Extatic welcome week, 22/9/2017

An Introduction to
Laser-driven X-ray Sources

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Fyzikální ústav
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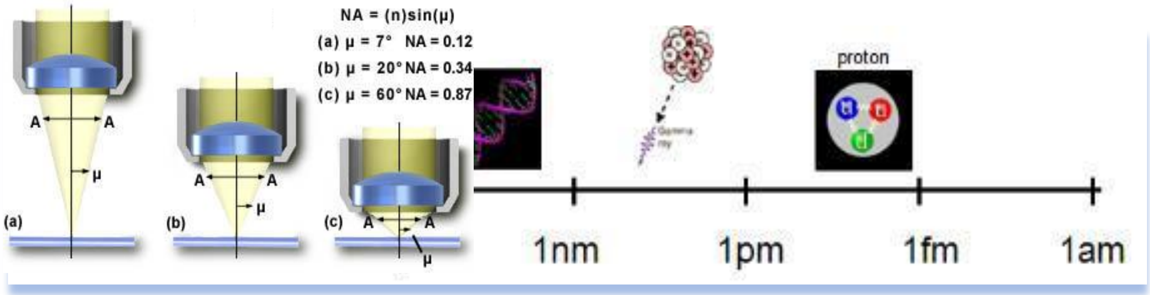
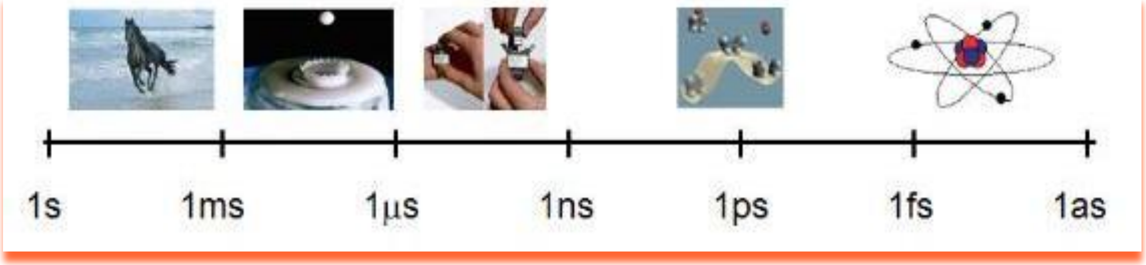
2007-13
OP Výzkum a vývoj pro inovace

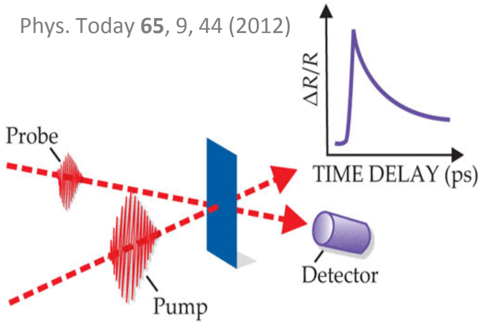
Motivation

Study nature in smaller spatial and shorter time scales

Spatial resolution (Rayleigh) $d = 0.61\frac{\lambda}{\mathrm{NA}}$, de Broglie: $\lambda = \frac{h}{p}$



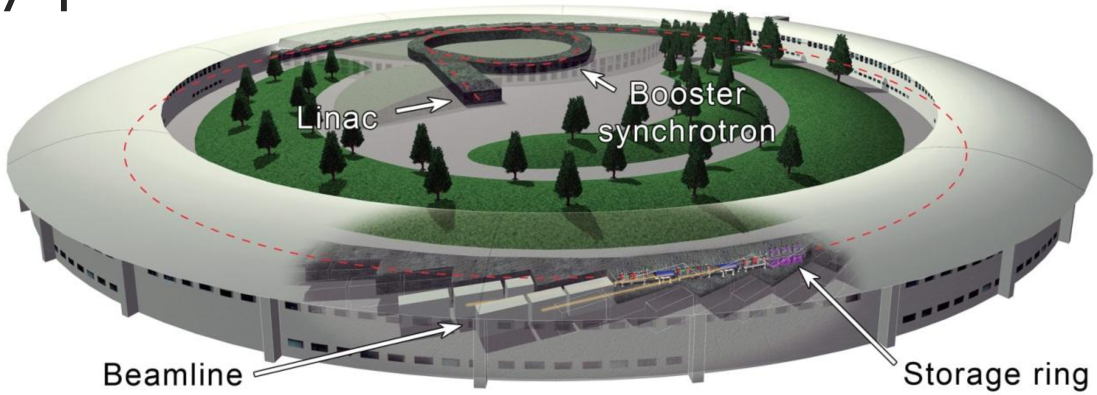



Phys. Today **65**, 9, 44 (2012)

Temporal resolution ~pulse duration in pump-probe experiments

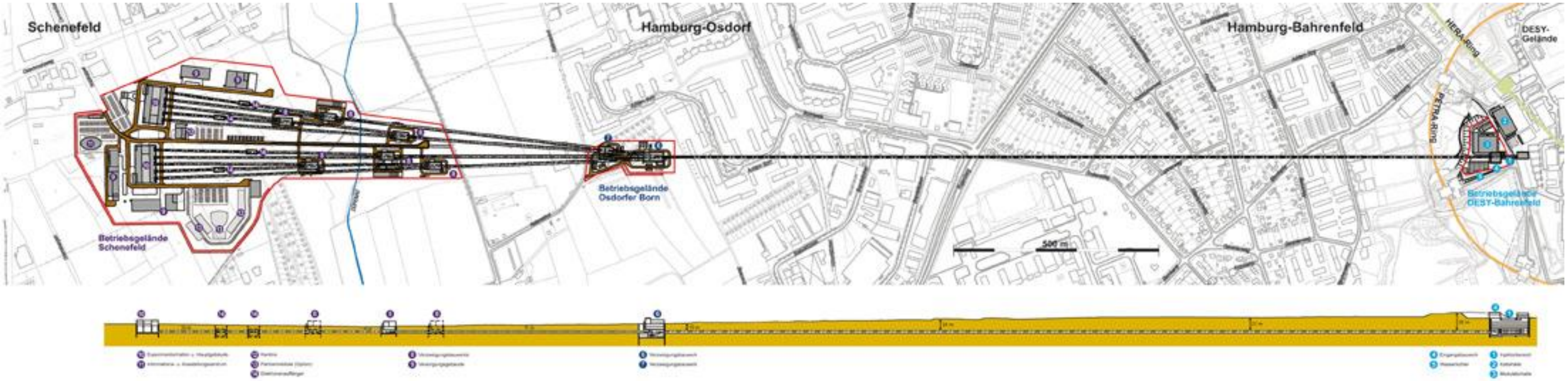
Motivation

Need for short X-ray pulses



Synchrotrons:
100 ps (fs)

XFEL (X-ray Free Electron Lasers): >10 fs



Superbright, **but** large ⇒ €€€€ ⇒ limitted ac
& difficult synchronization with pump pulses

⇒ laser driven X-ray sources

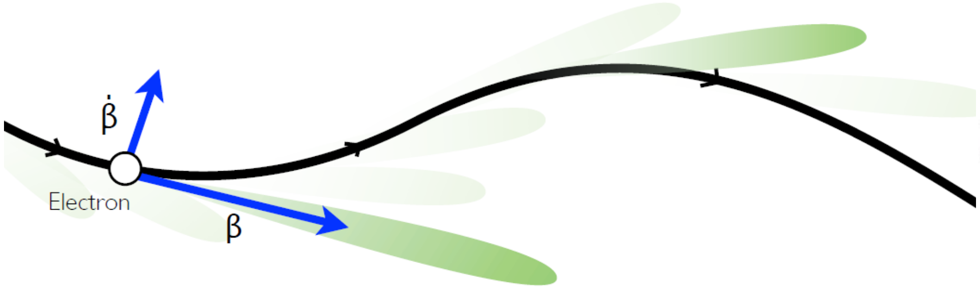
Outline

- Origin of Electromagnetic radiation
- Laser-driven sources of short-wavelength radiation
  - High-order harmonic generation from gas
  - Plasma-based X-ray lasers
  - Plasma X-ray sources
  - Sources based on laser driven electron beams
    - Plasma betatron
    - Inverse Compton source

Origin of EM radiation

Microscopically: accelerated motion of charge

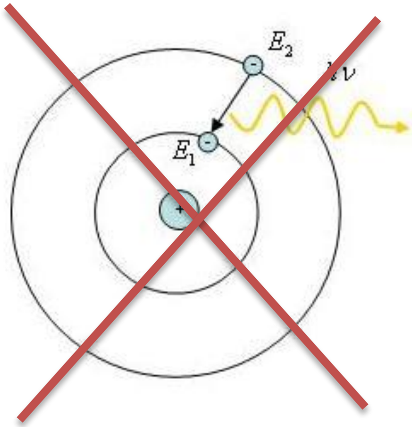
- Free:

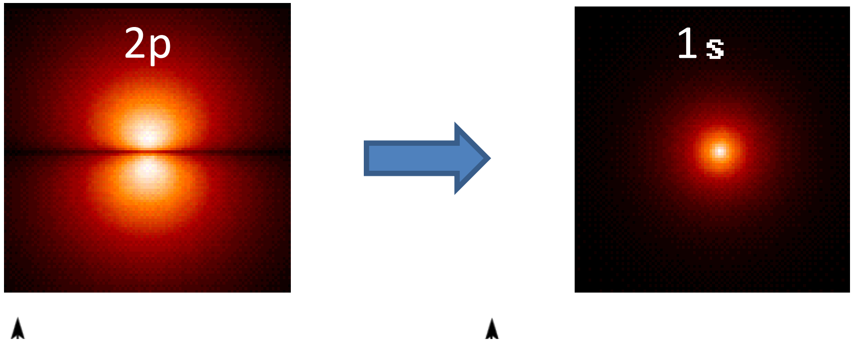


$$\frac{d^2I}{d\omega d\Omega}=\frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} e^{i\omega[t-\vec{n}.\vec{r}(t)/c]}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\,.\,\vec{n})^2}dt\right|^2$$

???

- Bound: radiative (allowed/dipole) transitions





$$\left[\frac{-\hbar^2}{2m}\nabla^2+V\right]\Psi=i\hbar\frac{\partial}{\partial t}\Psi$$

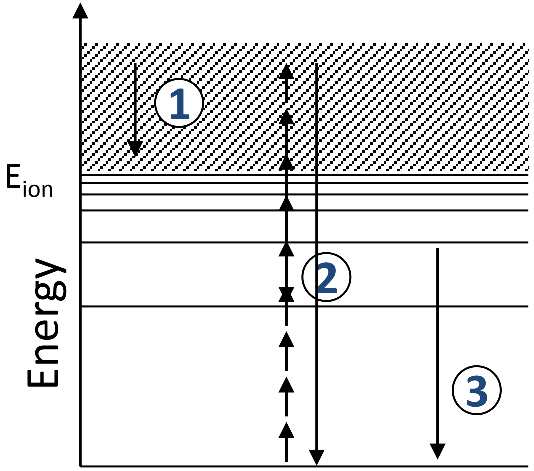
O I

Time

Origin of EM radiation

Mostly electrons being employed in this spectral range (large e/m ratio) $\mathrm{d}E/\mathrm{d}z \propto E^4/(m^4R^2)$

Types of radiative transitions (QM point of view):



1) Free-free (classical accelerated charge)

- Sources employing relativistic electron beams (undulator, betatron, Compton)
- Laser plasma source (bremsstrahlung)

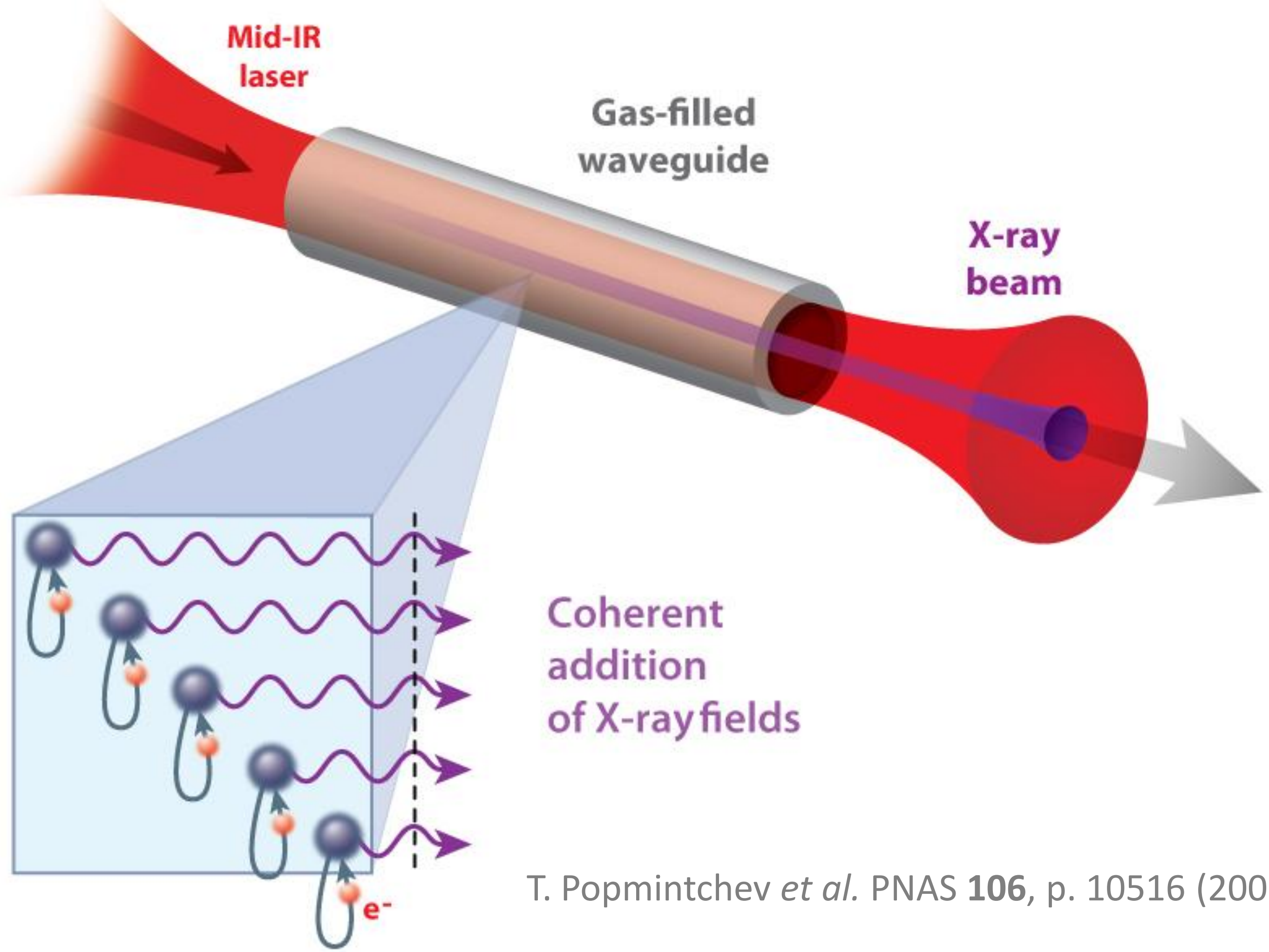
2) Free-bound

- High-order harmonic generation
- Laser plasma source (radiative recombination)

3) Bound-bound

- Soft X-ray lasers (stimulated emission)
- Laser plasma source (inner-shell transitions e.g. Kα)

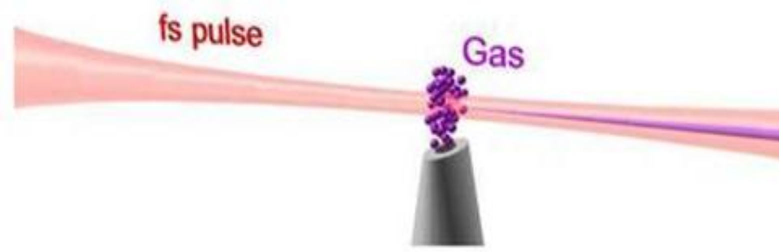
High-order harmonic generation (HHG)

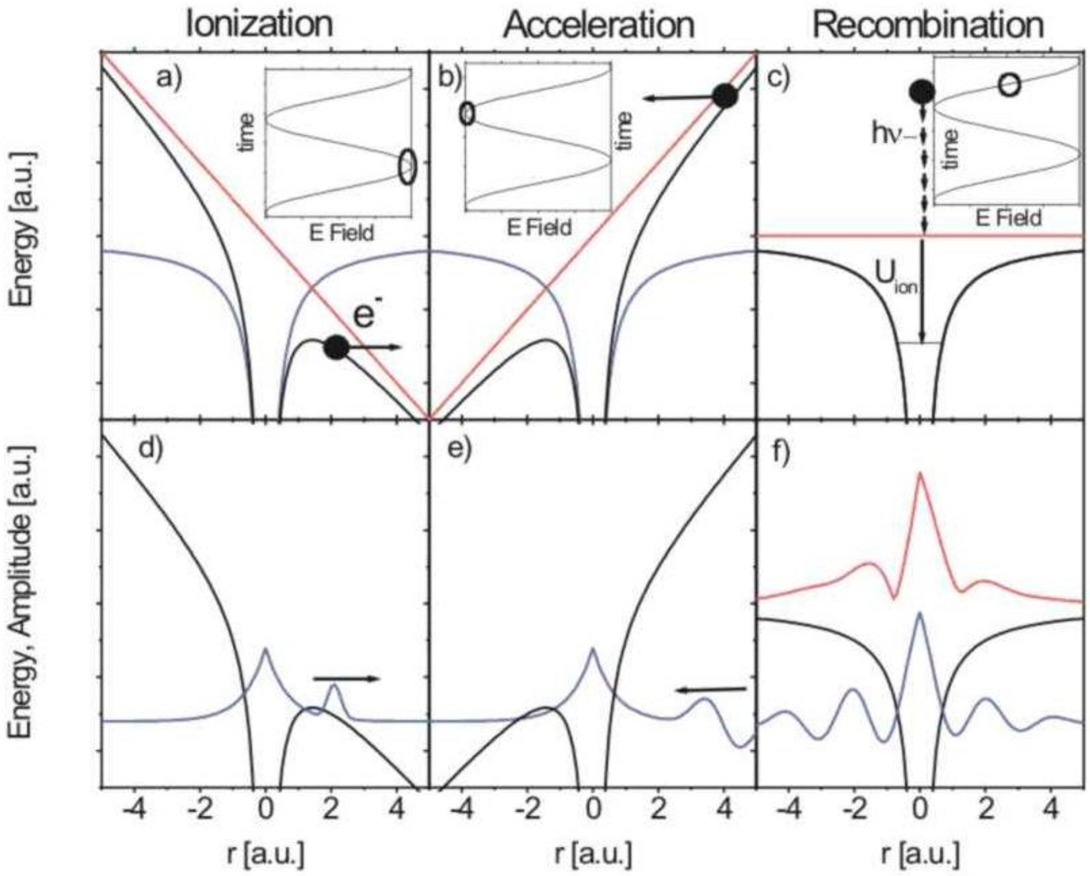


T. Popmintchev *et al.* PNAS **106**, p. 10516 (2008)

HHG in gas

- 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)

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

HHG in gas

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

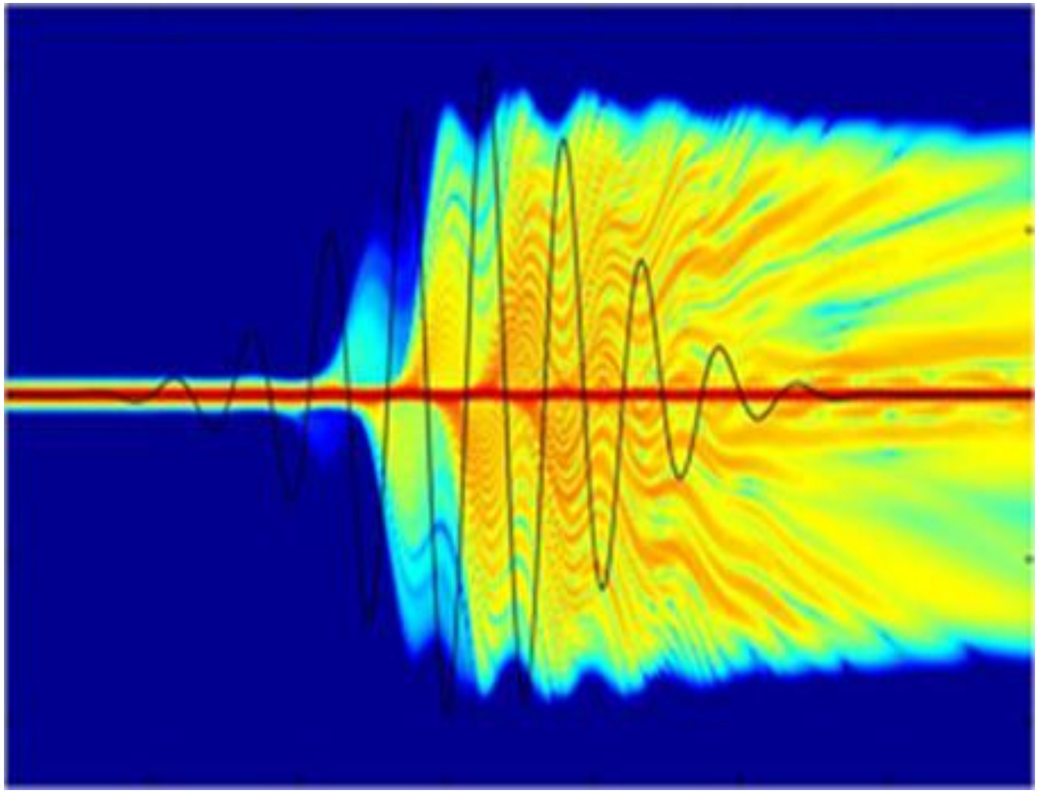
- Microscopic analysis

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

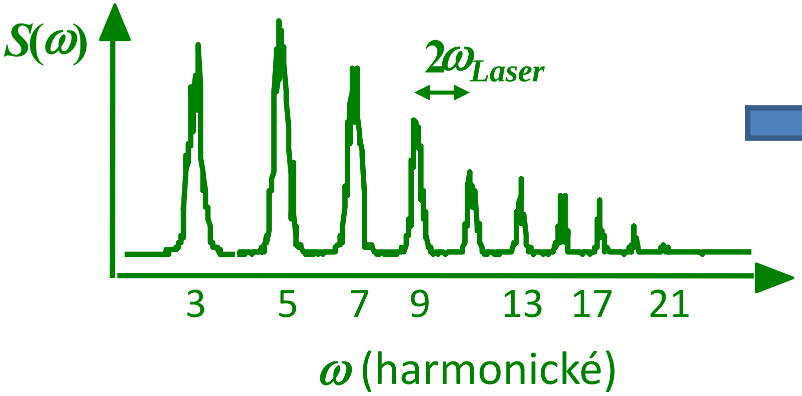
HHG: time vs frequency

- $\lambda = 800$ nm $\rightarrow$ $T = 2.7$ fs

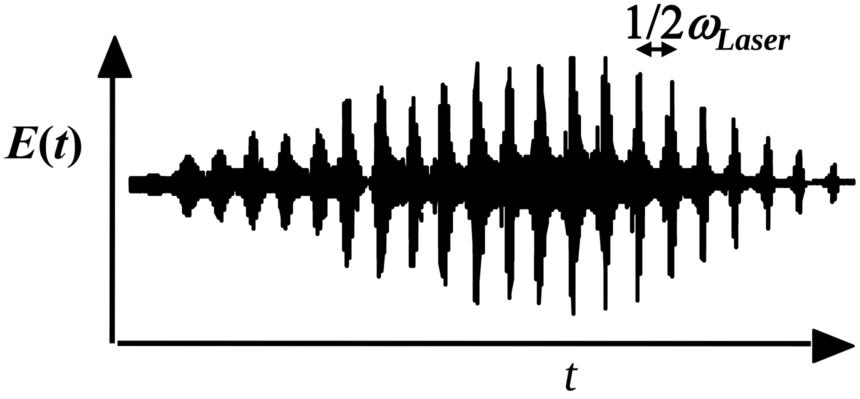
  $\rightarrow h\nu = 1.55$ eV

100fs laser pulse with short medium: attosecond pulse train

Measured spectrum

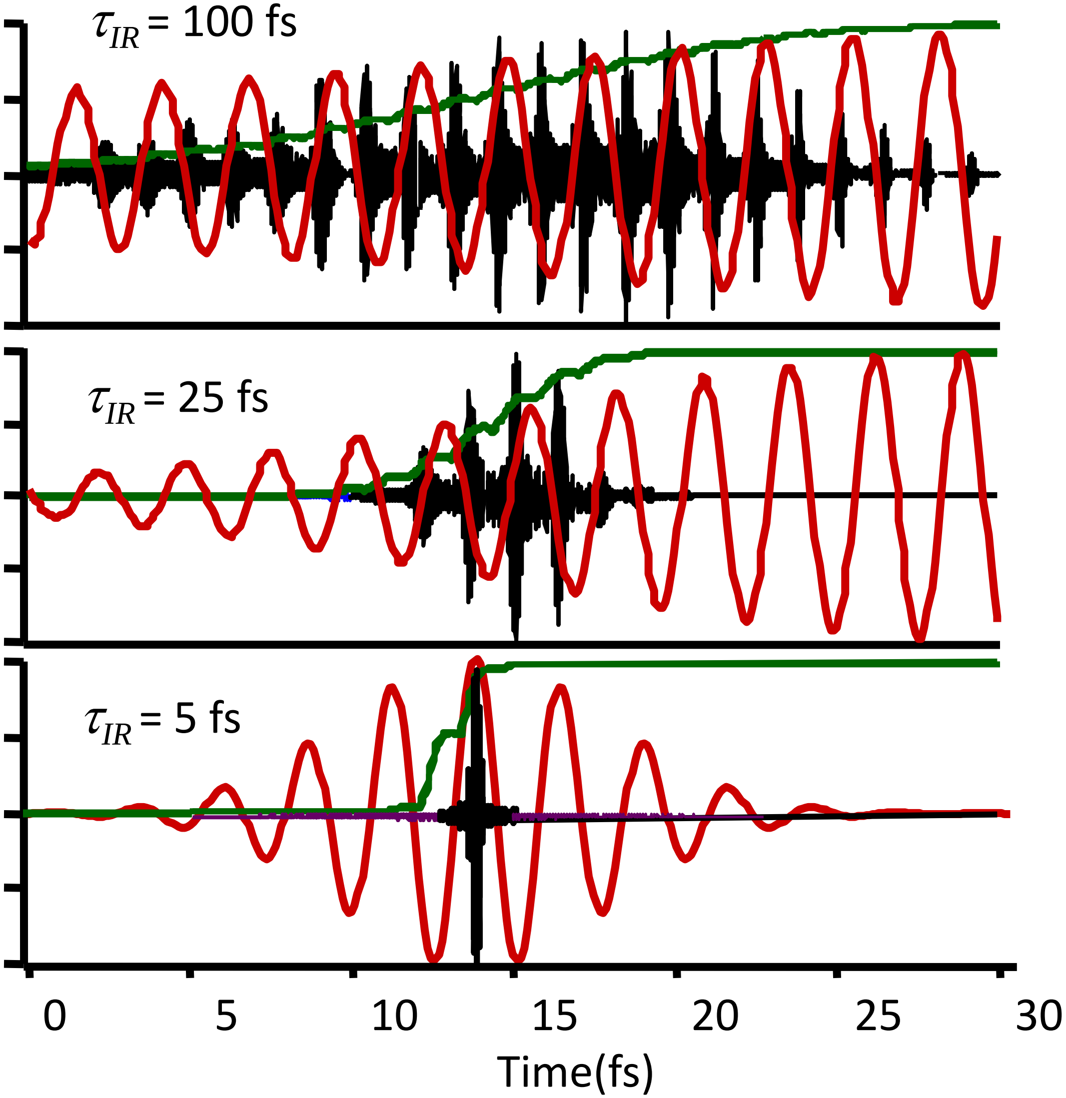


Estimated E-field evolution



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

HHG: time vs frequency



Ionization

Harmonic field

Laser field

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

HHG: time vs frequency

nature COMMUNICATIONS

ARTICLE

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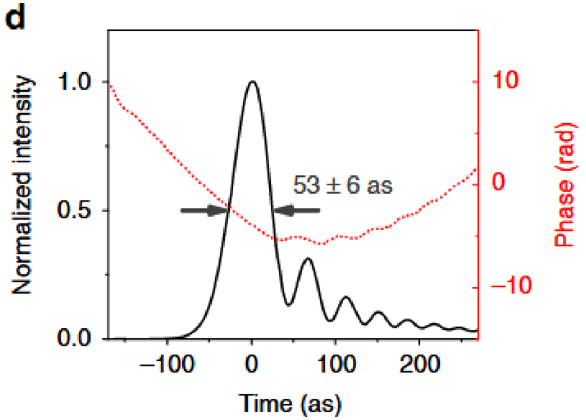
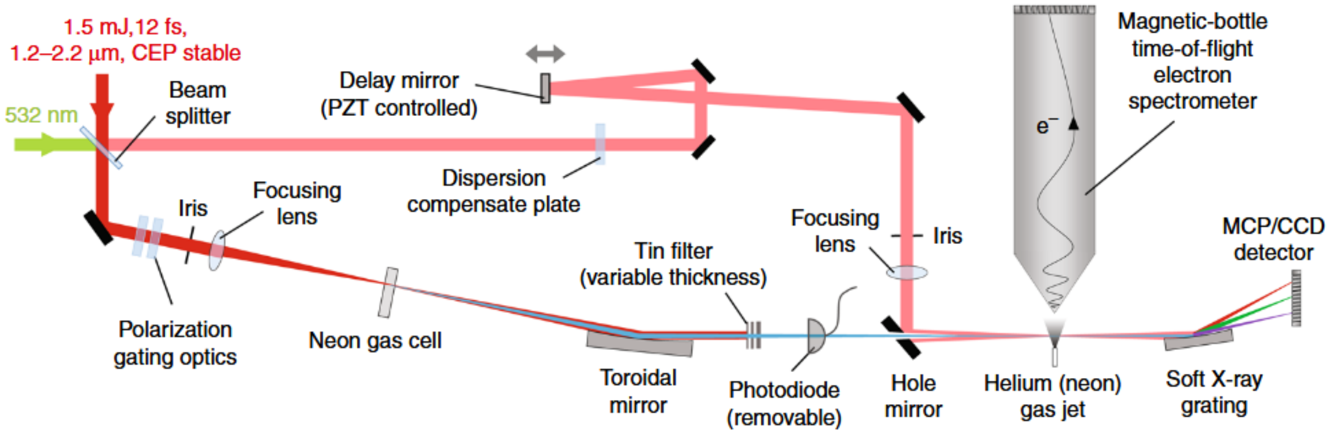
Published August 4th 2017

53-attosecond X-ray pulses reach the carbon K-edge

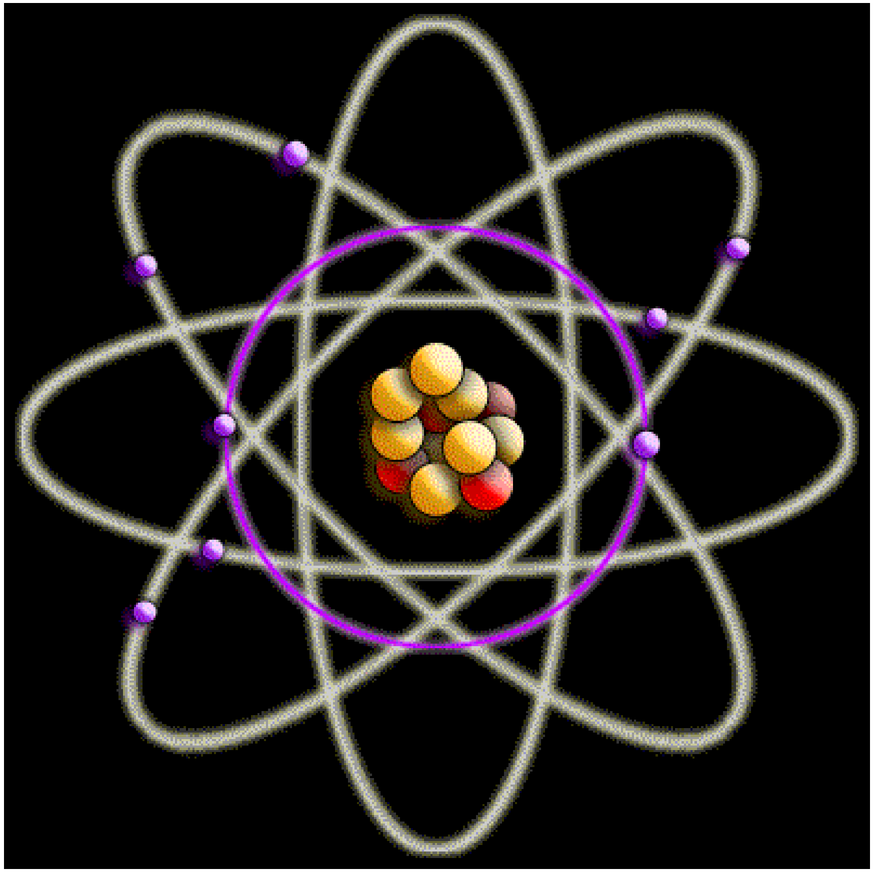
Jie Li[1], Xiaoming Ren[1], Yanchun Yin[1], Kun Zhao[1,2], Andrew Chew[1], Yan Cheng[1], Eric Cunningham[1], Yang Wang[1], Shuyuan Hu[1], Yi Wu[1], Michael Chini[3] & Zenghu Chang[1,3]

The motion of electrons in the microcosm occurs on a time scale set by the atomic unit of time—24 attoseconds. Attosecond pulses at photon energies corresponding to the fundamental absorption edges of matter, which lie in the soft X-ray regime above 200 eV, permit the probing of electronic excitation, chemical state, and atomic structure. Here we demonstrate a soft X-ray pulse duration of 53 as and single pulse streaking reaching the carbon K-absorption edge (284 eV) by utilizing intense two-cycle driving pulses near 1.8-μm center wavelength. Such pulses permit studies of electron dynamics in live biological samples and next-generation electronic materials such as diamond.



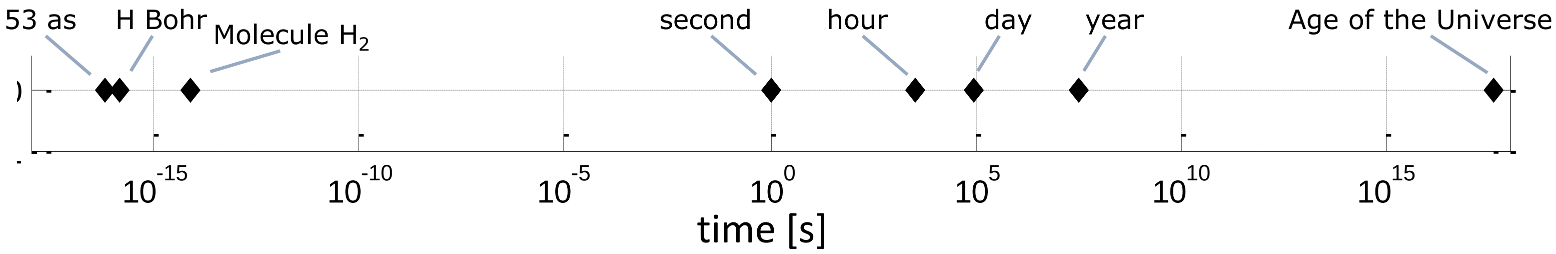


HHG: time vs frequency

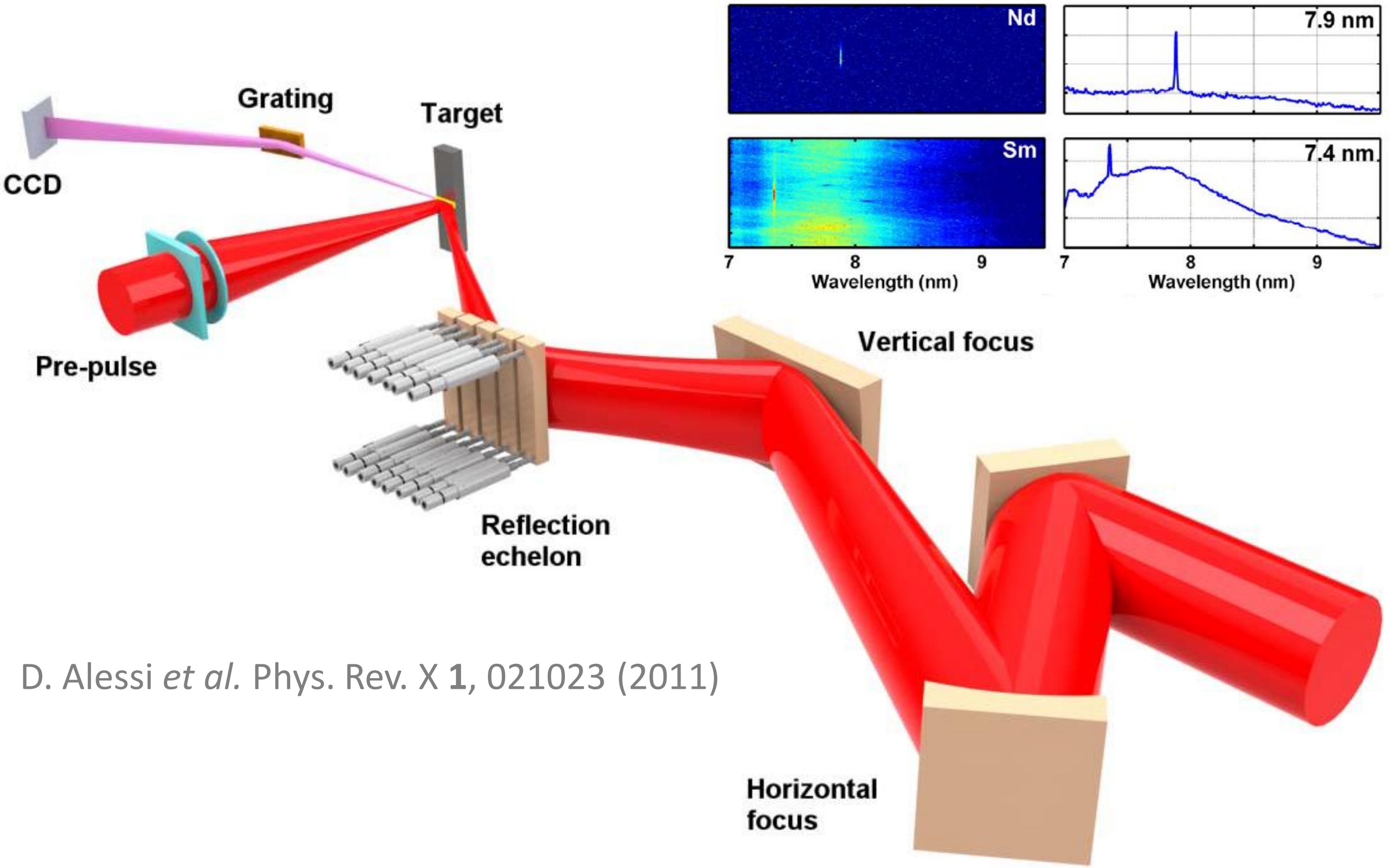


Period of an electron in Bohr’s orbital of hydrogen:
T= 152 as

Period of vibration of H_2
T= 8 fs



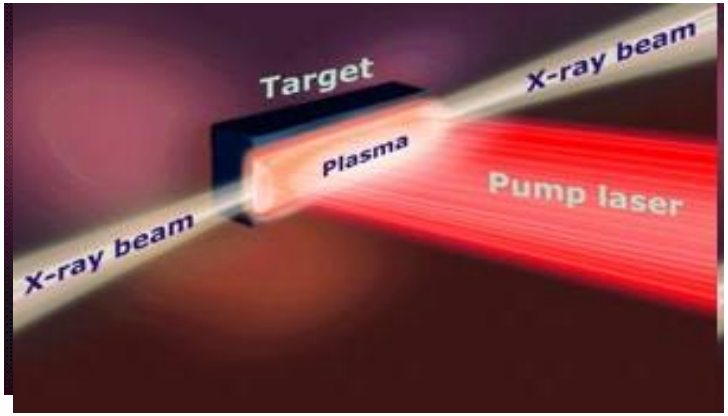
Plasma-based x-ray lasers



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 ionized plasma



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

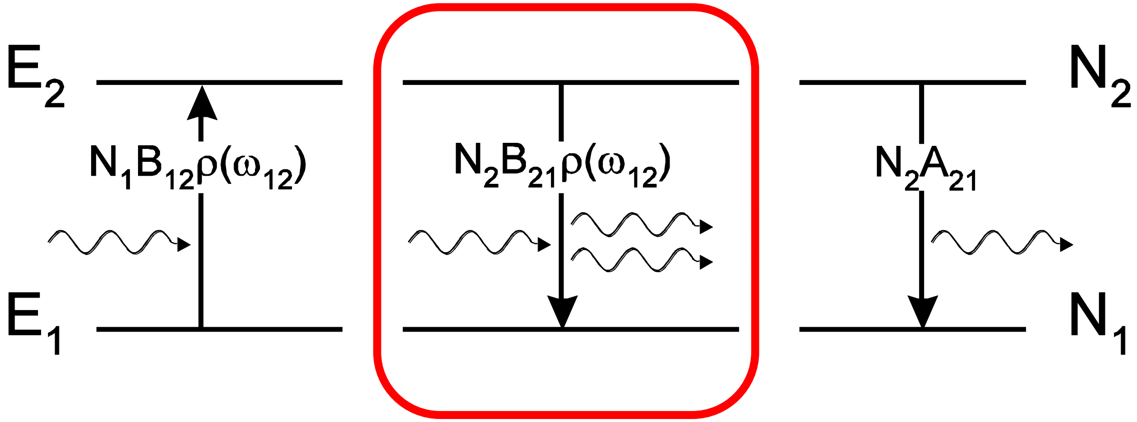
$$E_u - E_l = (13.6\,\mathrm{eV})\,Z^2\left(\frac{1}{n_l^2} - \frac{1}{n_u^2}\right)$$

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

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

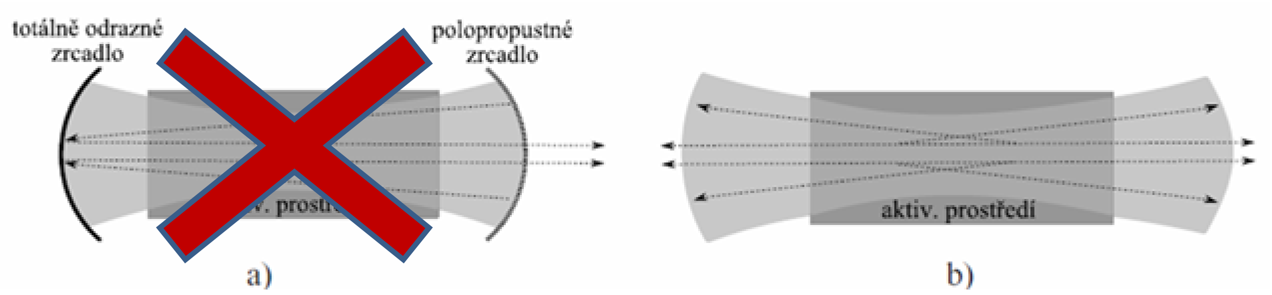
Pumping intensity is proportional to $1/\lambda^4$ ⇒ high pump power for shorter wavelengths – possible only in hot dense plasma

Plasma-based x-ray lasers

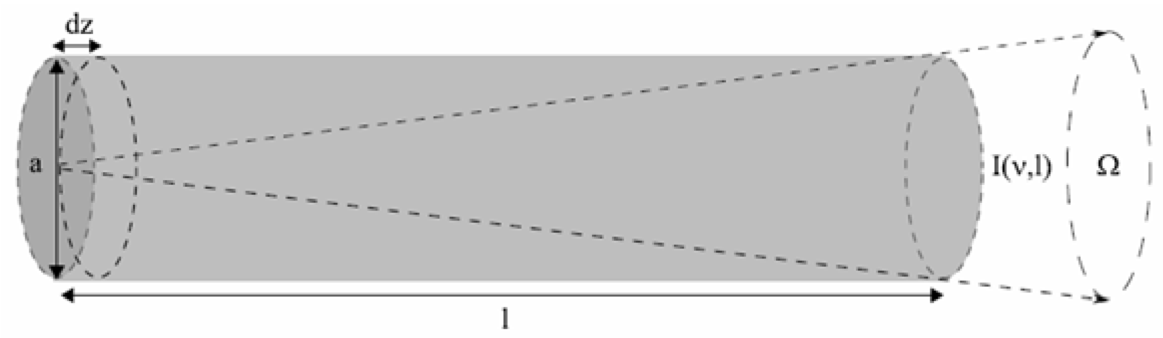
Due to short lifetimes of the gain, nonexistence of highly reflecting mirrors in XUV/x-ray and agressive plasma (damages nearby optics)
Laser resonator (cavity) cannot be used

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

$\Rightarrow$ Long narrow column of gain medium



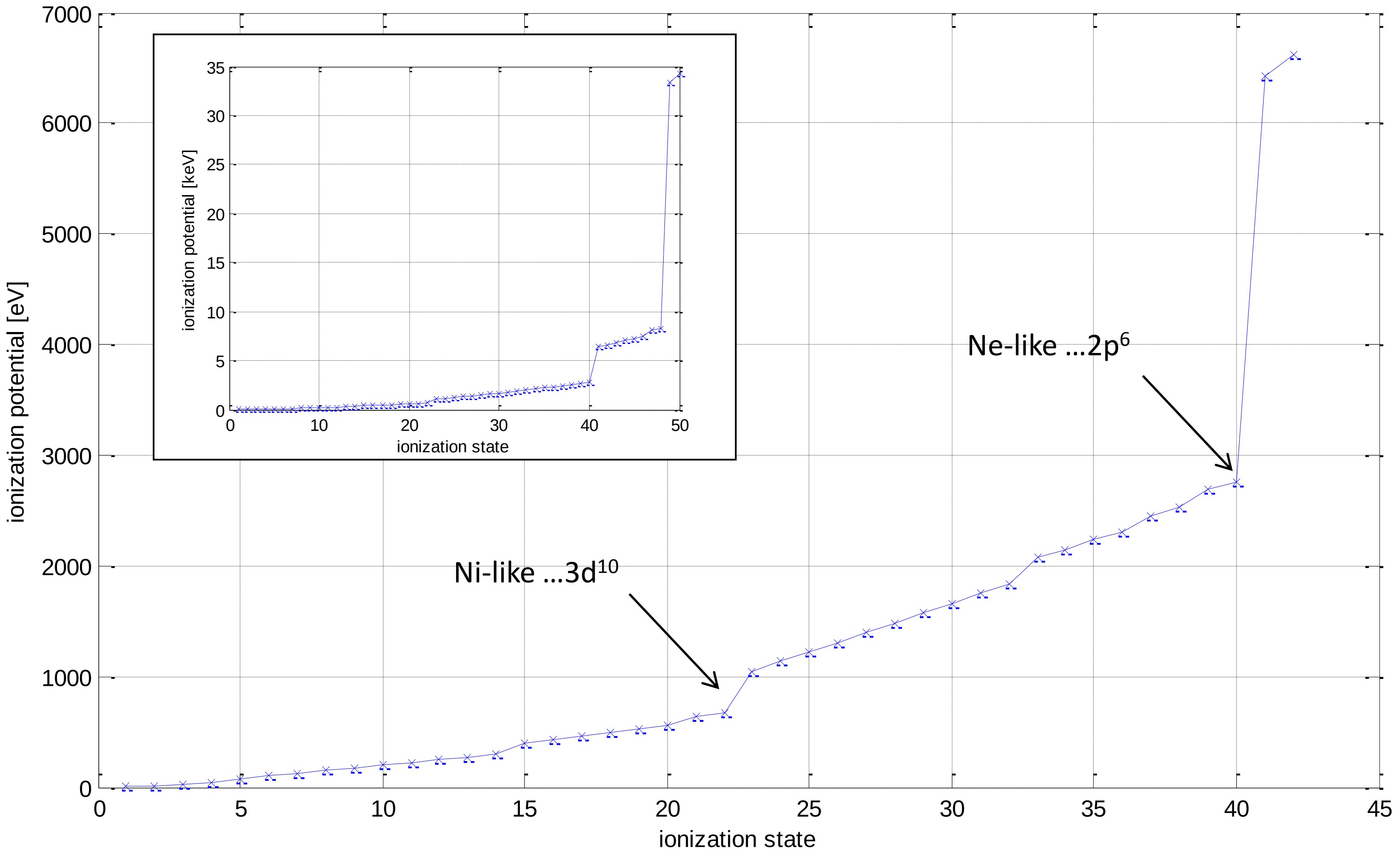
a) b)



Plasma-based x-ray lasers

Some ions are more stable than others

Example: Sn: Z=50, Ground state $1s^2\ 2s^2 2p^6\ 3s^2 3p^6 3d^{10}\ 4s^2 4p^6 4d^{10}\ 5s^2 5p^2$



Ni-like …$3d^{10}$

Ne-like …$2p^6$

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

Plasma-based x-ray lasers

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

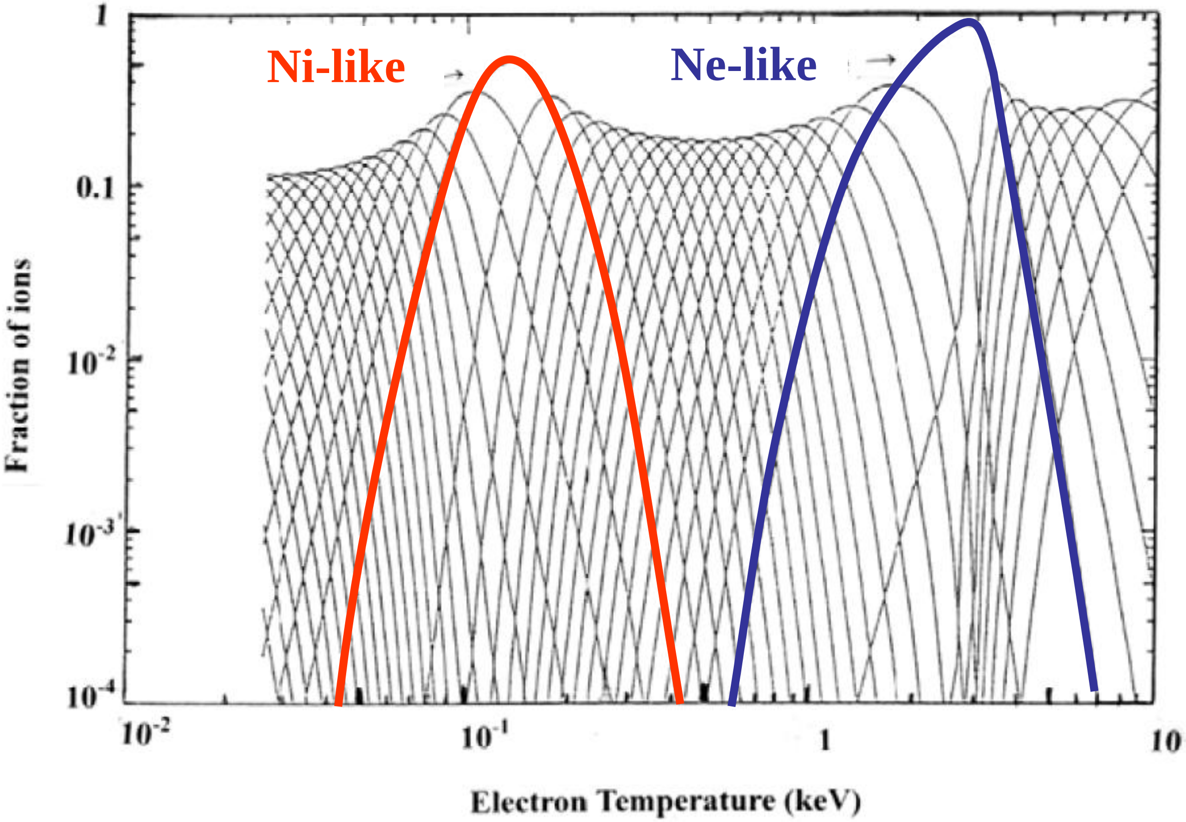


Figure 11. Ion abundance as a function of the electron temperature for tin plasma.

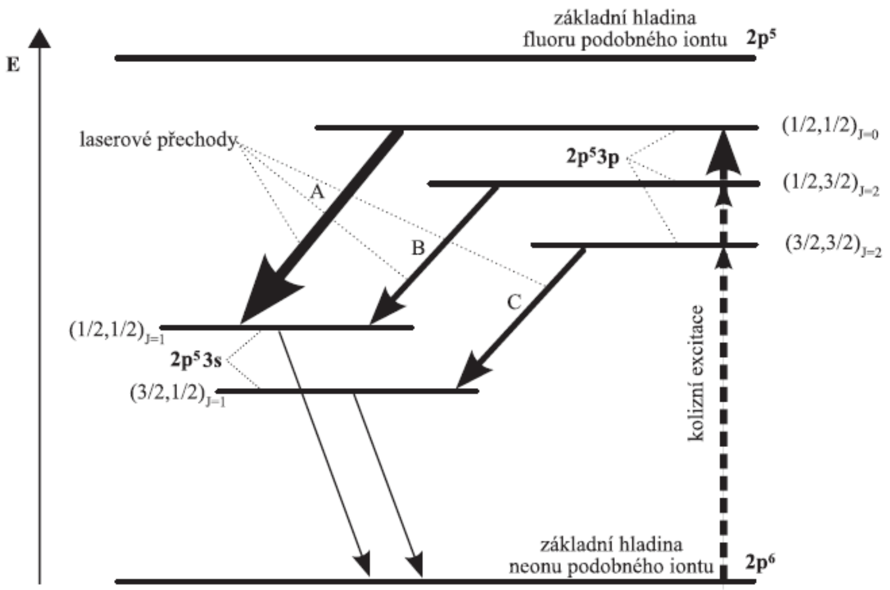
H. Daido, Rep. Prog. Phys. **65** (2002) 1513–1576.

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

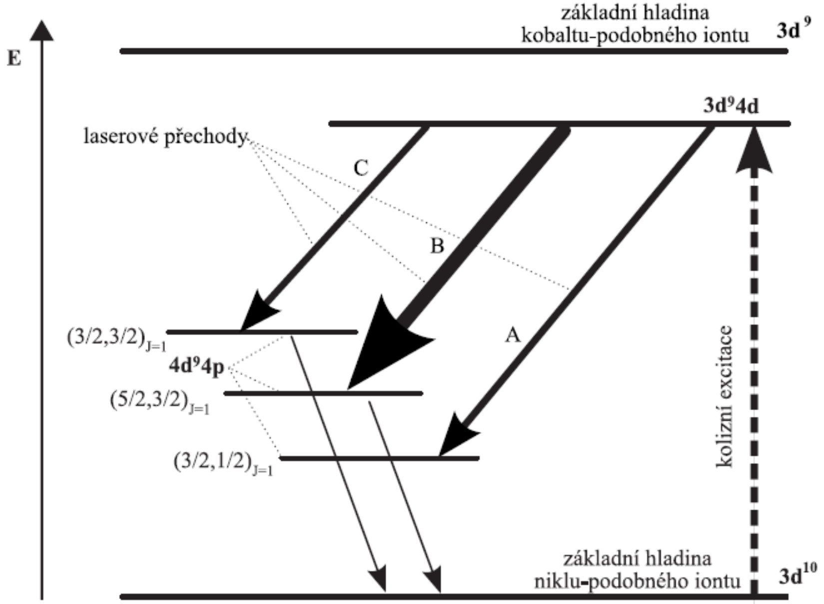
Plasma-based x-ray lasers

Collisional excitation

Ne-like ions



Ni-like ions



Fast depletion of the lower lasing level

Low quantum efficiency

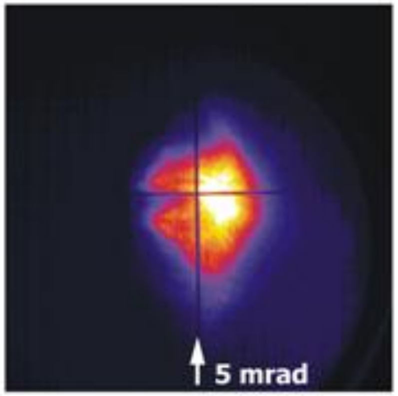
pumping: transition between shells (Ne-like:2-3 Ni-like 3-4)

Lasing: in a shell (Ne-like: 3p-3s; Ni-like: 4d-4p)

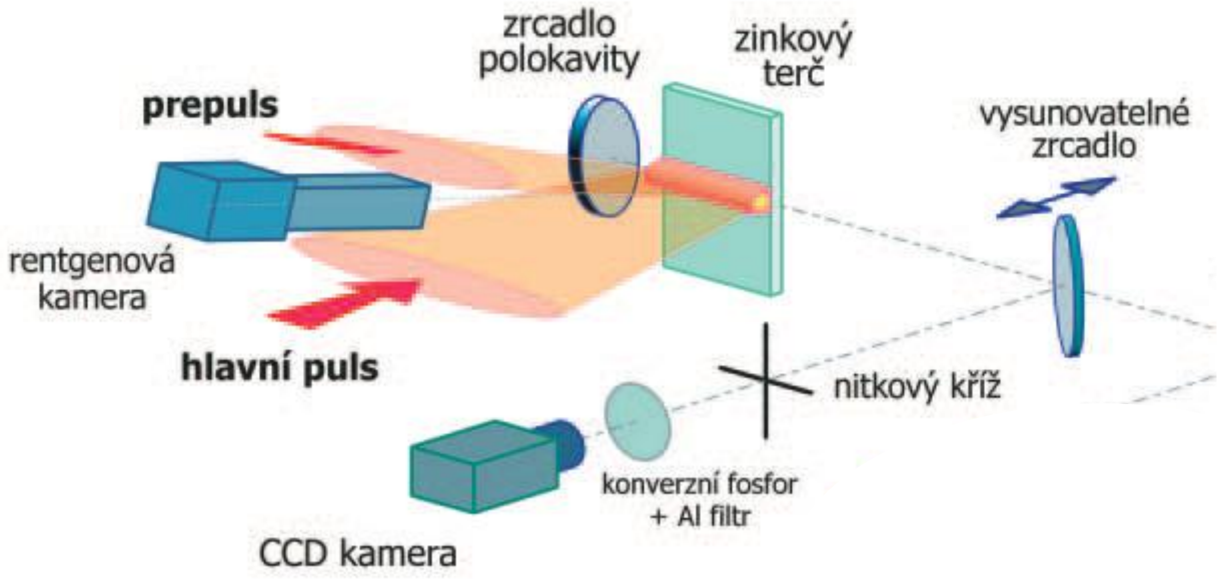
Ne-like Zn XRL @ 21.2 nm (1 shot/30min)

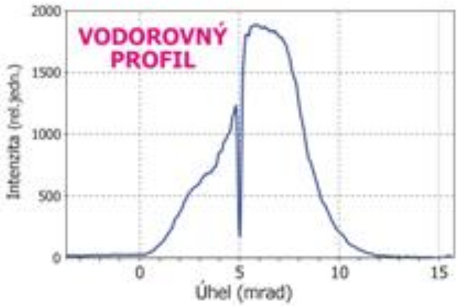
Quasi-steady state (normal incidence pumping)

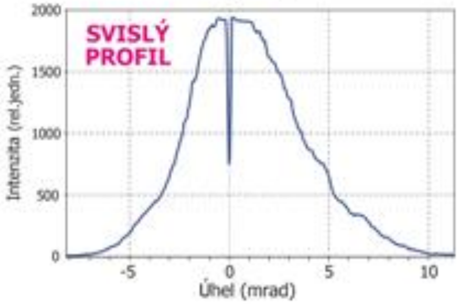
Prepulse (2J) and main pulse (500J) of ASTERIX focused down to a line(150μm) on a 3cm-long Zn target



- 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

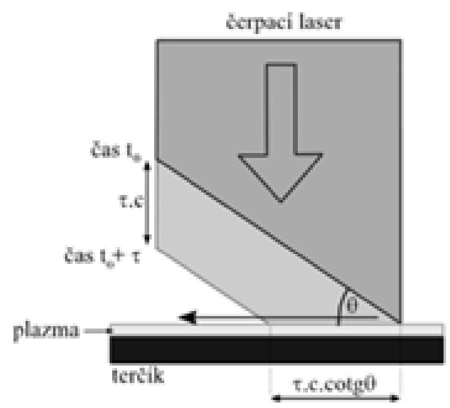
Ni-like ions:

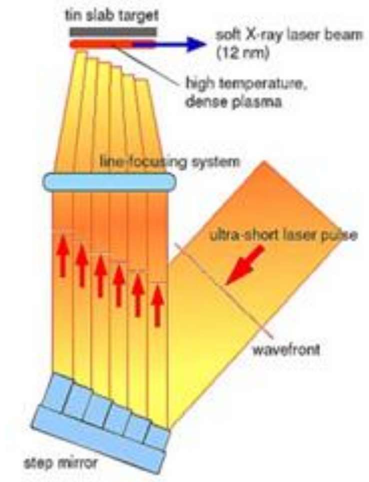
Suitable for shorter λ (faster pumping)

Usually short gain duration–
Faster (transient) pumping required

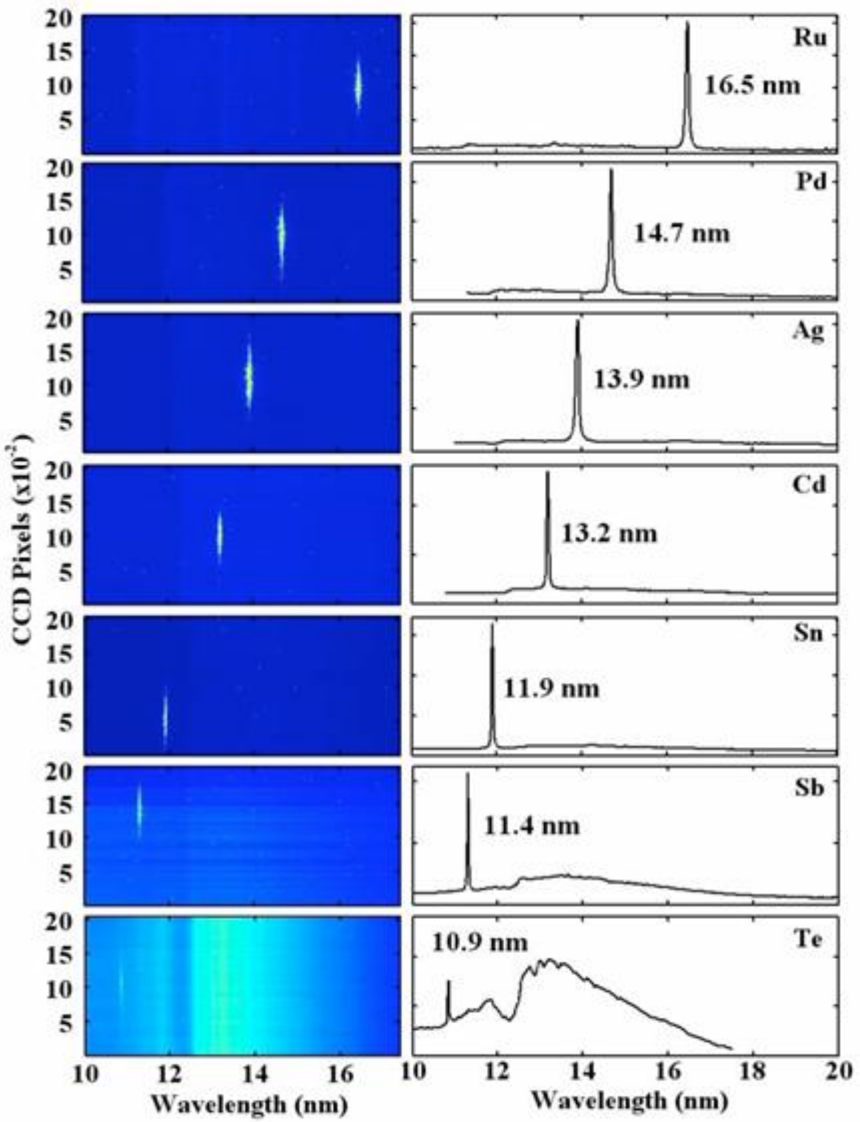
Space overlap of pumping with generated radiation

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





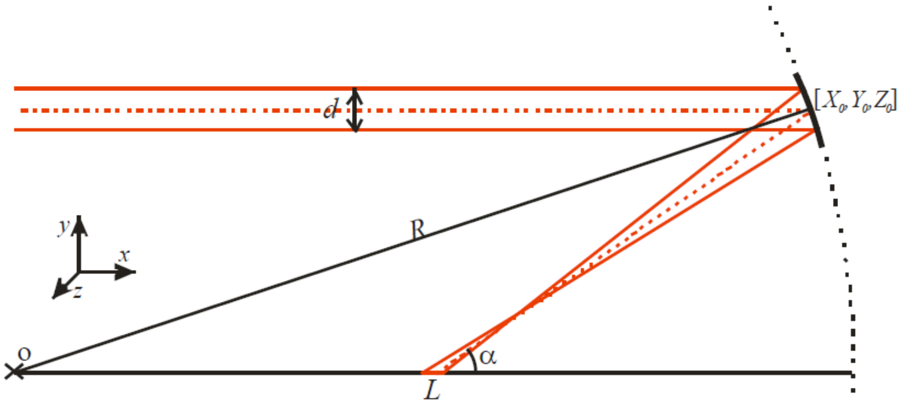
- Longitudinal pumping (gas target)
- GRazing Incidence Pumping

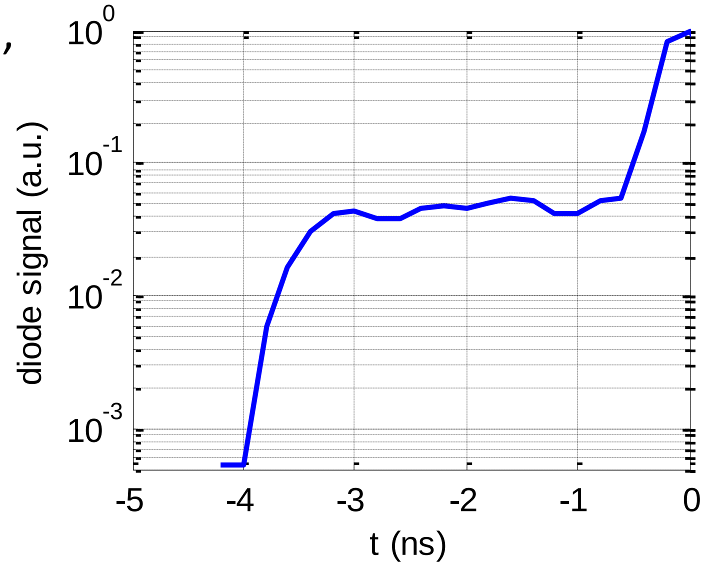


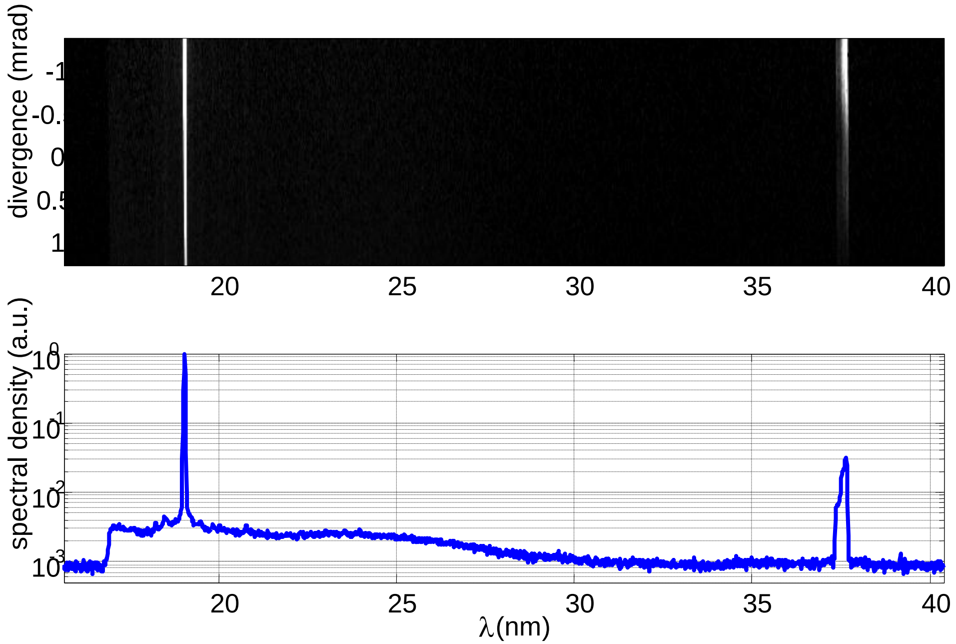
J. Rocca, Colo. State U. euverc.colostate.edu

GRIP Ni-like Mo XRL@ 18.9nm (10Hz)

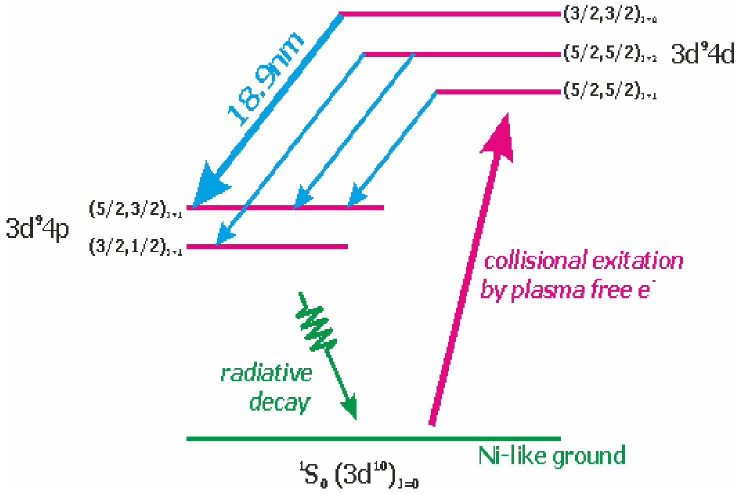
Pump: ~500mJ @ 810nm, 20 and 25deg grazing incidence,
Shaped pulse: 7ps main pulse, with 4ns ASE pedestal







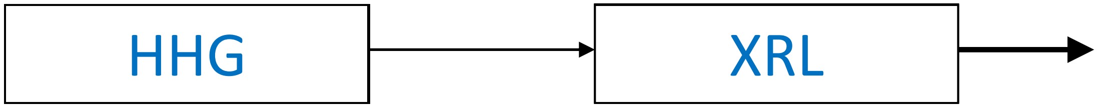
Ni-like Mo (Z=42)



Plasma-based x-ray lasers

HHG seed amplified in plasma amplifier (XRL)

Laser chain (Master Oscillator Power Amplifier) in XUV

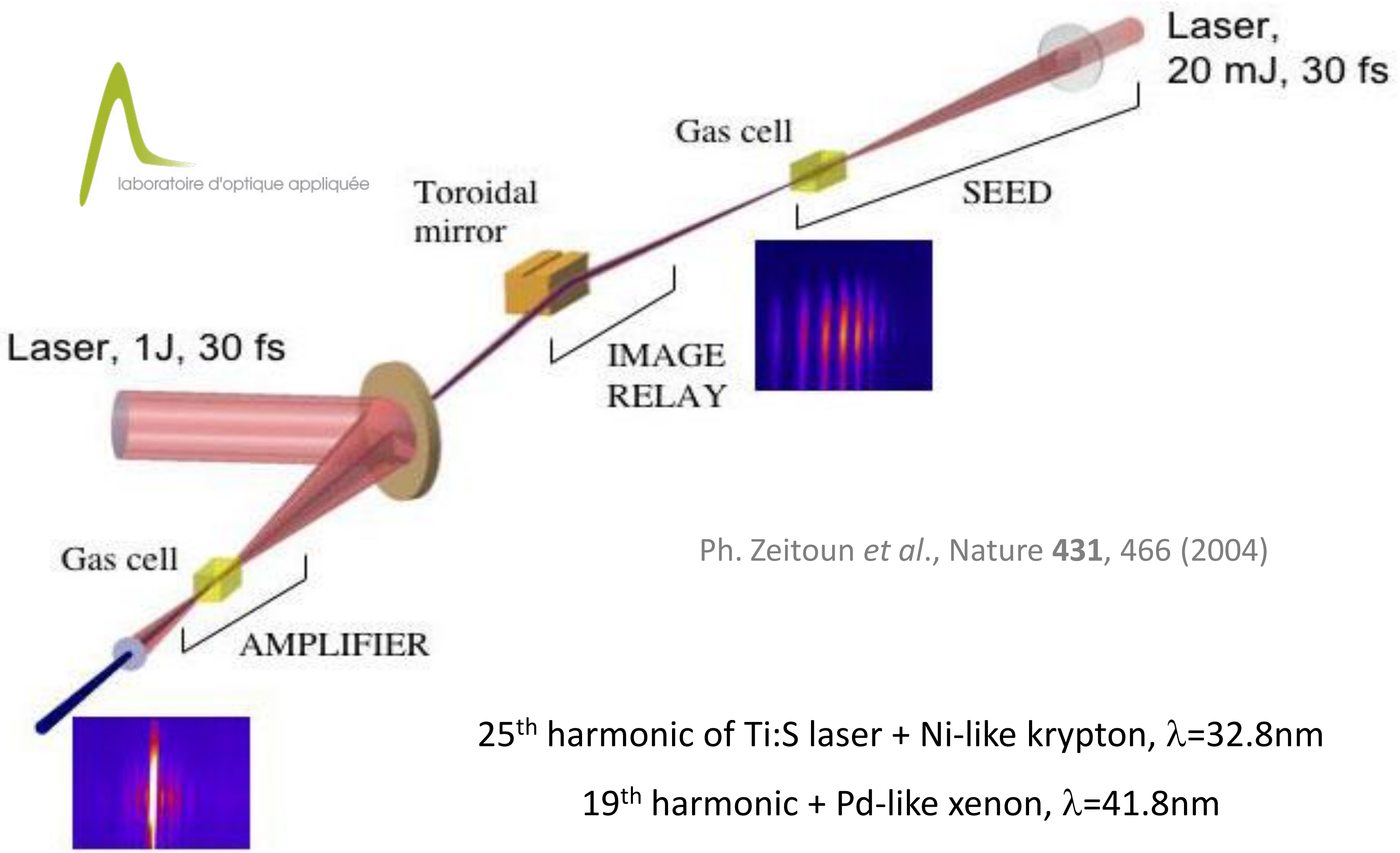


High quality of the beam
(wavefront, spatial coherence,
divergence)

ENERGY

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

Plasma-based x-ray lasers

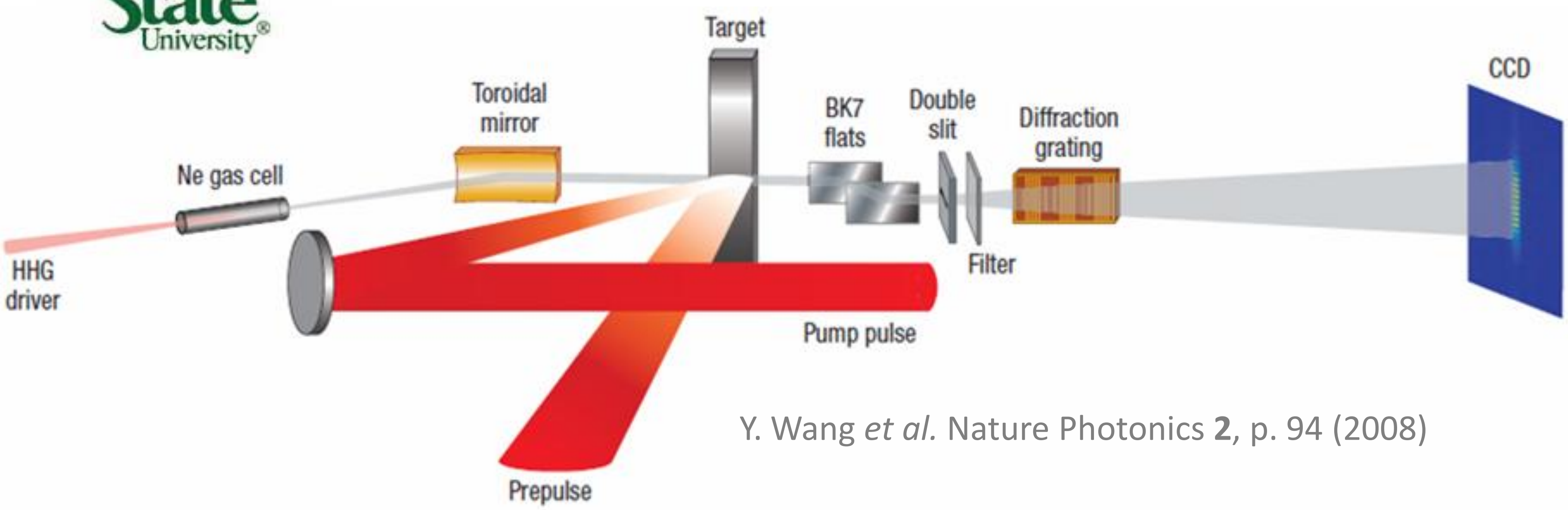


Ph. Zeitoun *et al*., Nature **431**, 466 (2004)

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

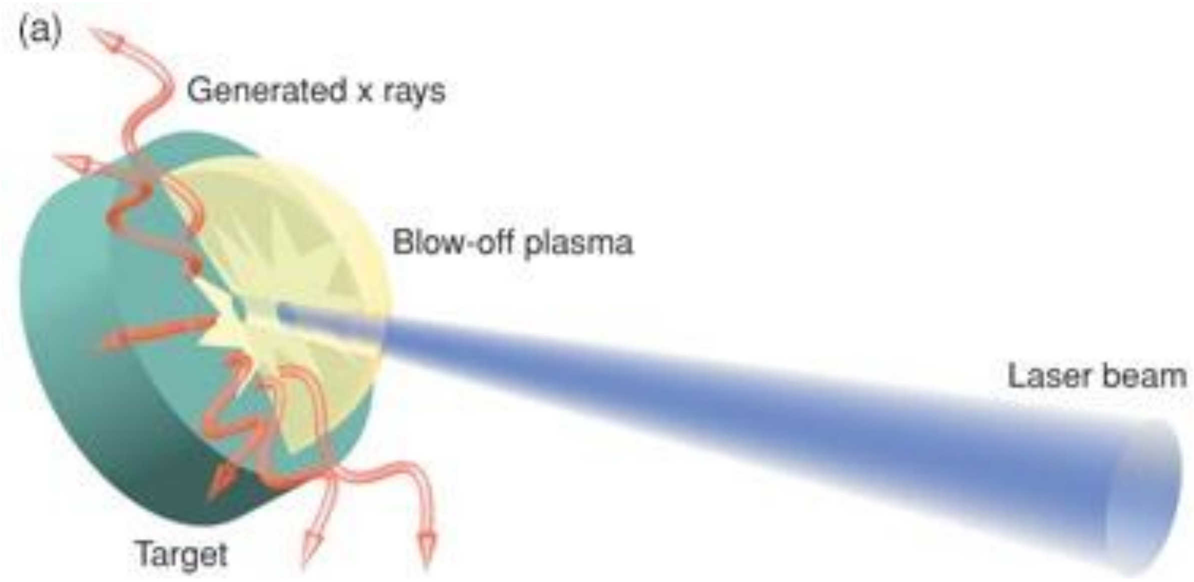
43th harmonic + Ni-like molybden, λ=18.9nm

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

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

Plasma X-ray source

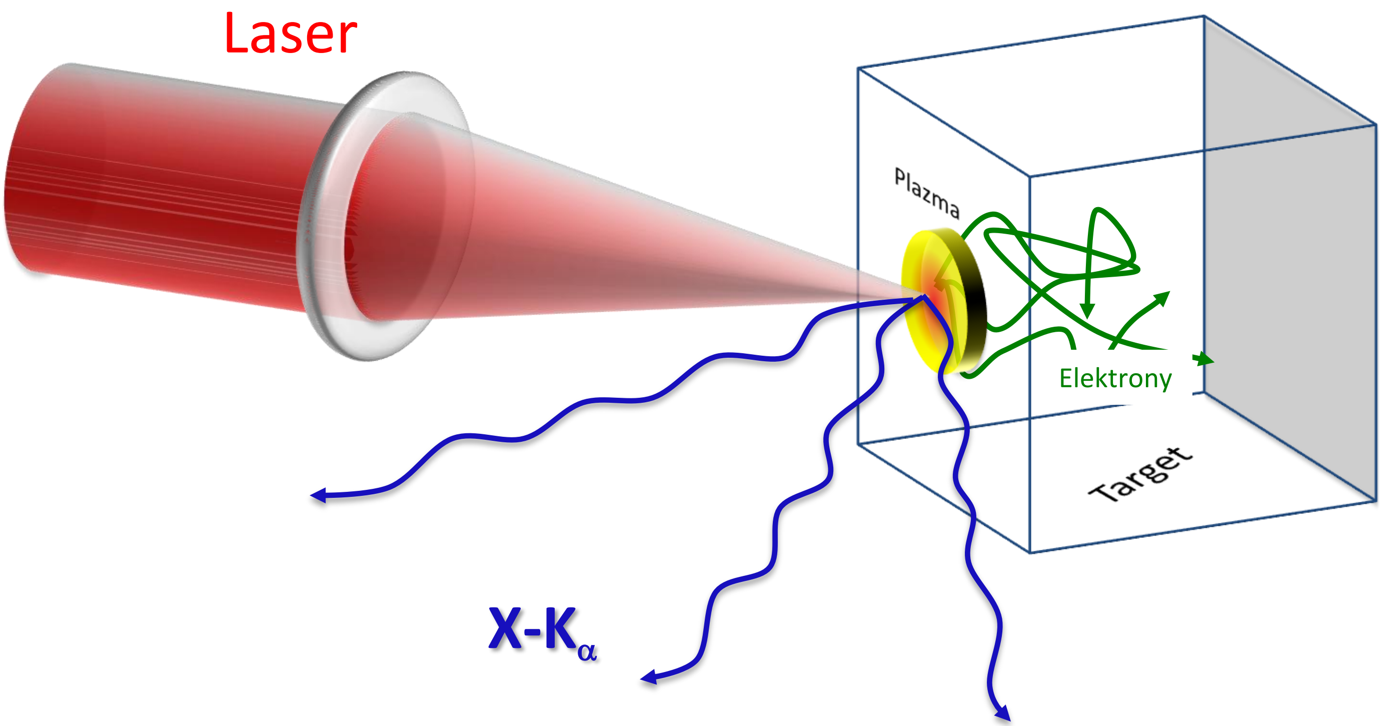
(Kα source)



LLNL Science and Technology Review, October 2005

Plasma X-ray source

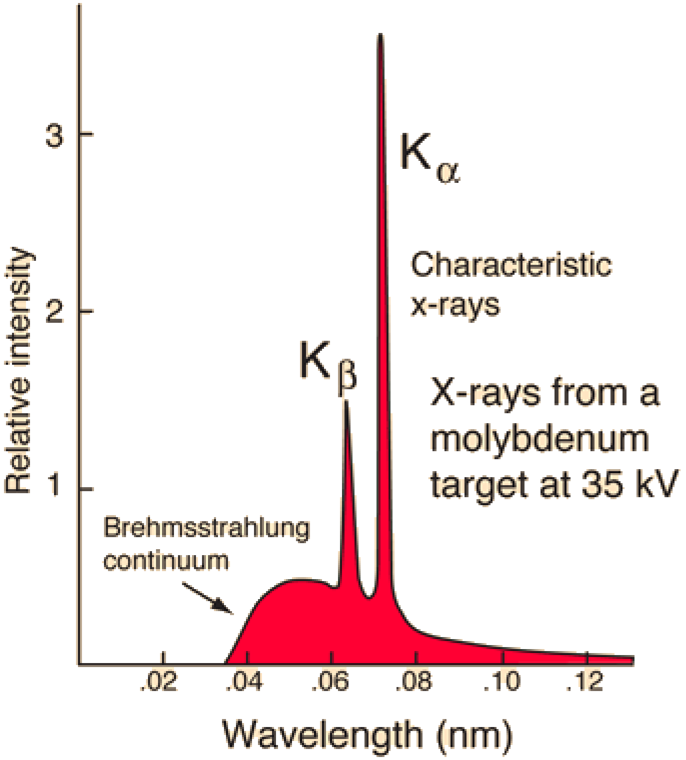
- Creation of “hot” electrons by interaction of intense laser pulse with matter ($I > 10^{16}\ \mathrm{Wcm^{-2}}$) $T_h \propto I\lambda^2$
- Energetic electrons are decelerated in the target
  - generation of bremsstrahlung and characteristic radiation

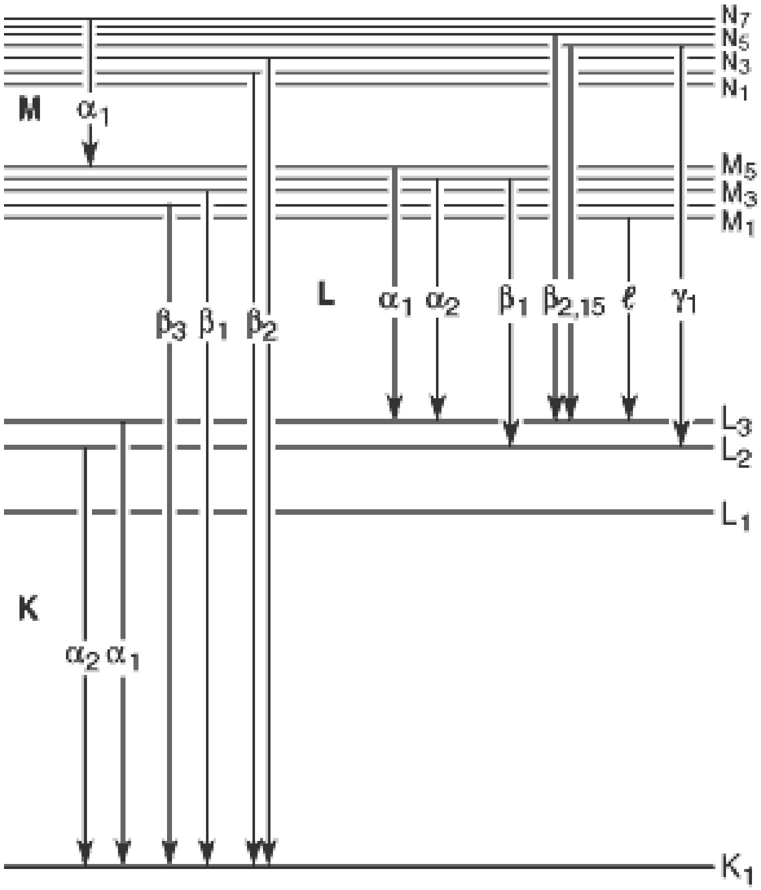


S. Sebban *et al.*

Plasma X-ray source

- Characteristic lines





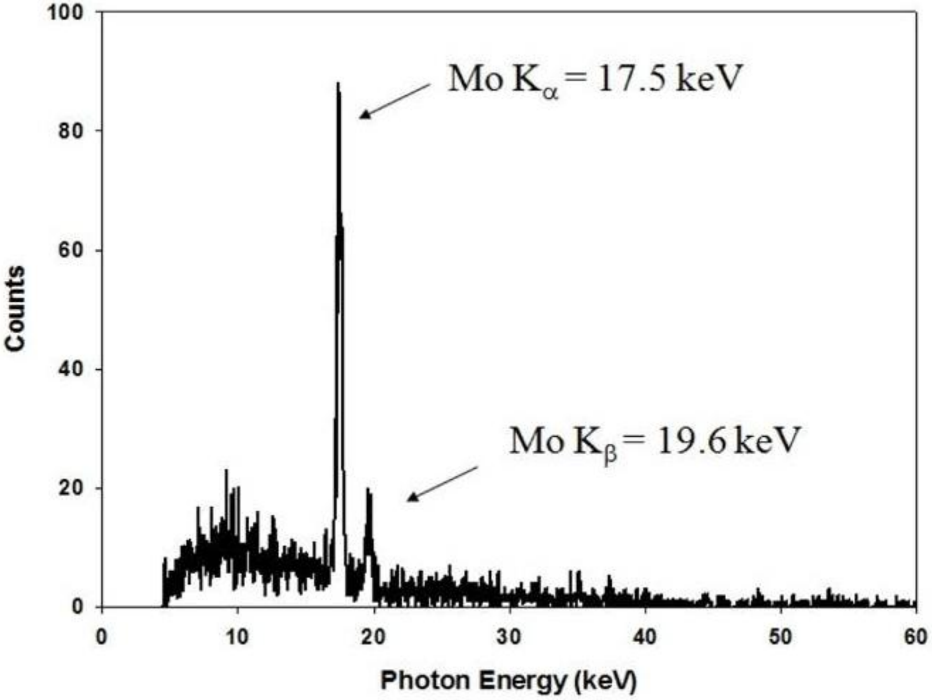
- Moseley’s law: a good approximation of line energy

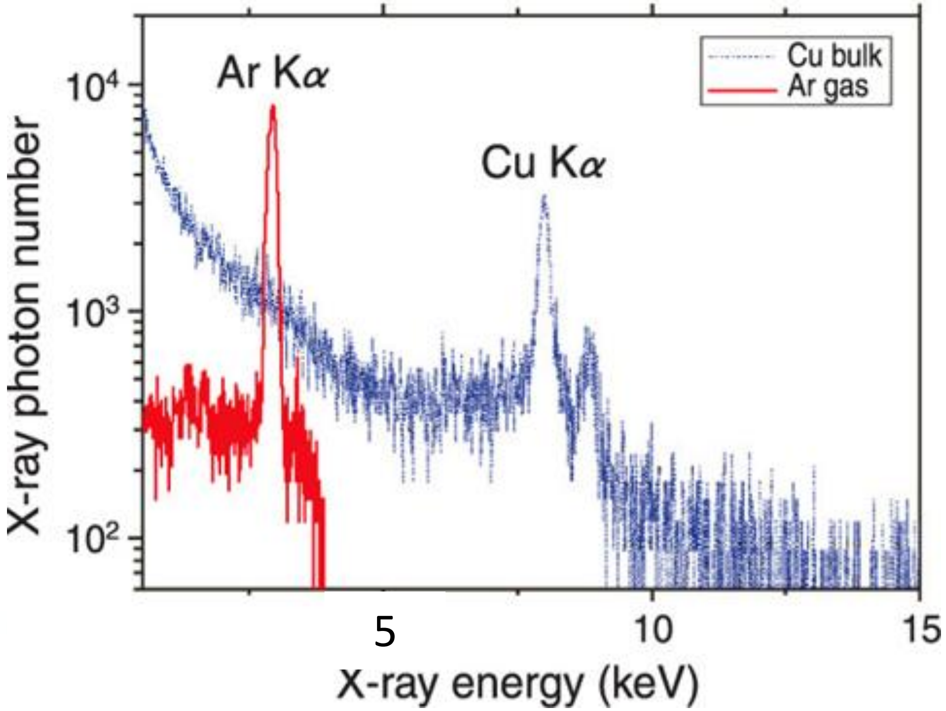
$$E_{K\alpha} \approx 10.2\text{eV} \times (Z-1)^2$$

$$E_{L\alpha} \propto (Z-7.4)^2$$

Plasma X-ray source

- Tuning parameters of interaction (*I, prepulse*) ⇒ strong K-α line



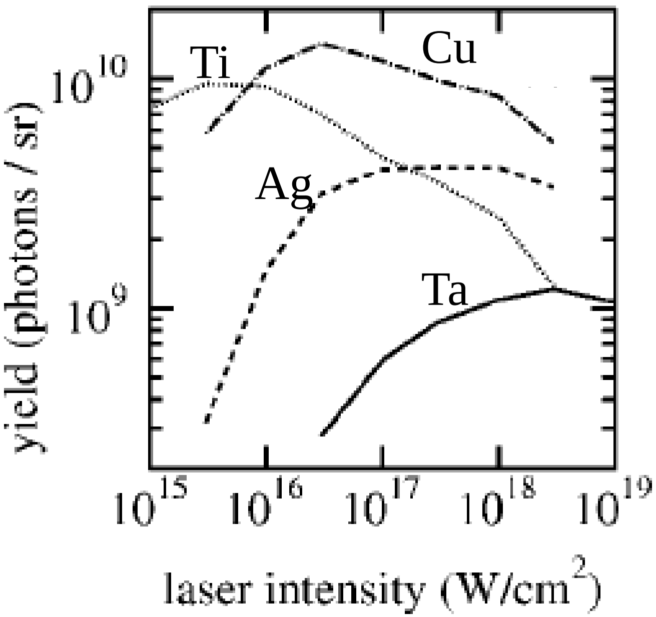


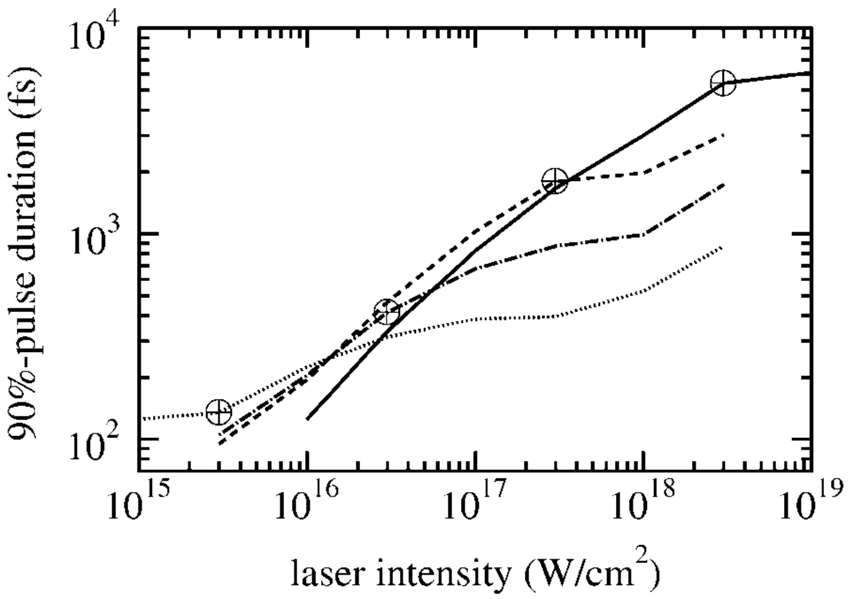
- Incoherent, polychromatic
- Isotropic emission (4π)
- Short pulse duration (~100 fs)

Plasma X-ray source

- There is an optimum driving intensity for given element

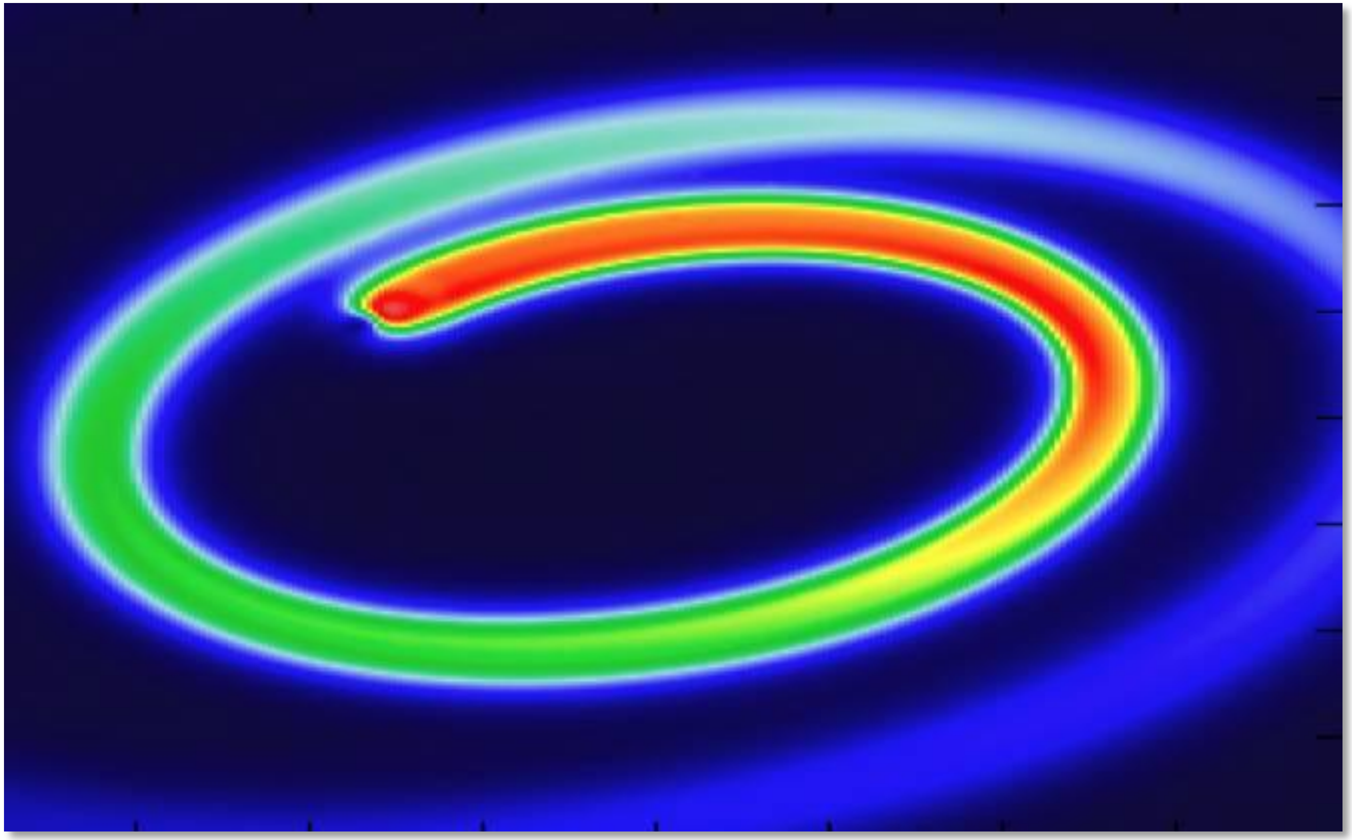
$$I_{opt}\left[\mathrm{Wcm^{-2}}\right]\approx 7\times10^{9}\,Z^{4.4}$$





Reich et al. PRL **84** 4846 (2000)

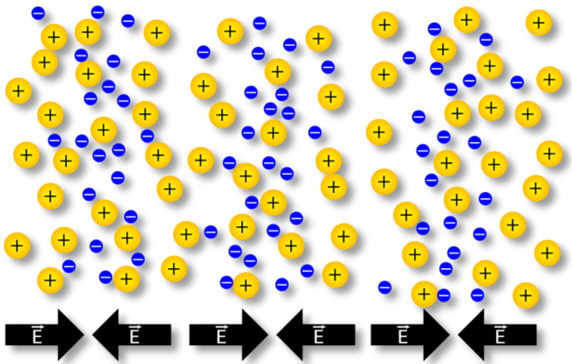
Radiation of laser-driven relativistic electron beams



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

Radiation of relativistic e^- beams

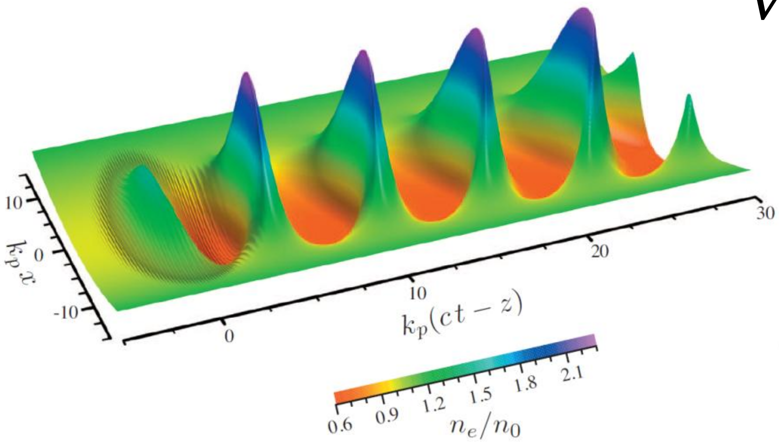
- Electron acceleration in laser plasma
  - Plasma wave behind the laser pulse
  - Huge E-filed >100 GV/m possible (conventional RF accelerators <0.1GV/m)

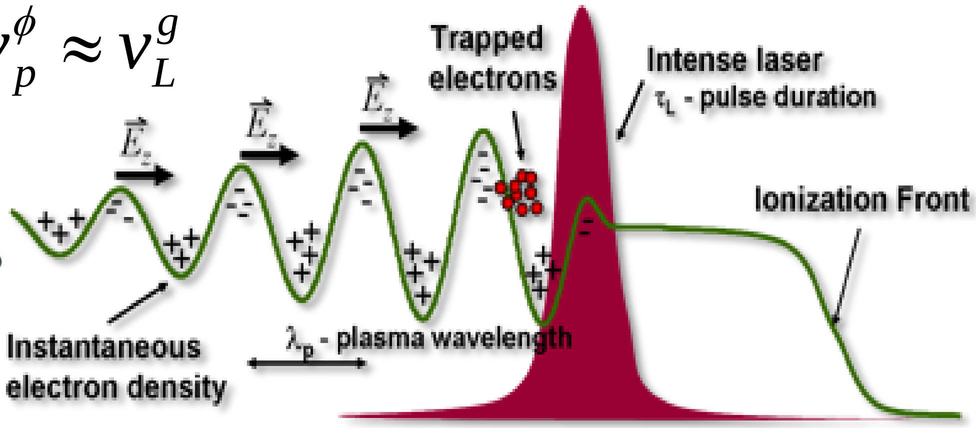


plasma frequency: $$\omega_p^2 = \frac{n_e e^2}{\varepsilon_0 m_e}$$

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

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



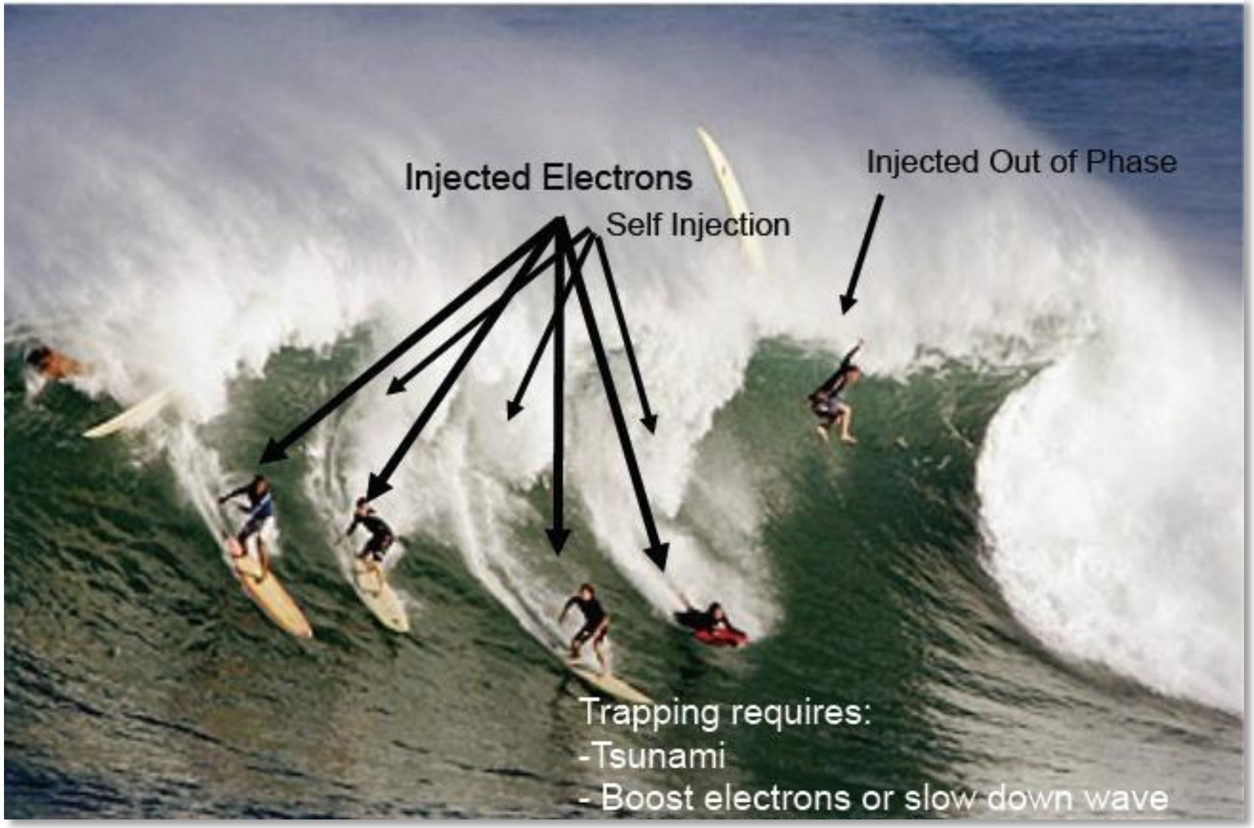


www.engin.umich.edu/research/cuos

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

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

$$a_0 = \frac{eA_0}{m_e c} \approx 0.855\sqrt{I_{[10^{18} W/cm^2]} \times \lambda^2_{L[\mu m]}}$$

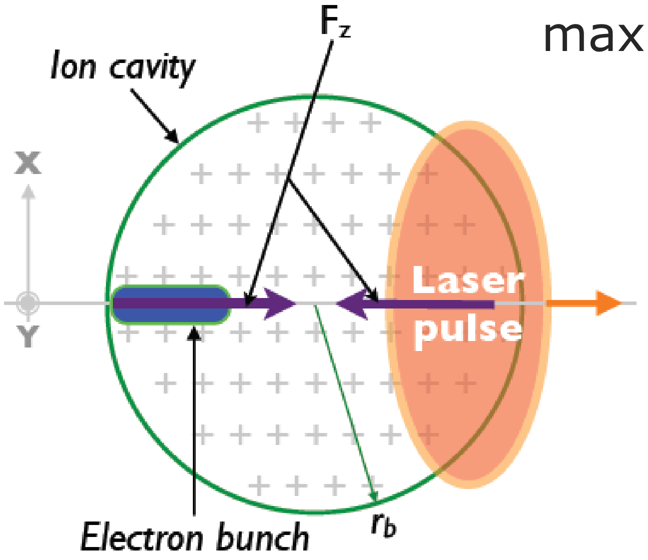
  - If the parameters are set right: bubble regime
    - Focus size and intensity vs. plasma density
    - Laser pulse duration vs. plasma density

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

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

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

wavebreaking or other injection mechanism – acceleration of e$^-$



S. Corde *et al.* Rev. Mod. Phys 2012

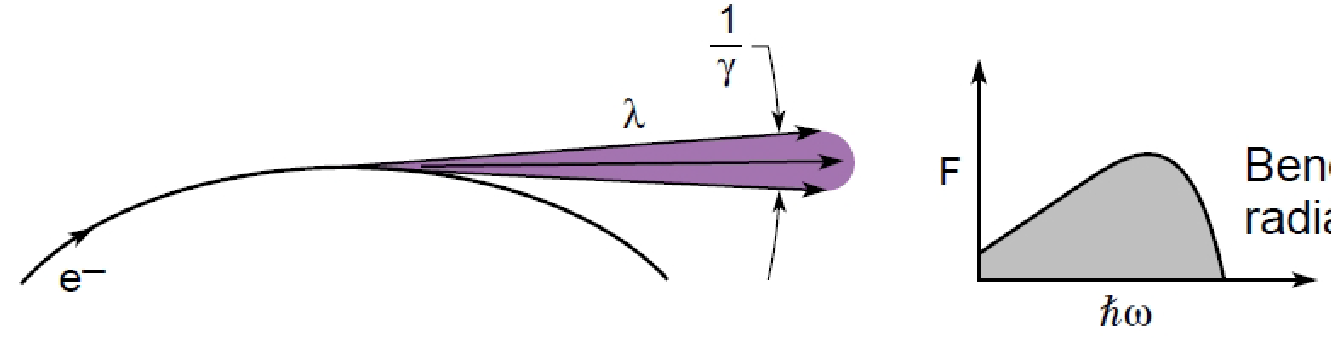
maximum field: $E_m = \frac{m_e c}{e}\omega_p\sqrt{a_0}$

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

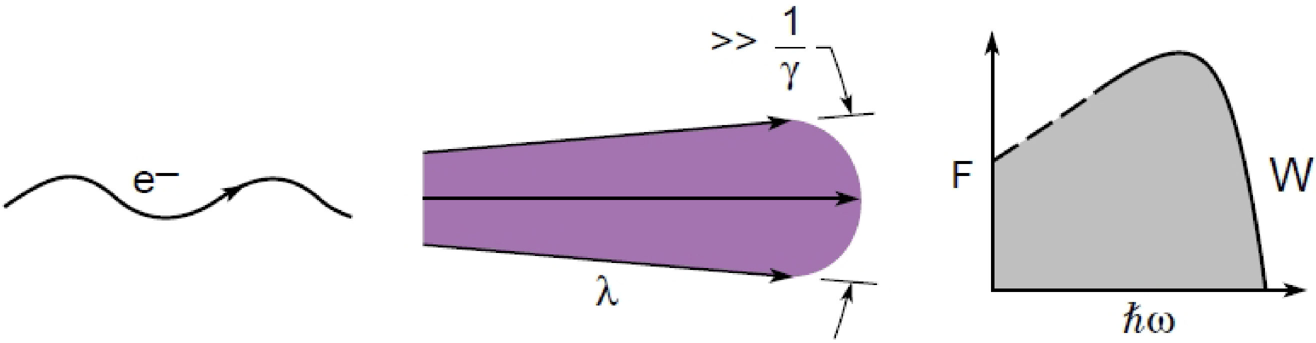
$$\mathbf{E_m \approx 600\ GV/m}$$

Radiation of relativistic e$^-$ beams

Rel. e$^-$ (with Lorentz factor γ) in (periodic) magnetic field B_0

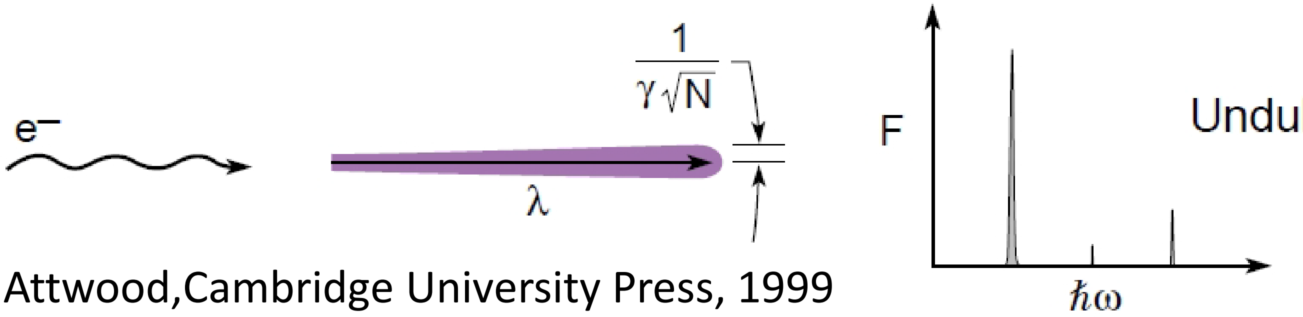


Bending magnet radiation



Wiggler radiation

$$K = \frac{e}{2\pi m_e c} B_0 \lambda_u \gg 1$$



Undulator radiation

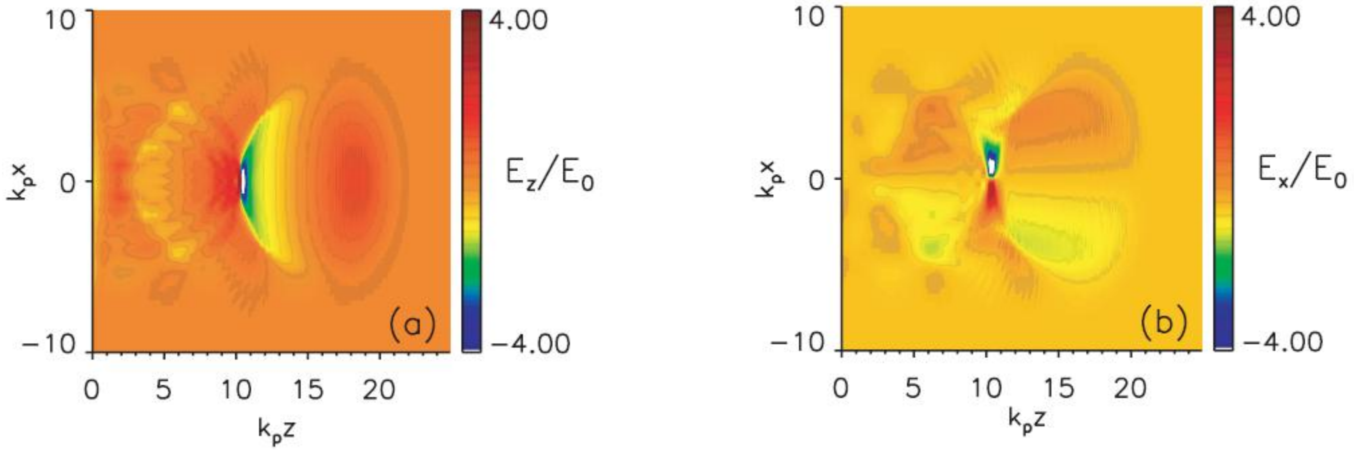
$$K < 1$$

$$\lambda \approx \frac{\lambda_u}{2\gamma^2}$$

D. Attwood,Cambridge University Press, 1999

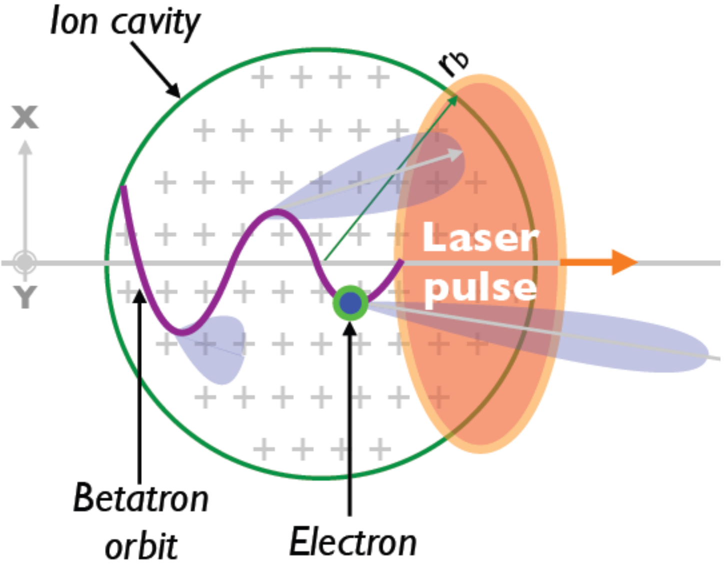
Radiation of relativistic e$^-$ beams

- Besides the longitudinal there is also transverse field



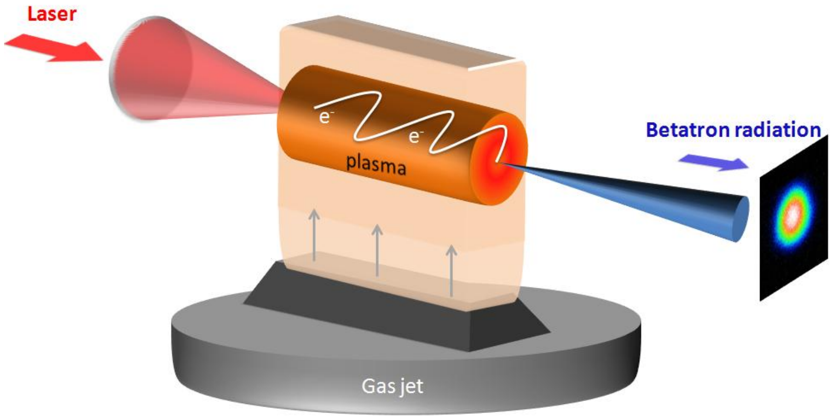
$\Rightarrow$ Oscillations of electron beam $\Rightarrow$ RADIATION

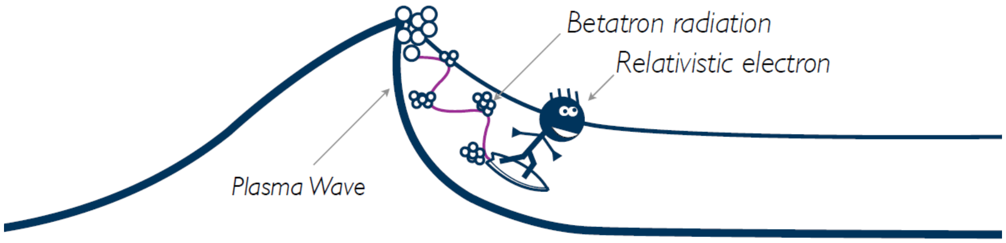
so called **plasma betatron**



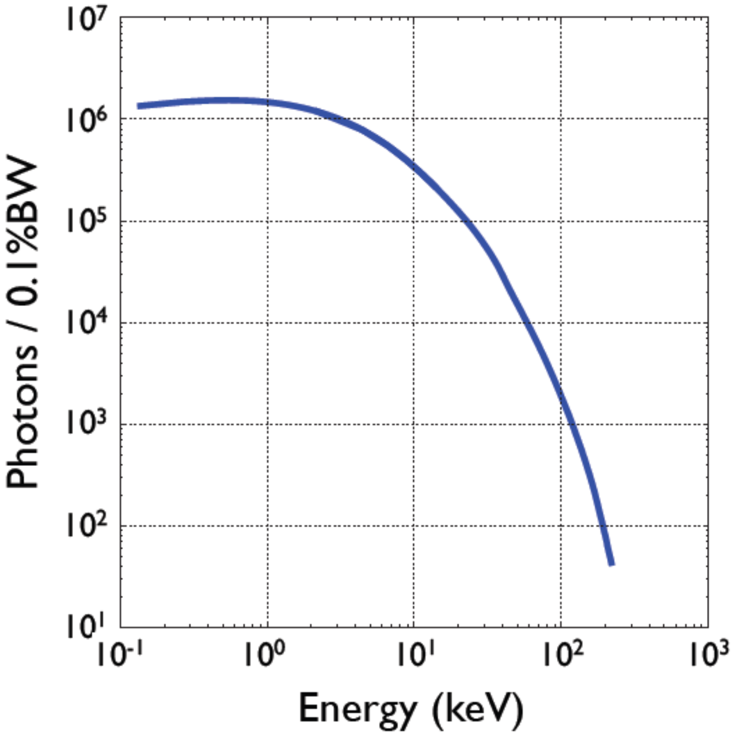
Radiation of relativistic e^- beams

- **Plasma betatron**





Typical spectrum:



- High energy radiation
- Polychromatic
- Ultra-short pulses (<50 fs)
- Small source size (<5 μm)
- Narrow beam (<20 mrad)

Radiation of relativistic e⁻ beams

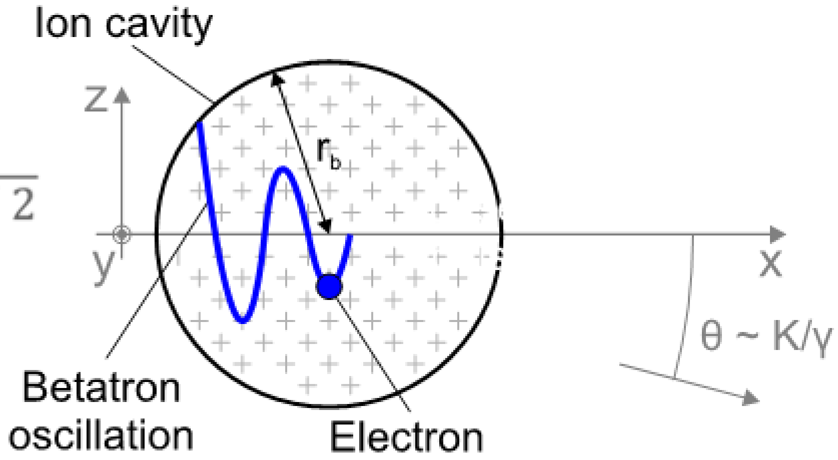
- **Betatron source parameters**

Electron period: $\lambda_u = \sqrt{2\gamma(t)}\lambda_p$

Strength parameter: $K(t) = r_\beta(t) k_p \sqrt{\gamma(t)/2}$

Critical energy: $E_c = \frac{3}{2} K \gamma^2 \hbar \omega_\beta$

Betatron frequency: $\omega_\beta = \omega_p / \sqrt{2\gamma}$



Acceleration length: $L_{acc} = 3T = 12 r_\beta$

Normalized vector potential: $a_0 = 0.855\sqrt{I[10^{18}\ \mathrm{W/cm^2}] \times \lambda_L^2[\mu\mathrm{m}]}$

Undulator strength parameter: $K = 1.33 \times 10^{-10} \sqrt{\gamma n_e[\mathrm{cm^{-3}}]} r_\beta [\mu\mathrm{m}]$

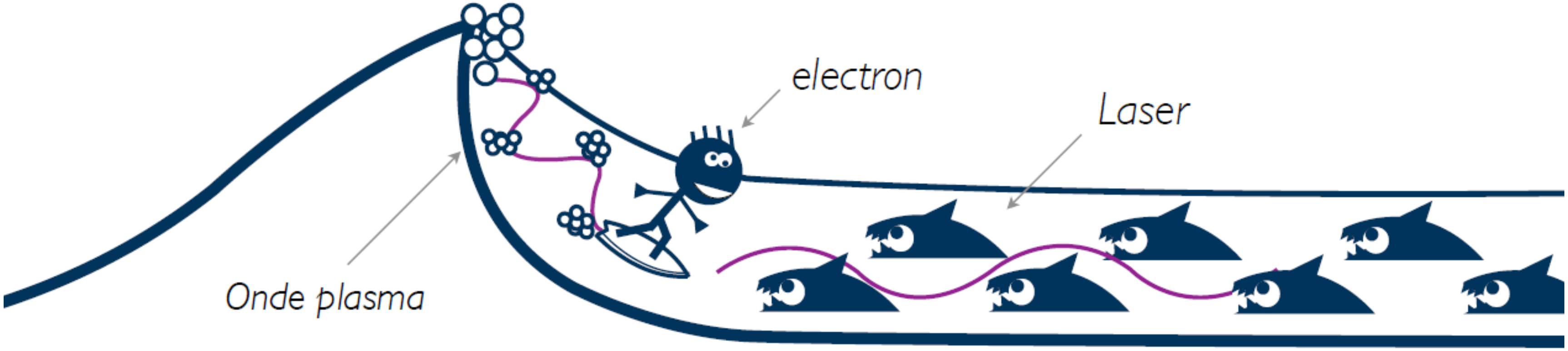
Betatron critical energy: $\mathrm{E_C}[eV] = 5.25 \times 10^{-21} \gamma^2 n_e[\mathrm{cm^{-3}}] r_\beta [\mu\mathrm{m}]$

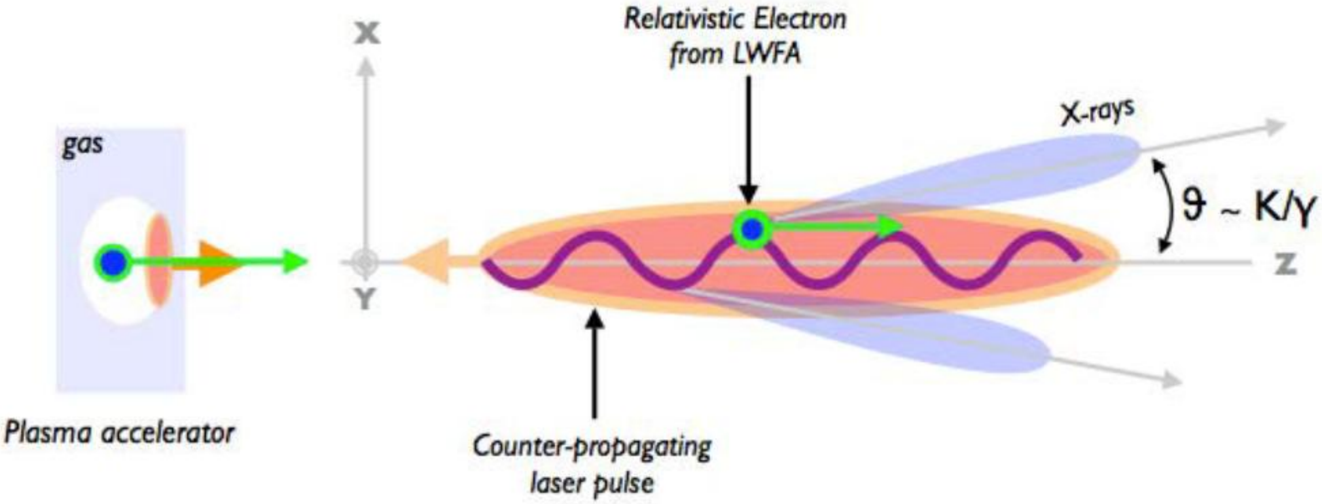
Number of photons: $N_\gamma = 3.31 \times 10^{-2} K N_e L_{acc}/T$

Radiation of relativistic e$^-$ beams

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

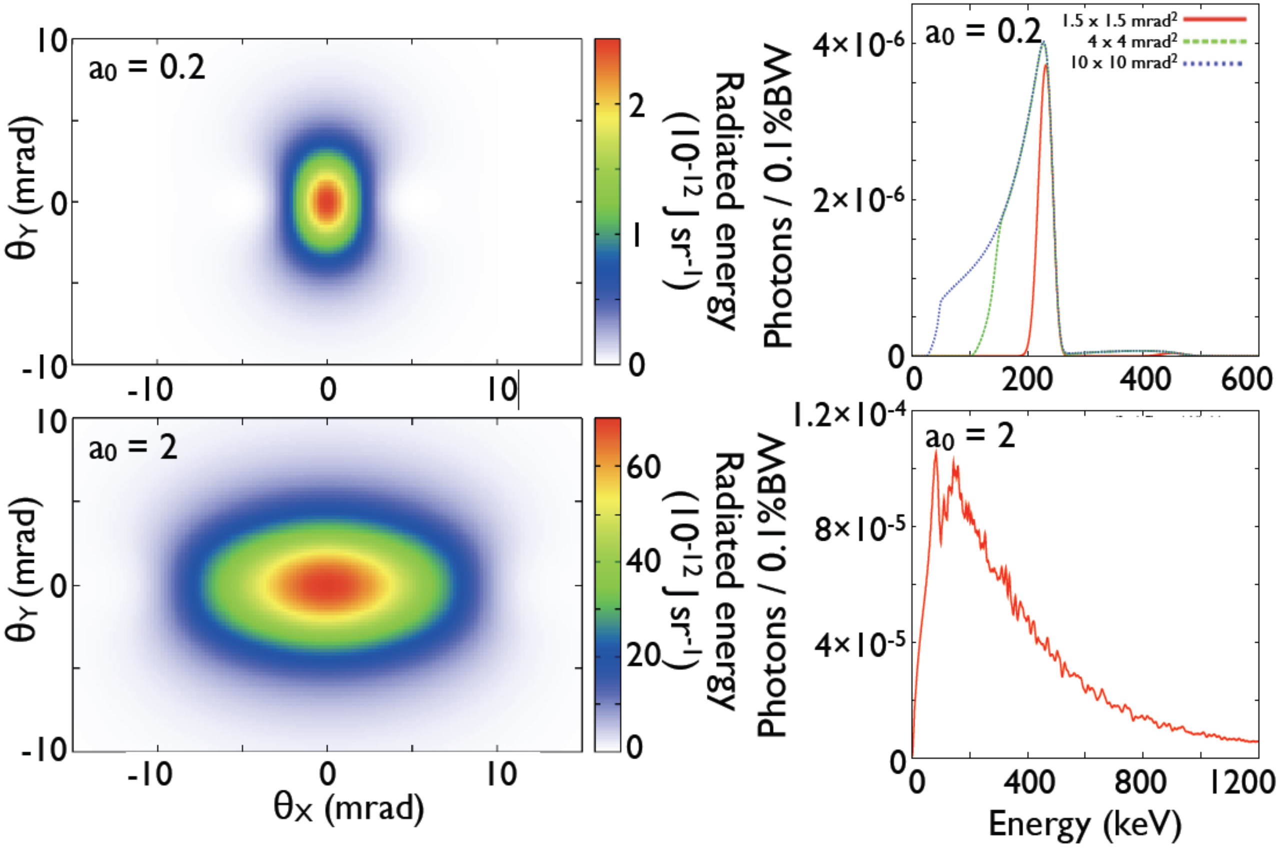
  Interaction of e$^-$ with an intense laser pulse





Radiation of relativistic e$^-$ beams

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

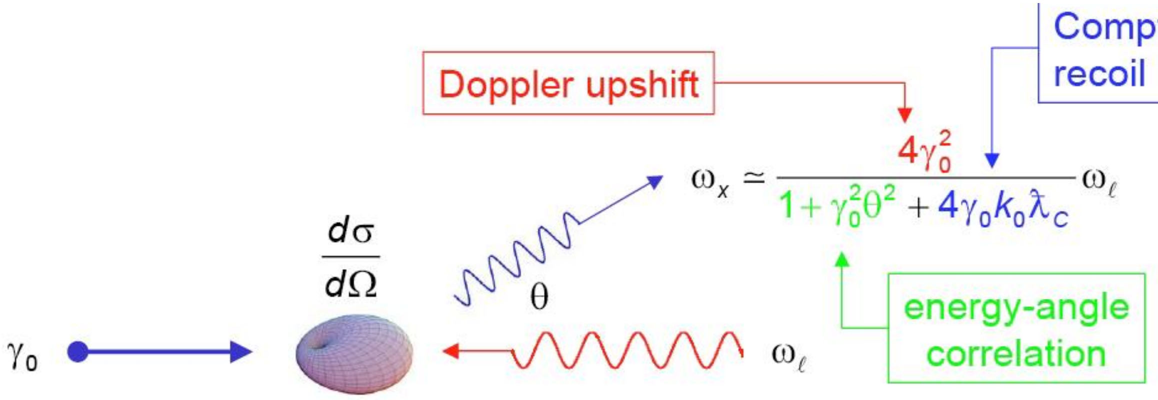


S. Corde *et al.* Rev. Mod. Phys 2012

Radiation of relativistic e^- beams

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

- low intensity limit (a_0<1) $N_\gamma \simeq 1.53 \cdot 10^{-2} \cdot a_0^2$



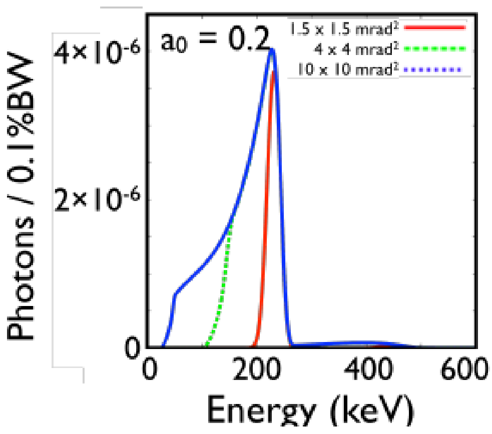
Doppler upshift

Compton recoil

$$\omega_x \simeq \frac{4\gamma_0^2}{1+\gamma_0^2\theta^2+4\gamma_0 k_0 \bar{\lambda}_C}\,\omega_\ell$$

energy-angle correlation

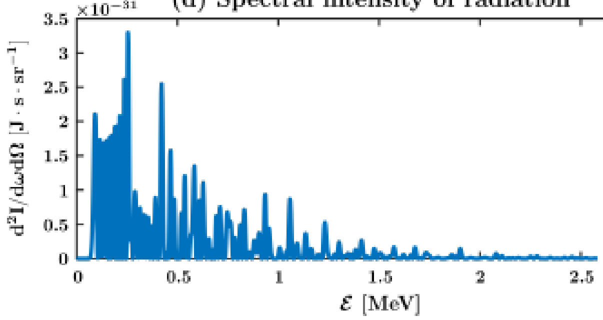
(b) Corde 2013 et. al.



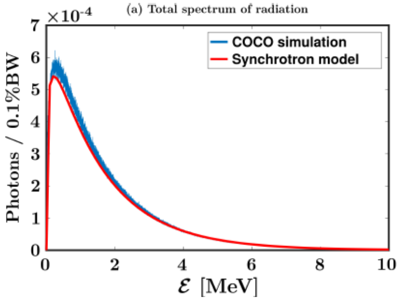
- $a_0\approx1$: harmonics

$$\omega_X = \frac{4\gamma^2}{1+\frac{a_0^2}{2}+\gamma^2\theta^2+4\gamma k_0 \bar{\lambda}_C}\,\omega_l$$

(d) Spectral intensity of radiation



(a) Total spectrum of radiation



- a_0>>1: Wiggler (synchrotron-like) spectrum

$$\hbar\omega_c[\mathrm{eV}] \approx 3\gamma^2\sqrt{I_{18}} \qquad N_\gamma \simeq 3.31\cdot10^{-2}\cdot a_0$$

Summary table

Typical parameters of the sources

Source	Driver	Energy	Coherence	Output
HHG (gas)	0.1-100 mJ 10s fs	10-200 eV	Full	pJ-uJ fs (as)
XRL	0.1-1000 J ps-ns	10-200 eV	Partial	nJ-mJ ps
PXS	0.1-100mJ 10s fs – ps	0-100 keV	Low	1e12 phot./shot 100s fs- ps
Betatron	0.1- few J 10s fs	1-100 keV	Part. Spatial	1e8 phot./shot 1-10s fs
Compton	0.1- few J 10s fs	0.01-10 MeV	Part. spatial	1e8 phot./shot 1-10s fs

Fyzikální ústav AV ČR, v. v. i.
Na Slovance 2
182 21 Praha 8
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www.eli-beams.eu

THANK YOU FOR YOUR ATTENTION

Jaroslav.Nejdl@eli-beams.eu

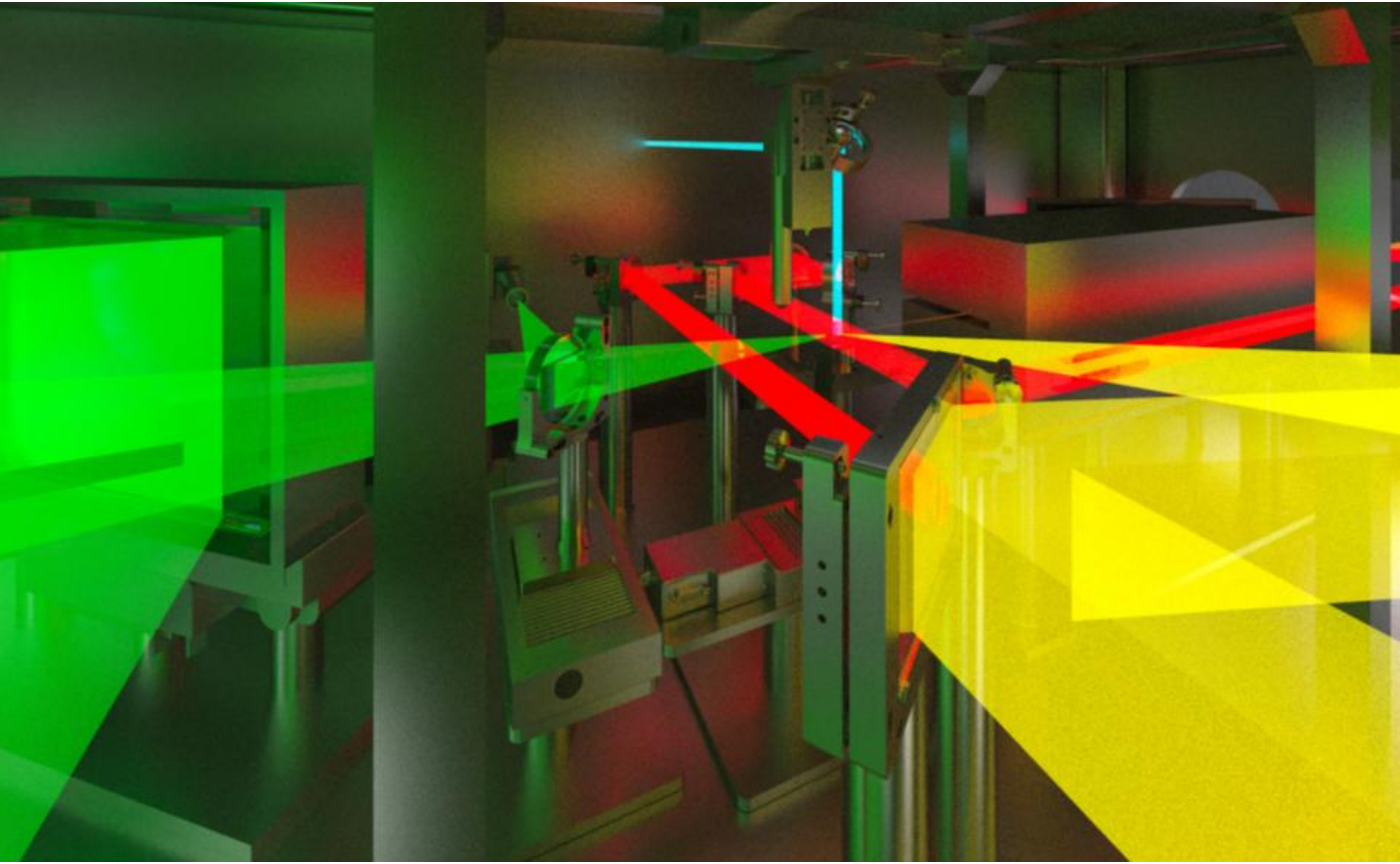
Fyzikální ústav
Akademie věd ČR, v. v. i.

projekt podporovaný:

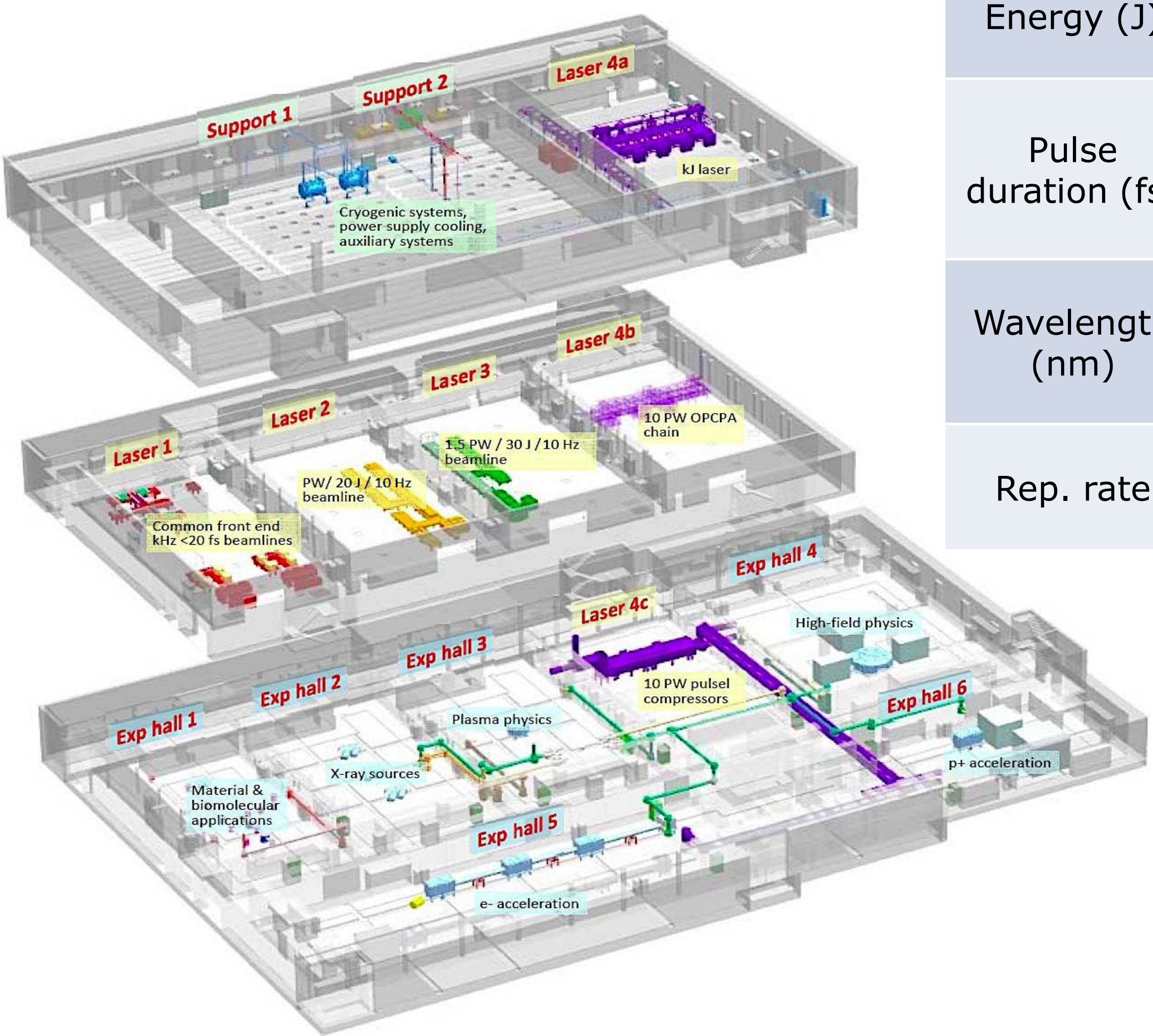
EVROPSKÁ UNIE
EVROPSKÝ FOND PRO REGIONÁLNÍ ROZVOJ
INVESTICE DO VAŠÍ BUDOUCNOSTI

2007–13
OP Výzkum a vývoj pro inovace

X-ray sources at ELI Beamlines



Facility layout and laser drivers for X-ray sources



Laser	L1	L2	L3	L4
Energy (J)	0.1	> 20	30	➢ 1200
Pulse duration (fs)	< 20	20 - 30	30	120
Wavelength (nm)	850	850	820	1060
Rep. rate	1 kHz	> 10 Hz	10 Hz	1/min

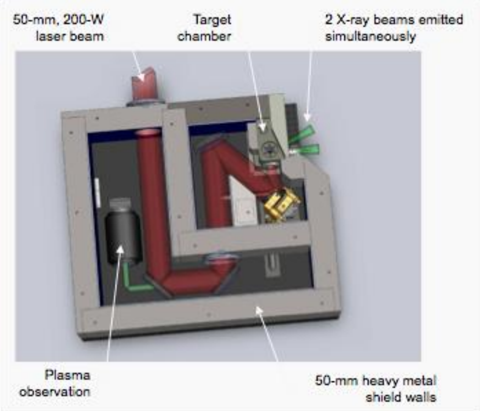
Laser-driven x-ray sources : several approaches

L1

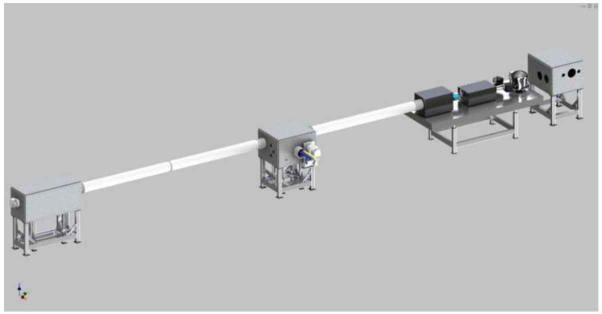
1 kHz

100 mJ

Plasma X-ray source (kHz)



High-order Harmonics (kHz)

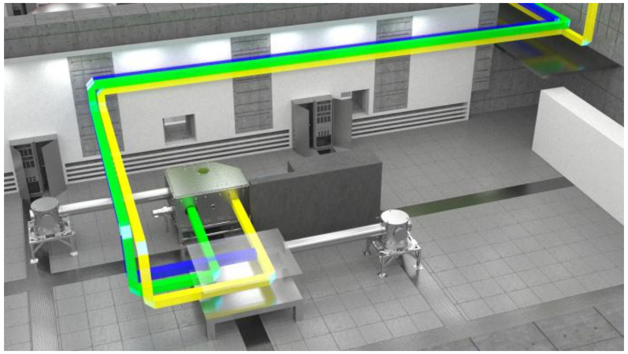


L3

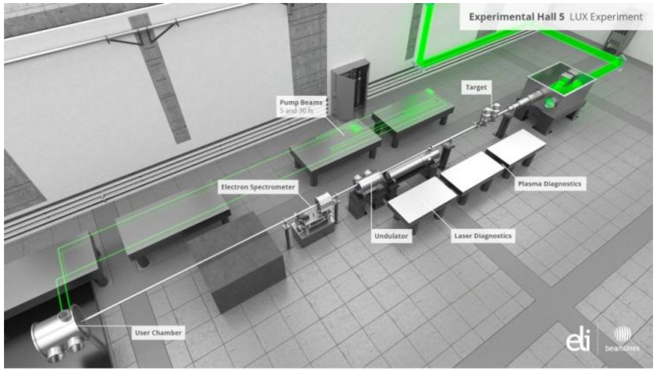
10 Hz

30 J

Betatron/Compton



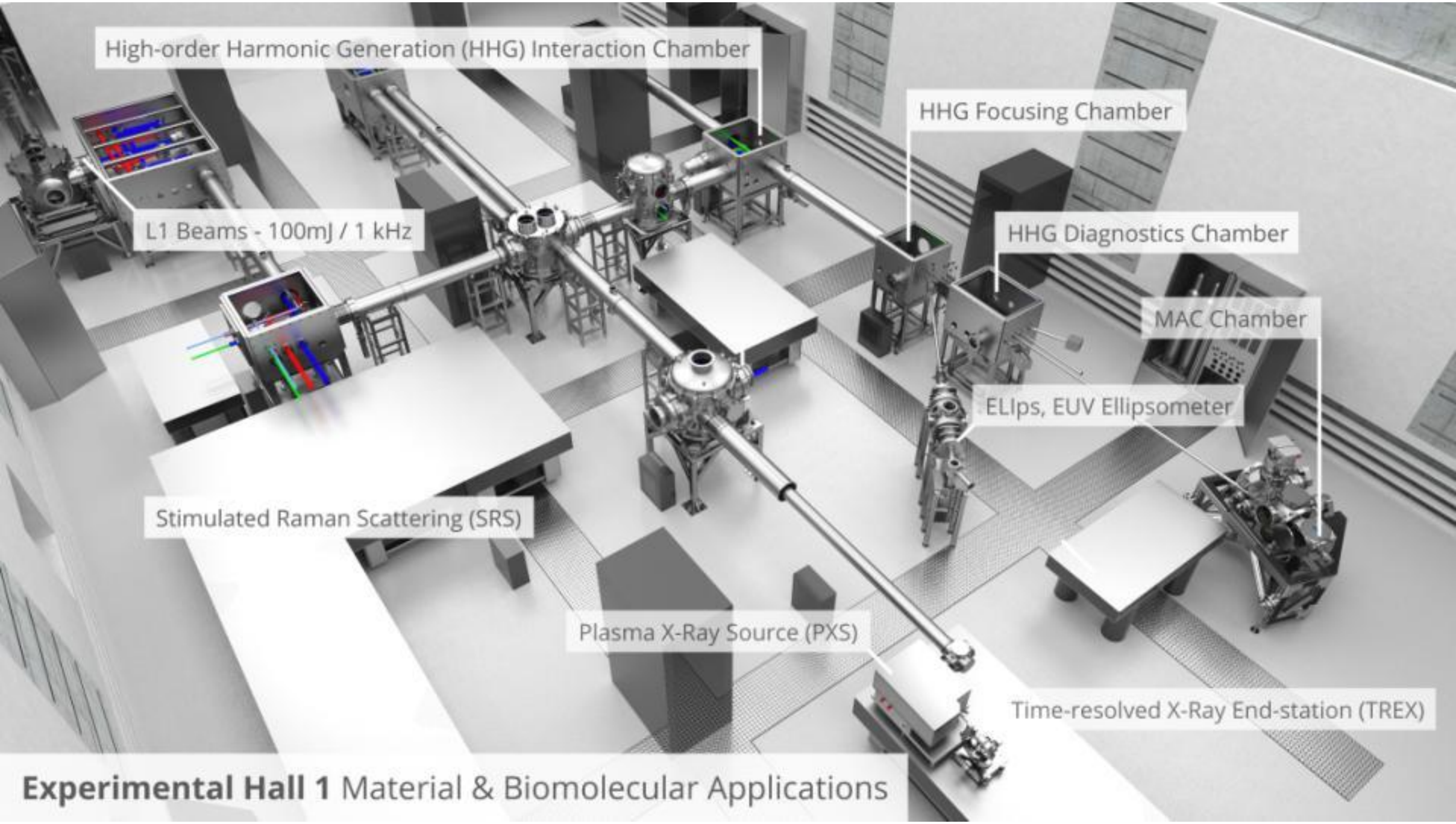
Laser driven undulator X-ray source



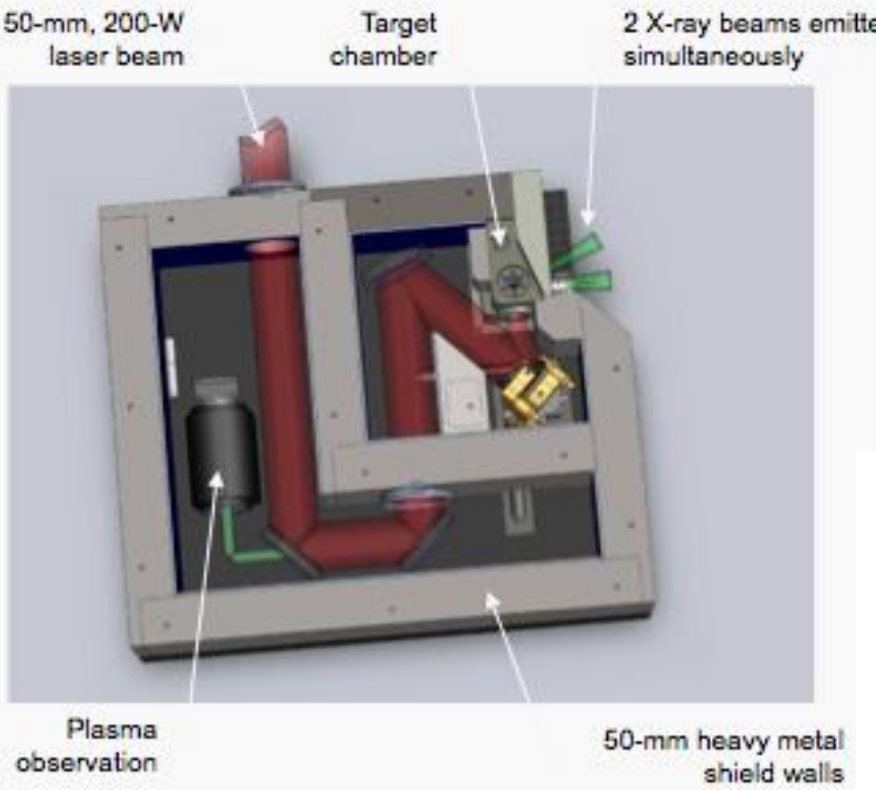
Coherent Diffractive Imaging (CDI), Atomic, Molecular and Optical (AMO) Science, Soft X-ray Materials Science, X-ray phase contrast imaging, X-ray Diffraction and spectroscopy, WDM

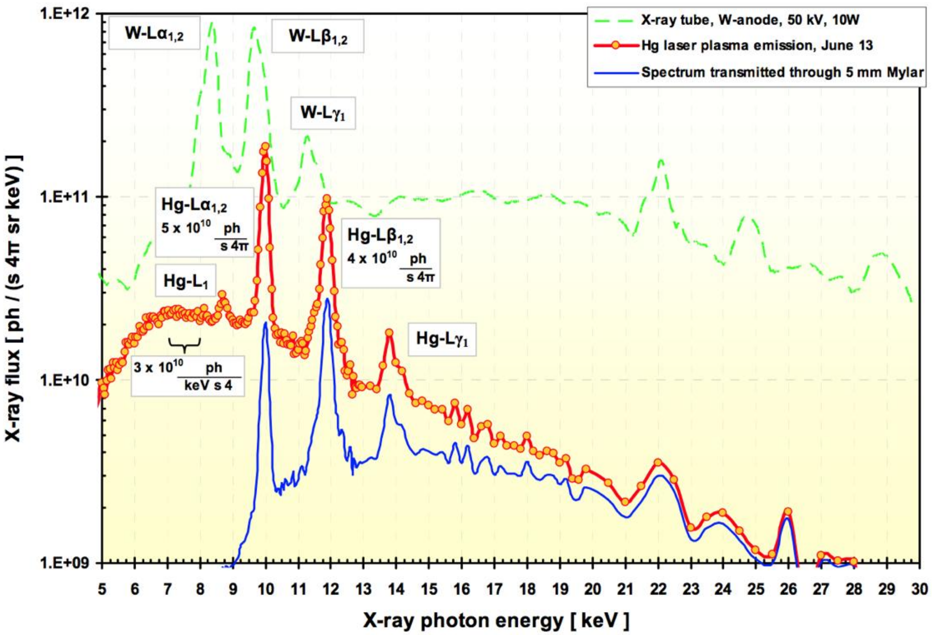
See the J. Andreasson talk on WED

E1 experimental hall

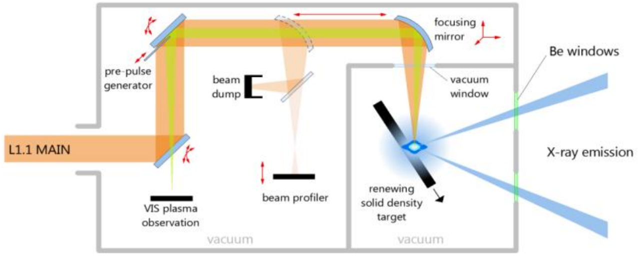


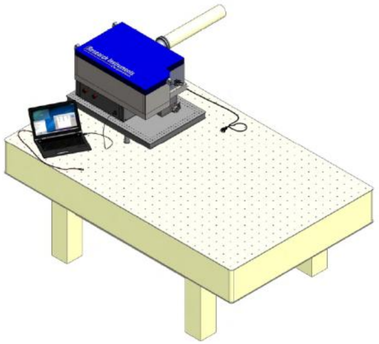
Plasma X-ray Source (PXS): femtosecond X-ray tube

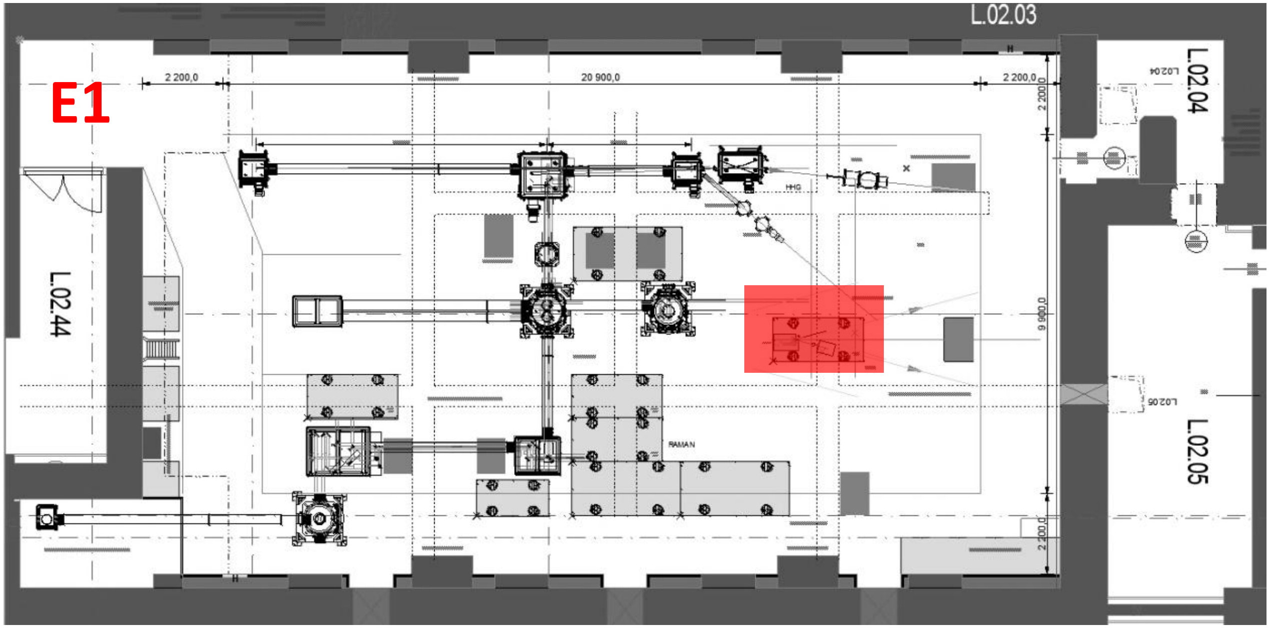




Plasma X-ray Source







Characteristics

4π sr emission, 3 – 30 keV
line + continuous spectra
100s femtosecond pulses
10s µm spot size

Applications

Time-resolved X-ray diffraction
X-ray Absorption Spectroscopy
Small- angle X-ray scattering
X-ray Imaging
Pulsed radiolysis

Table 1: X-ray source parameters	**Phase I (M0) (M1) 5 mJ laser pulse energy**	**Phase II (M2) 100 mJ laser pulse energy**	**User operation milestone (UOM)**
Minimum hard x-ray photon energy	**3 keV**	**3 keV**	**3 keV**
Photons per shot (photons/(4п sr line) or photons/(4п sr 1keV) @10keV)	**> 10^7**	**> 10^9**	**> 10^9**
Source size	**Less than 100 µm**	**Less than 100 µm**	**Less than 100 µm**
Hard X-ray pulse duration (FWHM)	**Less than 300 fs**	**Less than 300 fs**	**Less than 300 fs**

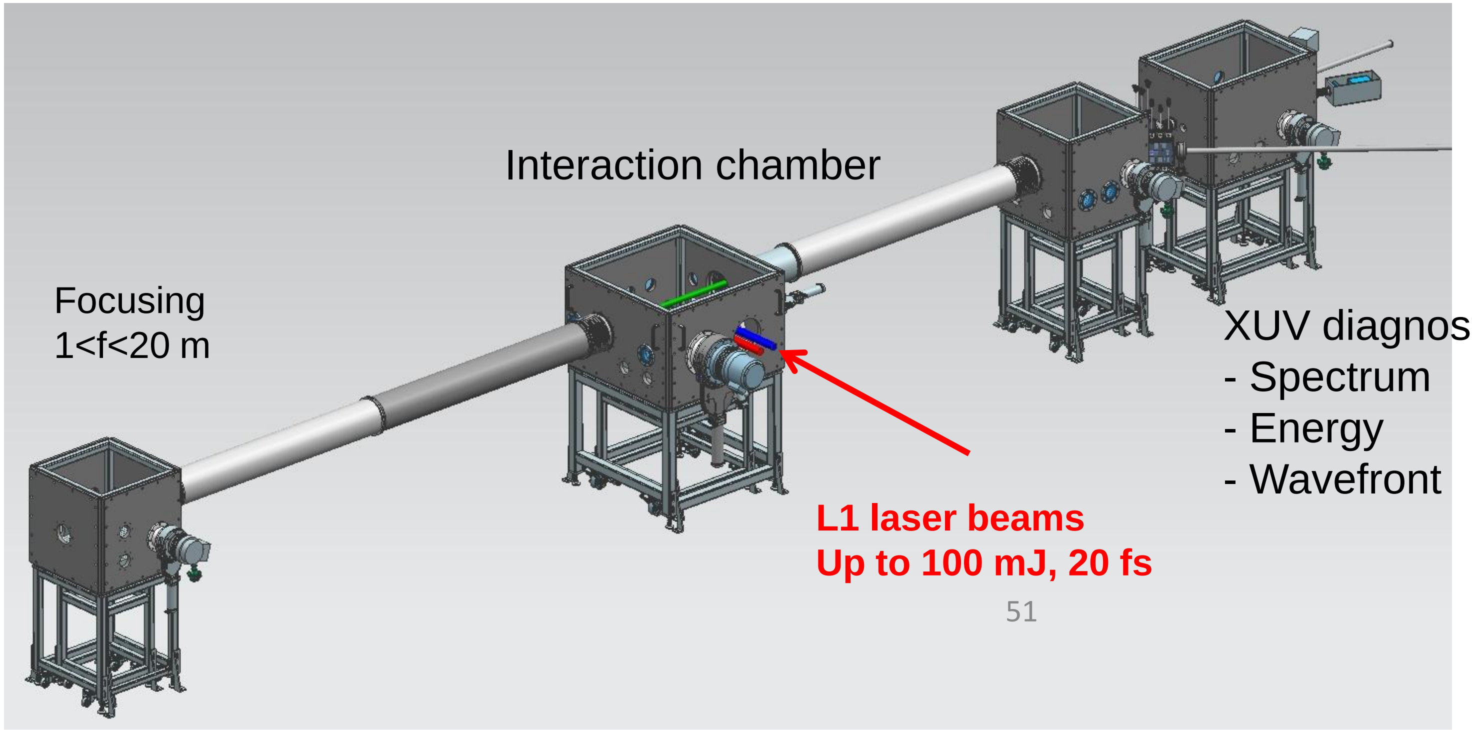
High-order harmonic Beamline

GOAL: high flux ultra-short pulses of tunable coherent XUV radiation

- High energy kHz laser driver (L1: up to 100mJ in 20fs)

⇒ **long focusing** ⇔ big generating volume

and/or **two color driver** (50mJ IR, ~30mJ blue)



Focusing
1<f<20 m

Interaction chamber

XUV diagnostics
- Spectrum
- Energy
- Wavefront

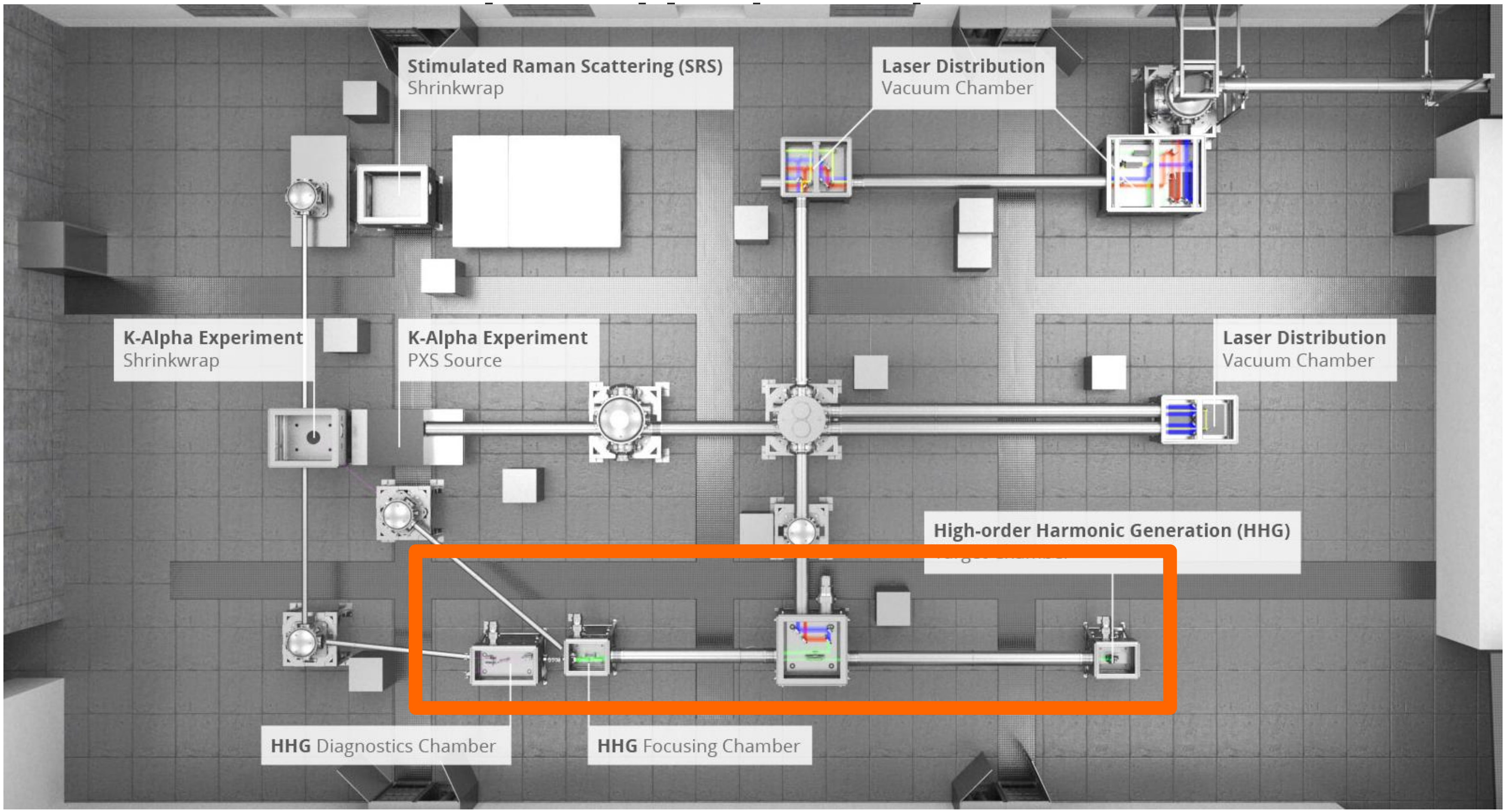
L1 laser beams
Up to 100 mJ, 20 fs

HHG Beamline

Two output arms:

- **Straight arm**: high flux output: CDI, AMO…
- **Side arm**: monochromatized output: Material sciences (Elipsometry…)

fs synchronization with PXS → coherent XUV and incoherent X-rays



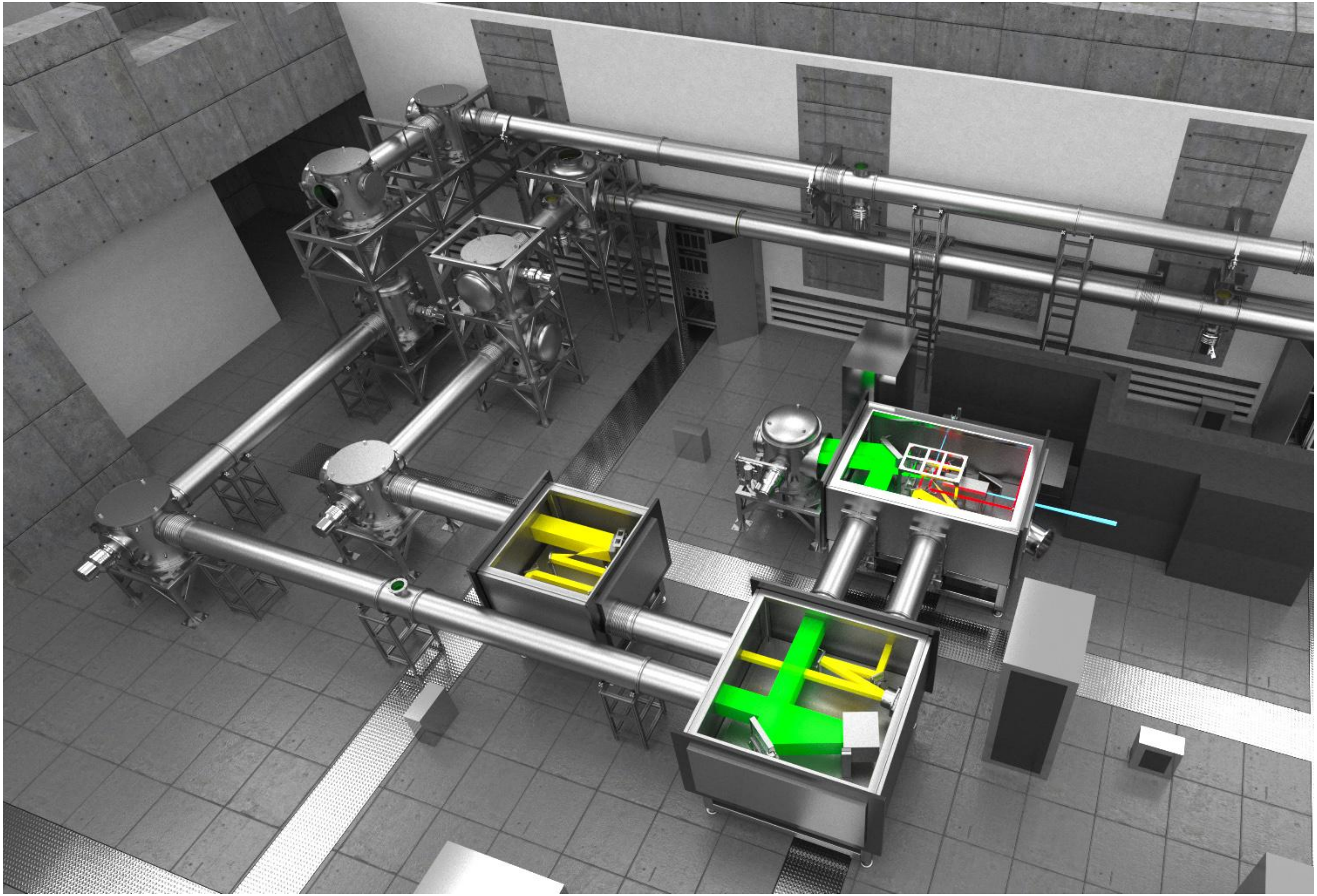
HHG Expected output parameters

Versatility / tunability

- Several focusing geometries & driving schemes: maximize eff. at given wavelength range
- Wavelength fine-tuning by changing chirp of the driver
- Polarization state of XUV by changing polarization of ω/2ω drivers

Driver	**kHz, 5 mJ, 35 fs**	**kHz, 100 mJ 20fs**
Wavelength	10 -120 nm	5 -120 nm
Photons/shot	10^7 to 10^9	few 10^9 -10^{12}
$\Delta\lambda/\lambda$	10^{-2}	10^{-2}
Divergence	<2 mrad	<1 mrad
Spatial profile	Gaussian-like	Gaussian-like
Wavefront	$\lambda/10$	$\lambda/10$
Duration	< 20fs	< 20fs
Polarization	Linear	Lin./Circ./Eliptical

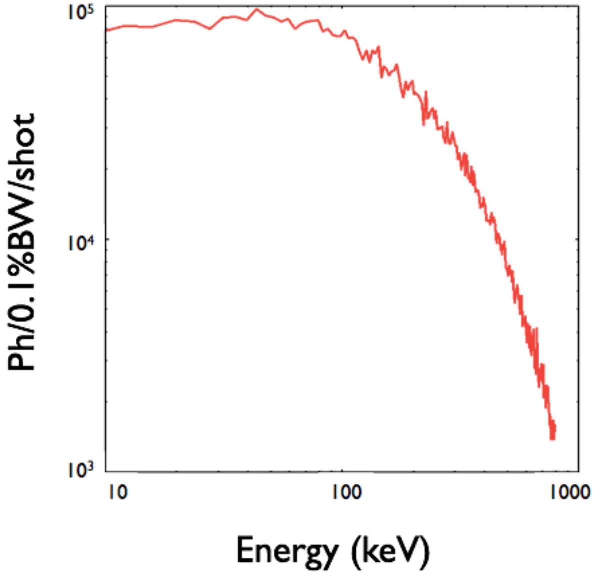
Betatron/Compton beamline in E2



10 Hz Betatron/Compton sources in E2

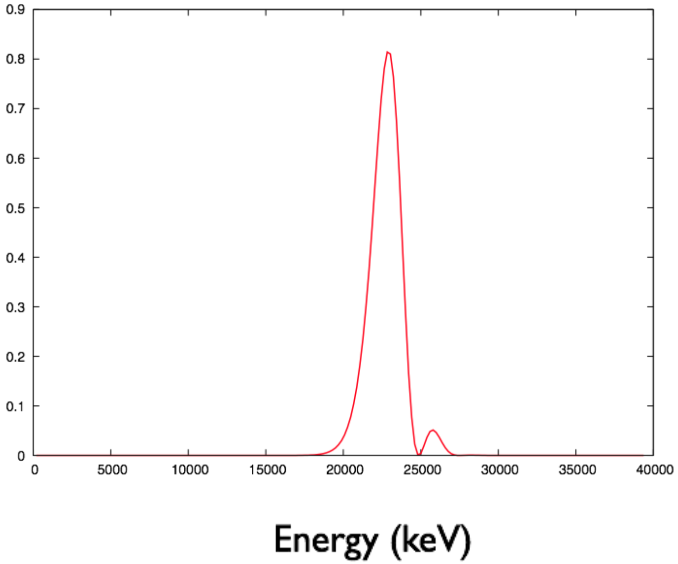
Radiation from laser-driven relativistic electron beam (1 GeV, 100 pC)

Betatron radiation



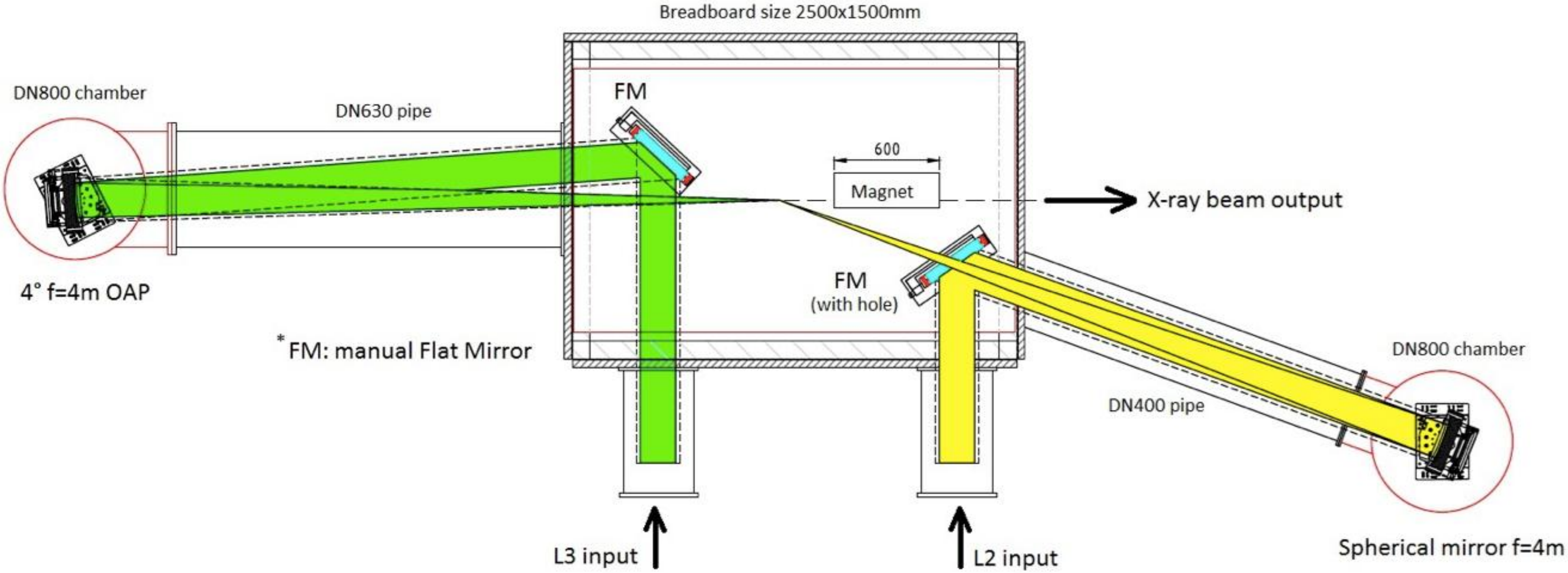
100 keV range
10^8 photons per shot
Source size : 2-5 µm
Divergence : <10 mrad

Compton back-scattering

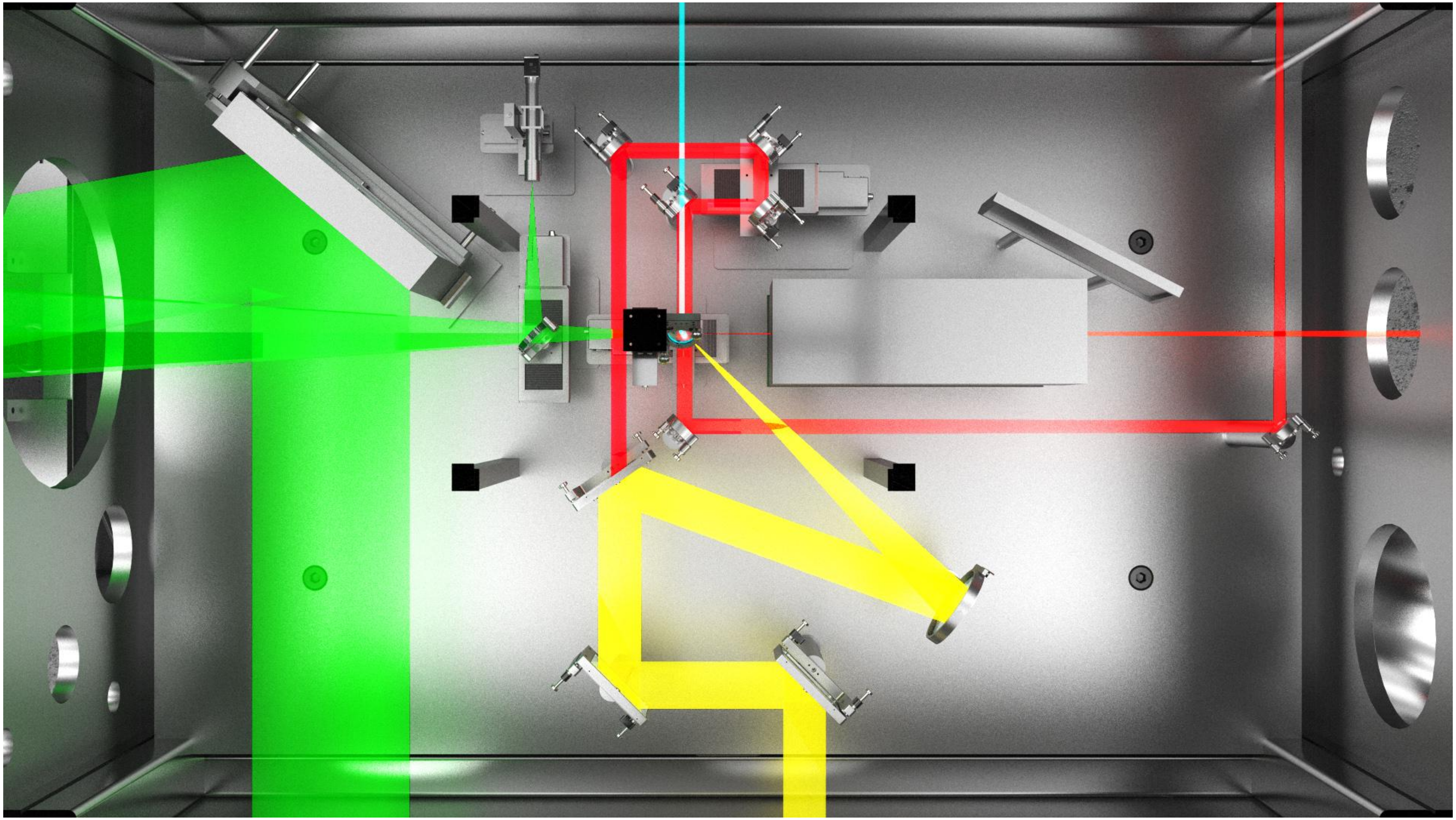


1-5 MeV range
10^8 photons per shot
Source size 2-5 µm
Divergence : <20 mrad

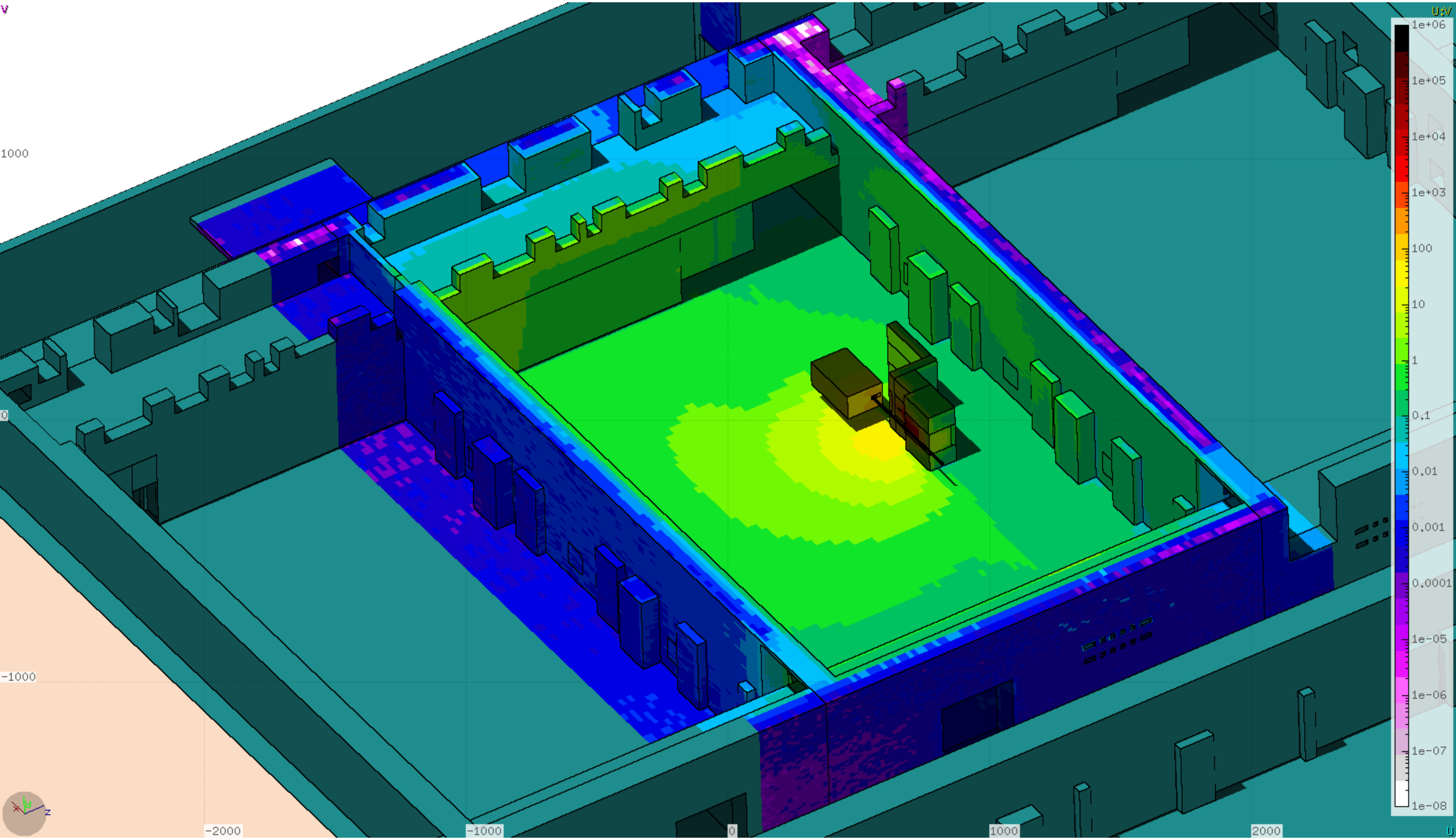
Betatron/Compton beamline in E2



10 Hz Betatron/Compton target chamber



Radiation shielding in E2

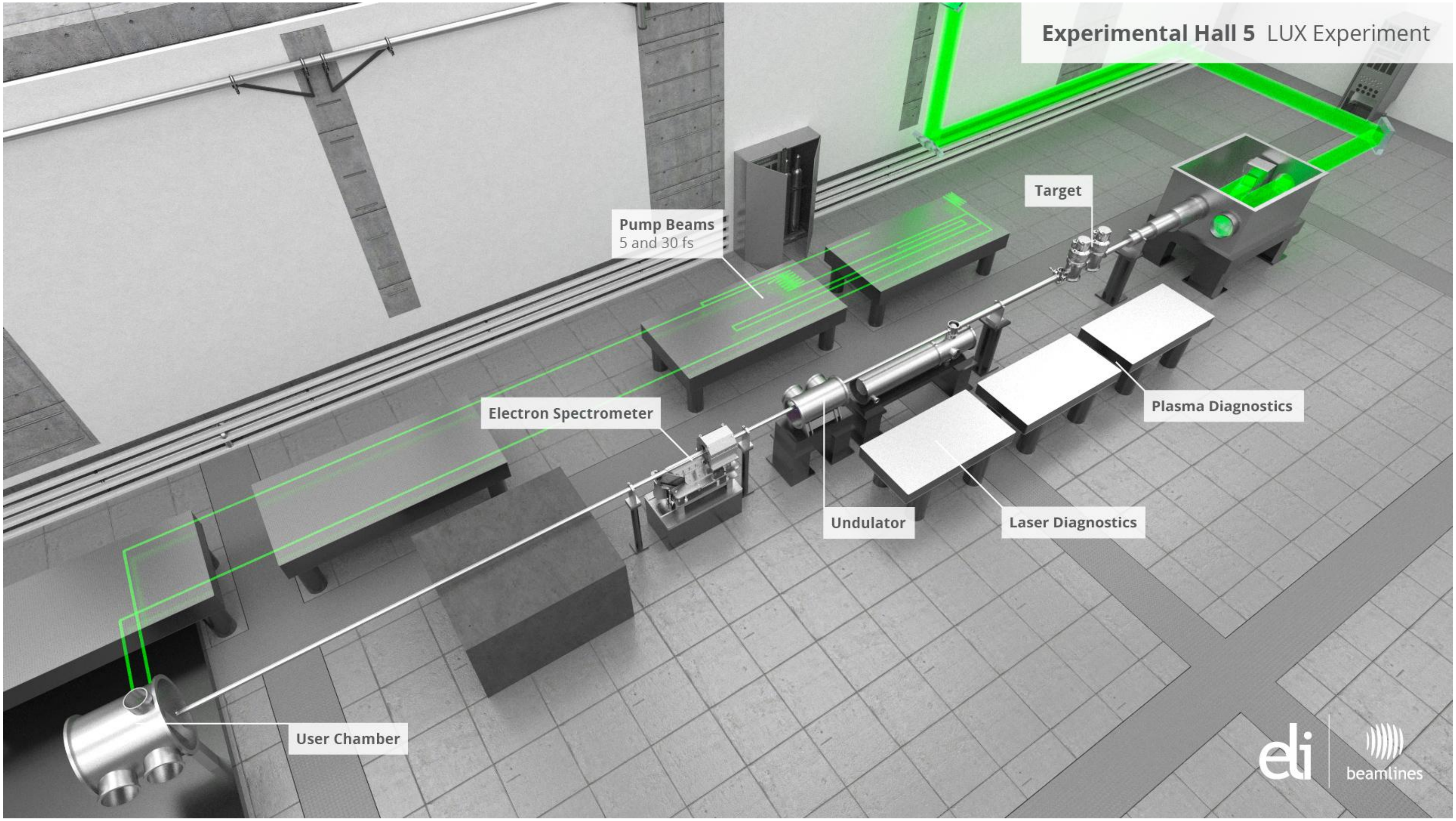


4 hours operation at 10 Hz (e-beam 200 pC, 1 GeV) ⇨ 0.1 to 1 μSv per day outside E2

Towards laser-driven XFEL in the E5 hall

Laser-driven Undulator X-ray source (LUX)

See L. Přibyl’s talk tomorrow



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THANK YOU FOR YOUR ATTENTION

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