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Development of high-repetition rate XUV lasers for storage-ring experiments

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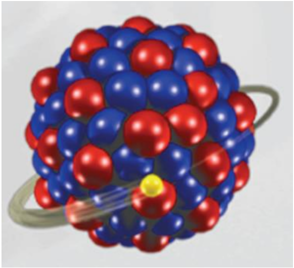
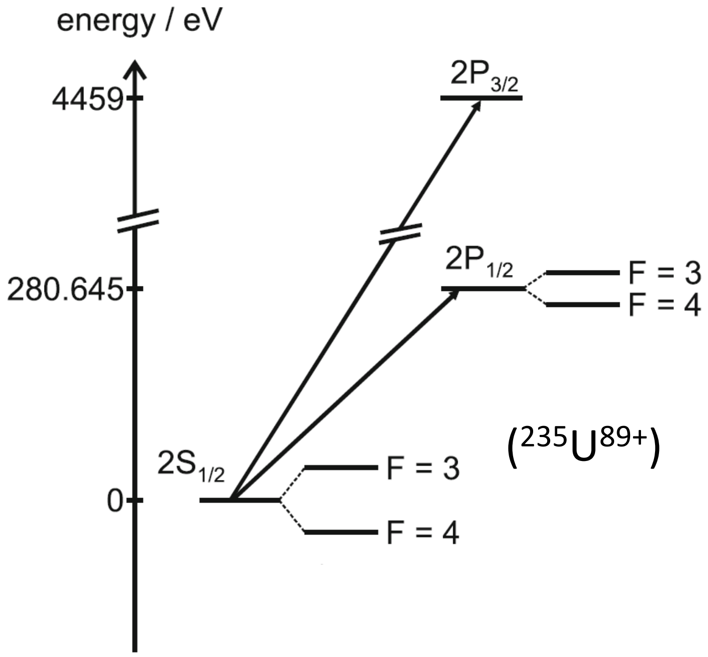
Motivation

highly charged ions:

- simple atomic systems (few electrons)
- strong electric and magnetic fields
- spectroscopy: access to QED, relativistic effects and nuclear properties



Li-like U^{89+} (Z=92)

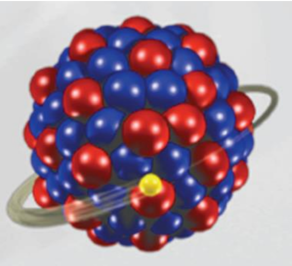


VIS and IR lasers: few eV photon energy

W. Nörtershäuser, "Laser spectroscopy for QED tests in highly charged ions," Hyperfine Interactions 199, 131–140 (2011).

Motivation

highly charged ions:



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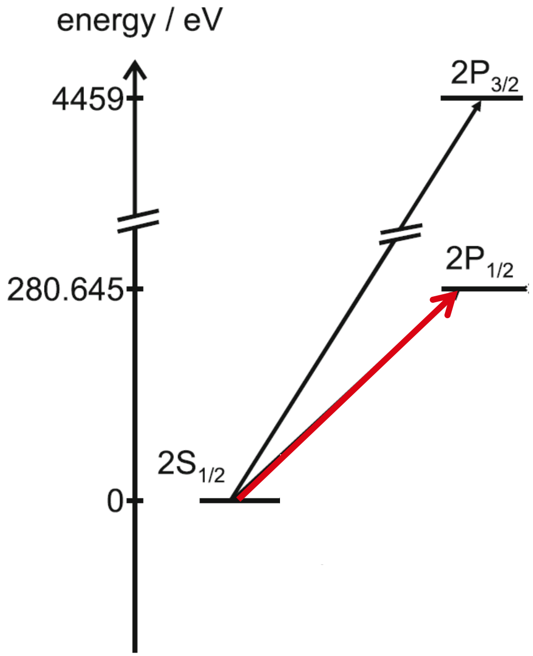
Li-like U^{89+} (Z=92)

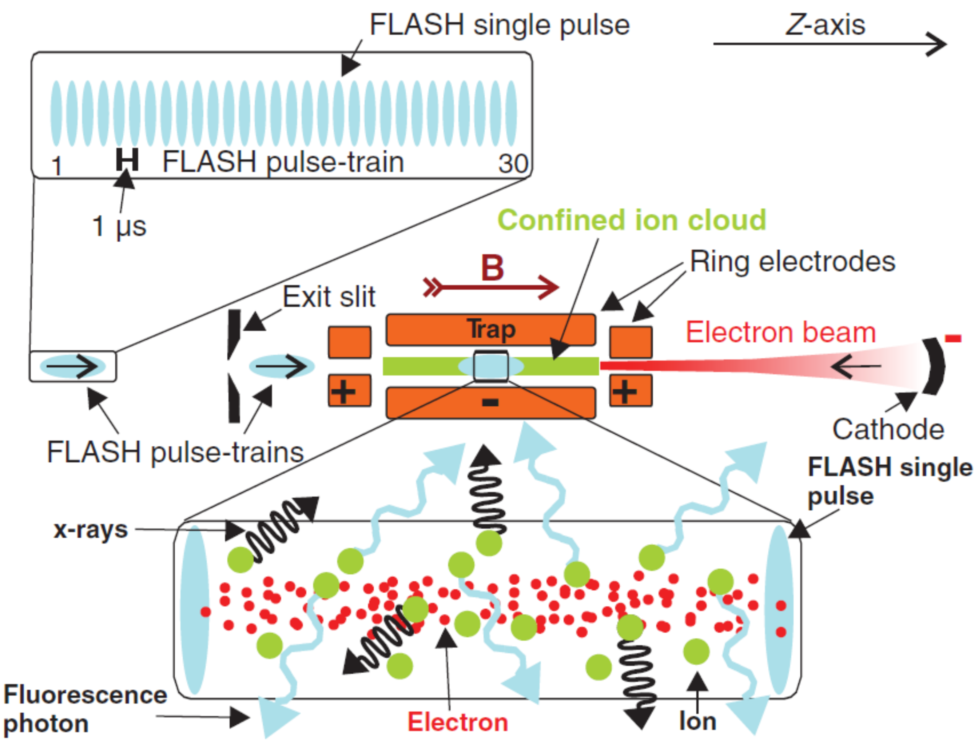


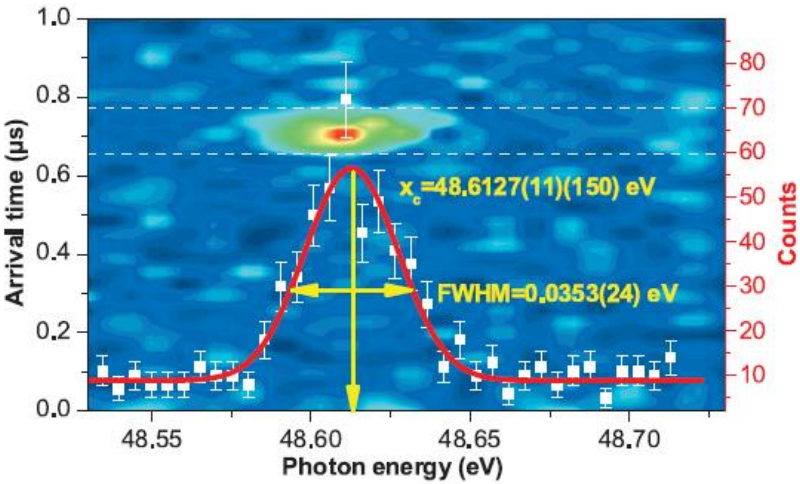
laser-like XUV (X-ray) sources required!

Extend the possibilities of laser excitation and spectroscopy to so-far not acessible transitions!

Laser spectroscopy of li-like Fe (EBIT+FLASH)

S. Epp et al., "Soft X-Ray Laser Spectroscopy on Trapped Highly Charged Ions at FLASH," PRL **98**, 183001 (2007).





- E/dE=2000
- ~10^{12} phot/s

-> stat. precision <10^{-5}

Where can we go with FAIR?

S. Epp et al., PRL 98, 183001 (2007).

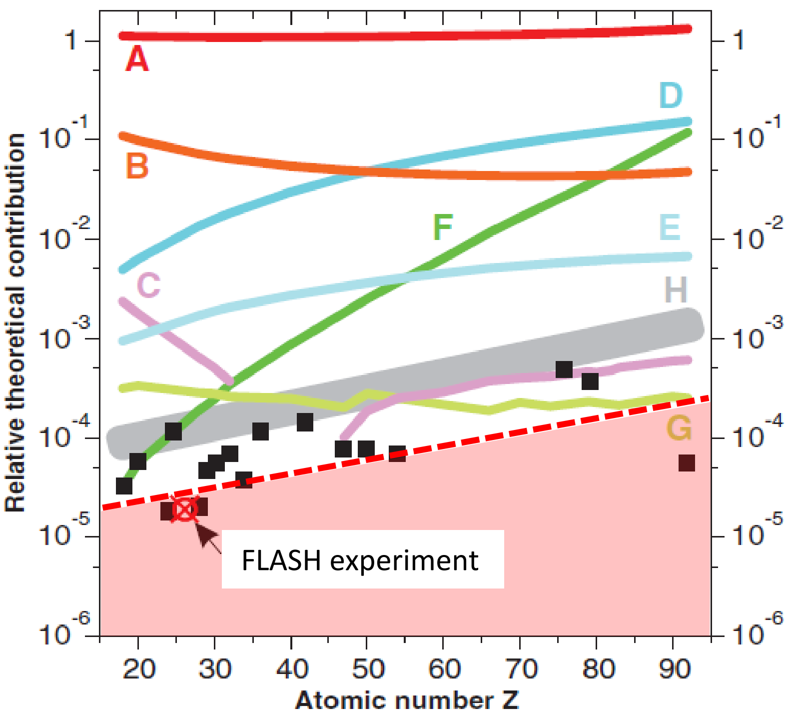
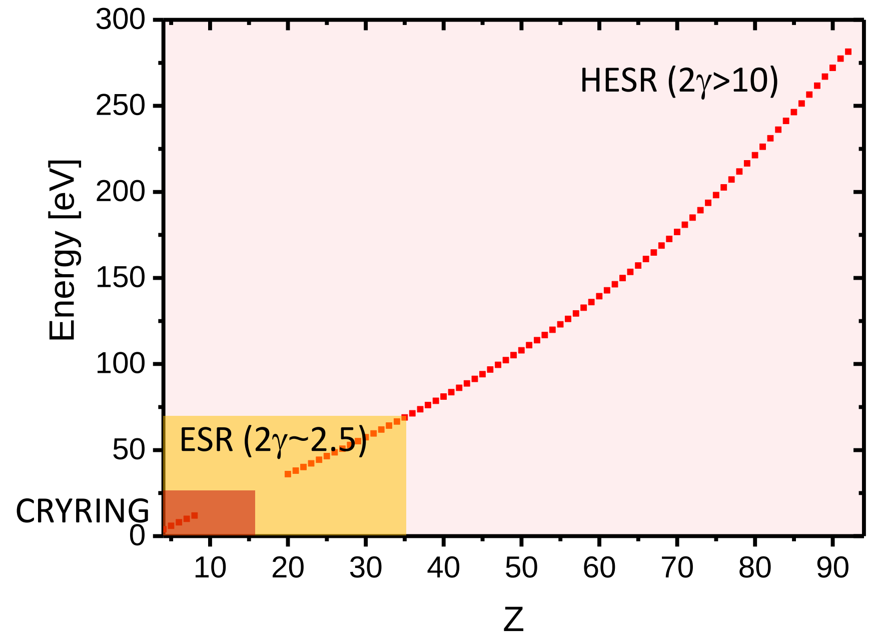


FIG. 4 (color). Different relative contributions (left scale) to the total $1s^2 2s - 1s^2 2p_{1/2}$ transition energy in Li-like HCI as a function of Z [18–20]. Interelectronic: (A) one, (B) two, and (C) three virtual photon exchange between the valence and core electrons. Radiative corrections: (D) one-loop self energy + vacuum polarization (H-like), (E) screening of (D) by core electrons. Nuclear corrections: (F) finite nuclear size, (G) relativistic recoil. Total relative uncertainties (right scale): (H) theoretical; (black squares) experimental ([15], [17,18], [23–26] and references therein), and (red cross) this work.

$2s_{1/2}$-$2p_{1/2}$ transition energy for li-like ions



- HESR: access the $2s_{1/2}$-$2p_{1/2}$ transition up to li-like uranium !
- follow isoelectronic and isotopic sequences

-> disentangle QED contributions and nuclear corrections

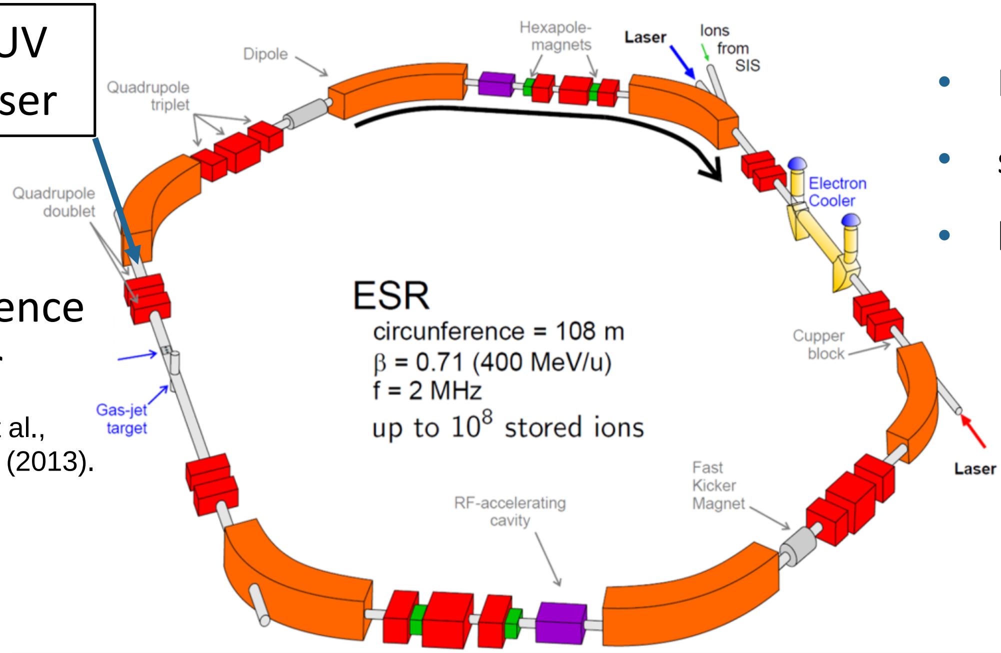
Potential experiment

In collaboration with W. Nörtershäuser, D. Winters, Th. Kühl , R. Sanchez, T. Stöhlker, V. Hannen, C. Spielmann

XUV Laser

fluorescence detector

V. Hannen et al., J. Instrum. **8**, (2013).



- Li-like ions Z>30
- significant Doppler up-shift
- high rep. rate XUV laser

Count rates: ~1000 s^{-1}

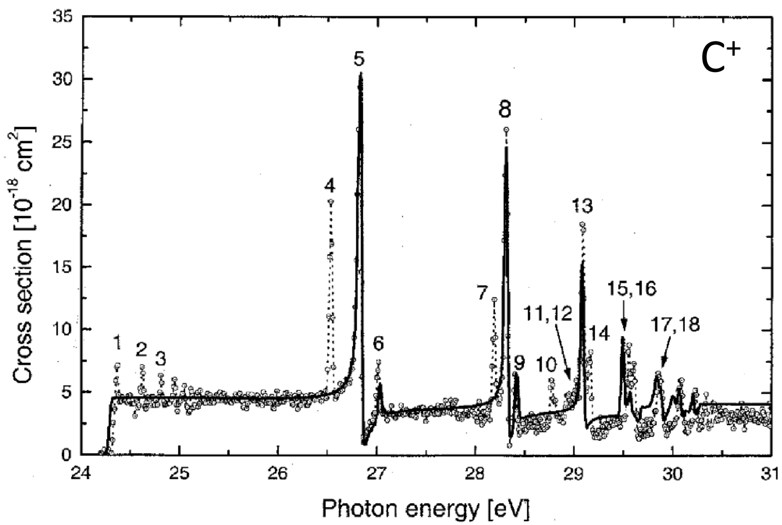
Requirements on the source: >10^{12} phot/s & $\Delta E/E$~10^{-4}

J. Rothhardt et al., Phys. Scr. T166, 14030 (2015).

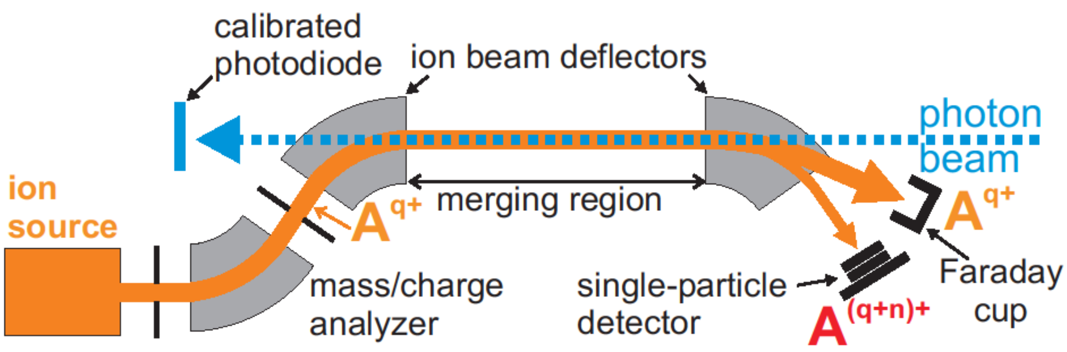
Experiment at CRYRING

Photoionization of ions:

In collaboration with S. Schippers



H. Kjeldsen et al. Astrophys. J. 524, L143 (1999).



- storage ring + XUV laser source: pure (ground state) targets and exotic nuclei
- will be first implemented at CRYRING
- future: much higher excitation energies at ESR and HESR

Requirements on the source: >10^{12} phot/s & $\Delta E/E \sim 10^{-4}$

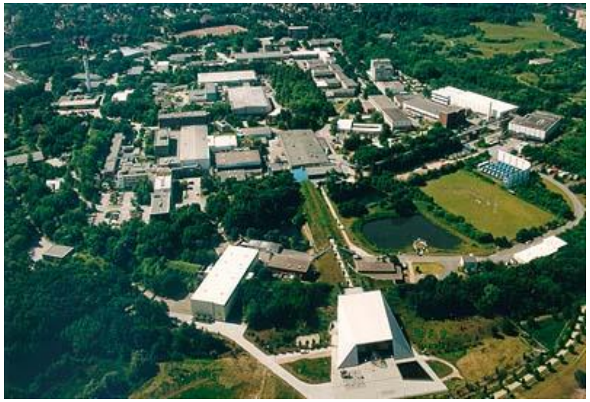
Potential sources

Requirements on the source: >10^{12} phot/s & $\Delta E/E \sim 10^{-4}$

Synchrotrons

BESSY / Helmholtz Zentrum
Berlin

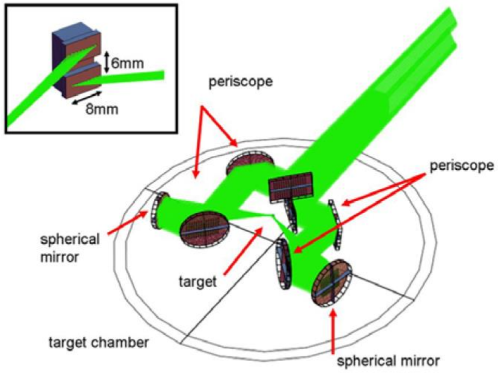
Free electron lasers



FLASH / DESY
Hamburg

X-ray lasers

PHELIX



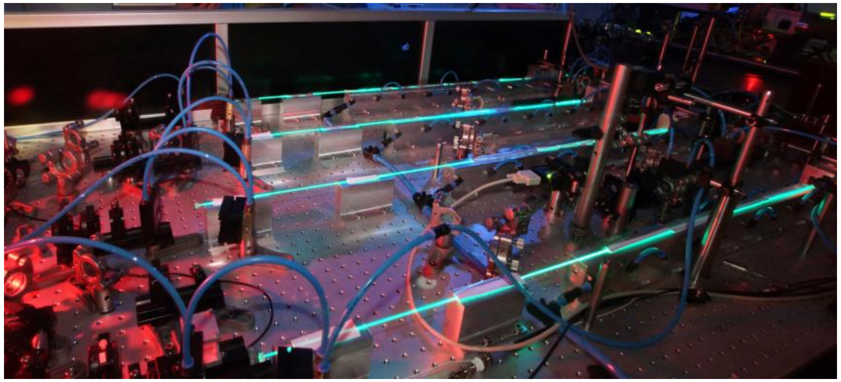
GSI Darmstadt

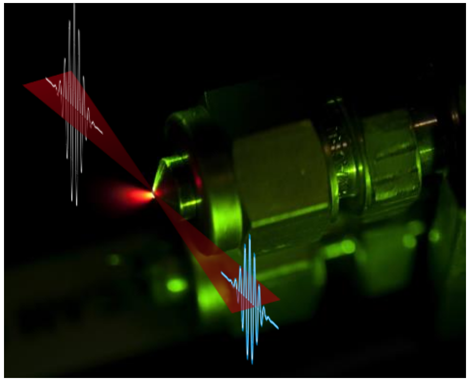
High average power HHG sources

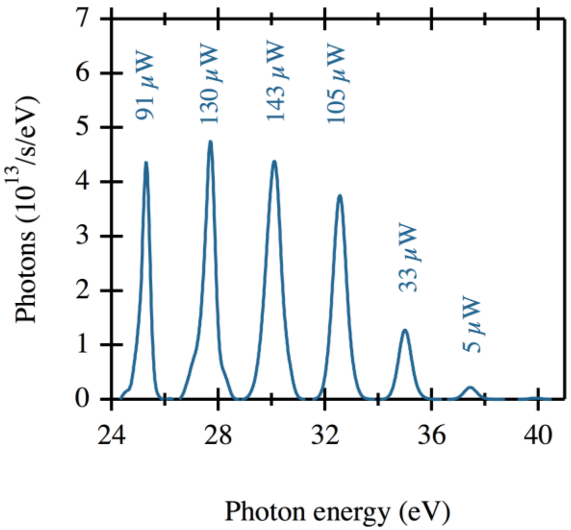
Fiber lasers

- High average power (up to 1 kW)
- High repetition rate (up to 1 MHz)

+ HHG = **table top source, high photon flux & high repetition rate**





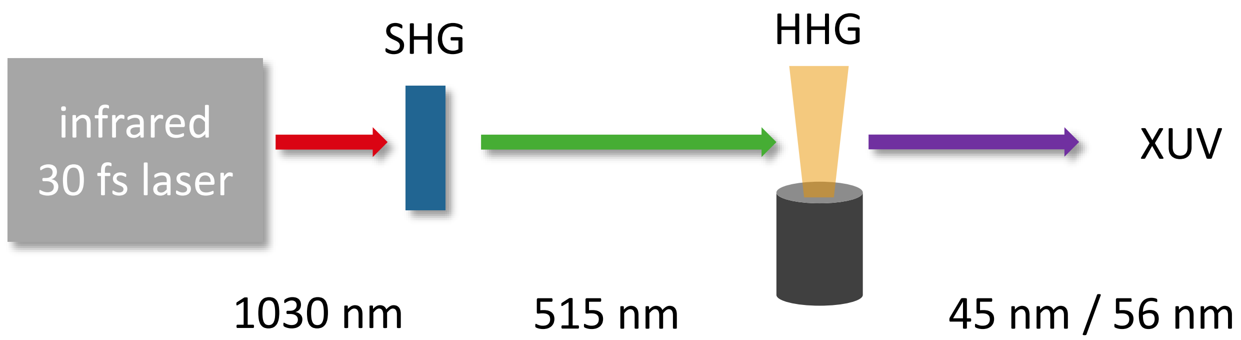


Current record:

- 143 µW average power @ 30 eV
- $dE/E=2x10^{-2}$

S. Hädrich et al., Nat. Photonics (2014).

Cascaded frequency conversion



- higher conversion efficiency
- smaller spectral bandwidth

Wang et al., Nature Communications 6, 7459 (2015)

Cascaded frequency conversion

Results: HHG in Krypton

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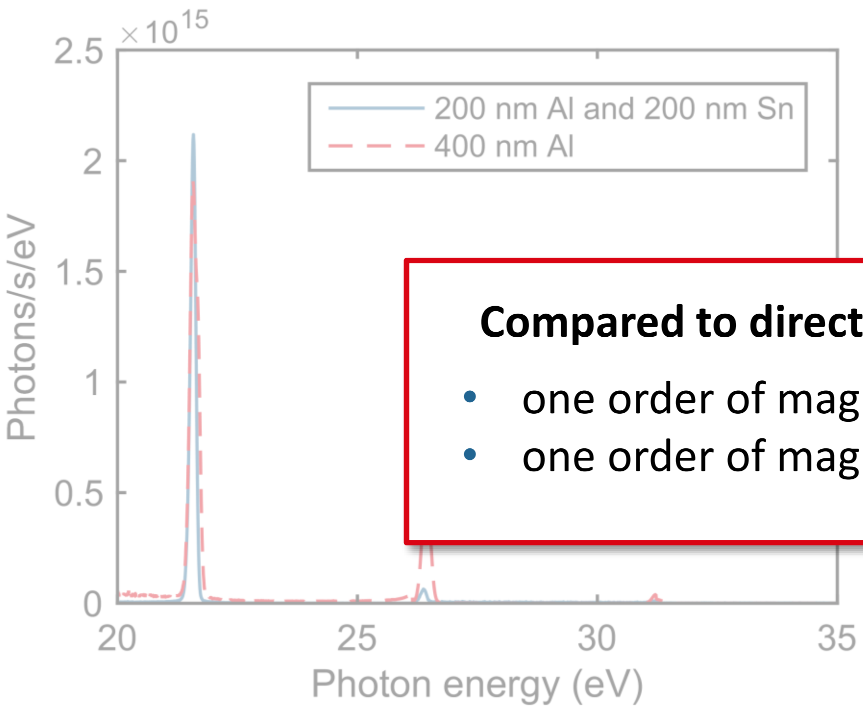

Calculation of generated photon flux:

- (1500 ± 600) µW @ 21.7 eV
- $4.4 \cdot 10^{14}$ Photons per second

Compared to direct HHG:

- one order of magnitude higher flux
- one order of magnitude lower bandwidth

t with

- (832 ± 204) µW @ 21.7 eV
- $2.5 \cdot 10^{14}$ Photons per second

Energy contained in small bandwidth:

$\Delta E/E \sim 9.8 \cdot 10^{-3}$

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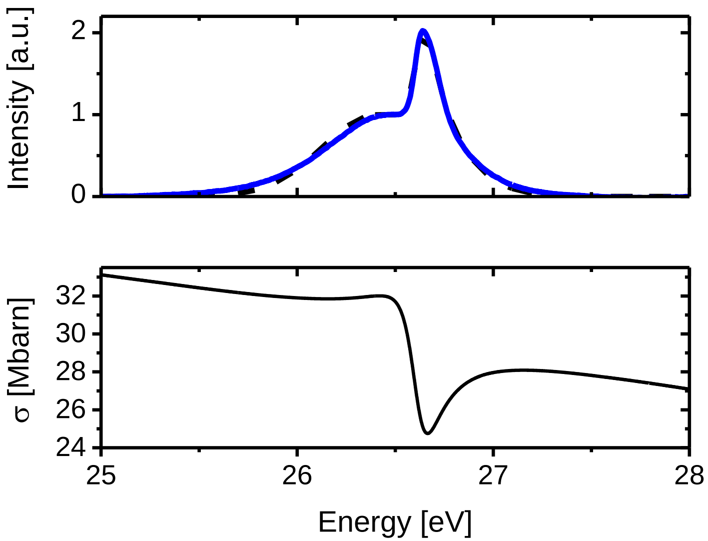
Cascaded frequency conversion

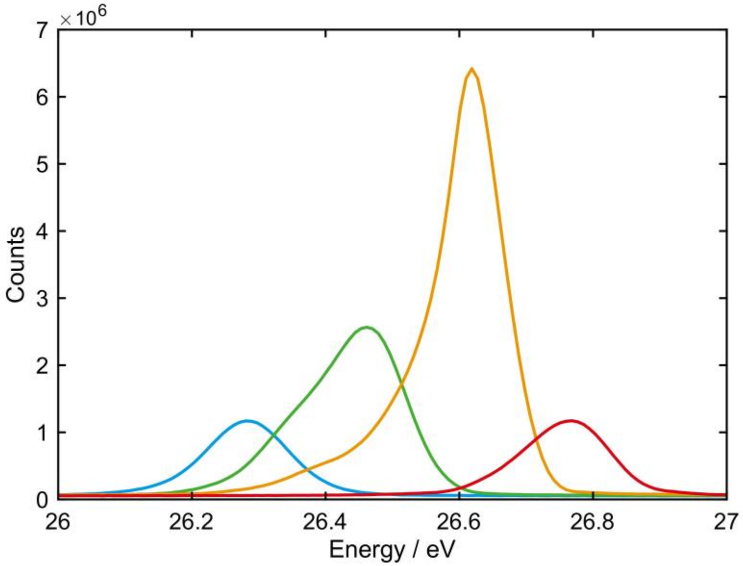
Narrowband harmonic lines?

Fano-resonances in the absorption spectrum of Argon



➡ enhanced macroscopic HHG yield in a narrow spectral region [1]

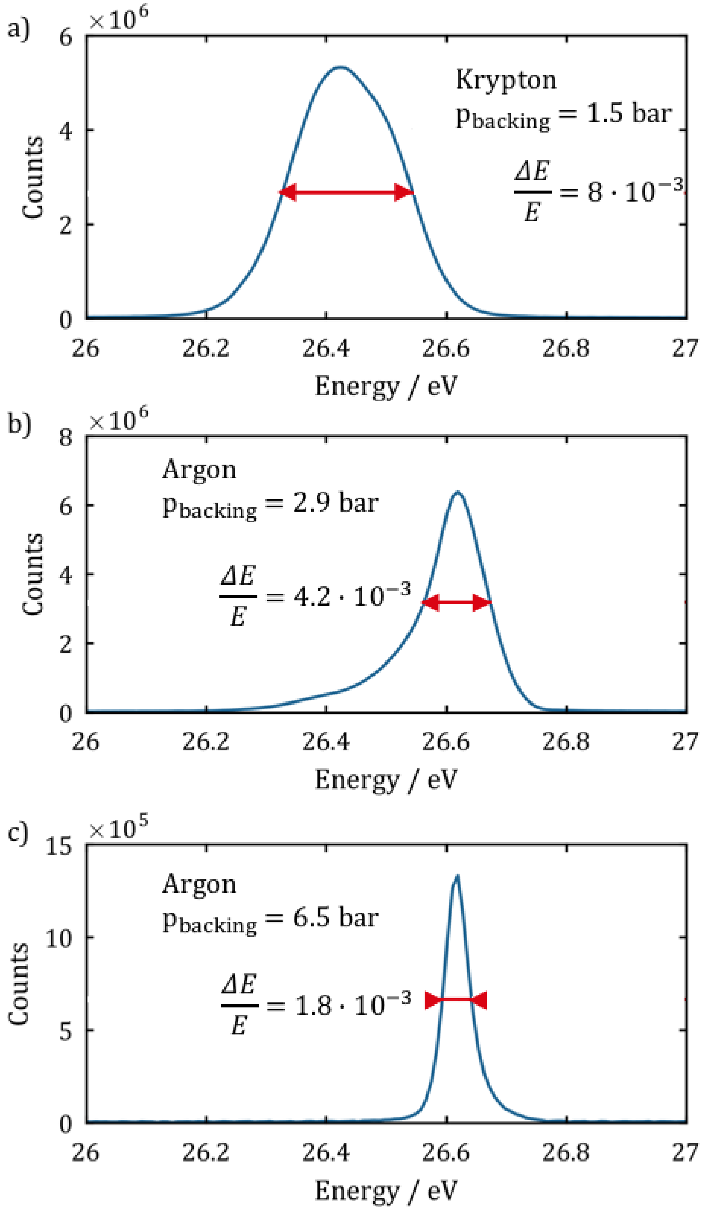
SHG phase matching allows for tuning onto the resonance



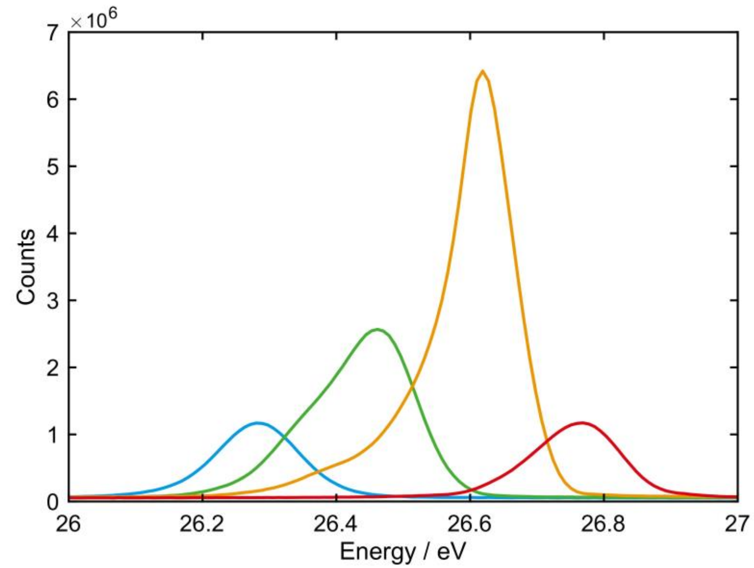
[1] J. Rothhardt et al. Phys. Rev. Lett. 112, 233002 (2014).

Cascaded frequency conversion

Narrowband harmonic lines?



SHG phase matching allows for tuning onto the resonance



relative energy bandwidth:

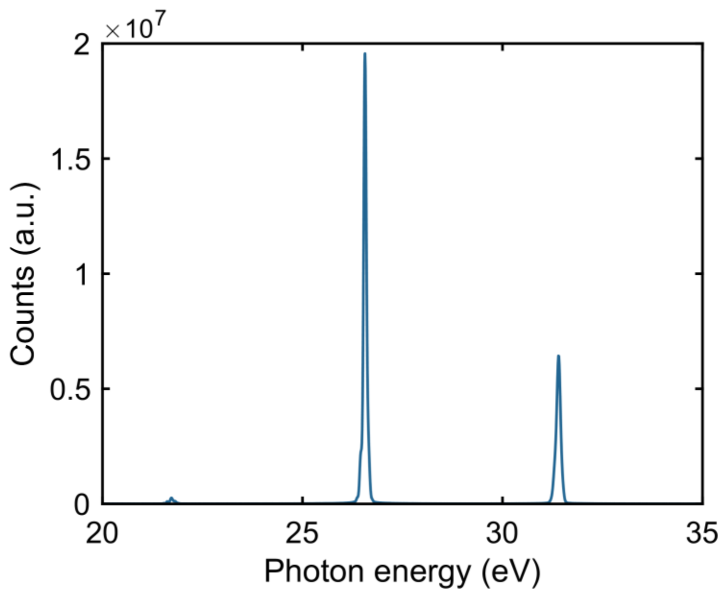
$\Delta E/E < 2 \cdot 10^{-3}$ (resolution limit)

R. Klas et al., Optica, accepted.

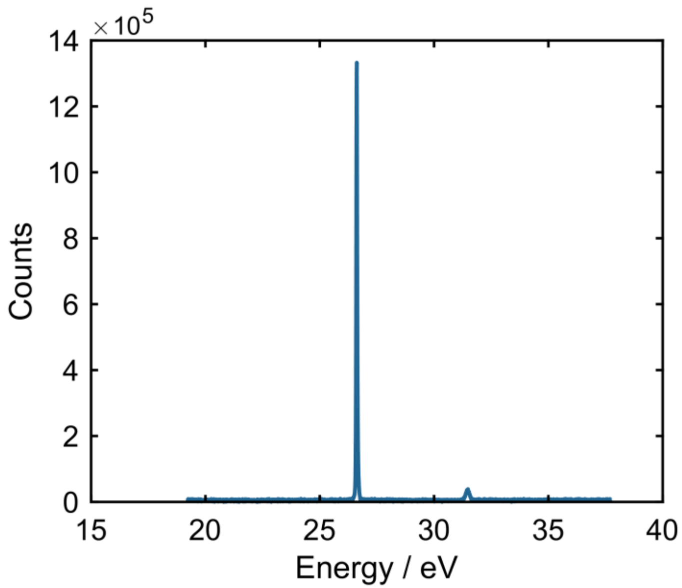
Cascaded frequency conversion

spectral filter

backing pressure: 2.9 bar



backing pressure: 6.5 bar

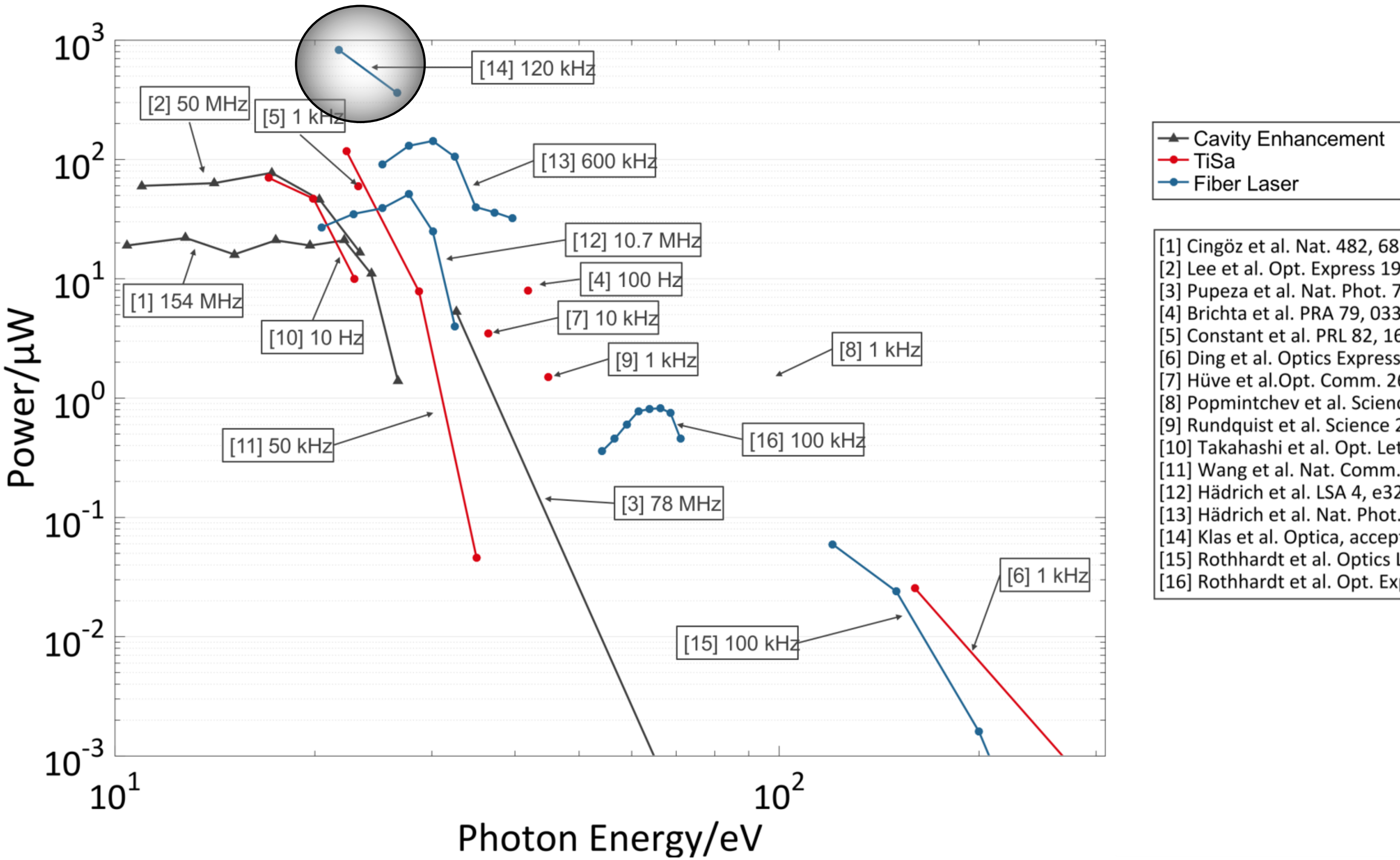


- adjacent 7th and 13th harmonic are suppressed by an order of magnitude
- built in spectral filter for 26.6 eV

Next steps: - new high resolution XUV spectrometer arrived
- longer pulses further reduce bandwidth towards 10^{-4}

R. Klas et al., Optica, accepted.

Overview on high power HHG sources



[1] Cingöz et al. Nat. 482, 68 (2012)
[2] Lee et al. Opt. Express 19, 23315 (2011)
[3] Pupeza et al. Nat. Phot. 7, 608 (2013)
[4] Brichta et al. PRA 79, 033404 (2009)
[5] Constant et al. PRL 82, 1668 (1999)
[6] Ding et al. Optics Express 22, 6194 (2014)
[7] Hüve et al.Opt. Comm. 266, 261 (2006)
[8] Popmintchev et al. Science 320, 1225 (2015)
[9] Rundquist et al. Science 280, 1412 (1998)
[10] Takahashi et al. Opt. Lett 27, 1920 (2002)
[11] Wang et al. Nat. Comm. 6, 7459 (2015)
[12] Hädrich et al. LSA 4, e320 (2015)
[13] Hädrich et al. Nat. Phot. 7, 608 (2014)
[14] Klas et al. Optica, accepted
[15] Rothhardt et al. Optics Letters 39, 17 (2014)
[16] Rothhardt et al. Opt. Express 24, 18133 (2016)

Specifications of the XUV source

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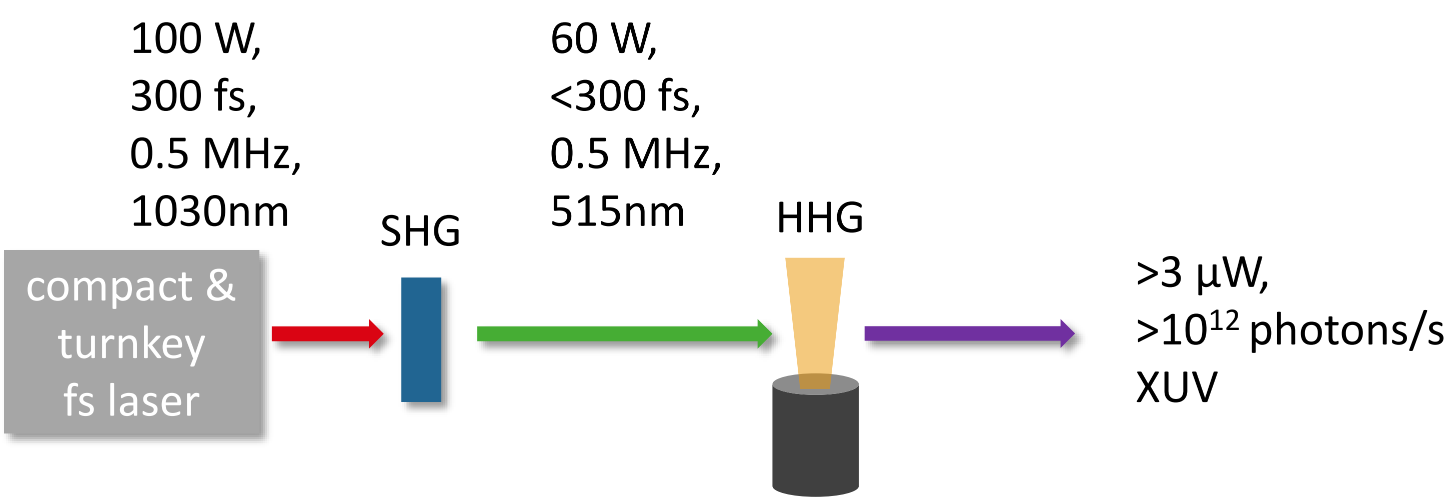
- Photon energy: 21.7 eV or 26.5 eV
- Relative energy bandwidth: $<10^{-3}$
- Average power ***on target***: > 3 µW, $>10^{12}$ photons/s
- Pulse repetition rate: 0.5 MHz (later: synchronized to ion bunches)
- Beam diameter (collimated): 3 mm
- Pointing stability: <0.2 mrad

Concept:



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Driving laser system

- compact 100W/200µJ turnkey femtosecond laser
- all parameters software controlled
- alignment-free operation
- single-mode output beam
- dust-sealed, temperature-stabilized housing
- average-power stability: <0.2% RMS

activefiber
systems

Funded via BMBF Verbundforschung

Delivery time: December 2016

Bring the Photons to the Ring

Experimental Setup

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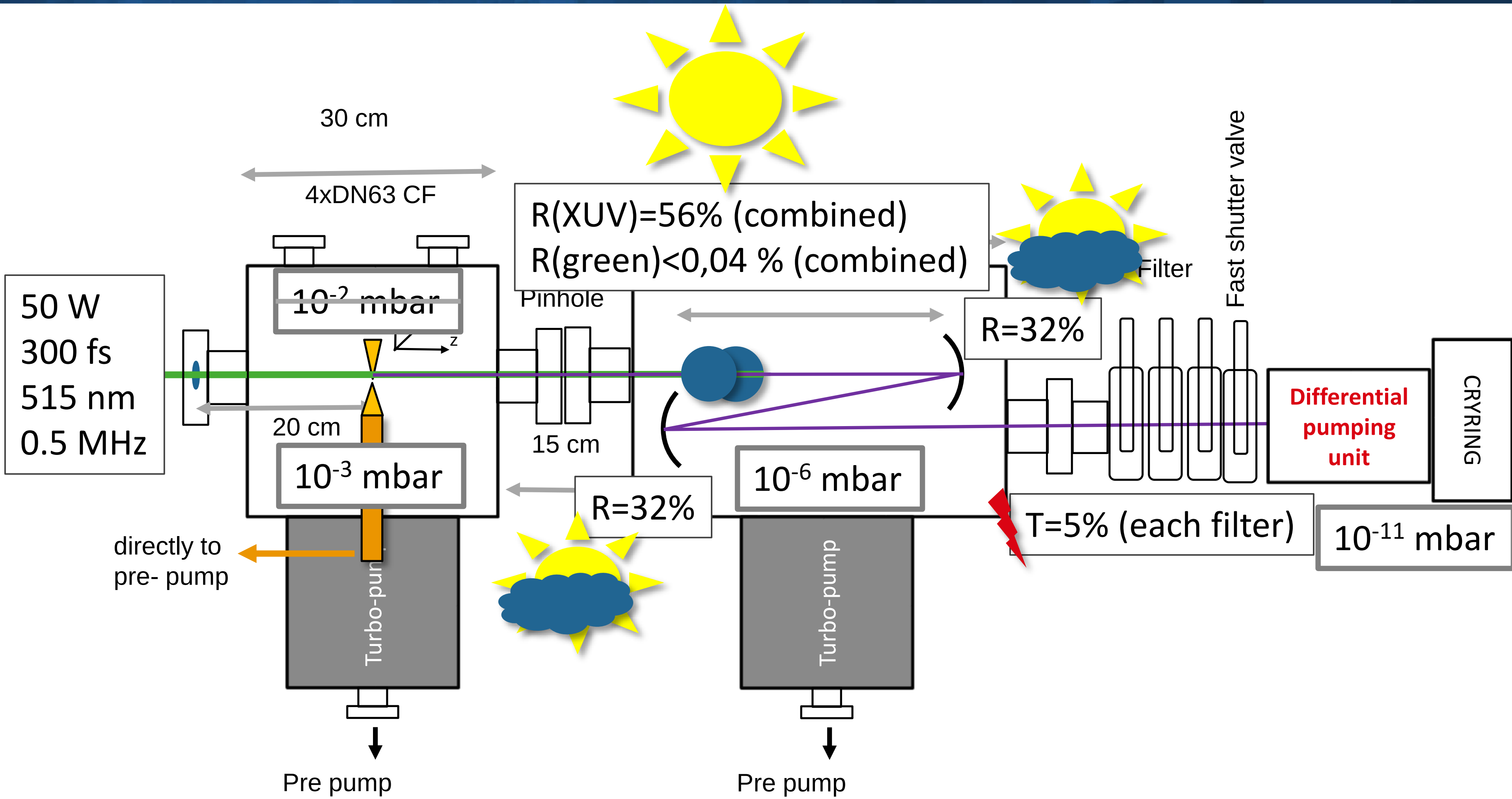

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Bring the Photons to the Ring

Filters

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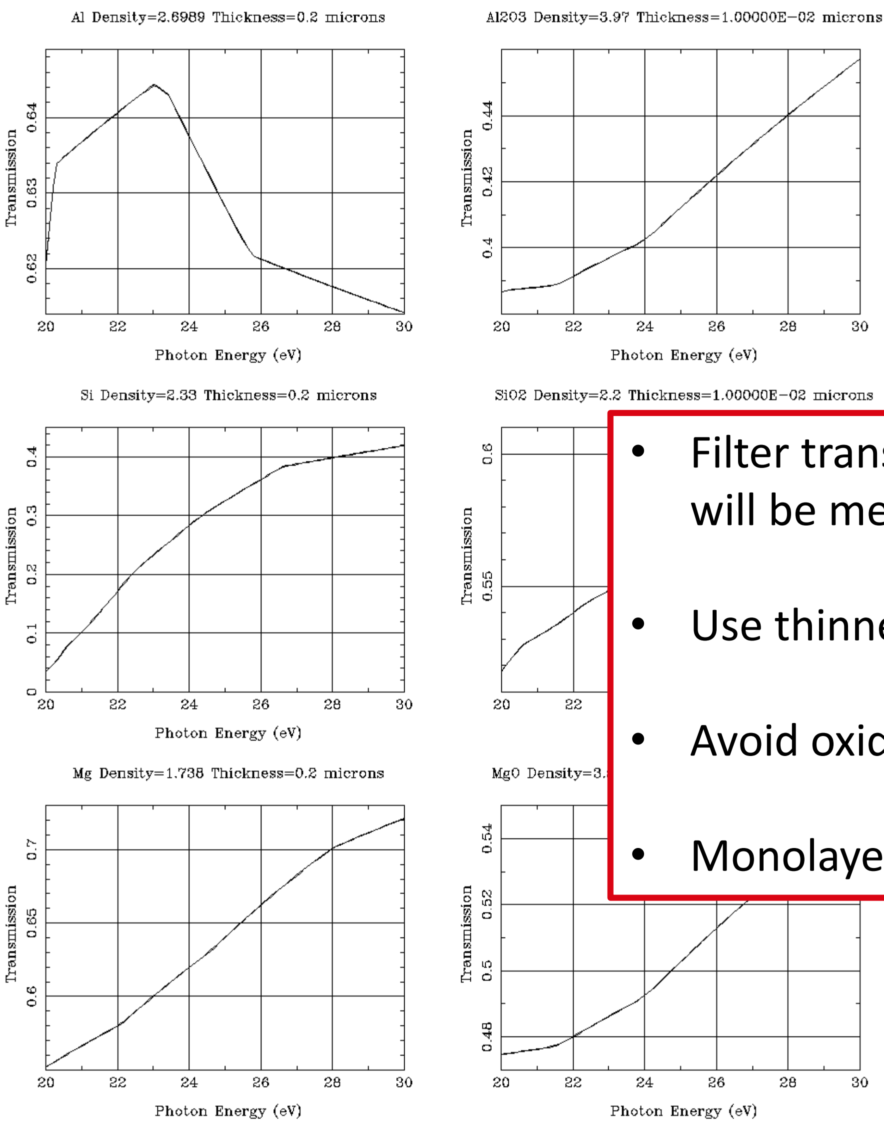
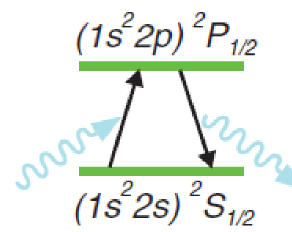


Element	Overall Transmission @26.6 eV
200 nm Al + 10 nm Al_2O_3	26% Experiment: 5%
	21%
200 nm Mg + 10 nm MgO	33%

- Filter transmission of other filters will be measured
- Use thinner filters (100 nm)
- Avoid oxidization (N2 storage)
- Monolayer films (Graphene etc.)

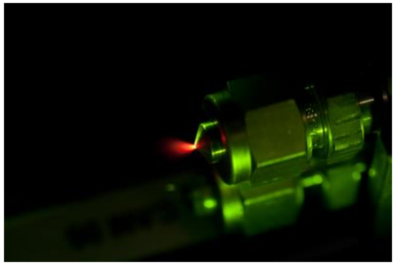
Summary

Concept for a XUV source for experiments @ FAIR



Combination of fiber laser & cascaded frequency conversion:

- mW-level average power per harmonic at 21 eV (>10^{14} Photons/s)
- Fano-resonance in Ar at 26.6 eV reduces bandwidth further to $1.8\cdot10^{-3}$



Turnkey, remote-controlled XUV Laser :

- high photon flux in the XUV, **>10^{12}** photons/s
- **MHz** repetition rate
- ΔE/E**<10^{-3}**
- ready for experiments mid/end of 2017

Outlook

Increasing the spectral resolution further

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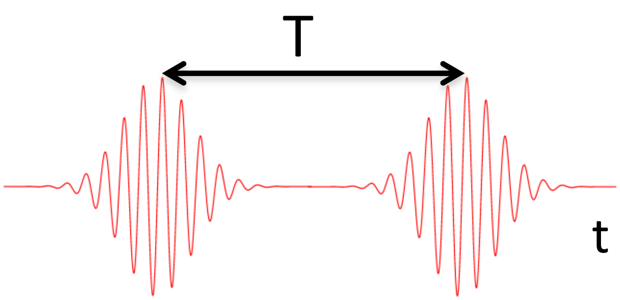
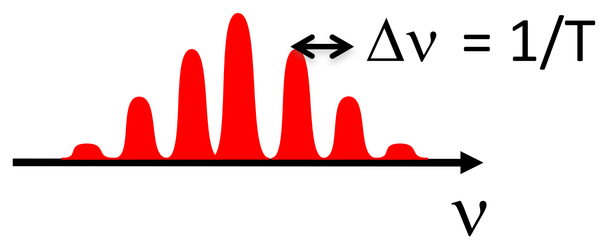
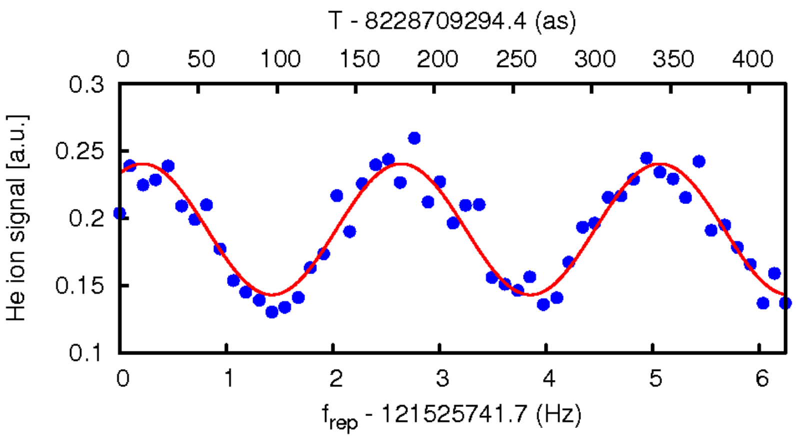
Ramsey-type spectroscopy

Time domain



Frequency domain





Ramsey comb excitation of helium at 51 nm already demonstrated

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D. Kandula et al. PRL **105**, 063001 (2010)
D. Kandula et al. PRA **84**, 062512 (2011)

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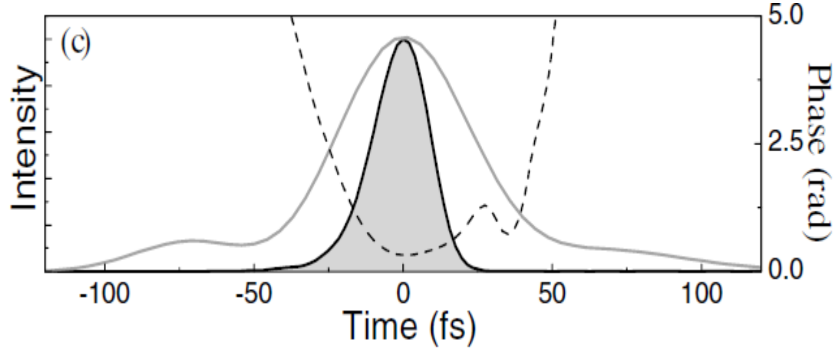
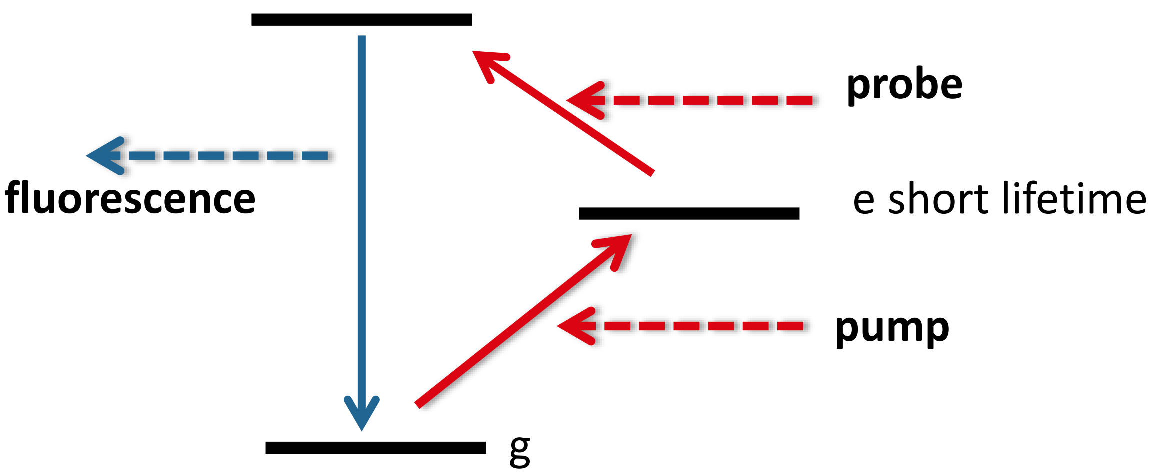
Pulse duration (envelope) of XUV is shorter than driving pulse!



Y. Mairesse et al. PRL **94**, 1–4 (2005).

Acess to lifetimes & dynamics on ps to as time scales



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