First realization of a photo-ionization based atomic inner-shell x-ray laser at the LCLS

EMMI workshop
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CFEL SCIENCE

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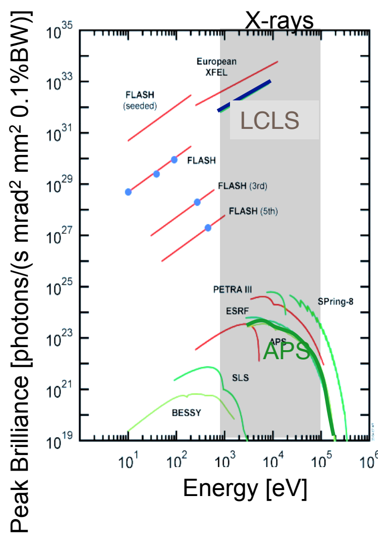
XFELs are the brightest X-ray sources

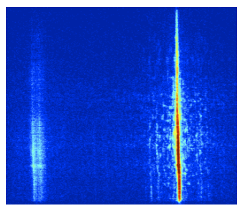


Up to 10^{11}-10^{13} photons
Pulse duration: 5 - 300 fs
Photon energies: 500 eV to 8 keV
Focus: 1 μm at 1 keV
100 nm at 8 keV

Resulting in intensities
of ≈ 5 x 10^{17} W/cm^2 @ 1 keV
on target

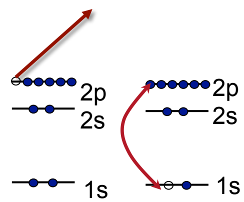
Think (non-linear) quantum optics with x rays !

Photoionization atomic inner-shell x-ray laser



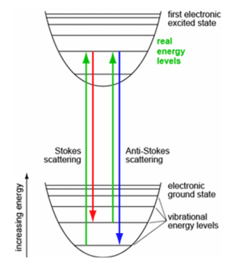
Rohringer et al., submitted

Rabi Flopping Resonant Auger



E. Kanter et al., PRL accepted

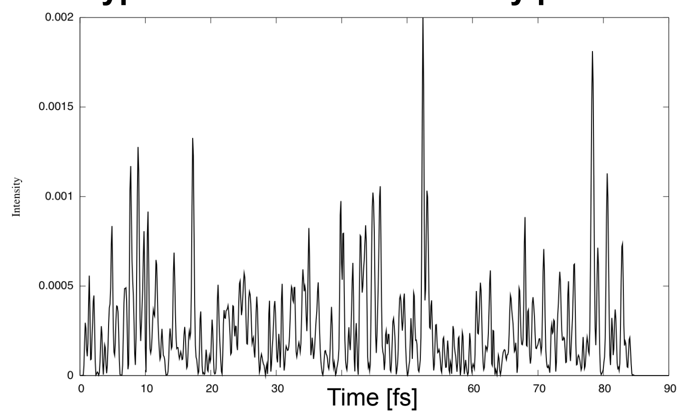
Self-stimulated Raman scattering



Recent experiment at the LCLS

X-ray free electron lasers are (1) not lasers and (2) certainly not free

Typical SASE XFEL intensity profile

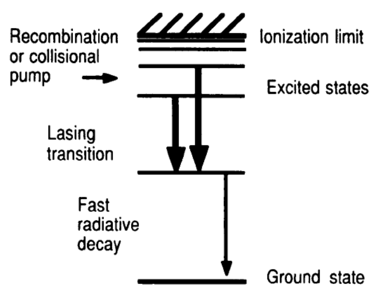


LCLS bandwidth at 1keV photon energy: $\Delta\omega$ = ~ 9 eV
Coherence time: ~ 0.3 fs

How to realize an atomic x-ray laser?

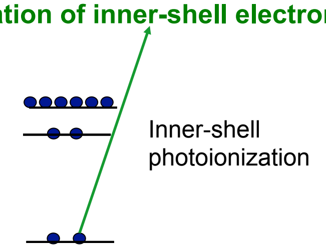
Create population inversion by

Traditionally:
3-body recombination or
collisional pumping in hot (typicall keV), dense plasmas of high ionization degree



1st soft x-ray laser realized at LLNL in 1985:
Ne-like Se laser, at 20 nm (60 eV)
5 MW optical laser in 200 ps
D. Matthews et al., Phys. Rev. Lett. 54, 110 (1985).

Ionization of inner-shell electrons



Idea dates back to 1967:
Duguay and Rentzepis,
Appl. Phys. Lett. 10, 350 (1967).

Realized in the optical regime:
Silfvast et al. 1983 (blue laser)

Fast, powerful x-ray pump required !

History of photo-ionization X-ray Lasing schemes

Pump with laser produced x-ray sources

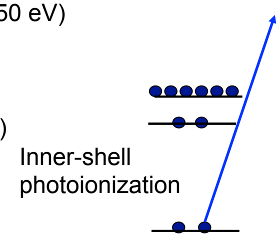
1967 (th.) Duguay and Rentzepis, Appl. Phys. Lett. 10, 350 (Na 33 eV, Cu 9 keV)
1976 (th.) Axelrod (Su)
1983 (exp.) Silfvast et al. 1983 (blue laser)
1992 (th.) Kapteyn, Appl. Opt. 31, 4931 (Ne, 850 eV)
1993-98 (th.) Eder, Strobel, Moon, London, et al.

Use laser-generated betatron source to pump XRL

2007 (th.) Jacquemot, Phuoc, Rousse, Sebban (N, Ne)

Use Synchrotrons to pump XRL

1975 (th.) Csonka and Crasemann (Li, LiH)



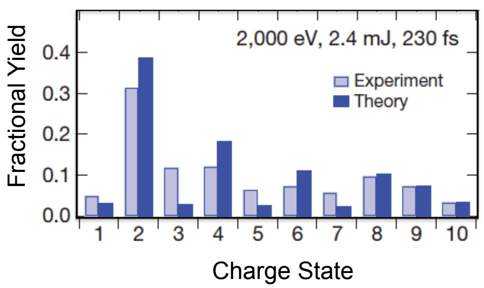
Use FELs to pump XRL

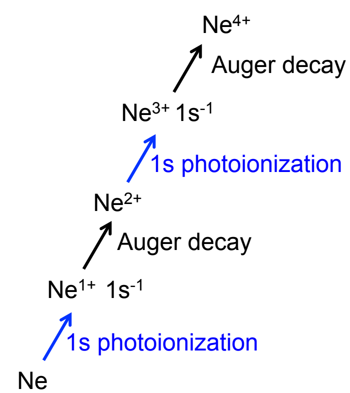
2003 (th.) Lan, Fill and Meyer-ter-Vehn (He)
2008 (th.) Zhao et al. (C, 280 eV)
2009 (th.) Rohringer and London, Phys. Rev. A 80, 013809 (Ne, 850 – 1022 eV)

1st successful demonstration @ LCLS, Sept. 9-13 2010

1^{st} User experiment at the LCLS
Efficient core-hole production in Neon

Charge-state spectrum of Neon subject to intense, focused LCLS pulse

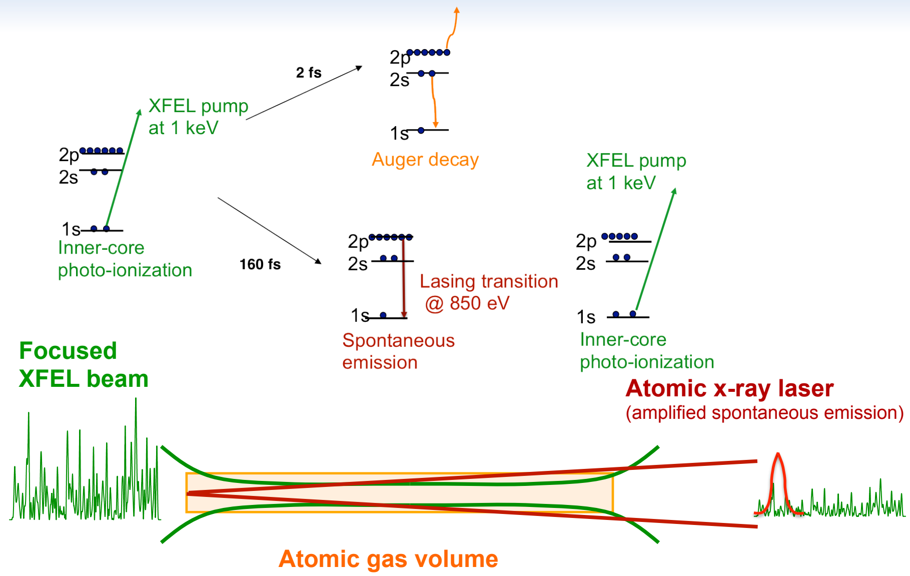




Kinetics is governed by K-shell photo-ionization followed by Auger decay

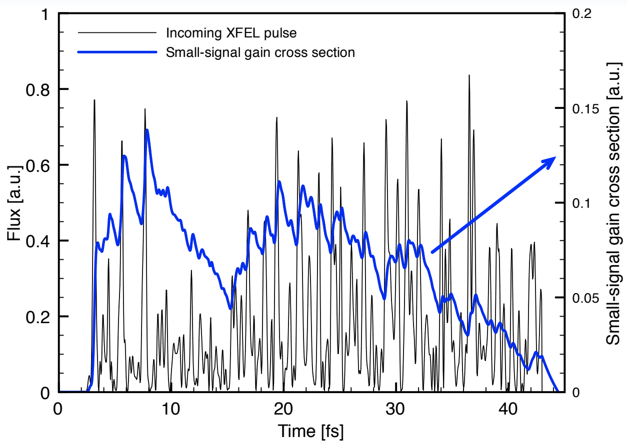
L. Young *et al.*, *Nature* **466**, 56 (2010).
N. Rohringer and R. Santra, Phys. Rev. A **76**, 033416 (2006)

Photo-ionization inner-shell x-ray laser, Neon



N. Rohringer and R. London, PRA 80, 013809 (2009)

Small-signal gain cross section for a SASE XFEL pulse



XFEL pulse:
ω=960 eV
1.6×10^{12} photons
Pulse energy: 0.25 mJ
Pulse duration: 40 fs
Coherence time: 0.3 fs
Focal radius: 2 μm

$$g(t) = n_U(t)\sigma_{stim} - n_L(t)\sigma_{abs}$$

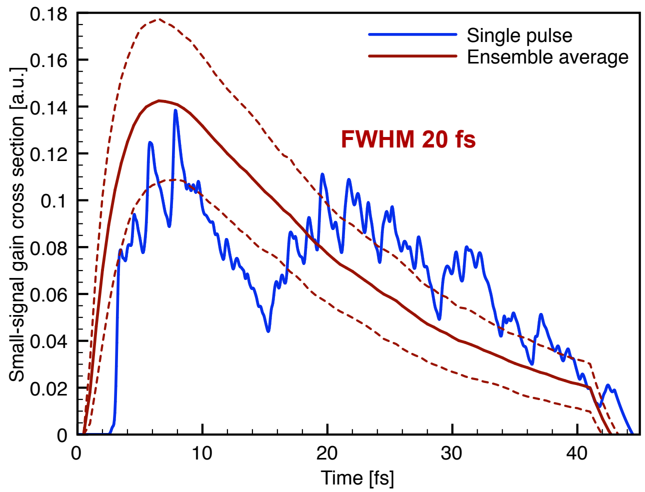
$$\sigma_{stim} = A_{U\to L}\frac{c^2\pi^2}{\omega^2\Delta\omega}$$

Δω=0.24 eV

Gain at gas density of 1.6e19 atoms/cm^3: G=ρσ =64 cm^{-1}

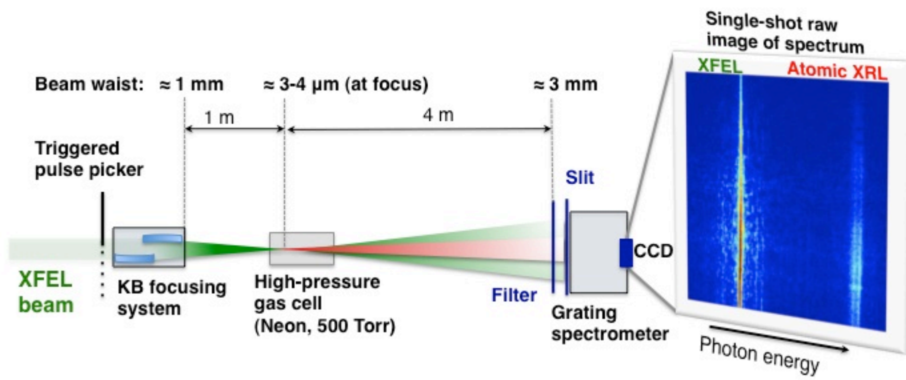
N. Rohringer and R. London, PRA 80, 013809 (2009)

Small-signal gain cross section
Single shot – versus ensemble average



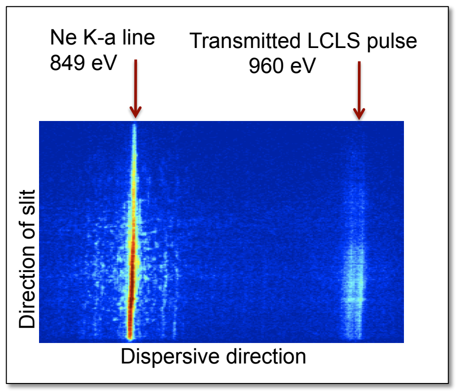
Gain at gas density of 1.6e19 atoms/cm^3: G=$\rho\sigma$ =64 cm^{-1}

Experiment carried out at LCLS' AMO instrument
Sept. 9-13, 2011



Single shot of highest intensity: 8×10^9 photons in Ne K-α line

corresponding to 1.1 μJ, GL 21-23

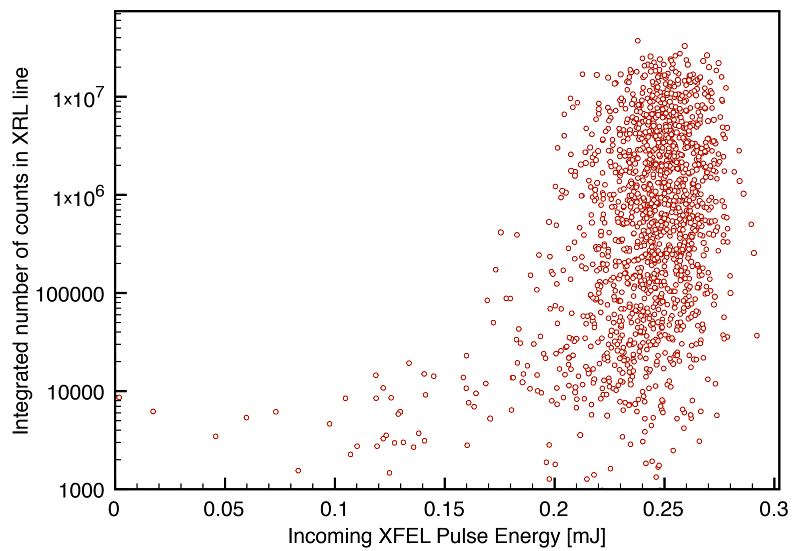


conversion efficiency:
$\approx 4 \times 10^{-3}$

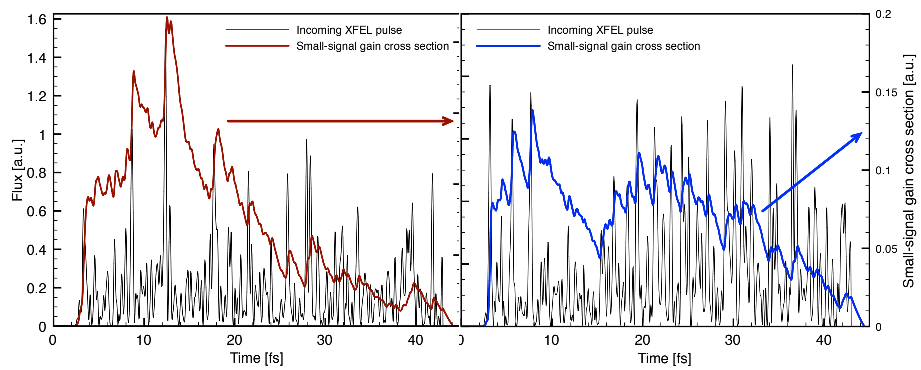
Input:
LCLS pump at 960 eV
pulse energy: 1.4 mJ (0.25 mJ on target)
focus diameter: ≈ 4 micron
Pulse duration: 40 fs

Gas pressure: 500Torr
Interaction length: 1.6 cm

Strong gain variations on a shot-to shot basis

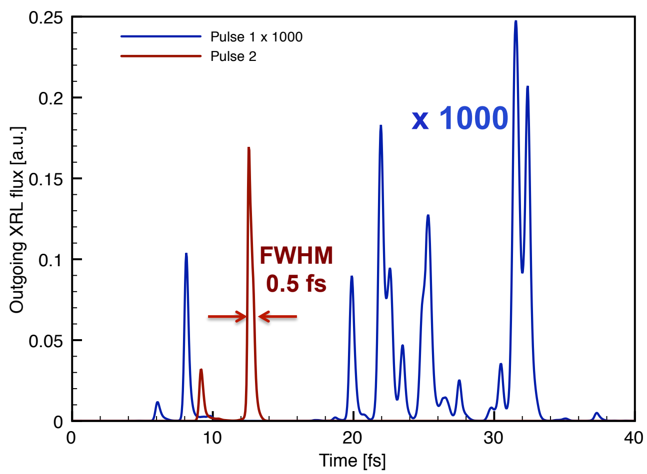


Numerical study on the gain fluctuations
Small-signal gain for two sample pulses of SASE ensemble



Huge fluctuations in output intensity and temporal structure

Peak intensity varies by 3 orders of magnitude !!!

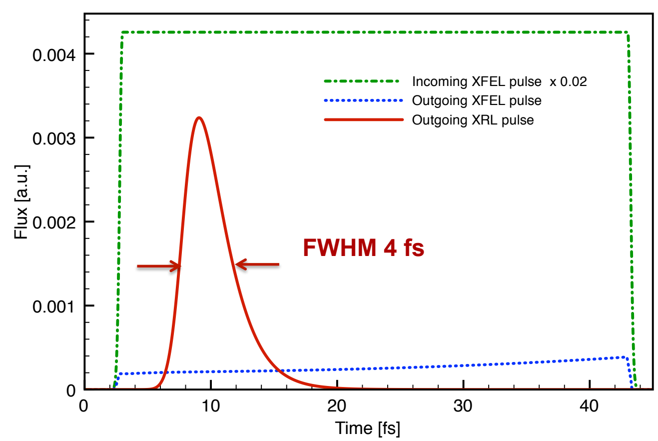


Kinetic equations to determine occupation of configuration states, coupled to x-ray flux propagation and amplification through medium

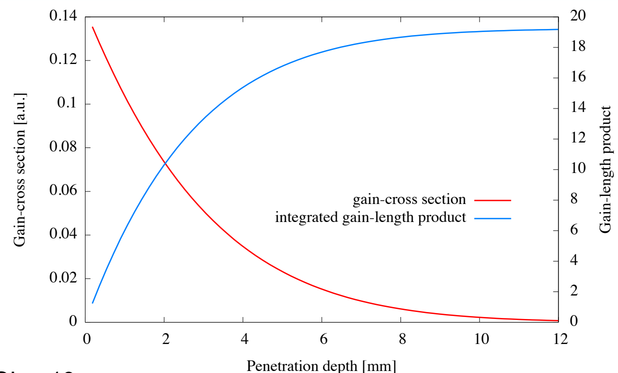
1-dimensional model

Temporal profile of XFEL and x-ray pulse for the ensemble average

We assumed an incoming flat-top pulse



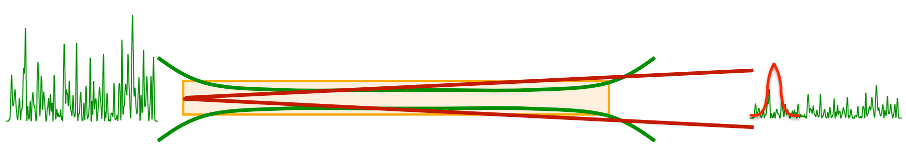
Gain-length product as determined by self-consistent gain model



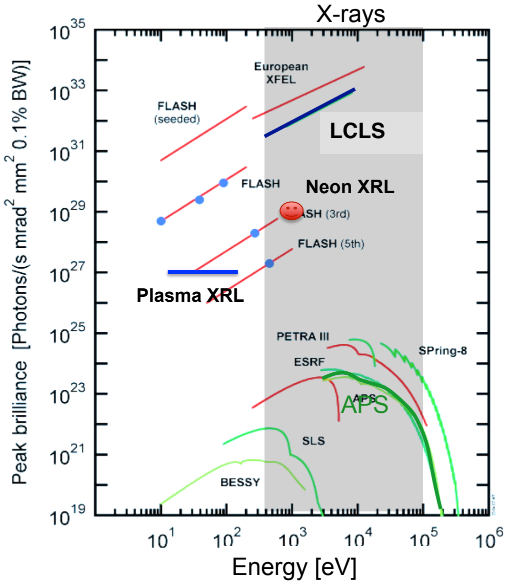
GL ≈ 19

Gain region ≈ 2.8 mm (1/e value of peak gain-cross section)

Good agreement with experimental values !!!



Peak Brilliance of several VUV and X-ray sources



LCLS
Spectral brightness:
1.5×10^{30} photons/s/mrad^2/mm^2/eV BW
on target @ ~ 1 keV:
Pulse energy: 0.3 mJ
10^{11}-10^{12} photons
Spectral width: 8 eV
Pulse duration: 5 - 300 fs
Focus: 1 μm

XRL 850 eV:
Spectral brightness:
1.5×10^{30} photons/s/mrad^2/mm^2/eV BW
Pulse energy: 1.1 μJ
10^{9}-10^{10} photons
Spectral width: 0.27 eV
Pulse duration: ~ 0.5-5 fs

Conclusions

1st demonstration of photo-ionization atomic inner-shell x-ray lasing scheme
- narrow, well defined and reproducible spectrum
- longitudinal coherence

Tuneable two-color x-ray source for pump/probe experiments

Use XFEL's capability of driving truly non-linear quantum optical effects

Acknowledgements

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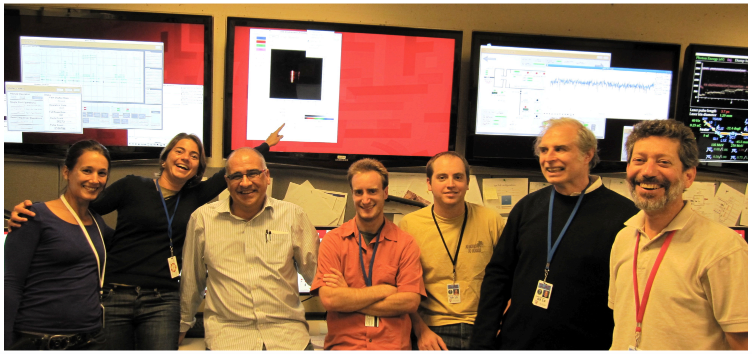
LCLS, SLAC J. Bozek, C. Bostedt, T.Tsai, accelerator/LCLS operating team



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