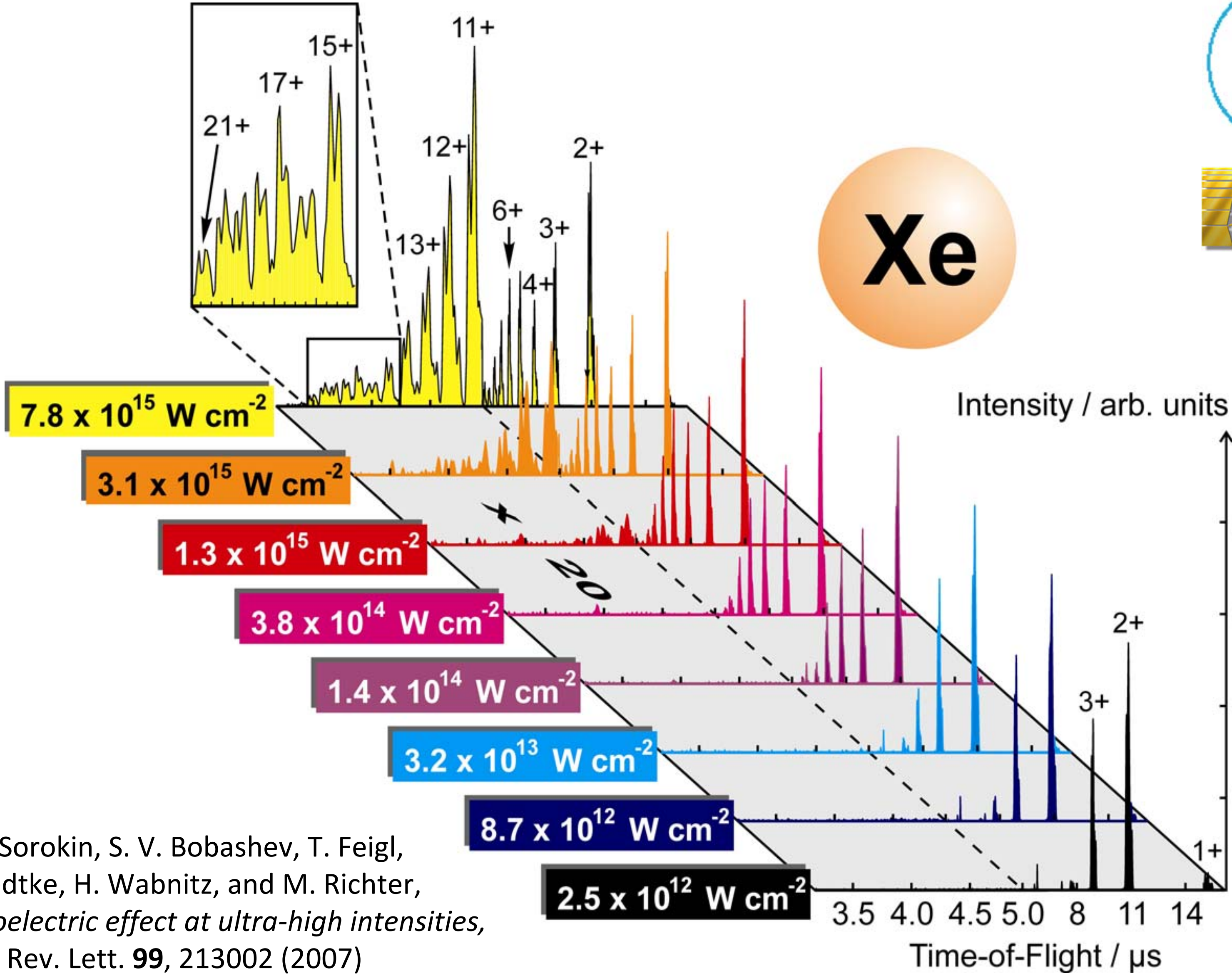
The Story of Xe^{21+} at FLASH

M. Richter

Physikalisch-Technische Bundesanstalt (PTB)

Multiple Ionization of Xenon in the EUV (13.3 nm / 93 eV)



A. A. Sorokin, S. V. Bobashev, T. Feigl,
K. Tiedtke, H. Wabnitz, and M. Richter,
Photoelectric effect at ultra-high intensities,
Phys. Rev. Lett. **99**, 213002 (2007)

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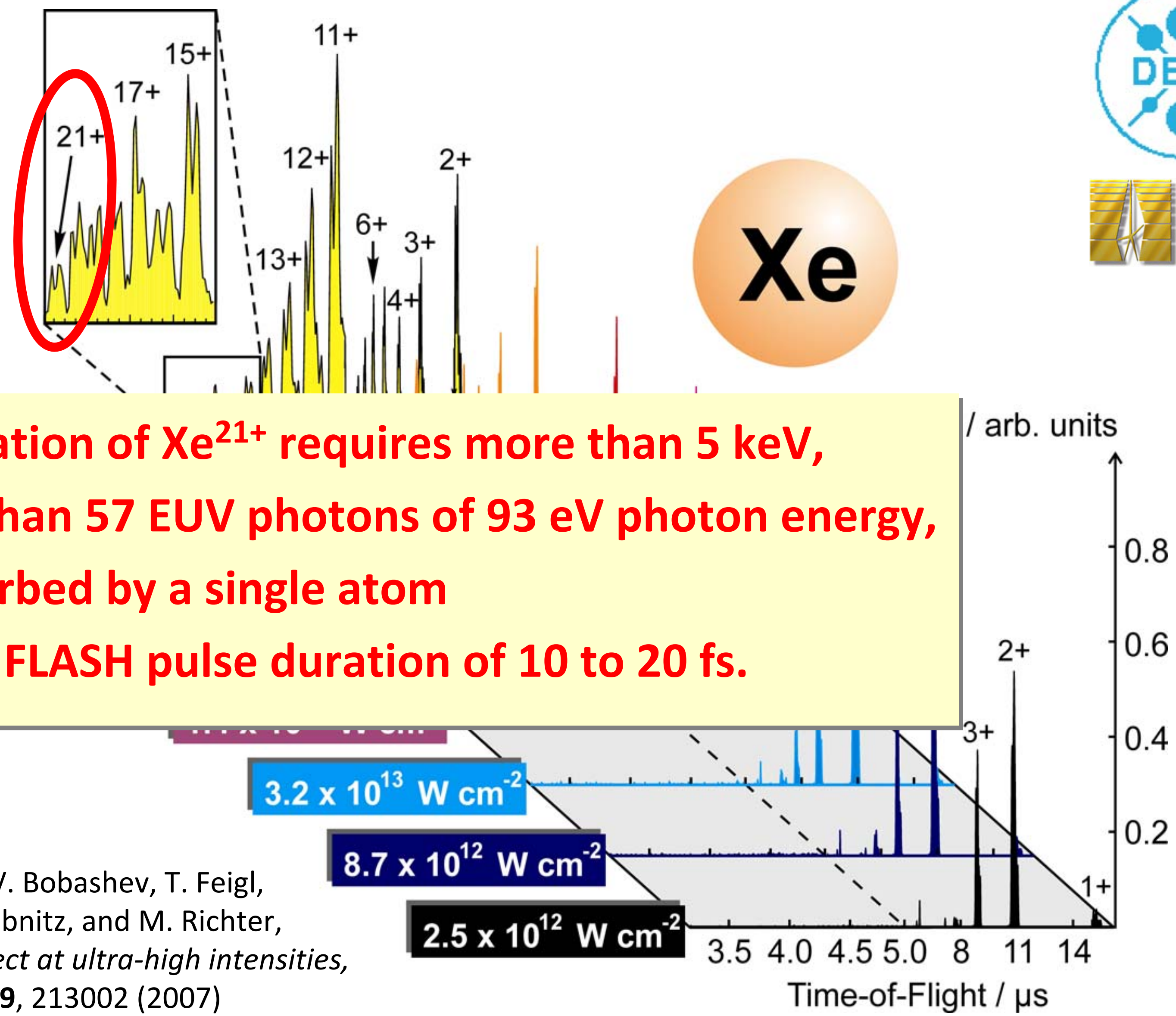

The generation of Xe^{21+} requires more than 5 keV,
i.e. more than 57 EUV photons of 93 eV photon energy,
to be absorbed by a single atom
within the FLASH pulse duration of 10 to 20 fs.

A. A. Sorokin, S. V. Bobashev, T. Feigl, K. Tiedtke, H. Wabnitz, and M. Richter, *Photoelectric effect at ultra-high intensities,* Phys. Rev. Lett. **99**, 213002 (2007)

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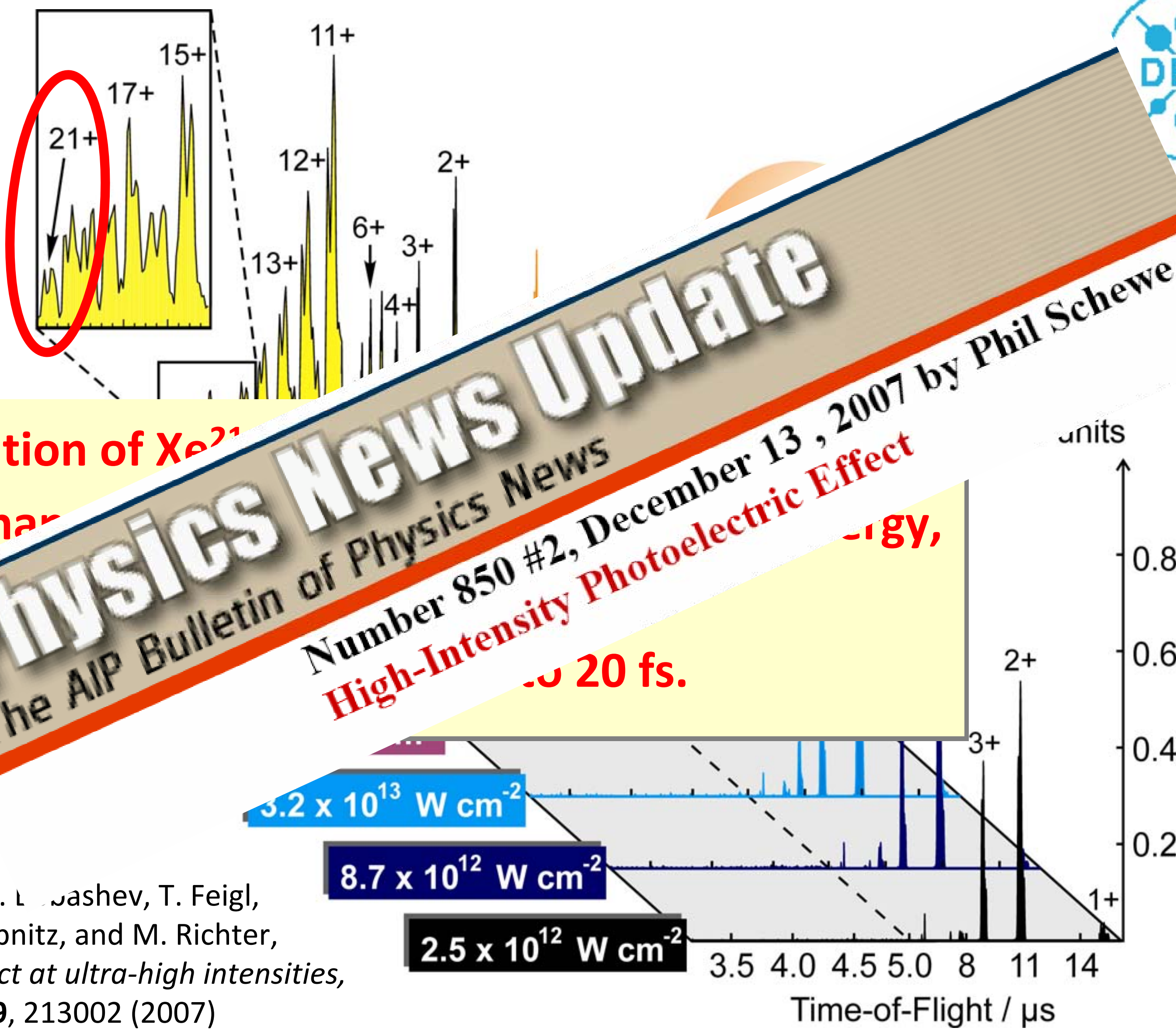

The generation of Xe^{21} ... i.e. more thar ... ergy, to be ... within ... 20 fs.

A. A. Sorokin, S. V. ...ashev, T. Feigl, K. Tiedtke, H. Wabnitz, and M. Richter, *Photoelectric effect at ultra-high intensities,* Phys. Rev. Lett. **99**, 213002 (2007)

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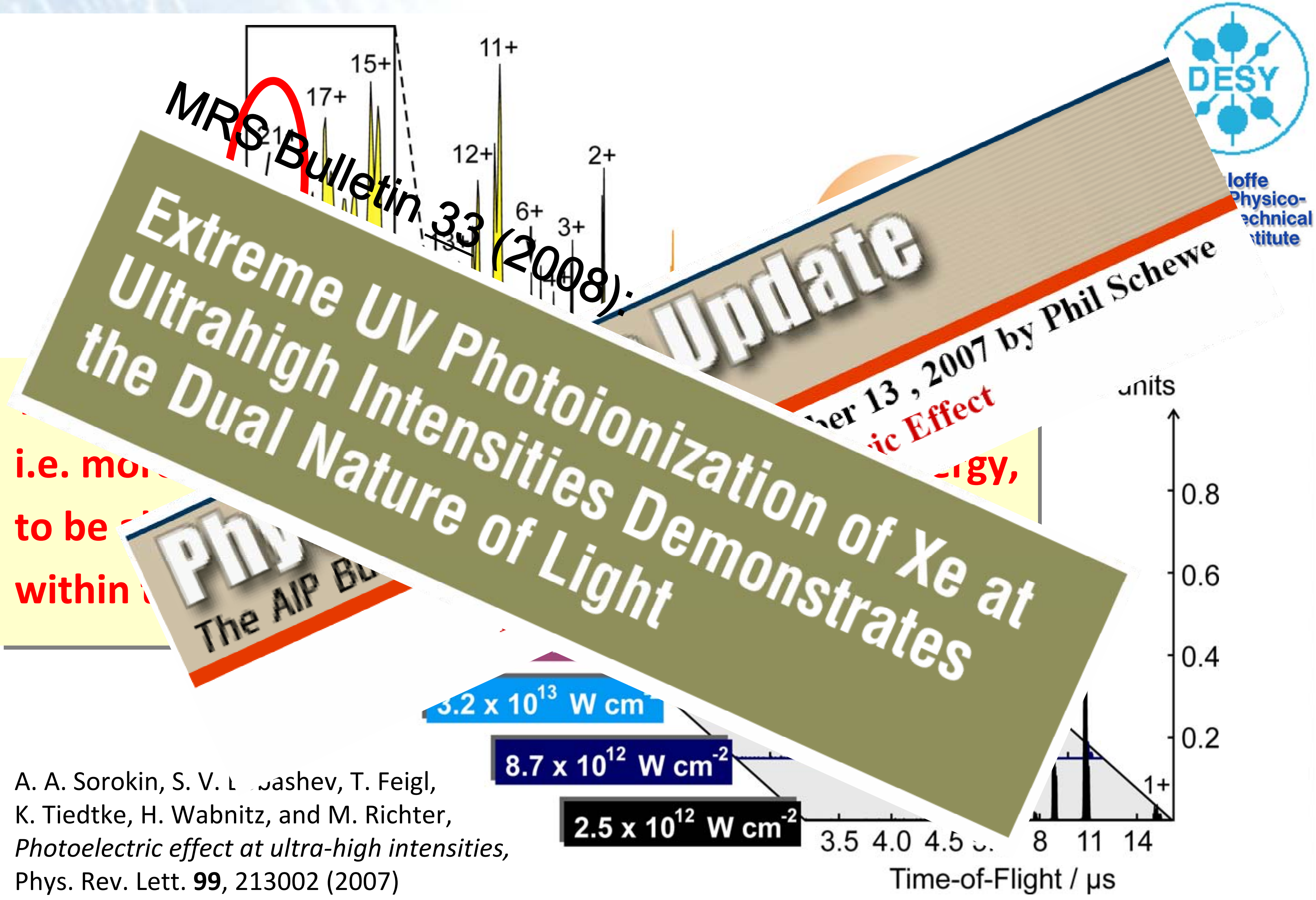

A. A. Sorokin, S. V. B[illegible]ashev, T. Feigl, K. Tiedtke, H. Wabnitz, and M. Richter, *Photoelectric effect at ultra-high intensities*, Phys. Rev. Lett. **99**, 213002 (2007)

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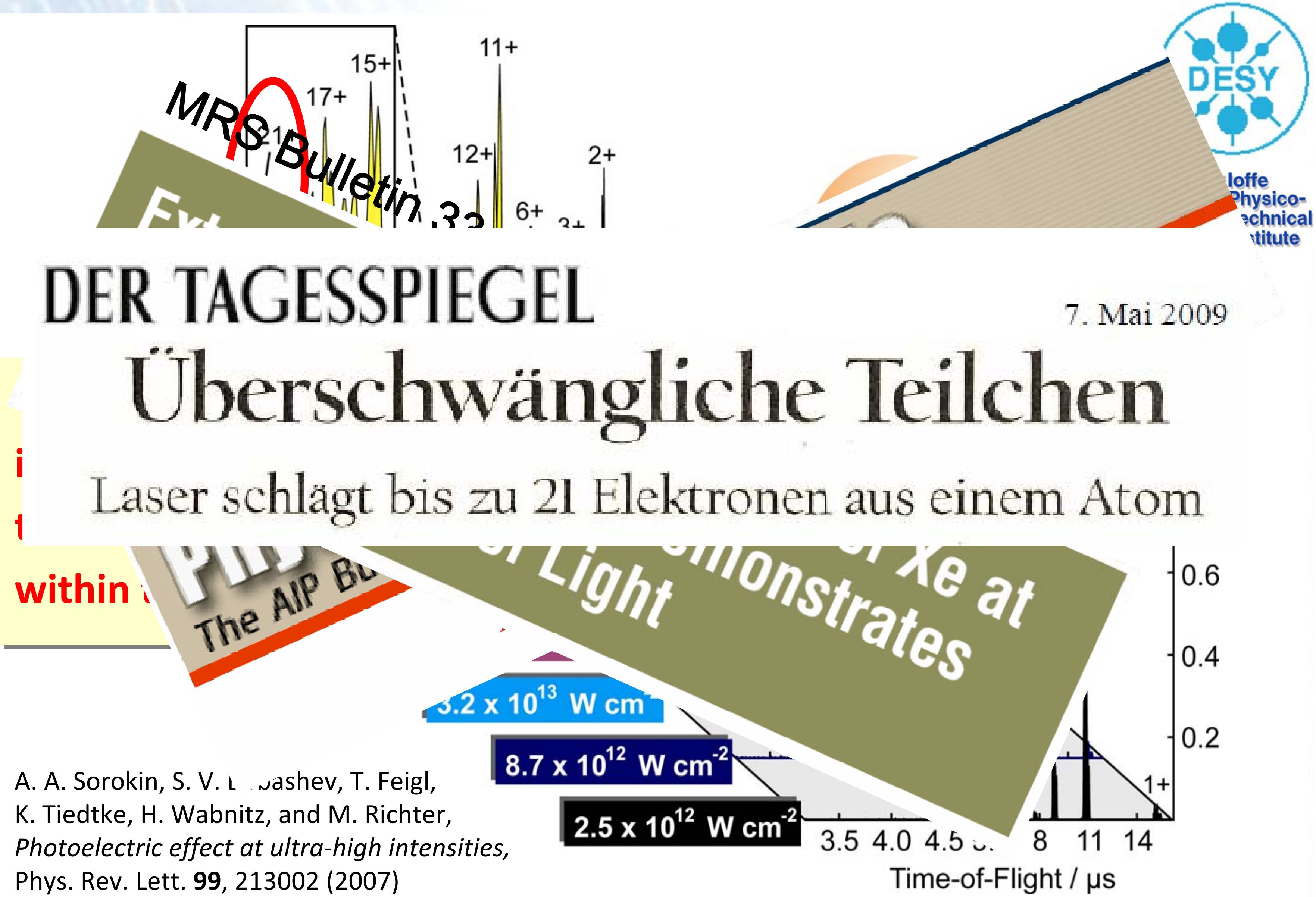

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The Story of Xe^{21+} at FLASH

M. Richter, A. A. Sorokin, S. V. Bobashev, K. Tiedtke

The Story of Xe^{21+} at FLASH: Outline

PTB

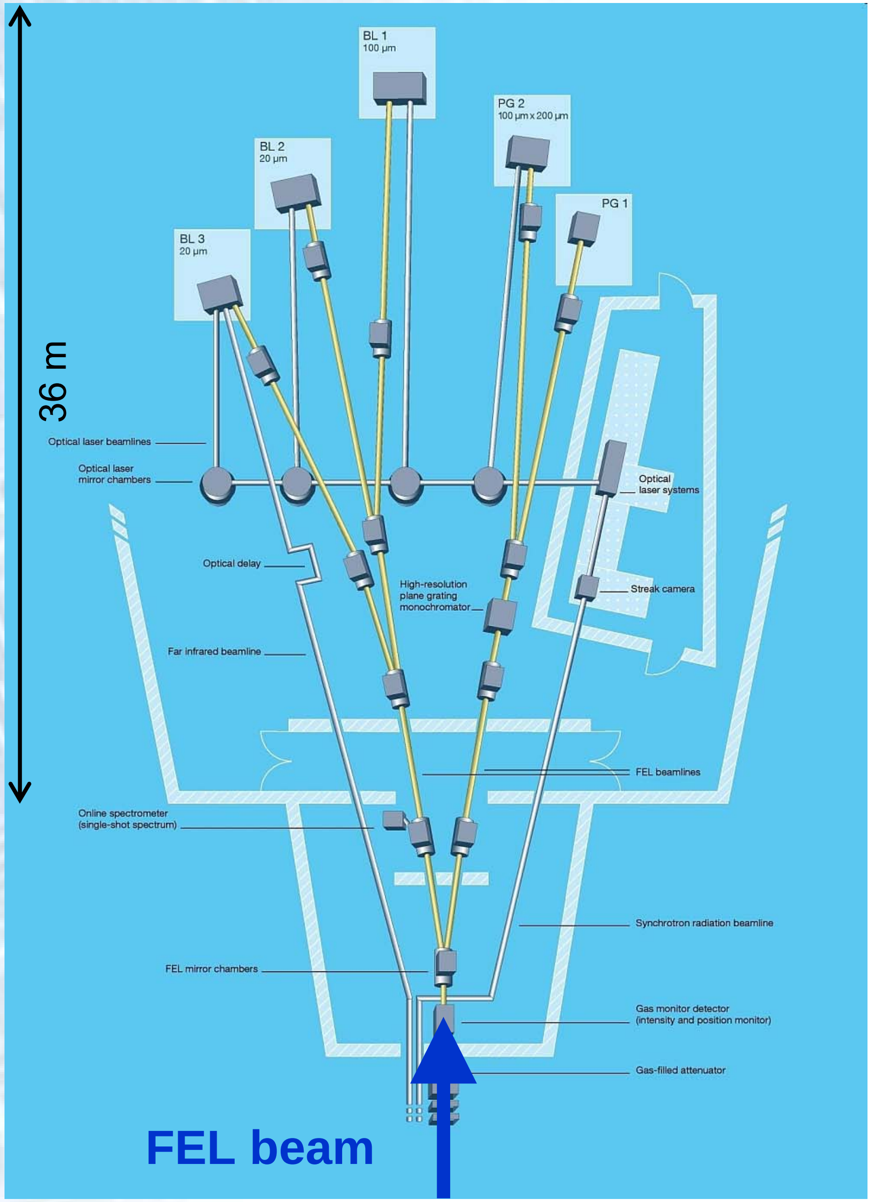
Background: FEL photon diagnostics

Experimental details

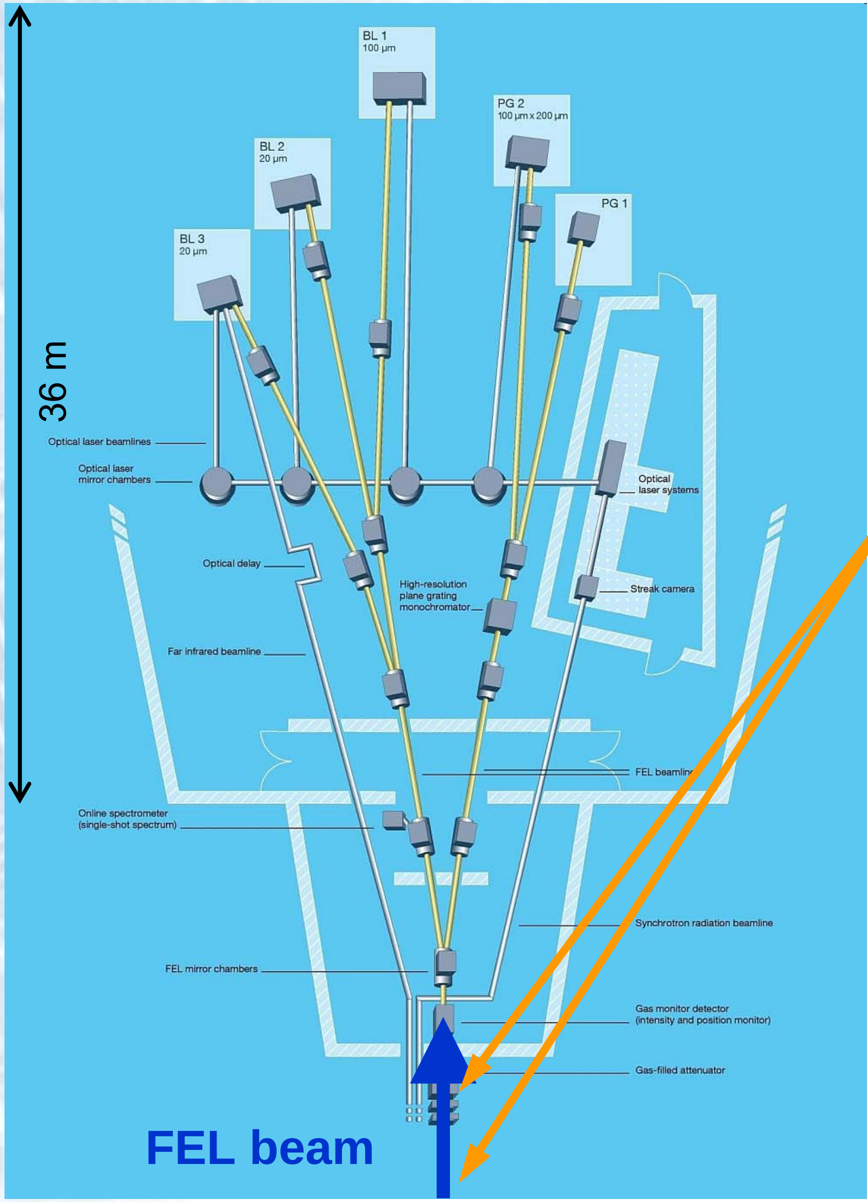
Multiphoton ionization of Ne and He

Experiments in the focus of EUV multilayer mirrors

Experimental Area at FLASH



Experimental Area at FLASH

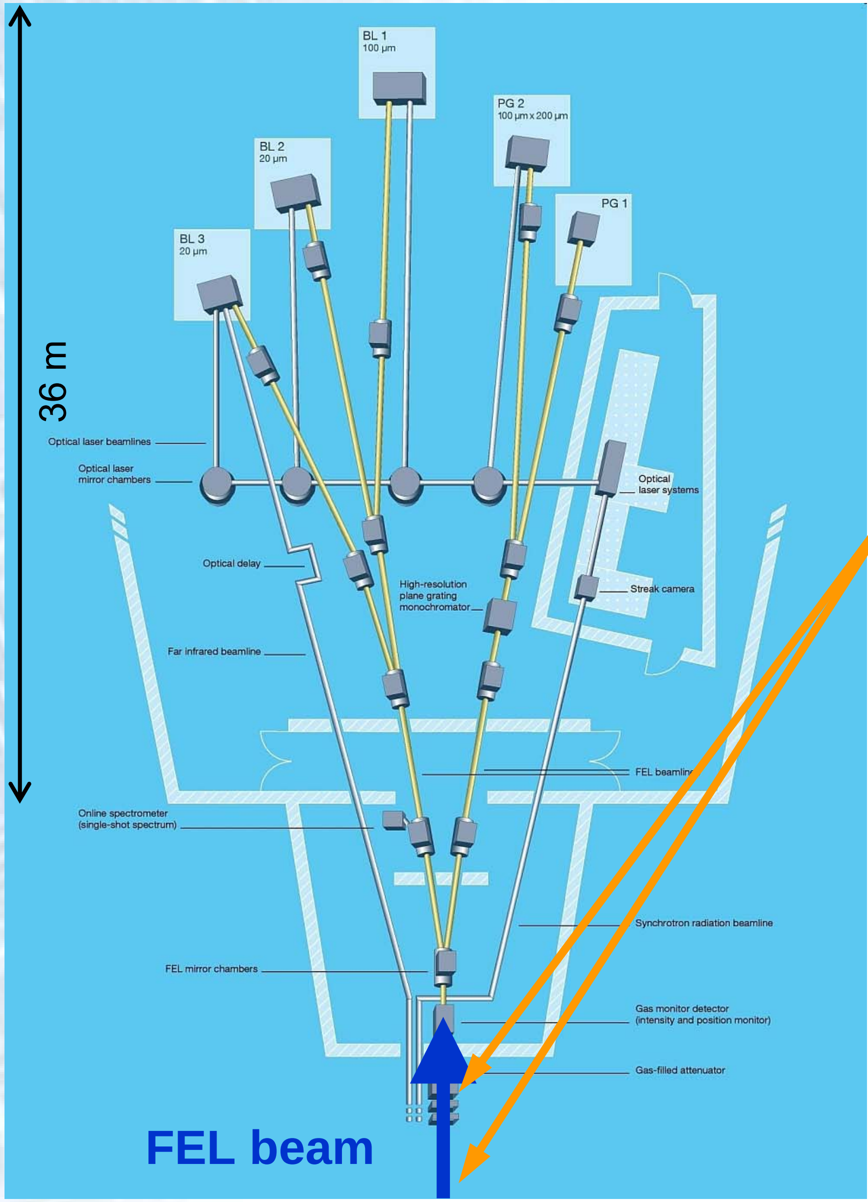


APL **83**, 2970 (2003)
JAP **103**, 094511 (2008)

Gas-Monitor Detectors (GMDs)

Experimental Area at FLASH

PTB



APL **83**, 2970 (2003)
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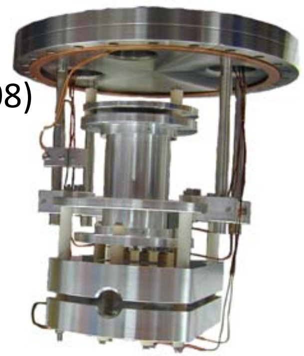
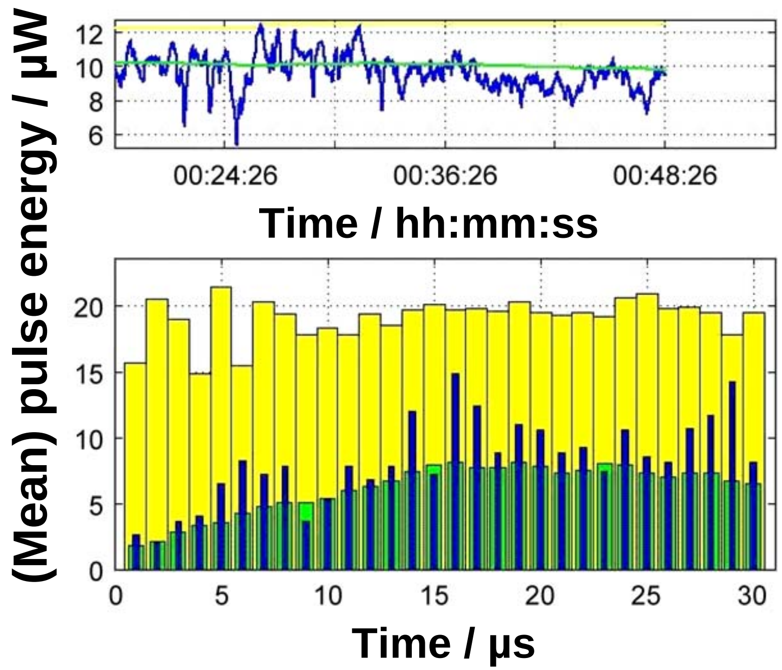


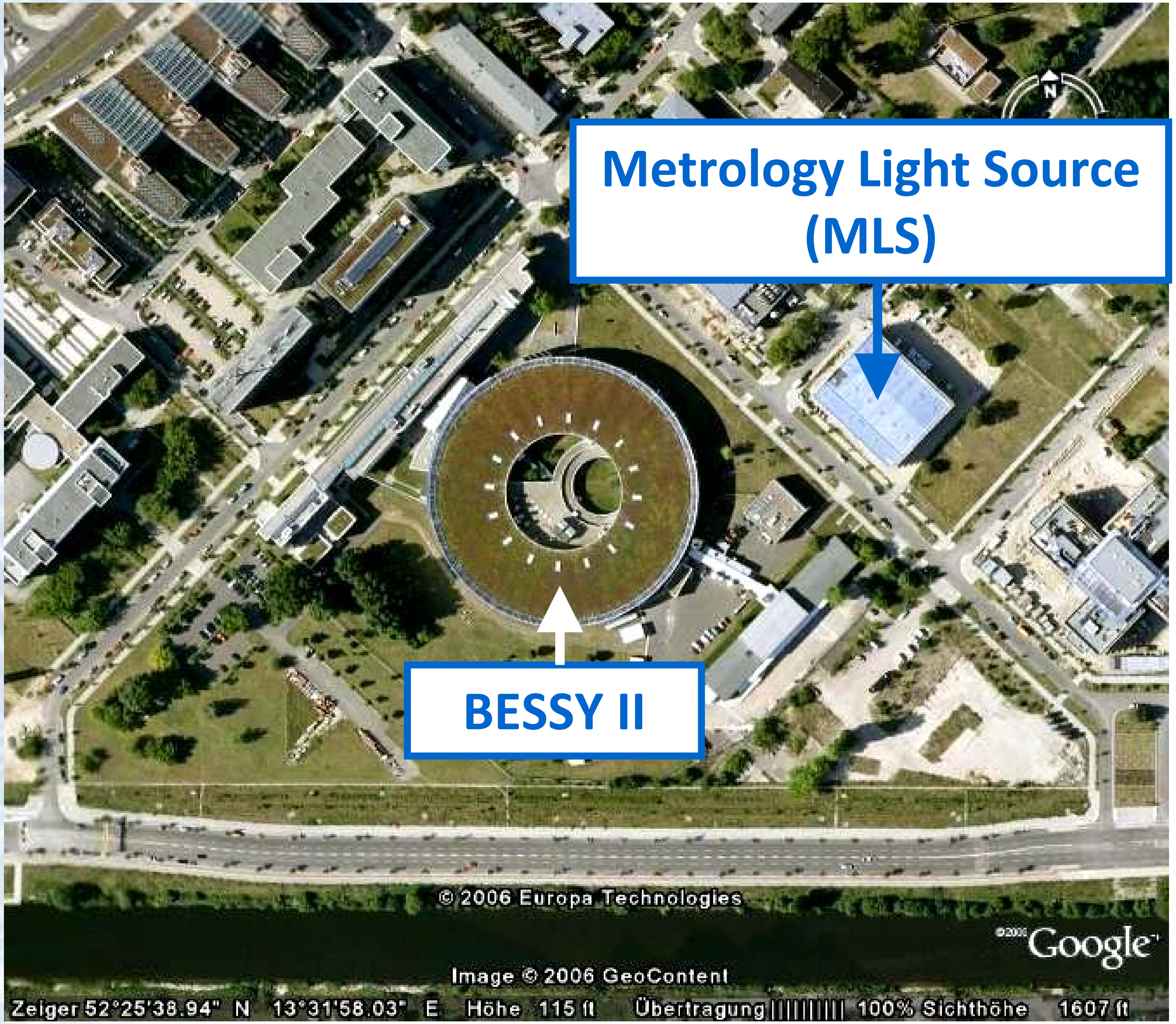
DESY

Ioffe Physico-Technical Institute

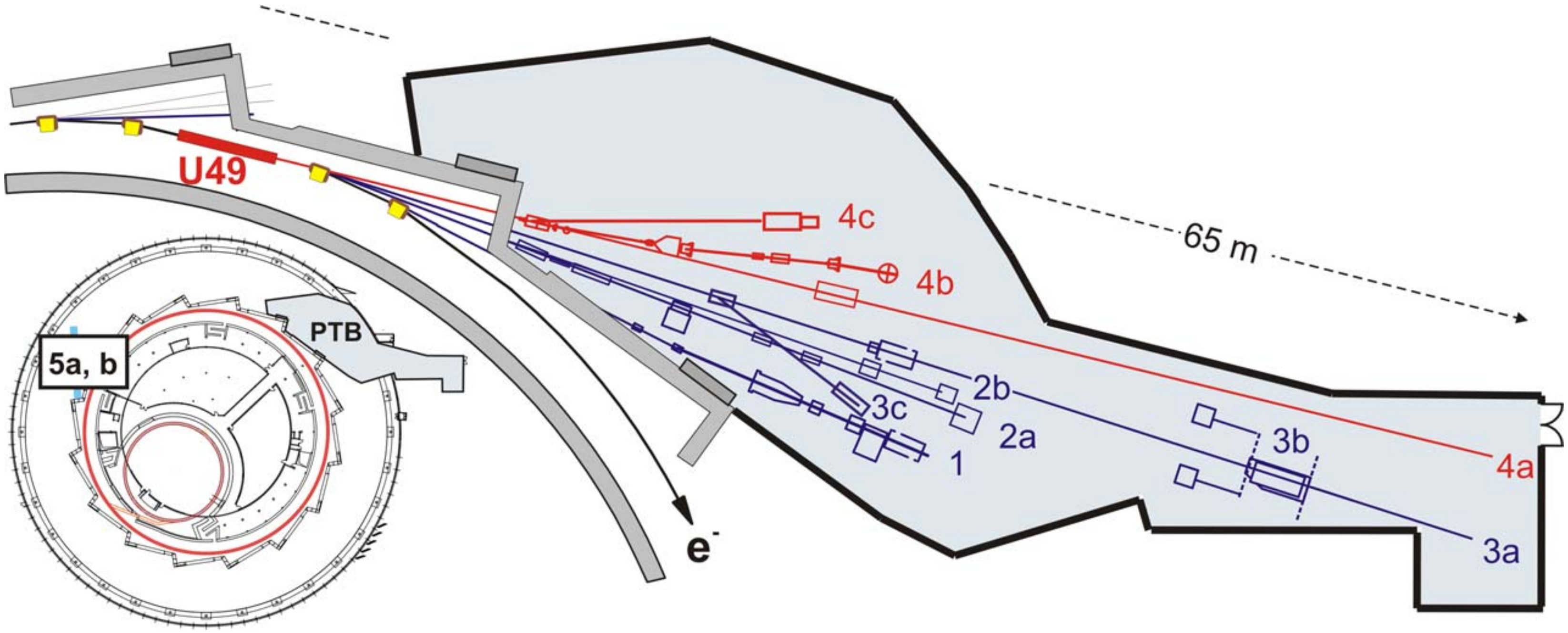
Gas-Monitor Detectors (GMDs)



PTB in Berlin-Adlershof



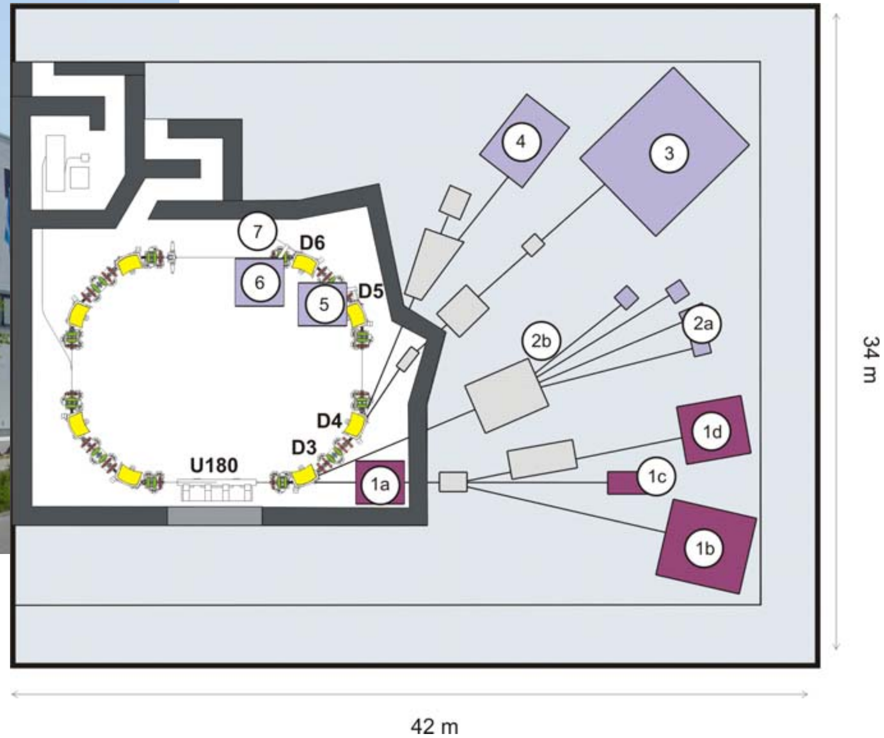
PTB Laboratory at BESSY II



Synchrotron radiation beamlines operating in the spectral range from the vacuum ultraviolet (VUV) to the hard X-ray regime

PTB's Metrology Light Source (MLS)

Starting operation in 2008



Synchrotron radiation beamlines operating in the spectral range from the THz to the extreme ultraviolet (EUV) regime

Staff of PTB in Berlin-Adlershof (52)

Daniel Ambos
Burkhard Beckhoff
Guido Brandt
Christian Buchholz
Levent Cibik
Jens Eden
Karl-Heinz Eitner
Andreas Fischer
Rolf Fliegauf
Gudrun Gleber
Roland Goernemann
Alexander Gottwald
Stephan Hain
Philipp Hönicke
Christine Hertzsch
Detlef Herzog
Arne Hoehl
Annett Kampe
Akiko Kato
Peter Kersten
Erk Kienitz
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Ulf Knoll
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Udo Kroth
Simone Kroth
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Wolfgang Paustian
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Jana Puls
Stephan Rehfeld
Thomas Reichel
Falk Reinhardt
Mathias Richter
Bernd Rieschel
Hartmut Scherr
Hendrik Schöppe
Frank Scholze
Anton Serdyukov
Christian Stadelhoff
Sylvia Struck
Bernd Taut
Reiner Thornagel
Gerhard Ulm
Rainer Unterumsberger
Jan Wernecke
Jan Weser

Fundamental methods

Source-based radiometry

Detector-based radiometry

Reflectometry

Metrology using Synchrotron Radiation by PTB in Berlin-Adlershof

PTB

Fundamental methods

Source-based radiometry

Detector-based radiometry

Reflectometry

Applications

Characterization of space instrumentation

X-ray dosimetry and medical applications

Optics development for (E)UV lithography

Nanometrology via X-ray reflectometry and small-angle scattering

X-ray spectrometry for reference free materials analysis

Photon diagnostics and research at X-ray lasers

Calibration of X-ray Lasers: EUV-FEL/Spring8 (2009)

PTB

IOP PUBLISHING METROLOGIA

Metrologia **47** (2010) 21–23 doi:10.1088/0026-1394/47/1/003

DESY

National Institute of Advanced Industrial Science, and Technology AIST

SPring-8

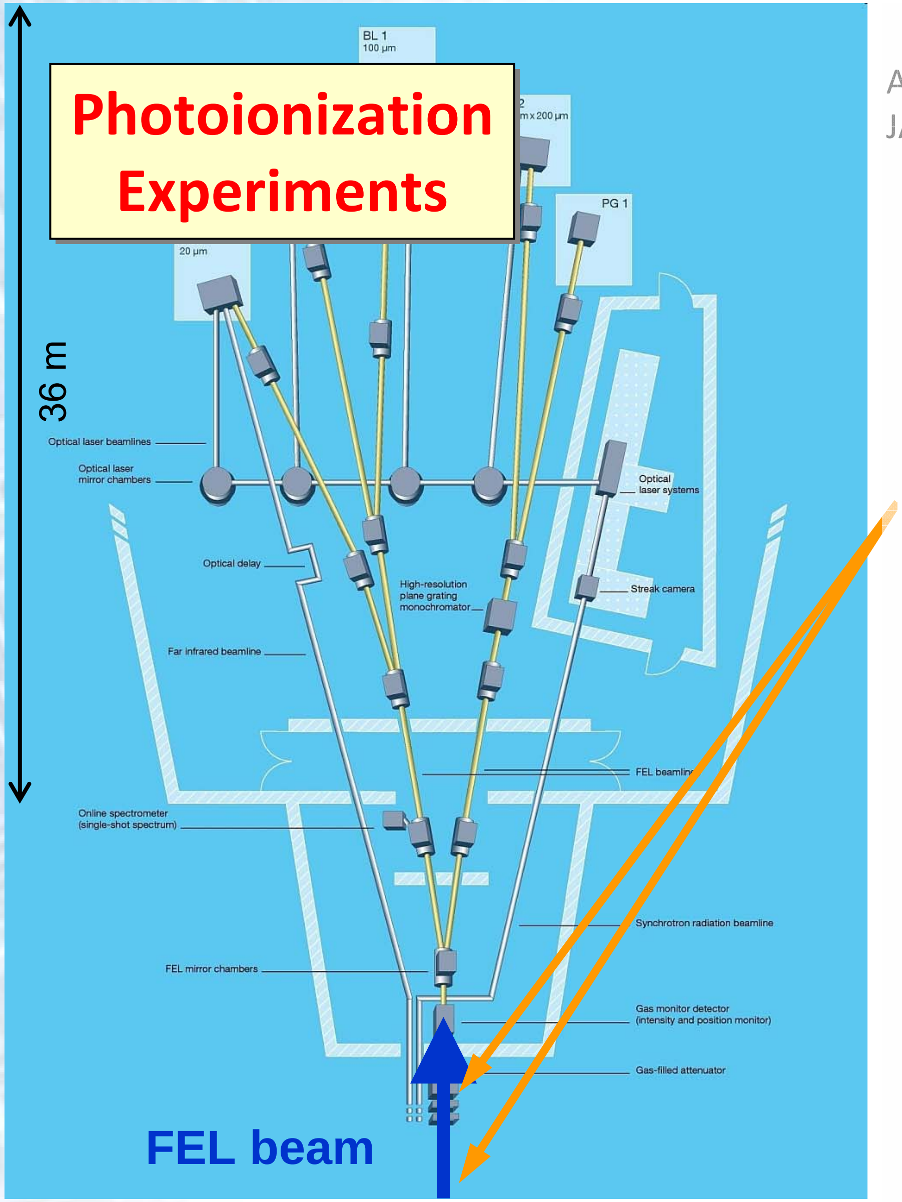
Radiometric comparison for measuring the absolute radiant power of a free-electron laser in the extreme ultraviolet

Table 1. Comparison results. The given uncertainties for the radiant power ratio refer to the FEL and signal statistics only.

Wavelength/ nm	Aperture size	Typical radiant power/ µW	Radiant power ratio of GMD to radiometer
51.3	2 mm × 2 mm	33.8	0.984 ± 0.01
56.1	4.2 mm ϕ	168	0.981 ± 0.01
61.2	4 mm × 4 mm	200	0.974 ± 0.01

Combined expanded (k=2) measurement uncertainty: 5.5 %

Experimental Area at FLASH



APL **83**, 2970 (2003)
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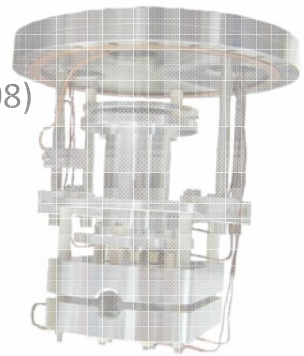
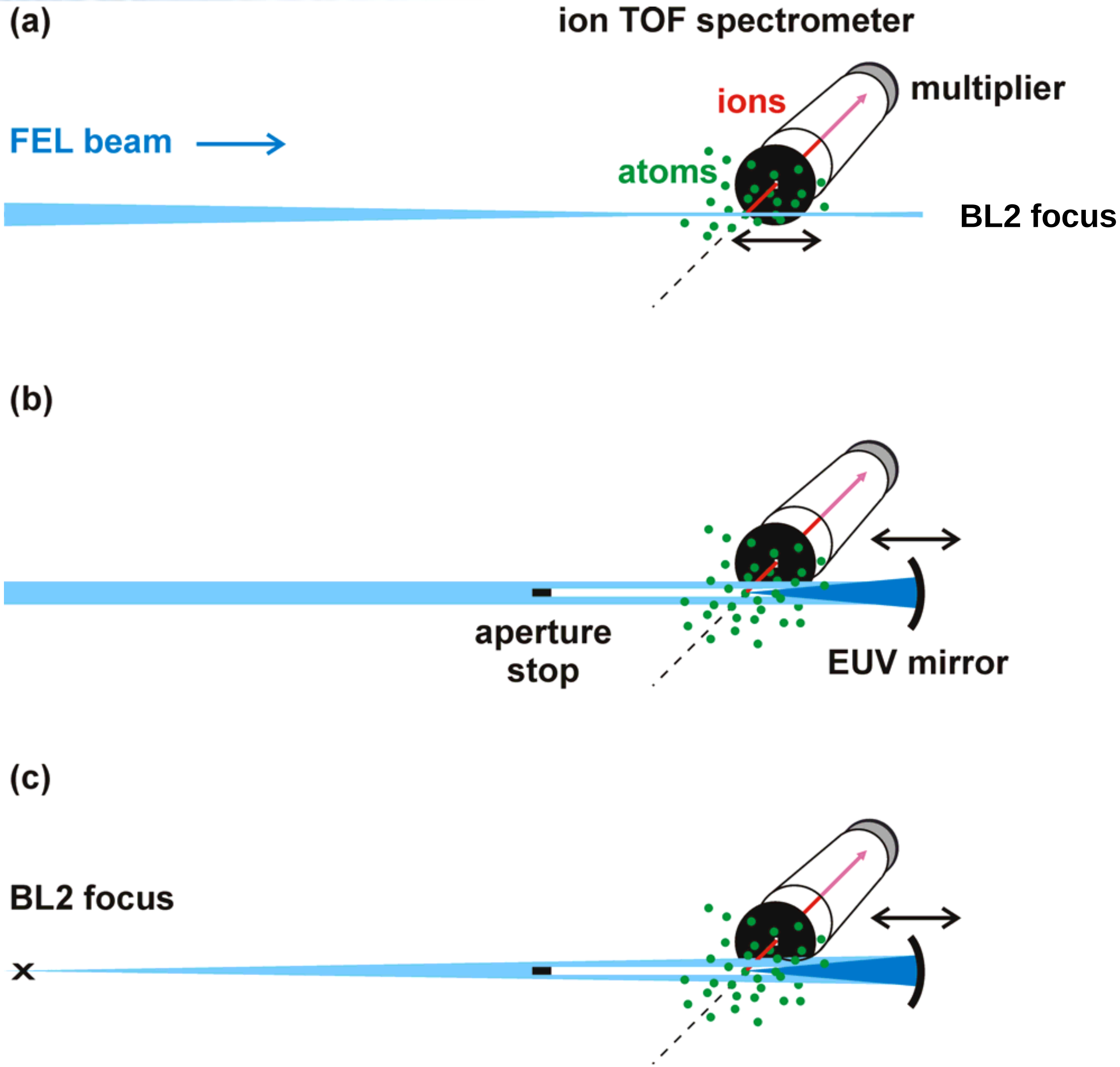


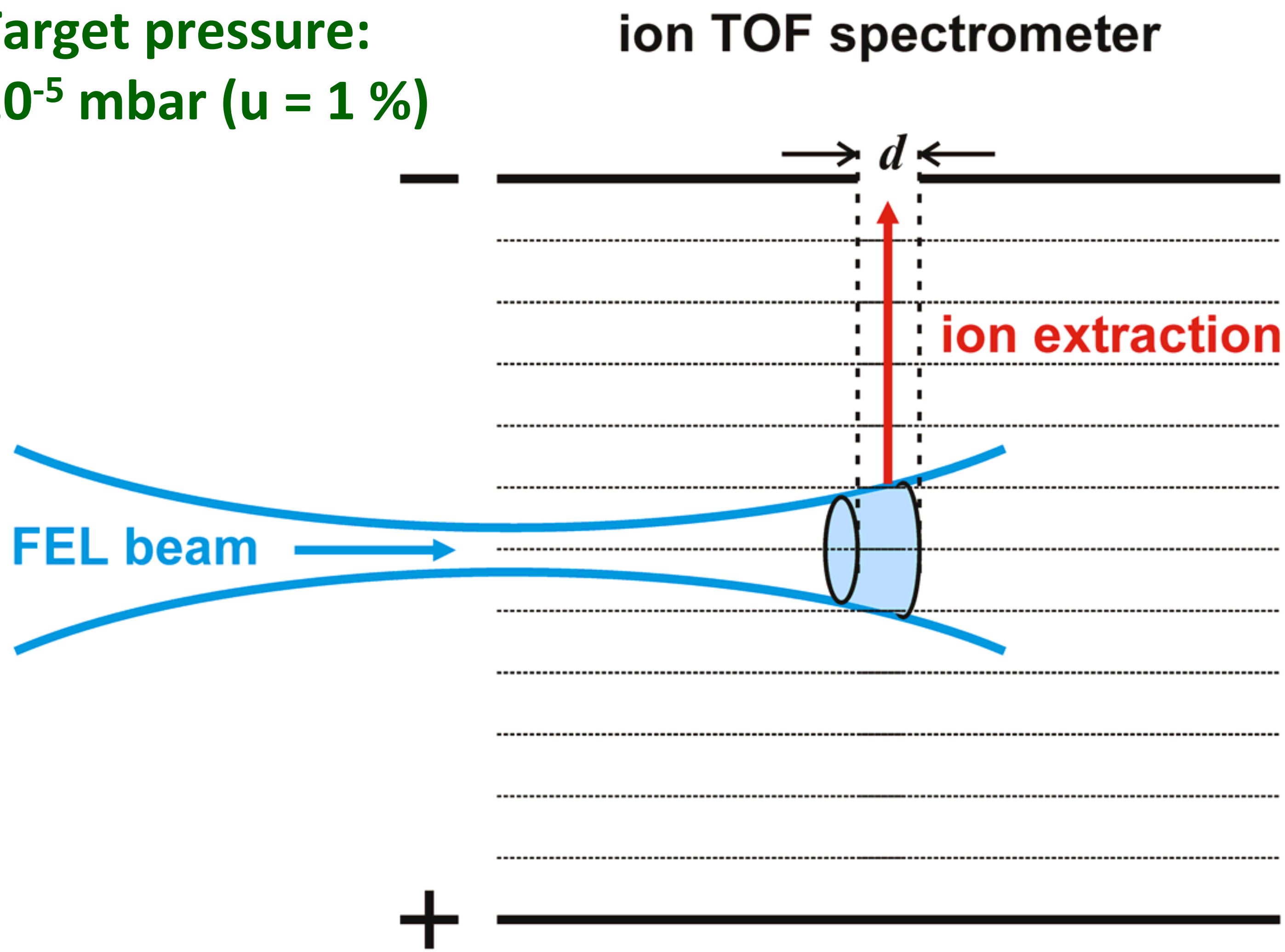
Gas-Monitor Detectors (GMDs)

Ion Mass/Charge Time-Of-Flight (TOF) Spectroscopy on Rare Gases and Molecules at FLASH

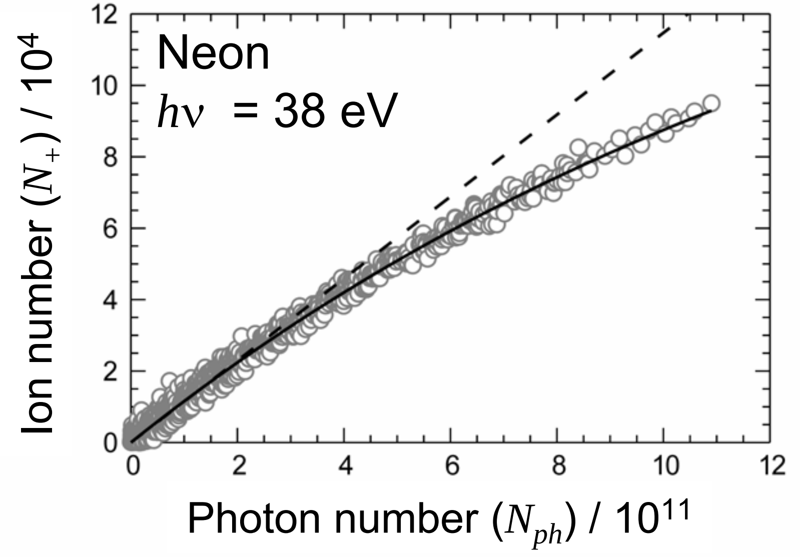


Ion Mass/Charge Time-Of-Flight (TOF) Spectroscopy on Rare Gases and Molecules at FLASH: Ion Extraction

Target pressure:
10^{-5} mbar (u = 1 %)



Saturation of Ion Signals due to Target Depletion: Determination of FEL Focus Size and Waist



A. A. Sorokin *et al.*, Appl. Phys. Lett. **89**, 221114 (2006)

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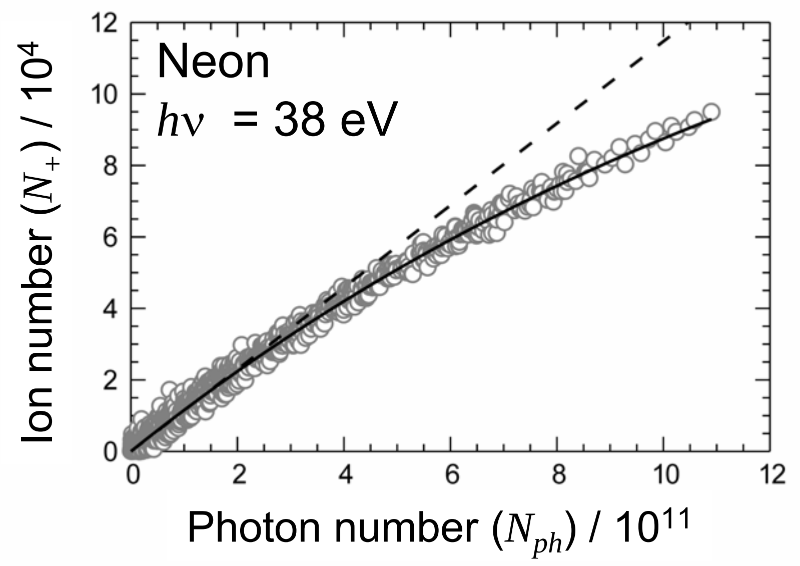

$$N_+(N_{ph}) = N\left(1 - e^{-\sigma \frac{N_{ph}}{A}}\right) \xrightarrow{\text{fit}}$$

cross section σ is known
photon number N_{ph} is measured
beam cross section A is derived

A. A. Sorokin *et al.*, Appl. Phys. Lett. **89**, 221114 (2006)

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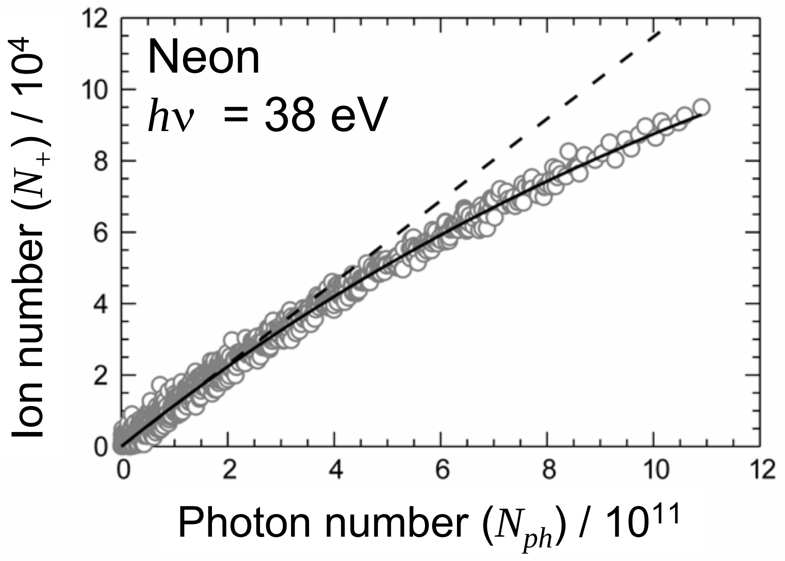

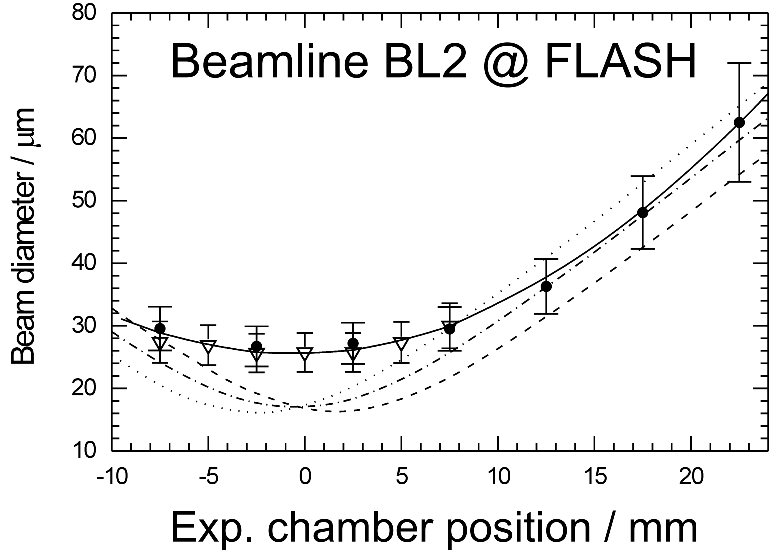

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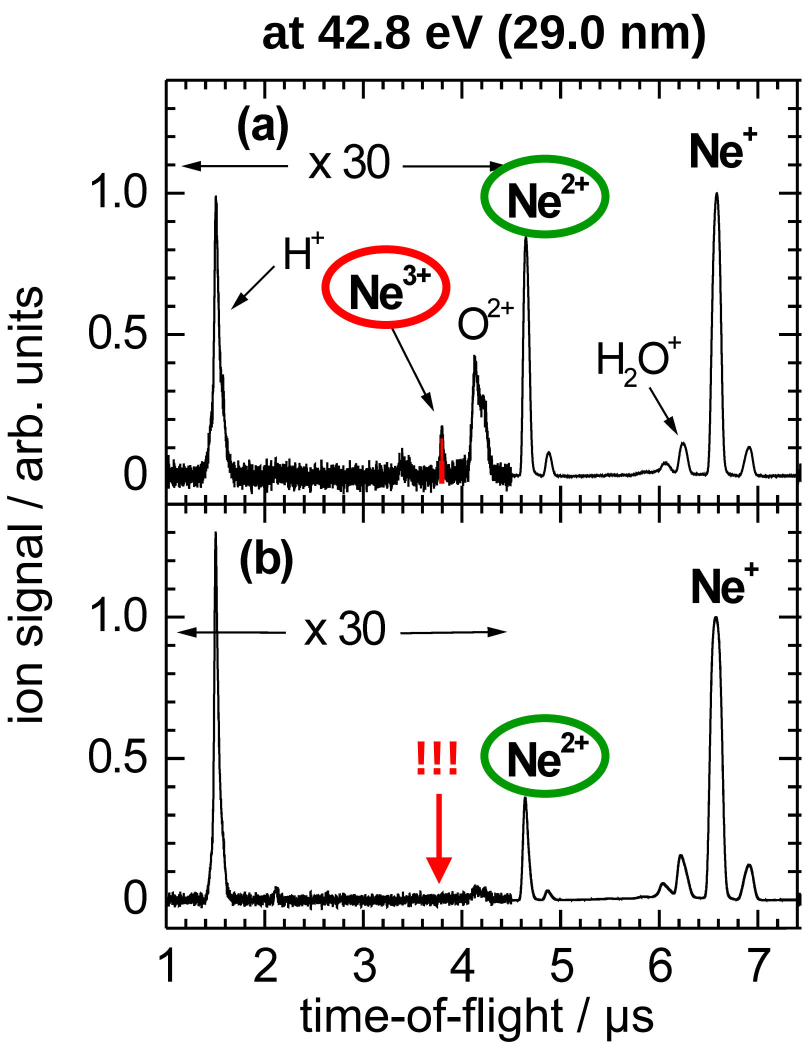
A. A. Sorokin *et al.*, Appl. Phys. Lett. **89**, 221114 (2006)

Multiphoton Ionization of Neon Atoms by Soft X-rays at FLASH: Ion TOF Spectra



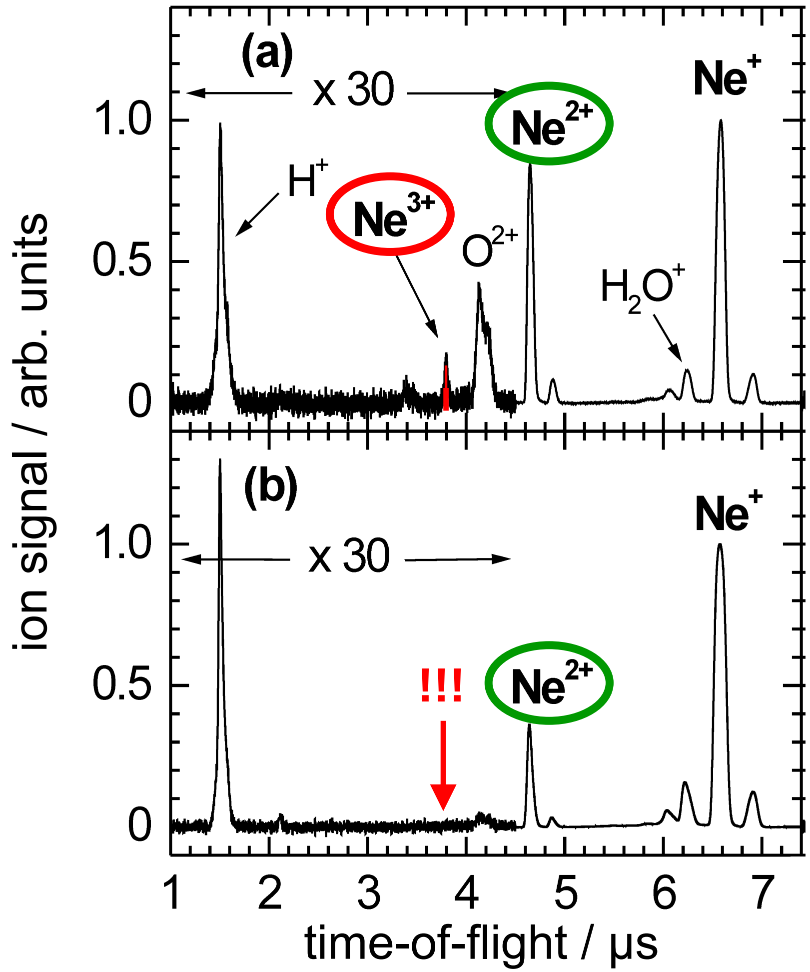
in the focus of BL2

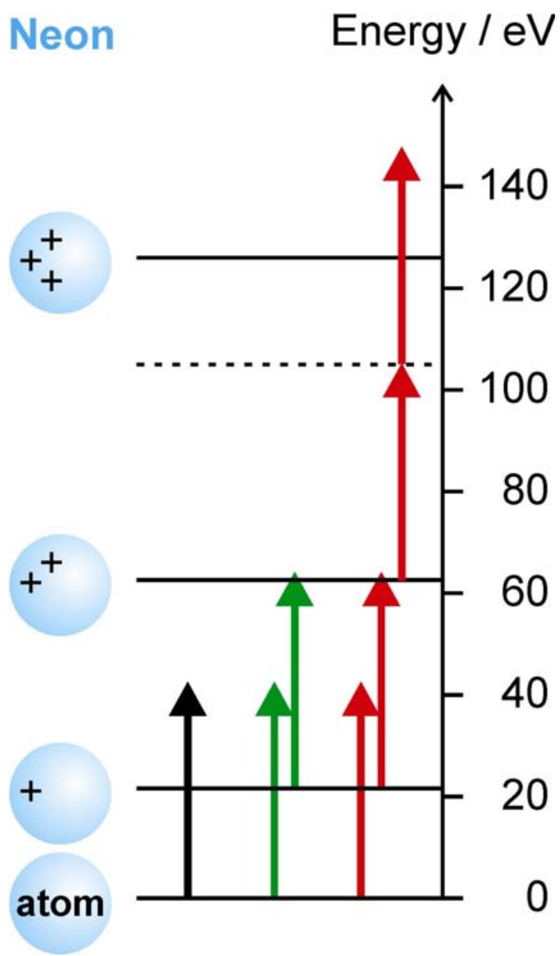
out of focus

A. A. Sorokin, S. V. Bobashev, K. Tiedtke, M. Wellhöfer, M. Richter, Phys. Rev. A **75**, 051402(R) (2007)

Multiphoton Ionization of Neon Atoms by Soft X-rays at FLASH: Ion TOF Spectra

at 42.8 eV (29.0 nm)





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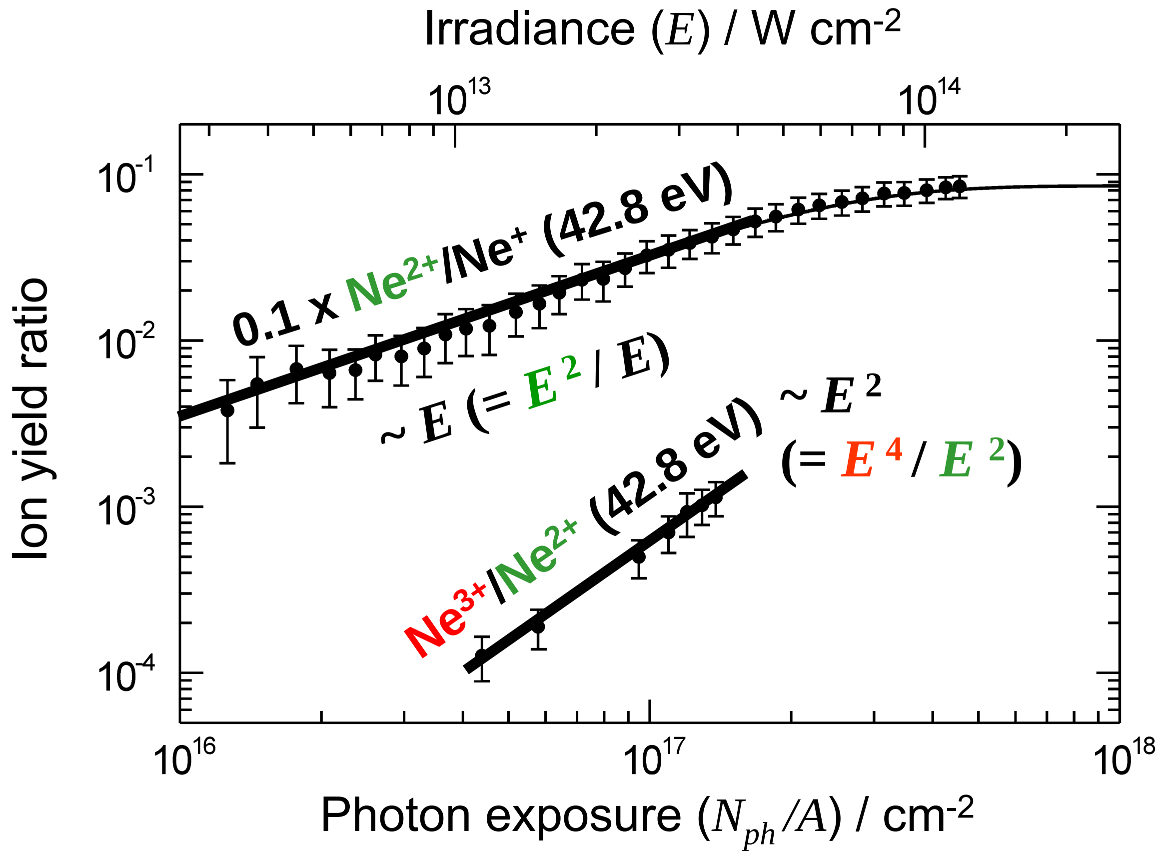
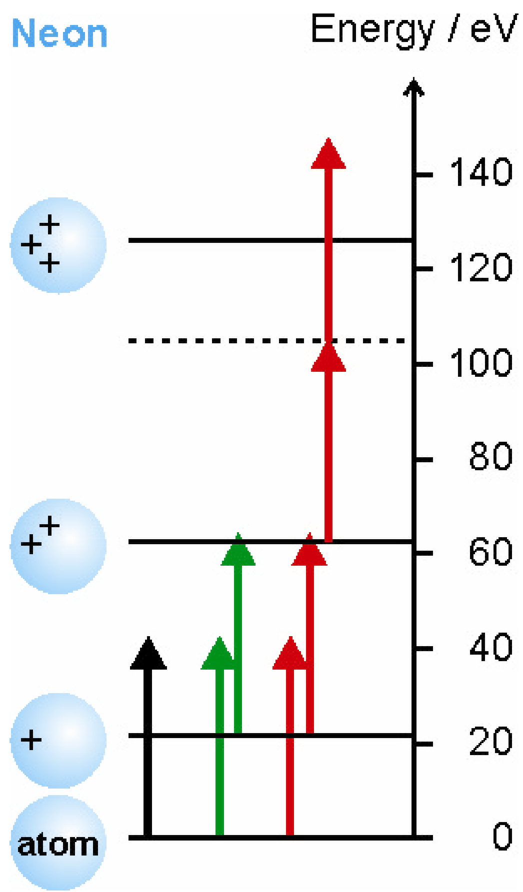
Multiphoton Ionization of Neon Atoms by Soft X-rays at FLASH: Photon Intensity Dependence

PTB

Perturbation theory: $\dot{N}^{(n)} = N\,\sigma^{(n)} \left(\frac{E}{\hbar\omega}\right)^{n}$





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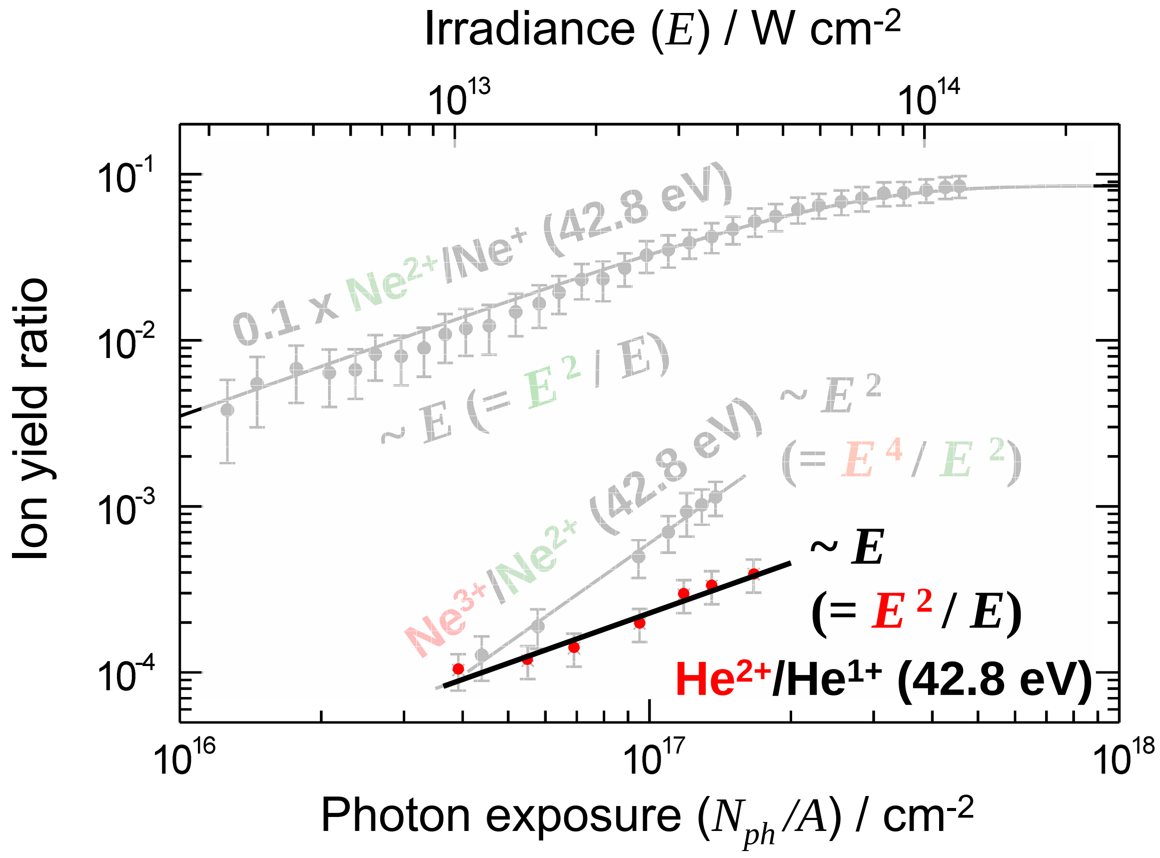

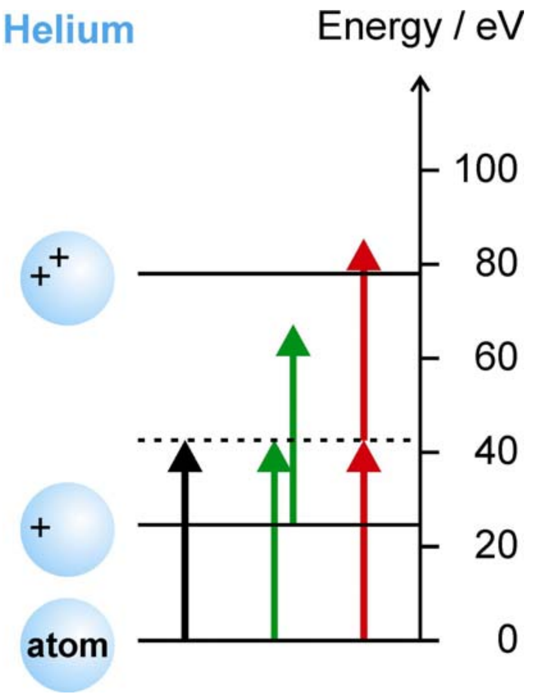

A. A. Sorokin, S. V. Bobashev, K. Tiedtke, M. Wellhöfer, M. Richter, Phys. Rev. A **75**, 051402(R) (2007)

Evaluation of FEL Pulse Duration by Autocorrelation and Non-linear Photoionization of Helium Atoms

PTB

Two-photon process:

$$\dot{N}^{(2)} = N\,\sigma^{(2)}\left(\frac{E}{\hbar\omega}\right)^2$$

Evaluation of FEL Pulse Duration by Autocorrelation and Non-linear Photoionization of Helium Atoms

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Two-photon process:

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Irradiance:

$$E(t) = E_1 f(t) + E_2 f(t-t')$$

$$\Rightarrow \frac{N^{(2)}(t')}{N^{(2)}(t'\to\infty)} = 1 + a\int_{-\infty}^{+\infty} f(t)\, f(t-t')\,dt$$

Evaluation of FEL Pulse Duration by Autocorrelation and Non-linear Photoionization of Helium Atoms

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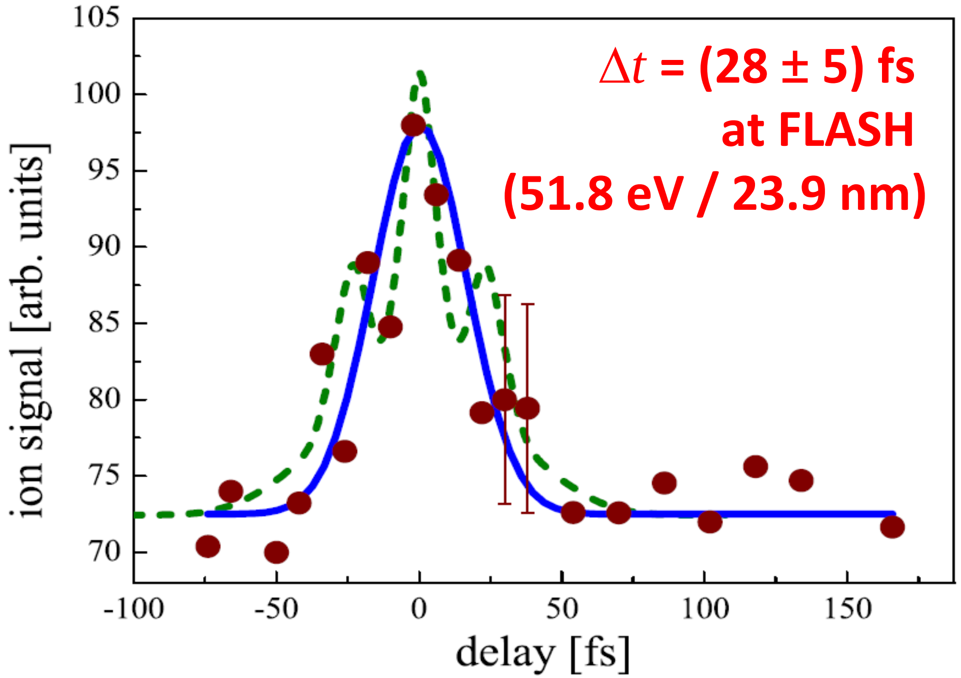


R Mitzner, A. A. Sorokin, B. Siemer, S. Roling, M. Rutkowski, H. Zacharias, M. Neeb, T. Noll, F. Siewert, W. Eberhardt, M. Richter, P. Juranic, K. Tiedtke, and J. Feldhaus, Phys. Rev A **80**, 025402 (2009)

Irradiance ('Intensity')

Pulse Energy

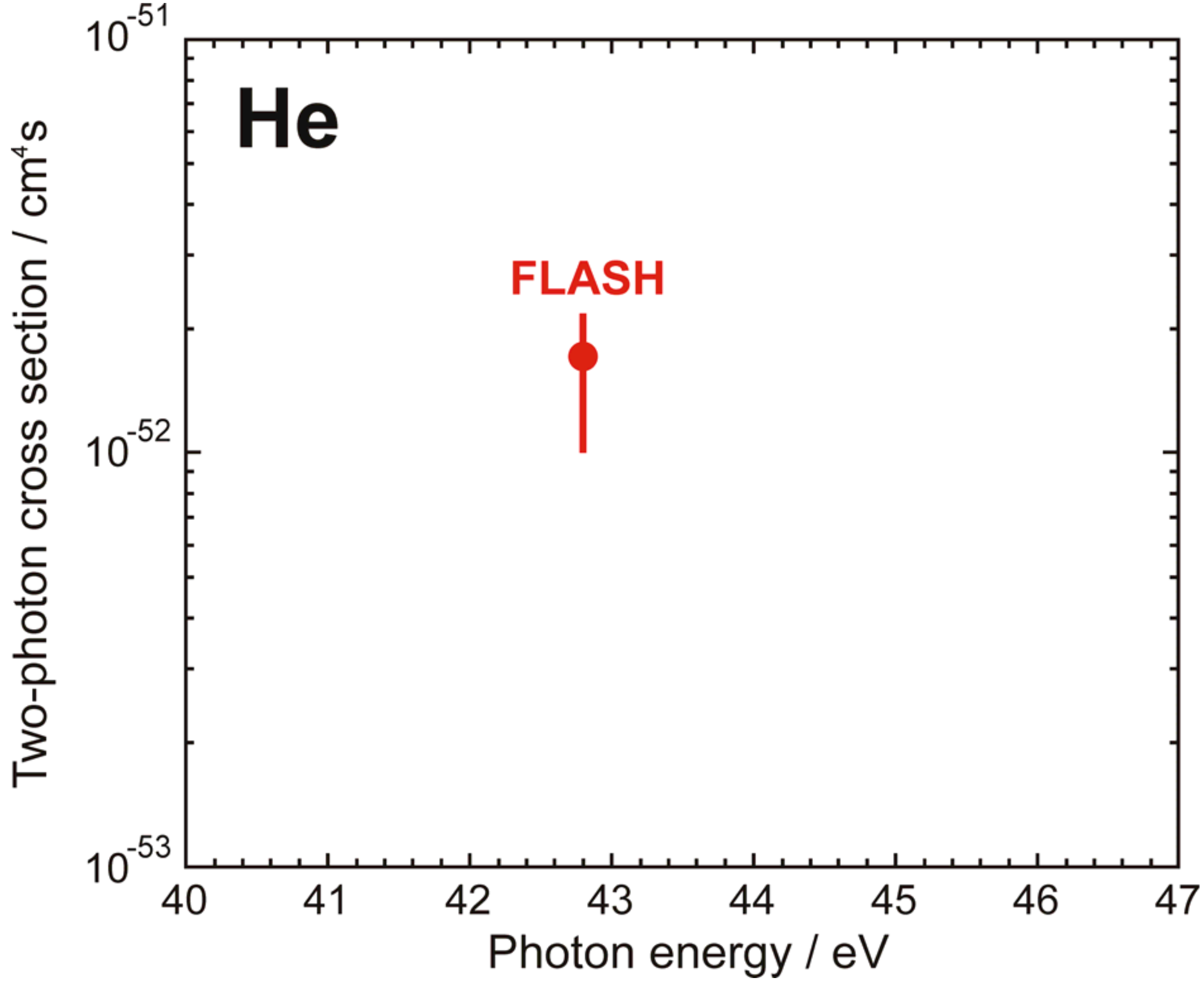
Irradiance

$$E = \frac{\Delta W}{\Delta t \, \Delta A}$$

Pulse Duration

Beam Cross Section

Direct Two-photon Double Ionization Cross Section of Helium: Experiment and Theory (2008)



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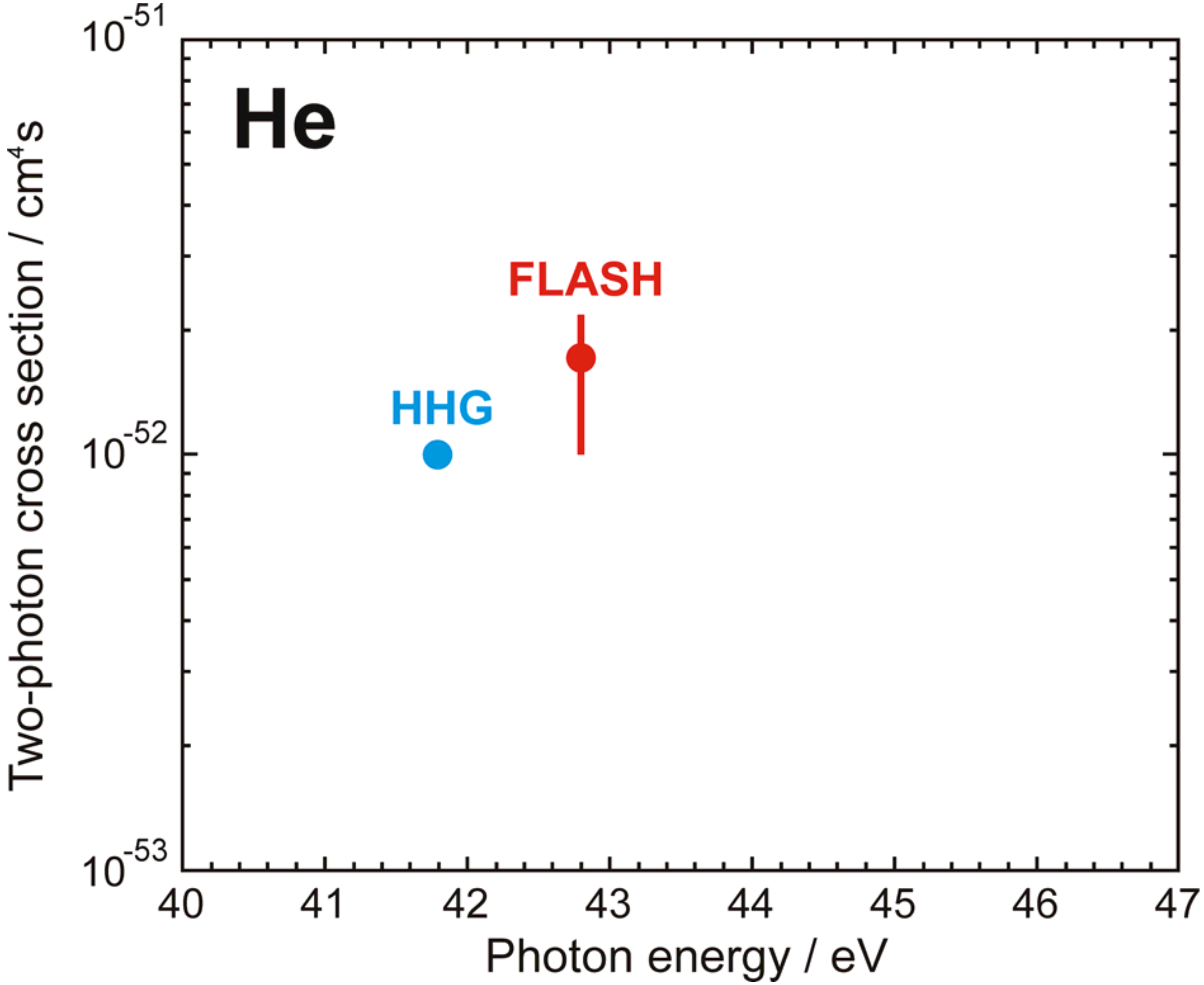

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H. Hasegawa *et al.*, Phys. Rev. A **71**, 023407 (2005)

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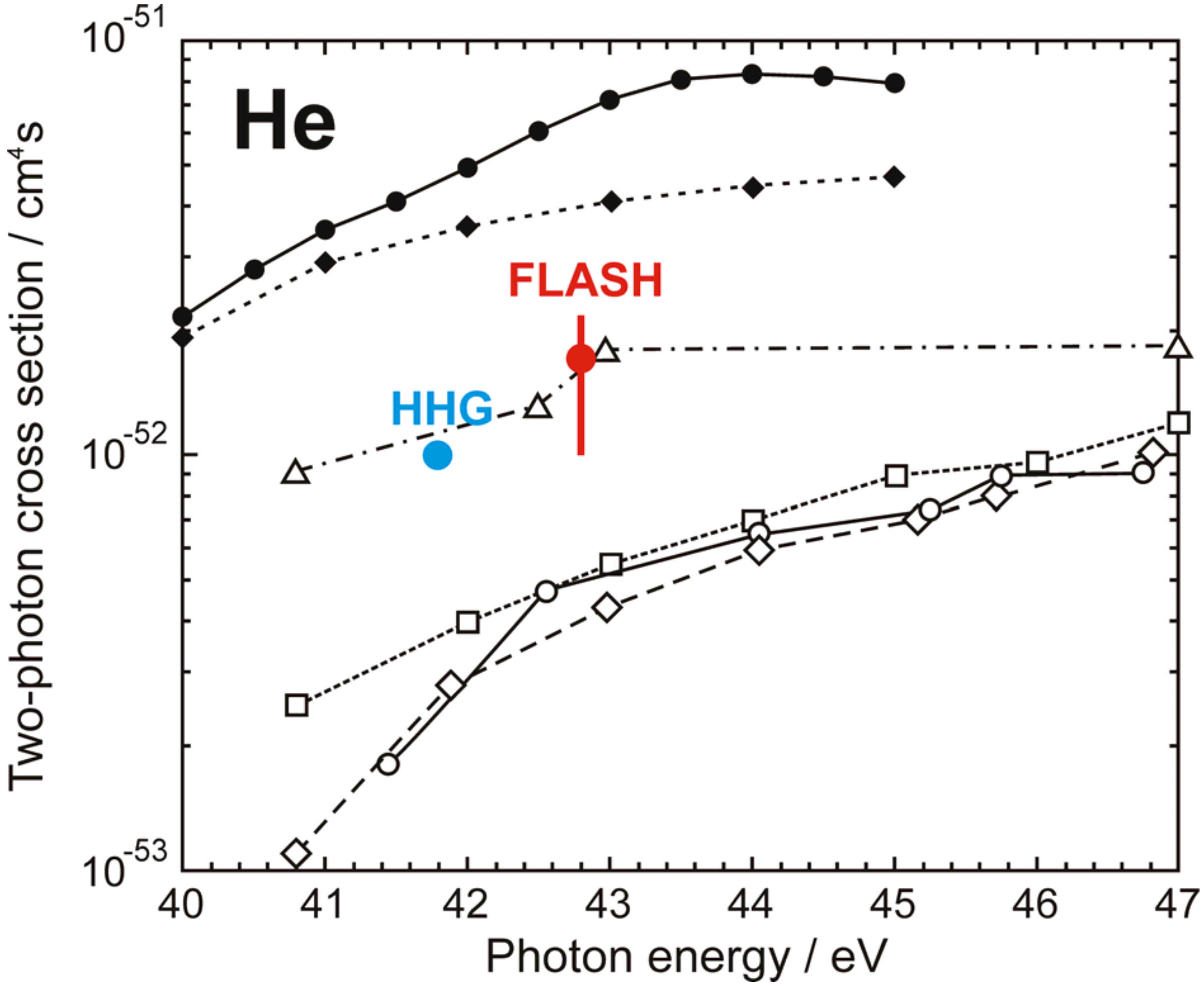
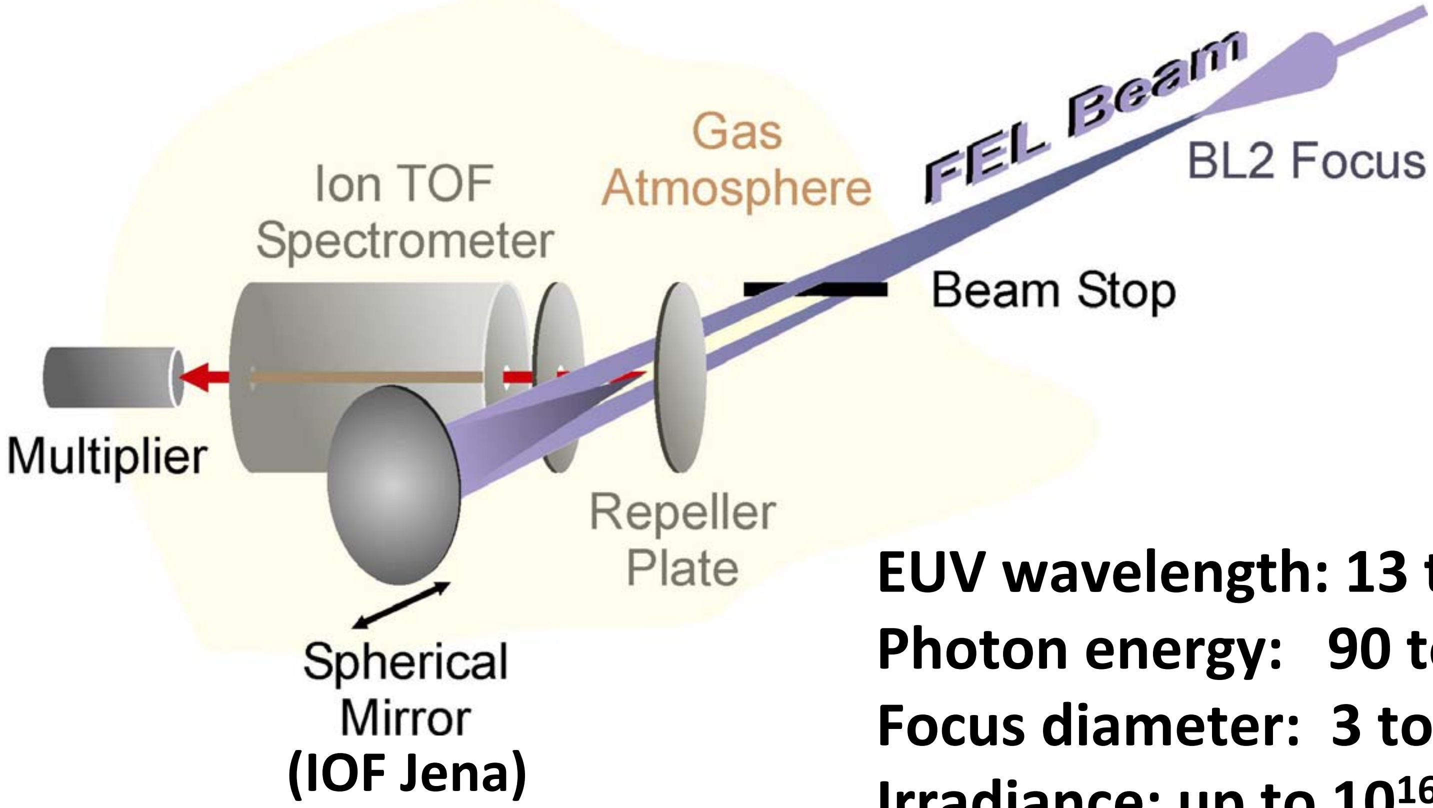


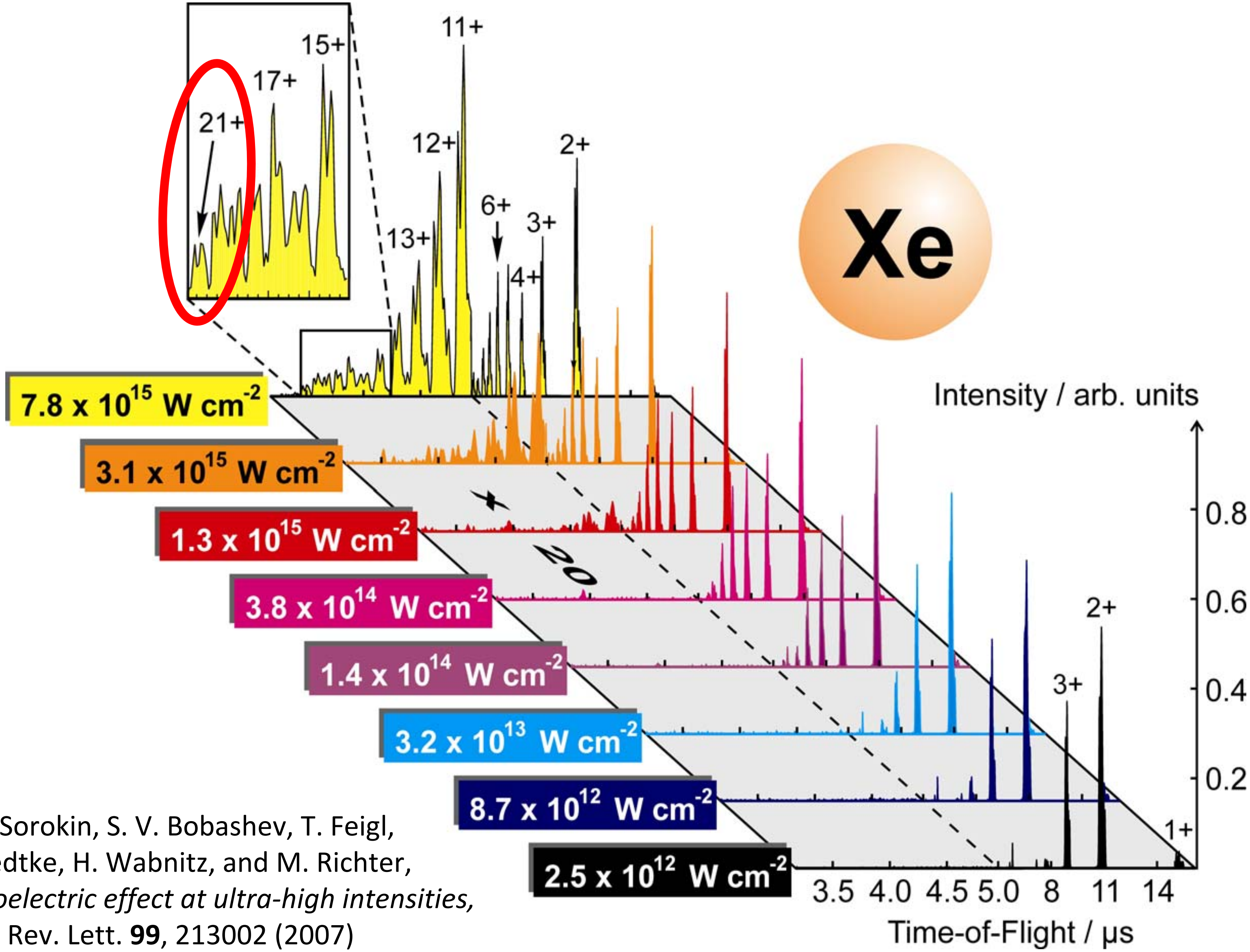
A. A. Sorokin, S. V. Bobashev, K. Tiedtke, M. Wellhöfer, and M. Richter, Phys. Rev. A **75**, 051402(R) (2007)
H. Hasegawa *et al.*, Phys. Rev. A **71**, 023407 (2005)
I. A. Ivanov and A. S. Kheifets, J. Phys. B **41**, 095002 (2008), and references therein

Ion Time-Of-Flight (TOF) Experiments in the Focus of EUV Lithography Multilayer Mirrors



- **EUV wavelength: 13 to 14 nm**
- **Photon energy: 90 to 93 eV**
- **Focus diameter: 3 to 5 µm**
- **Irradiance: up to 10^{16} Wcm^{-2}**

Multiple Ionization of Xenon in the EUV (13.3 nm / 93 eV)



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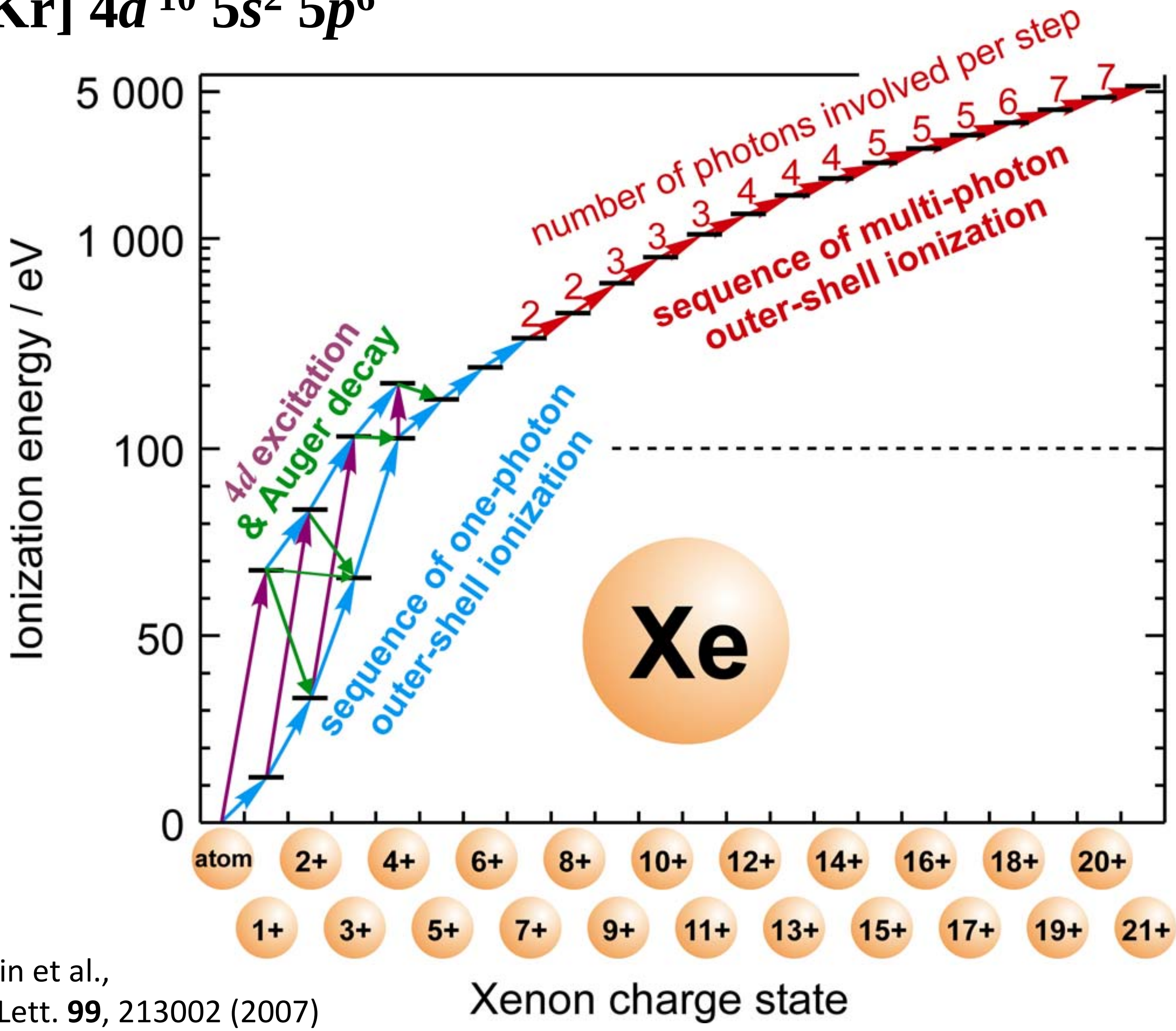
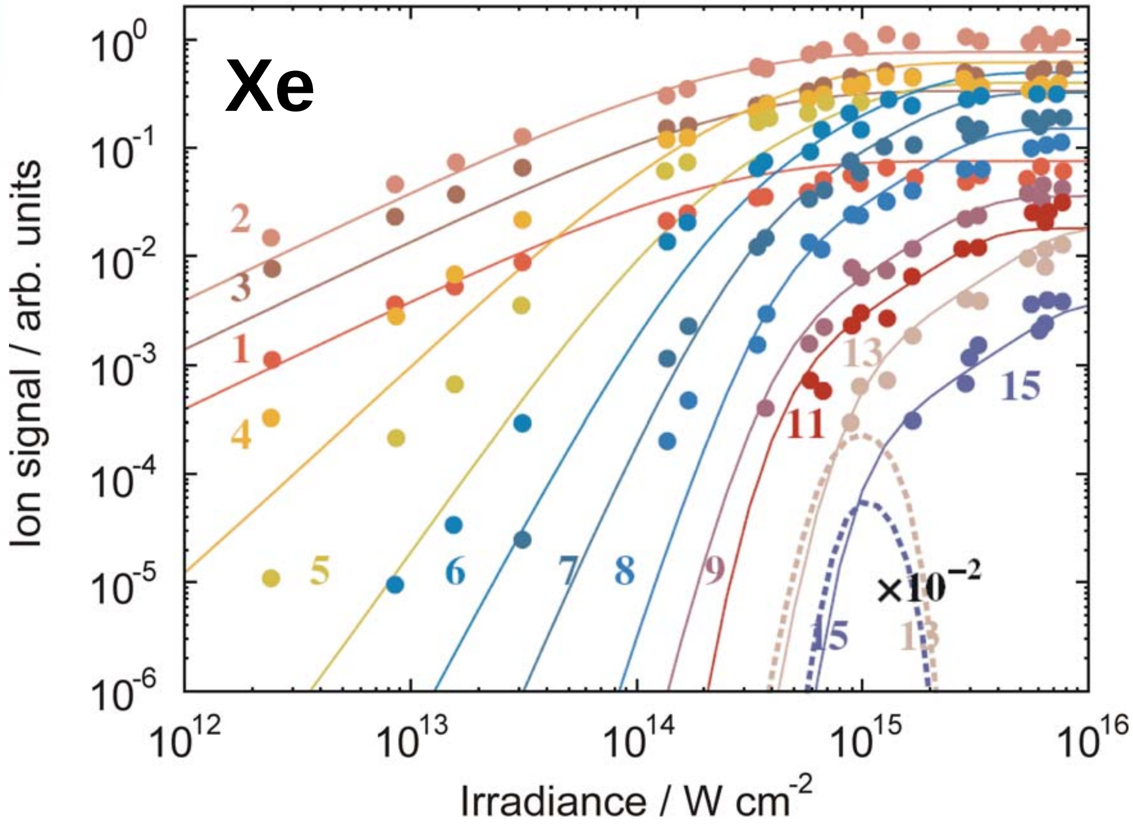
Multiphoton Multiple Ionization of Xenon in the EUV (13.3 nm / 93 eV)

Xe: [Kr] $4d^{10}\,5s^2\,5p^6$



A. A. Sorokin et al.,
Phys. Rev. Lett. **99**, 213002 (2007)

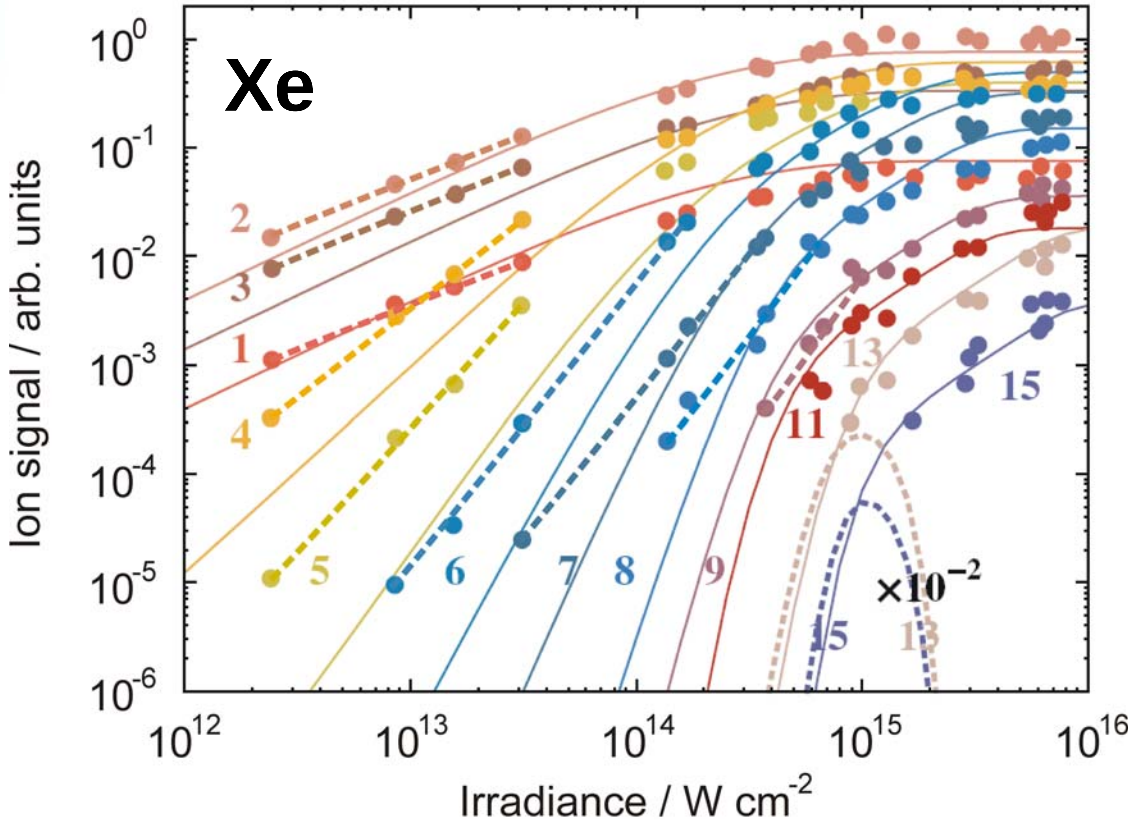
Multiple Ionization of Xenon in the EUV (13.3 nm): Photon Intensity Dependence



M. G. Makris, P. Lambropoulos, and A. Mihelic,
Phys. Rev. Lett. **102**, 033002 (2009)

Multiple Ionization of Xenon in the EUV (13.3 nm): Photon Intensity Dependence

Perturbation theory and *n*-photon processes: $\ln \dot{N}_{q+}(E) \sim n \ln E$



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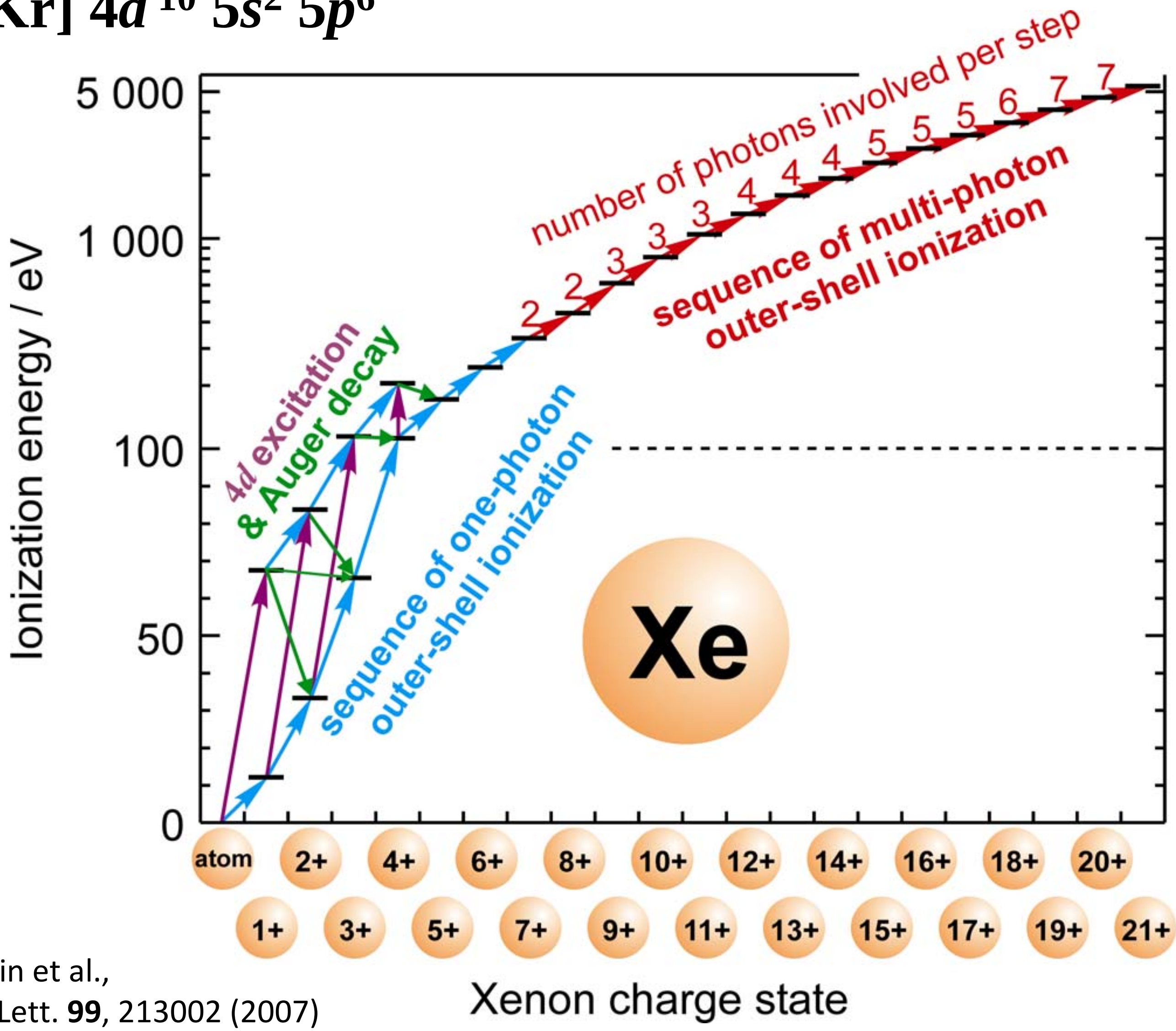

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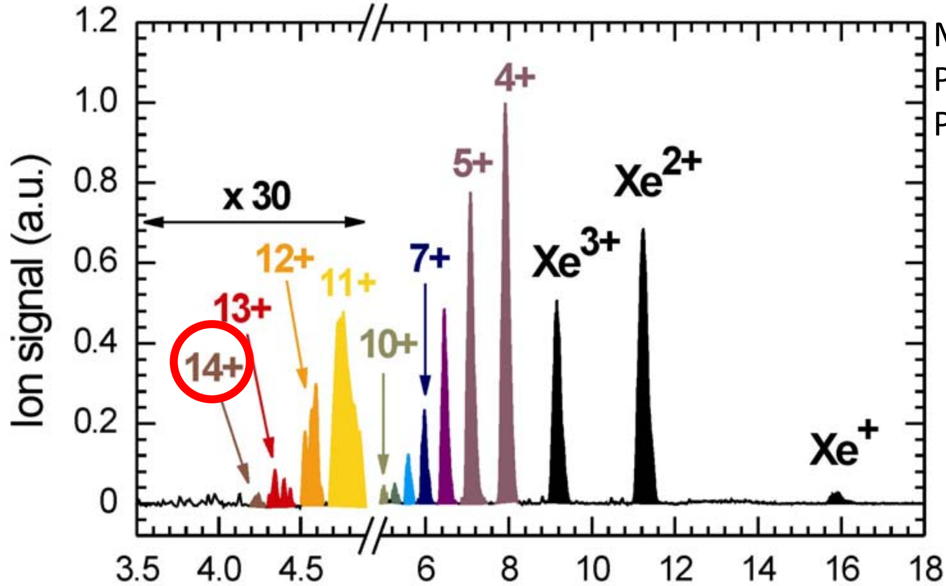
Phys. Rev. Lett. **99**, 213002 (2007)

Multiple Ionization of Rare Gases in the EUV: 13.7 nm / 90.5 eV; $(1.7 \pm 0.7) \times 10^{15}$ W cm^{-2}



M. Richter, M. Ya. Amusia, S. V. Bobashev, T. Feigl, P. Juranić, M. Martins, A. A. Sorokin, and K. Tiedtke, Phys. Rev. Lett. **102**, 163002 (2009)

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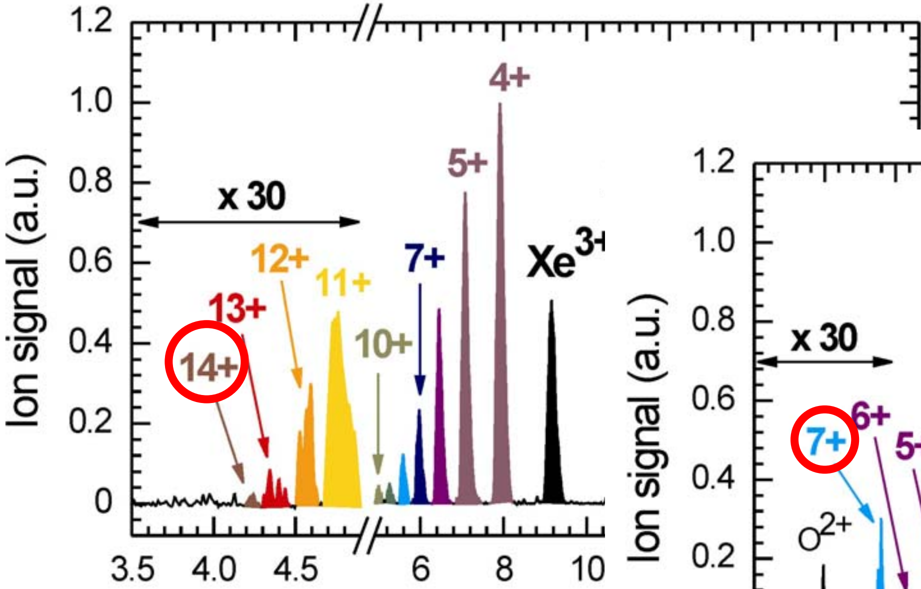

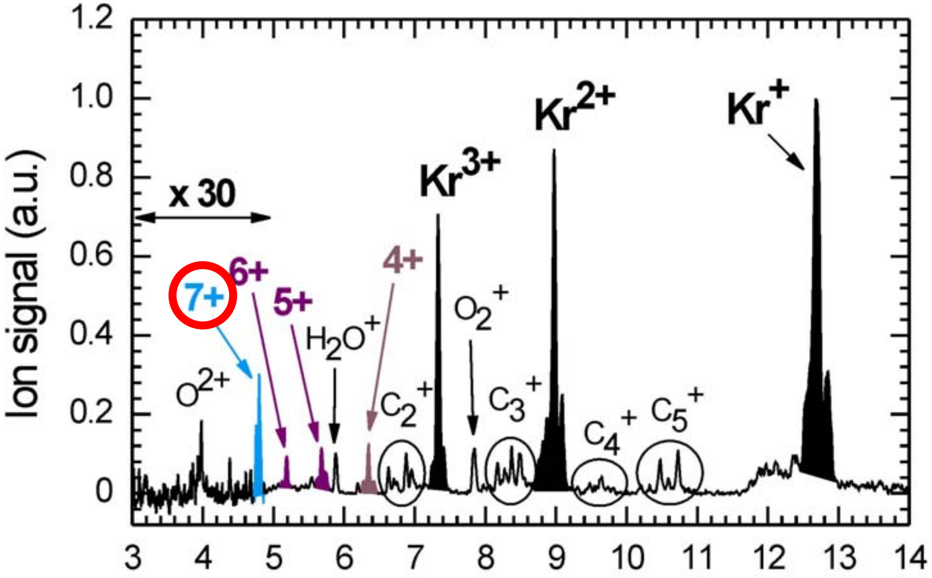

Multiple Ionization of Rare Gases in the EUV: 13.7 nm / 90.5 eV; $(1.7 \pm 0.7) \times 10^{15}$ W cm^{-2}

PTB

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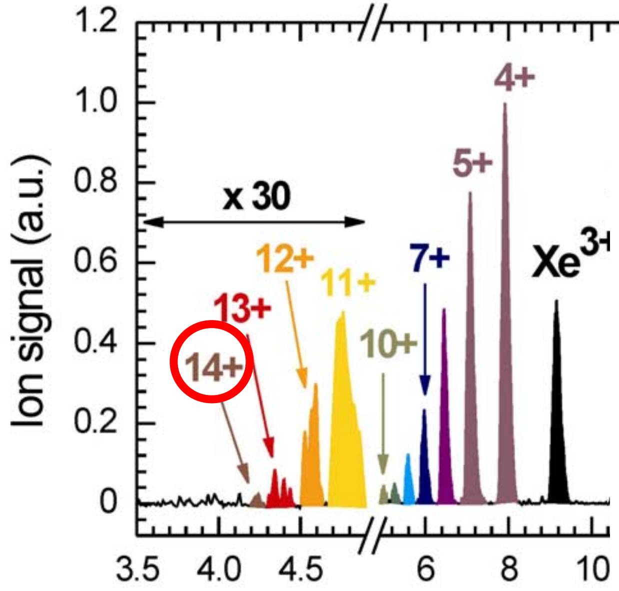

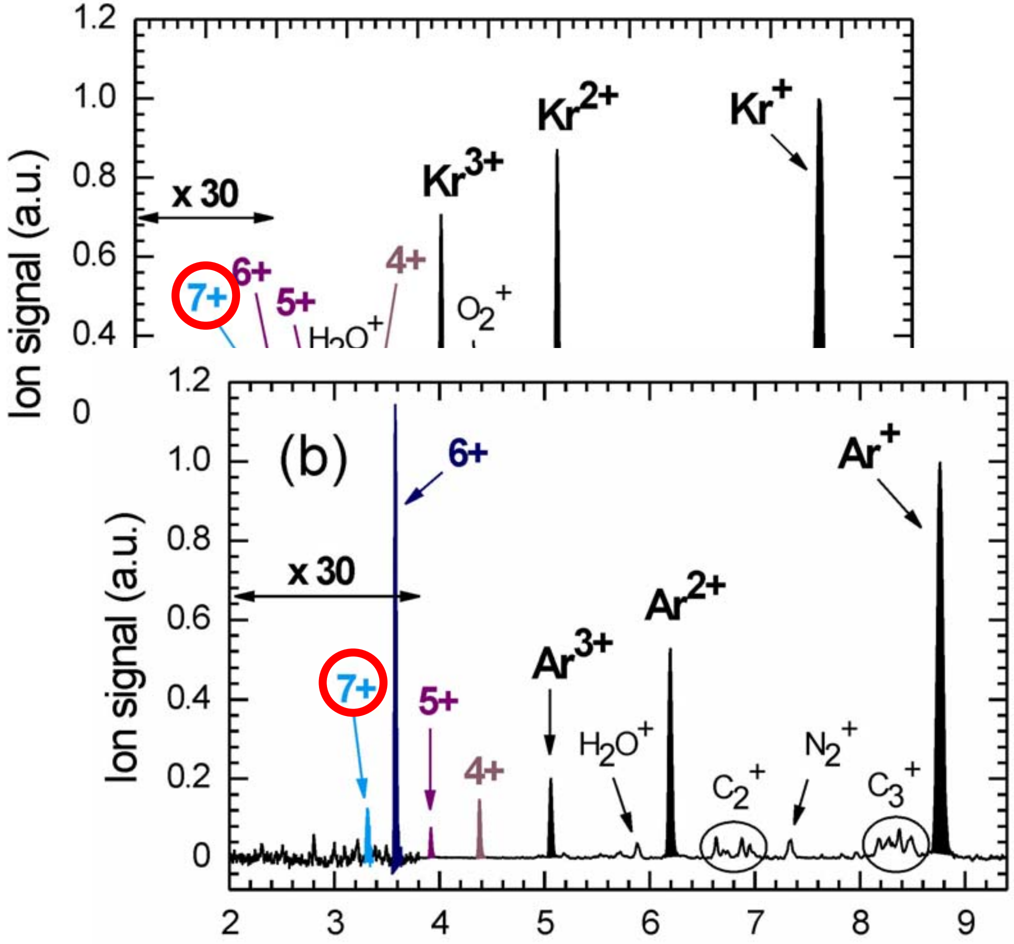

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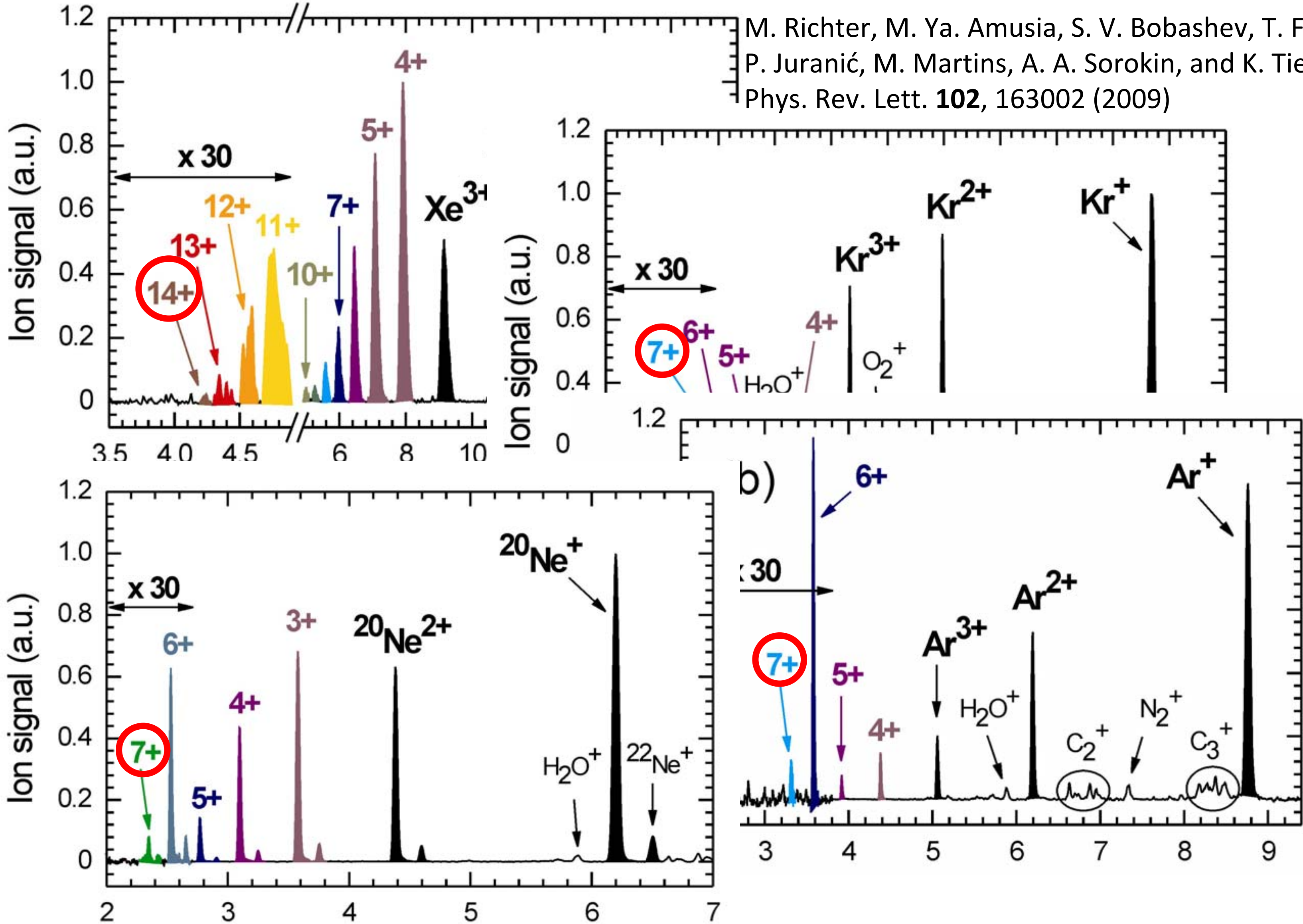

Multiple Ionization of Rare Gases in the EUV: 13.7 nm / 90.5 eV; $(1.7 \pm 0.7) \times 10^{15}$ W cm^{-2}

PTB

Gas	Highest charge q^+ observed	I_{q^+}/eV	Number of EUV photons absorbed per FEL pulse and atom
Ne	7+	715	8
Ar	7+	434	5
Kr	7+	383	5
Xe	14+	1930	22

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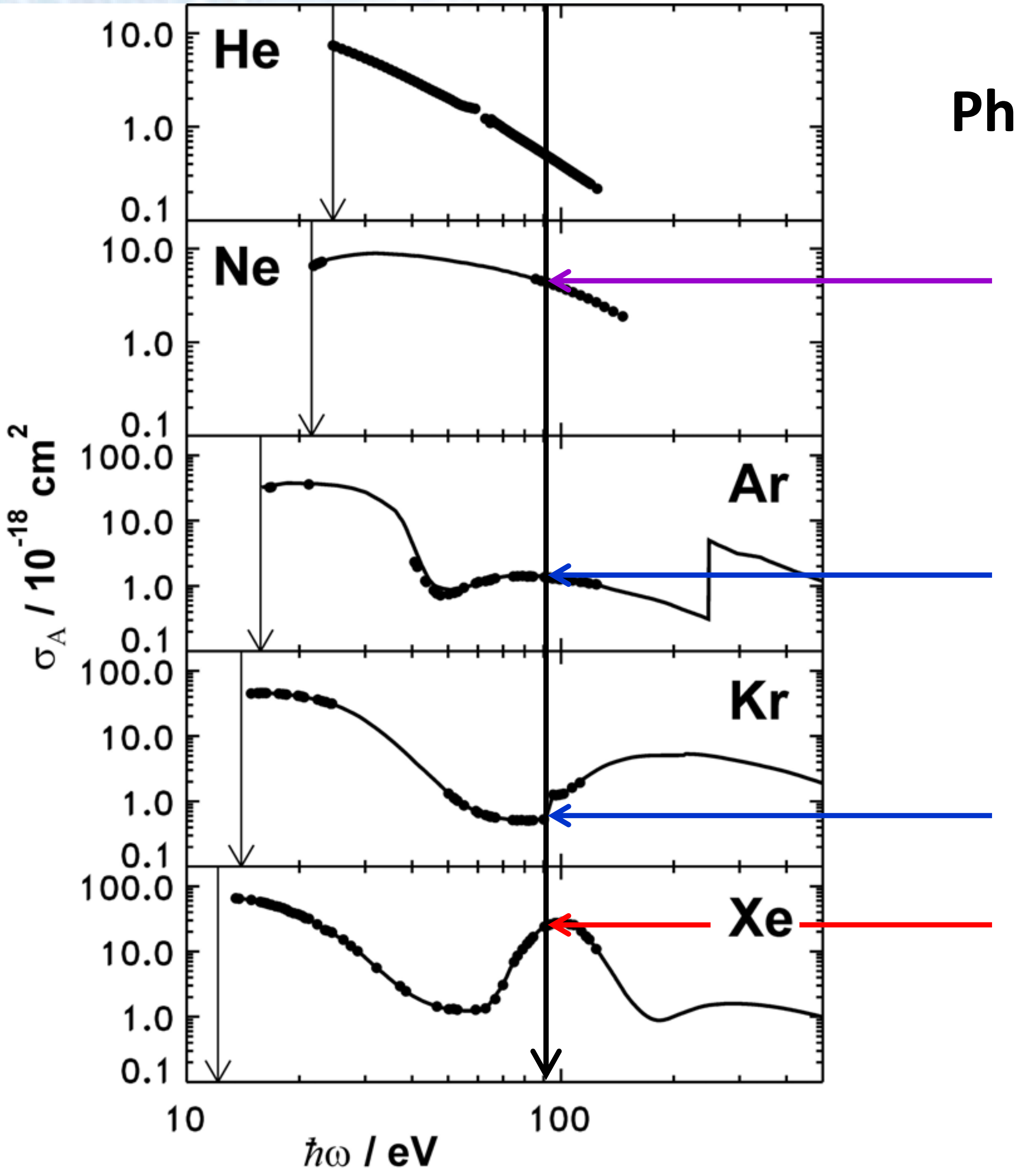
One-photon Absorption / Ionization Cross Sections of Rare Gases



Photon energy 90.5 eV:

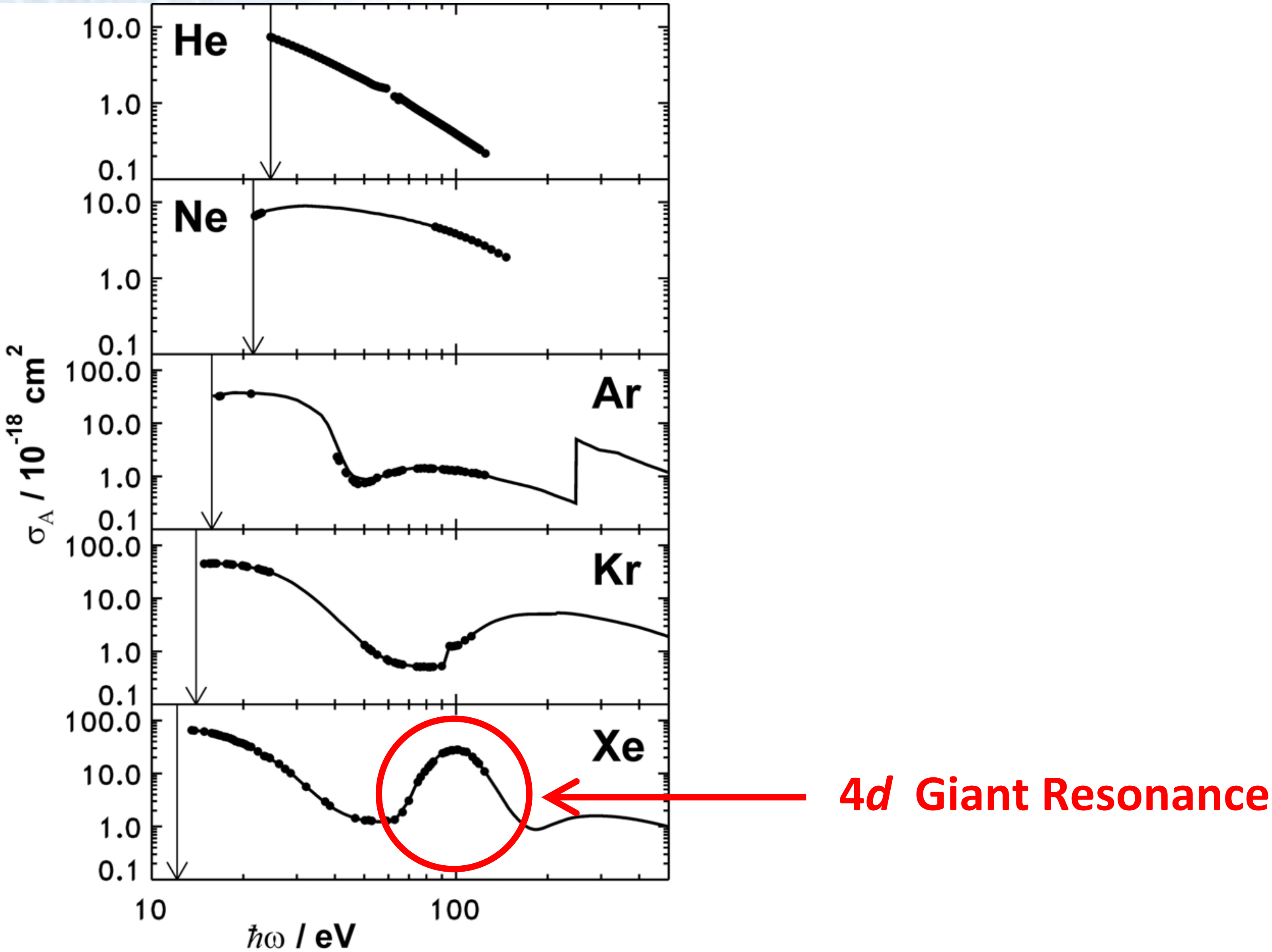
4.5×10^{-18} cm^2

1.4×10^{-18} cm^2

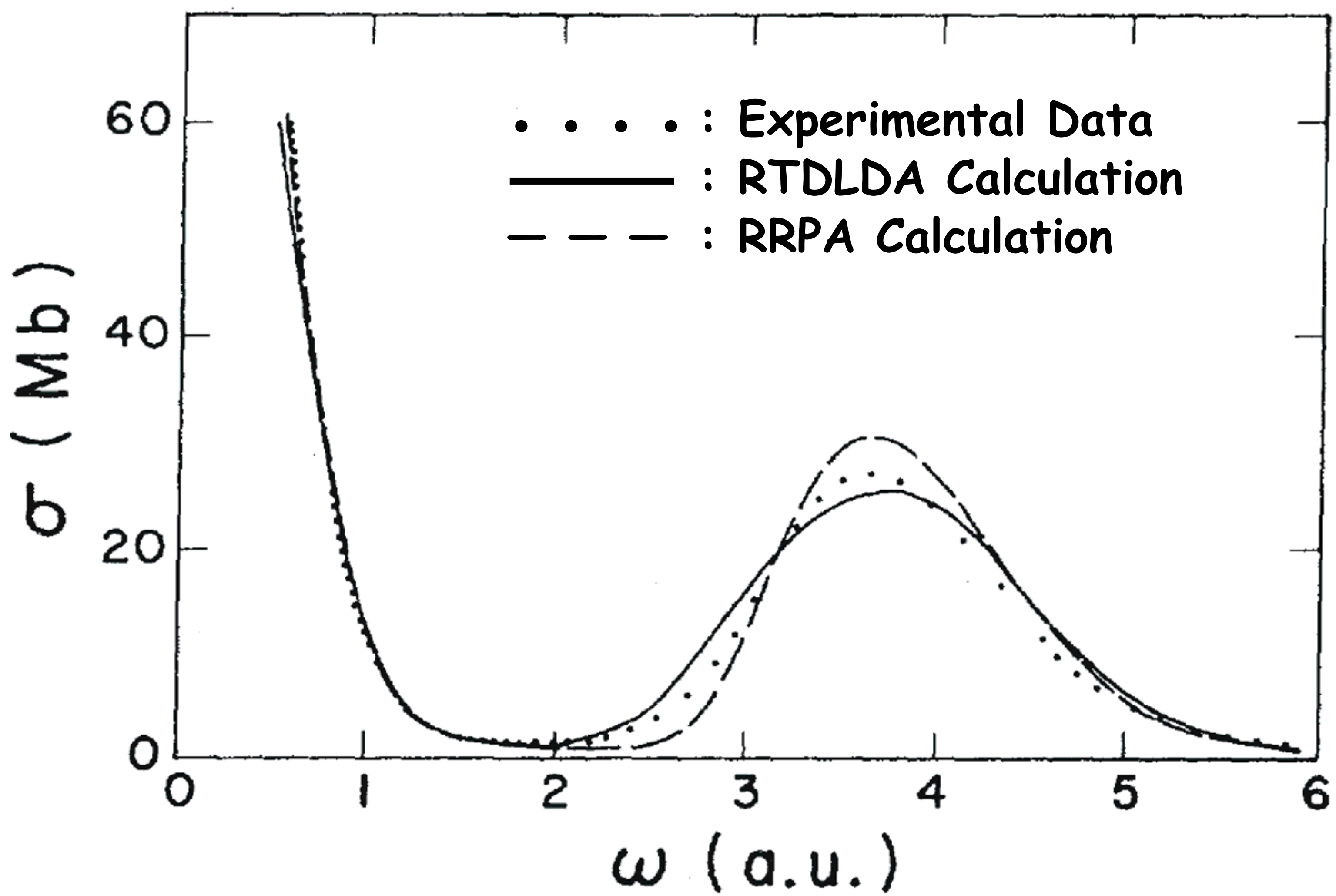
0.6×10^{-18} cm^2

23.9×10^{-18} cm^2

One-photon Absorption / Ionization Cross Sections of Rare Gases



4d Giant Resonance of Xenon: Total Photoionization Cross Section



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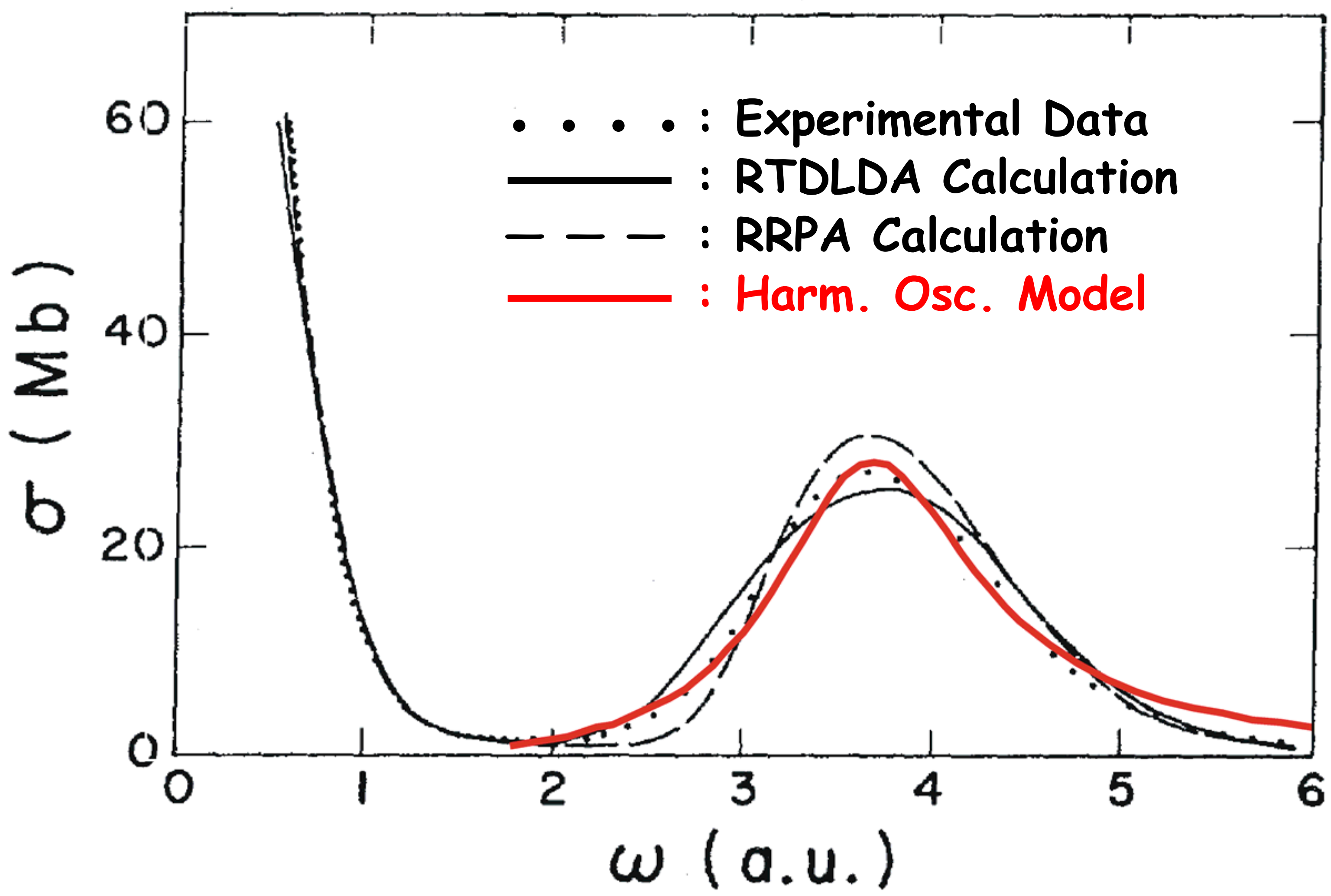

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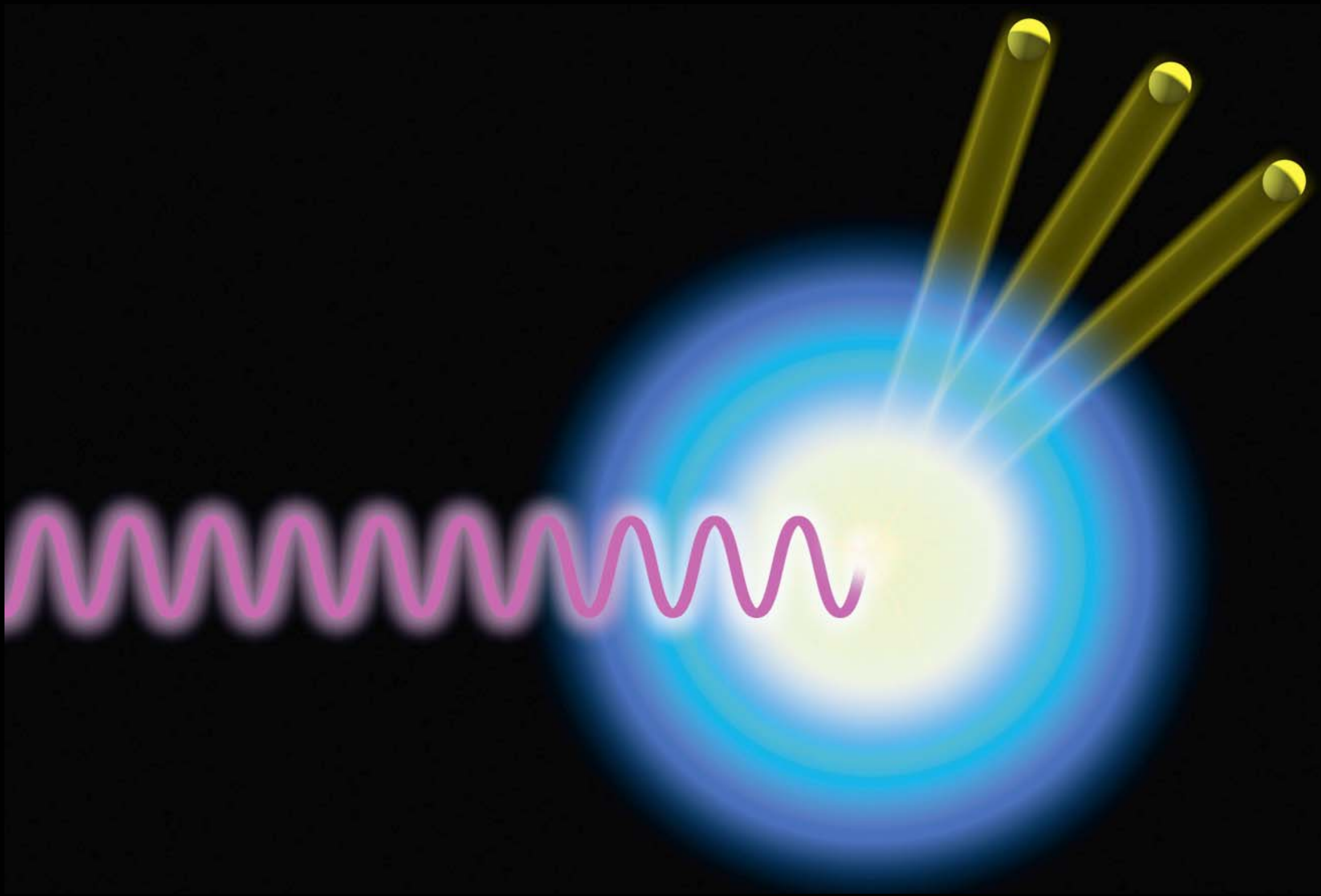
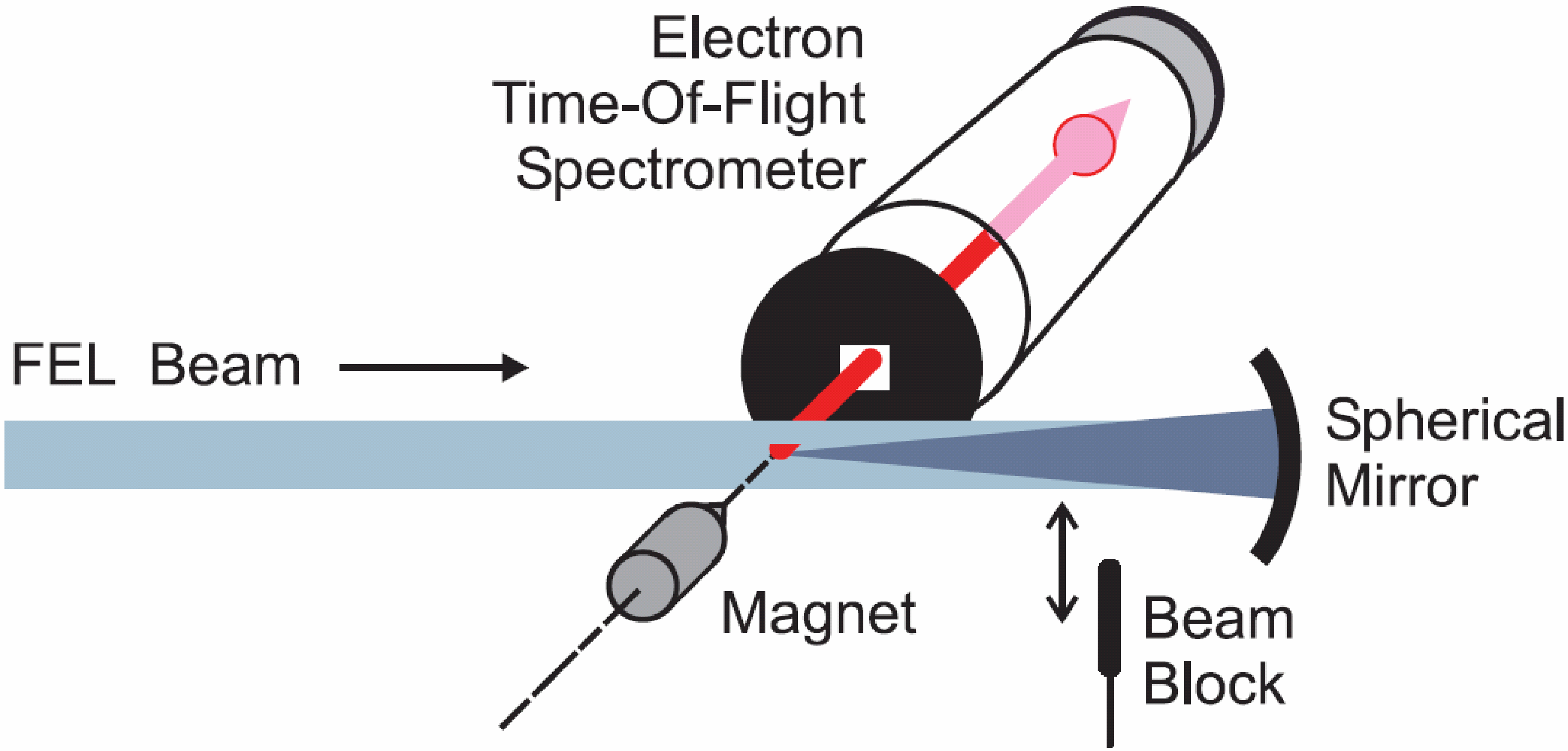
Strong-field Multiple Ionization in the Inner 4*d* Shell of Xe by EUV Radiation

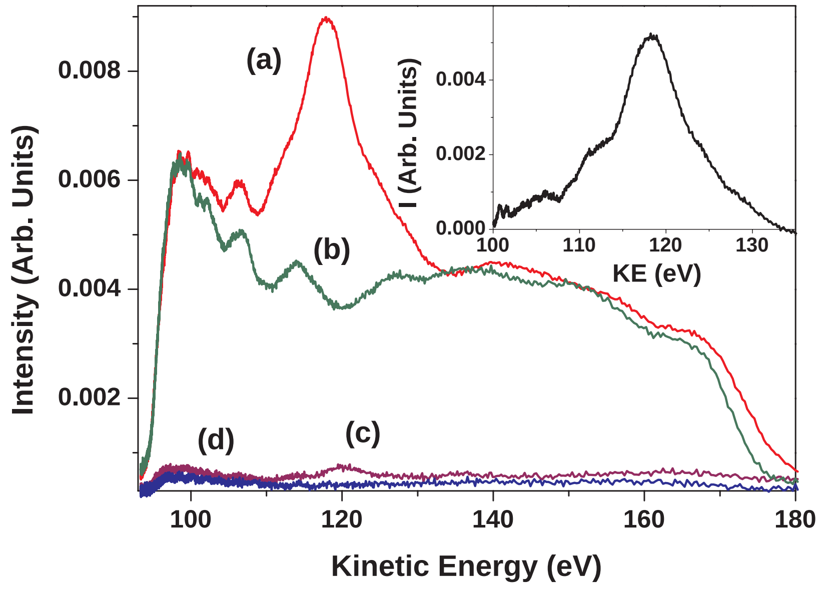


Electron Time-Of-Flight (TOF) Spectroscopy on Rare Gases and Molecules at FLASH



V. Richardson, J. T. Costello, D. Cubaynes, S. Düsterer, J. Feldhaus, H.W. van der Hart, P. Juranić, W. B. Li, M. Meyer, M. Richter, A. A. Sorokin, K. Tiedke, Phys. Rev. Lett **105**, 013001 (2010)

Two-photon 4*d* Ionization of Xenon at $h\nu$ = 93 eV: Electron Spectrum



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Irradiance > 10^{15} W cm^{-2}

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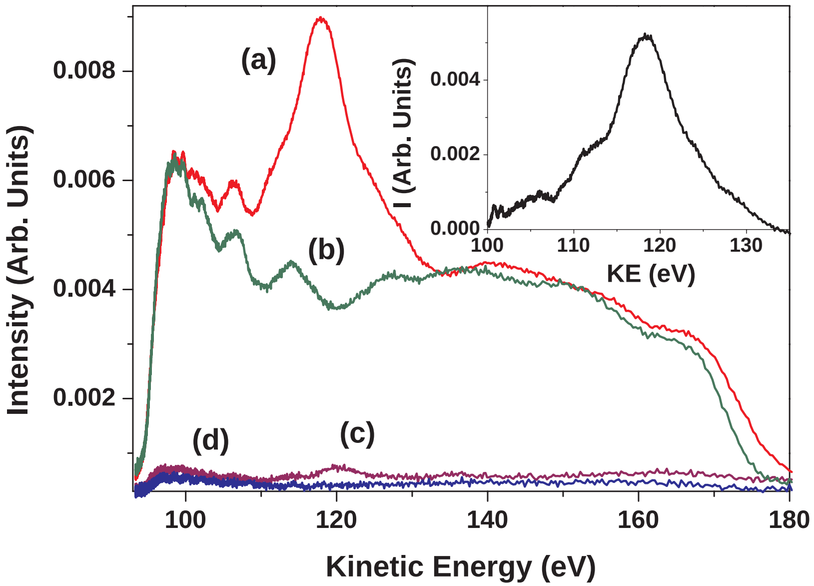

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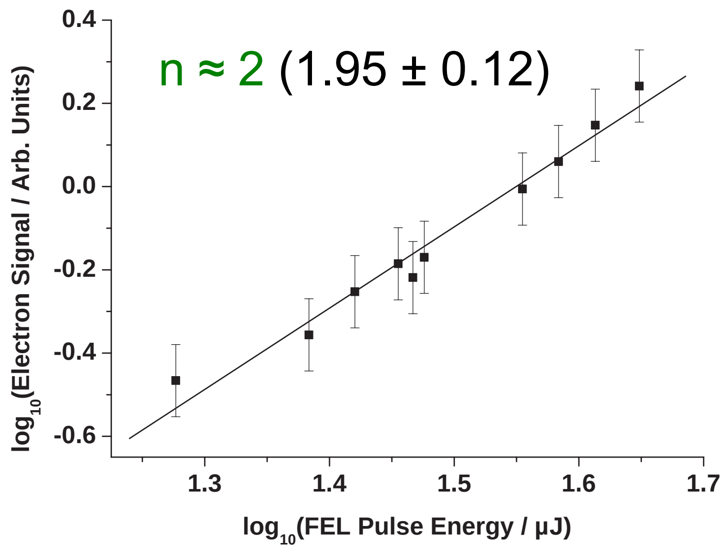
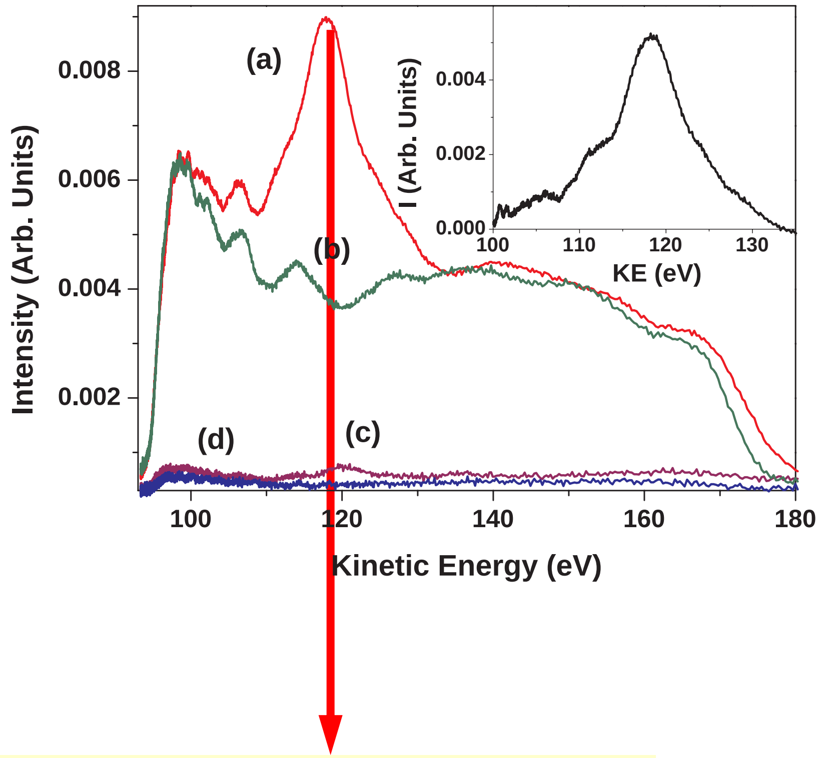


Two-photon 4*d* Ionization of Xenon at *hν* = 93 eV: Electron Spectrum



2×93 eV – 118 eV = **68 eV**

$(2 \times h\nu - \varepsilon_{e^-} = I_{4d})$

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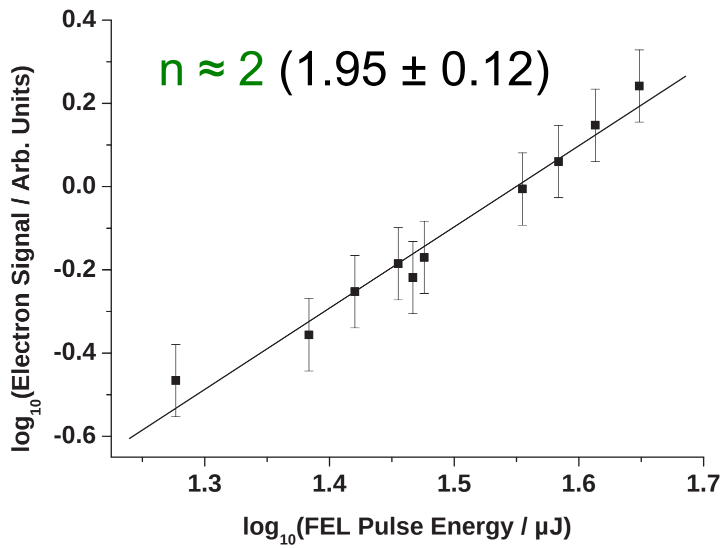

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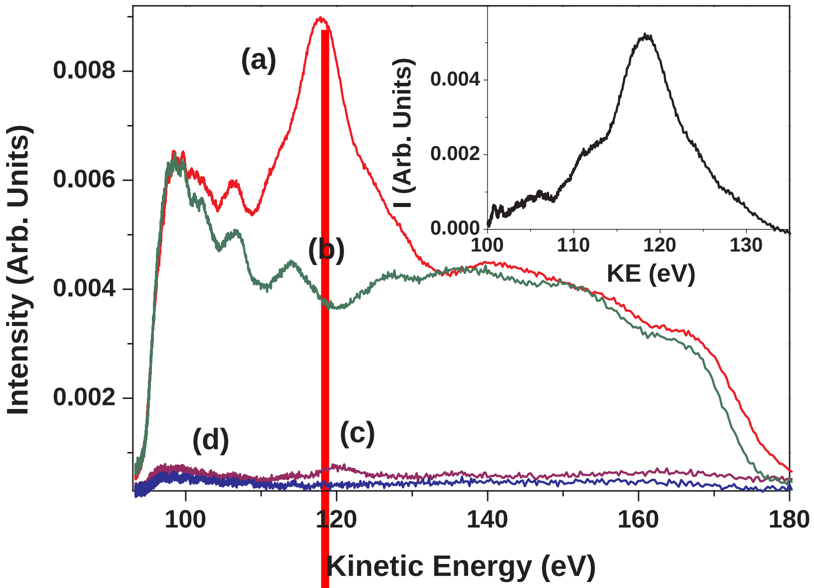

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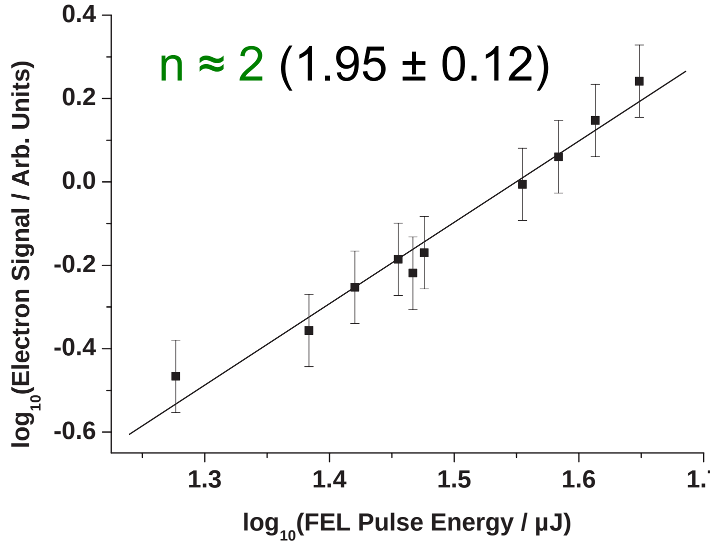

First detection of an Above Threshold Ionization (ATI) two-photon process in an **inner** electron shell

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