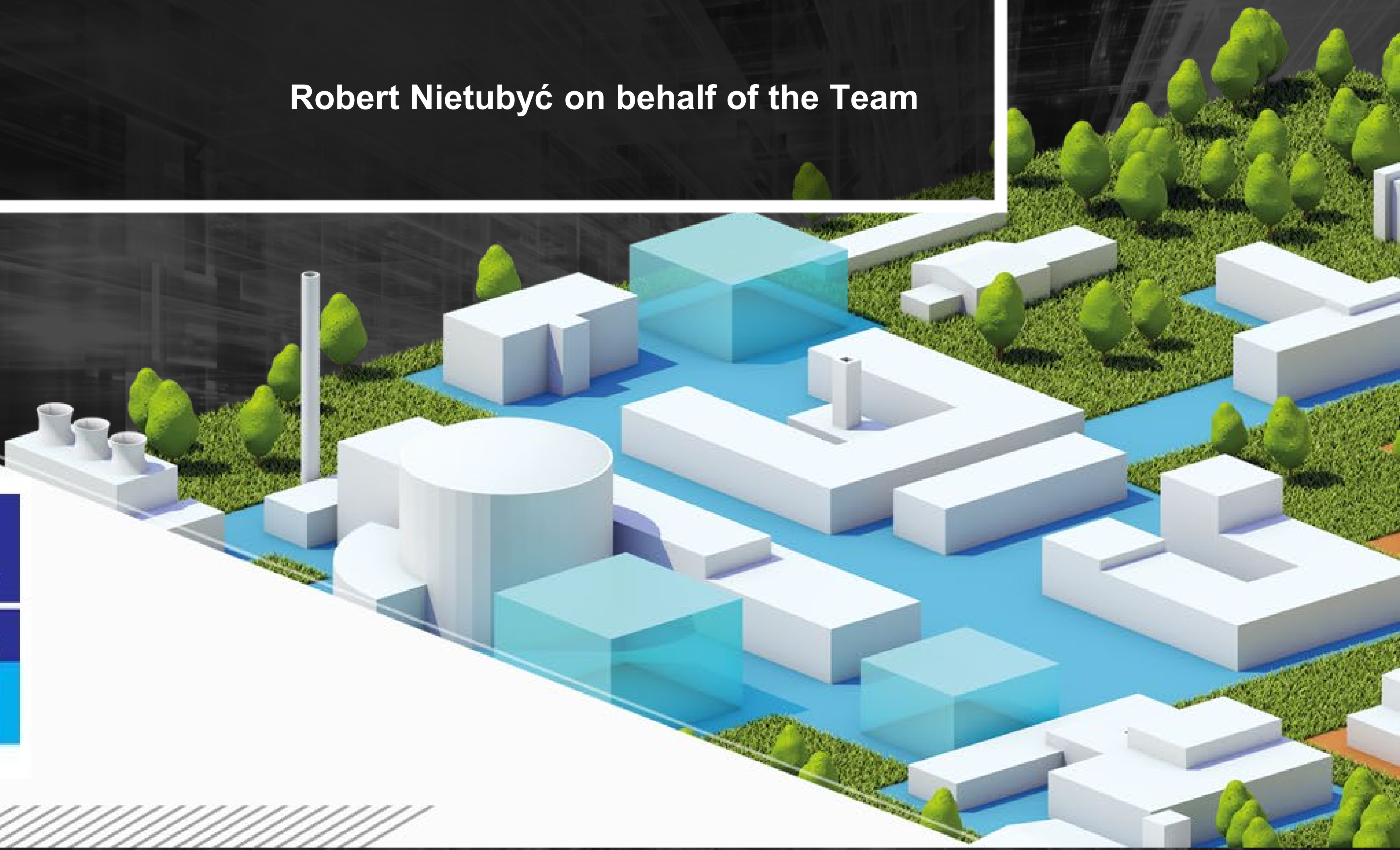
The PolFEL status

Robert Nietubyć on behalf of the Team



Introduction

PolFEL will be a scientific facility delivering broad spectrum of the radiation from **THz to EUV** and very short electron bunches for **UED** experiments. The PolFEL infrastructure includes two accelerators equipped with **sc accelerating cryomodules**. Advanced solid state laser system will be used to supply them with electron bunches and for high harmonic generation.

The aim:

- provide new research opportunities complementary to the synchrotron SOLARIS in Kraków.
- enable preparatory studies for experiments at large FELs, e.g. Eu-XFEL
- gather and foster accelerator physicists furnishing the capabilities for research and development activity,

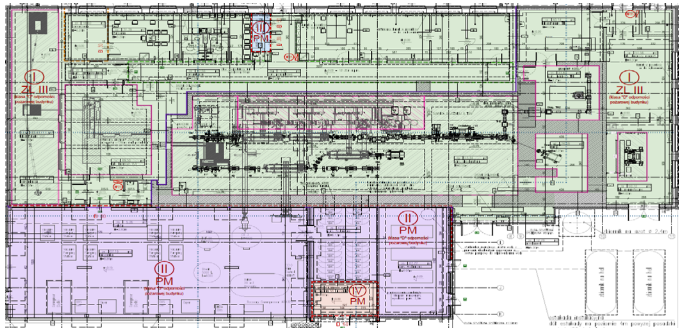
It will be built at the National Centre for Nuclear Research Świerk in Otwock (NCBJ)

The PolFEL facility has been designed by the Consortium of NCBJ and 7 Polish universities led by NCBJ:

- Military University of Technology - beamlines
- Warsaw University of Technology - LLRF
- Technical University Łódź - synchronisation
- Jagiellonian University -e beam diagnostics, survey
- Wrocław University of Science and Technology -cryogenics
- University of Zielona Góra – HVAC
- National Centre for Nuclear Research
- University of Białystok - inverse Compton scattering station

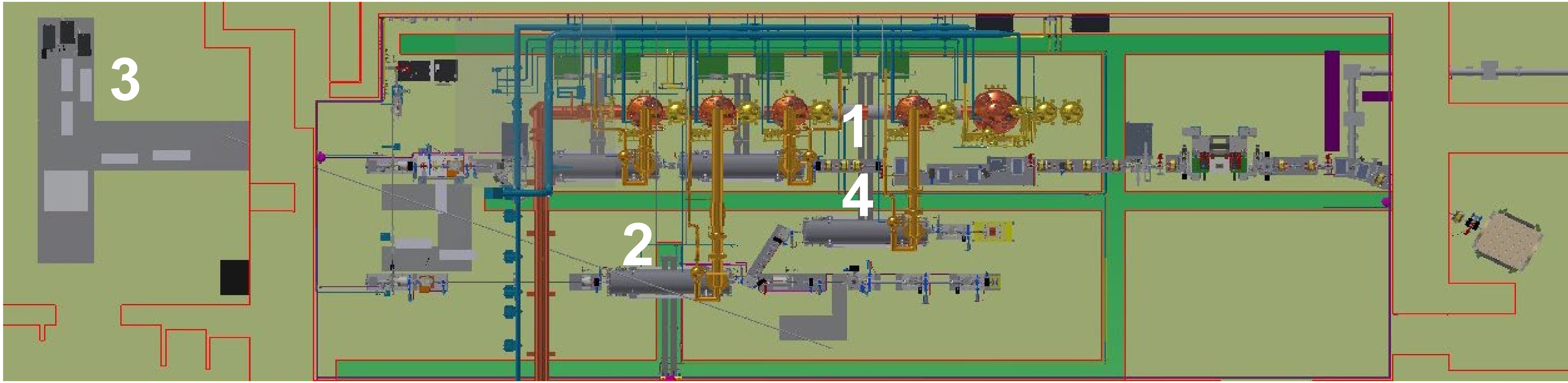
Design transformation

VUV source – 185 MeV all-sc, cw linac – 6 undulators -----------	THz source – half length linac - single undulator
IR source – ½ energy branch - 4 undulators ------------------------	
THz source – ½ energy branch - single undulator ---------------	
Cryomodule test stand ---	Cryomodule test stand
300 W liquefier --	170 W refurbished liquefier
Inverse Compton Scattering stage ------------------------------------	
Extended injector diagnostics --	Extended injector diagnostics
Gun assembly clean room ISO 4 ---------------------------------------	
Magnetic laboratory --	Magnetic laboratory
Computing centre---	Computing centre



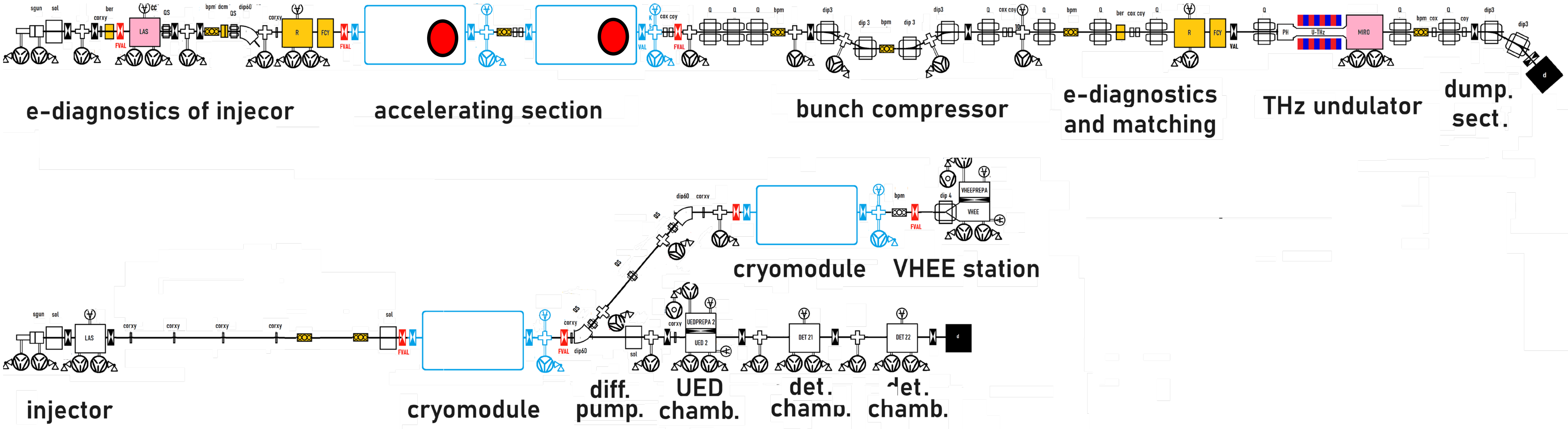
- cw-linac for UED
- HHG-EUV bemline tr-ARPES-TOF station
- 3.9 GHz 9-cells structure in THz linac
- 50 MeV electrons end station

Infrastructure



- THz linac with superradiant undulator and experimental station (1)
- UED linac and experimental station (2)
- HHG-EUV beamline (3)
- Cryomodules test stand (4)
- Solid state laser sources and experimental stands (in the separated laboratory)
- …

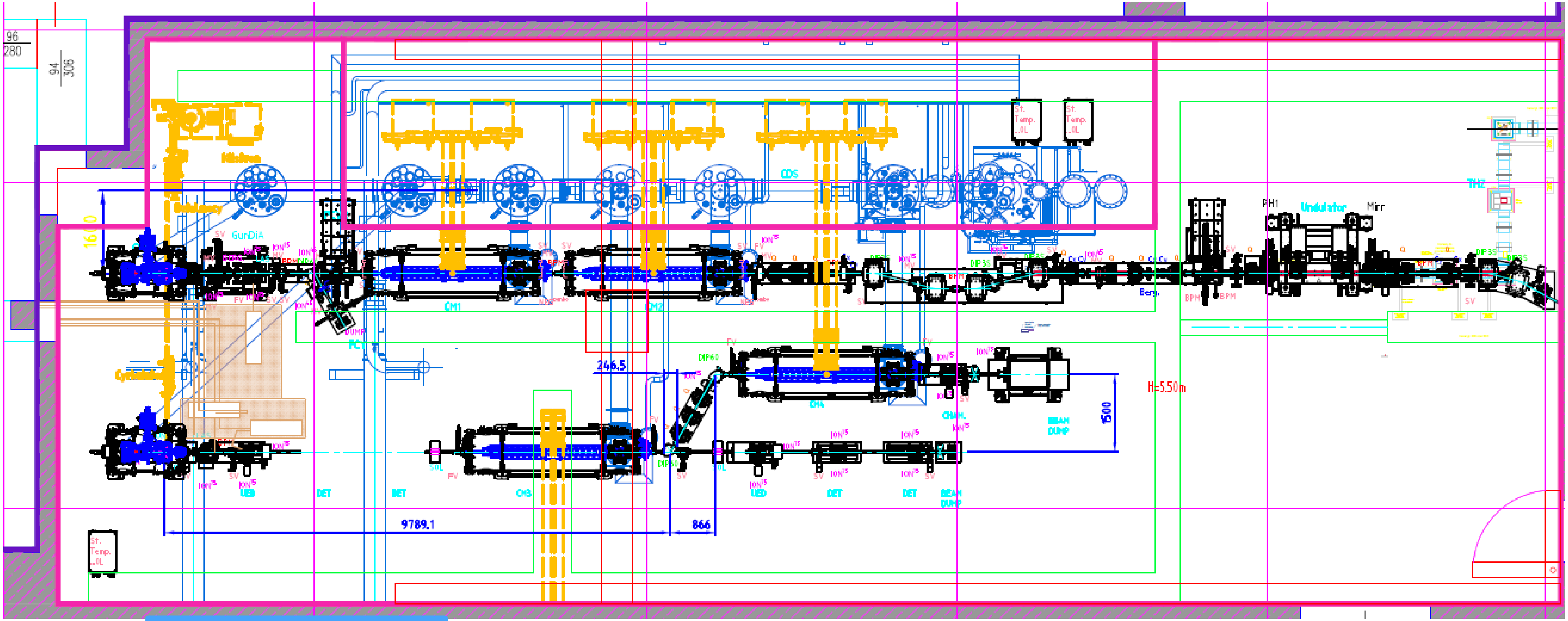
THz linac



- Initially a warm **S-band e-gun** will be installed, after commissioning it will be replaced with **an SRF injector**
- Accelerating section consists of **2 HZDR-RI-type cryomodules** powered with solid state amplifiers
- Diagnostic sections including Martin-Puplett interferometer for bunch length evaluation
- Air cooled magnets
- Planar tunable gap permanent magnet undulator

- **3rd harmonic RF structure** to replace one of Tesla structure aimed at bunch compression improvement

CDS and RF layout



cryoplant

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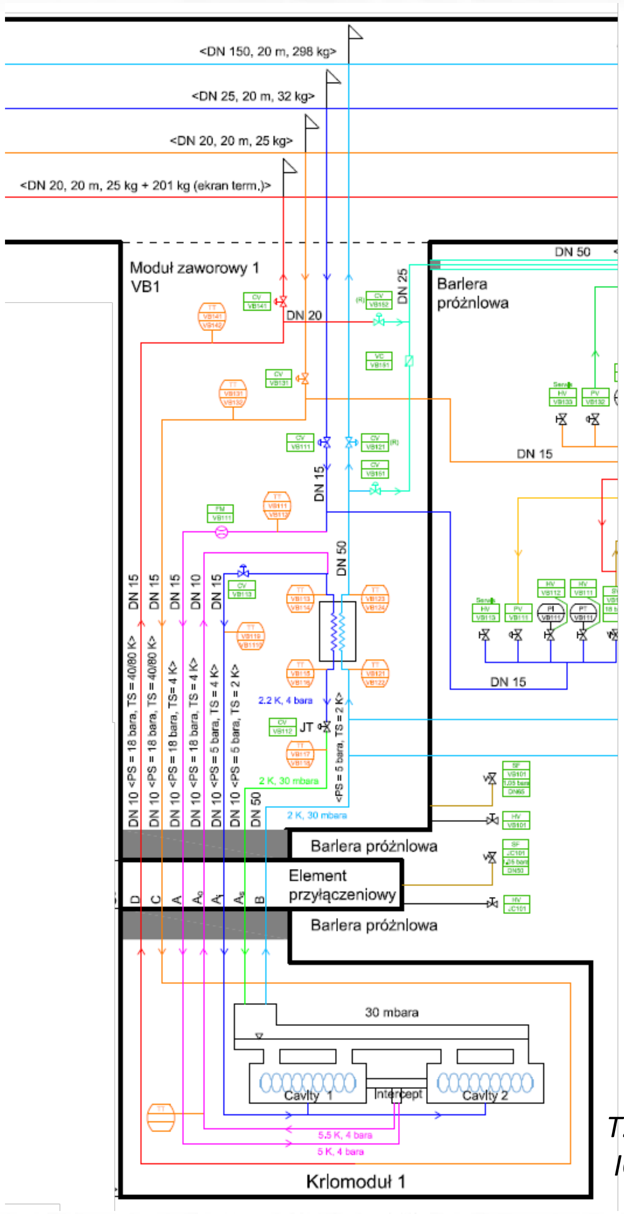
Cryogenics



Liquefier of:

- 170 W at 2 K
- 77 W at 5 K
- 500 W at 40 K
- 13 g/s He

Donated by STFC Daresbury, refurbished by Vorbuchner: original valve-box cleaned + additional valve-box

4-channels, 90 m long transfer line from liquefier to 6 valve-boxes,

- 40 K, 17 bara – thermal shieldings
- 5 K, 4 bara, – FPC
- 2 K 30 mbara– SRF structure

T. Banaszkiweicz et. al. Cryogenic Distribution System for Polish Free Electron Laser Facility
IOP Conf. Series: Materials Science and Engineering 1301 (2024) 012100

Politechnika Wrocławska

KrioSystem
CRYOGENICS IS OUR PASSION

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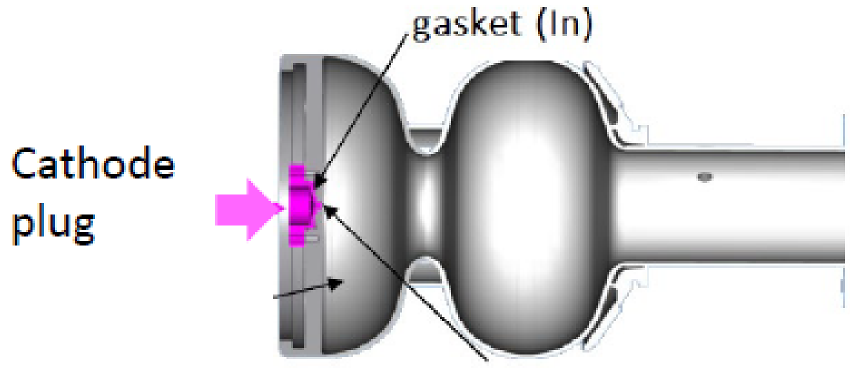
SRF injector

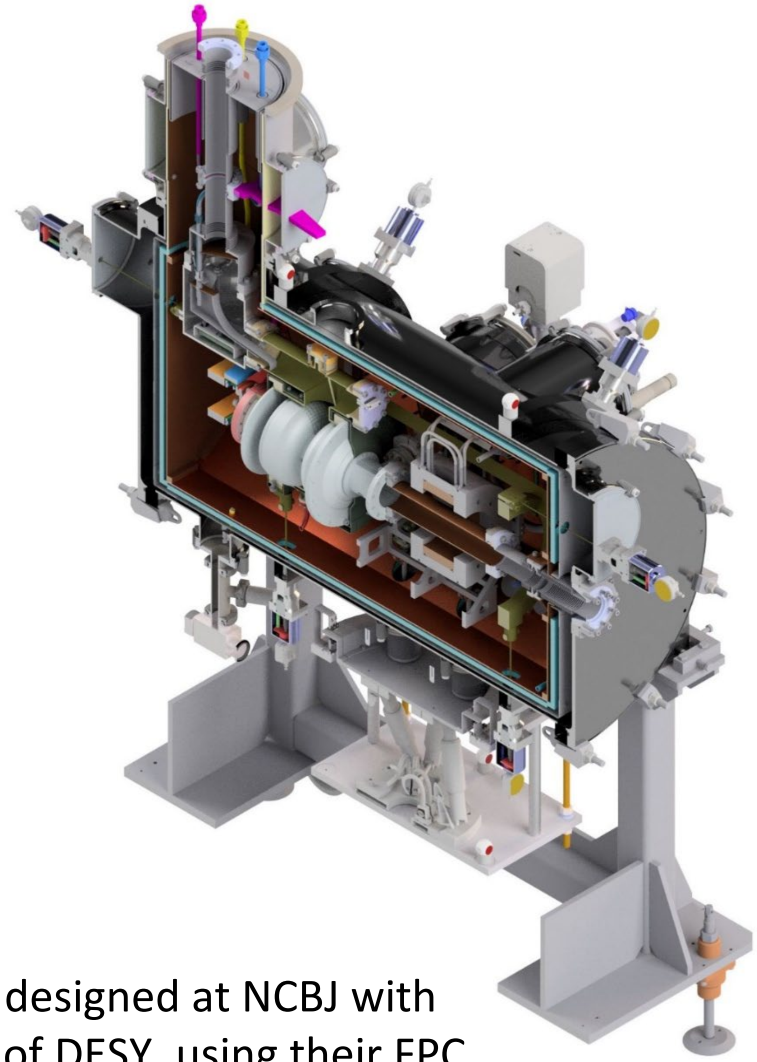
Parameters for the THz injector

parameter	value
Bunch charge	< 250 pC
Repetition rate	50 kHz
Bunch length	4 – 16 ps
Laser wavelength	257 nm
Pulse E on the cathode for 250 pC	6 μJ
Laser spot Φ on the cathode	50 μm
Available UV pulse energy	40 μJ



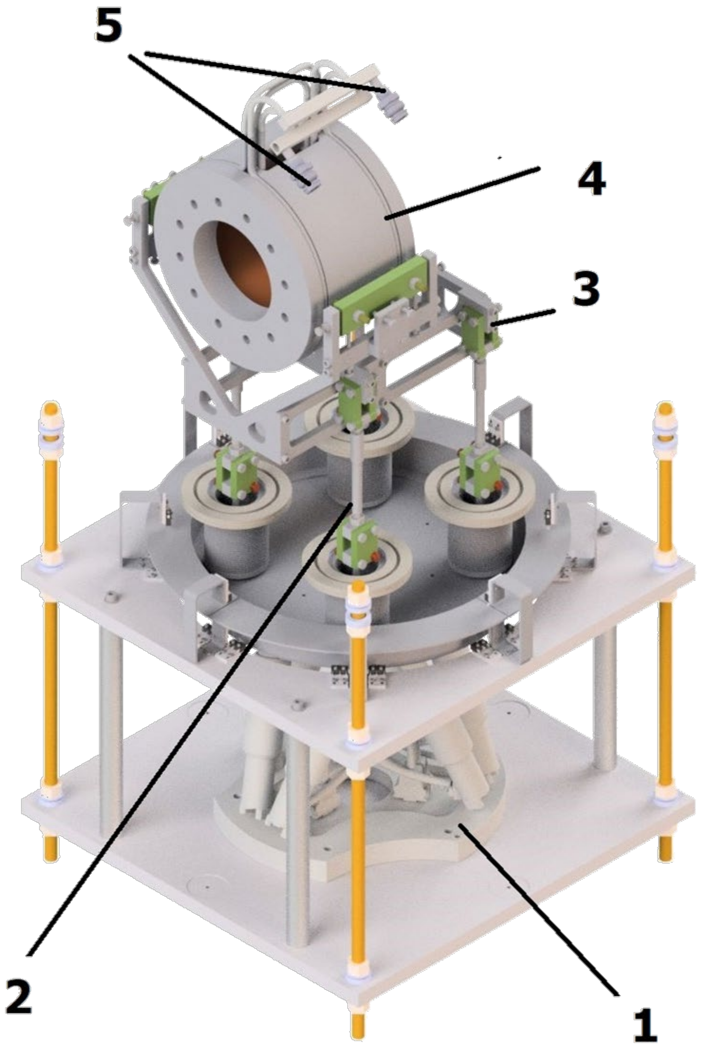
All Metallic Gun
Cavity under development at DESY

Considered metallic photocathodes:
Cu QE ≈ $2 \cdot 10^{-4}$
Mg/Mo QE ≈ $1 \cdot 10^{-3}$
at 257 nm



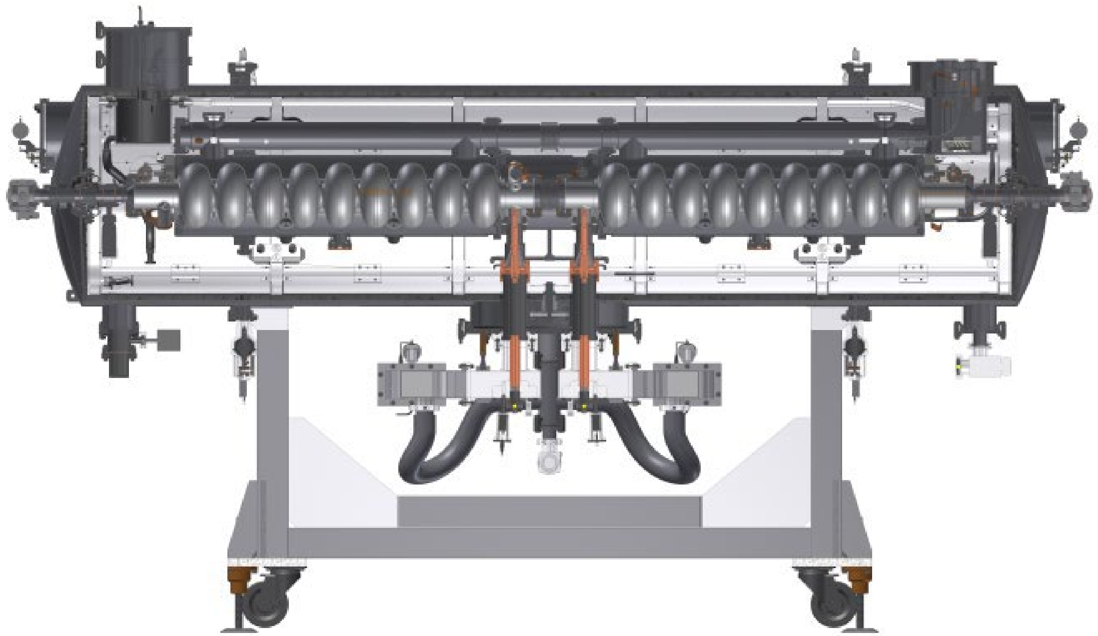
CM was designed at NCBJ with support of DESY, using their FPC and HZB/DESY tuner

Solenoid



1. Hexapod
2. Rods connecting cold and warm movable parts
3. Solenoid frame
4. Solenoid
5. LHe connections

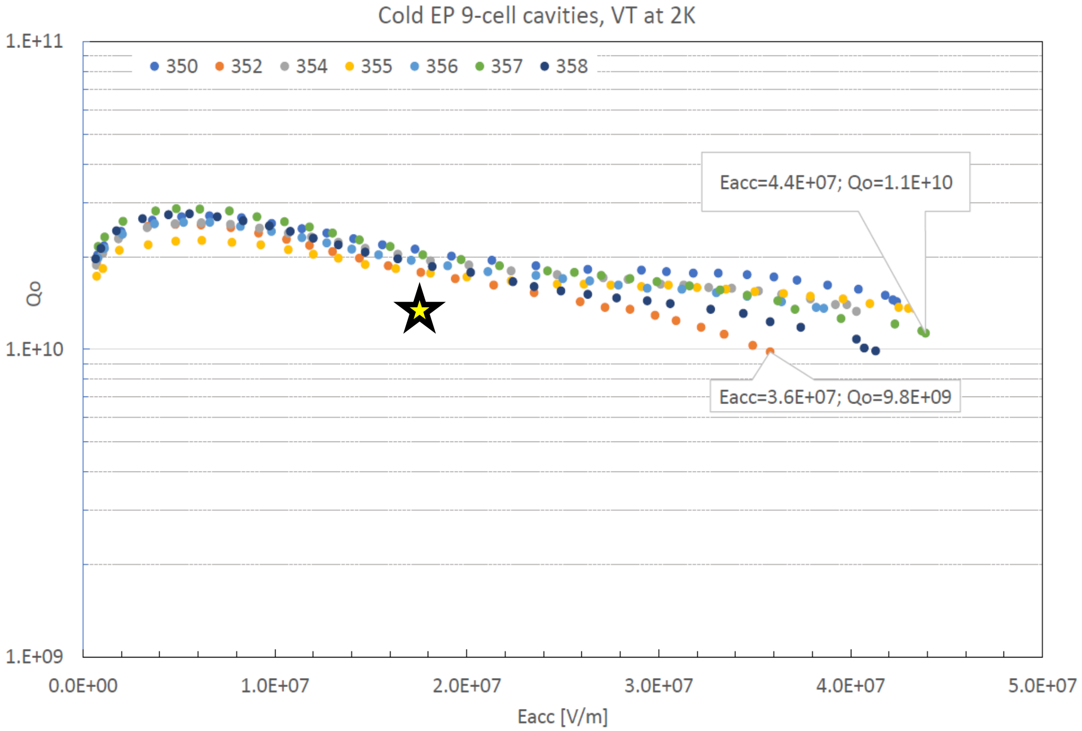
Polfel cryomodule based on HZDR – RI cryomodules



Required by order specification:

- **>18 MV/m while Q_0>1.2 10^{10}**
- Static cryogenic losses below 10 W at 2 K

Manufactured and delivered in 2023



Cold EP treatment significantly improved the quality
Vertical tests results Q_0 = 2.0 10^{10}

That saves the cryogenic power:
Dynamic losses at 18 MV/m Q_0 = 1.2 10^{10} : 57 W
Dynamic losses at 18 MV/m Q_0 = 2.0 10^{10} : 34 W
Acc. gradient at Q_0 = 1.2 10^{10} : 30 MV/m

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Cryogenic limitations vs E_e at cw

Assumptions:

- Total cooling power at 2 K: 170 W
- Stability margin: 30 %
- All structures always cold
- Gun static losses 7 W
- Cooling power in disposal at 2 K: 120 W (70% of total power)
- CM static losses 10 W

	Q_0	E_{acc} [MV/m]	E_e [MeV]	P_{dyn} [W]	P_{sta} [W]	P_{tot} [W]
THz in operation, UED stays cold	$2.0\cdot10^{10}$	13	54	43	54	97
THz in operation, UED in operation	$2.0\cdot10^{10}$	13	54	51	54	105
THz in operation, UED in operation	$1.5\cdot10^{10}$	13	54	63	54	117

THz and UED simultanous operation will be possible,

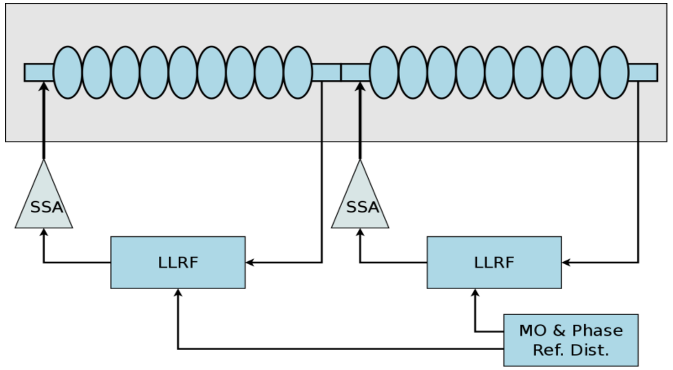
crossing the beams will be designed later on

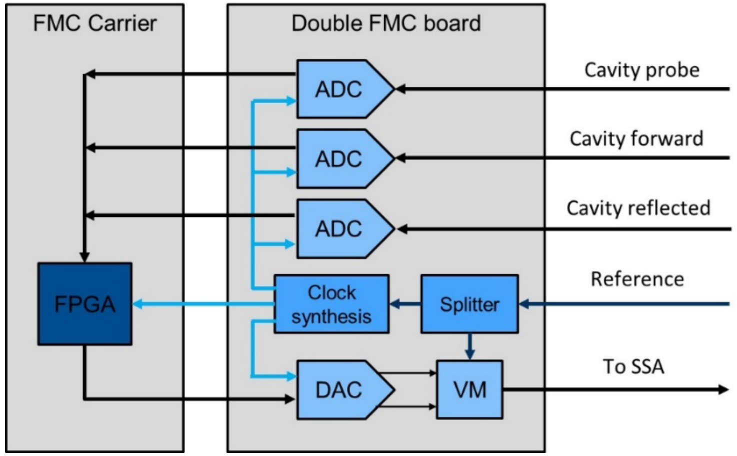
LLRF system architecture

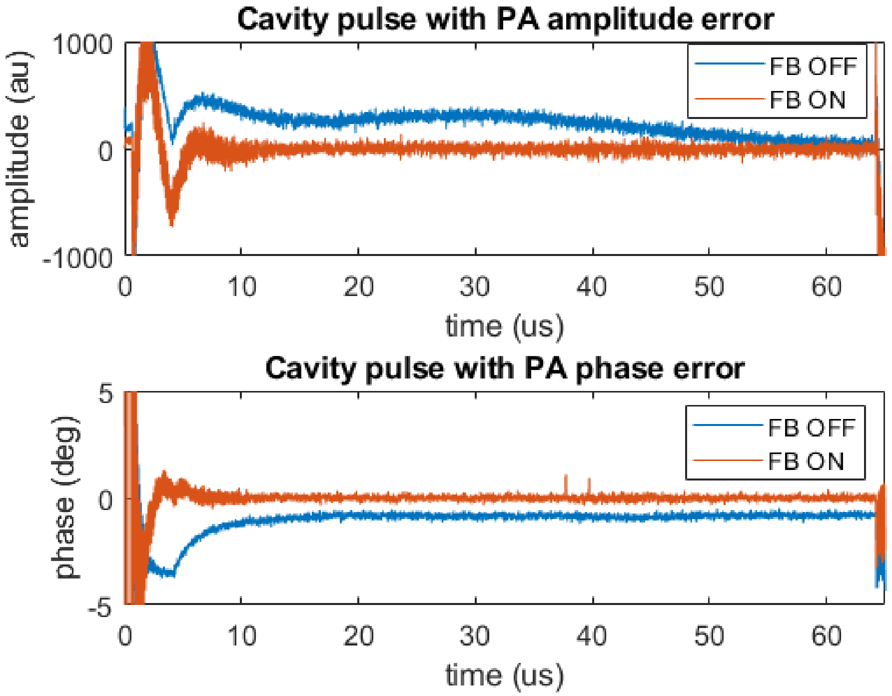
- Each cavity will be powered with a 5 kW SSA amplifiers
- Each cavity will be separately controlled by the LLRF loop enabling **individual setting of parameters** for operation

- Direct sampling RF detectors
- MTCA compatabile hardware

Performance:







dedicatedly for PolFEL

KUBARA LAMINA

Performance

THz linac: **E_{max} = 54 MeV at cw**
THz with two 3rd harmonic structures: **E_{max} = 30 MeV at cw**
f $\in$ 0.5 THz – 5 THz with E_{pulse} >1 µJ, at repetition up to 50 kHz

Higher electron energies will be available in long RF pulse operation

Further THz upward extension would be possible if only **the bunch is sufficiently short.** To facilitate that:

- Ti-sapphire laser for photocathode initialisation
- 3 rd harmonic structures installed in linac

Undulator

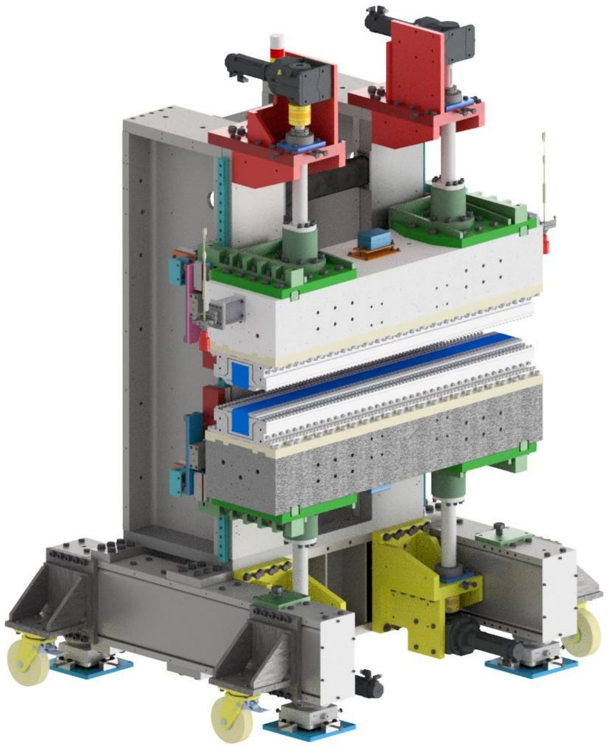
variable gap permanent magnet, planar

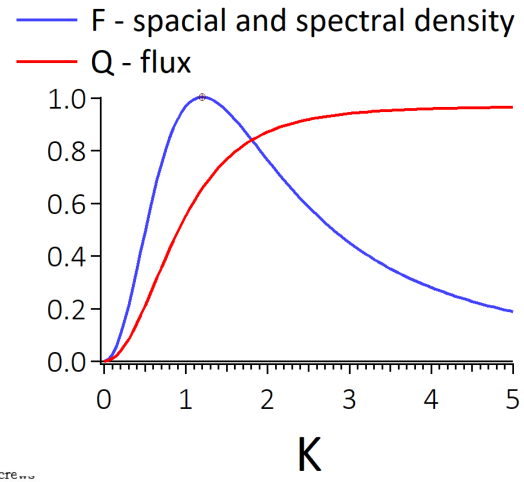
C-shaped frame

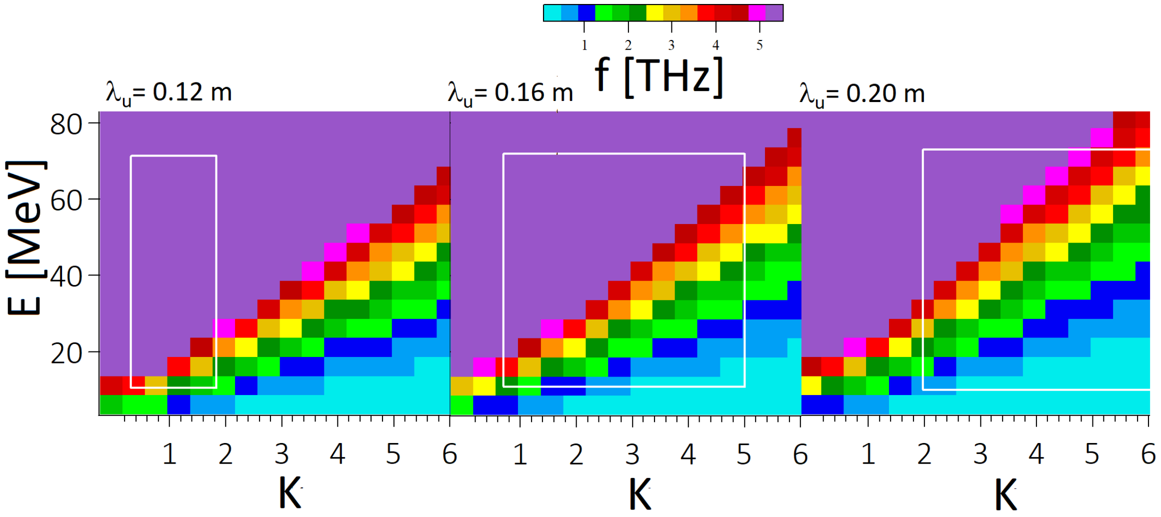
4 motors

Fully openable

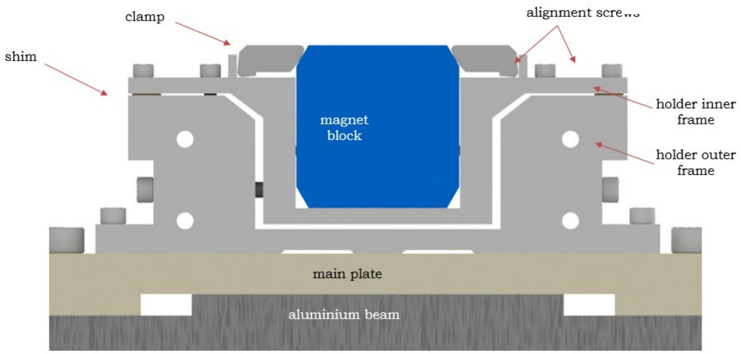
Has been in house designed and now beeing manufatured







will be published soon



parameter	value
material	NdFeB B_r=1.35 T
period	160 mm
number of periods	8
K range	0.7 – 5
gap	100 – 200 mm, 550 mm

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THz dynamics and photon output

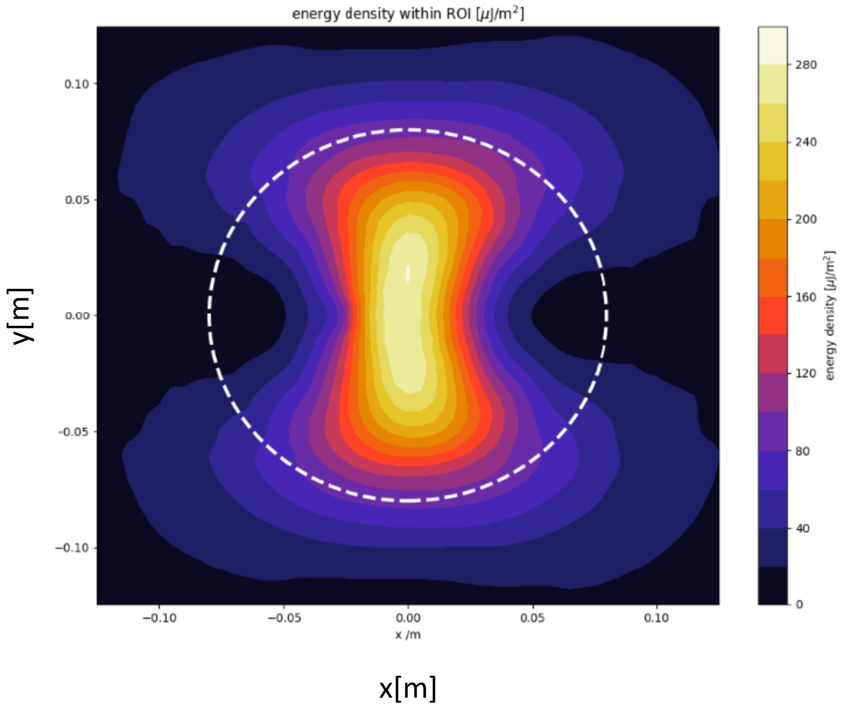
Simulations performed with Teufel programme for the in-house designed and manufactured superradiant 8 × 16 cm periods undulator for the beam of

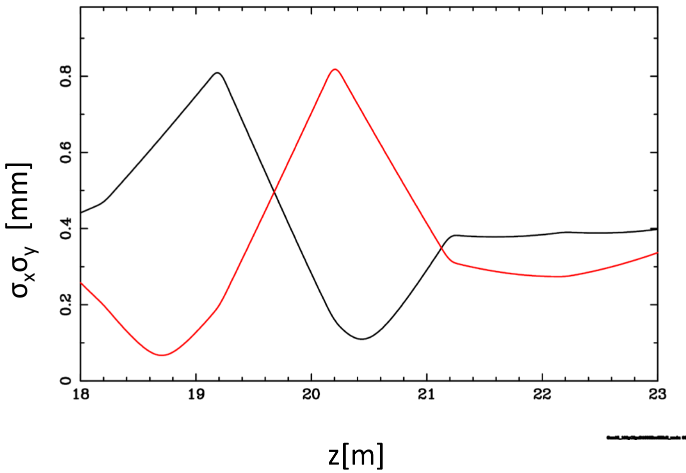
E_e=20 MeV, q_b = 75 pC, σ_z=65 μm, ΔE/E=0.001

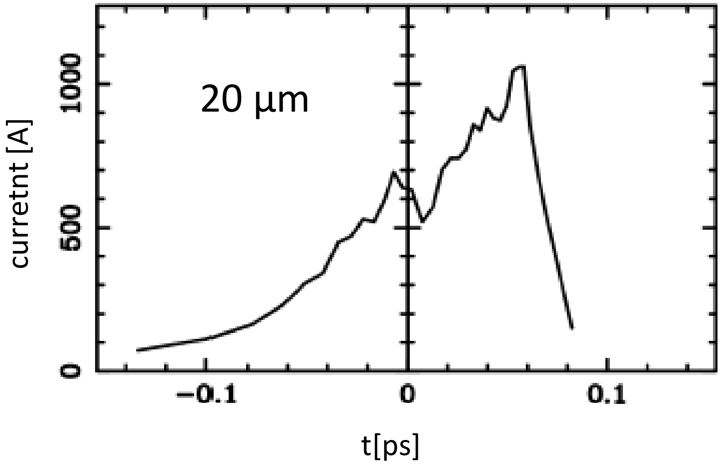
showed the beam imprint on the 75 cm distant decoupling mirror as shown on the figure.

Pulse energy deposited in the mirror **f= 1 THz** **E_{pulse}=1.5 μJ**

Recently much more effective beam have been simulated, so stronger THz pulse are expected. Simulations in progress.

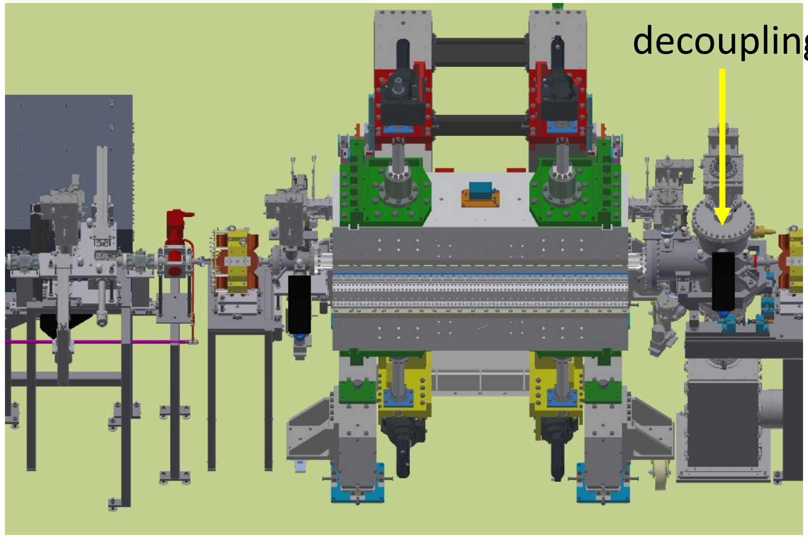






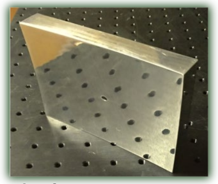
Bunch sizes as matched with 5 quadrupoles for 56.4 MeV, 100 pC

THz laboratory

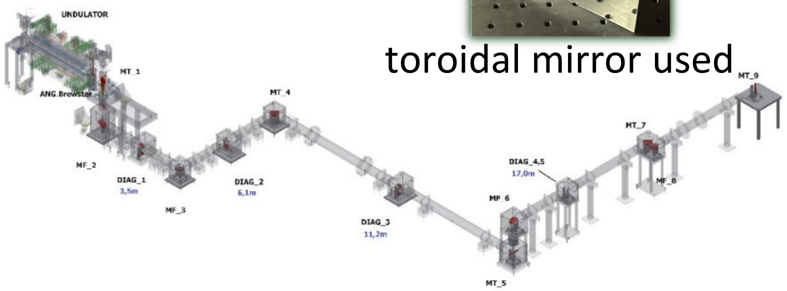


bemline elements as delivered

Beam transfer



toroidal mirror used



Instrumentation at experimental stand

- Cryofree refrigerator – 5K with transmission windows and reference detector
- Electrical measurement setup: oscilloscopes, multimeteres, lock-in voltmeters, SMUs, signal generators

The setup will be at the beginning fitted for temperature variable temperature transmission and reflection experiments

P&P setup with solid state IR laser pump and THz probe

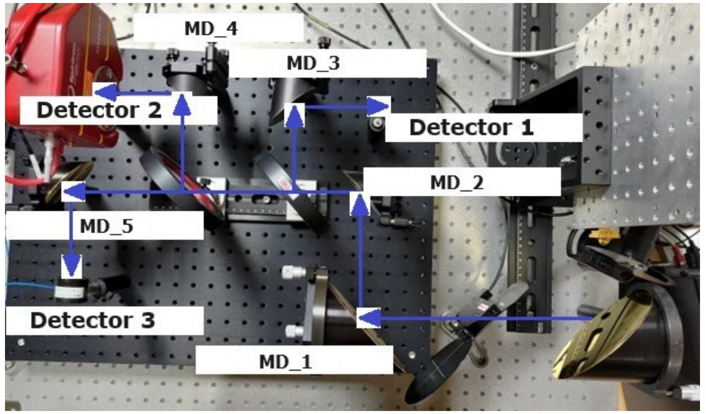
Diagnostics

Averaged

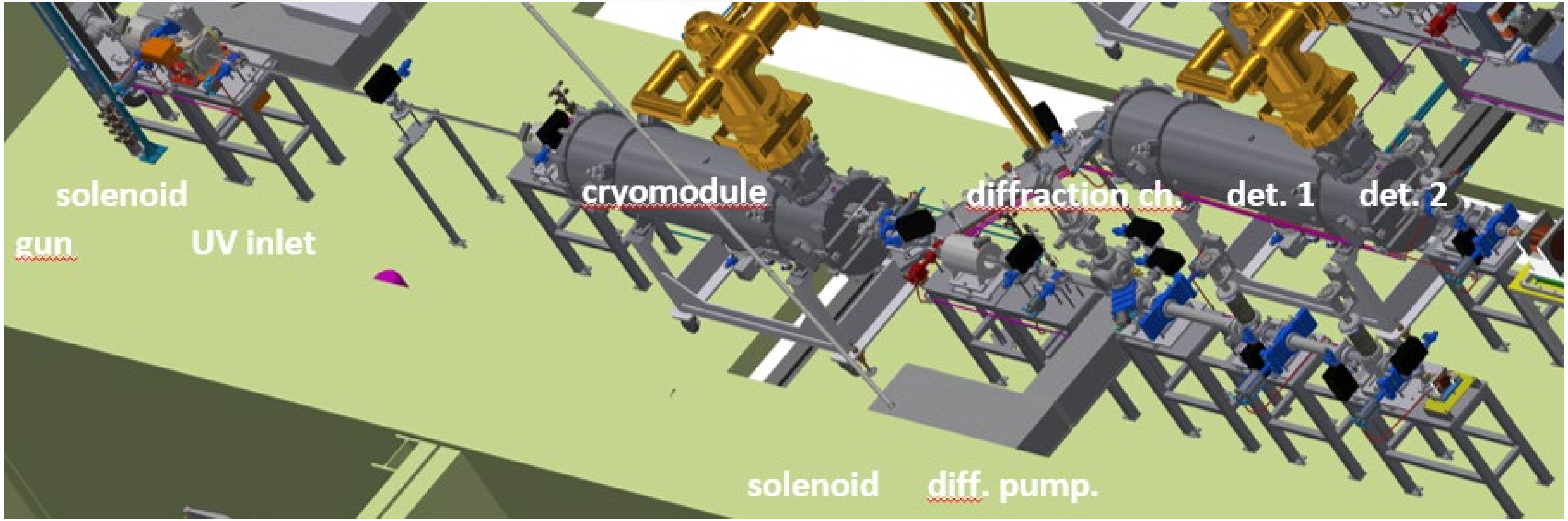
- Profilometer
- Power measurement
- MPI – wavelength measurement

Single pulse detection system:

- Pulse duration measurement
- Pulse energy measurement



UED



- Nd YLF 257 nm laser 250 fs pulse duration
- Two chambers will be available: for solid samples, and **for gasous** ones.

SRF injector

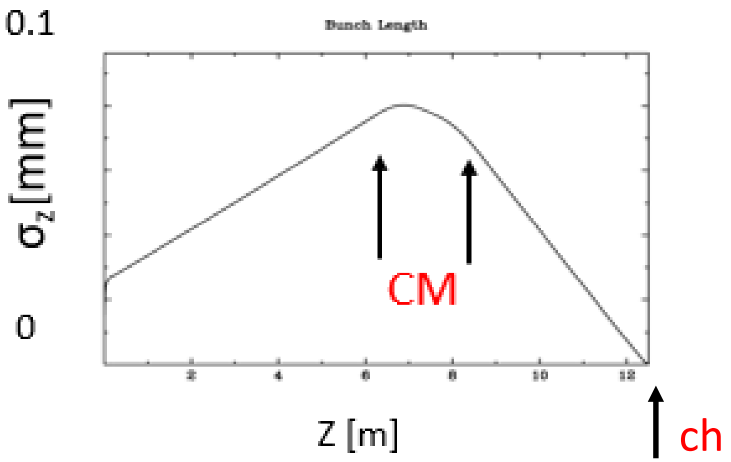
- makes it possible to operate in **cw operation with 200 kHz repetition** – advantageous for short low charged bunches

Cryomodule:

- energy tuning **2 MeV – 9 MeV**
- play with the RF amplitude and phases it is possible to achieve **ballistic compression of the bunch**

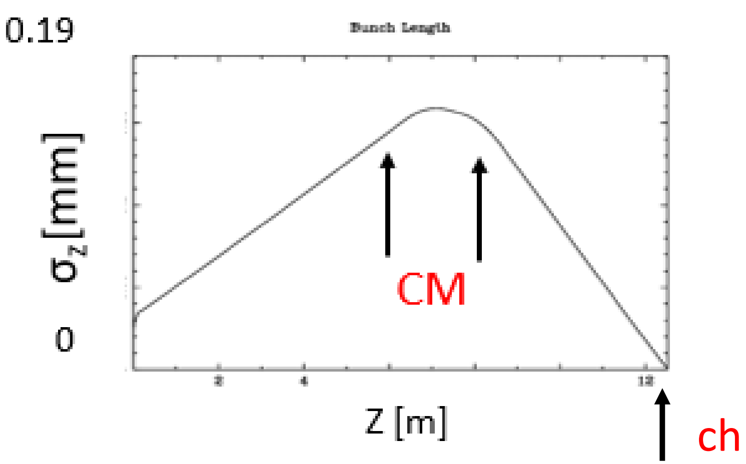
UED with SRF injector

ballistic bunch compression



For **35 µm** UV spot on and **1 fC** charge

σ_z = 1.1 µm



For **50 µm** UV spot and **100 fC** charge

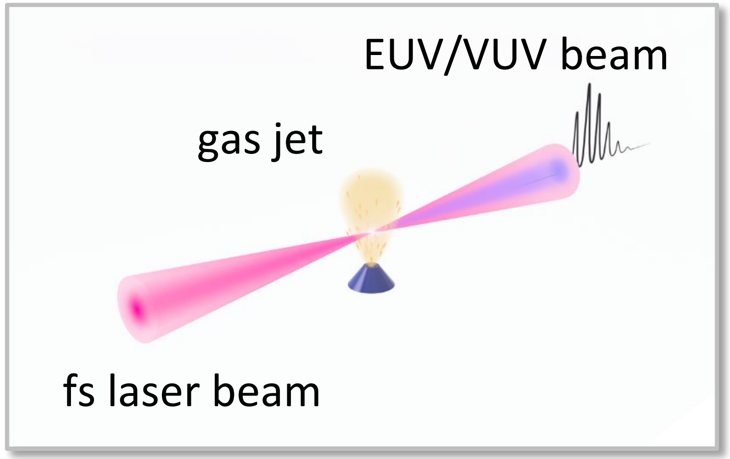
σ_z = 2.5 µm

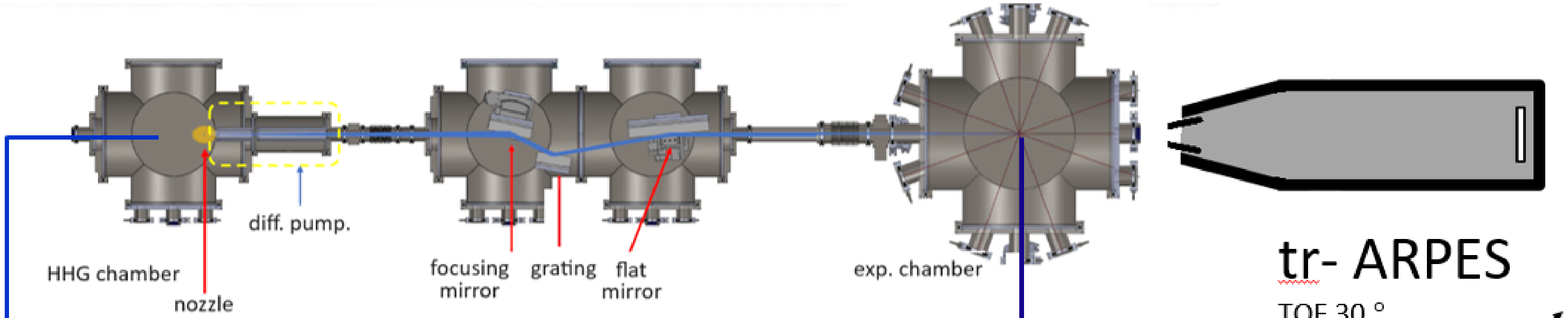
Spot FWHM [µm]	q [fC]	E [MeV]	Gun E_{acc} [MeV/m]	ε [π nm rad]	σ_t [fs]	σ_x [µm]	CM E_{acc} [MV/m]
10	1	2	20	2.9	1.5	104	0.7
10	1	5	25	3.1	0.6	83	5.0
50	100	2	20	23	7.9	88	0.7
50	100	5	25	23	8.9	94	19.4

will be published soon

VUV beamline based on high-order harmonic generation (HHG)

HHG process





For HHG probe: (1030 nm, 100 fs, 20 W avrage power, rep.rate up to 1 MHz)

Synchro-nization

Pump: (1030nm, 250 fs, 20 W av. power, rep. rate up to 1 MHz)

tr- ARPES

TOF 30 °

5000 e/imp · 1 kHz

LEED

PHAROS PH2-UP laser system

Center wavelength	1030 ± 10 nm
Maximum output power	20 W
Pulse duration	< 100 fs
Maximum pulse energy	0.4 mJ
Repetition rate	Single-shot – 1 MHz

$\varnothing = 50\ \mu m$

$2 \cdot 10^{18}\ W/m^2$

Ar

HHG EUV beam (probed with TR-ARPES)	
pulse energy	1 μJ
spectral width	8 nm
duration	< 100 fs
spectral range	25 nm – 80 nm
jitter	< 2 fs ?

Starting line to attosecond pulses

Support from Lund Laser Center (LLC) under Laserlab-Europe

Financing and implementation schedule

2018	Smart Growth Operational Programme,	25 MEUR
2024	National Recovery and Resilience Plan	31 MEUR
	NCBJ resources	30 MEUR
	Industrial in-kind contributions	4 MEUR
	total	**90 MEUR**

Status

- Linac design frosen
- Purchase and test of delivered devices go on
- Undulator, SSA, magnets assembly go on
- Hall reconstruction started week ago

Schedule

Linac sections assembly start	Dec 2024
Installation start	Aug 2025
Commissioning start	Jan 2026
THz beam	**June 2026**

European Funds Smart Growth
Republic of Poland
European Union European Regional Development Fund
NATIONAL RECOVERY PLAN
Republic of Poland
Funded by the European Union NextGenerationEU

Summary

- **THz source will be established complemented with UED and HHG-EUV source including tr-ARPES**
- Two sc linacs will be installed
- Installation will start in the mid of 2025, **first light in 2026**
- Domestic accelerator engineering capabilities (cryodistribution, SSA, injector, undulator, beamlines, LLRF, magnets, safety) have been involved…
- …supported and assisted with the experience of other laboratories: Daresbury, DESY, HZDR, HZB, Max IV…

Thank you for the attention

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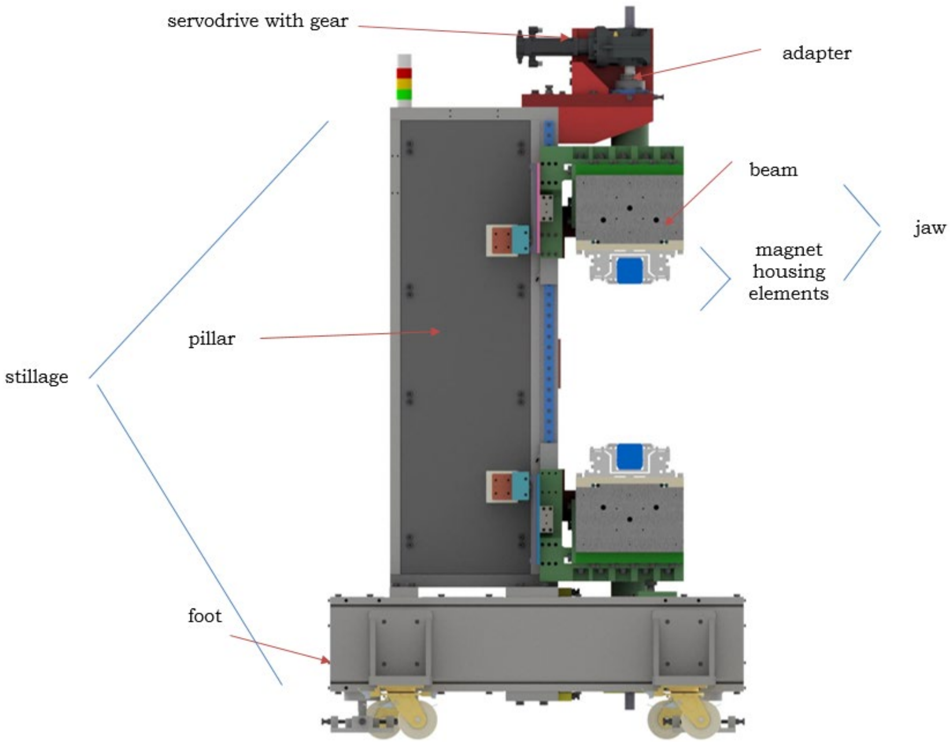
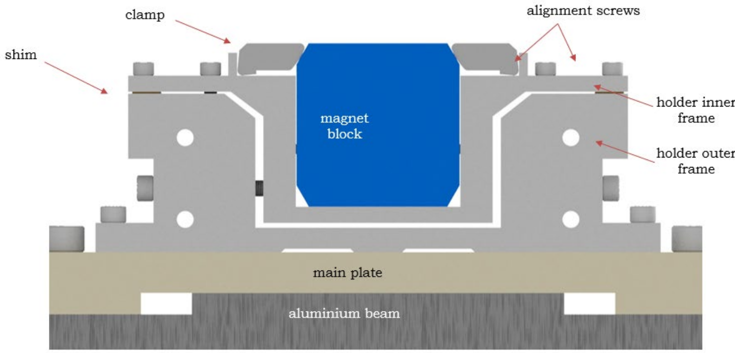
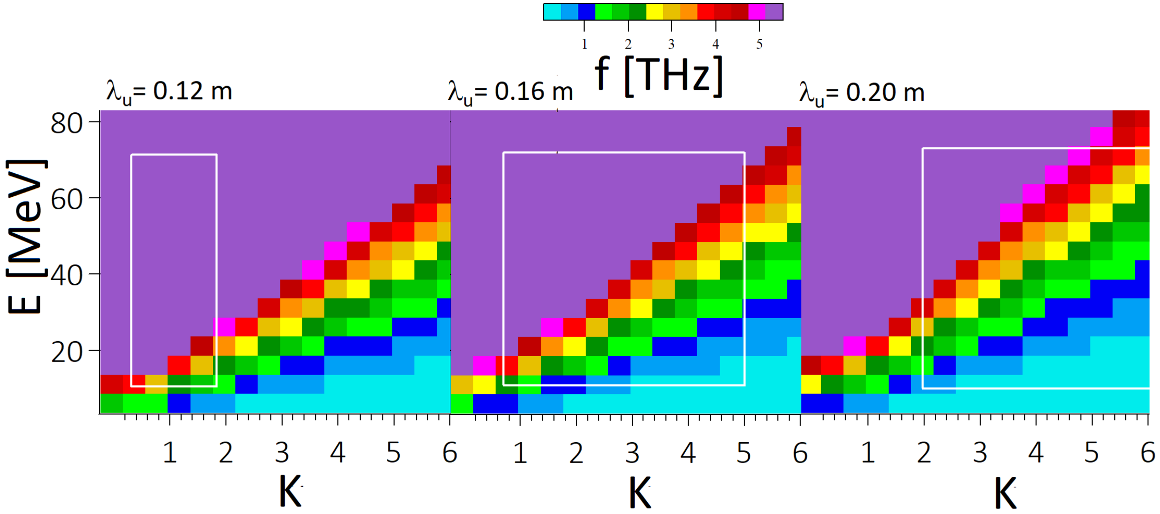
Undulator







For λ_u =16 cm the full f range 0.5 THz – 5 THz is available at reasonable K range

parameter	value
material	NdFeB B_r=1.35 T
period	160 mm
number of periods	8
K range	0.7 – 5
gap	100 – 200 mm, 550 mm

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 123106 (2014)

High-order harmonic generation using a high-repetition-rate turnkey laser

E. Lorek,[1,a)] E. W. Larsen,[1] C. M. Heyl,[1] S. Carlström,[1] D. Paleček,[2,3] D. Zigmantas,[2] and J. Mauritsson[1,b)]

TABLE I. The highest observed harmonic orders and corresponding photon energies generated in argon for different repetition rates and pulse energies.

Repetition rate/kHz	Laser pulse energy/μJ	Harmonic order	Photon energy/eV
20	<175	41	49.4
50	<90	35	42.1
100	54	33	39.7
200	30	27	32.5
300	20	21	25.3
400	15	19	22.9

TABLE II. The number of XUV photons per second as well as conversion efficiencies for the different harmonic orders generated in argon at 20 kHz and 100 kHz repetition rate. The pulse energy was 175 μJ and 54 μJ at the two repetition rates.

		20 kHz		100 kHz	
Harmonic order	Photon energy/eV	Number of photons generated/s $\times 10^{11}$	Conversion efficiency $\times 10^{-7}$	Number of photons generated/s $\times 10^{10}$	Conversion efficiency $\times 10^{-8}$
13	15.6	0.5	0.3	...	...
15	18.1	0.5	0.4	0.4	0.2
17	20.5	2.3	2.2	3.0	1.9
19	22.9	3.0	3.1	3.9	2.7
21	25.3	4.2	4.9	4.1	3.1
23	27.7	2.3	3.0	4.2	3.4
25	30.1	2.3	3.1	4.4	3.9
27	32.5	1.8	2.7	4.1	4.0
29	34.9	1.4	2.2	3.5	3.7
31	37.3	1.4	2.3	1.3	1.5
33	39.7	0.9	1.7	0.1	0.1
35	42.1	0.4	0.7	...	...
37	44.5	0.1	0.2	...	...
39	46.9	0.03	0.07	...	...
Total		21.1	27.0	29.0	24.3

PolFEL linacs

THz linac

parameter	value
Bunch charge	< 250 pC
Repetition rate	200 kHz
Electron energy	< 70 MeV at cw, 90 MeV at lp
Bunch length	0.2 – 5 ps
Beam current	< 50 μA
Transverse slice emittance	$< 0.6 \cdot 10^{-6}$ m·rad
Cooling power at 2 K	105 W
THz range	0.5 – 5 THz

UED linac

parameter	value
Bunch charge	10 – 100 fC
Repetition rate	200 kHz
Electron energy	< 9 MeV at cw,
Bunch length	3.5 fs
Beam current	< 50 μA
Transverse slice emittance	$< 0.6 \cdot 10^{-6}$ m·rad
Cooling power at 2 K	40 W
THz range	0.5 – 5 THz

Expected available cryogenic power at 2 K is 130 W (Daresbury liquifier) !

- **THz**: In the ultimate case, neglecting instabilities occuring while full cooling power operation, there will be possible to apply 15 MV/m and get 65 MeV electrons using 105 W + 27 W for UED cooling → 132 W
  Higher energies will be available with long pulsed mode (about 500 ms, duty factor = 0.5)

- **UED:** CM at most at 8 MV/m, cooling power expense will not exceed 40 W + 27 W for THz cooling → 67 W

The warm gun will be installed for the first beam commissioning. It will be replaced wit SRF cryomodule as soon as it is delivered

Spot sizes at UED

Warm S-band gun

Table 2: Beam parameters for the MaxLab photoinjector

Φ FWHM [μm]	q [fC]	E [MeV]	Gun E_p [MV/m]	ε [π nm rad]	σ_t [fs]	σ_x [μm]	Cryom E_p [MV/m]
10	1	2	55	3	**1.7**	**103**	0.8
10	1	5	55	3.2	**0.7**	**76**	5.3
10	1	9	55	S3.1	**0.4**	**24**	20.2
25	100	2	55	26.9	**5**	**109**	0.8
25	100	5	55	19.7	**2**	**94**	5.2
25	100	9	55	20.6	**5.4**	**91**	19.8

SRF L-band gun

Table 3: Beam parameters and Ep for the SRF photoinjector

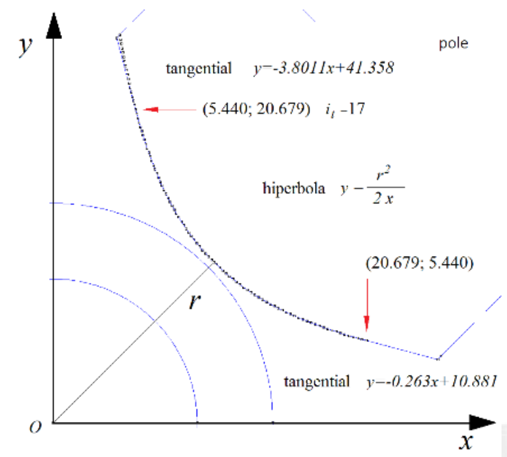
Φ FWHM [μm]	q [fC]	E [MeV]	Gun E_p [MV/m]	ε [π nm rad]	σ_t [fs]	σ_x [μm]	Cryom E_p [MV/m]
10	1	2	20	2.9	**1.5**	**104**	0.7
10	1	5	25	3.1	**0.6**	**83**	5.0
10	1	9	25	3.3	[illegible]	[illegible]	19.1
50	100	2	20	23,0	**7,9**	**88**	0.7
50	100	5	25	23.2	**2.1**	**110**	5.0
50	100	9	25	23.6	**8.9**	**94**	19.4

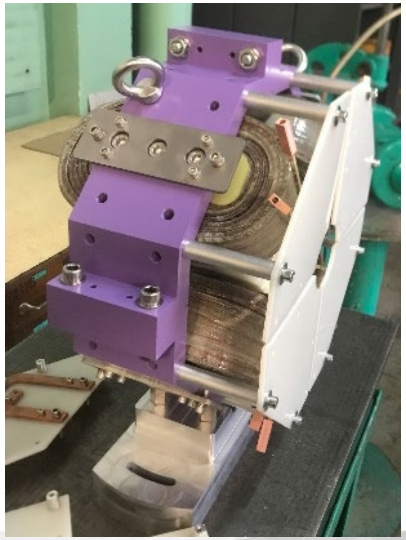
Obszar kreślenia

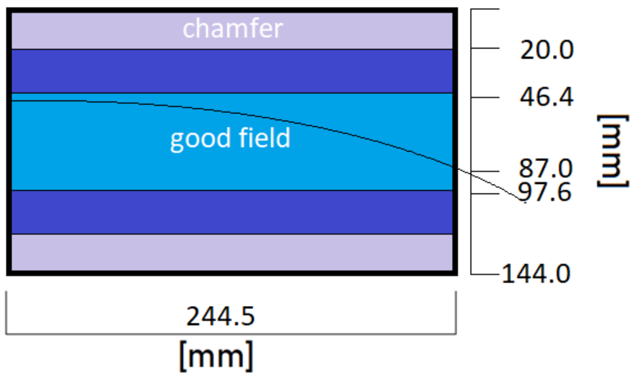
Magnets

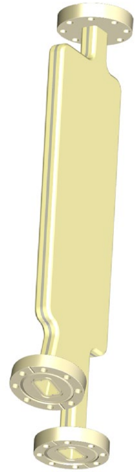
Main dipoles and quadrupoles have been designed and manufactured at NCBJ. Correctors and small dipoles and quads are being purchased

	number	gap or bore [cm]	B or B’ [T] or [T/m]	R or Leff [cm]	I [A]	N per coil	wire Ø [mm]	P [W]
solenoid	3		0.17	40				
small corrector	3	7.5	0.003	7.6	1.1	80	0.7	0.75
corrector	18	5	0.009	19	2.3	150	2.8	5
60° dipole	3	1.6	0.1	15	7	90	2	?
14° dipole	6	2	0.33	101	34	520	2.8	62
small quadrupole	5	2	4.3	4.8	1.7	110	0.5	?
quadrupole	10	3	17.4	10	20	150	2.8	40









NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Electron beam diagnostics

THz linac

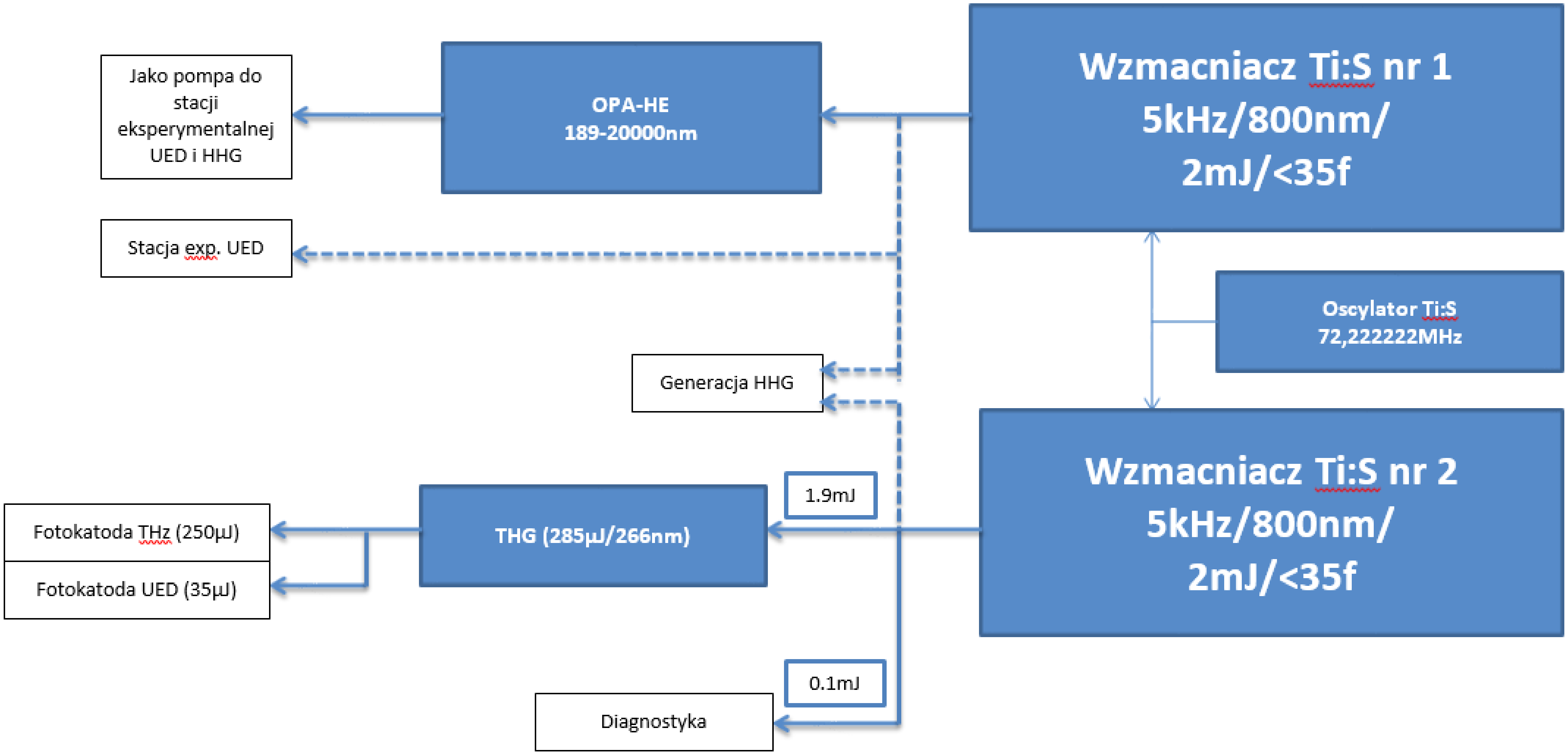
Location	diagnostics	instrument	comments
Injector E < 5 MeV τ < 8 ps	current	ICT	Bergoz
	Position and direction	2 × BPM	E-XFEL-type
	Bunch charge	Faraday cup	FCY chamber
	Beam profile	YAG screen	
	Bunch length	M-PI	Radiator chamber
	Dark current	DCM	E-XFEL like
	Emittance	2 × Quadrupoles	Together with YAG
	Energy spread	60˚ dipole spectrometer	with FCY chamber
prior to undulator E < 120 MeV τ < 1 ps	current	ICT	Bergoz
	Position and direction	2 × BPM	E-XFEL-type
	Bunch charge	Faraday cup	FCY chamber
	Beam profile	YAG screen	
	Bunch length	M-PI	Radiator chamber

more BPMs locations: between CM, behind CM, BC, dump sect.

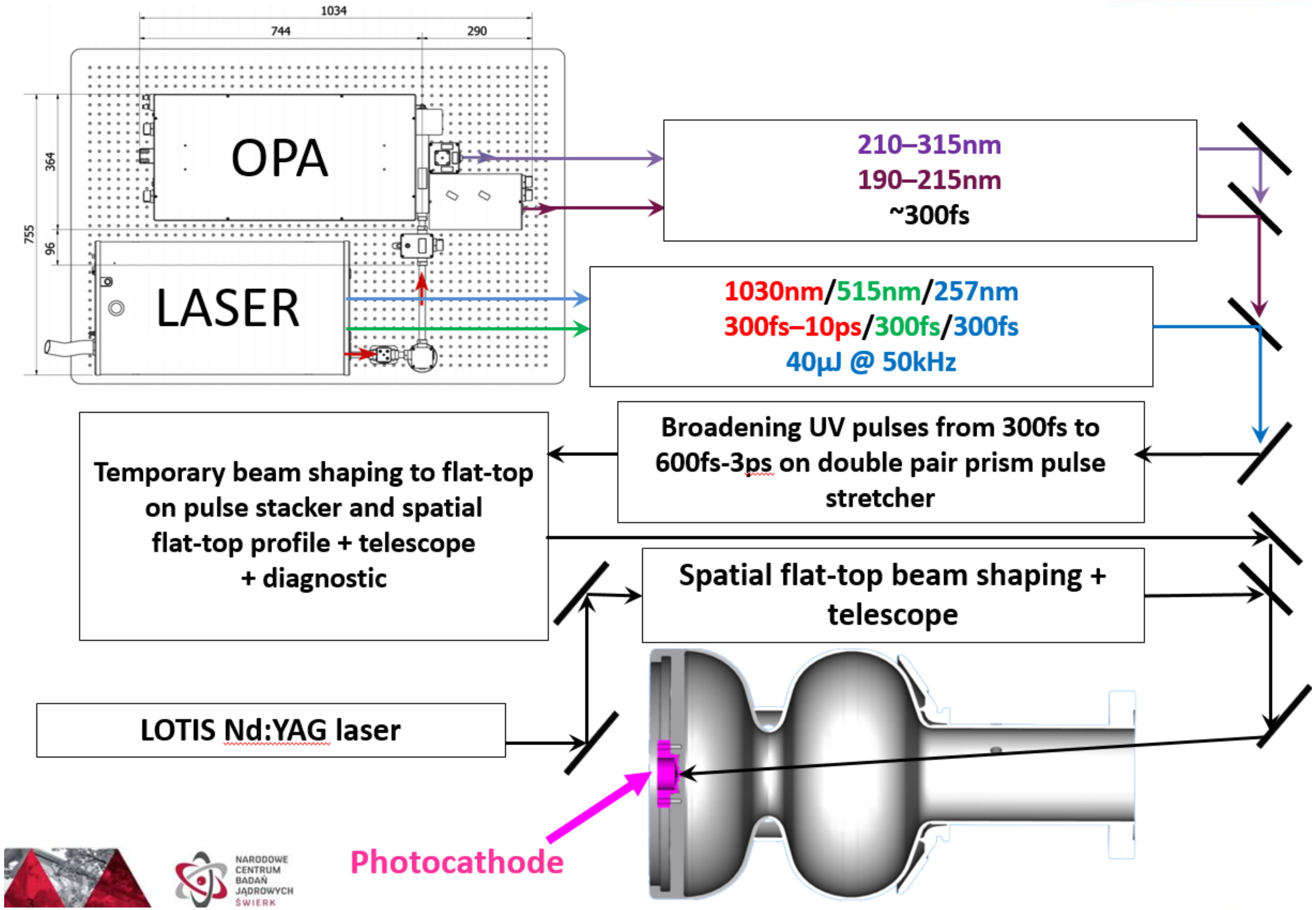
UED linac

2 × BPM in the injector section and YAG sceen in the experimental chamber. Diffraction pattern at the reference crystal.

Laboratorium fotokatodowe faza 1.1



Photoinjector laser system scheme



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