How to Exploit Synchrotron Radiation for MHz Frame Rate X-ray Imaging

Presented by:

OSA
Gamma, X-Ray and Extreme UV Optics Technical Group

Gamma, X-Ray and Extreme UV Optics Technical Group

Technical Group Leadership:

Daniele Pelliccia, Instruments & Data Tools Pty Ltd, Australia (Chair)

Committee members wanted!

Web

Gamma, X-Ray and Extreme UV Optics Technical Group

https://www.osa.org/FX

The Optical Society | Since 1916

Gamma, X-Ray and Extreme UV Optics (FX)

Get Involved

- Diversity & Inclusion in OSA
- Public Policy
- Chapters and Sections
- Technical Groups –
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation –
    - Fiber Modeling and Fabrication (FF)
    - Gamma, X-Ray and Extreme UV Optics (FX)
    - Holography and Diffractive Optics (FH)
    - Imaging Optical Design (FD)
    - Lasers in Manufacturing (FL)
    - NonImaging Optical Design (FN)
    - Optical Fabrication and Testing (FM)
    - Polarization (FP)

Gamma, X-Ray and Extreme UV Optics (FX)

This group explores design, characterization, fabrication, and calibration of X-ray, gamma, and EUV optics (including multilayer optics) for applications in the fields of photolithography, synchrotron radiation, free-electron lasers, astronomy, and others.

GROUP LEADERSHIP | UPCOMING MEETINGS | RECENTLY PUBLISHED

Name	Affiliation	Title
Daniele Pelliccia	Instruments & Data Tools Pty Ltd	Chair

Announcements

View OSA Technical Group webinars on-demand a any time or register for any of our upcoming webinars online. Each webinar is an hour long an features a technical presentation on a topic selected by your OSA Technical Groups.

Read the blog from the Compact EUV & X-Ray Ligh Sources Workshop, which took place in Masstricht Netherlands, in October 2015.

Join our Online Community

LinkedIn

Work in Optics

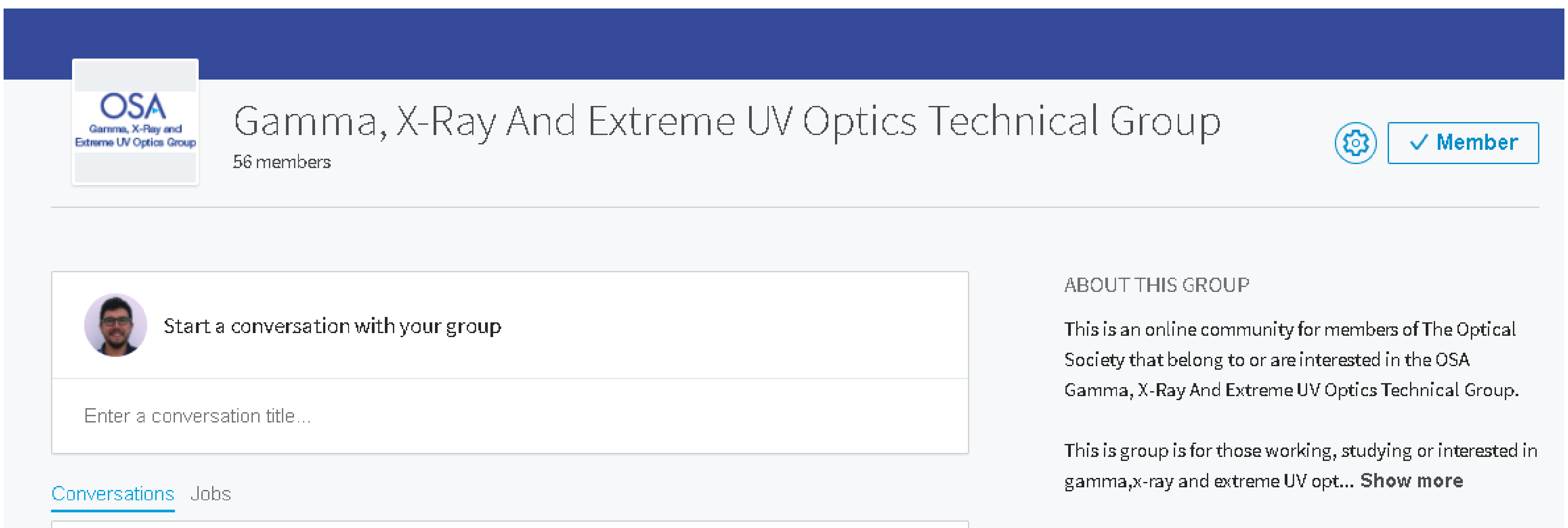
As a niche online job board, WORKinOPTICS.com

LinkedIn

OSA Gamma, X-Ray and Extreme UV Optics Technical Group

https://www.linkedin.com/groups/8235283

- Announce new activities, workshops, conferences, etc.
- Promote interactions



Activities

Gamma, X-Ray and Extreme UV Optics Technical Group

Webinars

If you are a PhD student (close to completion) or a junior postdoc in x-ray optics don't miss the opportunity to present a webinar in our series!

Newsletter

Disseminate information about conferences or workshops you are attending, or organising. Please send all information to pelliccia.dan@gmail.com

Events

Explore the possibility of organising sessions or social events at international meetings

Today

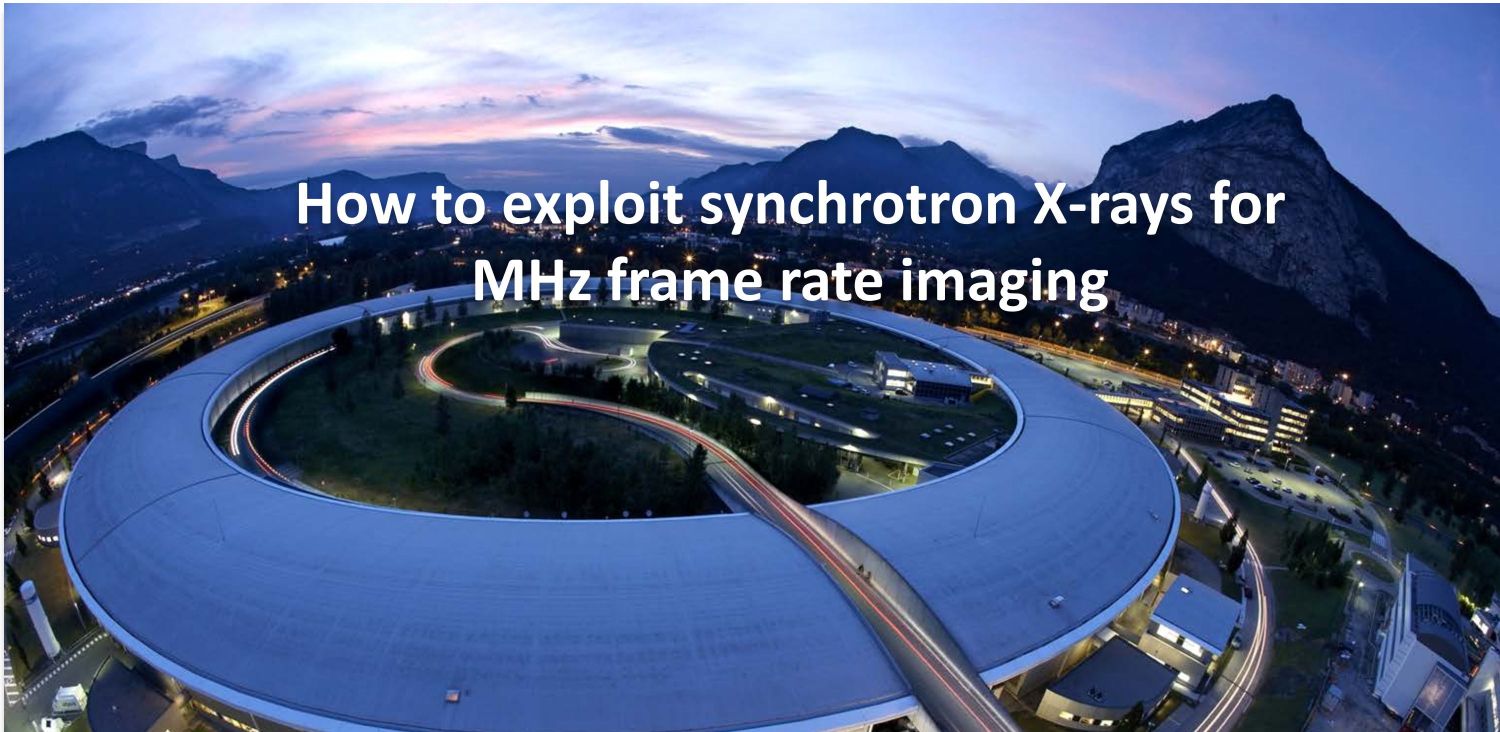
Gamma, X-Ray and Extreme UV Optics Technical Group

Margie Olbinado and Alexander Rack

The European Synchrotron ESRF, Grenoble (France)

ESRF | The European Synchrotron

How to exploit synchrotron X-rays for MHz frame rate imaging



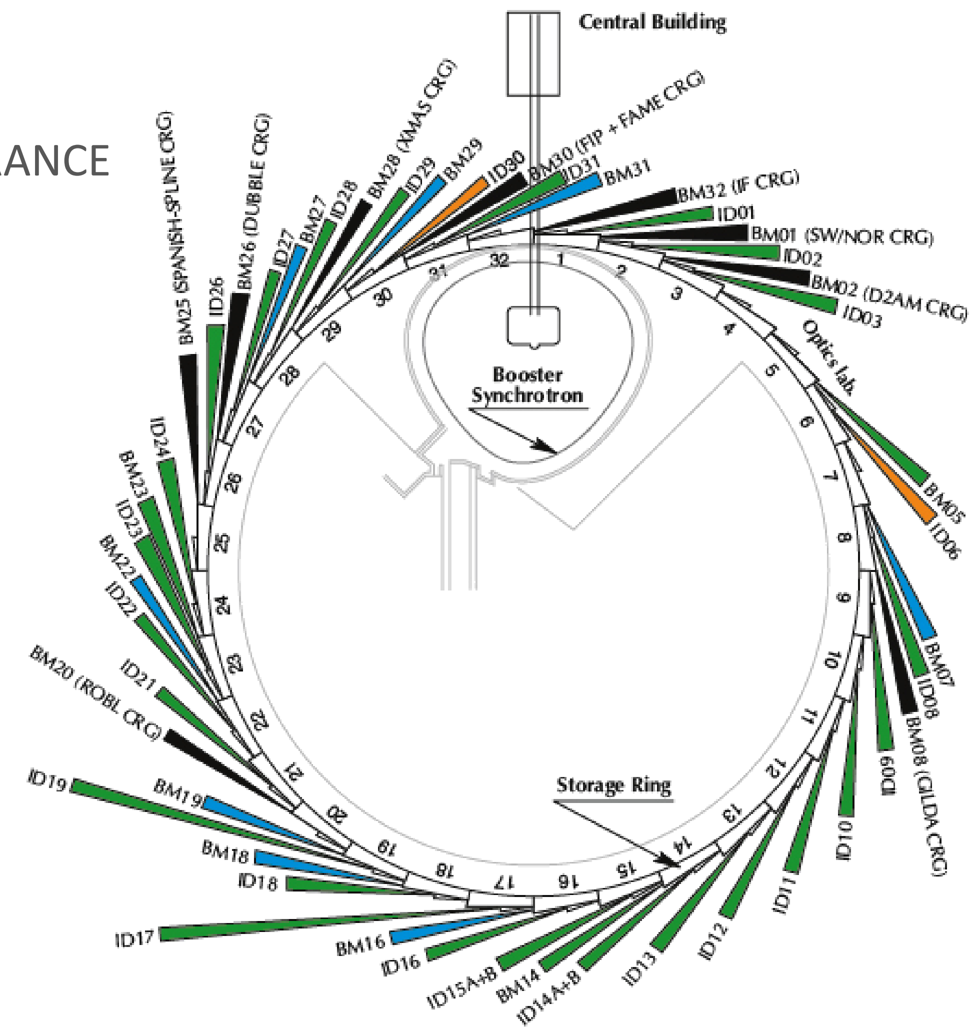
More than 50 light sources in the world (2018)

https://lightsources.org/lightsources-of-the-world/

ESRF Grenoble FRANCE

http://www.esrf.eu/

ESRF Grenoble FRANCE



5 Key properties of synchrotron X-rays for MHz frame rate imaging

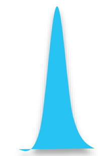
7 Key detector considerations for X-ray phase-contrast imaging

3 Demonstrations

5

Key properties of synchrotron X-rays for MHz frame rate imaging

5. Repetition Rate



4. ~100 ps Pulse Width

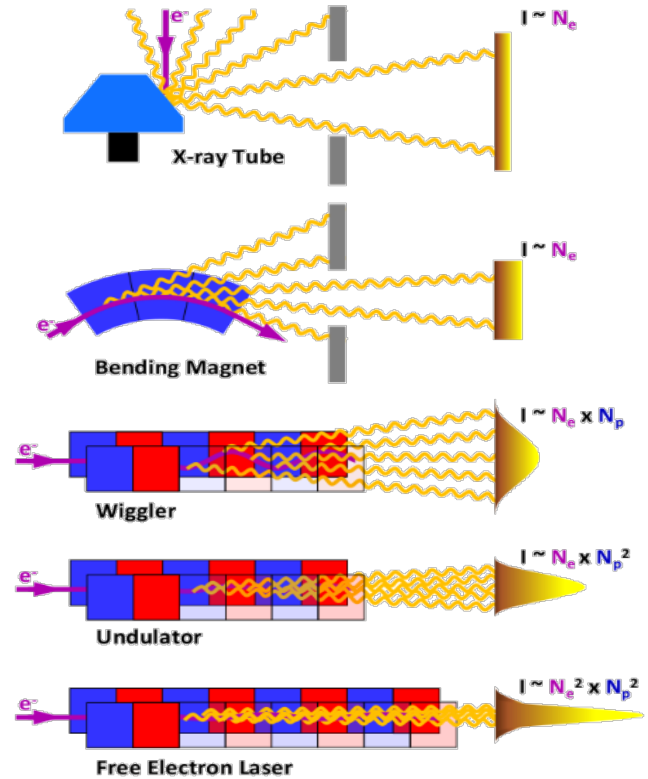
3. Spatial Coherence

1. Brilliance

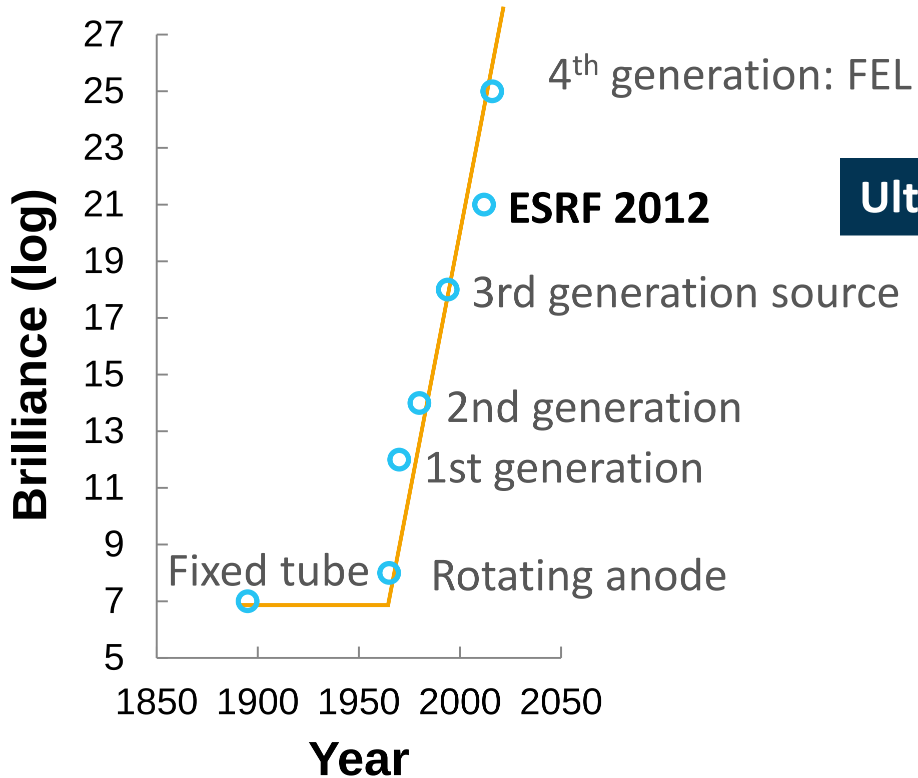
2. Hard X-rays

1. Brilliance

number of X-ray photons per second per mm^2 per mrad^2 per 0.1% bandwidth

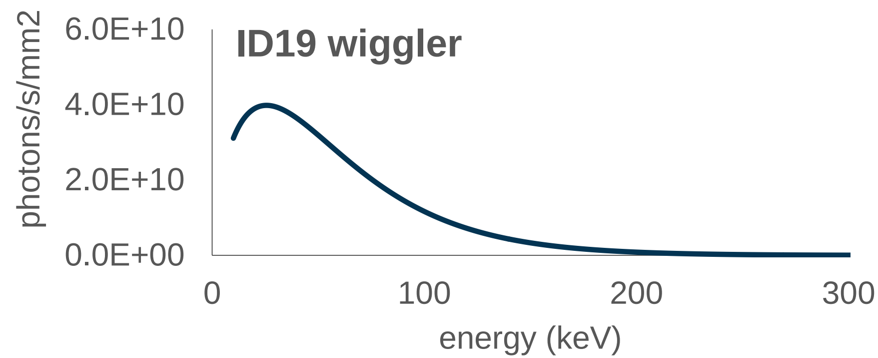


Adapted from Shabalin DOI 10.13140/RG.2.14004.5680

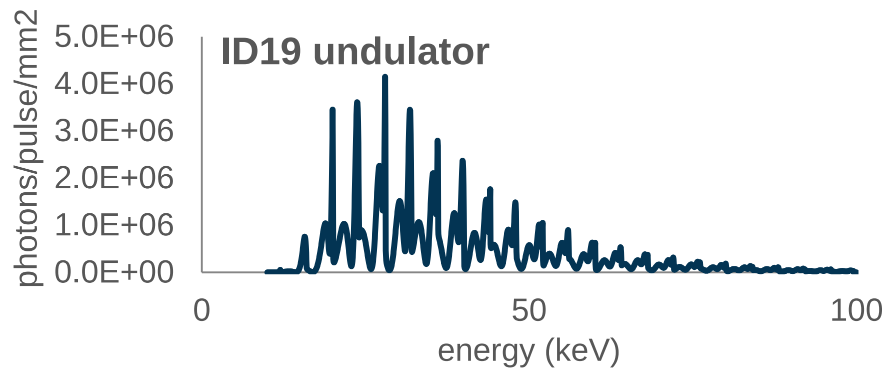


Ultra-short exposure imaging

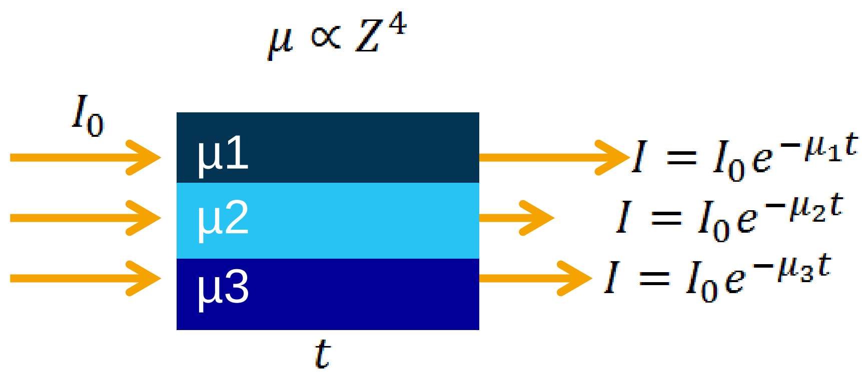
2. Hard X-rays

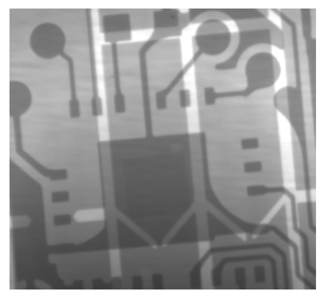


ID19 wiggler
photons/s/mm2
6.0E+10
4.0E+10
2.0E+10
0.0E+00
0
100
200
300
energy (keV)



ID19 undulator
photons/pulse/mm2
5.0E+06
4.0E+06
3.0E+06
2.0E+06
1.0E+06
0.0E+00
0
50
100
energy (keV)



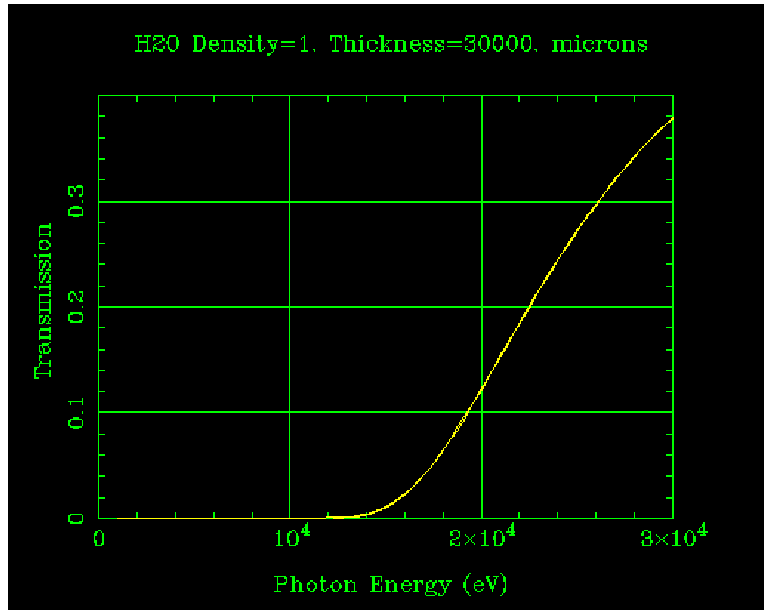


USB chip

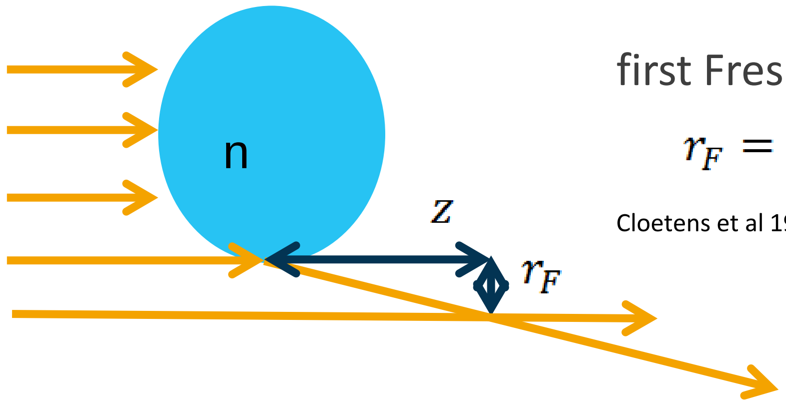
sea shell

X-ray attenuation contrast imaging

$$\mu \propto \frac{1}{E^3}$$



http://henke.lbl.gov/cgi-bin/filter.pl

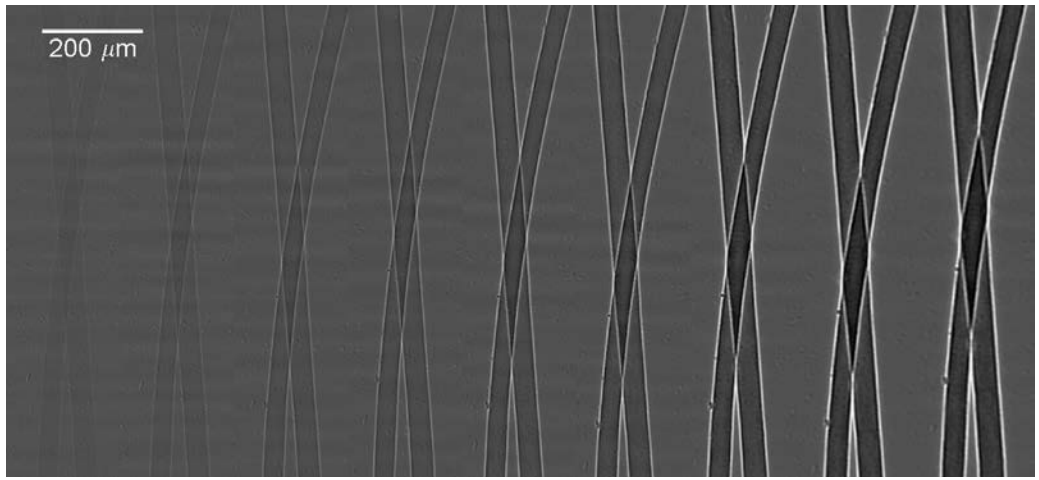


first Fresnel zone

$$r_F = \sqrt{\lambda z}$$

Cloetens et al 1996 J. Phys. D: Appl. Phys. 29 133

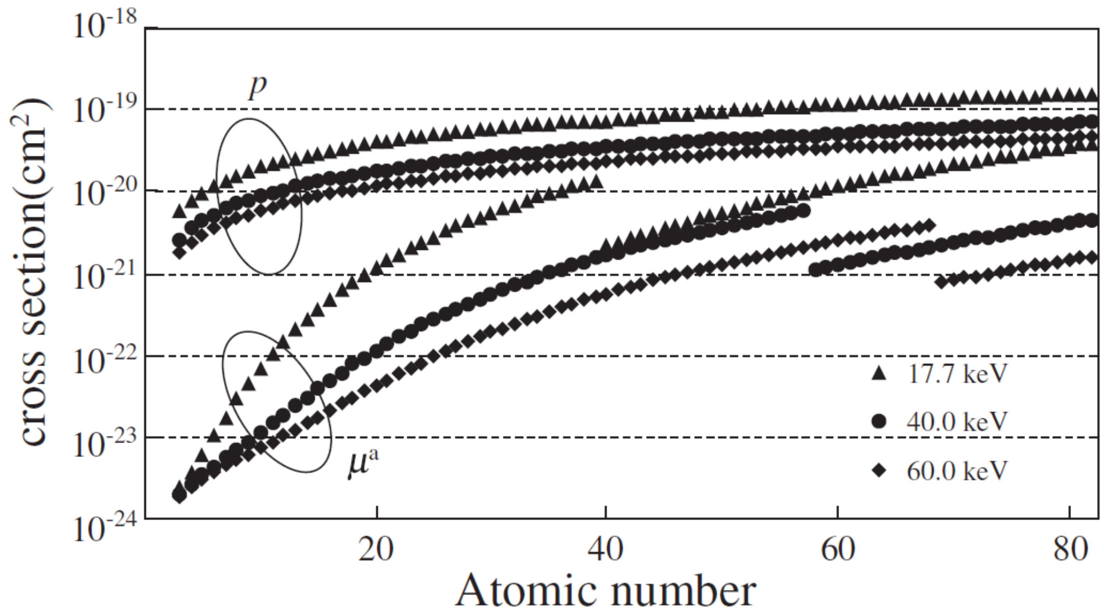
Example adapted from Rack DOI 10.1016/j.nima.2007.11.020



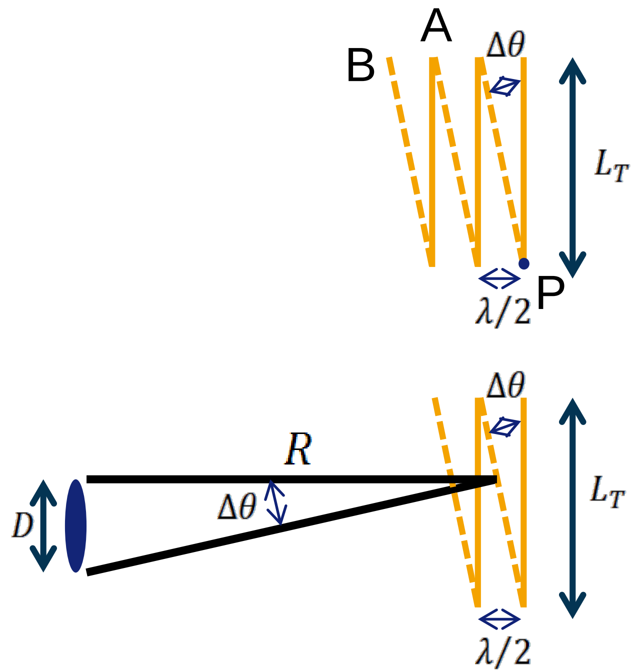
z

X-ray phase-contrast imaging

Adapted from Momose, Japanese Journal Applied Physics 44(9A) 6355 (2005).



3. Spatial coherence



Spatial Coherence Length

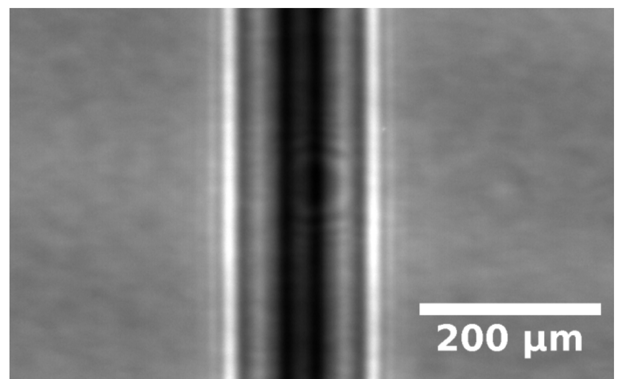
$$L_T \Delta\theta = \frac{\lambda}{2}$$

$$L_T = \frac{\lambda}{2}\left(\frac{R}{D}\right)$$

Adapted from Als -Nielsen and McMorrow, Elements of Modern X-ray Physics, Jon Wiley & Sons 2001

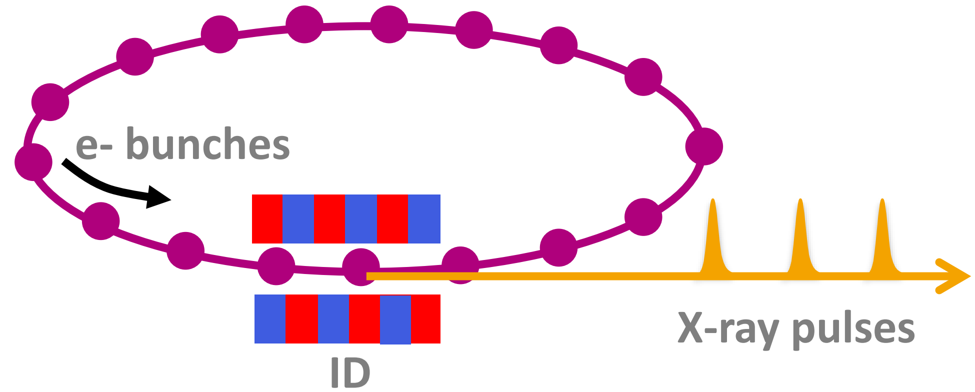
e.g. for 30 keV X-rays at ID19

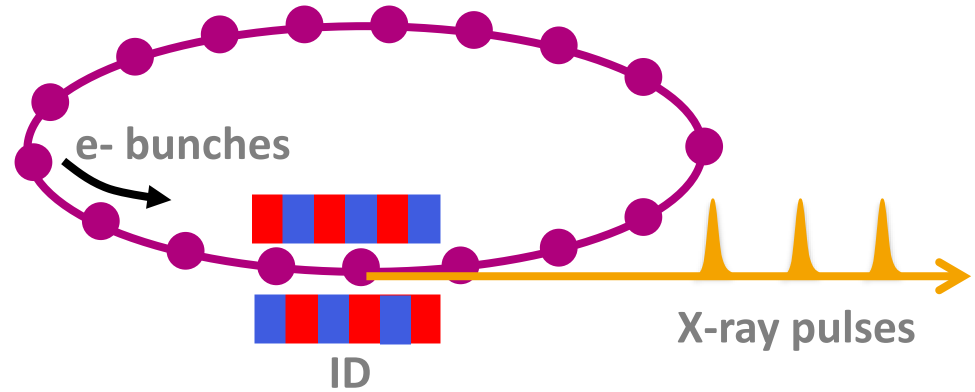
D	Horizontal (rms): **50 µm** Vertical (rms): **3.4 µm**
R	**145 m**
L_T	Horizontal: **60 µm** Vertical: **880 µm**
z	**13 m**
r_F	**22 µm**



X-ray phase-contrast image of a fiber, Olbinado et al (ID19) unpublished

4. Temporal pulse width

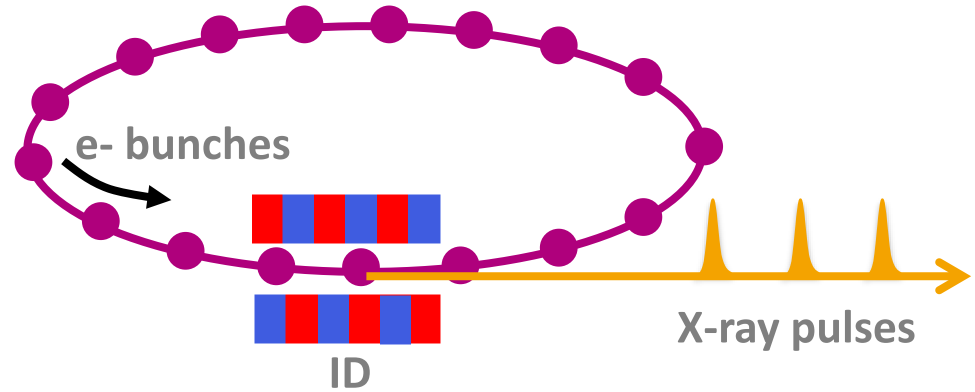




X-ray temporal pulse width ≡ electron bunch width

Single-bunch imaging with ~100 ps temporal resolution.

5. Repetition rate



ESRF maximum pulse rate ≡ 352.2 MHz (RF)

5. Repetition rate

filling mode	ring current (mA)	bunch repetition (ns)	X-ray photons per pulse (10^6 photons/mm^2)
single-bunch	12	2816	44
4-bunch	32	704	29
16-bunch	90	176	20
992-bunch 'uniform fill'	200	2.84	0.7

M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

5. Repetition rate

filling mode	ring current (mA)	bunch repetition (ns)	X-ray photons per pulse (10^6 photons/mm^2)
single-bunch	12	2816	44
4-bunch	32	704	29
16-bunch	90	176	20
992-bunch 'uniform fill'	200	2.84	0.7

Single-bunch imaging up to 5.6 Mfps

M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

5. Repetition rate

filling mode	ring current (mA)	bunch repetition (ns)	X-ray photons per pulse (10^6 photons/mm^2)
single-bunch	12	2816	44
4-bunch	32	704	29
16-bunch	90	176	20
992-bunch 'uniform fill'	200	2.84	0.7

Multiple-bunch imaging up to 80 ns integration time (or up to 10 Mfps).

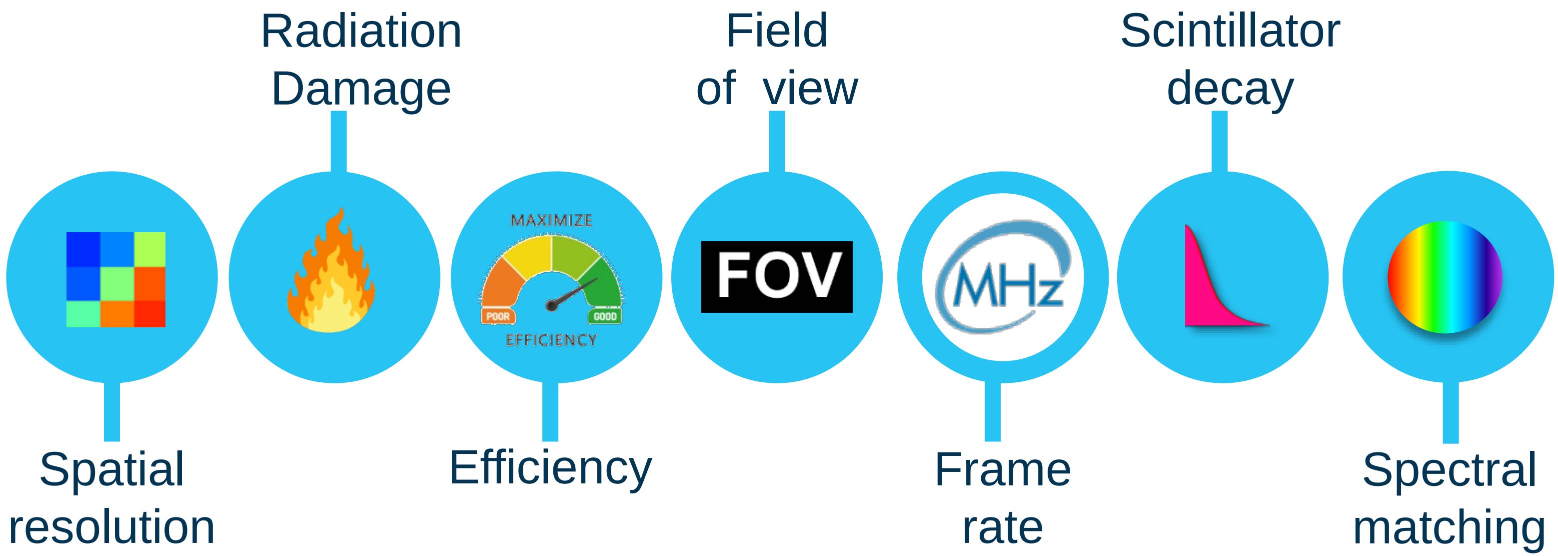
M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

Brilliance
Penetration power
Spatial coherence
Pulse width
Repetition rate

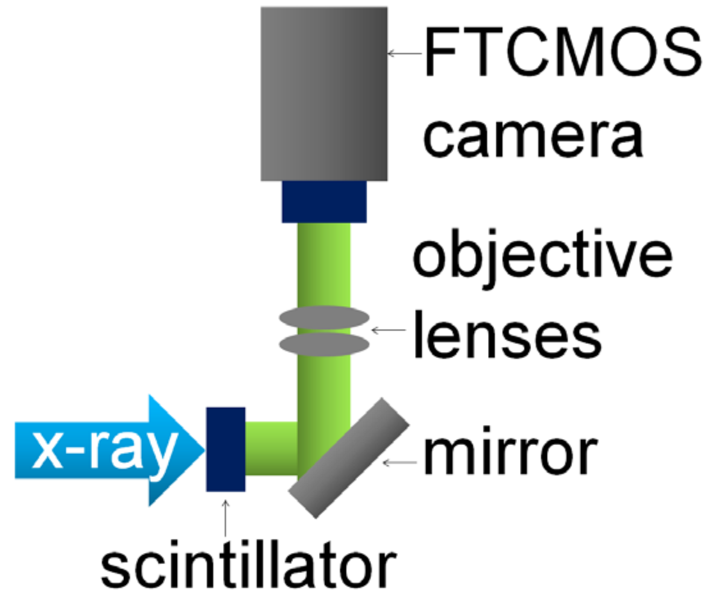
Hard X-ray
phase-contrast imaging
~100 ps temporal resolution
MHz frame rates

Opaque objects
Low density objects
Transient dynamics
Aperiodic dynamics

7 key detector considerations for X-ray phase-contrast imaging



1. Spatial resolution
2. Resistance to radiation damage
3. Efficiency for hard X-rays



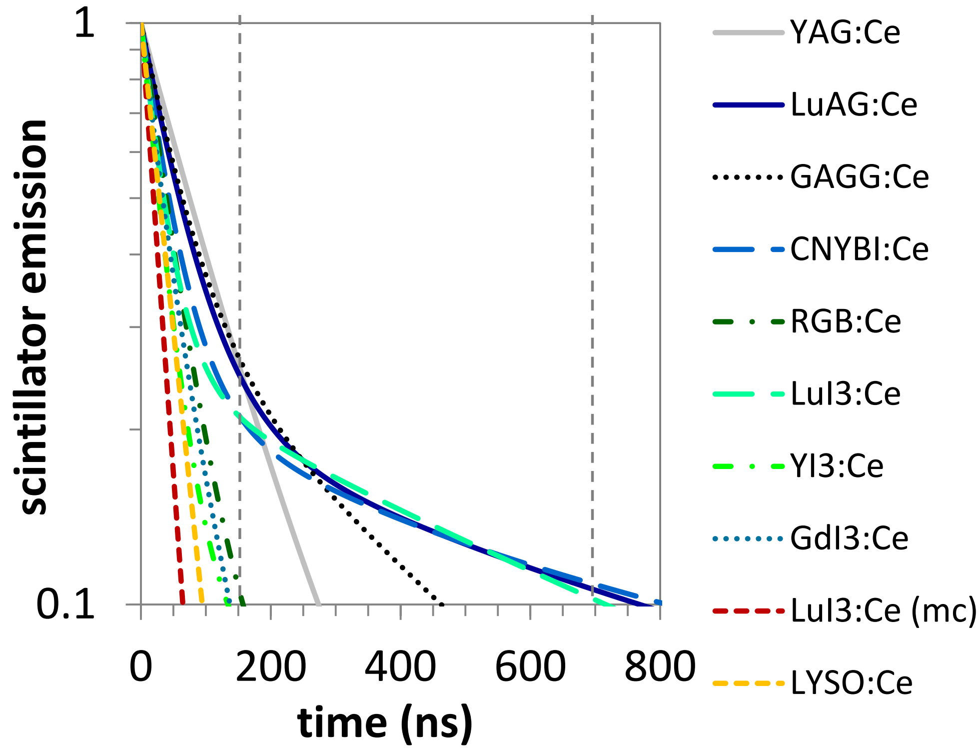
M. P. Olbinado, J. Grenzer, P. Pradel, T. De Resseguier, P. Vagovic, M.-C. Zdora, V. A. Guzenko, C. David, A. Rack, *Advances in indirect detector systems for ultra high-speed hard X-ray imaging with synchrotron light,* J. of Instrum. **13**, C04004 (2018).

4&5. MHz frame rate without reducing FOV

frame-transfer CMOS sensor

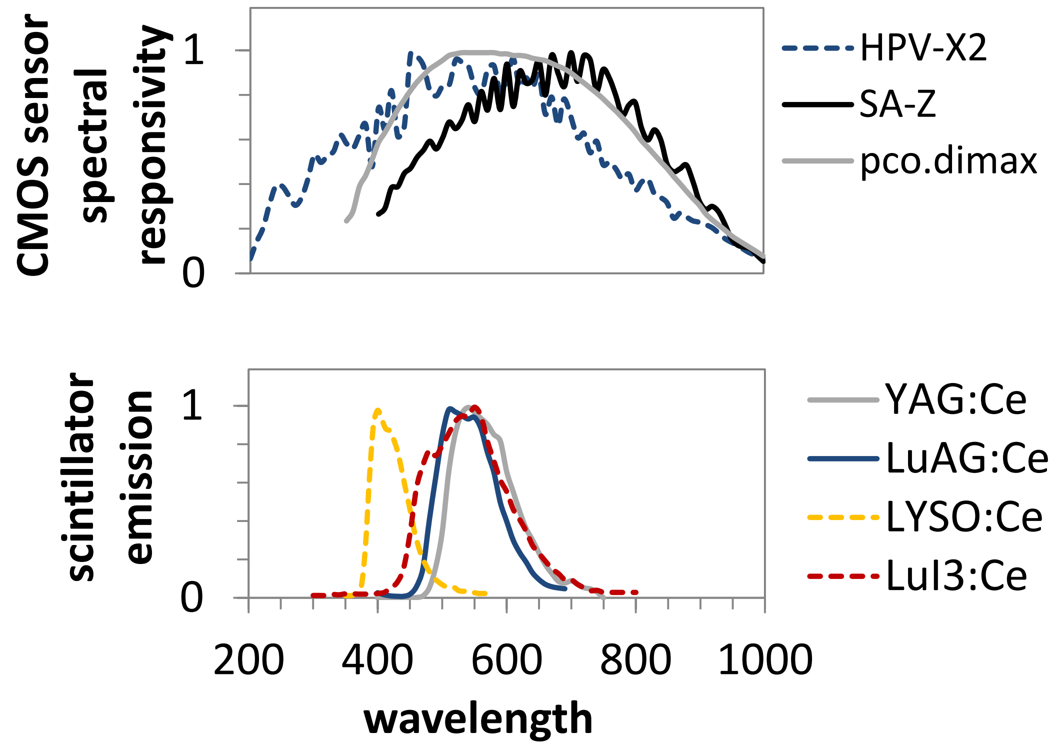
HPV-X2 (Shimadzu)
400 x 250 pixels, 128 frames on-chip storage
60 fps to 2 Mfps
fixed 5 Mfps (110 ns integration time)

6. Fast scintillator decay



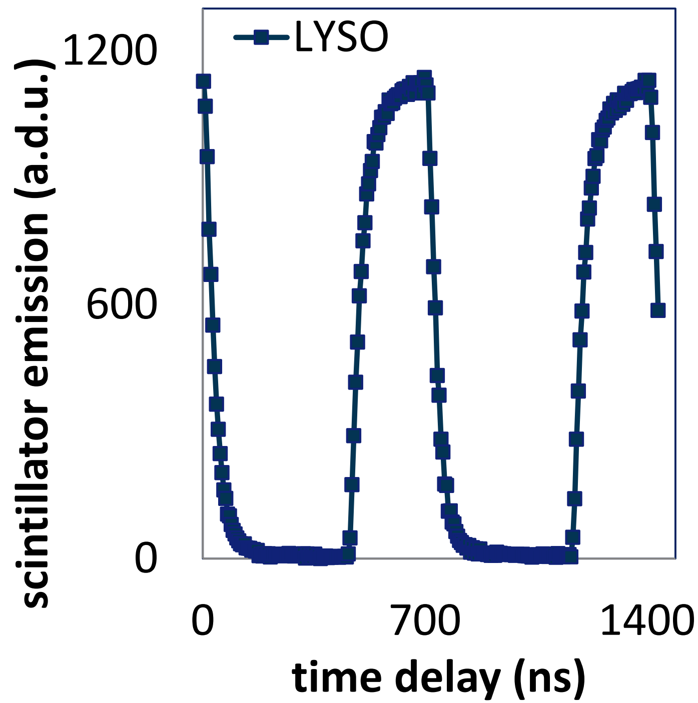
M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

7. Spectral matching



M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

Evaluation of the detector

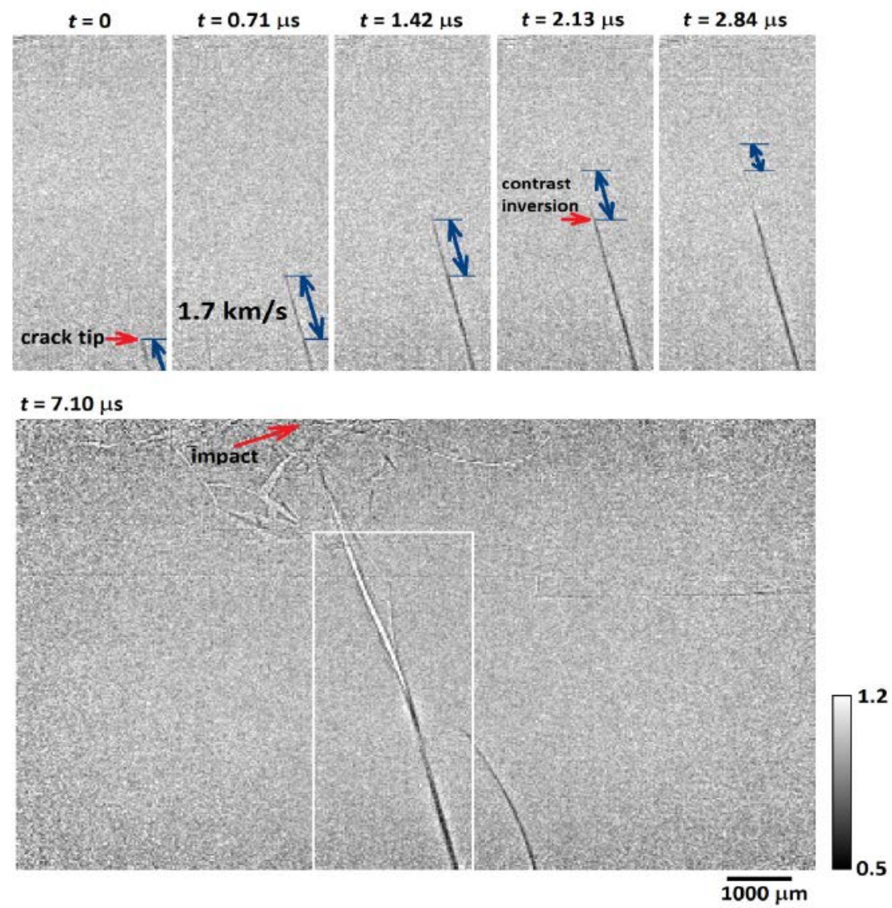


M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

3 Demonstrations

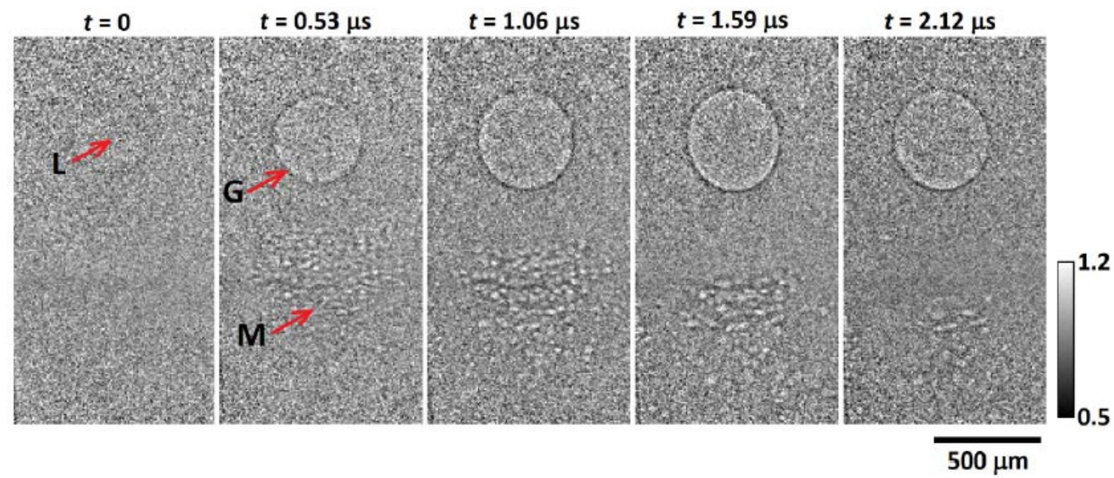
Experiment	X-rays		HPV-X2 Camera		Scintillator	
	storage ring filling mode	pulse width (ps, rms)	inter-frame time (ns)	exposure time (ns)	thickness (µm)	material
Crack propagation	4-bunch	48	710	400	250	LuAG:Ce
Shock wave propagation	16-bunch	55	530	200	250	LYSO:Ce
Electric arc ignition	uniform		200	110	250	LuAG:Ce

1. Crack propagation



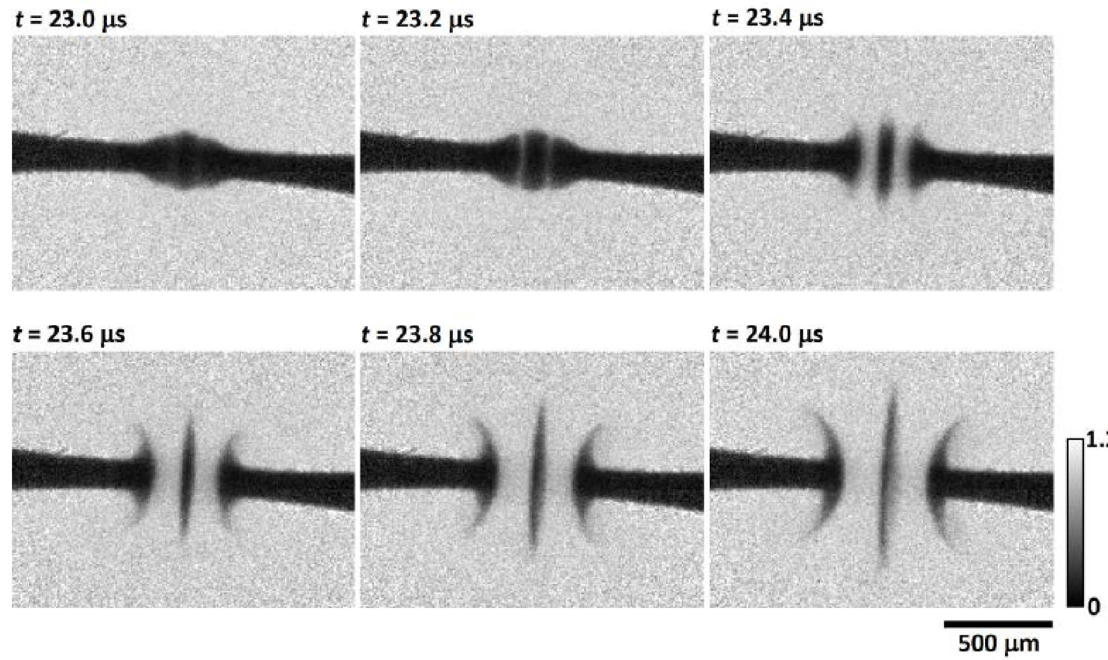
M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

2. Shock-induced microcavitation



M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

3. Electric arc ignition



M. P. Olbinado, X. Just, J.-L. Gelet, P. Lhuissier, M. Scheel, P. Vagovic, T. Sato, R. Graceffa, J. Schulz, A. Manusco, J. Morse, A. Rack, *MHz frame rate hard X-ray phase-contrast imaging using synchrotron radiation*, Opt. Expr. **25**(12), 13857 (2017).

5 Key properties of synchrotron X-rays for time-resolved imaging

7 Key detector considerations for X-ray phase-contrast imaging

3 Demonstrations

Thank you all for listening!

‘the most transitory of things, a shadow, the proverbial emblem of all that is fleeting and momentary. . . may be fixed for ever in the position which it seemed only destined for a single instant to occupy’

William Henry Fox Talbot, 1939

Stopping time: Henry Fox Talbot and the origins of freeze-frame photography, Chitra Ramalingam, Endeavour 32 (3) 2008.


Margie Olbinado
The European Synchrotron – ESRF