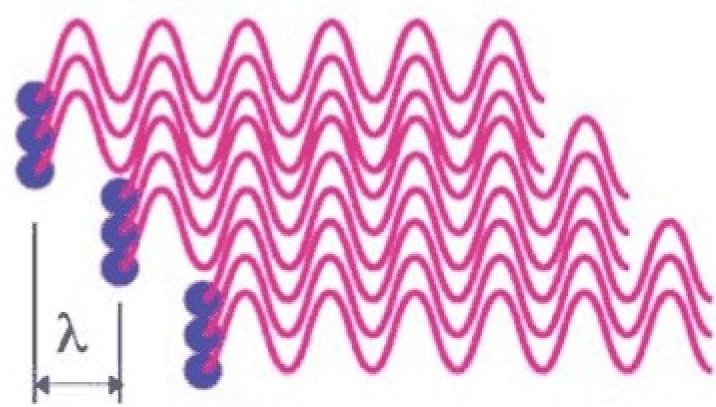
Spontaneous emission (SR)

Uncorrelated X-ray emission



Spontaneous emission (SASE)

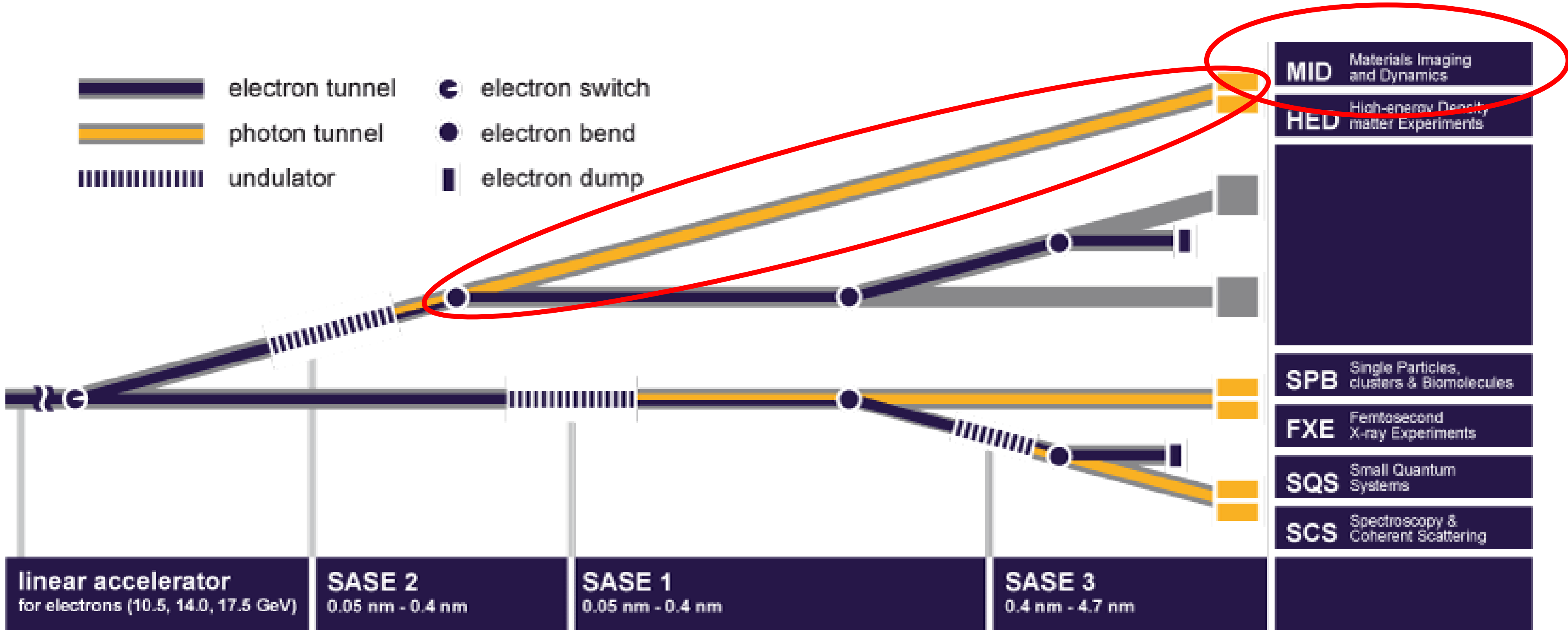
Correlated X-ray emission



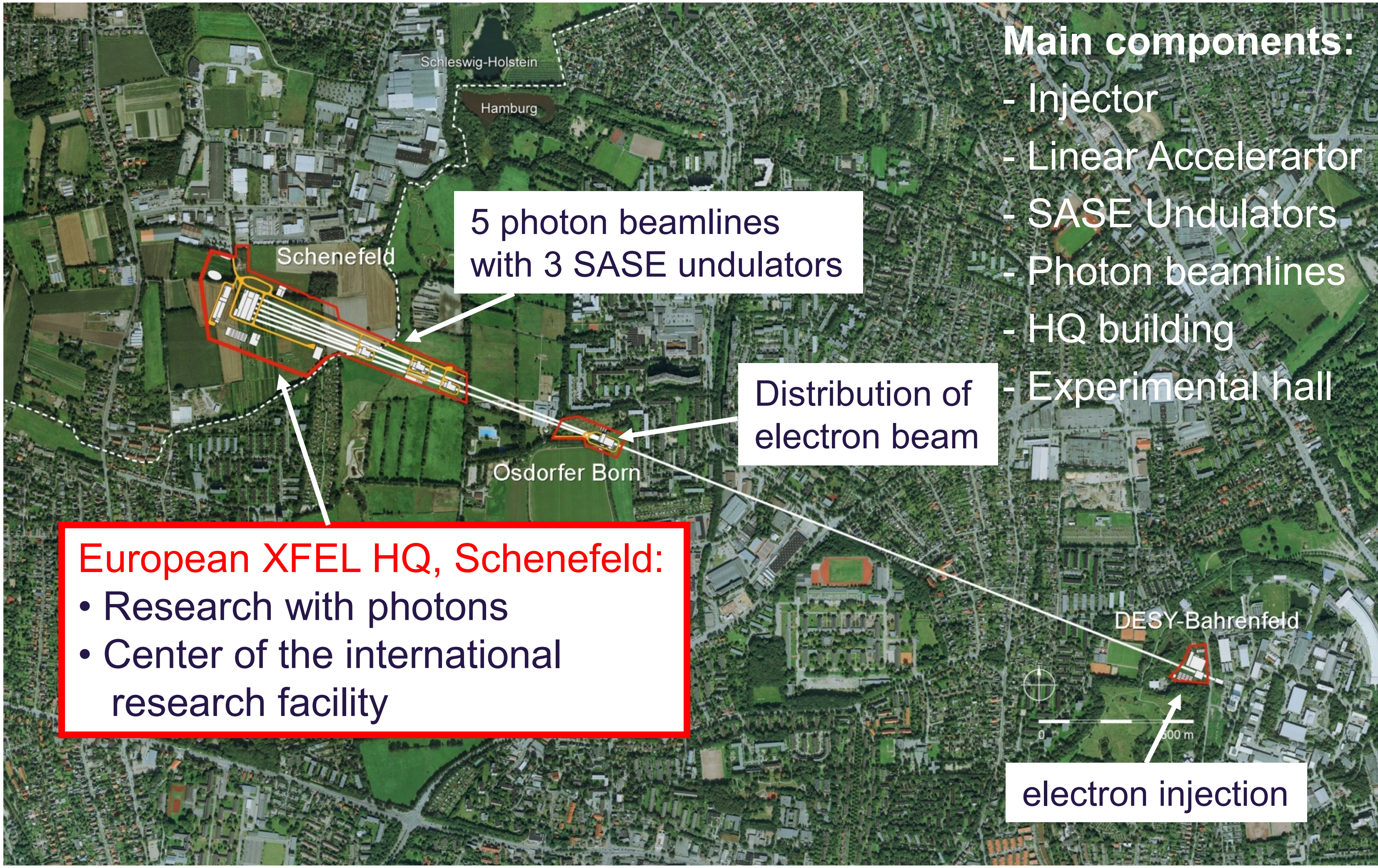
SASE: Self-Amplified Spontaneous Emission.

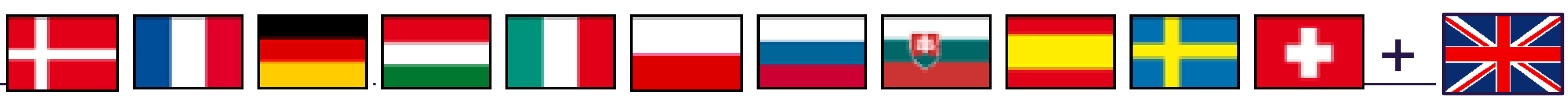
First demonstrated at DESY (FLASH) in the soft X-ray range

Materials Imaging and Dynamics Instrument @ SASE-2



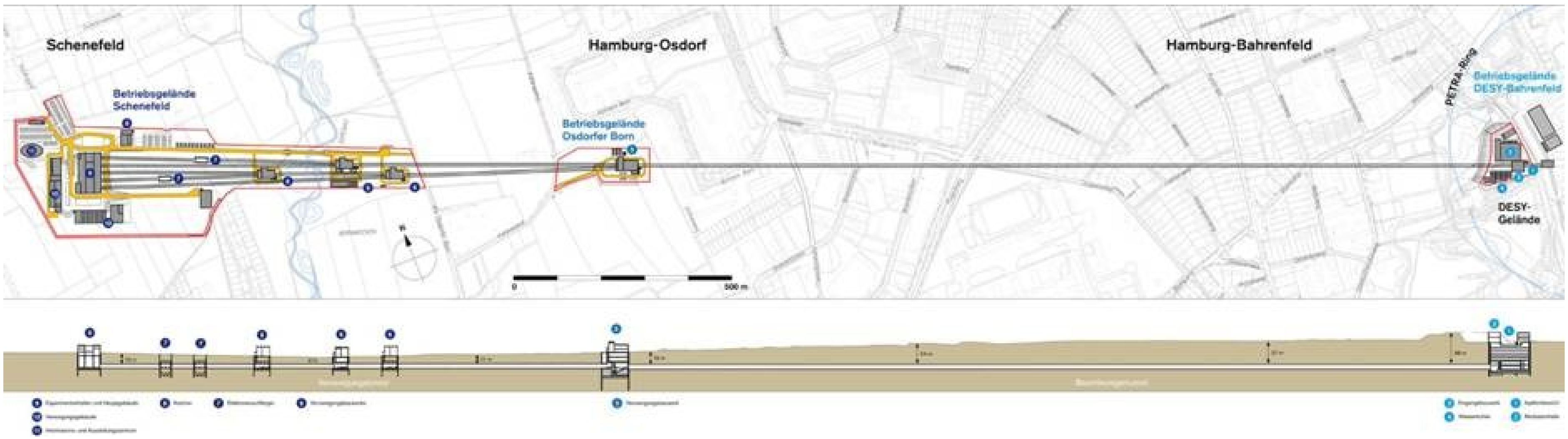
European XFEL. Overall layout





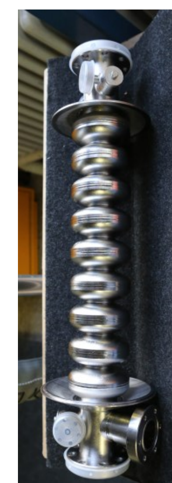
XFEL essentially an underground facility

Schenefeld Osdorfer Born Bahrenfeld

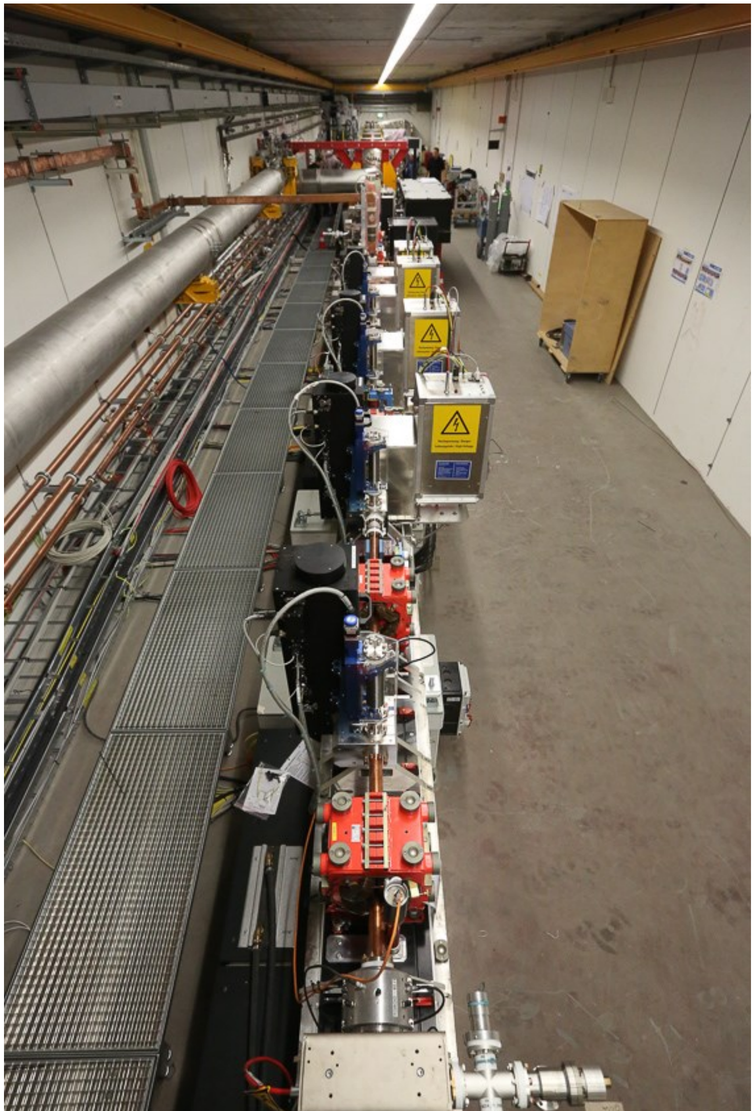


8 shafts and ca. 5.7 km tunnels, superconduction 2.1 km linac, 17.5 GeV
Total straight length of facility: 3.4 km
Underground experimental hall with 6 instruments, space for 6 more

XFEL Injector Installation and Commissioning



Injector Installation and First Electron Beam



3.9 GHz module installed in 9/2015

Welding connections finished 10/2015

Isolation vacuum created

TÜV inspection on November 16th

Injector cool-down started end of November

Christmas wish:

first accelerated beam before end of the year

YES, WE DID IT!

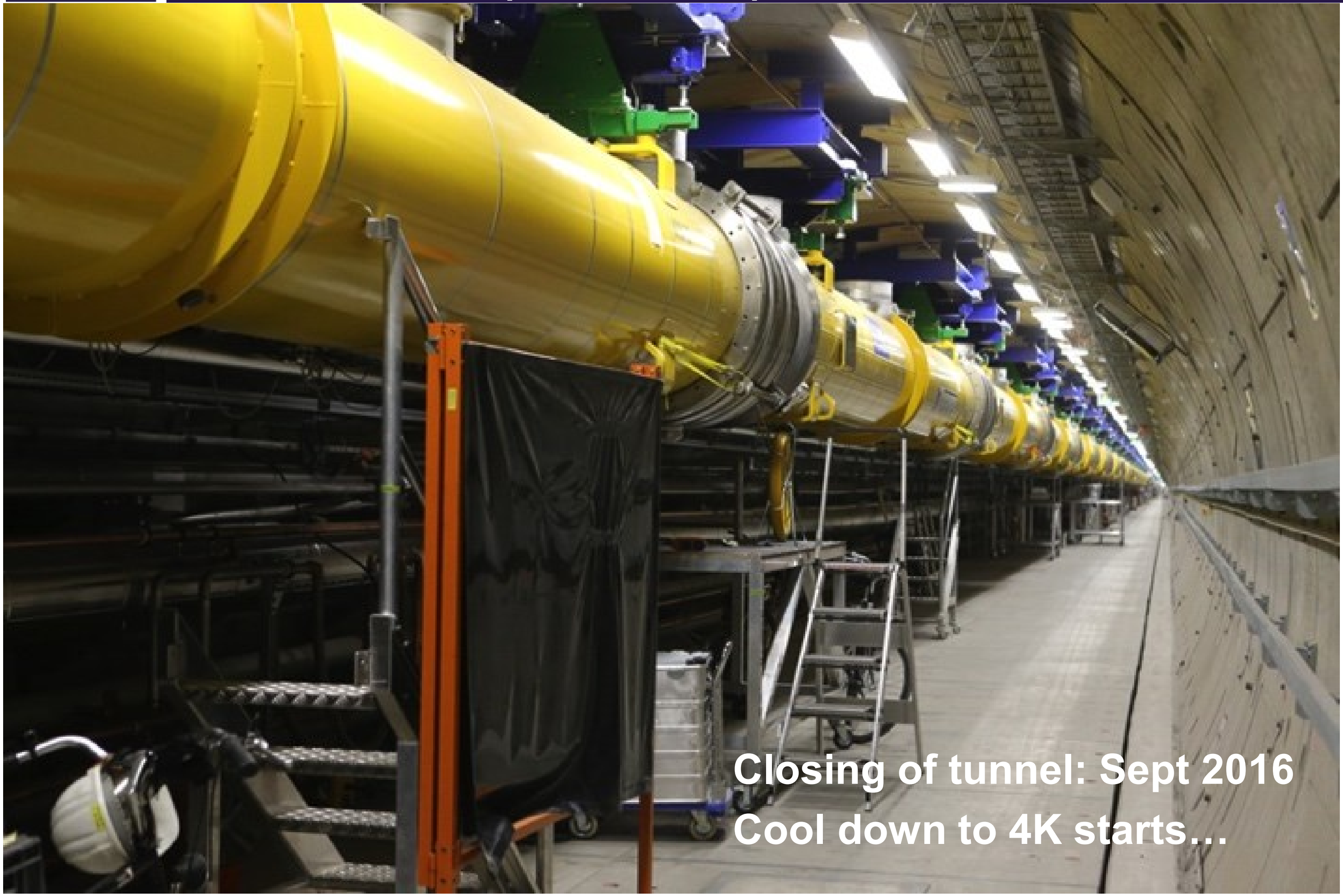
Dec 21, 2015: First electrons accelerated by injector (first 45 m of linac)

More info: www.xfel.eu

Linear Accelerator Modules

Fraunhofer IPA

>65 modules (out of 100) installed in tunnel



SASE-1 Undulator (175 m magnetic length)

First 5 m segment installed in July 2015

Installation of all segments finished by end of:

SASE-1: **02.2016**
SASE-3: 04.2016
SASE-2: 10.2016

Experiment Hall and Laboratory/Office Building


XHE2-4
XHPSC
XHQ
XHVAC
XHGATE
XHWS


Status September 2015

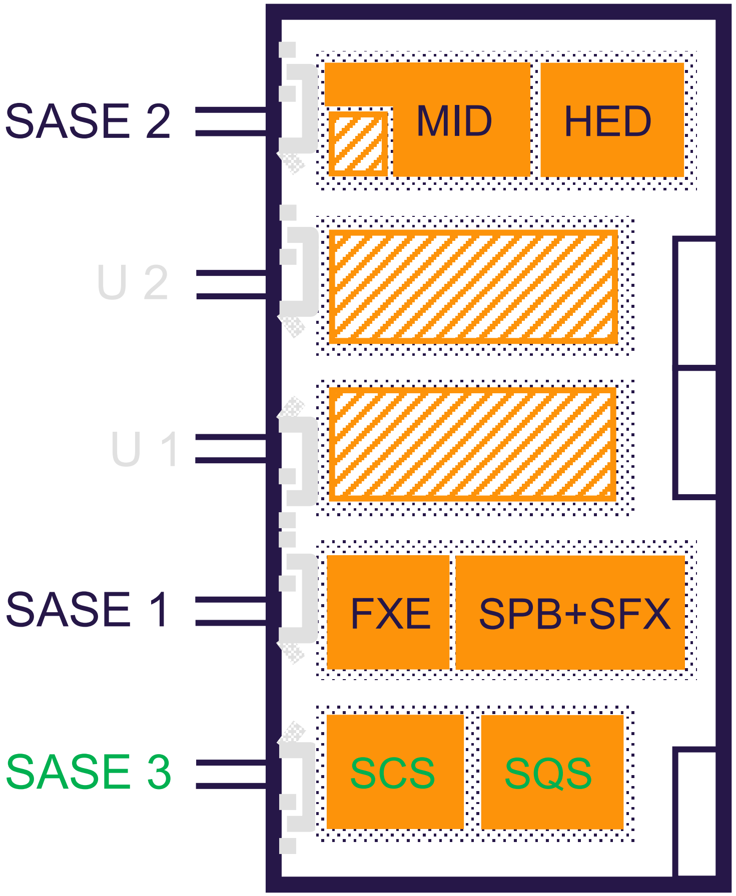

XHQ – moving-in date: 4. June 2016

Underground Experimental Hall

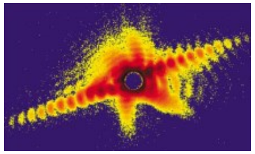
The First Experimental Stations

Experimental hall
~ 90 x 50 m

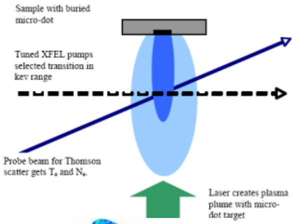
Link to webcams



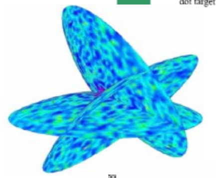
MID Materials Imaging & Dynamics



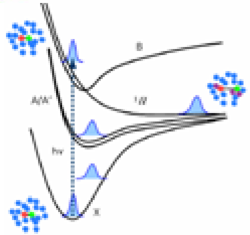
HED High Energy Density Science



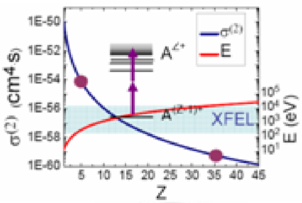
SPB Single Particles & Biomolecules



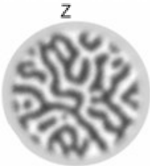
FXE Femtosecond X-ray Experiments



SQS Small Quantum Systems

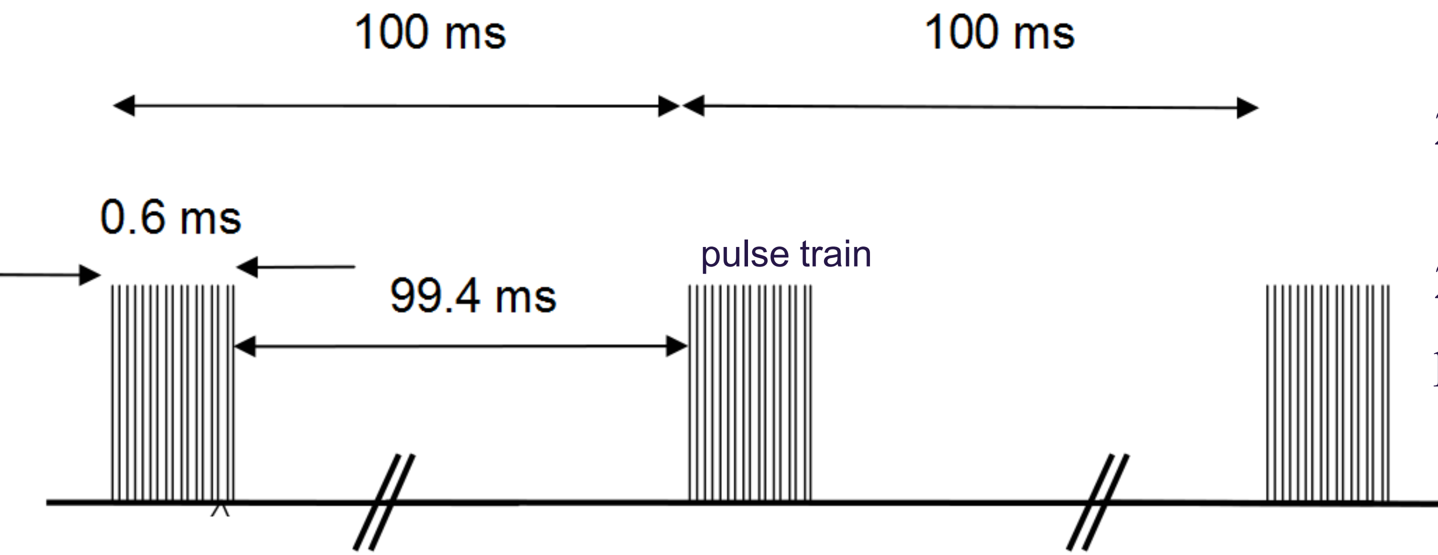


SCS Spectroscopy & Coherent Scattering



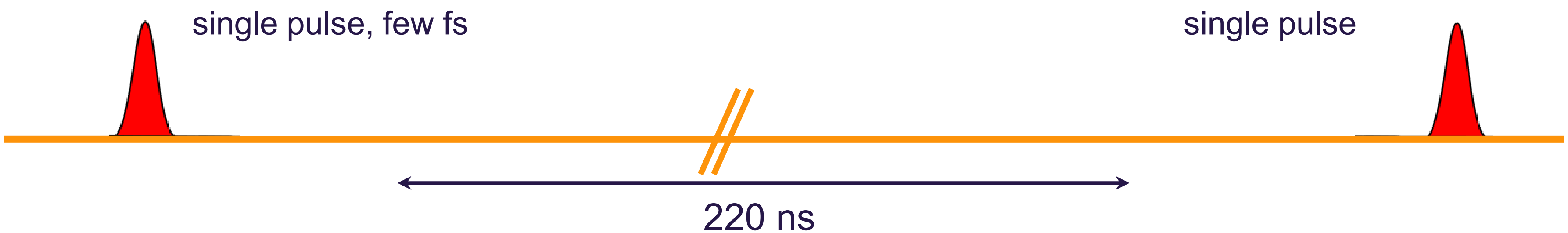
Source: www.xfel.eu

Time-structure of European XFEL



10 trains/sec
2700 pulses/train

220 ns between pulses
pulse duration: few fs
$10^{12} – 10^{13}$ ph/pulse



European XFEL repetition rate: 4.5 MHz, most other FEL sources ~100 Hz

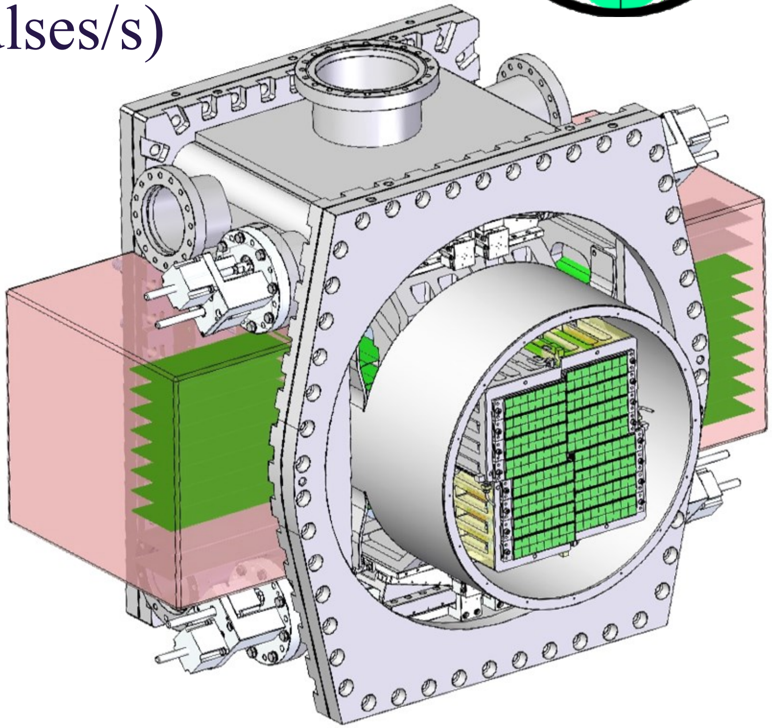
Mission statement

The unique properties:

- Ultrafast time resolution
- Ultrahigh peak Brilliance at 4.5 MHz rep rate
- Ultrahigh average Brilliance (27000 pulses/s)
- Coherence of the XFEL beam

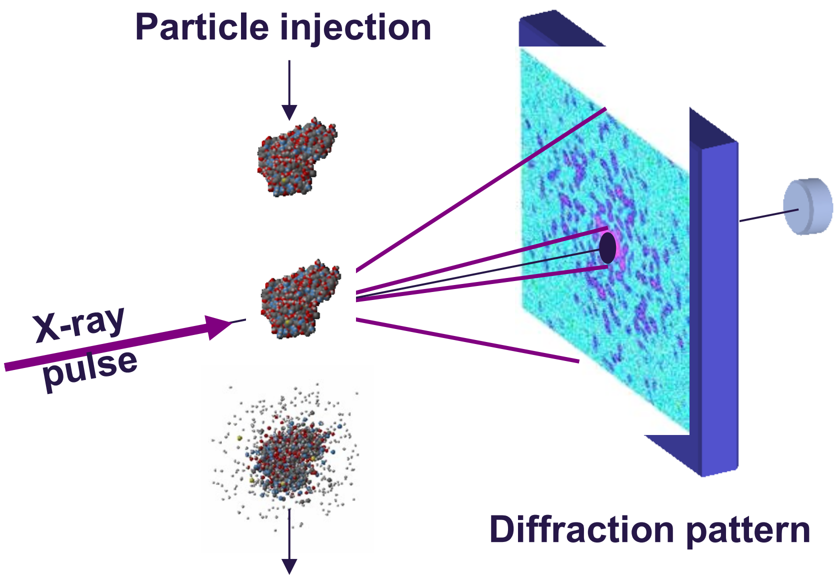
will enable completely new experiments to study structure and dynamics of materials

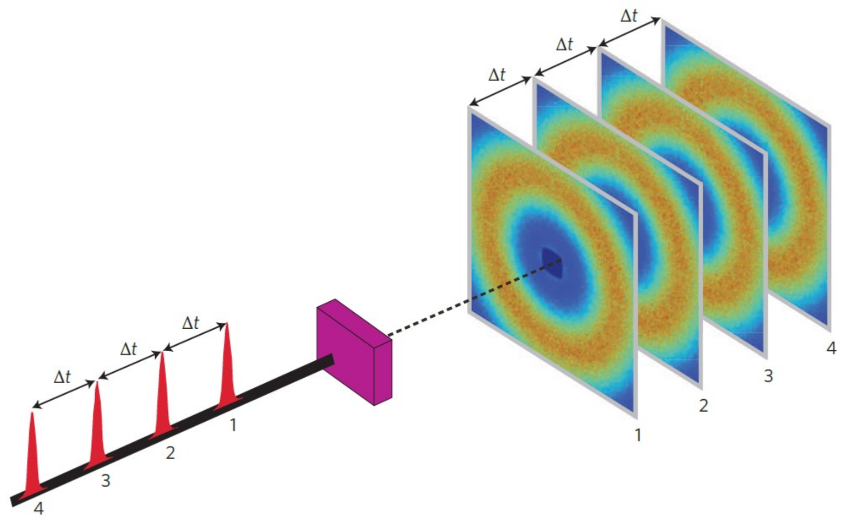
AGIPD



The XFEL Challenge

- Imaging of single molecules
- Ultra-fast dynamics of molecules and materials





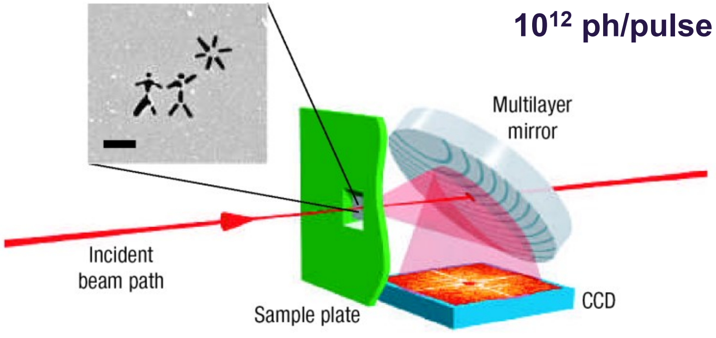
Gaffney and Chapman,
Science **316**, 1444 (2007)

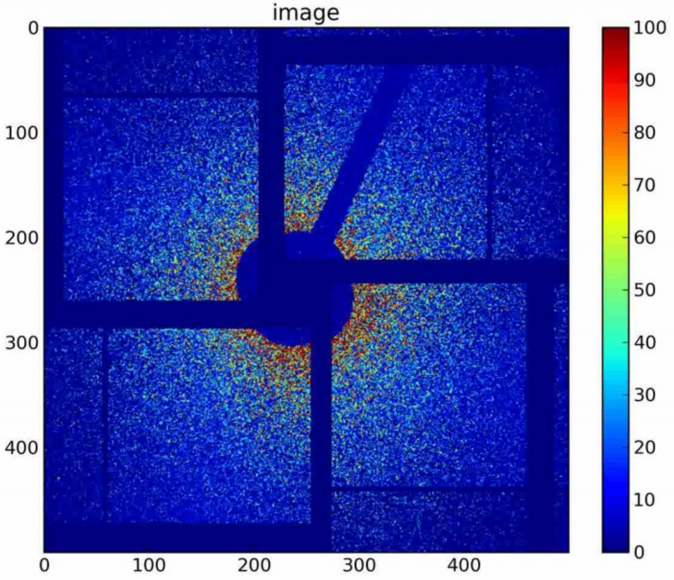
Stephenson *et al*,
Nature Materials **8**, 702 (2009)

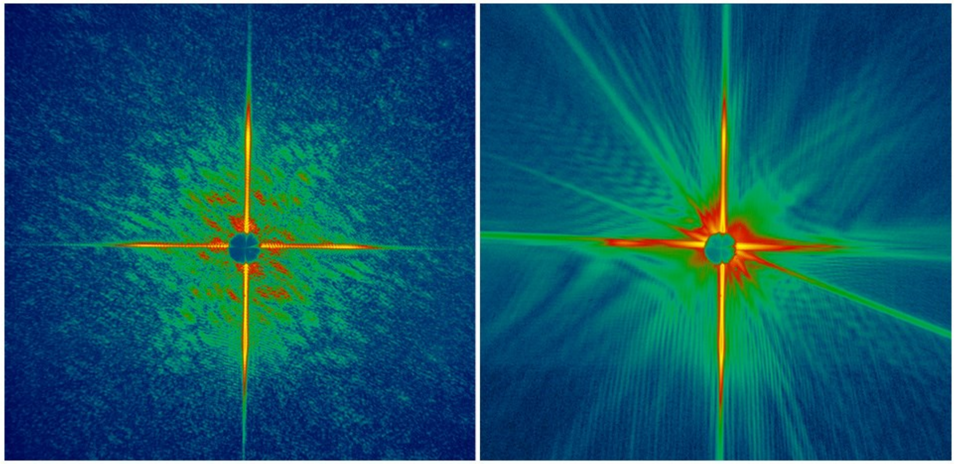
XFEL experiments can be destructive…

but not necessarily

FLASH (DESY)
Λ = 32 nm, 25 fs pulse duration, 10^{12} ph/pulse



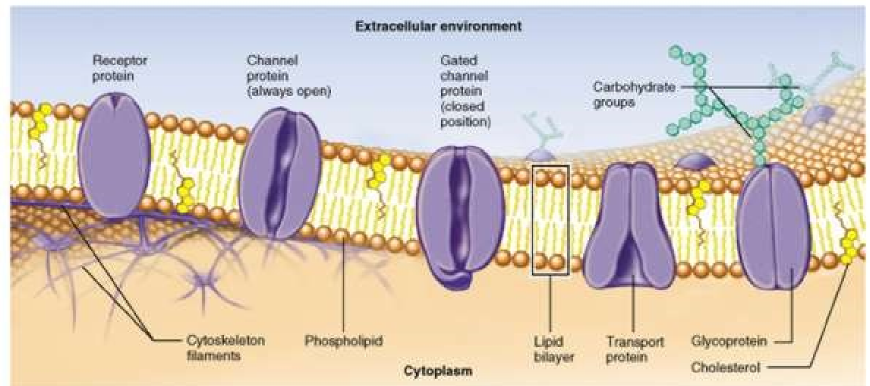




H. Chapman *et al*, Nature Physics **2**, 839 (2006)

Diffraction before destruction: Femto-second crystallography (destructive)

- Serial crystallography (sample injector)
- Femtosecond pulses (diffraction before destruction)
- Nanocrystals formed by most proteins



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Serial femtosecond crystallography: the first five years

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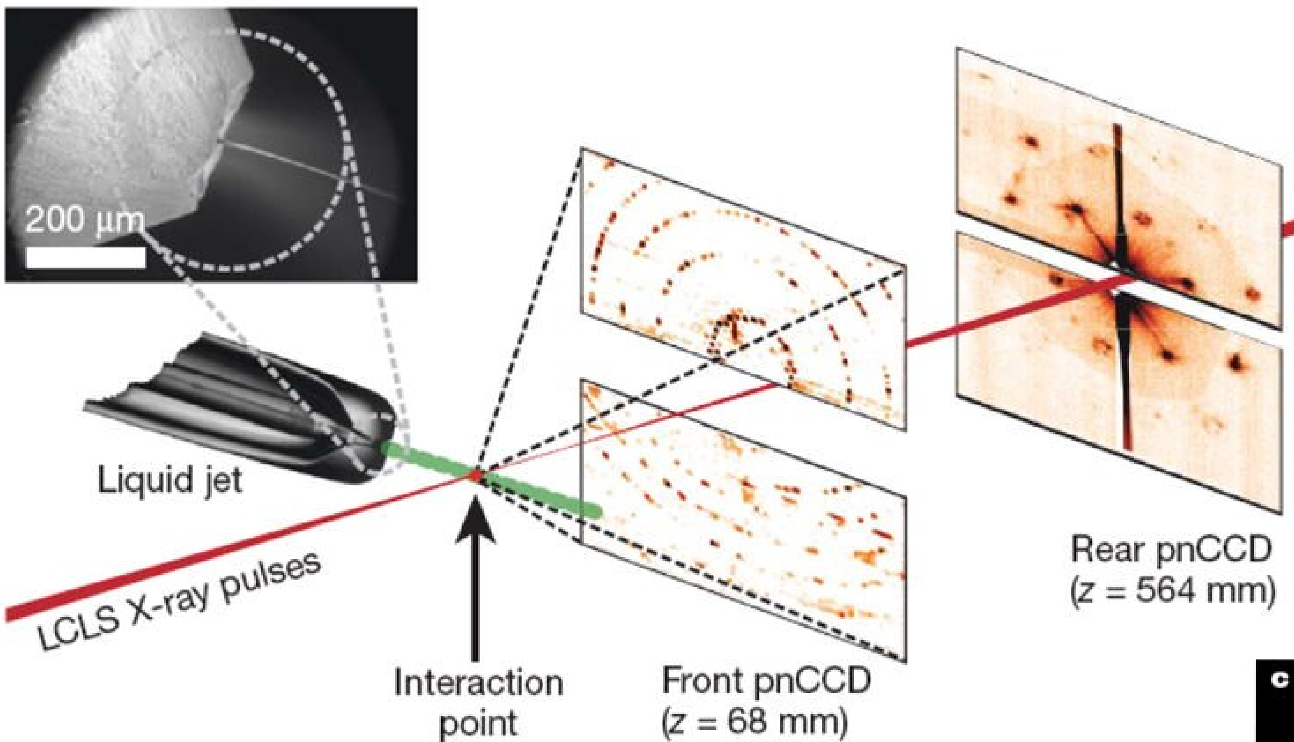
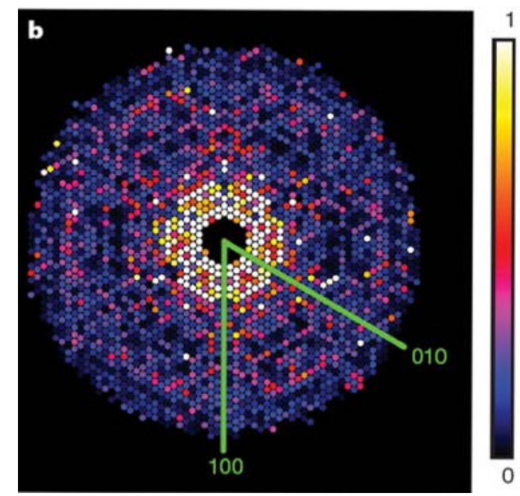
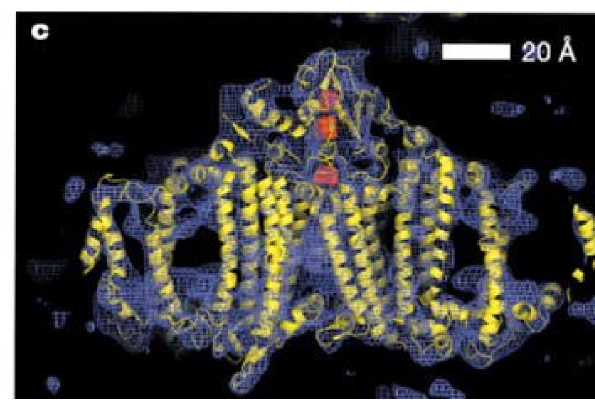
CrossMark

Edited by T. Ishikawa, Harima Institute, Japan (Received 6 August 2014; accepted 9 December 2014; online 3 February 2015)

Diffraction before destruction: Femto-second crystallography (destructive)







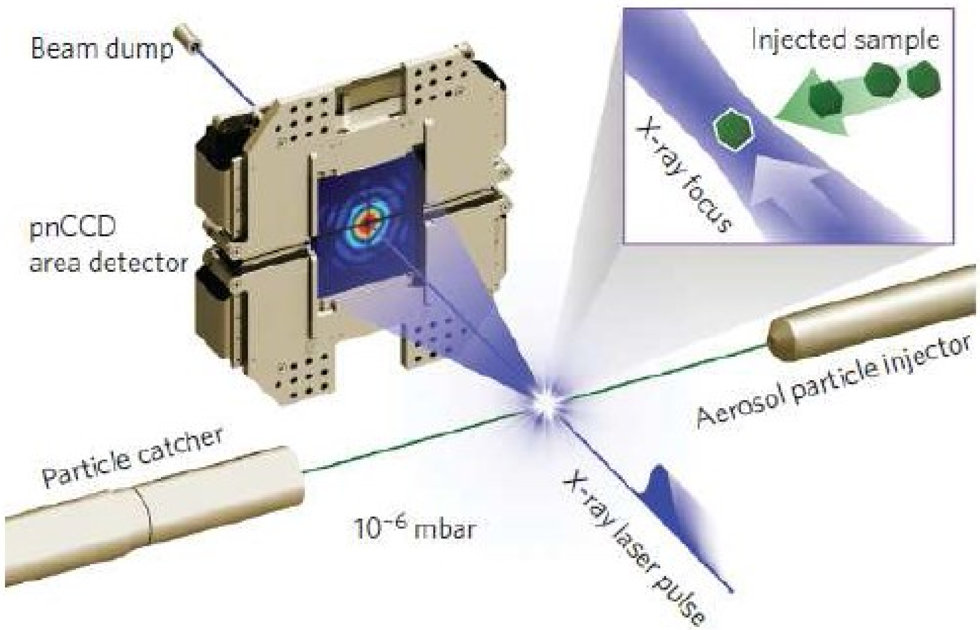
More than 3 million images collected

Structure of Photosystem I determined (already known)

Verification of diffraction before destruction in crystallography

Chapman *et al*, Nature **470**, 73 (2011)

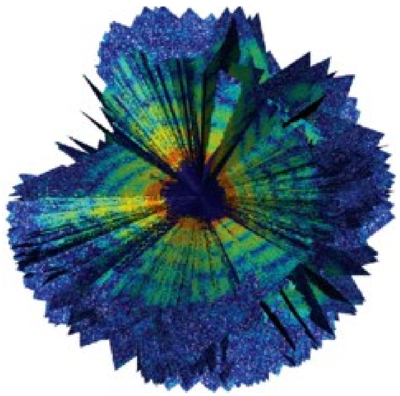
Diffraction before destruction: CDI using single shot exposures



X-ray Imaging of a virus in 3D

Ekeberg et al, PRL **114**, 098102 (2015)

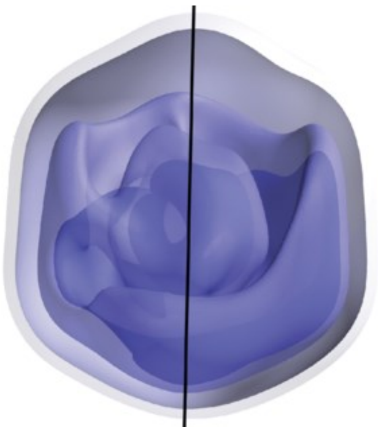
Particle injector at AMO, LCLS



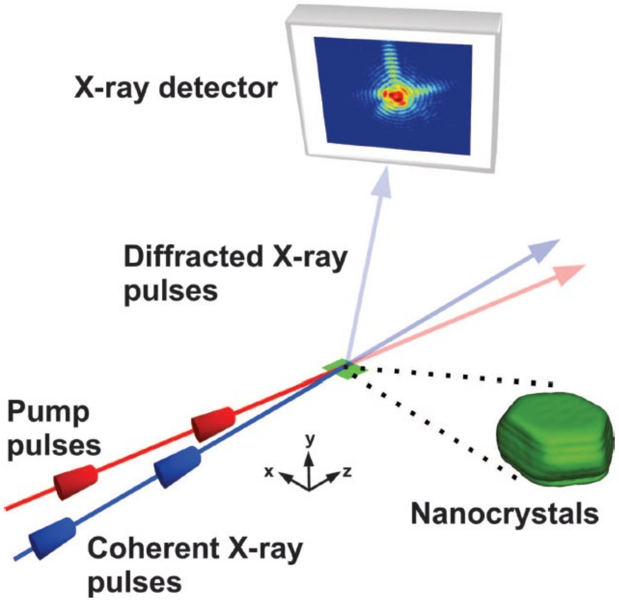
Phase retrieval

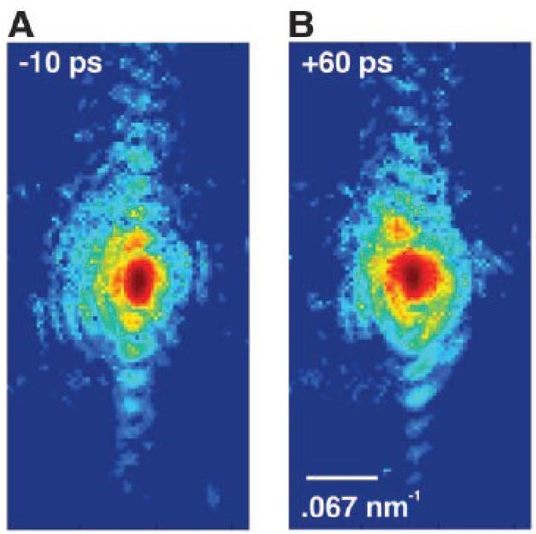
Tomographic reconstruction

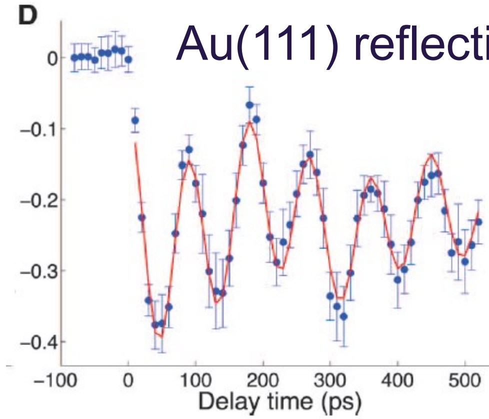
3D resolution

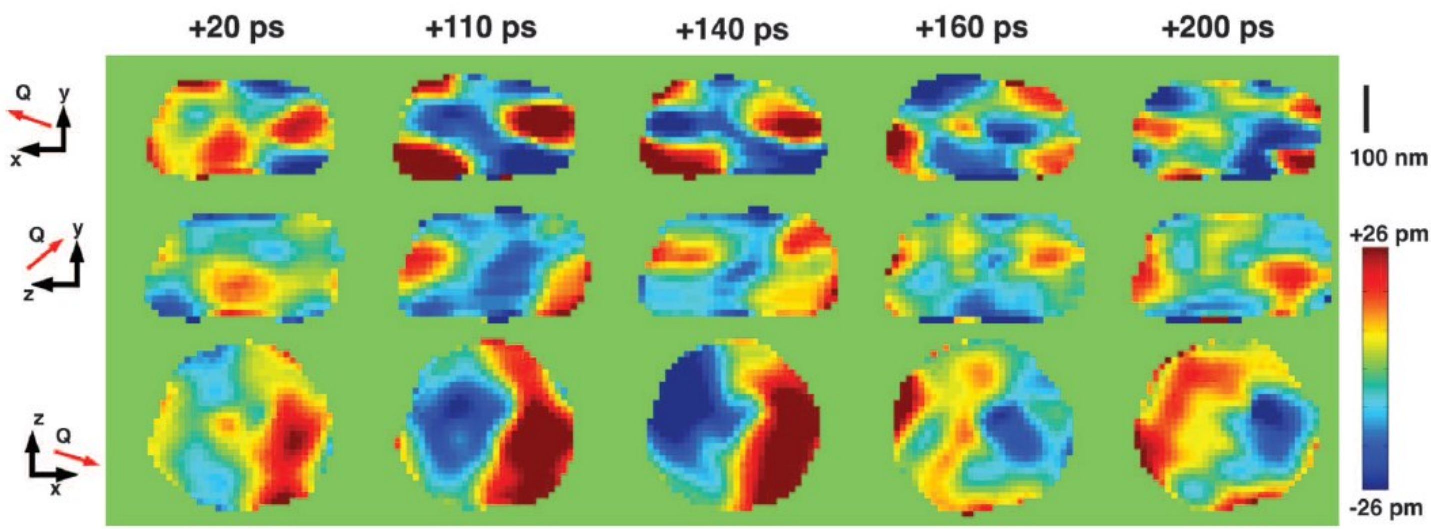


Non-destructive XFEL Imaging: Combining CDI and pump-probe









Measuring phonons in Au nanocrystals by PP CDI at LCLS

J. Clark,…& I. Robinson, Science **341**, 56 (2013)

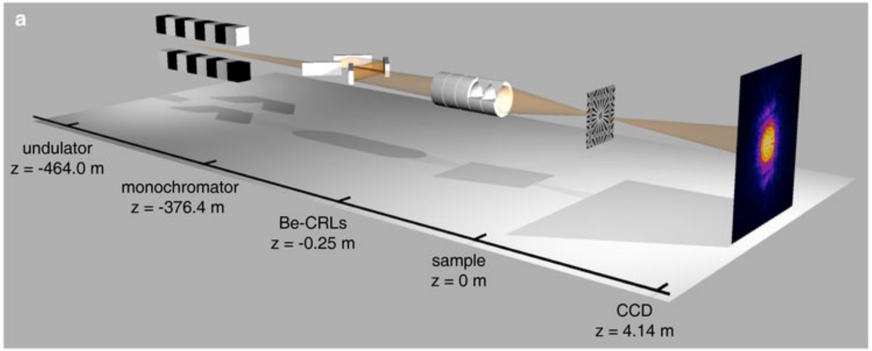
Non-destructive XFEL Imaging: Ptychography using a Free-electron Laser

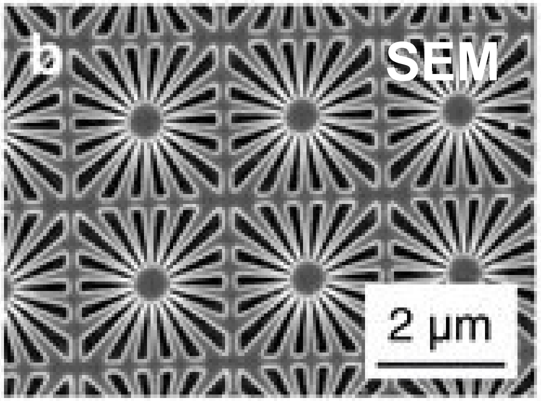
LCLS

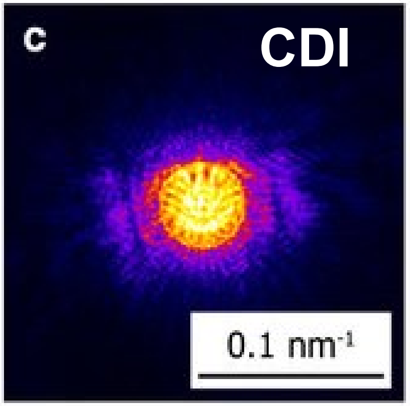
Full spatial characterization of a nanofocused x-ray free-electron laser beam by ptychographic imaging

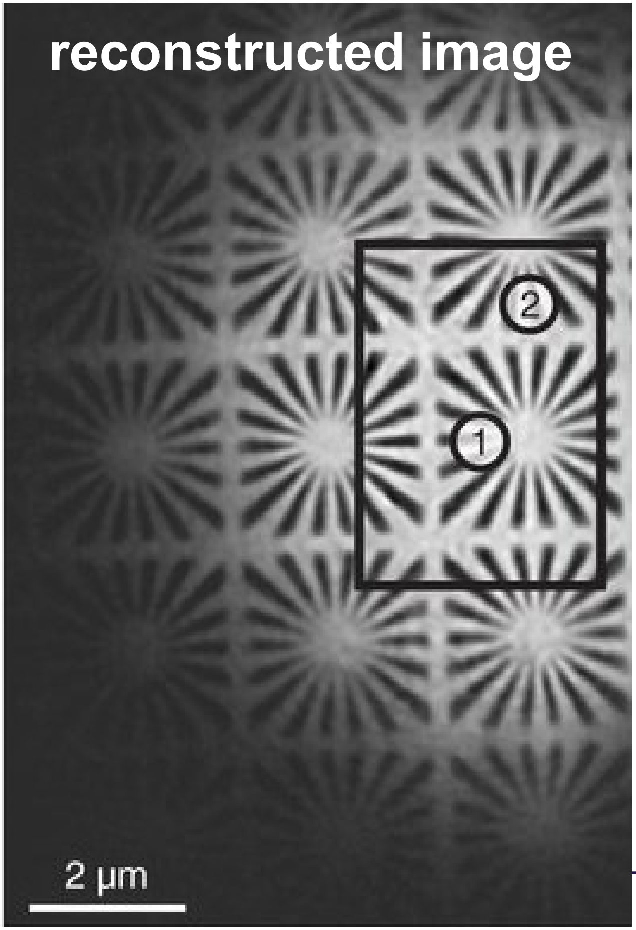
Andreas Schropp[1,2], Robert Hoppe[1], Vivienne Meier[1], Jens Patommel[1], Frank Seiboth[1], Hae Ja Lee[2], Bob Nagler[2], Eric C. Galtier[2], Brice Arnold[2], Ulf Zastrau[2], Jerome B. Hastings[2], Daniel Nilsson[3], Fredrik Uhlén[3], Ulrich Vogt[3], Hans M. Hertz[3] & Christian G. Schroer[1]

Sci. Rep. **3**, 1633 (2013)

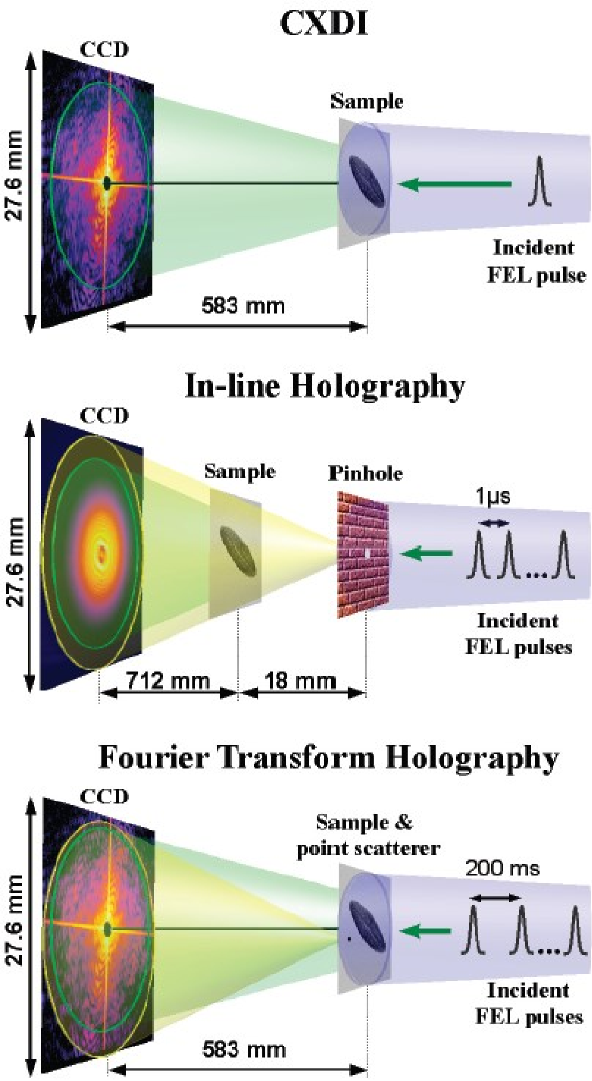


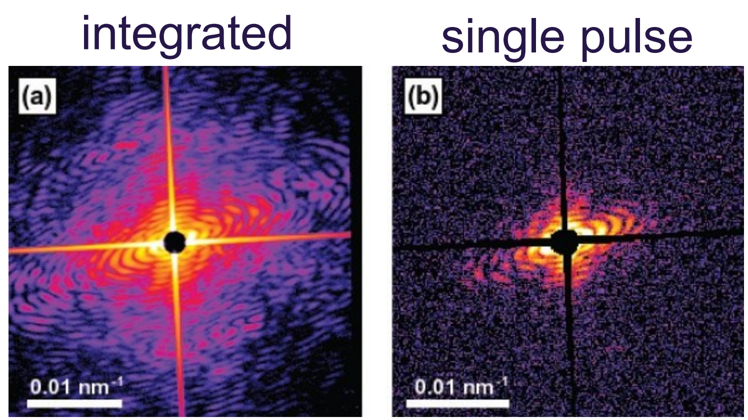






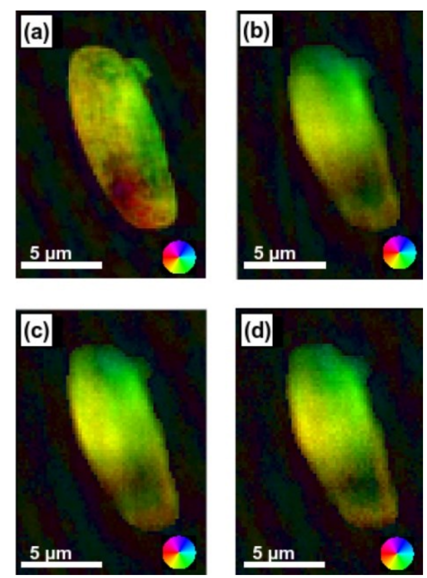
Non-destructive XFEL Imaging: comparison of Bio CXDI and Holography at FLASH





Unicellular algae
(*Navicula perminuta*)
10 fs pulses, λ=8 nm
~1e10 ph/pulse

Integrated vs. single-shot reconstructions



A. Madsen, European XFEL

Mancuso *et al.*, New J. Phys. **12**, 035003 (2010)

Summary

- Coherent Diffraction Imaging is a method developed at synchrotron sources to overcome limitations of optics
- The phase retrieval is difficult but necessary to reconstruct the image from the measured Intensities
- Related methods exist that sometimes can make the phase retrieval easier
- 3D resolution is of course desired in many cases
- Novel X-ray laser sources promise a bright future for coherent imaging techniques but new experimental strategies are needed
- Femtosecond nano-crystallography is, until now, the biggest success of XFELs overall
- The combination of CDI and ultrafast science (fs-ns) is promising but only few experiments so far…

?? QUESTIONS ??

Further reading without pay walls

www.xfel.eu

lcls.slac.stanford.edu/

PAPER • OPEN ACCESS

Materials science in the time domain using Bragg coherent diffraction imaging

Ian Robinson[1,2], Jesse Clark[3] and Ross Harder[4]

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Journal of Optics, Volume 18, Number 5

K. A. Nugent, Coherent methods in the X-ray sciences

https://arxiv.org/ftp/arxiv/papers/0908/0908.3064.pdf

The End