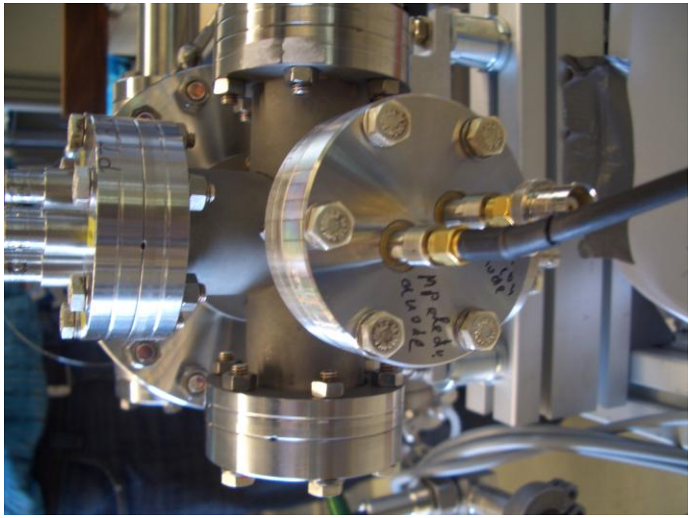
Photoelectron and Ion (Time-of-Flight) Spectroscopy

See the Light, Know the Light!



P. Juranić, M. Martins, J. Viefhaus, A. A. Sorokin, G. Brenner, S. Bonfigt, L. Jahn, M. Ilchen, S. Klummp, M. Richter, K. Tiedtke

XFEL Workshop
Ryn, Poland, Feb 14th – 17th, 2010

HELMHOLTZ
ASSOCIATION

DESY

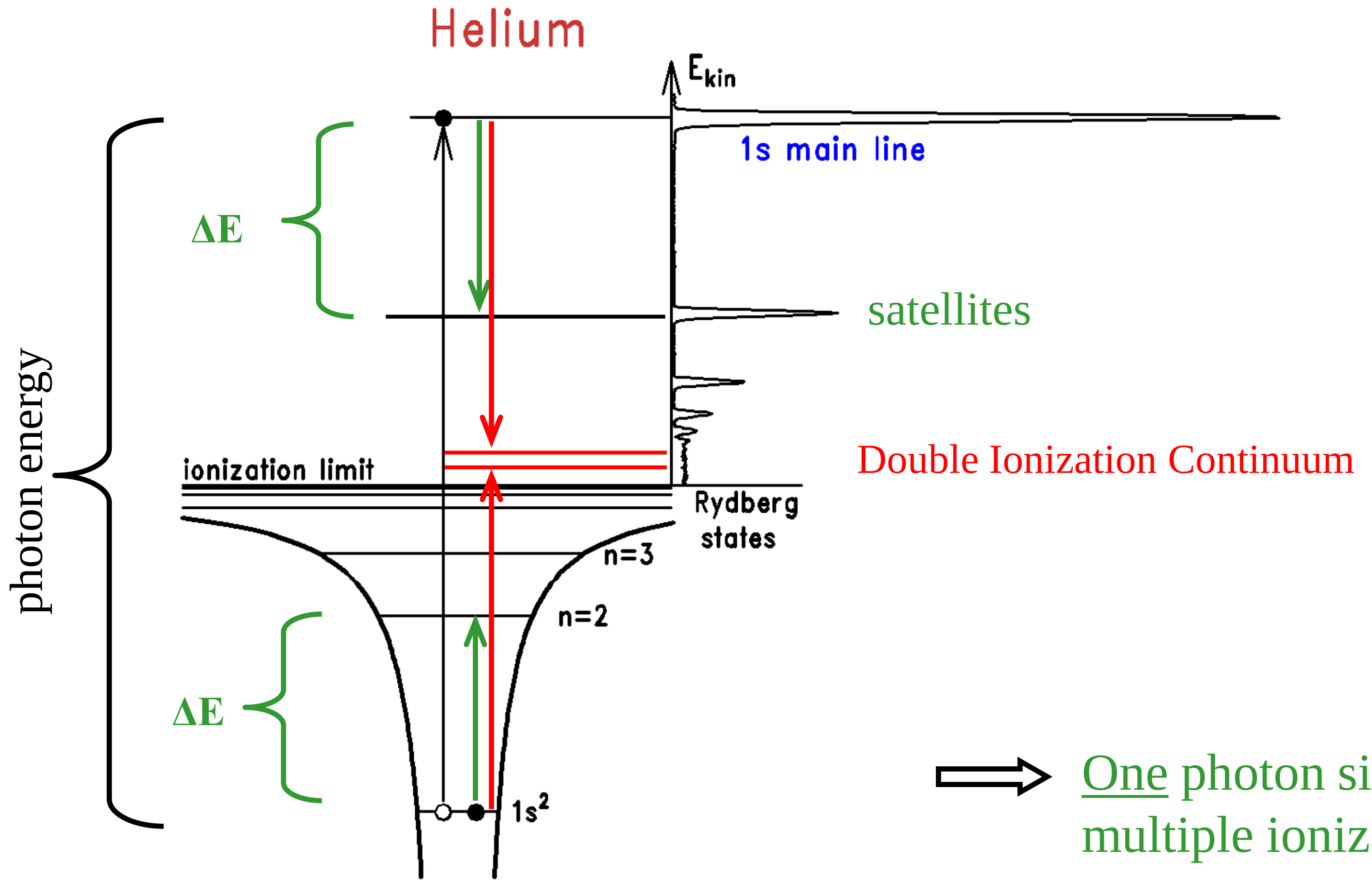
Outline

- A quick introduction to photoionization
  - Some basic concepts

- The on-line photoionization spectrometer
  - The electron time-of-flight spectrometer (eTOF)
  - The ion time-of-flight spectrometer (iTOF)

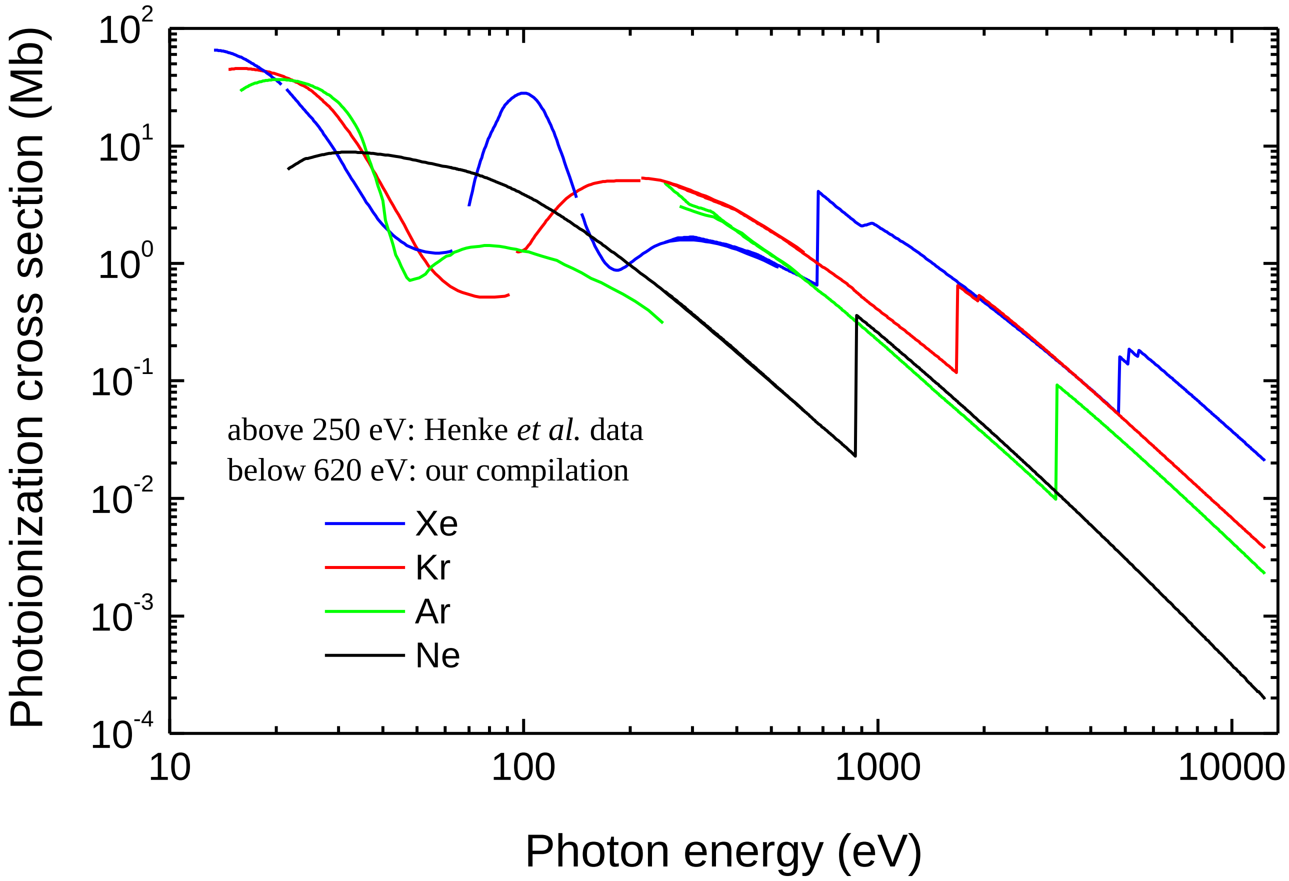
- Conclusion

Photoionization Theory



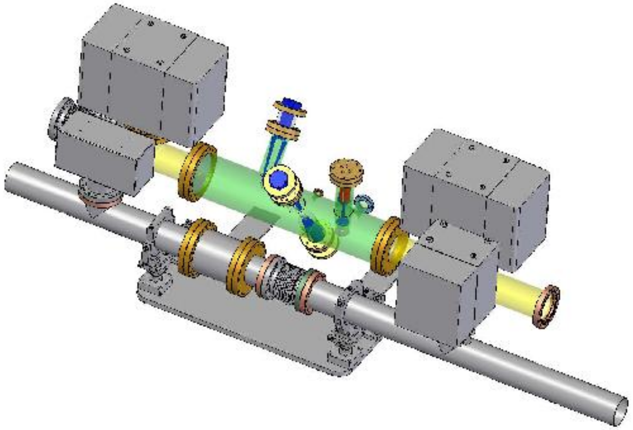
⇨ One photon single and multiple ionization!

Photoionization Cross Sections of Some Rare Gases

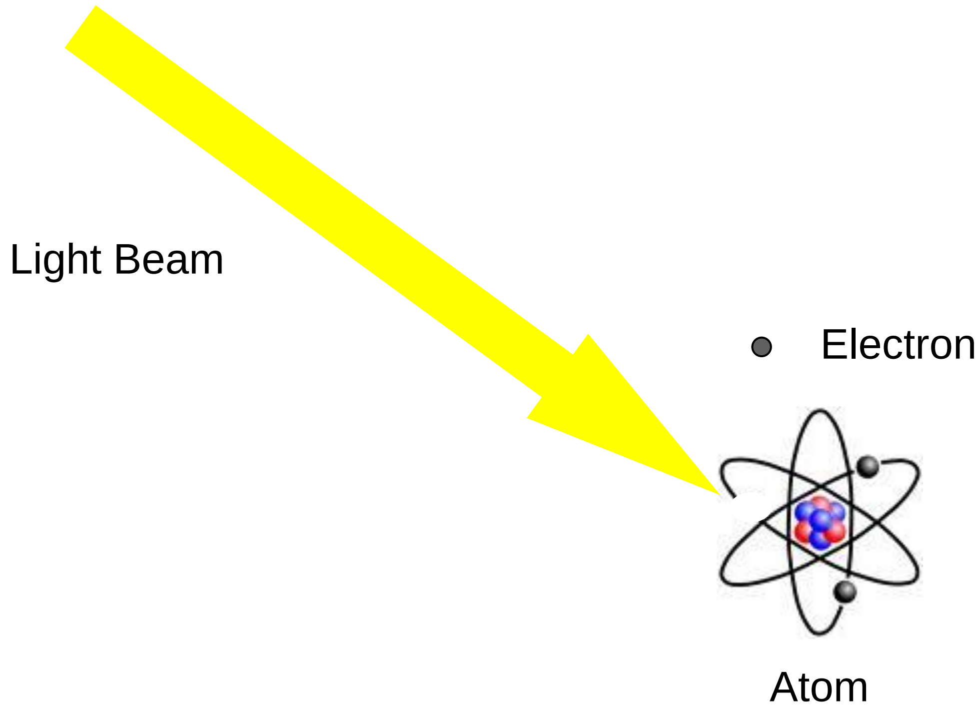


The Photionization Spectrometer

- Want to measure the FEL beam bunch properties, like wavelength, higher harmonics, multiple modes, etc.
- To do this, we will use electron and ion time-of-flight (TOF) spectrometers.



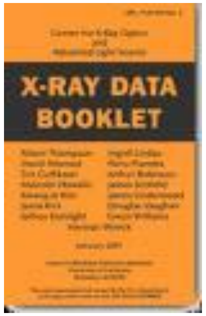
A Closer Look at the Interaction Region



$KE_{electron} = E_{photon} – \text{Binding Energy}$

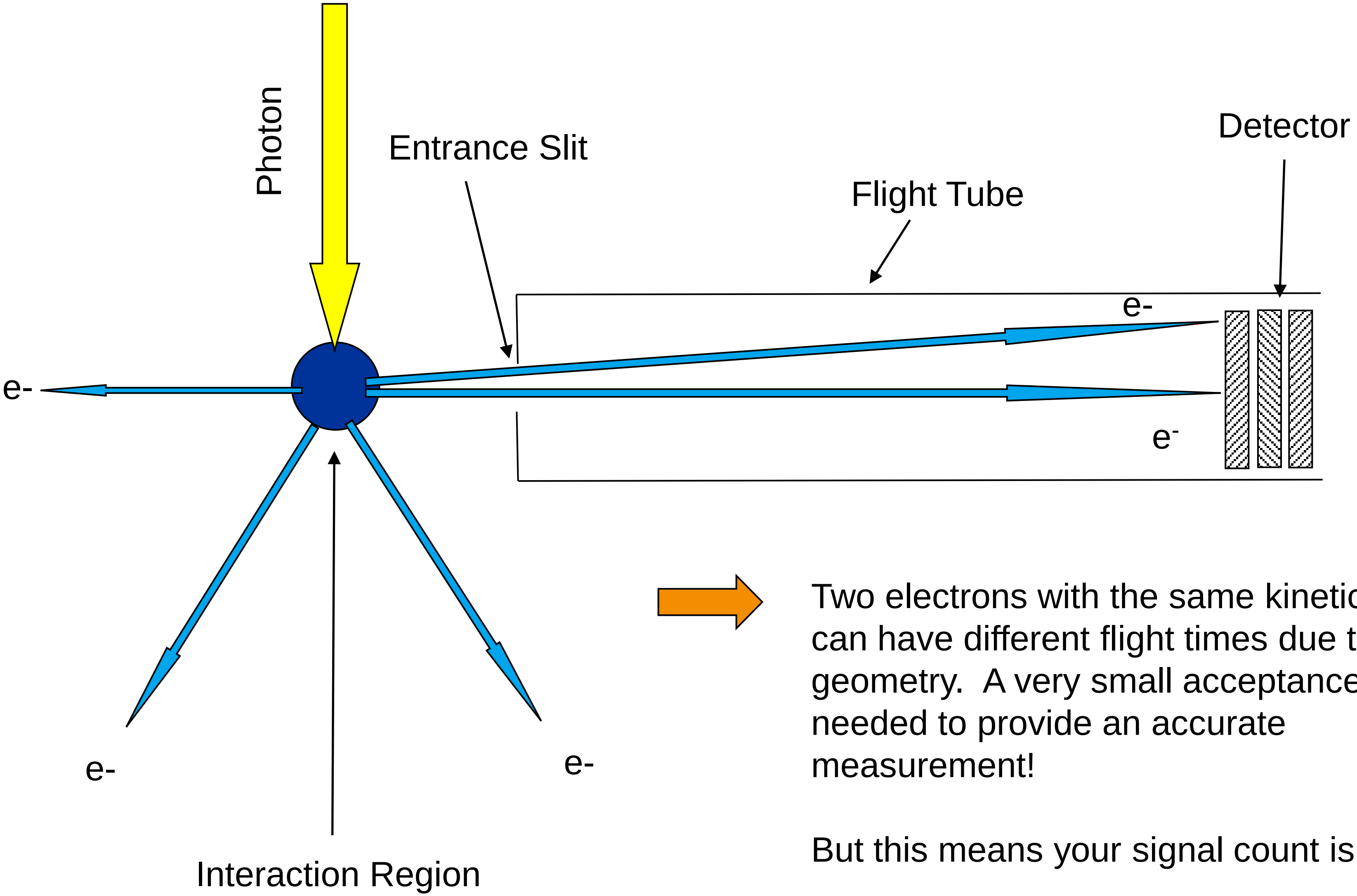
If you know the binding energy, and you can measure the electron kinetic energy, you can evaluate the energy of the photon!

The binding energies are easy . . .



X-RAY DATA BOOKLET

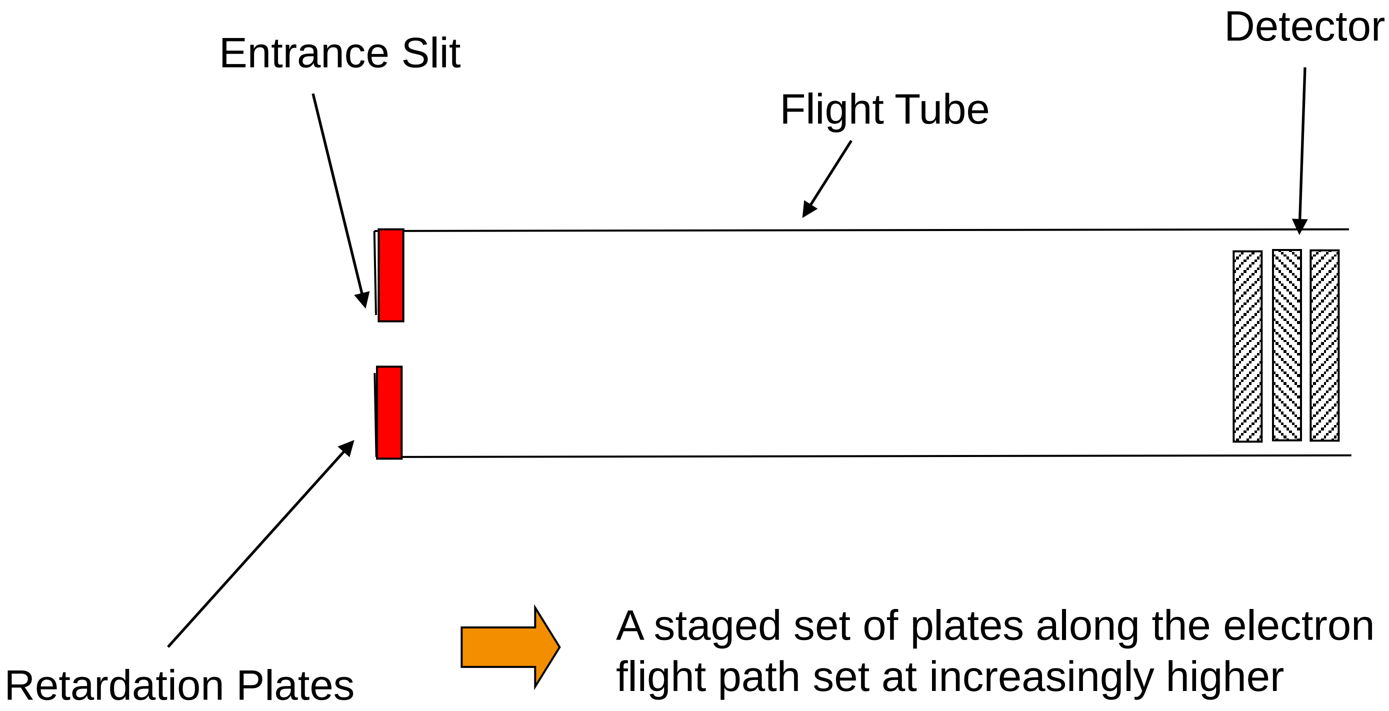
The Electron Time of Flight Spectrometer



Two electrons with the same kinetic energy can have different flight times due to bad geometry. A very small acceptance angle is needed to provide an accurate measurement!

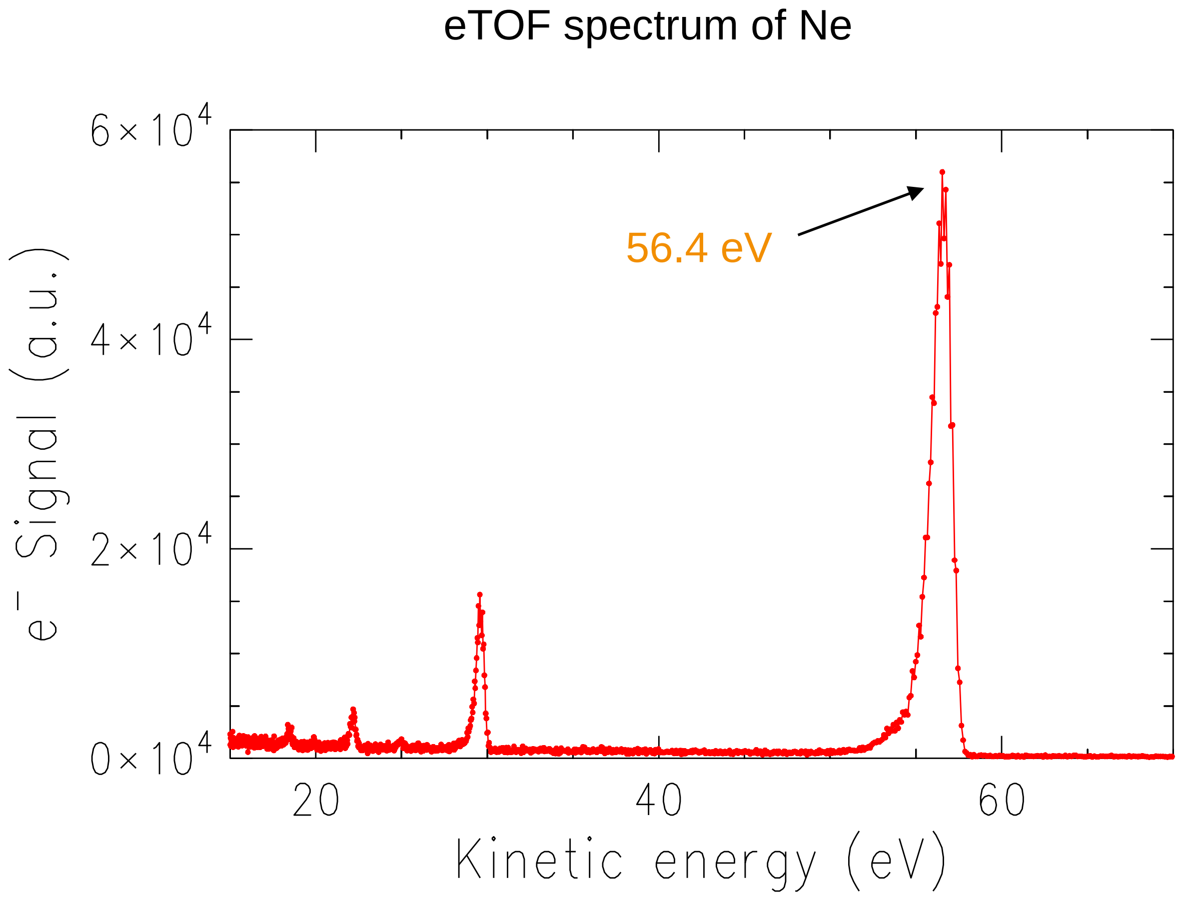
But this means your signal count is low . . .

eTOF Flight Time Retardation



A staged set of plates along the electron flight path set at increasingly higher voltages. It filters out the slower electrons, letting us see just the ones that we want. The slowed electrons are also easier to resolve.

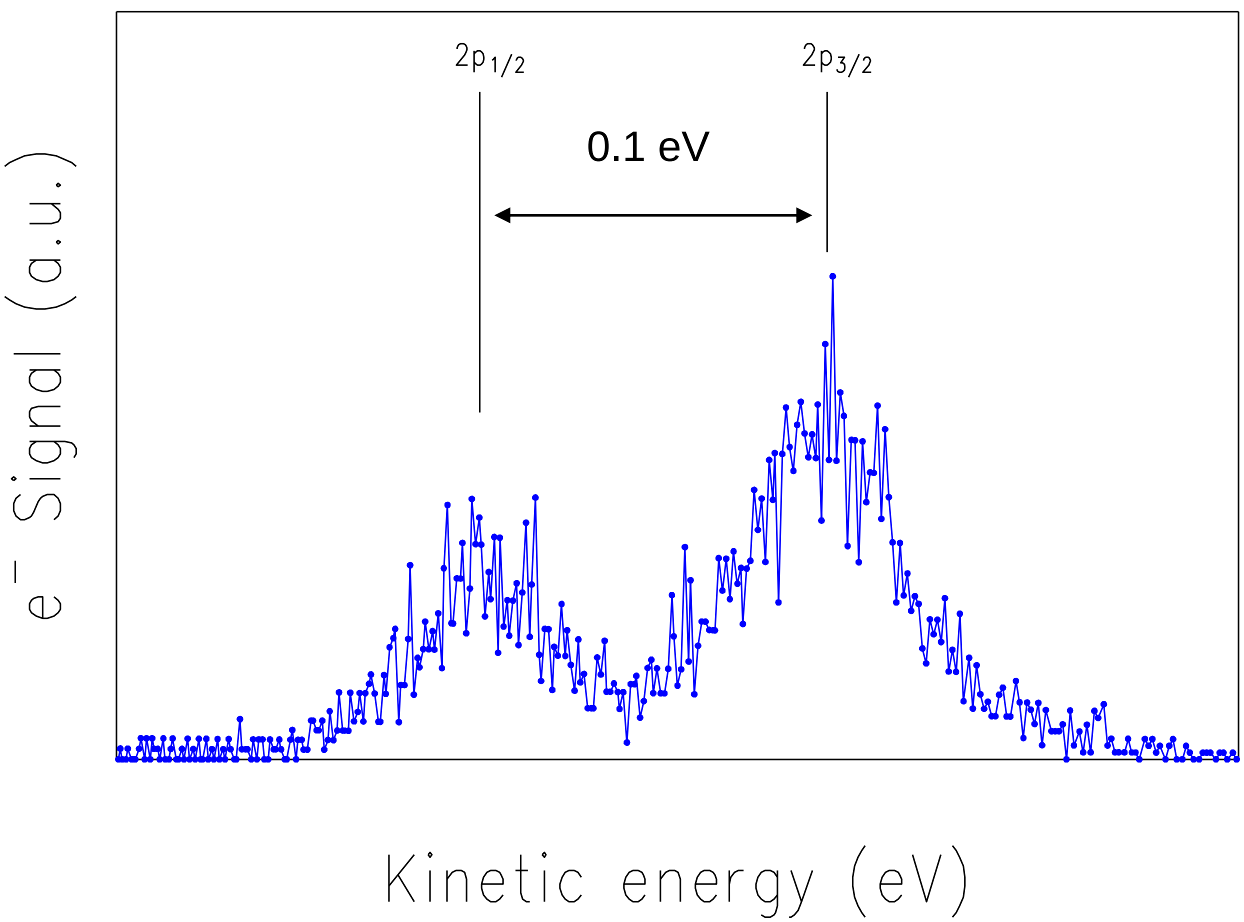
The Spectra



The $2p_{3/2}$ level for Ne has a binding energy of 21.7 eV. The $2p_{1/2}$ binding energy is 21.6 eV.

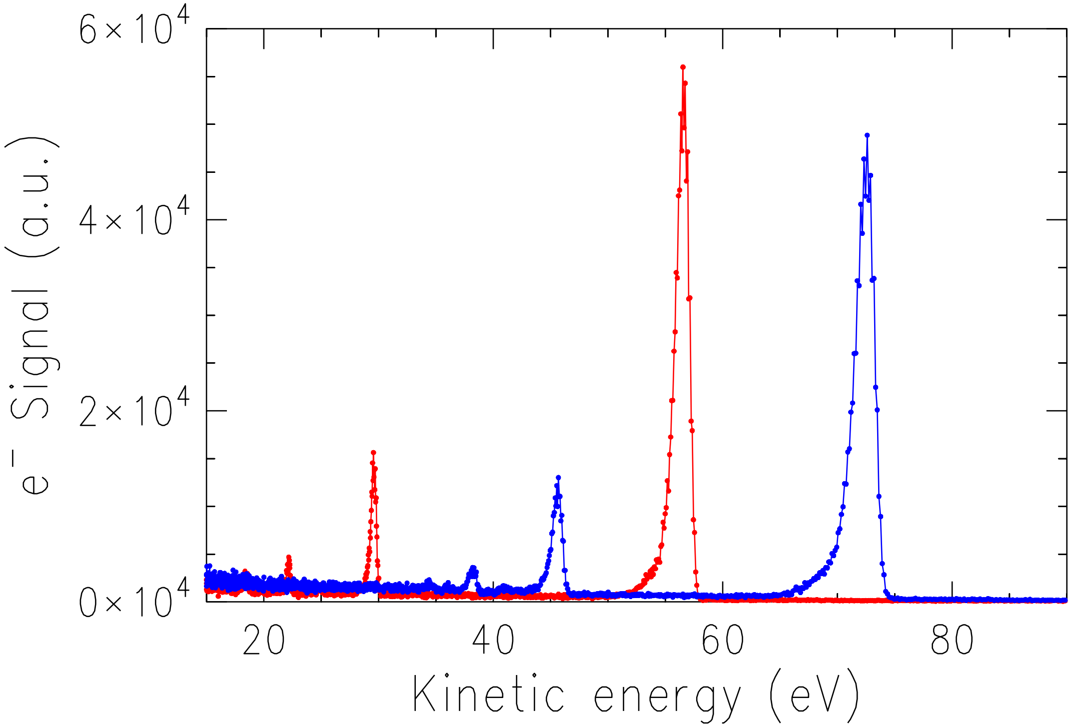
That would make the photon energy 78 or 78.1 eV. The set photon energy was 78 eV.

Resolving Power



But there’s more!

What if the light has photons of more than one wavelength?



Which means we can see the contribution of higher harmonics and other effects . . .

E-TOF advantages

- Fast Measurement: An electron flies fast, so you can get information about a beam pulse within nanoseconds.

- Wealth of Information: It can detect all qualities of the beam, like higher harmonics, multiple wavelengths, stray light, pulse structure, etc.

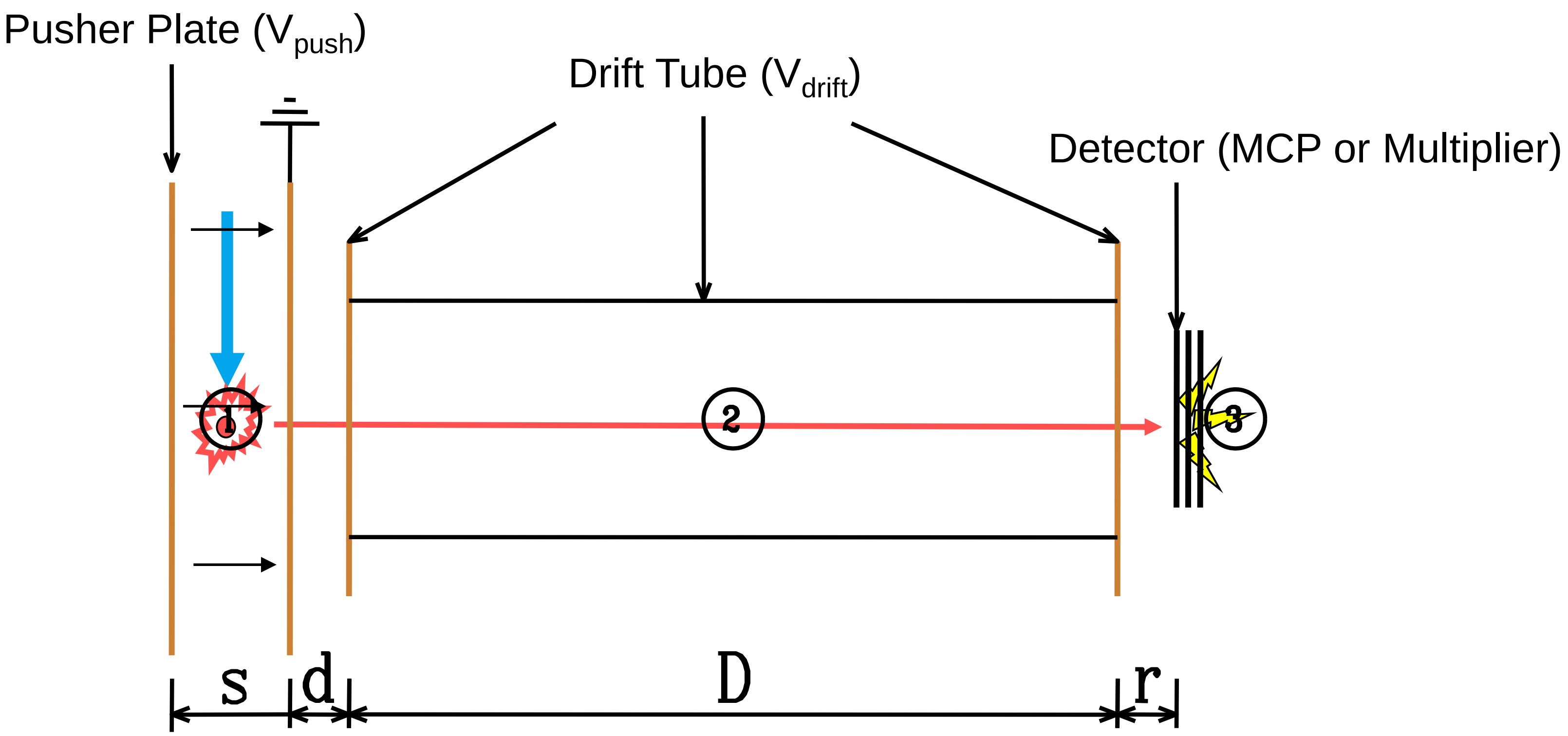
- Accuracy: Properly set up, the energy resolution of the eTOF can be better than 0.1 eV. The top of the line eTOFs can get down to 0.01 eV resolution.

- Flexibility: The energy resolution can be controlled by adjusting the retardation potential. We can isolate just the electrons we want to see.

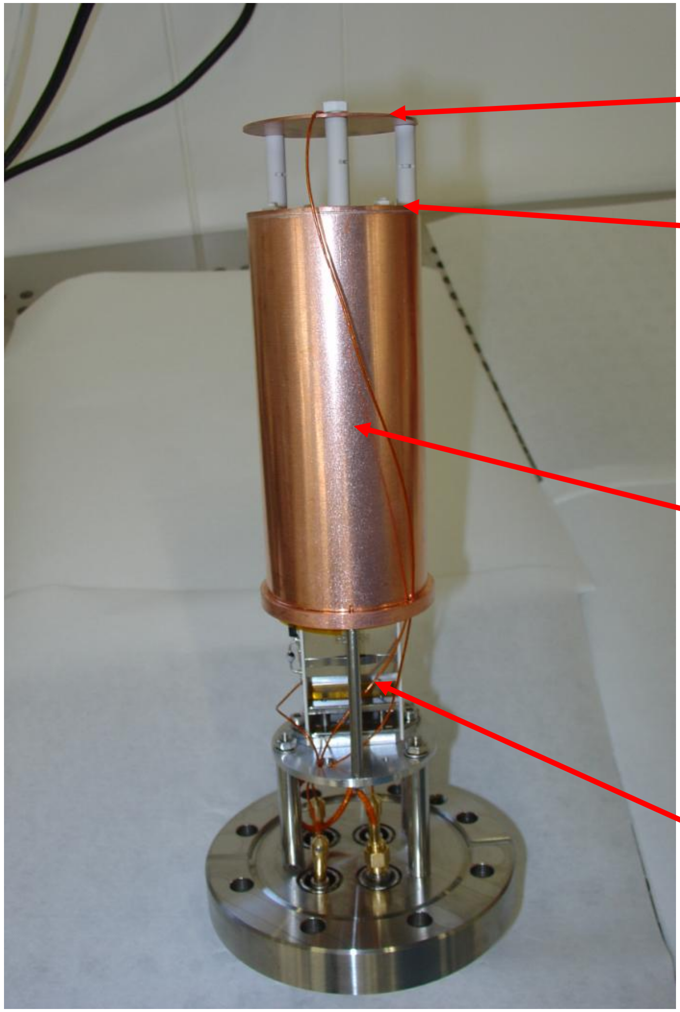
Things to Watch Out For the eTOF

- Stray magnetic fields (can be a problem near undulators).
  - Solved with μ-metal shielding or Helmholtz coils.
- Stray electric fields.
  - Solved with a Faraday cage (the chamber).
- Anything that can impact the electron flight time to give you a wrong time-of-flight reading (off-center beam, shifting beam, motion of the chamber, etc).
  - Just be careful and make sure you keep track of all parameters!

The Ion TOF


Pusher Plate (V_{push})
Drift Tube (V_{drift})
Detector (MCP or Multiplier)
①
②
③
s
d
D
r

The Outside View



Pusher Plate

Extractor Plate/Shield

Drift Tube (inside the shield)

Multiplier

Some Equations . . .

$$T_t = \sqrt{2m}\left(\frac{s}{\sqrt{qE_s}} + \frac{\sqrt{U_t}}{qE_d} - \frac{\sqrt{qsE_s}}{qE_d} + \frac{D}{2\sqrt{U_t}}\right)$$

$$\frac{dT}{dS} = \sqrt{\frac{m}{2}}\left(\frac{E_d - E_s}{\sqrt{qsE_s}E_d} + \frac{E_s}{\sqrt{U_t}E_d} - \frac{DqE_s}{2U_t^{\frac{3}{2}}}\right)$$

$$D = 2s_0\left(1 - \frac{E_s}{E_d}\right)\left(1 + \frac{dE_d}{s_0E_s}\right)^{\frac{3}{2}} + 2d\left(1 + \frac{s_0E_s}{dE_d}\right)$$

$$\Delta T_\theta = \frac{2v_0m}{qE_s} = \frac{2\sqrt{2mU_0}}{qE_s}$$

$$\Delta T_{\Delta s} = \sum_{n=1}^{\infty} = \left(\frac{d^nT}{ds^n}(s)\right)_{s_0}(\Delta s)^n$$

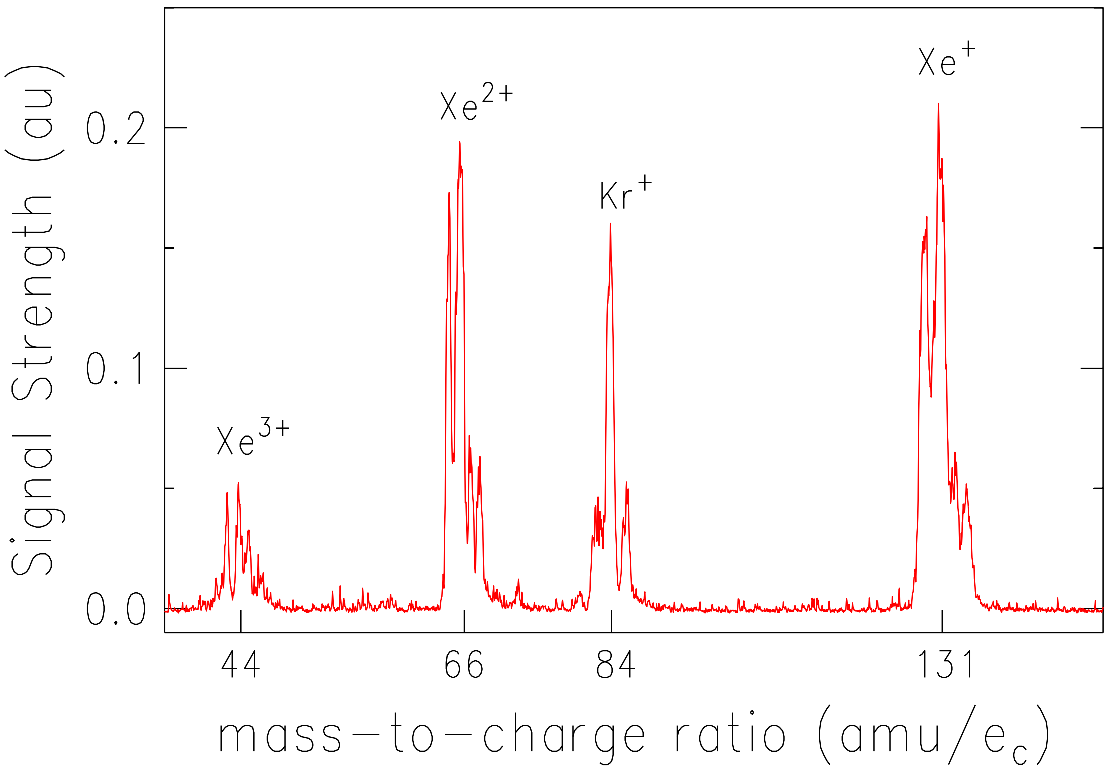
$$T_{m+1} - T_m = \left(\sqrt{1 + \frac{1}{m}} - 1\right)T_m \approx \frac{T_m}{2m}$$

$$M_\theta = \sqrt{\frac{U_t}{U_0}}\frac{1}{\sqrt{1 + \frac{sE_d}{s_0E_s}}}\left(1 + \frac{E_s}{E_d} + 3\frac{E_s}{E_d}\sqrt{1 + \frac{dE_d}{s_0E_s}}\right) + 2\left(1 + \frac{dE_d}{sE_s}\right)\left(1 - \frac{E_s}{E_d}\right))$$

$$\frac{1}{\frac{1}{M_s} + \frac{1}{M_\theta}} \leq M \leq \max(M_s, M_\theta)$$

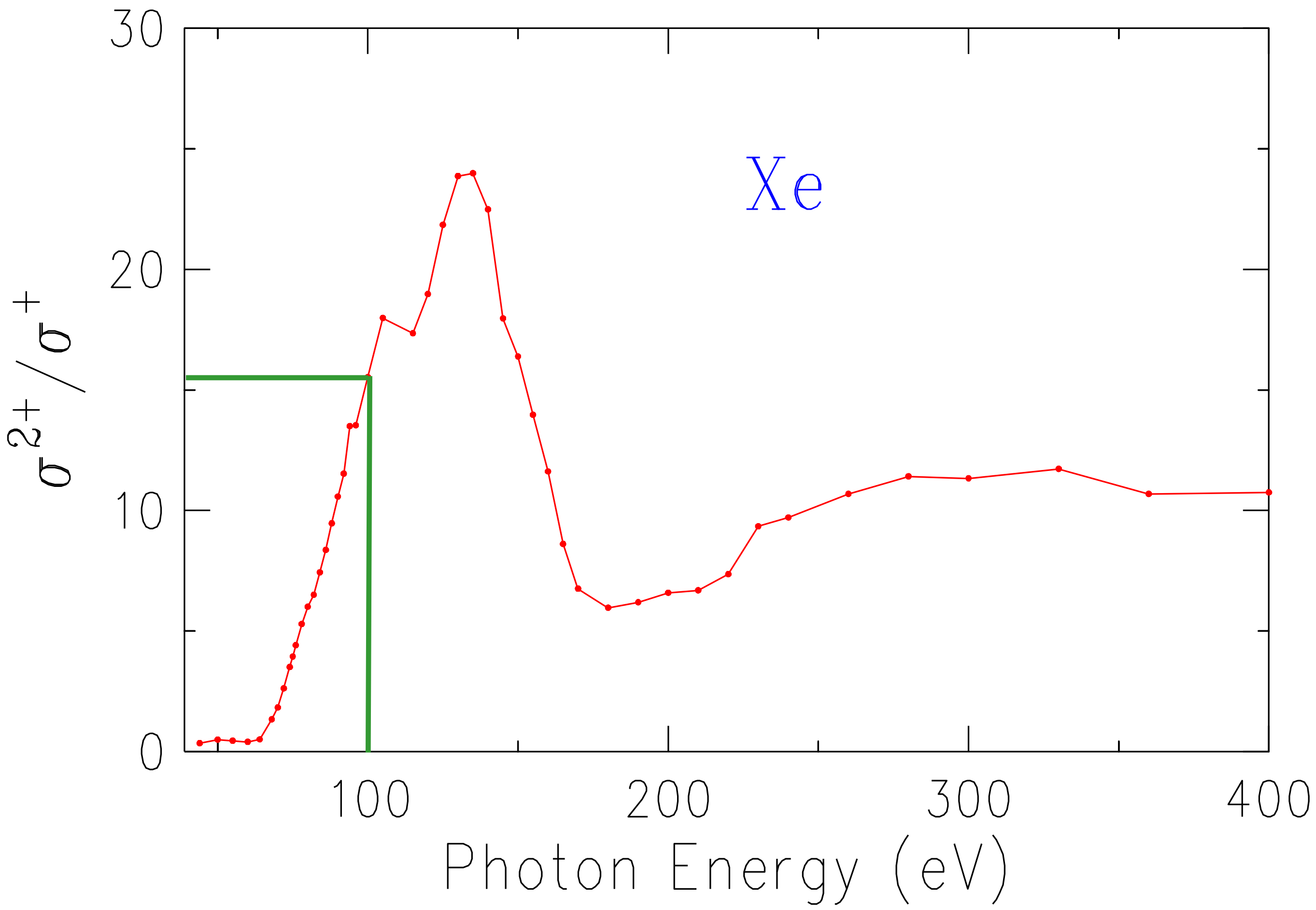
The field ratio lets us control the resolution of the I-TOF

Well-Resolved I-TOF Spectra



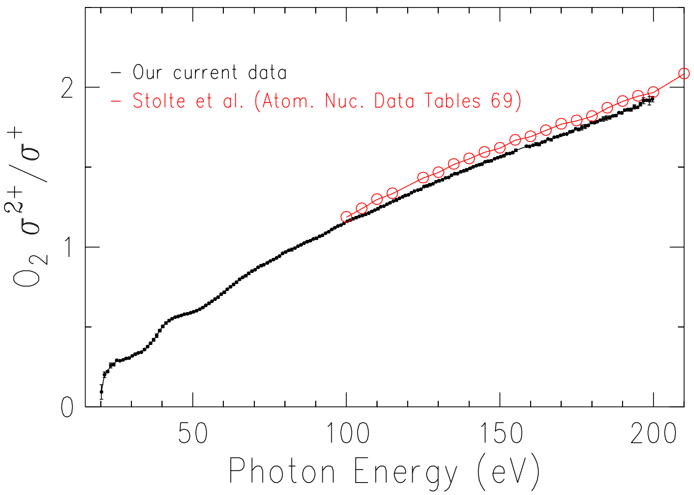
Isotope	Atomic mass (m_a/u)	Natural abundance (atom %)
^{124}Xe	123.9058942 (22)	0.09 (1)
^{126}Xe	125.904281 (8)	0.09 (1)
^{128}Xe	127.9035312 (17)	1.92 (3)
^{129}Xe	128.9047801 (21)	26.44 (24)
^{130}Xe	129.9035094 (17)	4.08 (2)
^{131}Xe	130.905072 (5)	21.18 (3)
^{132}Xe	131.904144 (5)	26.89 (6)
^{134}Xe	133.905395 (8)	10.44 (10)
^{136}Xe	135.907214 (8)	8.87 (16)

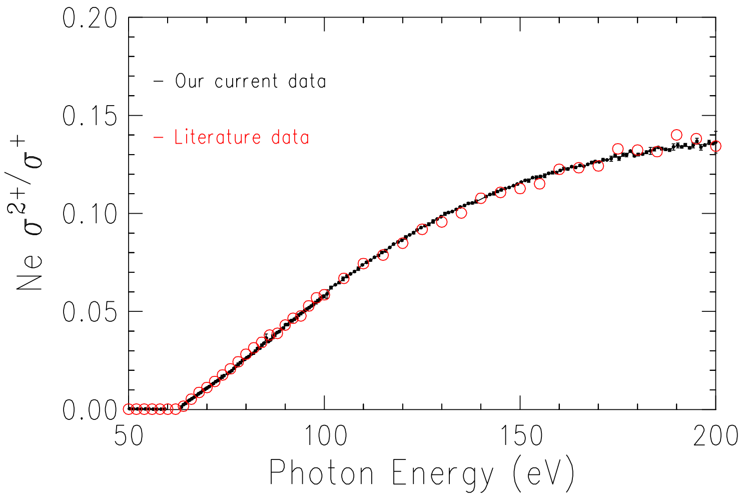
From the Spectra, Ratios

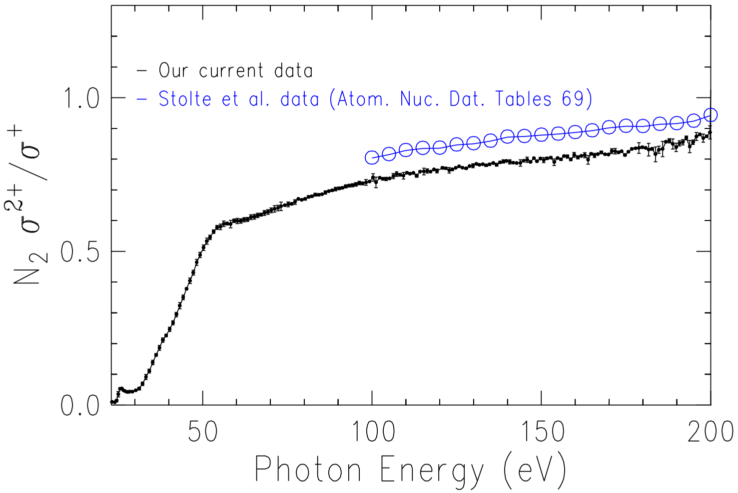


We must be at 100 eV photon energy! But it could also be 170 eV. . .

Other Gases

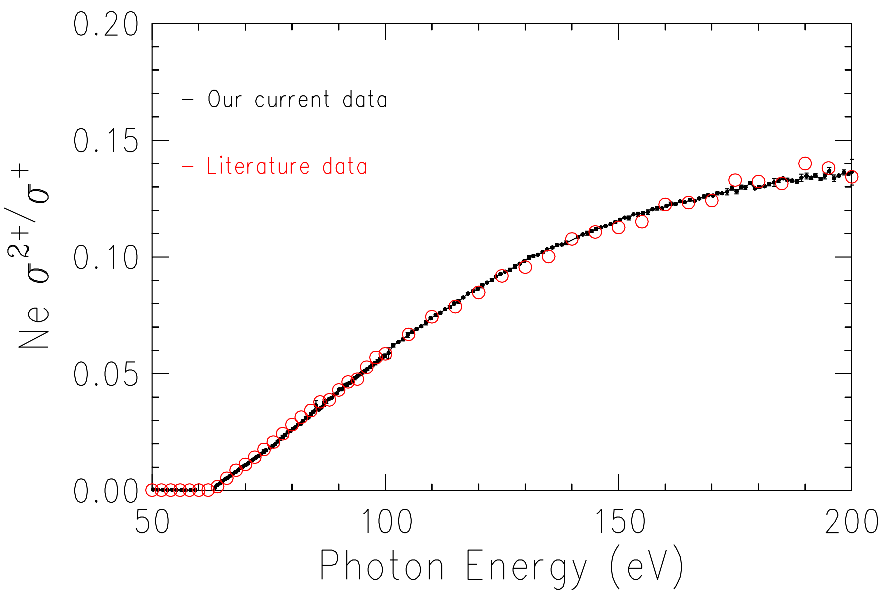


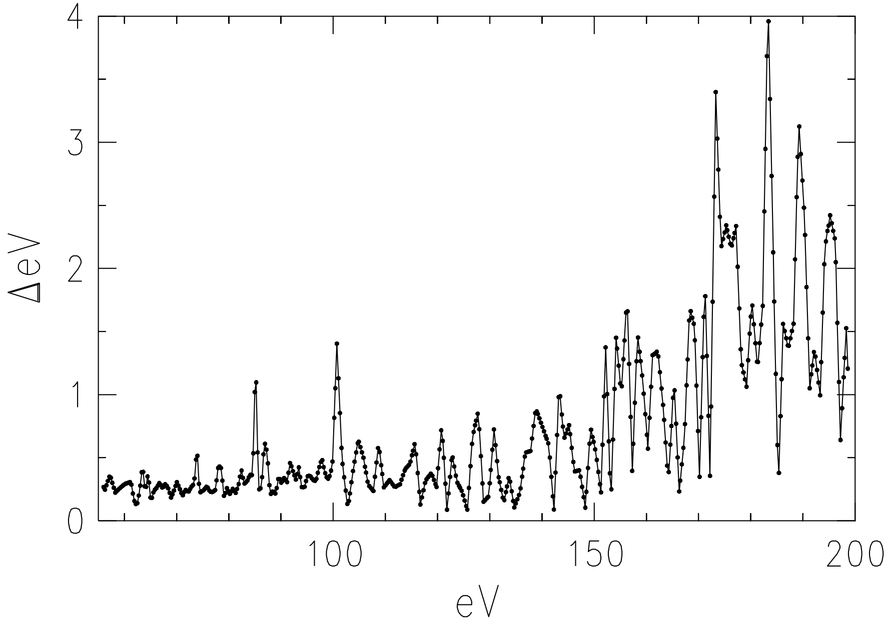




- Small Error Bars
- Lots of Literature Data
- Lots of Signal!

Uncertainty





Steep slopes are good! Oxygen looks particularly nice . . .

I-TOF Advantages

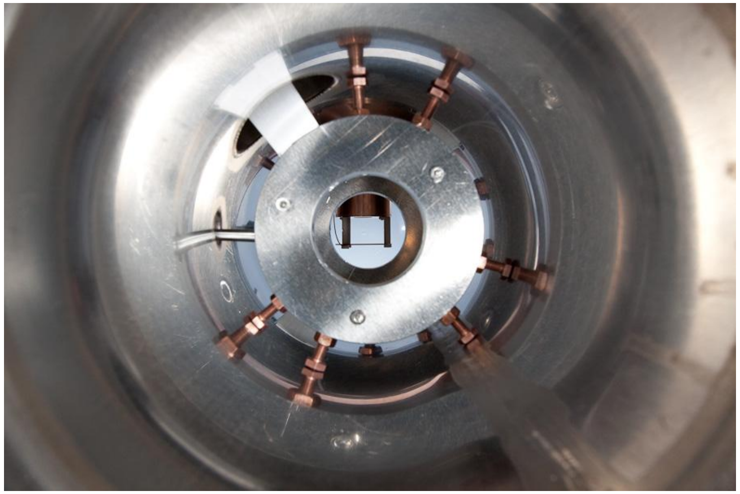
- Great signal: Since you get all the ions created in the interaction region, it means you get a lot of information.

- Simple to use: Once the potentials are set, the i-TOF will work for everything at every photon energy.

- Good Resolution: The i-TOF spectra can easily resolve isotopes, and the accuracy of their photon energy measurement can be better than 0.5% (depending on the target gas used).

Possible I-TOF Problems

- Multi-Photon Ionizations (we want single-photon)
  - Solved by installing the spectrometer out of focus, in the single-photon regime.
- Slow (hundreds of nanosaconds is the best you can expect).
- Not much else, really. It is quite nice.



A Final Comparison (for FLASH)

	E-TOF	I-TOF
Speed of measurement	Nanoseconds	Hundreds of nanoseconds to microseconds
Uncertainty of “center” photon energy measurement	0.1 to 0.05 eV	0.7 eV to 0.3 eV
Expected “bonus” information	Can see the whole spectral distribution of the pulse and higher harmonics of a pulse	Can see the average photon energy
Robustness	Sensitive to electric and magnetic fields, beam stability	Like a rock

Conclusion

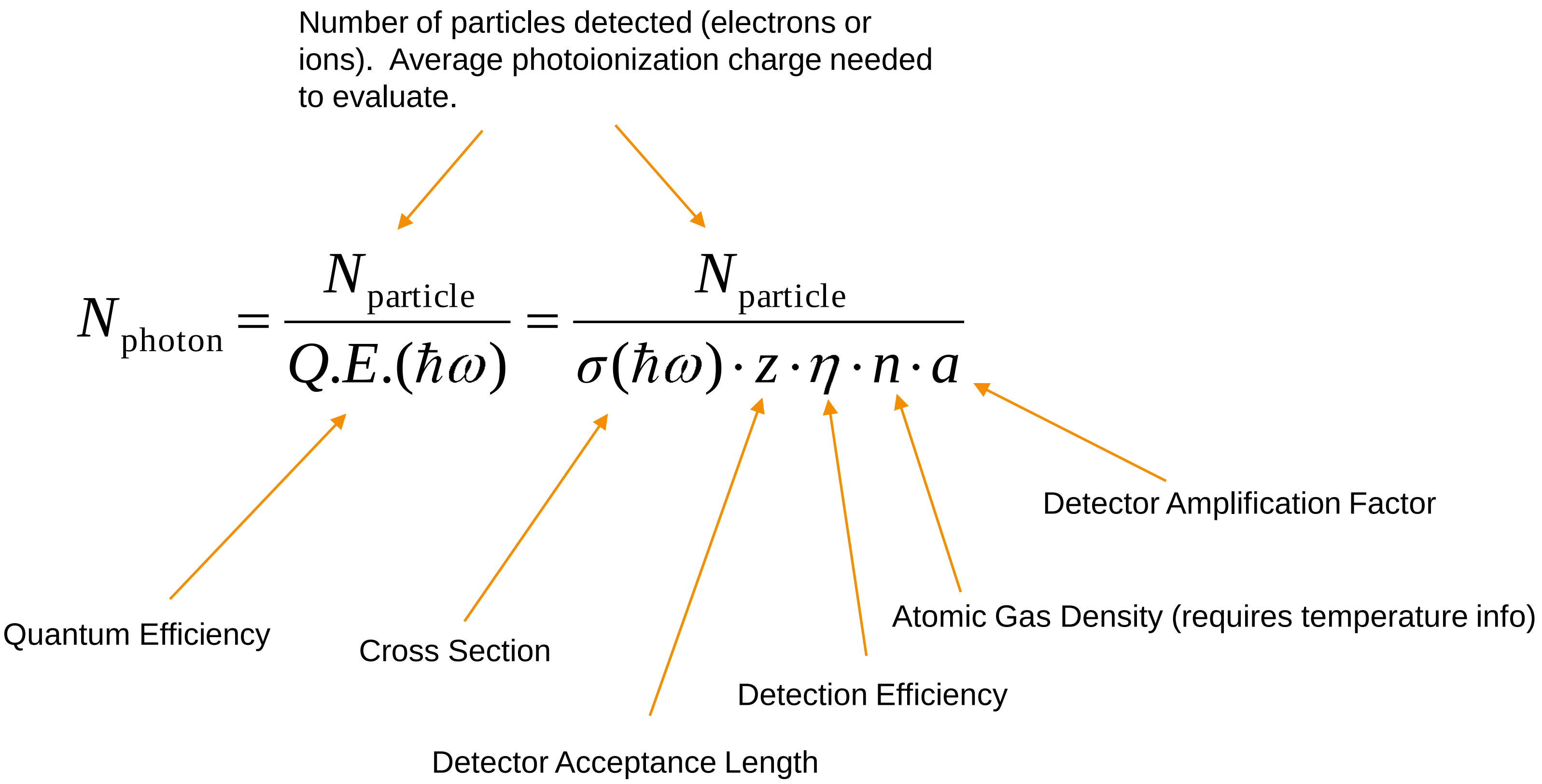
- The GMD’s can be used to reliably measure the FEL photon flux.
- The time-of-flight spectrometers can be used to figure out everything else about the beam.
- Everything should be up and operational at FLASH by late summer of 2010.
- Can be extended to work in harder x-ray regimes.

Acknowledgments

Many thanks to Svea Kapitzki, Ulf “Fini” Jastrow, Holger Weigelt, and all the people at FLASH, XFEL, and PTB who contributed to these projects in any way. You’ve helped the world see the light better!

The End

The Equation Behind the Picture



Number of particles detected (electrons or ions). Average photoionization charge needed to evaluate.

$$N_{\text{photon}} = \frac{N_{\text{particle}}}{Q.E.(\hbar\omega)} = \frac{N_{\text{particle}}}{\sigma(\hbar\omega)\cdot z\cdot \eta\cdot n\cdot a}$$

Detector Amplification Factor

Atomic Gas Density (requires temperature info)

Quantum Efficiency

Cross Section

Detection Efficiency

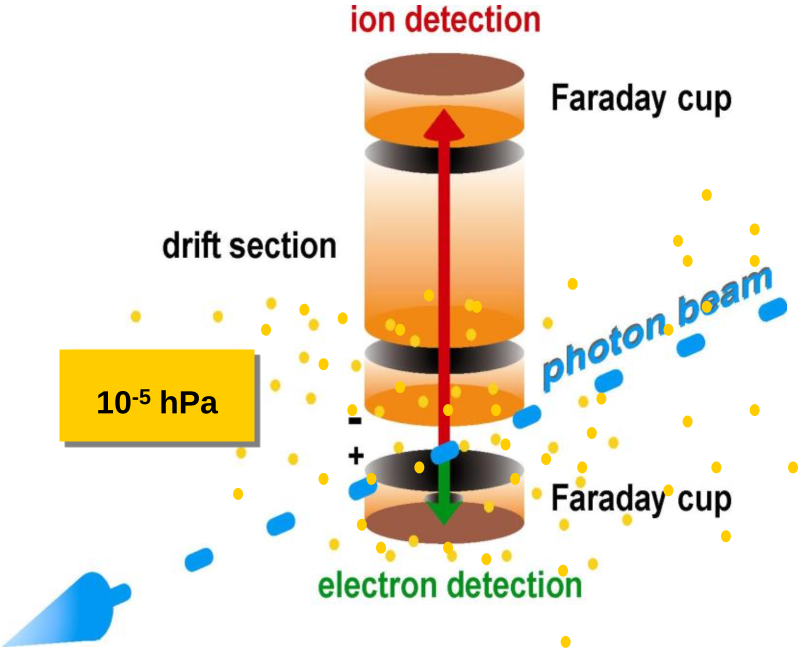
Detector Acceptance Length

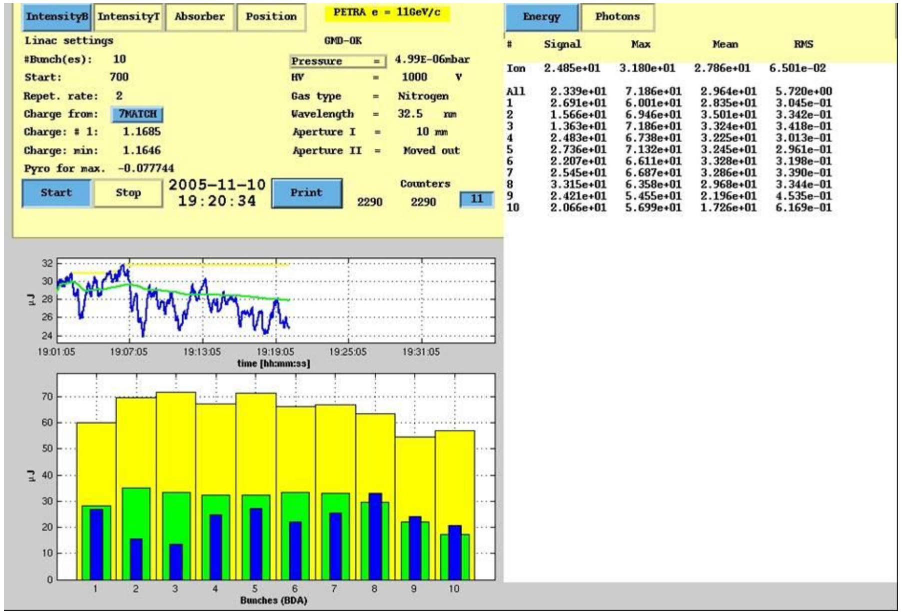
What Do You Need to Measure the Number of Photons?

- A calibrated detector: a Faraday cup, multiplier, or multi-channel plates to record the electrons or ions that impact it.
- A way to get the electrons or ions from the interaction region to the detector (often an electric field).
- An accurate gas gauge.
- An accurate temperature gauge
- Light.
- Gas or vapor (preferably with a decent cross section).
- Cross section and average photoionization charge data for a given photon energy

FLASH GMD

Already used to measure beam intensity at FLASH





PETRA e = 11GeV/c

Linac settings

#Bunch(es): 10
Start: 700
Repet. rate: 2
Charge from: 7MATCH
Charge: # 1: 1.1685
Charge: min: 1.1646
Pyro for max. -0.077744

GMD-OK

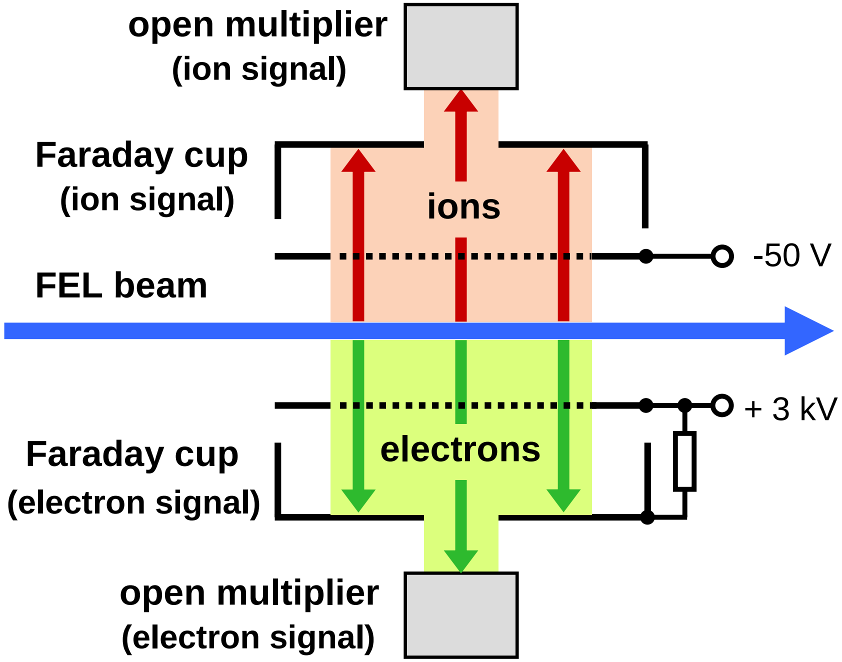
Pressure = 4.99E-06mbar
HV = 1000 V
Gas type = Nitrogen
Wavelength = 32.5 nm
Aperture I = 10 mm
Aperture II = Moved out

2005-11-10
19:20:34

Counters
2290 2290 11

#	Signal	Max	Mean	RMS
Ion	2.485e+01	3.180e+01	2.786e+01	6.501e-02
All	2.339e+01	7.186e+01	2.964e+01	5.720e+00
1	2.691e+01	6.001e+01	2.835e+01	3.045e-01
2	1.566e+01	6.946e+01	3.501e+01	3.342e-01
3	1.363e+01	7.186e+01	3.324e+01	3.418e-01
4	2.483e+01	6.738e+01	3.225e+01	3.013e-01
5	2.736e+01	7.132e+01	3.245e+01	2.961e-01
6	2.207e+01	6.611e+01	3.328e+01	3.198e-01
7	2.545e+01	6.687e+01	3.286e+01	3.390e-01
8	3.315e+01	6.358e+01	2.968e+01	3.344e-01
9	2.421e+01	5.455e+01	2.196e+01	4.535e-01
10	2.066e+01	5.699e+01	1.726e+01	6.169e-01

The X-ray Gas Monitor Detector (XGMD)



open multiplier
(ion signal)

Faraday cup
(ion signal)

ions

-50 V

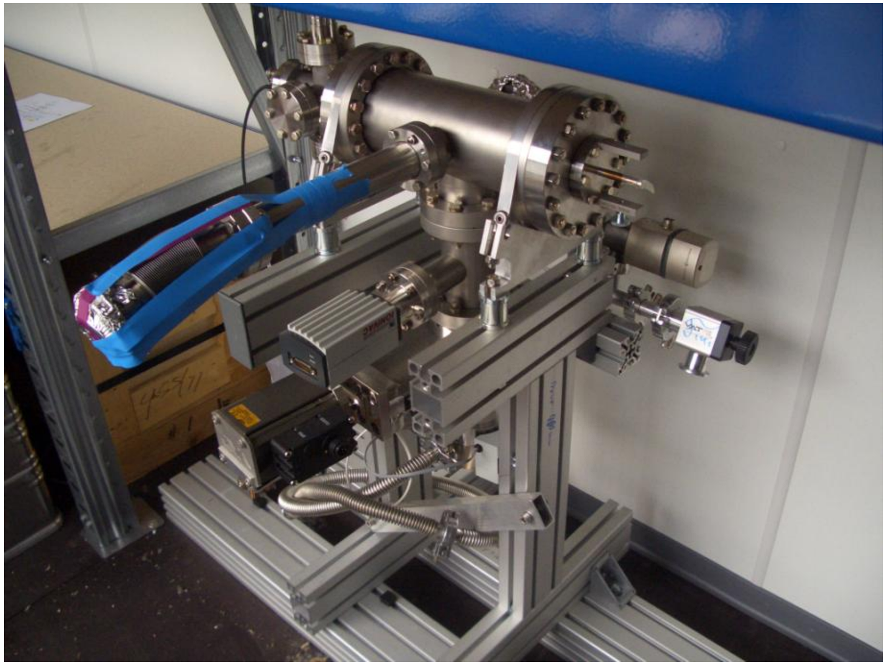
FEL beam

+ 3 kV

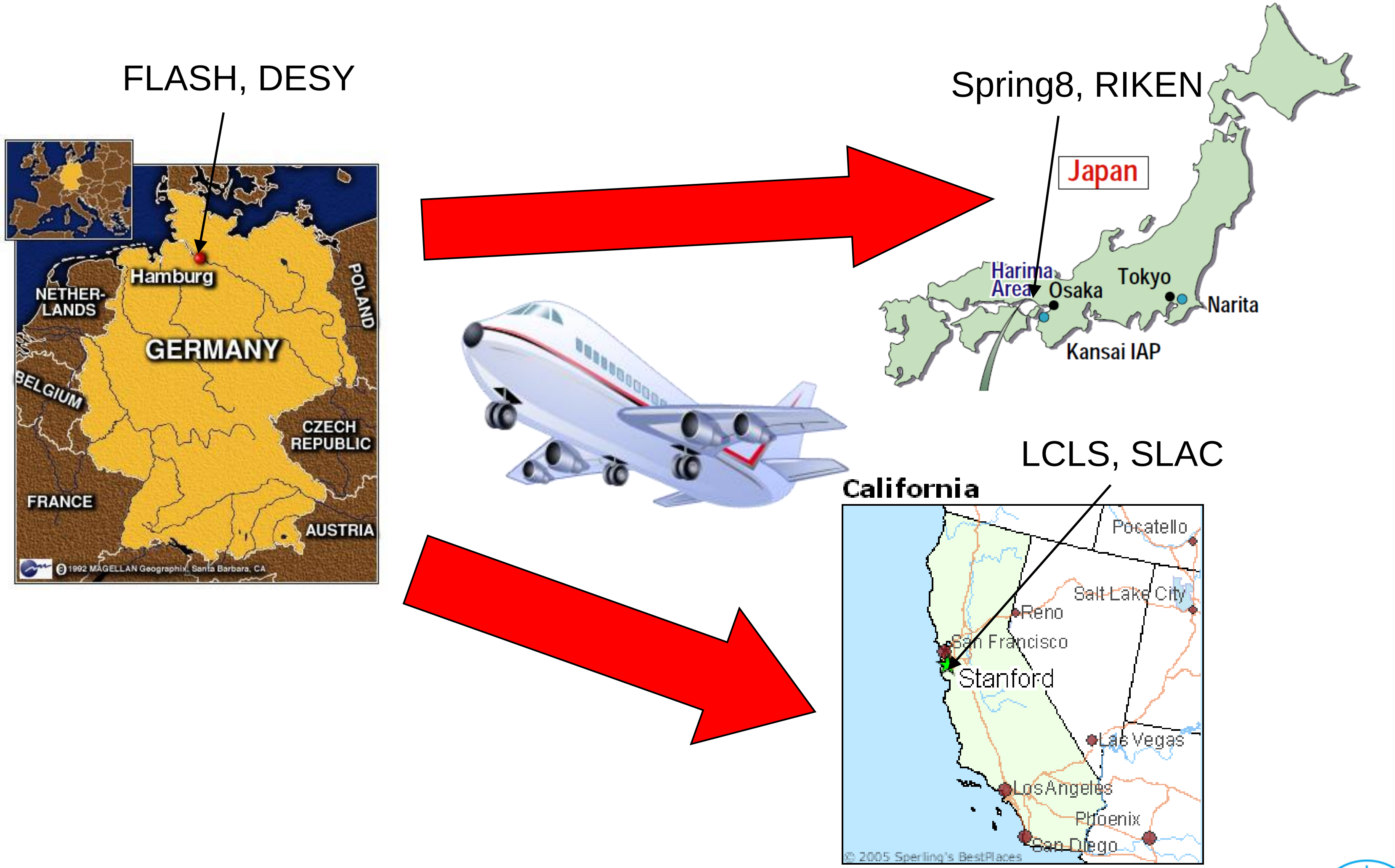
electrons

Faraday cup
(electron signal)

open multiplier
(electron signal)



The XGMD World Tour 2009

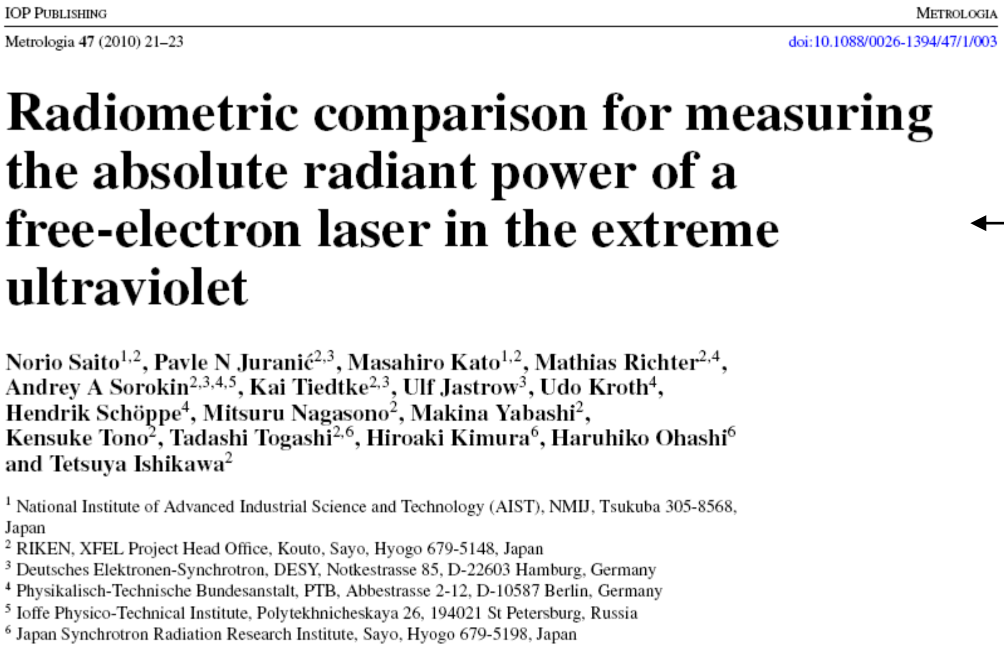


FLASH, DESY

Spring8, RIKEN

LCLS, SLAC

World Tour Results



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

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

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Spring8

LCLS

Report on
Pulse energy monitoring of X-ray FEL beam by gas-monitor detector
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Stefan Hau-Riege, LLNL