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GENERALIZED LONGITUDINAL STRONG FOCUSING: A RING-BASED BEAM MANIPULATION TECHNIQUE

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Abstract

Generalized longitudinal strong focusing (GLSF), a ring-based beam manipulation technique, has been proposed to generate steady-state, nanometer-long electron bunches in laser-driven storage rings. Coherent EUV radiation can thus be produced with greatly enhanced power and photon flux, benefiting a wide range of scientific and industrial communities. The GLSF mechanism invokes precise transverse-longitudinal coupling dynamics and exploits the ultralow vertical beam emittance. In a GLSF ring, kW-level coherent EUV radiation is attainable.

INTRODUCTION

Storage rings have driven great progress in science and technology for being stable, reproducible, and clean photon sources. Alongside the pursuit of low transverse emittance in recent decades, beam manipulation methods in storage rings flourish as well in longitudinal dimension. Bunches as short as picoseconds can be produced when rings operate in the low-α mode [1, 2].

Ambition to further shorten ring-stored bunches continues. Laser-driven storage rings have been proposed where laser modulators are used for bunching instead of RF cavities [3–6]. With a modulation wavelength reduction of roughly six orders of magnitude, the equilibrium bunch length can be notably decreased to tens of nanometers or even less. The longitudinal weak focusing (LWF) scheme employs low-α and low-partial-α optics to control bunch lengthening from stochastic photon emission [7, 8]. In a longitudinal strong focusing (LSF) ring, multiple laser modulators are included as longitudinal focusing elements, or 'longitudinal quadrupoles' [9, 10]. Bunches are strongly manipulated in longitudinal dimension and tailored to be short at specific locations of the ring.

It is challenging, yet rewarding, to manipulate steady-state bunches of nanoscale length in storage rings. These bunches are ideal producers of coherent extreme ultraviolet (EUV) radiation with greatly enhanced average power and photon flux desired by a wide range of applications. The boosted EUV photon flux within a narrow bandwidth has been craved by high-energy-resolution angle-resolved photoemission spectroscopy [11, 12]. In sub-meV bandwidth, key electronic structures may be probed, and findings in condensed matter physics could be made. The high average power of coherent EUV radiation suggests that a storage ring-based light source is a promising option for EUV lithography [13, 14]. Output power may be tripled from existing facilities, leading to a huge promotion in microchip production. In addition, the produced photon pulse trains with pulse duration of tens of attoseconds is longed for by attosecond physics studies [15]. Besides, once ignored features of beam dynamics may now come to light, opening up a thrilling new frontier for accelerator physics.

Obstacles, however, prevent existing methods from being fully competent when attempting to obtain steady-state nanometer-long bunches on a turn-by-turn basis. Reducing the bunch length in the LWF scheme to nanometers calls for momentum compaction that is presently too low to be technically feasible, while the power of the modulation laser required by the LSF scheme exceeds the capacity of current optical cavities in continuous-wave mode.

A ring-based beam manipulation technique is then desired where coherent EUV radiation could be generated turn by turn. The power of the modulation laser should be controlled below 1 MW, which optical cavities could bear for continuous-wave mode operation. Besides, the status of electron bunches should be recovered after compression. This is pivotal in storage rings, unlike in single-pass devices.

GENERALIZED LONGITUDINAL STRONG FOCUSING (GLSF)

In this paper, a ring-based beam manipulation technique, generalized longitudinal strong focusing (GLSF), is proposed to produce coherent EUV radiation turn by turn in laser-driven storage rings.

Strong manipulation is imposed and significant variation in bunch length is present in both LSF and GLSF schemes. The way electrons are handled, however, is different. Instead of manipulation in the longitudinal dimension alone, GLSF rings deliberately invoke transverse-longitudinal coupling beam dynamics. The GLSF scheme takes advantage of the extremely low vertical beam emittance in a horizontal-vertical-uncoupled planar ring, by projecting which a short bunch length can be attained with significantly reduced power of modulation lasers. Cancellation of the introduced coupling and modulation after the beam radiates is required to retain an uncoupled bunch and maintain the low vertical beam eigen-emittance, which is intended to be used again in following turns.

Calculation with practical beam parameters shows that kW-level quasi-continuous-wave coherent EUV radiation can be achieved turn by turn in a GLSF ring with a modulation laser power as low as 1 MW, allowing for continuous-wave operation of state-of-the-art optical cavities.

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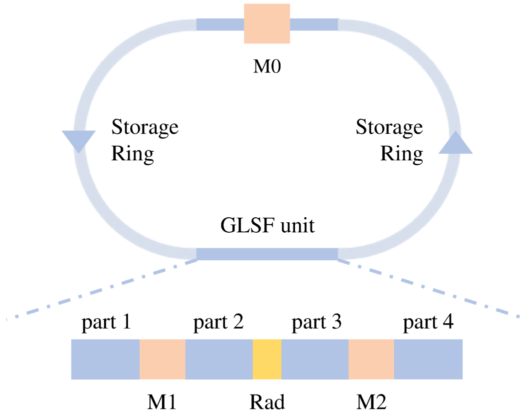

Figure 1: Sketch showing the general layout of a GLSF storage ring. GLSF unit includes four lattices (parts 1-4), two modulators (M1, M2), and a radiator (Rad).

The general composition of a GLSF storage ring is shown in Fig. 1. The GLSF unit consists of four dispersive lattices, two modulators, and one radiator. An additional modulator is placed in the storage ring for pre-bunching. In principle, however, this GLSF approach also works for RF-bunched or coasting beams.

The first half of the GLSF unit, or part 1, M1, and part 2, compresses the beam so that bunch length at RAD reaches the lowest possible degree and depends solely on beam vertical eigen-emittance. The de-compression is accomplished by the second half of the GLSF unit. The introduced modulation from M1 is canceled by M2 with the help of parts 2 and 3. And part 4 decouples the transverse and longitudinal dimensions, allowing an uncoupled bunch at the exit of the unit just as it is at the entrance. The low beam vertical eigen-emittance is then maintained.

It should be underlined that while the creation of EUV radiation is a typical application of GLSF, it is not the only one. The wavelength of coherent radiation could be further decreased, thus X-ray sciences may benefit. It might also be employed in traditional rings to produce coherent THz radiation and ultrashort pulses.

LINEAR BEAM DYNAMICS

For demonstration, the vertical dimension is taken to be the transverse dimension involved in coupling. Therefore, the particle coordinates of interest are (y, y', z, δ). The linear beam dynamics of the GLSF unit, including bunch compression, modulation cancellation, vertical-longitudinal decoupling, and bunching factor, are covered in this section.

The first step is bunch compression, realized from the unit entrance to the radiator. The idea is to project the vertical emittance ϵ_y to bunch length at the radiator $\sigma_z(\text{Rad})$ and eliminate the contribution from the longitudinal emittance ϵ_z. The modulator M1 is sandwiched by parts 1 and 2. By carefully choosing the dispersive terms of lattices and the modulation strength, the dependence of $\sigma_z(\text{Rad})$ on initial particle coordinates (z, δ) can be removed. And there is:

$$\sigma_z(\text{Rad}) = \sqrt{\epsilon_y \mathcal{H}_y(\text{Rad})}. \tag{1}$$

Here, $\mathcal{H}_y(\text{Rad})$ is a lattice-dependent function. $\sigma_z(\text{Rad})$ relies solely on vertical parameters. $\sigma_z(\text{Rad}) = 3$ nm can be expected with $\epsilon_y = 1$ pm·rad and $\mathcal{H}_y(\text{Rad}) = 9\,\mu\text{m}$.

The next to do is modulation cancellation, accomplished in between the two modulators. To reverse the modulation M1 has made to the beam, a new laser modulator, M2, is expected. Their modulations have the same waveform and amplitude but the opposite sign. The lattice between them, parts 2 and 3 as a whole, is made longitudinally 'transparent' to particles. In other words, it is both achromatic and isochronous. Coordinates in the z dimension at M1 and M2 are thus identical. Modulations, as a result, precisely add up and cancel each other out. The cancellation works for arbitrary modulation waveforms.

The following move is vertical-longitudinal decoupling, handled by the lattice at the end of the unit. The intention to decouple is to keep the vertical emittance low and retain beam status for manipulation turn after turn. With modulation canceled, the remaining coupling terms are dispersion-related. A final lattice, part 4, is employed at the end to ensure that the entire GLSF unit is an achromat.

And last, the bunching factor at the radiator b_n, to whose square the power of coherent radiation is proportional, is investigated. b_n in a GLSF storage ring is given by [16]:

$$b_n = e^{-\frac{1}{2}k_r^2\sigma_z^2(\text{Rad})} \Big| \sum_{p=-\infty}^{\infty} J_p(n) e^{-\frac{1}{2}(n-p)^2 k_m^2 \sigma_z^2(\text{Mod})} \Big|. \tag{2}$$

Here, $k_r = \frac{2\pi}{\lambda_r}$ ($k_m = \frac{2\pi}{\lambda_m}$) is the radiation (modulation) wave number, with λ_r (λ_m) the radiation (modulation) wavelength. $n = \frac{k_r}{k_m} = \frac{\lambda_m}{\lambda_r}$ is the harmonic number, and J_p is the p-th order Bessel function of the first kind. $\sigma_z(\text{Mod})$ is the bunch length measured at M1. The presence of $\sigma_z(\text{Mod})$ in b_n indicates that bunching factor can be degraded as the beam distribution is distorted by the nonlinear nature of the *sine*-wave modulation at M1.

The improvement of b_n is limited by [16]:

$$\sigma_{z\_y}(\text{Mod})\sigma_z(\text{Rad}) \geq \frac{\epsilon_y}{|h|}. \tag{3}$$

Here $|h|$ is the effective modulation strength. $\sigma_{z\_y}(\text{Mod})$ is the coupling part of $\sigma_z(\text{Mod})$. For a given radiation power, the product of bunch lengths is roughly decided. The demand for laser power can then be lowered by exploiting the ultralow ϵ_y. This is the exact gist of the GLSF scheme.

AN ILLUSTRATIVE CASE

An illustrative case with magnet arrangement of a GLSF unit has been produced. It is tested for 'tracking', in which the particle coordinates of a launched Gaussian-distributed beam have been iterated turn-by-turn. Lattice components are linear transfer matrices. The modulation of M0 is sinusoidal ($\Delta\delta = V_0 \sin(k_m z)$), while that of M1 and M2 is either linear ($\Delta\delta = hz$) or sinusoidal ($\lambda_m = 1\,\mu\text{m}$).

When a linear modulation is applied at M1 and M2, a steady-state bunch length of 3 nm is attained at the radiator, and the bunching factor at 13.5 nm is 0.372. With sinusoidal modulation at M1 and M2, the bunching factor at 13.5 nm is still as large as 0.153. The produced radiation power can be calculated given the particle coordinates [17]. Assuming beam energy to be $E_s = 400$ MeV, average beam current $I = 1$ A, period number N_u and period length λ_u of the radiator undulator 160 and 1.25 cm, at 13.5 nm and within a $\pm 2\%$ bandwidth, the average EUV radiation power is 1.2 kW. The modulation laser power is 1 MW, which is tolerable for up-to-date optical cavities in continuous-wave mode.

CONCLUSION

A ring-based beam manipulation technique, generalized longitudinal strong focusing, is proposed to produce steady-state nanometer-long bunches. Coherent EUV radiation of 1.2 kW can be obtained with 1 MW modulation laser.

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