X-RAY LASER PULSE CHARACTERISATION VIA THZ STREAKING

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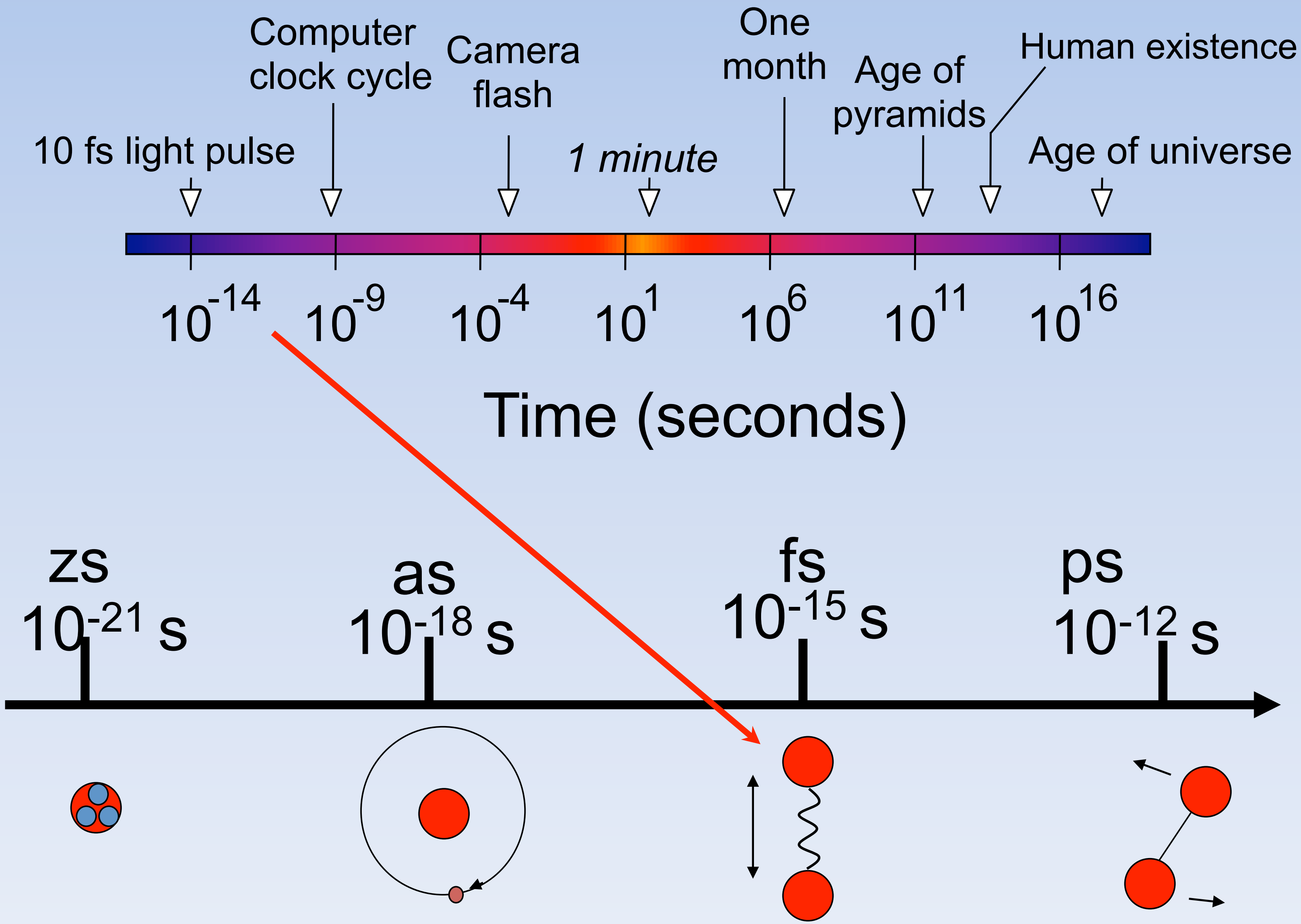
Photonics Ireland
Galway Sept. 13, 2017

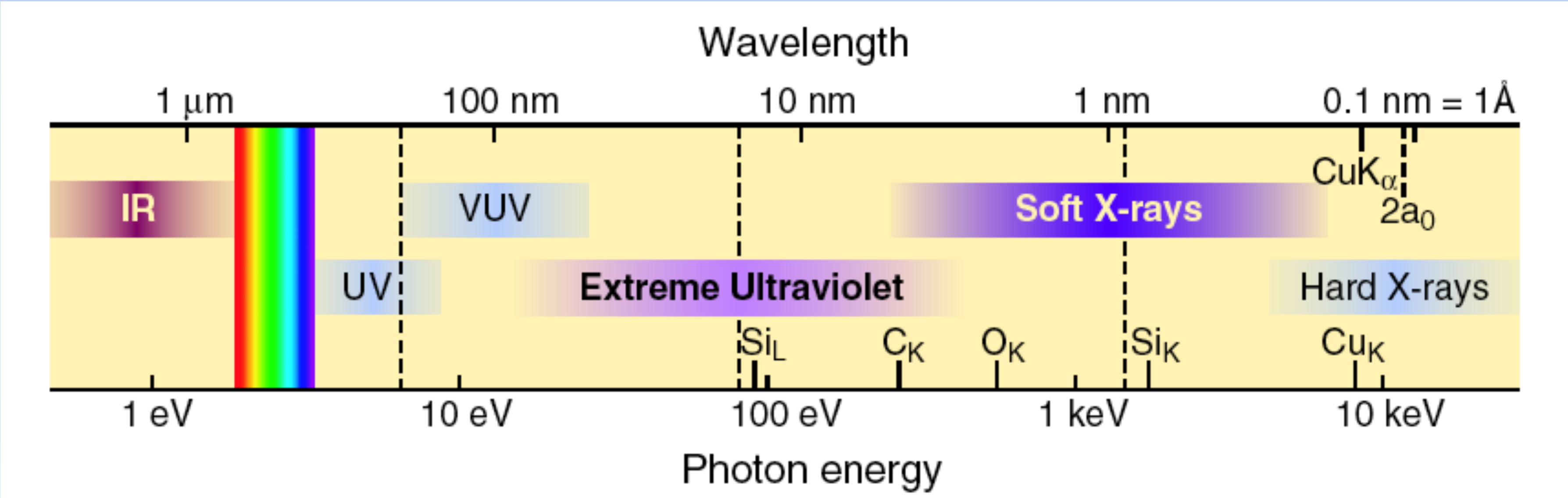
Some of the people in the THz collabration

TIMESCALES - HOW FAST IS FAST ?



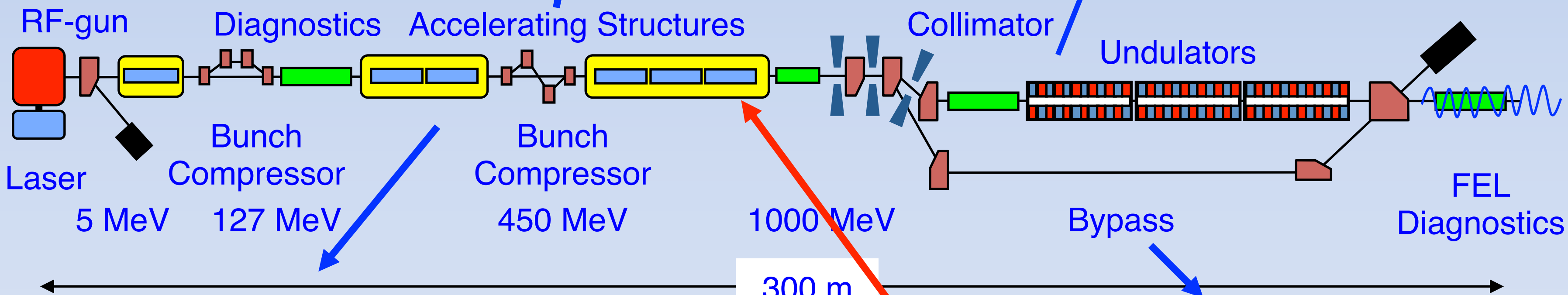
X-ray – How X-ray is X-ray ?

Spectral Range: IR to the X-ray



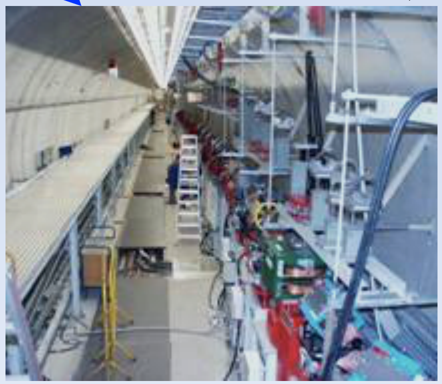
Graphic: Courtesy, Prof. David Attwood (Berkeley)

X-ray Free Electron Lasers (FEL)

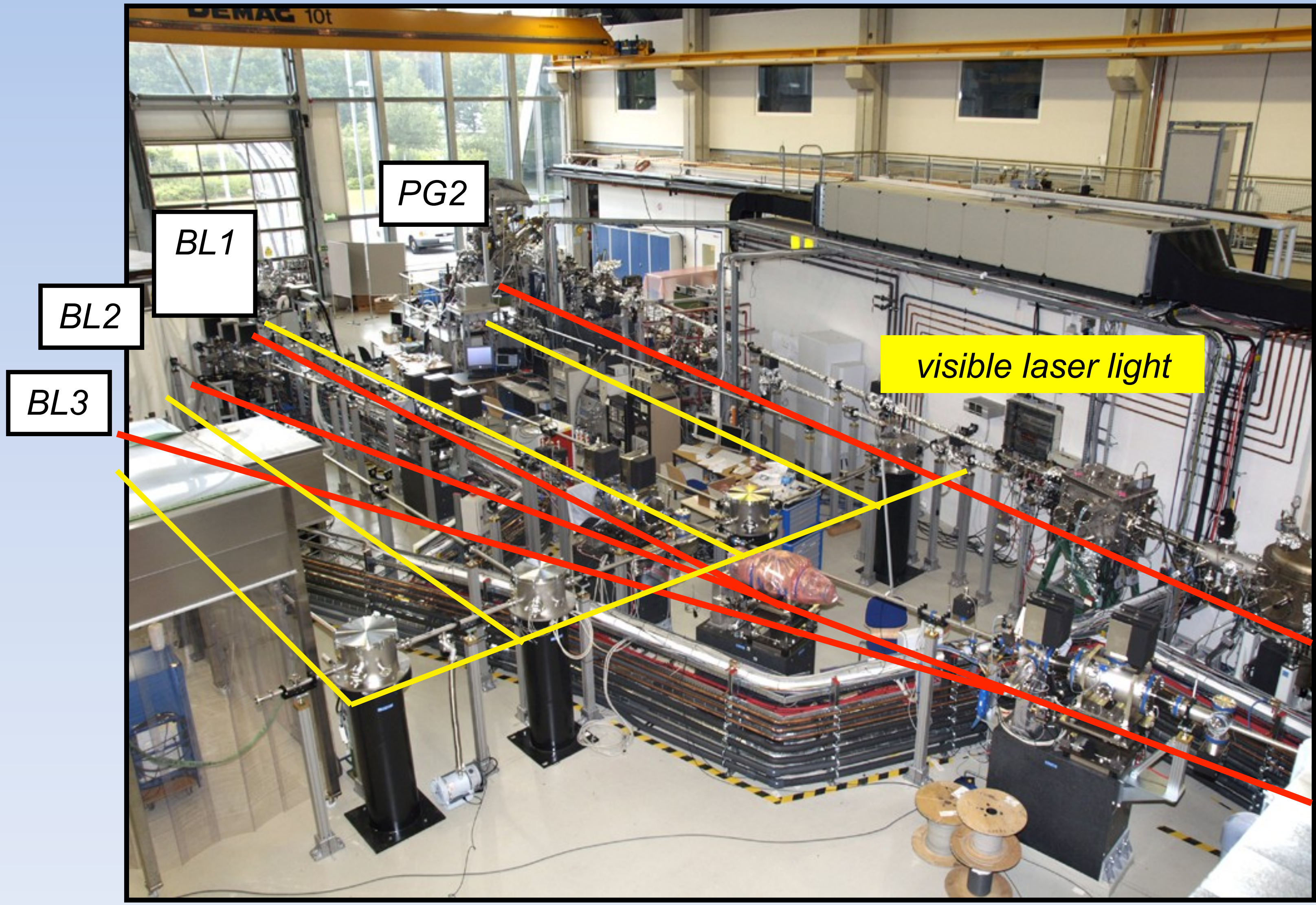


- LINAC Energy : ~ 1 GeV
  ~ 4 – 60 nm

FLASH - Operation & Physical Layout



FLASH NIR/UV and XUV Beam Layout

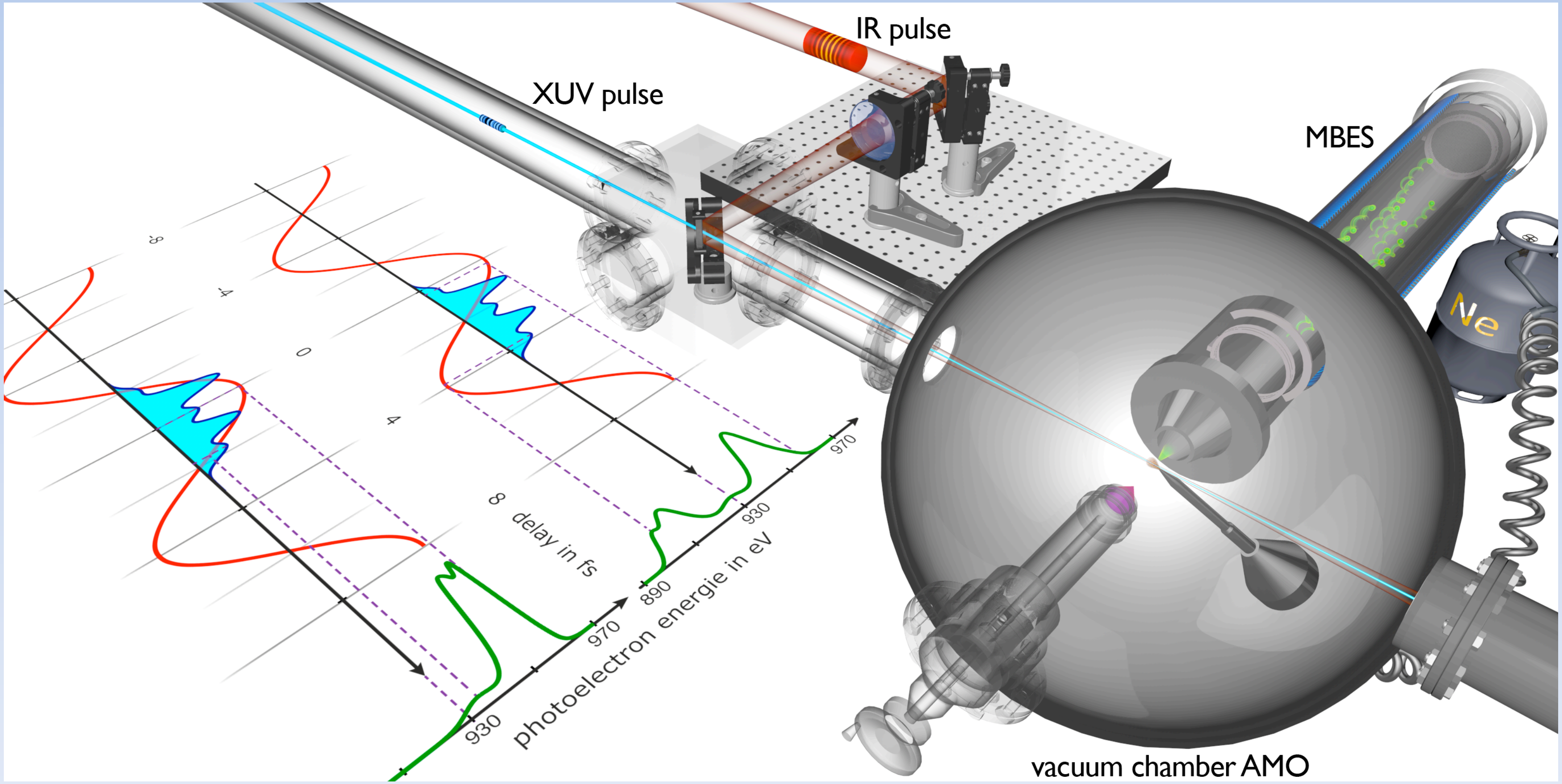


USPs of XUV & X-ray FELs (XFELs)

- *High flux per pulse – typ. 10^{13} photons/pulse*
- *Tunable pulsewidth – from 1 to few 100 fs*
- *High peak intensity – up to few 10^{20} W.cm^{-2} in principle*
- *Seeded and unseeded modes now possible*
- *Unseeded bandwidth – 0.2 – 1.0%*
- *Seeded bandwidth – 0.005% (typ.) / $\lambda/\Delta\lambda \geq 10^4$*
- *Synchronisation to optical fs lasers relatively easy*
- *EUV/EUV and X-ray/X-ray pump-probe possible*

Photoelectron Spectroscopy @ FLASH

Two colour (X-ray + NIR) experimental layout.



NCPST

EXTATIC

Nature Photonics **8**
pp950 - 957 (2014)

sfi inspire

DCU

Atoms in Intense Superposed *X-ray* + IR Laser Fields

Main objective

Study the effect of X-ray pulse width on fundamental photoionization processes in intense and ultrashort ionizing (X-ray) and dressing (Optical / IR) **laser** fields

Two Extremes:

X-ray pulse duration is 'many' optical cycles

X-ray pulse duration is less than ½ optical cycle

Atoms in Intense Superposed *X-ray* + IR Laser Fields - Sidebands

Case 1.

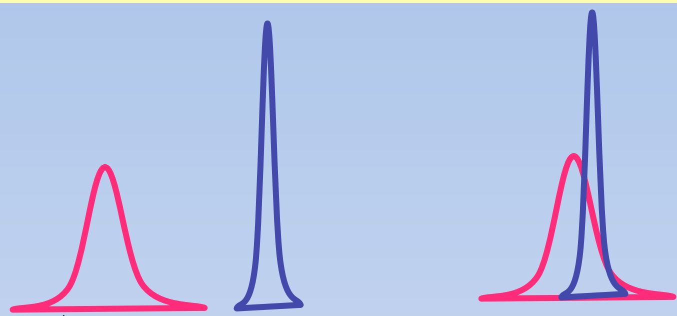
X-ray pulse duration is ‘many’ optical cycles

Two colour ATI/ Laser Assisted PES

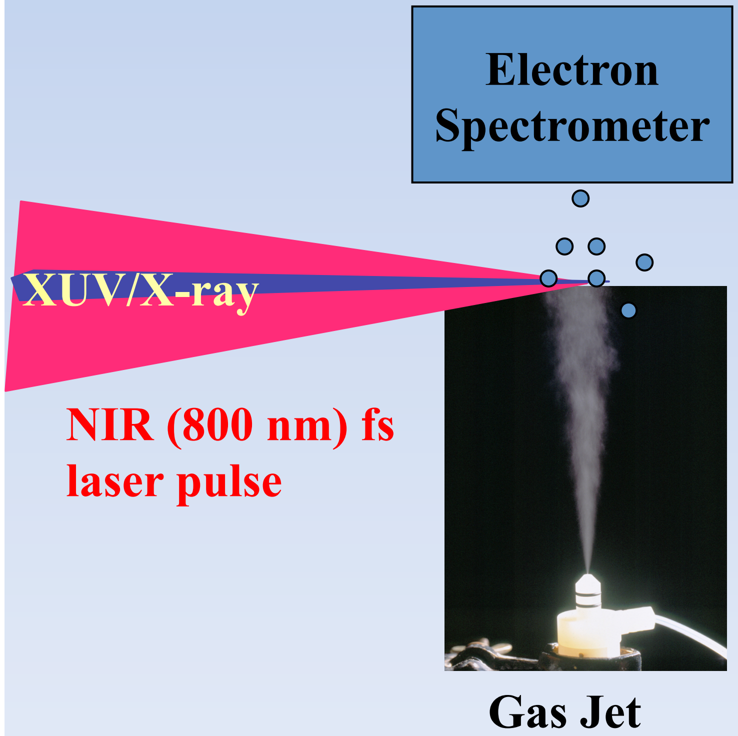
Superposition of visible and XUV pulses in a noble gas jet

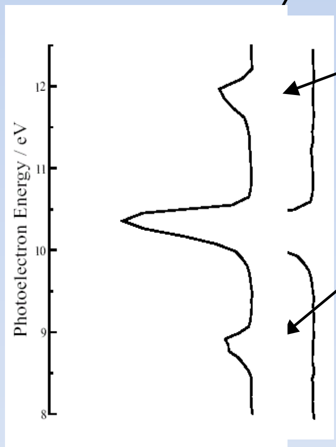
Schins et al. PRL ***73****, 2180 (1994)*

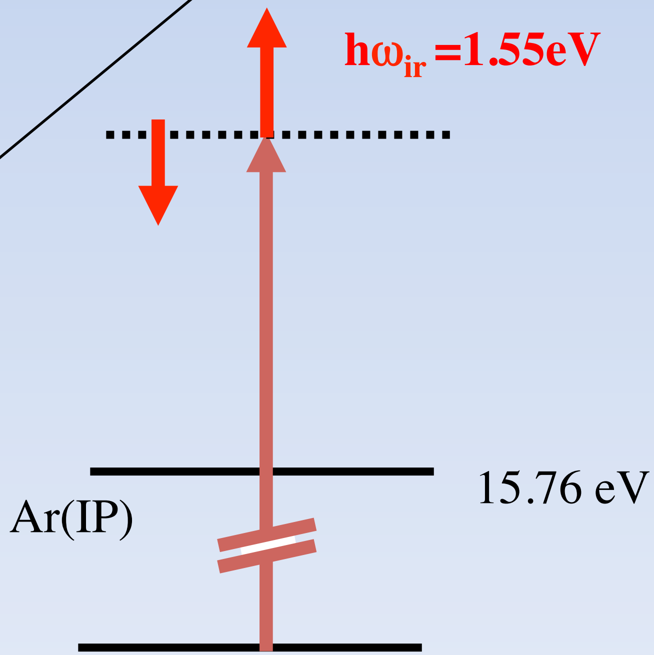
E.S. Toma et al. PRA **62** 061801 (2000)



$$A + \hbar\omega_{XUV} \rightarrow A^{+} + e^{-}(T_{KE}) \pm n\hbar\omega_{L} \rightarrow A^{+} + e^{-}(T_{KE} \pm n\hbar\omega_{L})$$



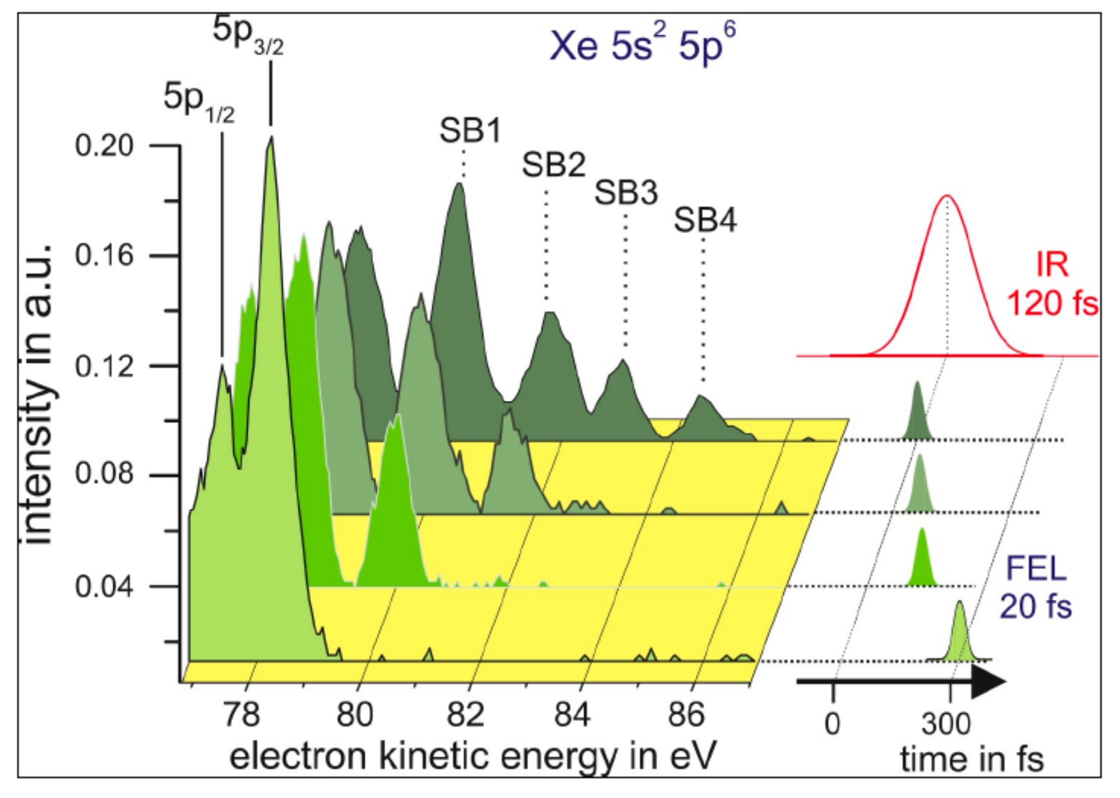


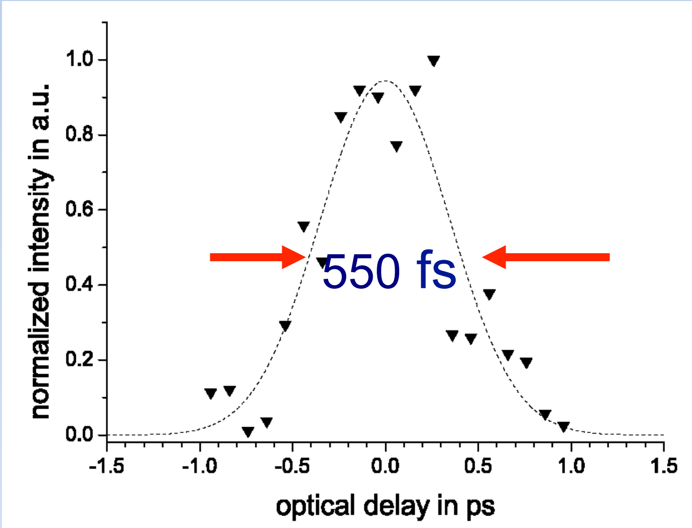


Sideband intensity *very sensitive* to XUV-IR pulse area overlap. - Cross Correlation…

Atoms in 'Long' XUV (X-ray) + IR Fields

Sideband number/intensity depend strongly on XUV/NIR overlap ⇒ by comparison with theory ***we are able to determine relative time delay to better than 100 fs***





1. Ultrafast XUV-modulated optical-reflectivity methods

C. Gahl et al., Nature Photonics **2** 165-169 (2008)

T. Maltezopoulos et al., New J Phys **10** Art. No. 033026 (2008)

2. 'TEO'

A. Azima et al., APL, **94** 144102 (2009)

NCPST sfi science foundation ireland

NIMA **83**, 516-525 (2007)

Appl. Phys. Lett **90** 131108 (2007)

inspire Integrated NanoScience Platform for Ireland DCU

Atoms in 'Long' XUV (X-ray) + IR Fields

'n' photon ATI cross-section

$$\left(\frac{d\sigma^{(n)}}{d\theta}\right) = \frac{k}{k_0} J_n^2\left(\vec{\alpha}.\vec{K}\right)\left(\frac{d\sigma^{(0)}}{d\theta}\right)_{\vec{E}_k}$$

One photon cross-section

$\vec{\alpha} = \dfrac{\vec{F}}{\omega_L}$ - Classical excursion vector of an electron in a laser field of amplitude $\vec{F}$

$\vec{K} = \left(\vec{k} - \vec{k}_0\right)$ - Momentum transfer

After a little work…………sideband strength is given by an expression like……

$$S^{(n)} \propto \int_0^{\pi} Sin\theta\left(1 + \beta P_2\left(Cos\theta\right)\right) J_n^2\left(\alpha_0 k_n Cos\theta\right) d\theta$$

J_n - Bessel function (first kind order 'n')

k_n - Shifted wavenumber of the ejected electron = $\sqrt{2\left(\omega_{IP} + \omega_{FEL} + n\omega_L\right)}$

β - Usual asymmetry parameter

A Maquet and R Taieb, J. Mod. Opt. 54 1847 (2007)

Streaking……

Case 2.

X-ray pulse duration is less than ½ optical cycle

Streaking……

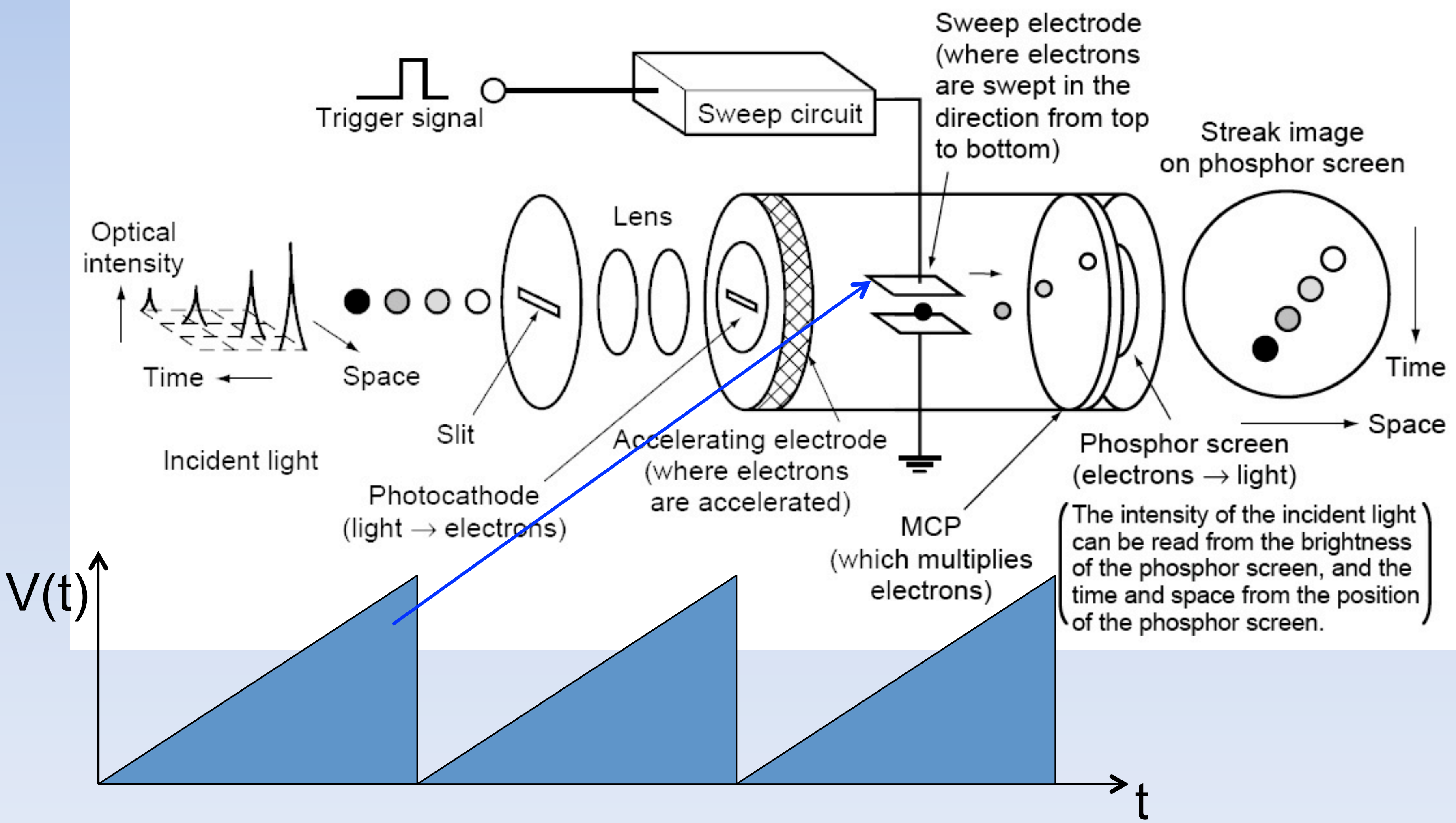
Two colour photoionization experiments – The Atomic X-ray Streak Camera

The key diagnostic in ultrafast laser and optical physics is the Streak Camera. It is essentially an optical oscilloscope where the input channel is a photocathode as opposed to the usual direct electrical BNC input…………..

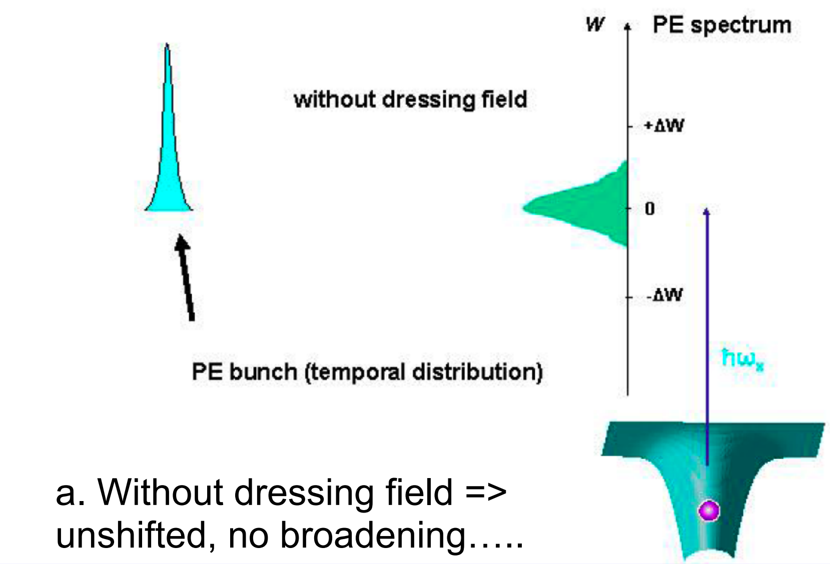
Hamamatsu Synchroscan at DCU

Streaking………

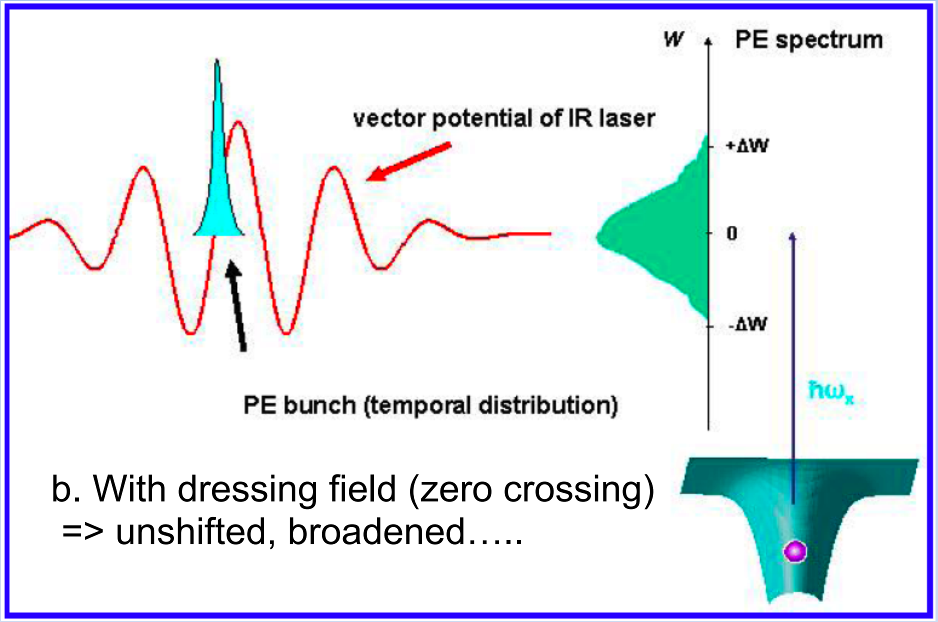
Streak Camera Operation – Courtesy Hamamatsu Corp.



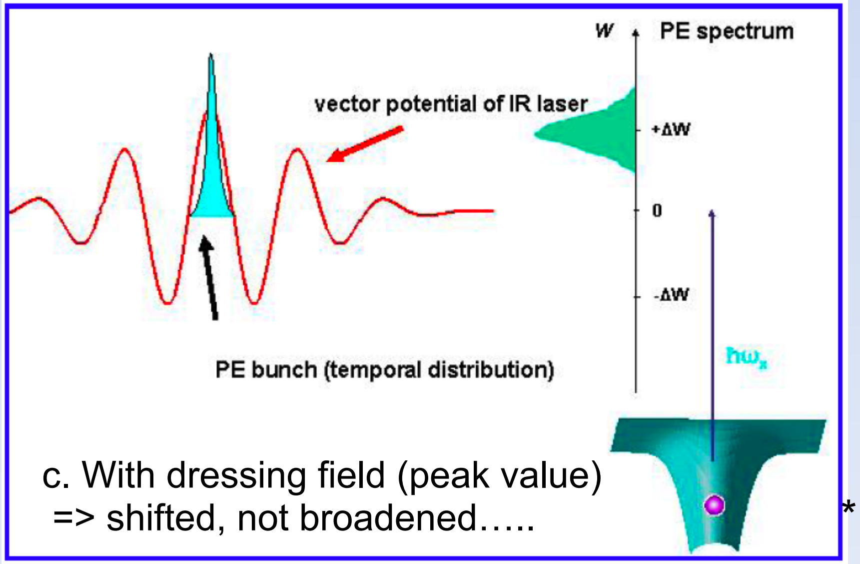
‘Short’ XUV (X-ray) + IR Fields (Streaking)



a. Without dressing field => unshifted, no broadening…..



b. With dressing field (zero crossing) => unshifted, broadened…..



c. With dressing field (peak value) => shifted, not broadened…..

Single Shot Atomic Streak Camera – SSASC => few fs pulse widths. **Target:** Neon, **LCLS: >**870 eV**,** ~1 - 4 fs**, Laser:** *OPA (2000 nm, ~ 7 fs),*

** R. Kienberger et al., J. Mod. Opt* ***52*** *261-275 (2005)*

‘Short’ XUV (X-ray) + IR Fields (Streaking)

Basic equation of photoelectron streaking in a laser field…..

$$\Delta\varepsilon(t_b) \approx -p_c A_{IR}(t_b) + \tfrac{1}{2} A_{IR}^2(t_b)$$

$$p_c = \sqrt{2\varepsilon_c} \text{ (in atomic units, au: } \hbar = e = m_e = \tfrac{1}{4\pi\varepsilon_0} = 1)$$

A = Vector potential of the laser field

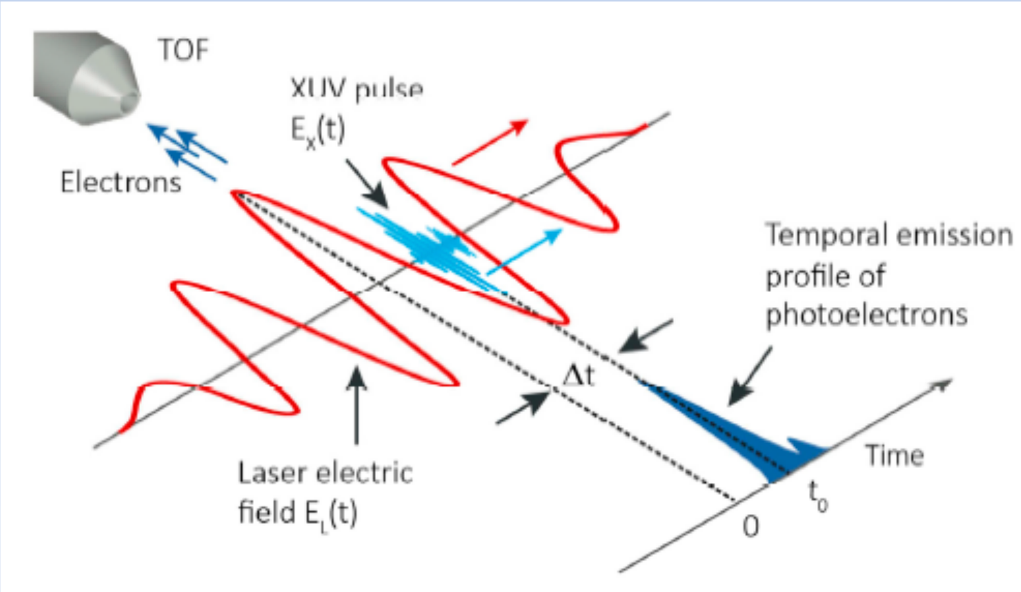
P_c is the momentum of the un-streaked electrons

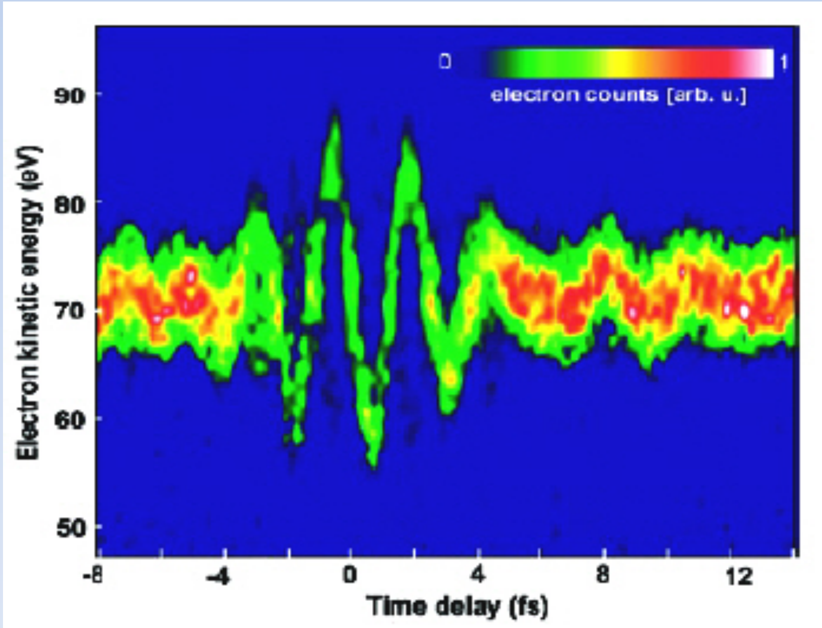
$$E_{IR}(t) = -\frac{dA_{IR}(t)}{dt}$$

* *R. Kienberger et al., J. Mod. Opt **52** 261-275 (2005)*

'Short' XUV (X-ray) + IR Fields (Streaking)

Experimental realisation - optical delay line used to sweep an attosecond X-ray pulse, focused into a gas jet, past an intense fs optical laser field measuring the photoelectron kinetic energy at each point => *the Electric Field of the optical laser revealed…….*





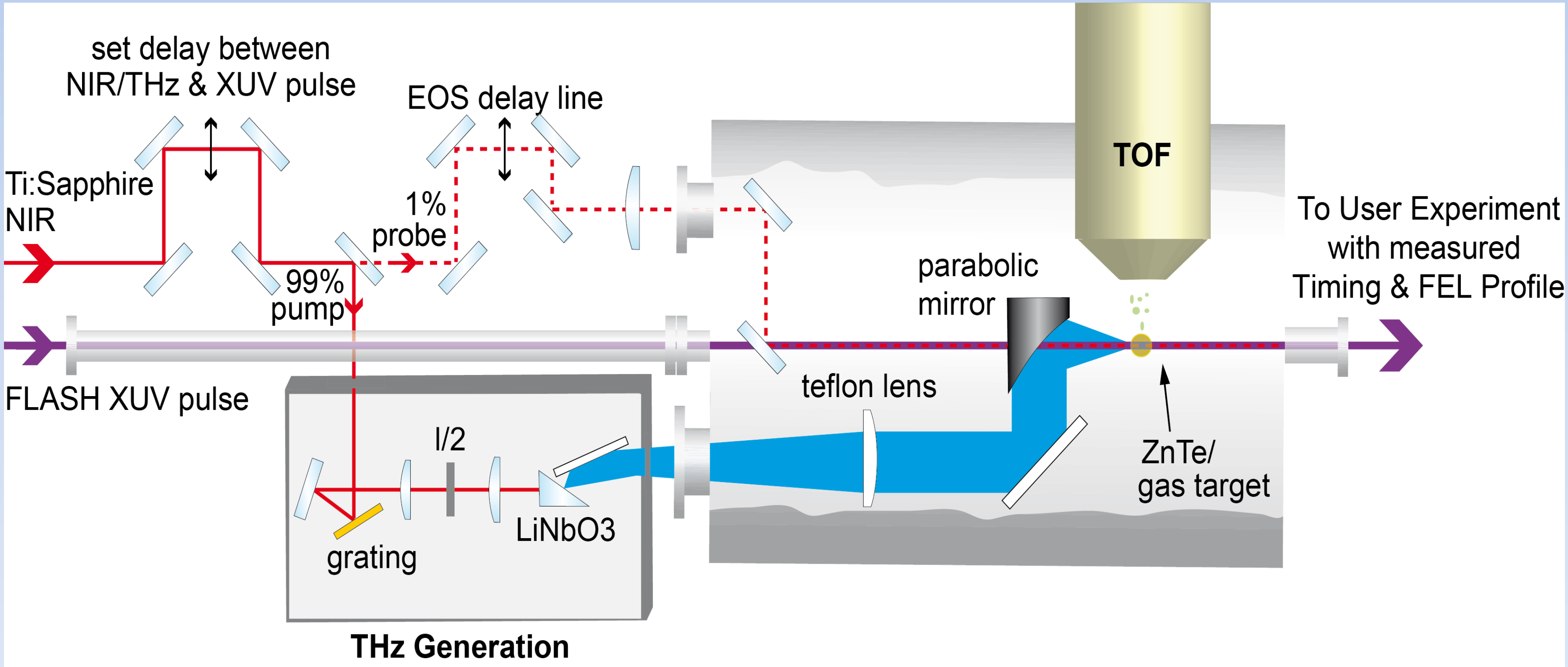
I Grguras, PhD thesis, Hamburg 2015

M Drescher et al. Nature **419**, 803–807 (2002)
R Kienberger et al., J. Mod. Opt **52** 261 (2005)

Single Cycle THz Streaking @ FLASH

Femtosecond Atomic Streak Camera

Generate single (picosecond) cycle pulse using optical rectification of Ti-Sappire laser pulses – field ~ 50MV/m maximum

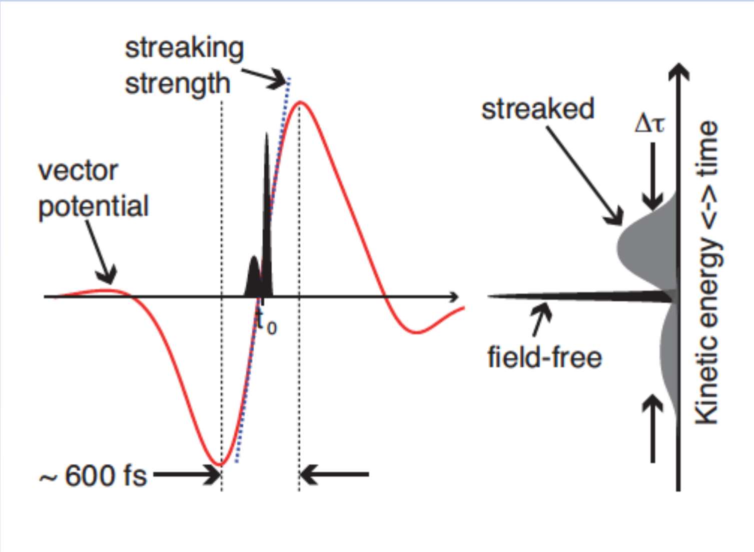


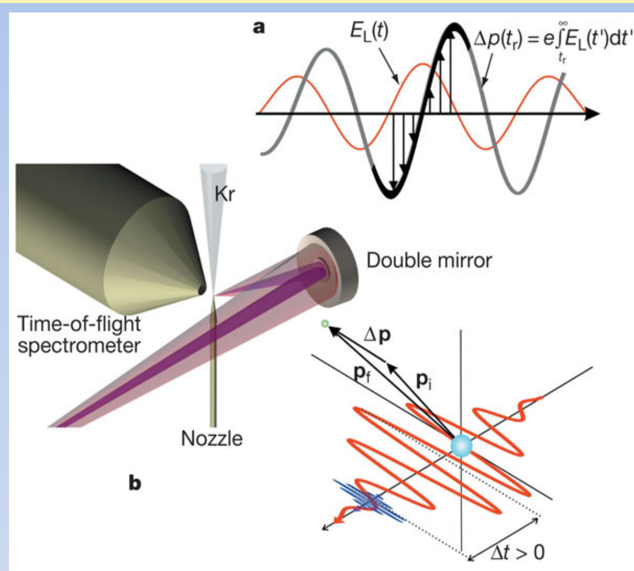
Schematic layout of the THz Streaking Experiment at FLASH

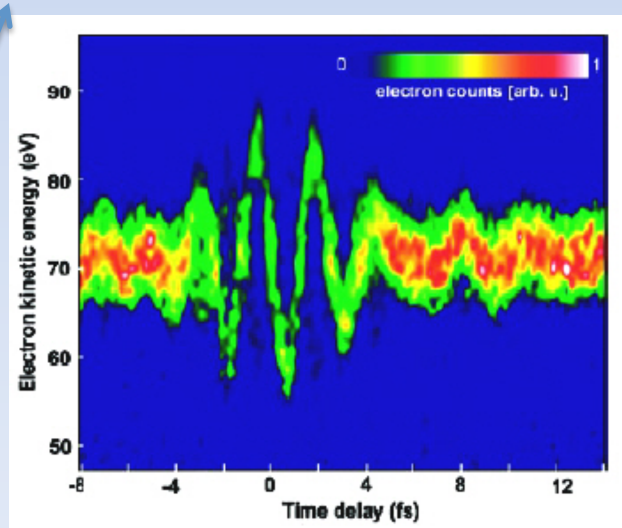
Single Cycle THz Streaking @ FLASH

Femtosecond Atomic Streak Camera

Generate single (picosecond) cycle pulse using optical rectification of Ti-Sappire laser pulses – field ~ 50MV/m maximum





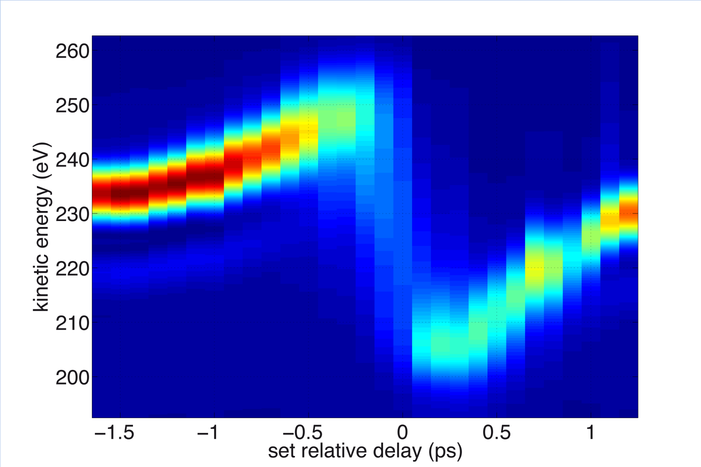


Principle of the experiment

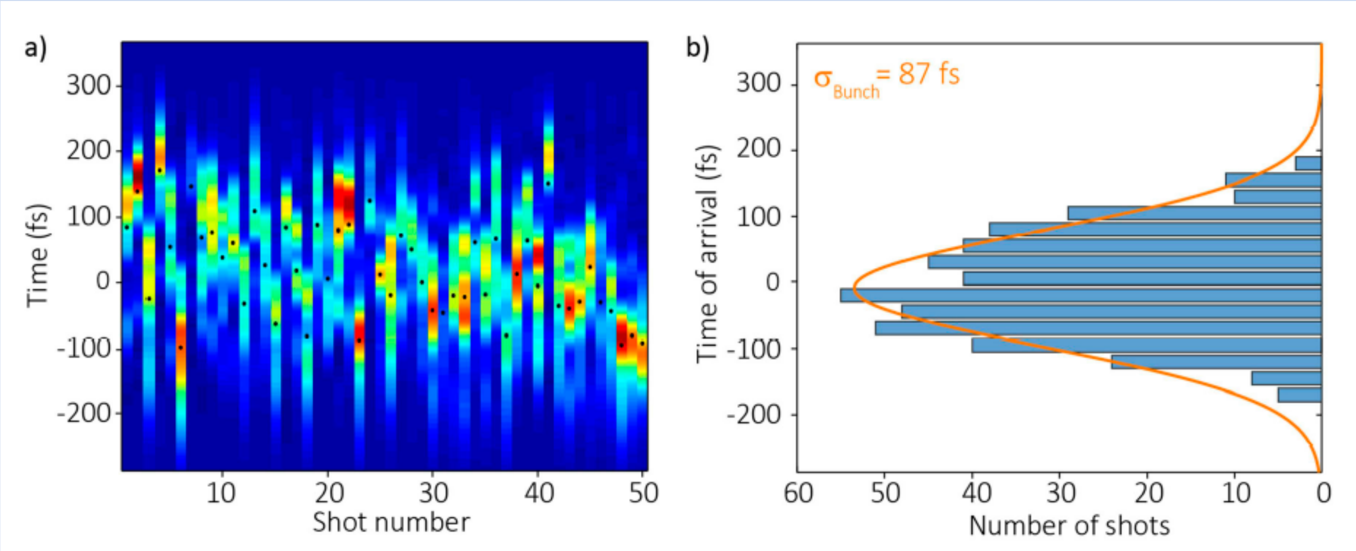
Attosecond Photoelectron Streaking showing how the E-field of a few cycle fs laser pulse can be mapped – MPI-Q.

Single Cycle THz Streaking @ FLASH

A Cavalieri et al. - CFEL, DCU, MPQ, XFEL & DESY



Single cycle THz Photoelectron streaking showing how the E-field of a single cycle picosecond (THz) pulse can be mapped out.



Jitter measurements on 50 consecutive streak traces

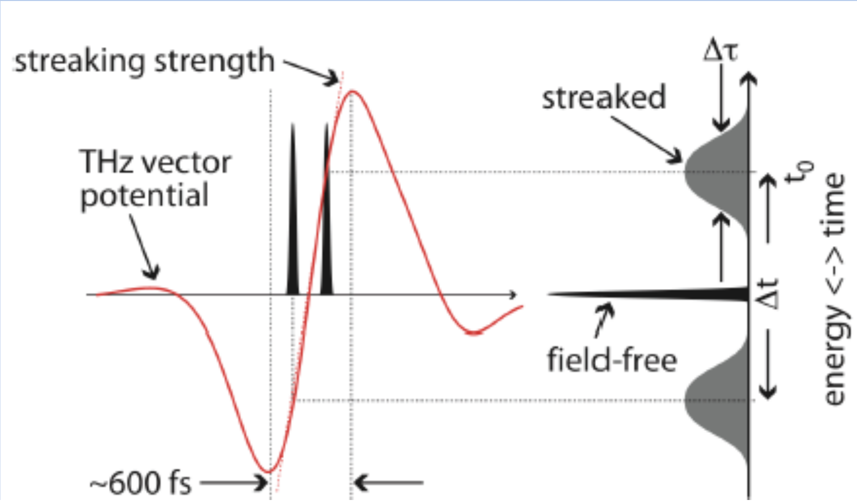
NCPST EXTATIC

Nature Photonics **6** pp852-857 (2012)

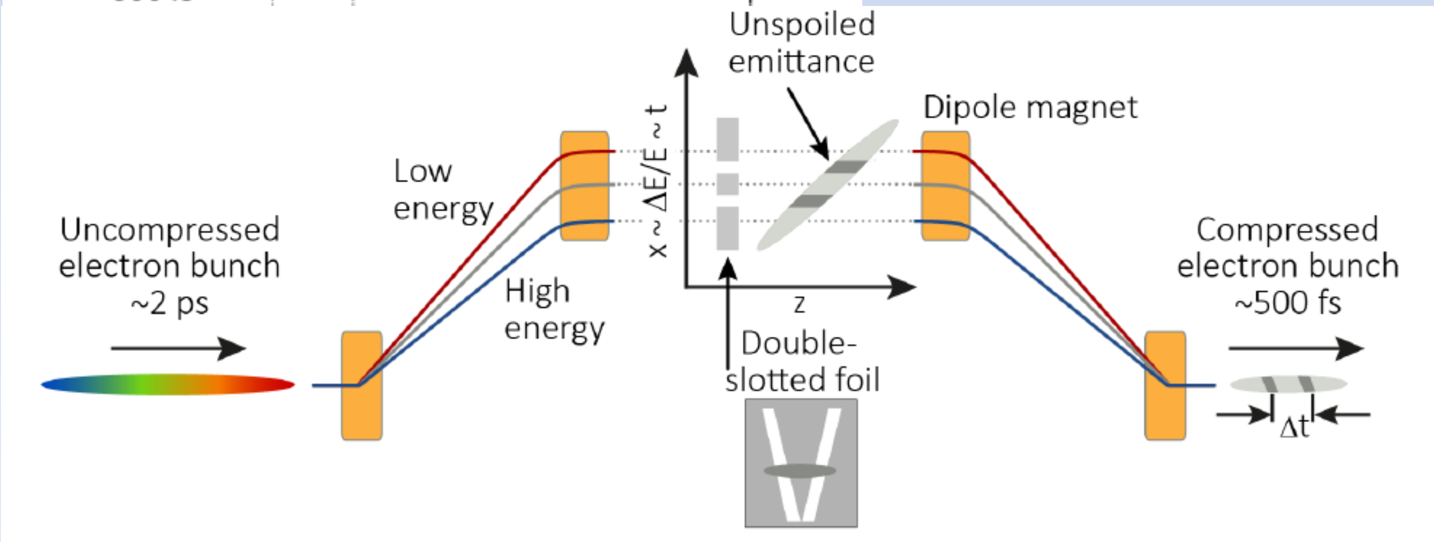
sfi science foundation ireland inspire Integrated NanoScience Platform for Ireland DCU

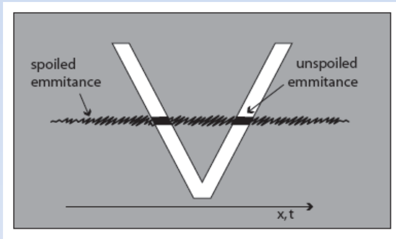
LCLS - Single Cycle THz Streaking

A Cavalieri et al. - CFEL, DCU, MPQ, XFEL & DESY



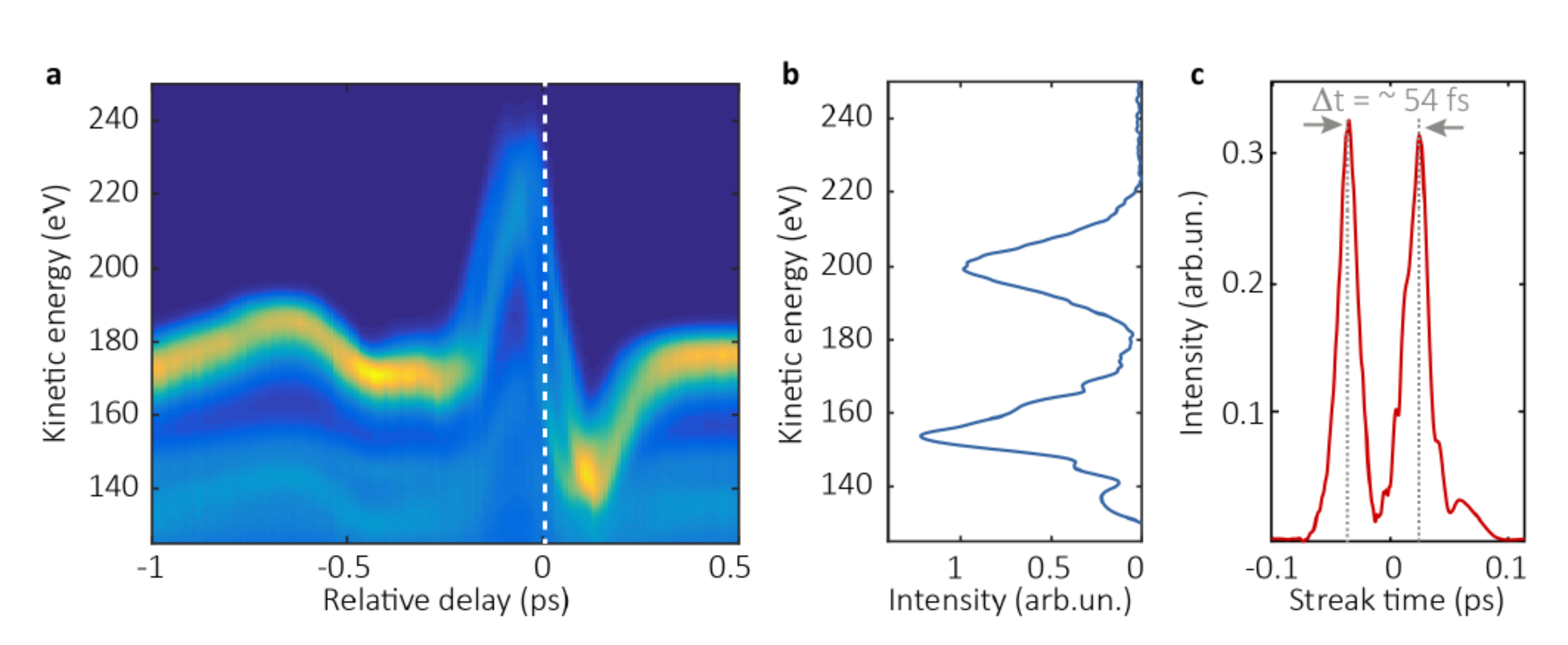
If the dispersed bunch is intercepted by a ‘V-shaped’ vertical slot, then **the emittance of the all but TWO small parts in space (time) of the bunch is ‘spoiled’** -=> 2 X ‘few fs’ pulses of variable separation result.





LCLS - Single Cycle THz Streaking

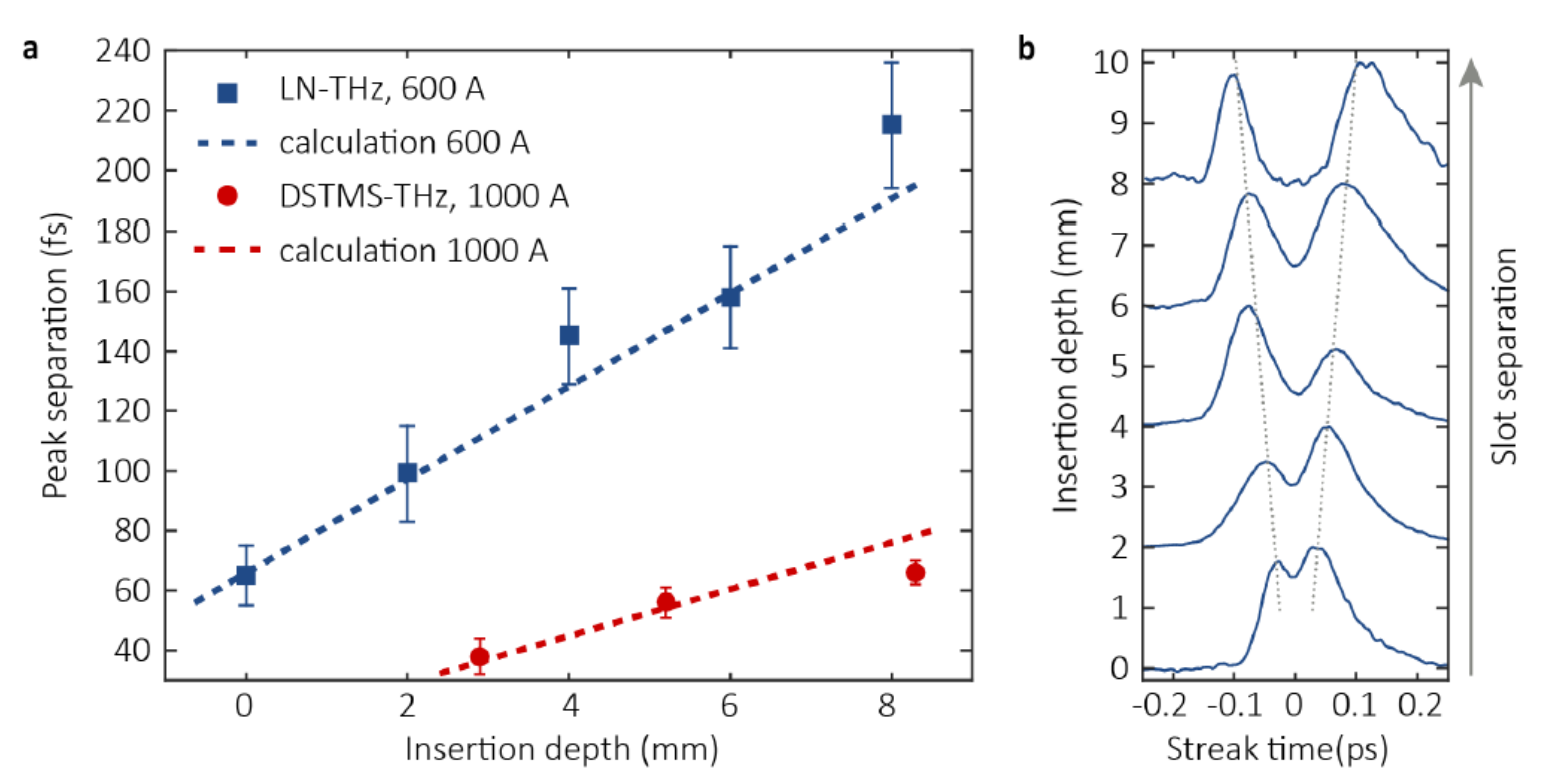
A Cavalieri et al. - CFEL, DCU, MPQ, XFEL & DESY



arXiv preprint arXiv:1705.01938

LCLS - Single Cycle THz Streaking

A Cavalieri et al. - CFEL, DCU, MPQ, XFEL & DESY



Result we can generate two pulses, each of few fs duration to few tens of fs duration and with a programmable delay of few fs to few 10 fs… So X-ray P-P experiments with fs resolution..!!

NEW !! All Optical Synchronisation - FLASH

A Cavalieri et al. - CFEL, DCU, MPQ, XFEL & DESY

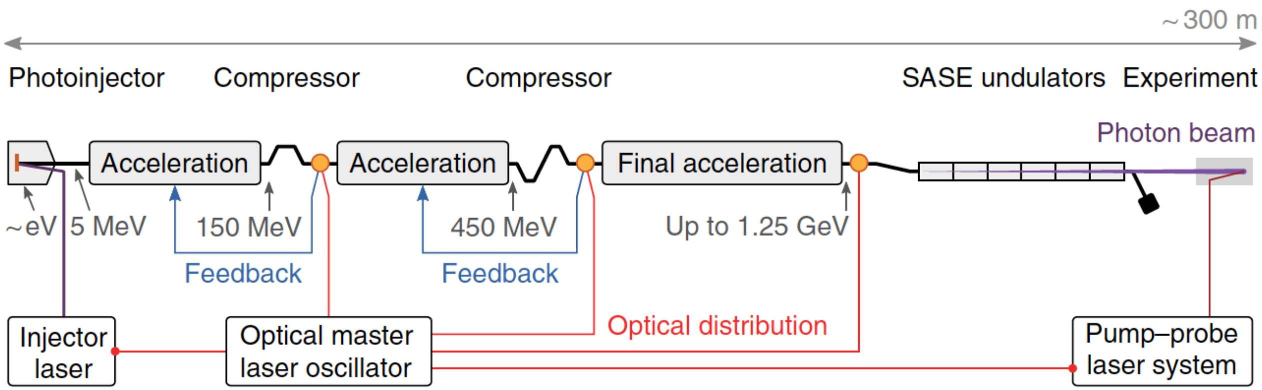
nature COMMUNICATIONS

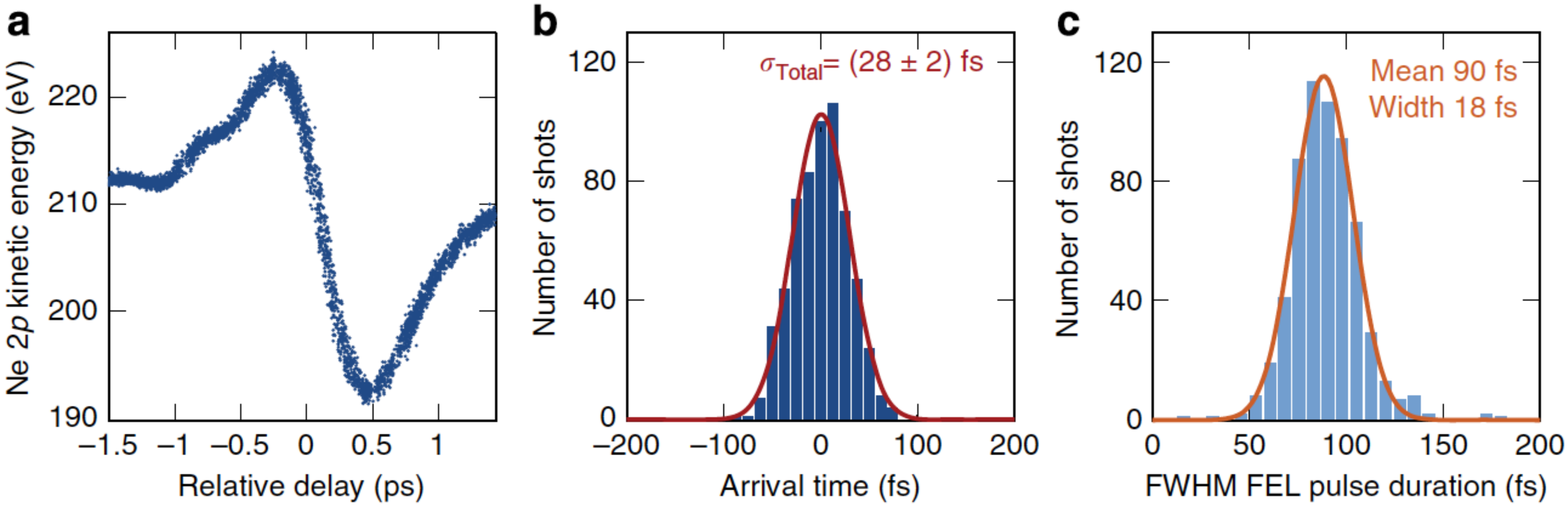
ARTICLE

Received 10 Apr 2014 | Accepted 24 Nov 2014 | Published 20 Jan 2015
DOI: 10.1038/ncomms6938 OPEN

Femtosecond all-optical synchronization of an X-ray free-electron laser

S. Schulz[1], I. Grguraš[2,3,4], C. Behrens[1,5], H. Bromberger[2], J.T. Costello[6], M.K. Czwalinna[1], M. Felber[1], M.C. Hoffmann[5], M. Ilchen[7], H.Y. Liu[2], T. Mazza[7], M. Meyer[7], S. Pfeiffer[1], P. Prędki[8], S. Schefer[4], C. Schmidt[1], U. Wegner[1], H. Schlarb[1] & A.L. Cavalieri[2,3,4]

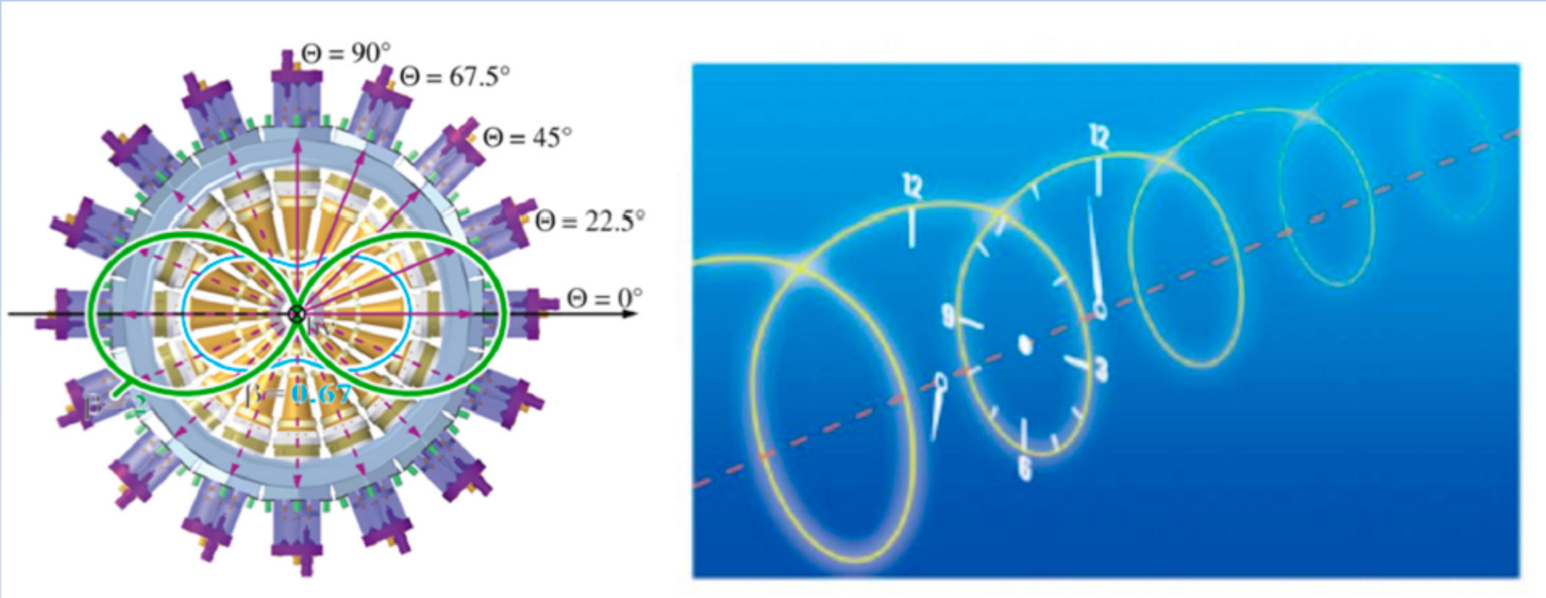




Nature Comms **6**
Art. No. 5938 (2015)

Angular Streaking

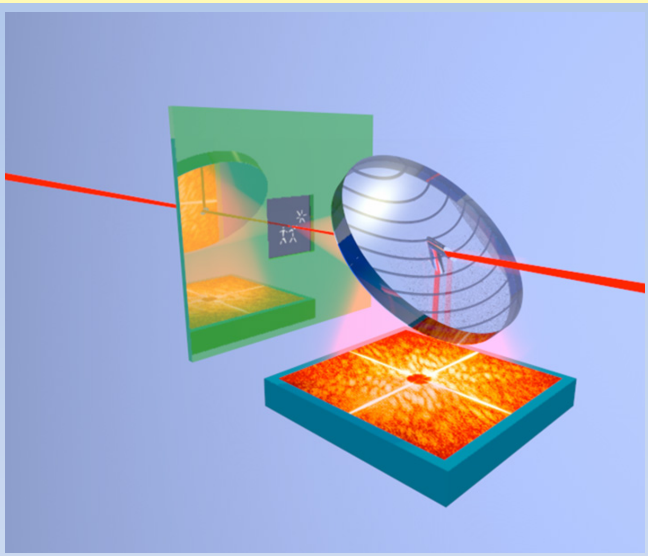
Circularly polarised streaking field: fs – ps. OPA - THz

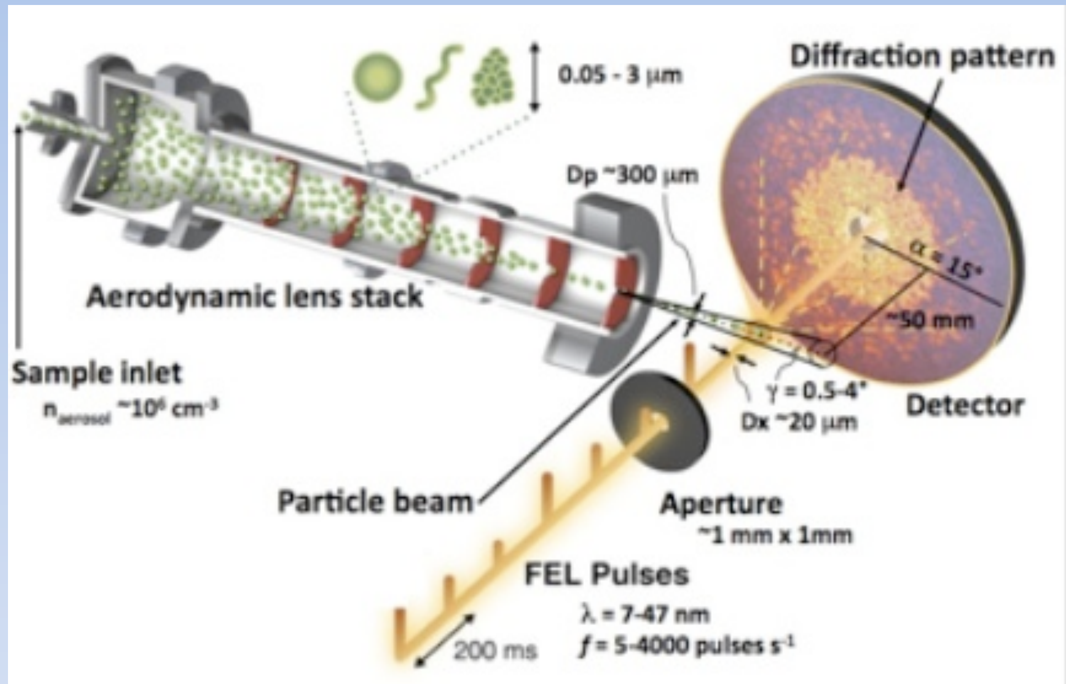


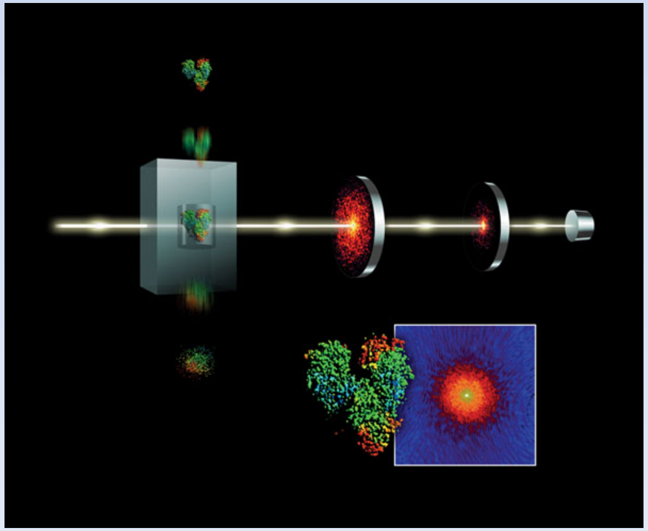
Map time to angle (as opposed to space or electron kinetic energy

Principle: Nat. Phys. **7**, 371, 2011)

Imaging single molecules !!!







Single shot dynamic coherent diffraction imaging on femtosecond timescales

Cf: CFEL, DESY, Uppsala, Stanford

PRL **114,** 098102 (2015) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Three-Dimensional Reconstruction of the Giant Mimivirus Particle with an X-Ray Free-Electron Laser

X-Ray Lasers - Future

Speculation

Ordinary X-rays are used in Diagnostics (Images) and Therapeutics (Cancer/Radiography).

X-ray lasers add the possibility to make 3D images (holograms) of the molecules that cause diseases and follow them on a femtosecond timescale as they do so !!

Molecular (Nanomedicine)……

Recent Open Access Review Article

Ultrashort Free-Electron Laser X-ray Pulses

W Helmi, I Grguras, P N Juranic , S Duesterer, T Mazza , A R Maier, N Hartmann, M Ilchen, G Hartmann, L Patthey, C Callegari, J T Costello, M Meyer, R N Coffee, A L Cavalieri and R Kienberger, Appl. Sci. **7** 915 (2017)

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