# Beam Physics of Extreme Bunch Compression
# LoI to Accelerator Frontier

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**Abstract:** High peak-current, high-brightness beams are of great importance to a large number of future DoE applications and facilities, providing access to new science and considerably advancing the current state-of-the-art in accelerator technology. Notable examples are significant power and thus cost reduction for future energy-frontier colliders, plasma-wakefield accelerators (with acceleration gradients 10,000's times higher than existing rf devices), attosecond X-ray FELs (allowing novel studies of atomic electronic processes) and compact, efficient $\gamma$-ray sources. The present level of understanding of the physics of such extreme beams remains, at best, incomplete, with wide gaps in both theoretical and experimental aspects. Compressing electron (and/or positron) bunches to attosecond durations and mega-ampere peak currents, while preserving the beam quality, remains a principal challenge in accelerator science and technology. The proposed R&D program will include theoretical, computational and experimental accelerator beam physics. This is one of five interconnected LoIs [1–5] that discuss a new paradigm of short, tightly focused bunches which opens various opportunities that were considered experimentally unreachable in the past.

Current designs for energy-frontier colliders are pushing the envelope of affordability. They are expensive to construct and operate due to the high beam power necessary to achieve the required luminosity. A reduction in beam power without sacrificing luminosity and physics potential is only possible through smaller transverse dimensions of the colliding beams: either via a reduced emittance of the source beam or through tighter focusing at the interaction point. In current designs, however, beamstrahlung radiation [6, 7] prevents further tightening of the beam focus in lepton colliders. Beamstrahlung is the fundamental process of synchrotron radiation as particles bend in the electromagnetic fields of the colliding, opposite bunch. Beamstrahlung radiation both smears out the collision energy spectrum and produces an unwanted background source for the detectors. The higher the collision energy the more challenging these effects become and eventually they will significantly degrade the physics potential of such a machine.

A very efficient beamstrahlung mitigation strategy is provided by longitudinal bunch compression [8–11]. Longitudinal bunch compression reduces the interaction time and thus the radiation probability. The required bunch length depends on the collision energy and is of the order of 100 nm for a 100 GeV-scale collider. Suppressing beamstrahlung via longitudinal bunch compression enables a reduction of the horizontal beam size by orders of magnitude in comparison to existing designs, with a corresponding reduction in beam power, while maintaining luminosity. Furthermore, this strategy prevents degradation of the energy spectrum. Therefore, a greater fraction of the luminosity is close to the peak collision energy – a key factor for lepton collision physics. The expected performance of the FACET-II facility at SLAC National Accelerator Laboratory will allow for the study of beam compression within a factor of four of the aforementioned goal, at higher than the required bunch charge.

The generation of sub-micrometer length bunches intersects with the scientific program at X-ray FELs through attosecond science. The aim here is to produce a single-spike FEL [12], thereby extend-

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ing the capabilities to generate harder x-rays. Attosecond pulses, previously generated using $\sim 1\ \mu$m-length current spikes, are required to study the quantum-mechanical motion of electrons in molecules and solids [13]. X-ray crystallography and spectroscopy require high-power, sub-femtosecond duration pulses that are typically generated by a single-spike process that ensures only a $1\ \mu$m component of the bunch engages in the FEL process [14]. Further motivation comes from additional high-impact technologies which will be unlocked by the new short-bunch paradigm. Current filamentation instabilities are an excellent example: electrons in a suitably dense bunch propagating through a plasma have been shown to be able to generate return currents in the plasma [15], leading to instabilities which cause self-formation of beam filaments and correspondingly very intense electromagnetic fields. These fields bent the electron trajectories and those electrons become strong emitters of synchrotron radiation. As a result, a gamma-ray source of unprecedented efficiency and brightness is obtained [16]. Finally, sub-micrometer long bunches with megaampere peak currents will facilitate new science opportunities by supporting TV/m acceleration gradients in plasmas and crystals [17–20].

Generating, accelerating, transporting, and compressing high-brightness electron beams presents numerous accelerator design challenges which require going beyond the current state-of-the-art. The final beam compression and de-magnification to the nanometer scale at the final energy of the accelerator is the most challenging task, with Coherent Synchrotron Radiation (CSR) being the key limitation. In a bending magnet the beam radiates photons and thus experiences a radiation reaction force. CSR in a relativistic beam during compression can lead to longitudinal modulation of the bunch with wavelengths smaller than the bunch length. It is regarded as one of the main sources of emittance growth in the bunch compressor. CSR limits the achievable brightness of electron beams in storage rings, free electron laser (FEL) light sources, and high-energy colliders.

Preliminary research into the design of the final bunch compressor stage shows some promise: using a multi-cell lattice with multiple sextupoles per cell, chromatic and geometric aberrations can be compensated in addition to first-order CSR energy kicks. The LoI to Energy frontier on "Particle colliders with ultra-short bunches" [1] discusses R&D challenges unique to this design. It proposes strategies, e.g., for further theoretical and experimental studies on designing high-order magnets within the bunch compressor, such that they can simultaneously compensate non-liner CSR kicks. Optimizing accelerator systems for extreme compression is a notoriously difficult task. This is an area where modern non-linear optimization tools like novel machine-learning (ML) algorithms could be brought to bear.

We will propose here an accelerator R&D program to advance theoretical, simulation, and experimental studies. Initially, this program is expected to be centered around the capabilities of FACET-II and aimed at the understanding of 3D-CSR using existing and upgraded bunch compressors. A proposal for a follow-up demonstration facility with stable, high quality, ultra-short bunches that will enable new (above-mentioned) research opportunities is expected to follow. This demonstration facility will experimentally support a future proposal for a 2x125 GeV-scale ultra-short bunch collider, enabling Higgs studies in a collisions with suppressed beamstrahlung, a laser-less $\gamma\gamma$ collider, fully non-perturbative QED physics at $\alpha\chi^{2/3} > 1$, as well as the production of pair plasma environments which are highly relevant to laboratory astrophysics and multi-messenger astronomy.

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