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# GENERATION OF COHERENT ATTOSECOND X-RAY PULSES IN THE SOUTHERN ADVANCED PHOTON SOURCE *

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*Abstract*

Southern Advanced Photon Source (SAPS) is a fourth-generation storage ring light source that has been considered for construction in Guangdong province of China, adjacent to the China Spallation Neutron Source. As a low-emittance storage ring, the natural emittance of SAPS is below 100 pm. One of the benefits is that the brightness is about 2 orders high than 3rd generation light sources. However, like many other storage ring-based light sources, the time resolution is limited by the electron bunch length in the range of picoseconds. In this work, we propose a new scheme for the generation of coherent attoseconds X-ray pulses with a high repetition rate in SAPS. A numerical demonstration of the scheme is presented.

## INTRODUCTION

The study of inner shell electron dynamics in pump-probe experiments requires isolated attosecond pules. Recent progress on the high harmonic generation (HHG) sources and the free electron lasers (FELs) sources have made this requirement possible [1–3]. Nevertheless, the intensity of the attosecond pulse delivered from HHG is still too weak to support a pump-probe experiment. FEL can generate an intensive attosecond pulse to cause a non-linear interaction with matter. However, the relatively low repetition rate is an obstacle for pump-probe experiments. Compared with the above two light sources, the storage ring light source has higher stability and repetition rate. However, due to the limitation of light pulse duration and temporal coherence, its not adequate for resolving the matter dynamics in the sub-picosecond regime. In order to achieve attosecond time resolution pump-probe experiments in storage ring light sources, a coherent radiation method is required. For example, an echo-enabled harmonic generation (EEHG) based scheme is proposed in the storage ring to generate a sub-femtosecond coherent pulse [4]. This scheme requires two lasers and two energy modulations. Compared with a single laser modulation scheme (e.g. [5]), it is more difficult to implement EEHG in a storage ring. In addition, the repetition rate of the scheme proposed in [4] is limited by the repetition frequency of the modulation laser and the damping time of the storage ring. In this paper, we propose an alternative scheme by combining a few-cycle laser and a coherent radiation scheme. This scheme is easy to implement and can achieve a high repetition rate of up to a few MHz.

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## METHOD

The layout of the proposed scheme is illustrated in Fig. 1. The lattice of the proposed scheme consists of two parts: laser modulation and the match section. The match section is used for dispersion suppression. For convenience, we named this lattice modu-cell. The laser modulation section includes four elements: a dipole, a shot undulator as a modulator, a dogleg, and a long undulator as a radiator. A laser modulation scheme with this structure was first proposed in Ref. [5] to generate EUV coherent radiation with a femtosecond duration in a storage ring. To generate a coherent pulse with attosecond duration, we adopt a few-cycle laser as a modulation laser. As shown in Fig. 2, compared with the many-cycles laser, the electric field envelope of the few-cycle laser varies dramatically in the longitudinal direction, which leads to a different energy chirp $h$ in different laser cycles after the energy modulation (see Fig. 2(d)). After passing the dogleg, the longitudinal position $z$ of an electron in one of the laser cycle is changed to

$$z_f = (1 + h\xi_D)z_0 + b(1 + h\xi_D)y_0 + (\xi - \eta b)\delta_0, \quad (1)$$

where $\xi_D$ and $\eta$ are the longitudinal and vertical dispersion respectively, $b$ is the bending angle of the first dipole and $\xi = \xi_M + \xi_D$, where $\xi_M$ is the longitudinal dispersion of the modulator. Form Eq. (1), one can see that if the following condition are satisfied:

$$\begin{cases} 1 + h\xi_D = 0, \\ \xi - \eta b = 0. \end{cases} \quad (2)$$

The final microbunch length (in one laser cycle ) is only determined by $\eta\sigma_{y'_0}$ , where $\sigma_{y'_0}$ is the beam divergence before the energy modulation. For many-cycles laser modulation, since in each cycle, $h$ is approximately equal, a microbunch train is generated. After the downstream radiator, this microbunch train will generate a coherent pulse with a duration similar to that of the many-cycle seed laser. When we adopt the few-cycle laser to modulate the electron beam, the situation is quite different. As shown in Fig. 2, the energy chirp of the electrons around the zero phase is larger than that of electrons at other phases. By matching the beamline parameters, it is possible to generate a single microbunch around this zero phase. Then after the radiator, the corresponding radiation pulse will be shorter than that

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of the seed laser. By using a laser with a suitable duration, the radiation pulse can be shorter than femtoseconds.

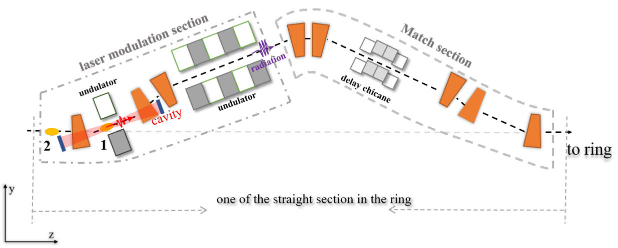


Figure 1: Layout of the proposed scheme.

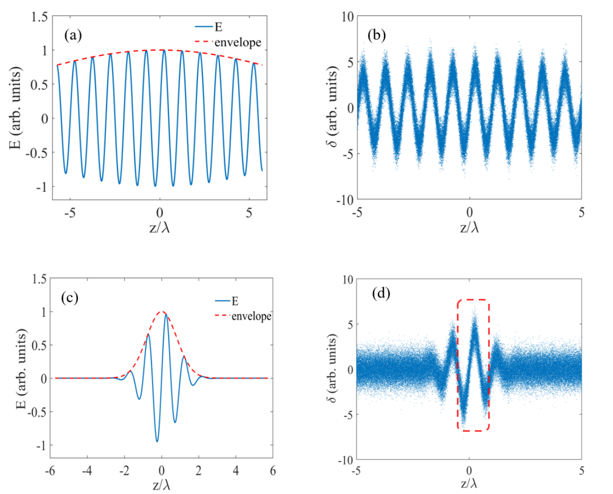


Figure 2: Electric field and the envelope of the many-cycle (a) and few-cycle (c) laser. Longitudinal phase space of the electron beam after the many-cycle (b) and few-cycle (d) laser modulation.

## SIMULATION

We take one design of the Southern Advanced Photon Source (SAPS) [6] as an example to demonstrate the feasibility of the proposed scheme. The mean parameters are listed in Table 1. The aim is to generate an attosecond pulse with a 4 nm wavelength. As shown in Fig. 3, by adding the modu-cell in one of the straight sections in SAPS, a local dispersion bump in the vertical direction is created. Simulation based on Elegant shows that this dispersion bump increases the vertical emittance to about 3 pm (see Fig. 4(b)). This vertical emittance increasing reduces the intra-beam scattering effect, resulting in a decrease in the horizontal emittance (see Fig. 4(a)).

The dynamic aperture (DA) and local momentum aperture (MA) for the cases with and without modu-cell are shown in Fig. 5. The modu-cell slightly reduces the DA in both horizontal and vertical planes. And due to the local vertical dispersion bump, the MA of the straight section where the modu-cell is located increases by about 30%. Since there is only one modu-cell in the SAPS ring, this MA increasing has little effect on the Touschek lifetime.

Table 1: Main Parameters of the SAPS

| Parameters | Value | Unit |
|---|---|---|
| Energy | 3.5 | GeV |
| Circumference | 1080 | m |
| Nature emittance | 31.8 | pm |
| Energy spread | 0.11 | % |
| Single bunch charge | 2 | nC |
| Bunch number | 300 | |

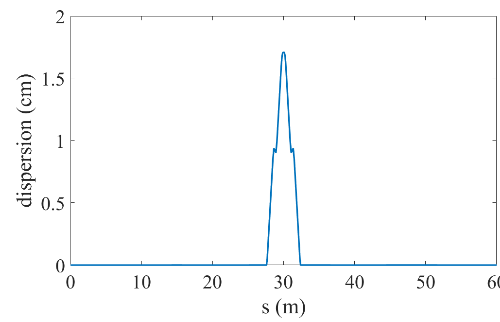


Figure 3: Vertical dispersion of the modu-cell.

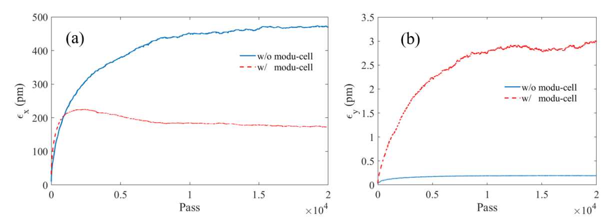


Figure 4: Horizontal (a) and vertical (b) emittance varying with different turns for the case of with and without the modu-cell.

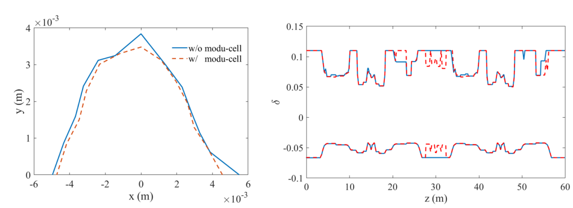


Figure 5: Dynamic aperture (left) and the momentum aperture (right) for the case with and without modu-cell.

Three-dimensional simulations are performed to demonstrate the performance of the proposed scheme. The movement of the electron beam is simulated by Elegant with second-order transport effect taken into account. We use a few-cycle laser with a duration(FWHM) of about 4 fs and pulse energy of about 460 μJ to modulate the electron beam. The longitudinal phase space of the modulated electron beam at the entrance of the radiator is shown in Fig. 6. Benefit from the few-cycle laser a single microbunch is generated.

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This modulated electron beam then generates a 4 nm coherent light pulse with 53 as duration after passing the radiator. As shown in Fig. 7, the maximum power of this radiation pulse is about 6.6 MW, and the bandwidth (bw) is about 7%. The photon flux of this attosecond pulse is $10^6/1\%bw$, which is about 2 orders higher than that of the attosecond pulse generated by the HHG technique [1]. And strong enough to support ultrafast pump-probe experiments [7].

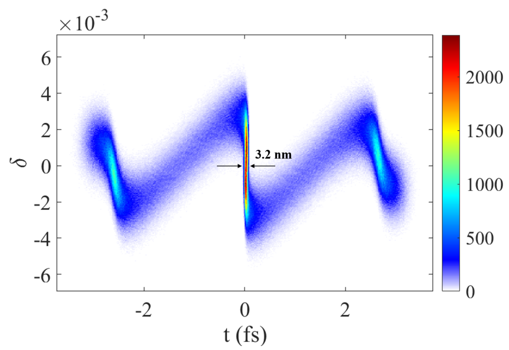


Figure 6: Longitudinal phase-space of the electron beam before enters the radiator.

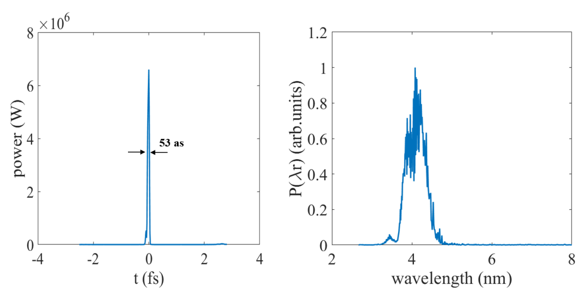


Figure 7: Power distribution (left) and spectrum (right) of the radiation pulse.

## REPETITION RATE

Note that due to the coupling and energy modulation in the modu-cell, the vertical emittance of electron beam is distorted. In order to restore the original value, this modulated beam has to be stored in the ring for sufficient time. The simulation result shown that after about $3 \times 10^4$ turns the vertical emittance of this modulated beam is recovered (see Fig. 8). The corresponding recovery time $\tau_r$ is about 108 ms. Under the assumption that there are $N_b$ bunches in the storage ring, the minimum repetition rate $f$ is

$$f = min(f_{laser}, \frac{N_b}{\tau_r}), \tag{3}$$

where $f_{laser}$ is the repetition rate of the modulation laser.

Under the current technology level, the repetition rate of a few-cycle laser with pulse energy belong 1 mJ is around 10 kHz [8]. We assume $N_b = 300$, so the repetition rate of the attosecond pulse is 3 kHz. This repetition rate is the minimum repetition rate of the proposed method.

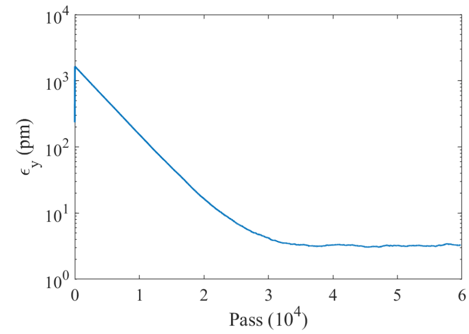


Figure 8: Vertical emittance obtained after a single energy modulation for the different turns.

To increase the repetition rate, we need to break the limit that a single bunch can only modulate once in a recovery period. To this end, a delay chicane is adopted in the modu-cell to delay the bunch. Note that, in the electron bunch, the modulation region is only about 4 fs, which is more than 3 orders shorter than the bunch length. Therefore it is possible to delay the bunch $N_{slippage}$ ($\gg 10$) times, which will result in a $N_{slippage}$ fold increase in repetition rate. For example, if we delay the bunch 1000 times, the repetition rate will increase to 3 MHz. However, this repetition rate is much larger than that of the few-cycle laser under the current technology level. To solve this problem, a laser cavity with a cavity loss of about 0.2% is adopted. Simulation shows that after 50 times modulation, due to the decay of the laser power, the photon flux is dropping to $10^5/1\%bw$. Assume this reduction is acceptable. To reach a repetition rate of 3 MHz, the repetition rate of a few-cycle laser is to be around 60 kHz, which is feasible under the current technology. In general, the repetition rate of the proposed method can be expressed as follows

$$min(f_{laser}, \frac{N_b}{\tau_r}) \le f \le N_{slippage}\frac{N_b}{\tau_r}. \tag{4}$$

## CONCLUSION

In this paper, we propose a new scheme to generate attosecond pulses in SAPS. The photon flux of the attosecond pulse is about $10^6$ /1%bw, and the repetition rate is up to 3 MHz. Note that to achieve the 3 MHz repetition rate, we need delay chicane and laser cavity. In the current study, we only explain the working principle of these systems. The detail simulation and design are in progress.

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