THE ATTOSECOND TECHNOLOGY PROGRAM AT THE EUROPEAN XFEL

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Abstract

In this contribution we will discuss the "Attosecond Technology" program at the European XFEL. This strategic program is being launched to cross a new frontier in ultrafast science, enabling experiments that probe and control electron dynamics on their natural timescales. The program is structured into tightly coordinated projects that address the full chain of challenges required for reliable attosecond operation at the European XFEL. These include the following three areas: first, attosecond pulse generation; second, development of next-generation diagnostics, capable of resolving sub-femtosecond temporal structures and, third, dedicated proof-of-principle experiments to validate performance under real experimental conditions and to provide increasing user access to attosecond-class capabilities. These efforts form a roadmap that integrates accelerator physics, FEL science, and experimental methodology. The program aims at delivering reproducible and well-characterized high-power X-ray attosecond pulses in single pulse, X-ray pump/X-ray probe or Optical pump/X-ray probe configuration.

MOTIVATIONS AND STATE OF THE ART

The generation of attosecond pulses in the soft and hard X-ray spectral range allows for imaging and spectroscopy experiments involving ultrafast dynamics in matter, enabling the probing and control of electron dynamics on their natural timescales [1–3]. Over the last twenty years, High Harmonic Generation techniques have been the main route to generating attosecond pulses. However, these techniques are intrinsically limited in spectral reach and pulse power [4–6]. As a consequence, XFEL-based methods are currently the only way to obtain high-power attosecond pulses that allow access to deeper and more complex regimes of matter. For this reason, many XFEL facilities worldwide devote significant effort to attosecond science, among many examples [7–9].

At the European XFEL, important milestones have been recently reached in terms of high-power attosecond pulse generation, diagnostics and usage. In the soft X-ray regime, single-frequency-spike pulses with energies up to the millijoule level have been generated at photon energies in the keV range [10]. Direct temporal measurements based on angular streaking techniques have confirmed pulse durations of a few hundred attoseconds [11]. In addition, two-color pulses with single-frequency-spike spectra and controllable delays have been demonstrated [10], lately also including polarization control of the probe pulse, as well as repeated delivery of short pulses to experiments, see [3] as an example.

In the hard X-ray regime, single-frequency-spike pulses have been generated at photon energies around 9 keV, with pulse energy reaching the hundreds of microjoule level [12]. Direct temporal diagnostics for hard X-ray attosecond pulses are still in an early stage of development. Nevertheless, indirect methods exploiting non-linear effects, together with start-to-end simulations and spectral analyses, consistently indicate pulse durations down to several hundred attoseconds, including moderate stretching due to dispersive transport optics. First demonstrations of two-color schemes and pilot experiments including dedicated diagnostics have also been successfully performed [13].

Despite these significant achievements, the delivery of fully characterized attosecond pulses to users during routine operation is still a very challenging task. Bridging the gap between current R&D stage and reliable user operation is a priority in the competitive research environment, which motivates a dedicated strategy program. Achieving this goal requires coordinating several development directions: standardization and optimization of attosecond pulse generation, acquisition and deployment of advanced diagnostics capable of resolving sub-femtosecond temporal structures, verification of consistent performance under realistic experimental conditions, and the gradual enablement of day-by-day scientific use of attosecond pulses. In parallel, albeit separately from the program itself, a strong users' community must gather around these capabilities.

Given these premises, the Attosecond Technology program is strictly based on attosecond generation methods that have already been experimentally demonstrated. The initial focus is therefore restricted to beamlines where attosecond pulses (single-spike) have been demonstrated, i.e. SASE2 and SASE3. SASE1 will be included in the program once comparable attosecond generation capabilities become available through separate R&D activities developed outside the scope of the program. At the same time, it is recognized that the state of the art in attosecond pulse generation and diagnostics is evolving rapidly. The program will therefore closely follow developments both at the European XFEL and worldwide, maintaining flexibility wherever possible within its phased structure.

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PROGRAM GOAL

Based on the motivations outlined above, the goal of the Attosecond Technology program is to deliver, in a reliable, verified, and usable way, well-characterized, high-power X-ray attosecond pulses at high repetition rate to users of the European XFEL by the beginning of the 2030s. In particular, the program aims at enabling three operational modes at the SASE2 and SASE3 beamlines of the European XFEL:

1. single attosecond pulses;
2. double attosecond pulses at different photon energies with variable delay (X-ray pump/X-ray probe);
3. optical pump synchronized/timed to an attosecond X-ray probe.

Here, “reliable” means that attosecond pulses can be delivered whenever requested, within standard operational constraints and planning times. “Verified and usable” means that the pulses are sufficiently characterized in time and frequency to enable meaningful and reproducible scientific output. The targeted performance includes pulse durations of a few hundred attoseconds, peak powers in the terawatt range, and operation at nominal repetition rates (typically at 1.1. MHz). In the two-color mode, temporal separations must be continuously tunable with sub-femtosecond resolution over ranges determined by beamline configuration and electron energy.

While the program is focused on these concrete deliverables, it also explicitly considers possible future developments, including new capabilities and the extention to additional beamlines of the European XFEL.

PROGRAM STRUCTURE AND PROJECT INTERPLAY

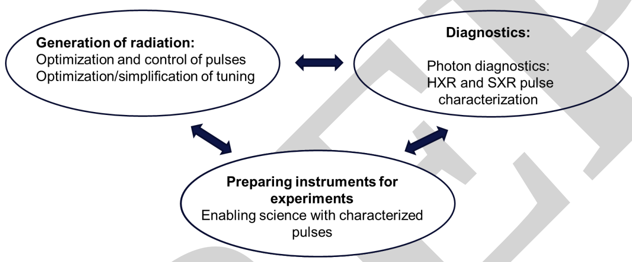

Figure 1: Three project areas of the attosecond strategy program and their interactions.

The Attosecond Technology program is structured into a set of tightly coordinated projects that, together with external synergies, address the full chain of challenges required for reliable attosecond operation at the European XFEL. These projects naturally fall into three strongly interconnected areas, see Fig. 1:

1. attosecond pulse generation;
2. development of advanced photon diagnostics;
3. dedicated proof-of-principle experiments to validate performance and enable increasing user access.

Attosecond pulse generation requires online feedback from diagnostics and experiments in order to produce pulses with the desired characteristics. Diagnostics require realistic radiation and experimental conditions to develop into robust and usable tools. Experiments rely on both generation and diagnostics, initially focusing on validation and characterization, and later evolving toward full scientific exploitation.

Attosecond Pulse Generation

Pulse generation activities focus on the optimization and control of single- and double-pulse attosecond operation in both the soft and hard X-ray regimes. This includes possible hardware adaptations, as well as optimization and simplification of tuning procedures, with the objective of making attosecond pulse production as robust and reliable as possible and compatible with routine operation.

Diagnostics

Advanced photon diagnostics constitute another central pillar of the program. They aim at providing direct, non-invasive temporal characterization of attosecond pulses at high repetition rate. Techniques such as angular streaking [6, 14–16], together with complementary approaches, need to be developed up to routine operation. In regimes where direct diagnostics remain challenging, extensive feasibility studies are included in the projects, while indirect and correlation-based methods are explored as complementary tools [13].

Transport of broadband attosecond pulses from the source to the experimental stations is another critical aspect. Although initial results indicate that transport-induced distortions are moderate, this topic will continue to be investigated as diagnostic capabilities expand.

Experiments

Dedicated experiments play a crucial role in validating attosecond performance under real experimental conditions. In the initial phases of the program, experiments focus on pulse characterization, synchronization, transport, and stability, in order to provide proof-of-principle demonstrations of attosecond operation. These activities are essential to enable increasing user access to attosecond-class capabilities. The definition and prioritization of detailed science cases are pursued through processes that are independent of this program.

Synergies

The Attosecond Technology program explicitly relies on synergies with activities conducted at DESY and the European XFEL, outside of the program itself:

- Optical pulses required for pump–probe experiments and generated by dedicated laser systems are an indispensable part of the ”pulse generation” area. Their development and deployment are pursued independently within a separate strategic program at the European XFEL in synergy with the attosecond program.

- Full exploitation of attosecond and other special XFEL operation modes requires detailed understanding and control of the longitudinal phase space of the electron beam, as well as direct access to the temporal structure of the emitted radiation. High-resolution electron-beam diagnostics capable of resolving sub-femtosecond structures are being developed independently of this program at DESY, and represent an important enabling condition.

- Synchronization between different radiation sources represents an additional major challenge. While X-ray pump/X-ray probe schemes benefit from intrinsic synchronization, optical pump/X-ray probe configurations rely on external timing systems and diagnostics that are developed independently at DESY, and closely followed by this program.

OUTLOOK

In summary, the Attosecond Technology program provides a coherent roadmap for transforming existing attosecond demonstrations at the European XFEL into a reliable, user-oriented operational capability. By integrating accelerator physics, FEL science, advanced diagnostics, and experimental methodology, the program aims to deliver reproducible and well-characterized high-power X-ray attosecond pulses in single-pulse, X-ray pump/X-ray probe, and optical pump/X-ray probe configurations. The success of the program critically depends on strong synergies with external developments pursued independently and on closing the full chain from generation to diagnostics to experiment.

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