Development of pulsed XUV and X-ray sources for spectroscopy of highly charged ions

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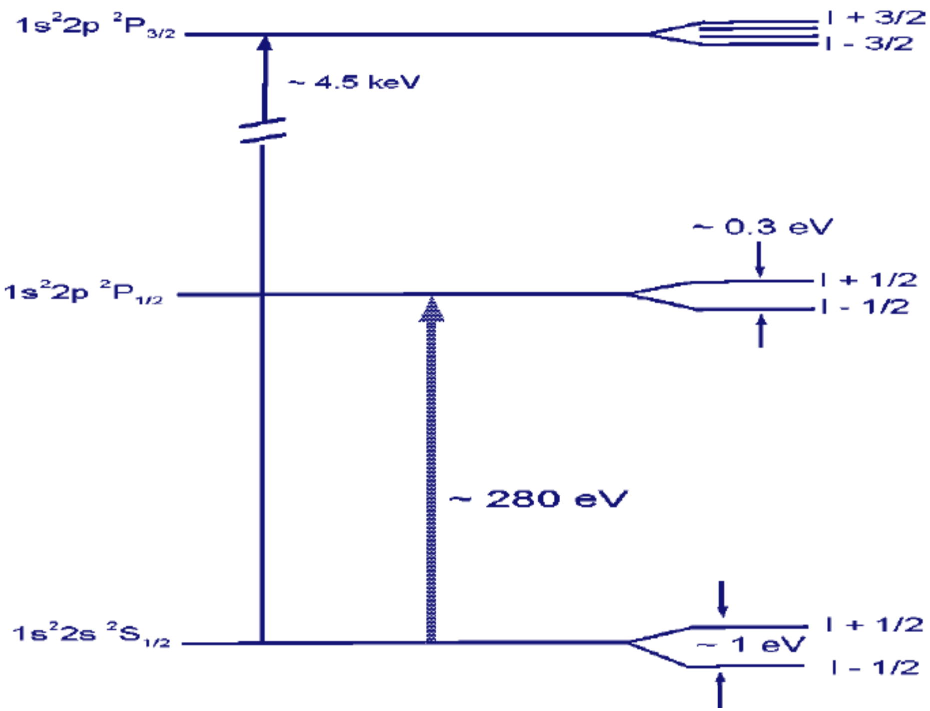
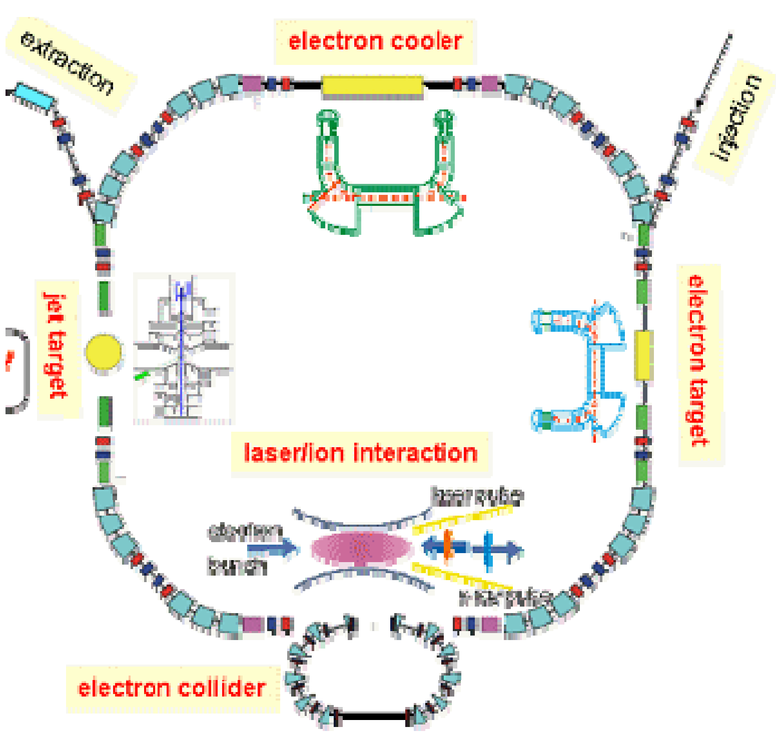
Spectroscopy of highly charged ions



Level scheme of Li-like U



Head on geometry

→ fixed XUV photon energy (approx. 100eV) tuning with ion energy

→ XUV rel. bandwidth ($\Delta E/E$) < 10^{-4} (below Doppler broadening 10^{-4})

excitation cross section 10^{-13} cm^2

For an excitation probability of 1%: 10^{11} photons per pulse

Detection: fluorescence Doppler shifted (several times laser frequency)

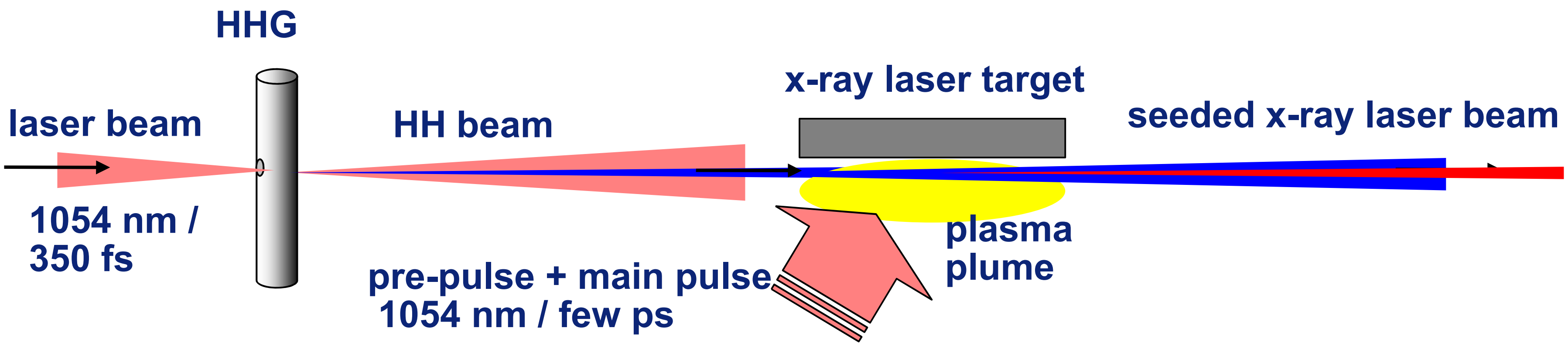
X-ray lasers

Already achieved:

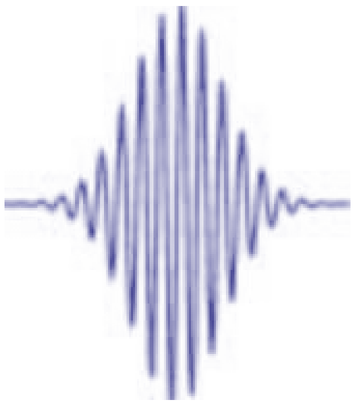
- At GSI, x-ray lasers have been realized in the wavelength range from 7 to 24 nm using the PHELIX laser with a pump energy from 30 to 0.1 J
- X-ray laser pulse energy: few µJ
- demonstrated rel. bandwidth $\Delta E/ E < 10^{-4}$

Challenge:

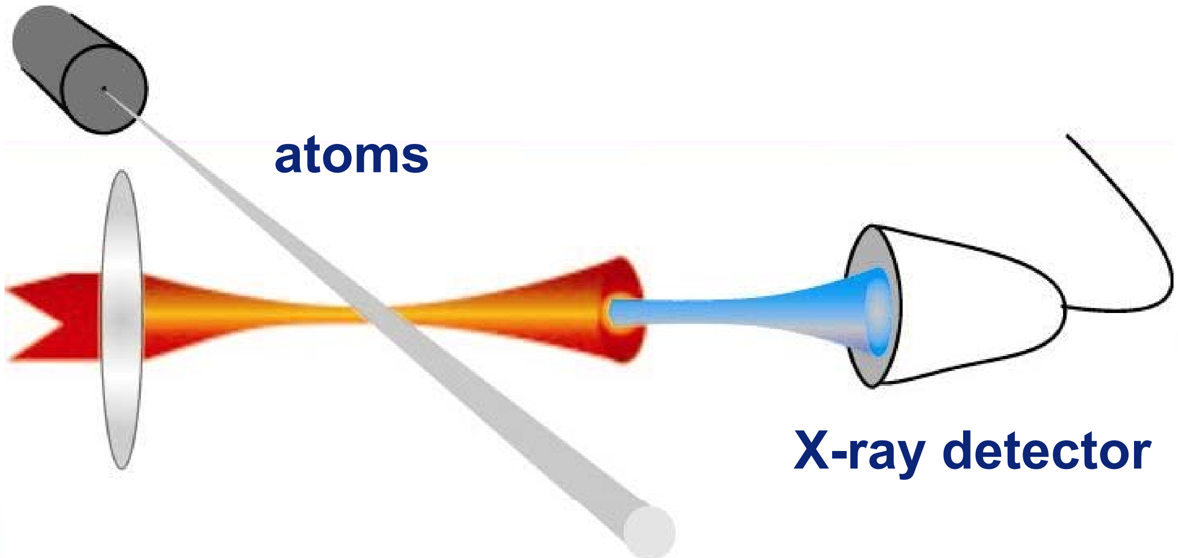
- X-ray laser are “mirror less laser” → parameters (energy, beam pointing, spectral position, ..) are very sensitive to pumping laser parameters
- Parameters of the x-ray laser beam must be improved by seeding with coherent soft x-rays generated via high harmonic generation (HHG)



High harmonic generation (HHG)



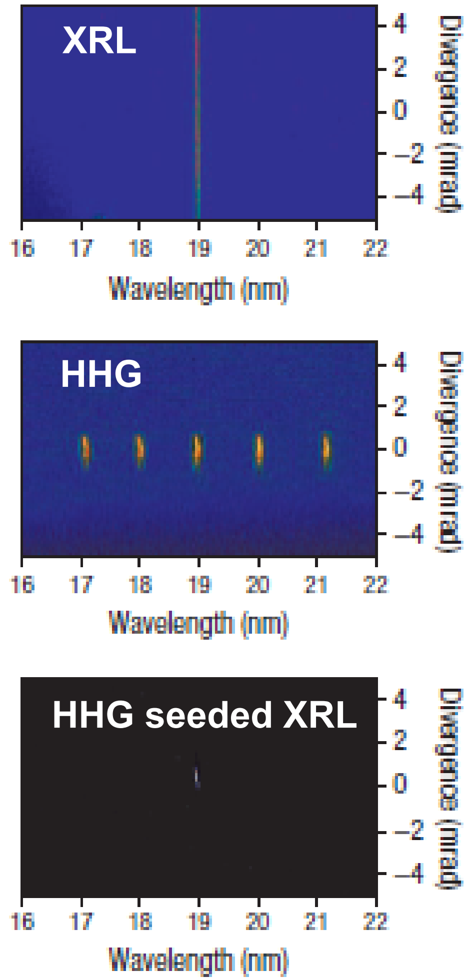
Femtosecond laser pulse



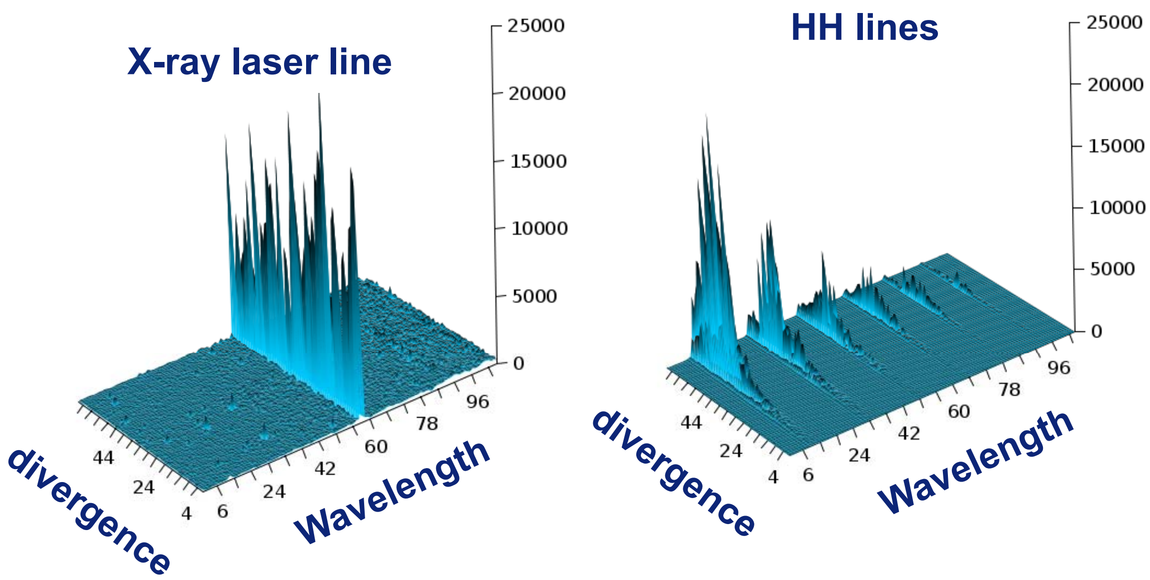
Laser radiation is up-converted into spatially and temporally coherent x-ray radiation at odd multiples of laser frequency (up to the keV range) conversion efficiency is rather low

Seeded x-ray laser

- better spatial properties:
  - smaller source size
  - less divergent
  - better spatial coherence
  - better beam pointing
- reduction of pulse duration (to the bandwidth limit)
- higher pulse-to-pulse stability is expected.

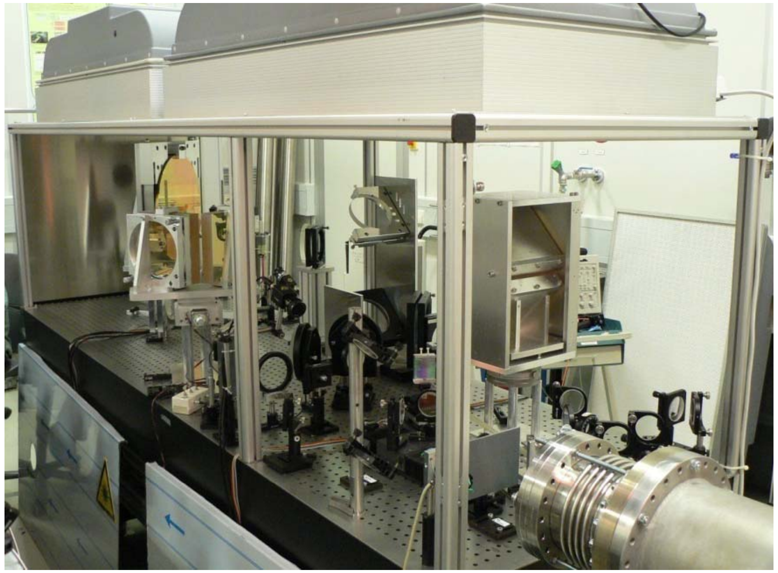


Wang et al. Nature Photonics 2008



Our measurement

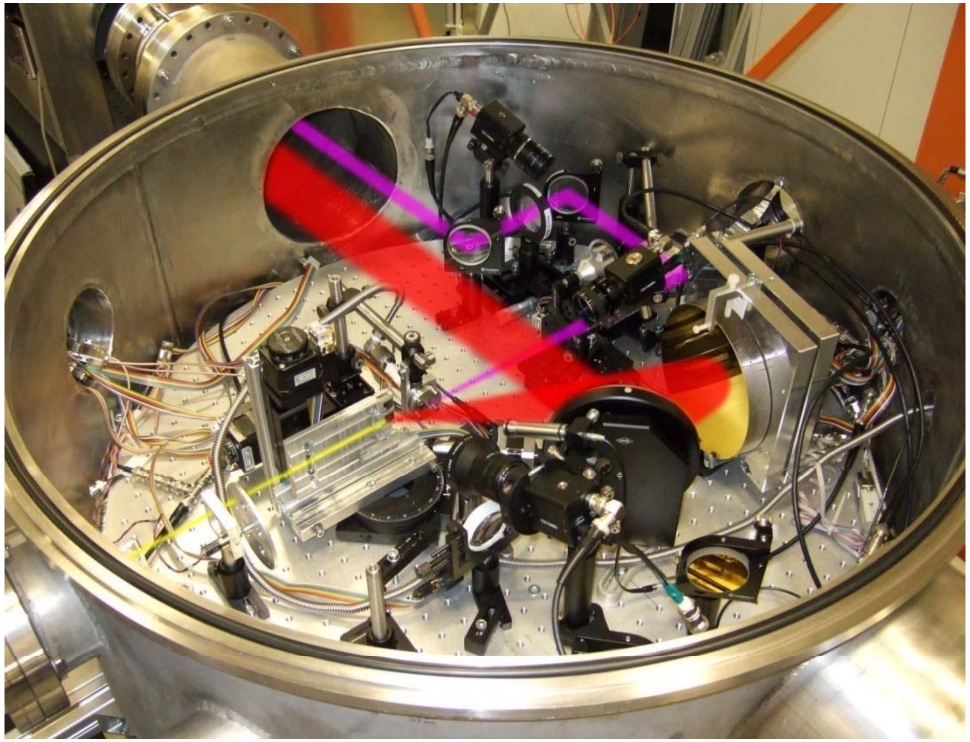
Details about the experimental setup @ GSI



fs front-end:
10 Hz / 350 fs / 10 mJ for HHG experiments

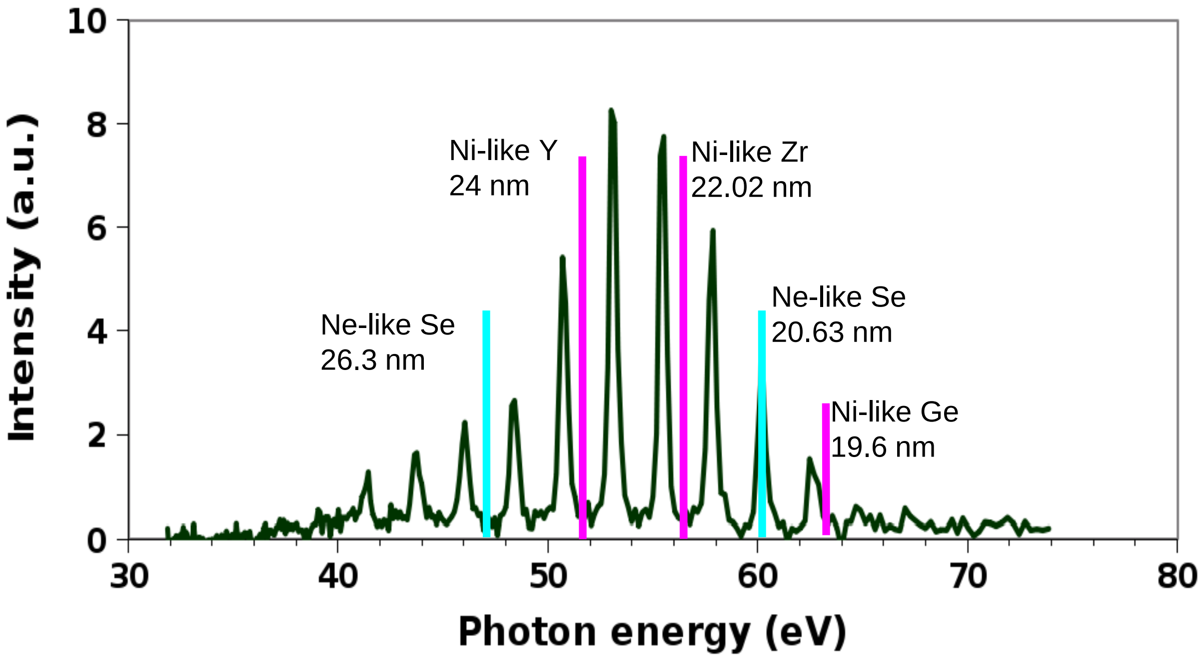
pre-amplifier:
10 min / few ps / 2 J for XRL experiments

X-ray lab:
- main grating compressor
  few ps / 1 J for XRL
- small grating compressor
  350 fs / 10 mJ



HHG
- HHG jet with pulsed valve
- IR and x-ray diagnostics

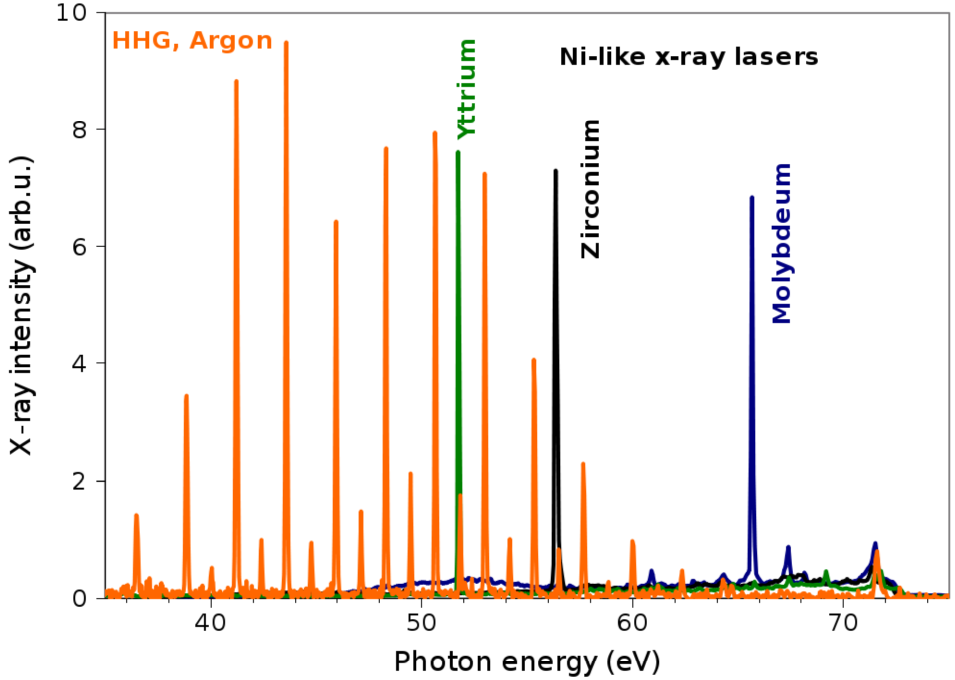
Amplification of HHG in a plasma x-ray laser



HH lines do not overlap with possible x-ray laser transtions

Generation and tuning of even and odd harmonics

Using two-color laser beam (second harmonic + fundamental), narrow-band even harmonics are generated reaching the x-ray laser lines of Ni-like Y and Zr

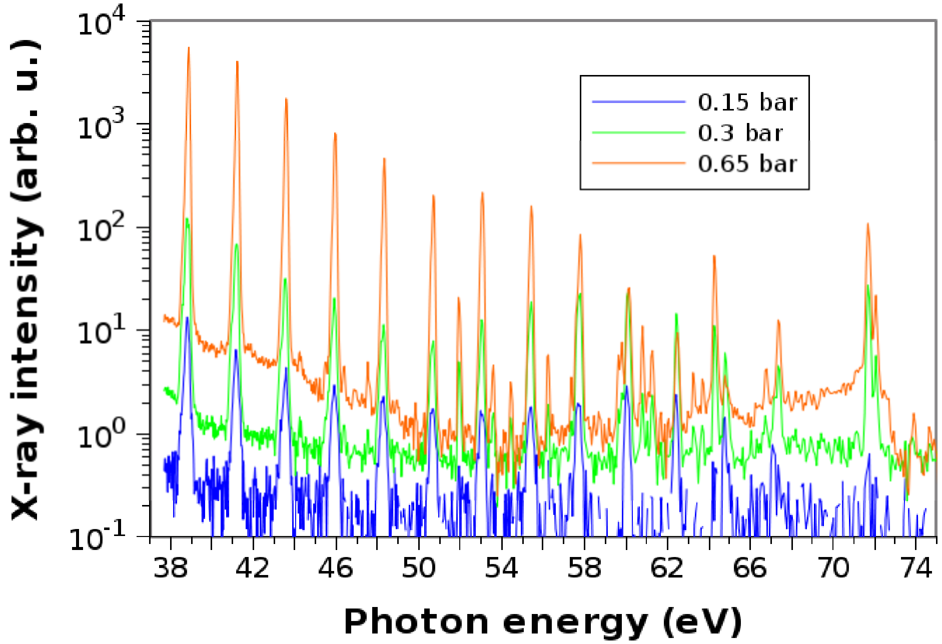


Several x-ray laser transitions can be seeded, but number of possible transitions (and spectral range) is limited

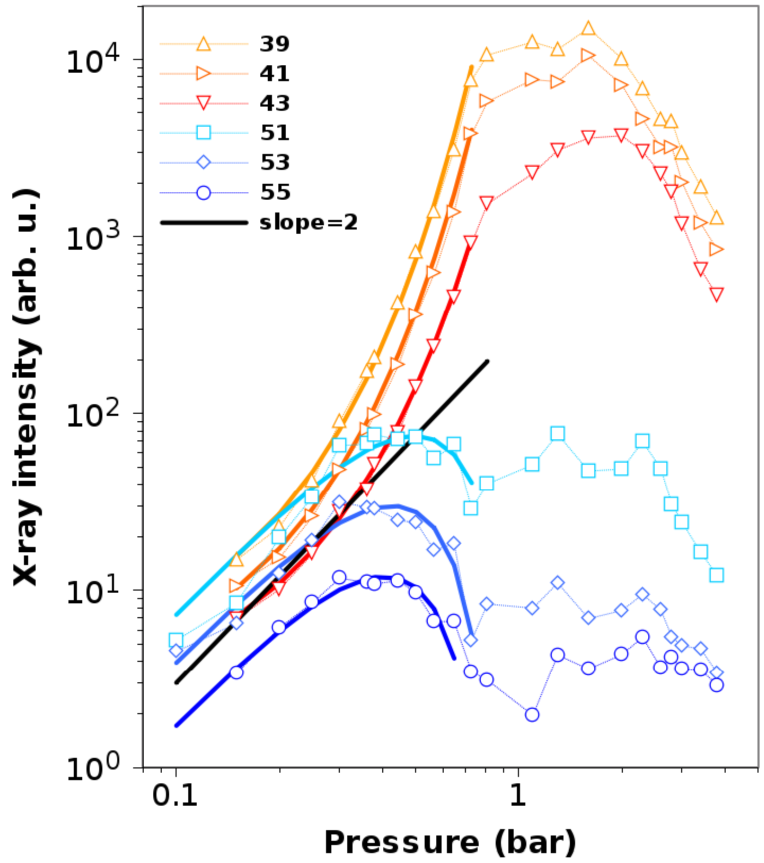
Overall performance depends on seed pulse energy

Non-quadratic scaling of the HH yield with pressure

Theory for phase matched HHG predicts quadratic increase with pressure (slope of 2 in log-log plot)

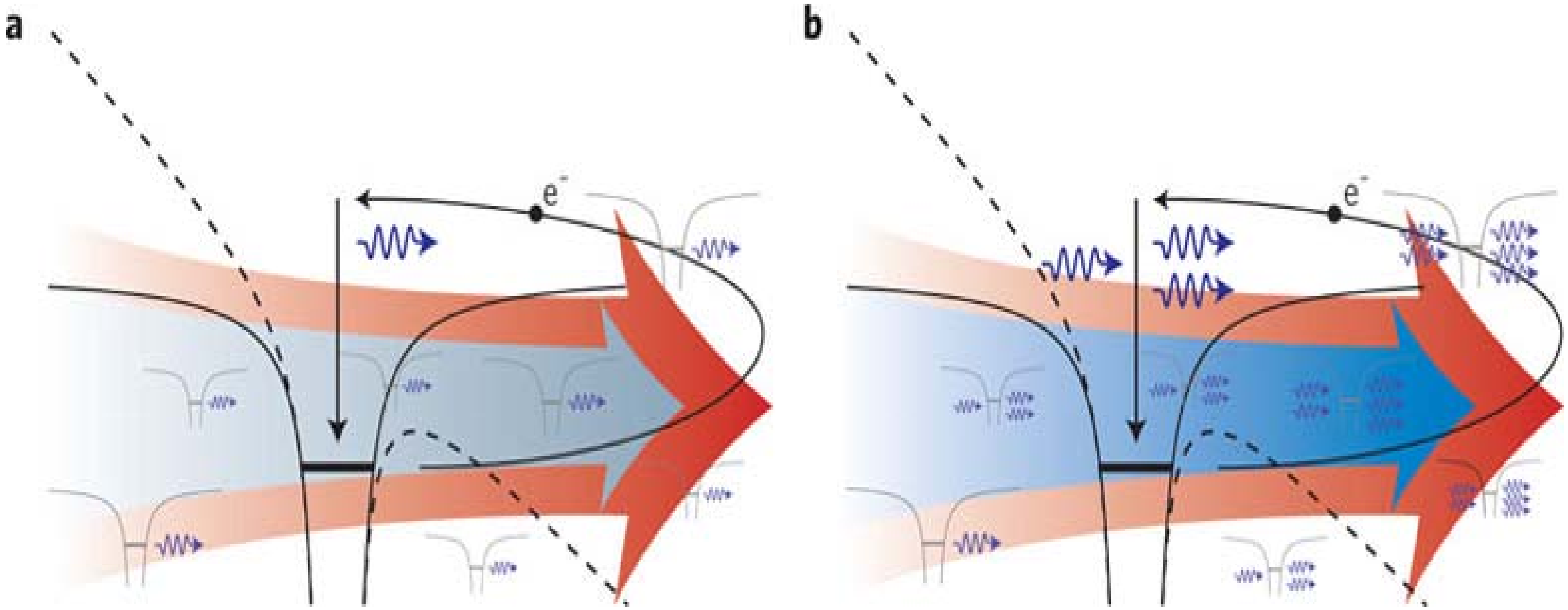


Measured HH intensity as a function of the gas backing pressure



In a limited range around 40-50 eV faster increase (exponential) of the signal with pressure

Strong-field physics: Unexpected gain



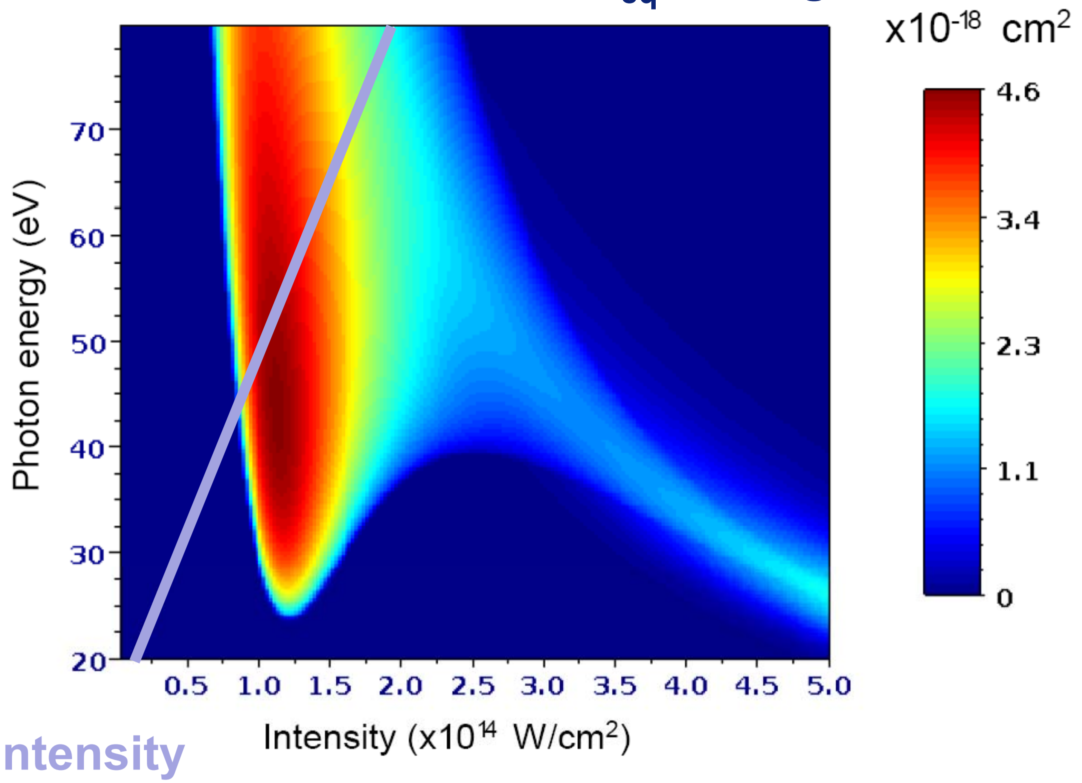
coherent superposition:
quadratic increase

amplification :
exponential increase
stimulated emission?
Raman or parametric gain?

Courtesy Lukas Gallmann ETH

XPA x-ray parametric amplification

Emission cross section σ_{eq} for Argon



Total gain at frequency ω_q: $g_q \approx \sigma_{eq} n_0$

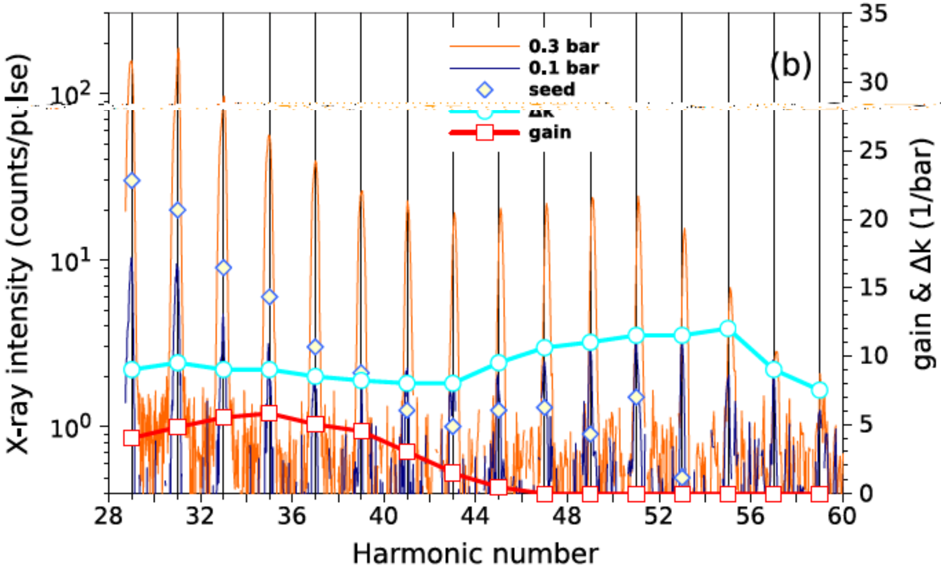
n_0 particle density prop to pressure

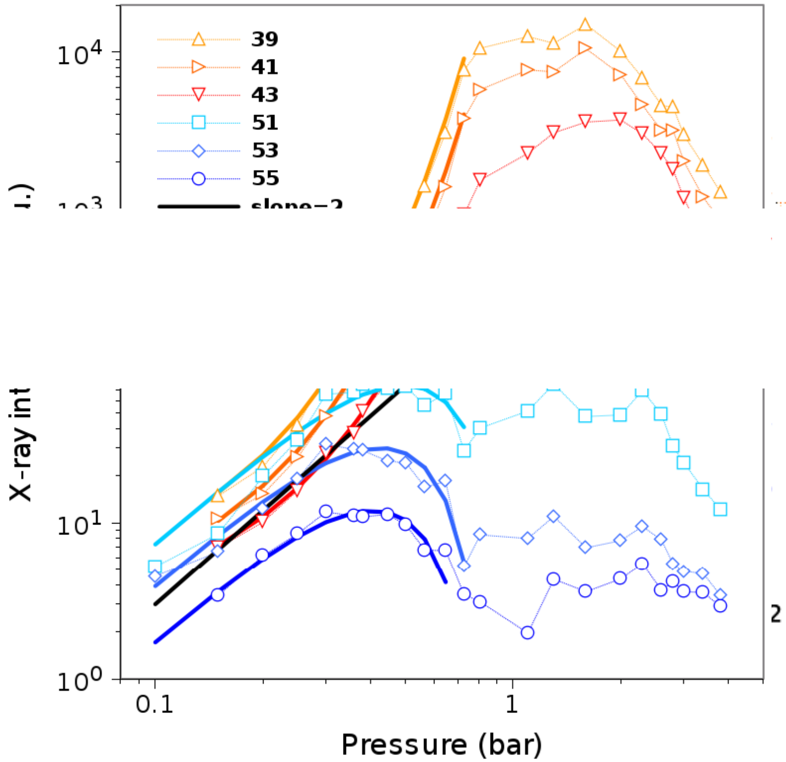
XPA x-ray parametric amplification

Theory

$$I_{out} = I_0 \frac{e^{gL} - 2e^{gL/2}\cos(\Delta kL) + 1}{(\Delta k)^2 + (g/2)^2}$$

gain g prop. pressure



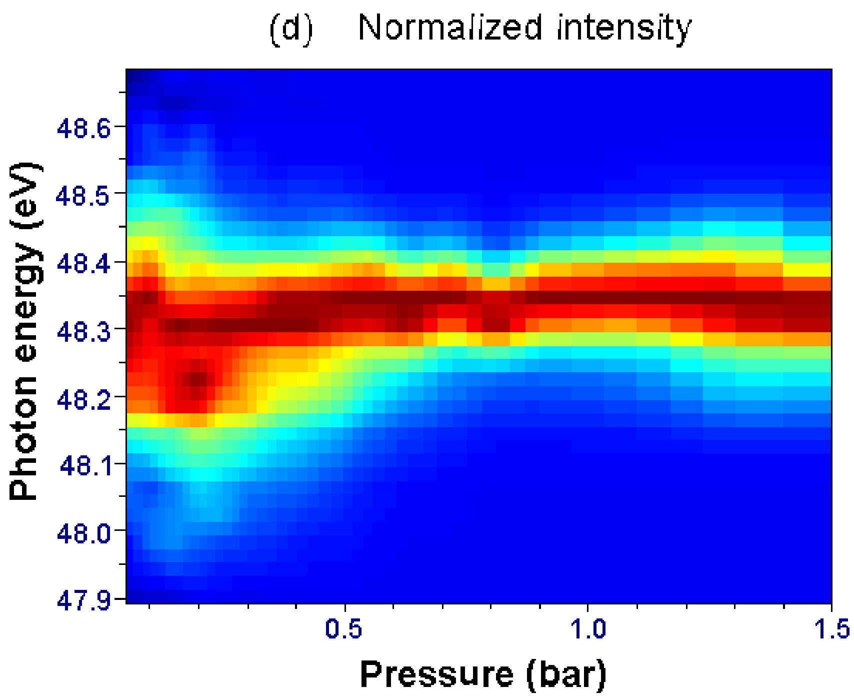


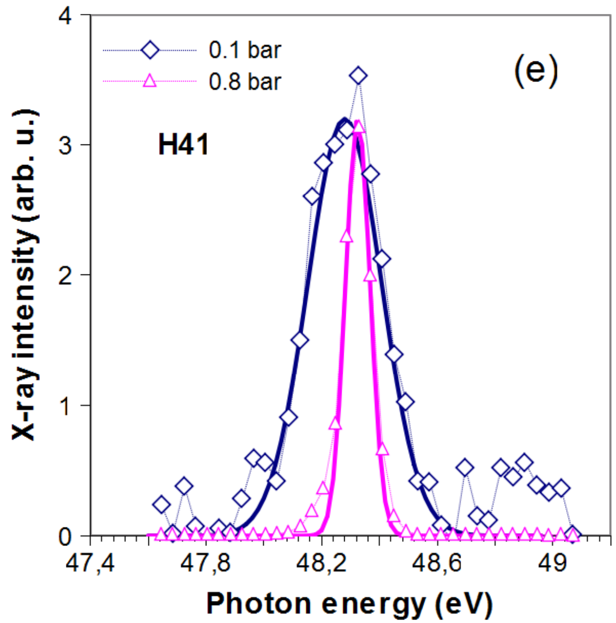
Laser intensity: 3 x 10^{14} W/cm²

small-signal gain of 8 x 10^3 !
pJ HHG signal amplified to nJ
(> 10^9 photons in each pulse)

J. Seres et al Nat. Phys 2010 doi:10.1038/NPHYS16381-7

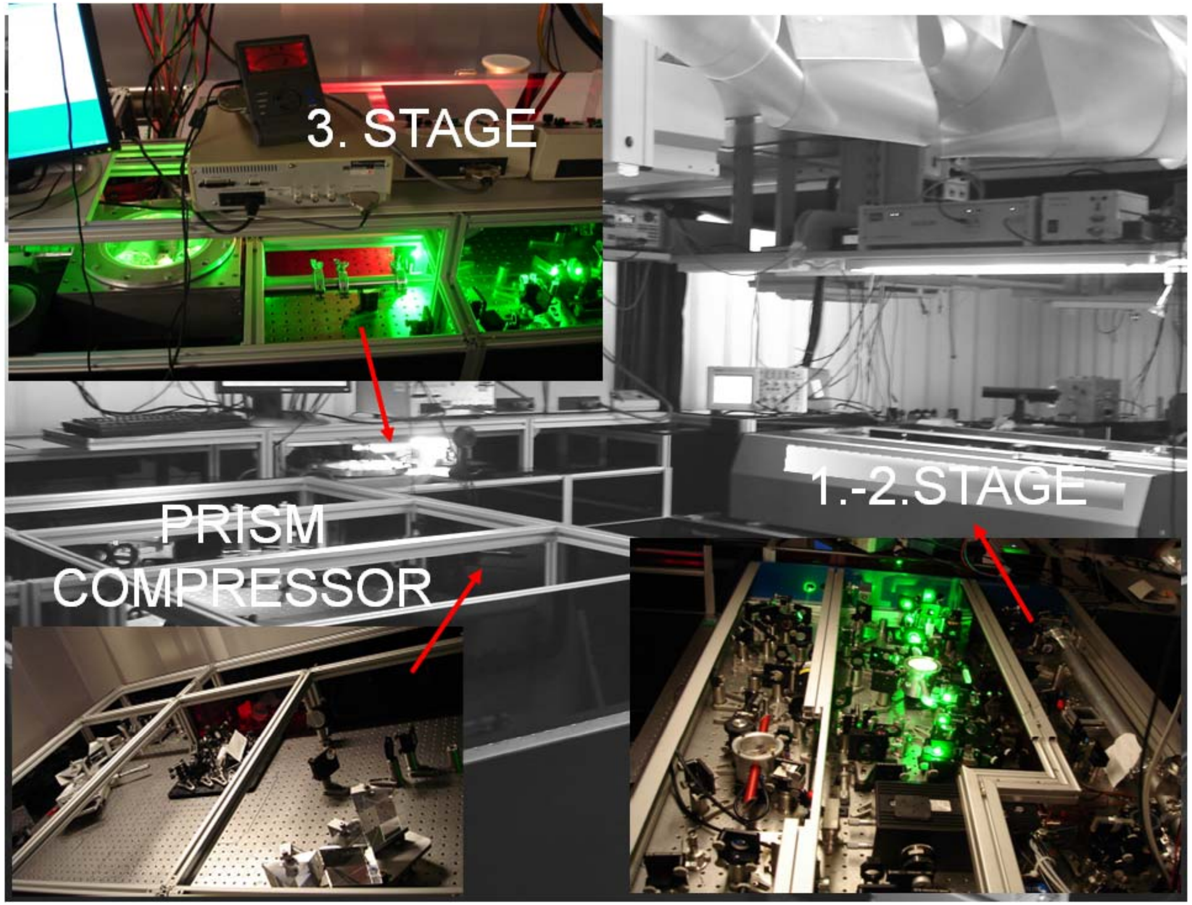
Spectral narrowing





The spectral narrowing of the emitted radiation around 48 eV (41st harmonic) as a function of the pressure is a further indication of amplification with a finite gain bandwidth. The spectrum for low and maximum pressure together with a fit to Gaussian line is also shown.
bandwidth $\Delta E / E < 10^{-3}$ needs to be narrowed → more gain

Towards shorter wavelengths: XPA using short laser pulses



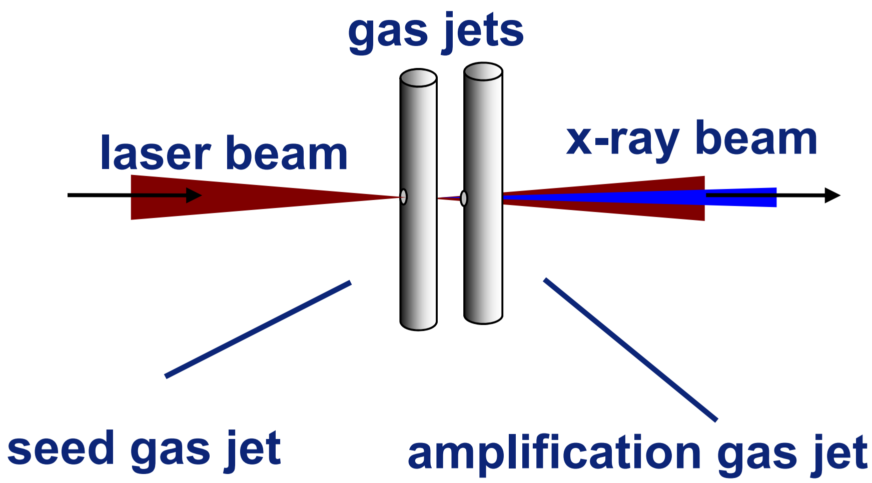
CPA Ti:sapphire amplifier

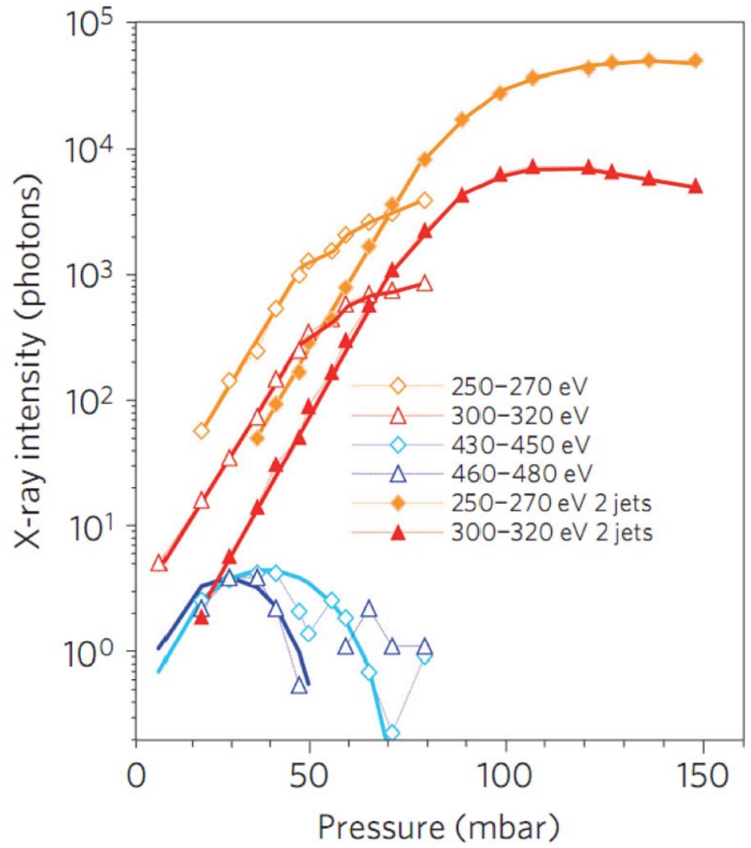
3 stages

1 kHz, 12 fs,
5 mJ
or
6 fs 1.5 mJ

Double stage XPA @ 300eV in He

Limitation for short pulses:
dephasing→ quasi phase matching

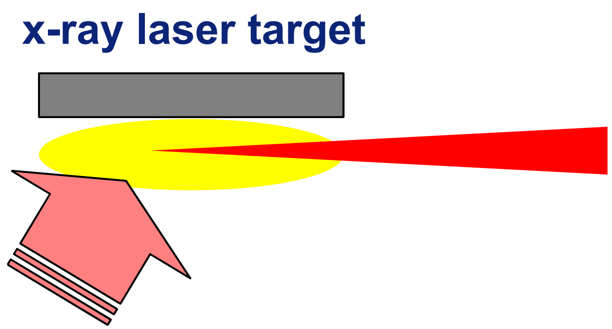


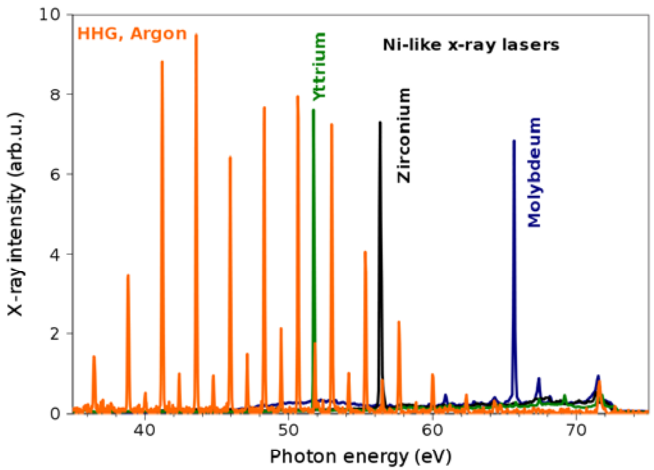


Laser intensity 2 x 10^{16} W/cm²

Conclusions and outlook

Laser- driven x-ray lasers are important tool for studying HCI





High harmonic generation: seeded XRL meet requirements and are under construction

Multi gas jet (HHG seed and XPA amplifiers) pave the way towards generation of µJ coherent XUV radiation