'LWFA-DRIVEN' FREE ELECTRON LASER FOR ELI-BEAMLINES

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CONTENT

- European Light Infrastructure (ELI) and ELI-beamlines
- ‘Demo’ FEL and ‘Water-window’ FEL in ELI-beamlines
- Dedicated electron beamline for ‘laser-driven’ FEL:
  main concepts and possible realization

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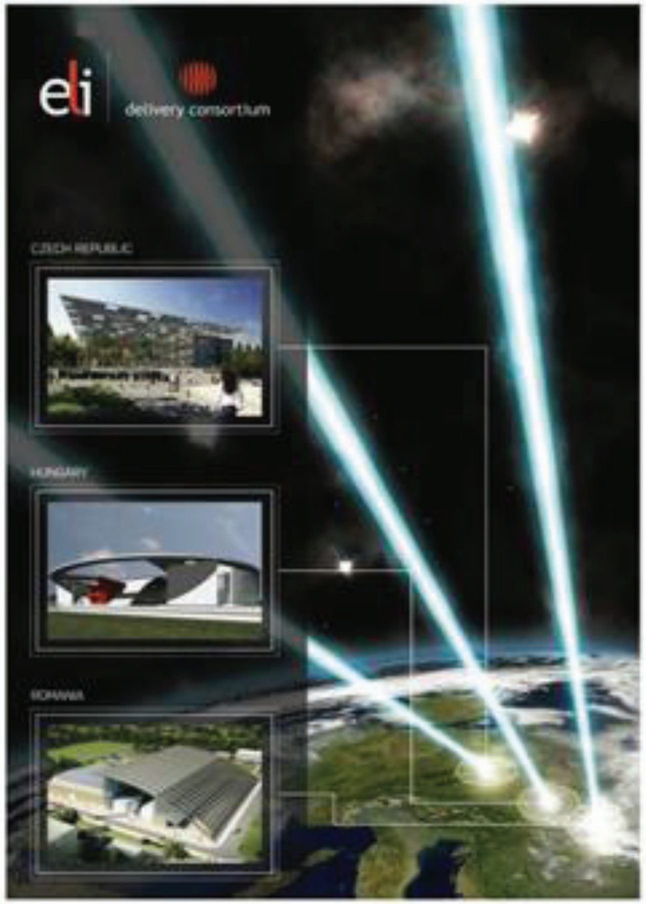
European Light Infrastructure (ELI)



- European Light Infrastructure (**ELI**) will be the world's first international laser research infrastructure, pursuing unique science and research applications

- **ELI** will be implemented as a distributed research infrastructure based initially on 3 specialized and complementary facilities, located in the Czech Republic, Hungary and Romania

Attosecond Laser Science – ELI-ALPS, Szegen, Hungary

High-Energy Beam Facility: development and use of ultra-short pulses of high-energy particles and radiation stemming from the ultra-relativistic interaction – ELI-Beamlines, Prague, CZ

Nuclear Physics Facility with ultra-intense laser and brilliant gamma beams (up to 19MeV) enabling also brilliant neutron beam generation with variety of energies – ELI-NP, Magurele, RO

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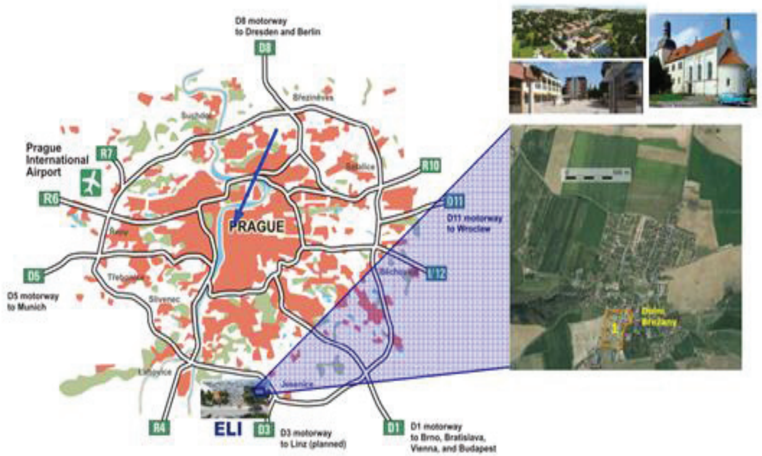
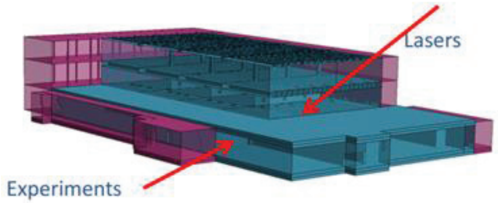
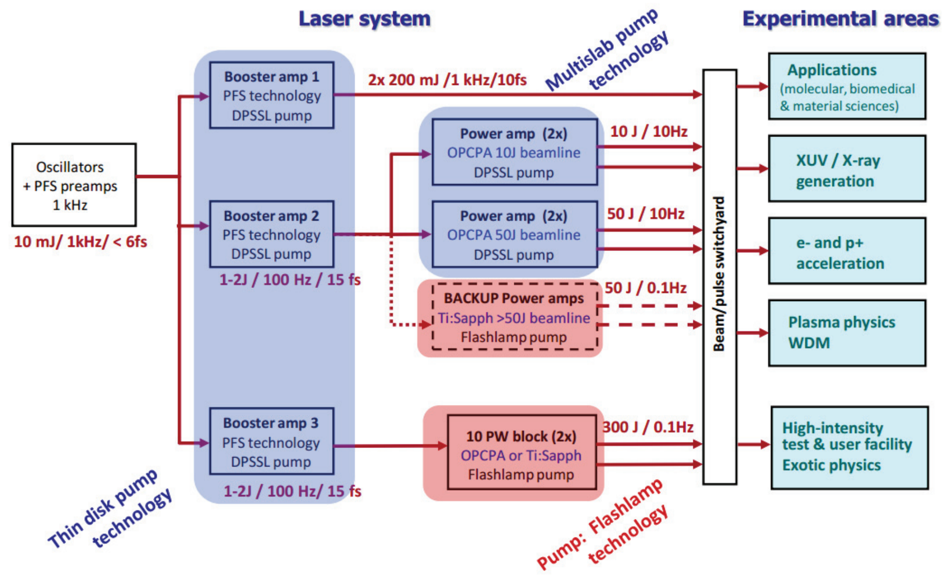
ELI-BEAMLINES



Location: Dolni Brezany (near Prague)

- Site area 65,000 m²
- Building(s) 28,645 m²
- Building volume 170,000 m³
- Experimental building 16,500 m²
- Laboratories 4,500 m²
- Offices 4,400 m²
- Multifunction areas 2,300 m²
- Total estimated construction costs of €65M
- Foundation raft slab thickness 1m;
- 1.6m shielded reinforced concrete walls in the underground;





Parameters of FOCUSED laser pulses

200mJ / 10fs	*	1 kHz	20 TW	$< 6\times10^{20}$ W/cm²
10J / 20fs		10 Hz	500 TW	$< 3\times10^{21}$ W/cm²
50J / 25fs	**	10 Hz	2 PW	$< 1\times10^{22}$ W/cm²
300J / 30fs		0.1 Hz	10 PW	$< 3\times10^{23}$ W/cm²

Installation in progress: (*) available during 2018
(**) available during 2019

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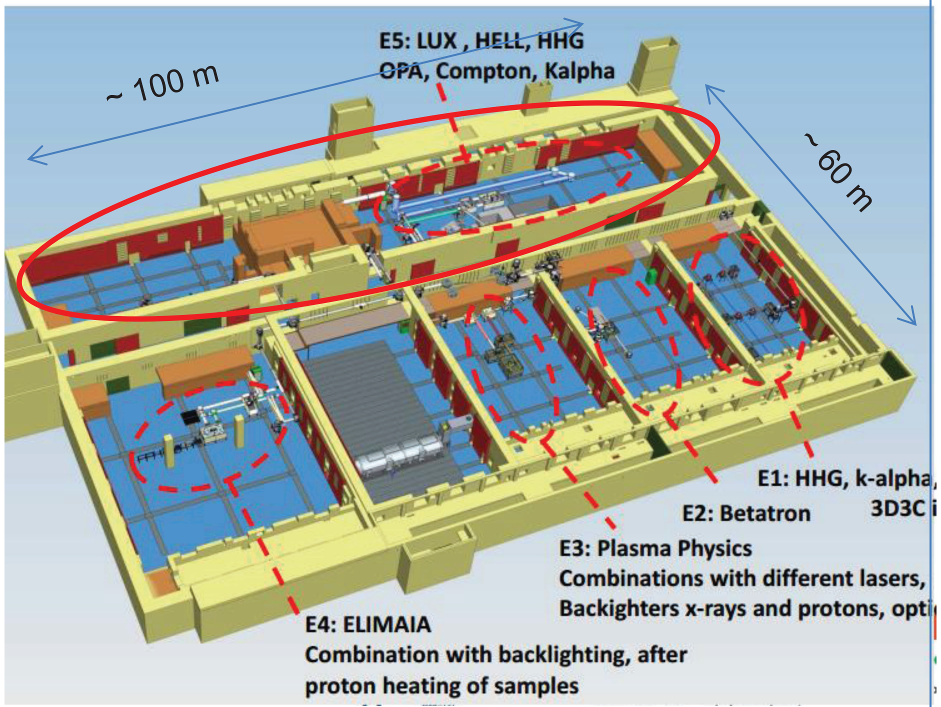
Fundamental and applied research

Underground experimental Hall



Generation femtosecond secondary sources of radiation and particles:

- XUV and X-ray sources
- **Accelerated electrons (< 2GeV/10Hz, >10GeV low rep-rate)**
- Accelerated protons (< 400MeV/10Hz, >3GeV low rep-rate)
- Gamma-ray sources (broadband)

Applications of rep-rated femtosecond secondary sources

- Medical research including proton therapy
- Molecular, biomedical and material sciences
- Physics of dense plasmas, laser fusion, laboratory astrophysics

High-field physics experiments with focused intensities 10^{23}-10^{24}Wcm^{-2}

- "Exotic" physics, non-linear QED

Development & testing new technologies for multi-PW laser systems

- Generation and compression of 10-PW ultrashort pulses, coherent superposition etc.

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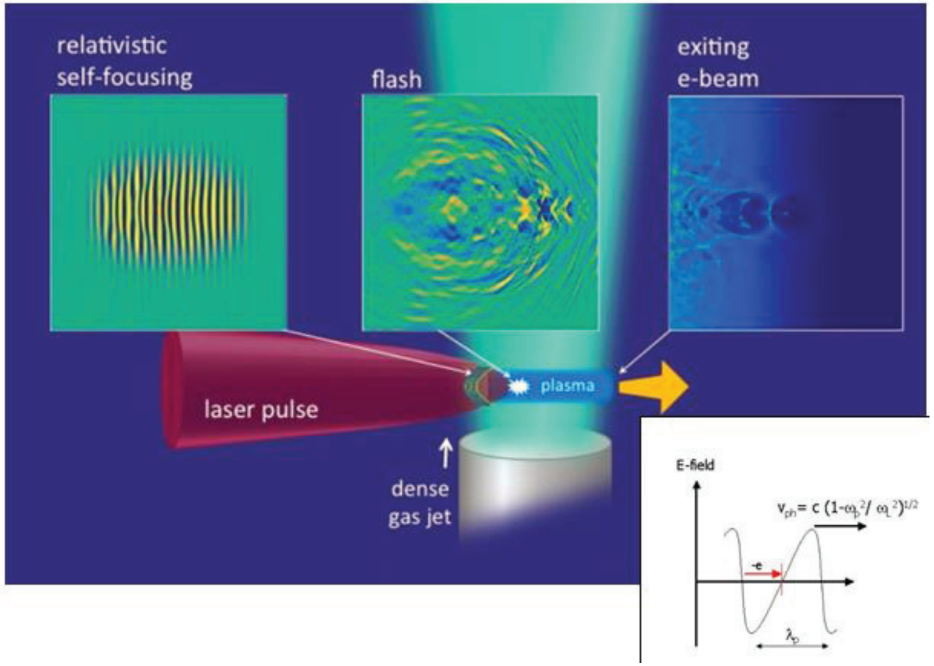
‘Laser-driven’ FEL

The principal of the ‘**laser-wake-field-acceleration**’ (LWFA) is based on an ultra-high longitudinal electric gradient, created by the high-intensity laser pulse focused in dense plasma



The plasma wavelength

$$\lambda_p[\mu m] \approx 3.3 \times 10^{10}/\sqrt{n_e[cm^{-3}]}\ ,$$

where n_e is the electron density of the plasma.
The plasma wavelength limits the bunch length which can be accelerated by the laser-wave.

The longitudinal field

$$E_0[V/m] = 96\sqrt{n_e[cm^{-3}]}\ .$$

Assuming ***$n_e \sim 5\times10^{19}$ cm^{-3}:***

$\lambda_p \sim 14.8$ µm → < 3 fs RMS pulse length
$E_0 \sim 215$ GV/m

W_{kin}= 1GeV … 4.7 mm accelerating channel.

Recent experimental achievement in LWFA [1]

Through manipulating electron injection, quasi-phase-stable acceleration, electron seeding in different periods of the wake-field, as well as controlling the energy chirp the high-quality electron beams have been obtained. The electron beams with energies in the range of **200÷600 MeV**, with the RMS energy spread of **0.4÷1.2 %,** the RMS transverse beam divergence of **0.2 mrad** with the bunch charge of **10÷80 pC** have been demonstrated experimentally for the new cascaded acceleration scheme.

Using recent experimental achievements one can define the parameters of the LWFA electron beam at the exit of the plasma channel as following:

$$\mathbf{W_{kin} = 300 \div 1000\ MeV;}$$
$$\sigma_{x,y} \sim 1\ \mu m\ ;\ \sigma_{x',y'} \sim 0.2 \div 0.5\ mrad;$$
$$\sigma_z \sim 1\ \mu m;$$
$$\sigma_{\Delta p/p} < 1\%\ (\sim 0.5\ \%)$$
$$\varepsilon_n \sim 0.2\ \pi\ mm.mrad;$$
$$Q_b \sim 20 \div 50\ pC.$$

[1] W.T.Wang et al., Phys.Rev.Lett 117, 124801 (2016)

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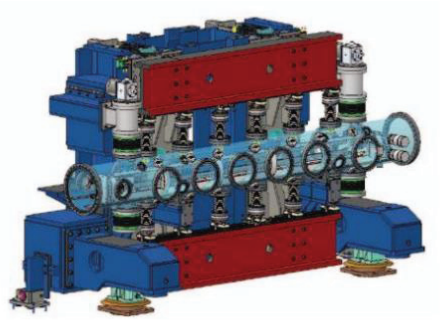
'Laser-driven' FEL

'Cryogenic' permanent magnet PLANAR undulator

HZ (Berlin) and University of Hamburg [2]



PLANAR undulator			
Normalized 'peak' undulator parameters	K	-	3.0
Normalized RMS undulator parameter	a_{w0}	-	2.121
Undulator period	λ_u	mm	**15**
Peak undulator field	B_p	T	**2.141**
Number of periods	N_u	-	133
Undulator gap	g_u	mm	2
Undulator length	L_u	mm	1995

[2] J.Bahrdt, in Proc. FEL2011 Conference, p.435, 2011

Goal of the 'demo' FEL experiment:

- demonstrate the amplification of radiation;
- reach the saturation in the short undulator (2m).

→ W_{kin} = 350MeV, Gap ≈ 4.5mm (K_0=1.77)

… next step → 'laser-driven' 'water-window' FEL

Table 1: Main parameters of (A) 'demo' FEL and (B) 'water-window' FEL

		A	B
Electron beam in Undulator			
Beam energy	MeV	350	1000
Bunch charge	pC	20	20
RMS bunch duration	fs	2	2
Peak current	kA	4	4
Matched beam size	μm	~ 30	~ 30
Normalized emittance	π mm.mrad	0.3	0.3
'Slice' energy spread	%	0.2	0.2
Photon coherent radiation in Undulator at saturation			
Photon energy, E_{ph1}	eV	30.1	246
Radiation wavelength	nm	41	5
Pierce parameter, ρ	$\times 10^{-2}$	0.85	0.29
Coherent normalized RMS emittance, $\varepsilon_{n,coh}$	π mm.mrad	2.24	0.785
Cooperation length (3D), L_{coop}	m	0.30	0.15
Gain length (3D), $L_{g,3D}$	m	0.107	0.45
Saturation length (3D)	m	~ 2.1	~ 8.5
Total photon flux	$\times 10^{13}$ #	1.23	0.5
Radiation bandwidth	%	0.72	0.2
Photon flux per 0.1%bw	$\times 10^{12}$ #	1.6	0.74
Photon brilliance	$\times 10^{30}$ #	0.44	7.05
Photon pulse power	GW	10.8	5.2
Photon pulse energy	μJ	60	30

 # corresponding units are shown in the text

Estimations using the 3D model [3]

[3] M.Xie, LBNL-44381, CBP Note-323, 1999

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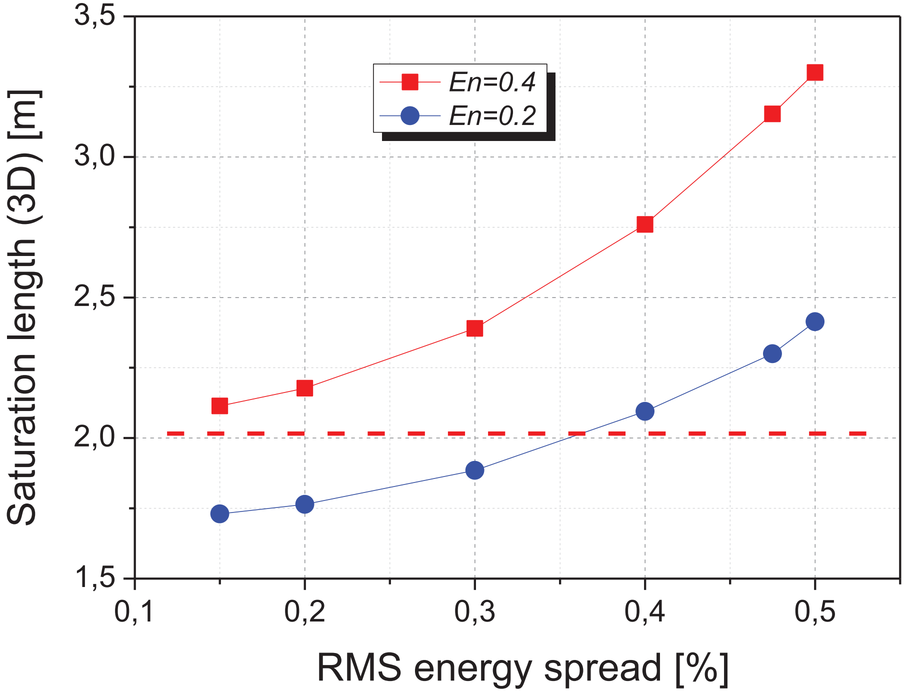
Estimation of the saturation length for different parameters of the electron beam, passing through the CPMU undulator (K_0=1.77)

W_{kin}= 350 MeV, I_{peak}= 4kA, $\sigma_{x,y}$= 30µm



$L_{sat,3D} \sim 20Lg_{1D}(1+\Delta)$,
where Δ is defined according to the Xie parametrization, $L_{g,1D}$ is the 1D gain length.

In order to obtain the saturation length (3D) of 2m for the energy spread of 0.3%, the normalized RMS transverse emittance of the electron beam should be less than 0.3 π mm.mrad → 'SLICE' parameters of the electron beam (L_{slice}<L_{coop}).

Conceptual solutions for a dedicated beamline for a ‘laser-driven’ FEL

WHAT	HOW	Effects	Pros	Cons
Capture of the ‘laser-driven’ electrons	Triplet of permanent quads	• Minimize normalized emittance growth • Allow a long drift space for out-coupling optics	• Compact setup • High gradient (~450T/m[#1])	○ Radiation damage ○ Position control
‘Momentum’ filter [#2]	Set of EM-quadrupoles	• Eliminate effects of ‘chromatic aberrations’, caused by large energy spread	• Compact setup • Without bending dispersive elements	○ Required collimator ○ Secondary particles
Beam manipulations[#3]	Magnetic chicane (decompressor)	• Electron beam manipulation in the longitudinal plane	• Control of ‘slice’ parameters	• Effect of CSR
Beam matching with undulator[#4]	Additional set of quad-magnets	• Matching to the undulator Twiss parameters	• Matching for FEL	• Triplet or quadruplet of QMs

[#1] *P.Winkler et al, in Proc. IPAC17 Conf., p.4145*
[#2] *I.Hofmann, Phys.Rev.STAB, 16, 0413302 (2013); A.Molodozhentsev et al, in Proc. IPAC16 Conf, p.4005, 2016*
[#3] A.Maier et al., Phys.Rev. X 2, 031019 (2012)
[#4] A.Loulergue et al., New J.Phys. 17, 023028 (2015)

‘Laser-driven’ FEL

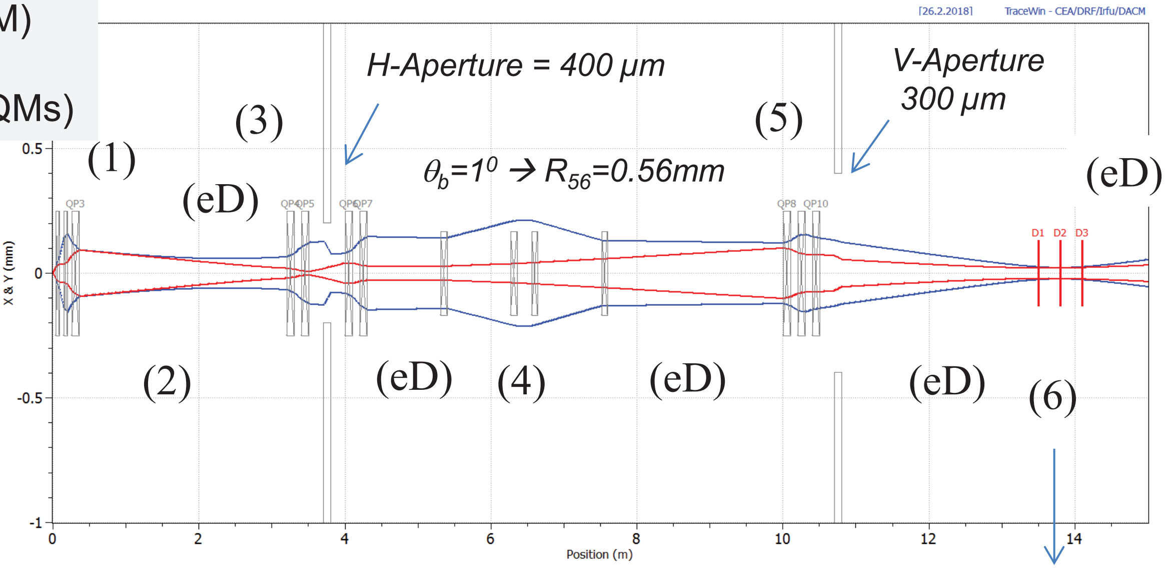
Electron beamline for a ‘laser-driven’ the ‘demo’ FEL (W_k=350 MeV)

(1) Capture (2PQMs+EQM)
(2) ‘Out-coupling’ drift
(3) ‘Momentum’ filter (4EQMs)

(4) C-Chicane (4DMs)
(5) Matching quads (3EQMs)
(6) Undulator
(eD) T&L diagnostics

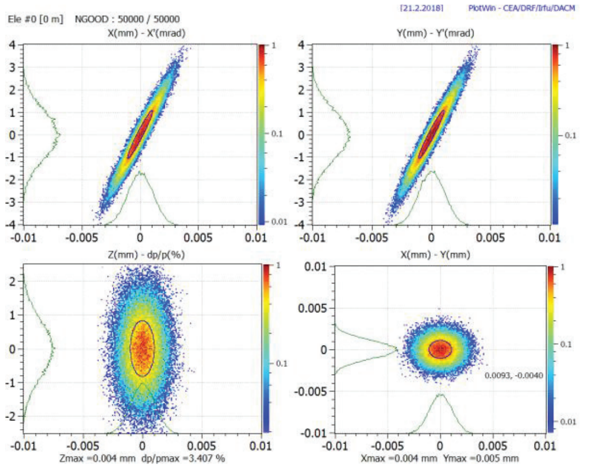
$\varepsilon_{n,x}$ = 0.2π mm.mrad *
$\varepsilon_{n,y}$ = 0.2 π mm.mrad
$\sigma_x = \sigma_y$ = 1.1 µm
$\sigma_{x'} = \sigma_{y'}$ = **0.55 mrad**
$\sigma_{\Delta p/p}$ = **1.05%**

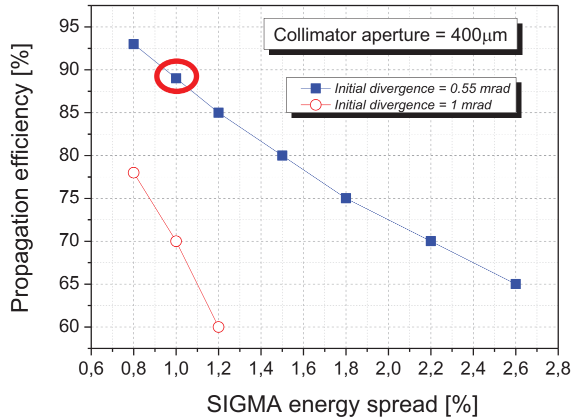
* ‘projected’ emittance

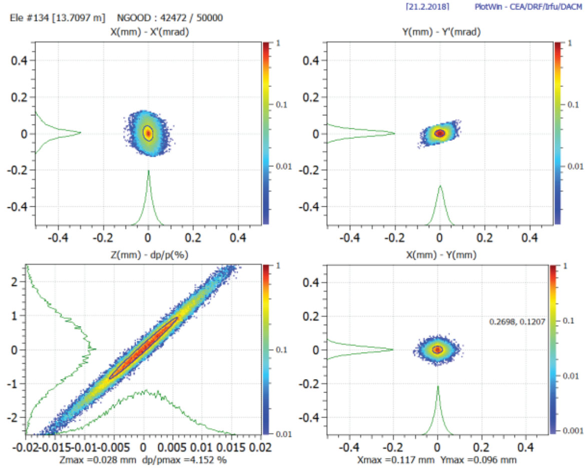


$\varepsilon_{n,x}$ = **0.64 π mm.mrad** *
$\varepsilon_{n,y}$ = **0.33 π mm.mrad**
σ_x = 22.4 µm
σ_y = 21.5 µm
$\sigma_{\Delta p/p}$ = **0.9%** *

* ‘projected’ value







Collimation (H&V):
beam-halo cut in undulator
with propagation efficiency ~
85% ($\sigma_{\Delta p/p}$ = 1.0%).

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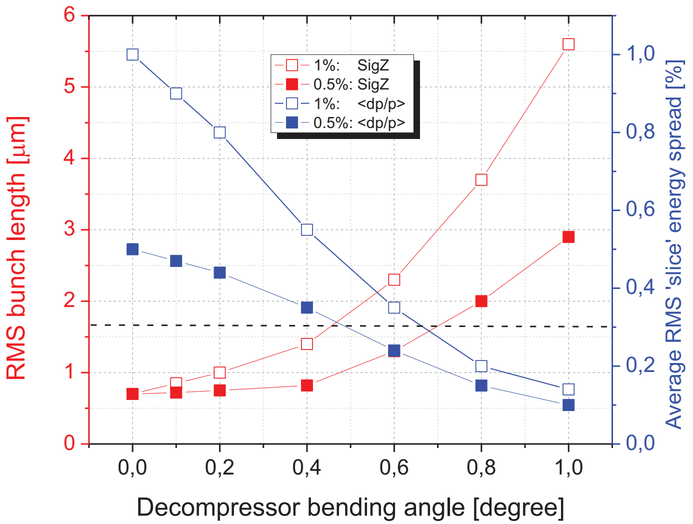
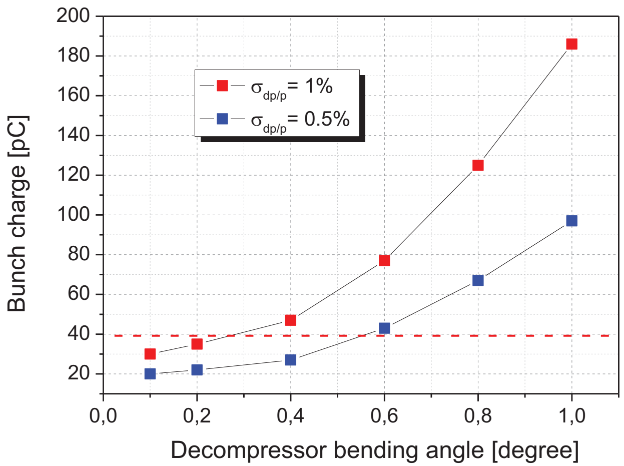
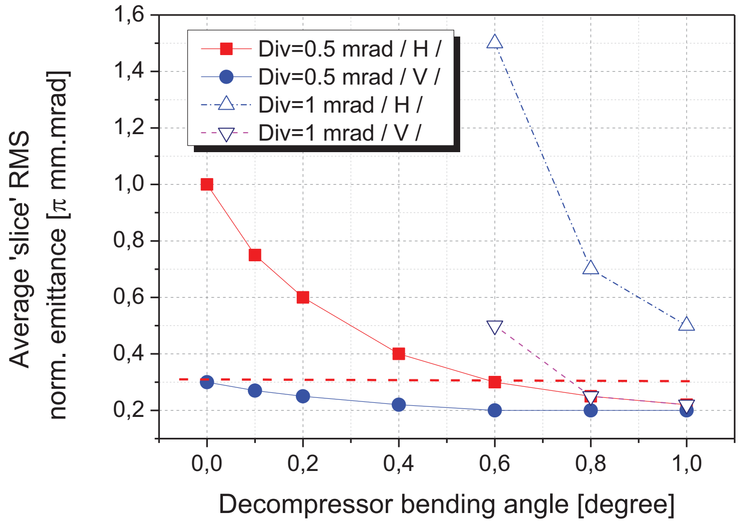
Control of the ‘slice’ beam parameters for the ‘demo’ FEL (W_k=350 MeV)

The ‘slice’ beam parameters for the ‘demo’ FEL experiment should meet the requirements:

- *the relative energy spread < 1/2 of the Pierce parameter … $\sigma_{\Delta p/p,S} < 0.4\%$;*
- *the transverse normalized emittance $\varepsilon_{n,S} < 0.3\pi$ mm.mrad;*
- *the bunch charge $Q_b < 40$pC, providing the peak current of 4kA for different R_{56}.*







Initial ‘projected’ RMS relative energy spread should be 0.5%
Initial RMS transverse divergence should be less 0.5mrad

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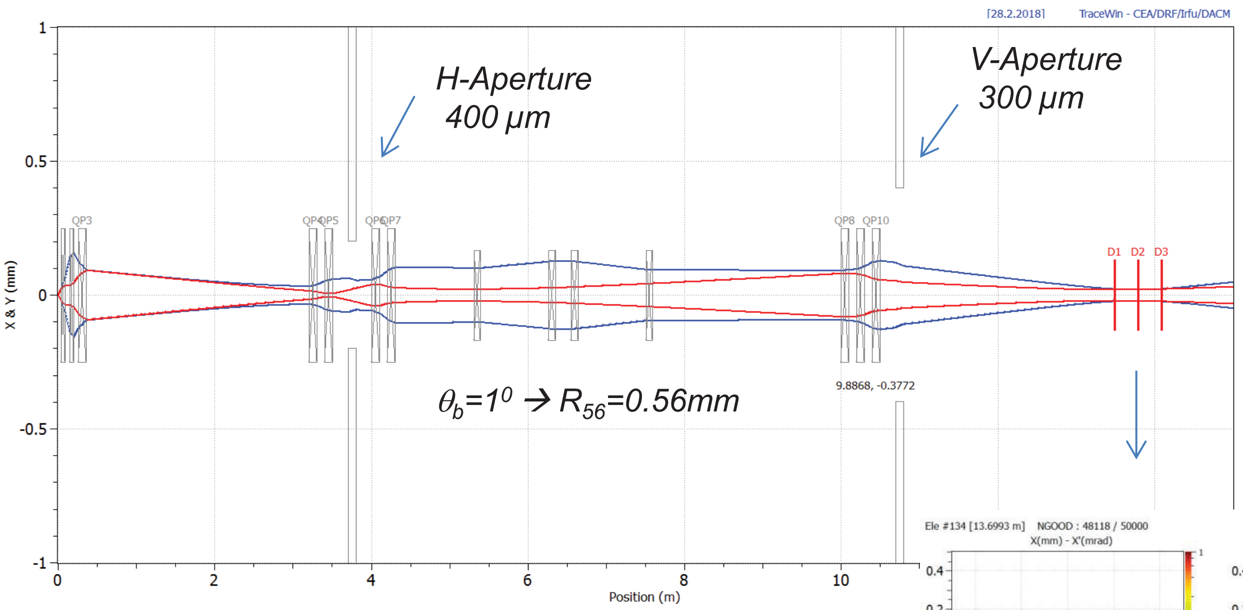
Electron beamline for a ‘laser-driven’ the ‘demo’ FEL (W_k=350 MeV)

$\varepsilon_{n,x}$ = 0.2π mm.mrad *
$\varepsilon_{n,y}$ = 0.2 π mm.mrad
$\sigma_x = \sigma_y$ = 1.1 μm
$\sigma_{x'} = \sigma_{y'}$ = **0.5 mrad #**
$\sigma_{\Delta p/p}$ = **0.5% #**

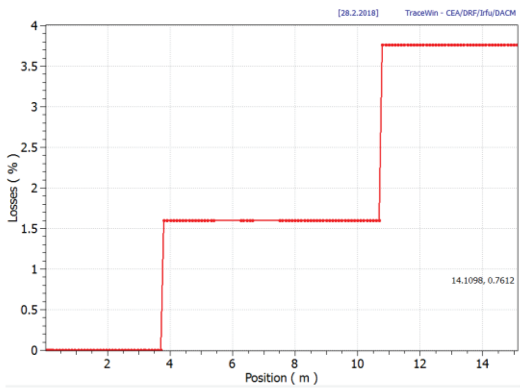
* ‘projected’ emittance

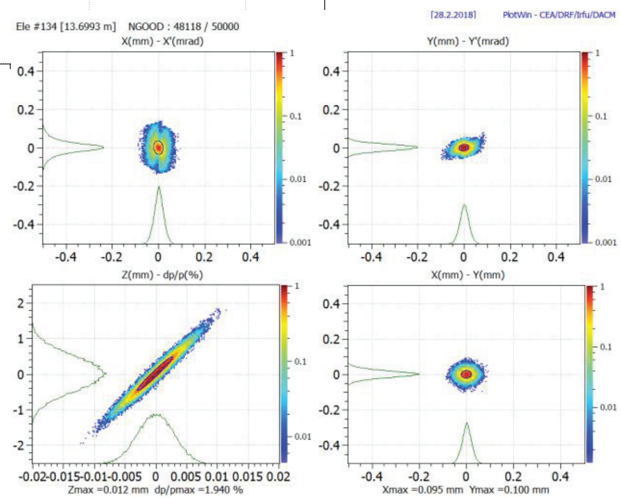


$\varepsilon_{n,x}$ = **0.51 π mm.mrad** *
$\varepsilon_{n,y}$ = **0.23 π mm.mrad**
σ_x = 21 μm
σ_y = 21 μm
$\sigma_{\Delta p/p}$ = 0.48 % *

* ‘projected’ value

Propagation efficiency ~ 96%





[#] Reachable experimentally:
W.T.Wang et al., Phys.Rev.Lett 117, 124801 (2016)

FEL ANALYSIS:

FEL demonstration experiment → W_{kin}=350MeV

Goal: … saturation in the 2m 'cryogenic' undulator

Photon pulse energy for different decompressor setup

The bending angle in the C-chicane:

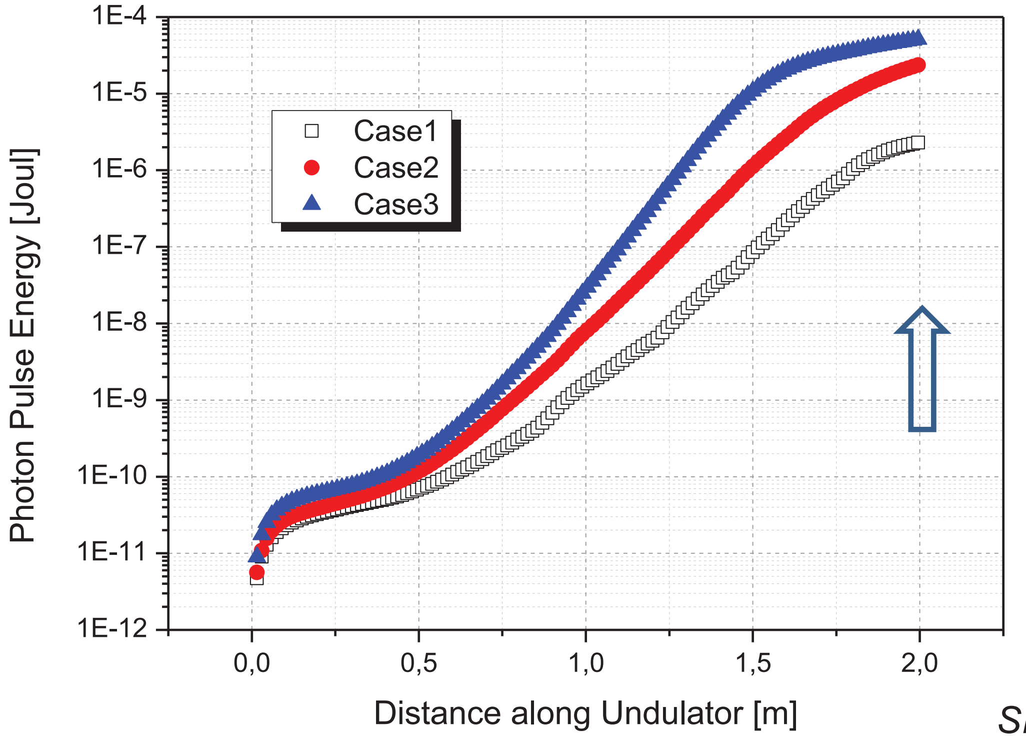
Case1: 0.2 degree;
Case2: 0.4 degree;
Case3: 0.6 degree.

After the decompressor:

The 'slice' RMS energy spread:
(1) 0.44%; (2) 0.35%; (3) 0.24%

The 'slice' RMS norm. (H/V) emittance:
(1) 0.6/0.25; (2) 0.4/0.22; (3) 0.3/0.2

To keep the peak current of 4kA for each set of the chicane magnets the bunch charge for each case is:
(1) 23pC; (2) 27pC; (3) 43pC, respectively.



SIMPLEX

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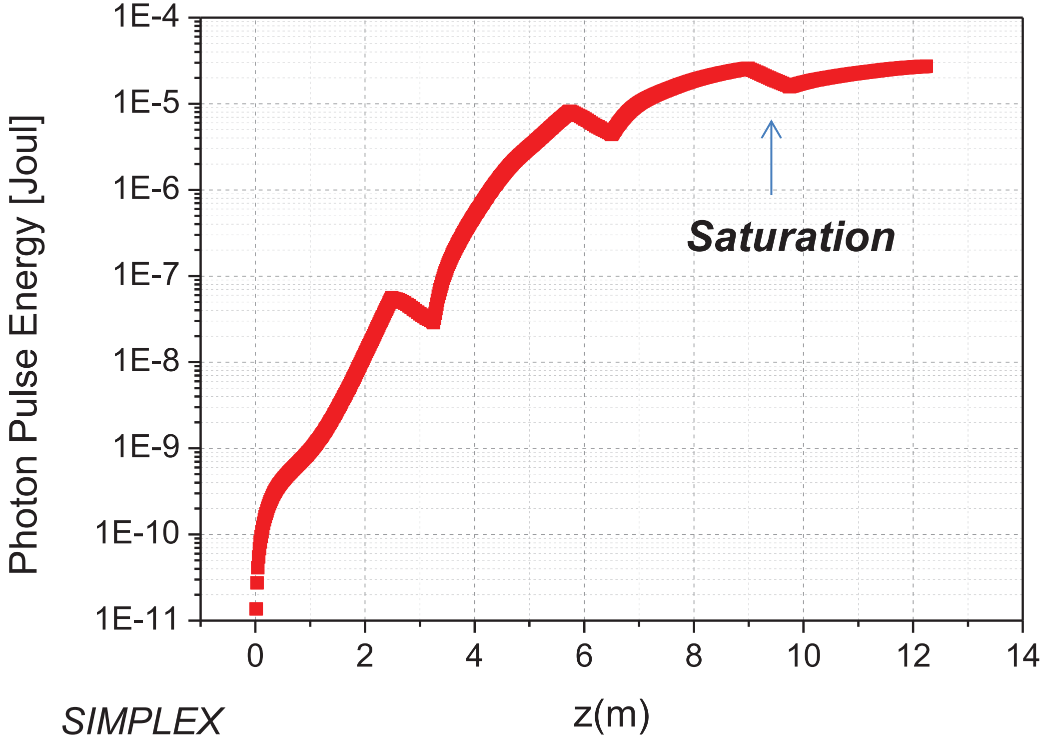
'Laser-driven' FEL

FEL ANALYSIS:

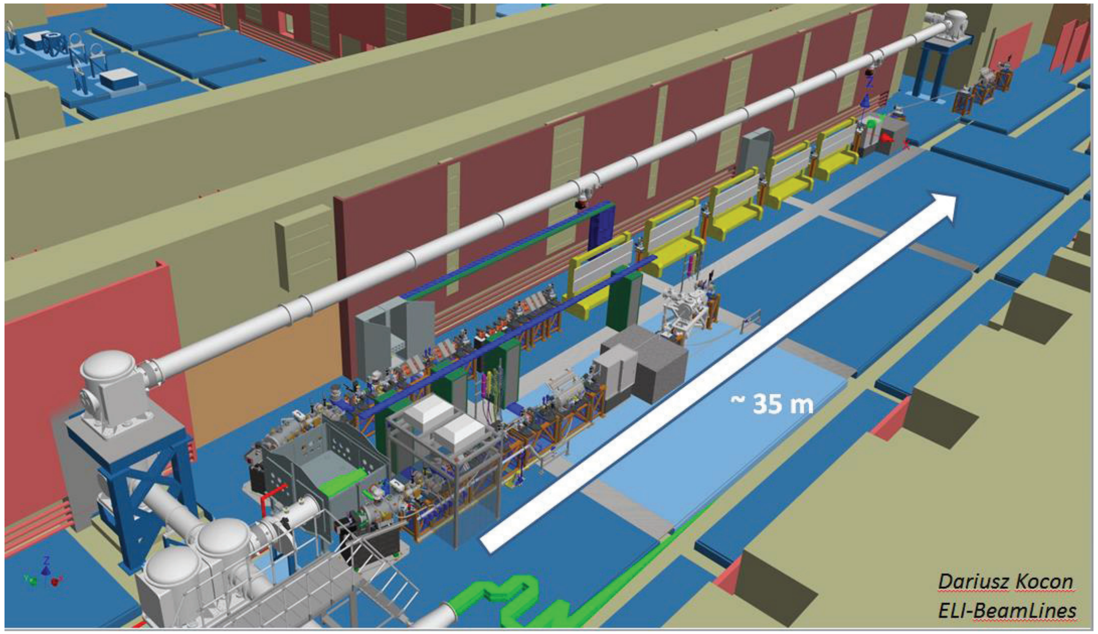
'water-window' FEL → W_{kin}=1000MeV ($\lambda_{r,1}$ = 5nm, $E_{ph,1}$=250eV)

- *'Cryogenic' undulator segments (K=1.8): L_{seg}=2.5m*
- *Space separation: 0.75m*
- *FODO focusing structure*
- *Main beam parameters in Table 1*



SIMPLEX

LWFA-based' water-window FEL
in ELI-BL experimental hall E5



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CONCLUSION

- ✓ The analyzed dedicated beamline to transport the ‘laser-driven’ electrons up to an undulator allows us to provide required parameters of the electron beam for the ‘demo’ FEL experiment.

- ✓ The required initial parameters of the ‘laser-driven’ electron beam are reachable experimentally.

- ✓ Dependence of the ‘demo’ FEL parameters on different strength of the ‘decompessor’ C-chicane has been discussed.

- ✓ Performed analysis of the ‘water-window’ FEL parameters, based on the 1GeV ‘laser-driven’ electron beam, shows that the total length of the whole setup (including the dedicated electron beamline and 3÷4 segments of the undulator) is ~ 30m. The peak photon brilliance is 7.05×10^{30} photons/pulse/mm^2/mrad^2/0.1%bw.

ACKNOWLEDGEMENT

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