EUROPEAN NETWORK FOR NOVEL ACCELERATORS
EuroNNAc4
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EuroNNAc Special Topics Workshop

Laser-plasma acceleration at ELI-Beamlines

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on behave of ELI-Beamlines

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ST-4:
Distributed Plasma Accelerator Landscape in Europe and Technical Progress towards Applications

This work is partially supported by the project Advanced research using high intensity laser produced photons and particles (CZ.02.1.01/0.0/16.019/0000789) from European Development Fund.

FZU Institute of Physics of the Czech Academy of Sciences
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Operational Programme Research, Development and Education
MINISTRY OF EDUCATION, YOUTH AND SPORTS

Content

- ELI-Beamlines (Institute of Physics, CAS): user-oriented facility
- Laser systems and laser beamlines at ELI-Beamlines
- Laser-plasma acceleration at ELI-Beamlines: current status

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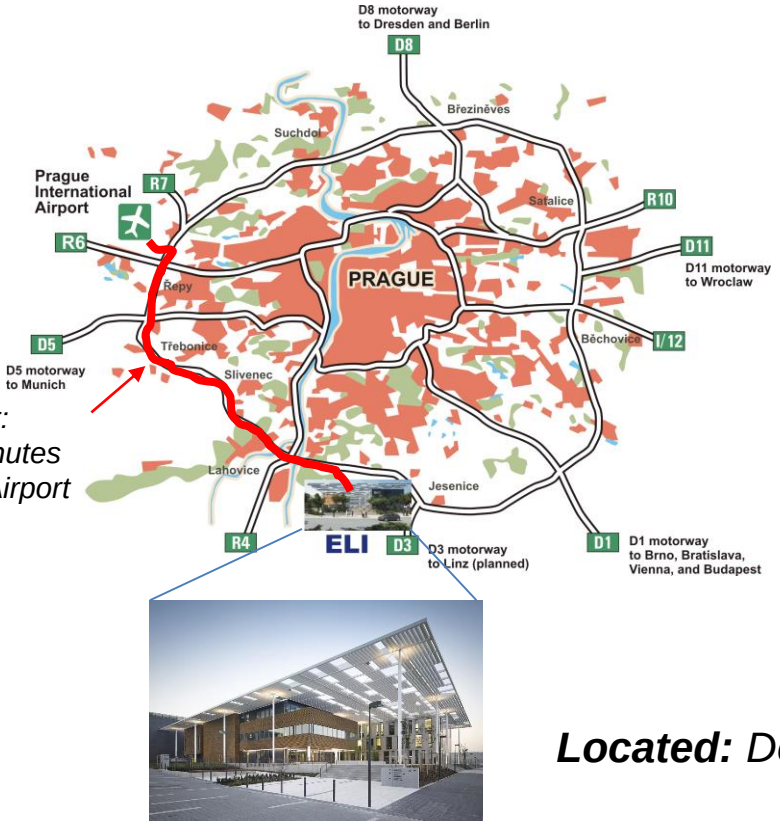
ELI-Beamlines on the Plasma Accelerator Landscape in Europe

The ELI Beamlines Facility (IoP) is a leading European laser research centre and part the pan-European Research Infrastructure to support scientific excellence in Europe.



By car:
25 minutes
from Airport

Bird-view on ELI-Beamlines

Located: *Dolni Brezany / near Prague, Czech Republic*

- ELI-Beamlines (IoP): user-oriented facility
- **Laser systems and laser beamlines at ELI-Beamlines**
- Laser-plasma acceleration at ELI-Beamlines: current status

ELI-BEAMLINES LASERS for Laser-plasma Acceleration

Synchronization within <100 fs by master facility clock

L1 – ALLEGRA

Technology
- OPCPA
- Circular
- Gaussian
- Synchronized probe beam

Parameters

Nominal	Current
100 mJ	55 mJ
1 kHz	1 kHz
15 fs	15 fs

Expected Electron / Ion Energy 100 MeV / 20 MeV

L2 – DUHA

Technology
- OPCPA
- Circular
- Flat-top
- Synchronized mid-IR pulse

Parameters

Nominal	Current
2J	WORK
25s Hz	IN
<40 fs	PROGRESS

Expected Electron / Ion Energy 1 GeV / 60 MeV

L3 – HAPLS

Technology
- Ti:Sapphire, DPSSL
- Square, 250x250 mm^2
- Flat-top

Parameters

Nominal	Current
30 J	13 J
10 Hz	3.3 Hz
30 fs	30 fs

Expected Electron / Ion Energy 10 GeV / 200 MeV

L4 – ATON

Technology
- Nd:glass
- Square, 550x550 mm^2
- Flat-top
- Longer beams (150 fs)

Parameters

Nominal	Current
1.5 kJ	WORK
3 min	IN
150 fs	PROGRESS

Expected Electron / Ion Energy 100 GeV / 600 MeV

L1-ALLEGRA laser system and laser beam transport at ELI-Beamlines

Optically synchronized 5 thin-disk commercial pump lasers

Total available pump power @515 nm: >370 W @ 1 kHz

7 OPCPA stages based on BBO and LBO crystals

Design: 100 mJ / <15 fsec (plan: end of 2023)

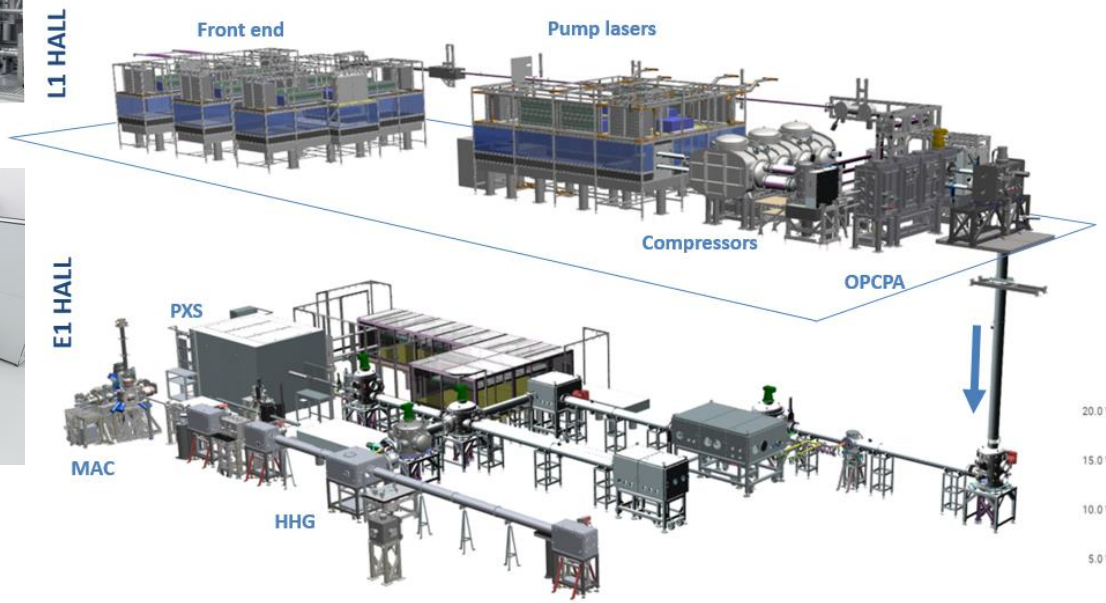
Current performance

>62 mJ OPCPA output (~16% pump-to-signal efficiency)

>55 mJ / 14.2 fs after compression

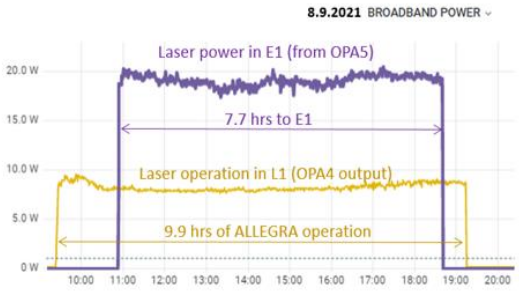
L1-to-E1 beam transport: ~ 10 m ➔ **READY**

Fully available



Routine user operation:
85 full experimental days in 2021

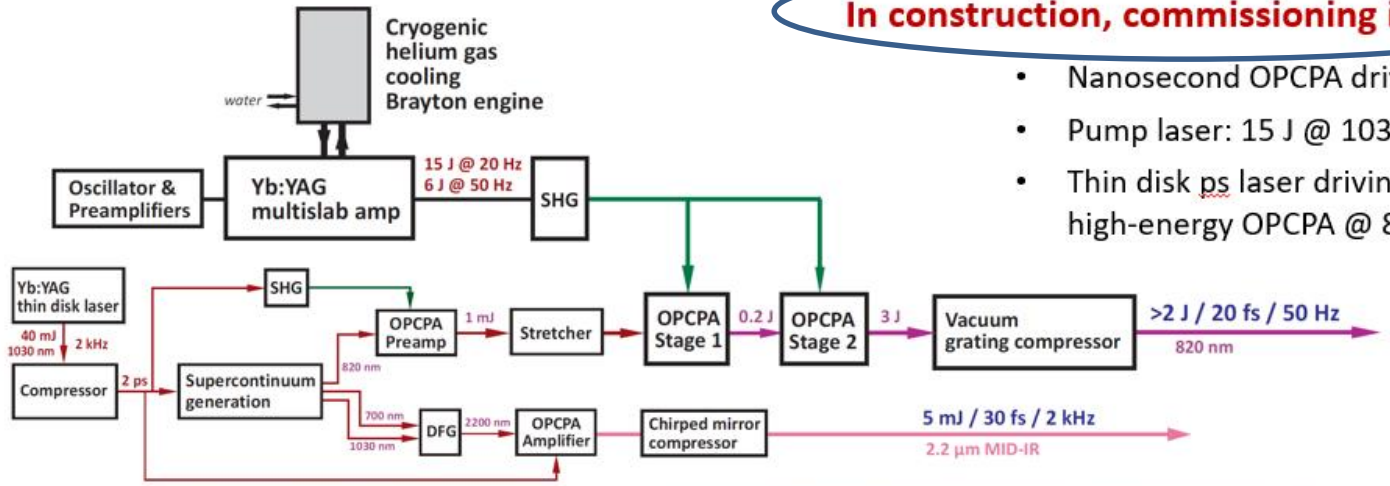
Typical operation day for experiments



Thanks to the L1-team / Pavel Bakule

L2-DUHA laser system and laser beam transport at ELI-Beamlines

L2 laser is the dedicated system for the E5-LUIS development (compact LPA-based FEL)

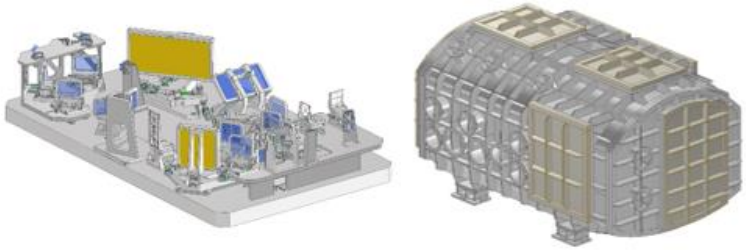


In construction, commissioning in 2024

- Nanosecond OPCPA driven by Yb:YAG diode-pumped laser
- Pump laser: 15 J @ 1030 nm
- Thin disk ps laser driving supercontinuum in bulk YAG: seed for high-energy OPCPA @ 820 nm & generation of 2.2 µm in DFG

Main 820-nm beam
3 J / 25 fs pulses @ 20 Hz → **5 J / 50 Hz**
expected availability in spring 2024

Upgrade & ramping to 50 Hz
proposed within the CREATE project

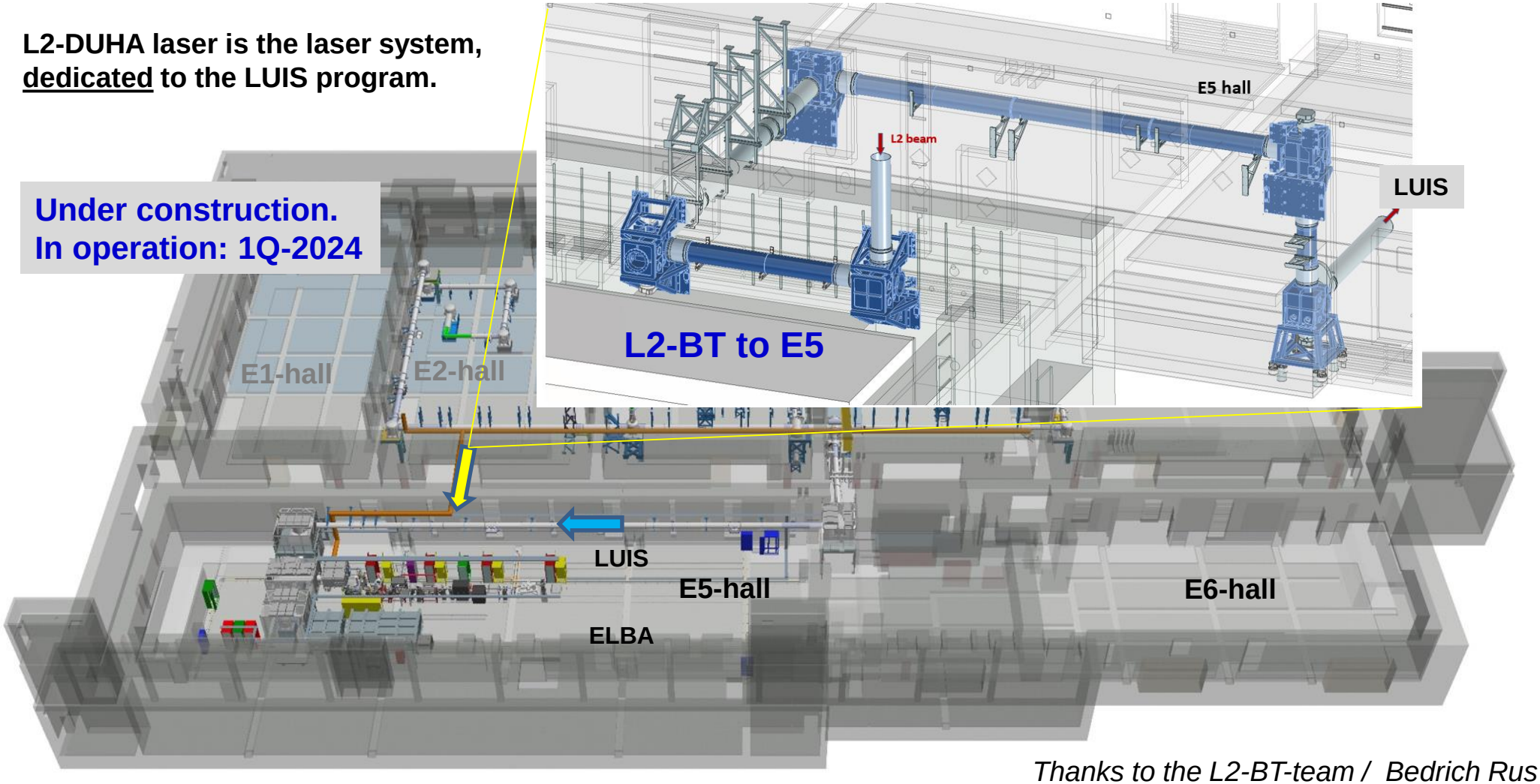


Thanks to the L2-team / Tyler Green

L2-DUHA laser system and laser beam transport at ELI-Beamlines

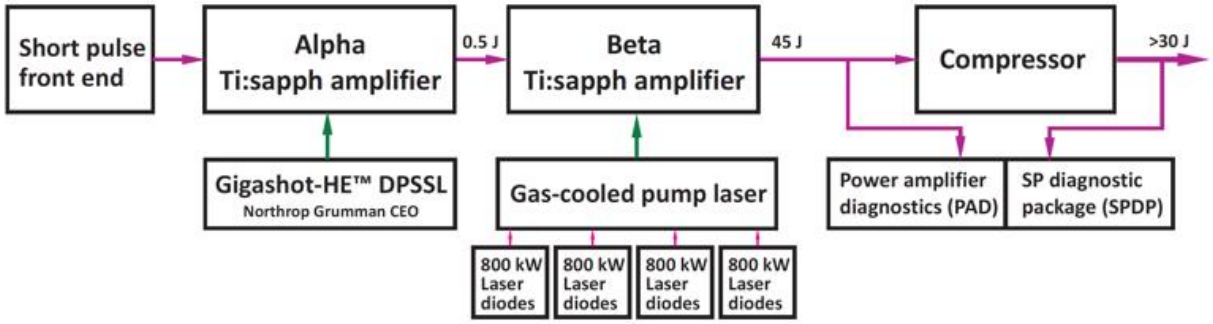
L2-DUHA laser is the laser system, dedicated to the LUIS program.

Under construction.
In operation: 1Q-2024



Thanks to the L2-BT-team / Bedrich Rus

L3-HAPLS laser system and laser beam transport at ELI-Beamlines

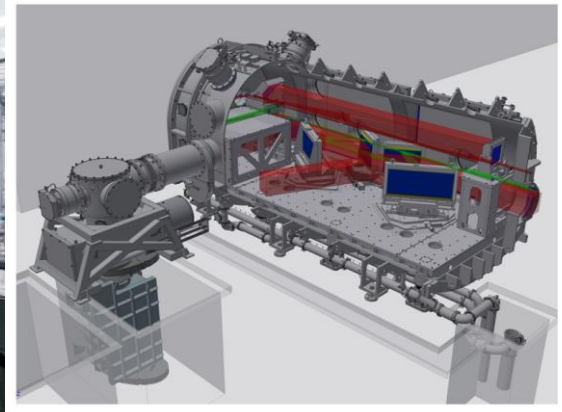


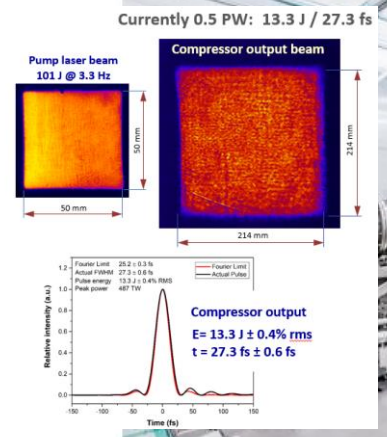
- Fully laser-diode-pumped laser
- Ti:sapphire short-pulse chain
- Advanced gas cooled power amplifiers

Design performance 1 PW / 10 Hz
>30 J / <30 fs

Current performance 0.5 PW / 3⅓ Hz
13.3 J / 27.3 fs

Performance ramping to design specs in progress





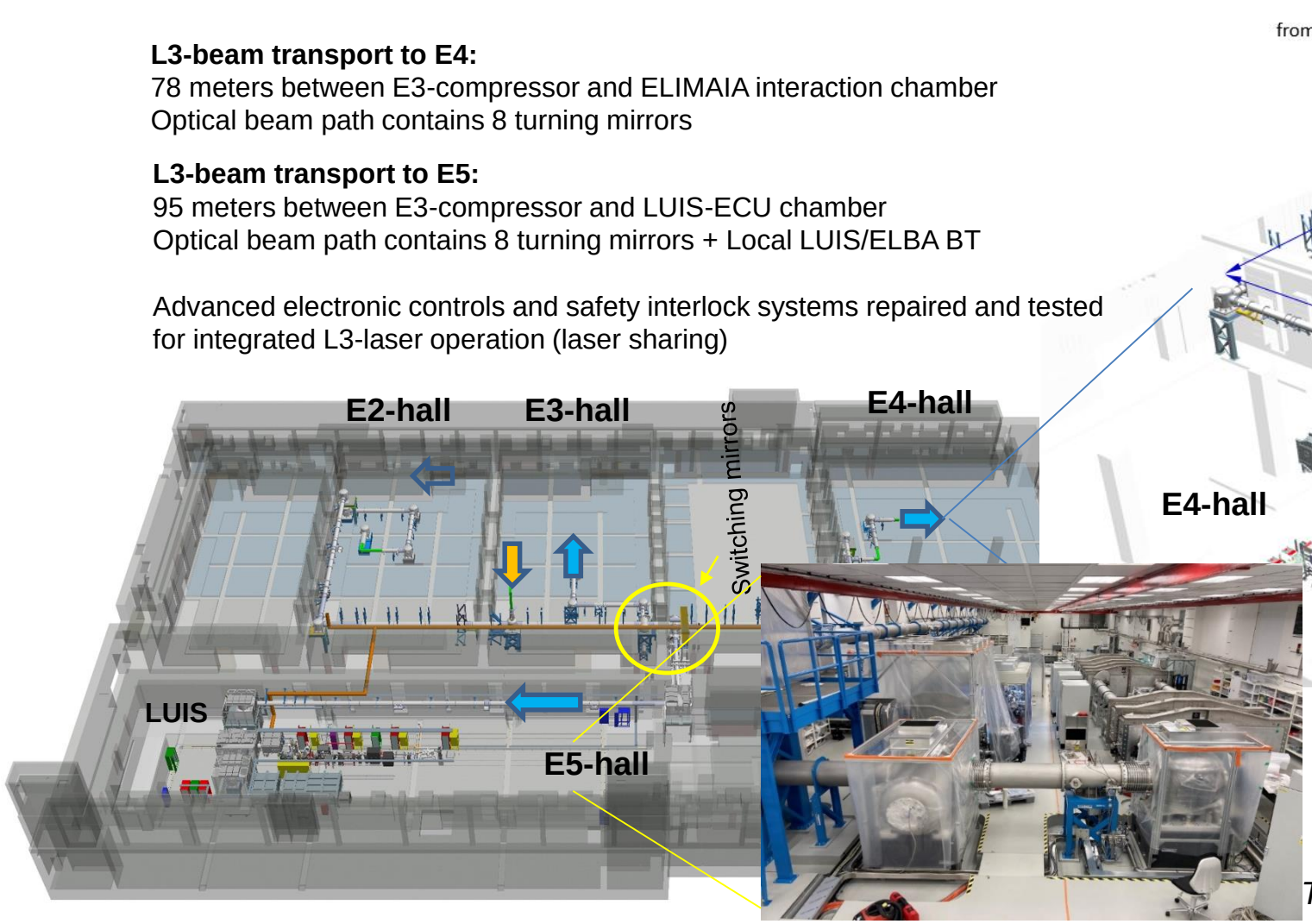
Thanks to the L3-team / Bedrich Rus

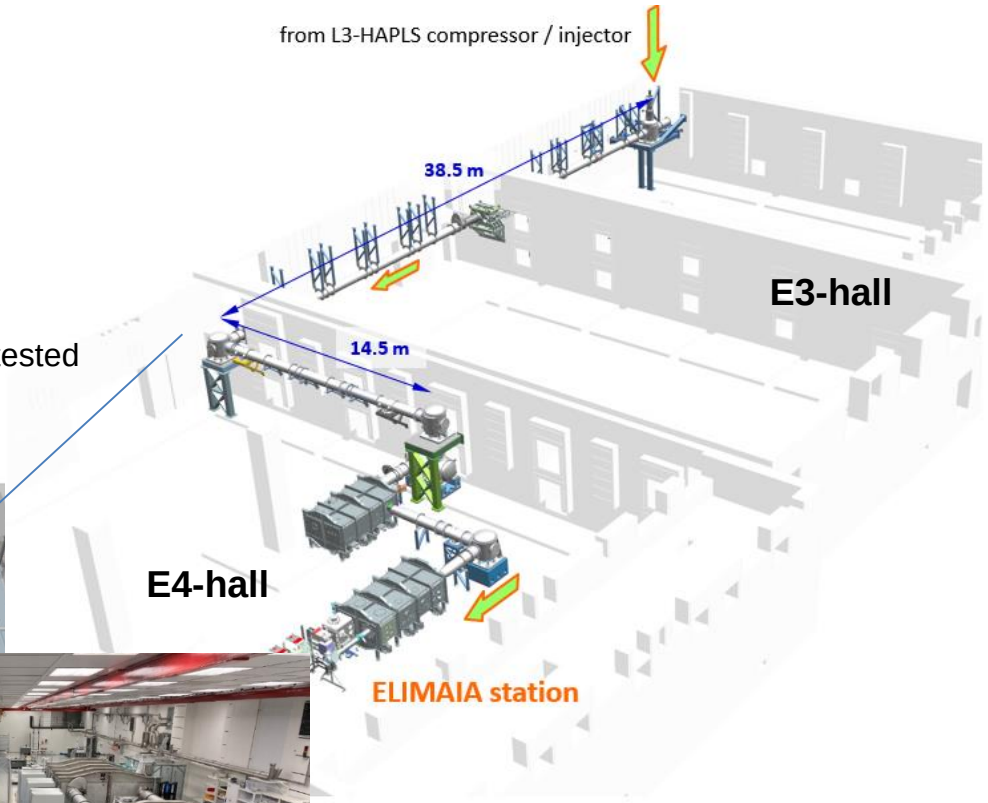
L3-HAPLS laser system and laser beam transport at ELI-Beamlines

L3-beam transport to E4:
78 meters between E3-compressor and ELIMAIA interaction chamber
Optical beam path contains 8 turning mirrors

L3-beam transport to E5:
95 meters between E3-compressor and LUIS-ECU chamber
Optical beam path contains 8 turning mirrors + Local LUIS/ELBA BT

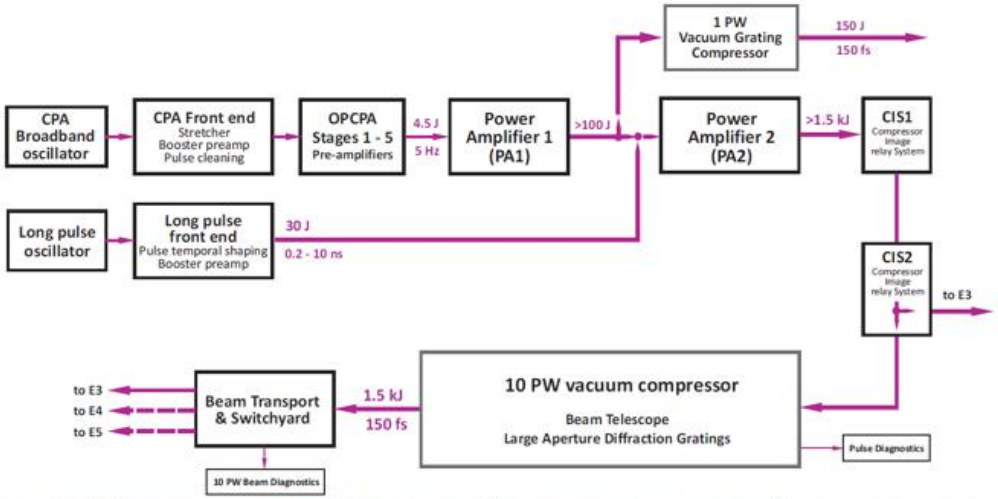
Advanced electronic controls and safety interlock systems repaired and tested for integrated L3-laser operation (laser sharing)





Thanks to the L3-BT-team / Bedrich Rus

L4-ATON: kJ CPA laser system to provide 10 PW peak power



Mixed Nd:glass providing spectral bandwidth >13 nm
Direct CPA pulse compression to ≤150 fs

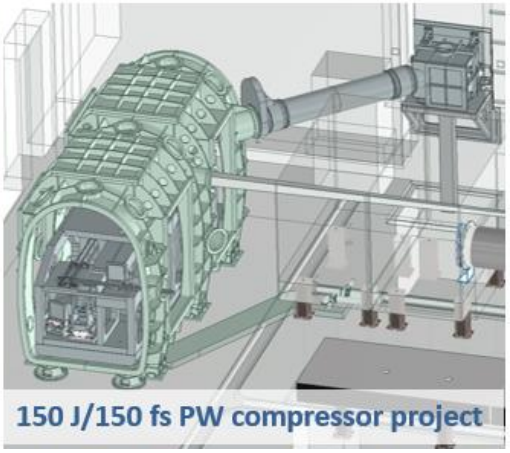
Advanced liquid cooling to ultimately achieve 1 shot /minute

Nanosecond kJ pulses with programmable temporal shape

10PW compressor in final phase of completion

Design performance:

10 PW capability	1.5 kJ / 150 fs / 1 shot per min
kJ ns pulse capability	1.5 kJ in 0.5 to 10 ns



Thanks to the L4-team / Bedrich Rus

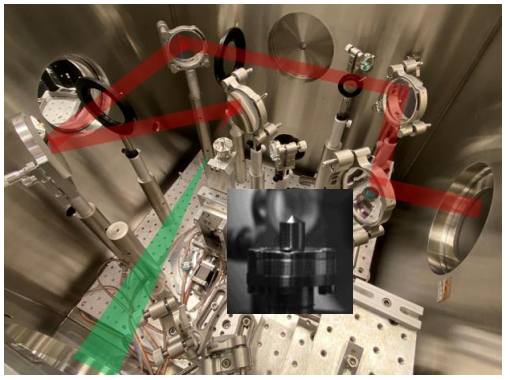
- ELI-Beamlines (IoP): user-oriented facility
- Laser systems and laser beamlines at ELI-Beamlines
- **Laser-plasma acceleration at ELI-Beamlines: current status**

Laser-plasma acceleration using the L1-ALLEGRA laser system /1

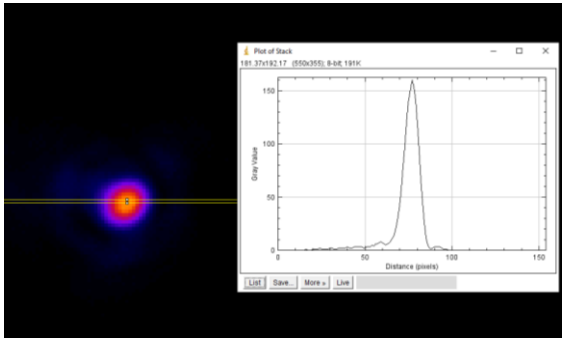
ALFA (Allegra Laser For Acceleration)

- Up to 55 mJ at moment (nominal plan 100 mJ)
- 1 kHz laser repetition rate
- Laser pointing stability 1-2 µrad
- 16 fs after compressor
- Laser focal spot size (FWHM) 3.6 µm
- Laser intensity 6.1×10^{18} W/cm^2 (~1.5$P_{critical}$)
- Normalized laser strength parameter a_0 ~ 1.7
- Laser-plasma interaction in the gas-jet

Setup with super-sonic nozzle



Laser focal spot



Thanks to the ALFA-team / Gabriele Grittani

Laser-plasma acceleration using the L1-ALLEGRA laser system /2

Manuscript is in preparation

Laser parameters on parabola (measured)

- Energy: 32 mJ
- Pulse duration: 16 fs
- Energy in the focal spot: 55%
- **Repetition rate: 1 kHz**

Measured electron beam parameters: Case (C)

Electron beam energy ~ 40 MeV
Estimated divergence FWHM ~ 5 mrad
FWHM average energy spread ~ 30%
Total charge ~ 10pC/pulse

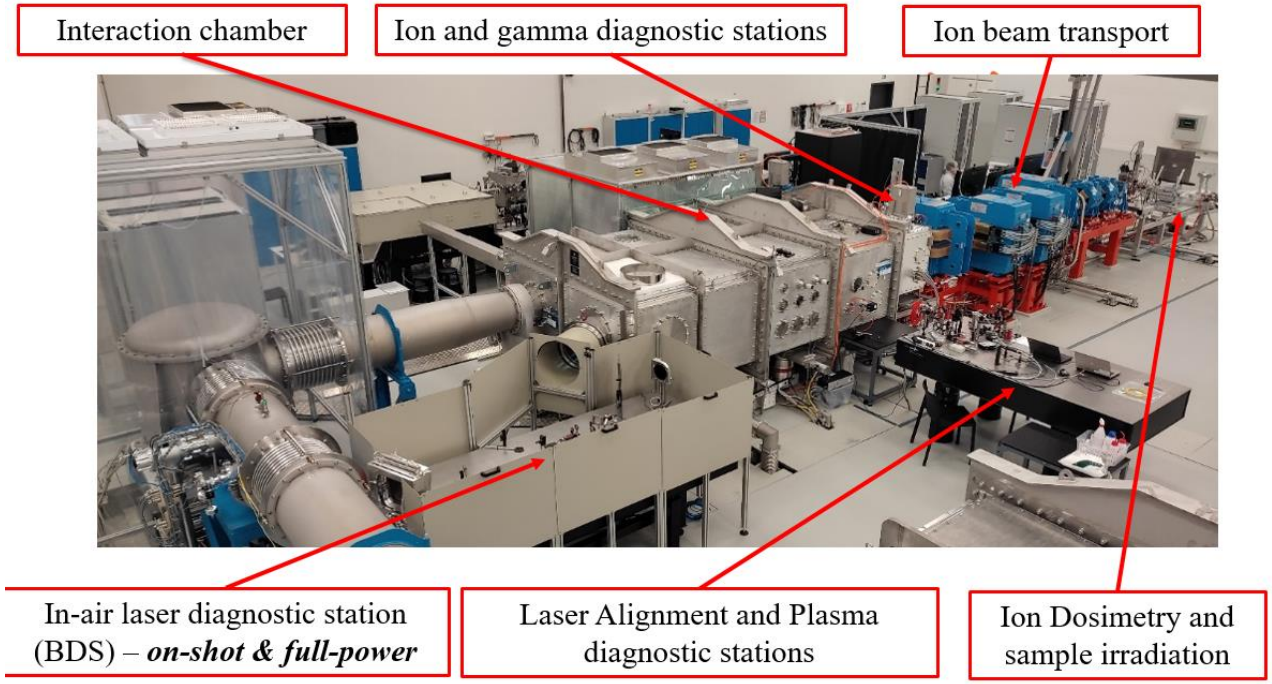
Plasma density measurement:
- Interferometry ± 30%

Possible injection mechanism: self-injection
PIC simulations – in progress

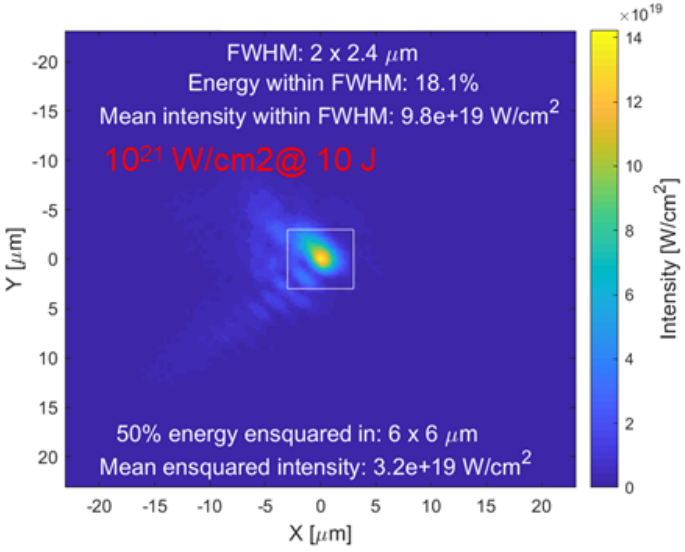
Thanks to the ALFA-team / Gabriele Grittani

Laser-plasma acceleration using the L3-HAPLS laser system /1

Laser-proton acceleration (**ELIMAIA / E4-Hall**) → Basic commissioning of Ion Accelerator



- Thin foil target (Al) … thickness = 5 μm
- Laser Intensity ~ 10^{21} W/cm^2
- Focal spot (FWHM) ~ 4.8 μm (f#3 OAP)
- Laser contrast ~ 1.4×10^{-9} (Dec.2021)

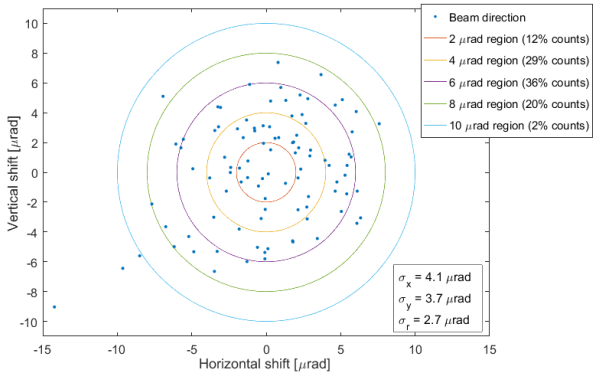


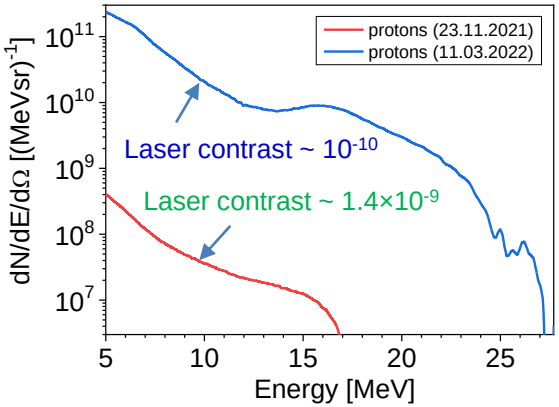
Thanks to the ELIMAIA-team / Lorenzo Giuffrida

ELIMAIA commissioning using L3-**10J** laser

Laser-plasma acceleration using the L3-HAPLS laser system /2

Laser-proton acceleration (**ELIMAIA / E4-Hall**) → Basic commissioning of Ion Accelerator





Excellent pointing stability of the integrated system <u>at full-power</u>:
L3-laser + Laser-Beam-Transport (~ 80m) + Target-Station

→ 2.7 μrad at full power (10J-level) over 54 min of continuous operation (1Hz)
→ Corresponds to shot-to-shot linear shift on ELIMAIA-target ~ 1μm

		Campaign: Dec.2021	
Laser energy	Joules	9.95 ± 0.025	→ ± 0.3 %
Laser intensity (FWHM)	10^{21} W/cm^2	1.39 ± 0.01	→ ± 0.8 %
Electron temperature T_{hot}	MeV	3.06 ± 0.12	→ ± 3.9 %
Maximum proton energy	MeV	14.48 ± 0.17	→ ± 1.2 %
Proton flux (> 3 MeV)	sr^{-1}	(6.1 ± 0.03)×10^{10}	→ ± 5.3 %
Pointing stability	μrad	2.7 (RMS)	

Thanks to the ELIMAIA-team / Lorenzo Giuffrida

ELIMAIA commissioning using L3-**10J** laser

Laser-plasma acceleration using the L3-HAPLS laser system /3

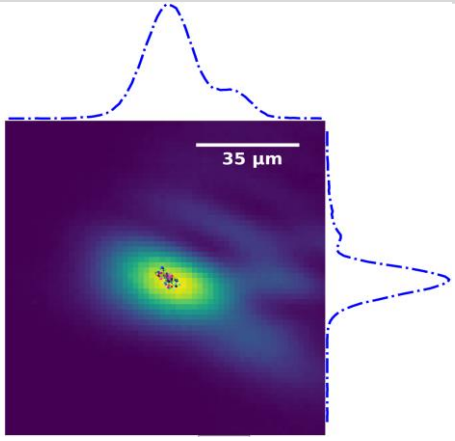
E5-LUIS (Phase0): high quality laser-driven electron accelerator for incoherent photon undulator radiation → pre-commissioning results (L3 low-energy operation / mJ / 30fsec / 3Hz)

Thanks to the LUIS-team / A.Molodozhentsev

MAIN results of the 1st experimental campaign (1-week: May 2022)

- Final verification of all technologies (control system, vacuum, safety)
- Final alignment of all components of the L3-to-E5/LUIS beam transport (5+4=9 flat mirrors + 2 switching mirrors + 1 OAP)
- Target: gas-cell
- Sapphire capillary gas-loading verification with Differential Pumping
- **Focal spot measurement (FWHM) ~ 25 µm**
- **Measured laser pointing stability → RMS ~ 1.5 µrad**
- Switching mirror test

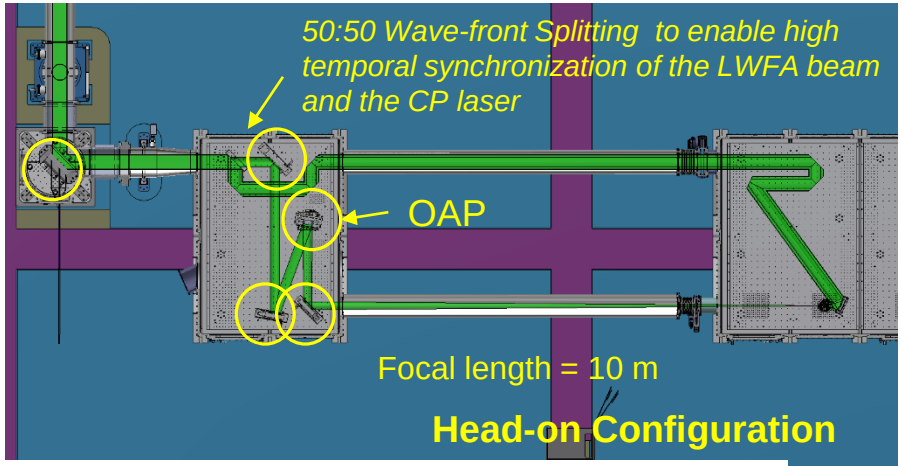
L3 laser (low-energy) beam in focus (May 2022) with the pointing stability



LUIS-Phase0 setup is ready for LPA-commissioning (4Q-2022)

Laser-plasma acceleration using the L3-HAPLS laser system /4

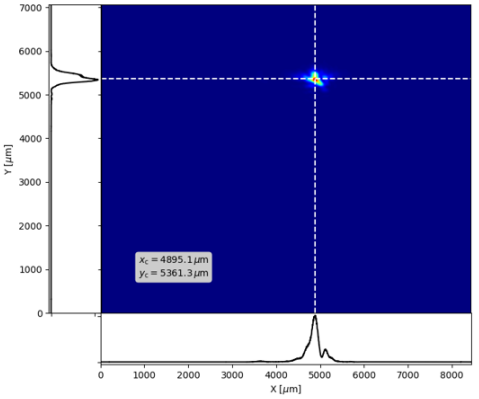
E5-ELBA: all-optical GeV electron beam collider with PW laser

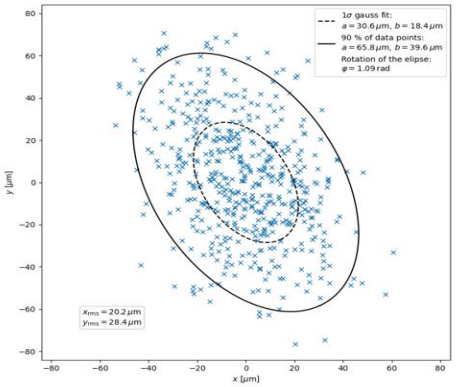


	Parameter	Current L3 Performance	Nominal L3 performance
LASER	Laser energy before WS splitting	13 J	30 J
	Laser time duration	27 fs	30 fs
	Repetition Rate	3.3 Hz	10 Hz
	Laser Wavelength	800 nm	800 nm
ELECTRON	Laser Energy for LWFA	> 5 J	> 10 J
	Electron beam energy (mean of QME peak)	> 1 GeV	> 2 GeV
	Energy spread (FWHM)	< 20%	< 20%
	Electron beam charge in QME peak	> 25 pC	> 40 pC
	Electron beam divergence	< 2 mrad	< 2 mrad
	Electron beam pointing stability	< 2 mrad	< 2 mrad
CP LASER	Laser Energy for Collider Laser	> 5 J	> 10 J
	Focal number	1.5	1.5
	Focal length	375 mm	375 mm
	Focal spot FWHM	< 2 µm	< 2 µm
	Peak intensity	> 1.5 x 10^{21} W/cm^2	>3 x 10^{21} W/cm^2
	Collision angle	0° and 40°	0° and 40°

Thanks to the ELBA-team / Gabriele Grittani

Pre-commissioning results (L3 “mJ” operation / May 2022)

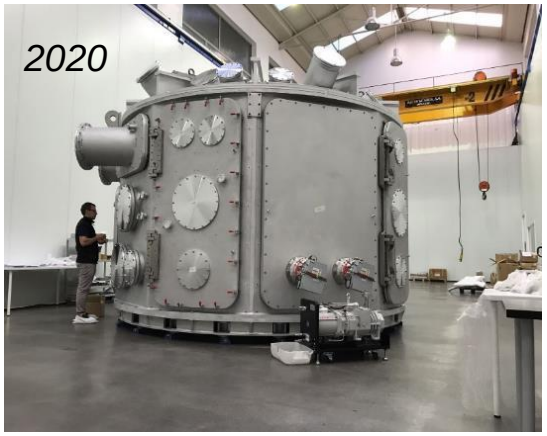


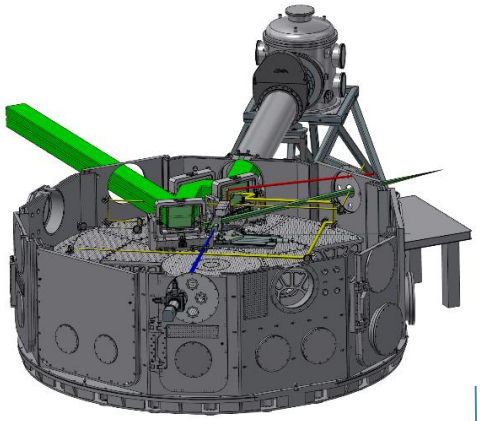


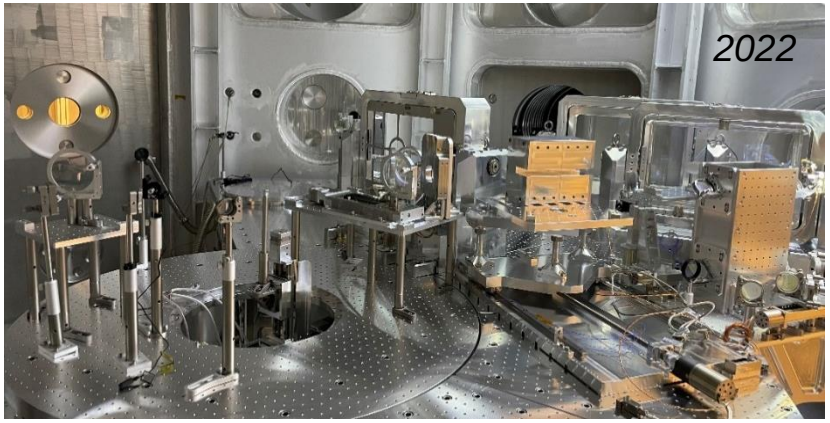
Measured laser pointing stability (RMS) ~ 2÷3 µrad
Measured laser spot size in focus (FWHM) ~ 150 µm

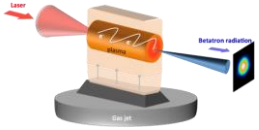
Laser-plasma acceleration using the L3-HAPLS laser system /5

E3-BETATRON: betatron radiation setup / gas-jet → Experimental Campaign: Plan → Nov-2022









Electron beam energy	MeV	500 ÷ 1000
Plasma density	10^{18} cm^{-3}	~ 10
Laser pulse energy	Joules	10 (30)
Laser pulse duration	fsec	30
Normalized vector field amplitude (a_0)		~ 2.5
Focal spot size (FWHM)	μm	~ 30 (f#25)
Expected betatron parameters		
Betatron source size	μm	~ 5 μm
Broadband critical energy	keV	20 ÷ 50
Number of Photons / shot		10^9 - 10^{10}
Photon beam divergence	mrad	< 20

Thanks to the BETATRON-team / U.Chaulagain

A **very big thank** you to colleagues who sent me slides, photos and thoughts including:

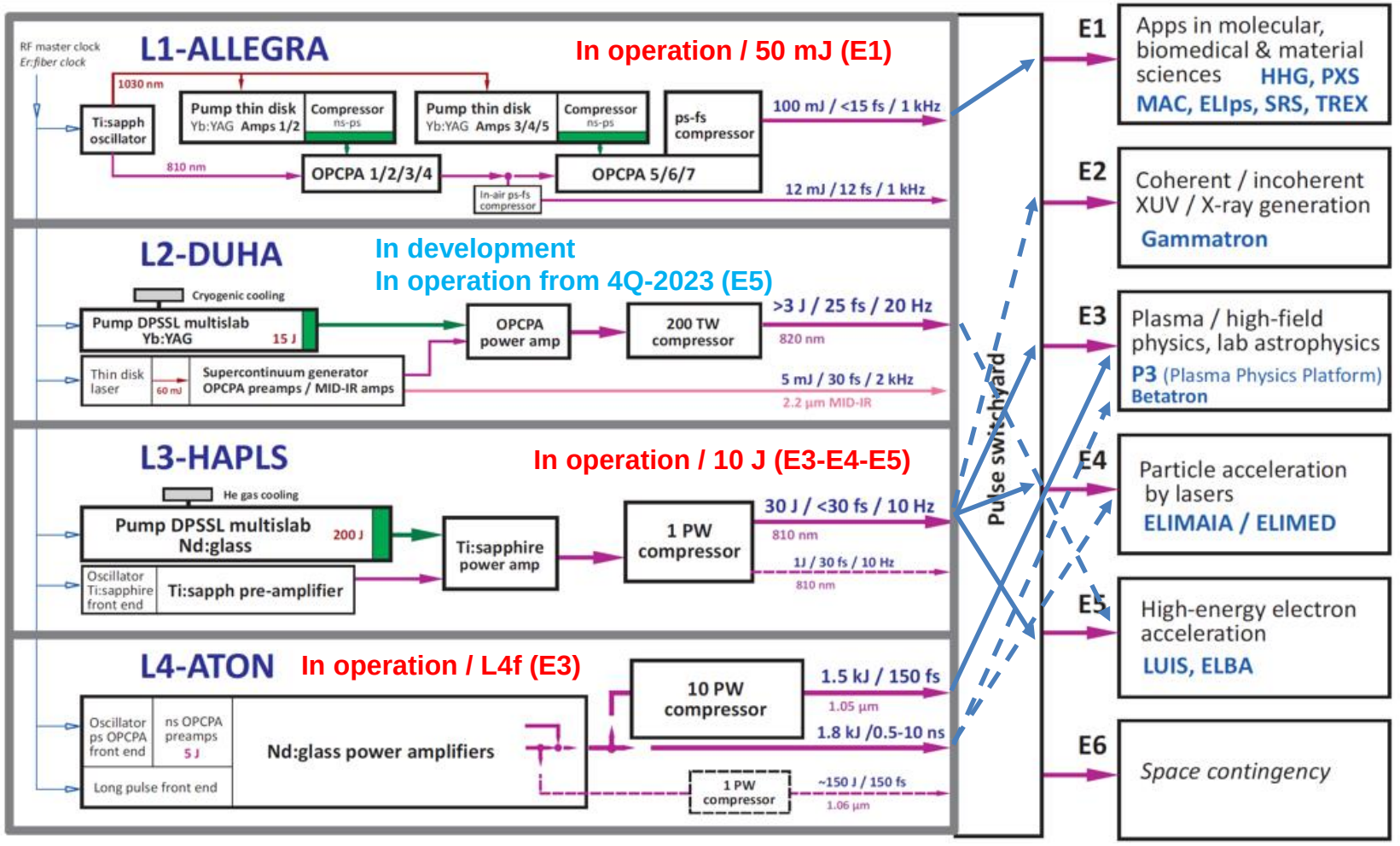
… in alphabetic order …

Bedrich Rus
Daniele Margarone
Gabriele Grittani
Jaroslav Nejdl
Lorenzo Giuffrida
Pavel Bakule
Tyler Green
Stefan Weber
Uddhab Chaulagain

Thanks you for your attention !

Laser systems at ELI-Beamlines (overview)

Experimental halls



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