X-Ray Lasers

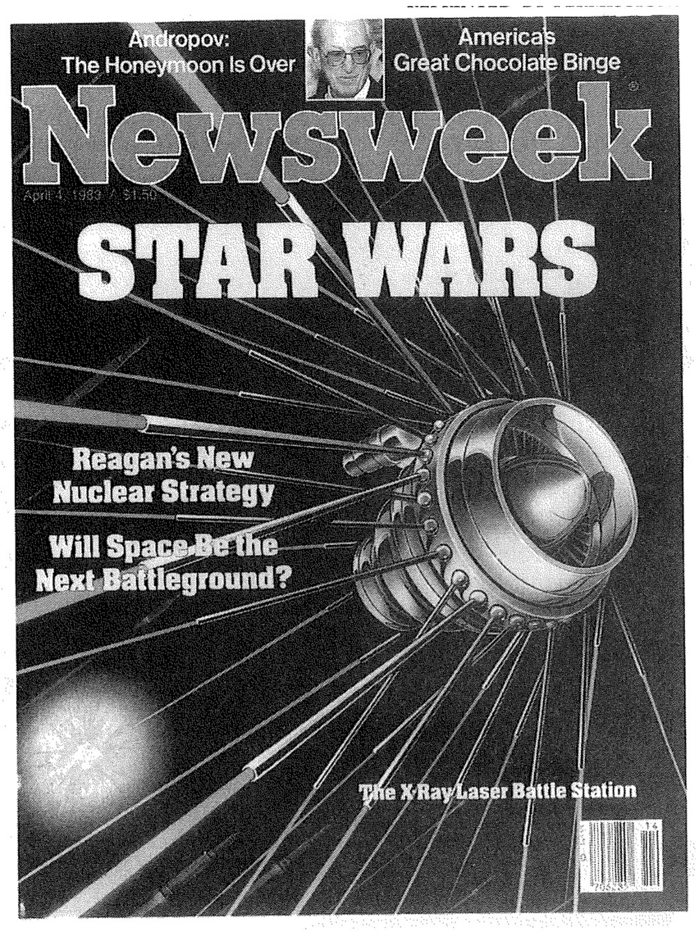
Nina Rohringer

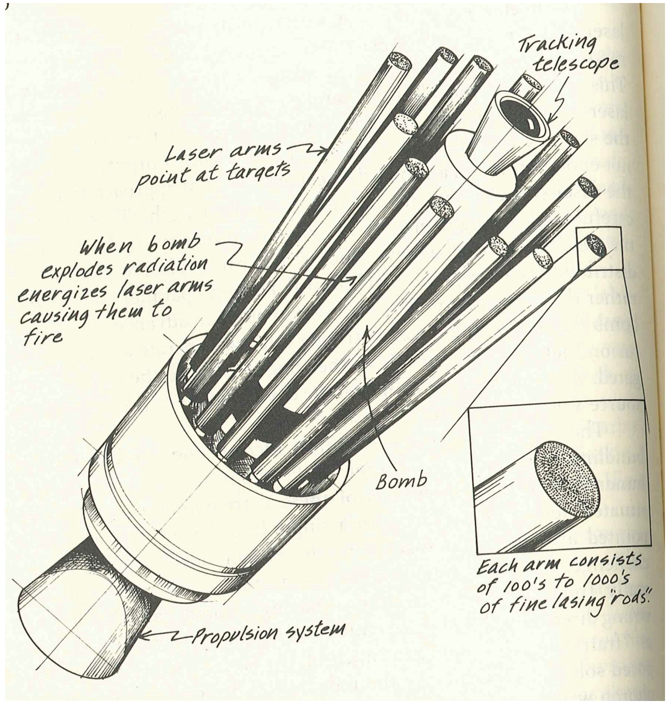
21st meeting on Atomic Processes in Plasmas

HELMHOLTZ DASHH MAX PLANCK SCHOOL of photonics CFEL SCIENCE Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG DESY.

US Strategic Defense Initiative (1984-1993)

Project Excalibur: Nuclear-explosion pumped XRL for ballistic missile defense





William J. Broad,
"*Teller's War, The top-secret story behind the star wars deception*"
(Simon & Schuster, New York, 1992)

D. M. Ritson, Nature 328, 487 (1987)
N. Bloembergen et al., Rev. Mod. Phys. 59,1 (1987)

3.7 Milliarden $ (1985-1991)

X-ray lasers pumped by nuclear explosion

List of (presumably) performed experiment from 1978 to 1988

Code Name	Date	Result
Diablo Hawk	Sep. 13, 1978	Test apparatus fails
Dauphin	Nov. 14, 1980	1st probable x-ray laser, though some experts say evidence is sketchy
Cabra	March 26, 1983	Sensors fail
Romano	De. 16, 1983	1st hard X-ray laser evidence
Correo	Aug. 2, 1984	Laser fails
Cottage	March 23, 1985	1st focusing attempt
Goldstone	Dec. 28, 1985	1st good measure of brightness shows basic laser is dimmer than previously believed
Labquark	Sept. 30, 1986	More focusing tests
Delamar	Apr. 18, 1987	1st fear that focusing has failed
Kenville	Feb. 15, 1988	1st high-quality data on basic laser

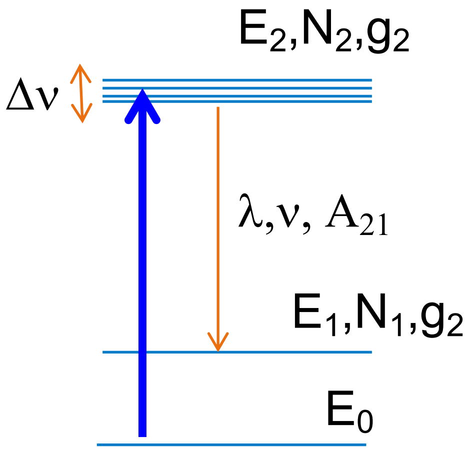
William J. Broad, "*Teller's War, The top-sectret story behind the star wars deception*" (Simon & Schuster, New York, 1992)

Pumping power requirements for x-ray lasers

Population inversion: $\Delta N = \left(N_2 - N_1 \frac{g_2}{g_1} \right)$

$$I(z) = I(0) \cdot e^{g \cdot z}$$

Gain coefficeint: $g = \sigma \Delta N \cong \frac{A_{21}\lambda^2}{8\pi\Delta\nu}\left(N_2 - N_1 \frac{g_2}{g_1} \right)$



Einstein A coefficient: $A_{21} \propto \lambda^{-2}$

Naturally broadened transition (rad. decay): $\Delta\nu \propto A_{21}$

➡ $g \propto \Delta N \lambda^2 \cong N_2 \lambda^2$

Required pump power density to compensate for level depletion:

➡ $P = N_2 A_{21} \frac{hc}{\lambda} \propto N_2 \lambda^{-3}$

Pumping power to maintain a specific gain: $\boxed{P \propto g \lambda^{-5}}$

J. J. Rocca, Rev. Scient. Instr. **70**, 3799 (1999).

Pumping power requirements for x-ray lasers

Pump power to achieve a given gain g scales as:

$$\boxed{P \propto g \lambda^{-5}}$$

$$\frac{P_{x-ray}}{P_{optical}} = \left(\frac{\lambda_{optical}}{\lambda_{x-ray}}\right)^5 = \left(\frac{800 \text{ nm}}{1 \text{ nm}}\right)^5 = 3.3\times10^{14}$$

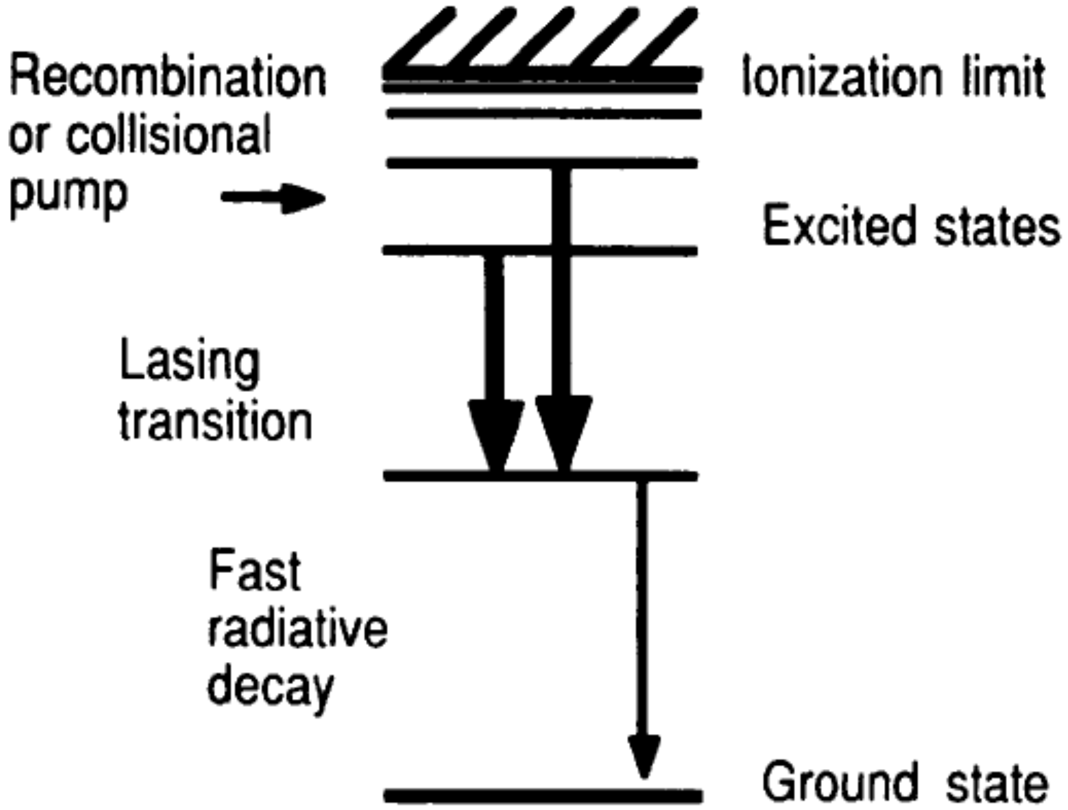
Optical Laser: 10 W ➡ X-ray Laser : 10^{15} W

Electric power production in Germany 2022 : (Source Statistisches Bundesamt).

500 TWh = 5 ×10^{14} Wh

Mechanisms for population inversion on x-ray transitions

Recombination or collisional pump

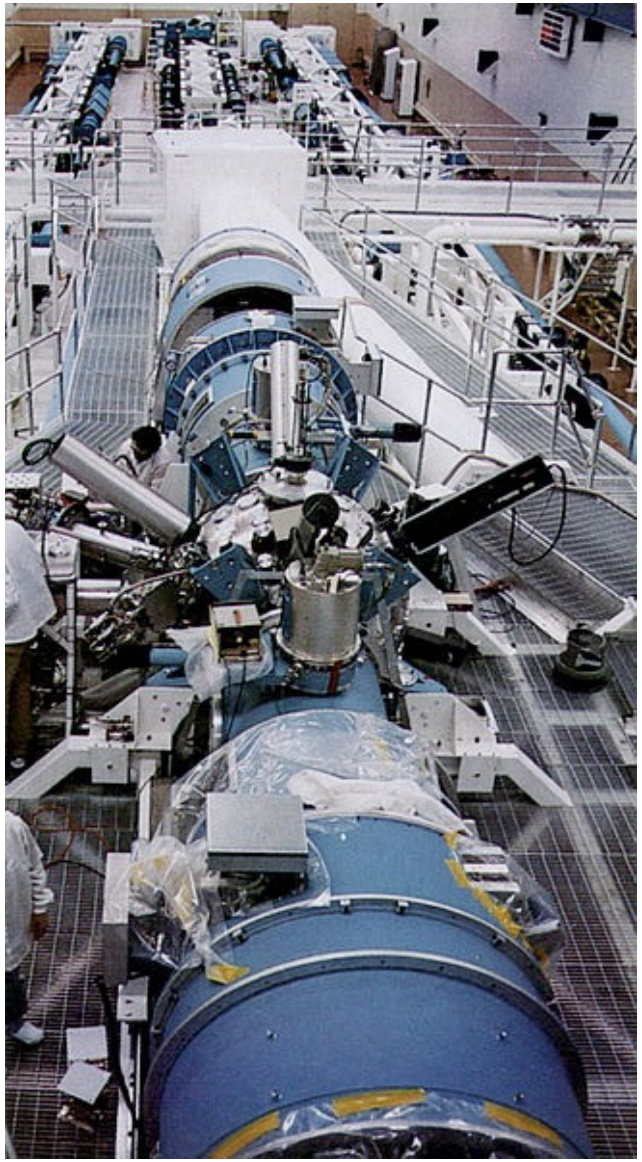


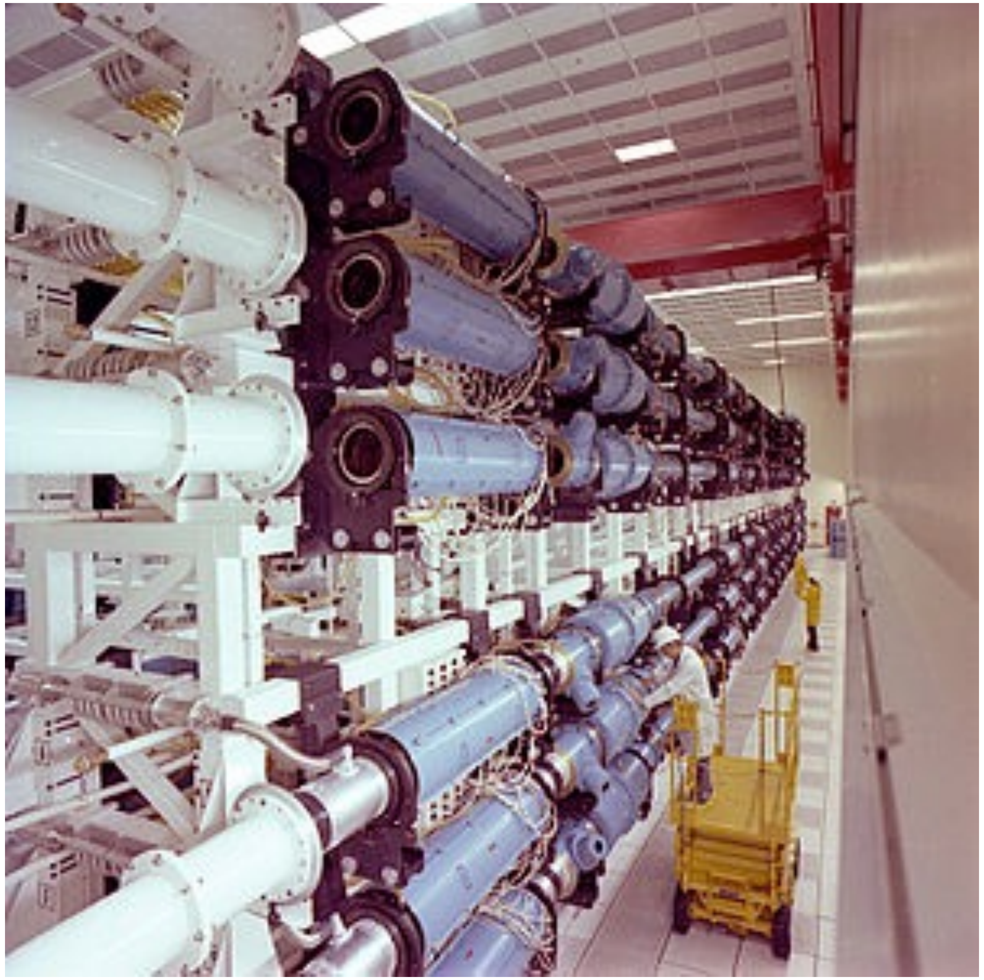
Create hot plasma, of high ionization degree

Electron temperatures: ~ keV

Densities: 10^{21} - 10^{22} cm^{-3}

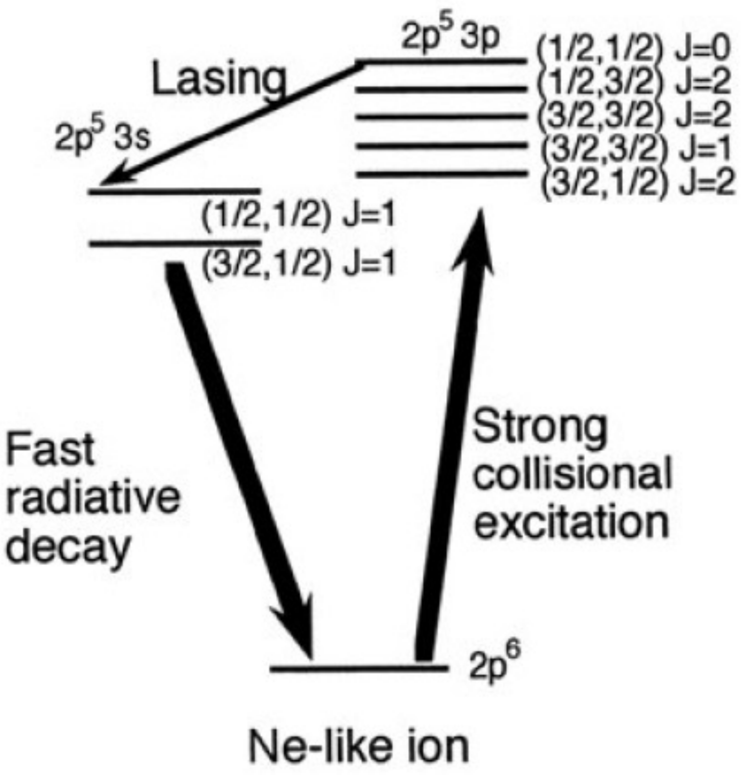
1st atomic XUV Laser at Novette Laser in 1984





Soft x-ray laser by electron impact excitation

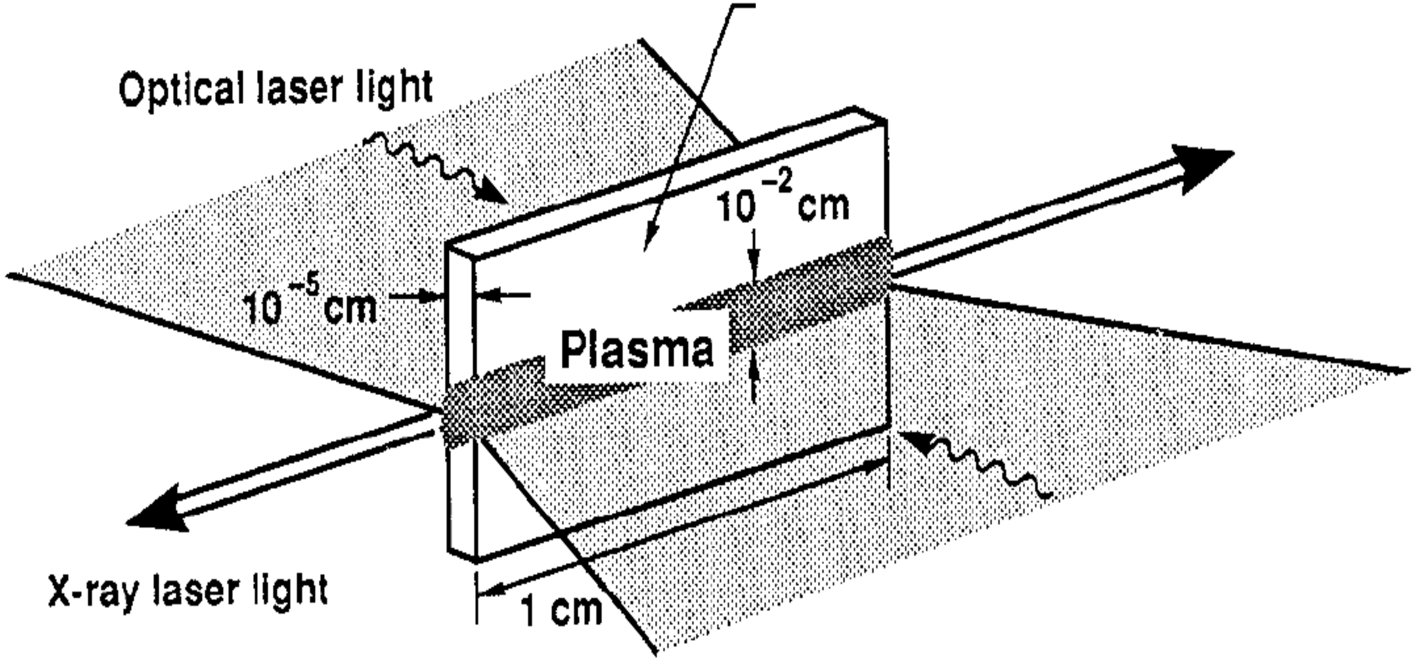
1st experimental realization at LLNL in 1984: Ne-like Se laser 20 nm (60 eV, 20 nm)



Electron temperature: T= 1 keV
Density: N= 1 x 10^{21} cm^{-3}

Transverse pumping:
Pump Energy 1 kJ
Line focus: 0.02 x 1.12 cm
Pump wavelength: 532 nm
Duration: 450 ps
Intensities on target: 5 x10^{13} W/cm^2

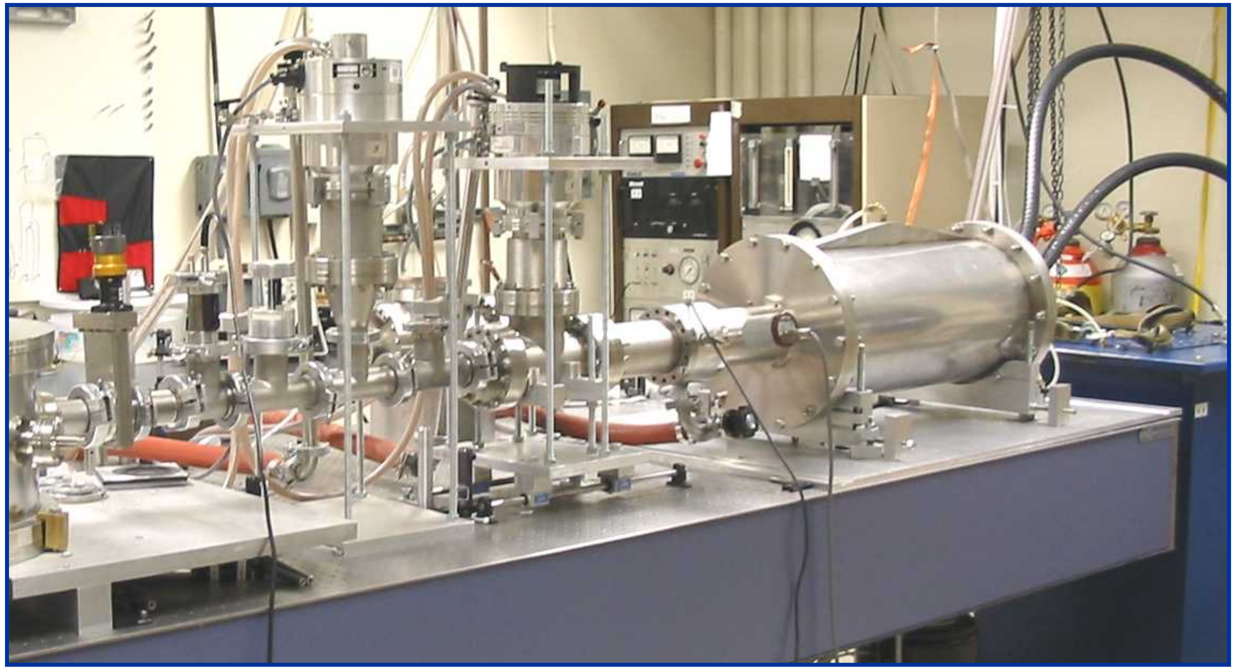
Exploiding foil target



D. Matthews *et al.*, Phys. Rev. Lett. **54**, 11 (1985).

Table-top XUV lasers in Ne-like Ar at 46.9 nm (26 eV)

Coherent average power is comparable to synchrotron beam line



(By courtesy of J.J. Rocca, Colorado State University)

Discharge current pulse:
37 kA, duration 70 ns

High average power: up to 3 mW

High pulse energy: 0.1 mJ - 0.8 mJ @4 Hz

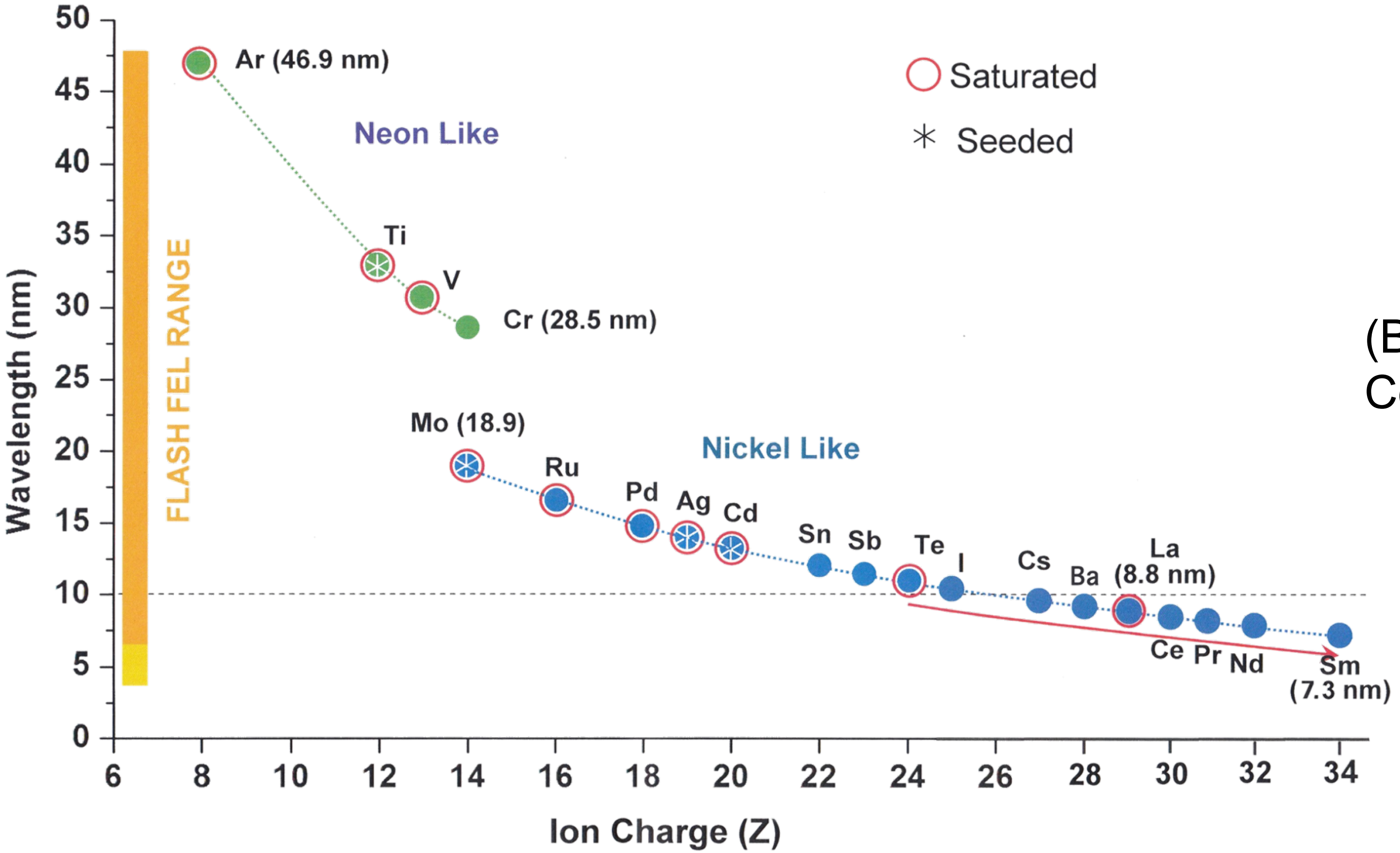
Narrow spectral bandwidth: $\Delta\lambda/\lambda = 3 \times 10^{-5}$

Beam divergence: $\theta = 4.5$ mrad

B. Benware et al. Phys.Rev.Lett. **81**, 5804, (1998)
C. Macchietto Opt. Lett. **24**, 1115, (1999)

Gain-saturated table-top soft X-ray Lasers

Wavelength region from 7.3 nm to 47 nm



(By courtesy of J.J. Rocca, Colorado State University)

Review Articles:

J. J. Rocca, ‘Table-top soft x-ray lasers’, Rev. Scient. Instr. **70**, 3799 (1999).

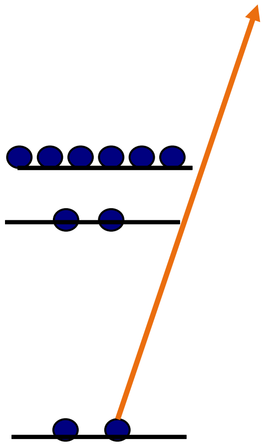
S. Suckewer and P. Jaegle, Laser Phys. Lett. **6**, No. 6, 411–436 (2009)

1st theoretical concept of an atomic inner-shell X-ray laser

Population inversion by inner-shell photoionization

1st X-ray laser proposed back in 1967:

Duguay & Rentzepis,
Appl. Phys. Lett. **10**, 350 (1967).



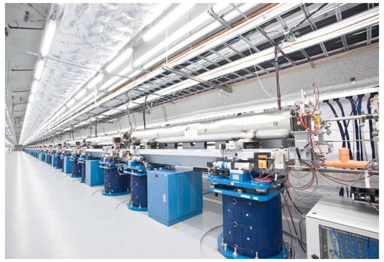
Ultrafast ionization of inner-shell electrons

1st realization in the optical regime (blue laser):
Silfvast et al., Opt. Lett. **8**, 551 (1983).

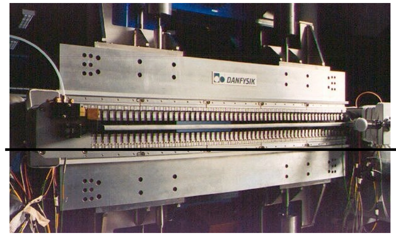
Fast, powerful x-ray pump required to beat Auger decay !

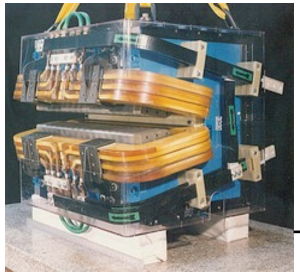
Evolution of accelerator-based x-ray sources over time

Free-electron Lasers



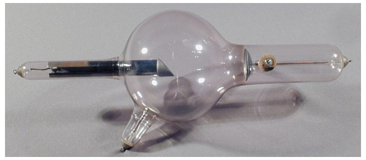
Undulators

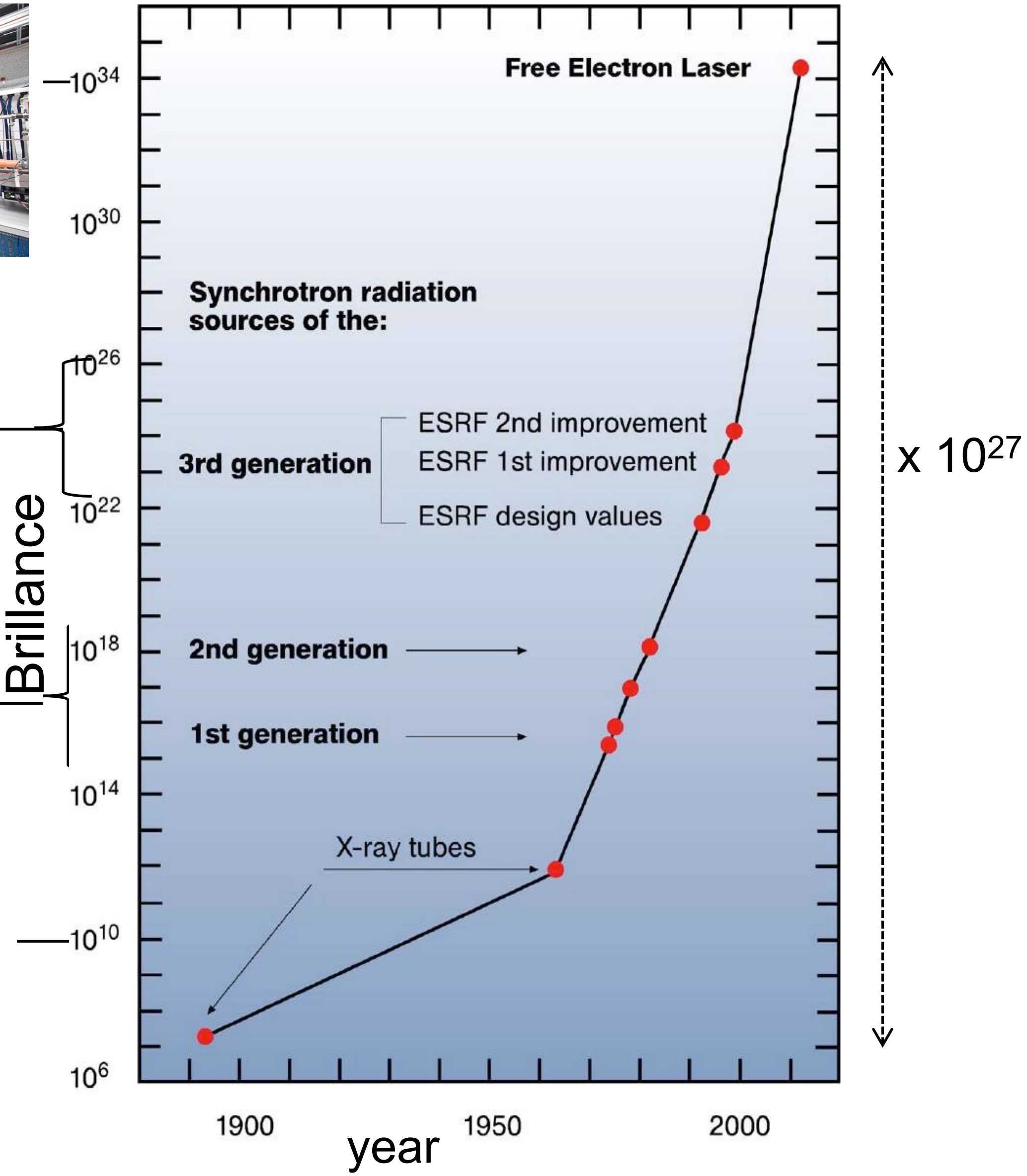




Bending magnets

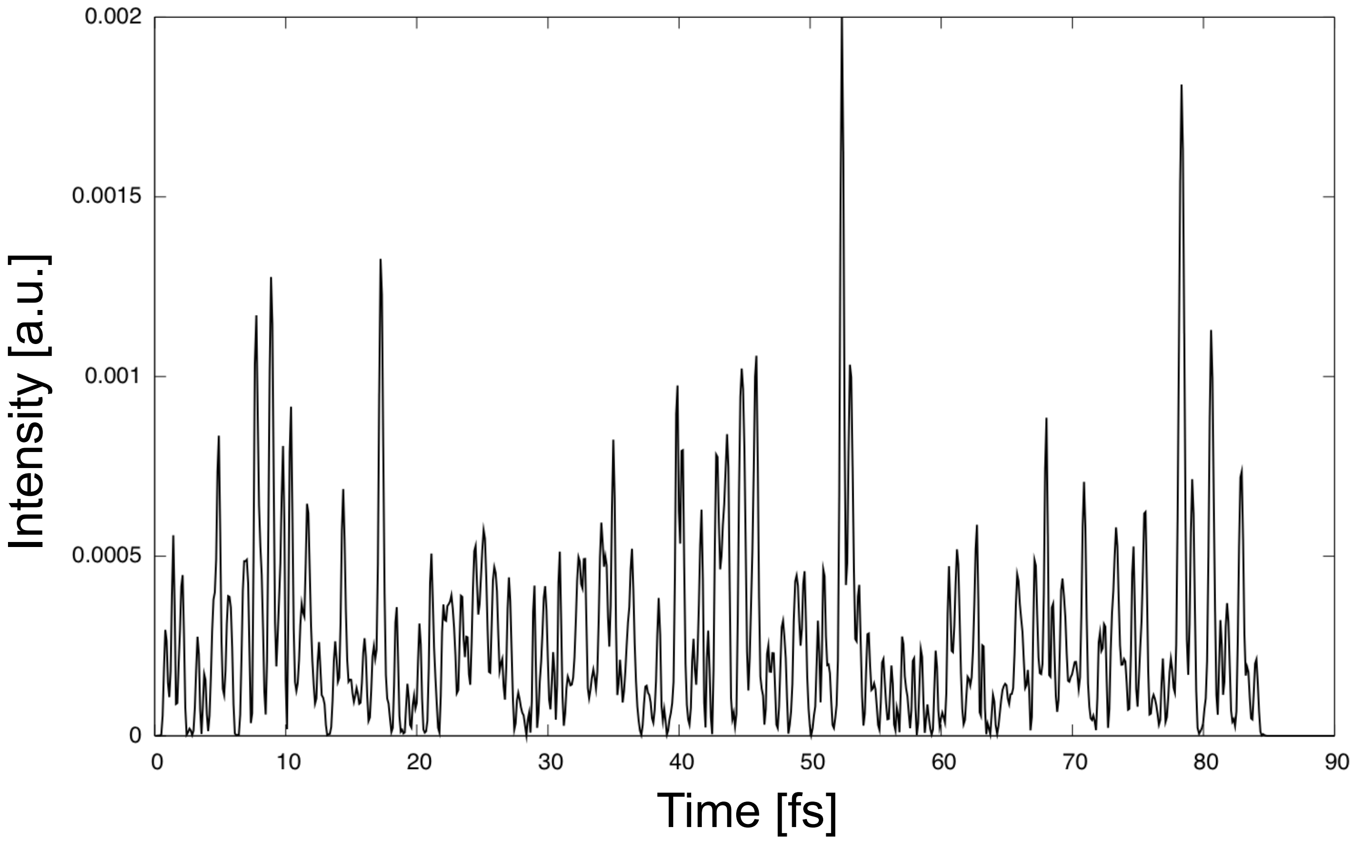
X-ray tubes





Self Amplified Spontaneous Emission (SASE)

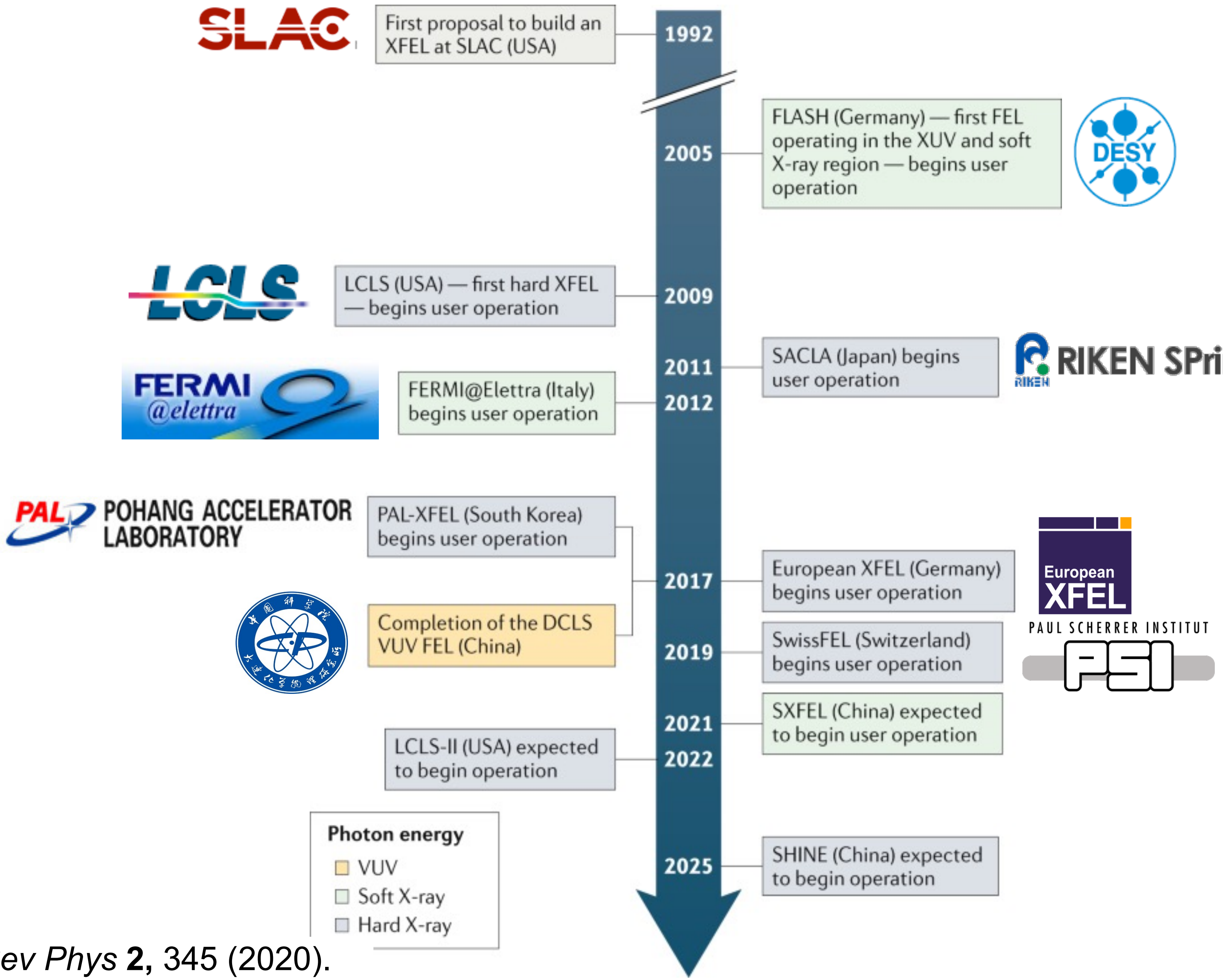
SASE XFELs have limited temporal coherence



Achievable intensities through focusing:
10^{18} W/cm2 @ 1 nm
10^{20} W/cm2 @ 0,1 nm

bandwidth @ 1keV photon energy: $\Delta\omega$ = 6-9 eV
Coherence time: 0.3 - 0.5 fs
Pulse Energy: 1 mJ (for 20 fs pulse duration)

A new era of coherent, bright x-ray sources



1992 – First proposal to build an XFEL at SLAC (USA)

2005 – FLASH (Germany) — first FEL operating in the XUV and soft X-ray region — begins user operation

2009 – LCLS (USA) — first hard XFEL — begins user operation

2011 – SACLA (Japan) begins user operation

2012 – FERMI@Elettra (Italy) begins user operation

2017 – PAL-XFEL (South Korea) begins user operation

2017 – Completion of the DCLS VUV FEL (China)

2017 – European XFEL (Germany) begins user operation

2019 – SwissFEL (Switzerland) begins user operation

2021 – SXFEL (China) expected to begin user operation

2022 – LCLS-II (USA) expected to begin operation

2025 – SHINE (China) expected to begin operation

Photon energy
- 🟨 VUV
- 🟩 Soft X-ray
- ⬜ Hard X-ray

I. Georgescu, *Nat Rev Phys* **2,** 345 (2020).

1st realization of an atomic inner-shell x-ray laser

Colorado State University:
J.J. Rocca, D. Ryan, M. Purvis
LLNL:
R. London, F. Albert, J. Dunn
SLAC:
J. Bozek

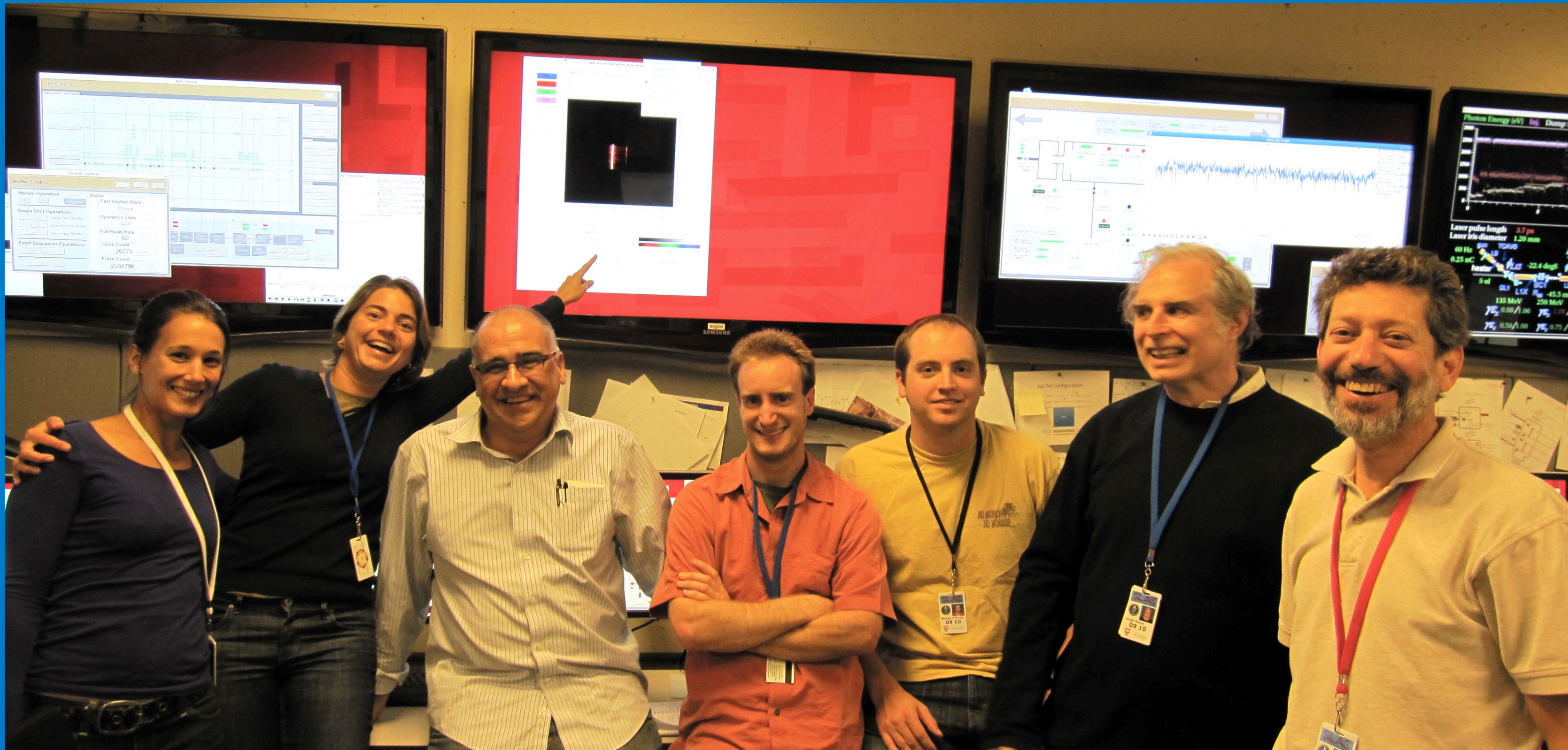
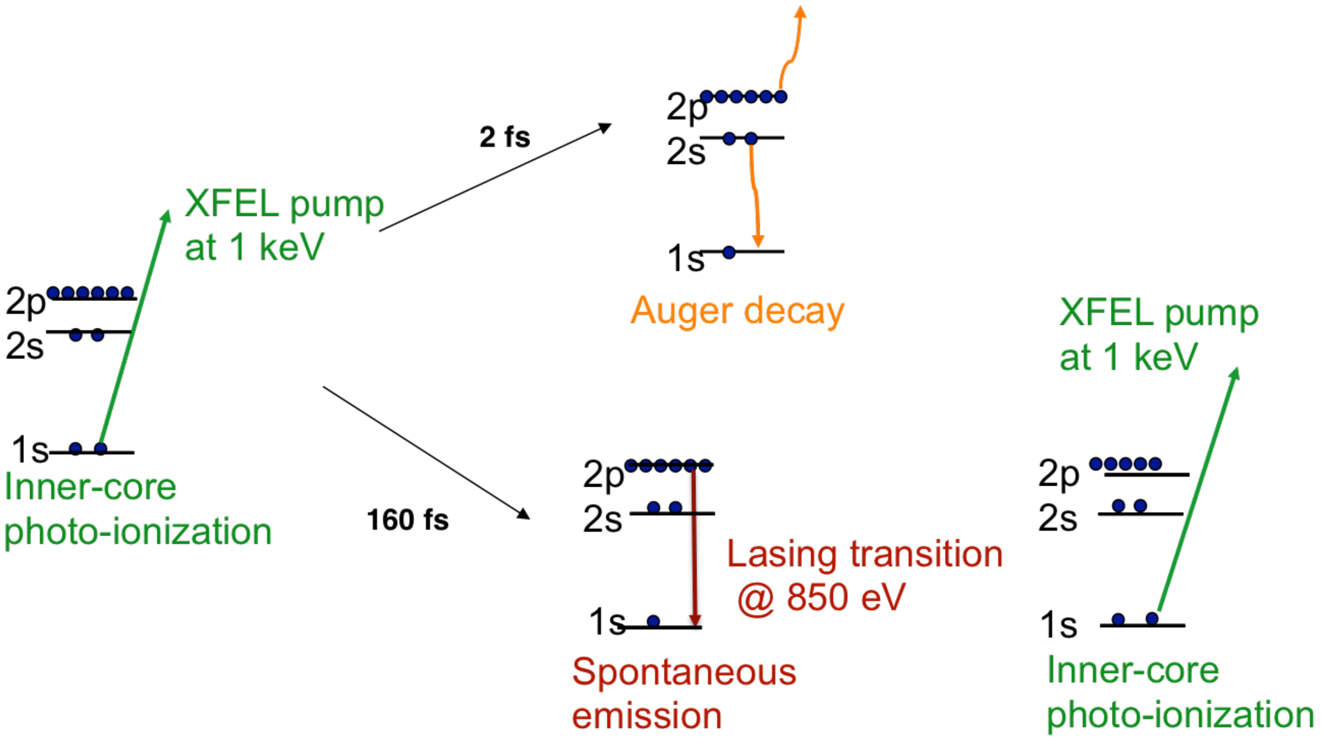


Photo-ionization inner-shell x-ray laser, Neon



Inner-core photo-ionization

Auger decay

Spontaneous emission

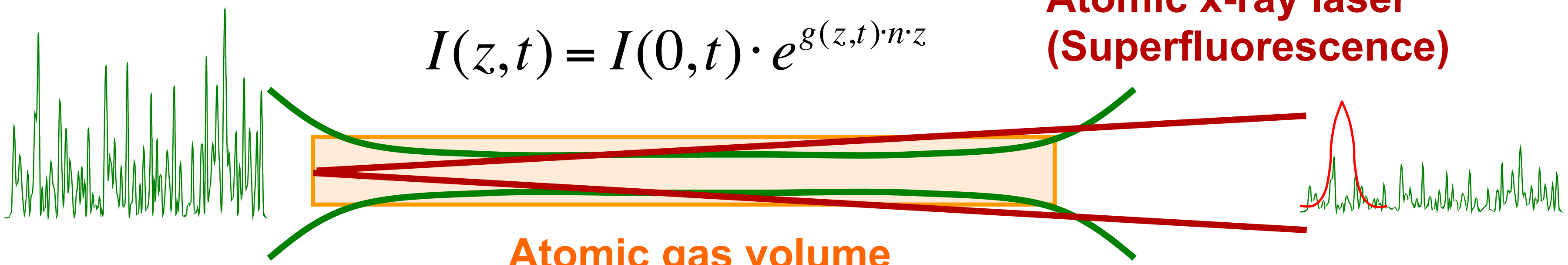
XFEL pump at 1 keV

Inner-core photo-ionization

Focused XFEL beam

$$I(z,t) = I(0,t)\cdot e^{g(z,t)\cdot n\cdot z}$$

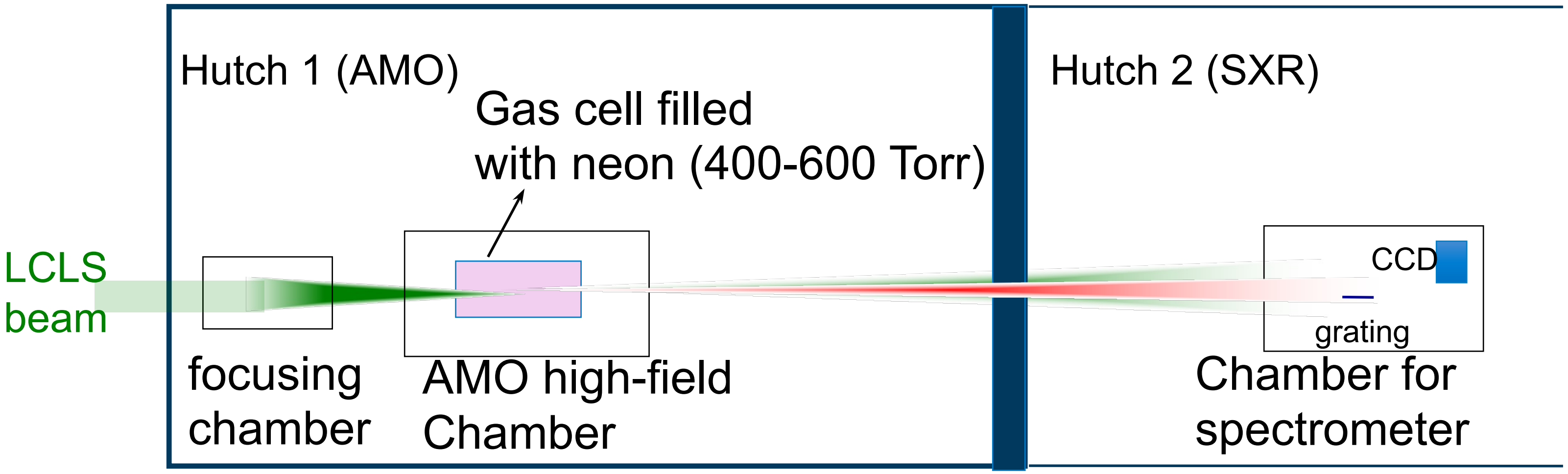
Atomic x-ray laser (Superfluorescence)



Atomic gas volume

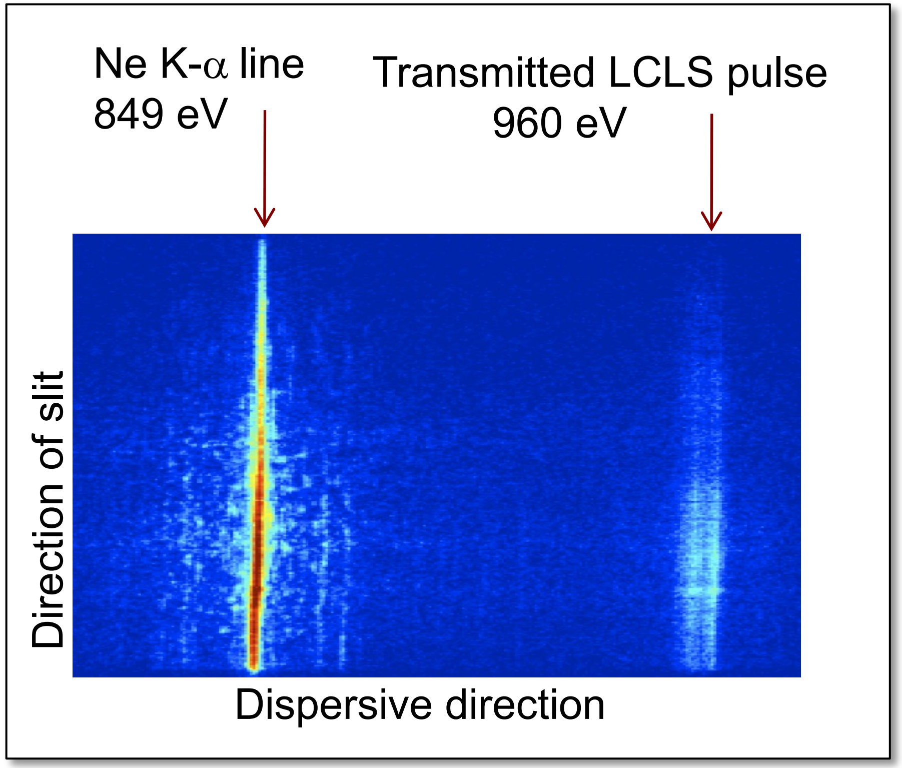
N. Rohringer & R. London, PRA **80**, 013809 (2009)

Experiment at the LCLS XFEL @ SLAC, Sept. 2010



8×10^9 photons in Ne K-α line in a single shot

1,1 μJ of energy in K-a line, corresponding to gain-length product of 21-23



$$I(z,t) = I(0,t) \cdot e^{g(z,t) \cdot n \cdot z}$$

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

conversion efficiency:
≈ 4 x 10^{-3}

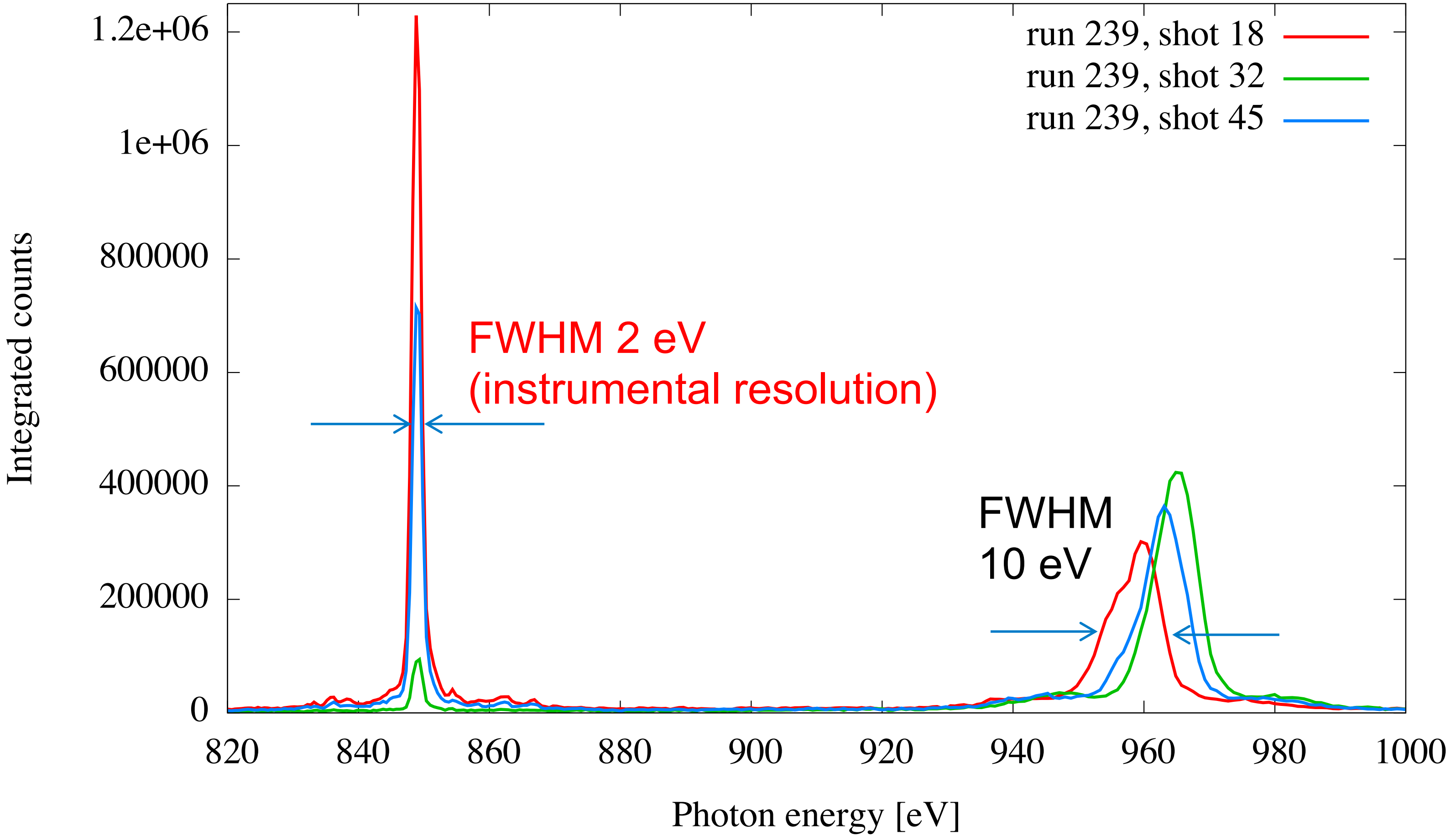
Input:
LCLS pump at 960 eV
pulse energy: 1.4 mJ (0.25 mJ on target)
focus diameter: ≈ 4 micron
Pulse duration: 40 fs

Gas pressure: 500Torr
Interaction length: 1.6 cm

Rohringer et al., *Nature* **481**, 488 (2012)

Integrated spectrum for three sample shots

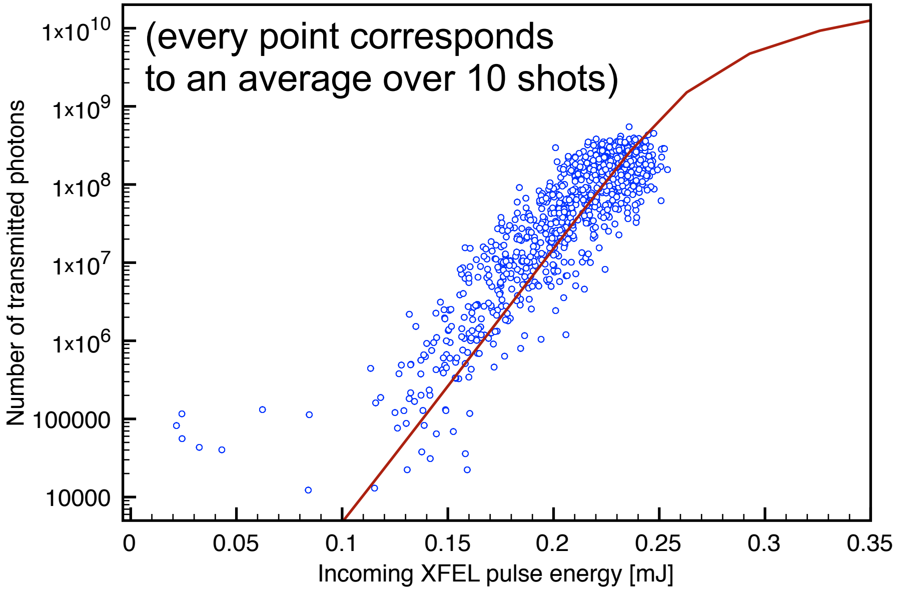
Stable spectrum, but high pulse-energy fluctuations from pulse to pulse



Rohringer et al., *Nature* **481**, 488 (2012)

Pumping-power dependence of Ne K-α transition

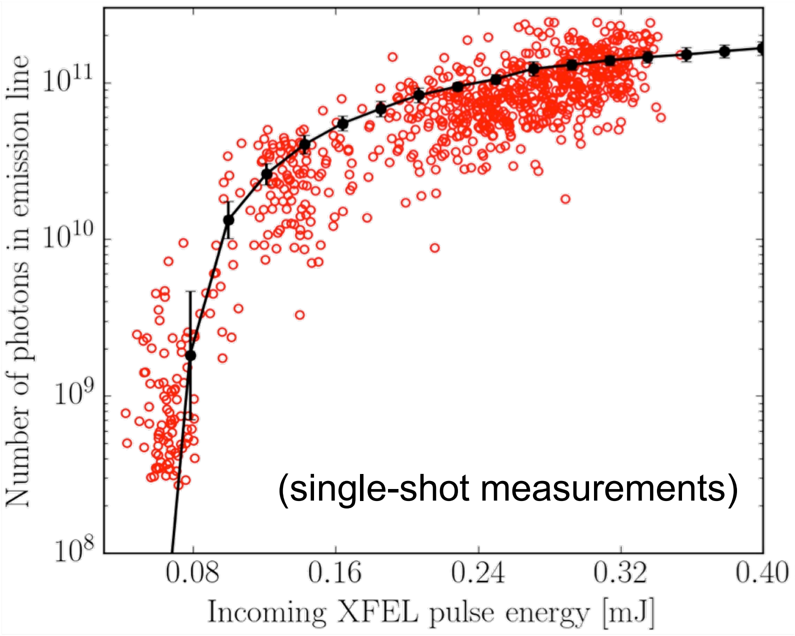
High gain-length products of 19-21 @ 0,25 mJ FEL pulse energy



(every point corresponds to an average over 10 shots)

1st experiment, Sept. 2010

Saturation of the amplification, > 10^{11} detected photons per pulse



(single-shot measurements)

2nd experiment, Aug. 2011

Rohringer et al., *Nature* **481**, 488 (2012)
Weninger et al., Phys. Rev. Lett. **111**, 233902 (2013).

Theory Intermezzo

Coherent x-ray pulses of narrow spectral bandwidth & high intensity

Jožef Stefan
Institute
Ljubljana, Slovenia

S. Chuchurka

A. Benediktovitch
V. Sukharnikov

A. Halavanau

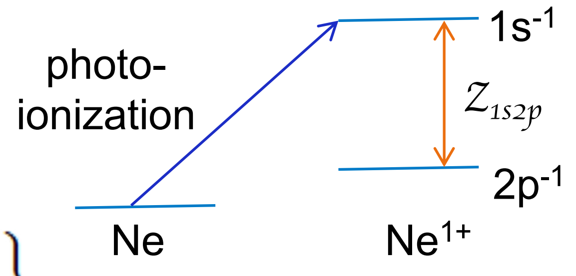
Š. Krušič

C. Weninger

Maxwell-Bloch approach for open quantum system

Ionisation of ground state creates inner-shell holes in ionic density matrix

Spatio-temporal evolution of
ground-state population and ionic densit matrix:



$$\frac{\partial \rho_0(\tau,z)}{\partial \tau} = -\sigma_{1s}J_p(\tau,z)\rho_0(\tau,z) - \sigma_{2p}J_p(\tau,z)\rho_0(\tau,z)$$

$$\frac{\partial \rho_{1s1s}(\tau,z)}{\partial \tau} = \sigma_{1s}J_p(\tau,z)\rho_0(\tau,z) - \Gamma_{1s}\rho_{1s1s}(\tau,z) + \left\{ i\rho^*_{1s2p}(\tau,z)\frac{\mu\mathscr{E}(\tau,z)}{2} + c.c. \right\}$$

$$\frac{\partial \rho_{2p2p}(\tau,z)}{\partial \tau} = \sigma_{2p}J_p(\tau,z)\rho_0(\tau,z) + \left\{ i\rho_{1s2p}(\tau,z)\frac{\mu\mathscr{E}^*(\tau,z)}{2} + c.c. \right\}$$

$$\frac{\partial \rho_{1s2p}(\tau,z)}{\partial \tau} = -\frac{\Gamma_{1s}}{2}\rho_{1s2p}(\tau,z) - i(\rho_{1s1s}(\tau,z) - \rho_{2p2p}(\tau,z))\frac{\mu\mathscr{E}(\tau,z)}{2},$$

Macroscopic polarization: $\mathscr{P} = 2nz_{1s2p}\rho_{1s2p}$

1D Maxwell equations (slow varying envelope, paraxial wave approximation)

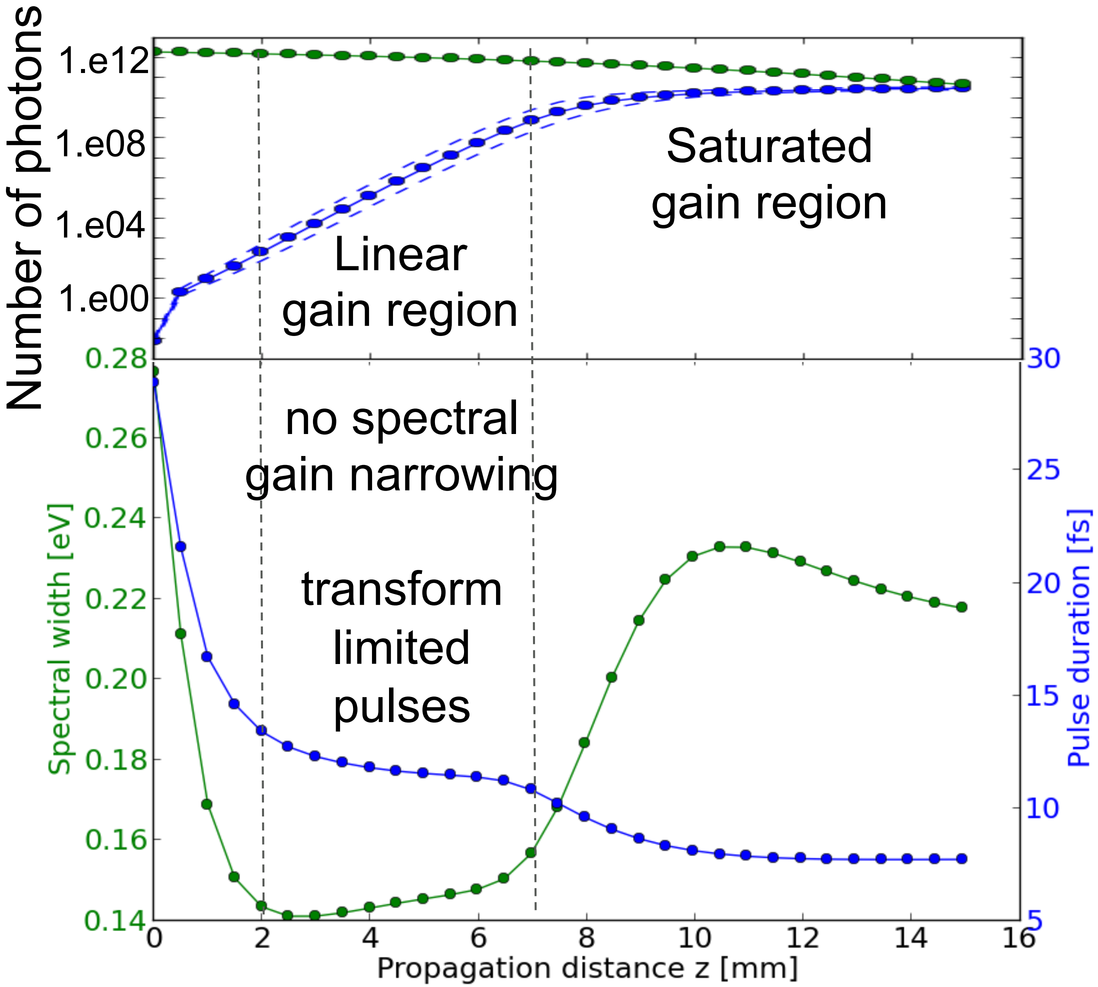
$$\frac{\partial \mathscr{E}}{\partial z} + \frac{1}{c}\frac{\partial \mathscr{E}}{\partial t} = i\frac{\mu_o \omega^2}{2k}\mathscr{P} + S \qquad \frac{\partial J_p(\tau,z)}{\partial z} = -\rho_0(\tau,z)n\left(\sigma_{1s} + \sigma_{2p}\right)J_p(\tau,z)$$

(solved in moving frame of propagating pump light)

Weninger and Rohringer, PRA 90, 063828 (2014).

The build-up of transform-limited pulses

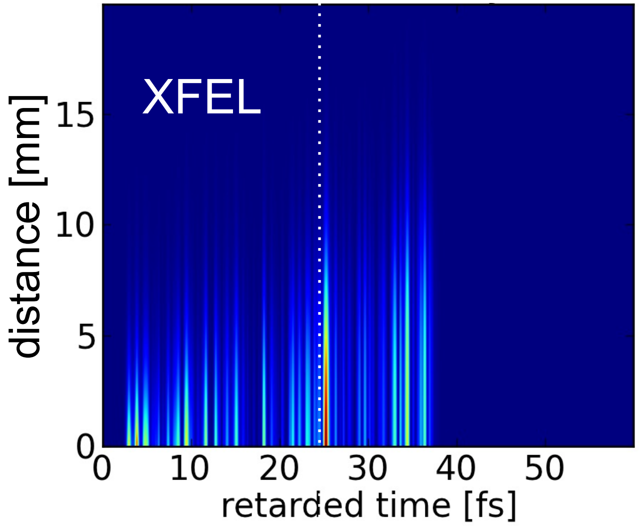
Gaussian pulse, 40 fs, 2 x 10^{12} photons; Length: 16 mm, Density: 1.6 x 10^{19} cm^{-3}



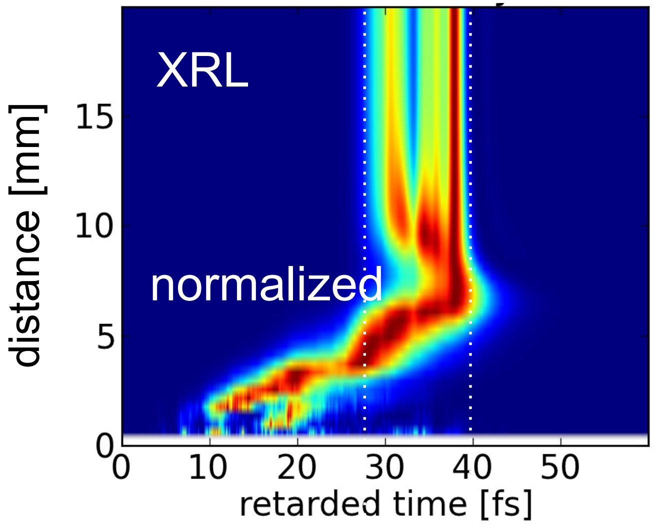
Weninger and Rohringer, PRA 90, 063828 (2014).

Prediction: phase-stable pulses of fs duration

Temporal structure of SASE pump Pulse

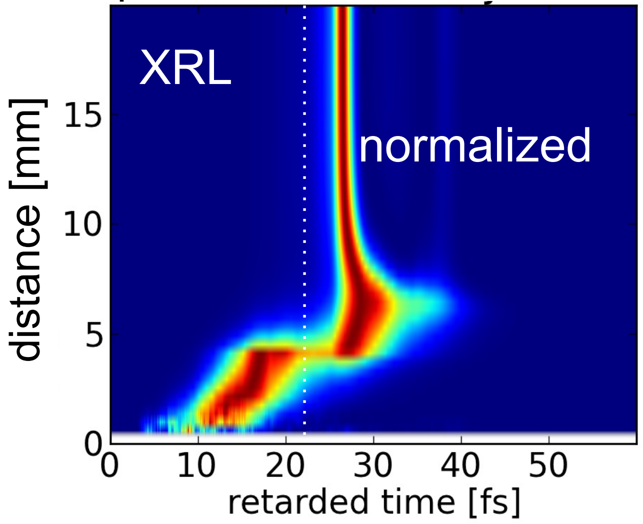


Temporal structure of emitted XRL

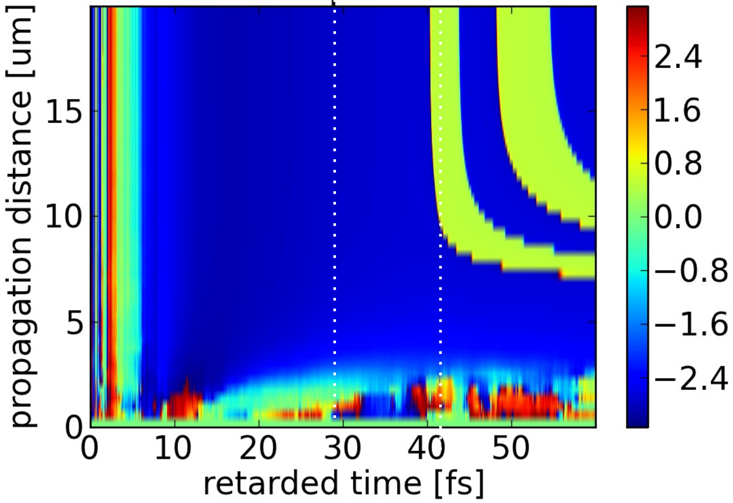


Example of 3 emission bursts

Temporal structure of emitted XRL



XRL phase

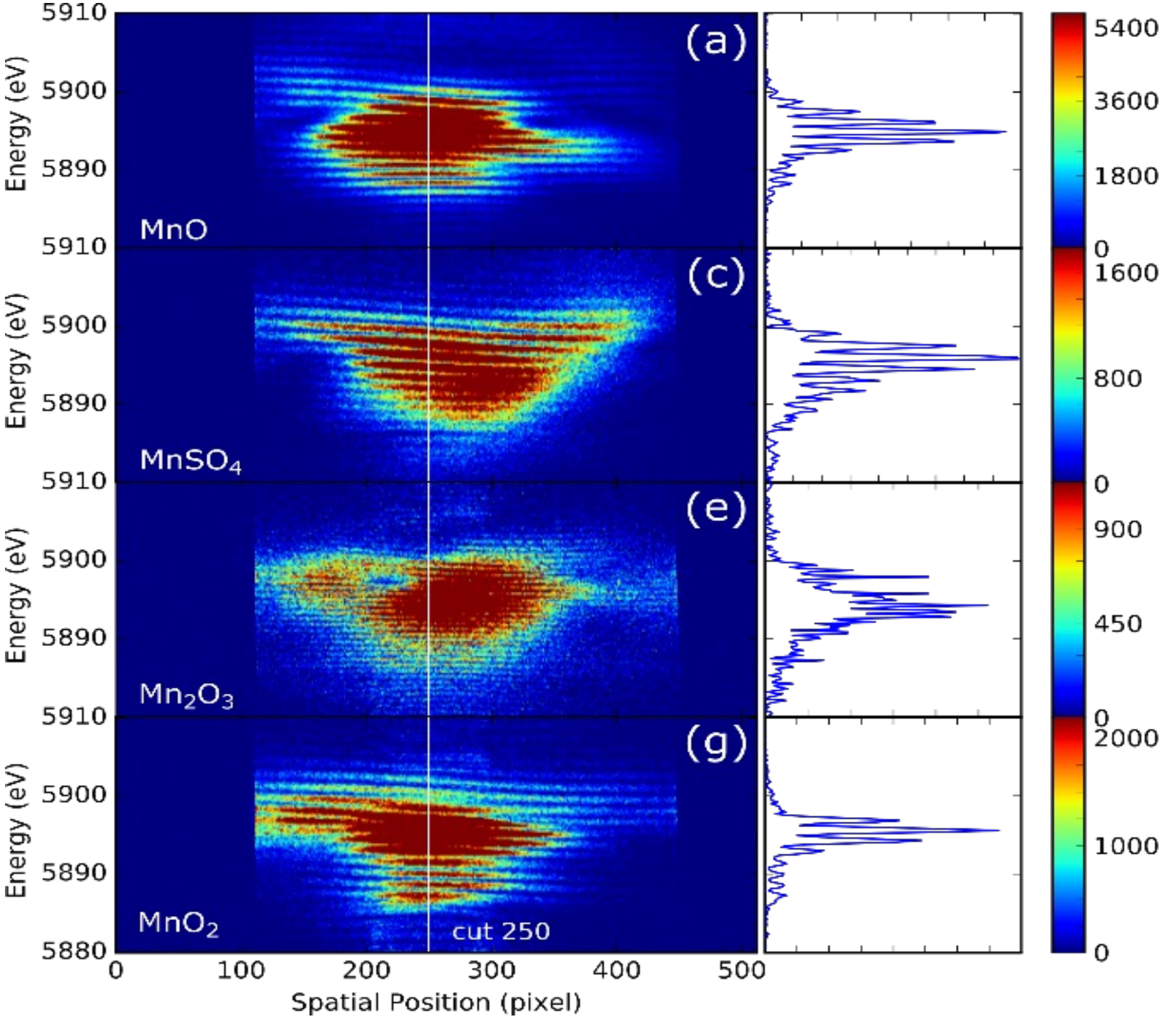


Emission bursts
are phase stable

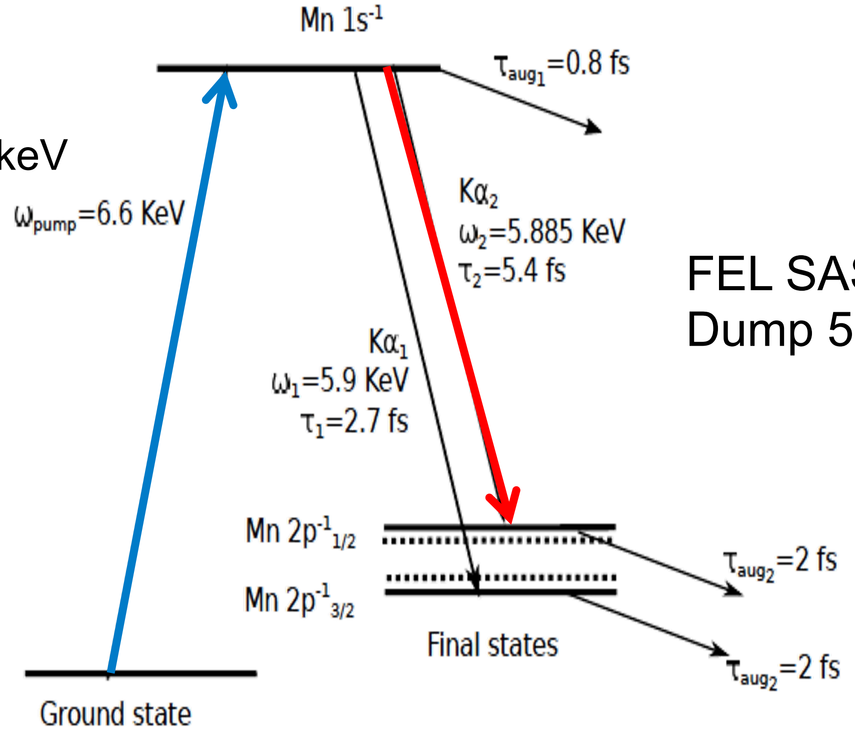
Recent results: Stimulated K-α emission

Interference pattern points to emission of 2 phase stable fs pulses of fs separation

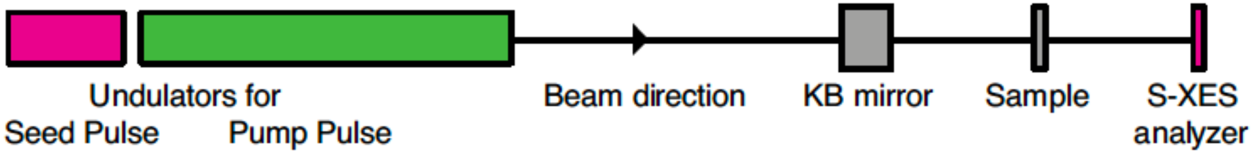
Spatial profile: several transverse modes



FEL SASE
Pump 6,6 keV



FEL SASE
Dump 5,9 keV

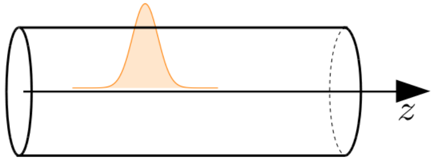


Experiment at SACLA, Nov. 2017

Y. Zhang et al., PNAS **119**, e2119616119 (2022).

3D model in paraxial symmetry for a 2-band electronic system

Field in paraxial approximation, in retarded time, in Rabi frequency units

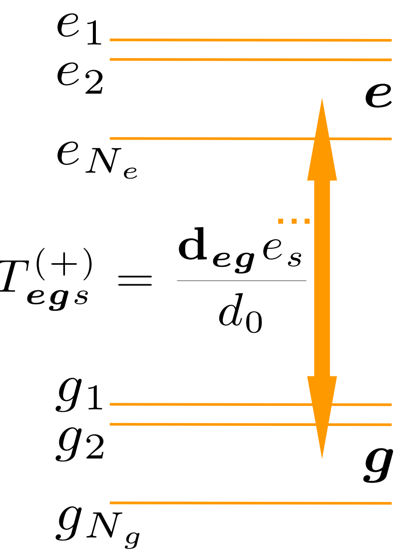


$$\mathbf{D}(\mathbf{r},t) = \sum_s \left(D_s^{(+)}(\mathbf{r},t) e^{i(k_0 z - \omega_0 t)} e_s + D_s^{(-)}(\mathbf{r},t) e^{-i(k_0 z - \omega_0 t)} e_s^* \right),$$

$$\Omega_s^{(\pm)}(\mathbf{r},t) = d_0 D_s^{(\pm)}(\mathbf{r}, t + z/c)/(\hbar\varepsilon_0)$$

$$\left[\frac{\partial}{\partial z} - \frac{i}{2k_0}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\right] \Omega_\sigma^{(+)} = -\frac{\mu}{2}\Omega_\sigma^{(+)} + i\frac{3}{8\pi}\lambda^2 \Gamma_{sp}\left(n T_{\mathbf{ges}}^{(-)} \rho_{\mathbf{eg}}^{(+)} + f_s^{(+)}\right)$$

Atomic gain medium: two set of levels, rotating-wave approximation



$$T_{\boldsymbol{egs}}^{(+)} = \frac{\mathbf{d}_{\boldsymbol{eg}} e_s}{d_0}$$

$$\frac{\partial}{\partial t}\rho_{\mathbf{ee'}} = i\left(\Omega_s^{(+)} T_{\mathbf{egs}}^{(+)} \rho_{\mathbf{ge'}}^{(-)} - \Omega_s^{(-)} \rho_{\mathbf{eg}}^{(+)} T_{\mathbf{ge's}}^{(-)}\right)$$

$$\frac{\partial}{\partial t}\rho_{\mathbf{eg}}^{(+)} = -i\Omega_s^{(+)}\left(\rho_{\mathbf{ee'}} T_{\mathbf{e'gs}}^{(+)} - T_{\mathbf{eg's}}^{(+)} \rho_{\mathbf{gg'}}\right) + f_s^{(-)*} \rho_{\mathbf{ee'}} T_{\mathbf{e'gs}}^{(+)}$$

$$\frac{\partial}{\partial t}\rho_{\mathbf{ge}}^{(-)} = +i\Omega_s^{(-)}\left(T_{\mathbf{ge's}}^{(-)} \rho_{\mathbf{e'e}} - \rho_{\mathbf{gg'}} T_{\mathbf{g'es}}^{(-)}\right) + f_s^{(+)*} T_{\mathbf{ge's}}^{(-)} \rho_{\mathbf{ee'}}$$

$$\frac{\partial}{\partial t}\rho_{\mathbf{gg'}} = i\left(\Omega_s^{(-)} T_{\mathbf{ges}}^{(-)} \rho_{\mathbf{eg'}}^{(+)} - \Omega_s^{(+)} \rho_{\mathbf{ge}}^{(-)} T_{\mathbf{eg's}}^{(+)}\right) + f_s^{(+)*} T_{\mathbf{ges}}^{(-)} \rho_{\mathbf{eg'}}^{(+)} + f_s^{(-)*} \rho_{\mathbf{ge}}^{(-)} T_{\mathbf{eg's}}^{(+)},$$

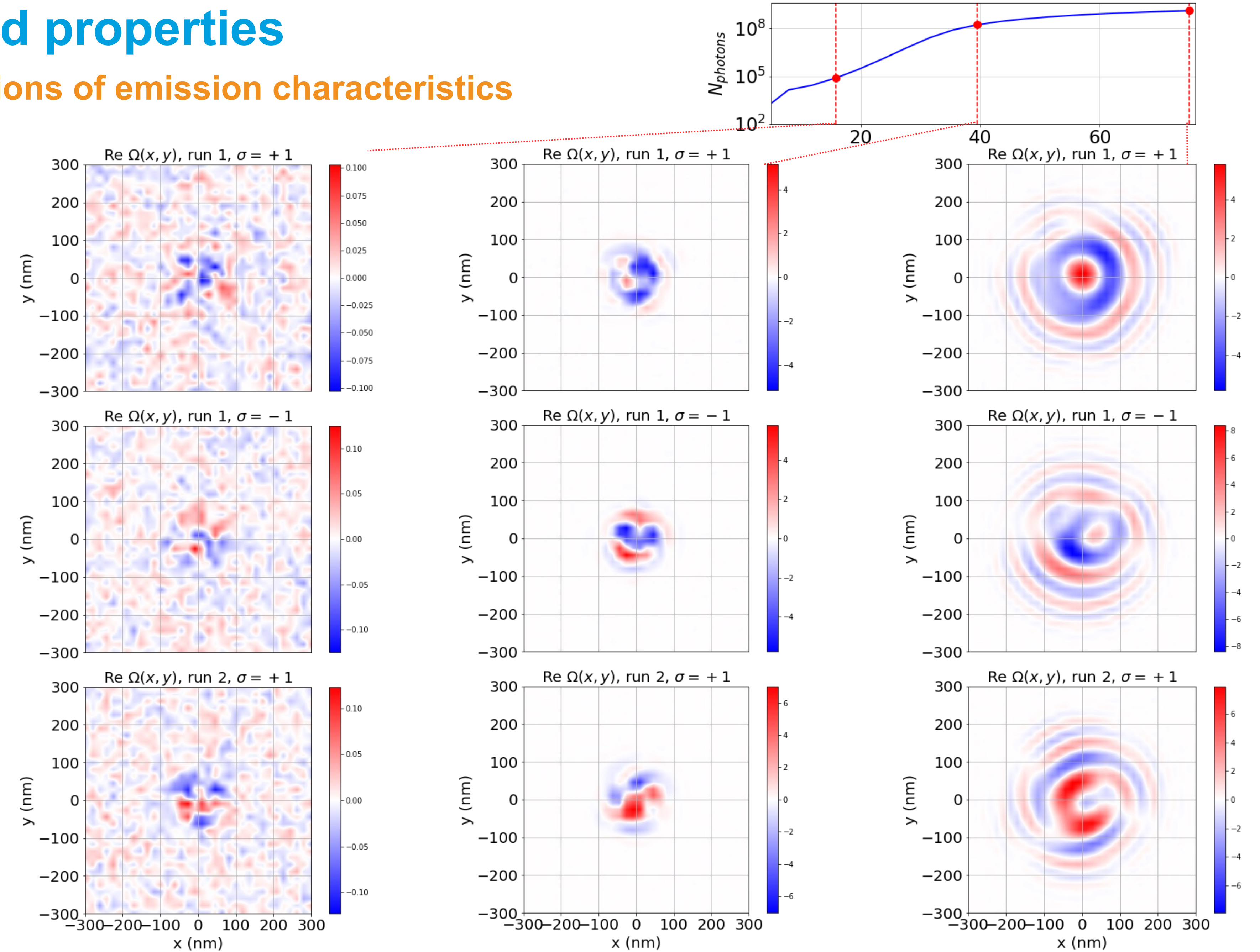
Noise correlation properties:

$$\langle f_s^{(\pm)}(\mathbf{r},t)\, f_{s'}^{(\pm)*}(\mathbf{r}',t')\rangle = \delta_{(\mathrm{Ito})}(t + z/c - t' - z'/c)\, \delta_{(\mathrm{space})}(\mathbf{r} - \mathbf{r}')\, \delta_{s\,s'}.$$

A. Benediktovitch, S. Chuchurka et al., arXiv:2303.00853 (submitted to PRA)

Transverse field properties

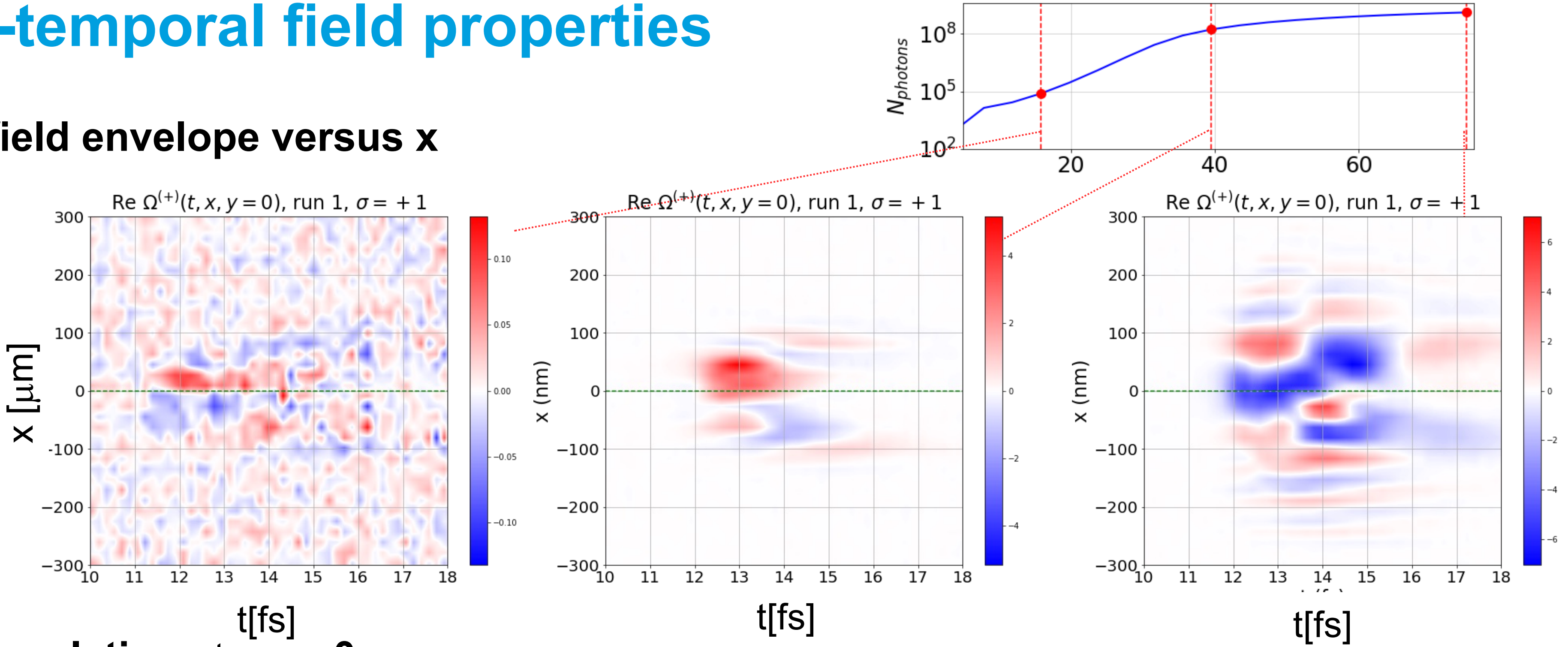
Shot-to-shot fluctuations of emission characteristics



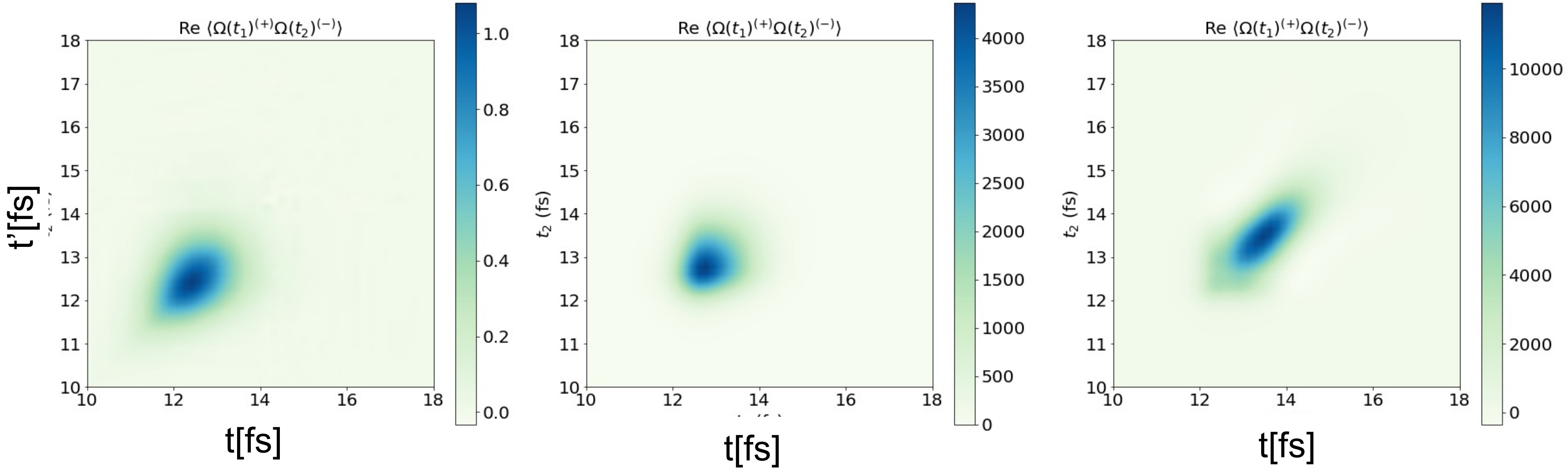
A. Benediktovitch, S. Chuchurka et al., arXiv:2303.00853 (submitted to PRA)

Spatio-temporal field properties

Temporal field envelope versus x



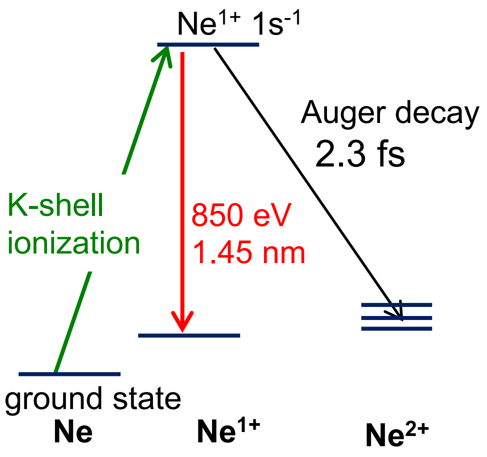
Temporal correlation at x=y=0



Amplified spontaneous x-ray emission (X-ray superfluorescence)

Photoionization K-α laser – from 1st demonstration to chemical analysis

Ne 849 eV (gas)

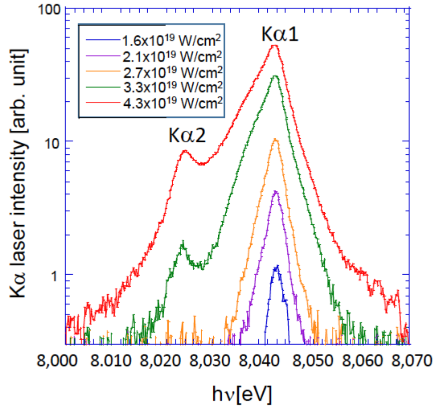


Rohringer et al.,
Nature **481**, 488 (2012).

Scheme first proposed by
Duguay and Rentzepis,
Appl. Phys. Lett. 10, 350 (1967).

Emission in forward direction,
up to e^{21} amplification of
spontaneous K-α emission

Cu 8,04 keV (solid)

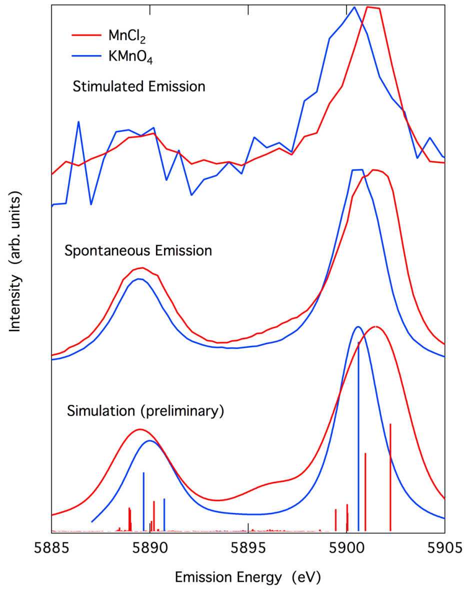


Yoneda et al.,
Nature **524**, 446 (2015).

Hard x-ray laser,
seeded by 2-color FEL
operation

Si L lines 70-100 eV (solid)
M. Beye et al.,
Nature **501**, 191 (2013)

Mn 5,9 keV (liquid)



Kroll et al.,
Manuscript in prep. (2016).

Stimulated emission for
Chemical analysis under
single FEL pulse
exposure

Stimulated Emission Spectroscopy

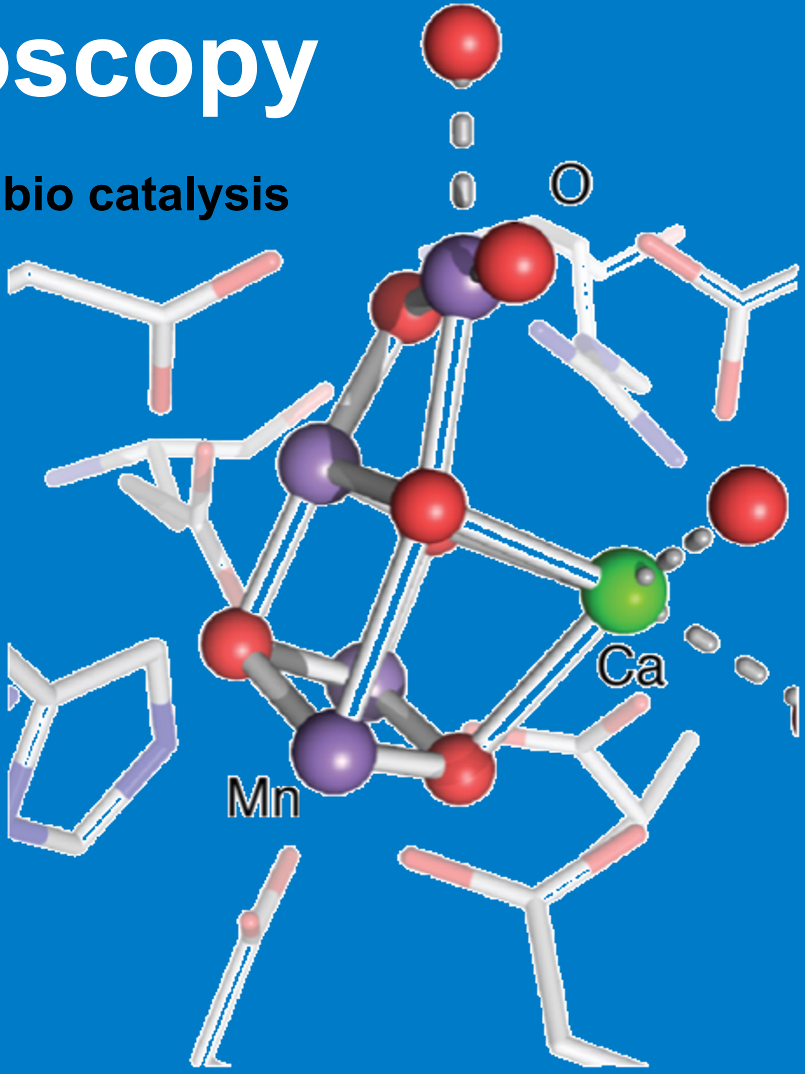
Characterization of the catalytic pathways and intermeditates in bio catalysis

X-ray supfluorescence maintains chemical sensitivity

U. Bergmann
T. Kroll
A.Marinelli
A. Lutman
S. Boutet
A. Aquila
C. Weninger

J. Yano
V. K. Yachandra
J. Kern

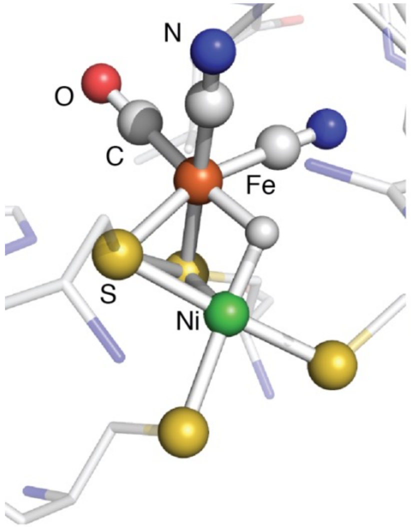
A. Benediktovitch



Mn$_4$Ca Water oxidase

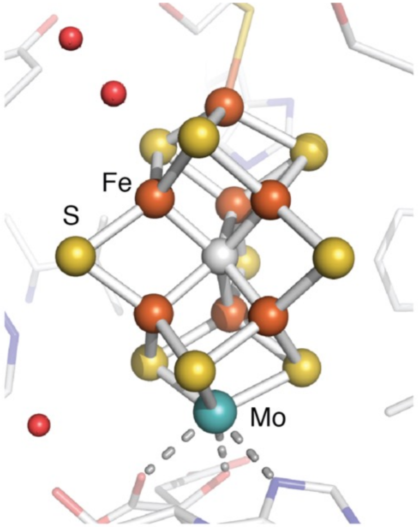
$2H_2O \rightarrow O_2 + 4H^+$

Importance of Metals in Biological Systems



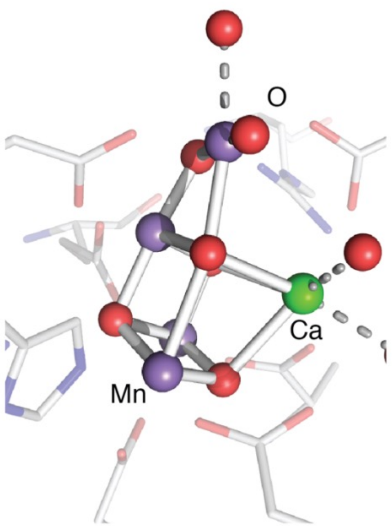
NiFe H_2ase

$2H^+ \rightarrow H_2$



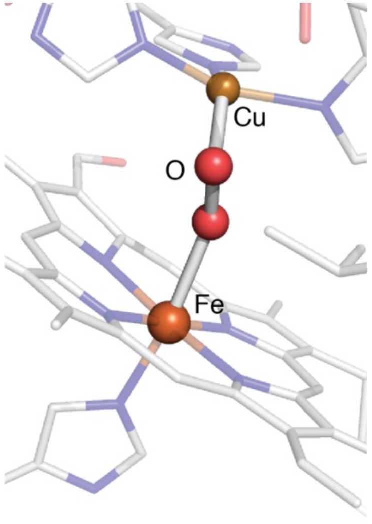
FeMoS Nitrogenase

$N_2 \rightarrow NH_3$



Mn_4Ca Water oxidase

$2H_2O \rightarrow O_2 + 4H^+$



FeCu Cyt c oxidase

$O_2 + 4H^+ \rightarrow 2H_2O$

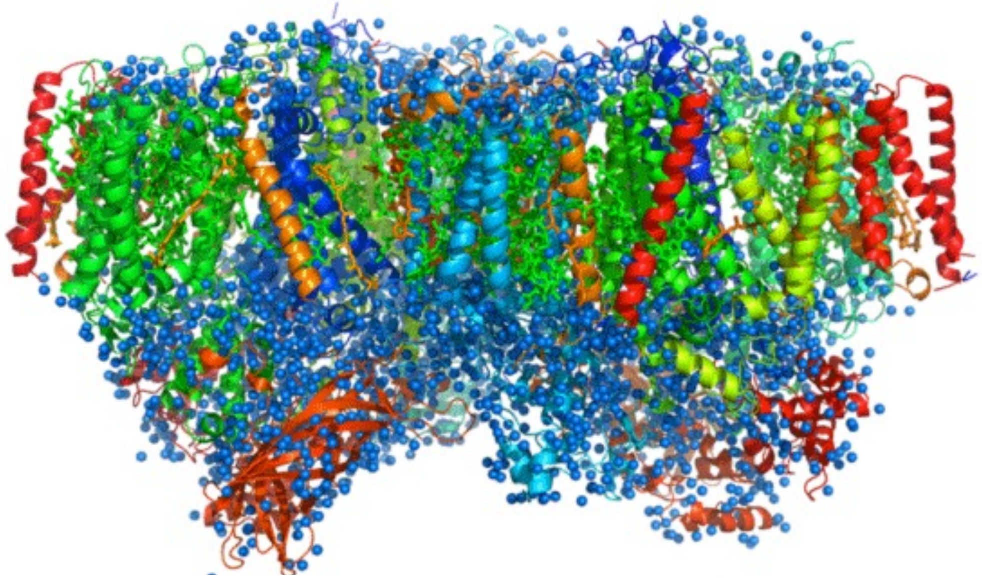
Respiration
Photosynthesis
Nitrogen fixation
RNA synthesis, Detoxification…

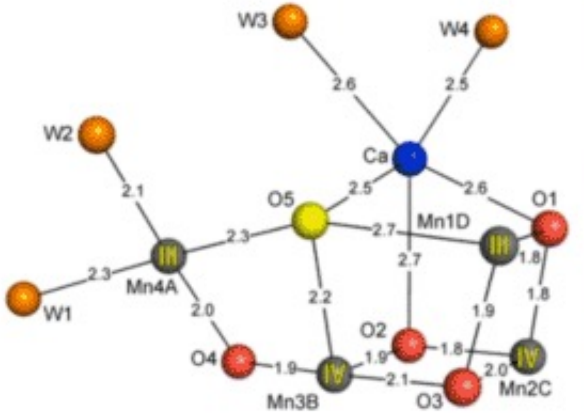
Catalyze thermodynamically demanding reactions under physiological conditions with minimized driving force!

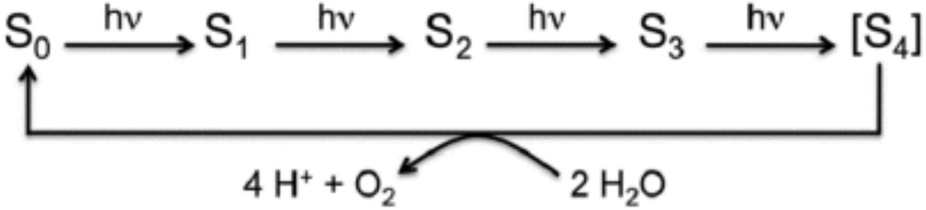
Holy Grail:
Characterization of the Catalytic Pathways and Intermediates

Slide with courtesy to U. Bergmann

Structure – Function Relationship







Coherent diffractive imaging:

Molecular structure in reciprocal space

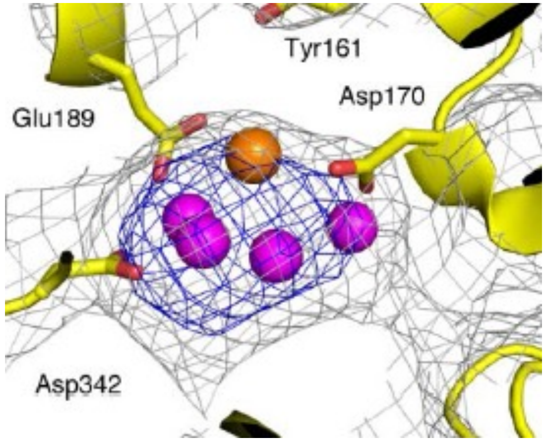
Structure (atomic positions) doesn’t give us the complete picture.
Consider for example:

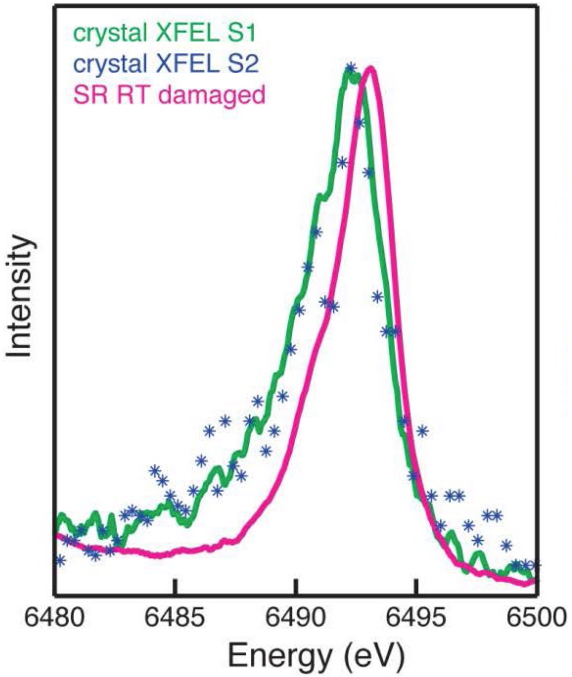
Pure electronic excitation transfer, energy transfer to reaction centers

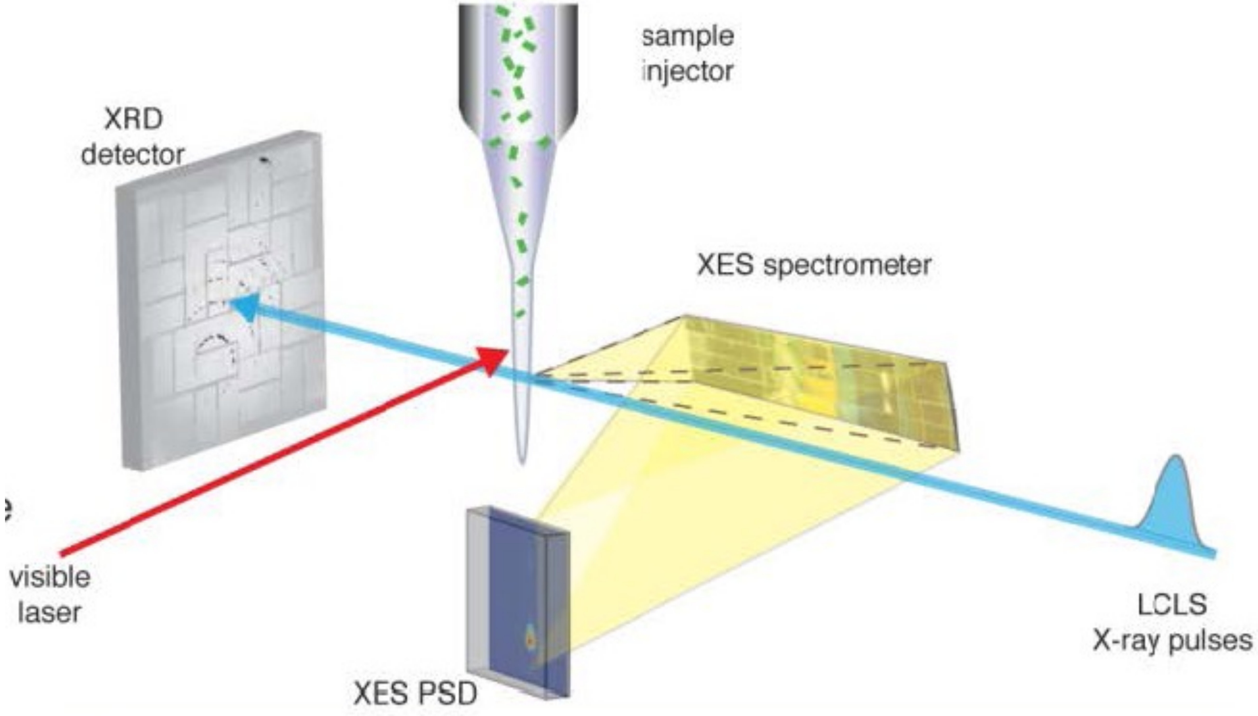
Change of valence electron distribution (chemistry) during catalytic reaction

X-ray spectroscopy
a complementary tool to
x-ray diffraction
to tackle these questions

Amplification of x-ray emission signal
Single-shot high-resolution spectroscopy







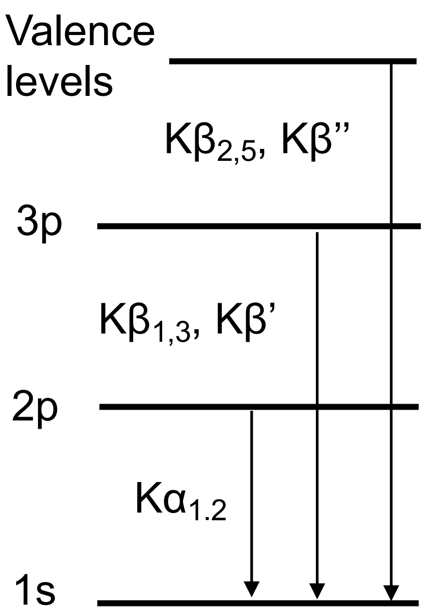
Probing the electronic structure of the Mn_4CaO_5 cluster in the oxygen-evolving complex of PS II

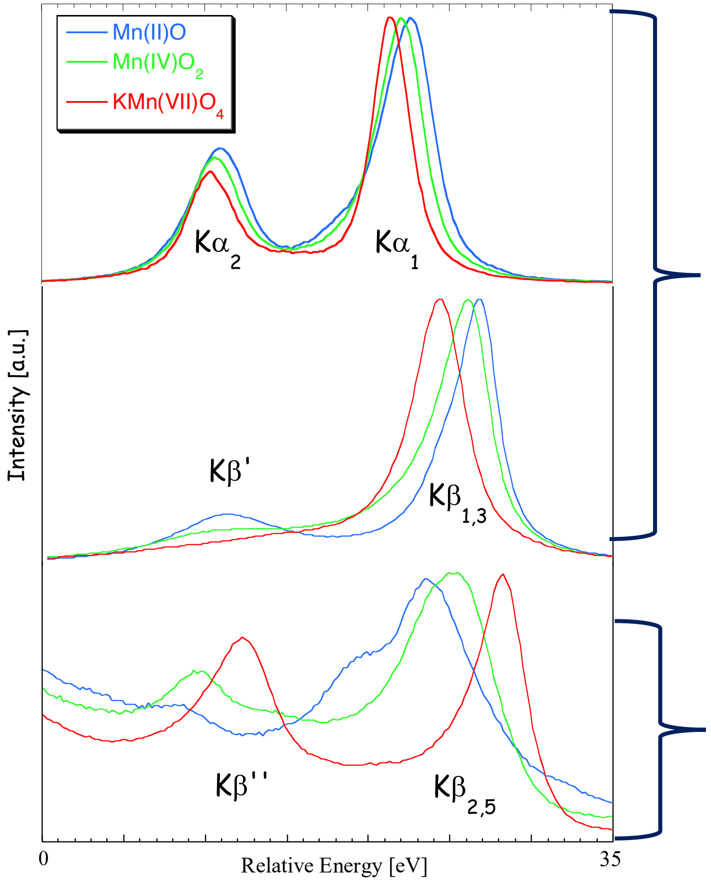
J. Kern et al, Sciencexpress, 14 February 2013, science.1234273

Towards stimulated emission spectroscopy

X-ray emission reveals chemically relevant information

Level Diagram





Spin/oxidation state of transition metals

Valence orbitals:
ligand type, structure, covalency, ligand protonation, etc.

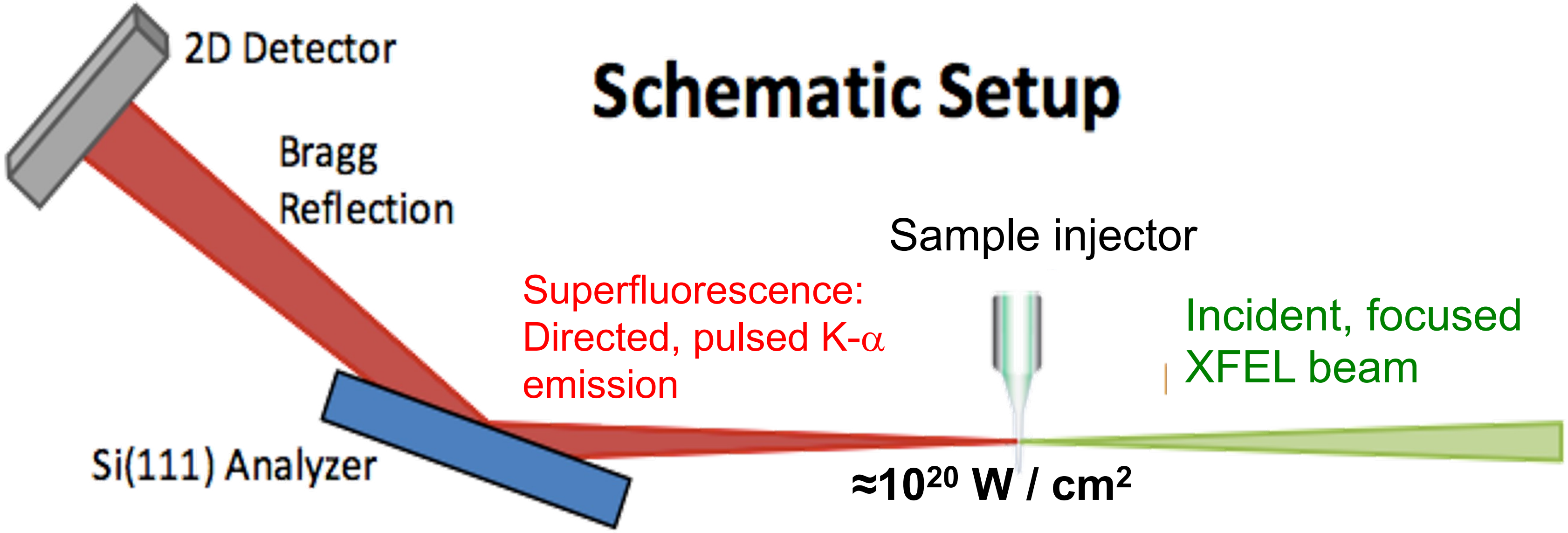
For reviews see: Glatzel & UB, *Coord. Chem. Rev.*, **249**, 65-95, (2005)
Pollock & DeBeer, *Accounts of Chemical Research* (2015)

U. Bergmann et al., *J. Synchr. Rad.* 8, 199 (2001)

Slide with courtesy to U. Bergmann

K-α lasing of Mn-salt aqueous solutions

10^{20} W/cm^2 on target creates population inversion on K-α transition



≈150 nm focus
≈ 10^{11} ph/pulse
≈ 50 fs pulse duration

Samples: $MnCl_2$ solution (5 and 1 molar), $KMnO_4$ (0.4 molar)

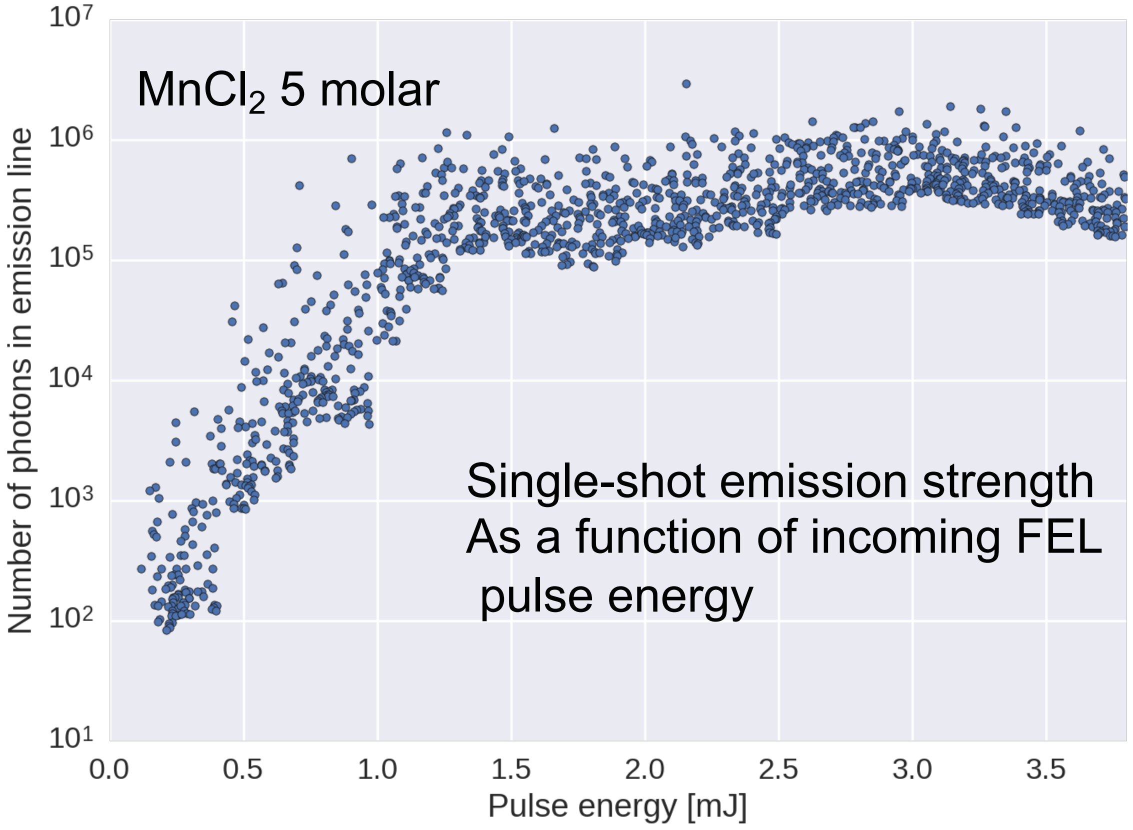
Collect 100% of emission in forward direction

Use flat analyzer crystal – high efficiency

Experiment @ CXI instrument (LCLS), July 2015

Gain Curve for the 5.9 keV Kα_1 emission

Exponential amplification over 4 orders of magnitude



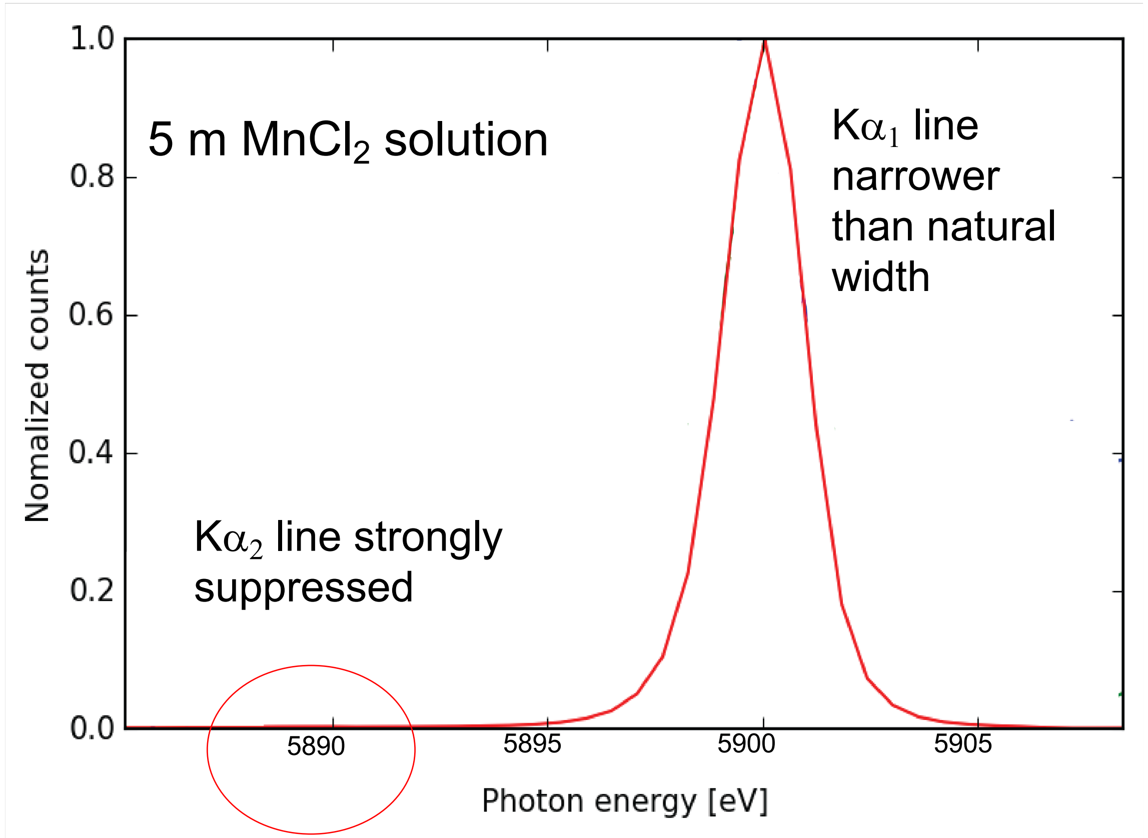
Single-shot emission strength
As a function of incoming FEL
pulse energy

Kroll et al., *Phys. Rev. Lett.* **120**, 133203 (2018).

Observation of strong lasing in Mn at 5.9 keV Kα_1

Strong gain up to 10^6 detected Mn Kα photons

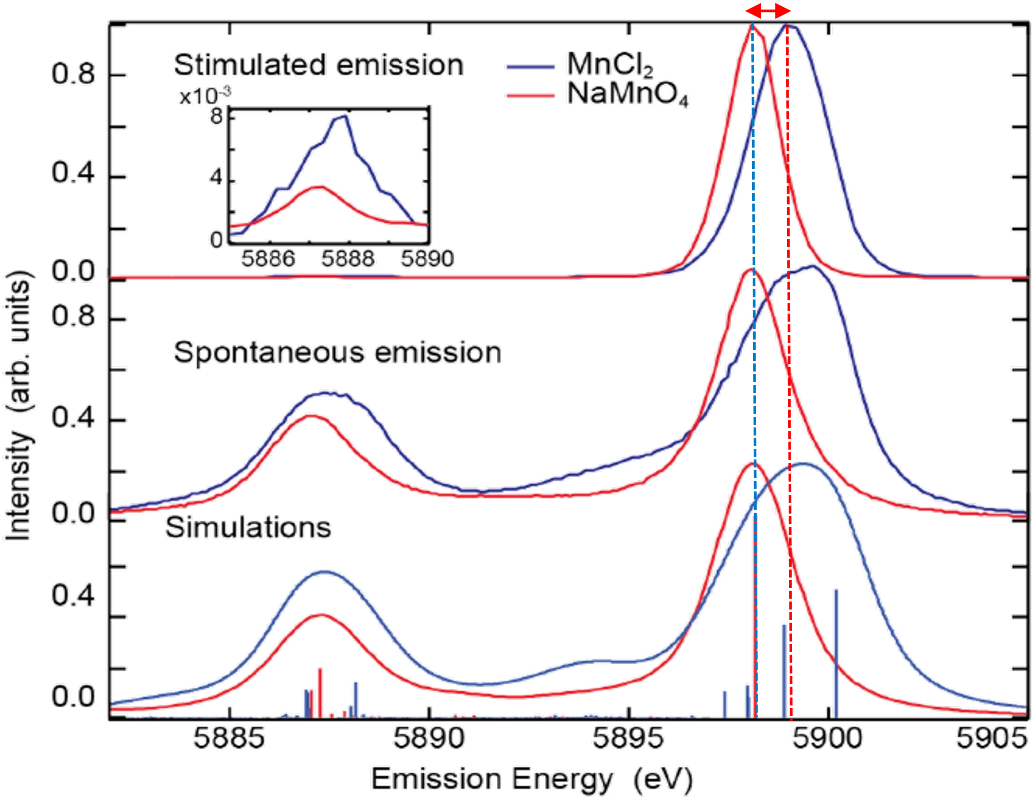
Single shot spectrum



5 m $MnCl_2$ solution

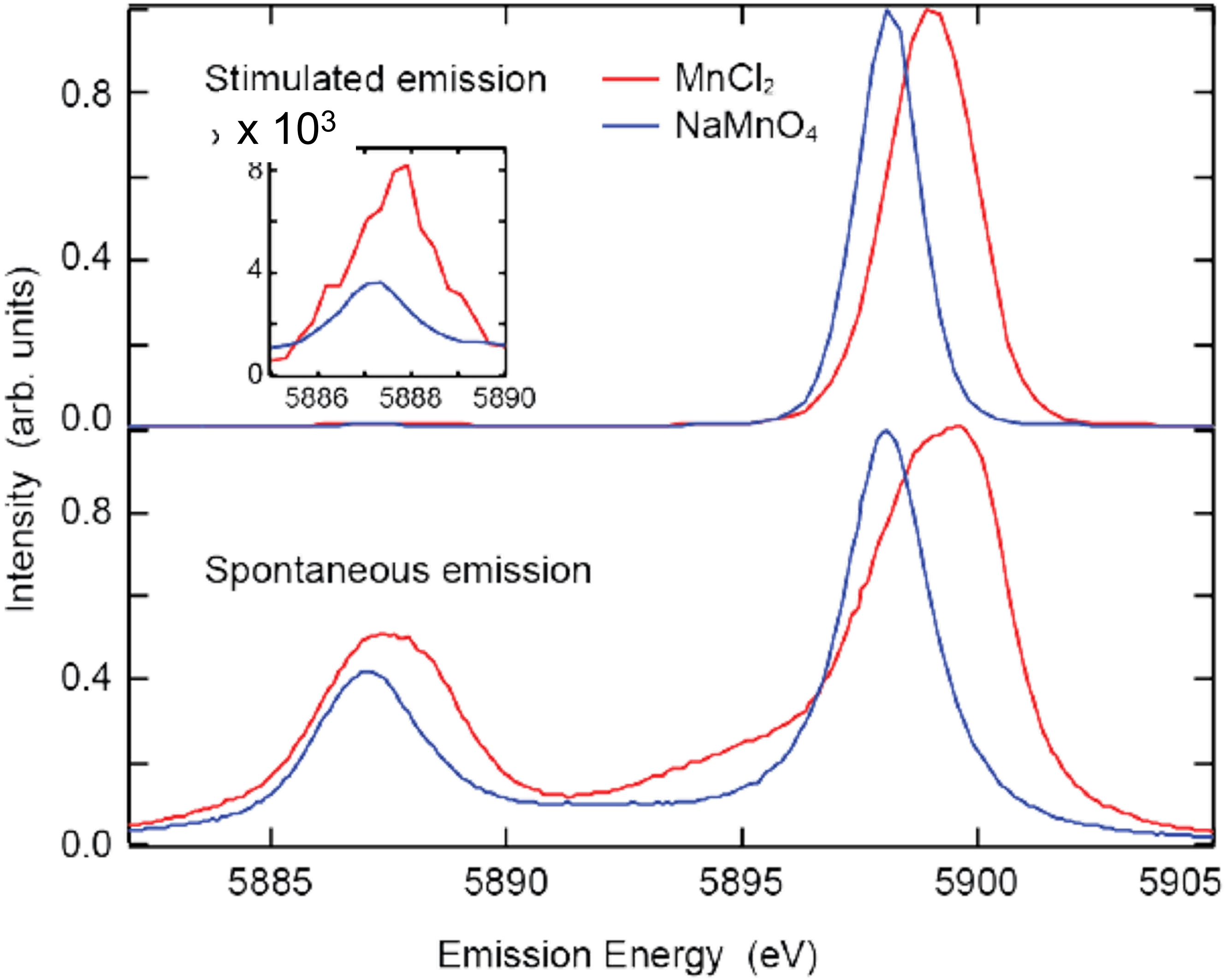
Kα_1 line narrower than natural width

Kα_2 line strongly suppressed



Kroll et al., *Phys. Rev. Lett.* **120**, 133203 (2018).

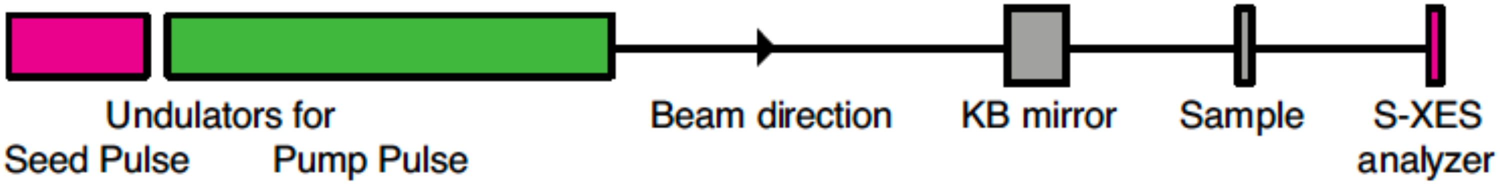
Chemical Sensitivity



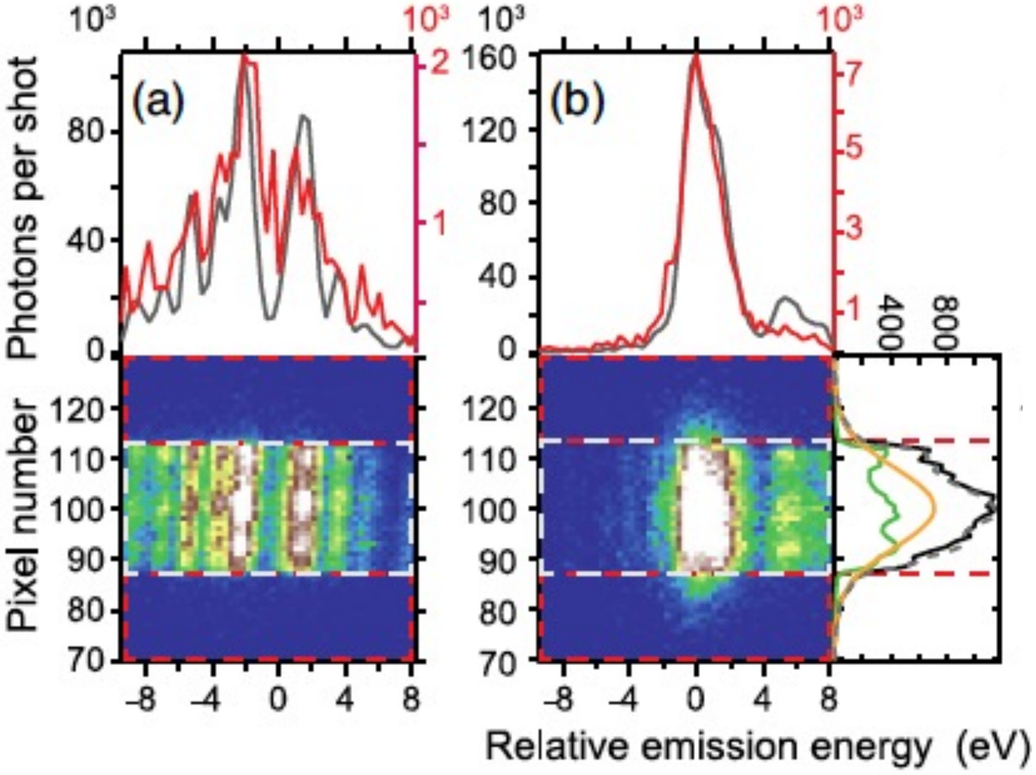
Stimulated emission retains the expected chemical shift !

Stimulated K-β emission in Mn salts – 2 colour FEL operation

Statistical evidence of stimulated K-β emission



Undulators for
Seed Pulse
Pump Pulse
Beam direction
KB mirror
Sample
S-XES analyzer



Analysis:
Spatial spectral profile

So far, proof-of-principle
(no improvement
on spectral information)

Kroll et al., *Phys. Rev. Lett.* **125**, 037404 (2020)

X-ray Laser Oscillator (XLO)

Coherent x-ray pulses of narrow spectral bandwidth & high intensity

SLAC NATIONAL ACCELERATOR LABORATORY

C. Pellegrini
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Y. Feng
Z. Huang
A. Marinelli
A. Lutman
F. J.Decker
S. Carbajo
F. Fuller

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Noah Welke

DESY.

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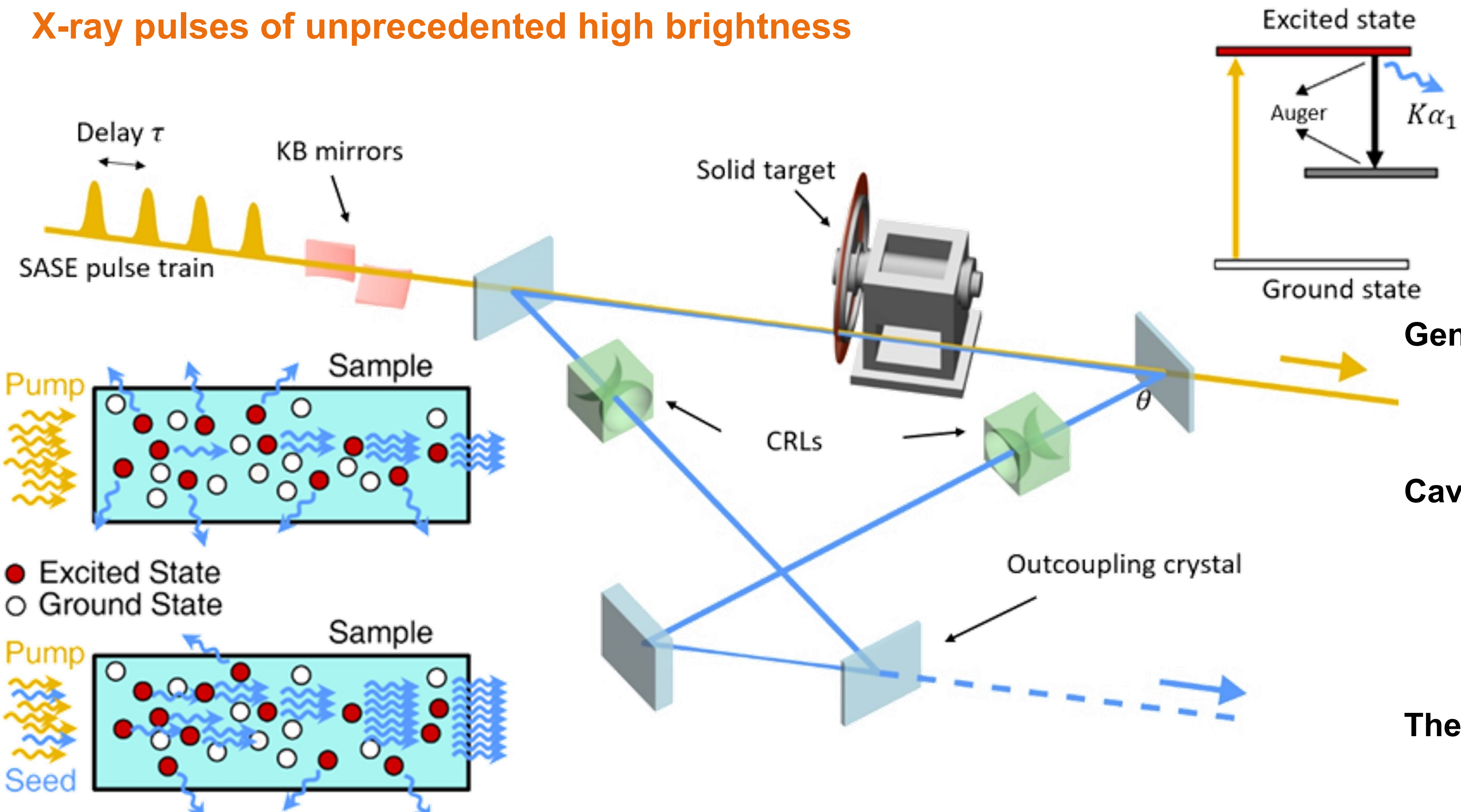
S. Chuchurka
V. Sukharnikov

Jožef Stefan
Institute
Ljubljana, Slovenia

Š. Krušič

Scheme of X-ray Laser Oscillator (XLO)

X-ray pulses of unprecedented high brightness



Picture with courtesy to A. Halavanau

Challenges

Generation of multiple bunches
- with 10 ns spacing
- acceleration in Cu linac

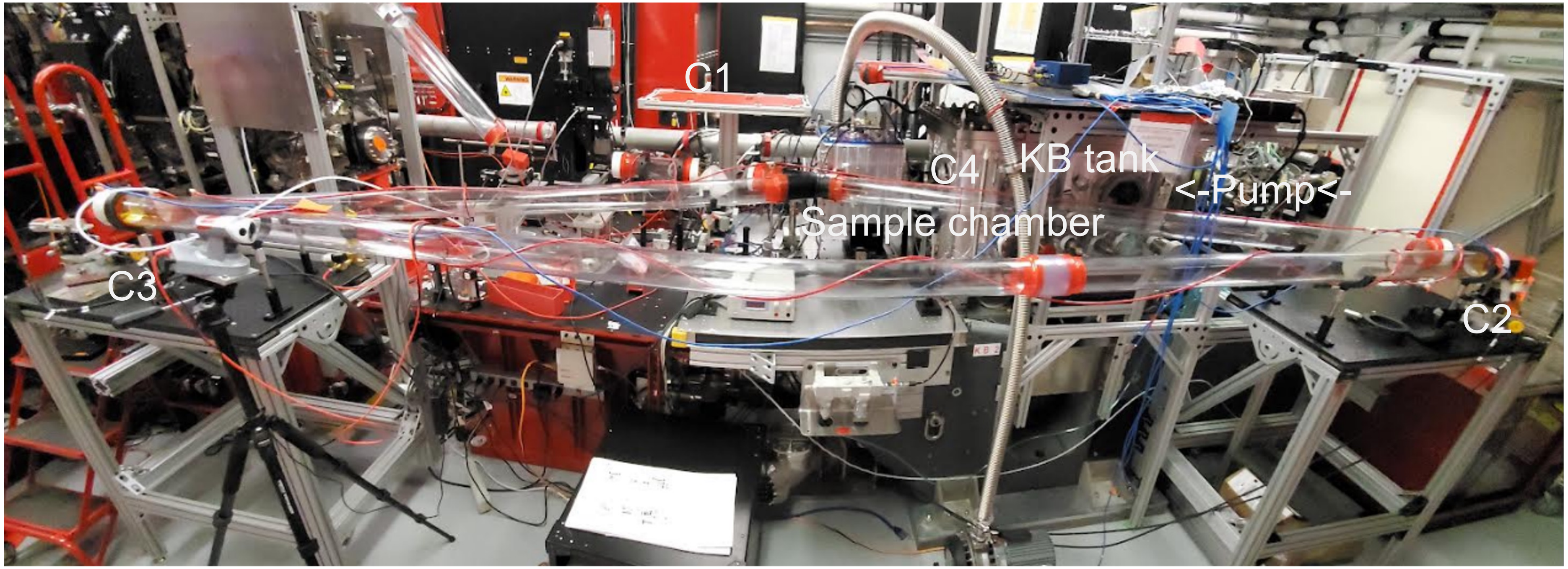
Cavity design:
- minimize losses
- maximize acceptance angle
- thermal issues
- Outcoupling of X-ray pulses

Theory:
- 3D simulations
- Quantitative predictions
- Optimization

A. Halavanau, et al., *PNAS* **117**,15511 (2020).

Current experimental setup at CXI

Time of flight – about 35 ns

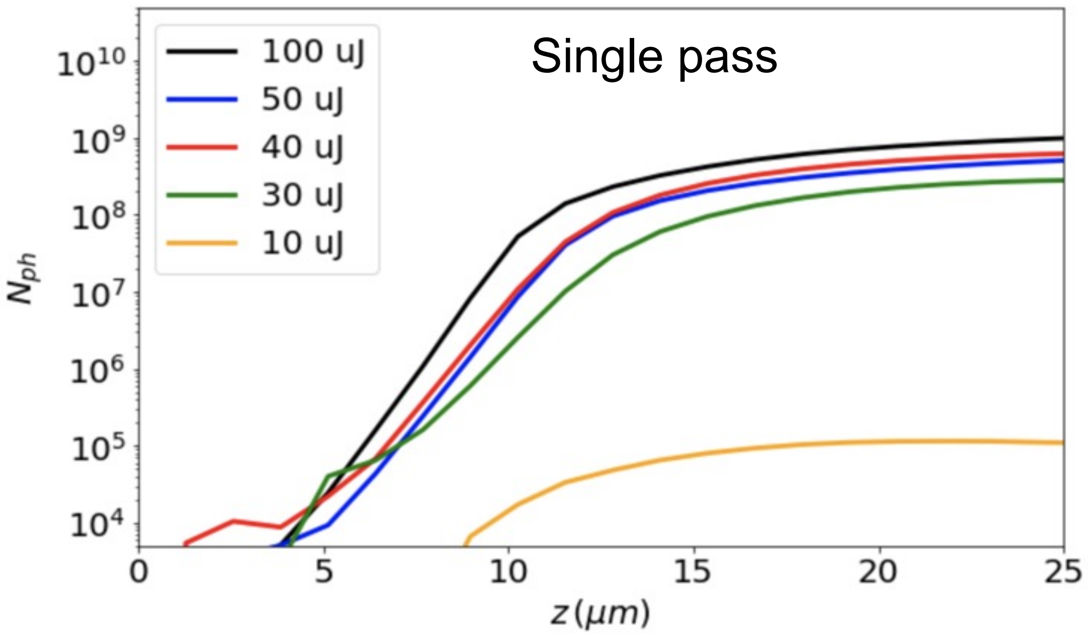


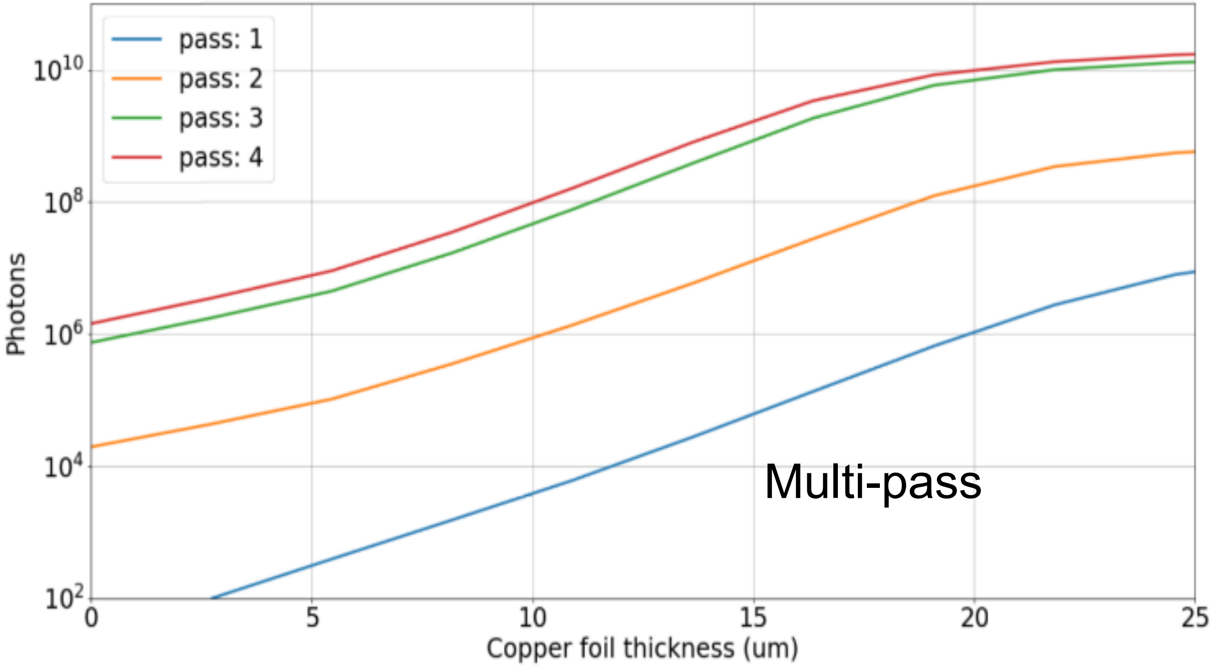
XLO v1.2, LCLS-CXI, November 15, 2022

Slide with courtesy to A. Halavanau

Numerical simulations – number of photons

Number of emitted photons at the Cu Kα_1 line as a fct. of target thickness for different pump-pulse energy



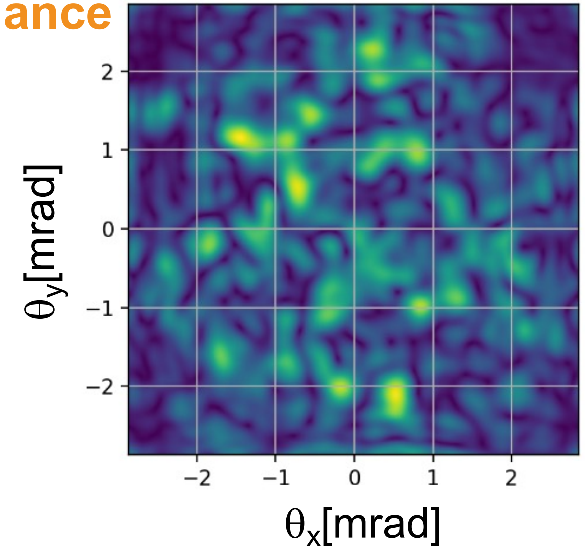


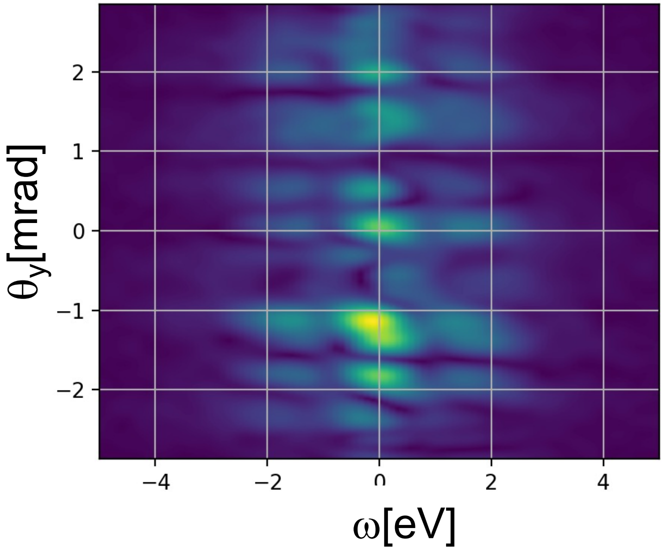
Slide with courtesy to A. Halavanau

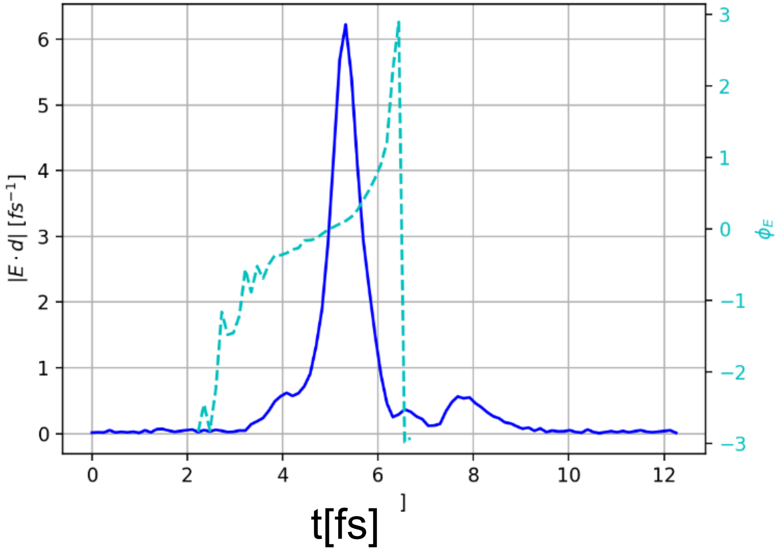
Evolution of transverse pulse properties

E(*t*, *x*=0, *y*=0, *L*)

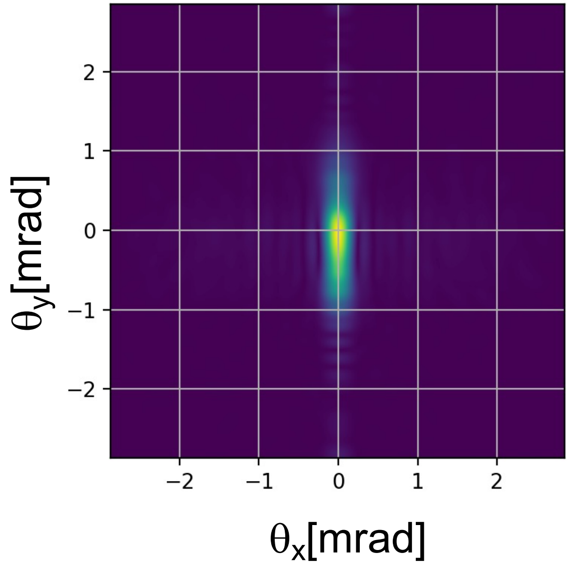
Superradiance

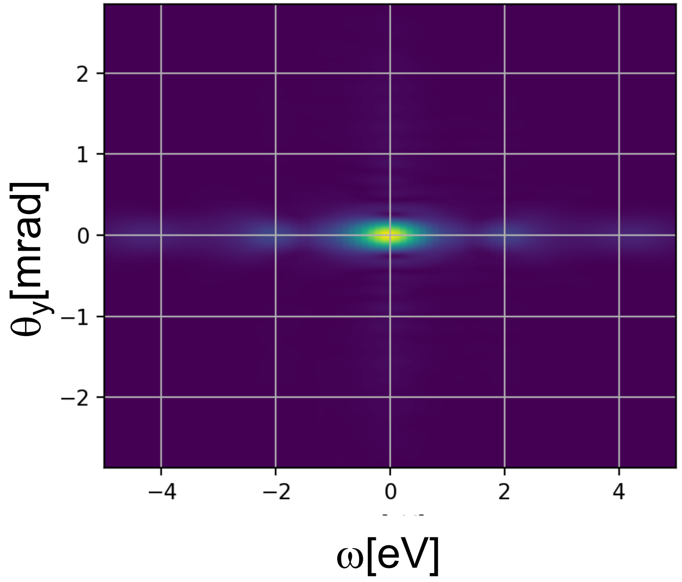

$E(\omega=0,\theta_x,\theta_y,z=150\mu m)$

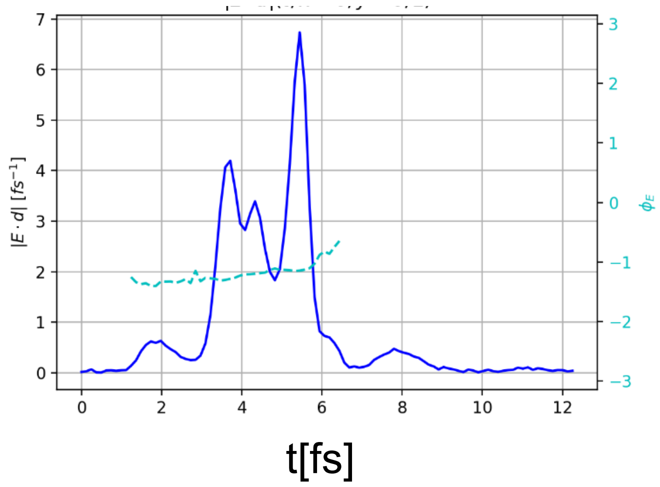

$E(\omega,\theta_x,\theta_y=0,L)$



After 3 rounds in the cavity:


$E(\omega=0,\theta_x,\theta_y,z=150\mu m)$

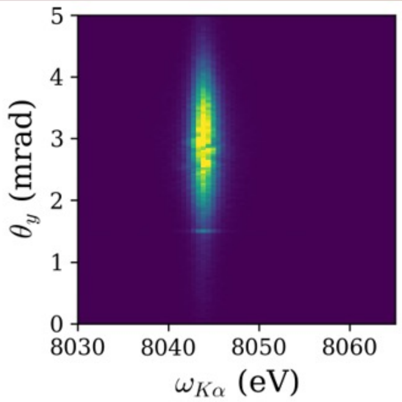

$E(\omega,\theta_x,\theta_y=0,L)$



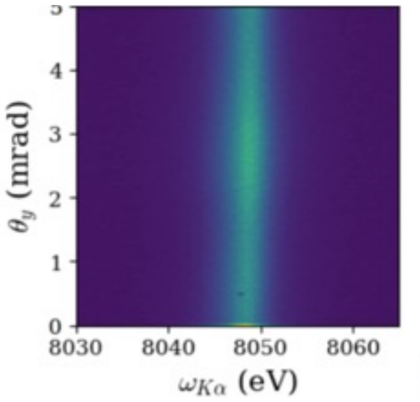
Seeding x-ray superfluorescence for improved gain

Slide with courtesy to
A. Halavanau

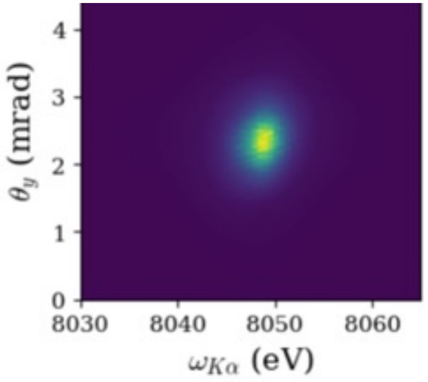
jet (ASE)
$Cu(NO_3)_2$
2.4 atoms/nm^3
up to 1 mJ pump

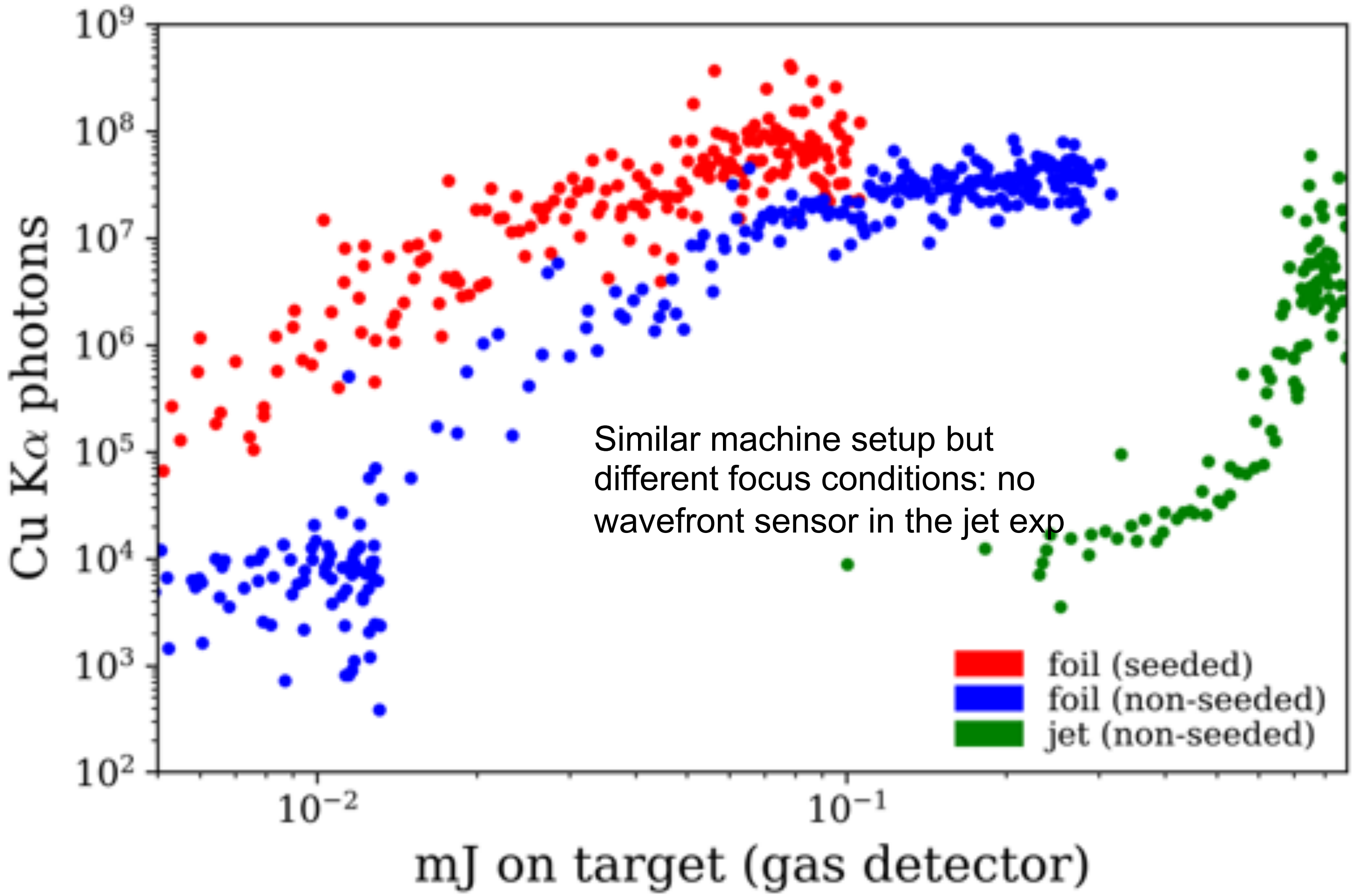


Solid foil
Cu
86 atoms/nm^3
up to 300 uJ pump



Solid foil (seeded)
Cu
86 atoms/nm^3
up to 100 uJ pump
10^4-10^5 seed photons





Similar machine setup but different focus conditions: no wavefront sensor in the jet exp

M. D. Doyle, A. Halavanau al., Optica 10, 513 (2023).

Summary and Outlook

XFELs open novel opportunities of nonlinear x-ray science

Inner-shell x-ray lasing

- Superfluorescence creates sub-fs transform limited x-ray pulses of high intensity
- Application in stimulated emission x-ray spectroscopy
- Source development: X-ray Laser Oscillator

Open PhD position (theory) and PostDoc position (experiment)

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Stasis Chuchurka

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