DEVELOPMENT OF LASER-DRIVEN PLASMA ACCELERATOR BASED UNDULATOR RADIATION SOURCE AT ELI-BEAMLINES

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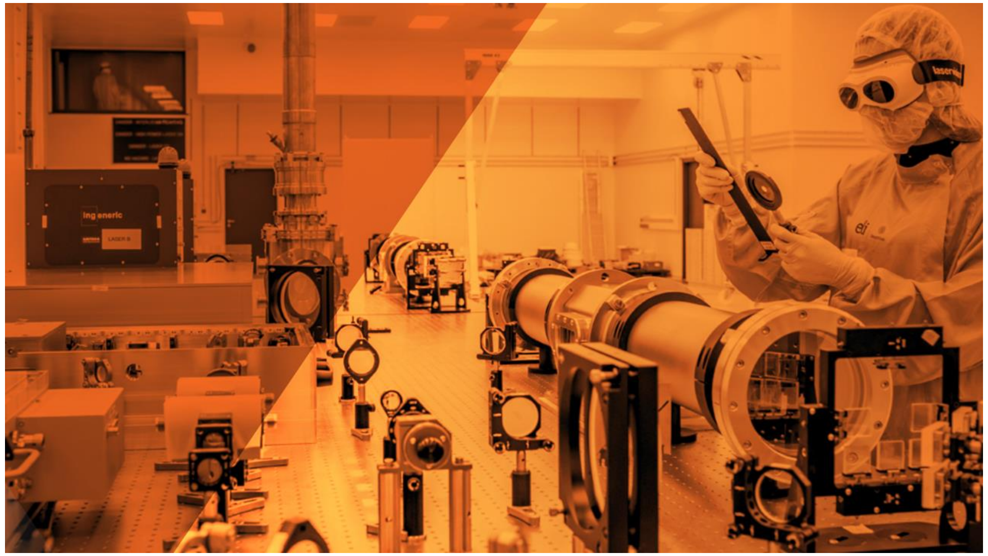

European Research Infrastructure Consortium / ERIC

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- Laser development at ELI-Beamlines
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- LPA-based Incoherent Undulator Radiation Source
- LPA-based Coherent Radiation Source

Work supported by the project "Advanced Research using High Intensity Laser produced Photons and Particles" (ADONIS) from European Regional Development Fund (CZ.02.1.01/0.0/0.0/16019/0000789)

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○ **ELI-Beamlines (ELI-ERIC)** and LUIS Project: main objectives

Multisite Infrastructure

ELI is on the European Roadmap since 2006!

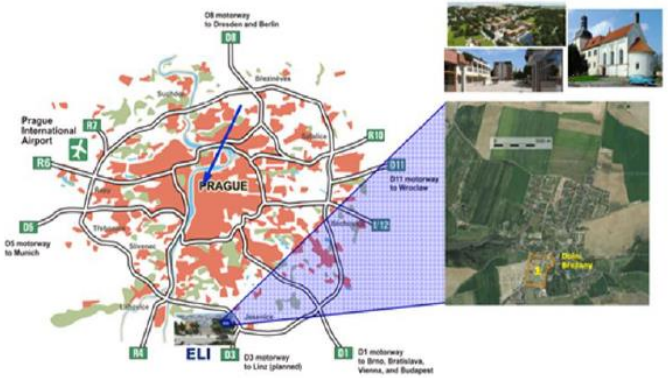
Investment has driven leadership in laser and photonics

Projected total peak power for high power laser systems operational and under construction is by far world-leading

ELI Facilities are introducing 3 @10PW and 6 @PW-class lasers,

Total investment ca 1 Billion EURO

○ **ELI-Beamlines (ELI-ERIC)** and LUIS Project: main objectives



eli | beamlines

ELI Beamlines explores the interaction of light with matter at intensities 10 times higher than previously achievable.

4 PW class laser systems, 4 support lasers

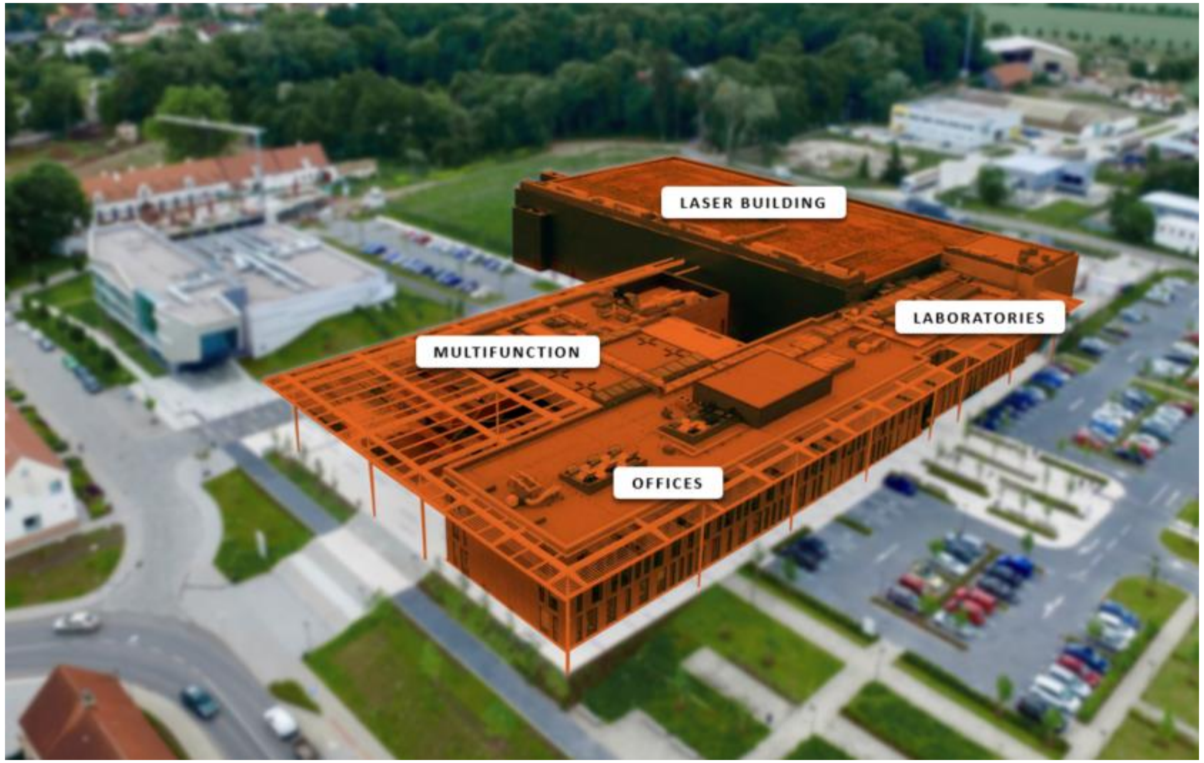
7 Secondary sources – EUV - X-rays, Electron and Ion Accelerators

10 User stations

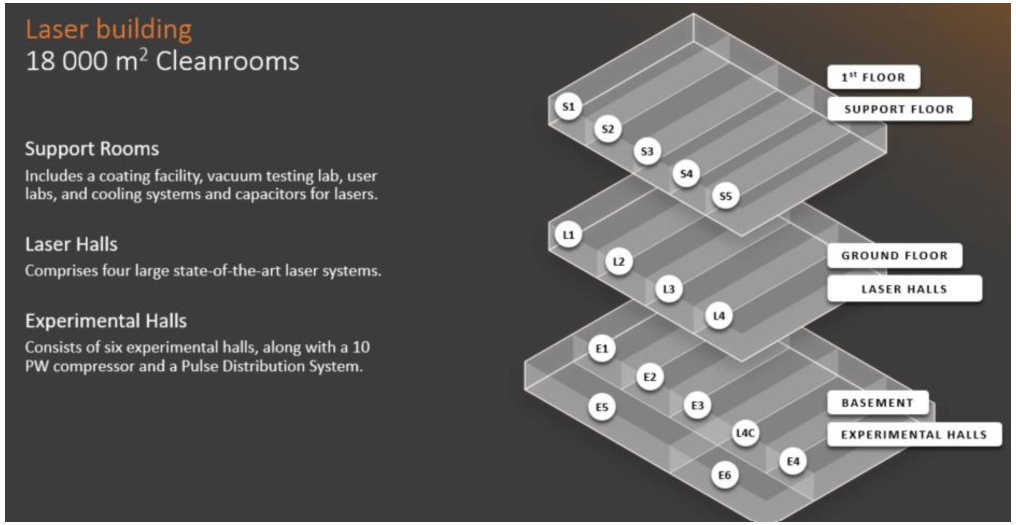
- 350 international staff
- Area 31,000 m2

- Structural Dynamics
- Particle Acceleration and Applications
- HED Physics and ICF
- High Field Physics

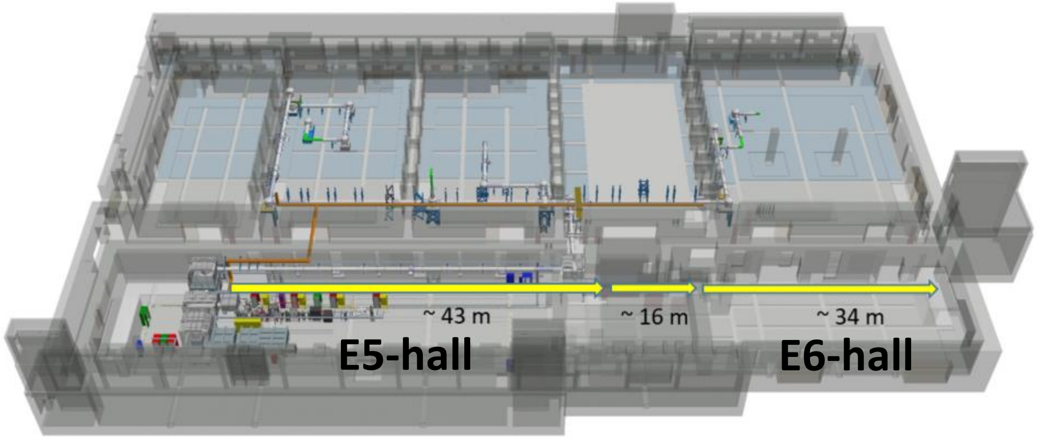
○ **ELI-Beamlines (ELI-ERIC)** and LUIS Project: main objectives



ELI-Beamlines facility (near Prague)



Experimental Halls

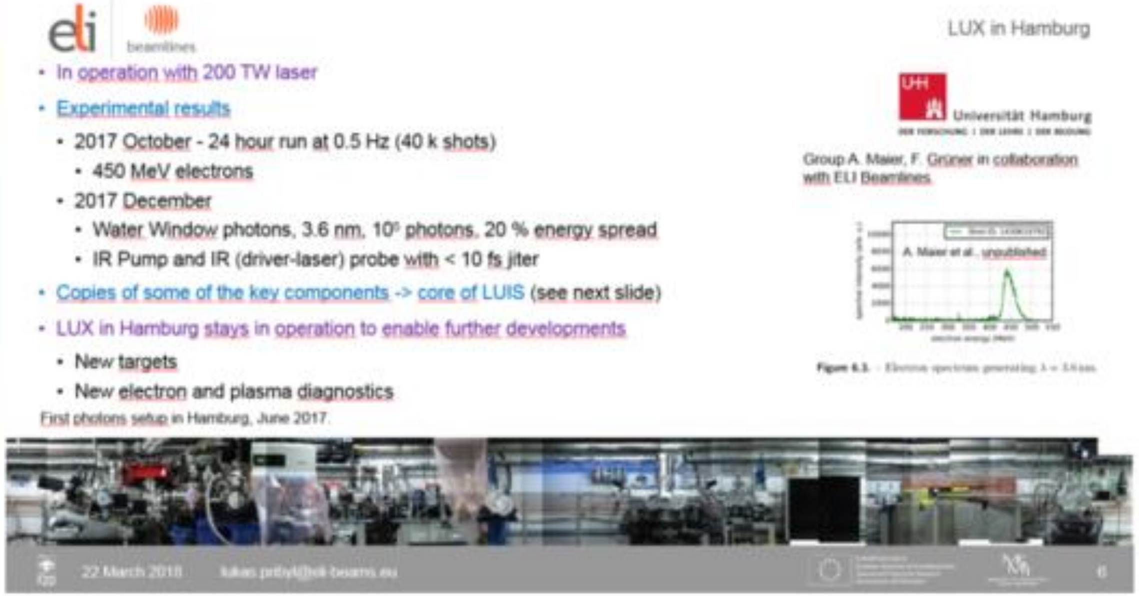


○ ELI-Beamlines (ELI-ERIC) and **LUIS Project: main objectives**

LUIS at ELI-Beamlines → LWFA-based undulator incoherent/coherent photon radiation source
→ based on the LUX development at DESY (UHH/ELI-Beamlines)
→ based on a novel high-repetition rate high-power laser system (L2-DUHA)

LUX team:
UHH-CFEL and ELI-Beamlines

Achievement: incoherent photon radiation



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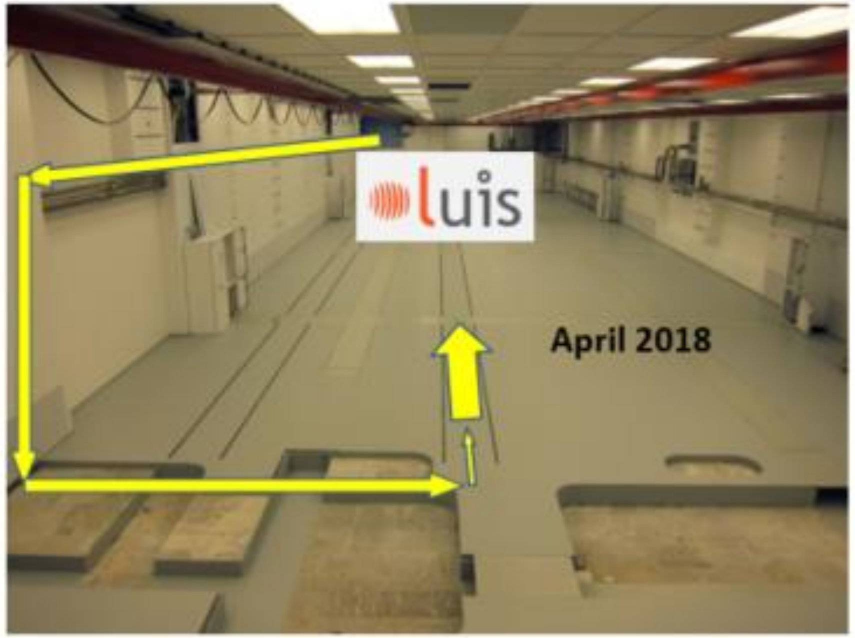
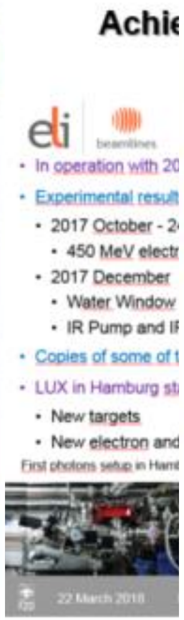
E5-Hall at ELI-Beamlines





○ Laser development at ELI-Beamlines

Parameters	Primary Acceptance Criteria	Design Requirement
Maximum pulse energy after compression, focused in the capillary	2 J	5 J
Minimum pulse energy after compression, focused in the capillary	0.5 J	0.5 J
Pulse energy variation	0.2 J	0.1 J
Pulse duration FWHM [1] (after compression)	30 ÷ 40 fs	30 ÷ 40 fs
Pulse duration adjustment	2 fs	1 fs
Maximum peak power (after compression), focused in the capillary	53 (30fs) TW 40 (40fs) TW	158 (30fs) TW 118 (40fs) TW
Minimum peak power after compression, focused in the capillary	13 (30fs) TW 10 (40fs) TW	15.8 (30fs) TW 11.8 (40fs) TW
Repetition rate	1 Hz	3.33 Hz (10-25-50 Hz)
Beam format [2]	Circular / 8th order SG	Circular / 8th order SG
Laser spot size (FWHM) on the off-axis parabola (focal length ~ 2 m)	80 mm	80 mm
Central wavelength	820 nm	820 nm
Beam quality (encircled energy in diffraction limited spot) [3]	0.80	0.95
Output relative pulse energy RMS stability	2.5 %	< 1%
Output beam RMS pointing stability	< 2 μrad	< 1 μrad

Main laser parameters, required for the LUIS development

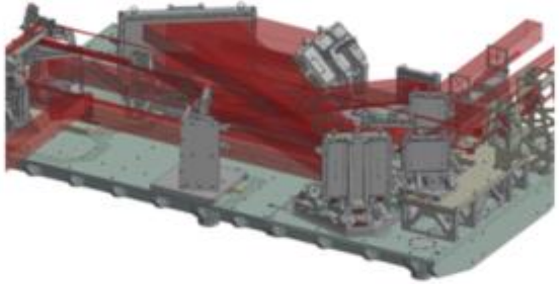
Main expected electron beam parameters

Electron beam parameters from the LPA-source	Units	Commissioning stage	User-operation stage
Energy	*MeV*	300 ÷ 600	300 ÷ 600
RMS energy spread	%	< 5	< 1 → 0.5
Energy fluctuation (shot-to-shot)	%	< 5	< 1
Bunch charge	*pC*	~ 100	~ 50
Bunch charge fluctuation (shot-to-shot)	%	< 20	< 5 → 1
RMS transverse beam divergence	*mrad*	< 5	< 1 → 0.5
RMS norm. transverse emittance	*π mm.mrad*	< 2	< 1 → 0.2
Bunch duration (FWHM)	*fsec*	< 5	< 2

LUIS technologies installed in E5

○ Laser development at ELI-Beamlines

L2-DUHA laser system (in collaboration with STFC/UK)



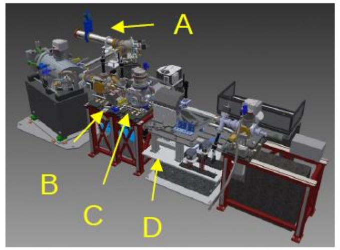
- Cryogenic helium-cooled pump laser using diode-pumped Yb:YAG slabs
- Designed for 50 Hz operation, currently at 20 Hz due to pump laser diodes
- Incorporates an OPCPA short-pulse chain
- Output pulses of 3 J with a duration of 25 fs
- Serves as the driver for a laser-driven XFEL testbed station
- Offers an auxiliary MID-IR (2.2 µm) beam
- Currently in the final phase of integration and testing
- Compressed pulses expected to be available in 2024

Credit: Bedrich Rus

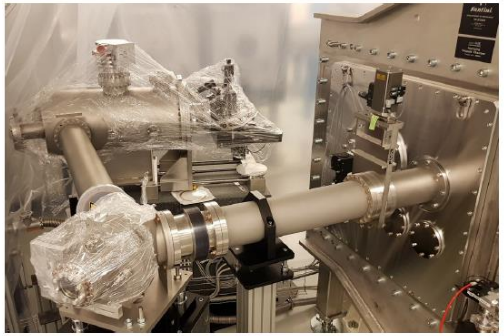
○ Laser-Plasma electron Accelerator

LUIS target chamber

Key technologies of LUIS-PHASE0



(A) LUIS laser local beam transport



(C) Target chamber

(D) Laser and e-beam diagnostics

Sapphire capillary
- ○ Gas-cell (~ 2 cm)
- ○ Option: Preformed plasma channel

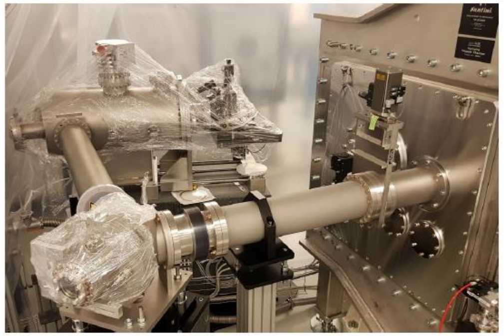
All technologies are fully integrated and tested in the E5-hall including support/safety subsystems (vacuum/gas, MSS, PSI, central control system)

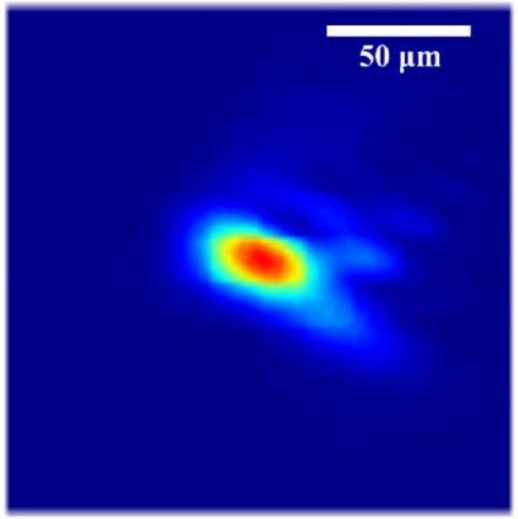
○ Laser-Plasma electron Accelerator

LUIS target chamber

Key technologies of LU

(A) LUIS laser local beam transport





Measurements: L3-laser "TERESA"-size beam ("low-power" mode) in focus. The laser spot size in the focus is about 30 µm at FWHM for the LUIS setup after the 1st attempt to minimize coma and astigmatism.

All technologies are fully
support/safety subsysten

Sapphire capillary

- ○ Gas-cell (~ 2 cm)
- ○ Option: Preformed plasma channel

○ Laser-Plasma electron Accelerator

PIC modeling of the laser-plasma interaction and electron beam acceleration
Motivation: high-quality high-energy electron beam, suitable for LPA-based FEL

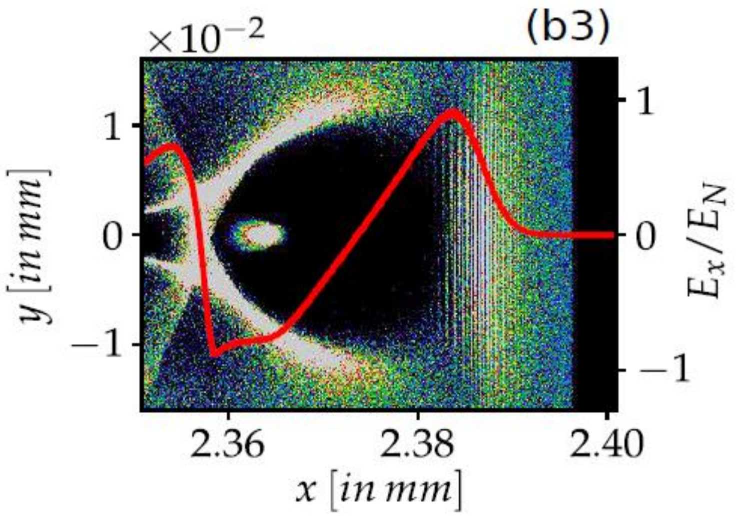
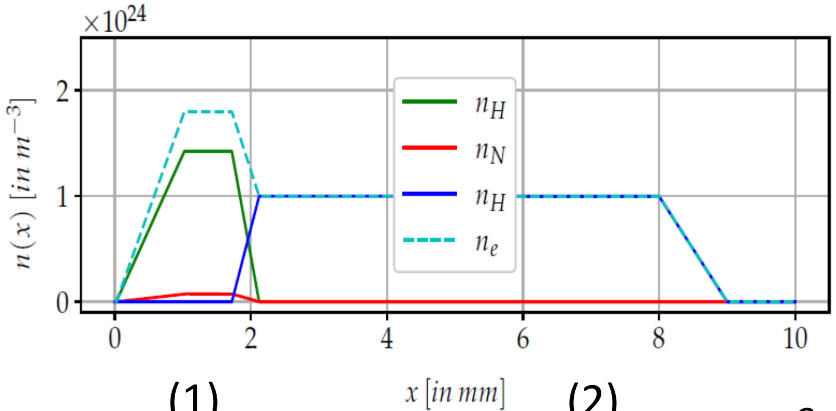


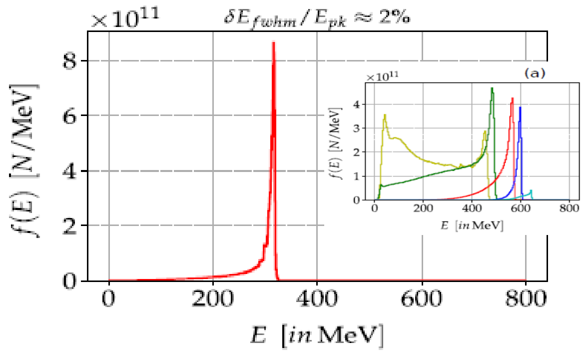
Table: Simulation Parameters ($I_0 = 1.0 \times 10^{19}$ W/cm^2; $P_L = 51$ TW)

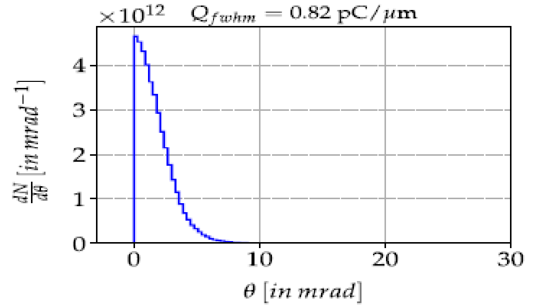
Wavelength (λ_L)	Spot size (w_{fwhm})	Pulse duration (τ_{fwhm})	I_0 (W/cm^2)
0.8 μm	30 μm	30 fs	1.0×10^{19}
Laser frequency (ω_L)	Laser energy (E_L)	a_0	Power (P_L)
2.35×10^{15} Hz	1.53 J	2.16	51×10^{12} W
Hydrogen density in platua (n_p)	Net mixed density (n_m)	Percentage of mixer	ω_L/ω_p
$(1.0 - 1.5) \times 10^{18}$ cm^{-3}	$(1.5 - 2.0) \times 10^{18}$ cm^{-3}	95% + 5% of n_m	33



(1) (2)

Credit: *S.Maity*





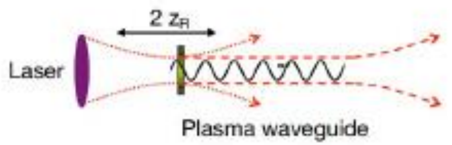
Staging approach in the gas-cell
(1) Self-truncated injection
(2) Acceleration

Energy ~ 300 (up to 600) MeV
Spread (FWHM) ~ 2%
Divergence (FWHM) ~ 2 mrad
Bunch charge ~ 15 pC

○ Laser-Plasma electron Accelerator

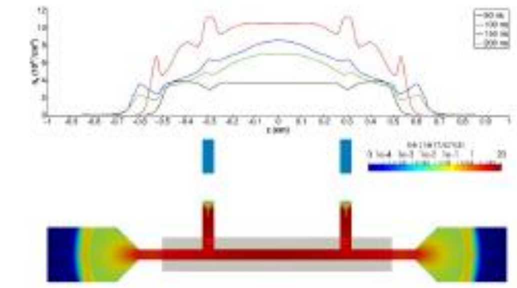
Test setup in LUIS-Lab: discharge in the Sapphire capillary

Plasma sources as waveguides

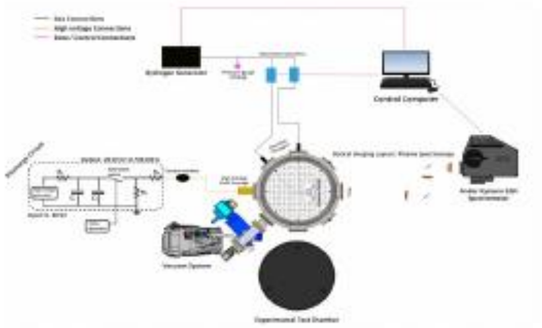


Advantages:

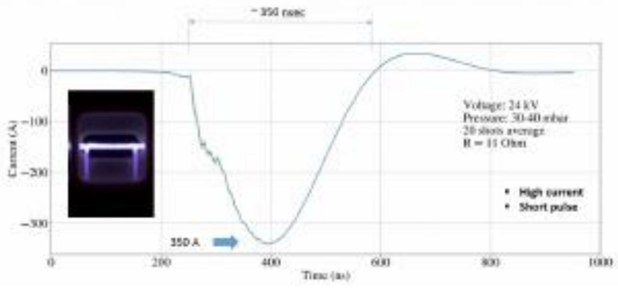
- overcome the diffraction limit
- increasing the LWFA acceleration length
- reduce required laser pulse energy
- use high repetition rate of the laser
- improve stability of LWFA using capillary
- active plasma lens with the magnetic field gradient ~ 400 T/m



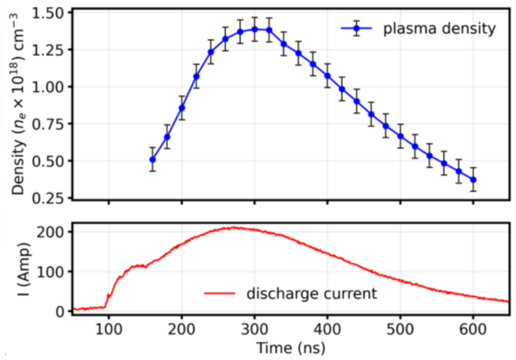
Modelling of the discharge plasma formation in the capillary (ELI-BL/KIAM collaboration)



Plasma diagnostics setup in the LUIS-Lab, using the emission spectroscopy



Plasma channel in the Sapphire capillary, created at ELI-Beamlines



Ref. Phys. Rev. Res. 4, 013063 (2022) by G. A. Bagdasarov et. al.

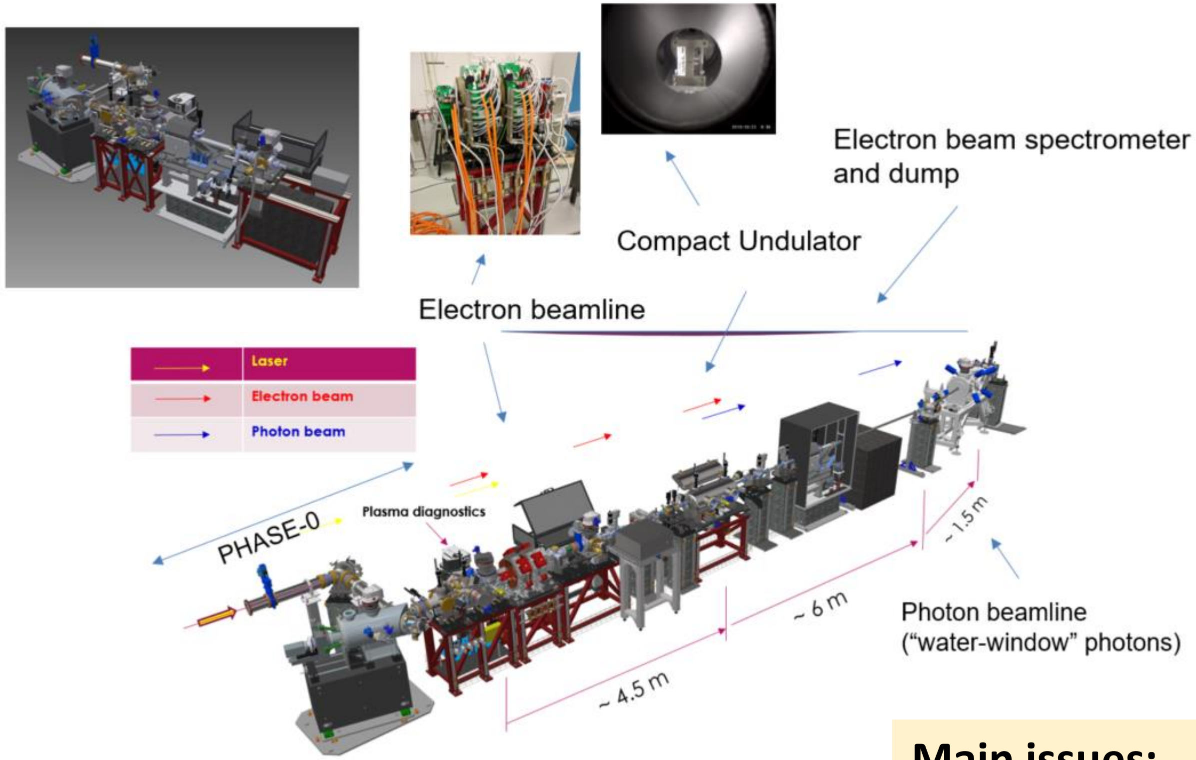
Credit: A.Mondal

○ LPA-based Incoherent Undulator Radiation Source

PHASE-0
Q4-2023

⇩

PHASE-1
2024



Undulator parameters

Undulator period	mm	5
Number of period		100
Total length	mm	500
On-axis magnetic field	T	0.6
K-value		0.28

➡ **LUX – collaboration**

Photon beam parameters (PHASE#1) / Estimation

		W_e = 300 MeV / Q_b=30pC	W_e = 600 MeV / Q_b=30pC
Photon energy (1st harmonic)	eV	165	658
Photon wavelength (1st harmonic)	nm	7.5	1.8
Number of photons (0.1%bw)		1.7×10^5	7.1×10^6
Peak Brilliance (at peak current of electron bunch)	*	4.8×10^{20}	1.9×10^{21}
Effective beam size and divergence of the photon beam (1st harmonic)			
Σx,y	µm	114	114
Σx′,y′	mrad	0.087	0.043

* photon/sec/mrad²/mm²/0.1%bw

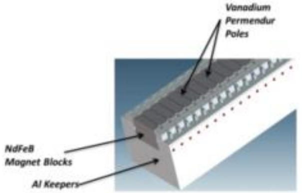
Main issues:
- High repetition rate (from 25 Hz up to 50 Hz), utilizing the L2-DUHA laser
- Stable and repeatable operation
- Improvement of the LPA-based electron beam quality
- Electron @ Photon beam diagnostics

○ LPA-based Coherent Undulator Radiation Source

UNDULATOR

'In-vacuum' hybrid PM planar
→ SwissFEL type ("Aramis" line)

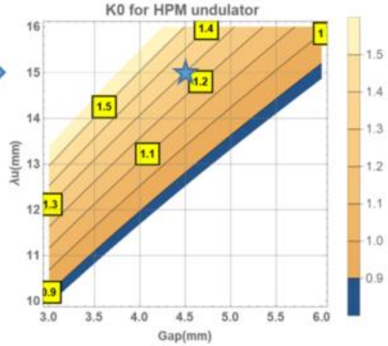
λ_u = 15 mm
Gap = 3÷6 mm
B_{peak} ~ **0.95 T** *
K_0 = 1.30 *
* gap=4.5mm



Well-established technology
(DANFYSIK, HITACHI Metal Ltd., ...)

'Swiss-FEL' type of undulator (HPM undulator)

K_0 = 1.3 (λ_u=15 mm, Gap=4.5mm)
$L_{undulator}$ = 4 m



Natural focusing of the planar undulator

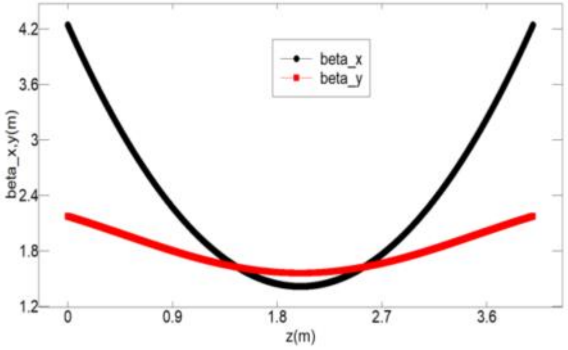
W_e= 350 MeV

Estimation: $<\beta> \sim \frac{\sqrt{2}\gamma\,\lambda_u}{2\pi\,K_0}$ ⇨ $<\beta> \sim 1.8\,m$

$<\beta_x> \sim 2.3\,m$
$<\beta_y> \sim 1.7\,m$

Matched Twiss parameters

SIMPLEX



SIMPLEX: T.Tanaka, doi: 10.1107/S1600577515012850

○ LPA-based Coherent Undulator Radiation Source

→ Reach the saturation in the 4-m undulator

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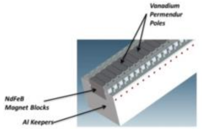

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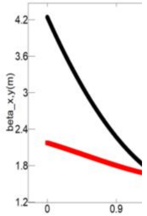
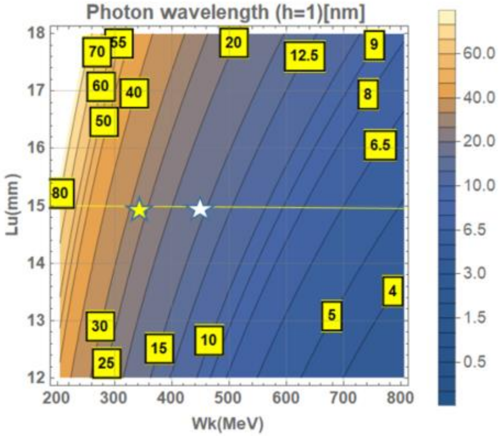


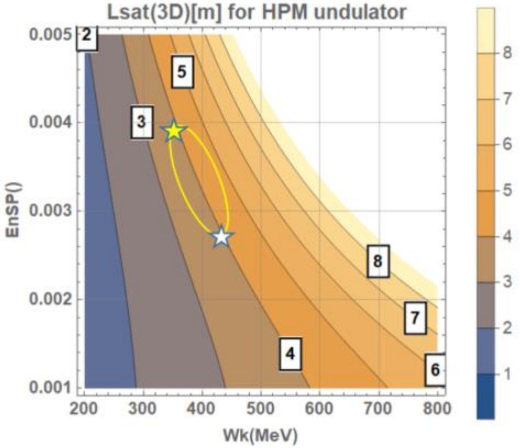
SIMPLEX: T.Tanaka, doi: 10.1107/S16005

SWISS-FEL "Aramis" type (HPM undulator)

Gap = 4÷6 mm, B_r = 1.3 T



σ_t = 5 fsec (σ_z ~ 1.5 µm) - Gaussian
Q_b = 40 pC (I_{peak} ~ 3.2 kA)
$\sigma_{x,y}$ = 30 µm (ε_n = 0.25 π mm.mrad)



λ_u = 15 mm
Gap = 4.5 mm
K_u = 1.2

Control: "slice" energy spread and normalized emittance as well as the peak current (bunch length, bunch charge)

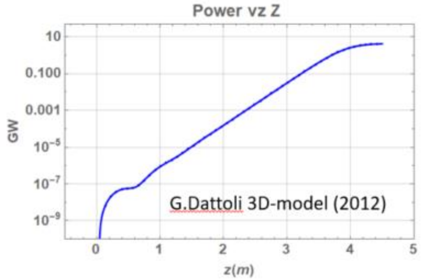
L_{sat} (3D) ~ 4 m

If $\sigma_{\delta\gamma}$ ~ 0.4 %
W_e ~ 350 MeV
$\lambda_{ph,1}$ ~ 27.8 nm
$E_{ph,1}$ ~ 44.5 eV
→ P_{pulse} ~ 3.5 GW

ρ_{1D} ~ 0.007
$\varepsilon_{n,coh}$ ~ 1.5 π µm

If $\sigma_{\delta\gamma}$ ~ 0.25 %
W_e ~ 430 MeV
$\lambda_{ph,1}$ ~ 18.2 nm
$E_{ph,1}$ ~ 68.1 eV
→ P_{pulse} ~ 4.7 GW

ρ_{1D} ~ 0.006
$\varepsilon_{n,coh}$ ~ 1.2 π µm



Required electron beam ' slice' parameters:
W_e ~ 350 ÷ 400 MeV; ε_n ~ 0.25 π mm.mrad; I_{peak} ~ 3 kA; σ_δ < 0.4 %

Similar parameters are demonstrated experimentally (SIOM-team / China)
doi:10.1038/s41586-021-03678-x

○ LPA-based Coherent Undulator Radiation Source

Dedicated electron beam transport is required in order to:

- Capture electrons from LPA → issue: preservation of the transverse normalized emittance *
- Clean the 'halo' of the electron beam, caused by the chromatic aberration effect
- Control the slice energy spread → 'decompression' chicane as a basic option **

In addition:
- 'capture' block of focusing elements has to be placed as close as possible to LPA
- high-power laser beam can be separated from the electron beam <u>only after</u> the 'capture' block.

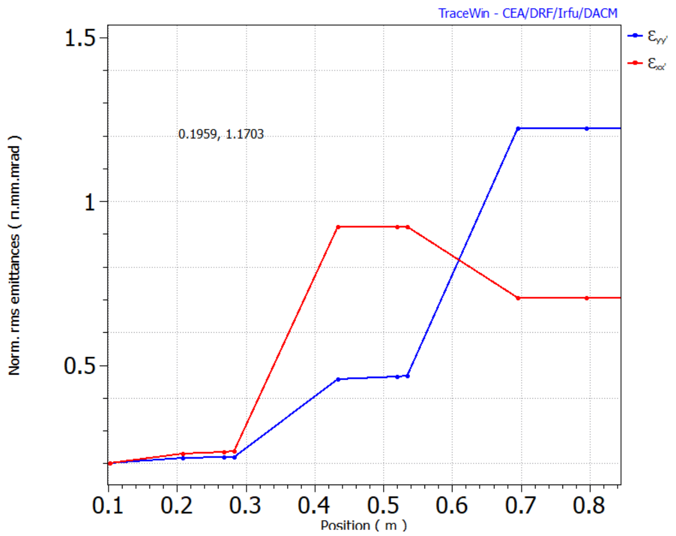
* M.Migliorati et. al., "Intrinsic normalized emittance growth in laser-driven electron accelerators", Phys.Rev. ST Accel. Beams 2013, 16, 011302. doi:10.1103/PhysRevSTAB.16.011302.

** A.Maier *et al.,* Phys.Rev. X 2, 031019 (2012)

○ LPA-based Coherent Undulator Radiation Source

Capture block

Triplet: 3 EQMs



INITIAL beam:

LPA-source

W_e = 350 MeV

Q_b = 70 pC

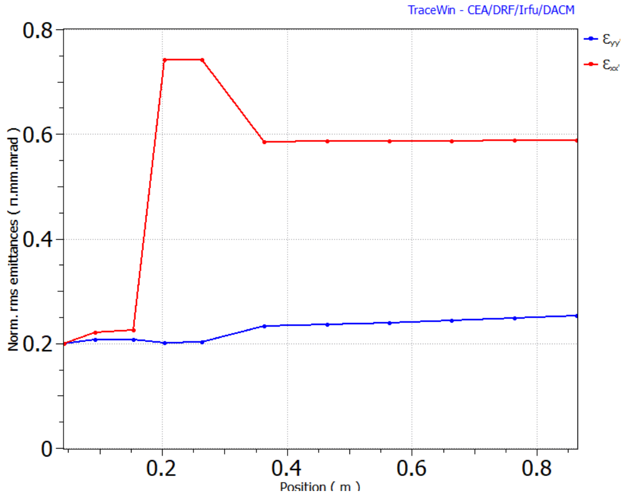
'Projected' values

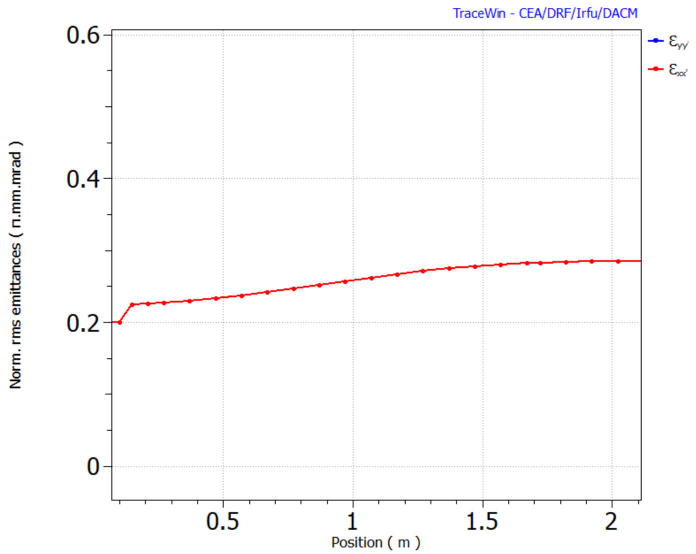
$\varepsilon_{n\ x,y}$ = 0.2 π m.mrad

$\sigma_{x',y'}$ = 0.5 mrad

σ_δ = 0.5 %

Triplet: 2 PQM + EQM





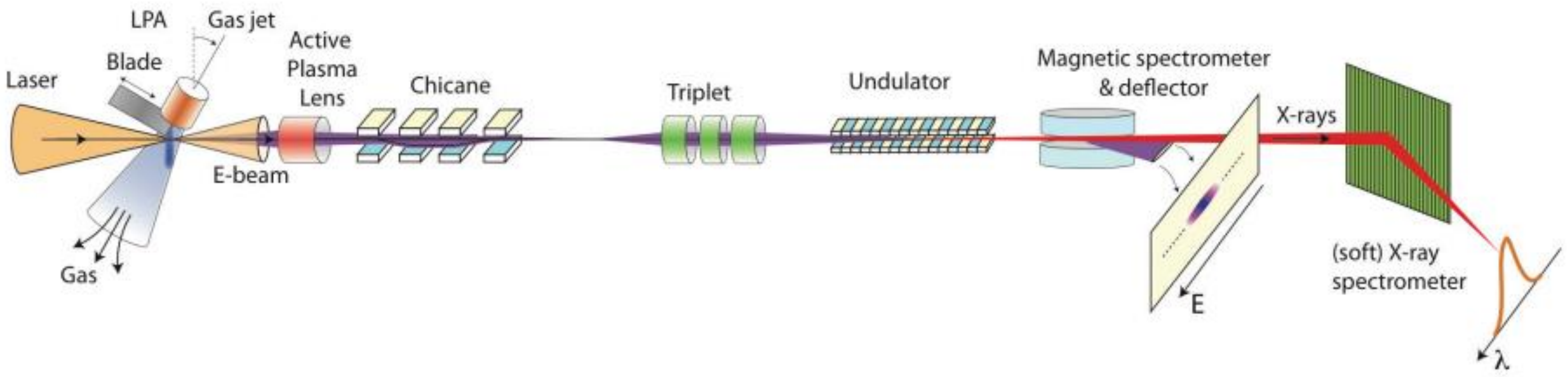
Active Plasma Lens
(concept)

○ LPA-based Coherent Undulator Radiation Source

Main issue: preservation of the LPA electron beam quality in a dedicated electron beam transport

Possible solution: LPA-based FEL / BELLA scheme, presented by van Tilborg (ICFA FLS2018, Shanghai, China)

Matching quads



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Main issue: preservation of the LPA electron beam quality in a dedicated electron beam transport

Possible solution: LPA-based FEL / BELLA scheme, presented by van Tilborg (ICFA FLS2018, Shanghai, China)

Matching quads

LPA-source

W_e = 350 MeV

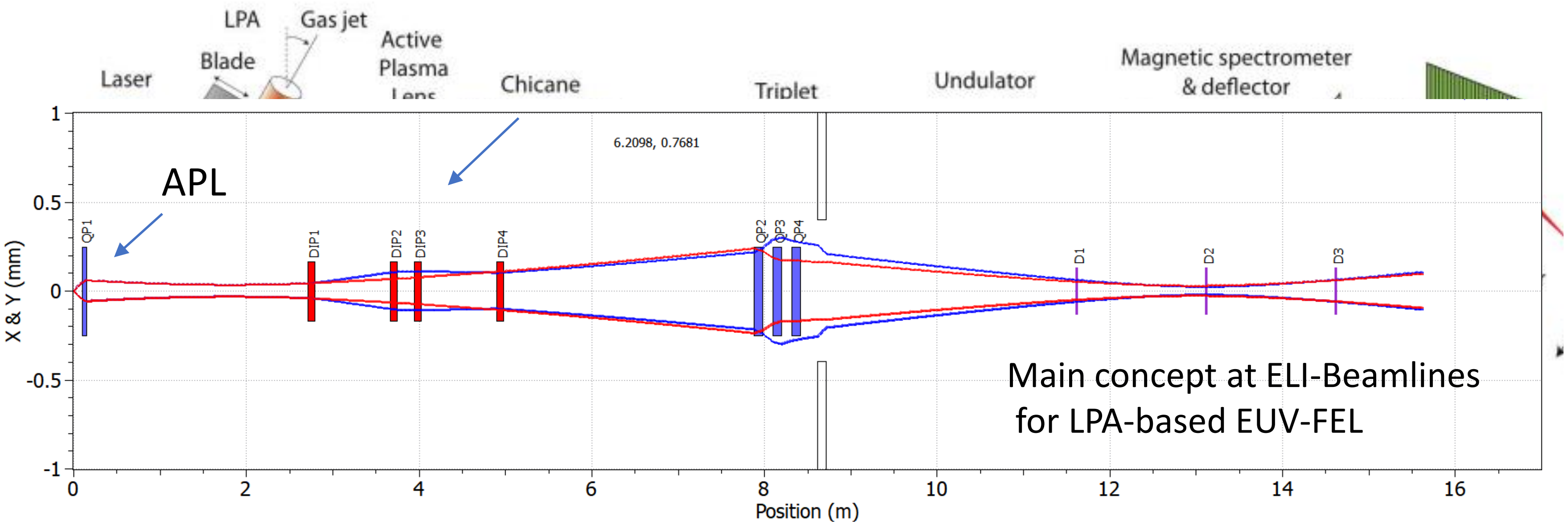
Q_b = 50-70 pC

'Projected' values

$\varepsilon_{n\,x,y}$ = 0.2 π m.mrad

$\sigma_{x',y'}$ = 0.5 mrad

σ_δ = 0.5 %



Main concept at ELI-Beamlines for LPA-based EUV-FEL

'Slice' parameters

< $\varepsilon_{n\,x}$ > = 0.35 π m.mrad

< $\varepsilon_{n\,y}$ > = 0.37 π m.mrad

< σ_δ >= 0.23 %

I_{peak} ~ 3 kA

Collimator:

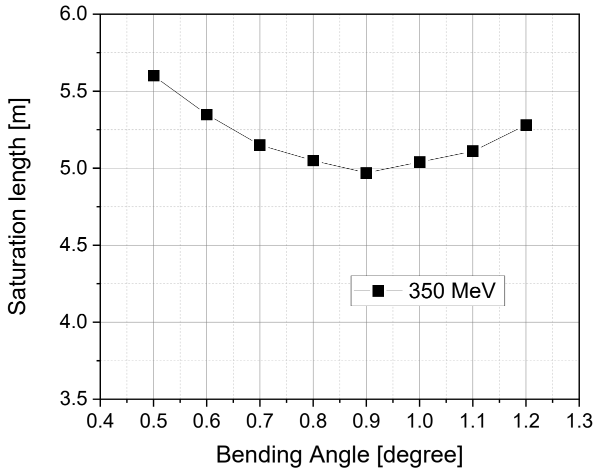
Propagation ~ 75 %

DC angle = 0.9 degrees

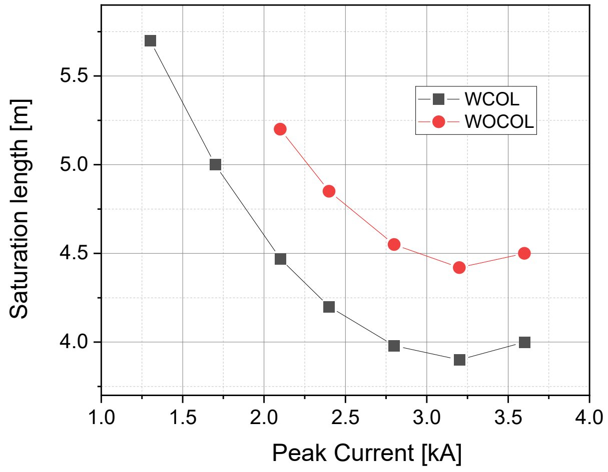
○ LPA-based Coherent Undulator Radiation Source

Sources of the transverse emittance degradation in the LPA-based electron beam line

- ○ Chromatic aberration → Intrinsic effect for the LPA-based electron beam
- ○ Collective effects (space charge)
- ○ Coherent synchrotron radiation
- ○ Imperfections (injection errors, misalignment of main components …)



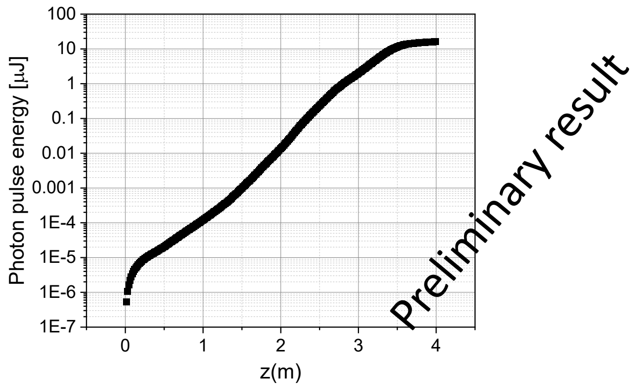
SIMPLEX: doi:10.1107/S1600577515012850



Undulator unit

Comprehensive "Star-to-End" simulations are needed

Photon beam parameters at saturation for the optimized case with Collimator



LPA-based EUV SASE-FEL (h=1, K_u=1.2)		
Energy	MeV	350
Rep-Rate	Hz	25 → 50
Wavelength (h=1)	nm	~ 27.8
Photon energy	eV	~ 44.5
Peak power	GW	~ 2.1
Undulator length	m	~ 4
Total photon flux		~ 1.6×10^{13}
Brilliance	0.1%bw	~ 4×10^{29}

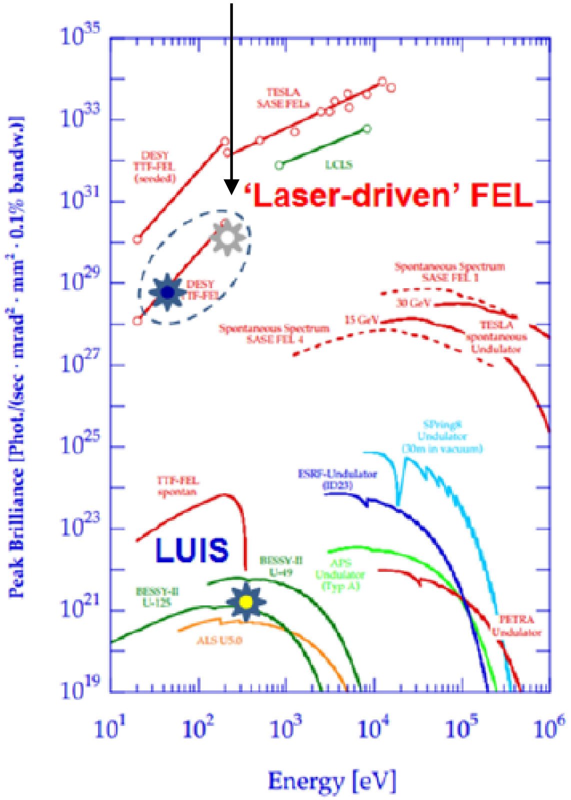
Summary

- ❖ High-power High-repetition rate novel Laser System (L2-DUHA) is under preparation at ELI-Beamlines → 1st operation (plan): Q1-2024

- ❖ High-quality High-energy compact Laser-Plasma Accelerator is under preparation (E5-LUIS experimental setup) → 1st commissioning run (plan Q4-2023), utilizing the 'cropped' L3-HAPLS laser system

- ❖ Incoherent undulator radiation source at ELI-Beamlines → commissioning during 2024

- ❖ Coherent undulator radiation source (LPA-based FEL) → next step … of the development



Thank you for your attention