An Overview of IR/THz FEL Facilities

Glances at their THz diagnostic systems and results

Prach Boonpornprasert
PITZ Physics Seminar
25.03.2021

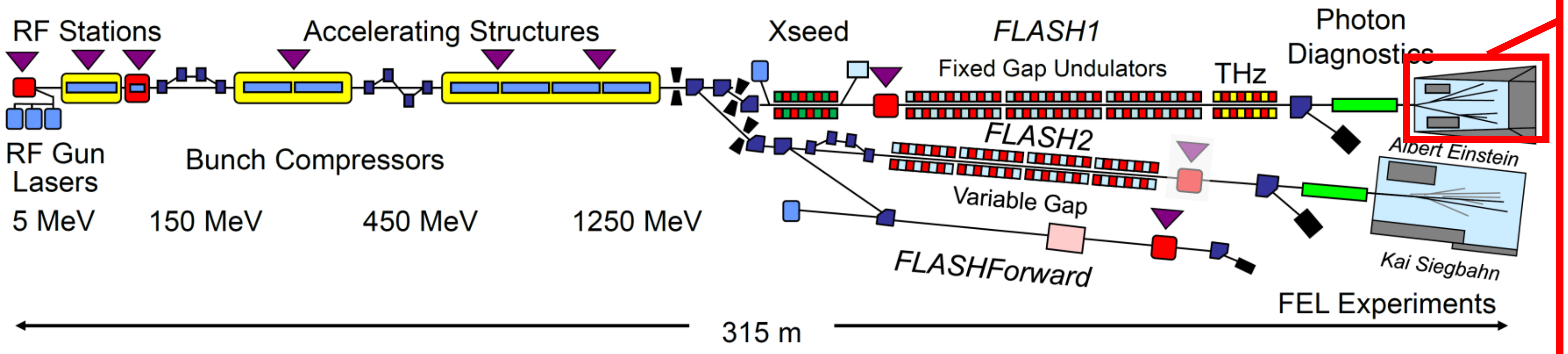
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

▪ FLASH THz Afterburner	@ Hamburg, Germany
▪ TELBE (ELBE-HZDR)	@ Dresden-Rossendorf, Germany
▪ Fritz Haber Institute (FHI)	@ Berlin, Germany
▪ CLIO (Paris University)	@ Orsay, France
▪ FELIX (Radboud University)	@ Nijmegen, the Netherlands
▪ Novosibirsk FEL (BINP)	@ Novosibirsk, Russia
▪ Kyoto University	@ Kyoto, Japan
▪ Tohoku University	@ Sendai, Japan
▪ CAEP THz FEL	@ Mianyang, Sichuan, China
▪ FELiChEM (USTC)	@ Hefei, Anhui, China
▪ 2 facilities in USA	
▪ Summary and Outlook	

FLASH: Superradiance undulator radiation

References:
- R. Pan et al., J. Synchrotron Rad. 26, 700–707, 2019
- T. Golz, PhD thesis, Universität Hamburg. 2018



Parameter	Value
Type	electromagnetic
Gap	40 mm
Period length	400 mm
Number of full periods	9
Total length	4455 mm
Maximum magnetic field	1.2 T
Maximum current	435 A
Maximum K value	49
Maximum total power	87 kW
Total weight	4490 kg

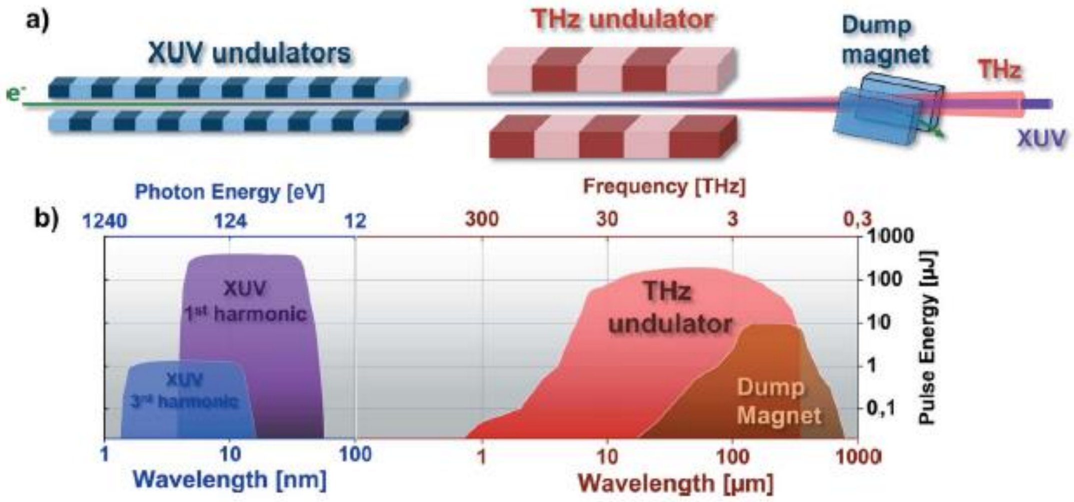


Figure 1
Scheme of the FLASH1 THz photon sources. (*a*) The THz undulator is located downstream of the XUV undulators, separated by free space. The electron beam dump magnet follows the THz undulator. (*b*) Representation of the pulse energies that can be obtained at FLASH1 from the XUV and THz sources over a wide spectral range.

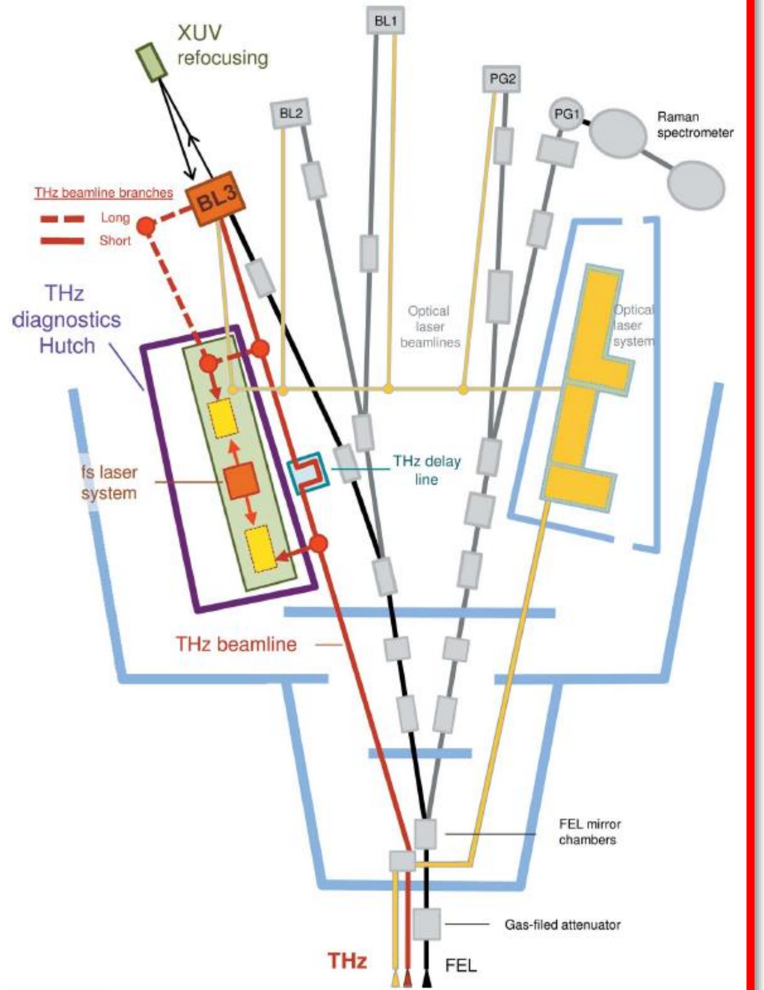


Figure 3
Scheme of the THz beamline in the FLASH1 experimental hall. THz beam is delivered to the end-station at the BL3 XUV beamline, via one of the two branches.

FLASH: Superradiance undulator radiation

References:
- R. Pan et al., J. Synchrotron Rad. 26, 700–707, 2019
- T. Golz, PhD thesis, Universität Hamburg. 2018

Topic	Detail
Gun	DESY L-band gun
Accelerator	Superconducting cavities
Bunch compressor	2 chicanes, 1 dogleg
Beam energy & bunch charge	< 1.25 GeV & 0.6 - 0.9 nC
Undulator parameters	Planar, λ_U = 400 mm, 9 periods, K_{max} = 49
Radiation mechanism	Afterburner undulator, edge radiation and bending radiation
Radiation wavelength/frequency	1 - 300 um (and 20 – 900 um)
pulse energy/power	Up to 150 µJ
Pulse repetition rate	1 MHz
Pulse duration	< 1 ps (micro), < 650 µs (macro)
Polarization	Linear and radial
THz window & environment	Diamond, UHV to HV
Power/energy measurement	- Radiometer RM3700 (Laser Probe) - Pyroelectric detector LMW-501(InfraTec)
Temporal profile measurement	- Electro-Optic Sampling (EOS) - Spectral decoding electro-optic detection (EOSD)
Transverse profile measurement	- Pyrocam III camera (Ophir) - Microbolometer camera
Spectral measurement	FTIR based on a reflective lamellar grating

The lamellar grating interferometer

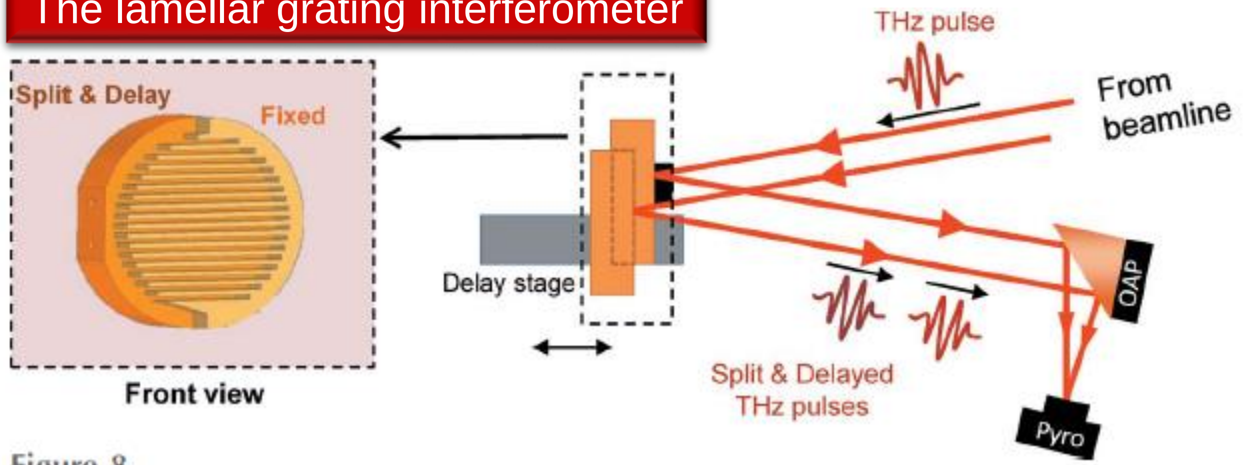
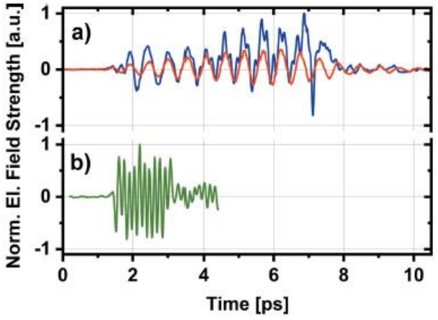
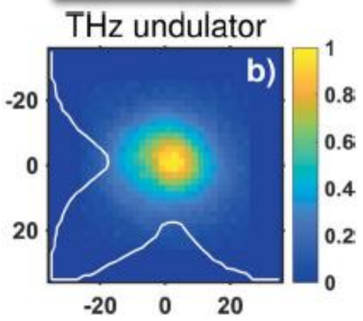


Figure 8
Scheme of the lamellar grating interferometer. OAP: off-axis parabolic mirror.

Measured EOSD



Measured transverse Profile



Measured interferogram

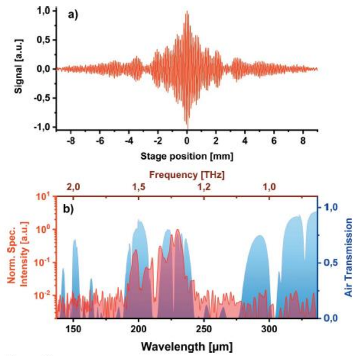
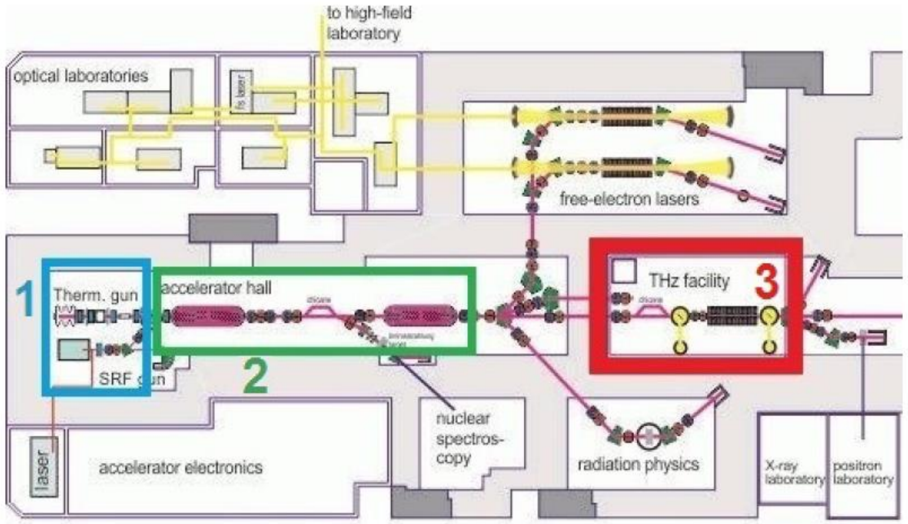


Figure 9
FTIR measurement for THz edge radiation with 215 µm (1.4 THz) THz bandpass filter. (*a*) Double-sided interferogram. (*b*) Respective spectrum (red curve) and air transmission with water vapor (in blue) show the strong absorption lines in this spectral range.

TELBE (ELBE-HZDR):
Superradiance Undulator Radiation

References:
- M. Gensch presentations
- B. Green, PhD thesis, KIT, 2017
- B. Green et al., Scientific Reports 6: 22256, 2016



THz pulse-resolved diagnostic system

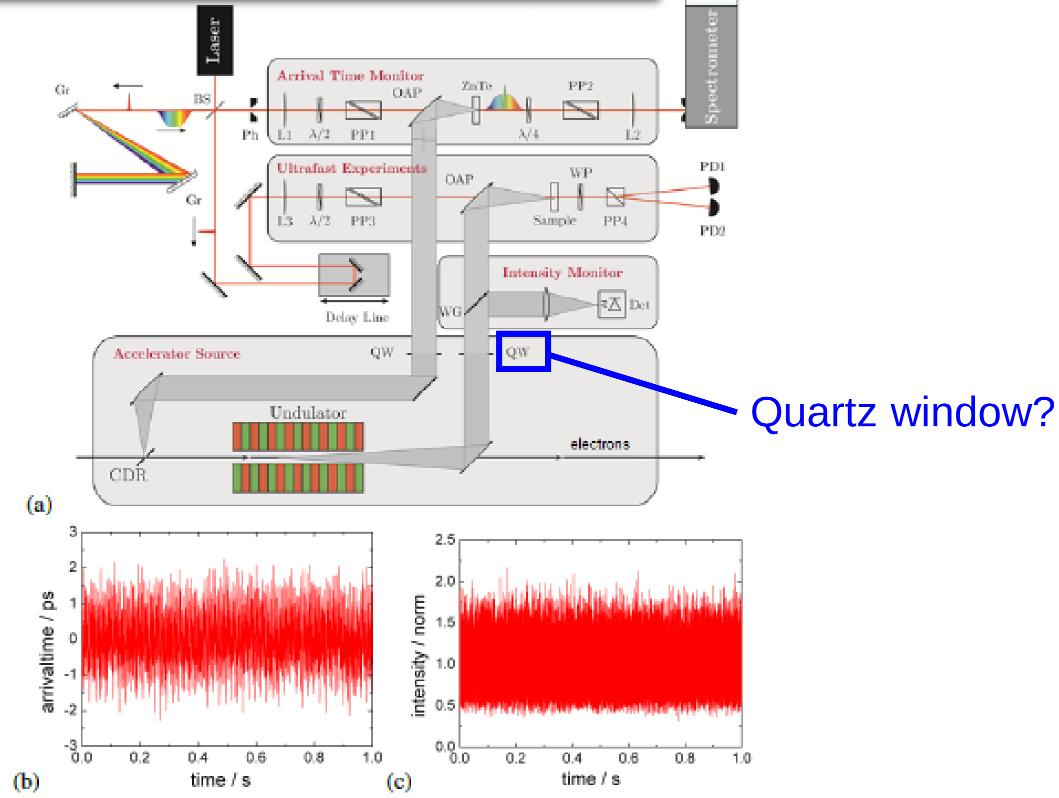
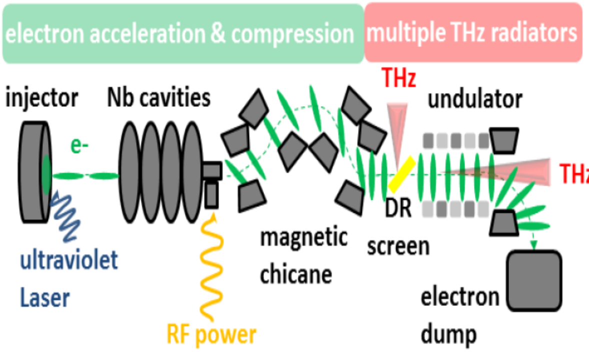
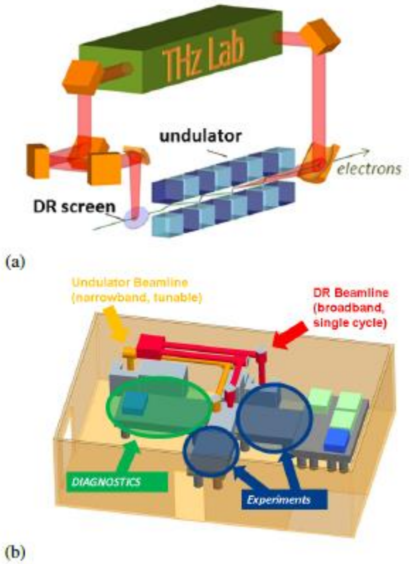


Figure 3.1: (a) Schematic diagram of the developed pulse-resolved diagnostic at the TELBE facility, combining a 30 fs (FWHM) resolution arrivaltime monitor with a pulse intensity monitor. (b) Arrival time of THz pulses over 1 second showing an arrivaltime jitter of around ±2 ps (FWHM). (c) Intensity of the THz pulses from the undulator tuned to 300 GHz taken over 1 second. Data taken using the thermionic injector, with a beam energy of 24 MeV and a bunch charge of 70 pC. Adapted from [7].





TELBE (ELBE-HZDR):
Superradiance Undulator Radiation

References:
- M. Gensch presentations
- B. Green, PhD thesis, KIT, 2017
- B. Green et al., Scientific Reports 6: 22256, 2016

Topic	Detail
Gun	Thermionic DC gun, SRF photo-gun
Accelerator	Two 1.3 GHz CW linacs
Bunch compressor	RF buncher, two chicanes
Beam energy & bunch charge	< 40 MeV & < 1 nC
Undulator parameters	Planar, λ_U = 300 mm, 8 periods, K < 8
Radiation mechanism	Undulator radiation
Radiation wavelength/frequency	0.1 – 3 THz
pulse energy/power	Several µJ – 100 µJ
Pulse repetition rate	1 - 200 KHz or 13 MHz (CW)
Pulse duration	Picoseconds (micro)
Polarization	Linear
THz window & environment	Quartz window
Power/energy measurement	- Pyroelectric detector - Schottky diode
Temporal profile measurement	- EOS - EOSD - Arival time monitor system
Transverse profile measurement	Pyrocam (Ophir)
Spectral measurement	FTIR (Bruker 80V)

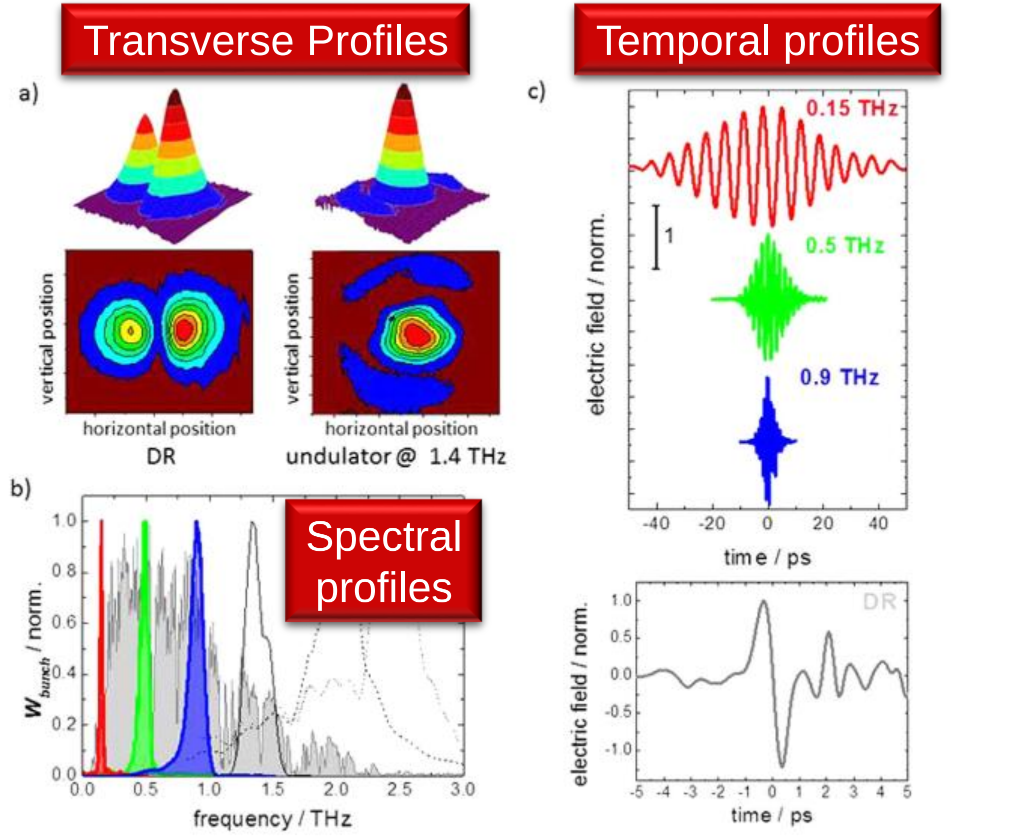


Figure 4. Experimentally observed source properties. (**a**) Beam profiles of DR and undulator radiation determined with a pyroelectric camera. (**b**) Normalized Spectra of a typical broadband DR pulse (grey-shaded) and narrow-band fundamentals of selected undulator tunes (0.15 THz–red-shaded, 0.5 THz–green-shaded, 0.9 THz–blue-shaded, 1.4 THz–black solid, 2.1 THz–dashed, 2.5 THz–dotted). The measurements for tunes to 0.15 THz and 0.5 THz were performed through appropriate band pass filters to remove the higher harmonic content. (**c**) (top) Electric-field transient of undulator pulse for tunes to 0.15 THz, 0.5 and 0.9 THz and (bottom) Electric field transient of a DR pulse taken under ambient conditions. Note that the notches in the frequency domain spectra as well as the ringing after the DR pulse in the time-domain measurements are due to water absorption lines from passage through air. Additional fringes are due to reflections in the ZnTe crystal.

Fritz Haber Institute (FHI) MIR FEL oscillator

References:
- W. Schoellkopf et al., Proc. of SPIE Vol.9512, 95121L, 2015

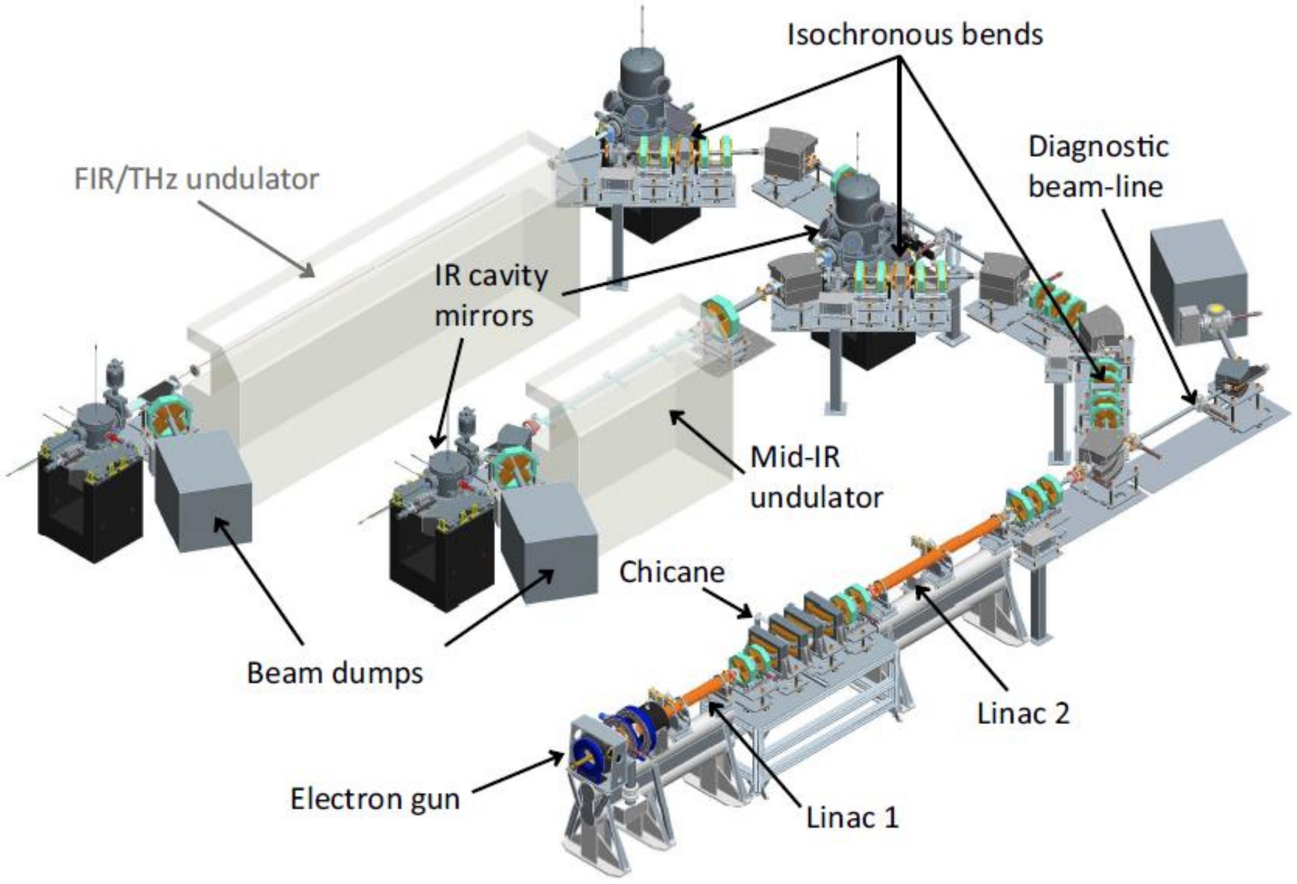


Figure 1. Overview of the FHI FEL installation showing the electron accelerator system, the MIR FEL (operational), and the FIR FEL (to be installed in the future).

Figure 3. MIR FEL with undulator (center to left) and cavity end-mirror chambers (right) as of 2015.

Parameter	Unit	Specified	Typical
Electron energy	MeV	15 - 50	18, 26 or 36
Energy spread	keV	50	< 50
Energy drift per hour	%	0.1	< 0.1
Bunch charge	pC	200	220
Micro-bunch length	ps	1 - 5	–
Micro-bunch rep. rate	GHz	1	1
Macro-bunch length	μs	1 - 15	10 or 12
Macro-bunch rep. rate	Hz	$\leq$ 20	5
Normalized rms transverse emittance	π mm mrad	20	–

	MIR	FIR
Undulator		
Type	Planar hybrid	Planar hybrid or PPM
Material	NdFeB	NdFeB or SmCo
Period (mm)	40	110
No. of periods	50	40
Length (m)	2.0	4.4
Krms	0.5 - 1.6	1.0 - 3.0
IR-cavity		
Length (m)	5.4	7.2
Waveguide	none	1-D 10 mm high

Fritz Haber Institute (FHI) MIR FEL oscillator

References:

- W. Schoellkopf et al., Proc. of SPIE Vol.9512, 95121L, 2015

Topic	Detail
Gun	Gridded thermiomic gun
Accelerator	Two S-band (2.99 GHz) standing-wave copper linacs
Bunch compressor	Subharmonic buncher, chicane, isochronous bends
Beam energy & bunch charge	15 – 50 MeV & 200 pC
Undulator parameters	Planar, λ_U = 40 mm, 50 periods, K = 0.5 - 1.6
Radiation mechanism	FEL oscillator
Radiation wavelength/frequency	4 – 48 µm
pulse energy/power	5 – 10 µJ (micro)
Pulse repetition rate	1 GHz (micro), 5 Hz (macro)
Pulse duration	1 – 5 ps (micro), 10 or 12 µs (macro)
Polarization	Linear
THz window & environment	Diamond, UHV to unknown
Power/energy measurement	- photovoltaic IR detector (VIGO PEM-10.6) - Powermeter (Ophir PE50BB) - Pyroelectric detector (Eltec 420M7-0) - a sensitive liquid-nitrogen cooled MCT (Judson J15D24)
Temporal profile measurement	?
Transverse profile measurement	?
Spectral measurement	an in-vacuum Czerny-Turner grating spectrometer (Acton VM-504)

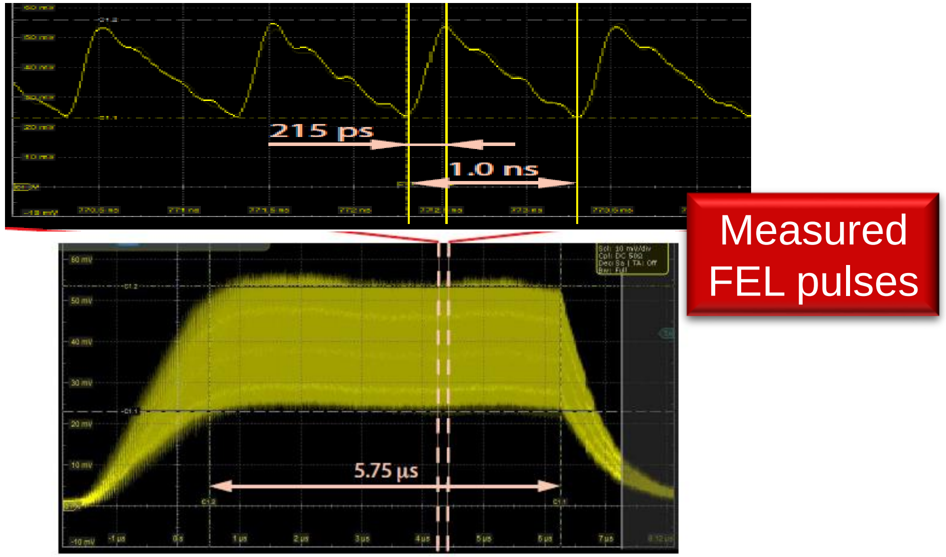


Figure 4. Detection of an FEL macro pulse at 6 μm wavelength with partial resolution of micro-pulses. The measurement was done using a fast detector from VIGO, model number PEM-10.6 in combination with a 4 GHz oscilloscope.

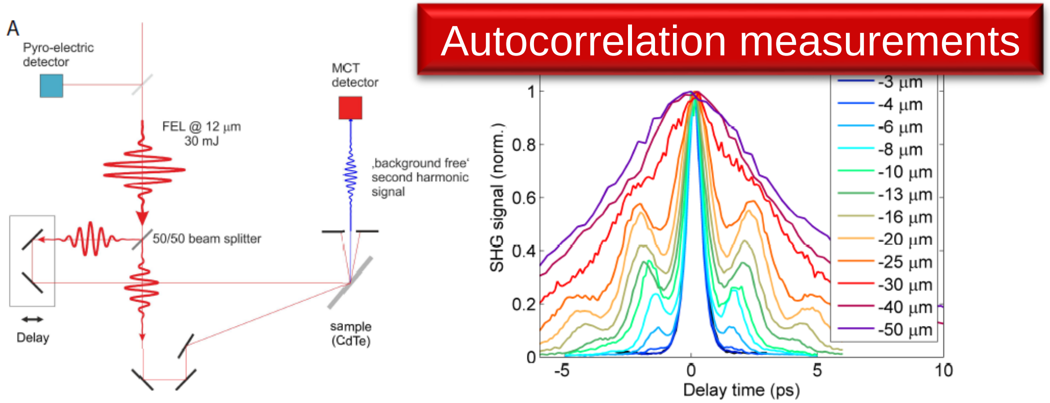
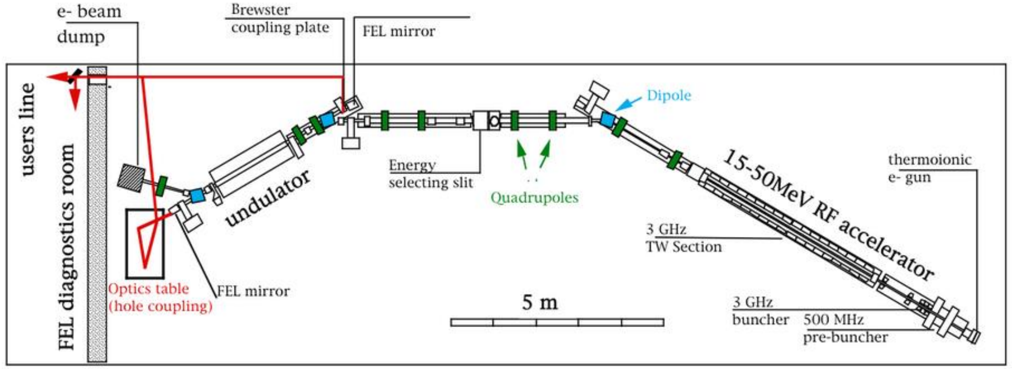


Figure 6. Autocorrelation measurements. A schematic of the autocorrelation setup is shown in (A). In (B) the second harmonic signal is plotted as a function of the path length difference for various cavity detunings. In these measurements at a wavelength of 12 μm the electron macro-bunch length was set to 6 μs leading to 1-4 μs long optical macro-pulses depending on the actual gain for a given detuning ΔL. The absolute values of ΔL might be shifted since the absolute cavity length corresponding to $\Delta L = 0$ is not exactly known and can only be estimated.

CLIO: FEL oscillator

References:
- http://old.clio.lcp.u-psud.fr/clio_eng/accel.html
- J.K.Ortega et al., IPAC2014, THPRO004



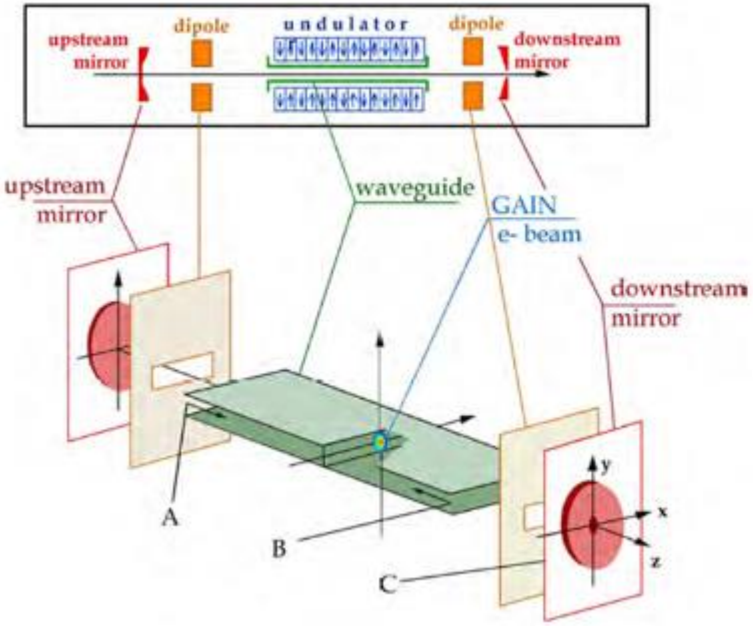
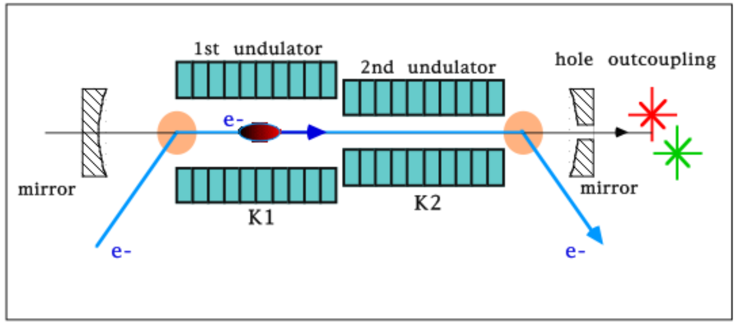
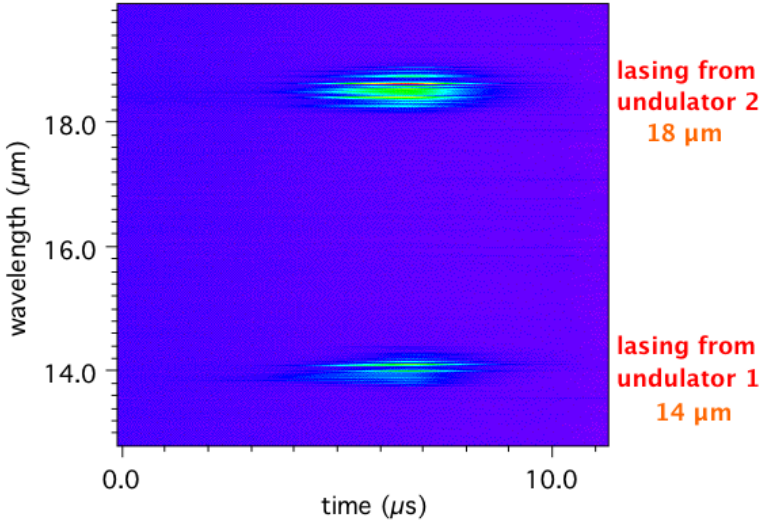


Figure 1: Scheme of the CLIO optical cavity.

Two-colors operation





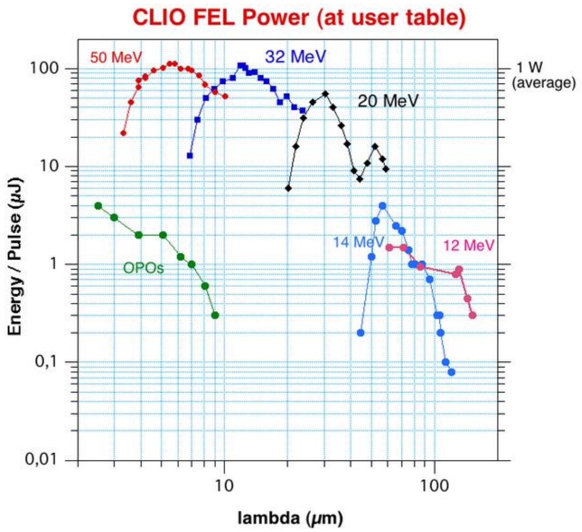
Time evolution of the wavelength spectrum
of CLIO in two-colour operation

CLIO: FEL oscillator

References:
- http://old.clio.lcp.u-psud.fr/clio_eng/accel.html
- J.K.Ortega et al., IPAC2014, THPRO004

Topic	Detail
Gun	Triode thermo-ionic gun
Accelerator	3 GHz accelerating section
Bunch compressor	500 MHz sub-harmonic buncher 3 GHz buncher
Beam energy & bunch charge	8 – 50 MeV & 100 A in 10 ps
Undulator parameters	Planar, λ_U = 46 mm, 50 periods, K = 0.5 – 3.2
Radiation mechanism	FEL oscillator
Radiation wavelength/frequency	3 – 150 µm
pulse energy/power	P_{avg} ~ 1 W @ 16ns/25Hz P_{peak} ~ 100 MW in 1ps ➔ 100 µJ
Pulse repetition rate	6.25 – 25 Hz (macro), 1/16 GHz (micro)
Pulse duration	0.5 – 6 ps (micro), 10 µs (macro)
Polarization	Linear
THz window & environment	?
Power/energy measurement	- Cooled IR-detectors (INSB, HgCdTe...) - Monochromator
Temporal profile measurement	?
Transverse profile measurement	?
Spectral measurement	FTIR

Energy vs wavelength



Measured THz transverse profiles (waveguide effects?)

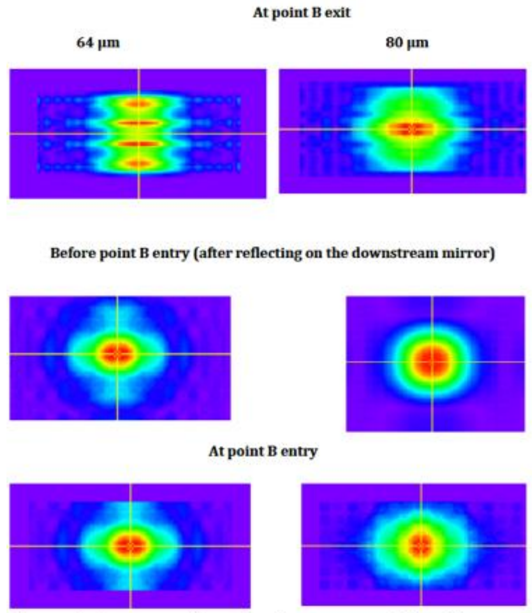


Figure 4 : beam profile at the downstream side of the optical cavity

Power vs wavelength

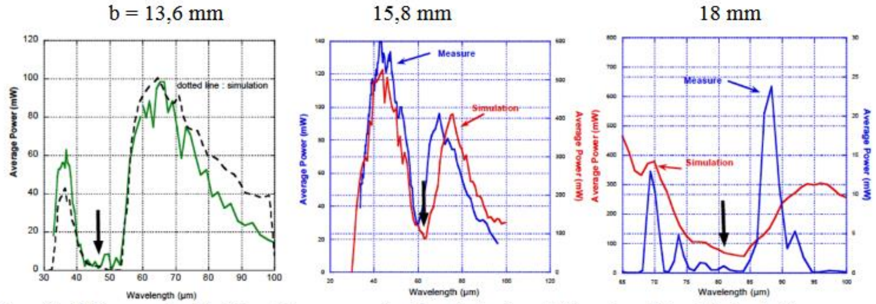
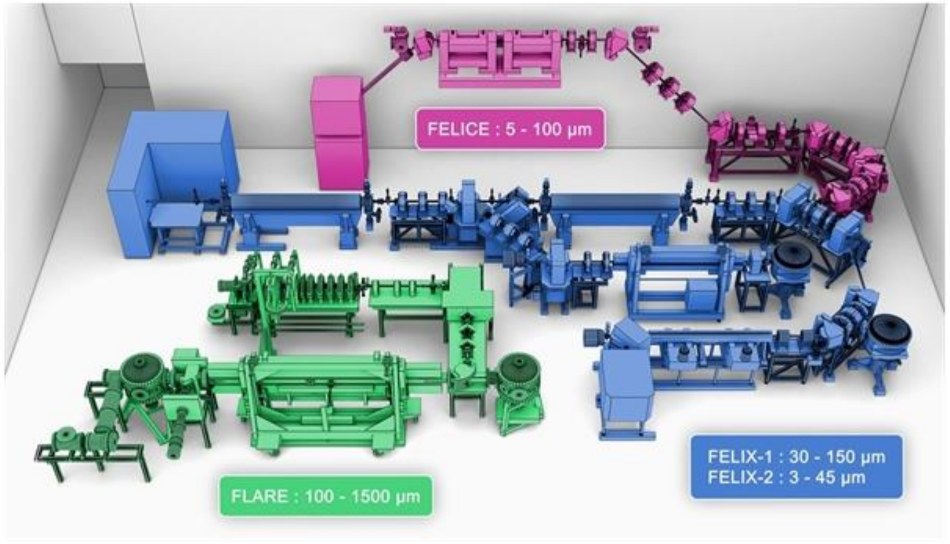


Figure 2 : FEL power for 3 heights of the vacuum chamber, the horizontal dimension (35 mm) being held constant.

FELIX: FEL oscillator

References:
- https://www.ru.nl/felix/
- R.Chulkov et al., Phys. Rev. ST Accel. Beams17,05070, 2014

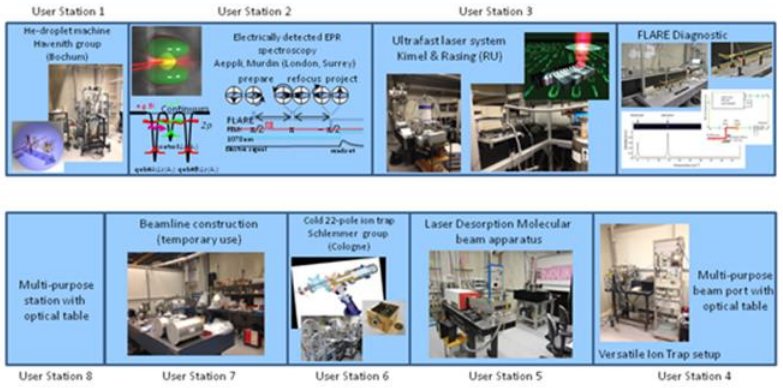


Overview of the FELIX laser hall

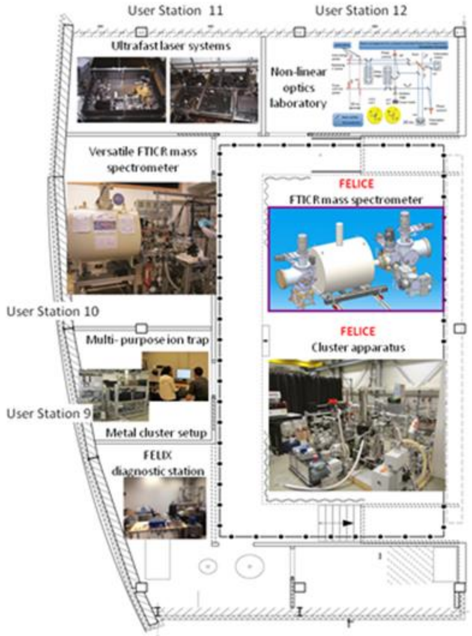
		FELIX	FLARE	FELICE
Spectral range	[mm]	2.7 - 150	100 - 1500	5 - 100
	[cm^{-1}]	3600 - 66	100 - 6	2000 - 100
	[THz]	120 - 2	3 - 0.25	60 - 3
	[meV]	450 - 8	12 - 0.75	250 - 12
Micropulse rep. rate	[MHz]	25, 50 or 1000	20, 40, 60 or 3000	16.6, 50 or 1000
Macropulse rep. rate	[Hz]	< 10	< 10	< 10
Micropulse energy	[uJ]	< 40	< 5	< 1000
Macropulse energy (@ 1GHz)	[mJ]	< 200	< 100	< 5000
Bandwidth (FWHM)	[%]	0.4 - 5	≈ 1	0.5 - 3
Micropulse duration (FWHM)	[optical cycles]	8 - 100	≈ 40	13 - 80
Peak power	[MW]	150	0.1	3
Polarization (linear)	[%]	> 95	> 95	> 95

User stations

User Laboratory I



User Laboratory II



FELIX: FEL oscillator

References:
- https://www.ru.nl/felix/
- R.Chulkov et al., Phys. Rev. ST Accel. Beams17,05070, 2014

Topic	Detail
Gun	Triode thermo-ionic gun
Accelerator	3 GHz accelerating section
Bunch compressor	500 MHz sub-harmonic buncher 3 GHz buncher
Beam energy & bunch charge	8 – 50 MeV & 100 A in 10 ps
Undulator parameters	Planar, λ_U = 46 mm, 50 periods, K = 0.5 – 3.2
Radiation mechanism	FEL oscillator
Radiation wavelength/frequency	3 – 150 µm
pulse energy/power	Macropulse energy <200 mJ @ 1 GHz Peak power 150 MW
Pulse repetition rate	25,50,100 MHz (micro), 10 Hz (macro)
Pulse duration	?
Polarization	Linear
THz window & environment	?
Power/energy measurement	?
Temporal profile measurement	?
Transverse profile measurement	?
Spectral measurement	?

Martens *et al.* Rev. Sci. Instrum. **87**, 103108 (2016)

Example of user's measured spectrum

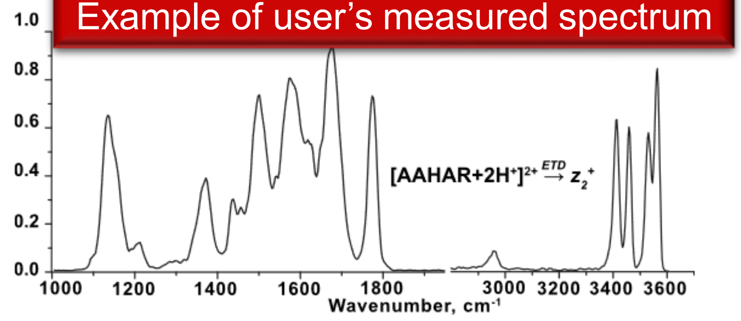


FIG. 8. IRMPD spectrum of the ETD-generated z_2^+ fragment from the doubly protonated peptide $[AAHAR+2H^+]^{2+}$, recorded with FELIX in the fingerprint region and with a pulsed-OPO in the 3-μm region.[34]

FELPower vs U.gap vs Cavity detuning

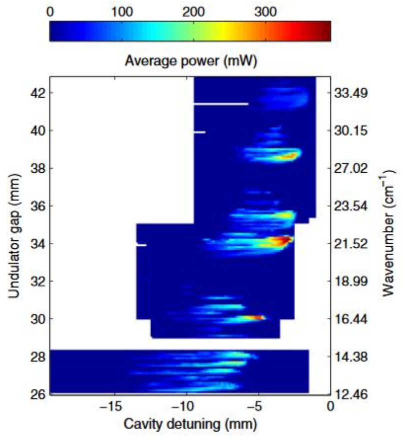


FIG. 1. 2D scan of power (false color) measured at different cavity lengths and undulator gaps. Wave numbers of the optical output as experimentally determined at the given undulator gap values are shown on the right side vertical axis. The measurements are performed at a beam energy of 15 MeV. The noncontinuous scanning of FLARE is clearly visible. The shift of the detuning curves to the longer cavity lengths with increasing wave number is due to the dispersion of the waveguide.

Measured transverse temporal profiles

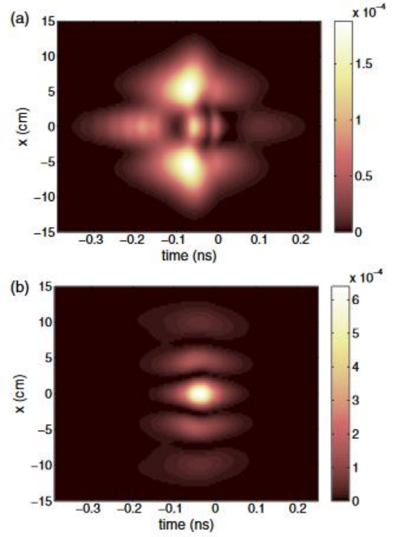


FIG. 8. The transverse temporal profiles of THz pulses at the undulator exit obtained at $z_R = 3.5$ m (a) and $z_R = 3.8$ m (b) with the cavity length detuned by $\delta L = -28$ mm.

Novosibirsk FEL Oscillator

References:
- O.A. Shevchenko et al., AIP Conf. Proceedings 2299, 020001 (2020)
- O.A. Shevchenko et al., Materials 2019, 12, 3063.

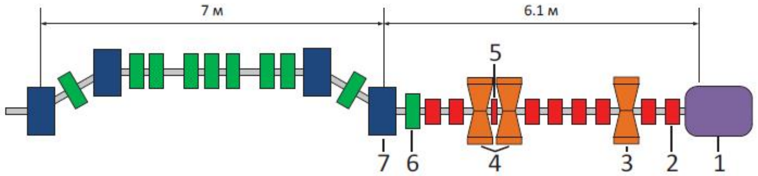


FIGURE 2. Injector layout: 1 - electron gun; 2 - electromagnetic solenoids; 3 – bunching cavity; 4 – accelerating cavities; 5 – permanent magnet solenoid; 6 – quadrupoles; 7 – merger bending magnet.

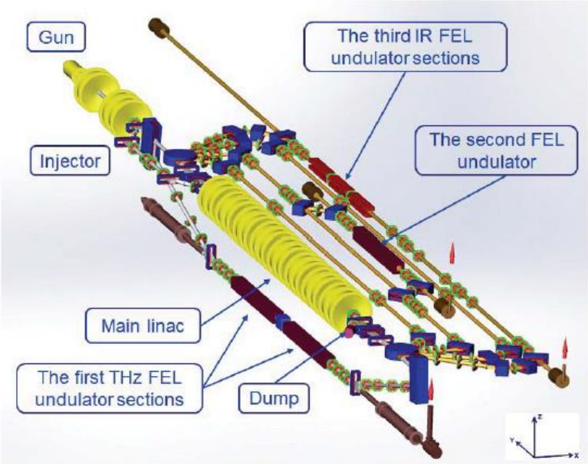


FIGURE 3. Novosibirsk ERL with three FELs (top view).

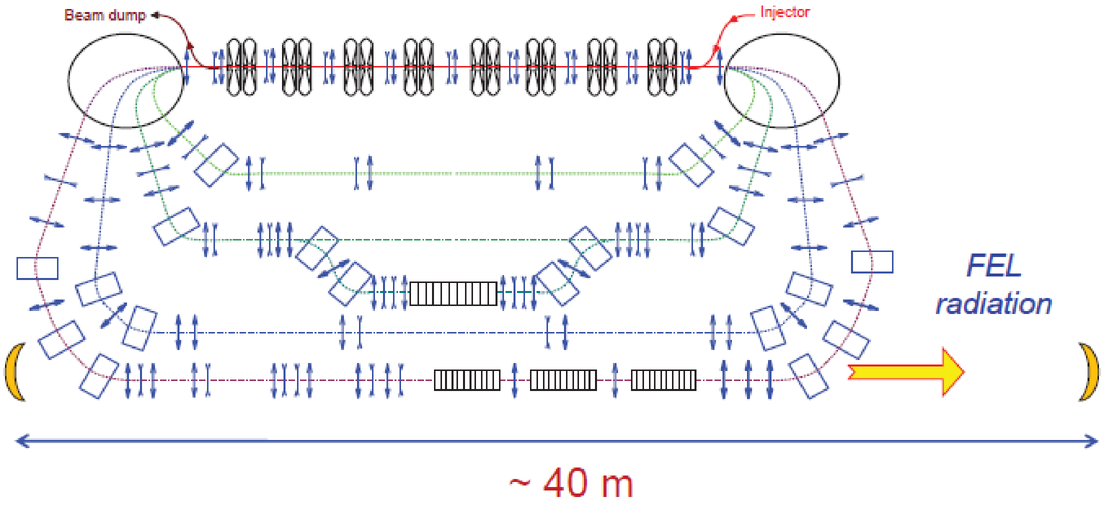


FIGURE 5. Third ERL with FEL undulators and optical cavity.

Novosibirsk FEL Oscillator

References:
- O.A. Shevchenko et al., AIP Conf. Proceedings 2299, 020001 (2020)
- O.A. Shevchenko et al., Materials 2019, 12, 3063.

Topic	Detail
Gun	300 kV electrostatic thermionic gun
Accelerator	two 180.4-MHz linacs Multi-turn ERL, 16 180.4-MHz RF cavities
Bunch compressor	180.4-MHz bunching cavity A chicane
Beam energy & bunch charge	11 – 42 MeV & < 1.5 nC
Undulator parameters	Planar, λ_U = 120 mm (first FEL)
Radiation mechanism	FEL oscillator
Radiation wavelength/frequency	5 – 340 µm
pulse energy/power	P_{avg} < 0.5 kW, P_{peak} ~ 1MW
Pulse repetition rate	5.6 MHz (micro)
Pulse duration	50 – 100 ps (micro), 10 µs (macro)
Polarization	Linear
THz window & environment	Quartz and diamond windows
Power/energy measurement	• a Gentec-EO UP19K-15S-VR detector • the Schottky-barrier detector • Scontel Superconducting bolometer 1a • MCT LN2 mid-IR detector
Temporal profile measurement	?
Transverse profile measurement	IR TV camera
Spectral measurement	• a modernized MDR-23 monochromator • fourier-transform infrared spectrometer Vertex 70v (Bruker)

THz macropulse

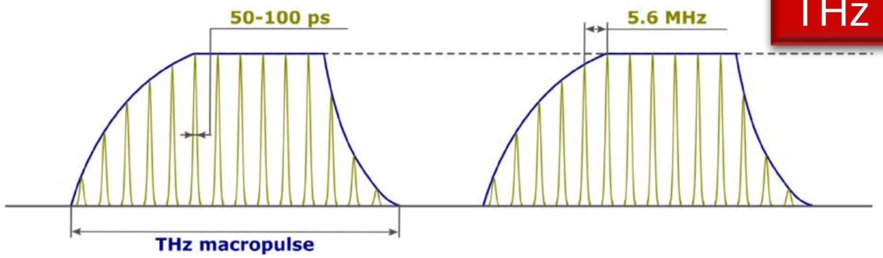


Figure 2. Schematic view of NovoFEL radiation macropulses. The length of the individual THz pulse and pulse repetition rate are shown for 1st FEL.

THz macropulse

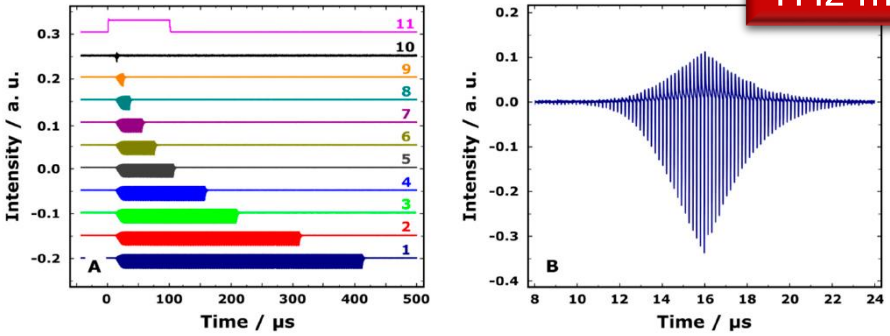
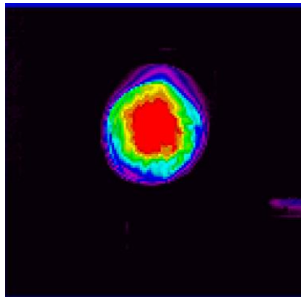


Figure 6. (**A**) Macropulses of THz radiation with wavenumber of 76.7 cm^{-1}. Macropulse durations are (1) 400 µs, (2) 300 µs, (3) 200 µs, (4) 150 µs, (5) 100 µs, (6) 70 µs, (7) 50 µs, (8) 30 µs, (9) 20 µs, (10) 10 µs (multiplied by 10 in intensity), (11) trigger signal. Each subsequent pulse is vertically shifted. (**B**) Macropulse with 10 µs duration. The individual pulses of THz radiation with the repetition frequency of 5.6 MHz are clearly visible.



Measured transverse profile

Kyoto University: Coherent Undulator Radiation (CUR)

References:
- S. Krainara et al., IOP Conf. Series 1067 032022, 2018
- N.Terunuma et al., NIM A Vol. 613 (1), 2010
- S. Suphakul et al., FEL2017, MOP049

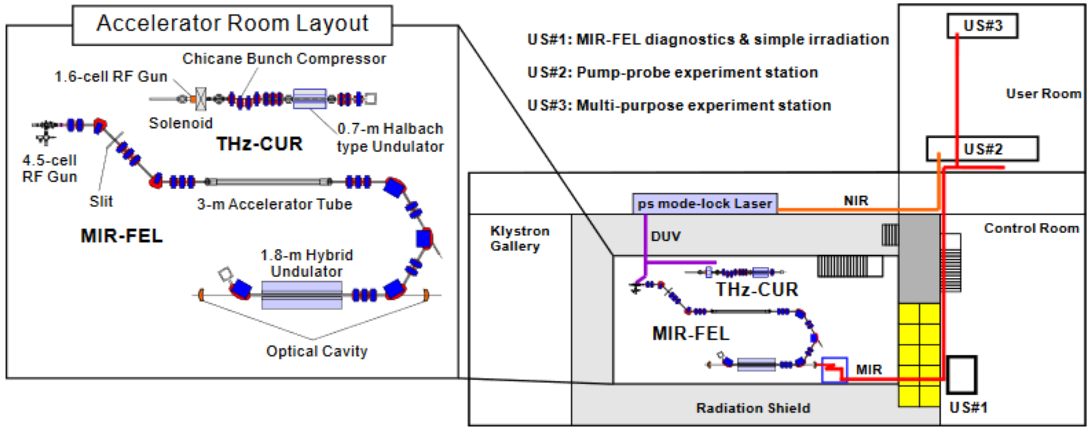


Figure 1: Layout of the infrared FEL facility in August 2017.

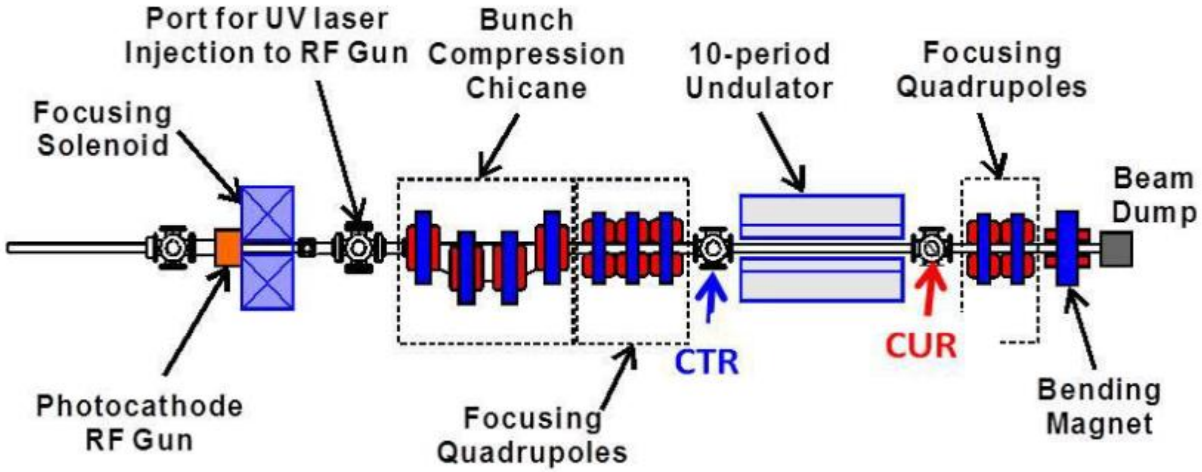


Figure 1. Schematic of THz-CUR at Kyoto University.

THz diagnostic layouts

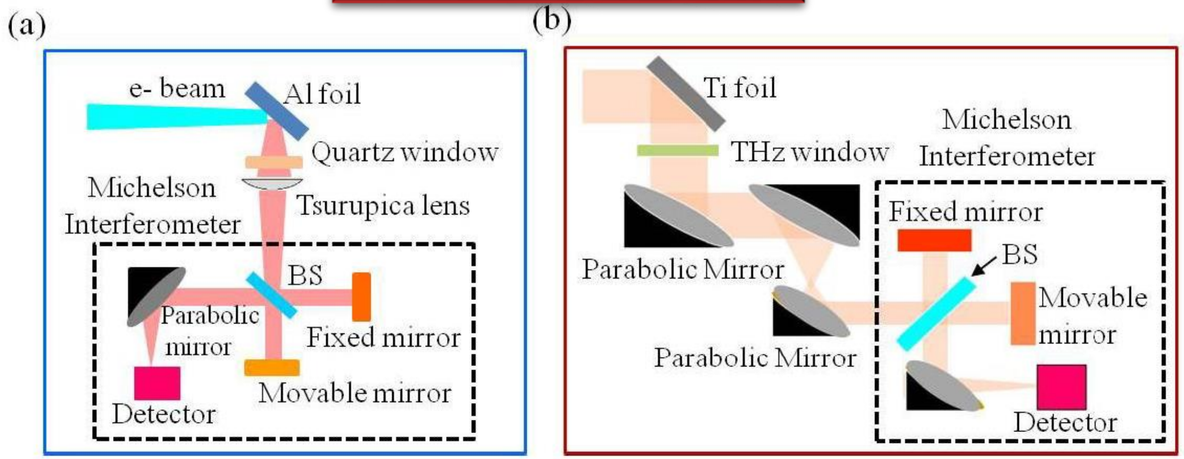


Figure 4. Experimental layout of (a) CTR and (b) CUR.

Measured electron beam parameters

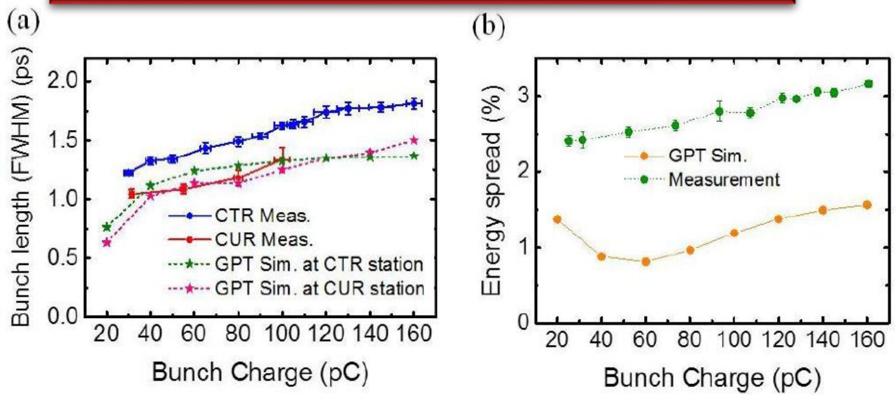


Figure 7. Comparisons of the bunch length (a) and energy spread (b) between the experiments and the simulation at the different bunch charges.

Kyoto University: Coherent Undulator Radiation (CUR)

References:

- S. Krainara et al., IOP Conf. Series 1067 032022, 2018
- N.Terunuma et al., NIM A Vol. 613 (1), 2010
- S. Suphakul et al., FEL2017, MOP049

Topic	Detail
Gun	Photocathode RF(S-band) gun
Accelerator	N/A
Bunch compressor	A chicane
Beam energy & bunch charge	4.6 MeV & 60 pC
Undulator parameters	Planar, λ_U = 70 mm, 10 periods, K = 0.1 – 3
Radiation mechanism	Coherent undulator radiation
Radiation wavelength/frequency	0.16 THz
pulse energy/power	1 µJ
Pulse repetition rate	1.56 Hz
Pulse duration	< 1 ps (micro), microseconds? (macro)
Polarization	Linear
THz window & environment	Quartz and fused silica windows
Power/energy measurement	THz10 + VPA
Temporal profile measurement	N/A
Transverse profile measurement	Pyroelectric detector (PYD-1, PHLUXi)
Spectral measurement	Michelson interferometer

Measured interferograms

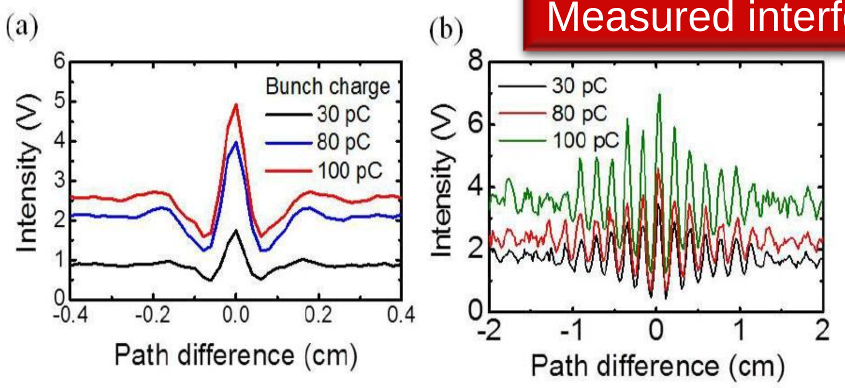


Figure 5. Interferograms of (a) the CTR and (b) the CUR with bunch charges of 30 pC, 80 pC, and 100 pC.

Measured transverse Profile

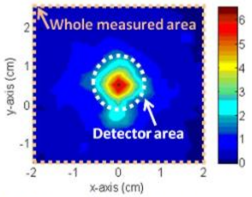


Figure 5: Spatial distribution (whole radiation area is in the orange box while the detector area is in white circle).

Spectra from FFT

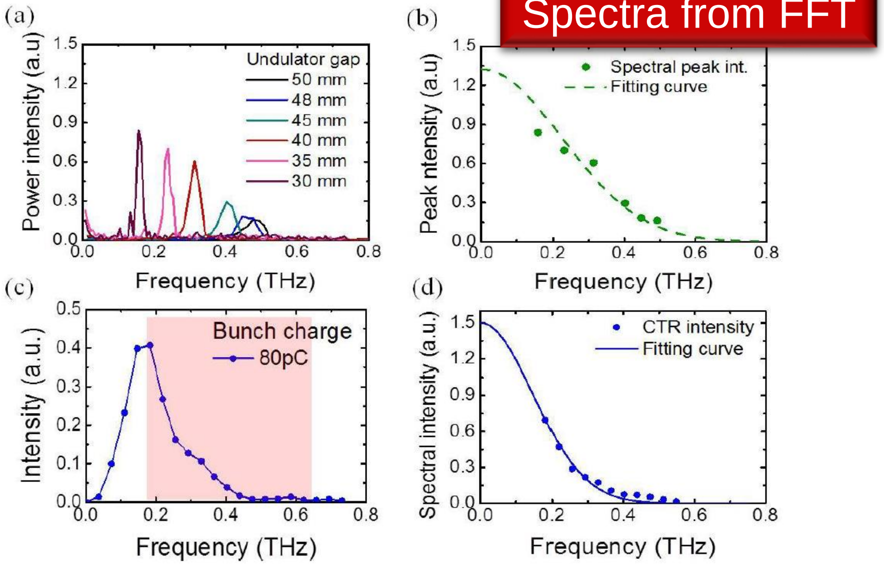
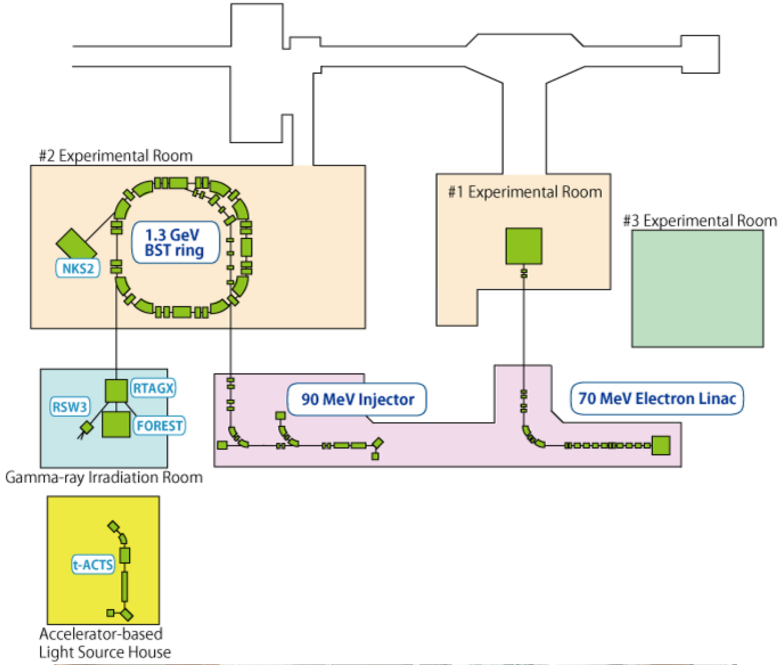
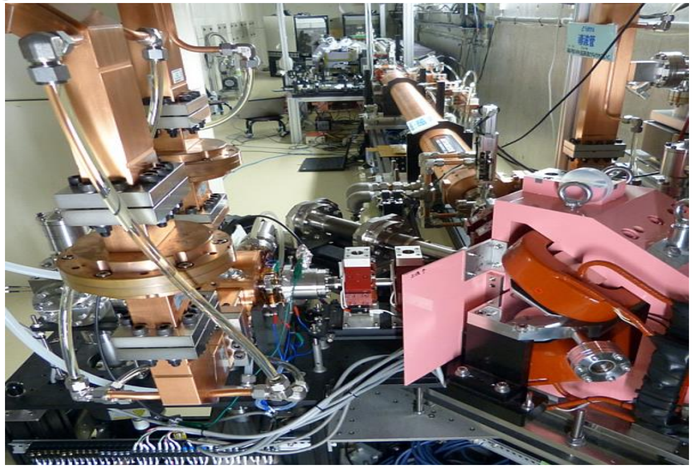


Figure 6. The measured spectral power intensity of (a) the CUR and (c) the CTR. The spectral intensity with the fitted curves for (b) the CUR and (d) the CTR with a bunch charge of 80 pC.

Tohoku University: Coherent Undulator Radiation (CUR)

References:
- S. Kashiwagi et al., Infrared Physics and Technology 106 103274, 2020
- S.Kashiwagi et al., IPAC2019, TUPGW033





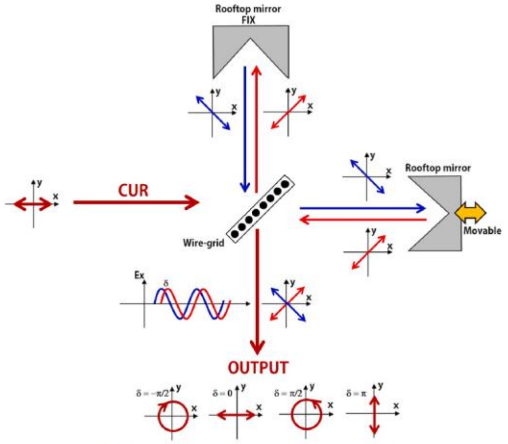


Fig. 1. Variable polarization manipulator (VPM) using a Martin–Puplett interferometer.

Variable polarization manipulator (VPM) using a Martin-pulpett interferometer

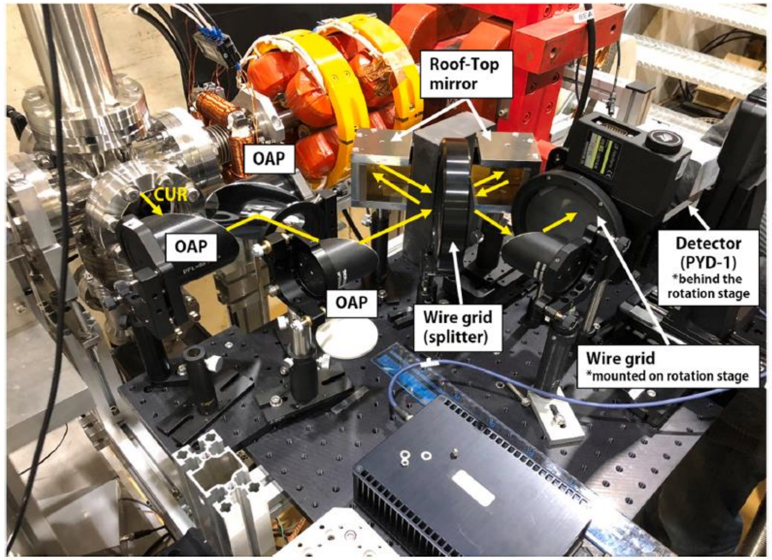


Fig. 2. Experimental setup. The VPM system was installed beside the beam line of THz-CUR. (OAP, off-axis parabolic mirror; CUR, coherent undulator radiation.)

Tohoku University: Coherent Undulator Radiation (CUR)

References:
- S. Kashiwagi et al., Infrared Physics and Technology 106 103274, 2020
- S.Kashiwagi et al., IPAC2019, TUPGW033

Topic	Detail
Gun	S-band thermionic RF gun
Accelerator	A 3m TW linac
Bunch compressor	An Alpha magnet, velocity bunching
Beam momentum / energy	30 – 50 MeV
Undulator parameters	Planar, λ_U = 100 mm, 25 periods, B_{max} = 0.41
Radiation mechanism	Coherent undulator radiation
Radiation wavelength/frequency	2.75 – 3.4 THz
pulse energy/power	?
Pulse repetition rate	5700 pulses / macropulse
Pulse duration	< 2 ps (micro), ~2 µs (macro)
Polarization	Linear
THz window & environment	Fused silica, UHV to air
Power/energy measurement	Pyroelectric detector (PYD-1 [PHLUXi])
Temporal profile measurement	N/A
Transverse profile measurement	Scan detector position
Spectral measurement	• Michelson interferometer • Martin-puplett interferometer

Measured interferograms and FFT spectra

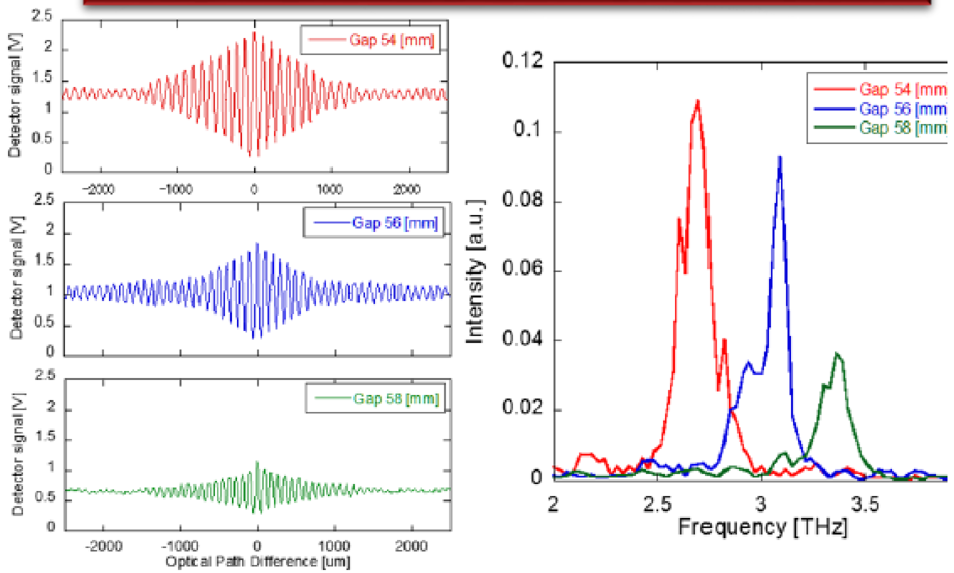


Figure 3: (Left) Interferogram and (Right) spectrum of coherent undulator radiation with different gaps.

Measured transverse Profile (CTR)

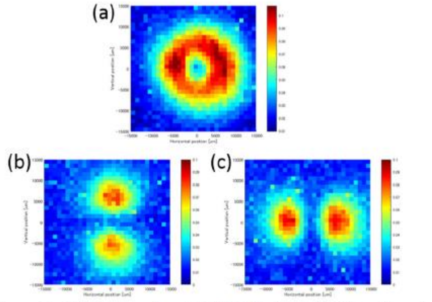


Figure 2: (a) Measured spatial distribution of CTR without the wire grid polarizer. (b) and (c) are measured vertical and horizontal components of CTR.

CAEP THZ FEL: FEL oscillator

References:
- Dai Wu et al 2018 J. Phys.: Conf. Ser.1067 032010

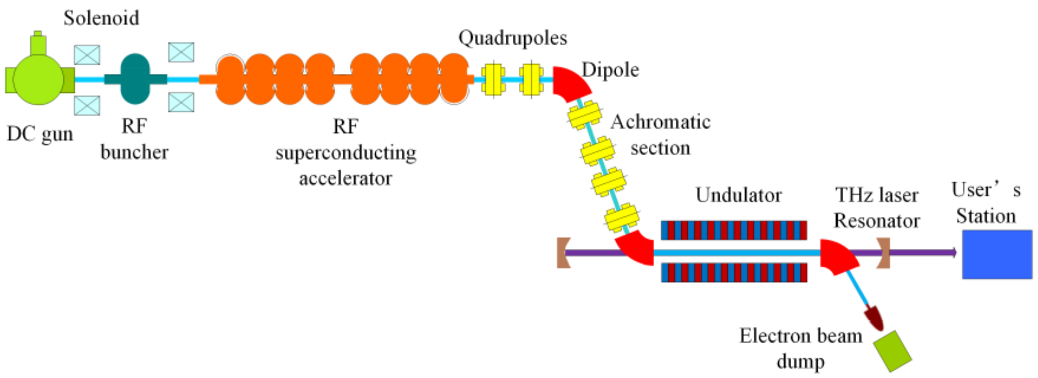


Figure 2: Block diagram of the CTFEL facility.

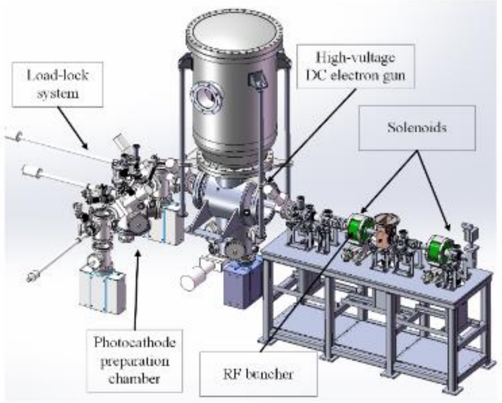


Figure 2. The high-voltage DC electron source

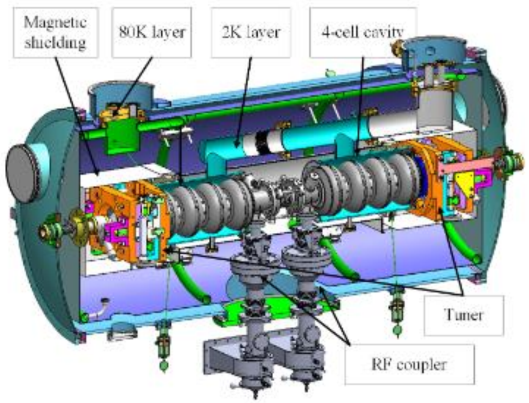


Figure 3. The RF superconducting accelerator

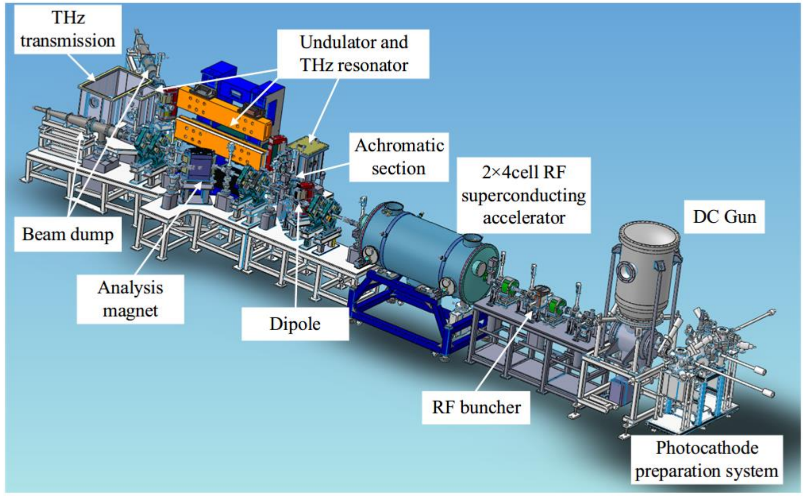


Figure 1: The Layout of the CTFEL Facility.

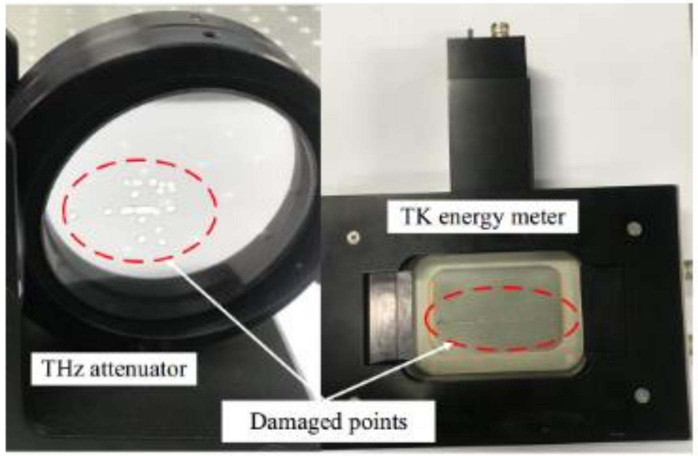


Figure 6. The damage caused by the THz laser

CAEP THZ FEL: FEL oscillator

References:
- Dai Wu et al 2018 J. Phys.: Conf. Ser.1067 032010

Topic	Detail
Gun	GaAs photocathode DC gun
Accelerator	1.3 GHz SCRF linac
Bunch compressor	RF buncher
Beam energy & bunch charge	6 – 8 MeV & 10 – 100 pC
Undulator parameters	Planar, λ_U = 38 mm, ? periods, B = 0.2 – 0.55 T
Radiation mechanism	FEL oscillator
Radiation wavelength/frequency	0.7 – 4.2 THz
pulse energy/power	Micro-pulse power >0.3 MW
Pulse repetition rate	54.167 MHz (micro), 1 – 20 Hz (macro)
Pulse duration	Picoseconds (micro)
Polarization	Linear
THz window & environment	A diamond window
Power/energy measurement	TK energy meter a GeGa detector a graphene detector
Temporal profile measurement	N/A
Transverse profile measurement	Pyrocam IIIHR
Spectral measurement	A Fourier spectrometer (Bruker VERTEX 80V)

FEL energy

Measured transverse Profile

FEL macropulse

Interferogram

E-beam signal from CT

FEL macropulse

Measured spectra

FEL signal from graphene detector

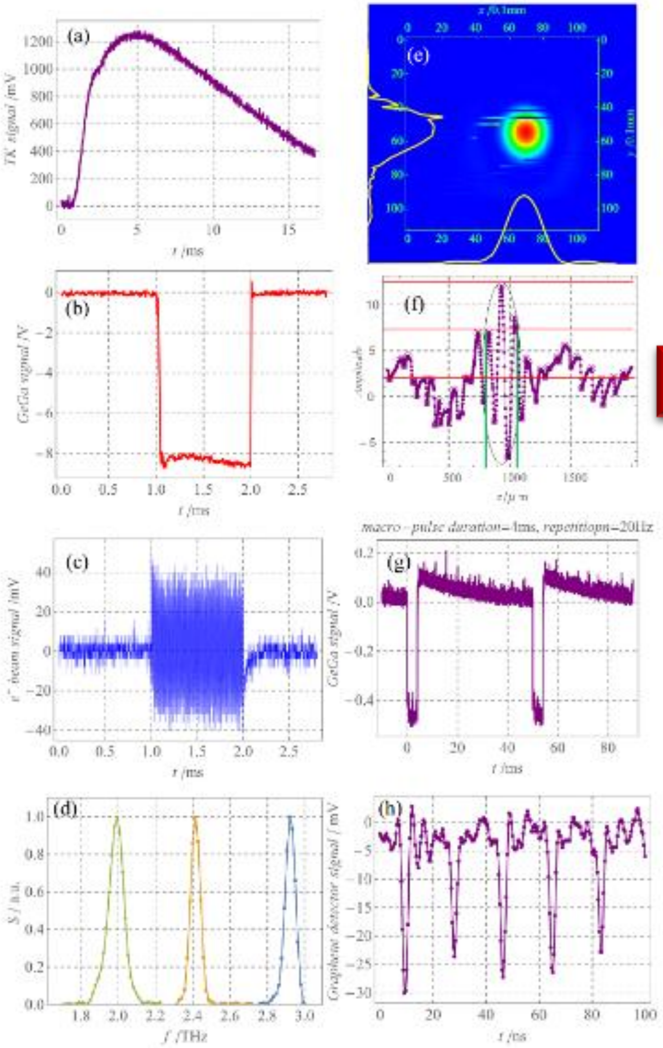


Figure 5. The THz laser measurement

FELiChEM: FEL oscillator

References:
- H.Li et al., FEL2019, MOA07

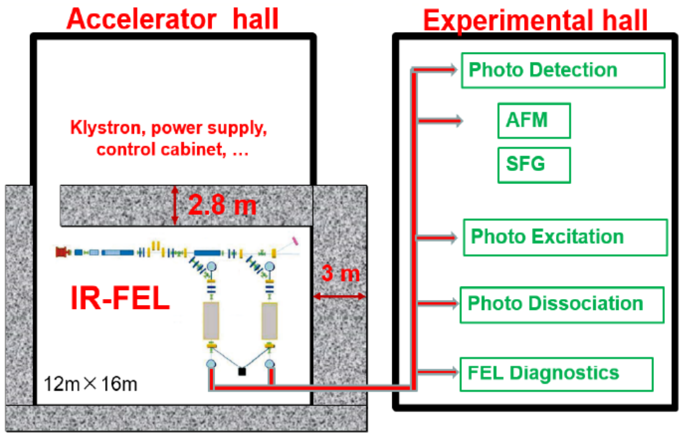


Figure 1: Schematic layout of FELiChEM.

Figure 2: Photo of the accelerator and FEL oscillators in the semi-underground tunnel.

FELiChEM: FEL oscillator

References:
- H.Li et al., FEL2019, MOA07

Topic	Detail
Gun	An 80 KeV electron gun
Accelerator	Two s-band linacs
Bunch compressor	A 476MHz SW pre-buncher, A chicane
Beam energy & bunch charge	25 – 60 MeV & 1.2 nC
Undulator parameters	Planar, λ_U = 46 mm, 50 periods, K = 0.5 – 3.2
Radiation mechanism	FEL osclillator
Radiation wavelength/frequency	15 µm
pulse energy/power	> 1 µJ
Pulse repetition rate	29.75 MHz (micro), 10/20 Hz (macro)
Pulse duration	< 5 ps (micro), 5-10 µs (macro)
Polarization	Linear
THz window & environment	Diamond window
Power/energy measurement	A liquid-nitrogen cooled MCT (HgCdTe) detector
Temporal profile measurement	N/A
Transverse profile measurement	Pyroelectricity camera
Spectral measurement	N/A

Measured transverse Profile

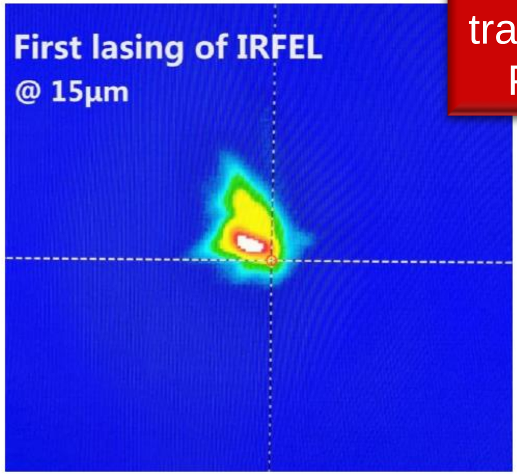


Figure 4: The photo of the light spot of the first lasing at 15 µm detected by pyroelectricity camera.

Blue: Beam current (gun)
Red: Beam current (linac)
Green: Beam current (dump)

Black: FEL intensity

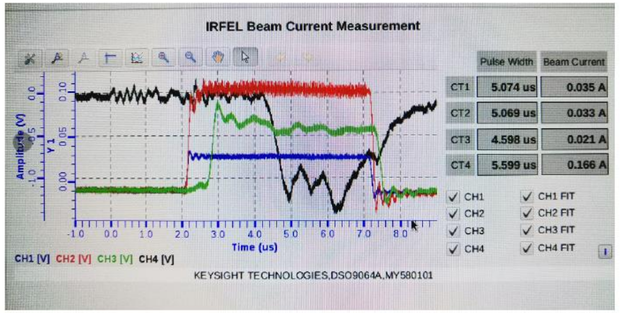


Figure 5: The measured electron beam current and FEL intensity. CT1: blue line, beam current at the exit of electron gun, 0.035 A corresponding to 1.2 nC per microbunch; CT2: red line, beam current at the exit of linac; CT3: green line, beam current before entering the beam dump; CT4: black line, FEL intensity detected at the photo dissociation station.

UCSB FEL Oscillator Santa Barbara, USA

References:

- http://www.itst.ucsb.edu
- http://sbfel3.ucsb.edu/

THE 6 MV FEL LABORATORY

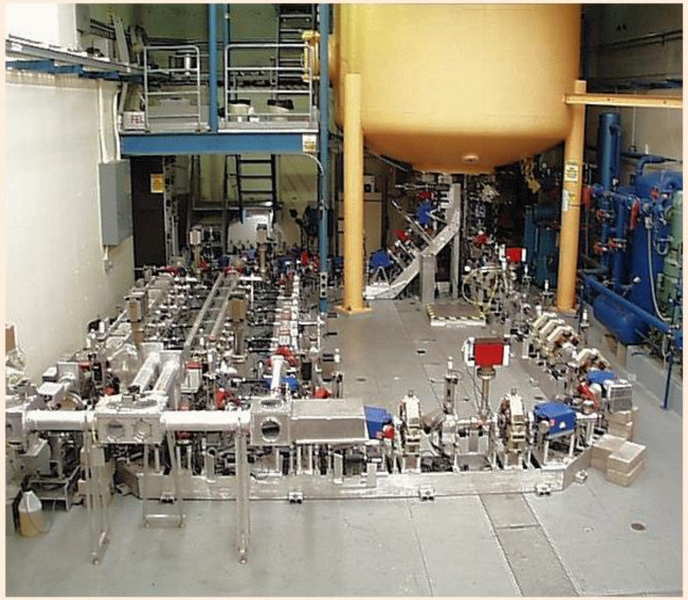


photo - GR 3-99

The main FEL laboratory room showing the MM, FIR, and 30 µm FELs (center), part of the optical transport system (left), the beam switchyard, and the lower portion of the 6 MV Electrostatic accelerator tank (yellow). Two foot thick concrete walls provide radiation shielding.

PBPL UCLA PEGASUS FEL, USA

References:

- http://pbpl.physics.ucla.edu/Research/Facilities/PEGASUS/
- G. Andonian et al., PAC2003, 1220-2111

Undulator used for 12 µm SASE at LANL (M. Hogan, et. al., PRL, 81 22 (1998))

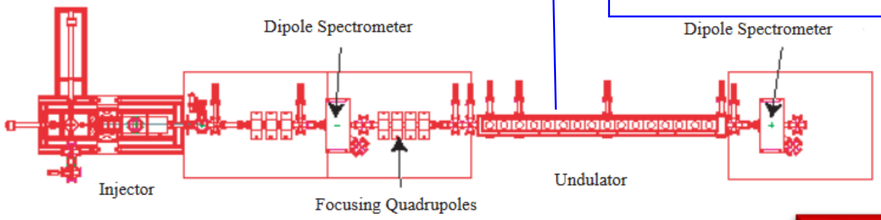
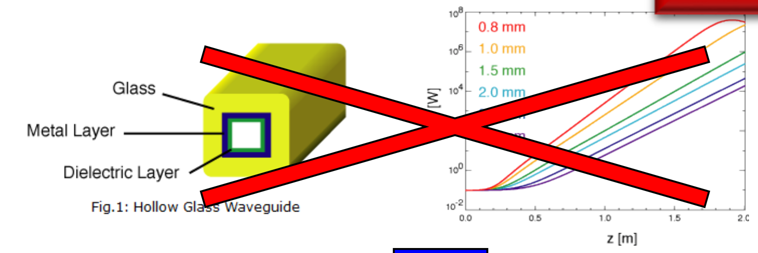


Figure 1: CAD Drawing of the PEGASUS Beamline.

Waveguide THz SASE FEL



Since 2007: Research in ultrafast beam sources and diagnostics

Summary & Outlook

- Popular THz FEL mechanisms: Oscillator ➔ SUR ➔ SASE
- Most popular THz power/energy meter: Pyroelectric detector
- Popular THz spectrometer: Fourier Transform Interferometers
- Temporal profile measurement methods: EOS and EOSD
- Transverse profile measurement: Pyroelectric camera

- Find ways to measure
  - pulse-to-pulse energy stability ➔ Fast detector with response time + decay time constant < 1 µs
  - Arrival time
- Future presentations
  - Review of THz detectors
  - Final design and simulation of THz diagnostic system for PITZ4