Fs-Laser driven secondary sources of x-rays and particles within ELI-Beamlines and their applications

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for the ELI-Beamlines team

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OP Vzdělávání pro konkurenceschopnost
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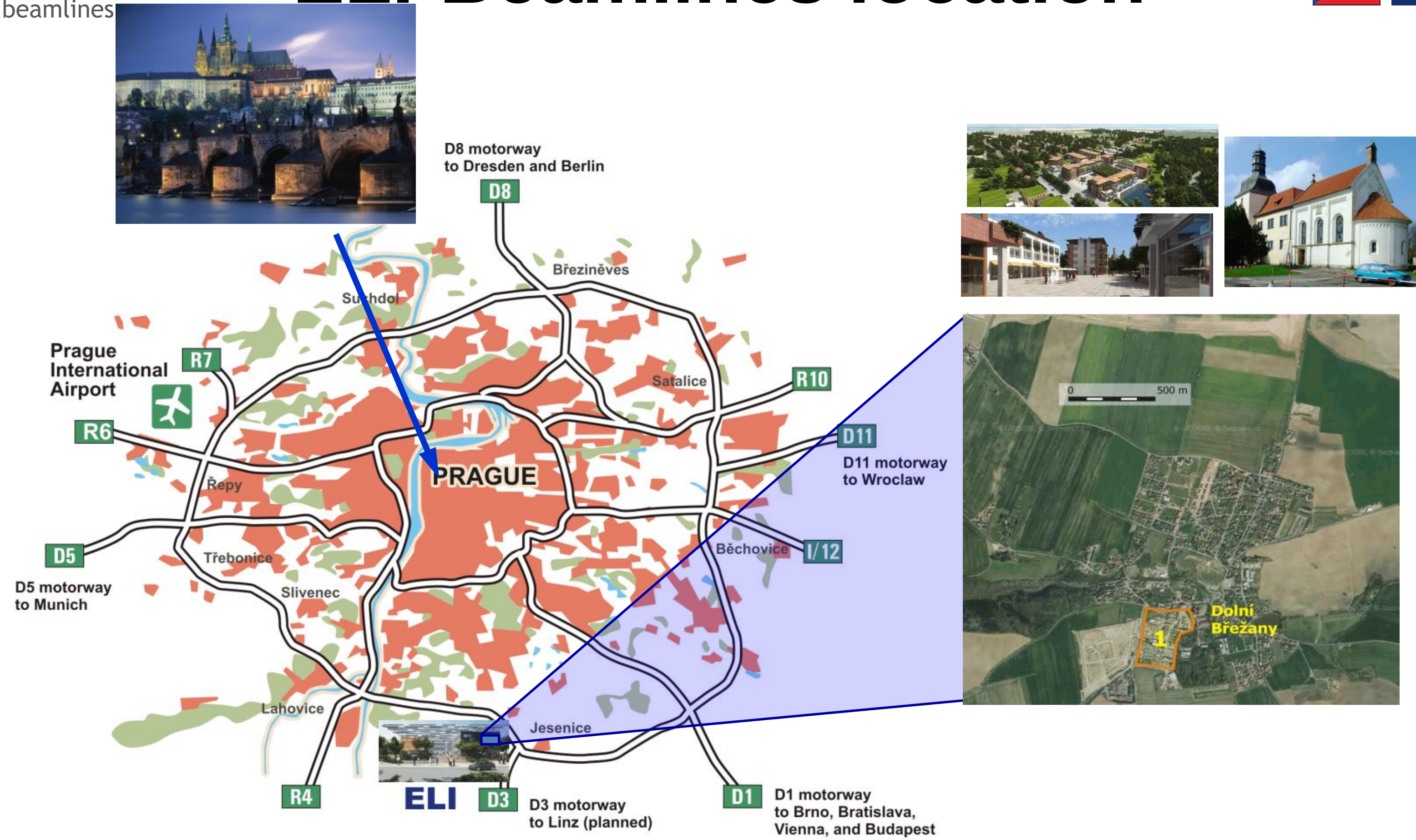
OP Výzkum a vývoj pro inovace

Outline

- ELI Beamlines
  short intro
- Facility
- Lasers
- Physical concepts of beamlines and their realization
- Experimental areas and stations
- Applications

ELI-Beamlines location



- Proximity of international airport (15 min drive), enjoyable surroundings, behind the border of Prague (funding issues)
- Synergy with planned large biotechnology center BIOCEV (2 km distance)
- Direct connection to Prague outer ring and the European motorway network

eli beamlines

Facility aerial view

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Science Case at ELI-Beamlines

ELI-Beamlines bid: balance between fundamental science and applications

ELI-Beamlines will be international user facility, partnership experiments & projects
over 100 researchers

Research Program 1
Lasers generating rep-rate ultrashort pulses & multi-petawatt peak powers

Research Program 2
X-ray sources driven by rep-rate ultrashort laser pulses, L1, 1 kHz and L3, 10 Hz lasers

Research Program 3
Particle acceleration by lasers, stepwise going from 0.1 Hz to 10 Hz with L3

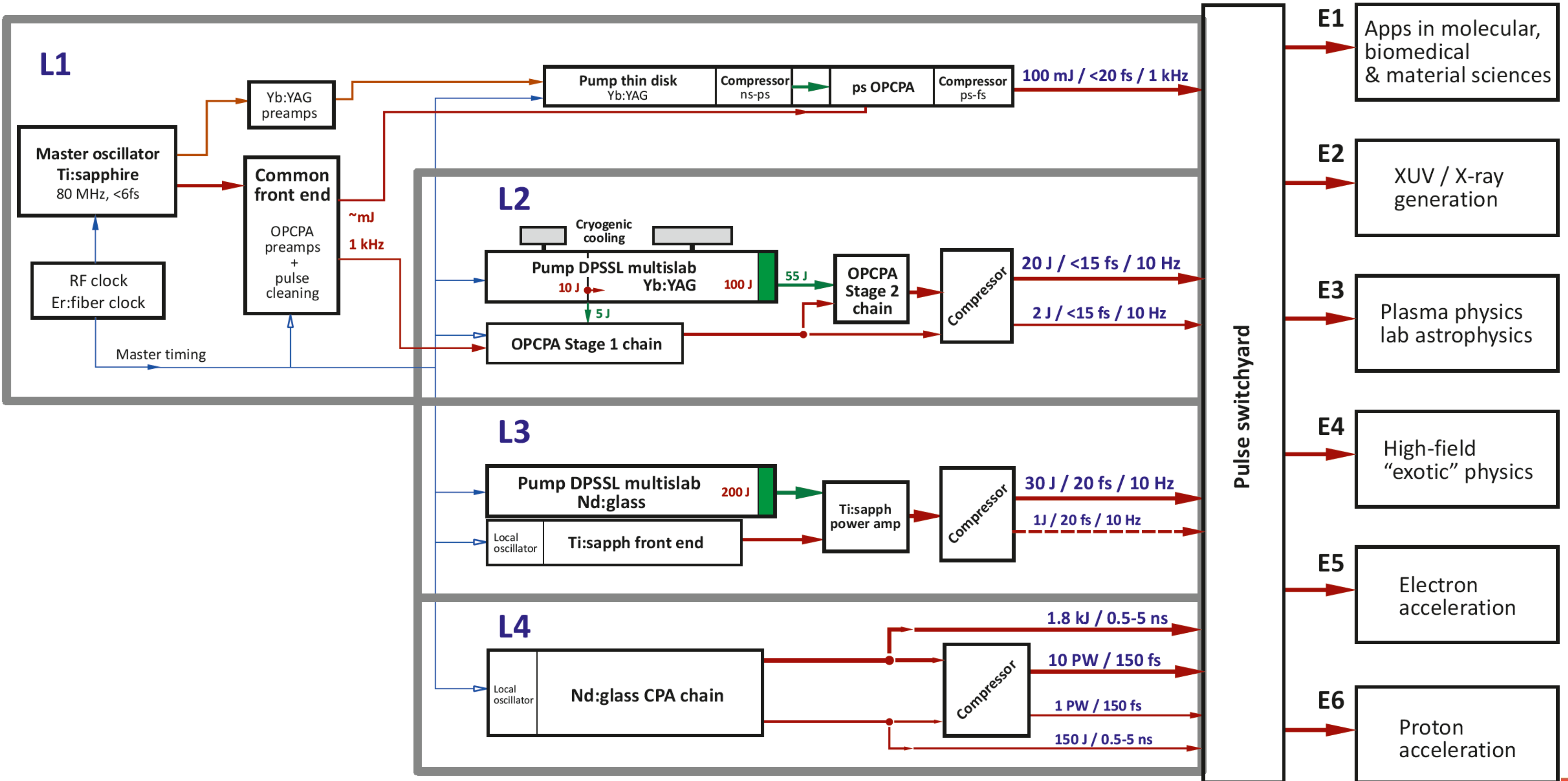
Research Program 4
Applications in molecular, biomedical, and material sciences, strong cooperation BIOCEV

Research Program 5
Laser plasma and high-energy-density physics, lab astrophysics, plasma optics for foc.

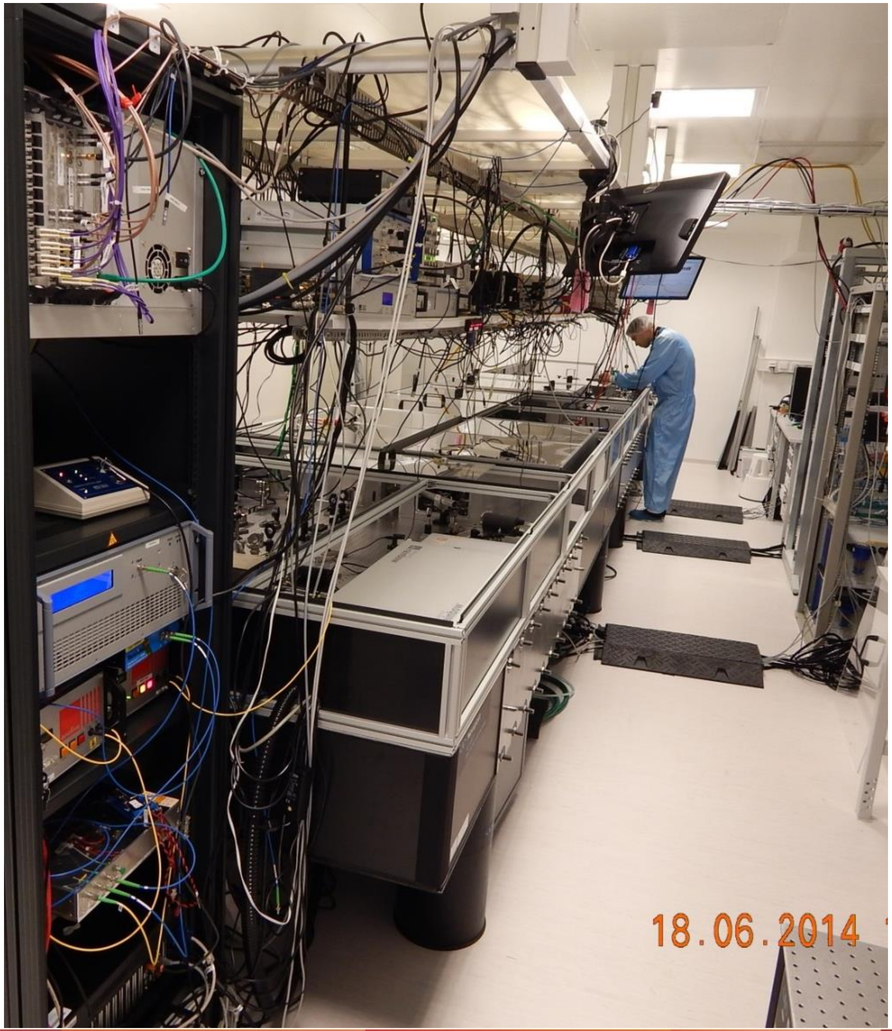
Research Program 6
High-field physics and theory (steps to 10^{23}W/cm^2, radiation reaction plays role)

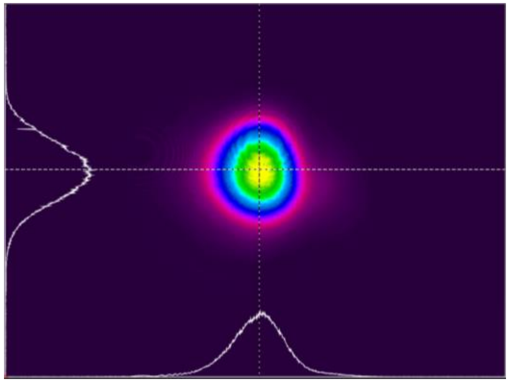
eli beamlines

ELI-Beamlines master scheme



L1 development

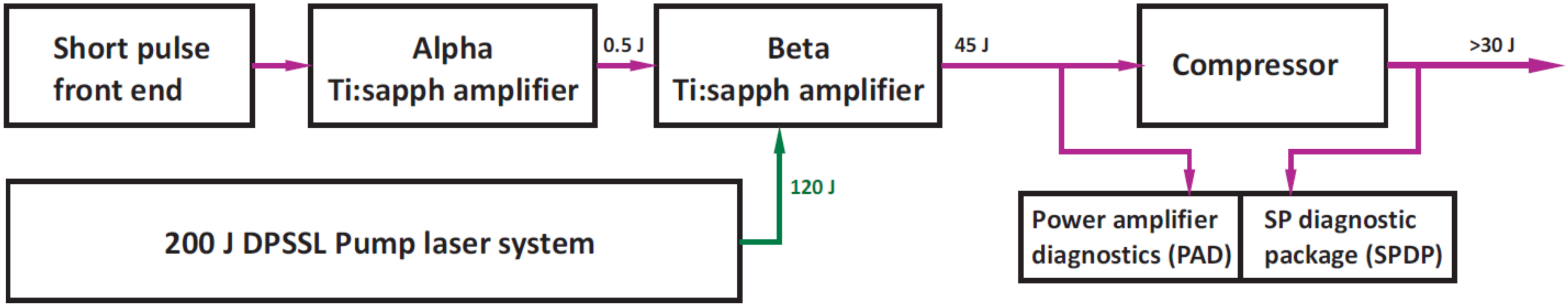




OPACP 15mJ, 1 kHz demonstrated

Pulse compressed to 16.5 fs
Next year > 50 mJ, <20 fs

L3 schematics and performance



Parameter	Value
Peak power	≥1PW
Repetition rate	10 Hz
Pulse energy after compression	≥30 J
Pulse duration	≤30 fs
Central wavelength	820 nm
Output pulse energy RMS stability	better than 0.6%
Temporal power contrast	1:10^9 initial, 1:10^{11} optimized
Electrical consumption	<150 kW

eli beamlines

L4

10 PW kJ CPA laser: mixed Nd:glass providing spectral bandwidth for direct pulse compression to ≤150 fs

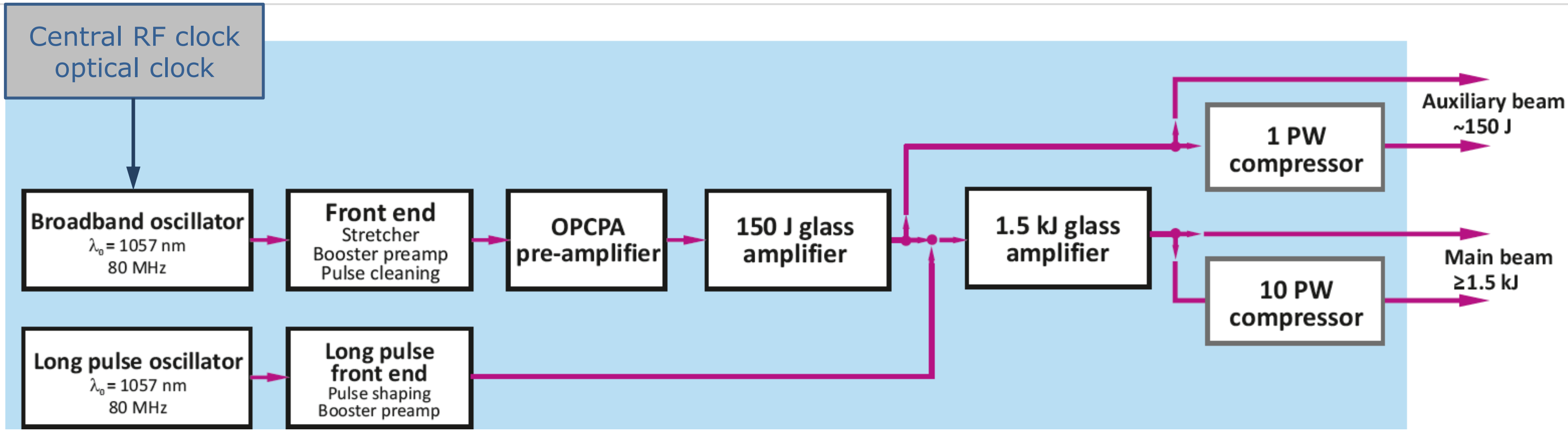
Nanosecond pulses with programmable temporal shape for sophisticated laser-plasma experiments

PW auxiliary beam for plasma probing

Possible future use as OPCPA driver for generation >10 PW power

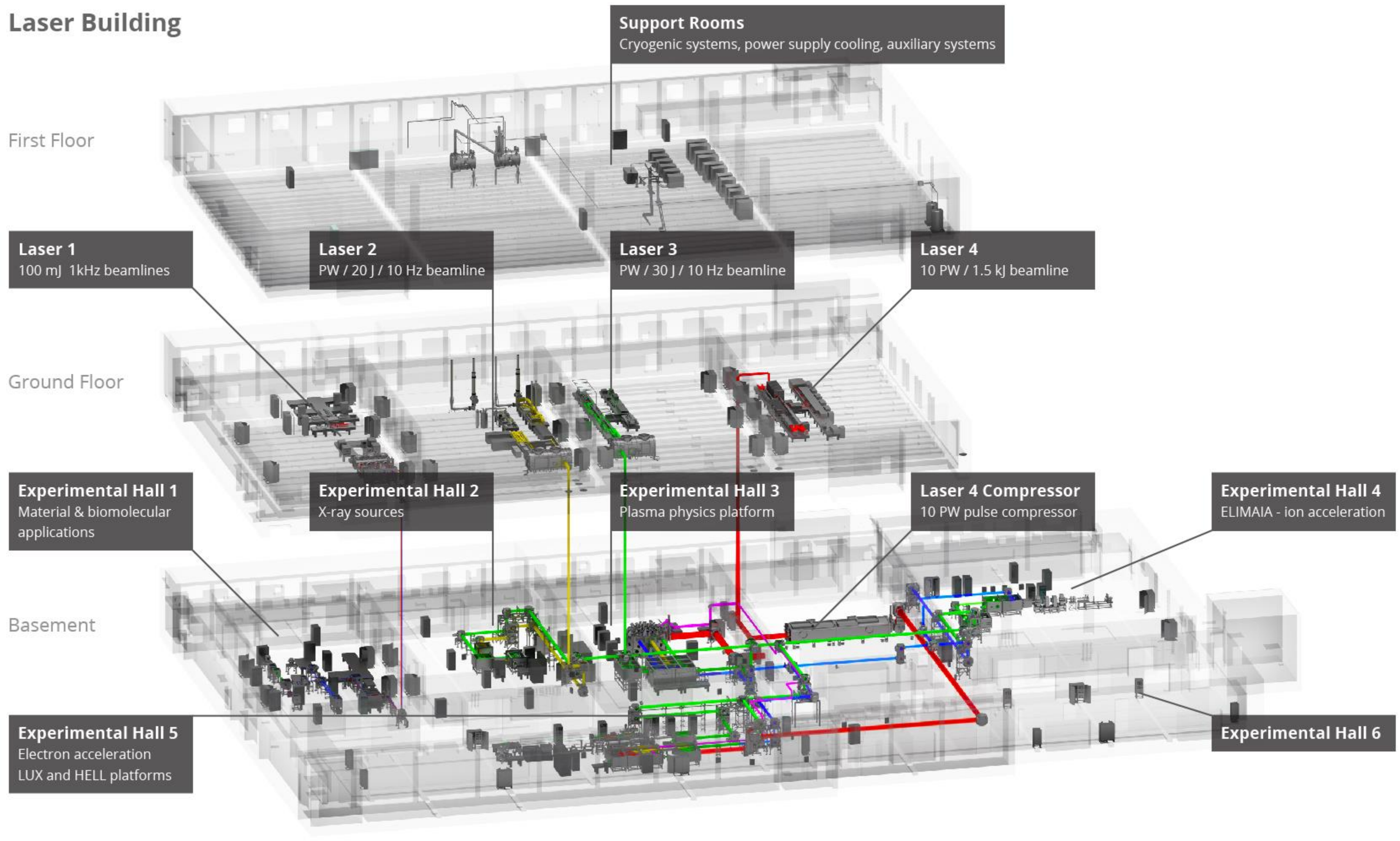
Supplier: NE-EKSPLA
ELI-Beamlines co-develops 10 PW compressor + diagnostics + timing system

L4 schematics and performance



Parameter	Value
Main beam energy	1.5 kJ (compressed)
Main beam peak power	10 PW
Auxiliary beam energy	150 J (compressed)
Auxiliary beam peak power	1 PW
CPA pulse duration (FWHM)	≤150 fs
Long pulse duration	0.5 to 10 ns (adjustable in 100 ps steps)

Facility, extremely stable monolitic structure of building



RA 2, LUX

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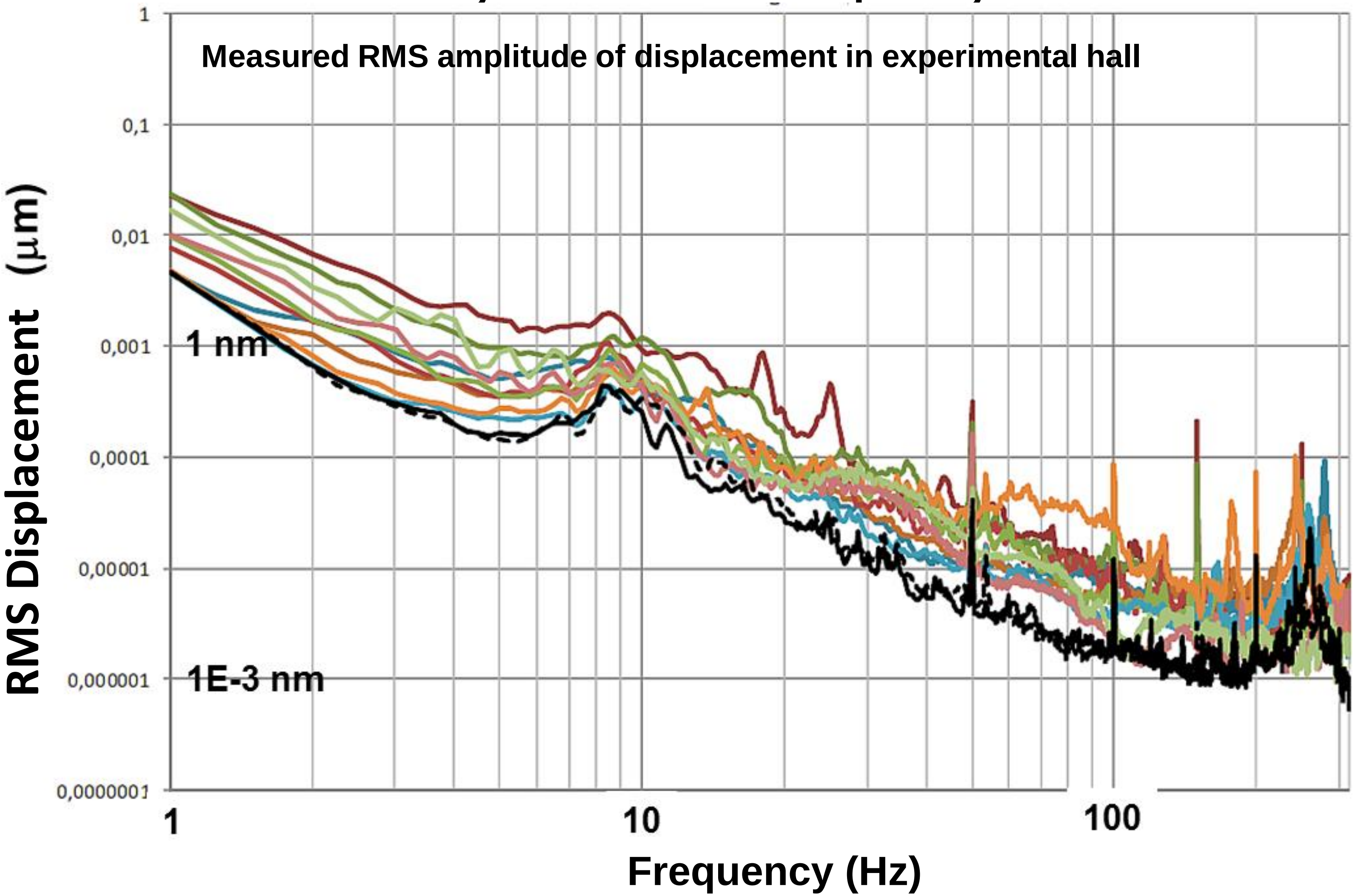
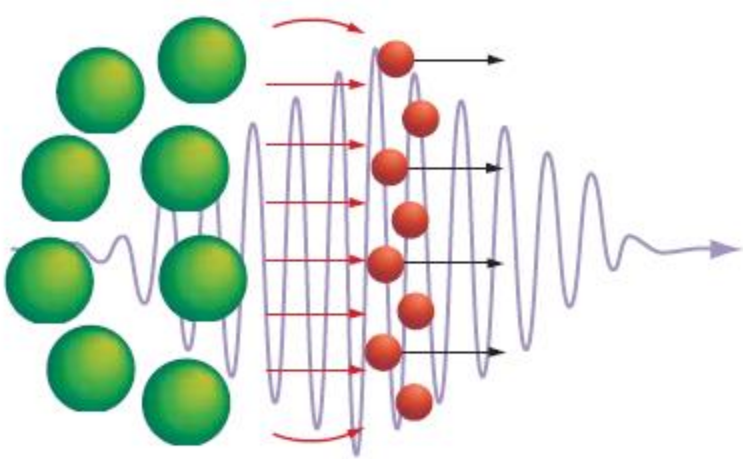
We have measured an outstanding ambient vibration level in our laser and experimental halls, this enables us to build an extremely stable beam transport system

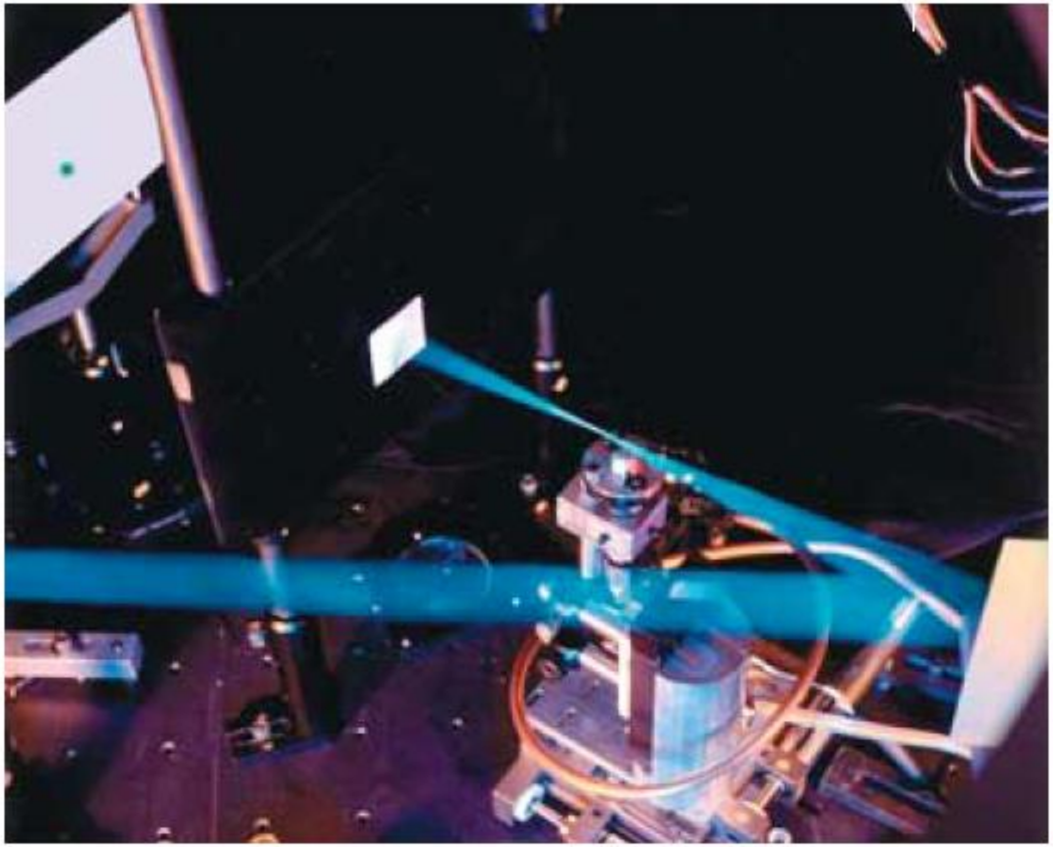


electron acceleration, very compact few cm long Interaction with gas, 4.2 GeV in 9cm, Wim L. , talk

WAKE-FIELD ACCELERATION

HIGH-INTENSITY LIGHT striking a plasma (*below*) pushes the electrons to very high speeds, leaving the heavier positive ions (*green*) behind and producing a powerful electric field (*red lines*) between these separated charges. This separation of charges and the associated electric field trails along in the wake of the light and can accelerate other charged particles to very high energy.



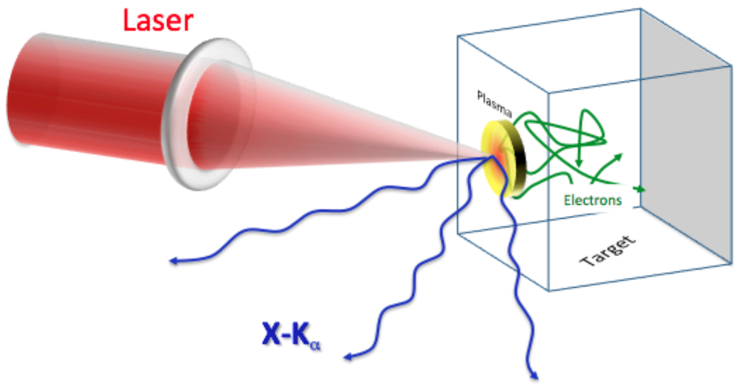


ULTRAHIGH-INTENSITY LASER PULSE (*added in blue*) focused on a jet of helium gas by a parabolic mirror accelerates electrons from the gas to 60 MeV in one millimeter. A fluorescent screen (*upper left*) detects the high-energy electron beam.

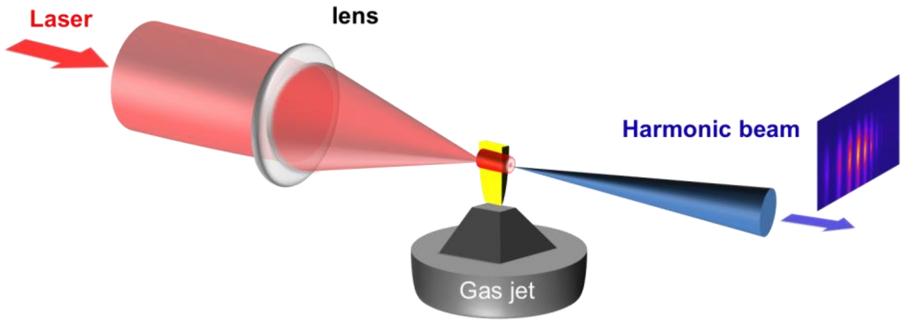
RP2: Laser-driven X-ray sources

talk N. Nejdl about details

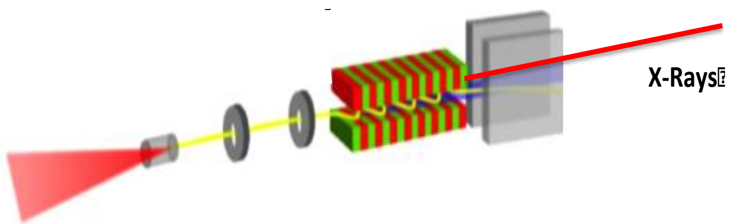
Plasma sources



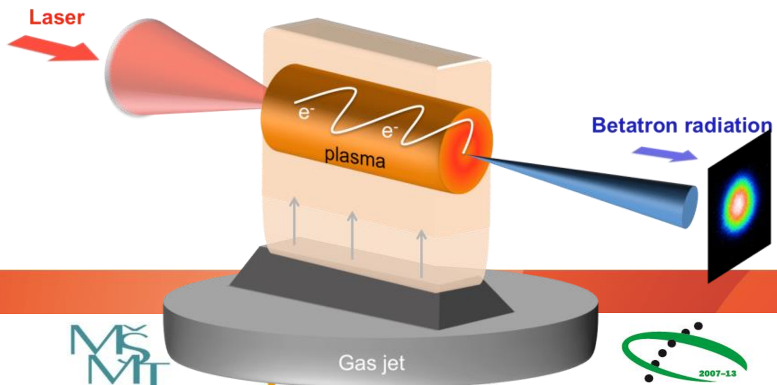
Harmonics (gas), or solids



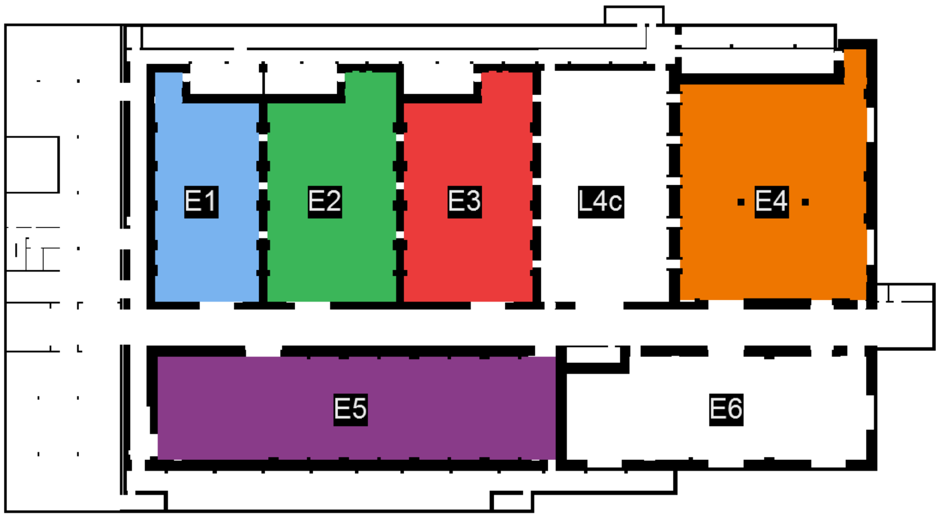
LUX/XFEL



X-rays from relativistic e-beams,
Betatron and Compton



What users get

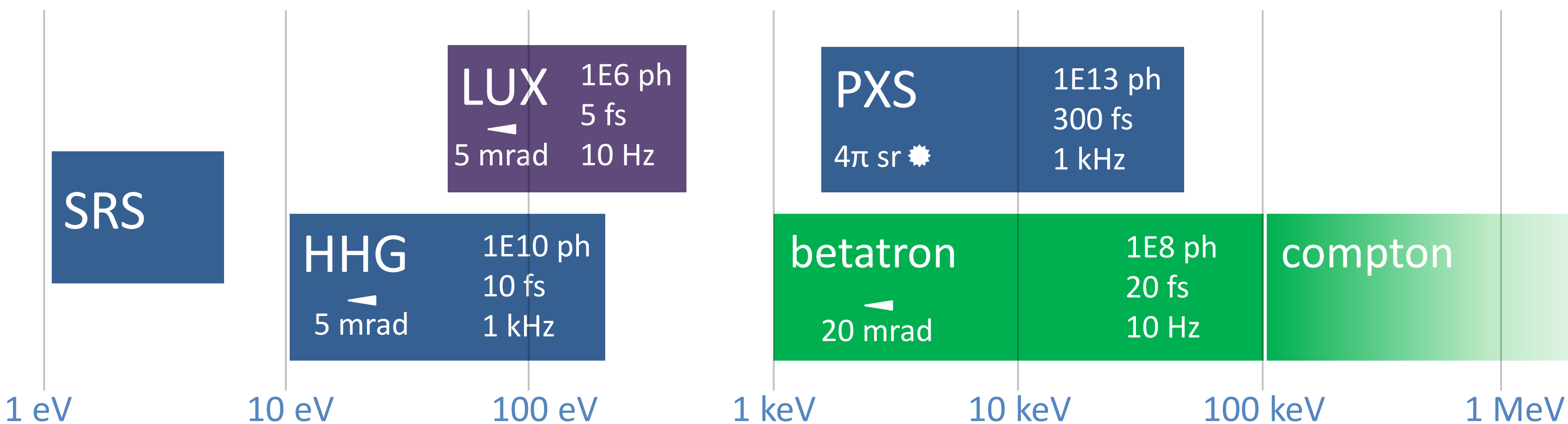


Coherent Diffractive Imaging
Atomic, Molecular and Optical Science
Soft X-ray Materials Science
X-ray phase contrast imaging
X-ray Diffraction and spectroscopy
Optical Spectroscopy and Molecular Dynamics

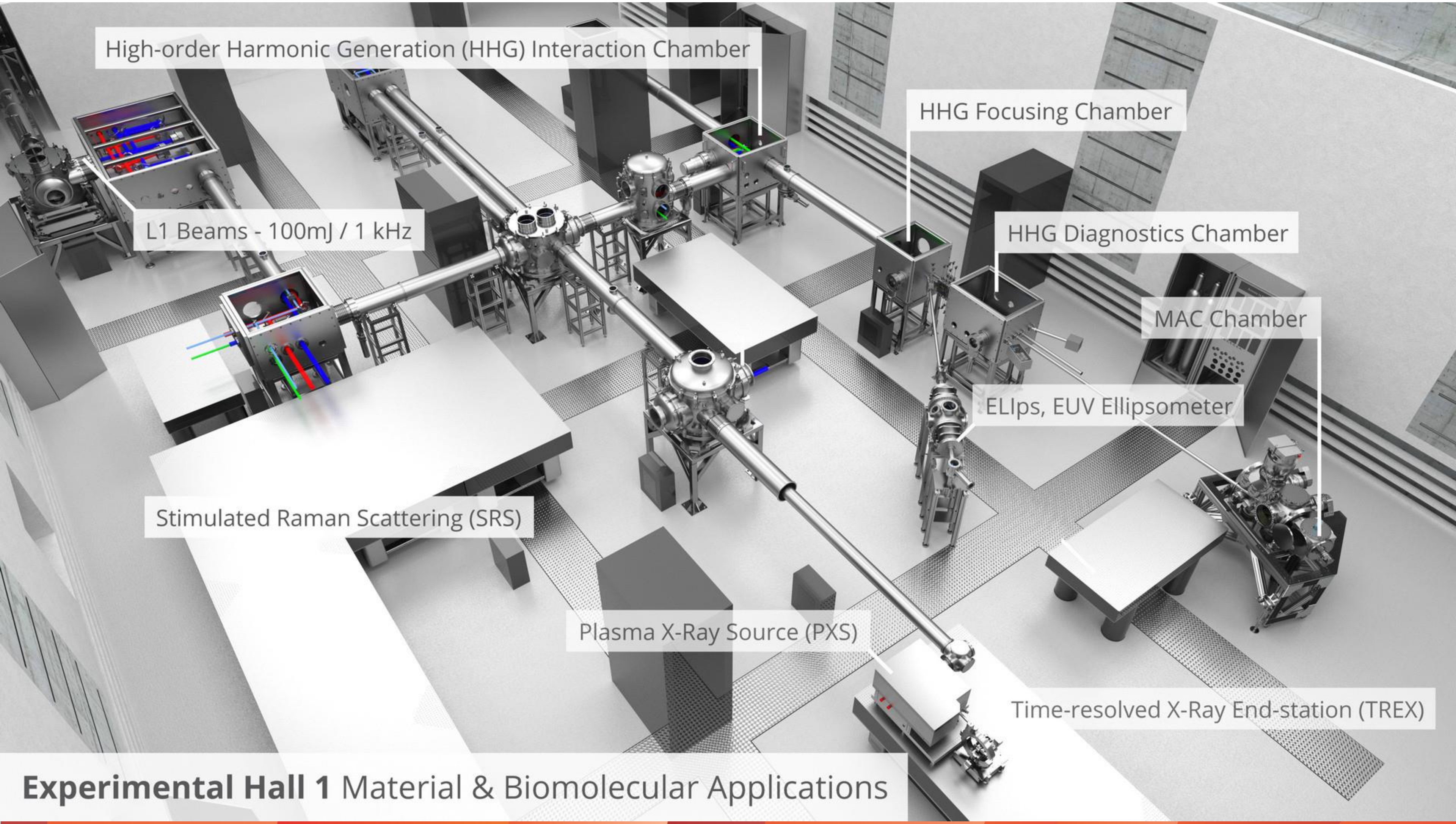
X-ray Phase contrast imaging
X-ray fluorescence/absorption spectroscopy

Coherent Diffractive Imaging (concept)

Secondary photon sources for users , short pulse



Hall E1 applications, L1 OPCPA laser, virtual beamline browser supported 3D tool for users using 3D glasses



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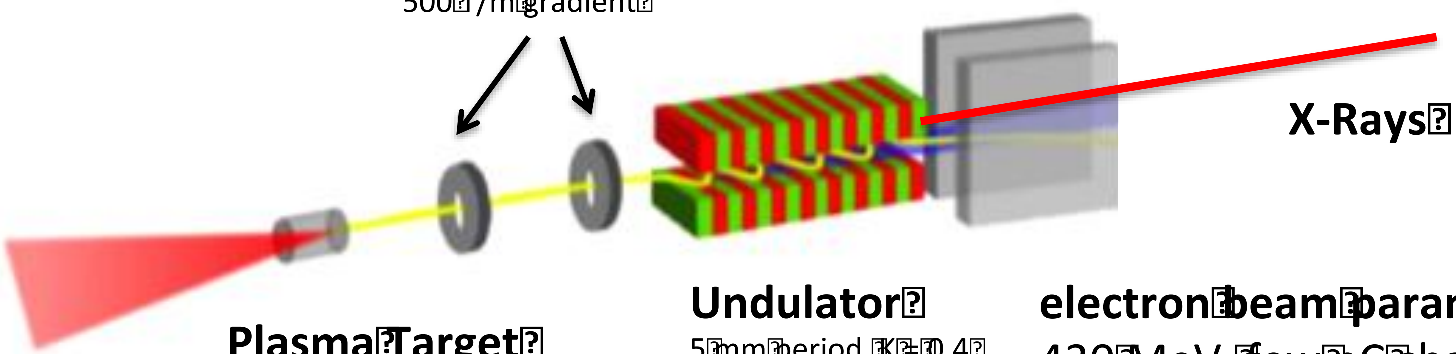
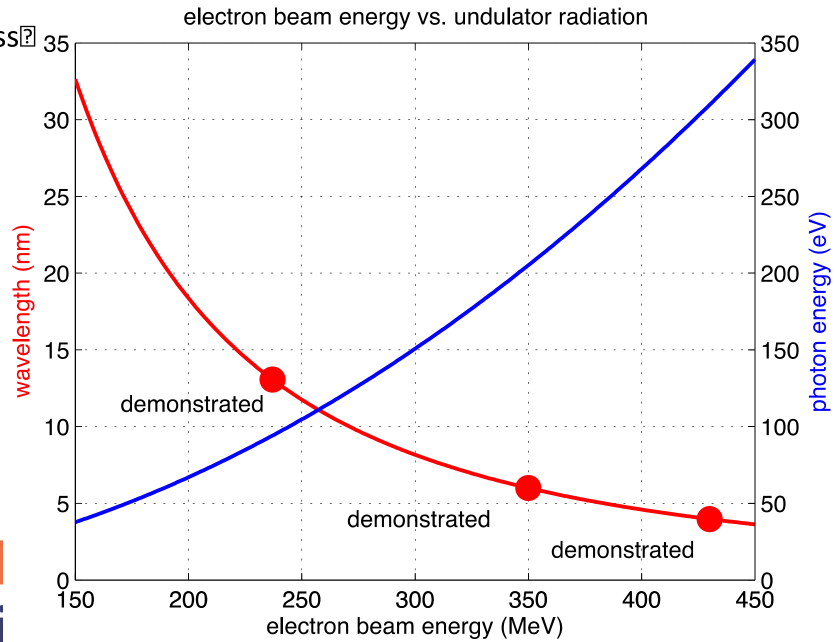
eli beamlines

LUX beamline, UH, DESY





electron beam parameters:

430 MeV, few pC charge

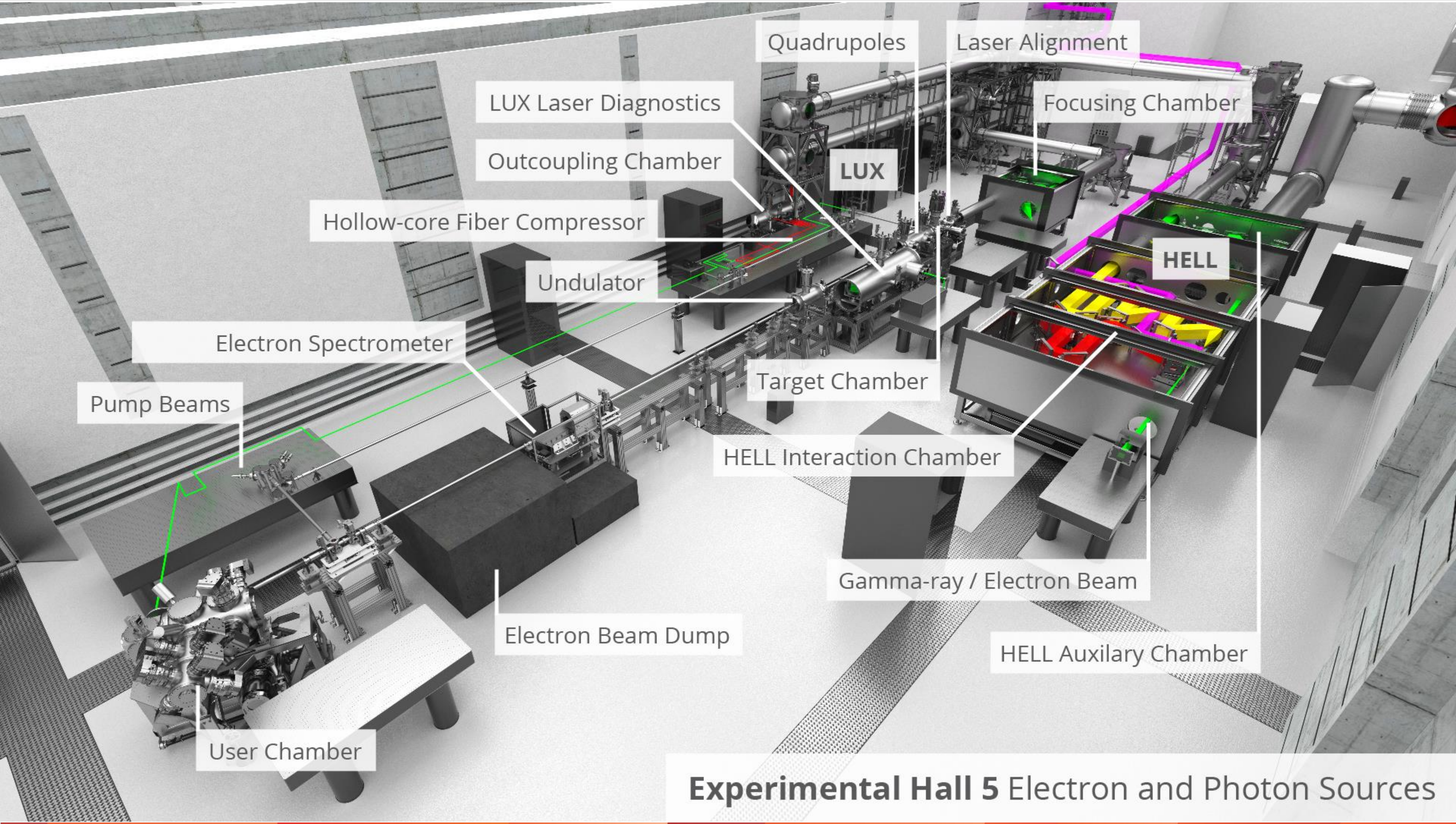
0.2 mm.mrad norm emittance

photons (2016)

- bandwidth stabilized to 2%
- pointing stabilized
- $10^{5...6}$ photons per pulse
- down to 3 nm
- pump-probe experiments

M. Fuchs et al., *Nature Physics* ***5****, 826 (2009)*

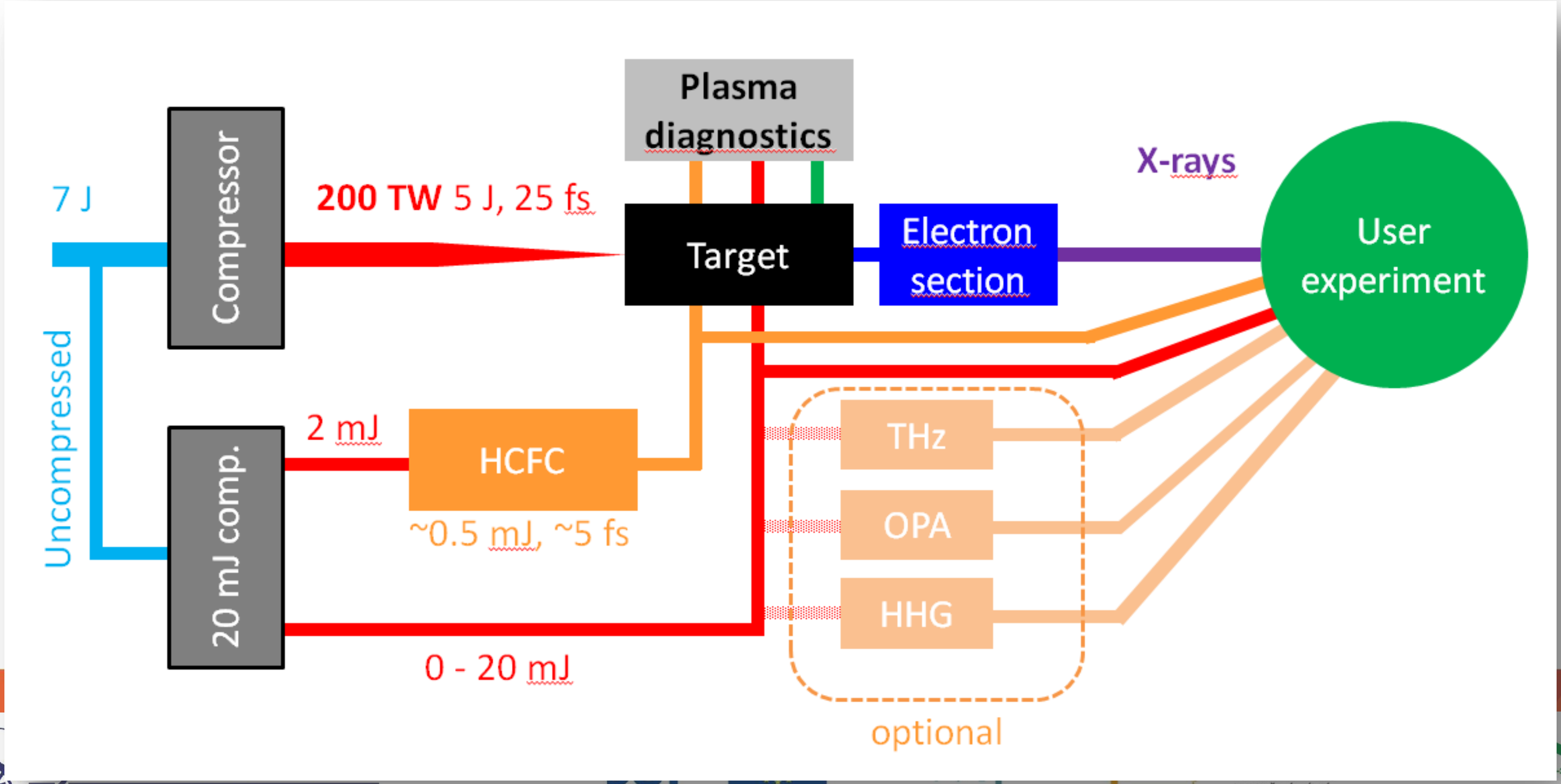
LUX Beamline and HELL



Experimental Hall 5 Electron and Photon Sources

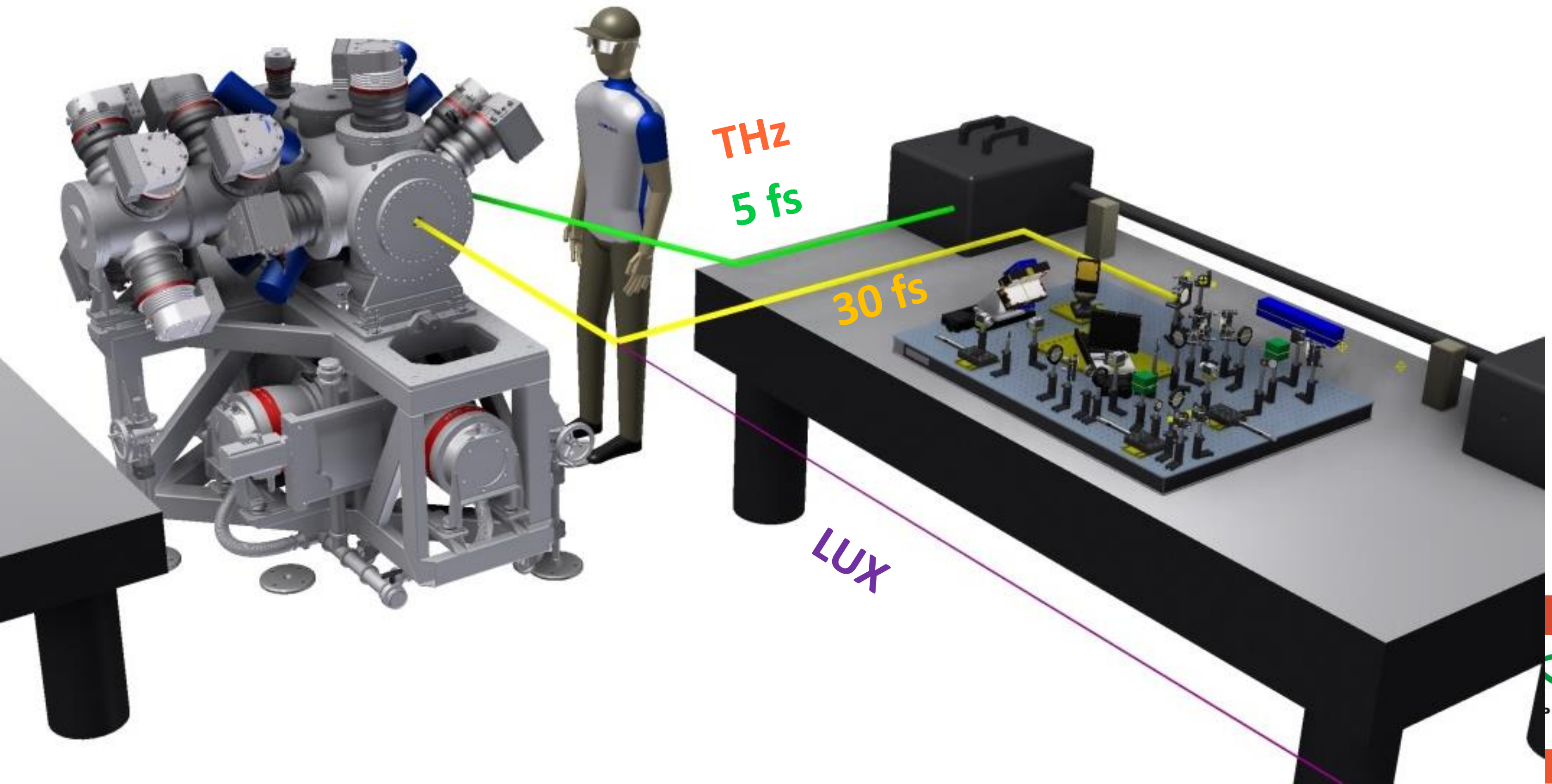
Energy range and auxiliary beams

- The main beam photon energy will be **tunable** in two ranges:
  - **Water window** (290 – 700 eV)
  - **K edges** (700 – 2500 eV) – Na, Si, P and S



User experiments

- At ELI Beamlines users may use either the MAC chamber (**M**ulti purpose chamber for **A**tomic Molecular and Optical sciences and **C**oherent Diffractive Imaging, see below) or install their own.
- Auxiliary beams may be adjusted according to the experiment needs.
- Biological and chemical laboratories will be available in ELI



LUX Collaboration

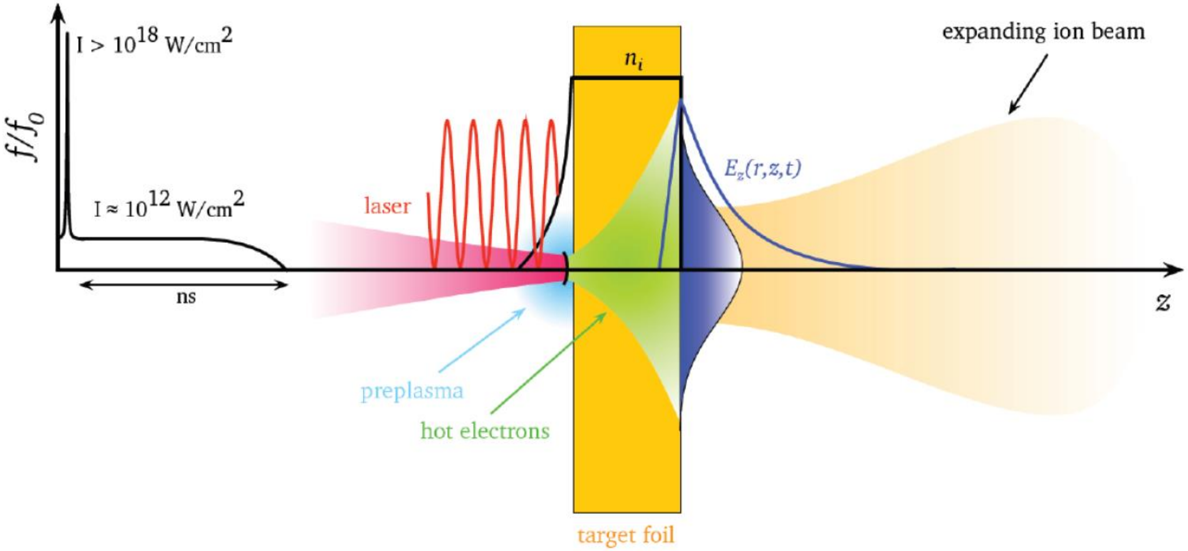
Review Meeting 12th January 2016, Hamburg

Group F. Gruener, A. Maier (Hamburg)
Group G. Korn, L. Pribyl (ELI Beamlines)

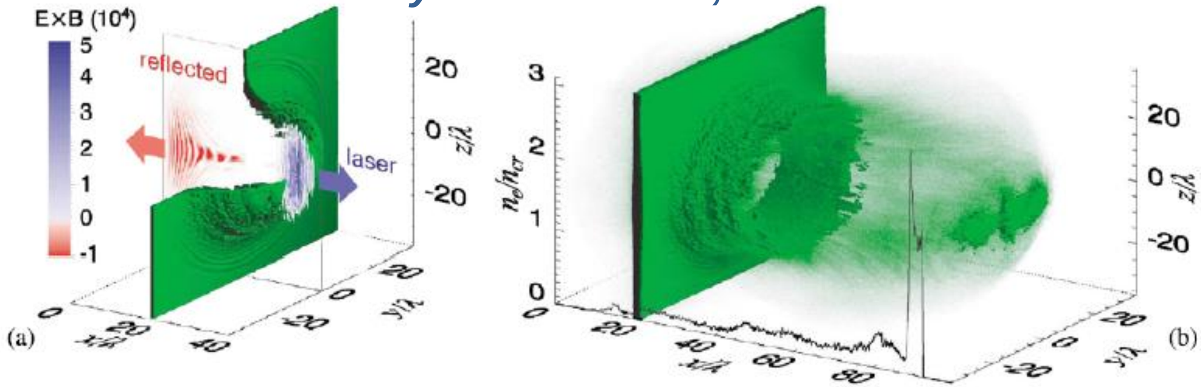
Majority of design (and parts production) efforts done.
Experimental phase with laser started.

Ion Acceleration:

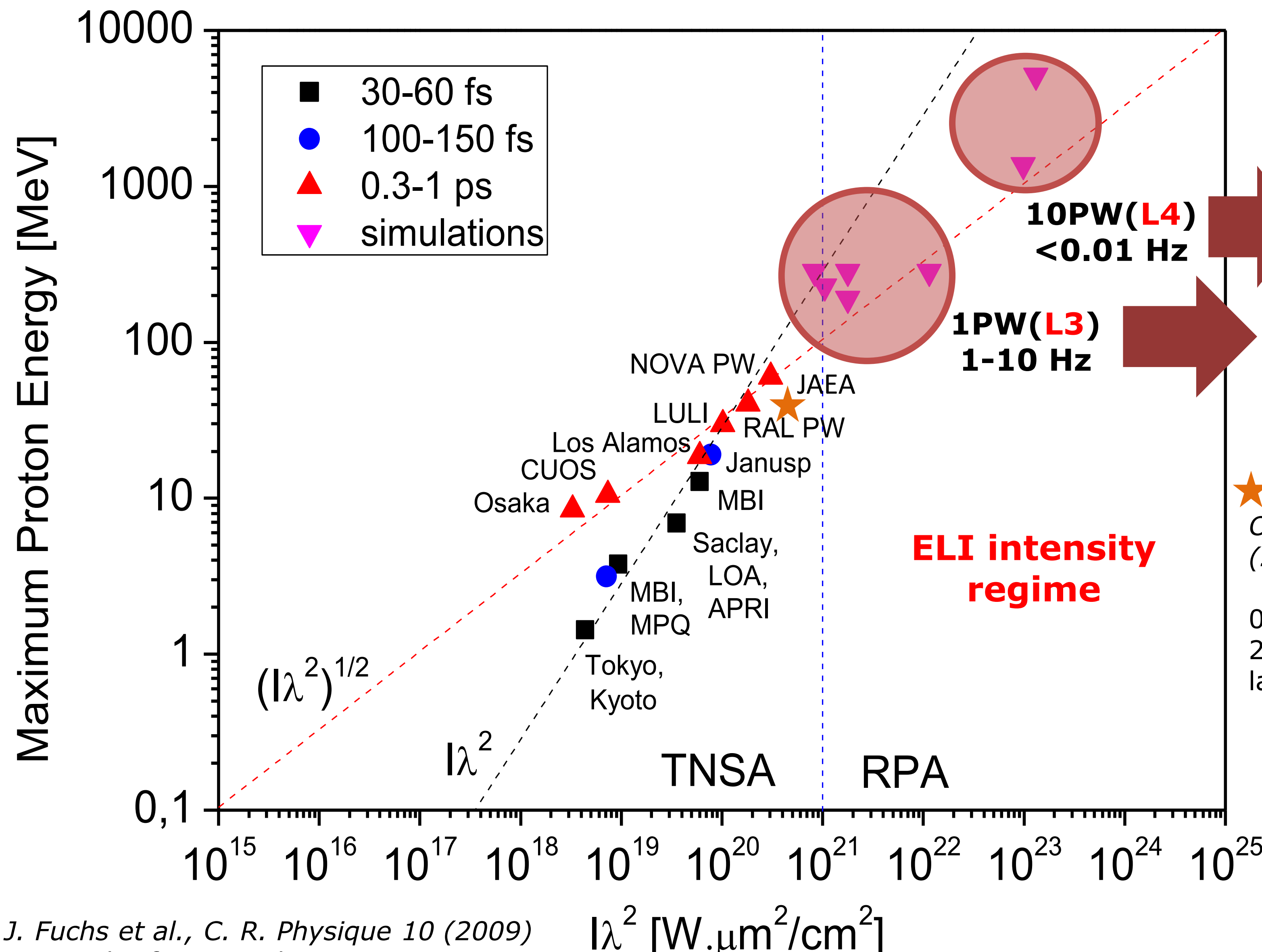
Target Normal Sheath Acceleration



Radiation Pressure Acceleration, High intensity required courtesy S. V. Bulanov,

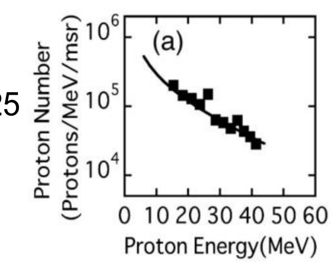


Proton Acceleration: Scaling Laws



K. Ogura et al., Optics Letters 37 (2012) 2868

0.8 µm Al target; 200 TW (8J/40fs) laser



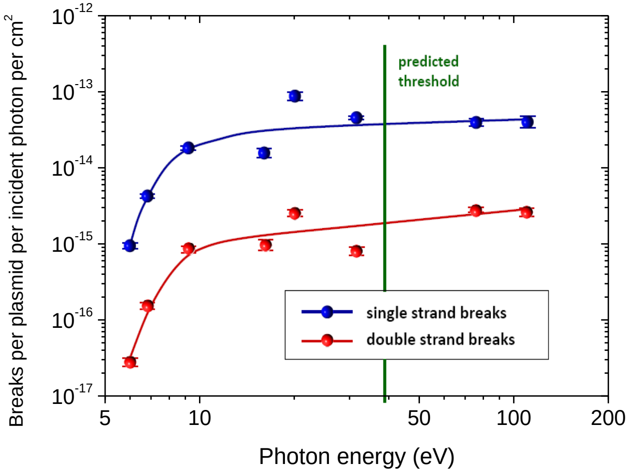
J. Fuchs et al., C. R. Physique 10 (2009) 176 and references therein

Potential applications of laser driven protons

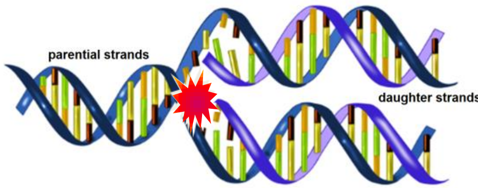
Application field	Energy range	Bibliography
Time-resolved Proton Radiography of dense materials	>3 MeV	*Borghesi et al., PPCF (2001)*
Pump-probe investigations (WDM,…)	>1 MeV	*Patel et al., PRL (2003)*
ICF fast ignition with proton beam	10-30 MeV	*Roth et al., PRL (2001)*
Pitcher-catcher nuclear reactions (neutrons, alphas,…)	≥1 MeV	*McKenna PRL (2005)*
Innovative approaches to hadrontherapy	60-300 MeV	*Bulanov, Khoroshkov, PPR (2002); Bulanov et al, UFN (2014)*
Radiobiology with short ion bunches (0.1-10 ns)	3-300 MeV	*Yogo et al, APL (2009) Kraft, et al. NJP (2010)*
Radiation chemistry – pulsed radiolysis of water (radiobiology, nuclear power plant industry)	10-20 MeV	*Baldacchino, RPC (2008)*
Radio-isotopes for positron emission tomography (PET)	~30 MeV	*Spencer et al., NIMB (2001)*
Space Radiation for testing space-grade electronics (protons, electrons, X-rays)	>1 MeV	*Hidding et al., NIMA (2011)*
PIXE analysis for cultural heritage	>3 MeV	*Pappalardo et al., NIMB (2008)*
………………………………………………………………		

DNA-Strand Breaks

Radiotherapy: The goal is to hit to nucleus.

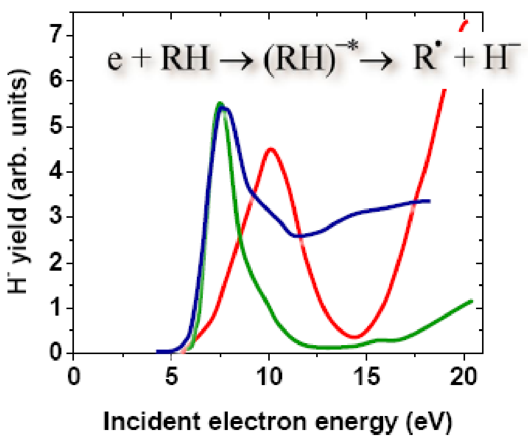


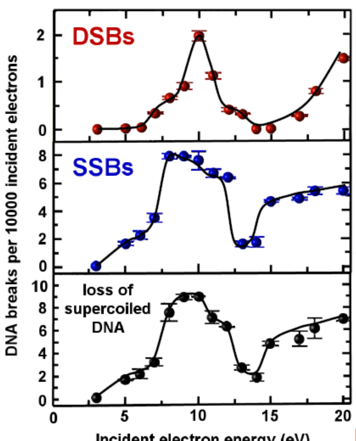
M. Folkard, et al., *J. Phys. B* 32, 2753 (1999)



Double-strand-cut due to chemical, resonant, ionization and direct impacts.

Most of the energy deposited in cells by ionizing radiation is channeled into the production of abundant free secondary electrons with ballistic energies 1~20 eV.

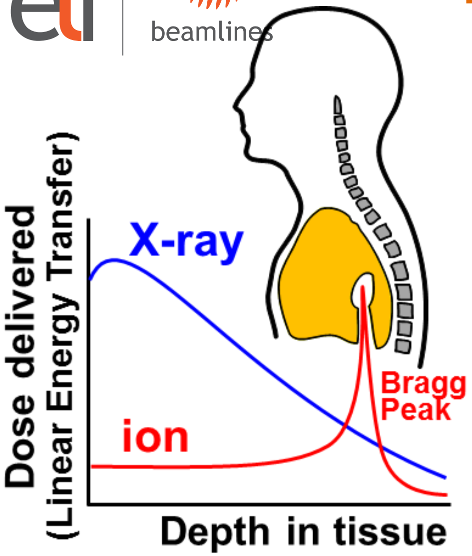




Even electrons with energies well below ionization thresholds induce substantial yields of single- and double-strand breaks in DNA

B. Boudaïffa, et al., *Science.* 287, 1658 (2000)

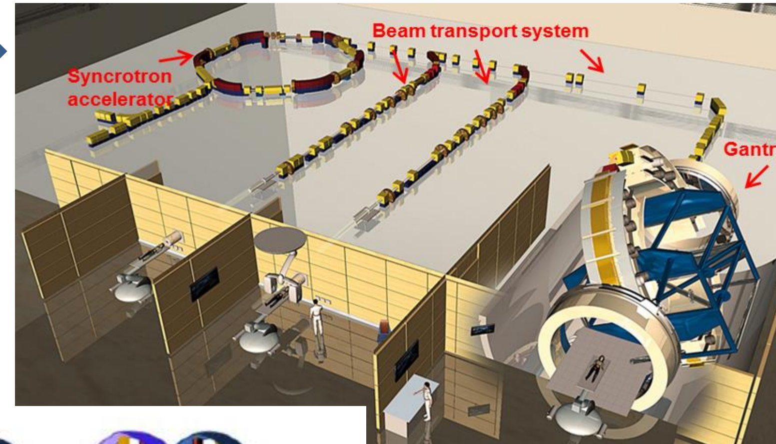
Laser-based hadrontherapy???



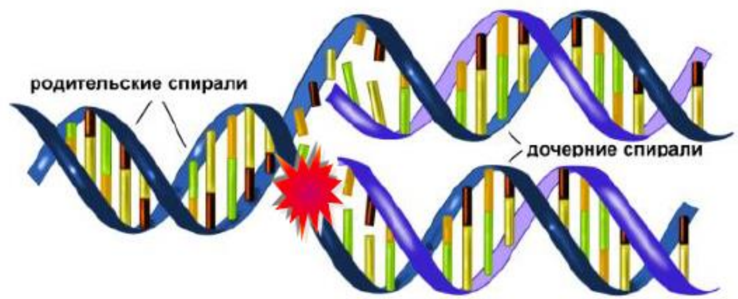
Conventional hadrontherapy

- ***High complexity of beam transport & delivery***
- ***High cost***

http://newscenter.lbl.gov/2010/10/18/ion-beam-therapy/



DNA double-strand-break (hadrons)

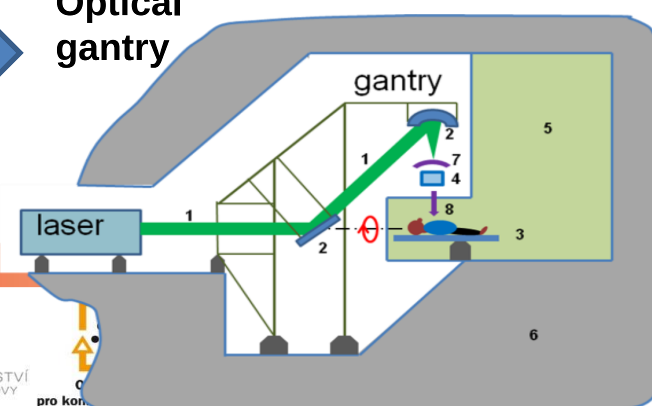


Laser-based hadrontherapy

- ***Compactness*** (hospital-room size)
- ***Cost-reduction*** (optical gantry)
- ***Advantages:***
  - Variable energies in the accelerator (no degraders needed)
  - Hybrid treatment (p, ions, e^-, γ, n)
  - In-situ diagnostics (PET, X-rays)
  - Low emittance: normal-tissue sparing
  - High fluence rate (ultrashort pulses): higher LET, enhanced Bragg peak, higher RBE???

Bulanov & Khoroshkov, Plasma Phys. Rep. (2002)

Optical gantry



Hadrontherapy: THE user case

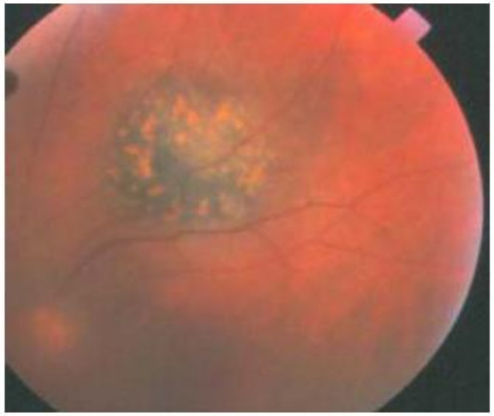
ELIMAIA Goal: use laser-driven ion beams for user applications

Good candidate as **demonstration-case** since medical applications are the most demanding in terms of:

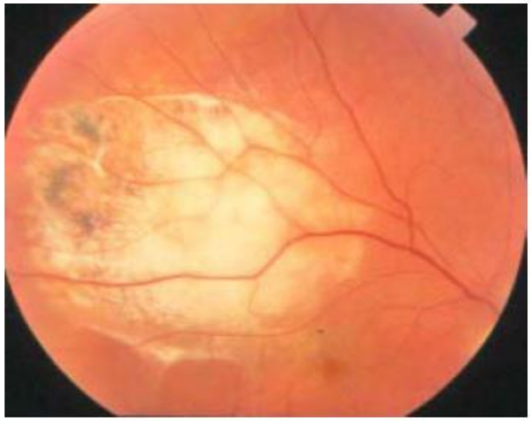
- beam delivery system
- absolute and relative dosimetry

Courtesy of P. Cirrone

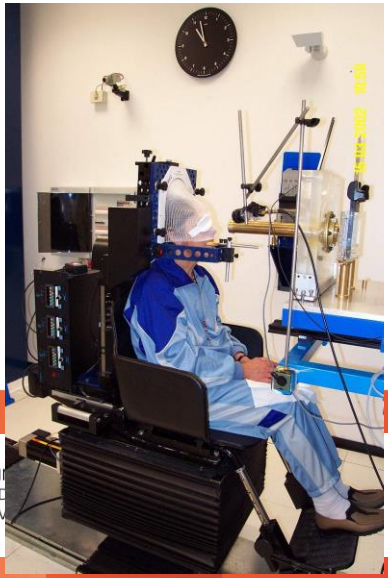
Eye tumor treatment (62 MeV protons @ CATANA)



Melanoma (90%)



Hemangioma (10%)



ELIMED idea and network…

ELIMED aims at building an international network with a **long-term goal**: demonstrate future applicability (proof-of-principle) of laser accelerated ion beams in **hadrontherapy**

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User requirements

Typical user requirements

- Wide **energy** and **fluence** range
- Small energy spread (**quasi-monoenergetic** beams)
- **Homogeneous** transverse beam distribution
- Shot-to-shot **stability** (energy and fluence)
- Variable beam spot size
- Full beam **control** (fluence and dose) with < 5% error
- Possibility of **in-air irradiation** (e.g. bio-samples)
- Use of **different ion species** (H, He, Li, C)

Ion Beam Features (PW)	Enabling Experiments	Flagship Experiments
Energy range	3-60 MeV/u	3-300 MeV/u
Ion No./laser shot	$>10^9$ (0.1 nC) in 10% BW	$>10^{10}$ (1 nC) in 10% BW
Bunch duration	1-10 ns	0.1-10 ns
Energy spread	±5%	±2.5%
Divergence	±0.5°	± 0.2°
Ion Spot Size	0.1-10 mm	0.1-10 mm
Repetition rate	0.01-1 Hz	0.01-10 Hz

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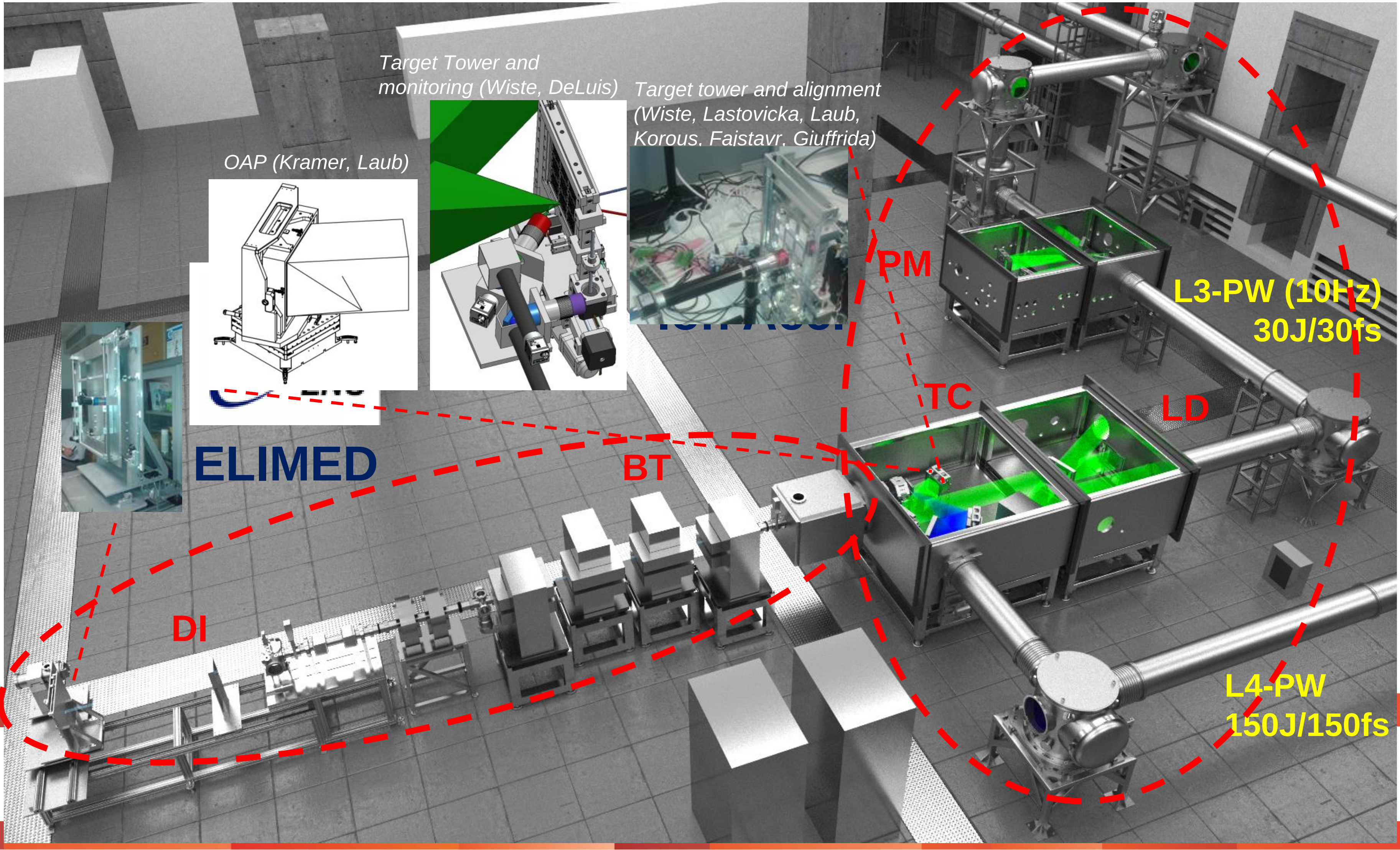
ELIMAIA

(daniele.margarone@eli-beams.eu)

ELI Multidisciplinary Applications of laser-Ion Acceleration



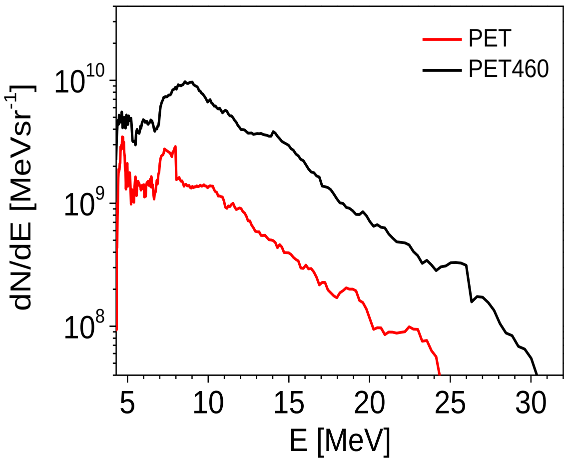
What the users get

Typical user requirements

- Wide **energy** and **fluence** range
- Small energy spread (**quasi-monoenergetic** beams)
- **Homogeneous** transverse beam distribution
- Shot-to-shot **stability** (energy and fluence)
- Variable beam spot size
- Full beam **control** (fluence and dose) with < 5% error
- Possibility of **in-air irradiation** (e.g. bio-samples)
- Use of **different ion species** (H, He, Li, C)

Ion Beam Features (PW)	Enabling Experiments	Flagship Experiments
Energy range	3-60 MeV/u	3-300 MeV/u
Ion No./laser shot	$>10^9$ *(10%BW)*	$>10^{10}$ *(10%BW)*
Bunch duration	1-10 ns	0.1-10 ns
Energy spread	±5%	±2.5%
Collimation Degree	±0.5°	± 0.2°
Ion Spot Size	0.1-10 mm	0.1-10 mm
Repetition rate	0.01-1 Hz	0.01-10 Hz
User Applications	Radiobiology, Neutron/Alpha source, PET, space-radiation, radiation chemistry, cultural heritage	Hadrontherapy

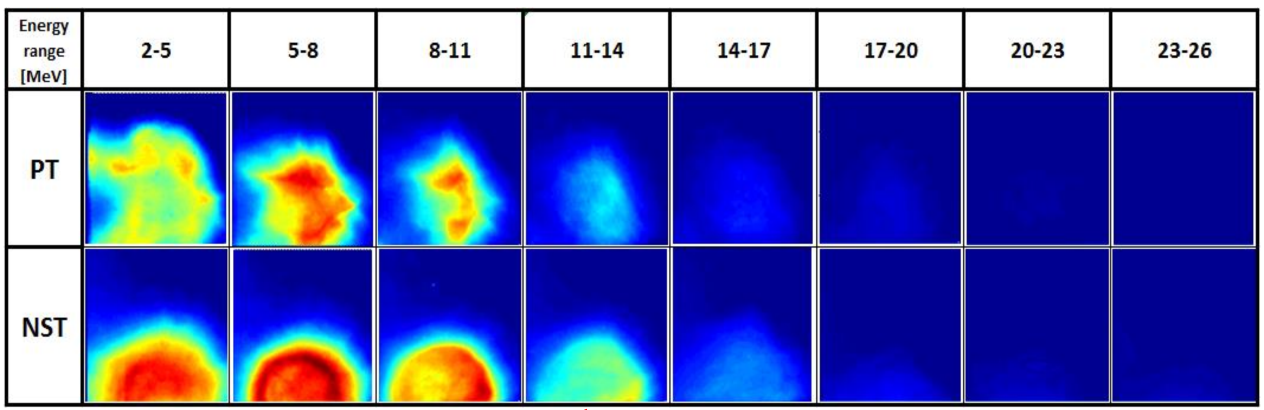
Ion Acceleration R&D (beam quality)

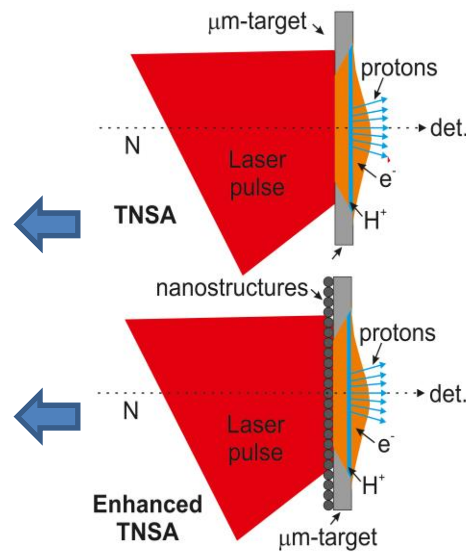


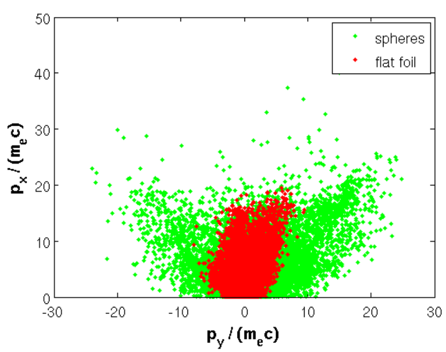
PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 071304 (2015)

Laser-driven high-energy proton beam with homogeneous spatial profile from a nanosphere target

D. Margarone,[1] I. J. Kim,[2,3] J. Psikal,[1,4] J. Kaufman,[1,4] T. Mocek,[5] I. W. Choi,[2,3] L. Stolcova,[1,4] J. Proska,[4] A. Choukourov,[1,6] I. Melnichuk,[6] O. Klimo,[1,4] J. Limpouch,[1,4] J. H. Sung,[2,3] S. K. Lee,[2,3] G. Korn,[1] and T. M. Jeong[2,3,*]

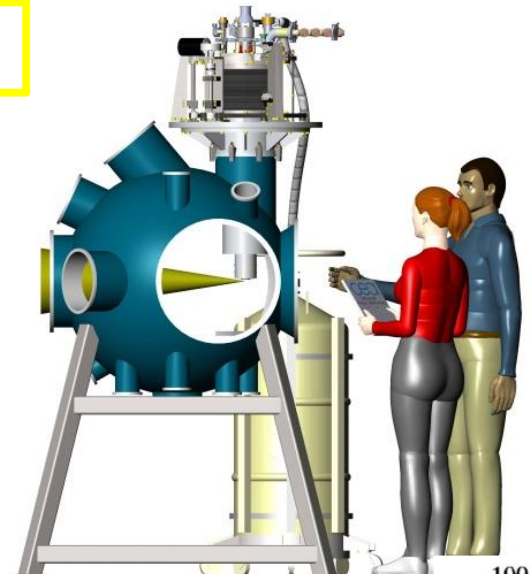




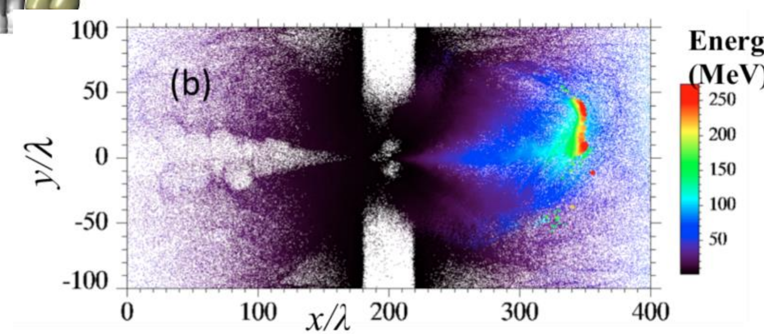


ELISE: p acc. from solid H ribbon

ELISE test-3 @ PALS (*August 2015*)
Margarone, Perin, Velyhan, Chatain et al.

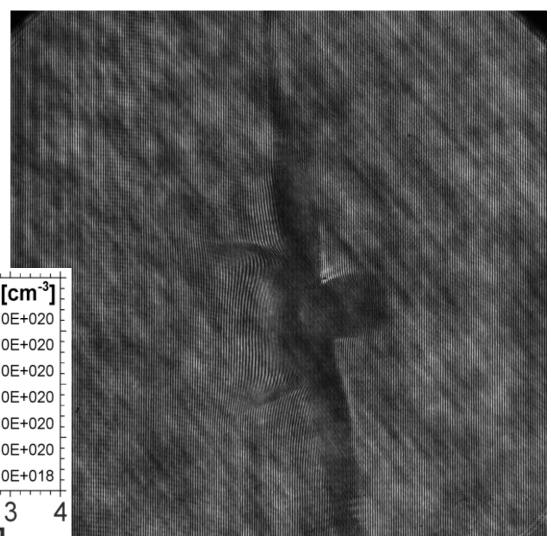


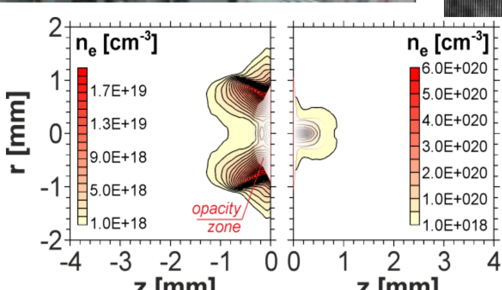
VULCAN: PW (600 fs), solid-H target (20 μm)



Courtesy of T. Esirkepov

Interferogram taken 3ns after the main pulse peak





ELISE exp.-4 @ PALS (Dec. *2015)*

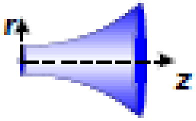
ELISE exp.-5 @ LFEX/RAL (*2016)*
Margarone, Borghesi, Esirkepov et al.
(proposal for VULCAN)

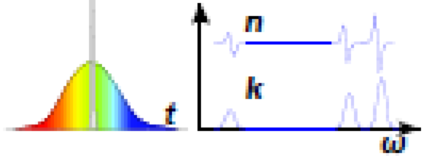
Subexawatt few-cycle lightwave generation via multipetawatt pulse compression

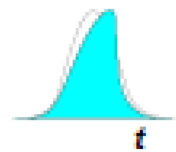
Numerical model

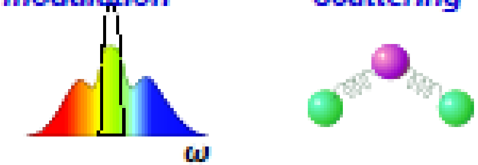
$$\frac{\partial}{\partial z}A = \frac{i}{2k(\omega)}\Delta_{\perp}A + i\left[k(\omega)-k(\omega_0)-\frac{\partial k}{\partial \omega}\bigg|_{\omega=\omega_0}(\omega-\omega_0)\right]A + \frac{i\omega^2 n_0 n_2}{c^2 k(\omega)}\hat{F}^{-1}\left[(1-f_R)I + f_R\int_{-\infty}^{t}R(t-t')I(z,r,t')\,dt'\right]$$

Diffraction — *Dispersion and linear loss* — *Self-steepening* — *Self-phase modulation* — *Raman scattering*





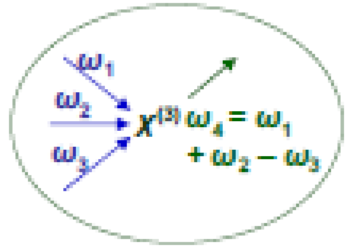




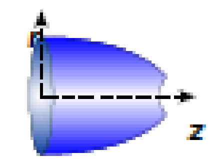
$$-\frac{\mu_0 \omega J(z,r,\omega)}{2k(\omega)} - \hat{F}^{-1}\left[\frac{(U_i+U_{pond})W(I)}{2I}A\right]$$

Plasma-current modulation — *Photoionization loss*

Four wave mixing

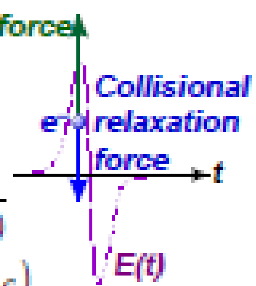


Self-focusing



$$\frac{\partial J(z,r,t)}{\partial t} + \nu_e J(z,r,t) = \frac{e^2}{m_e}\rho(z,r,t)E(z,r,t)$$

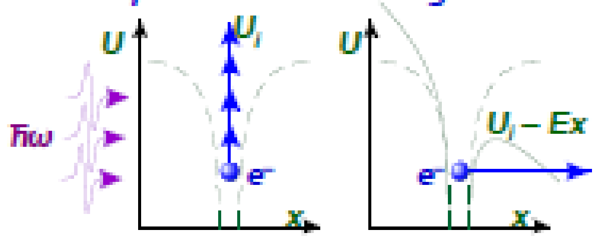
Equation of motion for an electron

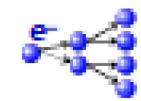


$$E(z,r,t)=\sqrt{\mu_0 c/(2n_0)}\times\left(A(z,r,t)e^{i(k_0 z-\omega_0 t)}+c.c.\right)$$

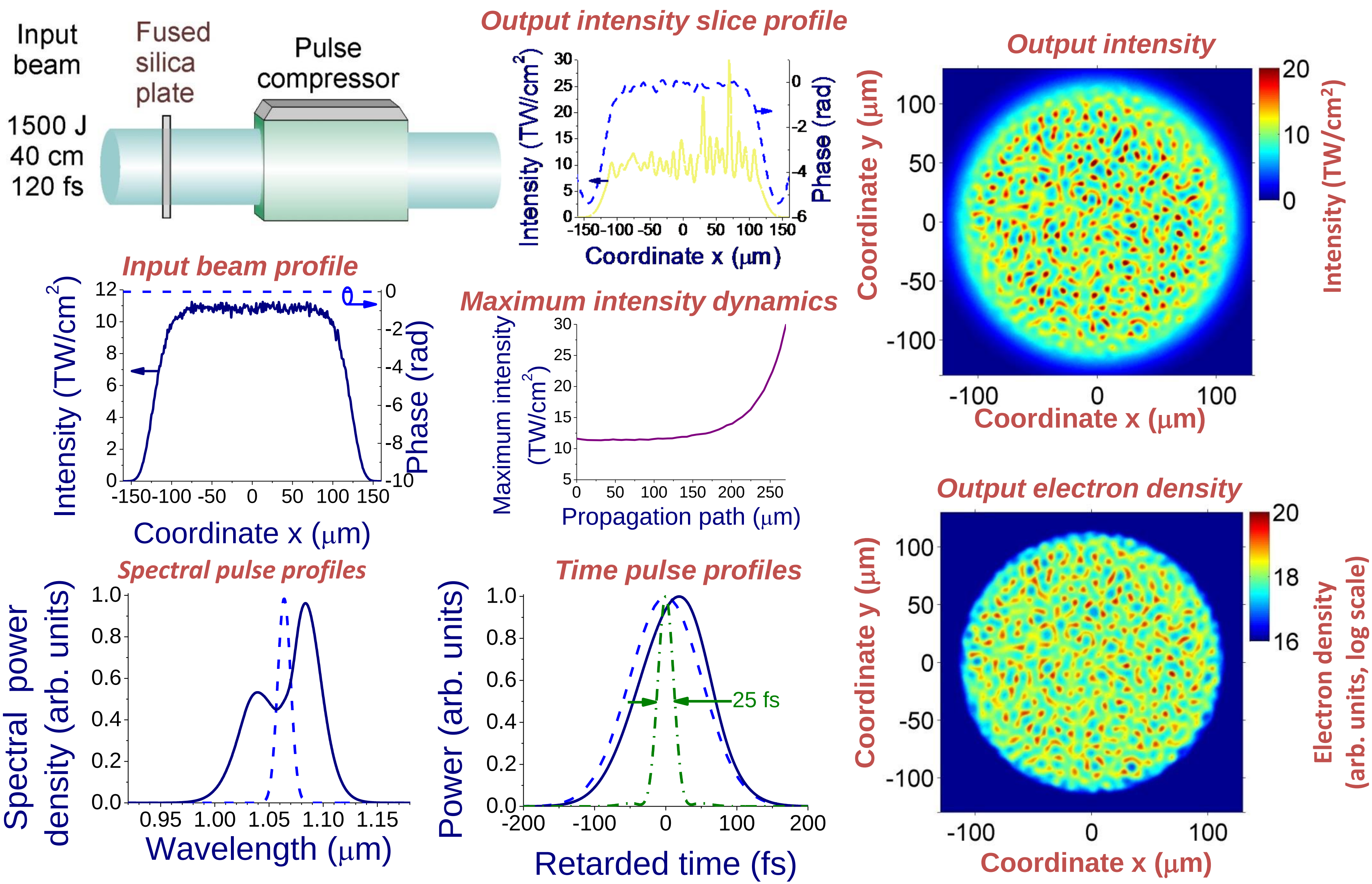
$$\frac{\partial \rho(z,r,t)}{\partial t} = W(I) + \frac{\sigma(\omega_0)}{(U_i+U_{pond})}\rho(z,r,t)I(z,r,t)$$

Multiphoton and tunneling ionization — *avalanche ionization*



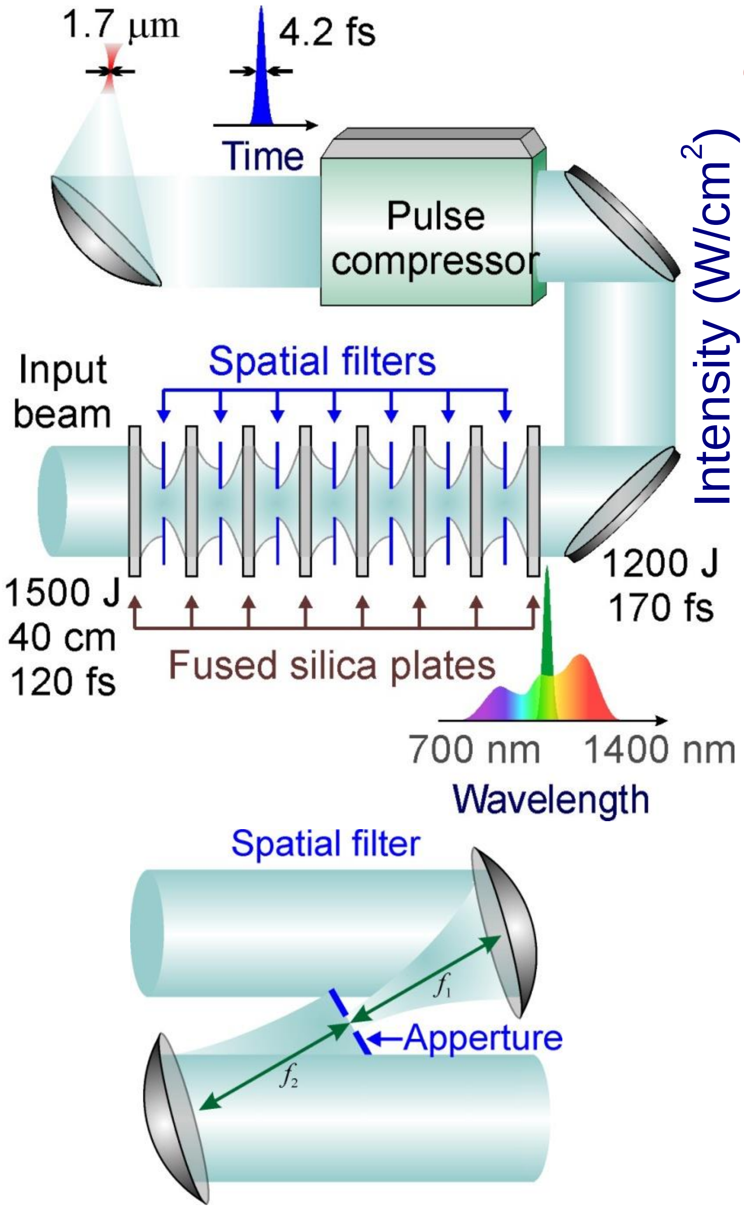


$$I(z,r,t)=|A(z,r,t)|^2$$

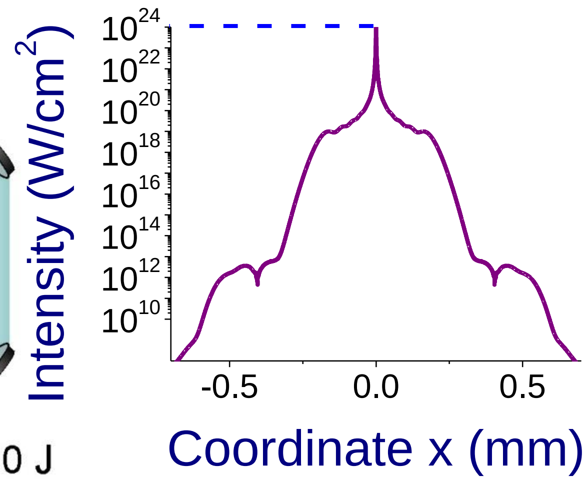


Input beam
1500 J
40 cm
120 fs
Fused silica plate
Pulse compressor
Output intensity slice profile
Intensity (TW/cm2)
Phase (rad)
Coordinate x (μm)
Output intensity
Coordinate y (μm)
Coordinate x (μm)
Intensity (TW/cm2)
Input beam profile
Intensity (TW/cm2)
Phase (rad)
Coordinate x (μm)
Maximum intensity dynamics
Maximum intensity (TW/cm2)
Propagation path (μm)
Output electron density
Coordinate y (μm)
Coordinate x (μm)
Electron density (arb. units, log scale)
Spectral pulse profiles
Spectral power density (arb. units)
Wavelength (μm)
Time pulse profiles
Power (arb. units)
25 fs
Retarded time (fs)

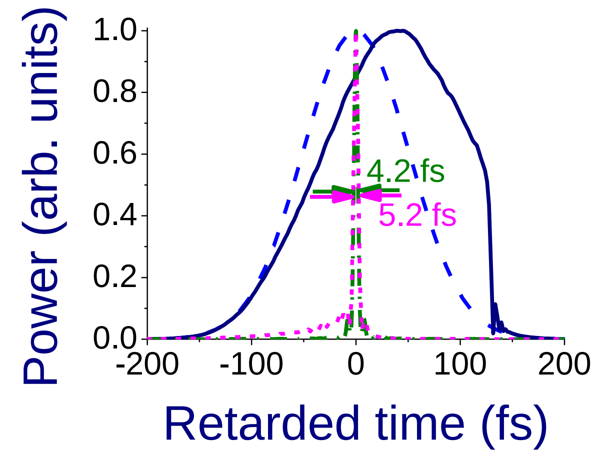
Subexawatt few-cycle lightwave generation via multipetawatt pulse compression,
OC 2012,



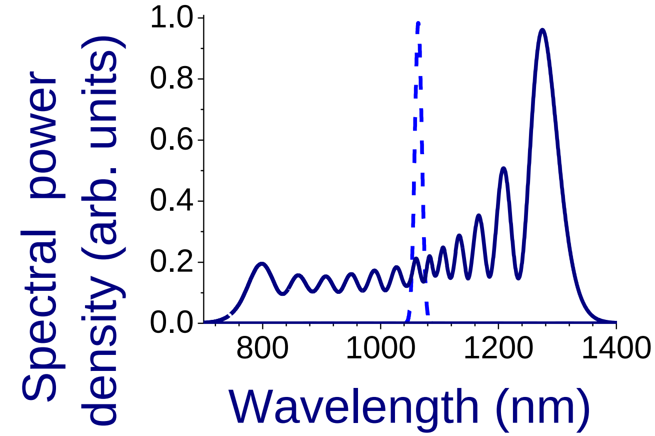
Output focused beam profile



Output time pulse profiles



Output spectral pulse profiles



Scaling shows
4GeV protons

eli beamlines

Timeline