Title: Longitudinal electron beam control for cost-effective, fully coherent, high repetition rate light sources from THz to X-rays.

Acronym: LECOPS (Longitudinal Electron dynamics for COherent Photon Sources)

Supporters: HZDR, MAX IV, Elettra, HZBR, INFN-LNF, ENEA, STFC(?). **Leader:** HZDR or MAX IV

Scope: significantly increase the cost effectiveness and performance of existing and planned free-electron laser facilities, while extending the frequency range, improving longitudinal coherence and the spectral brightness by few orders of magnitude, and advancing pump-probe capabilities. Relevant for sources in THz to X-rays.

Methods: analytical, numerical, and experimental investigations of yet unclear physical processes in electron beam manipulation techniques applicable to high brightness electron beams in normal and superconducting linacs, in a wide energy range of few 10's of MeV to GeV's.

<u>Key questions:</u>

1. Contribution of intrabeam scattering to the uncorrelated energy spread in modern photo-injectors.
2. Design and verification of linear and nonlinear electron optics for the preservation of almost monochromatic bunching factor through complex beam transport lines, and coherent radiation emission (e.g., multi-THz superradiant emission, EEHG + HGHG seeded FELs in soft X-rays).
3. Design and verification of linear and nonlinear electron optics for the magnetic linearization of beam longitudinal compression, simultaneous to suppression of broadband microbunching instability (e.g., in replacement of superconducting harmonic cavities at high rep. rate linacs, exploitation of beam manipulation in transfer lines, etc.).

Tasks: the project develops through parallel and complementary tasks.

1. *Control of electron beam uncorrelated energy spread at photo-injectors.*
   Better understanding of the origin of space charge-induced microbunching instability, of the role of intrabeam scattering in space-charge dominated beams, and limitations of the 1D approximation.
   a. Development of a time-dependent software environment for one-to-one particle simulations, and of a semi-analytical tool for low energy particle beams.
   b. Development of a sub-keV energy resolution electron spectrometer measurement station for benchmarking with experimental tests at MAX IV, HZDR and INFN-LNF.

c. Start-to-end self-consistent and reliable simulations of externally seeded soft x-ray FEL schemes. Specification of external UV lasers at high repetition rates. Simulations and codes to include microbunching instability.

2. *Longitudinal phase space linearization.*
   Magnetically linearized beam time-compression for a cost-effective production of linac-driven high brightness electron beams at very high repetition rate, alternative to high harmonic RF cavities, and merged to optics design for minimization of microbunching instability in the multi-bend line.
   a. In depth analysis of a MAX IV-like achromat bunch compressors with a focus on the ability of passive (magnetic) linearization of the longitudinal phase space. A TDC system for LPS characterization is under commissioning.
   b. Development of a high resolution-electron spectrometer line for the characterization of the 2-D beam bunching factor.
   c. Development of an infra-red spectrometer for characterization of the beam bunching factor through coherent transition/diffraction radiation emission. Preliminary development at FERMI.

3. *Use of longitudinally modulated beams*
   Laser-induced and wakefield-induced electron beam pre-modulation and preservation of the bunching factor at micron scale through beam transport and acceleration, as complimentary to very short pulses,
   a. Simulations of electron beam-laser interaction, inclusive of microbunching instability, linear and nonlinear optics. Studies based on manipulation of the cathode laser distribution (time, space), transport through the accelerator system and analysis with the TDC.
   b. Benchmarking with experiment at FERMI, HZDR and INFN-LNF.
   c. Prototyping of metallic corrugated structures for the electron beam modulation and coherent emission in IR – THz regime. Investigation both at low (10s MeV) and high energies (GeV).

Duration: 3 – 4 years

Total budget: 150 kEuro for personnel cost and organization of in-person workshops.

Hardware not included (corrugated structure, laser components, electro-magnets), whose cost would then approach several 100s kEuros. The proposal can rely on existing hardware, codes and know-how, shared among the LEAPS partners.

Motivations for THz coherent emission

Beam-driven THz sources are well established and operate as user facilities in their own right as well as part of larger short-wavelength FEL user facilities. The presently operating sources provide single-cycle broadband pulses generated via coherent diffraction (CDR) or transition radiation (CTR) and multi-cycle pulses generated in super-radiant undulators. In all these sources, the significant bunching factor at the radiation wavelength is achieved via strong bunch compression. This allows to reach few THz in the frequency range, and the pulse energies between ~1 and ~100 μJ depending on the beam energy and repetition rate, i.e., accelerator technology (NC RF vs. SRF) used. User communities of such facilities, present strong science cases for the need to extend the frequency coverage of such sources from 0.1 THz up to 30 THz, and simultaneously reach pulse energies on the order of a few 100 μJ or reaching E-field strength of few MV/cm, as outlined in the next paragraph. Such requirements exist at standalone FIR-THz facilities in combination with the required repetition rate of up to ~1 MHz. At the short-wavelength facilities where FIR-THz sources are used mainly for pump-probe experiments, the repetition rate of pumps naturally needs to match the repetition rate of the short-wavelength probes. The physics of the longitudinal phase space dynamics would not allow reaching such parameters with presently used architectures of the radiation sources. This is especially true in the high-frequency part of the range.

Despite its prominent importance it is still challenging to cover the 5-30 THz range with high peak power and sub-ps pulse duration with one single photon source. The production of coherent, multi-THz light, tunable both in wavelength, intensity and repetition rate, would however open new doors in THz control of matter for standalone experiments as well as in THz pump-FEL probe self-synchronized experiments in condensed matter physics, chemistry and biology. In particular, the energy range between 5 and 30 THz is rich of excited modes (phonon modes, vibrational modes, electronic and magnetic resonances, etc.) which can be used as knobs to induce phase transitions (as in light induced superconductivity, ferroelectricity and insulator to metal transitions) and to drive material's properties in the desired direction. Intense THz pulses can be used to transiently orient dipoles in molecules, thereby allowing for instance to address the solvation properties of liquid water, and may be employed to excite low-frequency inharmonic large amplitude modes of macromolecules thereby affecting their conformational properties.

In summary, we aim at the design study, prototyping and experimental test of a sub-picosecond coherent multi-THz light source compatible with MHz repetition rate, delivering several hundreds' μJ pulse energy and MV/cm peak electric field at the sample. We envision that R&D on two avenues will allow us to achieve the required parameters, which were outlined above. The first direction is the use of longitudinally modulated beams in place of strongly compressed ones. The second direction is the development of optimized bunch compressors.

An electron beam of 0.1-1 GeV can be energy-modulated with corrugated metallic (or dielectric) structures in the range 5-30 THz and successively compressed in time through a dedicated self-linearizing magnetic arc. A large bunching factor (>10%) at relatively high bunch charges (0.1-5 nC) will generate intense and collimated multi-THz radiation. The scheme is intrinsically passive, thus free from time-varying radiofrequency and e.m. sources, and adaptable to any repetition rate and duty cycle (in case of bunch trains), compatible with FEL-spent beamlines in large scale x-ray FEL facilities as well as with small-scale standalone light sources managed for example by universities or private companies. The two-step model proposed (energy modulation, magnetic compression) is flexible enough to be beneficial for normal-conducting accelerators at low repetition rates, where the energy modulation is implemented through low gap corrugated structures, as well as to superconducting accelerators in which a pre-existing FIR-THz FEL oscillator can be used instead for the energy modulation.

The project will provide to industries in the field of advanced mechanics specifications for the production of corrugated structures as a function of the range of electron beam and THz light parameters, and the possibility of developing/advancing internal know-how in the manufacturing of the structure in the perspective of massive and therefore cost-saving production.

The science case covers:

- ❖ Solid state: advanced material development, discovery of new phases of matter
  - – new high T_c superconductors
  - – new materials for information technology … (faster transistors, storage devices)
- ❖ Chemistry: ~ MV/cm E-field comparable to intra-molecular fields
  - – electronic charge transfer in molecular systems
  - – deformational modes
- ❖ Biology:
  - - protein(s) understanding (controlled deformation / folding)

Specification of THZ source:

- ✣ pulse energy: 100 µJ ... 1 mJ *(as high as possible)* E-field of few MV/cm
- ✣ frequency range: 0.1 THz … 30 THz
- ✣ repetition rate: 100 kHz … 1 MHz *(high flexibility)*
- ✣ Bandwidth: ∽ 1 % (multi-cycle) and ∽ 100 % (single-cycle)
- ✣ Synchronization: ∽ 10 fs level
- ✣ Spectral phase: CEP stable

Work breakdown structure (work packages) - tentative

1. Conceptual design study of electron beam manipulation through corrugated structure, self-linearized magnetic bunch compressor (chicane and/or dog-leg) and simulation of coherent THz generation. The design study would advantageously profit of beam parameters at an existing source of high brightness electron beam, capable of electron beam and THz

diagnostics, e.g., 25 - 50 MeV beam energy, 0.1 - 1 nC bunch charge, emission in the frequency range 5 - 30 THz.

2. Prototyping of module of corrugated structure with fixed period and variable gap, acquisition of DC magnets and diagnostics
3. Implementation of the corrugated structure and self-linearizing magnetic compressor at an existing infrastructure for proof-of-principle production of >5 THz coherent light
4. Physics design of 2^{nd}-order magnetic bunch compressor for the energy range of 25 - 50 MeV and 1 nC bunch charge
5. Contraction and beam test of such compressor prototype at an existing facility
6. Physics design of optimized dispersion section for the energy range 25 - 50 MeV, and 1 nC bunch charge, to allow high bunching factor in the wavelength range from 200 µm down to 10 µm (30 THz)
7. Contraction and beam test of the dispersion section
8.

Motivations for longitudinally coherent soft x-ray FELs – to be done

- Requirements come from diverse areas of applications
- Ultrafast phenomena in condensed matter
  – New materials: low-dimensional, high T_c superconductors, “THz transistors”, …
  – Exotic phases and phase transitions; electronic and lattice
  – Spin dynamics
- Chemistry / Physical-Chemistry
  – Control and triggering of chemical reactions / electronics distributions
  – Catalysis
- Biology
  – Cellular mechanisms in high E-fields

Maybe contacts with Steady-State Microbunching, through development of sophisticated simulations and possible benchmarking with experiments