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Editorial: Global developments towards continuous-wave free-electron lasers

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Editorial on the Research Topic
Global developments towards continuous-wave free-electron lasers

Linear accelerator-based free-electron lasers (FELs) provide fully coherent X-rays with ultra-high peak powers and femtosecond-duration pulse lengths. The X-ray peak brightness is approximately one billion times greater than that available at synchrotron radiation facilities. This enables high-resolution analysis of the atomic structure of crystalline matter, opening up new frontiers across many fields of science and motivating a vast amount of interdisciplinary applications.

Self-amplified spontaneous emission (SASE) is the most common operational mechanism for FELs. While proving excellent performance, the SASE FEL is rapidly approaching towards its next-generation for delivering intense SASE radiation at a MHz-level repetition-rate in a continuous-wave (CW) mode. The MHz-level CW FEL can significantly extend the capability of existing FELs by allowing for more flexibility in the photon beam time patterns and an increased average brightness.

The pulse repetition rate is determined by the acceleration technology, and it is much higher in superconducting facilities. Confronting challenges in developing MHz-level CW X-ray FELs, several world-class FEL machines are put into practice, the Linac Coherent Light Source II in the USA [1], [2], the Shanghai high repetition rate XFEL and extreme light facility in China [3], and the European X-ray Free-Electron Laser in Germany [4]. Tremendous efforts are being made worldwide, not only by the afore-stated pioneering facilities, but also almost every facility in the FEL community contributing to individual technical aspects of this global development.

Realization of MHz-level CW X-ray FELs calls for dedicated research and development (R&D) programs in physical design and technical development. This includes necessary modifications of relevant sub-systems in an existing FEL facility, and also start-to-end beam physics simulation of the developed accelerator and photon beam lines. Specific R&D programs are demanded in many aspects including but not being limited to CW electron sources, superconducting radio-frequency (SRF) accelerator cryomodules, cryogenics, cavities, RF power sources, Low-Level RF (LLRF), controls and undulators. The goal of this Research Topic is to summarize the obtained achievements and report on the development status of MHz-level CW X-ray FELs covering a selection of the aforementioned aspects. A state-of-the-art summary of the Research Topic is thus given.

A suitable electron source should demonstrate stable performance at a MHz-level repetition rate and deliver high-quality beams. Stringent requirements are thus posed on the choice of photocathode and its drive laser system, CW electron gun and the associated photoinjector configuration. As included in this Research Topic, Zhang et al. report a high repetition-rate photoinjector laser system, capable of generating 257.5 nm ultraviolet (UV) laser of more than 2 W average power with both spatial and temporal shaping functionalities. This has been tested for long-term stability showing good operating performance for a planned CW FEL facility located in Shenzhen, China. Zhao et al. address an important aspect in photocathode research by theoretically evaluating the quantum efficiency (QE) of semiconductor cathodes at cryogenic temperature. This is exemplarily demonstrated for the K-Cs-Sb photocathode used in a DC-SRF photoinjector at Peking University in China. A comprehensive summary of the requirements for an electron injector to operate in a high-duty-cycle (HDC) X-ray FEL is given by Sannibale, with a focus placed on the technological choices that the high duty cycle imposes, and on the beam dynamics implications that such choices cause. It is generally well known, that the most critical component in a photoinjector is the electron gun. As for this aspect, Zhou et al. provide a detailed overview of CW electron guns, including diverse types of DC, SRF, hybrid DC-SRF and normal-conducting RF. In particular, the gun performance, evaluated from the very recent commissioning for the LCLS-II injector, is demonstrated. A 0.5-μm emittance for 50 pC bunches with the desired bunch length has been obtained. It is also worth summarizing, for the past two decades, the highly valuable results obtained in the R&D of the SRF technology based photoinjectors, as the SRF guns have great potential to provide the high-brightness, high-current beams as required for the CW X-ray FELs. From this perspective, Xiang et al. have provided a detailed summary of the SRF photoinjectors worldwide.

A crucial role still plays by the electron-beam-physics based design and optimization of the key accelerator components and the whole transfer line from the electron source to the entrance of the undulators. Here two Research Topics are selected. Zhang et al. propose a so-called multiplexed configuration for the beam dynamics optimization of the LCLS-II photoinjector, aiming to enhance the flexibility of beam manipulation for the improvement of multiplexing capabilities of the FEL facility. Downstream the photoinjector, it is of significant importance to preserve the quality of the optimized electron beam as traveling through the whole beam transfer line. Effects that may lead to the dilution of the transverse bunch emittance and the longitudinal bunch length must be eliminated to a large extent. Zhang and Jiao re-address noteworthy issues with the emission of coherent synchrotron radiation (CSR) and the longitudinal dispersion causing degradation of the bunch quality. An advanced design and optimization are further proposed for a compact 180 deg transport arc, comprised of muti-triple-bend achromat (TBA) cells, for efficiently suppressing the undesirable effects mentioned above and thus maintaining the achieved bunch quality from the injector.

Another key aspect of an HDC upgrade (e.g., an improvement in the present machine duty factor from about 1% at the European XFEL to more than 5% and up to CW) of existing FELs lies in the production of required SRF cavities with high Q values and high gradients. This has motivated extensive studies of cavity production via nitrogen doping and infusion; Interrelated R&D topics, as a request of operating SRF modules in the CW mode, are under investigation aiming to bring the cryogenic load and the capacity of the cryogenics systems in line with each other; Attention has also been drawn to the development of CW RF power sources and couplers. Of equal importance is the development of the precision low-level RF (LLRF) controls which are mandatory for stabilizing the very narrow bandwidth associated with CW-operated SRF cavities. Specifically, in this Research Topic, development of a feedforward resonance control scheme is proposed by Bellandi et al. for the HDC upgrade of the European XFEL. This allows the LLRF system to accurately track and control the cavity resonance frequency for acheiving the desired accelerating gradient.

Superconducting undulators (SCUs), capable of reaching higher peak field on axis with respect to all other available technologies, covering a larger photon energy tunable range and showing stronger radiation hardness with respect to permanent magnet undulators, have drawn great attention in the community for potential applications in the high repetition rate FELs. Here we collect two articles on the R&D of SCUs. Wei et al. explicitly present the development of NbTi planar SCUs at the institute of high energy physics (IHEP) in China. Casalbuoni et al. introduce SCU activities at the European XFEL describing the general potential of SCUs for X-ray FELs and corresponding R&D efforts. In additional consideration of generating variable polarization, a Research Topic by Yu et al. is included for developing an APPLE III undulator prototype for SHINE, where it is planned to install several elliptically polarizing undulators (EPUs) as afterburners behind the planar undulator section to obtain nearly-saturated circularly polarized FEL radiation.

Closely following the development status of CW FELs worldwide, the editorial team notes that, first lasing results have been obtained at the LCLS-II, successfully demonstrating soft X-ray lasing from 250 eV to 1000 eV and hard X-ray lasing up to 3.8 keV [5]. In the meantime, commissioning of the soft X-ray FEL line of SHINE is expected in 2025 as explicitly introduced by Liu et al. The working principle of few-femtosecond X-ray pulse generation and pulse duration control is demonstrated by Fan et al. using the Shanghai Soft X-ray Free Electron Laser Test Facility (SXFEL-TF) [6], [7]. At the European XFEL, extensive R&D studies have been carried out [8–10]. Detailed technical developments of relevant subsystems for an HDC upgrade of the facility are on the way.

This editorial is devoted to briefly present the overall scope of the Research Topic and the included papers regarding selected aspects towards the development of CW FELs. The editorial team takes the opportunity to thank all authors of the articles published on this Research Topic for their valuable contributions and the Frontiers in Physics team for the technical assistance with publishing.

Author contributions

YC: Investigation, Project administration, Validation, Writing–original draft, Writing–review and editing. JB: Investigation, Project administration, Validation, Writing–review and editing. WD: Investigation, Project administration, Validation, Writing–review and editing. YD: Investigation, Project administration, Validation, Writing–review and editing. BL: Investigation, Project administration, Validation, Writing–review and editing. JQ: Investigation, Project administration, Validation, Writing–review and editing. TR: Investigation, Project administration, Validation, Writing–review and editing. NW: Investigation, Project administration, Validation, Writing–review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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