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High intensity attosecond electron and photon beams

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1 Abstract

This contribution discusses the study and generation of attosecond Mega Ampere (MA) electron bunches and 10s of attosecond TW power X-ray pulses. These first of their kind beams would enable experiments at the intensity frontier of high-brightness beams, as well as enable X-ray based studies of electronic dynamics with an order of magnitude better time resolution than existing XFELs. This contribution also addresses electron beam compression to unprecedented peak currents, opening research opportunities for studying collective effects such as Coherent Synchrotron Radiation (CSR) in a regime which has never been accessed experimentally. Strong interest in ultra-high intensity electron beams with MA peak current was raised by recent proposals for high-field colliders for non-linear QED studies and featured in the recent GARD workshop as a topic of high interest for the accelerator research community [1-3]. The results of these studies will shed light on the complex beam dynamics experienced by such ultra-short beams and inform design choices for future accelerator facilities aiming to use such beams for a broad swath of scientific experiments in high energy physics and beyond.

2 Introduction

The generation of attosecond electron and photon beams has recently become a topic of significant interest, motivated by applications in future high luminosity linear colliders [1-3] and high power tunable X-ray generation [4]. While progress has been made in generating ultra-short bunches using conventional RF linacs, the bunch length and beam brightness are limited by the trade-off between compression and emittance dilution due to collective effects. Compared to standard RF accelerators, plasma-based accelerators [5-7] can generate electron bunches with a brightness that is 2 orders of magnitude larger. The large fields driving the acceleration process typically produce beams with a strong time-energy correlated chirp at the exit of the plasma. In this contribution we discuss leveraging such strong chirps to further compress the bunch to MA-level current and attosecond duration. We also explore generating strong correlated chirps passively using CSR in a magnetic wiggler. With a strongly chirped electron bunch, a bunch compressor with weak bends can be used to achieve nm-level bunch lengths while limiting beam brightness dilution during the compression process. Generating such beams experimentally would serve as a stepping stone towards understanding the beam dynamics of ultra-short bunches which are being considered as alternatives for future collider applications [1-3]. As a corollary benefit, these electron beams are capable of generating TW-class X-ray pulses through coherent undulator radiation that are naturally spatio-temporally synchronized to the beam [8]. We propose a concerted and phased effort for studying the generation of attosecond electron and photon beams, both in a preliminary design phase and with experiments aimed at validating the concepts outlined in this approach.

3 Approach/Method

The approach towards generating MA-class, nm-long electron bunches using plasma accelerated beams involves using standard bunch compressors to compress the beam following the PWFA stage. Numerical work has shown that PWFAs can generate GeV energy, um-length bunches with correlated energy chirps h on the few $\%/\mu$m level and uncorrelated (slice) energy spread $\sigma_\delta \sim O(10^{-4})$ [9]. Due to the large chirps, the momentum compaction required to fully compress such beams in a standard chicane is very small ($R_{56} = h^{-1} < 100$ μm) and similarly the smallest achievable bunch length, limited by the slice energy spread, is very short ($\sigma_{z,min} = h^{-1} < 10$ nm). This represents an opportunity for compressing beams to bunch lengths two orders of magnitude shorter than has ever been generated while avoiding spoiling the beam quality through collective effects such as CSR in the compressor bends.

A further possibility for generating large chirps to enable extreme compression involves exploiting the self-interaction of e-beams with the CSR emitted by the beam inside a magnetic wiggler. This has been previously successfully used to generate short um-length current spikes in X-ray FELs [10]. Applying similar methods to higher charge (nC range) e-beams, such as those that will be available at the FACET-II facility, may offer a path to 100-nm length MA-current bunches. A further benefit of this approach is that the energy chirp imparted on the electron bunch is naturally synchronized to the beam. This eliminates the sensitivity to phase jitter which results in variations in bunch compression for typical RF systems.

4 Objectives

The main goals of the proposed work include both simulation and experimental studies. For the start-to-end simulations of attosecond electron and photon beam generation our main objectives are to:

- Explore the parameter space, optimize the performance of these techniques with respect to the main plasma, wiggler and beam parameters for collider and light source applications.
- Understand collective effects in MA beams. The generation of MA bunches opens an entirely new set of parameters for high-brightness beams, understanding the collective behaviour of these beams will require detailed simulations with well established beam dynamics codes (e.g. ELEGANT, Lucretia), as well as Particle In Cell codes such as OSIRIS.
- Studying extension to higher energy. We will study the scaling of these methods to higher e-beam (> 10 GeV) and photon energies (> 10 keV).

On the experimental side we will study the challenges which need to be addressed to transition these methods from the design phase to experimental realization. We will outline what, if any, are the plasma source advances needed compared to the state-of-the-art to satisfy the requirements of the schemes. We will also address what are the advanced diagnostics which can be used to optimally measure, characterize and optimize these extreme beams. Finally, we will outline what can be done at existing facilities (e.g. FACET-II) to make progress towards demonstration of the proposed concepts.

5 Summary

The development of lower-cost linear colliders and next generation X-ray photon sources may be revolutionized by use of ultra-short high intensity attosecond electron bunches. We propose a research thrust towards studying the generation, characterization and optimization of such bunches for future accelerator applications.

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