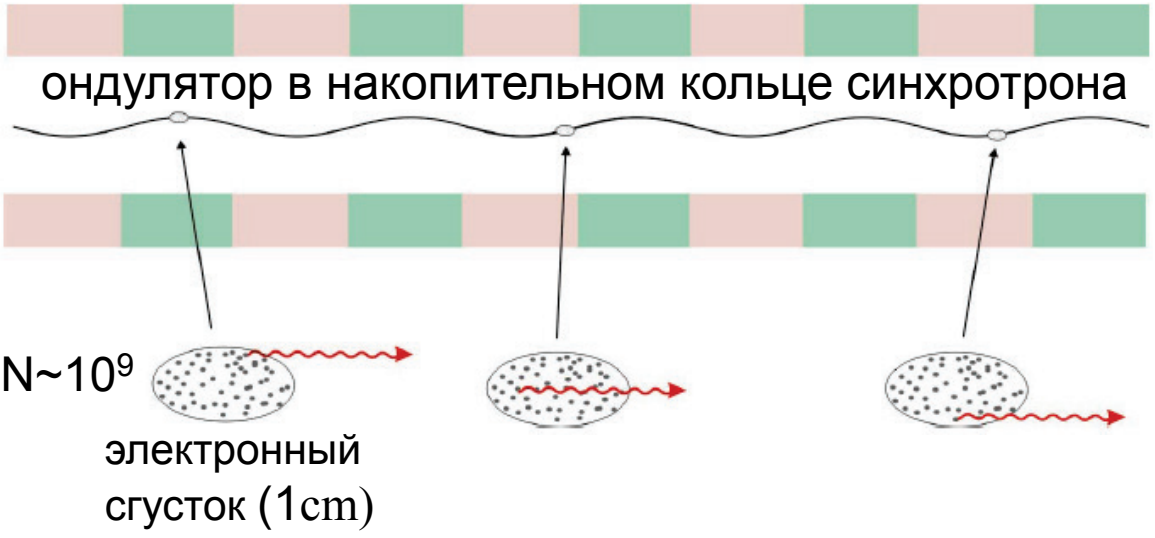
Lecture 8

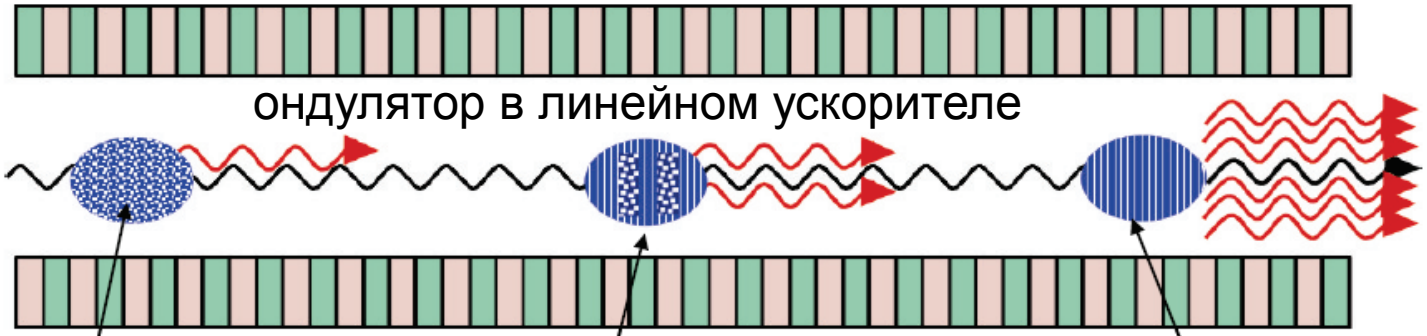
Free electron lasers (continuation)

Почему источники 4-го поколения настолько интенсивнее?



Интенсивность ~ N

электроны излучают спонтанно и излучение не когерентно



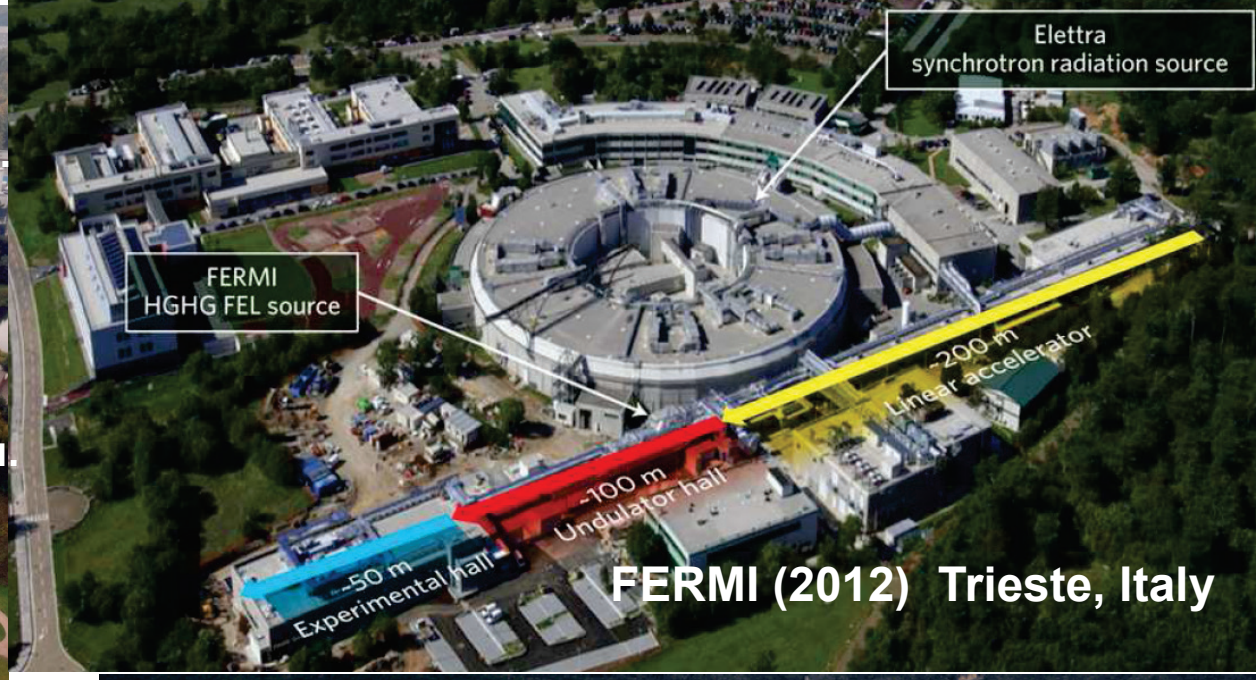
Интенсивность ~ N^2

короткий электронный сгусток (1μm)

взаимодействие излучения задней части сгустка с остальным сгустком порождает порядок

упорядоченные электроны излучают когерентно (в фазе)

FLASH (2006),
Hamburg
Источ.
Эксп.


Elettra
synchrotron radiation source
FERMI
HGHG FEL source
200 m
Linear accelerator
~100 m
Undulator hall
~50 m
Experimental hall
FERMI (2012) Trieste, Italy

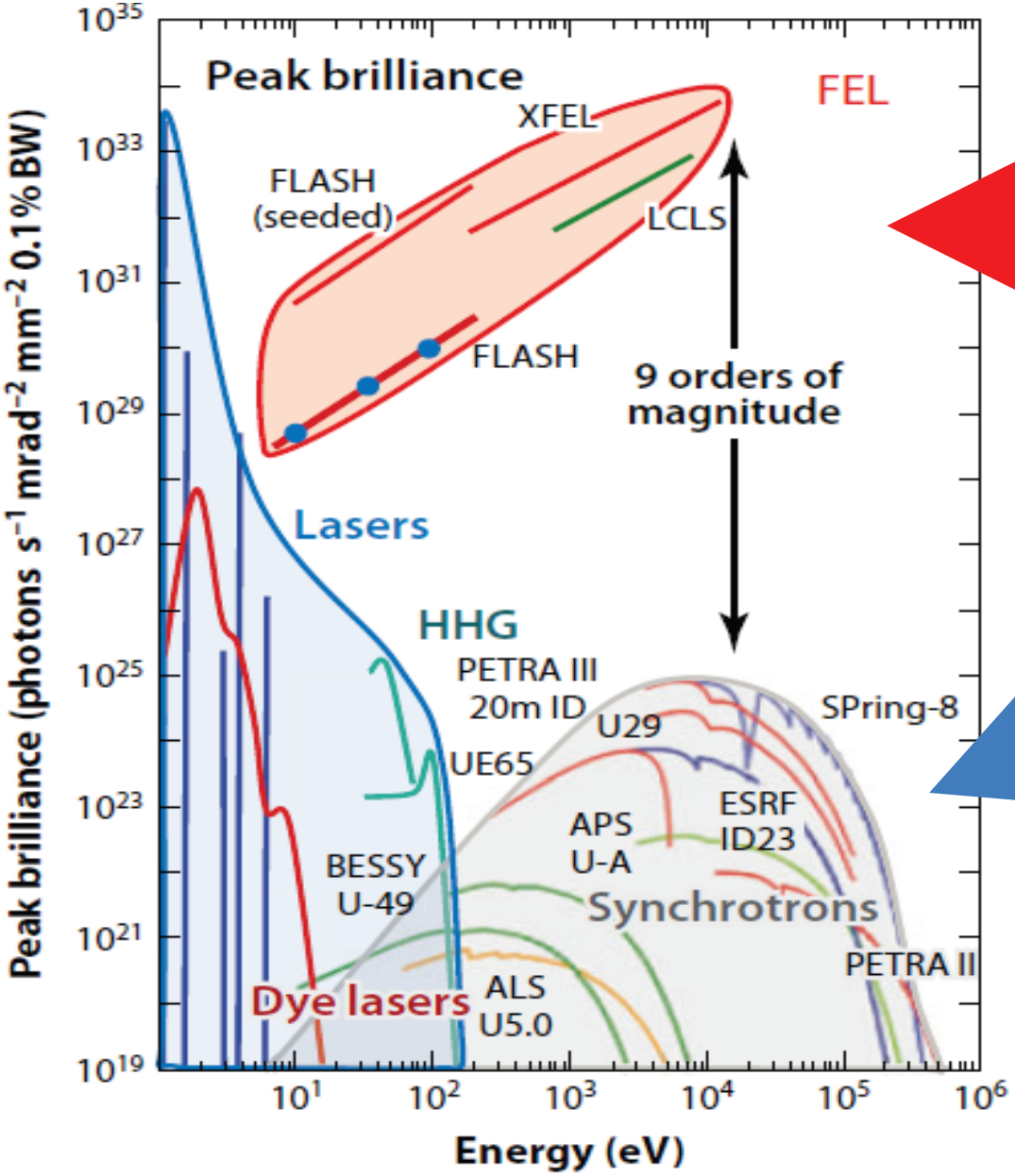
LCLS (2009) Stanford

SPring-8
SACLA
SACLA(2011), Japan

FEL in VUV and X-ray

FLASH (Germany) 2005	FERMI (Italy) 2012	LCLS (USA) 2009	SACLA (Japan) 2011	XFEL (EU) 2016
30 – 300 eV	12 - 310 eV	0.27 - 9.5 keV	4.4-16.8 keV	0.25 - 24 keV
50 - 200 fs	30-100 fs	10 - 300 fs	30 fs	< 100 fs
~ 10^{13} ph/pulse	10^{13} -10^{14} ph/p	10^{12} – 10^{13} ph/p	$5 \cdot 10^{11}$ ph/p	10^{12} – 10^{14} ph/p
> 10^{11} W /cm^2	$5 \cdot 10^{12}$ W/cm^2	> 10^{11} W /cm^2		> 10^{11} W /cm^2
VUV		**X-ray**		**Starting**

Man made sources of radiation



Synchrotron radiation sources of 4th generation (XFELs)

Synchrotron radiation sources of 3rd generation

J. Ullrich, A. Rudenko, R. Moshammer, Annu. Rev. Phys. Chem. **63**, 635 (2012)

Яркость искусственных источников излучения рентгеновского и ВУФ диапазона

"It is an historical fact that scientific revolutions are more often driven by new tools than by new concepts"

Freeman Dyson

Является историческим фактом, что научные революции чаще обусловлены новыми инструментами, чем новыми идеями

«Закон Мура» для полупроводников

число транзисторов на кристалле удваиваться каждые 24 месяца

Unique **set** of characteristics of XFELs:

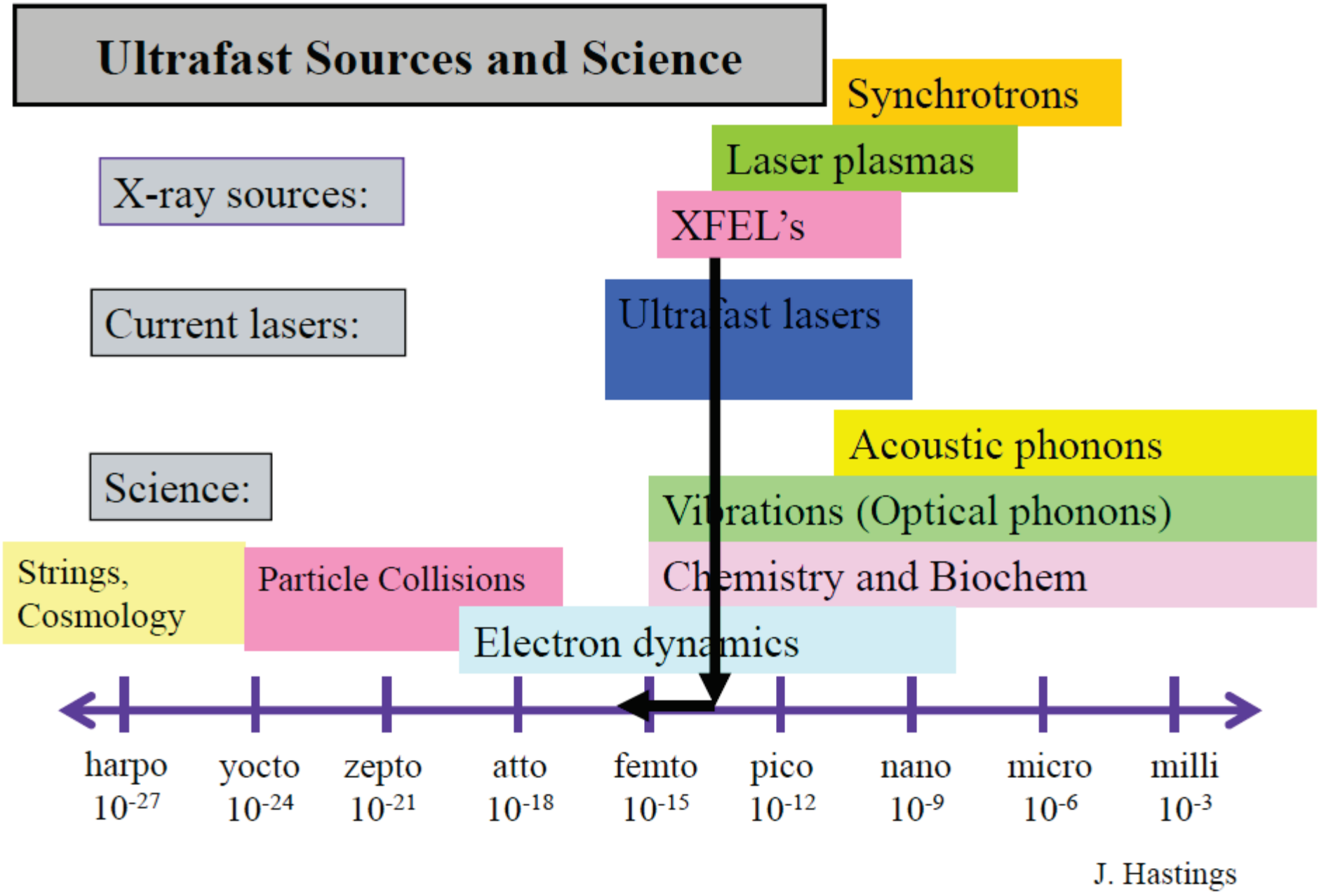
1. Wavelength (VUV and X-ray)
2. Intensity
3. Pulse duration (femtoseconds 10^{-13}-10^{-15} s)

+ coherence of the beam

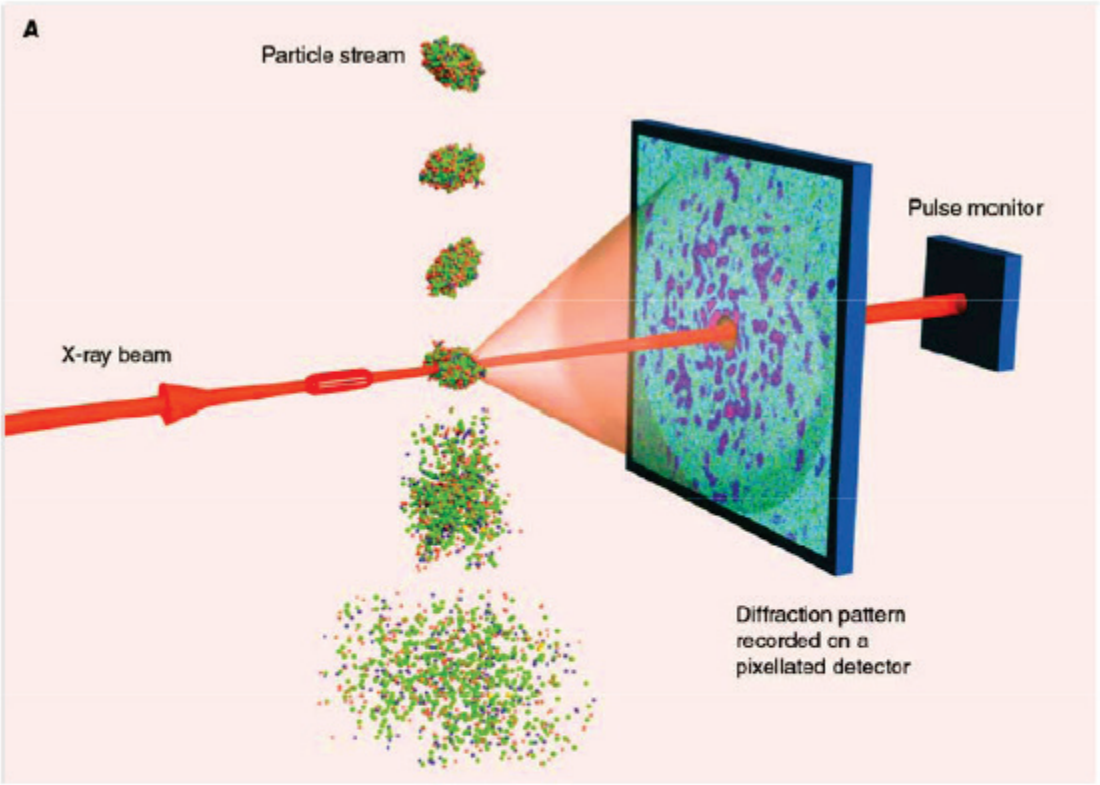
Example: imaging of large biomolecules

One of the key problems of structural biology is the difficulty in determining the structure of macromolecules that can not be crystallized (e.g. some viruses, proteins, ...)

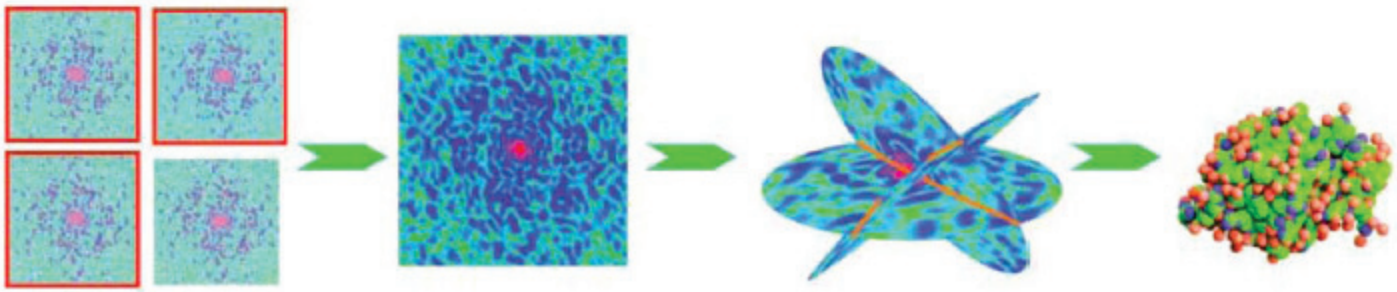
A nanoobject can be displayed by a single femtosecond FEL pulse before the sample turns into plasma and explodes.


Ultrafast Sources and Science
X-ray sources:
Synchrotrons
Laser plasmas
XFEL's
Current lasers:
Ultrafast lasers
Science:
Acoustic phonons
Vibrations (Optical phonons)
Chemistry and Biochem
Strings, Cosmology
Particle Collisions
Electron dynamics
harpo 10-27
yocto 10-24
zepto 10-21
atto 10-18
femto 10-15
pico 10-12
nano 10-9
micro 10-6
milli 10-3
J. Hastings

Structure determination of single molecules before the Coulomb explosion

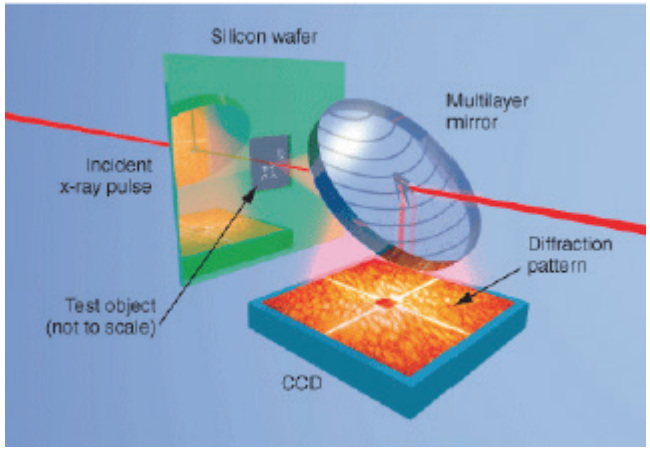


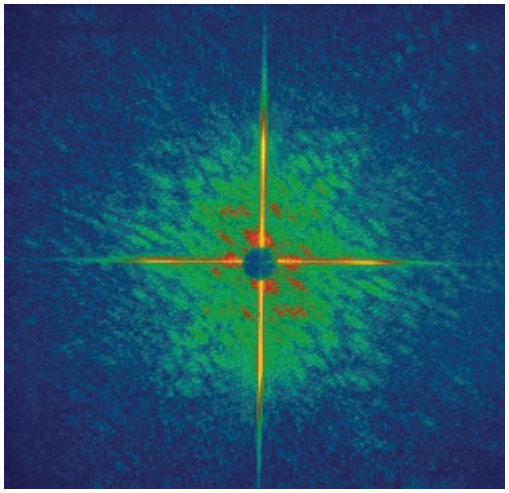
H. Chapman (2007)

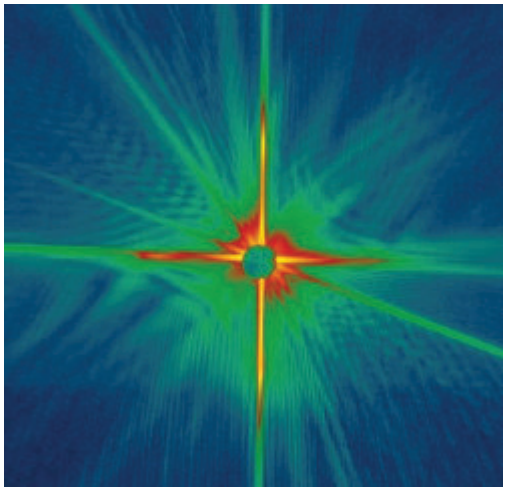


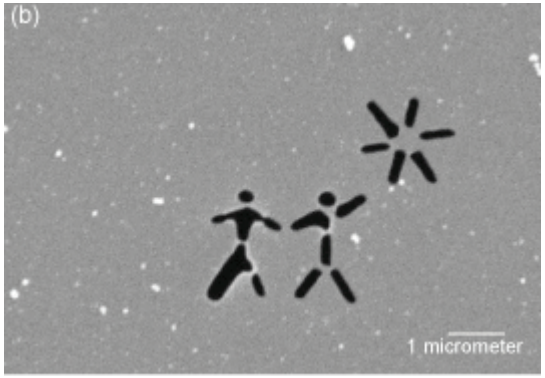
Prototype experiment atFLASH:

(A team of Livermore, Univ. of California at Davis, Stanford Synchrotron Radiation Laboratory, Uppsala Univ. in Sweden, the Deutsches Elektronen-Synchrotron (DESY) in Germany)



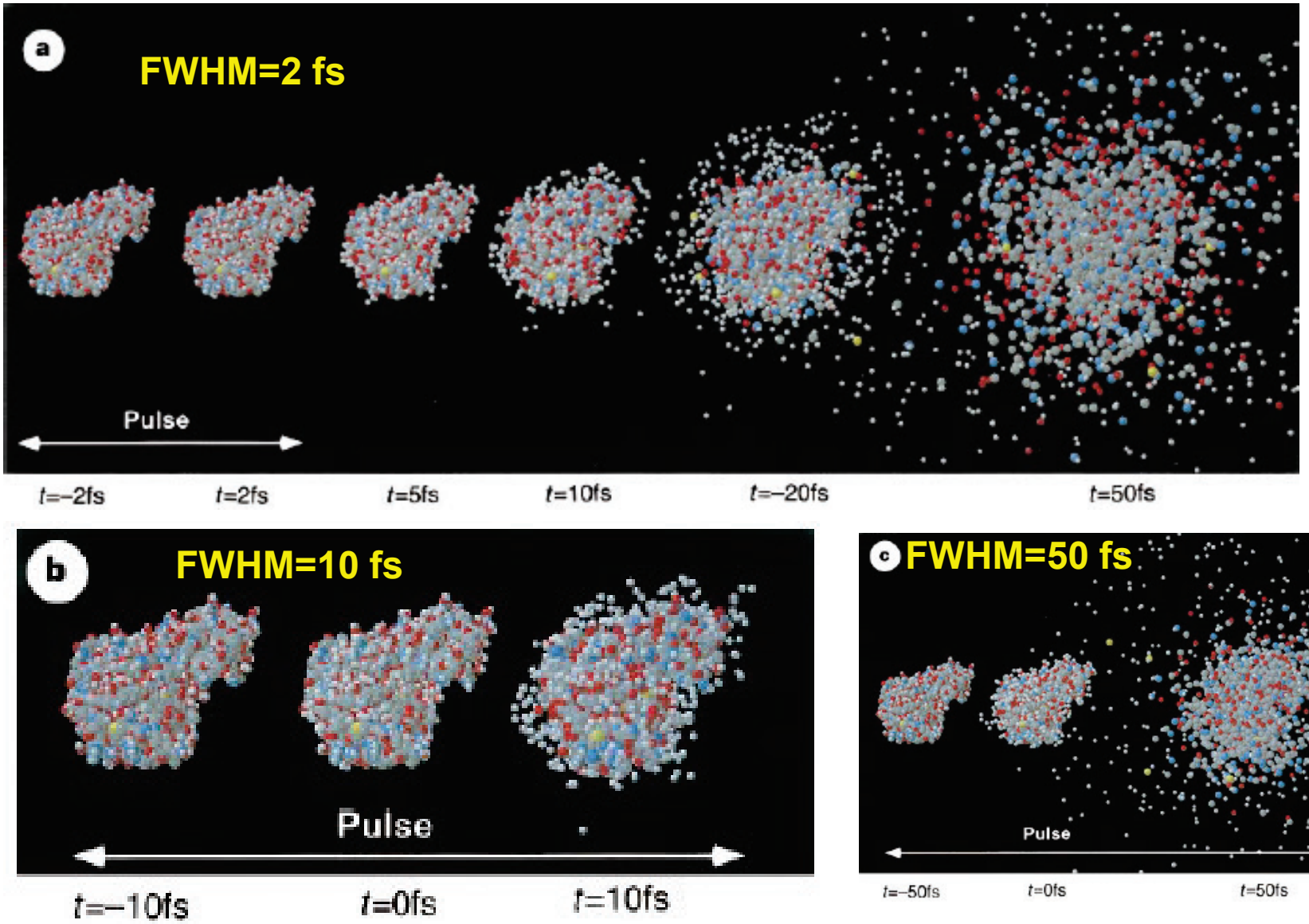






from the next pulse: no object

Imaging and holography of nanostructures with time resolution up to 10 fs (10^{-14}s) and even higher.

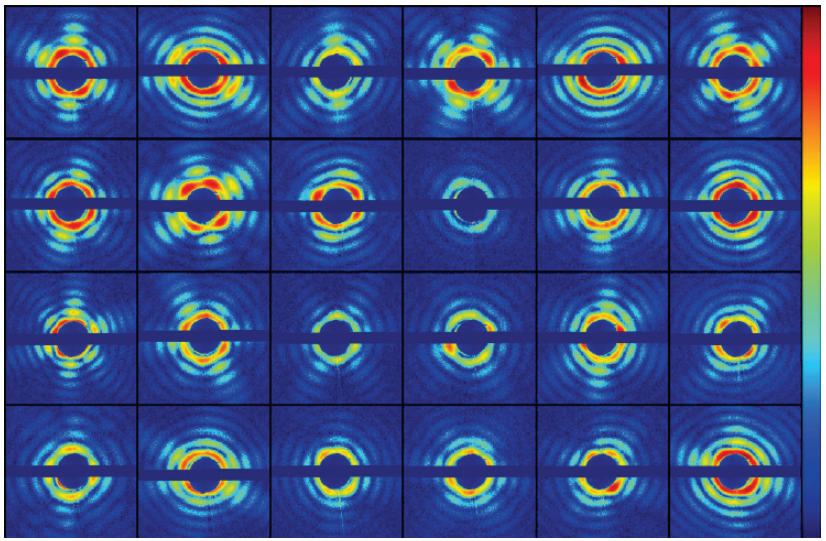


Lysozyme. White – H, grey – C, blue – N, red – O, yellow - S

12 keV, $3 \cdot 10^{12}$ photons, diameter of the beam 100 nm, i.e. Flux = $3.8 \cdot 10^{6}$ ph/Å^2

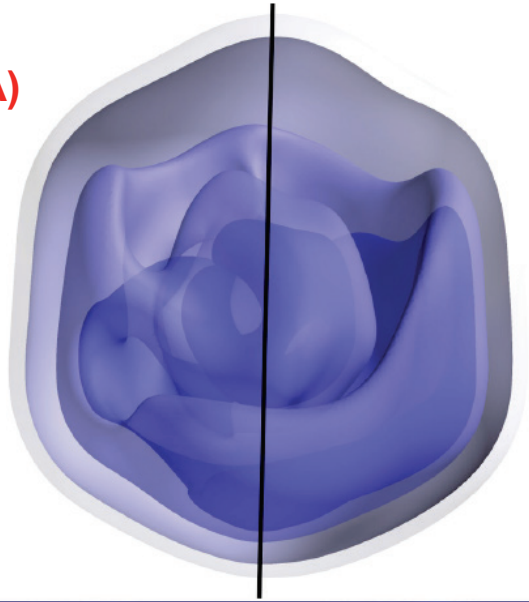
R. Neutze et al, Nature 406, 752 (2000)

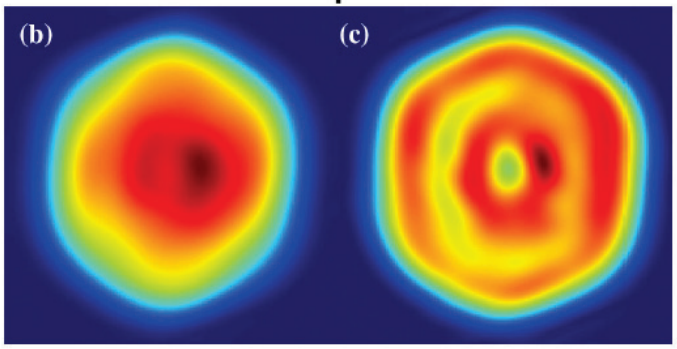
3D reconstruction of giant mimivirus by isolated pulses of XFEL



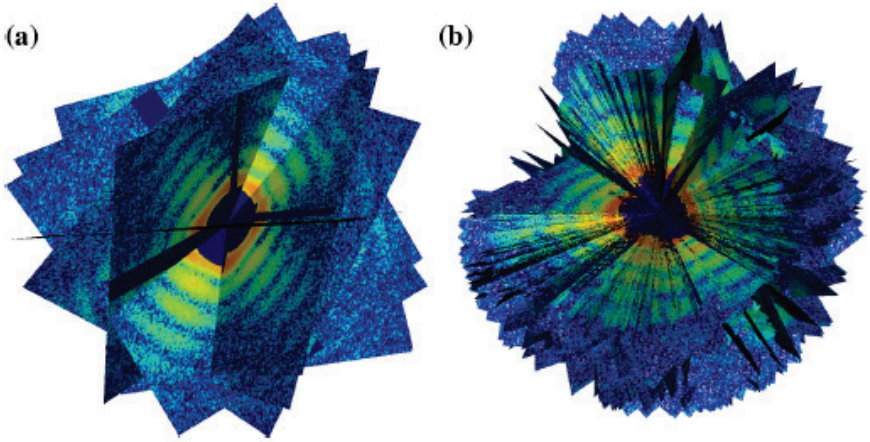
Experiments At LCLS (USA)

Electron cloud



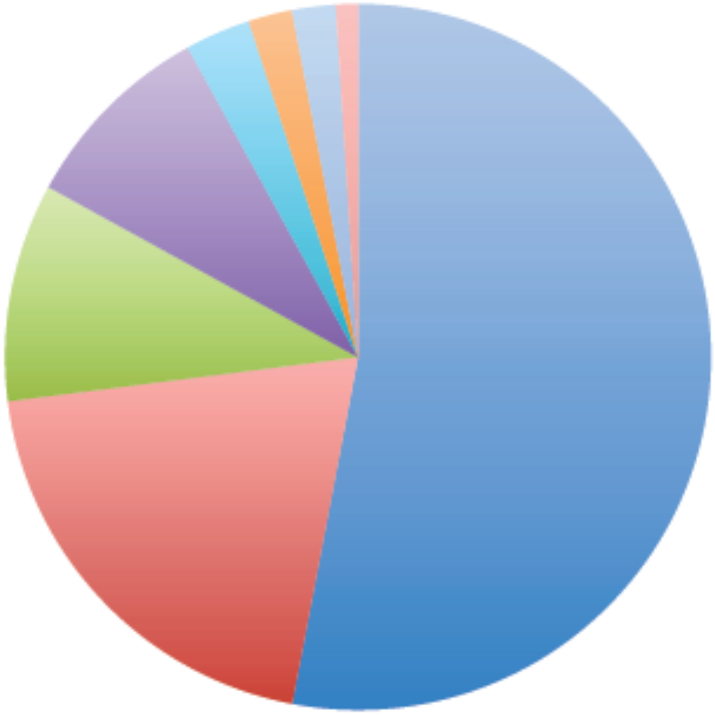


projection cut



T. Ekeberg et al. Phys. Rev. Lett.**114,** 098102 (2015)

Статистика по LCLS



Пользователи
по областям

- Физика
- Науки о жизни
- Химия
- Материалы
- Приборостроение
- Инженерия
- Оптика
- Науки о Земле и экология

With the creation of the XFELs -ray scientists associate the possibility of progress in a number of very important scientific and practical areas

1. The flow of chemical reactions in real time on the atomic level.

2. Investigation of the structure of proteins: new opportunities in medicine, genetics, biology; approaches to new technologies for creating new medicines.

3. Study of chemical and physical processes in the creation of new materials and nanostructures.

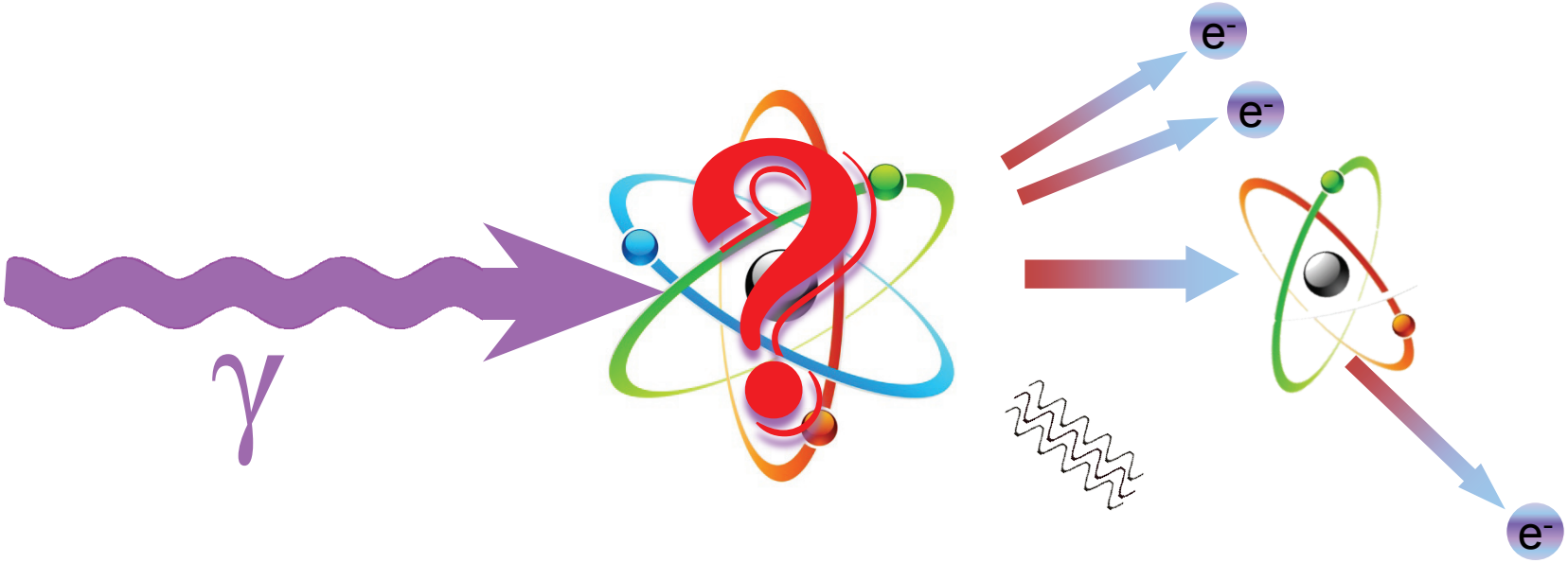
4. Recording holographic images on an atomic level.

5. Recreating conditions inside stars and large planets, studying the transition from condensed state to plasma

etc.

To explain phenomena in complex systems, it is necessary to understand how radiation interacts with simple systems.

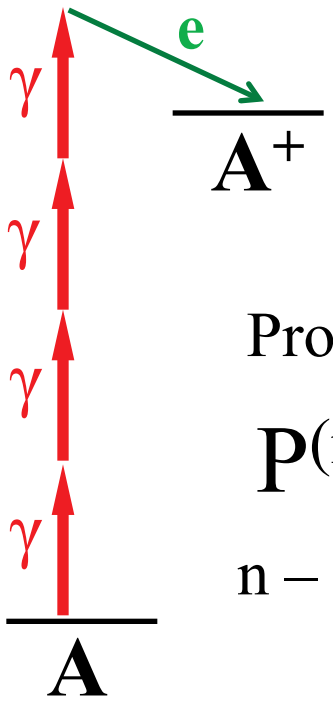
What is going on with atoms under the beam of X-ray free electron laser?



On some new phenomena, which were not possible to observe before

Nonlinear processes in XUV

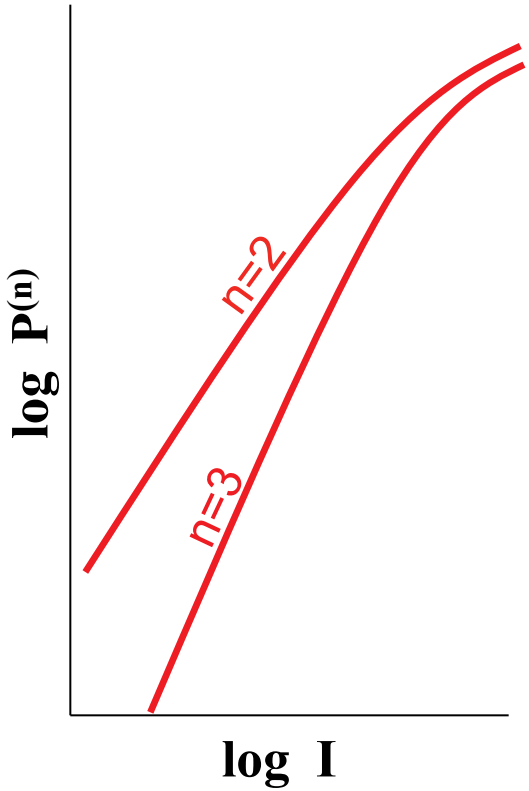
$$n\gamma + A \longrightarrow A^+ + e$$



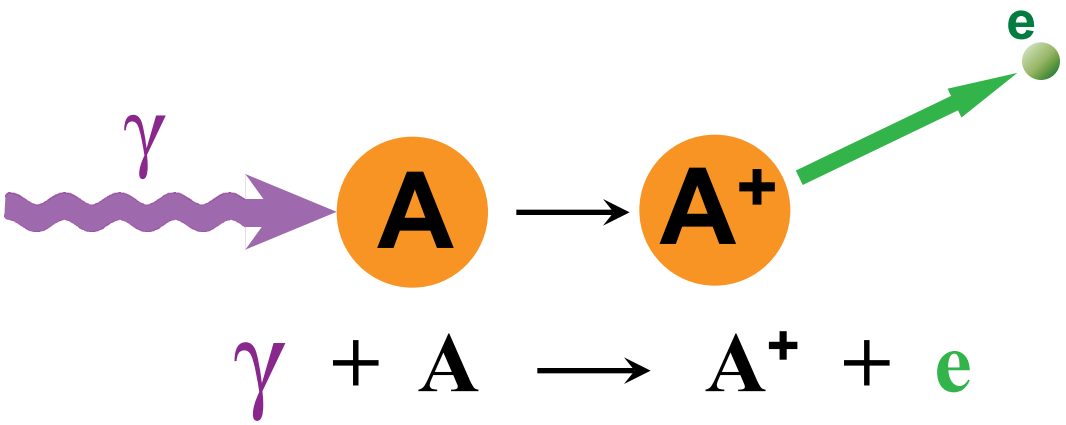
Probability of the process:

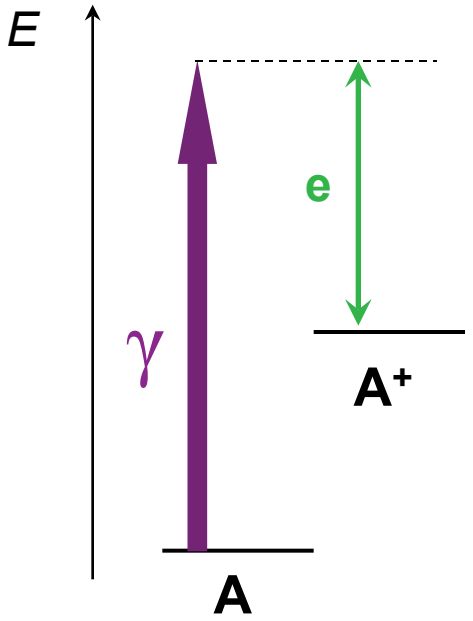
$$P^{(n)} \sim I^n$$

n – “degree of nonlinearity”

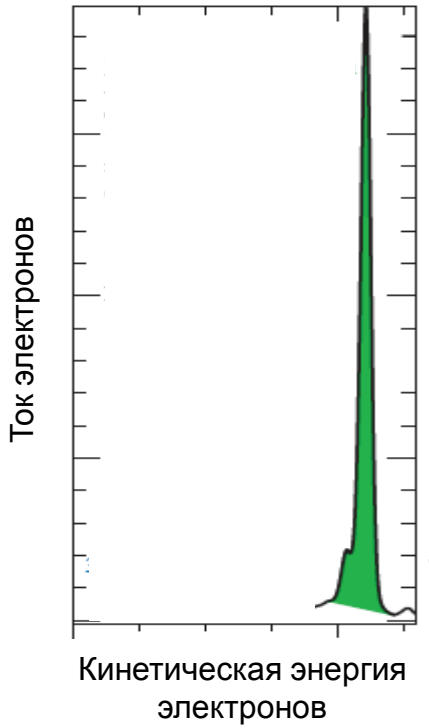


Single photon ionization

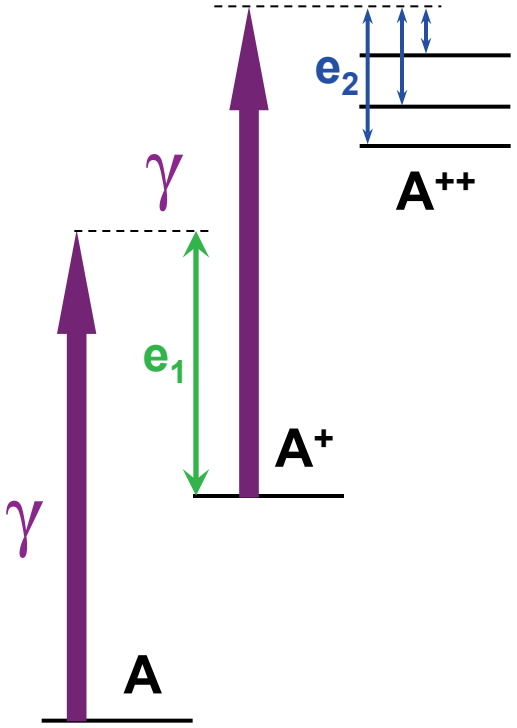


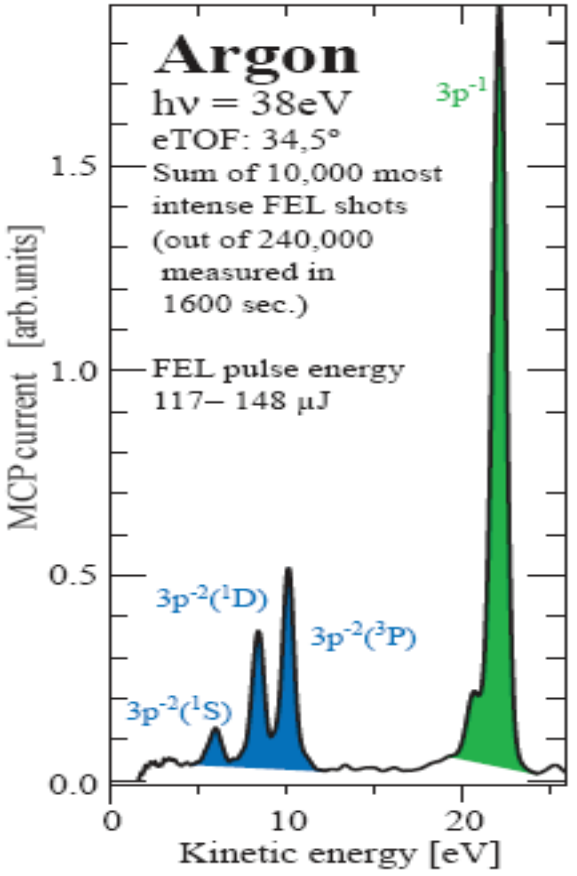


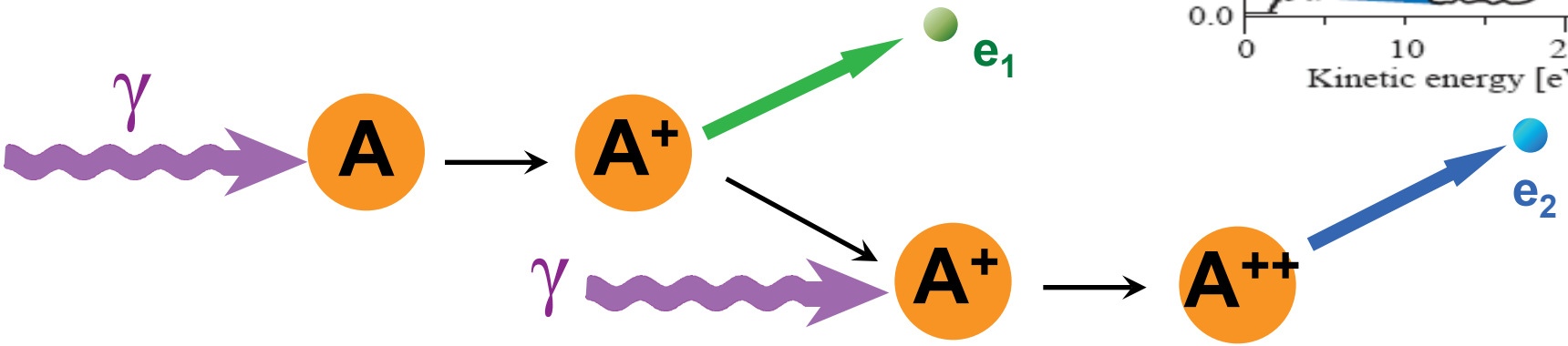
Atomic photoeffect



First experiments at FLASH, Hamburg (2006)



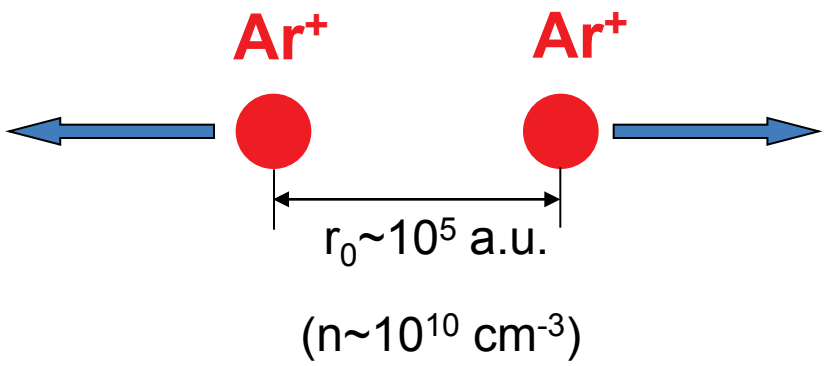


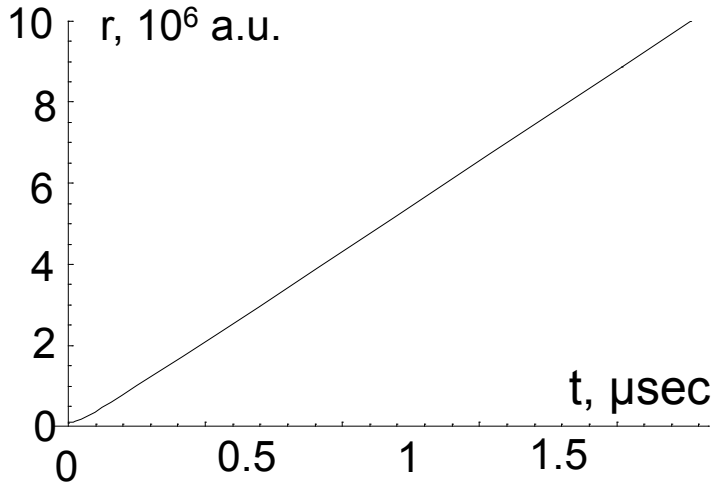


$$\gamma + A \longrightarrow A^+ + e_1$$

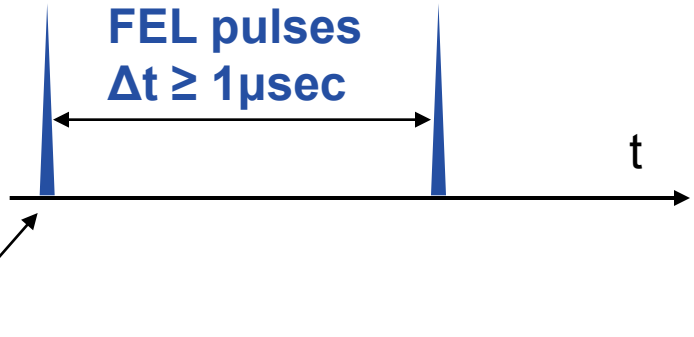
$$\gamma + A^+ \longrightarrow A^{++} + e_2$$

Photoionization of ions: Why is it possible to observe with FEL?



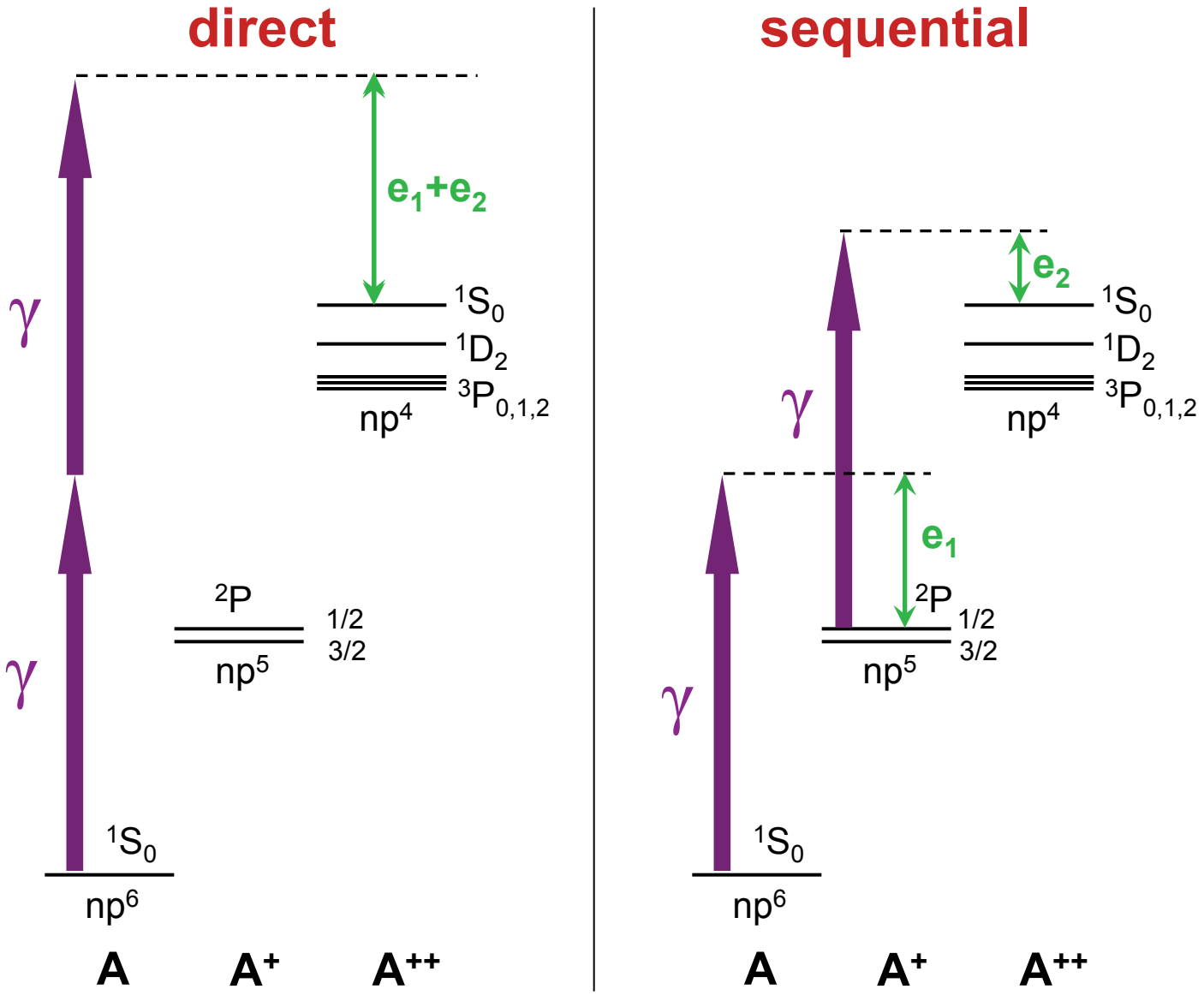


During the time of the femtosecond pulse the ions keep their positions



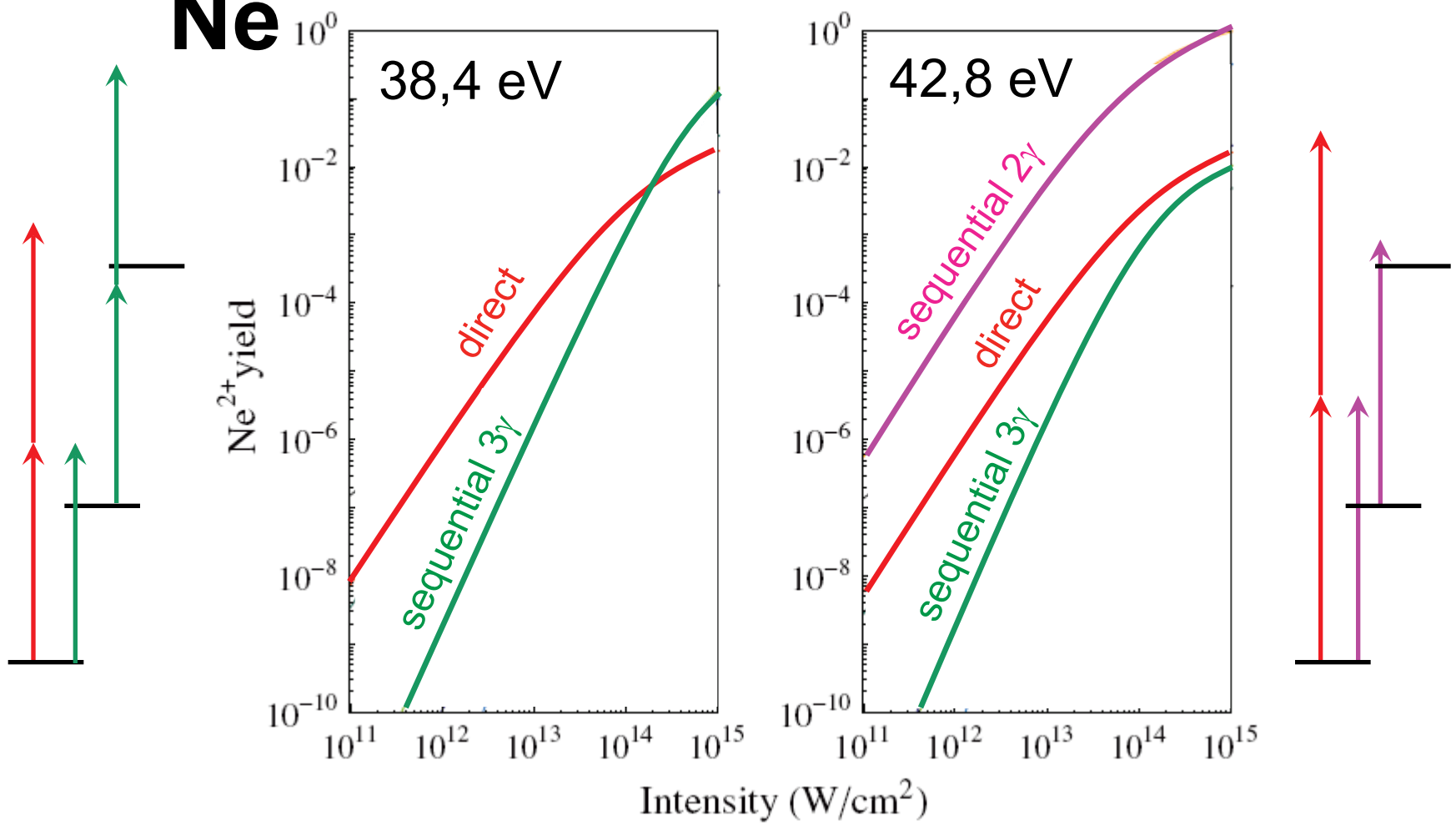
pulse duration
Δt ≈ 20-100 fs

Two-photon double atomic ionization (example of noble gases)



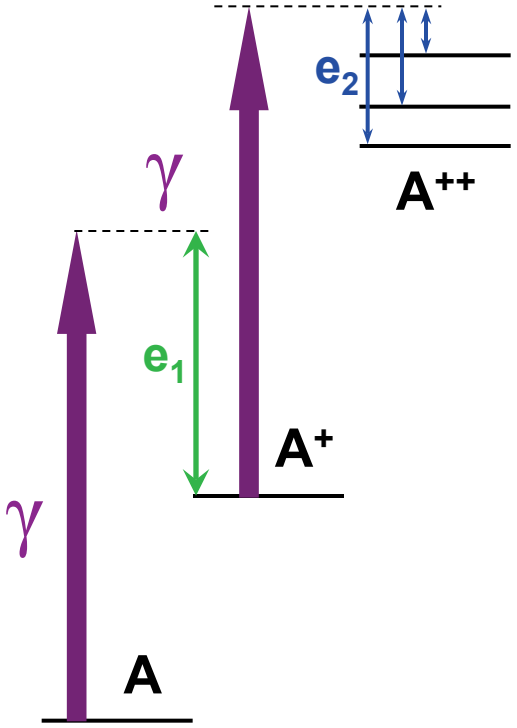
Yield of doubly charged ions for different mechanisms

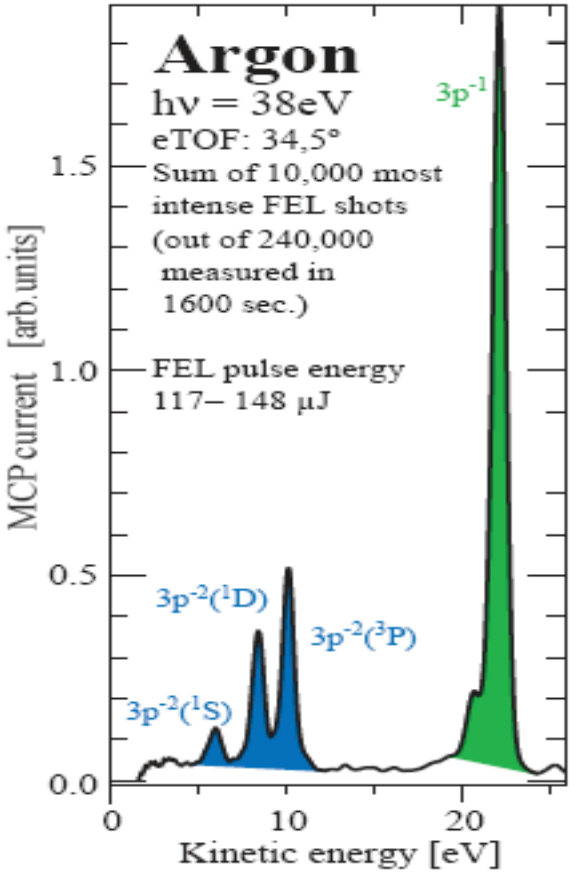
Makris and Lambropoulos, Phys. Rev. A **77**, 023401 (2008)

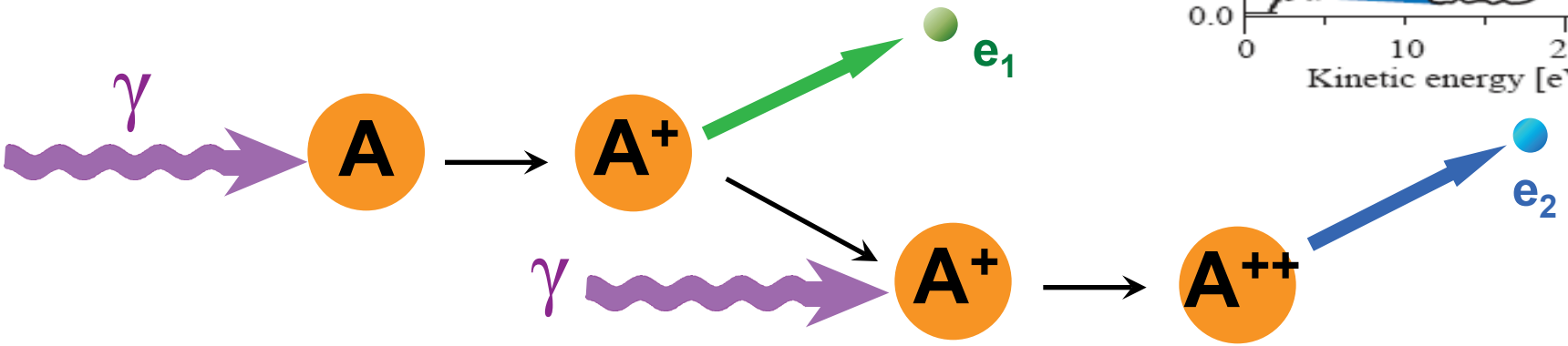


The sequential ionization starts to dominate when it is allowed by the energy conservation: To produce the 2nd step the energy of the photon should be larger than the ionization threshold of the ion.

First experiments at FLASH, Hamburg (2006)







$$\gamma + A \longrightarrow A^+ + e_1$$

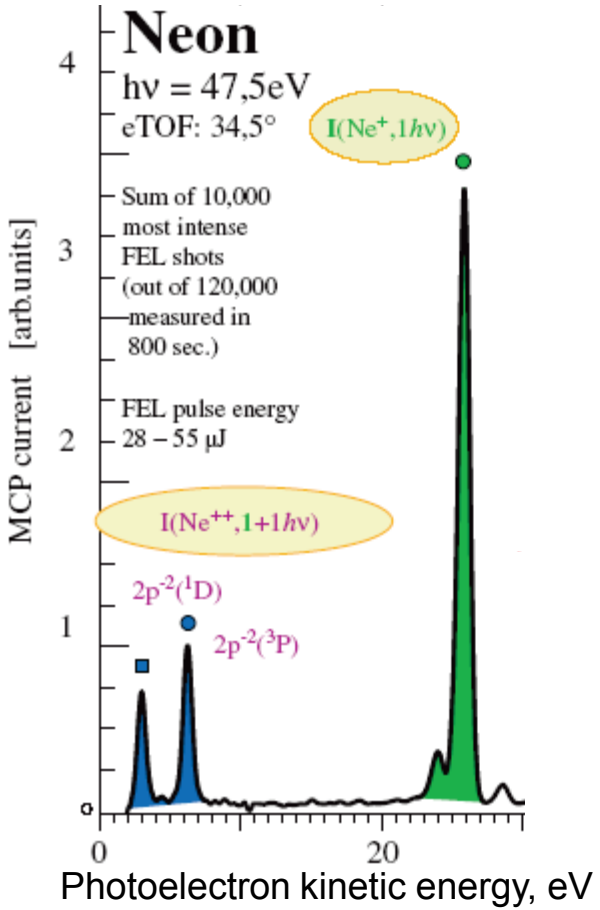
$$\gamma + A^+ \longrightarrow A^{++} + e_2$$

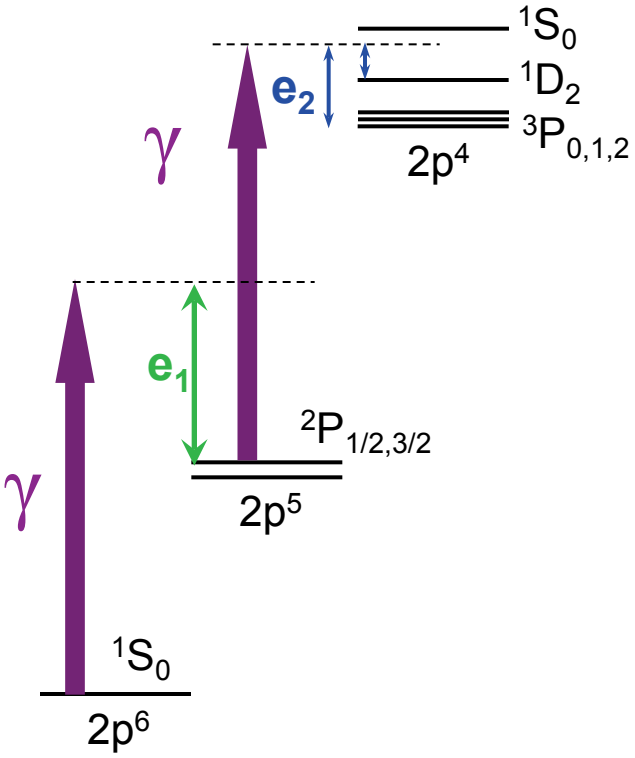
Why it is possible with XFEL?

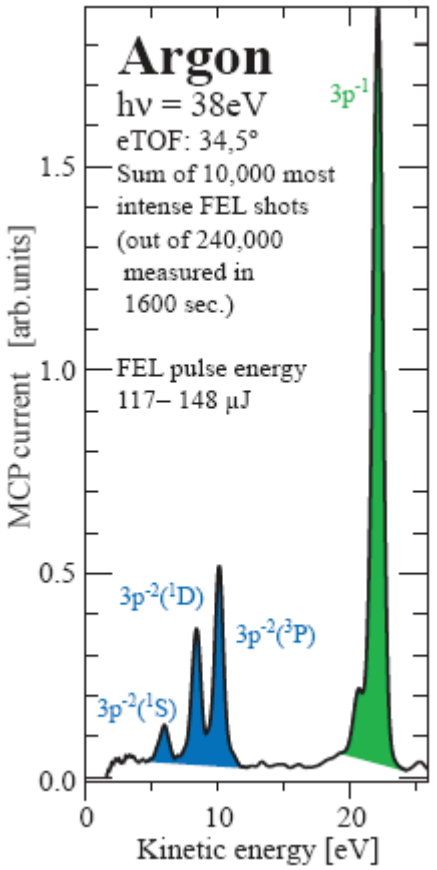
	Synchrotron	FEL
hν	IR-X-Ray (1 eV-keV)	VUV-XUV 15-200 eV
ΔE/E	10^{-5}	10^{-3}
ph/s	10^{14}	10^{15}
ph/pulse	10^{7}	10^{14}
Tunability	Easy	Possible
repetition rate	pulsed MHZ	pulsed 10 Hz
temporal width	30-50 ps	15 – 200 fs

Combination of these parameters allows observing two-photon sequential double ionization

Photoelectron spectrum of Ne denerated by FEL





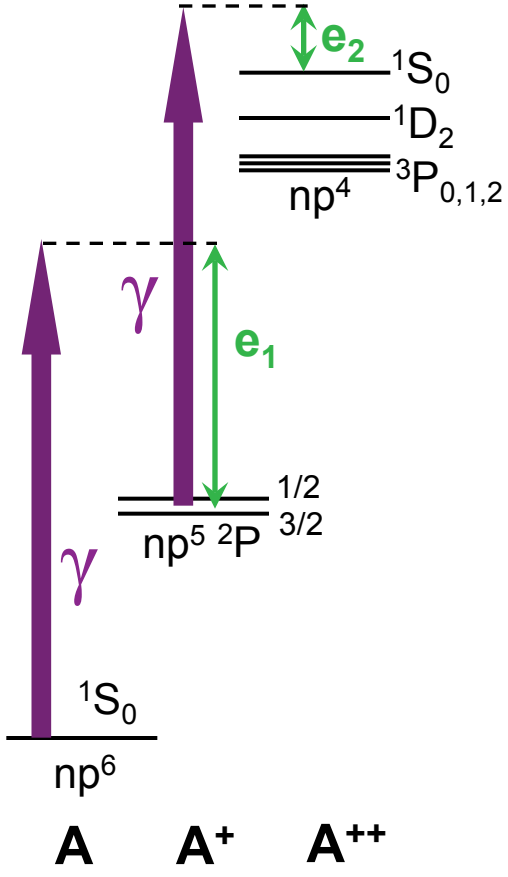


$$\gamma_{FEL} + Ne(2p^6) \longrightarrow Ne^+(2p^5) + e_1$$

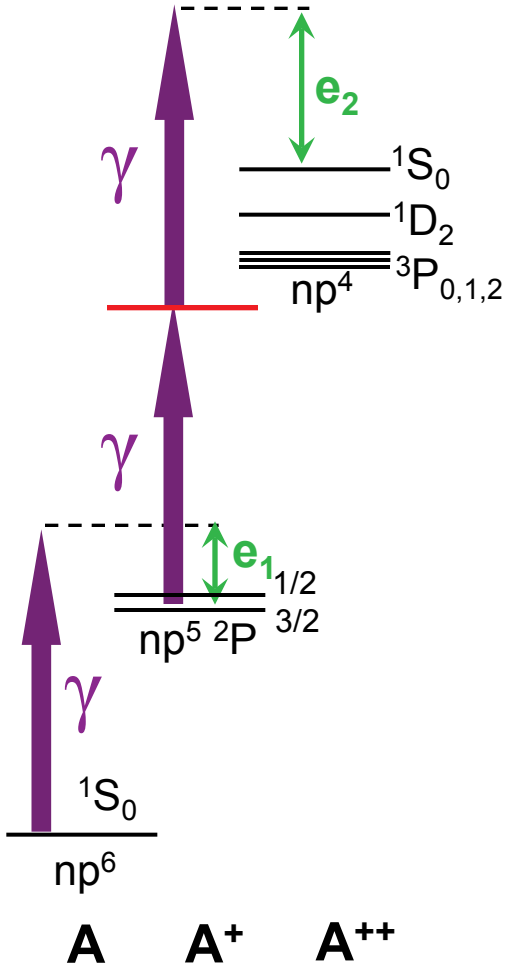
$$\gamma_{FEL} + Ne^+(2p^5) \longrightarrow Ne^{2+}(2p^4) + e_2$$

Two- and three-photon sequential processes:

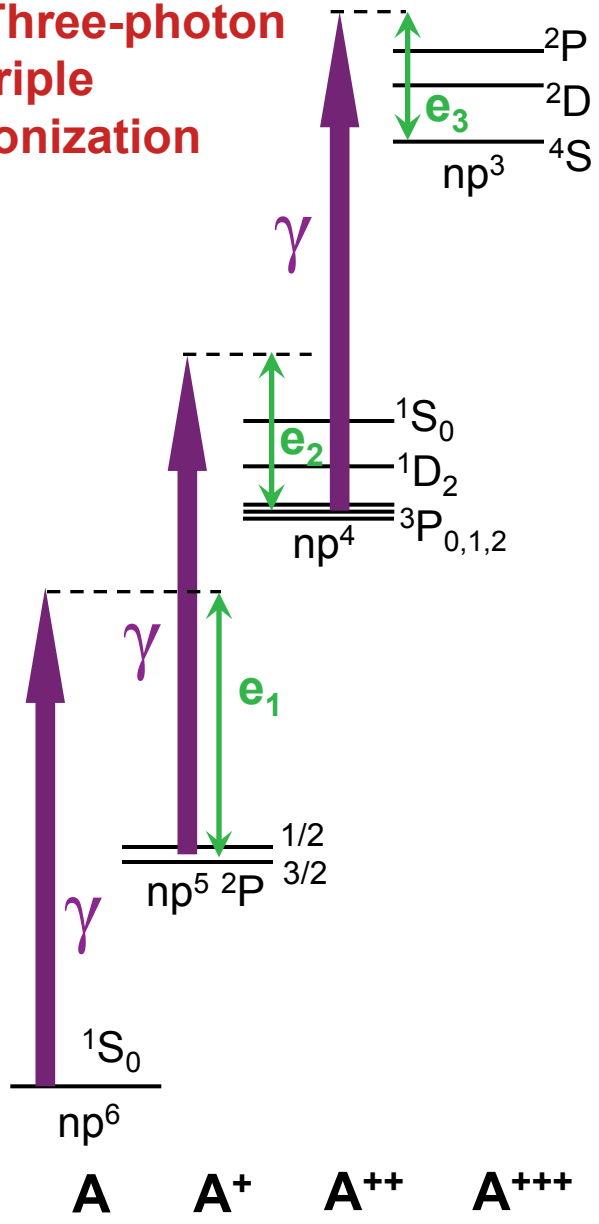
Two-photon double ionization



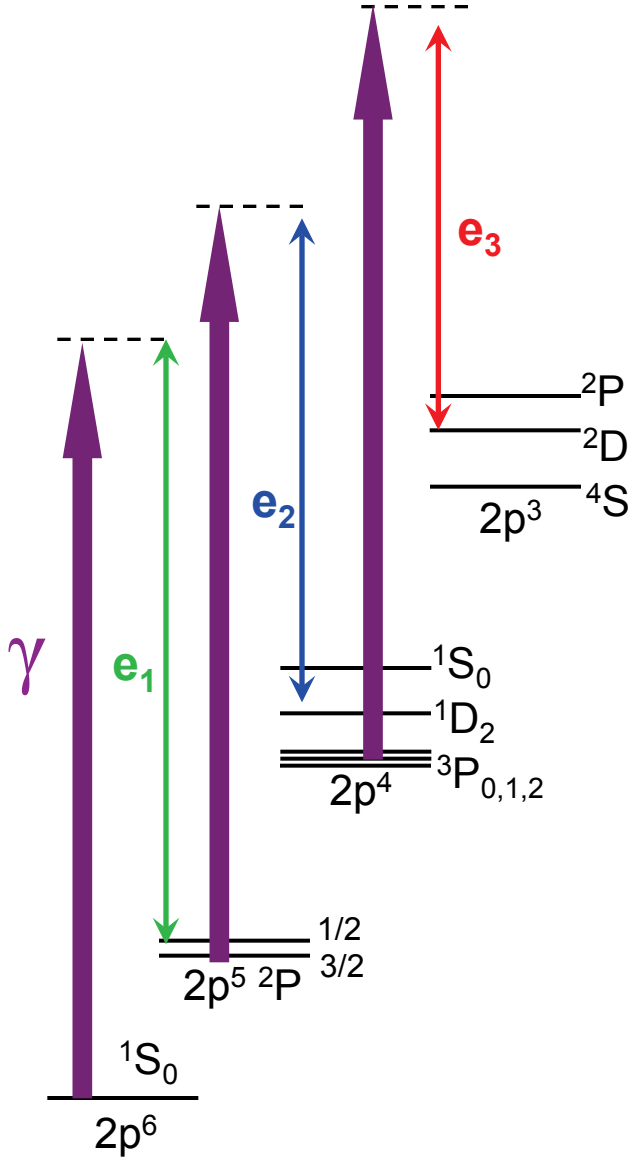
Three-photon double resonant ionization



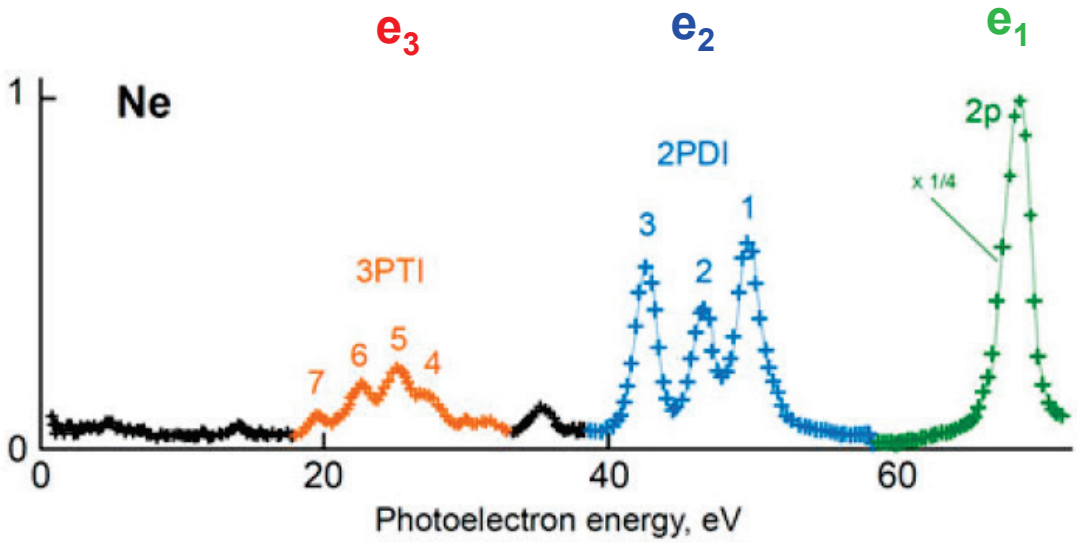
Three-photon triple ionization



Three-photon sequential triple ionization of Ne



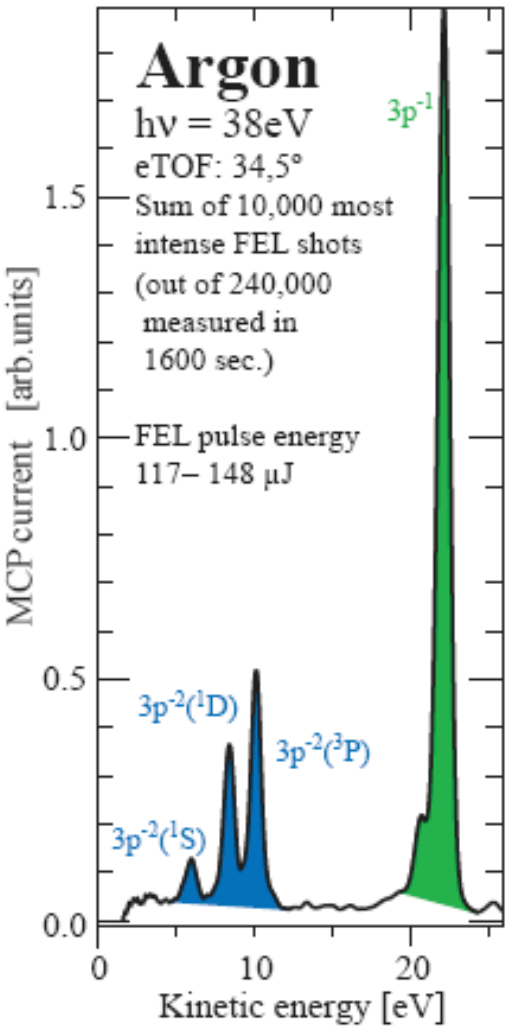
FLASH
5 Hz, ~20 fs
$1 \cdot 10^{13}$ W/cm²
90.5 eV (13.7 nm)

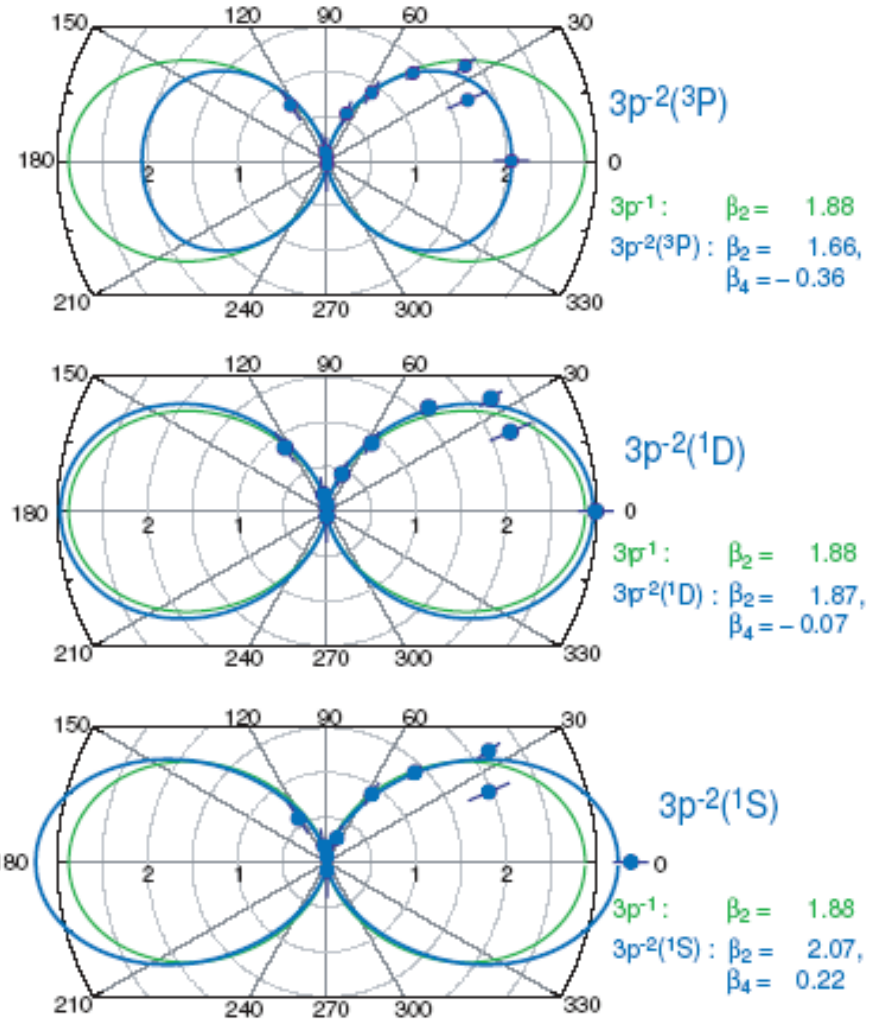


A. Rouzée et al, Phys. Rev. A **83**, 031401(R) (2011)

Angular distributions of the second-step photoelectrons

(electrons from the 1st step are not observed)





The strength of the photoelectron lines from ionic ionization is so large that allows to measure the photoelectron angular distribution!

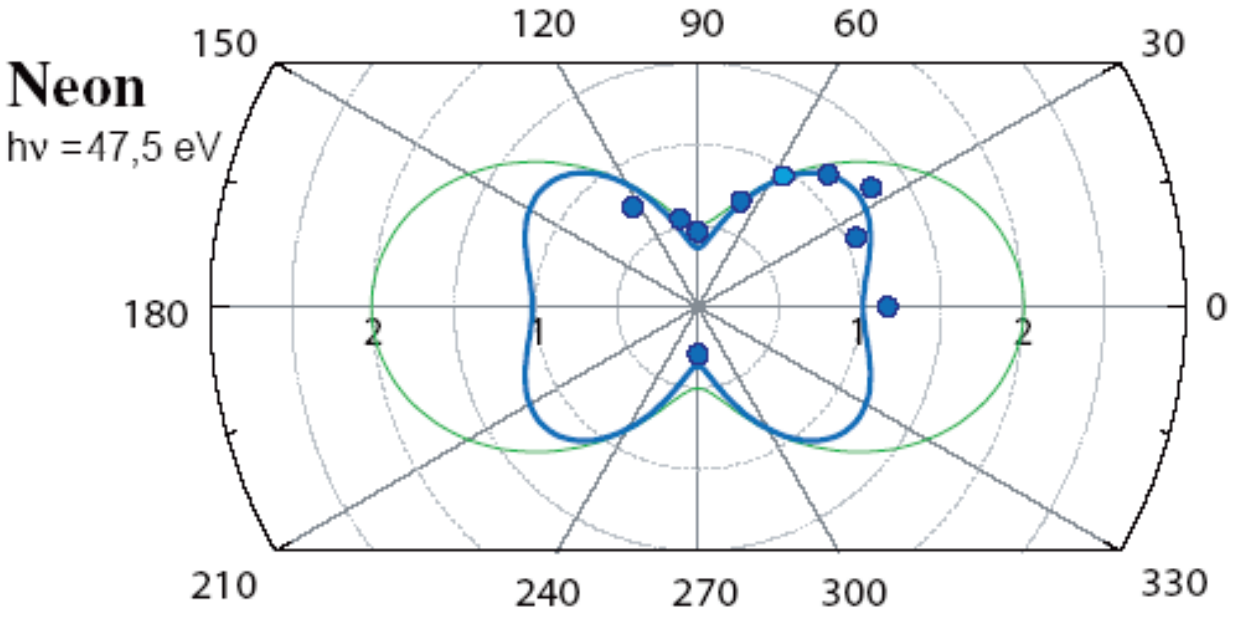
Angular distributions of the second-step photoelectrons

M. Braune et al, 2007

(electrons from the 1st step are not observed)

Second step: $\gamma_{FEL} + Ne^+(2p^5) \longrightarrow Ne^{2+}(2p^4) + e_2$

Linearly polarized FEL E



Ne
↓ 1·hν
Ne^+
↓ 1·hν
Ne^{2+}

$2p^{-1}$: $I(\theta) = C\left[1 + \beta_2 P_2(\cos\theta)\right]$ $\beta_2 = 1.00$

$2p^{-2}(^3P)$: $I(\theta) = C\left[1 + \beta_2 P_2(\cos\theta) + \beta_4 P_4(\cos\theta)\right]$ $\beta_2 = 0.74,\ \beta_4 = -0.50$

Due to the alignment of singly charged ion after the first step, the second-step electron gains one more Legendre polynomial in the angular distribution.

Angular distribution of photoelectrons

$$M_{\text{length}} = \langle \psi_f \mid z \mid \psi_i \rangle$$

$$= \sum_{\ell m} \mathrm{i}^{-\ell} e^{\mathrm{i}\delta_{E\ell}} \Re_{i \to E\ell} \sqrt{\frac{2\ell_i + 1}{2\ell + 1}} \, (\ell_i 0, 10 \,|\, \ell 0) \, (\ell_i m_i, 10 \,|\, \ell m) \, Y_{\ell m}(\Omega_e)$$

where $\Re_{i \to E\ell} = \int_0^\infty r^2 dr R^*_{E\ell}(r) \, r \, R_{n_i \ell_i}(r) = \int_0^\infty dr P^*_{E\ell}(r) \, r \, P_{n_i \ell_i}(r)$

$$\sum_{\alpha\beta\delta} (-1)^{a-\alpha} C^{c\gamma}_{\alpha\alpha\, b\beta} C^{e\varepsilon}_{d\delta\, b\beta} C^{f\varphi}_{d\delta\, a-\alpha} = x_1 \amalg_{cf} C^{e\varepsilon}_{c\gamma\, f\varphi} \begin{Bmatrix} a & b & c \\ e & f & d \end{Bmatrix}$$

$$x_1 = (-1)^{b+c+d+f}$$

$$\amalg_{ab\ldots c} = \sqrt{(2a+1)\,(2b+1)\ldots(2c+1)}$$

$$\sigma_{n_i \ell_i} = \frac{C}{3} \sum_{\ell} (\ell_i 0, 10 \,|\, \ell 0)^2 \left|\Re_{\ell_i \to E\ell}\right|^2$$

$$= \frac{C}{3(2\ell_i+1)} \left[\ell_i \left|\Re_{\ell_i \to E, \ell_i - 1}\right|^2 + (\ell_i + 1) \left|\Re_{\ell_i \to E, \ell_i + 1}\right|^2\right]$$

Differential cross section (photoelectron angular distribution)

Linearly polarized light (z ∥ ***E***)

$$\frac{d\sigma}{d\Omega_e} = \frac{\sigma}{4\pi}\left(1 + \beta\, P_2(\cos\theta_e)\right)$$

Circularly polarized light (z ∥ $\boldsymbol{k}_\gamma$)

$$\frac{d\sigma}{d\Omega_e} = \frac{\sigma}{4\pi}\left(1 - \frac{\beta}{2}\, P_2(\cos\theta_e)\right)$$

Particular cases of the asymmetry parameter

s-subshell: $\beta = 2$

always a constant in the case of one Ionization channel!

s- cross section $\sigma_{ns}(\omega) = \dfrac{4\pi^2\alpha\omega}{3}\,\Re^2_{E,p}$

p-subshell:

$$\beta = 2\,\frac{\Re^2_{Ed} - 2\Re_{Ed}\Re_{Es}\cos(\xi_{Ed} - \xi_{Es})}{\Re^2_{Es} + 2\Re^2_{Ed}}$$

p-cross section $\sigma_{np}(\omega) = \dfrac{4\pi^2\alpha\omega\cdot 2}{3}\left[\Re^2_{E,s} + 2\Re^2_{E,d}\right]$

d-subshell:

$$\beta = \frac{2}{5}\,\frac{\Re^2_{Ep} + 6\Re^2_{Ef} - 18\Re_{Ep}\Re_{Ef}\cos(\xi_{Ef} - \xi_{Ep})}{2\Re^2_{Ep} + 3\Re^2_{Ef}}$$

End of lecture 8