AMO Physics with Intense XUV and X-ray Free Electron Lasers

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http://www.ncpst.ie

http://www.physics.dcu.ie/~jtc

AICQT, Maynooth
1 June 2016

DCU Laser Plasma-AMO Physics Group

pulsed laser matter interactions (spectroscopy/ imaging / particle detection)

Principal Investigators (6): John T. Costello, Eugene T. Kennedy (Emeritus), Lampros Nikolopoulos (T), Jean-Paul Mosnier & Paddy Hayden (SFI SIRG PI)

Current Postdocs (2): Dr. Pramod Pandey & Dr. Mossy Kelly

Current PhD students (9): Nichola Walsh, Ben Delaney, Stephen Davitt, Hu Lu, Getasew Wubetu, William Hanks, Muhammed Alli, Sadaf Syedah & Lazaros Varvarezos

Recent Int'l Interns (2012-16): K Nishant/R Tejaswi, (LNMIIT, Jaipur), C Hand, (NUIM), S Reddy/R Namboodiri/A Neettiyath (IIT Madras), R Singh/S Gupta (IIT Kanpur), S Howard (Notre Dame), I-M Carrasco Garcia (Malaga), R. Black (Notre Dame), P Colley (Notre Dame)

Recent PhD Grads (2009-2016): Padraig Hough, Conor McLoughlin, Rick O'Haire, Vincent Richardson, Dave Smith, Tommy Walsh, Jack Connolly, Jiang Xi, Leanne Doughty, Eanna MacCarthy, Colm Fallon, Mossy Kelly, D Middleton, Cathal O'Broin, Brian Sheehy & Saikumar Inguva

Recent Past Postdocs (2012-2015): Satheesh Krishnamurthy (Open Univ. UK), Pat Yeates (Elekta Oncology UK) & Subhash Singh (U. Allahabad), Colm Fallon (IC4 – DCUBS)

Collaboration @ FLASH-DESY & FERMI-ELETTRA

XFEL: P. Radcliffe & M. Meyer

Paris (UPMC): R. Taieb (T) & A. Maquet (T)

FERMI: P. O'Keefe, L. Avaldi & K. Prince

DESY (Hamburg): K. Tiedke, S. Düsterer, W. Li, A. Sorokin & P. Juranić,J. Feldhaus

Orsay: D. Cubaynes

Queen's University Belfast: C. L. S. Lewis

Moscow State University : A. N. Grum-Grzhimailo, E. V. Gryzlova, S. I. Strakhova

Crete: P. Lambropoulos (T)

Oulu/GSI: S. Fritzsche (T)

DCU: T. J. Kelly, T. Kennedy, L. Nikolopo llo

Collaboration @ LCLS X-ray FEL (SLAC)

DESY (CFEL): I. Grguras, M Hoffmann & A. Cavalieri

DESY (FLASH): S. Düsterer & J. Feldhaus

DCU: T. J. Kelly, E. Kennedy, V. Richardson, L. Nikolopoulos (T) & J. T. Costello

MPQ/TU-Munich: A. Maier, W. Helml, W. Schweinberger & R. Kienberger

Ohio (OSU): C. Roedig, G. Doumy* & L. DiMauro

Tohuku University: K. Ueda

Hiroshima University: S. Wada

SLAC: R. Coffee, J. Hastings, C Boestedt, J. Bozek et al.

XFEL Gmbh: P. Radcliffe, T. Tschenscher & M. Meyer

Moscow State University: N. Kabachnik

Thanks to Paul E

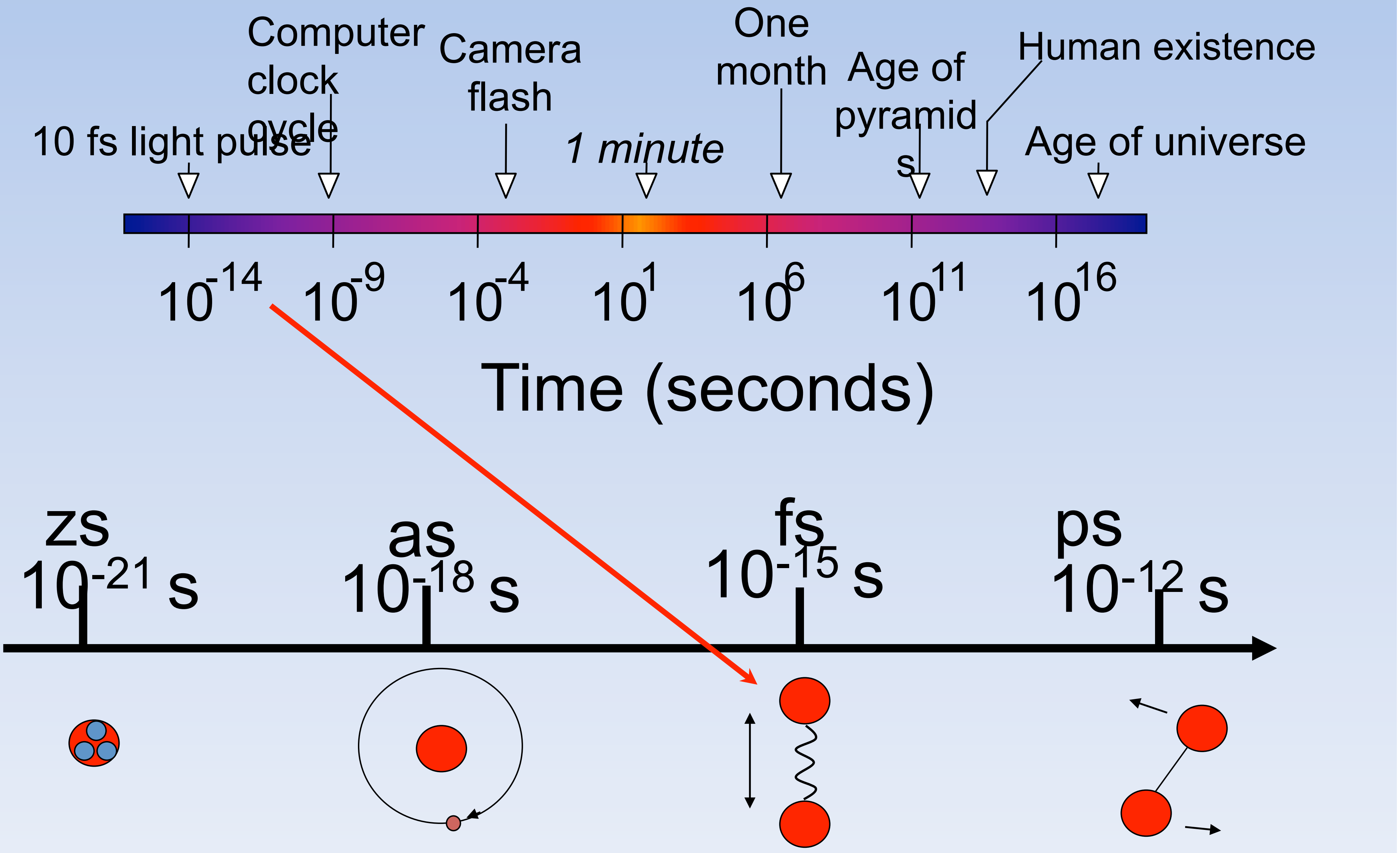
Some members of the LCLS collaboration

NCPST EXTATIC

AICQT, Maynooth
1 June 2016

sfi science foundation ireland inspire Integrated NanoScience Platform for Ireland DCU

TIMESCALES - HOW FAST IS FAST ?



10 fs light pulse

Computer clock cycle

Camera flash

1 minute

One month

Age of pyramids

Human existence

Age of universe

10^{-14} 10^{-9} 10^{-4} 10^{1} 10^{6} 10^{11} 10^{16}

Time (seconds)

zs 10^{-21} s

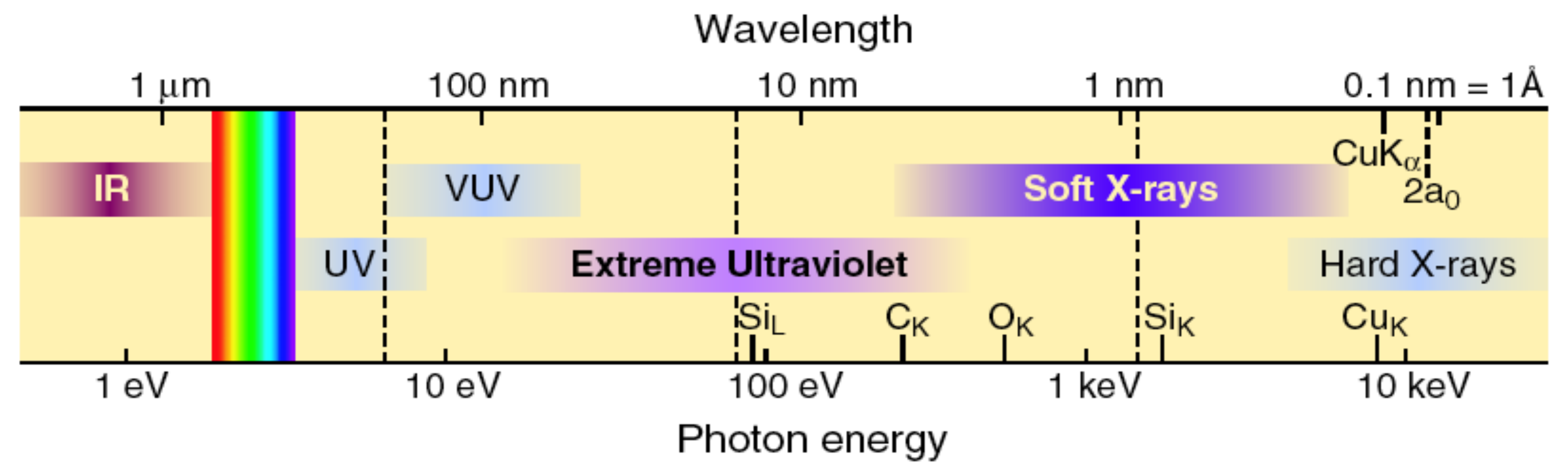
as 10^{-18} s

fs 10^{-15} s

ps 10^{-12} s

X-ray – How X-ray is X-ray ?

Spectral Range: IR to the X-ray



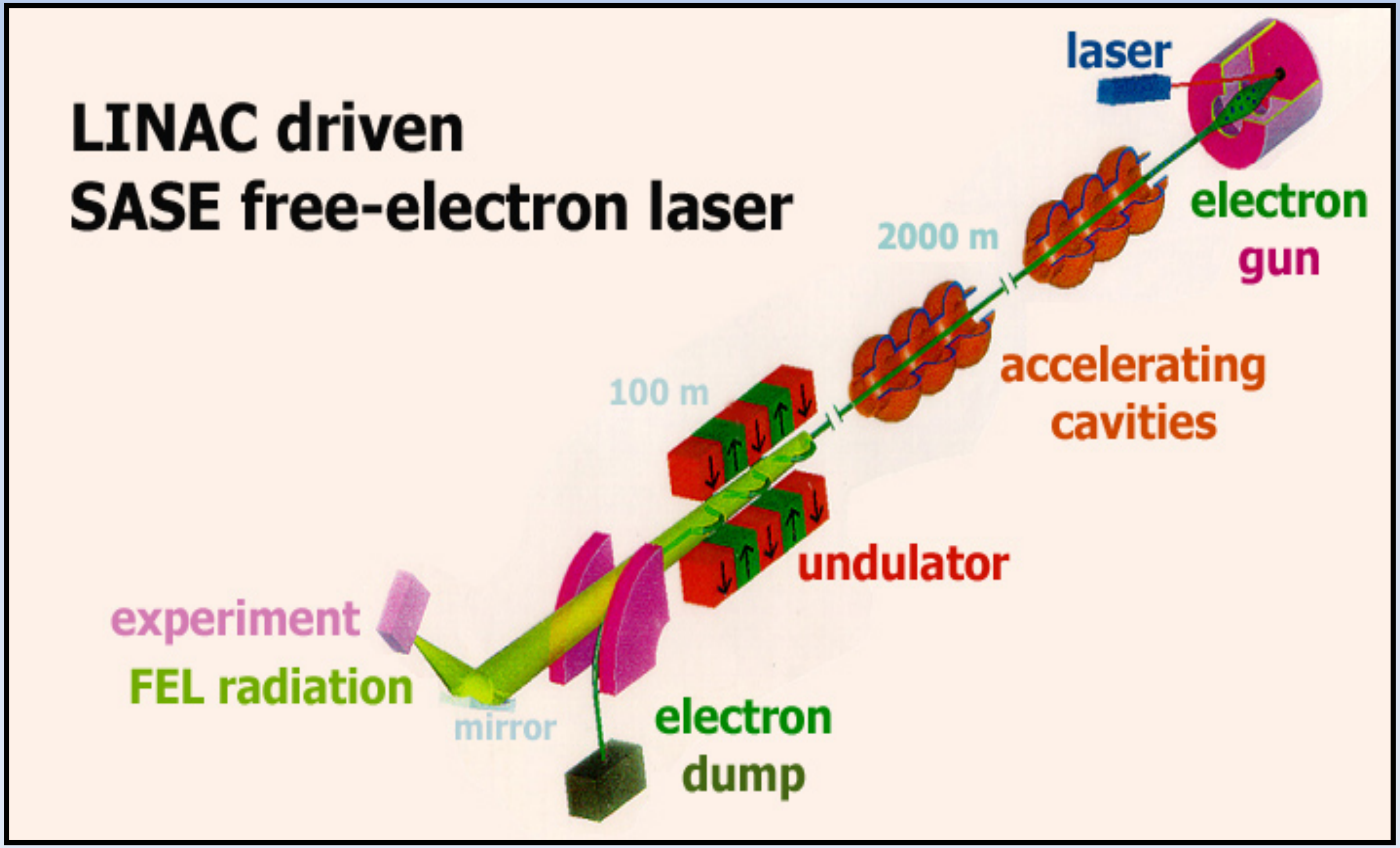
Graphic: Courtesy, Prof. David Attwood (Berkeley)

What do we want in an X-ray laser ?

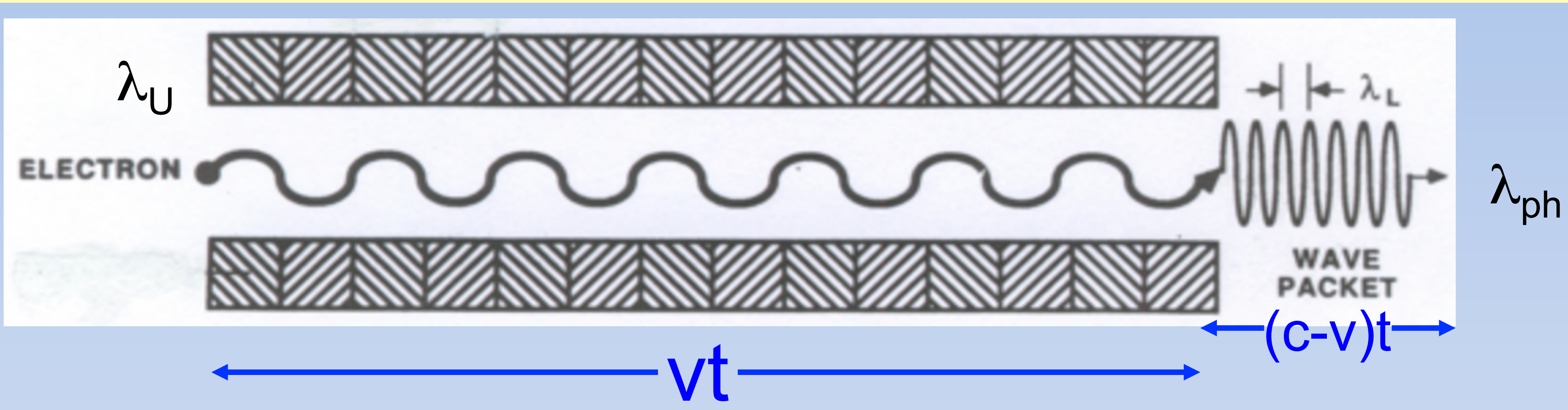
The Holy Grail is an X-ray laser with variable pulse duration on the femtosecond to attosecond timescales with tunable wavelength, variable polarisation and high energy per pulse (few 100 μJ to few 10 mJ).....

X-ray Free Electron Lasers (FEL)

Main Components of an X-ray FEL



SASE-FEL, Fundamental Principle



$N_u\lambda_U = vt$ $N_u\,\lambda_L = (c-v)t$ $\Rightarrow\ \lambda_L \sim \lambda_U\,(c-v)/v \sim \lambda_u/2\gamma^2$

1GeV machine $\gamma \sim 2000$

$\lambda_u \sim 2.7$ cm / $\lambda_{laser} \sim 6$nm

$\lambda_L = \lambda_u(1+K^2/2)/2\gamma^2$ $\gamma = E/mc^2$

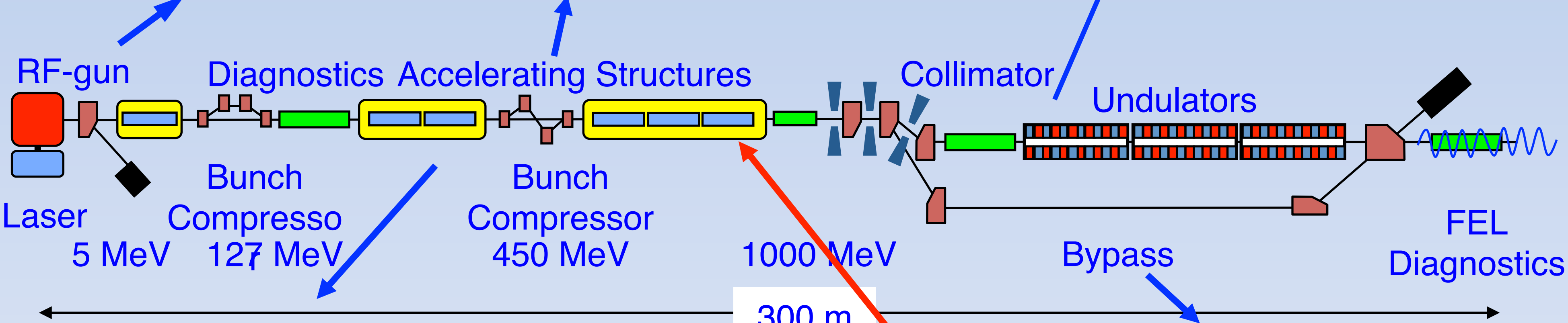
$K = eB\lambda_u/2\pi mc$

Wavelength tunable –
by electron beam energy or
by tuning the undulator gap

Electron bunch slips behind the lightwave by λ per undulator period

X-ray Free Electron Lasers (FEL)



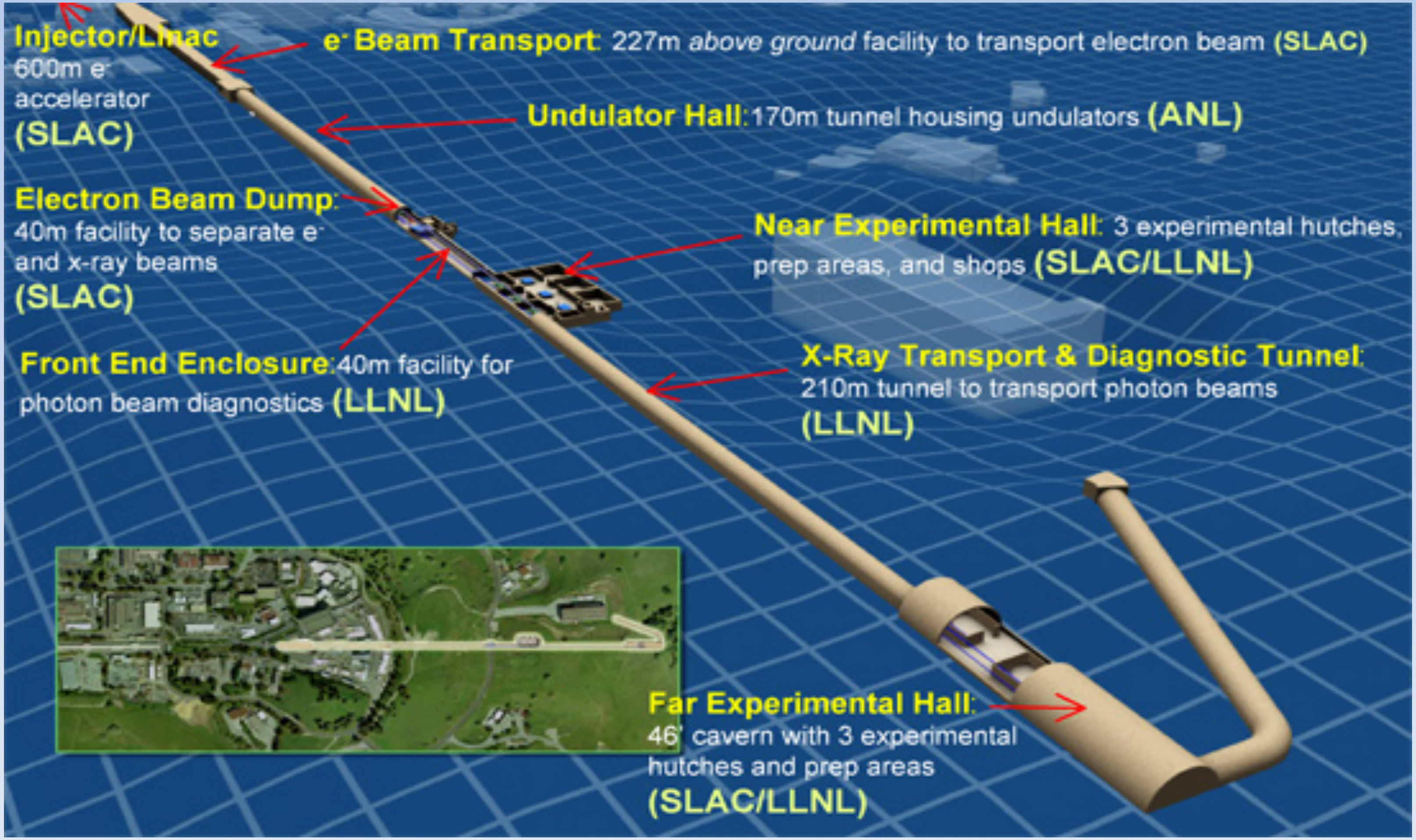
- LINAC Energy : ~ 1 GeV

  ~ 4 – 60 nm

FLASH - Operation & Physical Layout

X-ray Free Electron Lasers (FEL)

LCLS Overview and Specifications



Injector/Linac 600m e^- accelerator (SLAC)

e^- Beam Transport: 227m *above ground* facility to transport electron beam (SLAC)

Undulator Hall: 170m tunnel housing undulators (ANL)

Electron Beam Dump: 40m facility to separate e^- and x-ray beams (SLAC)

Near Experimental Hall: 3 experimental hutches, prep areas, and shops (SLAC/LLNL)

Front End Enclosure: 40m facility for photon beam diagnostics (LLNL)

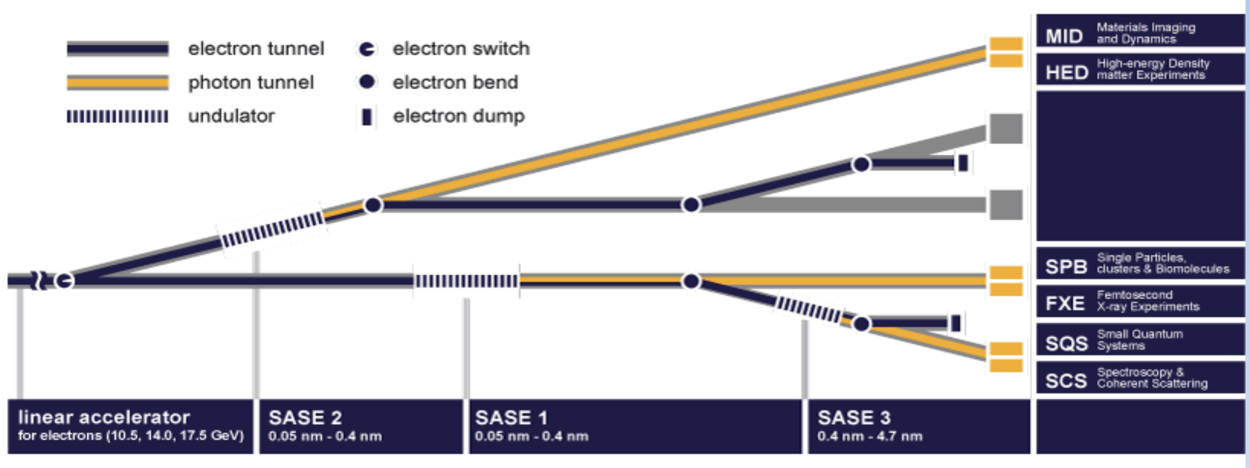
X-Ray Transport & Diagnostic Tunnel: 210m tunnel to transport photon beams (LLNL)

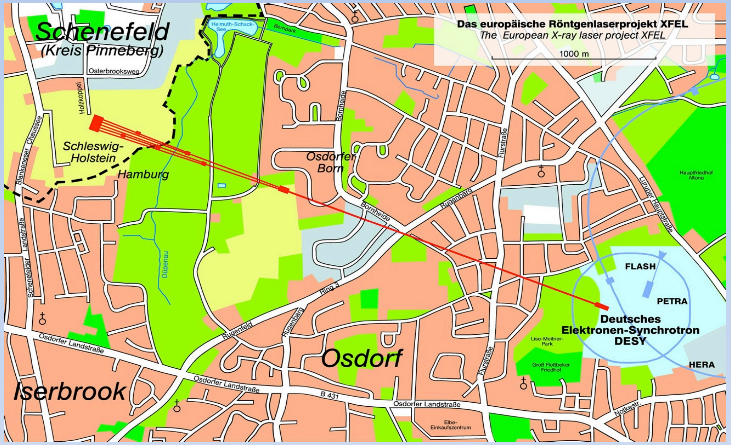
Far Experimental Hall: 46' cavern with 3 experimental hutches and prep areas (SLAC/LLNL)

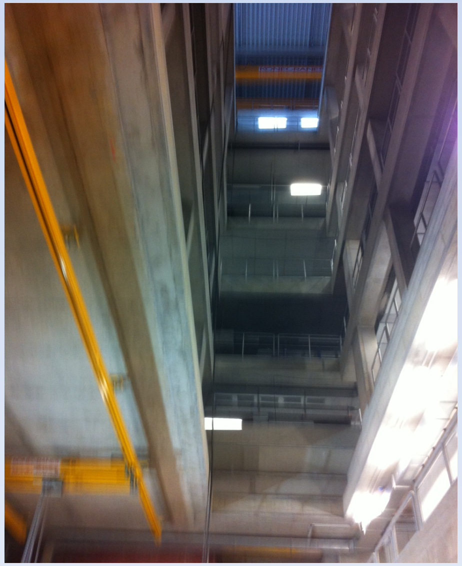
lcls.slac.stanford.edu

X-ray Free Electron Lasers (FEL)

XFEL – Under Construction…… 2017

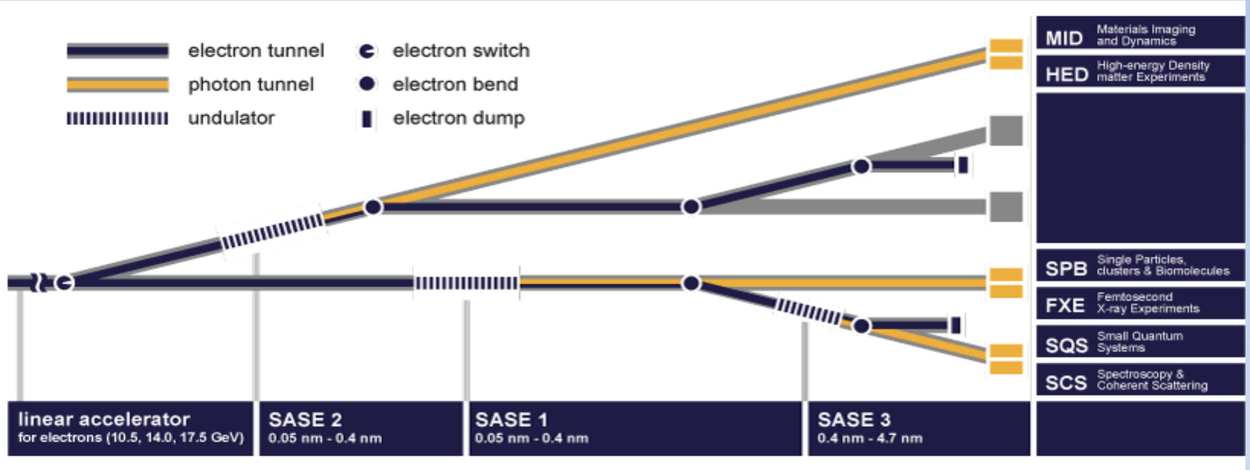






X-ray Free Electron Lasers (FEL)

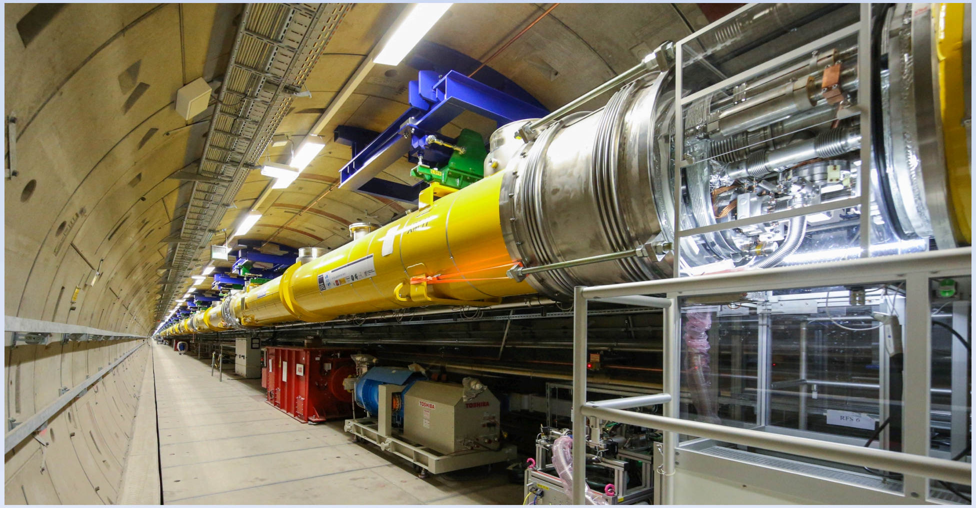
XFEL – Under Construction…… 2017



electron tunnel
photon tunnel
undulator
electron switch
electron bend
electron dump

MID Materials Imaging and Dynamics
HED High-energy Density matter Experiments
SPB Single Particles, clusters & Biomolecules
FXE Femtosecond X-ray Experiments
SQS Small Quantum Systems
SCS Spectroscopy & Coherent Scattering

linear accelerator for electrons (10.5, 14.0, 17.5 GeV)
SASE 2 0.05 nm - 0.4 nm
SASE 1 0.05 nm - 0.4 nm
SASE 3 0.4 nm - 4.7 nm



USPs of XUV & X-ray FELs (XFELs)?

- ***High flux per pulse* – typ. 10^{13} photons/pulse**
- ***Tunable pulsewidth* – from 1 to few 100 fs**
- ***Ergo high peak intensity* – up to few 10^{20} W.cm^{-2} possible**
- ***Seeded and unseeded* *modes now possible***
- ***Unseeded bandwidth* – 0.2 – 1.0%**
- ***Seeded bandwidth* – 0.005% (typ.) / $\lambda/\Delta\lambda \geq 10^4$**
- ***Synchron* *o optical fs lase***

Technology Now…..

So the Holy Grail is now largely realised as the SASE EUV and X-ray FELs at SLAC-Stanford, SCSS & SACLA-RIKEN, FLASH-DESY (+future European XFEL), FERMI@ELETTRA-Trieste, SwissFEL-PSI, Pohang, Shanghai, Dalian, etc……..

Very recently [20 of LCLS, SCSS and

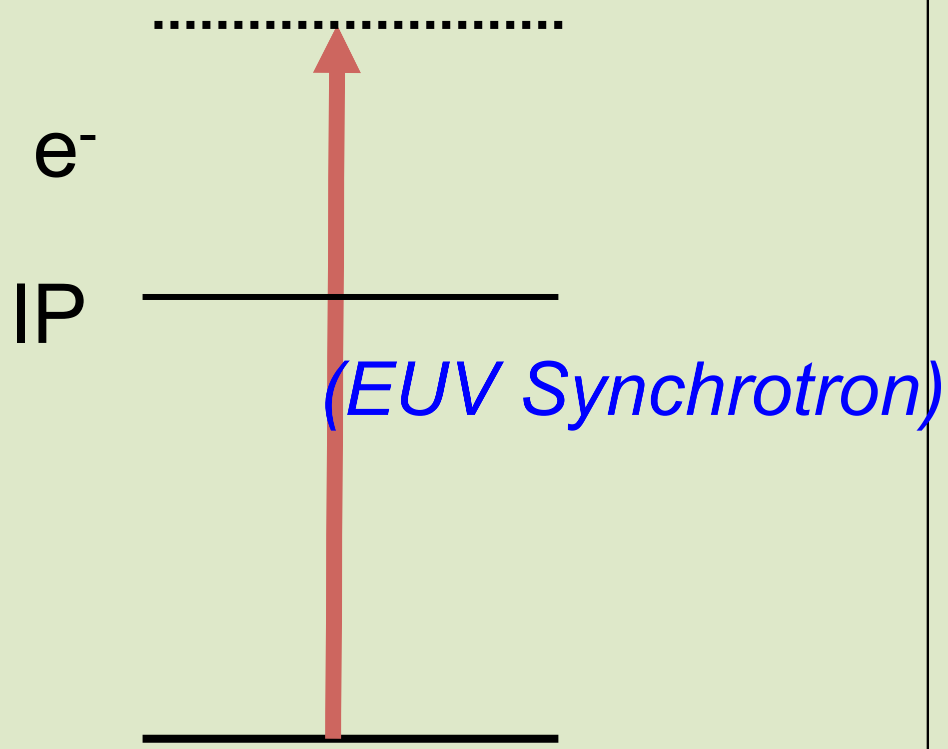
Ionization in Intense Fields

1. **Rudiments of ionization processes in intense laser fields**
2. Photoionization experimental setups (FLASH & DESY)
3. One colour – two photon ionization
4. Two colour Ionization – physics and characterisation
5. Some co

The Atomic Photoelectric Effect

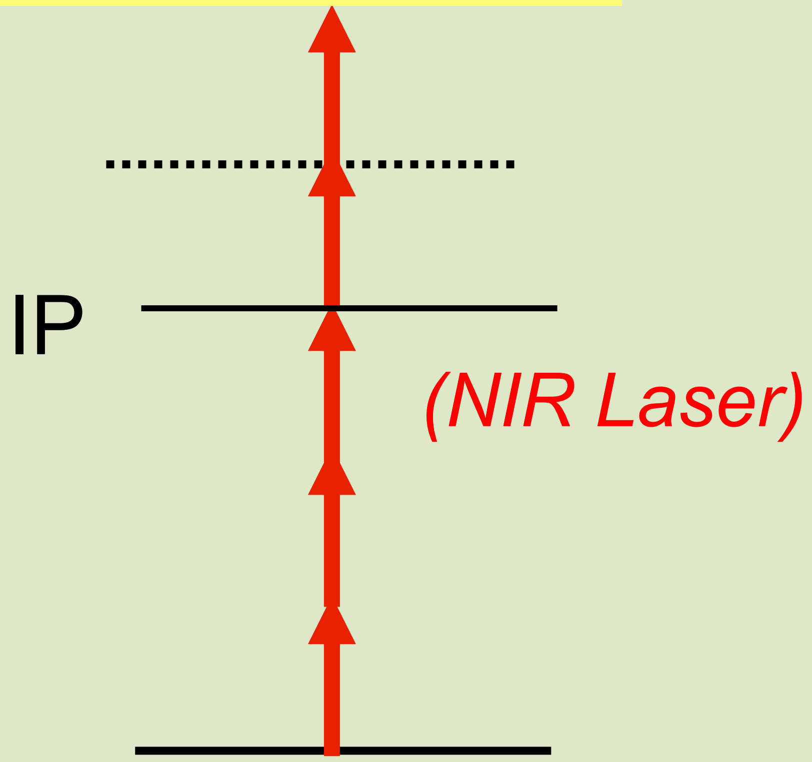
a) Single Photon Ionization (SPI)

$KE(e^-) = h\nu_{EUV} - IP$

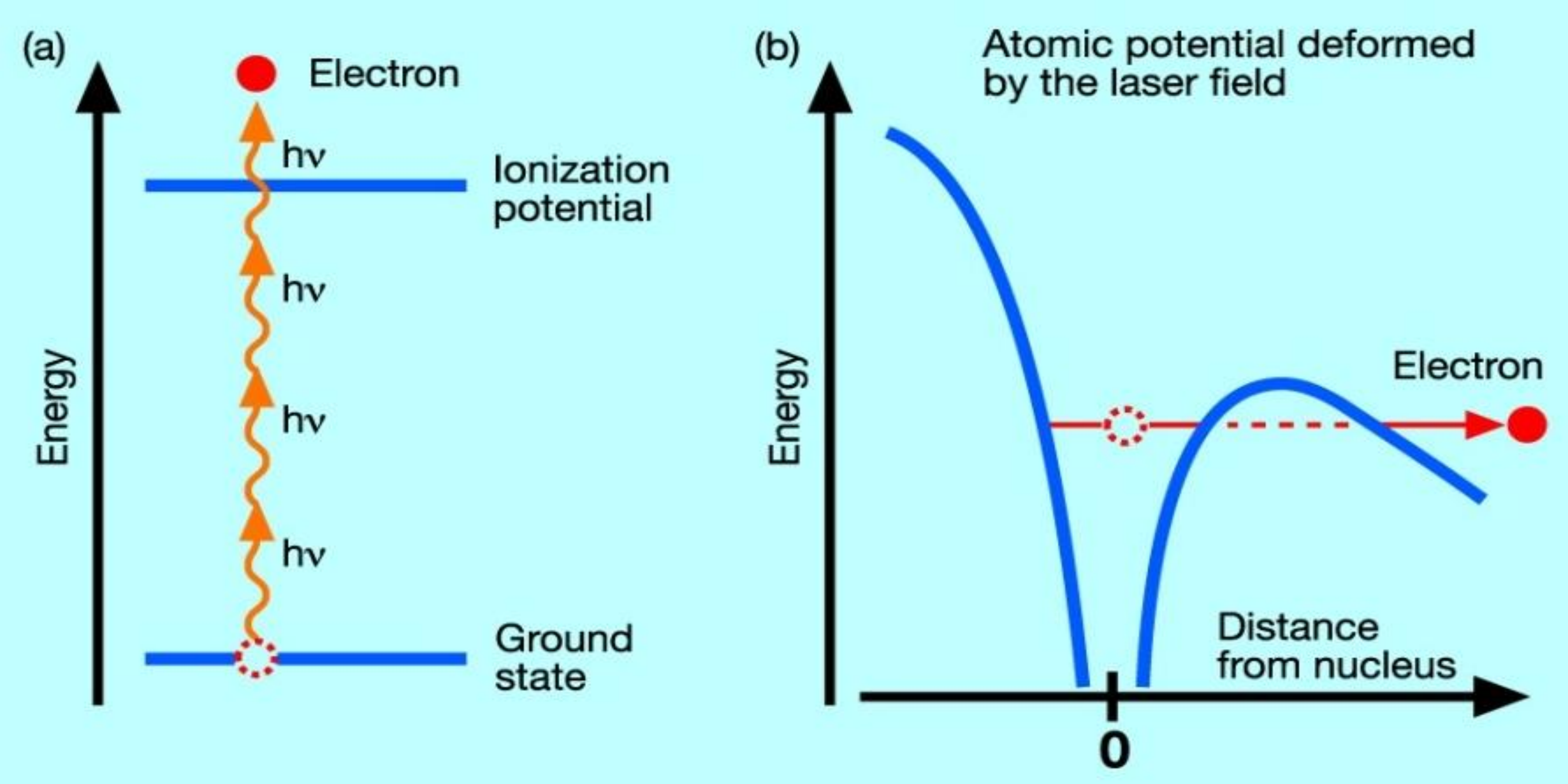


b) Multi Photon Ionization (MPI)

$KE(e^-) = nh\nu_{NIR} - IP$



What happens as the laser intensity (field strength) grows ?



Intensity/ Wavelength

Photon Energy

How can you determine in which regime the interaction resides ?

$$\gamma = \sqrt{\frac{IP}{2U_p}}$$

Keldysh Parameter

IP = Ionization Potential
Up = Ponderomotive Pot.

$$U_P = 9.3\times10^{-14}\, I\left(Wcm^{-2}\right)\, \lambda^2(\mu m) \quad eV$$

*L V Keldysh, Sov.Phys-JETP 20 1307 (1965)

Keldysh - Ionization Regime

Multiphoton Ionization	Tunnel Ionization	Field Ionization
$\gamma >> 1$	$\gamma \sim 2$	$\gamma << 1$

Example: ***Helium*** in intense laser fields

For Ti-sapphire laser: 800 nm, 10^{15} Wcm^{-2}, γ ~0.45 (TI/FI regi

For an EUV laser: 8 nm, 10^{15} Wcm^{-2}, γ ~45 (MPI regime)

So for EUV lasers, multi-photon ionization is th
primary processs and will involve
few photons and *potentially few electrons*

USPs of XUV & XFELs in AMO Physics ?

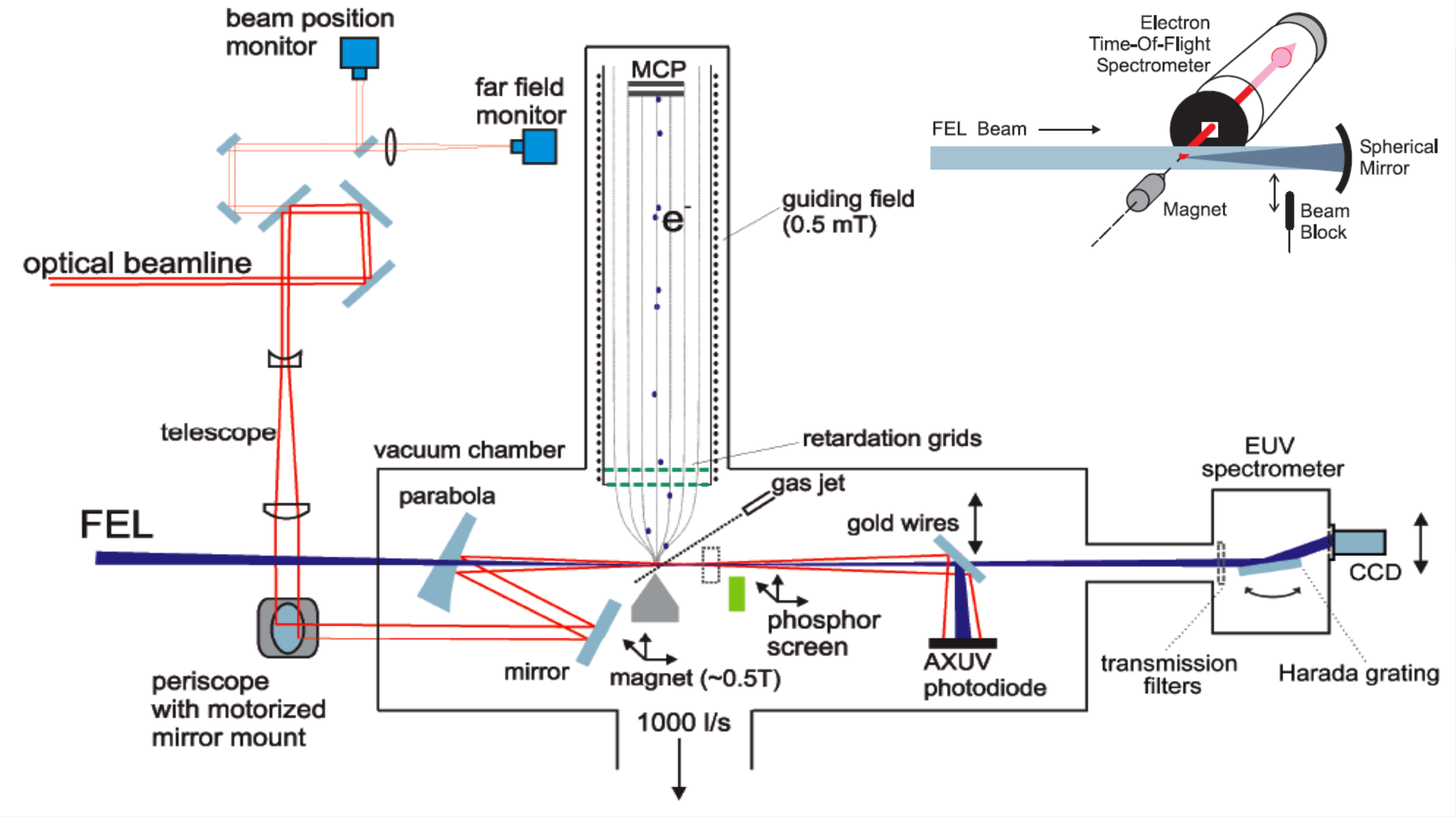
- *Photo*-processes with *ultralow cross-sections*
- *Pump and probe* experiments (EUV + EUV or EUV + Opt.)
- *Single shot* measurements
- *Few-photon* single and multiple *ionization processes*

NB1: Makes *inner-shell* electrons key actors in non-linear p for the first time

Experimental Setups (DESY & SLAC)

1. Rudiments of ionization processes in intense laser fields
2. **Photoionization experimental setups (FLASH & LCLS)**
3. One colour – two photon ionization
4. Two colou

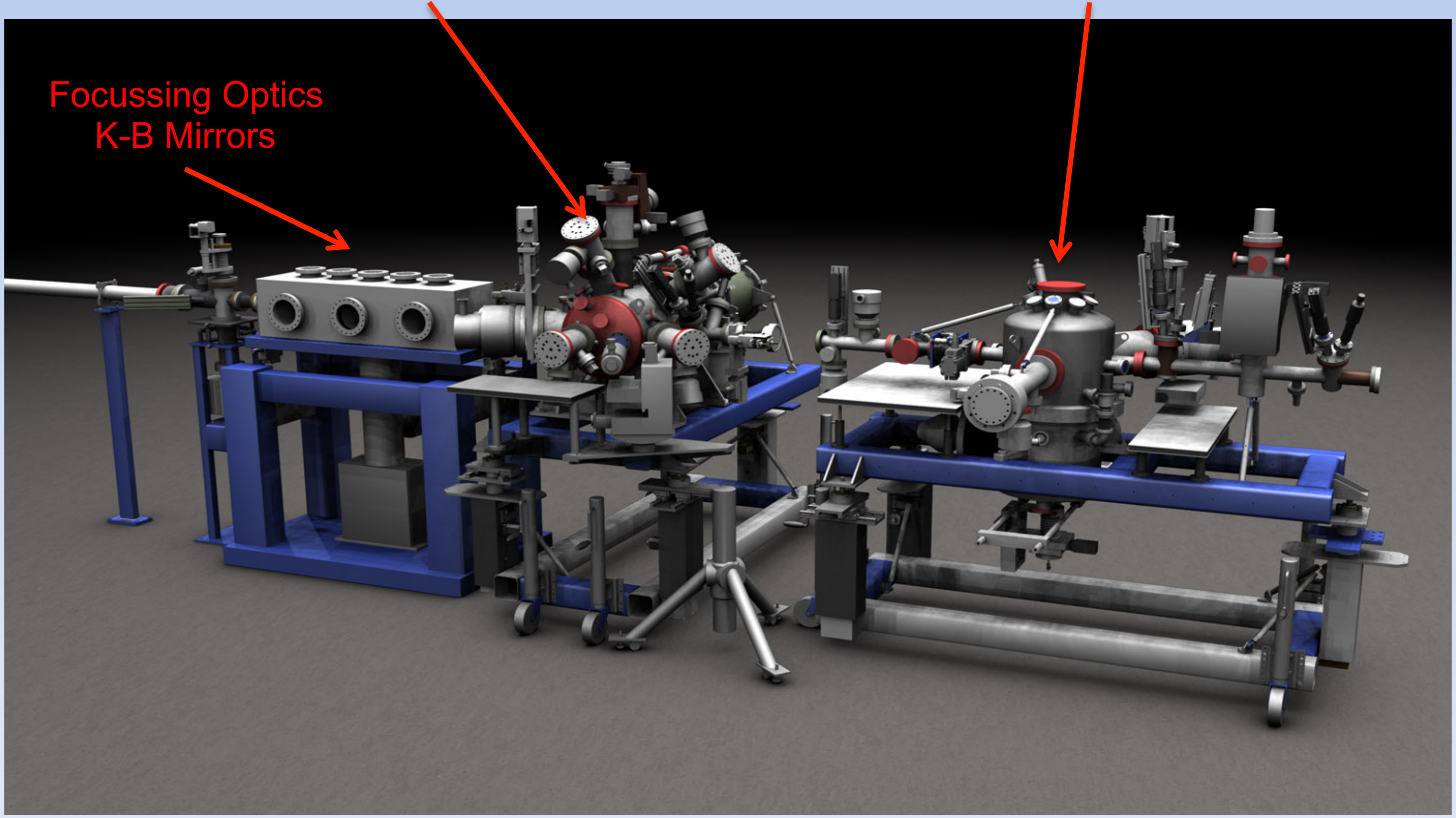
Photoelectron Spectroscopy @ FLASH



AMO PES Chamber at LCLS

Rendered Image:

High Field Chamber (AR-ETOF) and Diagnostics (MBES) Chamber



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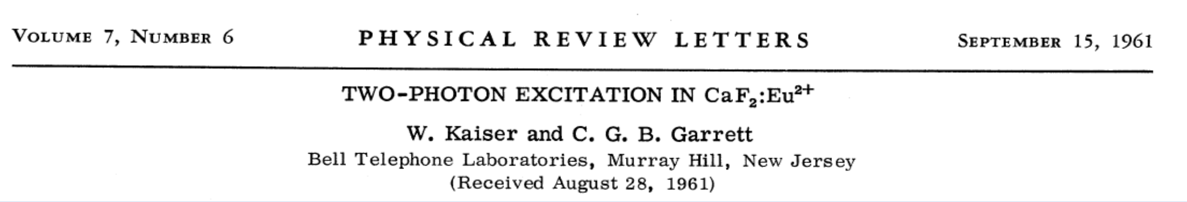
Two Photon Ionization (TPI) of Xe and Kr atoms in an Intense Field

1. Rudiments of ionization processes in intense laser fields
2. Photoionization experimental setups (FLASH & DESY)
3. **One colour - two photon ionization**
4. Two colour Ionization
5. Some co

Non-linear processes in the EUV & X-ray

Question. What is the simplest experiment you can carry out in non-linear optics ? Answer. Either two-photon absorption (TPA) or second harmonic generation (SHG)



VOLUME 7, NUMBER 6 PHYSICAL REVIEW LETTERS SEPTEMBER 15, 1961

TWO-PHOTON EXCITATION IN CaF$_2$:Eu^{2+}

W. Kaiser and C. G. B. Garrett
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received August 28, 1961)

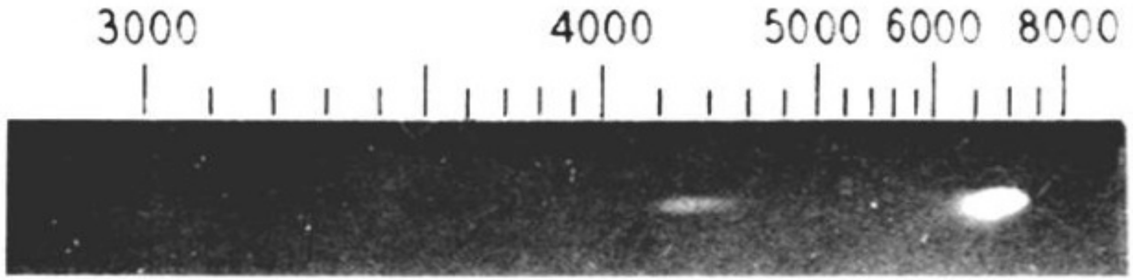
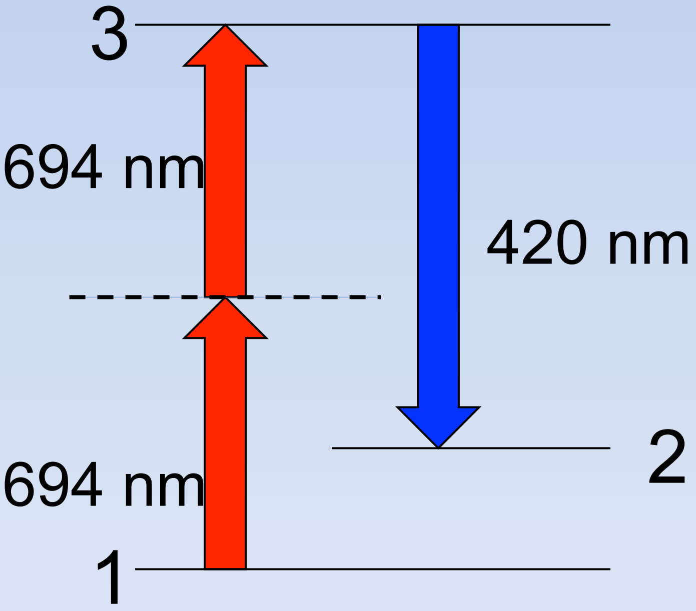


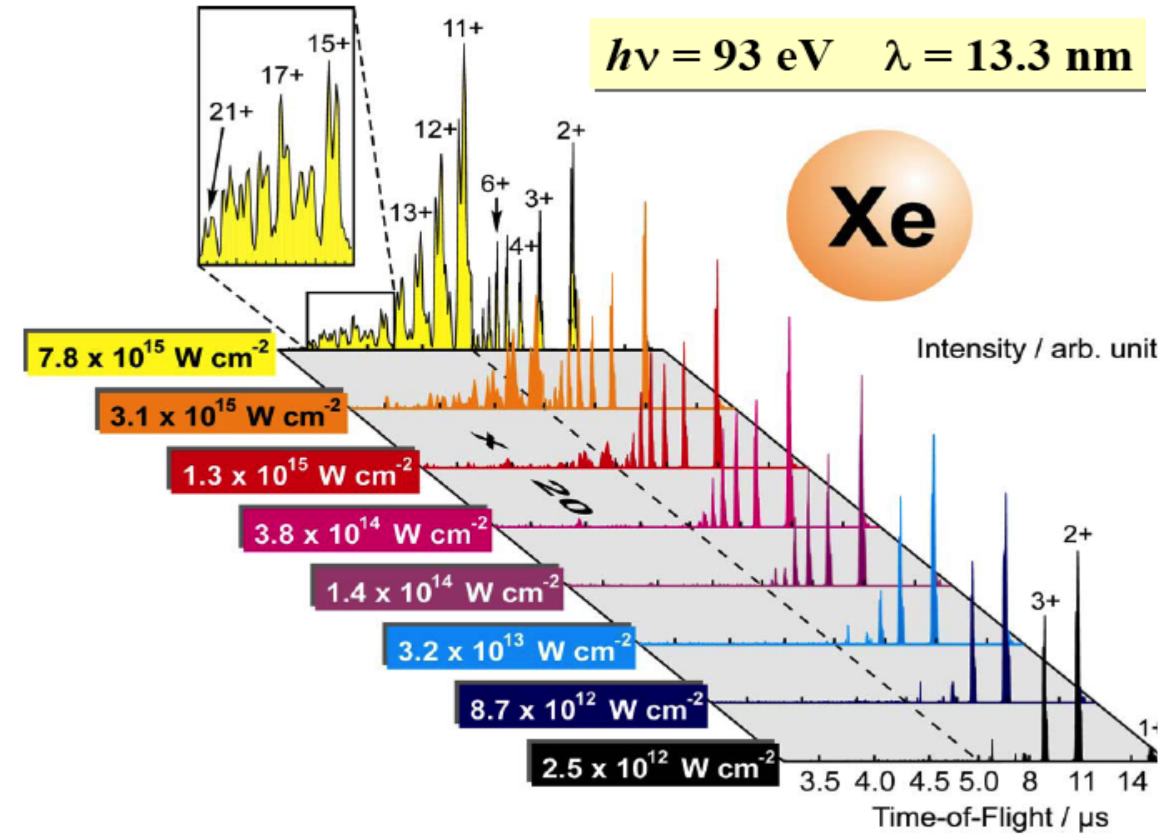
FIG. 1. Positive of photographic plate, indicating the blue emission of a CaF$_2$:Eu^{2+} crystal under strong illumination with $\lambda_\gamma = 6943$ A.

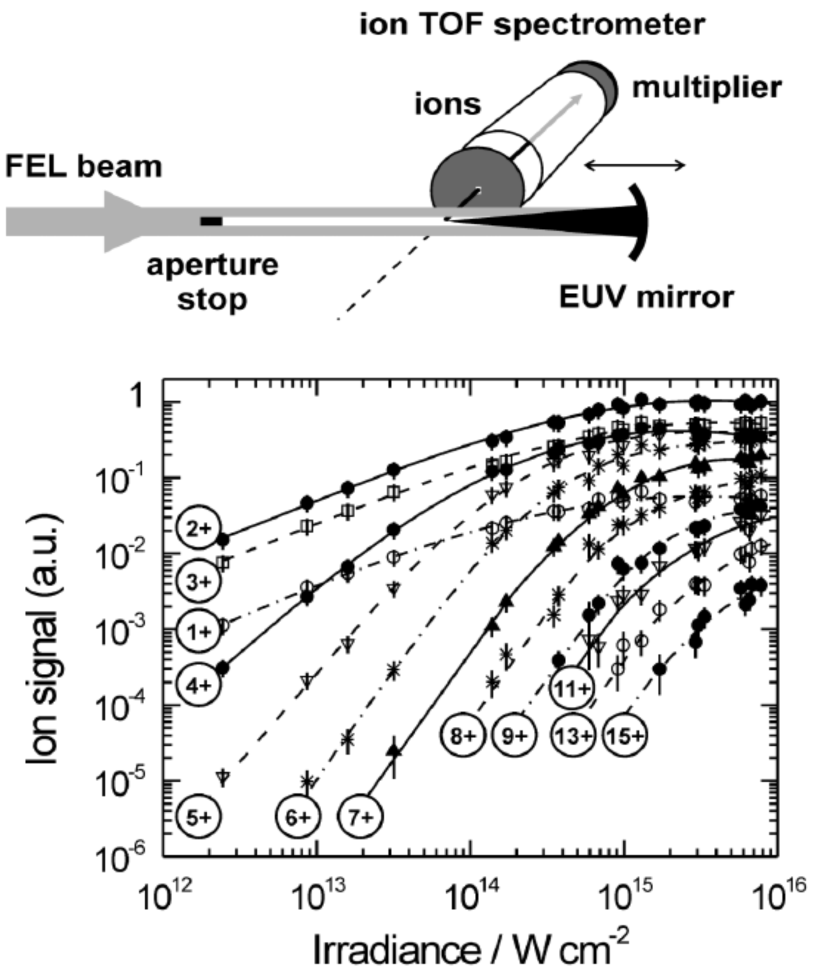


Motivation - Xe TPI in intense EUV fields

Sorokin, Richter et al., PTB, PRL 2007 – *Ion Spectroscopy !!*

Photoionization of xenon atoms in the EUV at ultra-high intensities: ion time-of-flight spectra

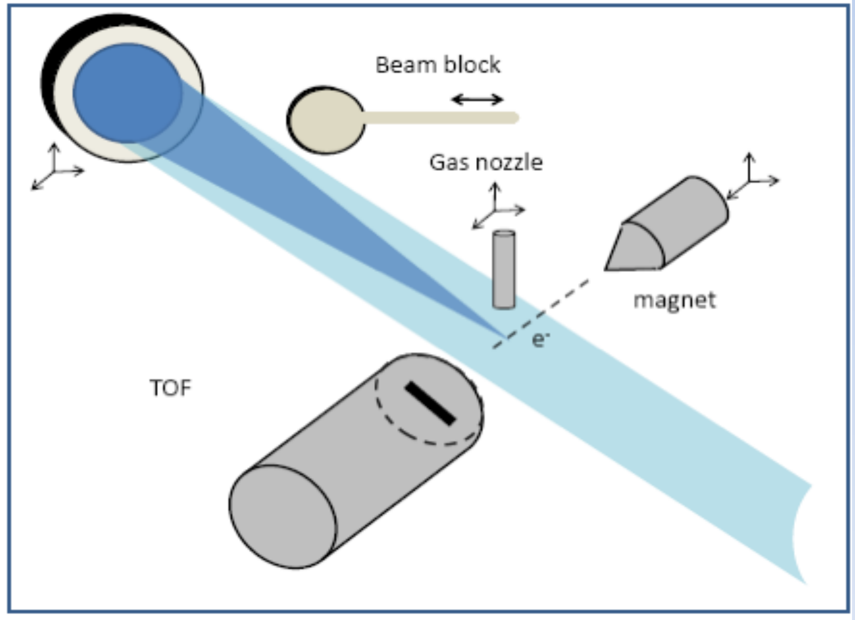




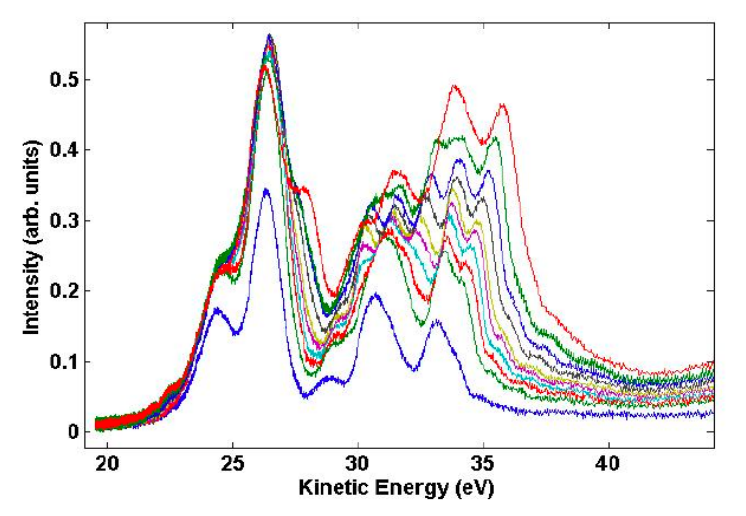
Xe + hν (93 eV) - Xe$^+$(4d^{-1}) + e$^-$ (~25 eV)

FEL only. hν ~ 93 eV

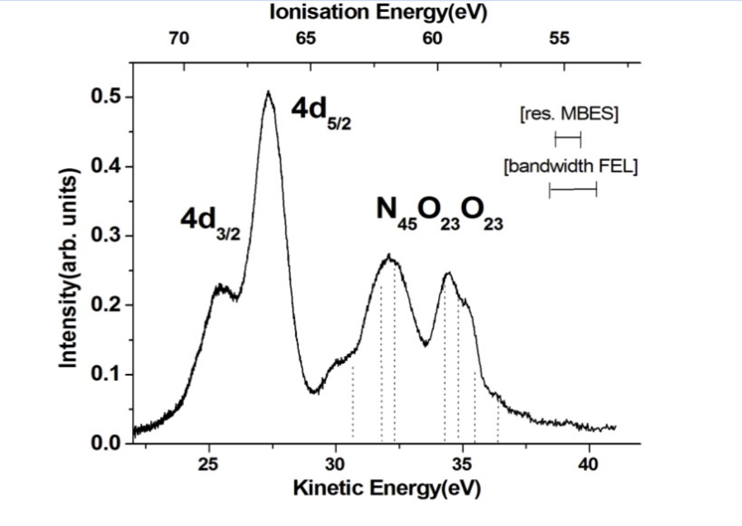
$$\mathrm{Xe} + h\nu \rightarrow \mathrm{Xe}^{n+} + e^-$$



Replace Ion TOF by MBES – photoelectron spectroscopy



Intensity scaling...



Weakest field…

Xe + 2hν (93 eV) - $Xe^+(4d^{-1})$ + e^- (~ 118 eV)

Now ramp up the intensity to > 10^{15} $W.cm^{-2}$ ....

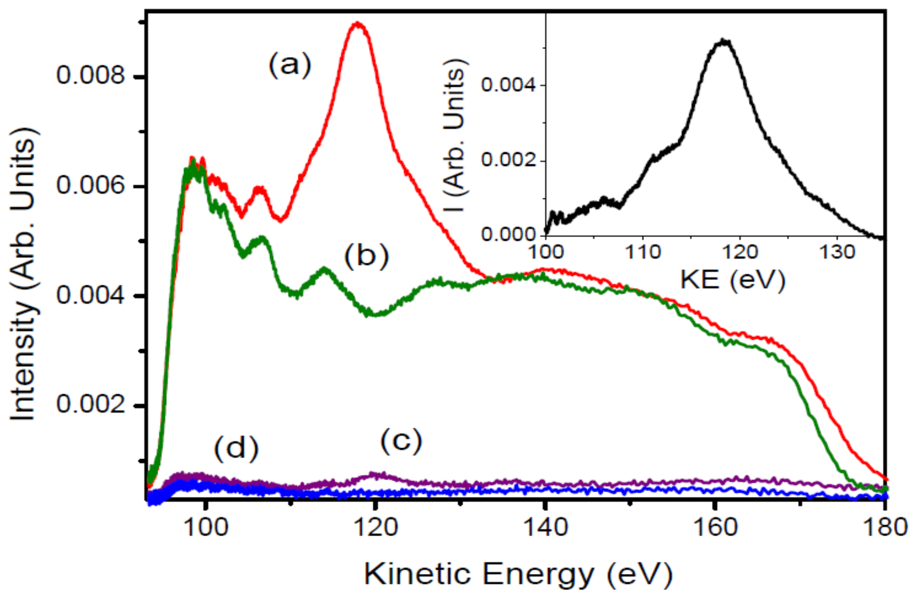
- Using MBES, first evidence of two photon ***inner*** shell ionisation, (in this case) of 4d electron –

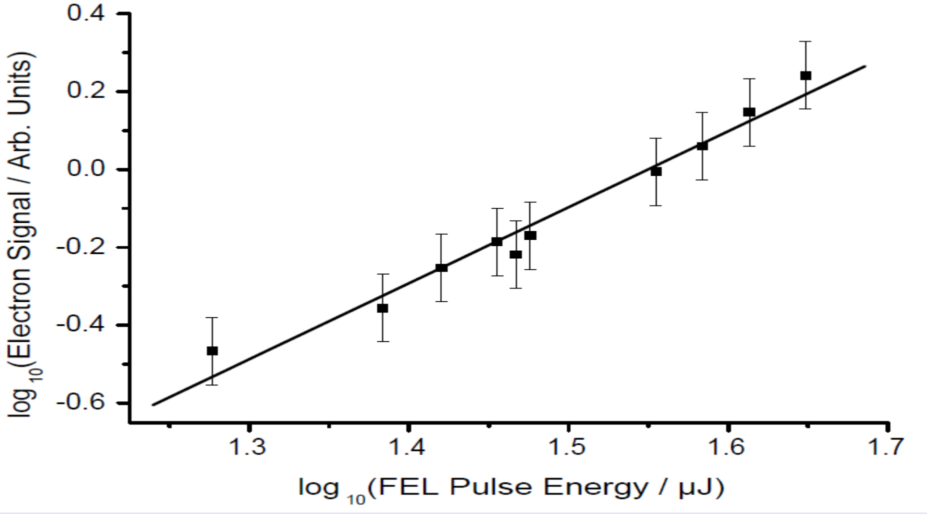
$Xe + 2h\nu \rightarrow Xe^+ \, 4d^9 + e^-$

- 'Retardation field' applied to suppress low KE electrons (one photon processes) – hence electrons detected are due solely to multiphoton events

- Energetically –

2 × (93) e 8 eV = 68 eV





Phys Rev Lett **105** 013001 (2010)

Summary - One Colour

- Xenon – Demonstration of an ‘above threshold absorption-ionization’ two-photon process involving an *inner shell electron*.

- It is clear that the although single photon ionization processes dominate, they are sufficiently important at high irradiance that, for a given intensity, much higher ionization stages can be reached compared to optical lasers.

- The strength and the nature of the 4*d* → ε*f* resonance may open up, at high irradiance, additional ionization channels, namely the *simultaneous multiphoton / multi-electron from the inner 4d shell, ‘inside-out ionization’ or ‘peeling the onion from the inside out’*

- *Kr (Not Shown) – was the first step on the road to resonant NL processes with EUV/X-rays….* ***REMPI at X-rays.***

Xe - Richardson e

/ 2 – 2010), Kr - Meyer

XUV (X-ray) + IR Ionization

1. Rudiments of ionization processes in intense laser fields
2. Photoionization experimental setups (FLASH & DESY)
3. One colour – two photon ionization
4. **Two colour Ionization**
5. Some con

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:

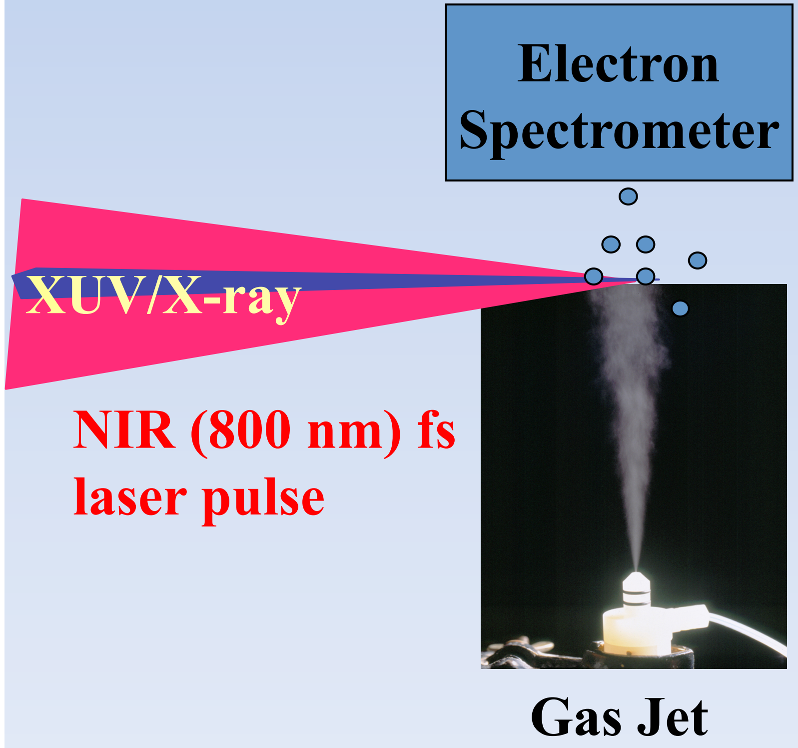
X-ray pulse duration comprises ‘many’ optical cycles
X-ray pulse duration is less than ½ optical cycle

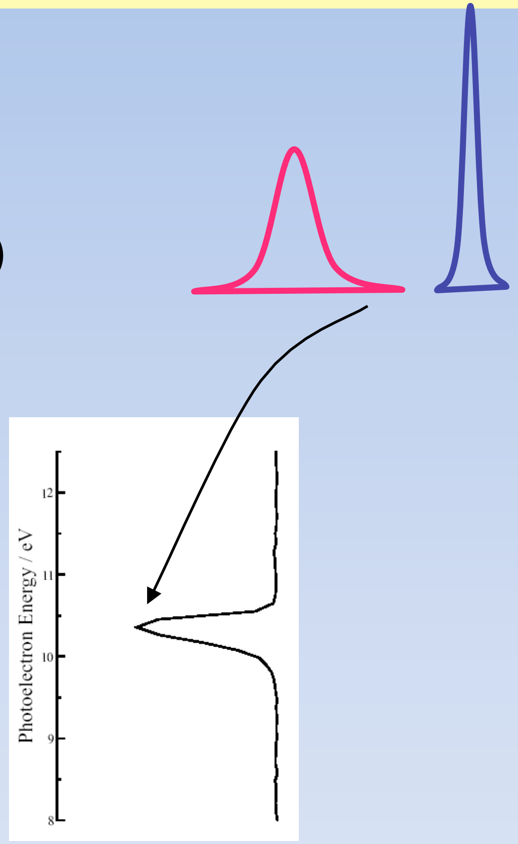
Two colour ATI/ Laser Assisted PES

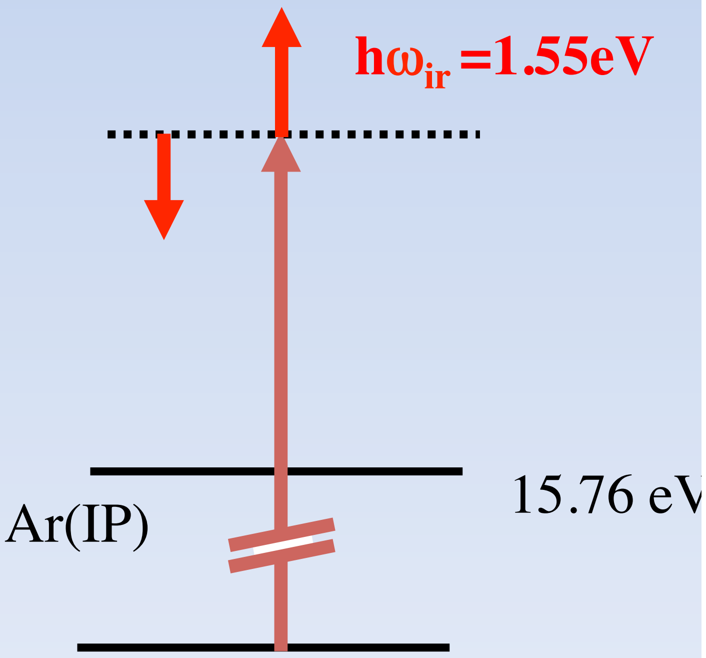
Superposition of visible and XUV pulses in a noble gas jet

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

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







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

Two colour ATI/ Laser Assisted PES

Superposition of visible and XUV pulses in a noble gas jet

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

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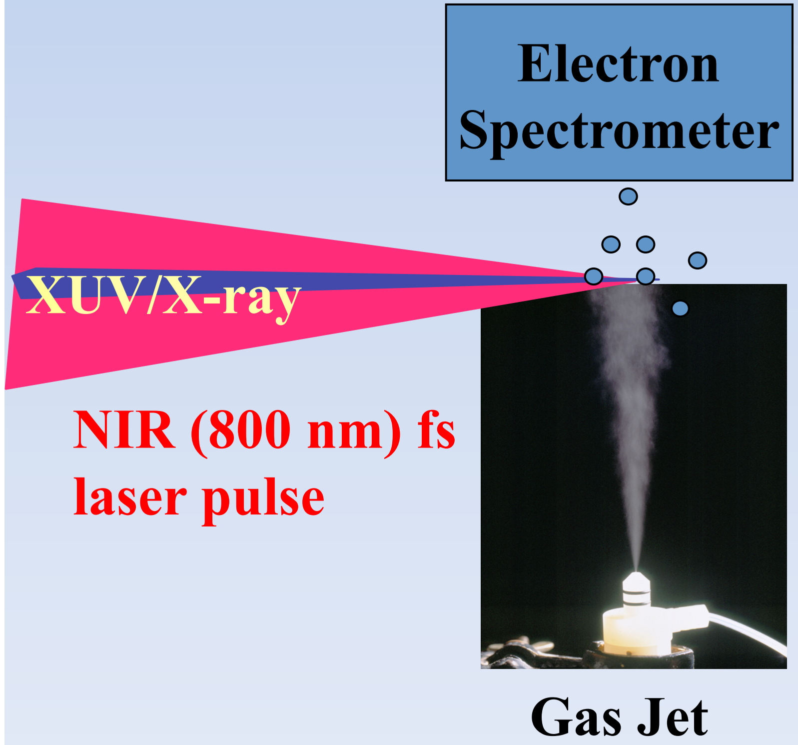
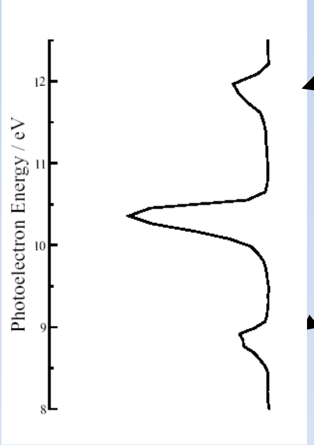


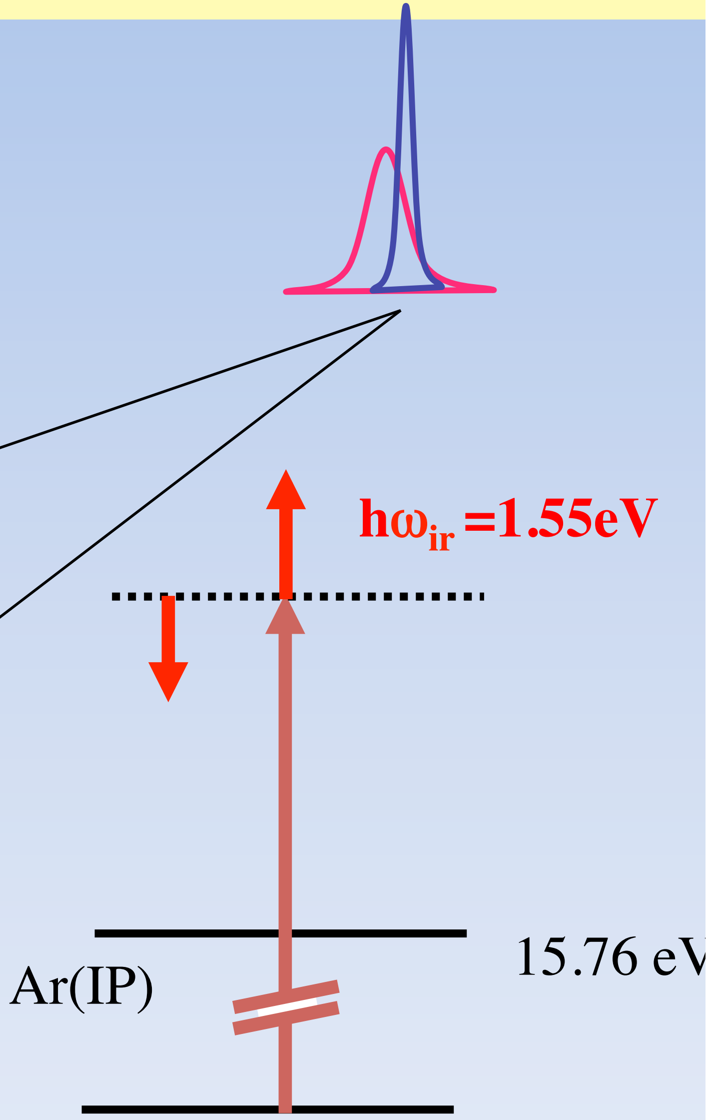
Electron Spectrometer

XUV/X-ray

NIR (800 nm) fs laser pulse

Gas Jet

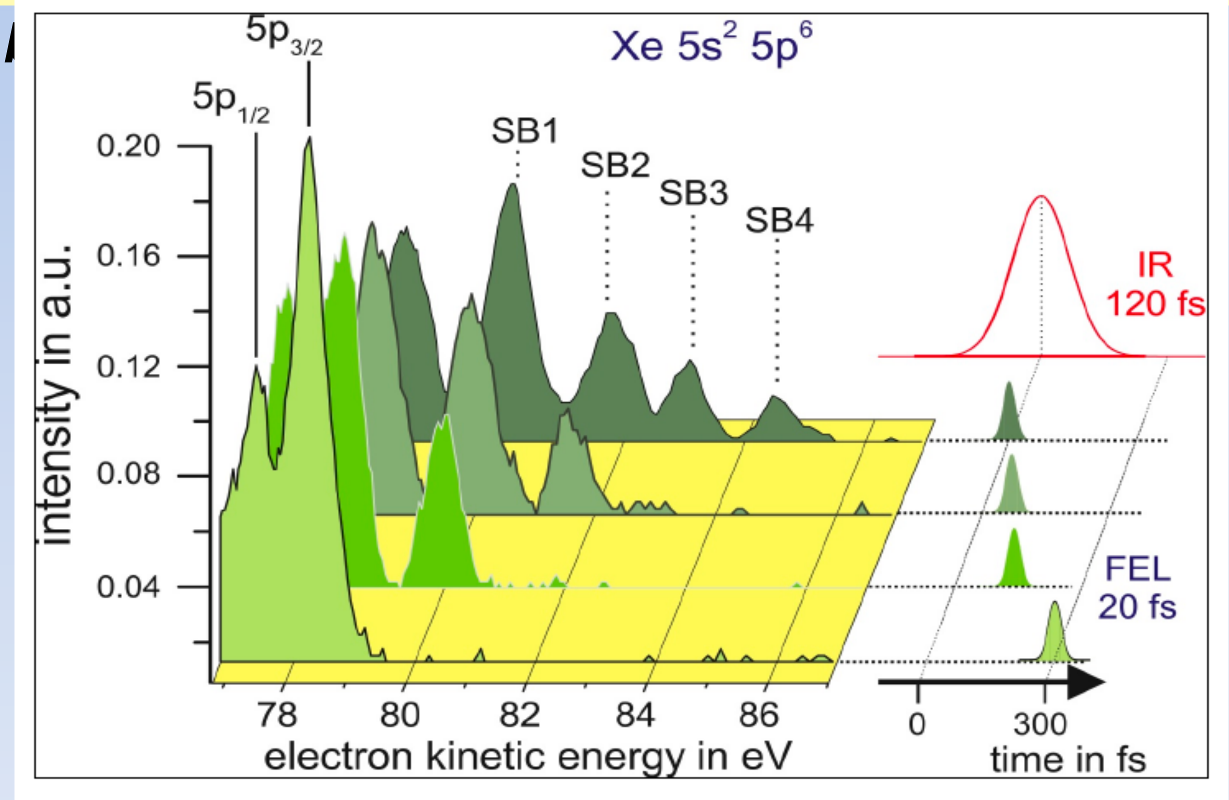


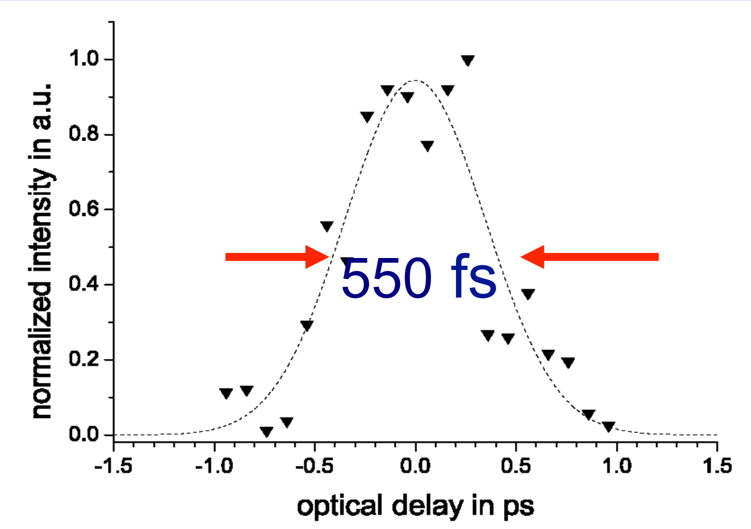


Sideband intensity *very sensitive* to XUV-IR pulse area overlap. - Cross Correlation…

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***





1. Ultrafast XUV-modulated optical-reflectivity methods

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

2. 'TEO'

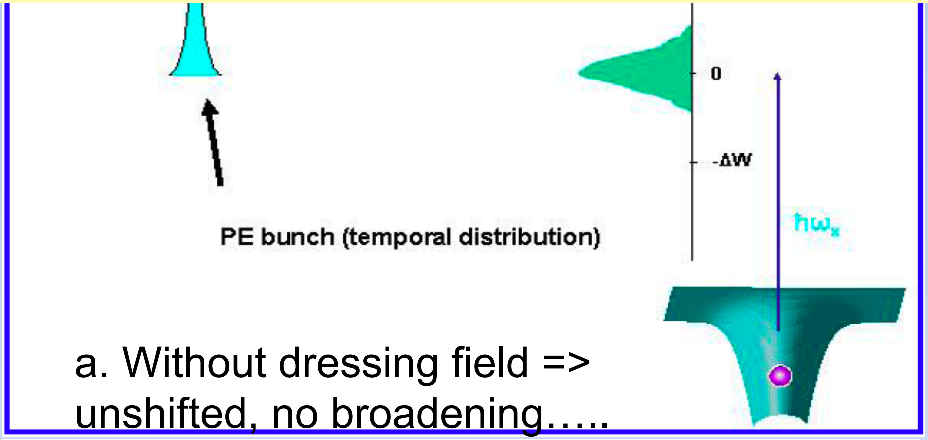
A. Azima et al., APL, 144102 (2009

T. Maltezopoulos New J Phys **10** Art No 033026 (200

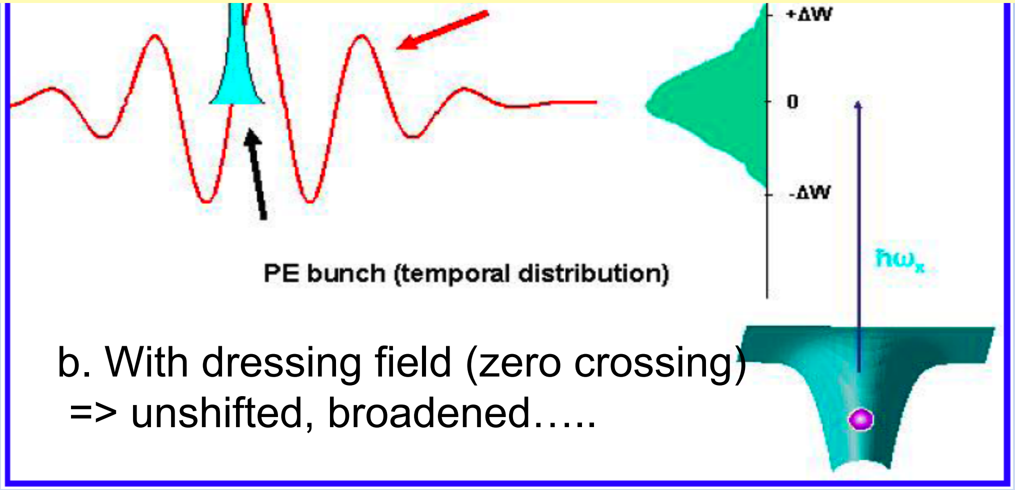
NIMA **583**, 516-525 (2007)

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

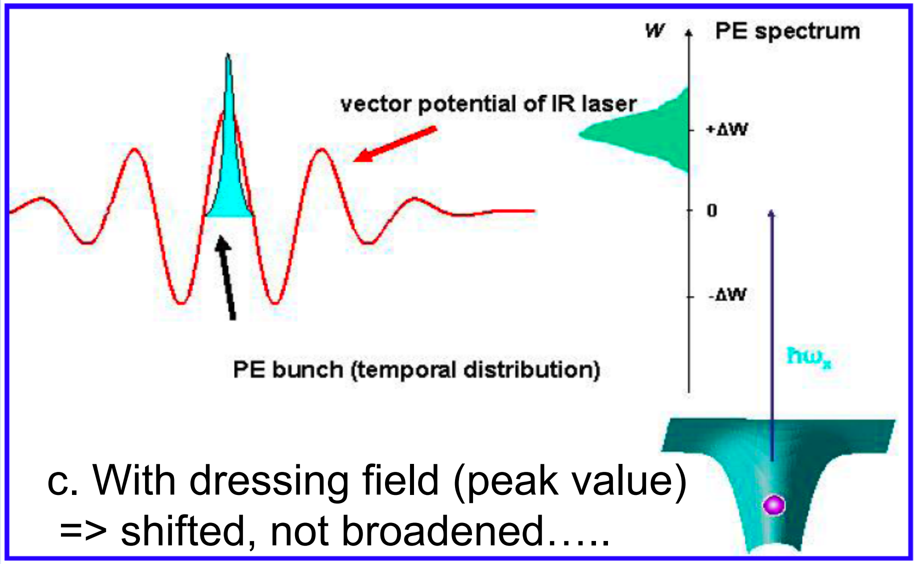
Atoms in ‘Short’ XUV (X-ray) + IR Fields



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



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



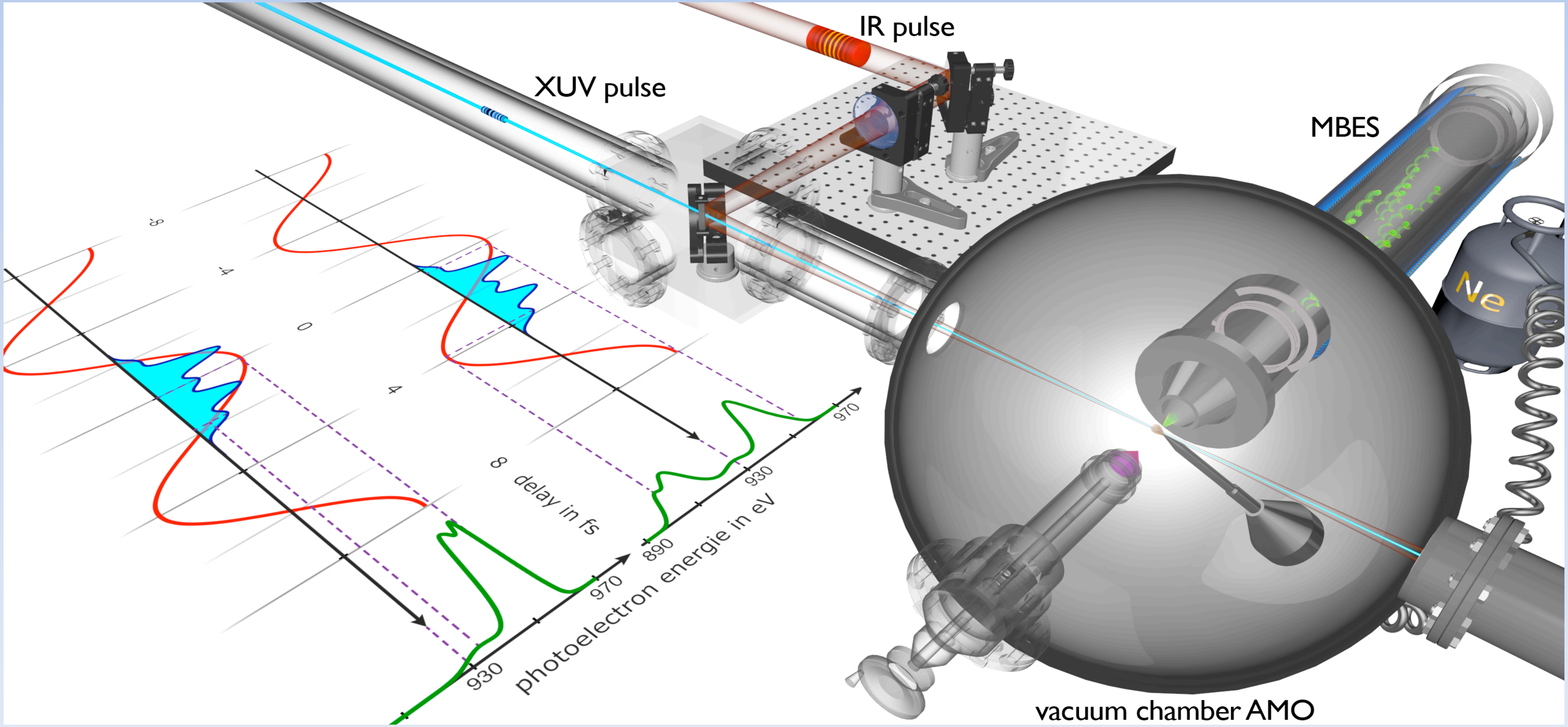
c. With dressing field (peak value) => shifted, not broadened…..

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)*

Measurement of few fs pulses @ LCLS

Experimental Layout at LCLS



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

Measurement of few fs pulses @ LCLS

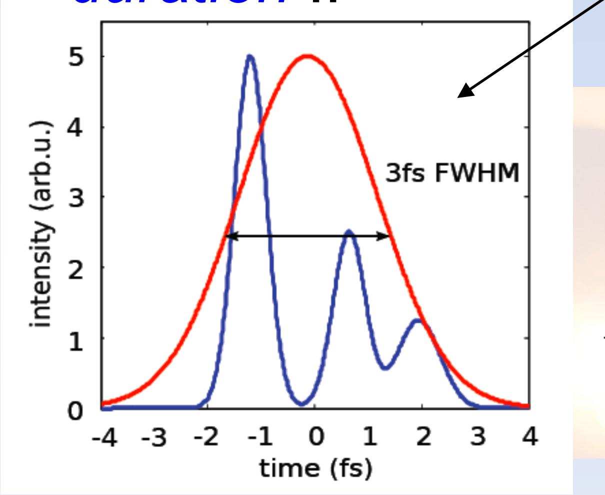
LCLS low current/ slotted spoiler/ few fs mode -

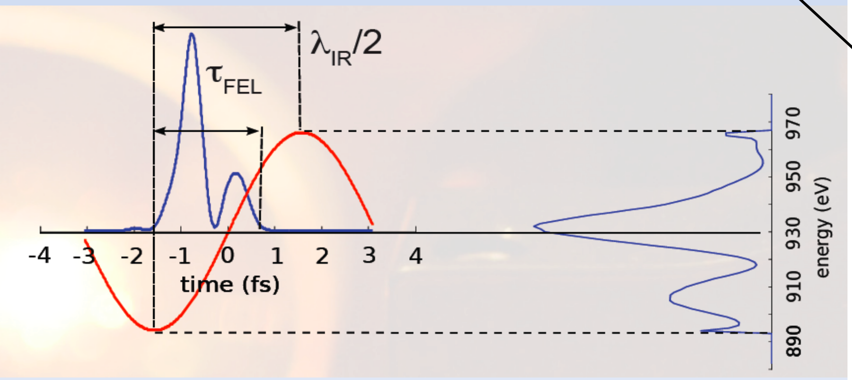
Data still under analysis……

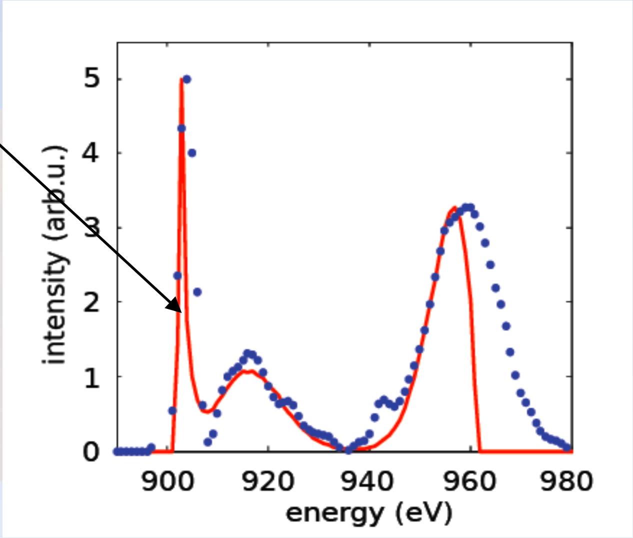
Process. Ne + hν (1.8 keV) -> Ne^+ ($1s^{-1}$) + e- +I_L (10^{14} $W.cm^{-2}$)

Essentially mapping time (fs) to energy in (eV) allows one to measure X-ray (and EUV) pulse widths to attosecond accuracy provided the *X-ray (EUV) pulse width is less than one half cycle of the optical laser in duration* !!

3fs case- simulation and experiment……



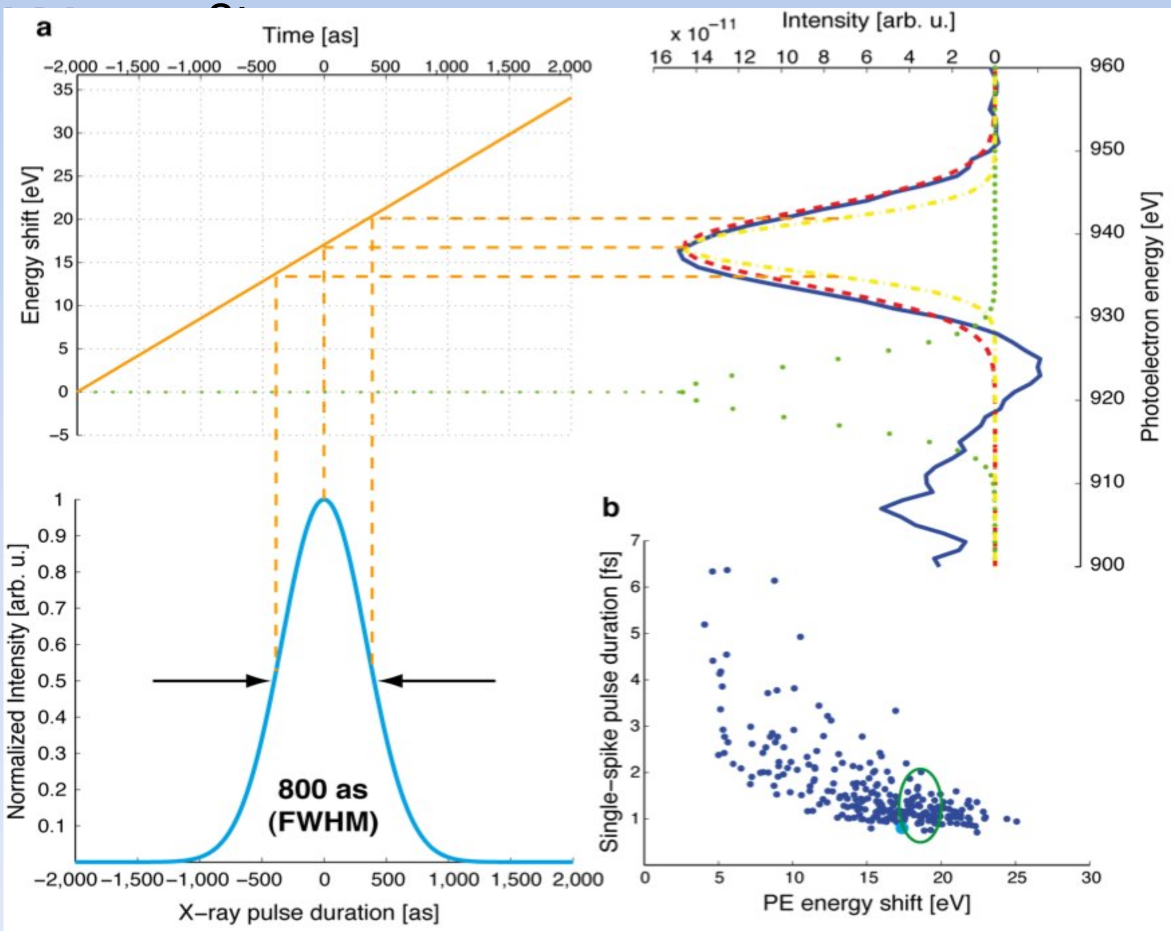




Sub-femtosecond pulses @ LCLS

800 as X-ray pulse !!

Process. Ne + hν (1.8 keV) -> Ne^+ ($1s^{-1}$) + e- +I_L (10^{14}



200 uJ in 800 as =

2 x 10^{-4} J/ 8 x 10^{-16} s =

0.25 TW peak power

Focused to a spot of 10 um = 10^{-6} cm^2 =>

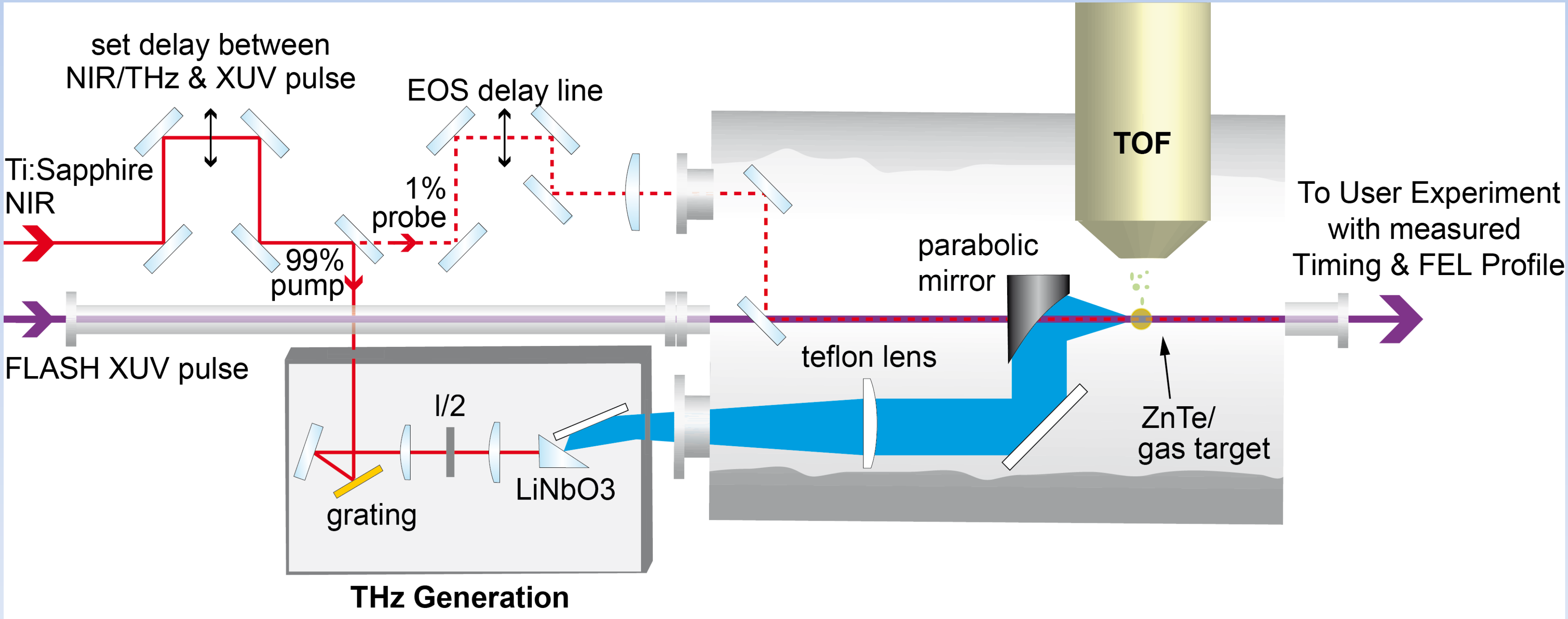
A radiance of:

2 10^{17} $W.cm^{-2}$!!!

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



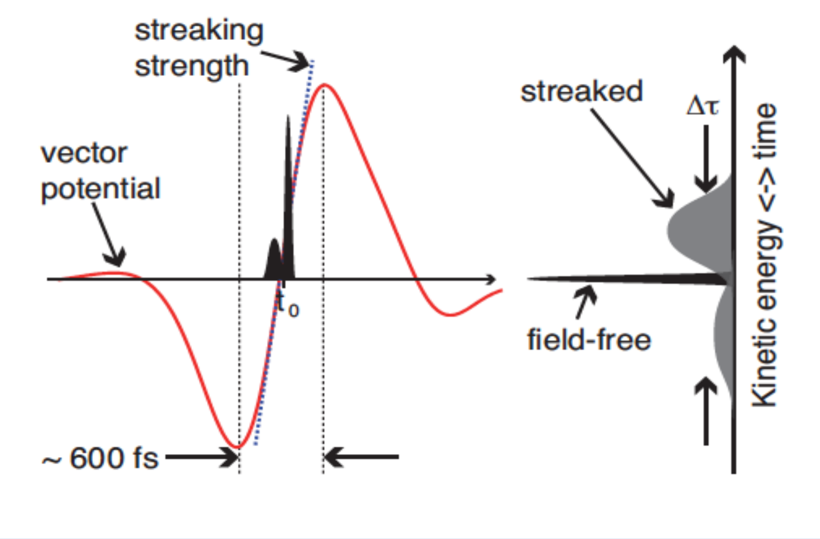
Schematic layout of the THz Streaking Experiment at FLASH

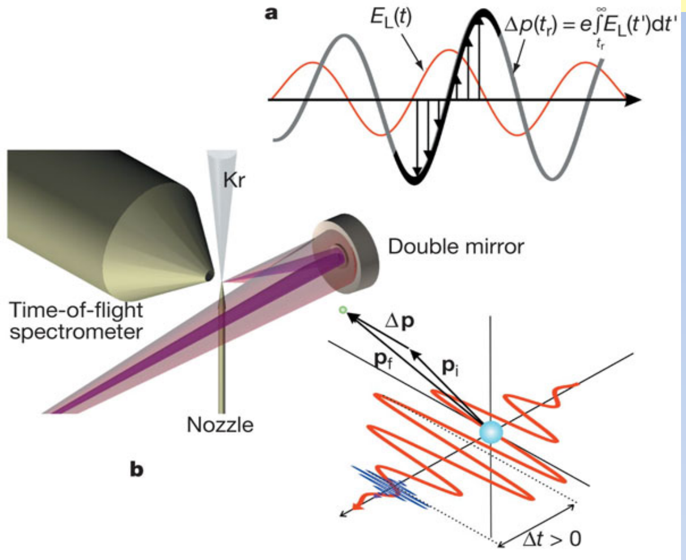
Nature Photonics **6** pp852-857 (2012)

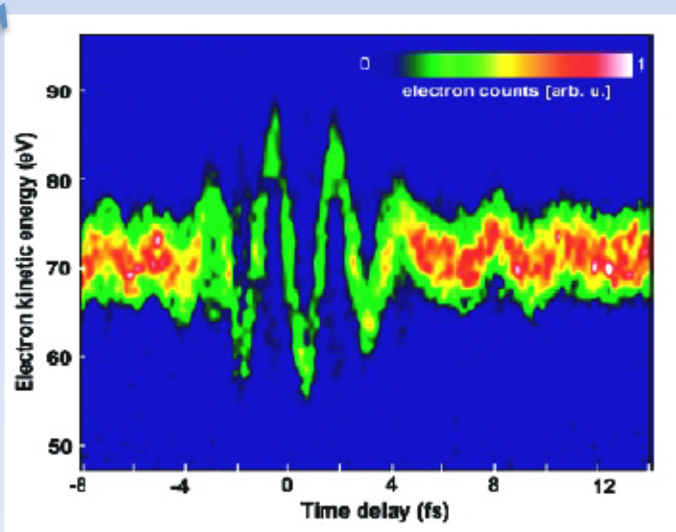
Single Cycle THz Streaking @ FLASH

Femtosecond Atomic Streak Camera

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





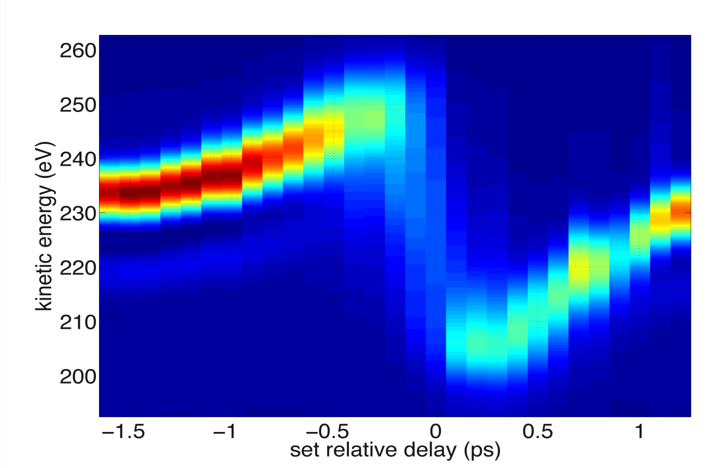


Principle of the experiment

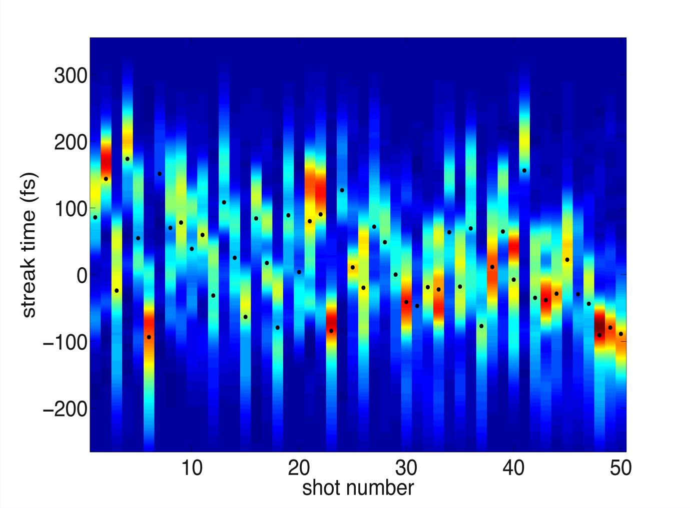
Attosecond Photoelectron Streaking showing how the E-field of a few cycle fs laser pulse can be mapped – MPI-Q.

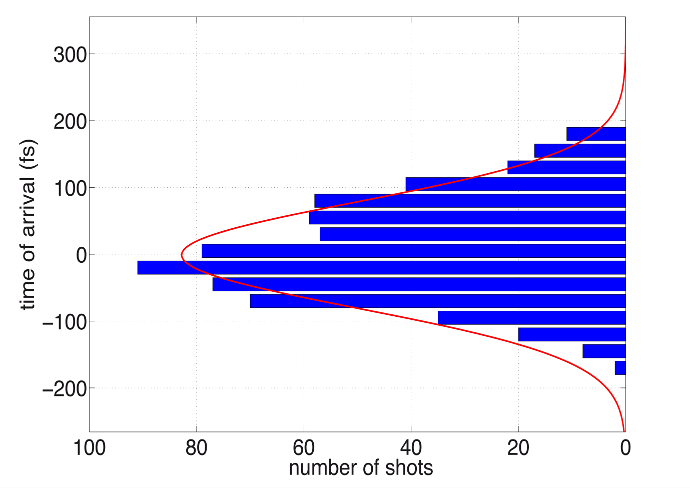
Single Cycle THz Streaking @ FLASH

A Cavalieri et al. from CFEL, DCU, XFEL & DESY



Single cycle THz Photoelectron Streaking showing how the E-field of a single cycle ps laser pulse can be mapped



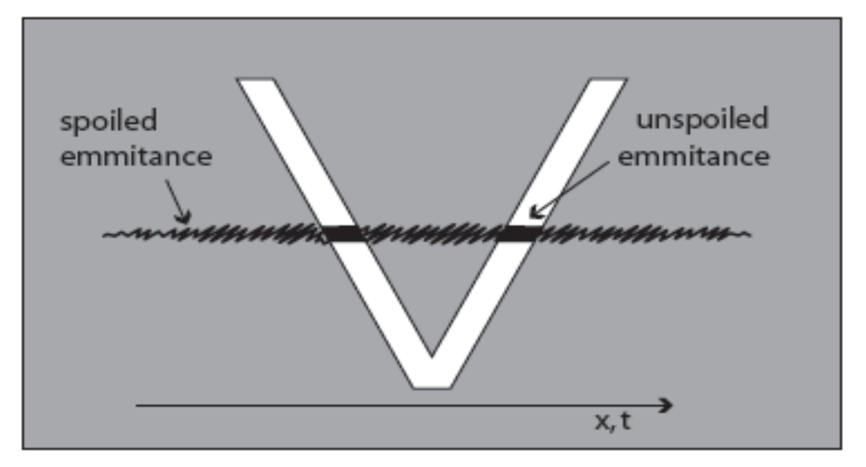


Jitter measurements on 50 consecutive streak traces

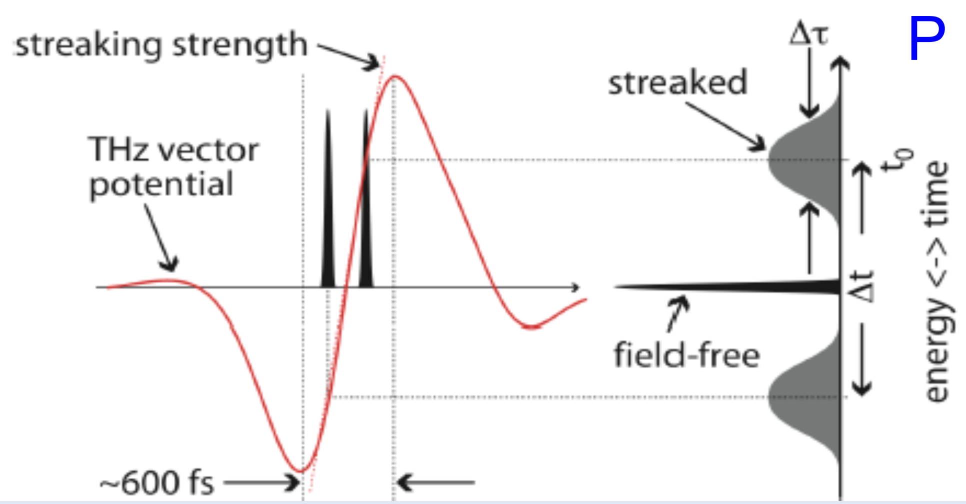
Nature Photonics **6**
pp852-857 (2012)

LCLS - Single Cycle THz Streaking

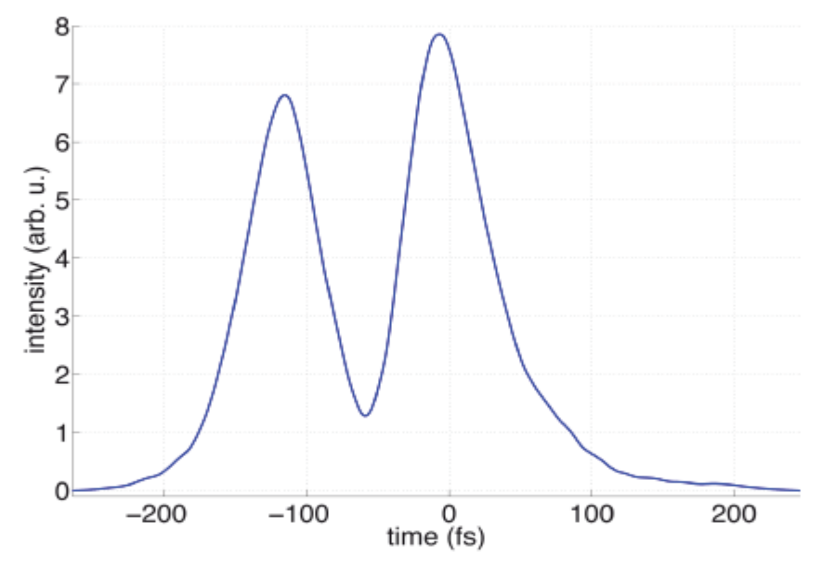
A Cavalieri et al. from CFEL, DCU, XFEL & SLAC



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.



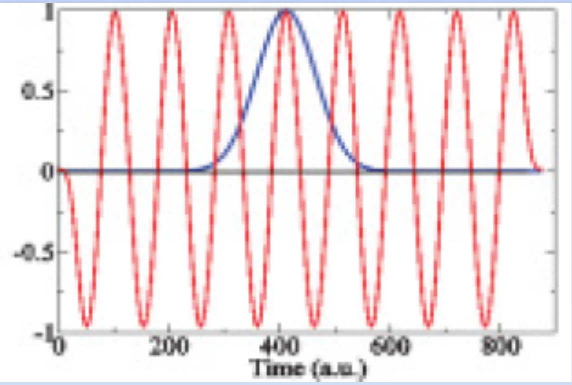
P En 12)



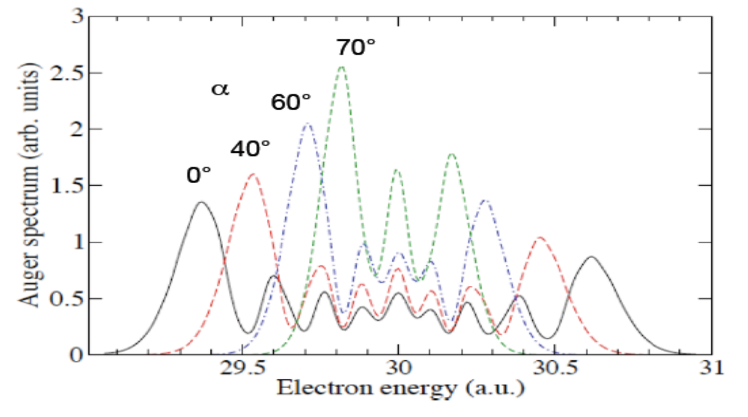
But what about the intermediate (few optical cycle) regime ?

Based on theoretical work by: Nikolay Kabachnik et al., Moscow State Univ.

Auger lifetime similar to optical (800 nm) cycle



Angle Resolved Sideband Spectra



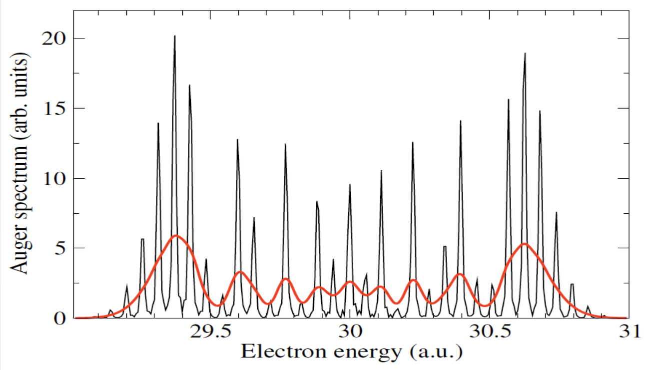
Core hole lifetime
τ (Ne 1s) = 2.4fs

Optical cylce
T (800nm) = 2.6fs

LCLS: 1 keV, 2-5 fs

NIR: 800 nm,
1 x 10^{12} W/cm^2

Simulated spectrum for electron emission in the direction of the field (0

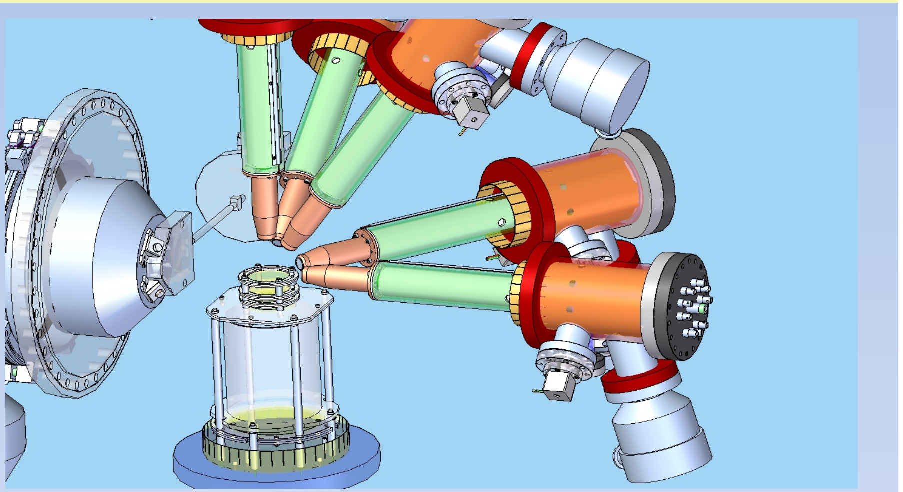


A.K. Kazansky, N.M. Kabachnik, JPB 42, 121002 (2009)

A.K. Kazansky, N, JPB 43, 035601

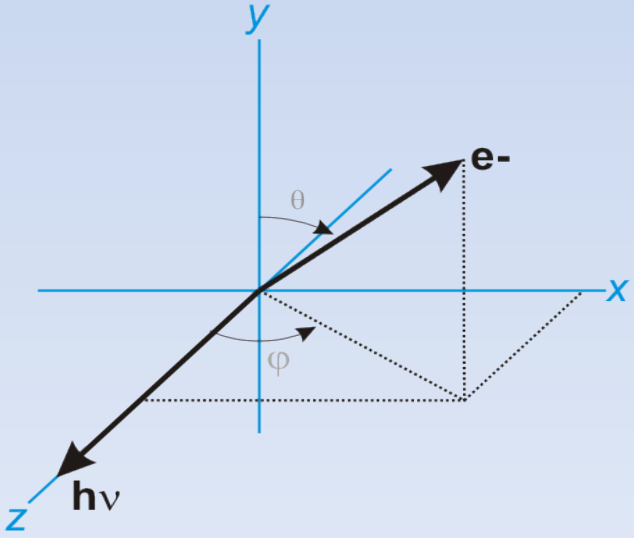
AMO Chamber and Specifications

High Field Chamber (AR-eTOF)



1. Based on a successful design used by the Denis Lindle (RIP) group at ALS – designed for up to 5keV electrons
2. Transmission flat for E_{kin}> 20 eV
3. E/ΔE up to 5,000

•	θ	φ	**comment**
1	0º	90º	Along y-axis
2	35.3º	90º	Magic angle in xy dipole plane
3	90º	90º	Along x-axis
4	54.7º	0º	Non-dipole
5	90º	35.3º	Non-dipole



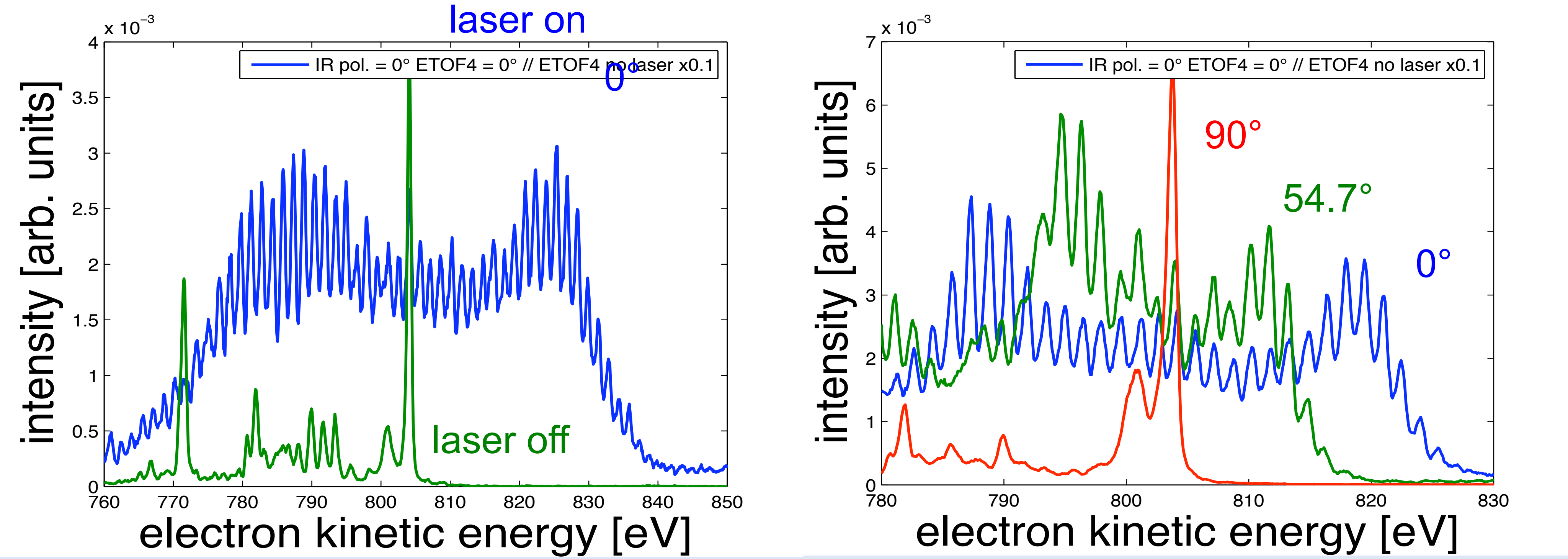
lcls.slac.stanford.edu

SB modulation – few/sub-optical cycle effects

NIR : 800nm, 1 mJ, 3ps

1 x 10^{12} W/cm^2

6 x 10^{11} W/cm^2



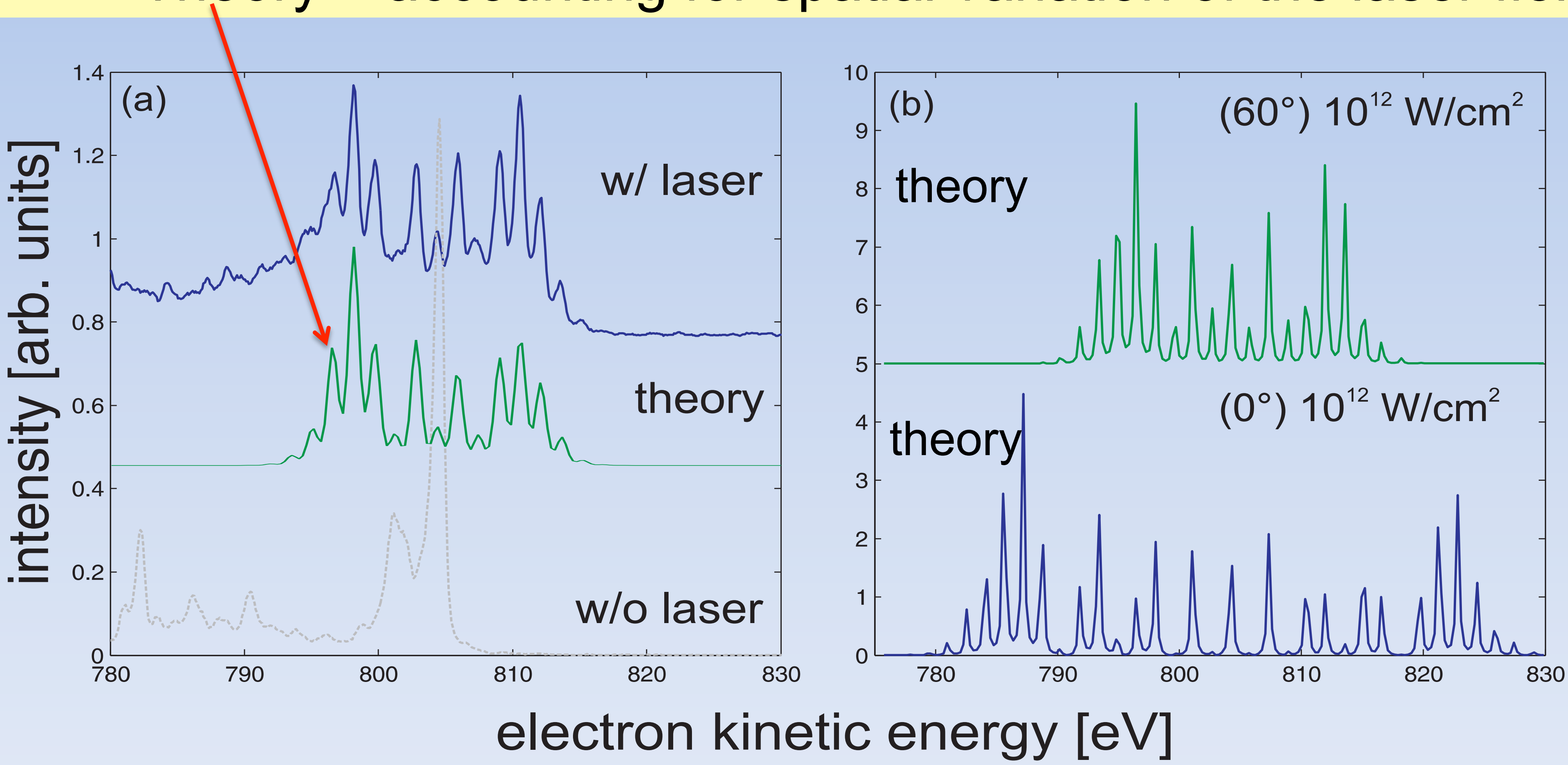
Strong sideband structure

Strong angular effect

Phys. Rev. Lett **108** 063007 (2012)

SB modulation – few/sub-optical cycle effects

Theory – accounting for spatial variation of the laser field



Phys. Rev. Lett **108** 063007 (2012)

NEW !! All Optical Synchronisation - FLASH

A Cavalieri et al. from CFEL, DCU, MPI (SDM), SLAC & XFEL

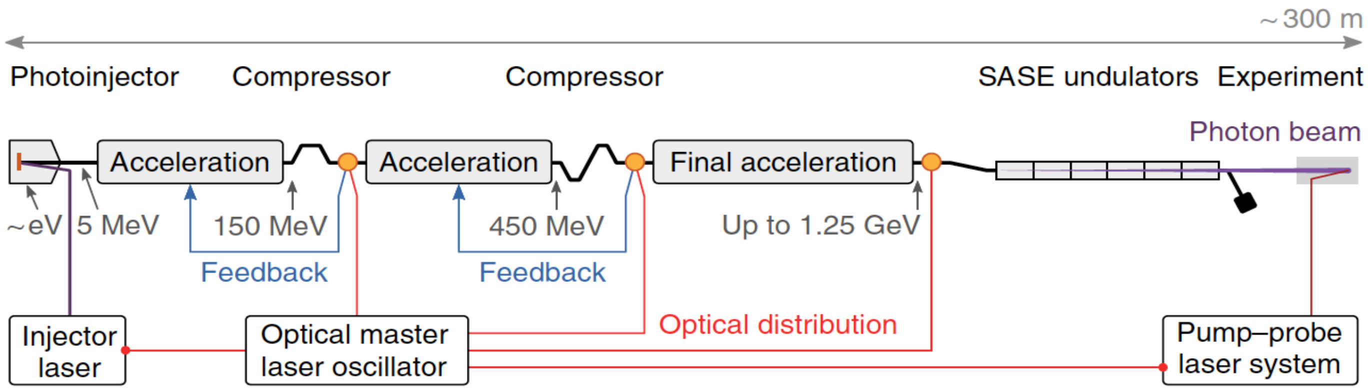
nature COMMUNICATIONS

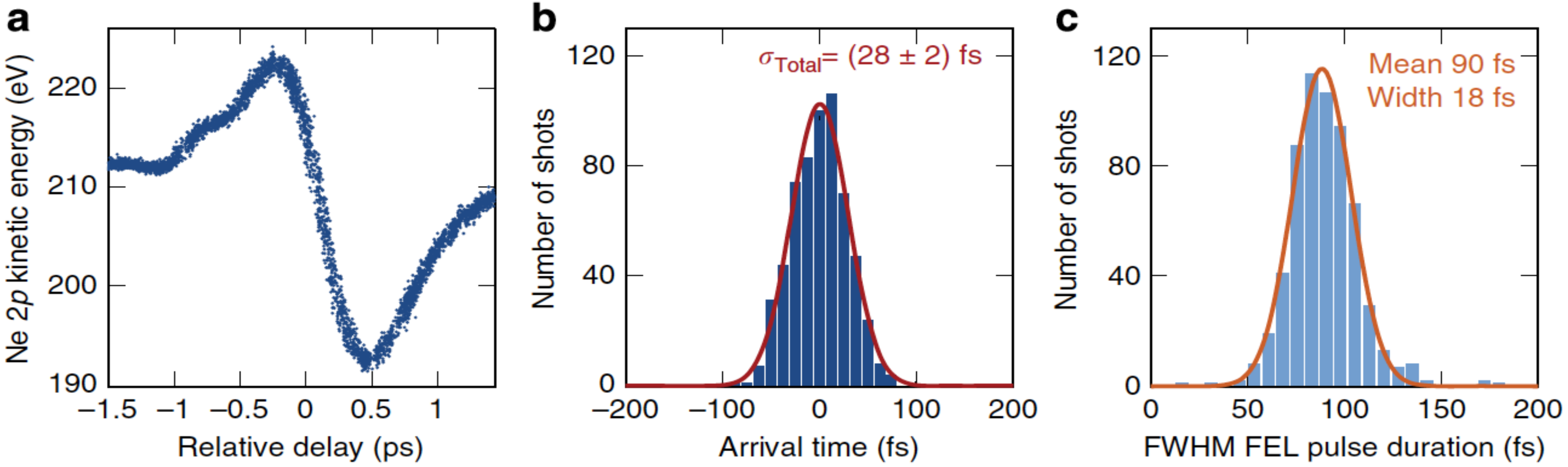
ARTICLE

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]





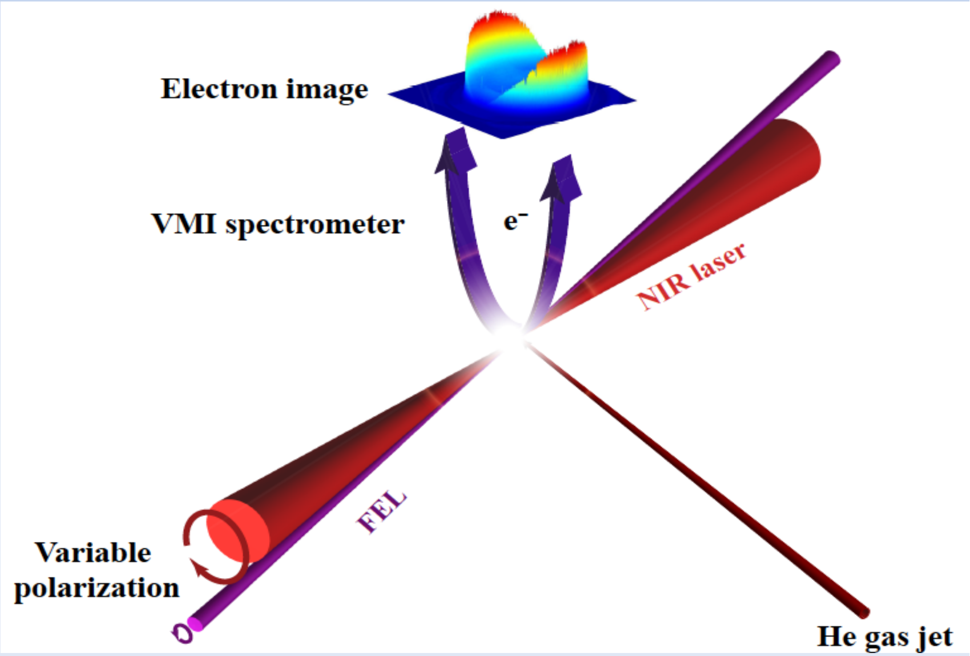
Nature Comms **6**
Art. No. 5938 (2015)

Measuring Polarisation of XFELs

T Mazza et al. (XFEL GmbH, DESY, FERMI@ELECTTRA, DCU, MSU, et

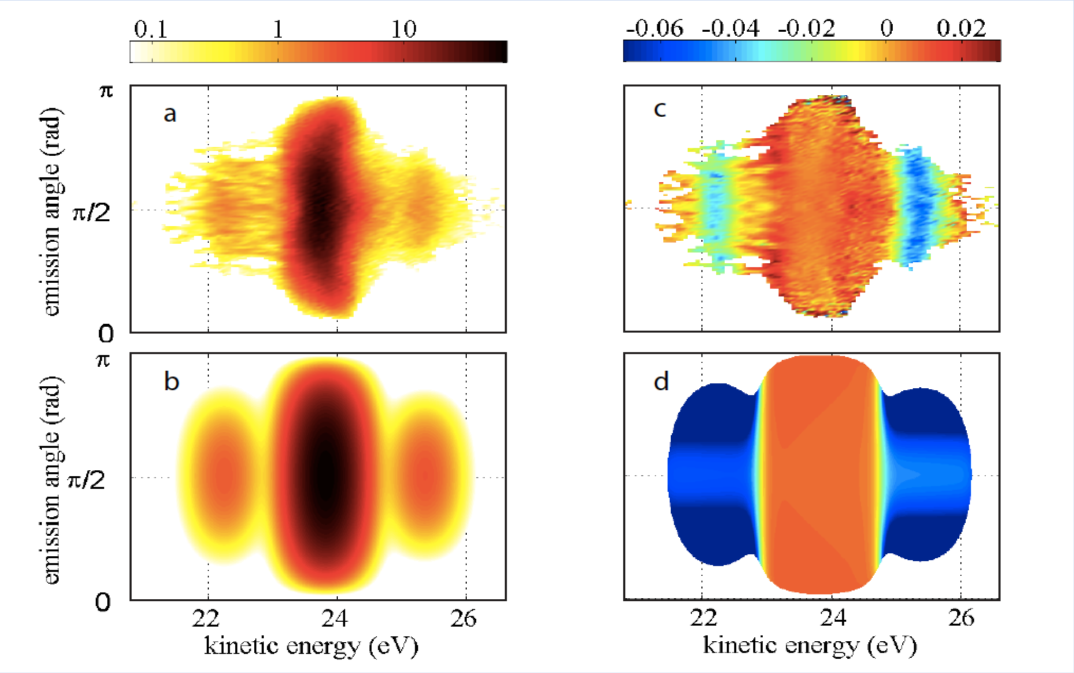
Theory - Kazansky, A. K., Grigorieva, A. V. and Kabachnik, N. M. Circular Dichroism in Laser-Assisted Short Pulse Photoionization. Phys. Rev. Lett. 107, 253002 (2011).

DDCS (Expt./Th.)



DDCS (Expt./Th.)

CD (L-R/L+R.)

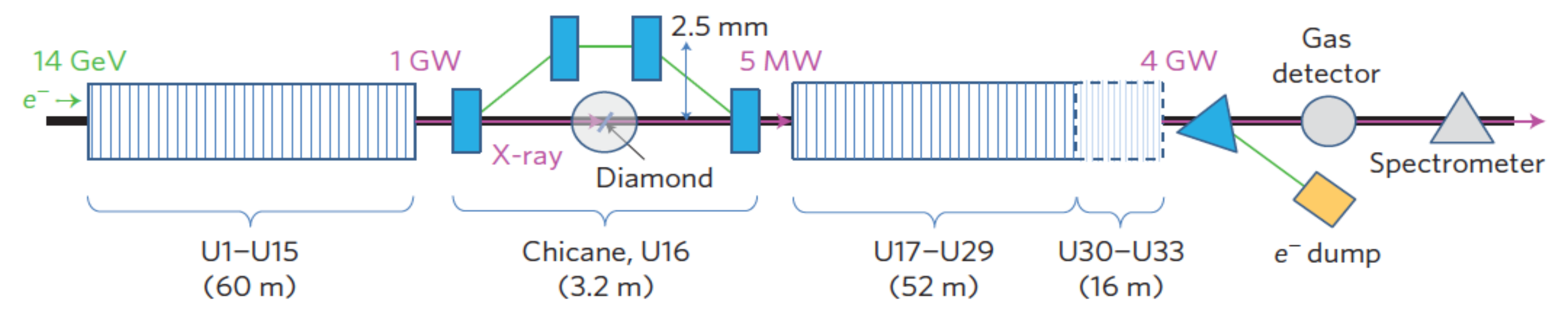


Nature Comms **5**
Art. No. 3628 (2014)

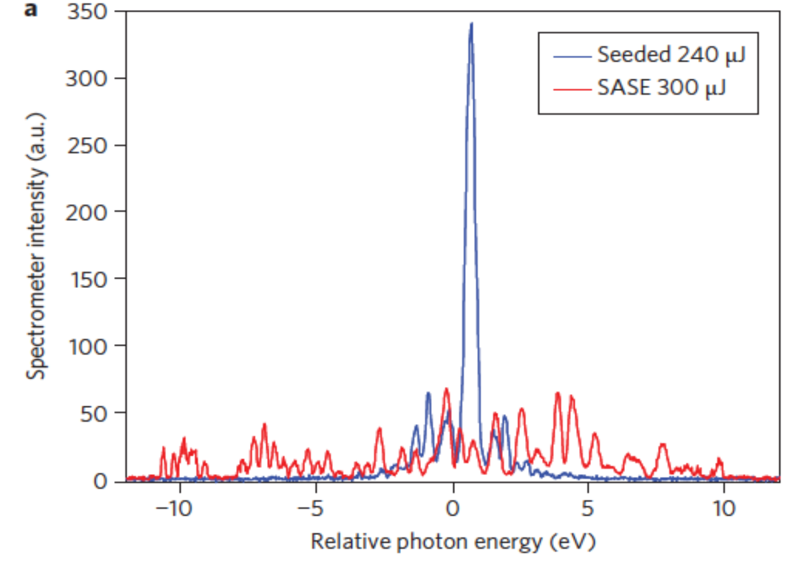
Next Steps

1. Rudiments of ionization processes in intense laser fields
2. Photoionization experimental setups (FLASH & DESY)
3. One colour – two photon ionization
4. Two colour Ionization
5. **Some co**

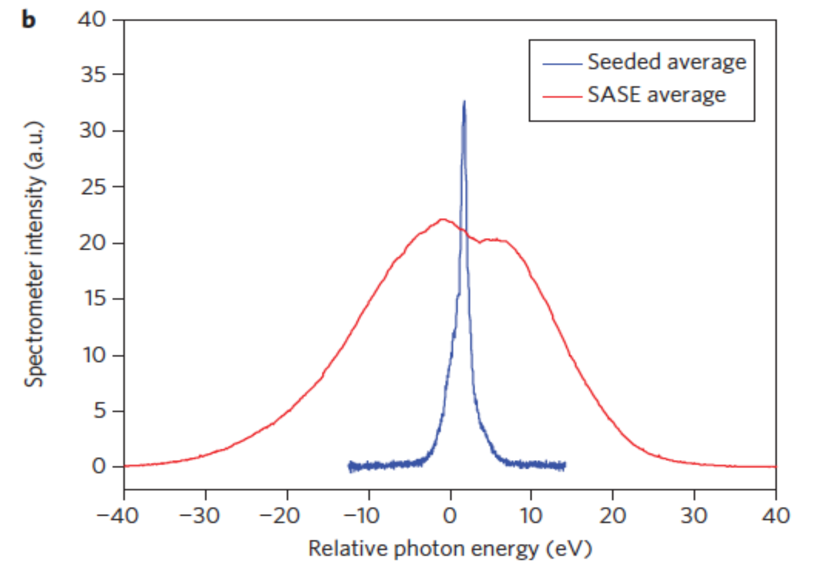
Self - Seeded FELs, e.g., LCLS…..



Single-Shot Spectra



Multi-Shot Averaged Spectra



Lutman et al., PRL 113 Art. No. 254801 (2014)/Amann et al. *Nature Photonics* **6**, 693 (2012)

In Conclusion

1. To date we have looked only at one and two colour non-resonant photoionization processes
2. Now – FELs seeded and easily tunable - we can explore resonant processes where inner shell electrons dominate

Next steps (XFEL Technology): X-CPA

XFELs are finally becoming real lasers – truly monochromatic, fully phase coherent, collimated…... If it can be done with an optical laser – we can now propose it for XFELs….

Regular Articles

1. *Spectroscopic characterization of vacuum ultraviolet free electron laser pulses*, Optics Letters **31** 1750 (**2006**)
2. *Two-color photoionization in xuv free-electron and visible laser fields,* Phys. Rev. A **74**, Rapid Communications, Art. no. 011401 (2006)
3. *Single-shot characterization of independent femtosecond extreme ultraviolet free electron and infrared laser pulses*, Appl. Phys. Lett **90**, Art. no. 131108 (2007)
4. *Operation of the Free Electron Laser FLASH in the water window*, Nature Photonics **1** 336 (2007)
5. *An experiment for two-color photoionization using high intensity extreme-UV free electron and near-IR laser pulses*, Nucl. Inst. Methods in Res. A **583** pp516-525 (2007)
6. *Polarization control in atomic 2-color above threshold ionization*, Phys. Rev. Letts **101** Art. no. 193002 (2008)
7. *Time-resolved pump-probe experiments beyond the jitter limitations at FLASH*, Appl. Phys. Letts **94** Art. no. 144102 (2009)
8. *Two-Photon Excitation and Relaxation of the 3d-4d Resonance in Atomic Kr*, Phys. Rev. Letts **104** Art. no. 213001 (2010)
9. *Two-photon inner-shell ionization in the extreme-ultraviolet (XUV)*, Phys. Rev. Letts **105** Art. no. 013001 (2010)
10. *Two-color experiments in the gas phase at FLASH*, J. Electron. Spec. Relat. Phenom. **181** pp111-115 (2010)
11. *Femtosecond x-ray pulse length characterization at the LCLS FEL*, New J. Phys. **13** Art. no. 093024 (2011)
12. *Theory of ac-Stark splitting in core-resonant Auger decay in strong x-ray fields*, Phys. Rev. A 84 Art. no. 063419 (2011)
13. *Angle-resolved electron spectroscopy of laser-assisted Auger decay induced by a few-fs x-ray pulse*, Phys. Rev. Letts. 108 Art. no. 063007 (2012)
14. *Atomic photoionization in combined intense XUV free-electron and infrared laser fields,* New J. Phys. **14** 043008 (2012)
15. *Dichroism in the above-threshold two-colour photoionization of singly charged neon*, J. Phys. B: At. Mol. Opt. Phys. **45** 085601 (2012)
16. *Controlling core hole relaxation dynamics via intense optical fields*, J. Phys. B: At. Mol. Opt. Phys. **45** 141001 (2012)
17. *Ultrafast X-ray pulse ten* *n for free-electron lasers,* Nature s **6** 852-857 (2012)
18. *Determining the polariza* *free-electron laser beam using at* *ular dichroism*, Nature Communications **5**, 3628 (2

Review Articles

1. Photoionization experiments with the ultrafast XUV laser FLASH
J. T. Costello, *J. Phys. Conf. Series* 88 Art No. 012057 (2007)

2. Experiments at FLASH
C. Bostedt, H. N. Chapman, J. T. Costello, J. R. Crespo Lopez-Urrutia, S. Duesterer, S. W. Epp, J. Feldhaus, A. Foehlisch, M. Meyer, T. Mšller, R. Moshammer, M. Richter, K. Sokolowski-Tinten, A. Sorokin, K. Tiedtke, J. Ullrich and W. Wurth, *Nucl. Inst. Meth. in Res. A* 601 108-122 (2009)

3. Non-linear processes in the interaction of atoms and molecules with intense EUV and X-ray fields from SASE free electron lasers (FELs)
N. Berrah, J. Bozek, J. T. Costello, S. Duesterer, L. Fang, J. Feldhaus, H. Fukuzawa, M. Hoener, Y. H. Jiang, P. Johnsson, E. T. Kennedy, M. Meyer, R. Moshammer, P. Radcliffe, M. Richter, A. Rouzee, A. Rudenko, A. Sorokin, K. Tiedtke, K. Ueda, J. Ullrich and M. J. J. Vrakking,
Journal of Modern Optics 57 1015-1040 (2010)

4. Two-colour experiments in the gas phase
M. Meyer , J. T. Costello , S. Düsterer , W. B. Li and P. Radcliffe
J. Phys. B: At. Mol. Opt. Phys. 43 Art No. 194006 (2010)

5. Two-Color Ex *he Gas Phase at FLAS*
M Meyer et al., J ec. Relat. Phenom **18** 115 (2010)

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Science Foundation Ireland – Investigator Programme – 12/IA/1742 & 07/IN.1/I1771

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