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GENERATING HIGH REPETITION RATE X-RAY ATTOSECOND PULSES IN SAPS

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Abstract

Attosecond, which refers to 10^{-18} seconds, is the timescale of electron motion within an atom. Accurate observation of electron motion helps deepen the understanding of microscopic quantum processes such as charge transfer in molecules, wave packet dynamics, and charge transfer in organic photovoltaic materials. To meet the needs of relevant research, the South Advanced Photon Source (SAPS), currently in the design phase, is considering the construction of an attosecond beamline. This paper presents relevant research on achieving high-repetition-rate coherent attosecond pulses on the fourth-generation storage ring at SAPS. Realizing attosecond pulses in a storage ring requires femtosecond to sub-femtosecond-level longitudinal modulation of the beam, and the modulation scheme needs to consider multiple factors to avoid a significant impact on other users. The study shows that with high-power, few-cycle lasers, and advanced beam modulation techniques, the photon flux of attosecond pulses can be significantly enhanced with a minimal impact on the brightness of synchrotron radiation. Adopting high-repetition-rate lasers and precise time delay control, the repetition rate of attosecond pulses at SAPS can reach the megahertz level. To separate the attosecond pulse from the background synchrotron radiation, a pulse separation method was proposed. This mehtod improves the signal-to-noise ratio of attosecond pulses by more than an order of magnitude. Currently, the design wavelength range for attosecond pulses covers the water window (2.3-4.4 nm), which is “transparent” to water but strongly absorbed by elements constituting living organisms. This wavelength range has significant application value in fields such as biology and chemistry.

INTRODUCTION

Attosecond, which represents the natural time scale of electron motion in atomic and molecular systems, holds significant implications for several cutting-edge fields, such as quantum physics, biology, chemistry, and medicine. To advance scientific research in these fields, it is considered crucial to develop high-flux and high-repetition-rate Attosecond light sources [1].

The storage ring based light source is a stable, high-repetition-rate, and multi-user tool for light generation, which has been at the forefront of high-brilliance experiments. Currently, it has evolved from the third generation to the fourth generation, also known as the diffraction-limited storage ring (DLSR), resulting in an increase in Brilliance by more than two orders of magnitude. The ability to achieve attosecond pulses in DLSR would make it highly attractive due to the aforementioned advantages. During the design phase, the Southern Advanced Photon Source (SAPS) [2], aims to provide this new attosecond tool for attosecond science study. By pursuing high Brilliance and providing high flux and high repetition rate attosecond pulses, SAPS hopes to contribute to the development of attosecond science.

The natural pulse duration of light in storage rings typically ranges from 10 to 100 ps. To effectively reduce pulse duration while maintaining a high pulse flux, various laser-based beam modulation techniques have been proposed and applied to storage rings, such as echo-enabled harmonic generation (EEHG) and angular dispersion-induced microbunching (ADM) [3]. Recently, we propose a method by combine ADM with a few-cycle laser for the generation of attosecond pulses in a DLSR [4].

In this paper, we adopt this method for SAPS to generate attosecond pulses. Potential problems related to the ADM section were discussed, such as vertical dispersion bump-induced vertical emittance growth, and DA and MA reduction. And to increase the signal-to-noise ratio of the attosecond pulse, we propose a pulse separation method. This method improves the signal-to-noise ratio of attosecond pulses by more than an order of magnitude.

PARAMETERS OPTIMIZATION OF THE ADM

The ADM structure, located within one of the straight sections of SAPS as illustrated in Fig. 1, initially couples the electron beam in both transverse and longitudinal directions using a vertical dipole. Subsequently, the beam undergoes energy modulation through interaction with a short wiggler (known as a modular) and a few-cycle laser. Finally, a dogleg consisting of two vertical dipoles with equal strength but opposite deflection angles imparts transverse and longitudinal dispersion, which converts the energy modulation into density modulation, resulting in microbunching or a large local peak current in the electron beam. The modulated beam then passes through an undulator (known as a radiator) to generate coherent attosecond pulses. After this process, the radiated electron beam passes through four dipole magnets, which have been designed specifically in position and strength to eliminate the vertical dispersion and allow the beam to return to the ring. The design of the ADM

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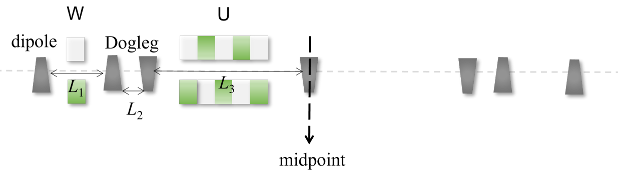

Figure 1: The layout of the ADM section in a straight section. Seven dipoles are symmetrically arranged and the center point shared by the straight and ADM sections are marked as the "midpoint".

section must meet optimal radiation performance and minimal impact on the storage ring for a given set of machine parameters. To achieve this goal, a optimization has been performed in Ref. [4] based on the SAPS parameters given in Table 1. It found that when the dogleg dispersion η is 0.48 mm, a optimal local current and local bunching factor can be achieved. All optimal parameters are presented in Table 2.

Table 1: SAPS Main Parameters

Parameters	Value	Unit
Energy	3.5	GeV
Circumference	810	m
Nature emittance	33.4	pm
Energy spread	0.11	%
Momentum compaction factor	2.5×10^{-5}	
Bunch number	405	

Impact of the Beam Dynamics

This subsection presents a study of the beam dynamics in the ring, both with and without the ADM section. We investigate the linear and nonlinear behaviors separately, starting with the linear dynamics followed by an investigation of the nonlinear dynamics.

Table 2: Optimal Parameters of ADM Elements

Parameters	Value	Unit
Dipole		
Bending angle	6.6	mrad
Dogleg		
Bending angle	7.4	mrad
Distance between dipoles	0.45	m
Modulator		
Peak field	0.52	T
Period length	0.4	m
Radiator		
Peak field	0.996	T
Period length	0.04	m

In the context of linear dynamics, we present the linear lattice function for the ADM section as shown in Fig. 2. Corresponding detailed parameters can be found in Table 2. Upon inclusion of the ADM section, a dispersion bump with a maximum amplitude of approximately 12 mm is generated in the vertical direction. As for Twiss parameters, this ADM section only affects the vertical beta and alpha functions, with changes of less than 1%. It is important to recognize that such a low beta beating has only a small impact on the overall beta beating caused by other IDs with reasonable errors and misalignments. Therefore, it is possible to correct the root mean square (rms) beta beating of the ring to an acceptable value.

To study the nonlinear dynamic, we conducted simulations to obtain the dynamic and local momentum apertures of the SAPS, both with and without the ADM section, using the ELEGANT code. These simulations took into account the effects of radiation damping and quantum excitation.

The reduction of the on-momentum dynamic aperture (DA) by the ADM section is illustrated in Fig. 3. The DA area decreased from 29.7 mm² to 27.6 mm², with maximum horizontal and vertical size reductions of less than 2%. The MA of the ring is also reduced, particularly at the location of the ADM section, with a maximum reduction of 25%. However, given their small magnitudes, these reductions are negligible in terms of their impact on ring injection [5]. We evaluate the effect of the ADM section on the ring lifetime. The method estimates that the ring with and without the ADM section both have a lifetime of approximately 10 hours, which is sufficient for normal operation of the storage ring.

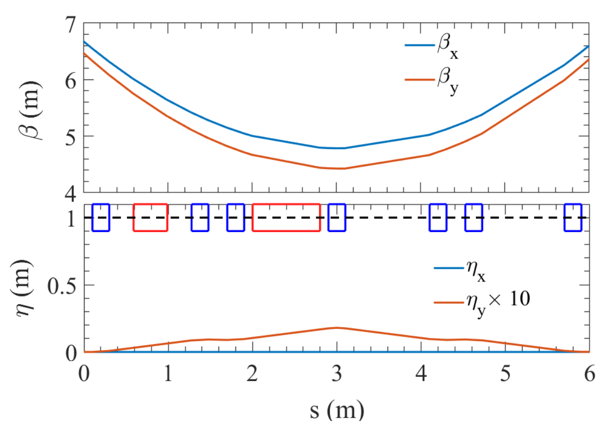

Figure 2: Lattice function for the straight section containing the ADM structure: blue squares represent the dipole, green represents the undulator.

PERFORMANCE AND REPETITION RATE

The modulated beam can generate coherent radiation pule with wavelength of 4 nm and different time duration in the radiator with different period number N. The time duration Δt are proportional to N. For short time duration one require $N < 10$, which will let $\Delta t < 100$ as. However, small N resulting lower photon flux per pulse and larger FWHM bandwidth (Bw). For instant, when $N = 4$, the time duration can be as short as 50 as, but the flux is above one order of

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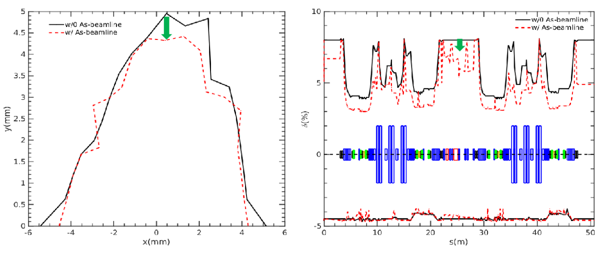

Figure 3: Dynamic and local momentum apertures comparison between different SAPS without (black line) and with ADM section (red dashed line).

magnitude lower than that of $N = 20$. Given the presence of 405 bunches in the ring, the repetition rate can reach up to 6.75 kHz, provided that each bunch is modulated only once in each recovery period (~ 60 ms) [4]. The average flux for pulses of 50 as, 122 as, and 252 as FWHM duration are 1.28×10^8, 6.4×10^8, and 2.29×10^9 photons/pulse/1%Bw, respectively.

When each bunch in the ring undergoes only one modulation during the 60 ms recovery period, the corresponding repetition frequency is 6.75 kHz. It is worth noting that during each modulation, only a small part of the beam (with beam length σ_b) is modulated by the few-cycle laser (with duration σ_l). If multiple modulations of different parts of the bunch are carried out during each recovery period, the repetition rate can be increased by approximately σ_b/σ_l times.

To consider the Gaussian longitudinal distribution of the beam, as a delay distance that is too large can result in a decrease in local current. We take delay length of 0.1 mm and 200 modulations are performed on the beam, the corresponding reduction in local current is maximally 6%, and there is a decrease in radiation power of approximately 10%. This suggests that multiple modulations generate radiation pulses with a variation magnitude of less than 10%. On average, the flux per second of the radiation pulses with pulse duration of 48, 122, and 252 as can reach 2.47×10^{10}, 1.23×10^{11}, and 4.4×10^{11} photons/s/1%Bw, respectively.

SEPARATION OF THE ATTOSECOND PULSE

For a few femtoseconds to attosecond pulses obtained by the seeding method, the signal-to-noise ratio of the ultrashort pulses is low due to the large difference in pulse length (1e-4 to 1e-2) from the storage ring synchrotron pulses, despite the large peak power due to coherence. In order to improve the signal-to-noise ratio of the attosecond pulses generated using the scheme of this paper, a pulse separation scheme with microbunches beam dynamics is given in this section.

Beam dynamics and certain FEL experiments have shown that microbunches rotate in the new direction of travel when the electron beam is kicked and defocused. This can be used for multiplexing in the FEL. Under a weak focusing kicker, the direction of the microbunches remains unchanged [6]. Inspired by this effect, we add a kicker of suitable strength at the entrance of the beam section to deflect the beam horizontally. a kicker of suitable strength to deflect the beam horizontally. As shown in Fig. 4, since the direction of the microbunch is unchanged, there will be an angular difference between the direction of the coherent radiation and the synchrotron radiation, thus realising the separation of coherent pulses.

The simulation results show (Fig. 4) that for a kicker angle of 200 µrad, placing an aperture of size [-0.4 mm, 1mm]×[-1mm, 1mm] at a distance of 10m from the source can separate out 99% of the coherent radiation, improving the signal-to-noise ratio of the attosecond pulse by a factor of 10-100.

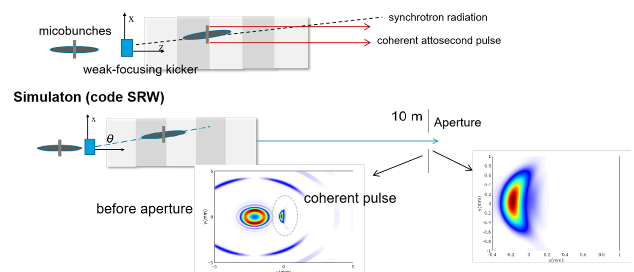

Figure 4: Layout and simulation results of the pulse separation scheme.

DISCUSSION AND CONCLUSION

We proposed a method to generate attosecond pulses in SAPS by combining ADM and few cycle laser. simulations show attosecond pulse with repetition rate of 6.75 kHz can be generated. By introducing a suitable time delay between the laser and the beam, the modulation can be performed repeatedly on a beam, thereby increasing the repetition rate to 1.35 MHz. To separate the attosecond pulse from the background synchrotron radiation, a pulse separation method was proposed. There are still some open issues with this scheme, such as the need for a large kicker angle in the pulse separation scheme. The larger the angle, the greater the degradation of the coherent radiation. In the future, a full optical beamline design will be required to see if these degradations are acceptable for the experimental requirements.

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