Motivation for tunable IR/THz source for pump probe experiments at the European XFEL

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Generation of IR/THz radiation by relativistic electron beams

- Attractive features are: clean production of the radiation in vacuum, tunability of radiation, potential to provide high power (high field), polarization control.
- Radiation occurs due to rearrangement of the field of electrons which happens when electrons are accelerated, pass boundary of media, pass trough an aperture:

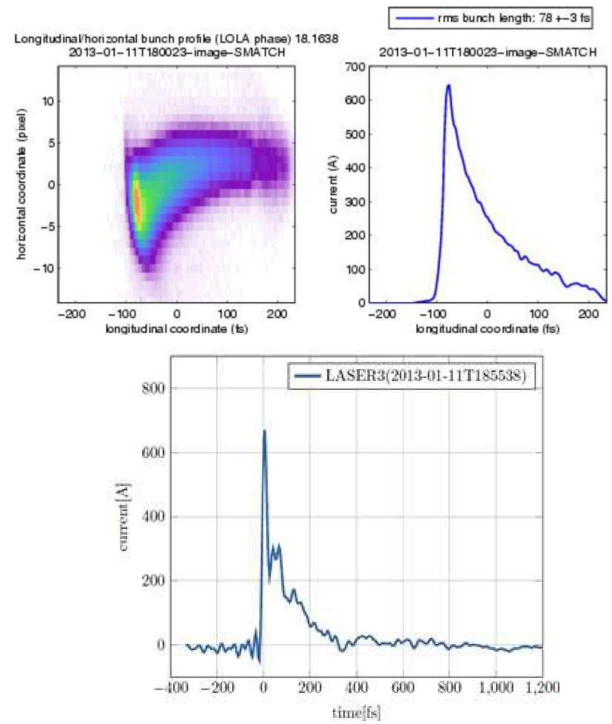
– Radiation in bend magnet.
– Undulator radiation.
– Transition radiation (i.e., crossing metallic foil).
– Diffraction radiation (i.e. passing an aperture).
– Edge radiation

- First discussions on the radiation source at PITZ related to the electron beam diagnostics
- Coherent enhancement of the radiation intensity occurs for short or tailored electron bunches:

Radiation power, averaged over an ensemble of N electrons:

$$\langle P(\omega)\rangle = p(\omega)[N + N(N-1)|\bar{F}(\omega)|^2] \ ,$$

Radiation power of single electron is $p(\omega)$, and bunch form factor is: $F(\omega) = \frac{1}{N}\Sigma\, e^{i\omega t_k}$



Axial profile of the bunch at FLASH: measurements with transverse deflecting cavity versus reconstruction using a broadband THz spectrometer

Scientific case

During last several years many of you:

P. Boonpornprasert, M. Khojoyan, M. Krasilnikov, F. Stephan (DESY, Zeuthen)
B. Marchetti (DESY, Hamburg)
S. Rimjaem (Chiang Mai University, Thailand)
M. Izquierdo (European XFEL GmbH, Hamburg)
M. Gensch (HZDR, Rossendorf)

pushed forward an idea to build dedicated accelerator-based IR/THz source for pump-probe experiments at the European XFEL:

Presentations at the European XFEL
2012-2015 FEL Conferences

Scientific case

Scientific case is described in XFEL TDR. An activity on revision / extension of the scientific case using pump-probe techniques is in the progress (by M. Izquierdo):

- the study of protein dynamical transitions and tertiary native proteins with structural motions
- the characterization of ions and molecules where solvation process plays a relevant role in the modification of their structure and properties.
- Condensed matter physics: the study of non-linear effects aiming to the control the state of material which could lead to new applications.
- Phase change of materials.
- Highly correlated materials (magnetoresistance, ferroelectrocity, superconductivity, insulator-to-metal transitions, etc).
- …

Pump-probe experiments at x-ray FEL user facility

General requirements to the pump source:

- Time structure of IR/THz source must follow time structure of operation of x-ray pulses.
- IR/THz source should have wide tunability range .
- IR/THz source should provide wide possibilities for generation of different temporal and spectral patterns, polarization. For instance, some applications require strong single-cycle pulses. There is rather big amount of applications requesting narrow band radiation. Thus, different radiators are required.
- Many applications require strong peak power (field strength) or high pulse energy.
- Time jitter of pump and probe pulses should be small enough for resolving time-dependent phenomena.

Specific for the European XFEL:

- The European XFEL operates in the burst mode: 10 x 0.6 ms pulse trains per second, 2700 pulses per train (4.5 MHz rep. rate).
- Current wavelength range of interest spans from 6 microns (50 THz, 0.206 eV) to 1000 microns (0.3 THz, 1.2 meV).
- Recalculation of user's requirements in terms of pulse energy spans a lot: microjoules ➔ hundreds of microjoules ➔ millijoules) .
- Time jitter: there are two types of experiments: (i) field driven dynamics where temporal resolution should be a few fs; (ii) "intensity" driven dynamics where temporal resolution is given by the longest pulse (e.g. if THZ pulse is 3 ps than timing only need to be 3 ps).

Laser based sources

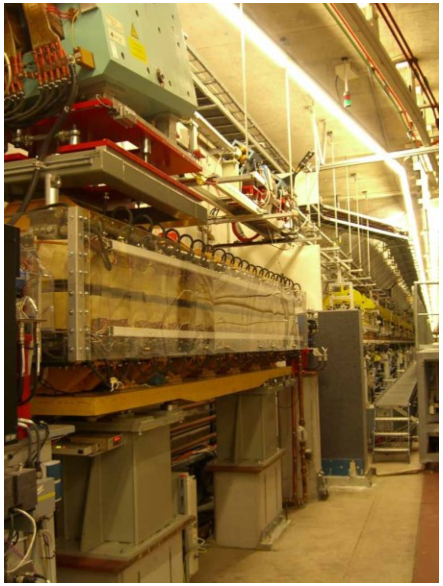
Above 15 THz: optical parametric amplifiers can provide photon fluence in the mJ/cm^2 range through different-frequency mixing.

0.1–1 THz: Technique of tilting the pump pulse front for efficient phase-matched THz generation by optical rectification of femtosecond laser pulses in LiNbO3.
The main challenge with these set-ups is the optimization of the poor efficiency ($\eta \sim 10^{-4}$) in the optical rectification processes. Recently, a conversion efficiency up to $\eta \sim 10^{-3}$ has been reported, thus providing 125 μJ per pulse. However, this was achieved at the expenses of the pulse duration (>1 ps) and spectral content. Other means to improve the overall THz pulse intensity by making use of ever increasing laser power, need employing larger LiNbO3 crystals and larger spot sizes, at the expenses of brightness.

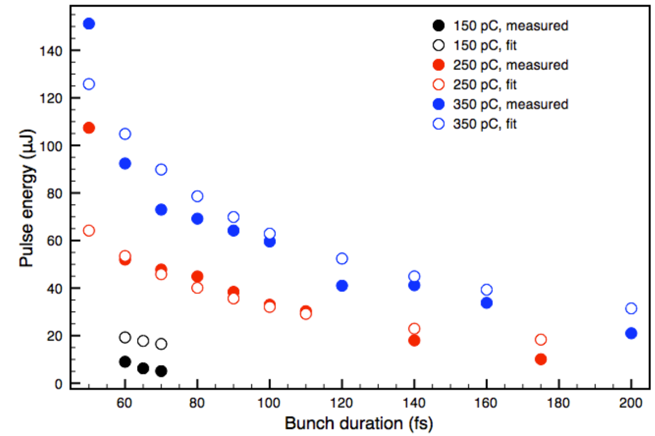
1-10 THz: generation of radiation in organic crystals (DAST, OH1, DSTMS). THz pulses up to 20 μJ have been demonstrated in DAST. Still, the usage of organic crystals is intrinsically limited by the rather low radiation damage threshold.

Accelerator based THz source does not suffer from any of the limitations described above, both in terms of maximum power and broadband coverage. The extraction of THz light presents complications and costs comparable (if not even minor) with respect to the set-up of a laser based facility.

Coherent radiation of electron beams
Examples for undulator and CTR

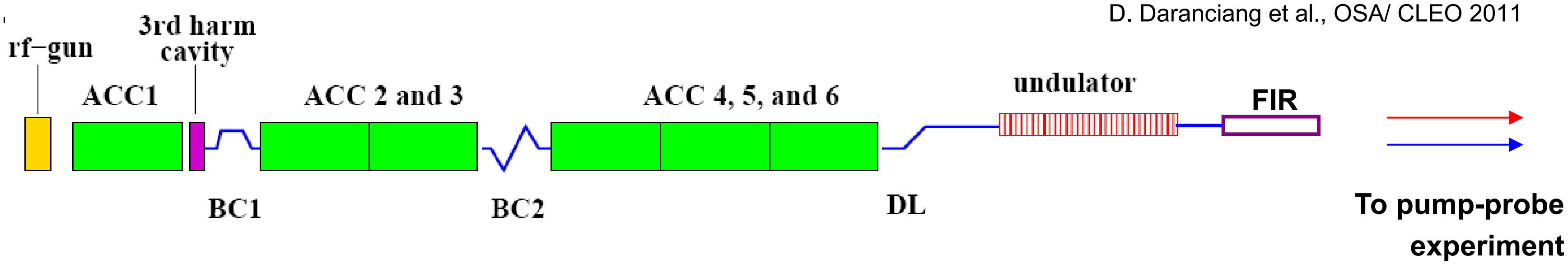


FIR coherent source at FLASH (DESY/HHU/JINR): THz pulse energies are in the range of 100 uJ



SLAC: Highly compressed, relativistic electron bunches are fired through a thin Be foil to generate intense, broadband, high-field THz transients. Pulse energies greater than 100 µJ and field strengths greater than 10 MV/cm are measured.

D. Daranciang et al., OSA/ CLEO 2011



Pump-probe experiments at x-ray FEL user facility

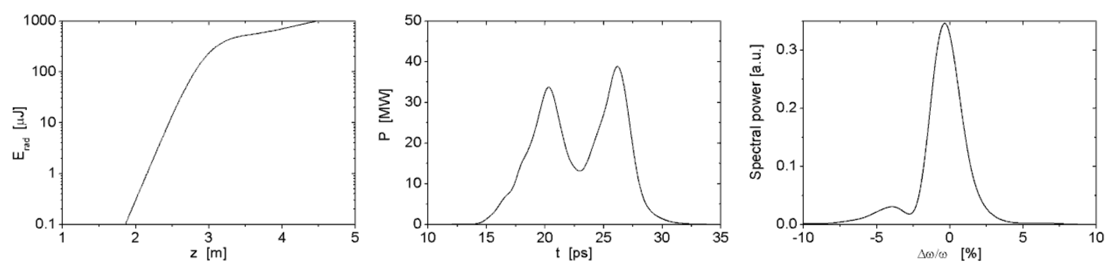
Dedicated accelerator based IR/THz source

- Electron accelerator (similar to PITZ): warm rf gun (up to 6 MeV) + warm accelerating section(s). With one (two) accelerating section electron energy is up to 25 (45) MeV. Bunch charge: from a fraction of nC to 4 nC
- Undulator: APPLE-II, period: 4 cm, length 5 meters
- Radiation with wavelength below 200 um is generated by SASE FEL.
- Powerful coherent radiation with wavelength above 200 um is generated in the undulator by tailored (compressed) electron beam.

Properties of the radiation:

- Wavelength range: 10 um … 1 mm (30 THz - 0.3 THz)
- Radiation pulse energy: a few 100 uJ
- Peak power: 10 ... 100 MW
- Spectrum bandwidth 2 .. 3%.

Example: operation at 100 um

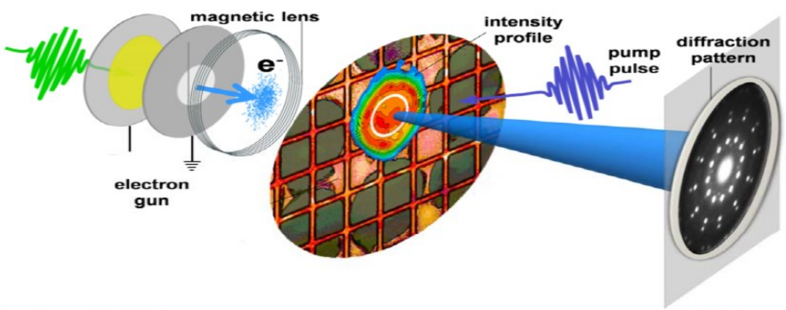


- Also installation of radiators for the production of a single-cycle radiation field using the mechanism of transition and edge radiation.
- Other types of diffraction radiators (e.g., Smith-Purcell, Cherenkov, etc.) can be implemented as well.

Pump-probe experiments at x-ray FEL user facility

Dedicated accelerator based IR/THz source

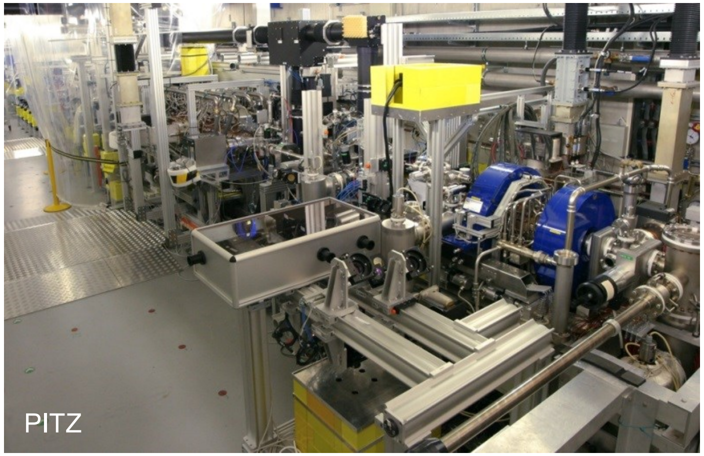
Potential to extend pump-probe experiments with femtosecond electron pulses.

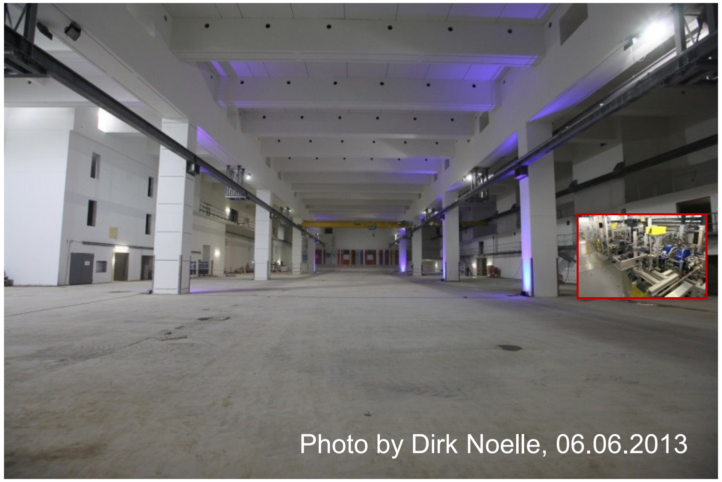


REGAE pump-probe (photon/electron) facility at CFEL/DESY

Summary

- Accelerator based IR/THz source meets all requirements for pump-probe experiments.
- Construction of a radiation shielded annex (like present PITZ facility) is possible as an extension of the European XFEL.
- Scale of IR/THz beamline is comparable with those operating at FLASH and TELBE.
- Prototype of the accelerator already exists – it is PITZ facility in Zeuthen.
- Can be excellent investment of efforts of accelerator consortium after finishing construction phase of the European XFEL.





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