eli beamlines

Athens 2013, CTU18
21. 11. 2013

FJFI

X-ray Sources

Driven by high-intensity lasers

Jaroslav Nejdl

nejdl@fzu.cz

Fyzikální ústav
Akademie věd ČR, v. v. i.

projekt podporovaný:

EVROPSKÁ UNIE
EVROPSKÝ FOND PRO REGIONÁLNÍ ROZVOJ
INVESTICE DO VAŠÍ BUDOUCNOSTI

OP Výzkum a vývoj pro inovace

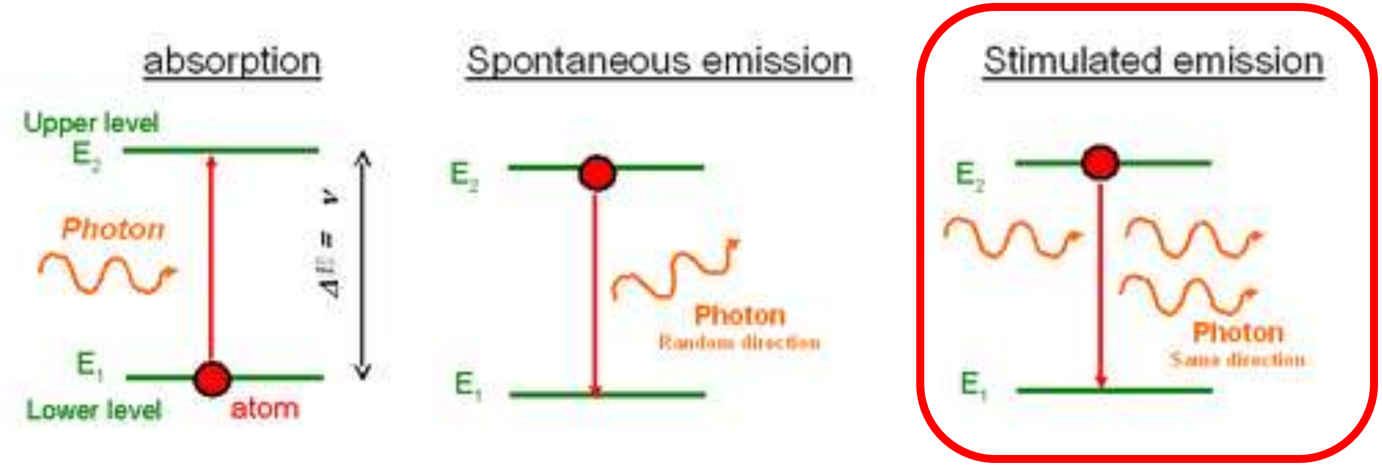
Content

- Lasers with high peak power
- Origin of EM radiation: accelerated motion of charge
- High order Harmonic Generation
- Plasma-based X-ray lasers
- Laser-driven relativistic electron beams
  - Plasma betatron
  - Compton back-scattering
- X-ray plasma source (Kα)
- X-ray sources within ELI Beamlines research facility

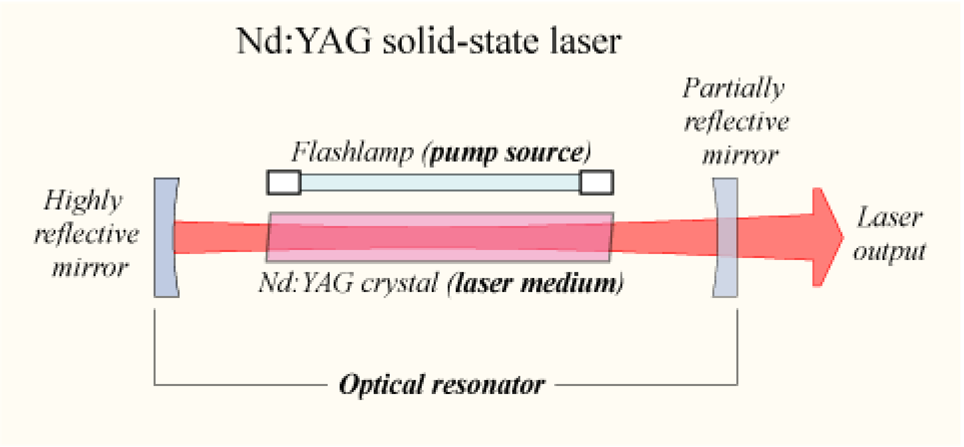
Lasers with high peak power

- Basic principles of laser

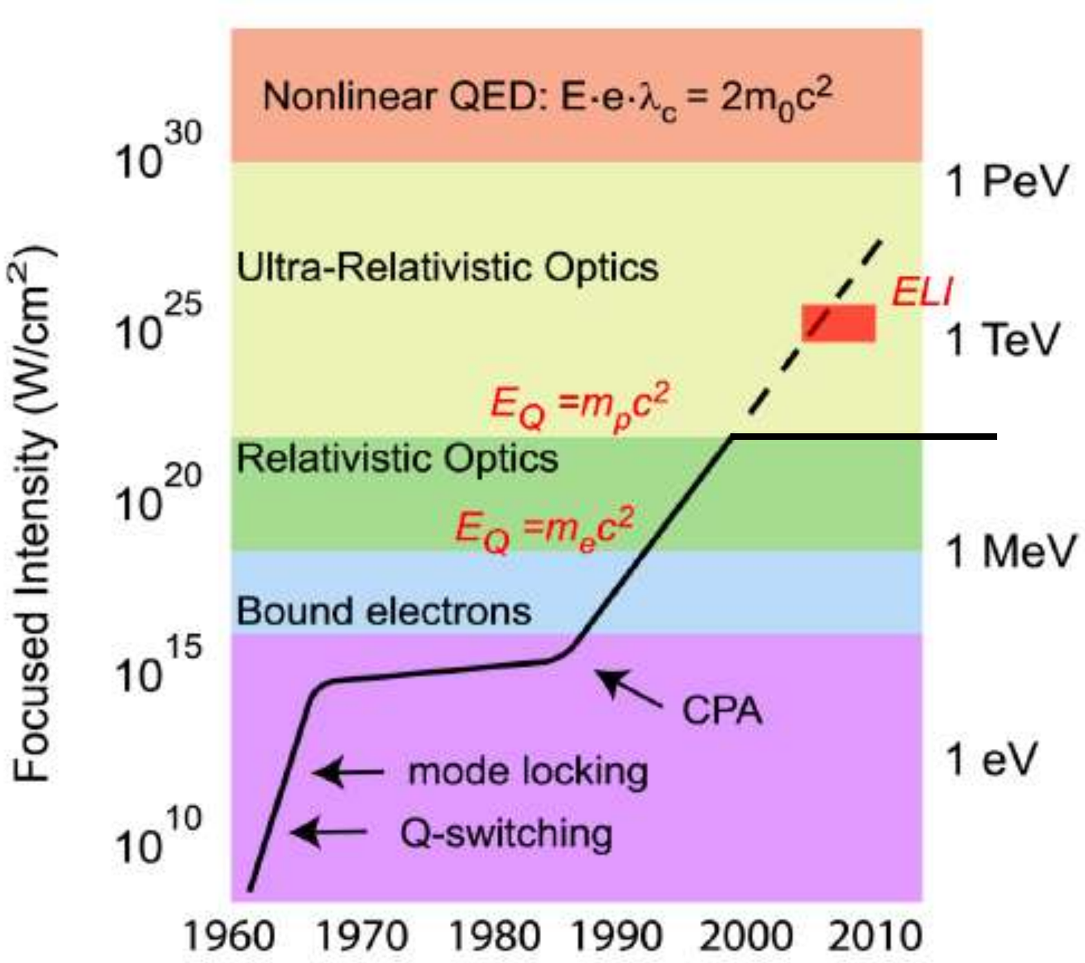
  (**L**ight **A**mplified by **S**timulated **E**mission of **R**adiation)



  - Elements of lasers
    - Gain medium
    - Pumping
    - Optical resonator (cavity)



Lasers with high peak power

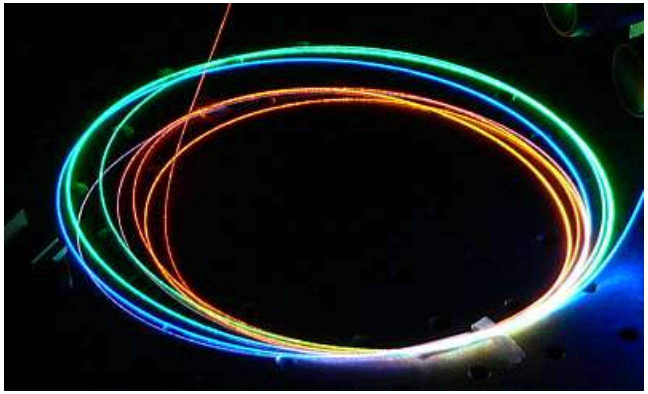


G. Mourou *et al.* Rev. Mod. Phys . **78**, p. 309 (2006)

Lasers with high peak power

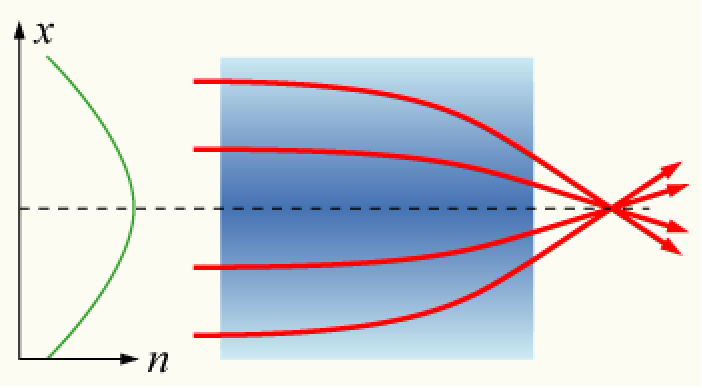
Optical Kerr effect: $n(\mathbf{r},t)=n_0+n_2 I(\mathbf{r},t)$

- solid (glas, crystals): $n_2 \approx 10^{-16} \div 10^{-10}\,\mathrm{cm}^2/\mathrm{W}$
- air: $n_2 \approx 4\times10^{-19}\,\mathrm{cm}^2/\mathrm{W}$
- $I=I(t)$ self-phase modulation
  - Generation of new frequencies (supercontinuum)



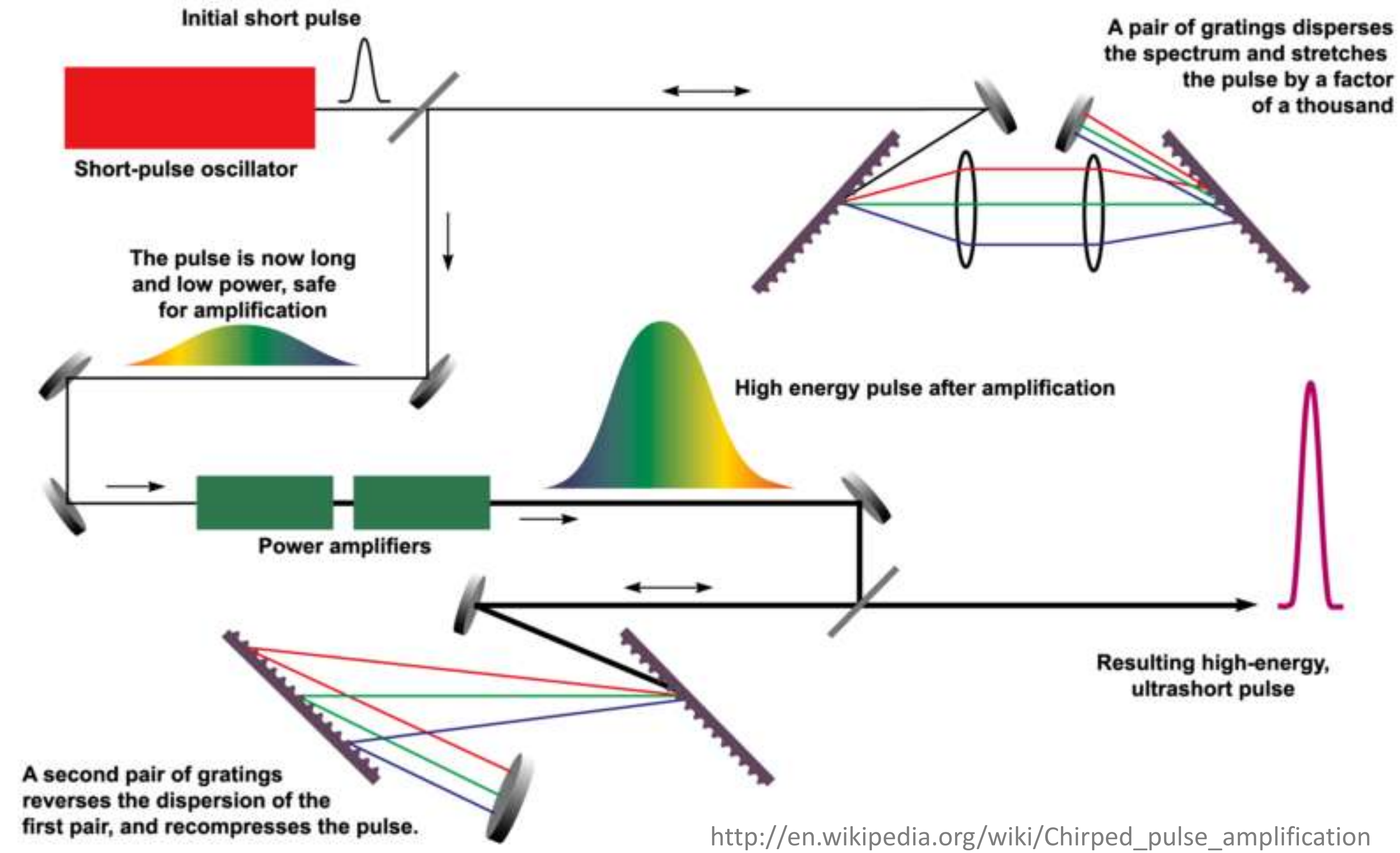
- $I=I(\mathbf{r})$ self-focusing
- Critical power $P_{cr} \approx 0.15\dfrac{\lambda^2}{n_0 n_2}$
- 800nm : glass: $P_{cr} \approx 2\mathrm{MW}$

  air: $P_{cr} \approx 2\mathrm{GW}$



Lasers with high peak power

- Increasing the peak power→ self-focusing → DAMAGE
- Solution : Chirped pulse amplification (CPA)



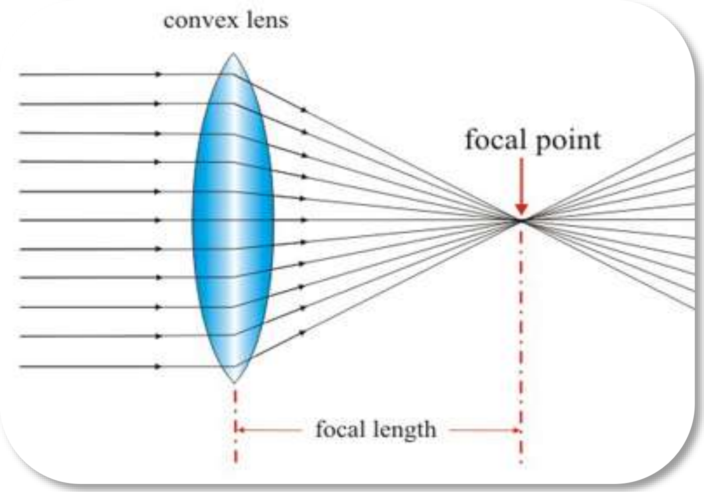
http://en.wikipedia.org/wiki/Chirped_pulse_amplification

Lasers with high peak power

- Intensity (Irradiance)

  Energy delivered per unit time to unit area

$$I \approx \frac{E}{\tau\, S} = \frac{P}{S}\ [\mathrm{Wm}^{-2}]$$



  - Area depends on the focusing
    - Focus diameter given by $d \propto \dfrac{f\lambda}{\Phi}$
      - Laser wavelength λ, focal length f, beam size Φ, wavefront quanlity
      - Mostly given by the laser parameters ($\lambda \approx 1\mu$m, $\Phi < 50$cm)

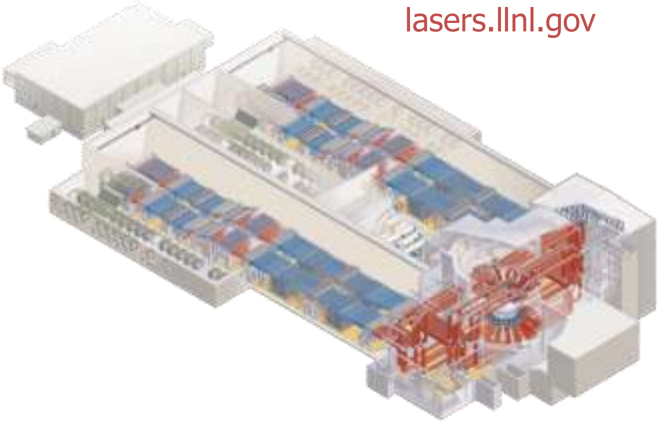
  - World records:
    - Energy in a pulse E = 4 MJ = 4×10^{6} J (NIF, LMJ)
    - Pulse duration τ = 3 fs = 3×10^{-15} s

      These extremes weren't achieved simultaneously, $P_{\max} \approx$ 1 PW = 10^{15} W
    - Intensity I = 10^{22} Wcm^{-2}

Lasers with high peak power

Highest energy in a (long) pulse

NIF: National Ignition Facility, USA 2009
lasers.llnl.gov



Shortest pulses

Highest peak power

ELI: Extreme Light Infrastructure (2015)
eli-beams.eu

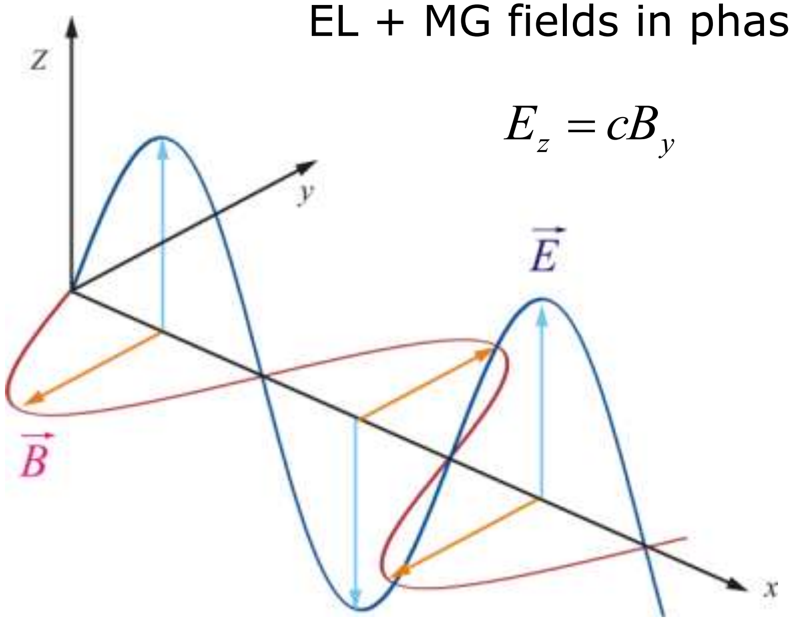
Lasers with high peak power

Electron / proton motion in the intense laser field

$$\frac{d\mathbf{p}}{dt} = q\left(\boxed{\mathbf{E}} + \boxed{\mathbf{v}\times\mathbf{B}}\right)$$

EL + MG fields in phase

$$E_z = cB_y$$



If $v << c$ (I<10^{18} Wcm^{-2})

Effect of the magnetic field negligible

If $v \approx c$ contribution of E and B comparable

$\Rightarrow$ Force pushing the particles

in the direction of laser propagation

If $I = 10^{18}$ Wcm^{-2} the amplitude of the field $E = 2.75\text{x}10^{12}$ Vm^{-1}

electron: for $\lambda = 800$ nm $v = 0.974c$ in ½ cycle of the laser field

If $I = 10^{24}$ Wcm^{-2} the field amplitude $E = 2.75\text{x}10^{15}$ Vm^{-1}

proton: for $\lambda = 800$ nm $v = 0.92c$ in ½ cycle of the laser field

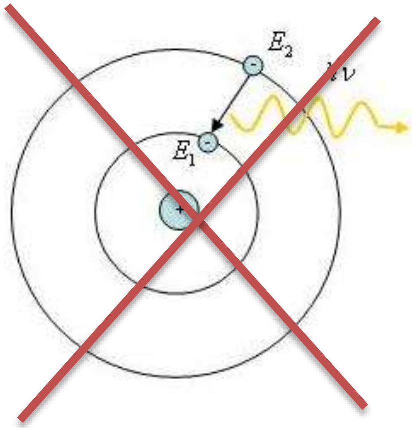
Origin of EM radiation

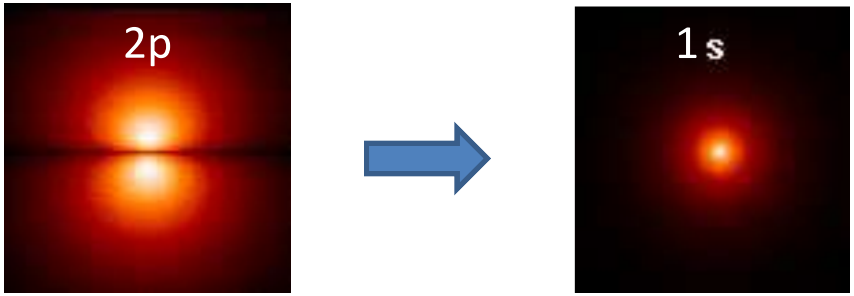
Microscopically: accelerated motion of a charge

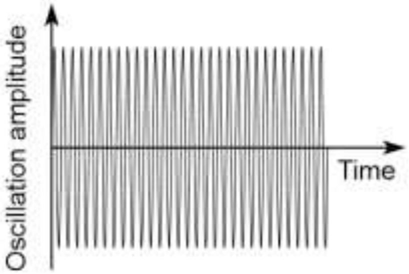
- Free:

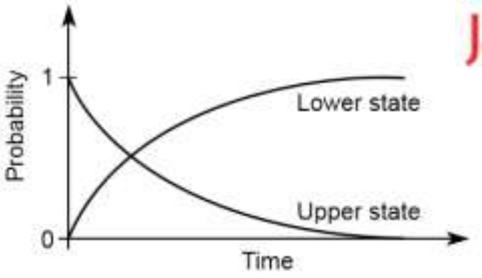
$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} e^{i\omega[t-\vec{n}.\vec{r}(t)/c]}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}.\vec{n})^2}dt\right|^2$$

- Bound: radiative (allowed) transitions

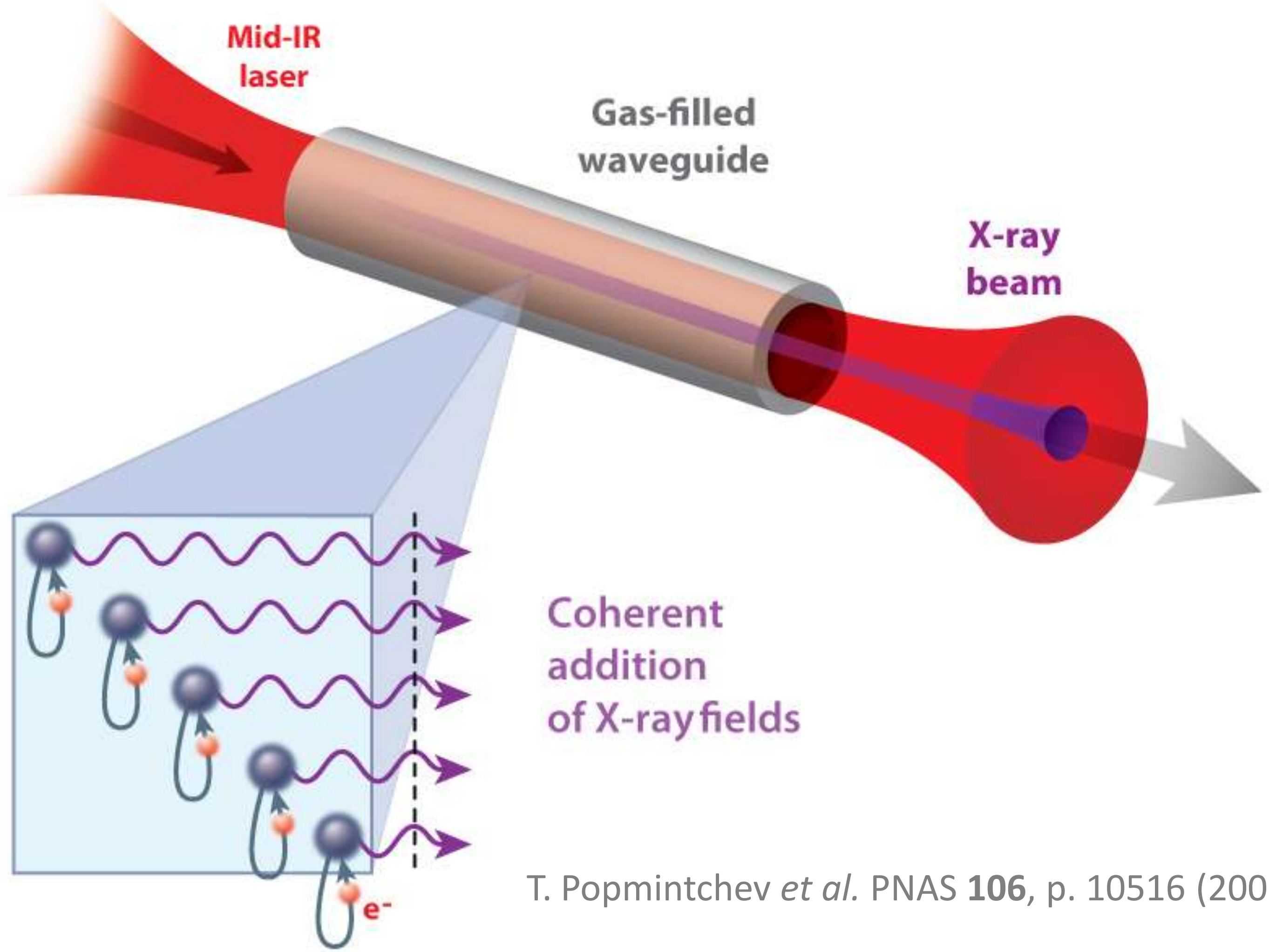








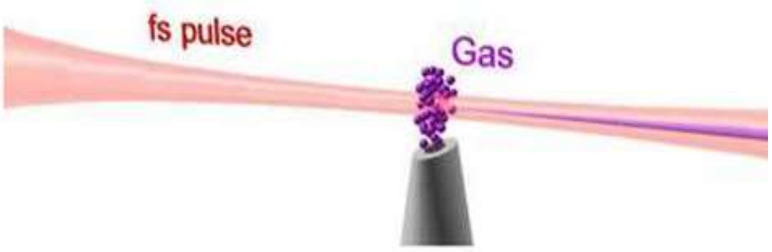
High-order harmonic generation

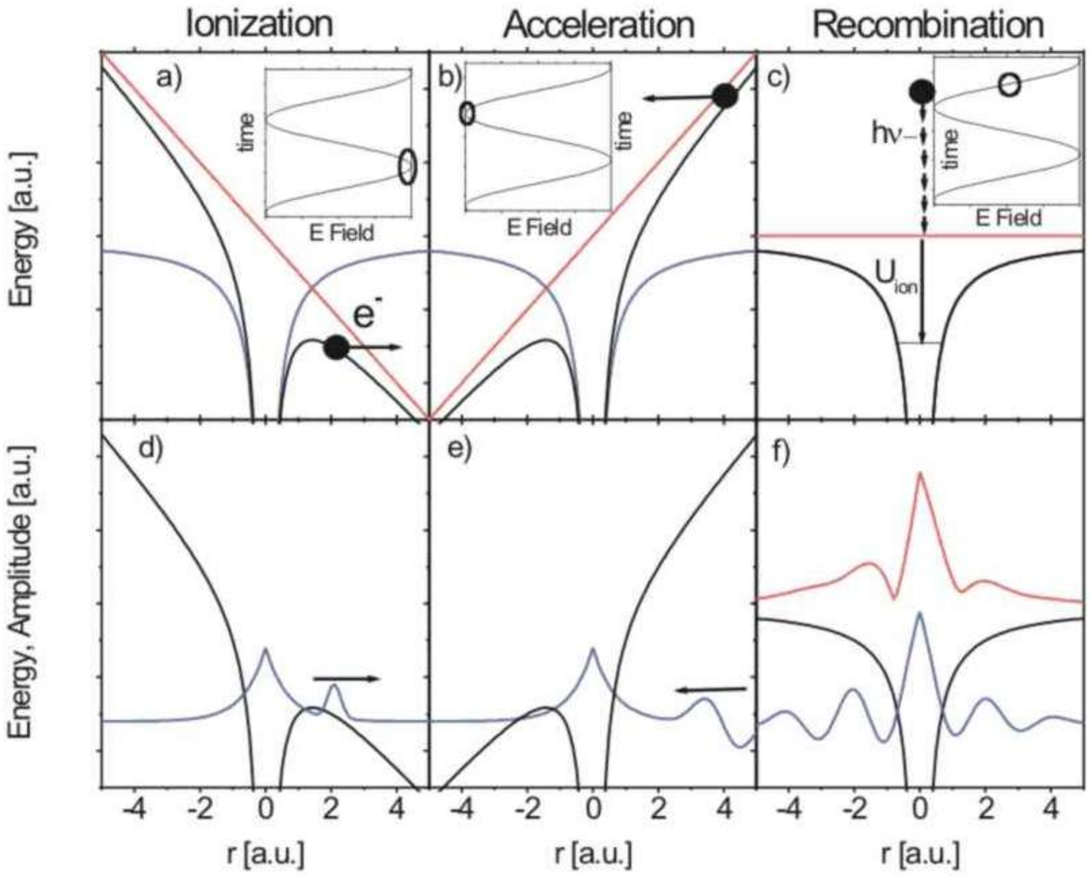


T. Popmintchev *et al.* PNAS **106**, p. 10516 (2008)

High-order harmonic generation

- Interaction of linearly polarized intense laser pulse with matter (valence electron)





- Three step model:
  - Ionization
  - Acceleration
  - Recombination

P. B. Corkum, Phys. Rev. Lett., **71**, 1994 (1993)

KAIST
한국과학기술원
Korea Advanced Institued of Science and Technology

http://www.stanford.edu/~mguehr/research_HHG.html

High-order harmonic generation

- Quasi-monochromatic radiation + centro-symmetrical medium → **odd harmonics only**

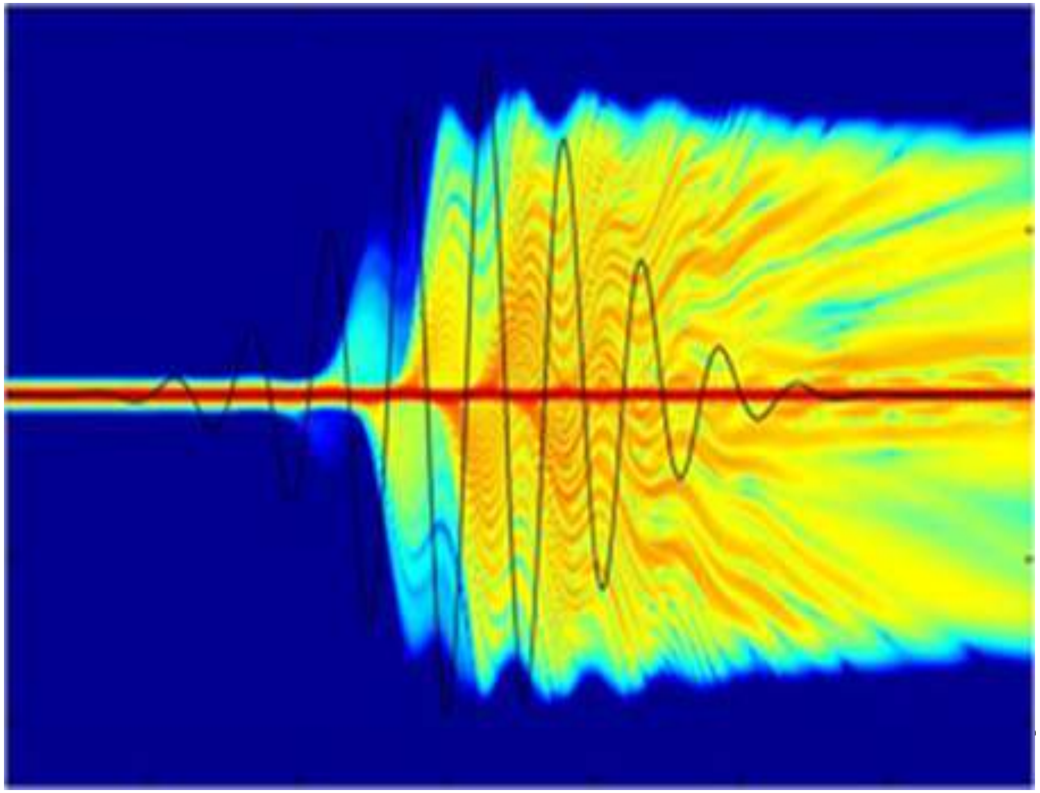
- Microskopic analysis

Dipole momentum of a single atom

$$E_{cutoff} \approx I_p + 3.17\,U_p$$

- Macroscopic analysis

absorbtion, phase-matching, diffraction



Electron density $|\psi(x,t)|^2$

http://www.orc.soton.ac.uk/xray.html

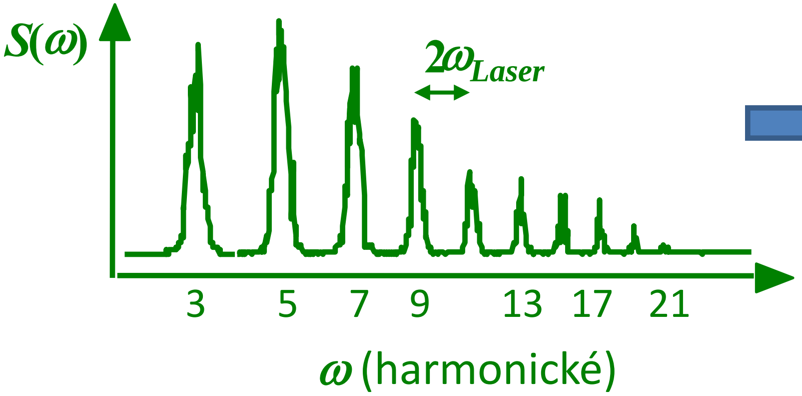
High-order harmonic generation

- $\lambda = 800\ \mathrm{nm} \rightarrow T = 2.7\ \mathrm{fs}$

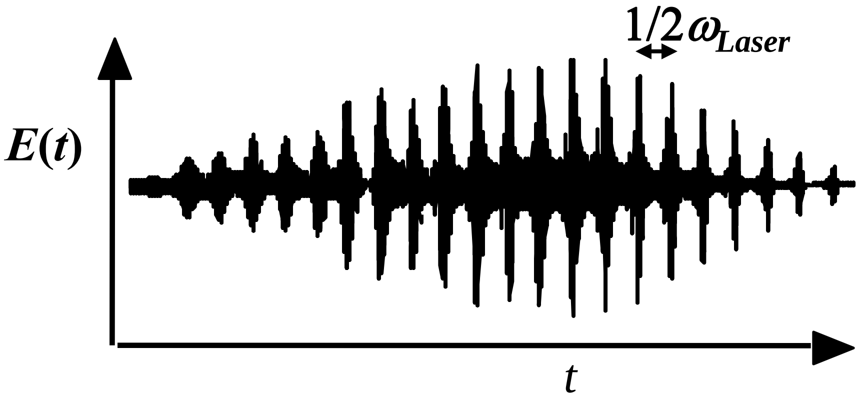
  $\rightarrow h\nu = 1.55\ \mathrm{eV}$

100fs laser pulse: attosecond pulse train

Measured spectrum

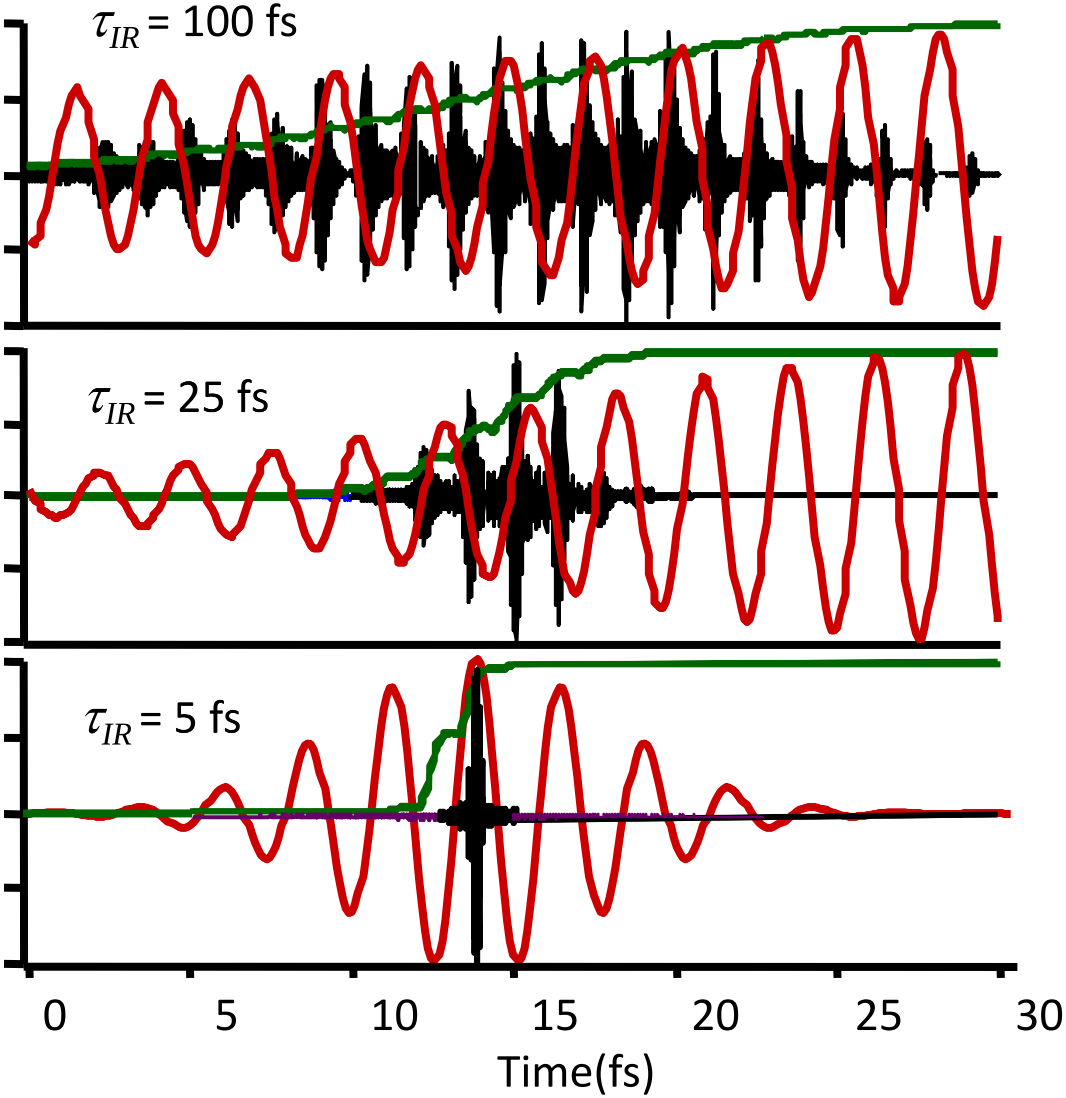


Estimated E-field evolution



Prof. R. Trebino, Lectures on Ultrafast Optics, Georgia Institute of Technology

High-order harmonic generation



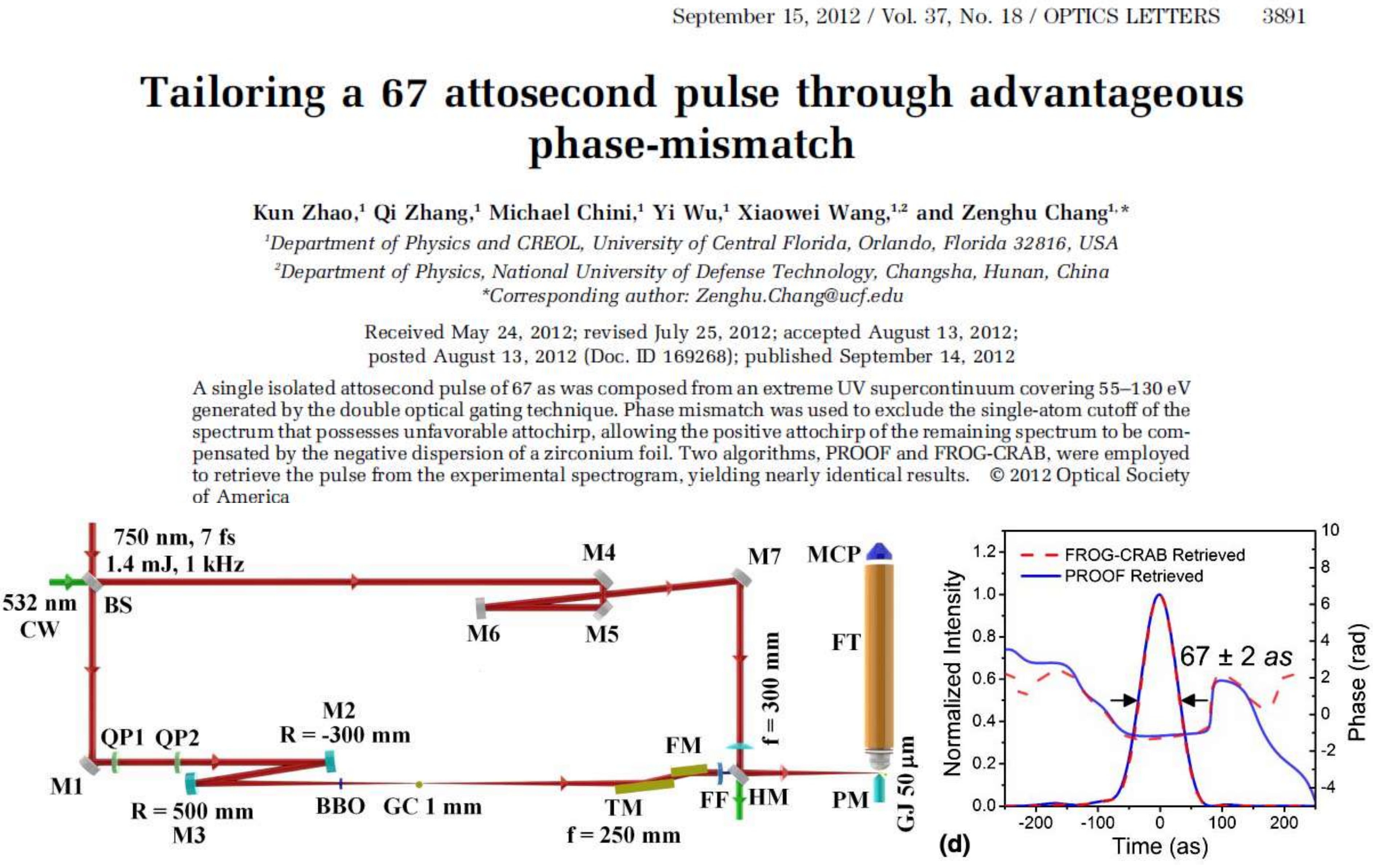
Ionization

Harmonic field

Laser field

Prof. R. Trebino, Lectures on Ultrafast Optics, Georgia Institute of Technology

High-order harmonic generation



September 15, 2012 / Vol. 37, No. 18 / OPTICS LETTERS 3891

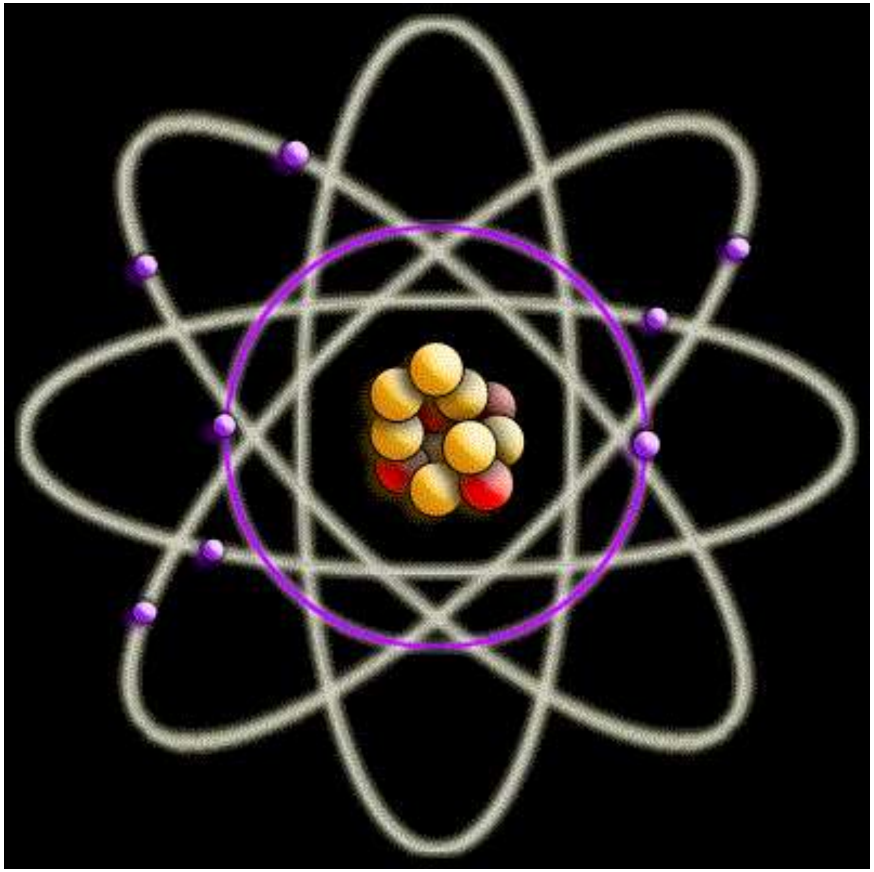
Tailoring a 67 attosecond pulse through advantageous phase-mismatch

Kun Zhao,[1] Qi Zhang,[1] Michael Chini,[1] Yi Wu,[1] Xiaowei Wang,[1,2] and Zenghu Chang[1,*]
[1]*Department of Physics and CREOL, University of Central Florida, Orlando, Florida 32816, USA*
[2]*Department of Physics, National University of Defense Technology, Changsha, Hunan, China*
**Corresponding author: Zenghu.Chang@ucf.edu*

Received May 24, 2012; revised July 25, 2012; accepted August 13, 2012;
posted August 13, 2012 (Doc. ID 169268); published September 14, 2012

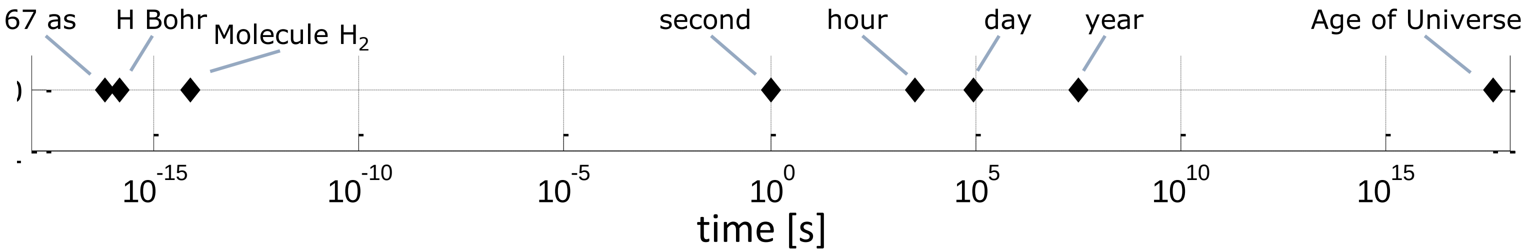
A single isolated attosecond pulse of 67 as was composed from an extreme UV supercontinuum covering 55–130 eV generated by the double optical gating technique. Phase mismatch was used to exclude the single-atom cutoff of the spectrum that possesses unfavorable attochirp, allowing the positive attochirp of the remaining spectrum to be compensated by the negative dispersion of a zirconium foil. Two algorithms, PROOF and FROG-CRAB, were employed to retrieve the pulse from the experimental spectrogram, yielding nearly identical results.

High-order harmonic generation

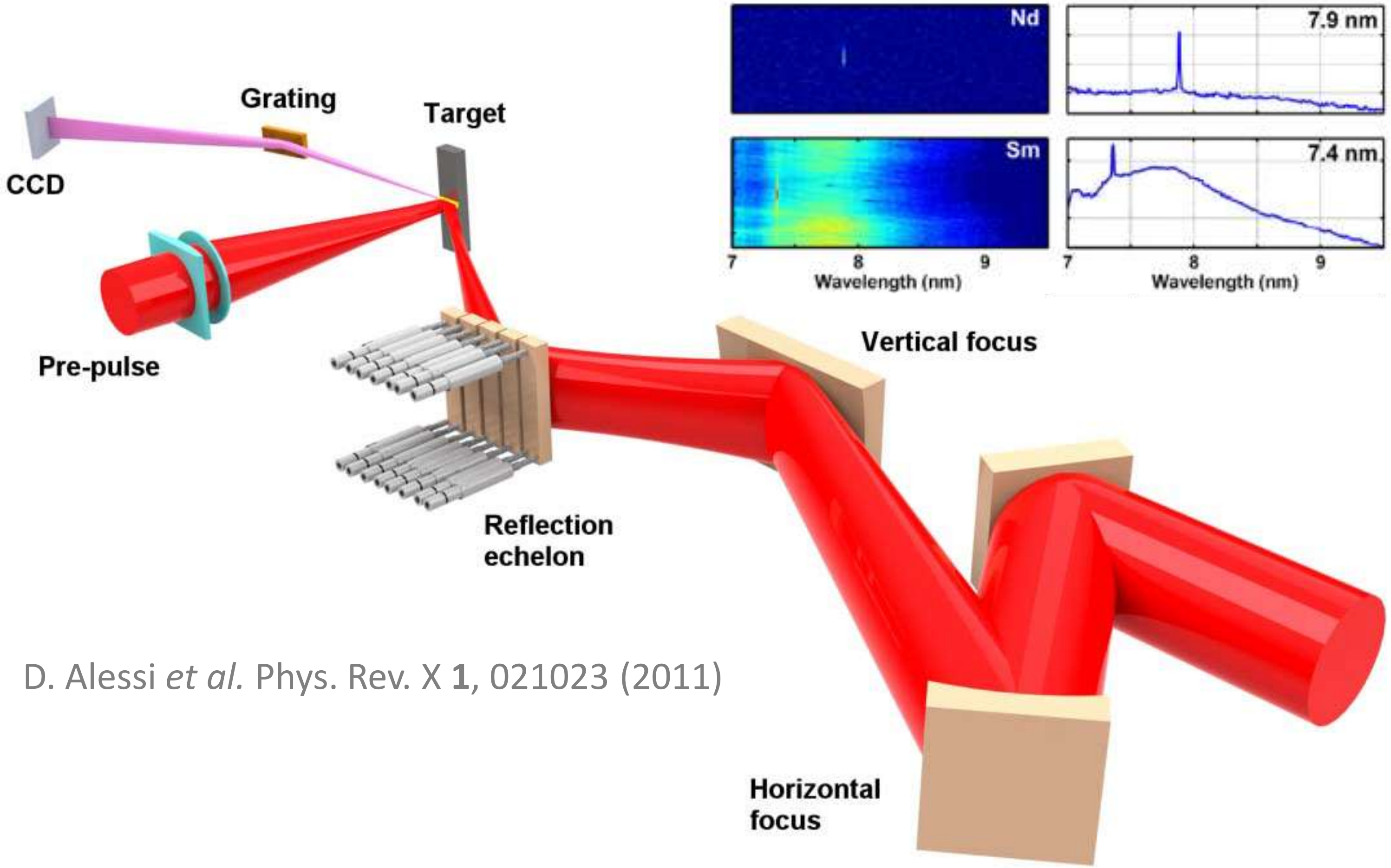


Period of an electron in Bohr’s orbital of hydrogen:
T= 152 as

Period of vibration of H_2
T= 8 fs



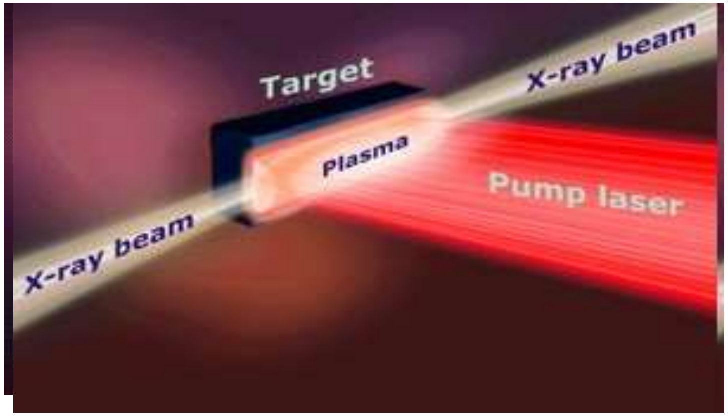
Plasma-based x-ray lasers



D. Alessi *et al.* Phys. Rev. X **1**, 021023 (2011)

Plasma-based x-ray lasers

- Employ radiative transitions of multiply ionized matter
  - Energy difference between levels increases with the charge
  - Gain medium is a narrow column of hot highly inozed plasma



Ex] hydrogen-like ion (H-like)
Z – proton number
n_i – principal quantum number
τ – lifetime of upper level

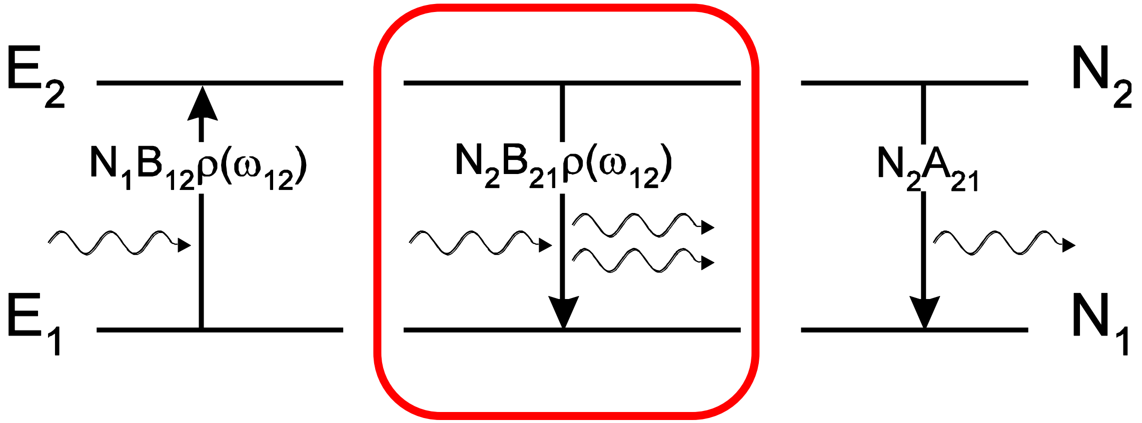
$$E_u - E_l = (13.6\,\mathrm{eV})\,Z^2\left(\frac{1}{n_l^2} - \frac{1}{n_u^2}\right)$$

$$\hbar\omega \propto Z^2, \quad \tau \propto 1/Z^4$$

H-like C $\equiv$ C^{+5} $\equiv$ C VI (spectroscopical notation):
transition 2p – 1s: $\hbar\omega =$ 367eV, $\lambda = 3.4$ nm, $\tau = 1.2$ ps

Plasma-based x-ray lasers

Einstein’s coefficients



From the detailed balance:

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{\hbar\omega_{21}^3}{\pi^2 c^3} \propto \lambda^{-3} \qquad (1)}$$

A,B depends only on the quantum system ⇒ relation (1) is valid even outside equilibrium

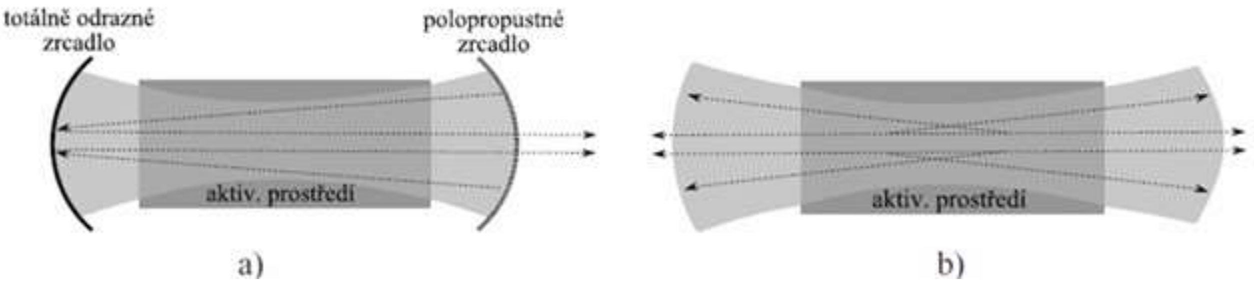
Pumping intensity is proportional to $1/\lambda^4$ ⇒ high pump power for shorter wavelengths – possible only in hot dense plasma

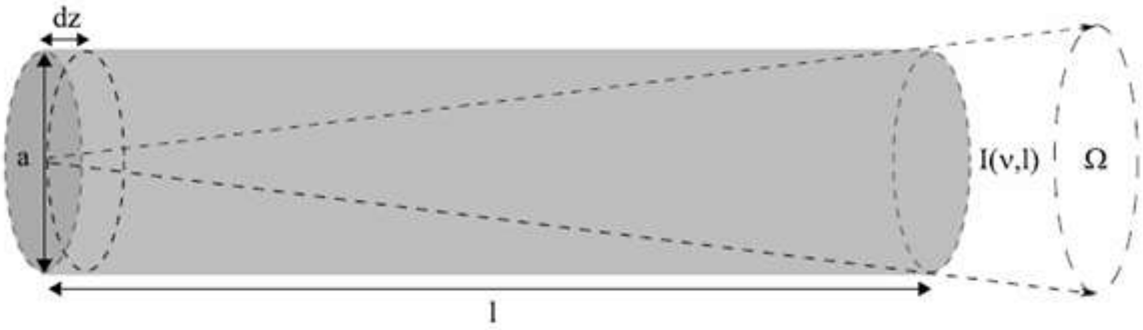
Plasma-based x-ray lasers

Due to short lifetimes of the gain, nonexistence of highly reflecting mirrors in XUV/x-ray and agressive plasma (damages nearby optics)

Laser resonator (cavity) canot be used

We rely on Amplified Spontaneous Emission (ASE)
(amplified noise– effects on wavefront, coherence…)

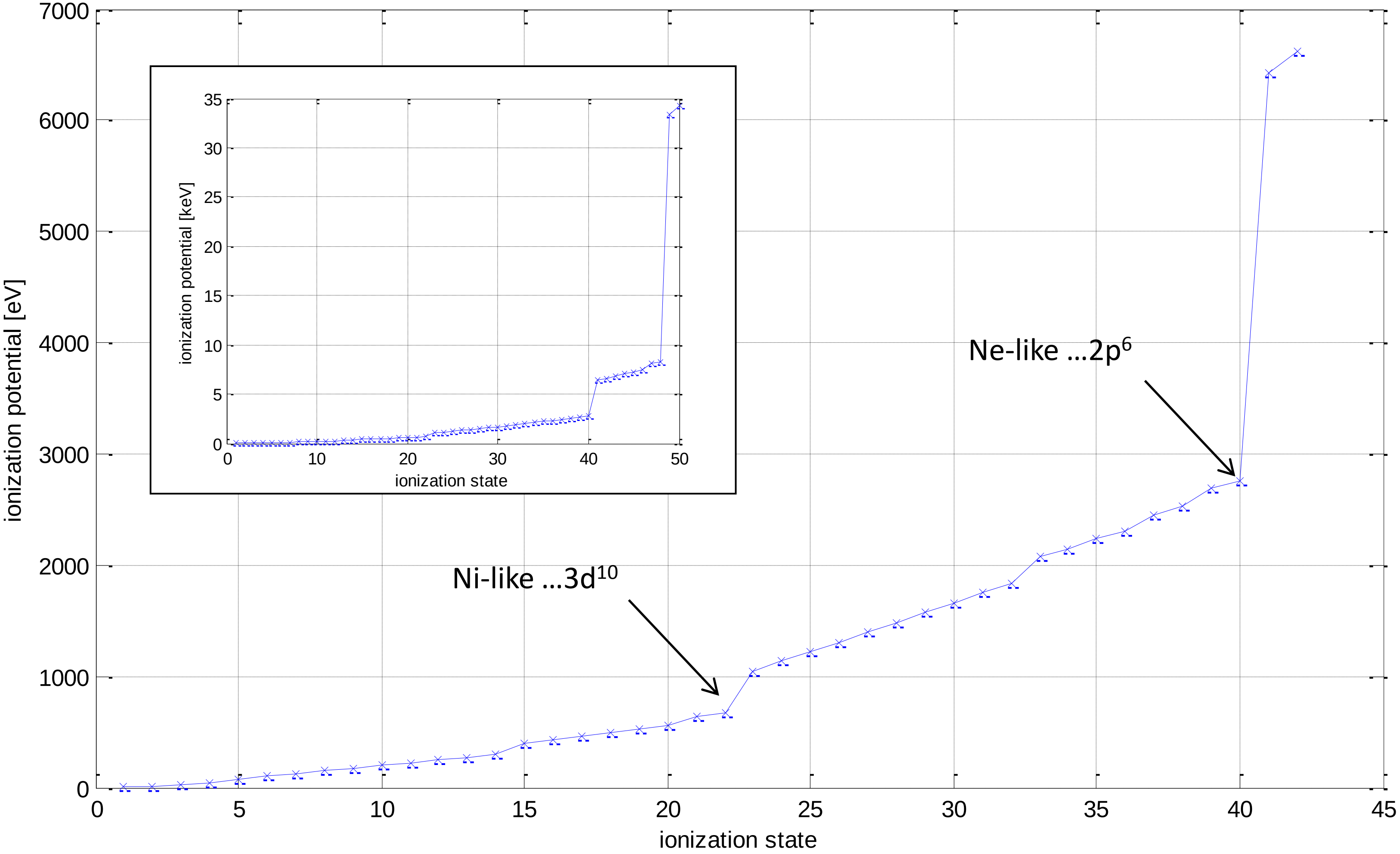




Plasma-based x-ray lasers

Example: Sn: Z=50

Ground state $1s^2\ 2s^2 2p^6\ 3s^2 3p^6 3d^{10}\ 4s^2 4p^6 4d^{10}\ 5s^2 5p^2$



Source: http://spectr-w3.snz.ru

Plasma-based x-ray lasers

Solving Saha equation for (Sn) plasma: Z=50

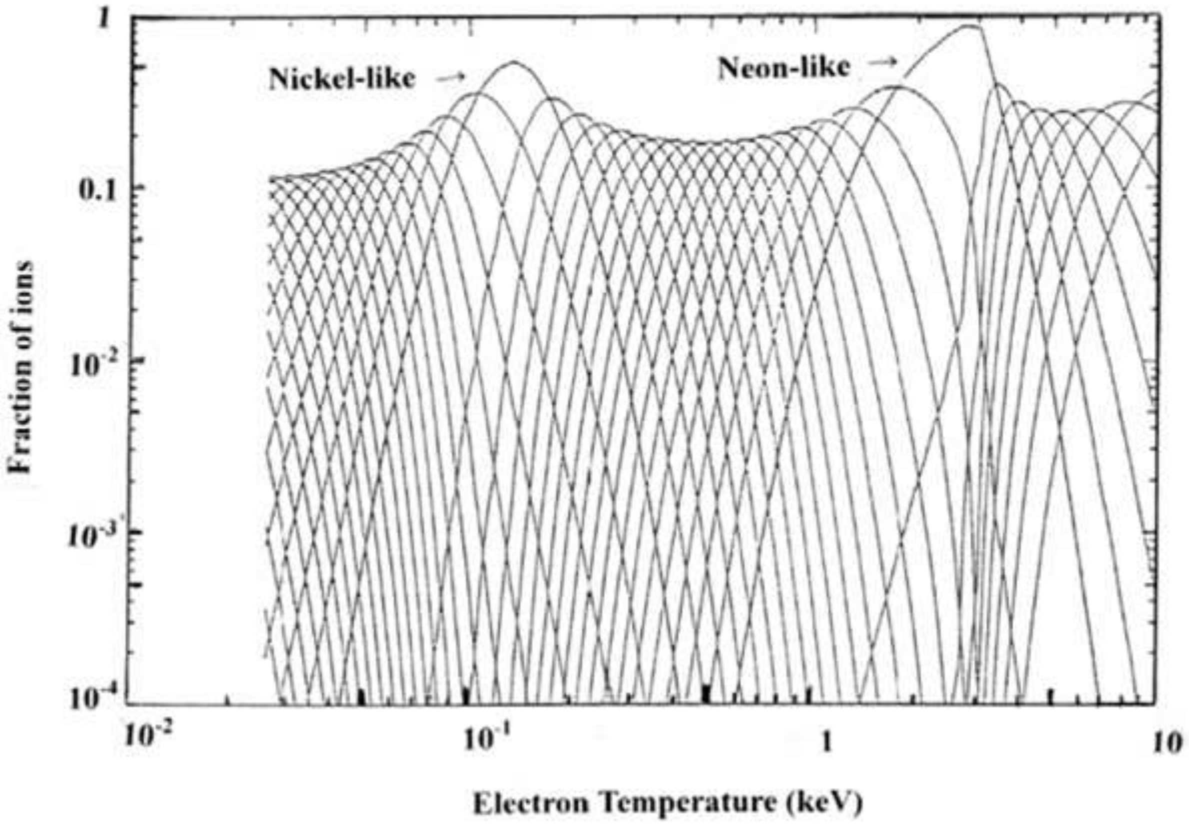


Figure 11. Ion abundance as a function of the electron temperature for tin plasma.

H. Daido, Rep. Prog. Phys. **65** (2002) 1513–1576.

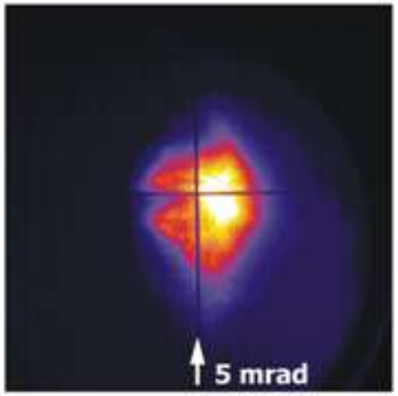
Ne and Ni-like ions are present for wide temperature ranges.

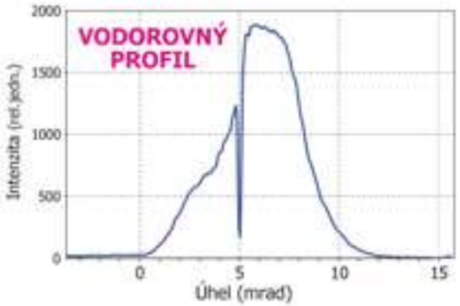
Plasma-based x-ray lasers

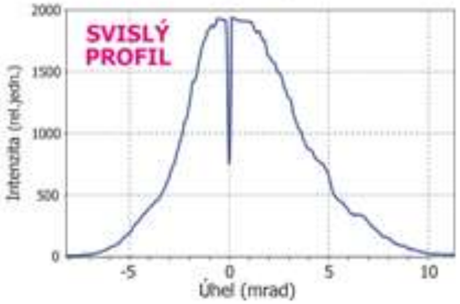
Ne-like Zn laser at PALS

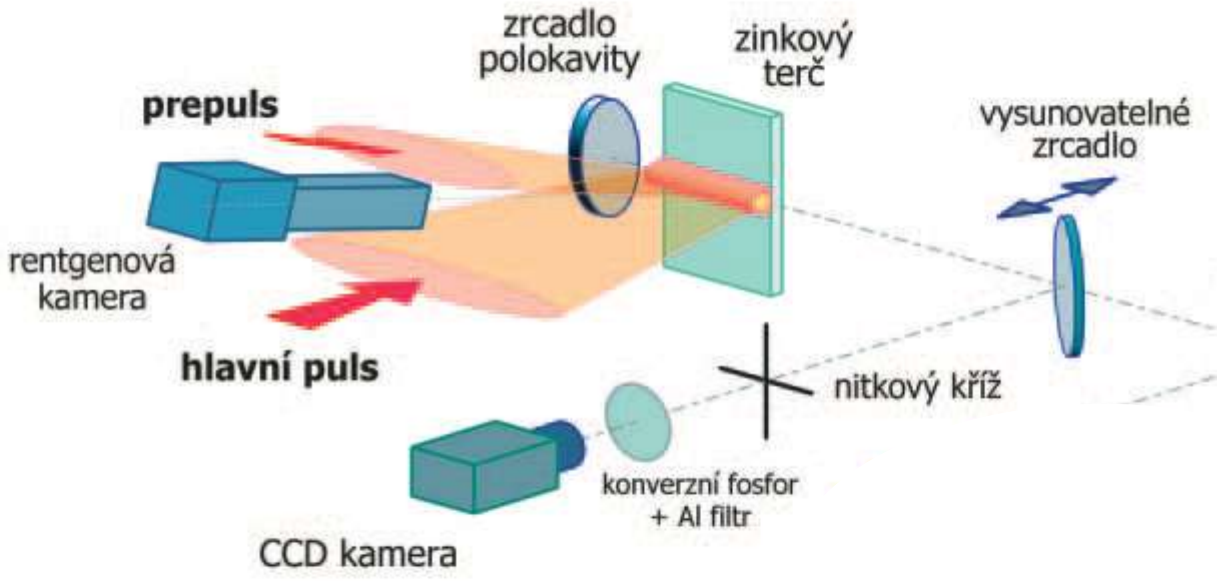
Prepulse (2J) and main pulse (500J) of ASTERIX focused down to a line(150µm) on a 3cm-long Zn target

- Energy 4-10mJ @ 21.2nm ($\Delta\lambda/\lambda \approx 5\text{x}10^{-5}$)
- Pulse length 150ps
- Beam divergence 3.5×5.5mrad





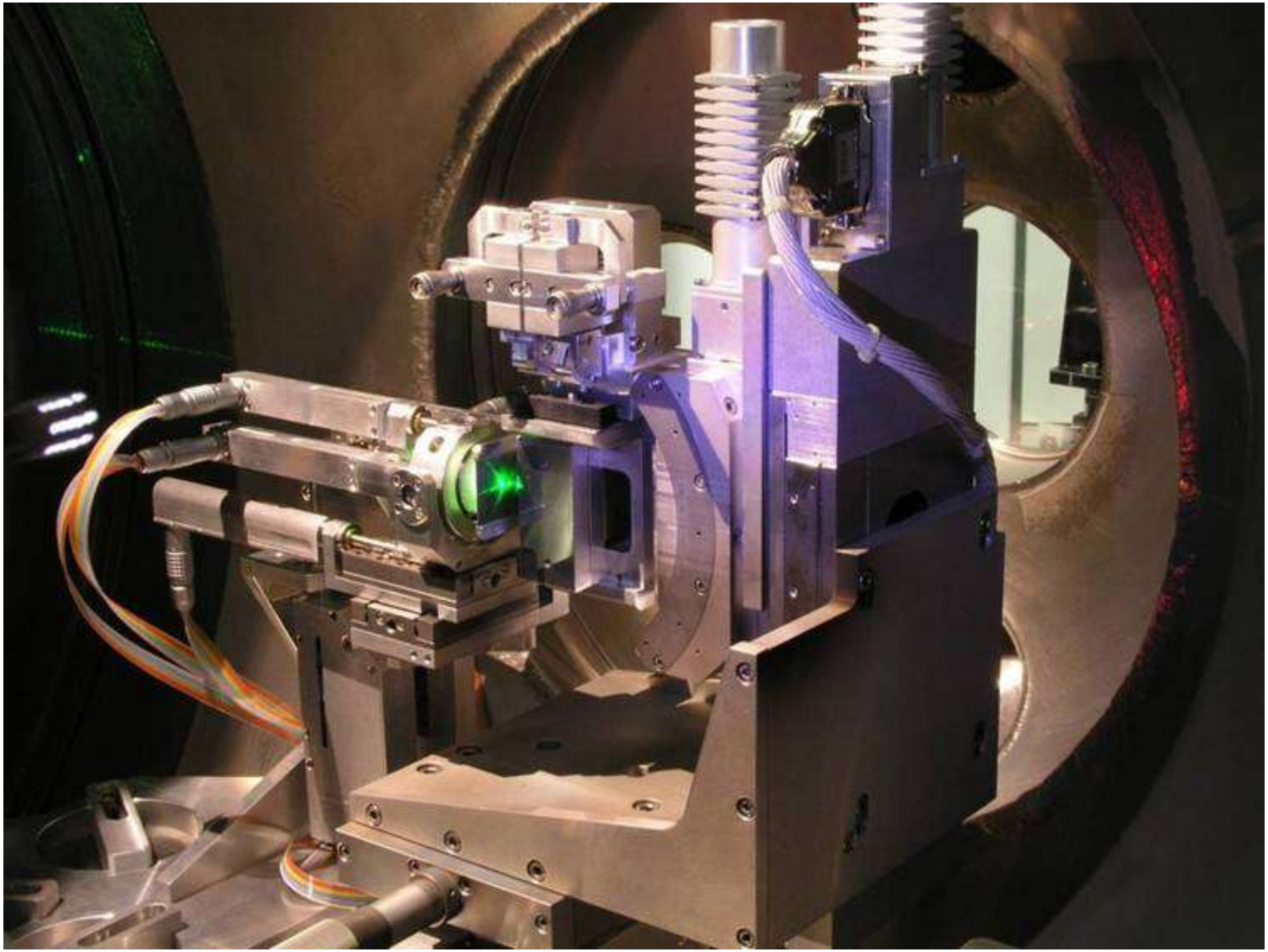




B. Rus *et al.* Čs.čas.fyz. **52** , p. 9 (2002)

Plasma-based x-ray lasers

Ne-like Zn laser at PALS



Plasma-based x-ray lasers

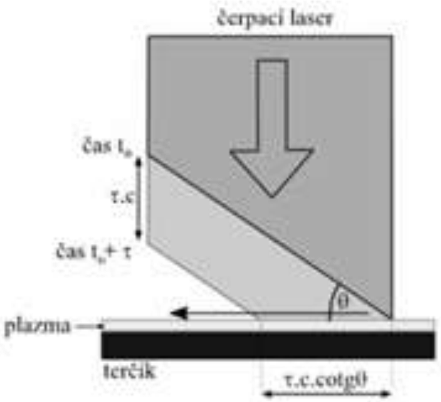
Ni-like ions:

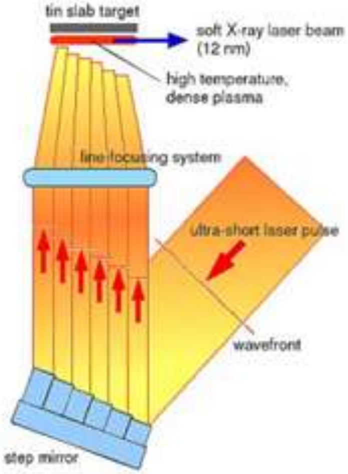
Suitable for shorter λ

Usually short gain duration– Transient pumping

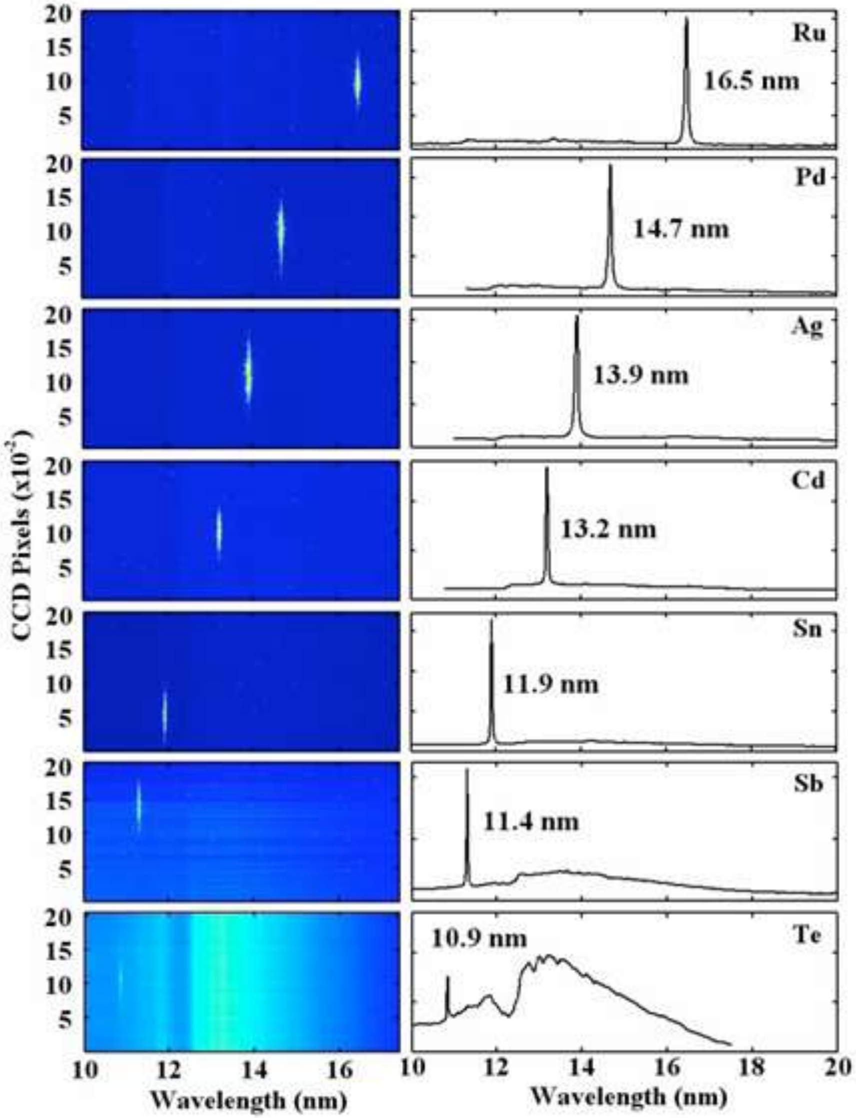
Space overlap of pumping with generated radiation

- **Travelling wave**
  - Step mirror
  - Tilt of the compressor grating





- Longitudinal pumping (gas target)
- GRazing Incidence Pumping

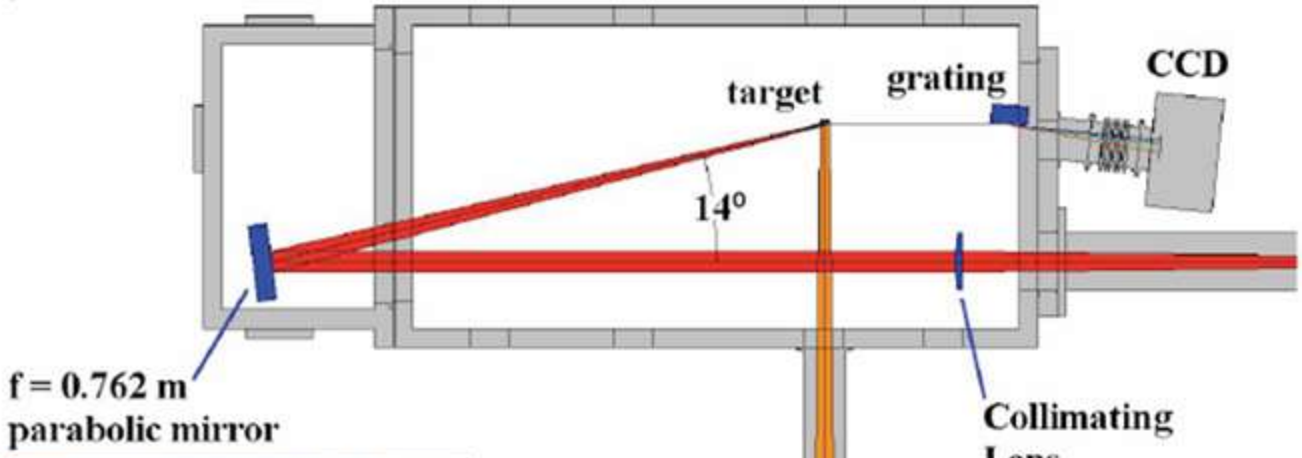


J. Rocca, Colo. State U. euverc.colostate.edu

Configuration for 30 µm wide short pulse line focus at 14 to 26 degrees grazing incidence

Line Focus

- Pre-pulse: 30µm FWHM,
- Short-pulse: 30µm FWHM,



Courtesy of J. Rocca, Colo. State U.

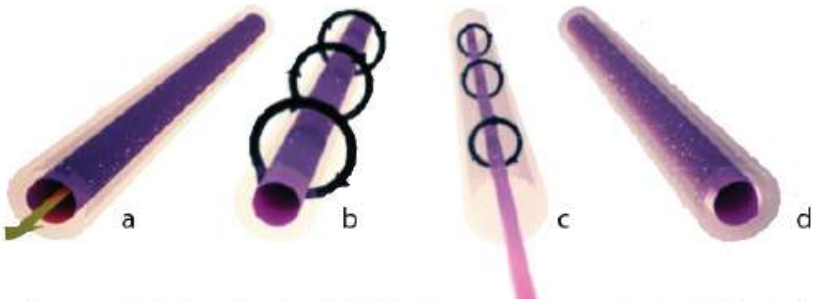
Plasma-based x-ray lasers

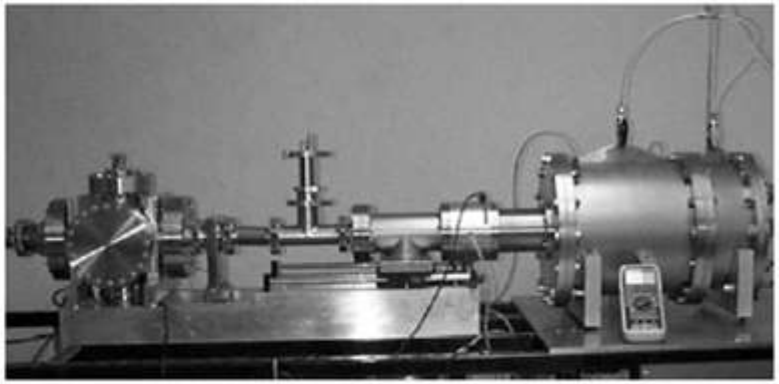
X-ray laser generated with capillary discharge

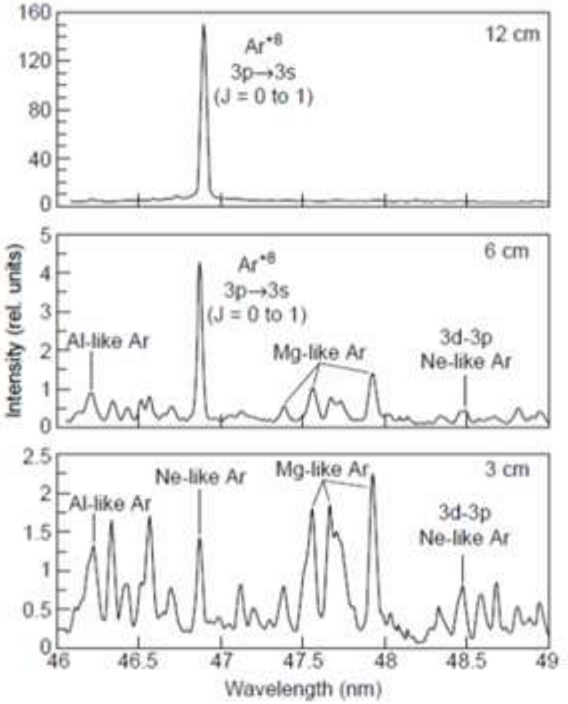
Pinch: Strong current compresses (Lorentz force: **J**×**B**) and heats plasma

- Preionization (~10A, ~5μs)
- Fast strong current pulse ($I \geq$ 20kA, $\tau \leq$ 200ns)

Example: Ne-like Ar (Ar^{+8}) na 46.9 nm – suitable for applications





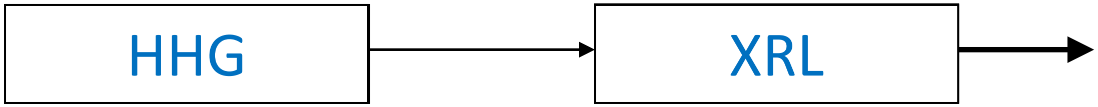


Courtesy of J. Rocca (1995), Colorado State University

Plasma-based x-ray lasers

HHG seed amplified in plasma amplifier (XRL)

Laser chain (Master Oscillator Power Amplifier) in XUV



HHG

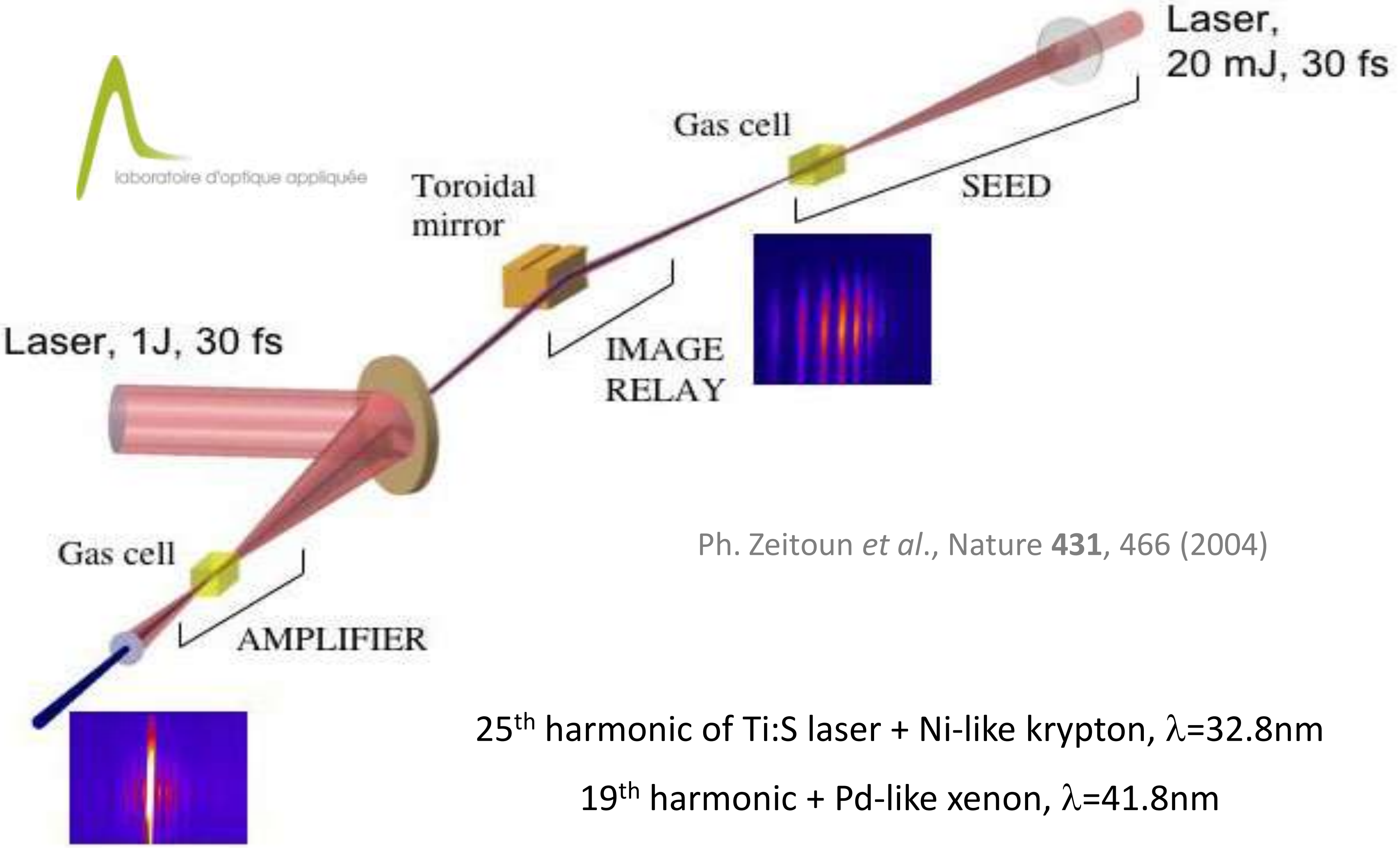
XRL

High quality of the beam
(wavefront, coherence,
divergence)

ENERGY

Strong source of fully coherent radiation in XUV/soft x-ray

Plasma-based x-ray lasers

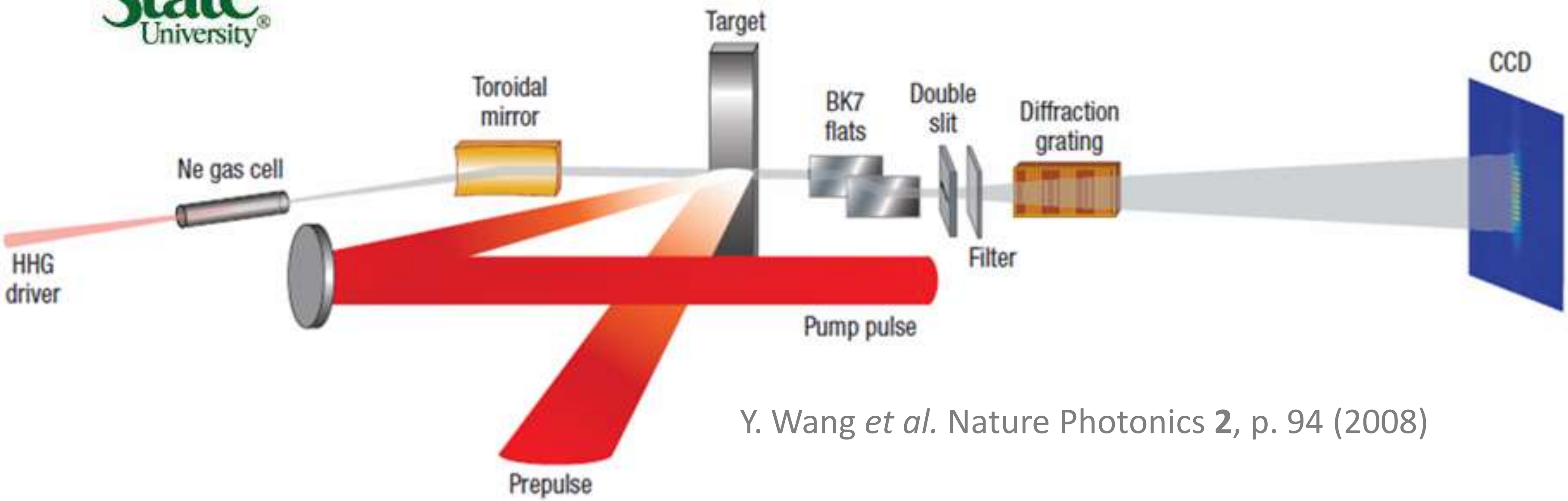


Ph. Zeitoun *et al*., Nature **431**, 466 (2004)

25th harmonic of Ti:S laser + Ni-like krypton, λ=32.8nm

19th harmonic + Pd-like xenon, λ=41.8nm

Plasma-based x-ray lasers



Y. Wang *et al.* Nature Photonics **2**, p. 94 (2008)

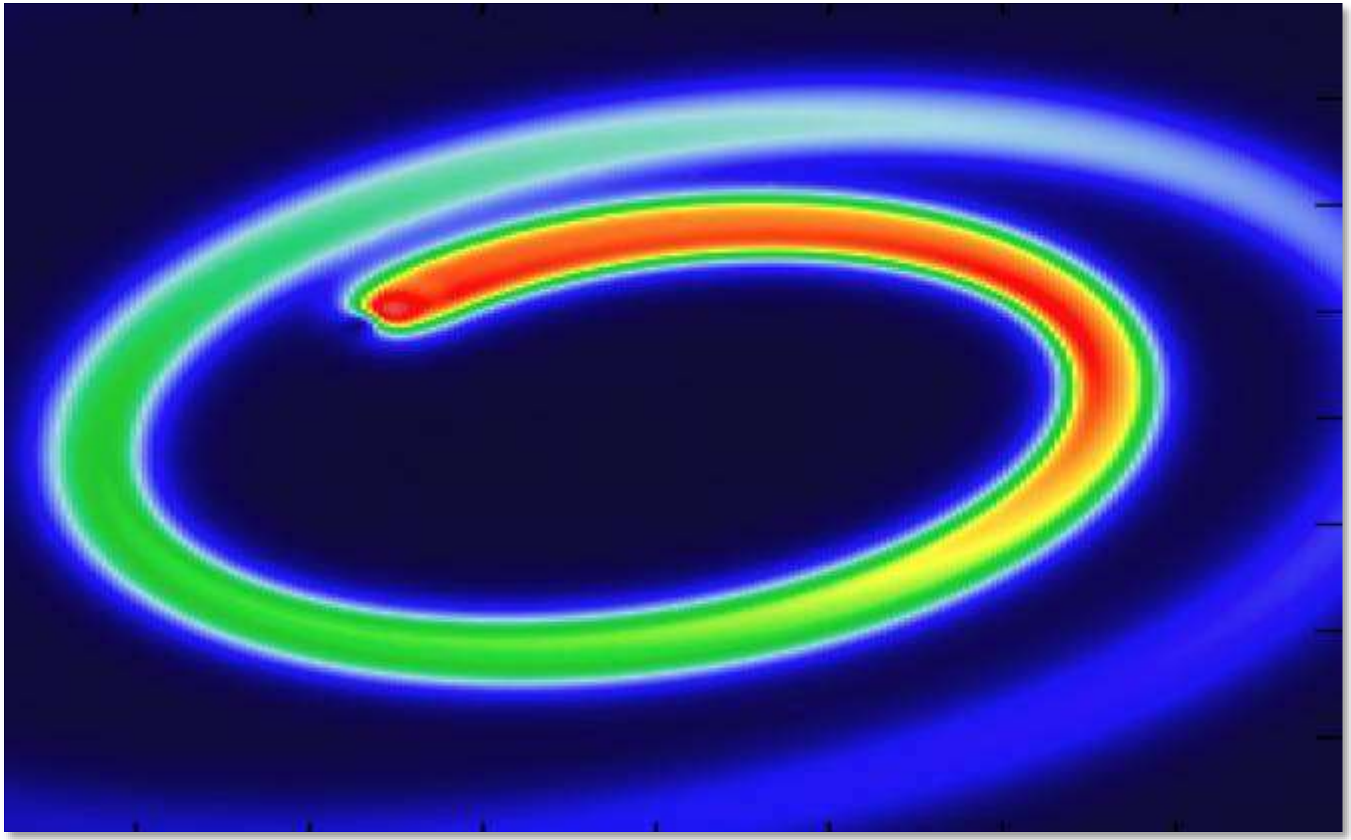
25th harmonic of Ti:S laser + Ne-like titan, λ=32.6nm

43th harmonic + Ni-like molybden, λ=18.9nm

59th harmonic + Ni-like silver, λ=13.9nm

59th harmonic + Ni-like cadmium, λ=13.2nm

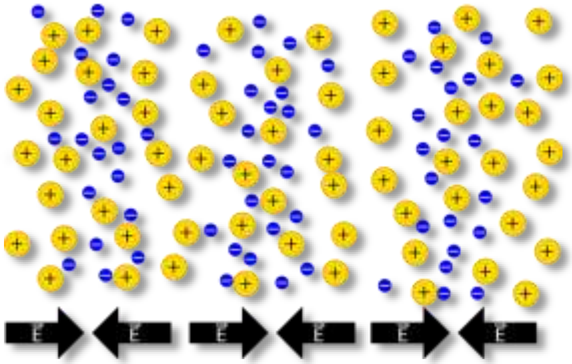
Radiation of laser-driven relativistic electron beams



http://loa.ensta-paristech.fr/

Radiation of relativistic e^- beams

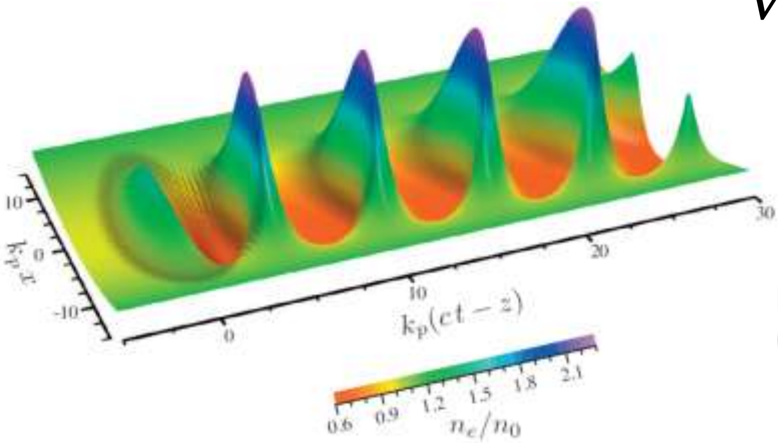
- Electron acceleration in laser plasma
  - Plasma wave behind the laser pulse
  - Huge E-filed >100 GV/m possible (conventional RF accelerators <0.1GV/m)



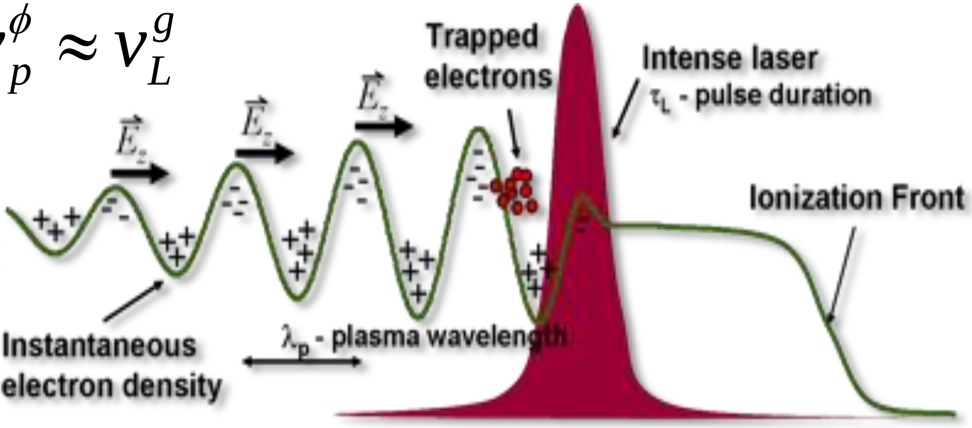
plasma frequency: $$\omega_p^2 = \frac{n_e e^2}{\varepsilon_0 m_e}$$

ponderomotive force: $$F_p = -\frac{e^2}{2\varepsilon_0 c m_e \omega^2} \nabla I$$

$$v_p^\phi \approx v_L^g$$



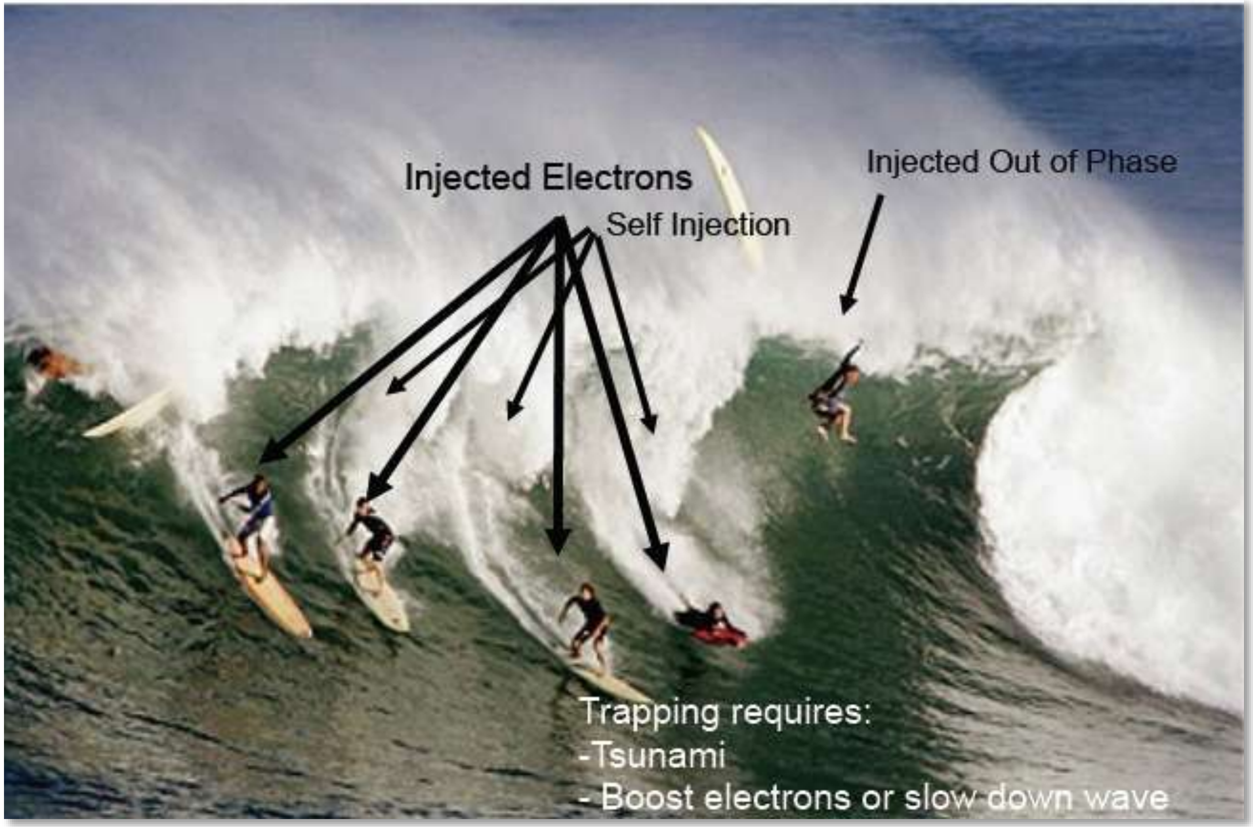
E. Esarey *et al.* Rev. Mod. Phys. **81**, p. 1229 (2009)



www.engin.umich.edu/research/cuos

Radiation of relativistic e⁻ beams

- Electron acceleration in laser plasma
  - Plasma wave behind the laser pulse
  - Huge E-filed >100 GV/m possible (conventional RF accelerators <0.1GV/m)



Radiation of relativistic e^- beams

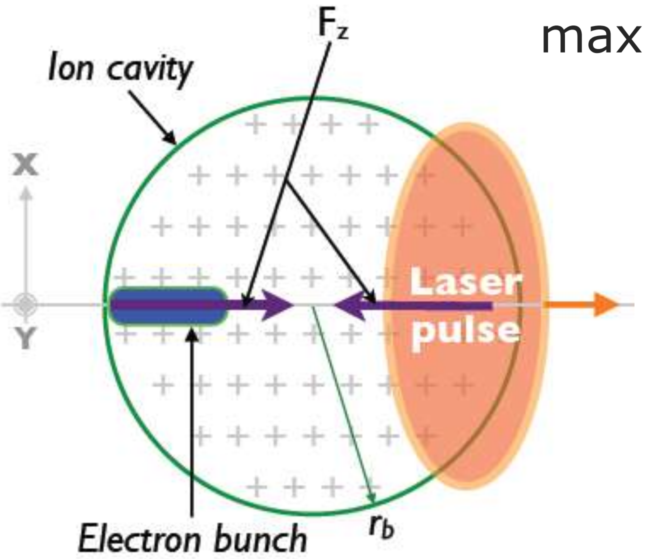
- Electron acceleration in laser plasma
  - If the parameters are set right: buble regime
    - Focus size and intensity vs. plasma density
    - Laser pulse duration vs. plasma density

$$\frac{2\sqrt{a_0}}{w_0} \approx \frac{\omega_p}{c}$$

$$\tau \approx \frac{\pi}{\omega_p}$$

$a_0 > 2 \Rightarrow$ ion cavity (no electrons) behind the laser pulse

wavebreaking – acceleration of e^-



maximum field: $E_m = \frac{m_e c}{e} \omega_p \sqrt{a_0}$

$a_0 \approx 4,\ \tau \approx 30\ \text{fs} \Rightarrow n_e = 10^{19}\ \text{cm}^{-3}$

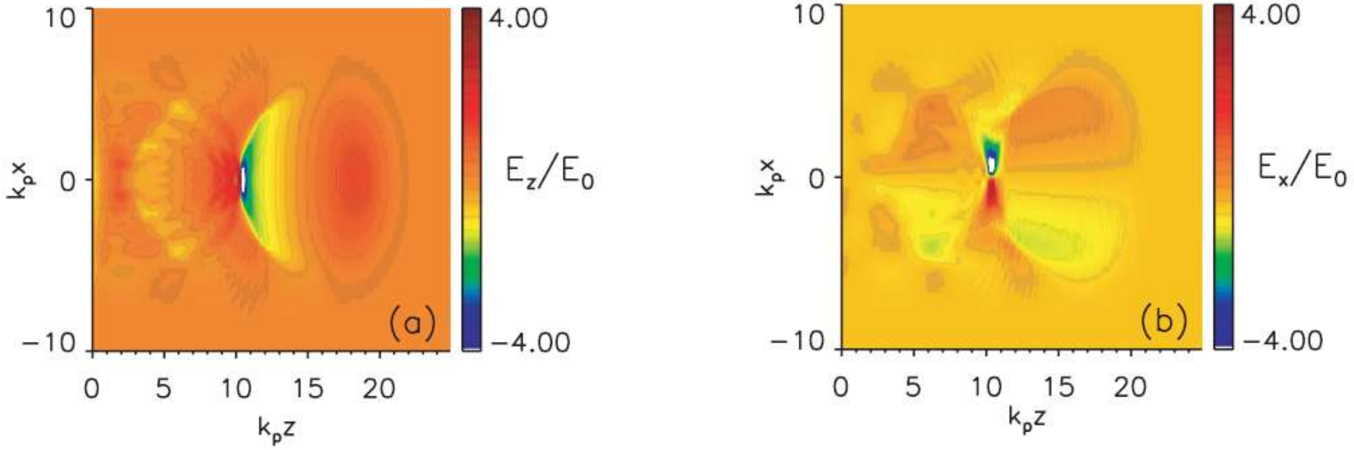
$\mathbf{E_m \approx 600\ GV/m}$

http://picongpu.fzd.de

S. Corde *et al.* accepted for publication in Rev. Mod. Phys 2012

Radiation of relativistic e^- beams

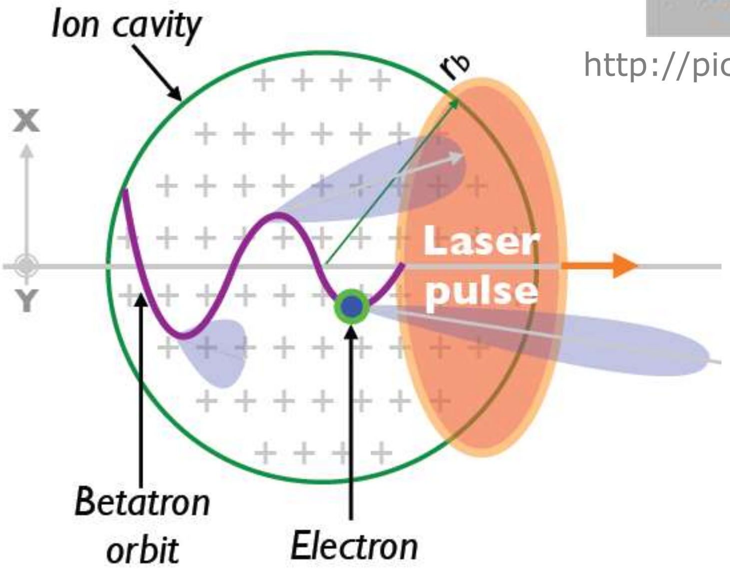
- Besides the longitudinal there is also transverse field



$\Rightarrow$ Oscillations of electron beam $\Rightarrow$ RADIATION

http://picongpu.fzd.de

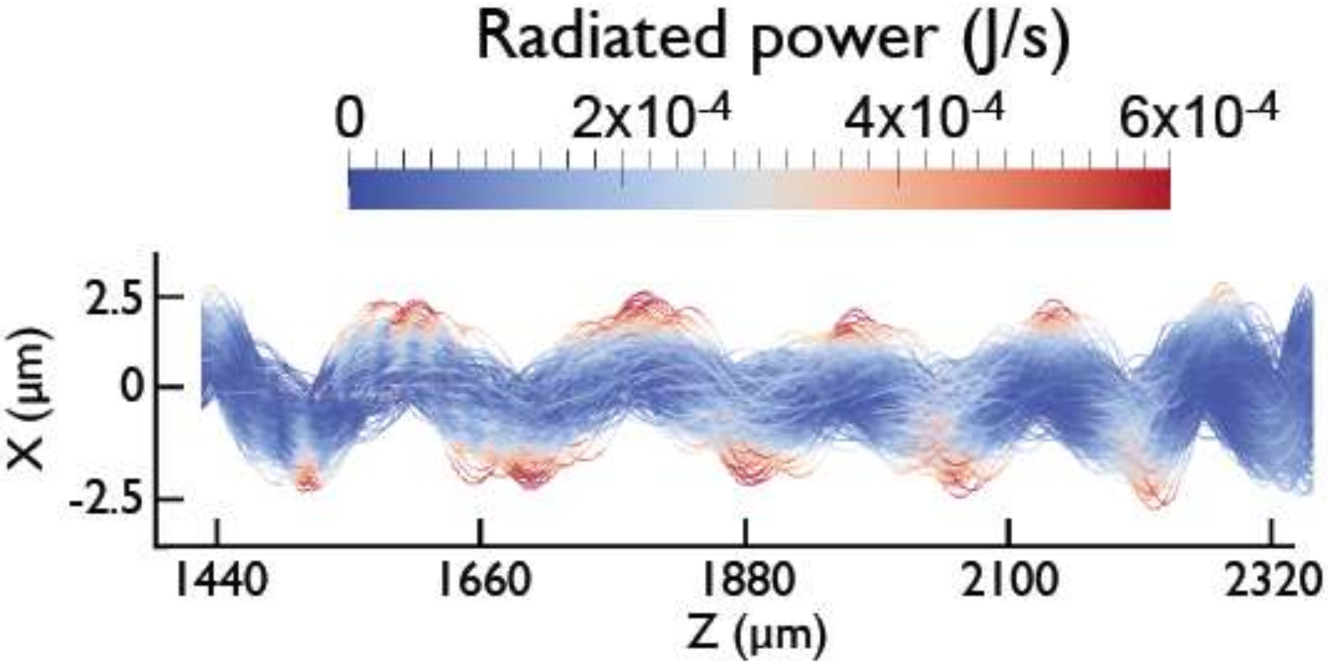
so called **plasma betatron**



Radiation of relativistic e⁻ beams

Plasma betatron

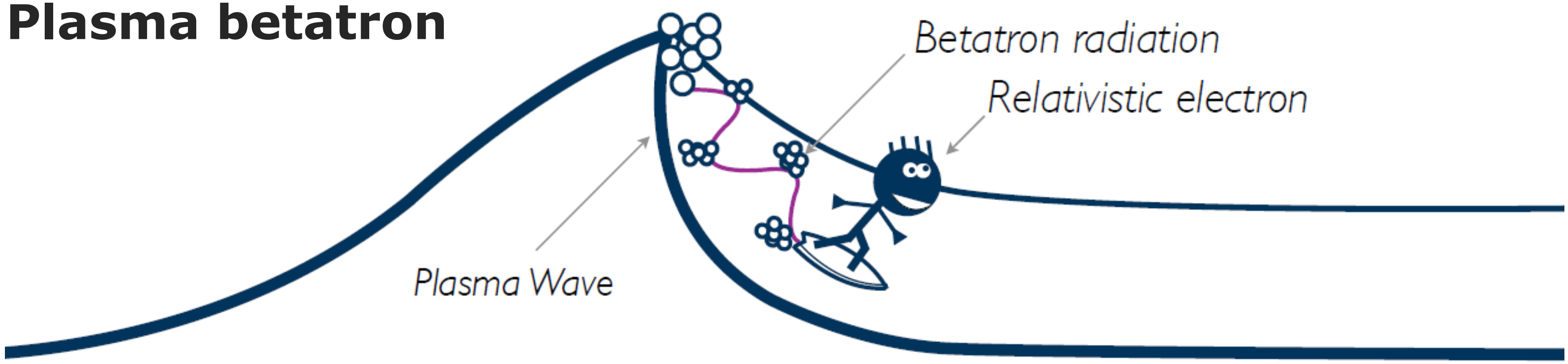
$$\frac{d^2I}{d\omega d\Omega}=\frac{e^2}{4\pi^2c}\left|\int_{-\infty}^{+\infty}e^{i\omega[t-\vec{n}.\vec{r}(t)/c]}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\,.\,\vec{n})^2}dt\right|^2$$



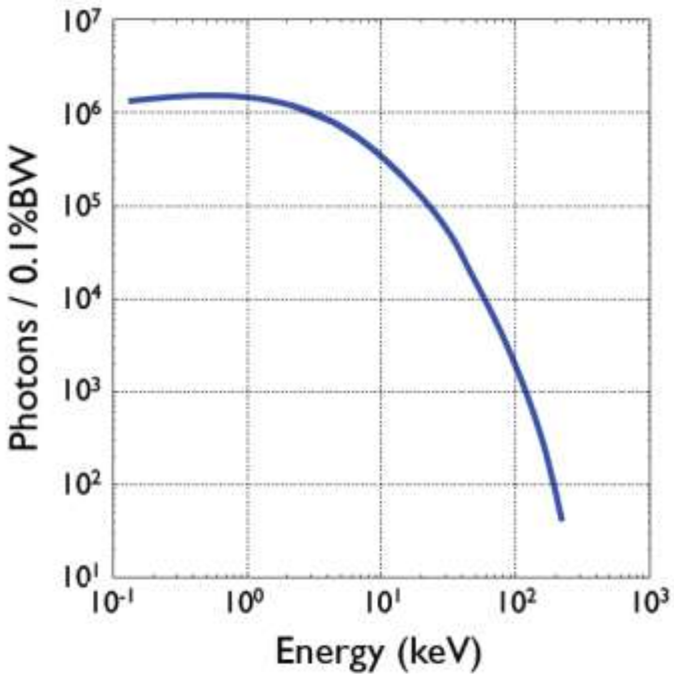
S. Corde *et al.* accepted for publication in Rev. Mod. Phys 2012

Radiation of relativistic e^- beams

- **Plasma betatron**



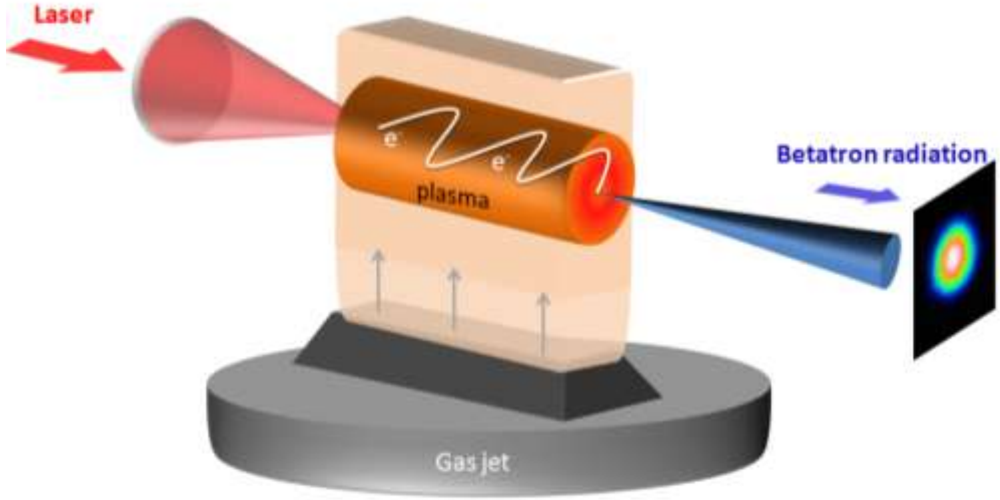
Typical spectrum:



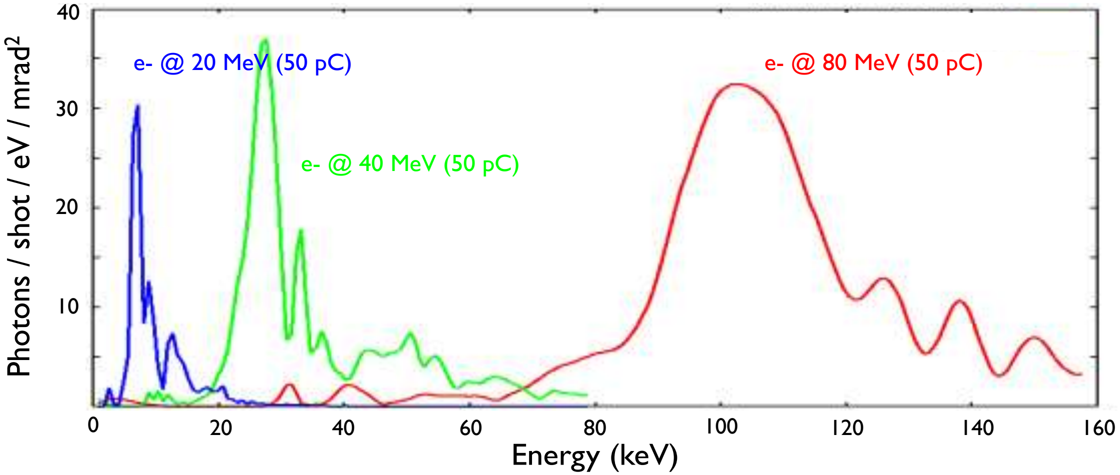
- High energy radiation
- Polychromatic
- Ultra-short pulses (<50fs)
- small source size (<10µm)

Radiation of relativistic e^- beams

- **Plasma betatron**



In the case of monoenergetic electron beams:

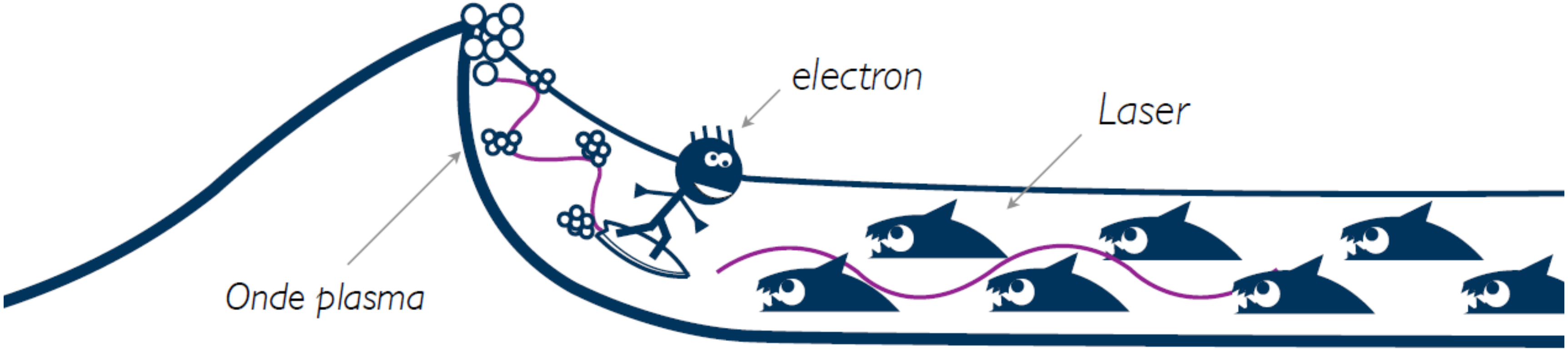


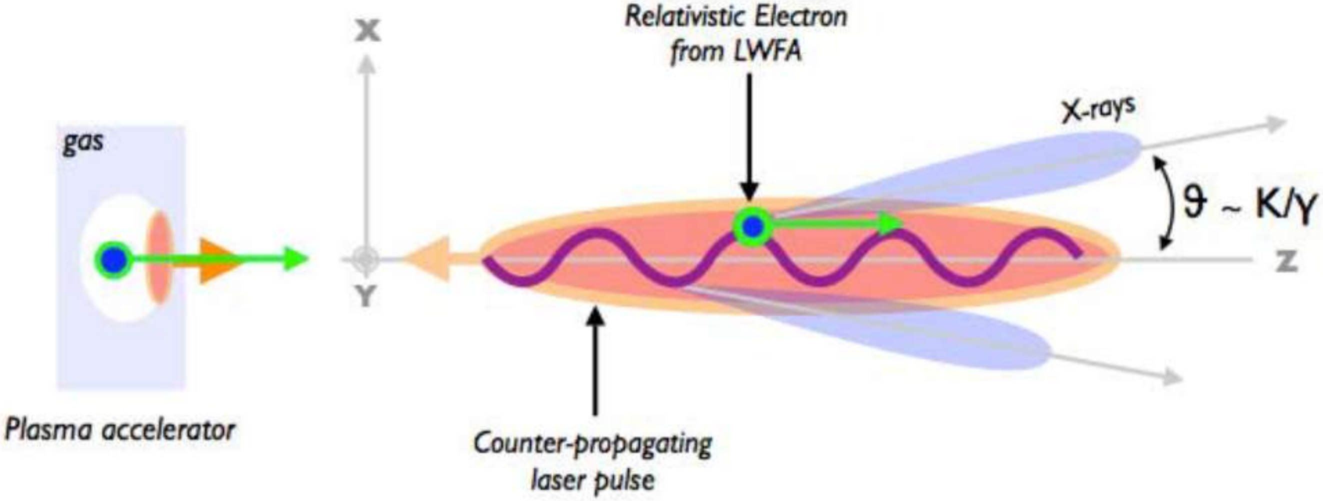
K. Ta Phuoc *et al.*

Radiation of relativistic e^- beams

- **Thomson back-scattering** (inverse Compton scattering)

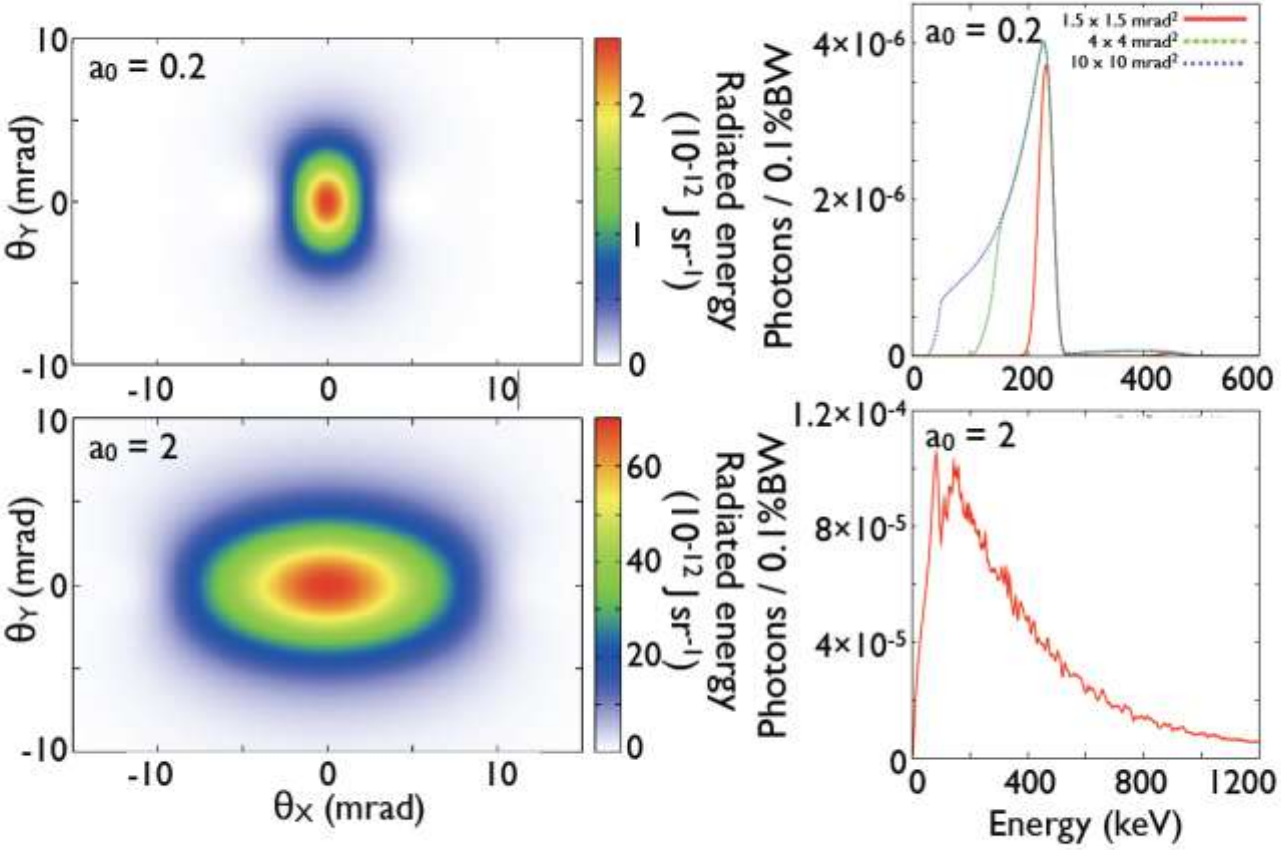
  Interaction e^- with an intense laser pulse





Radiation of relativistic e^- beams

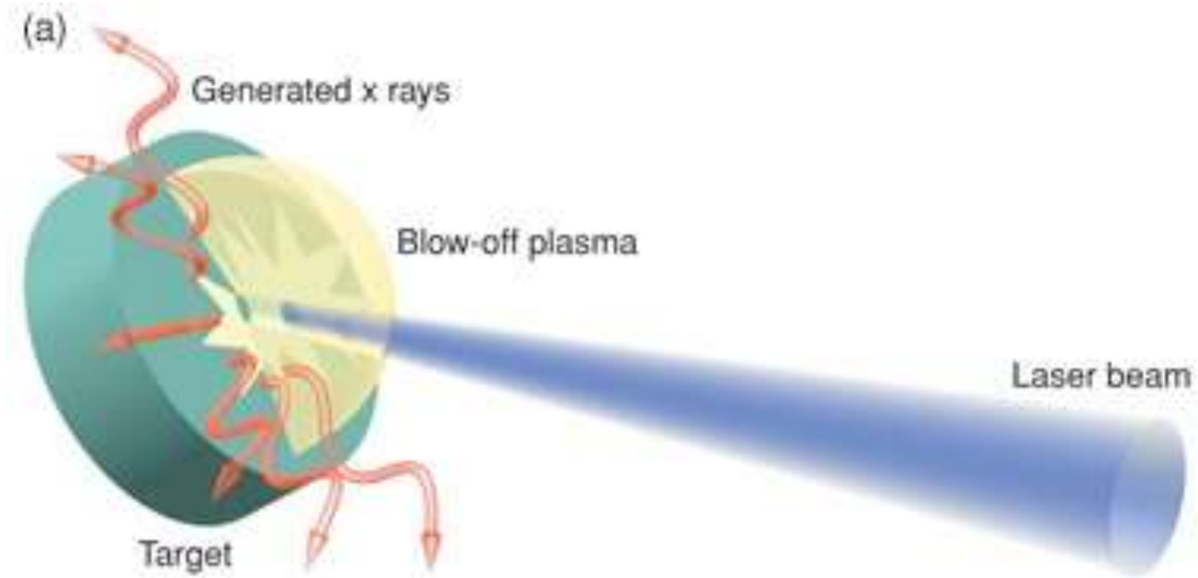
- **Thomson back-scattering**
- very hard radiation (up to MeV) $\omega_X = 4\gamma^2\omega_L$



S. Corde *et al.* accepted for publication in Rev. Mod. Phys 2012

X-ray plasma source

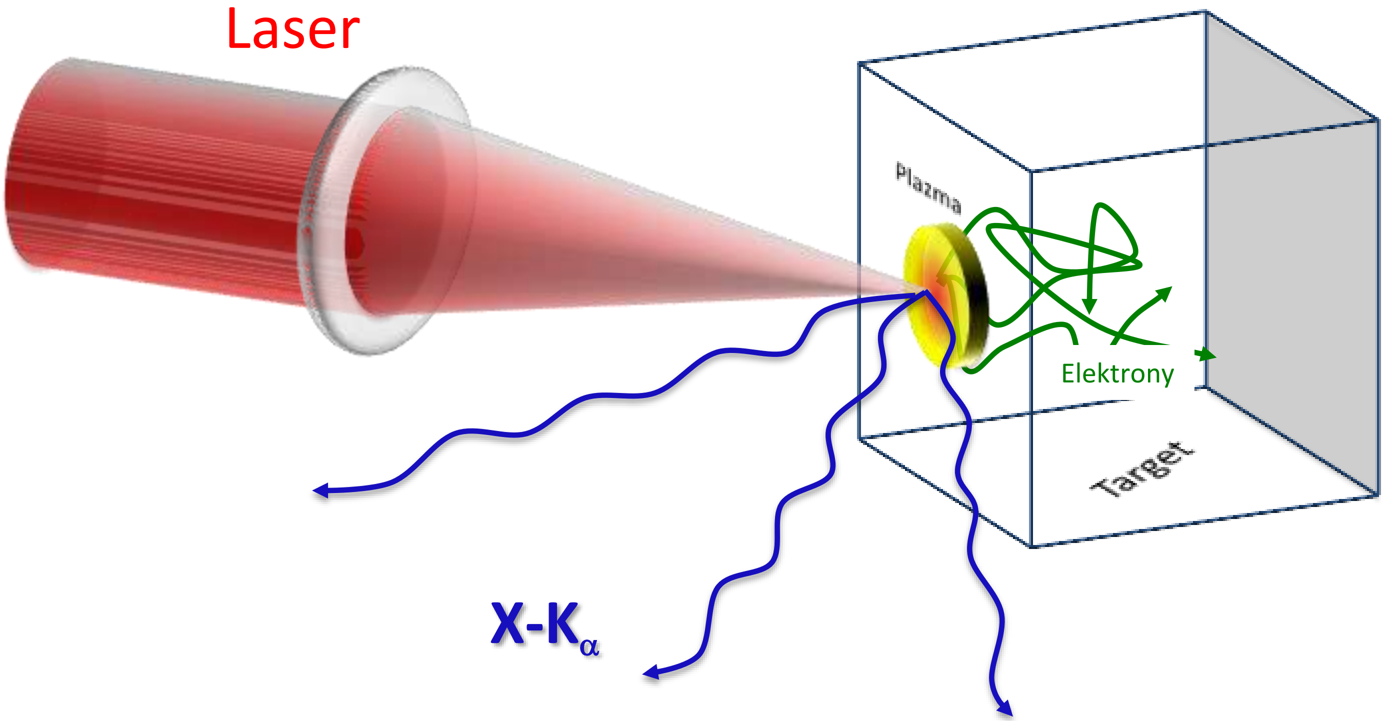
(Kα)



LLNL Science and Technology Review, October 2005

X-ray plasma source

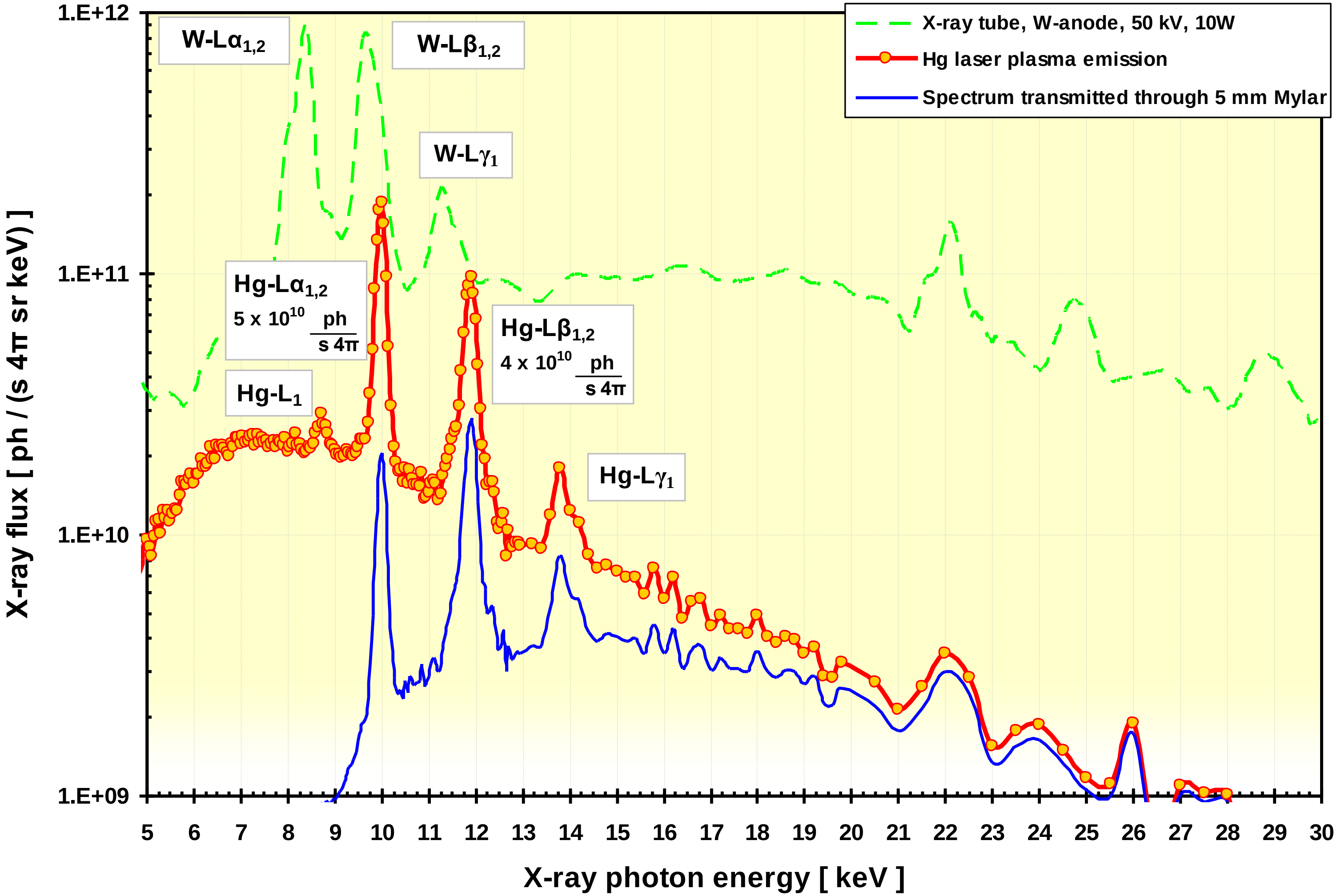
- Creation of "hot" electrons by interaction of intense laser pulse with matter ($I > 10^{16}$ Wcm^{-2}) $T_h \propto I\lambda^2$
- Energetic electrons are decelerated in the target
  - generation of bremsstrahlung and characteristic radiation



S. Sebban *et al.*

X-ray plasma source

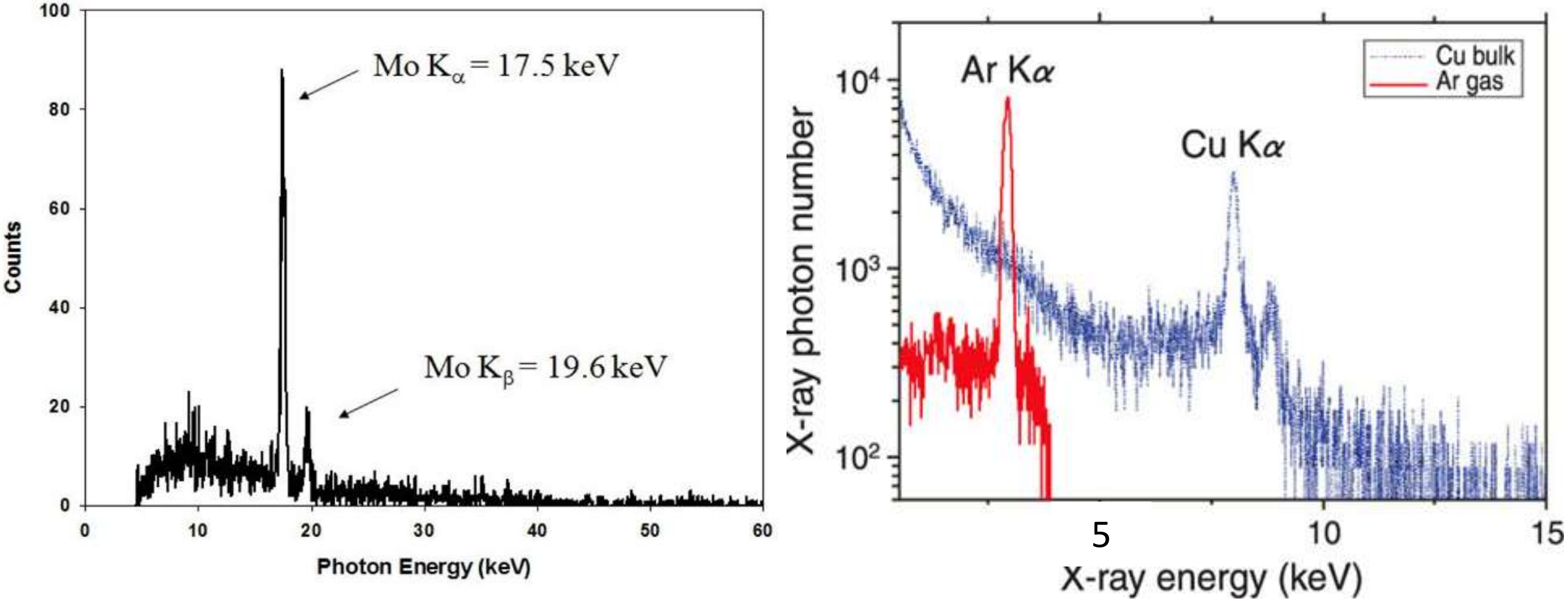
- Spectrum similar with an x-ray tube



Reich, C. *et al.* Optics *Letters* 2007, *32*, 427

X-ray plasma source

- Tuning parameters ⇒ strong K-α line emission

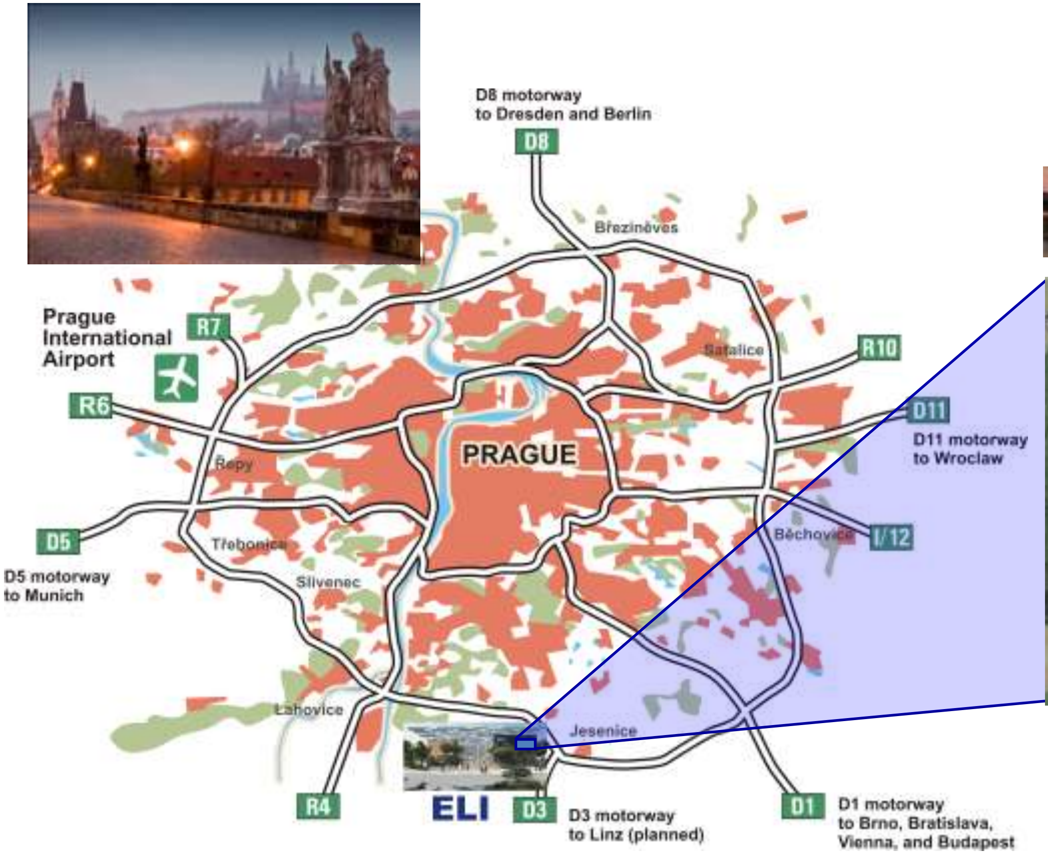


- Incoherent, polychromatic
- Isotropic emission (4π)
- Short pulse duration (~100 fs)

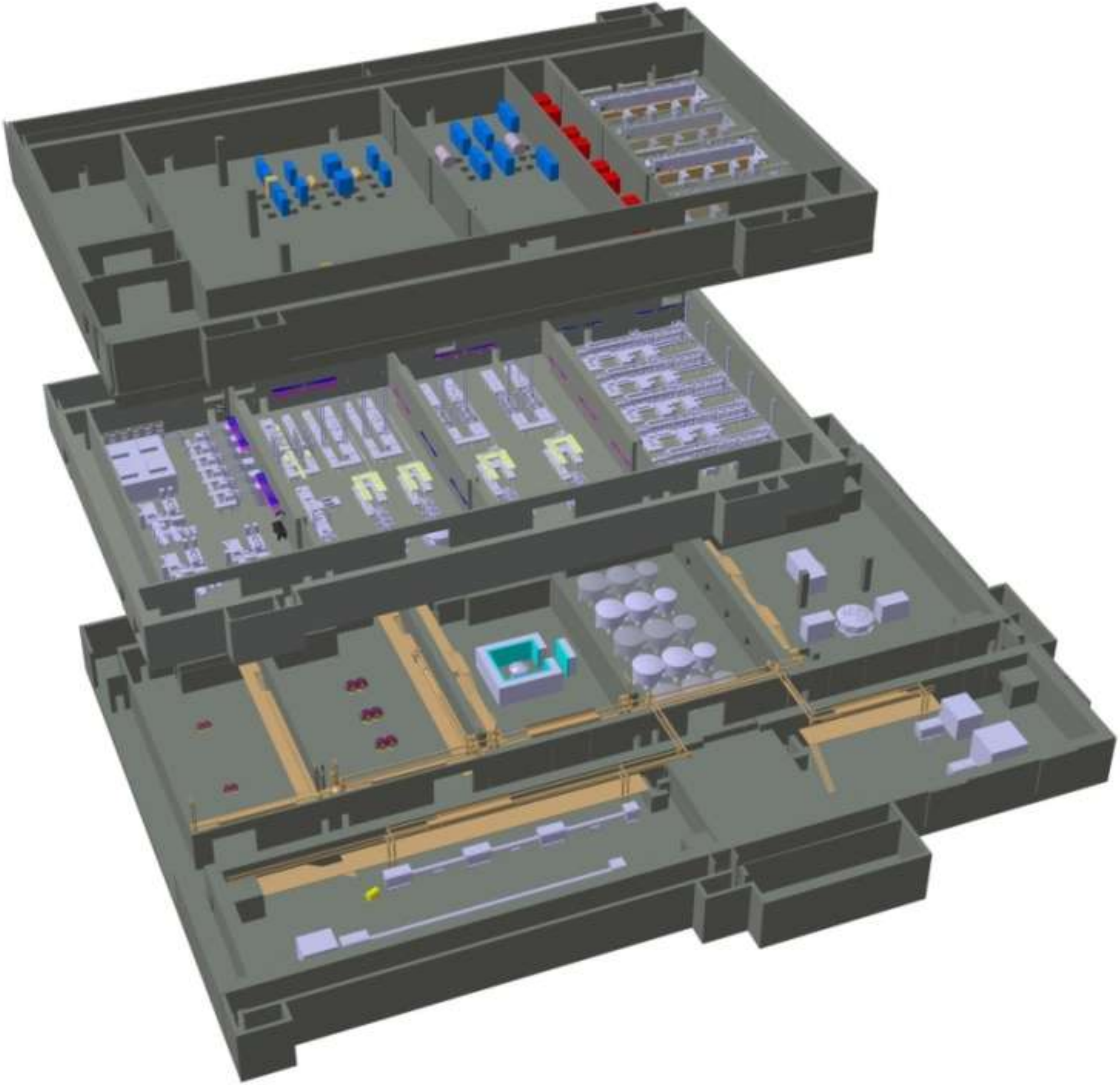
Future research facility ELI Beamlines

Future research facility ELI Beamlines

Dolní Břežany near Prahy

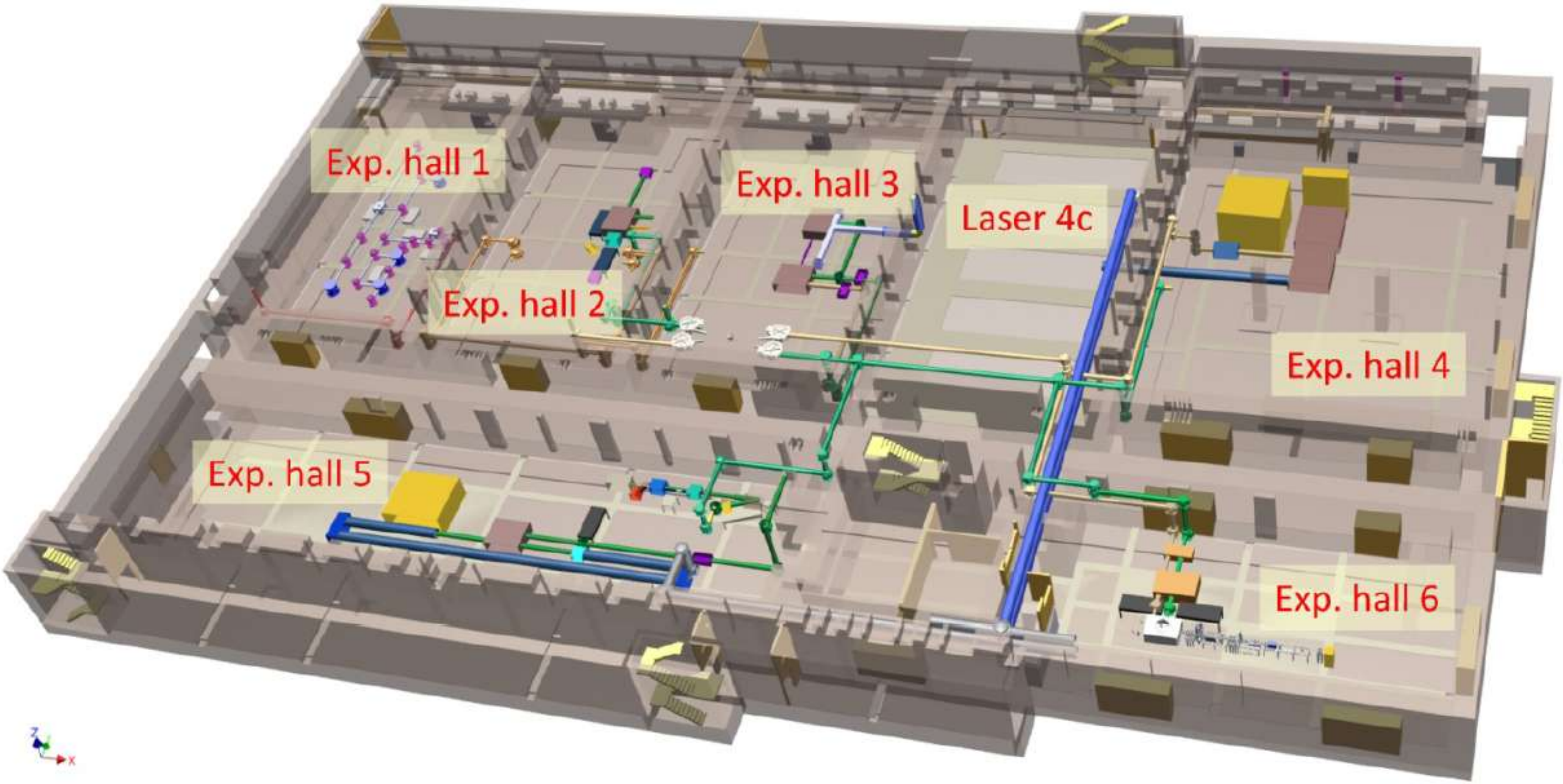


Dolni Brezany



Future research facility ELI Beamlines

Experimental halls



THANK YOU FOR YOUR ATTENTION

Any cooperation is highly welcome

Jaroslav Nejdl
nejdl@fzu.cz