SUBPICOSECOND LASER SLICING X-RAY SOURCE FOR TIME-RESOLVED RESEARCH AT TPS

W.K. Lau, M.C. Chou, C.S. Hwang, A.P. Lee, Y.C. Liu, G.H. Luo, NSRRC, Hsinchu 30076, Taiwan
N.Y. Huang, Institute of Photonics Technologies, NTHU, Hsinchu 30013, Taiwan

Abstract

The feasibility of using a high intensity short pulse laser to produce ultrafast x-ray pulses from the Taiwan Photon Source (TPS) by bunch slicing is being investigated. In our study, a modulator wiggler with period length of 25 cm is placed in one 7 m straight section and is operated at low field strength to minimize possible side-effects that may limit the performances of the low emittance TPS ring. With proper beam separation technique, undulators in straight sections at downstream of the modulator wiggler can be used to produce ultrafast soft and hard x-ray 100 fs pulses at moderate flux. This installation will offer the opportunity to study ultrafast phenomena of condensed matters at atomic resolution.

INTRODUCTION

The TPS is a 3 GeV third generation synchrotron radiation source that is under construction at NSRRC [1]. It should be ready for user operation in 2014 and will benefit x-ray users in many research areas. We have been exploring ways to make the most from this high brilliance facility. One possibility is an ultrafast laser slicing x-ray source for time-resolved research.

The first laser slicing experiment to produce fs x-ray pulses was demonstrated at the ALS in Berkeley with a bending magnet as the radiator [2]. The tunable laser slicing soft and hard x-ray sources at BESSY II [3] and SLS [4] have been operating successfully as user facilities with improved photon flux at exceptional spatiotemporal stability [5]. In their designs, modulator wiggler and radiator are installed in the same straight section and chicanes are employed to provide necessary dispersion for efficient angular beam separation in the horizontal direction. However, significant modification of ring lattice is necessary in this case. As suggested by Nadji et al for laser slicing at SOLEIL, it is attractive to put wiggler in one straight section and more radiators (undulators) in downstream straight sections. In this way, the natural dispersion of the ring lattice can be used for beam separation without modification of ring lattice [6]. New laser slicing facility of this kind has been planned for NSLS-II in Brookhaven [7].

In this design study, we adopt the so-called "separate-straight-section" scheme and use long period wiggler to avoid high field strength for laser-beam interaction at resonance condition to minimize the side-effects that may limit the TPS performances. These side-effects include the degradation of beam emittance, shrinkage of beam dynamic aperture etc. [8].

TENTATIVE LAYOUT

The 3 GeV TPS is a 518.4 m, 24-cell DBA low emittance ring with six-fold symmetry. It provides one 12 meters long straight section and three 7 meters medium straight sections per superperiod (1/6 of the ring) [1]. The natural emittance at low emittance operation mode is 1.6 nm-rad. In phase I of the TPS project, insertion devices like elliptical polarization undulator EPU48 and in-vacuum undulator IU22 will be installed to produce high flux photon beams at 500 mA stored beam current with energy ranging from 0.4 to 20 keV [9].

For laser slicing, energy modulation wiggler will be installed in one of the 7 m straight sections. The pulse energy of the laser should be high enough to provide a modulation of about 1% of the nominal TPS beam energy. On the other hand, the required pulse energy of the laser should be within reach of commercially available systems at kHz repetition rate. For evaluation purpose, either IU22 (2x2m) or EPU (2x3.5m) is considered to be in the nearest 12 m long straight section at downstream of the modulator. Other radiators can be put into 7 m medium straight sections adjacent to the long straight (Fig.1). A more realistic layout will depend on user applications.

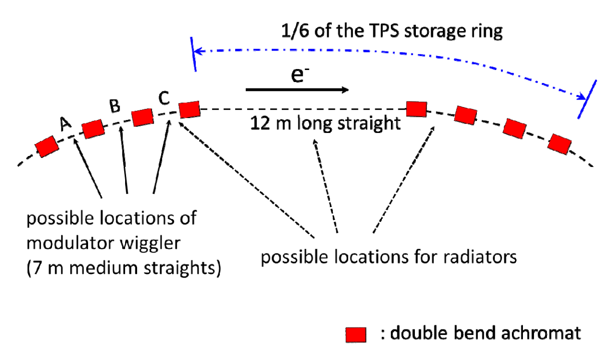

Figure 1: Possible locations of modulator wiggler and radiators in this evaluation study.

THE MODULATOR WIGGLER

As long as the resonance condition for laser-electron interaction in the wiggler is kept, energy modulation of electrons in a bunch by the 800 nm femtosecond Ti:Sapphire laser will be most effective when the number of periods of the laser pulse equals to that of the modulator wiggler [10]. For a 50 fs laser pulse, the number of wiggler periods should be set at 18. If the availability of space is a concern, short period wiggler operating at high magnetic field can be used. However, the equilibrium emittance and energy spread of electron

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beam in the storage ring can be modified by the use of wiggler magnet due to the emission of synchrotron radiation. This problem is much more server for low emittance ring and when the wiggler is operated at high magnetic field. Therefore, it is desirable to use modulator wiggler with longer period such that operating field can be lowered. The available space of a 7 m medium straight section for installation of the modulator wiggler at TPS is about 5 meters. It allows us to use W250 wiggler and the operating field can be set at ~0.9 T. This number is slightly lower than the critical field for a damping wiggler [11]. The parameters of the W250 modulator wiggler and the femtosecond laser we used in this study are listed in Table 1.

Table 1: Parameters of the W250 Modulator Wiggler and the Femtosecond Laser

W250 wiggler	
Number of periods	18
Period length [cm]	25
Wiggler constant	0-33
Maximum field [T]	1.8
Minimum gap [mm]	22.5
Operating wiggler constant	21.47
Operating field [T]	0.92
Total length [m]	4.5

Laser	
Wavelength [nm]	800
Pulse energy [mJ]	3.2
Pulse duration [fs]	50
Repetition rate [kHz]	10
Maximum energy modulation [%]	1.4

The emittance of the TPS beam as a function of magnetic field strength of W250 is calculated (other insertion devices are not considered in this calculation). As shown in Fig.2, the beam emittance increases rapidly at wiggler field higher than 1 T (Fig.2).

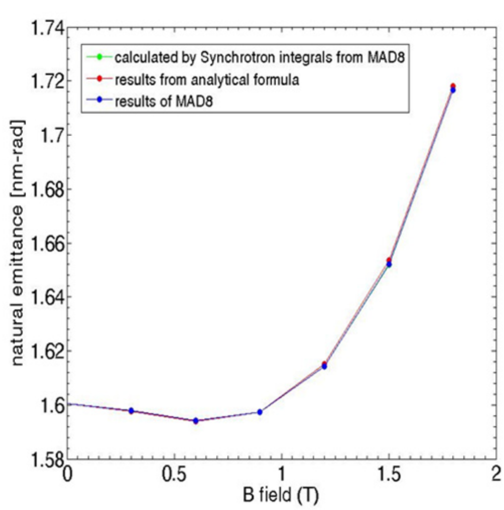

Figure 2: The dependence of TPS beam emittance on the W250 modulator wiggler field strength.

Dynamic apertures are calculated with the OPA code [12]. The results show that the impact of W250 wiggler operation for laser slicing at 0.92 T on dynamic aperture is insignificant (Fig. 3).

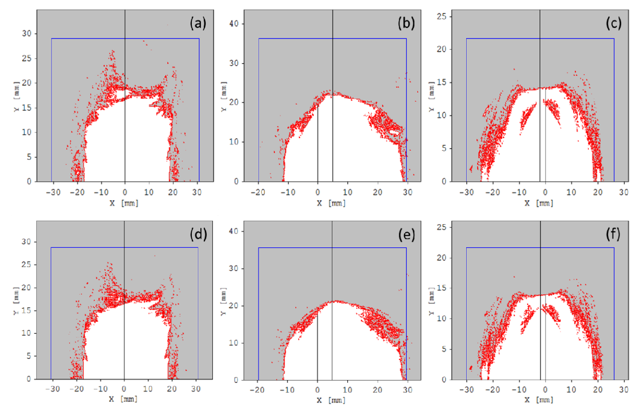

Figure 3: A comparison of TPS dynamic apertures calculated by using OPA with and without W250 wiggler. The subplots (a), (b) and (c) show the dynamic apertures of TPS bare lattice for 0%, +3.0% and -3.0% off energy particles respectively. Subplots (d), (e) and (f) show the dynamic apertures of TPS lattice with W250 operating at magnetic field strength of 0.92 T for 0%, +3.0% and -3.0% off energy particles respectively.

BEAM SEPARATION AND EXPECTED PERFORMANCES

Beam Separation

We now look at the possibility to separate the "satellite" bunch from the core bunch by the natural lattice of TPS. The horizontal displacement Δx of the "satellite" bunch from the core bunch is related to the effective dispersion function D_{eff} as:

$$\Delta x = D_{eff} \frac{\Delta E}{E_0} \quad (1)$$

$\Delta E/E_0$ is the energy modulation by the modulator wiggler that is set at 1%. D_{eff} is defined in Eq. (2).

$$D_{eff} = \eta_2 - \left(\sqrt{\beta_1 \beta_2}\,\eta_1' + \alpha_1 \sqrt{\frac{\beta_2}{\beta_1}}\,\eta_1 \right) \sin \mu_{12} - \sqrt{\frac{\beta_2}{\beta_1}}\,\eta_1 \cos \mu_{12} \quad (2)$$

where α and β are the Twiss parameters and η is the dispersion function. The subscripts 1 and 2 refer to the centre of the modulator and radiator respectively. With the TPS low emittance bare lattice, the effective dispersion functions and horizontal displacements are calculated with MAD8. Fig.4 shows horizontal displacement (normalized to RMS horizontal beam size) of the "satellite" bunch from core bunch as a function of *s* when the modulator is placed in the middle of straight section "A". With modulator either in position "A" or "B", the horizontal displacement at the centre of the 12 m long straight is larger than 5 times of the horizontal beam size. This should be enough for effective beam separation. Energy modulation assumed in these calculations is 1%. Shorter undulators can be put into the 7 m straight sections adjacent to the long straight. Modulator in position "C" cannot provide enough beam separation at the 12 m long straight downstream with reasonable laser energy.

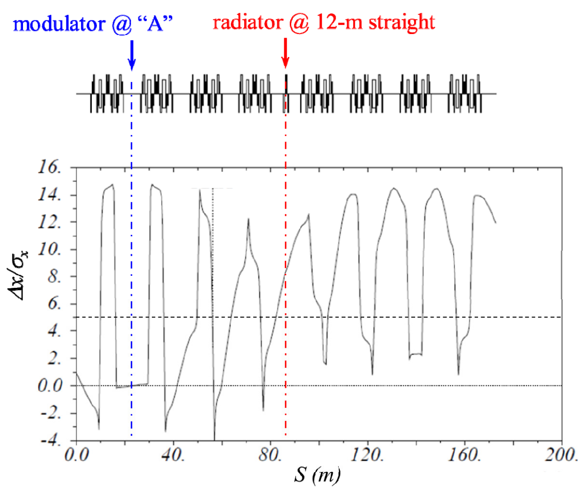

Figure 4: Calculated horizontal displacement of "satellite" bunch from core bunch with wiggler in position "A".

Expected Performances

If we consider the average current of a bunch in the TPS ring is 0.5 A and the repetition rate of the Ti:Sapphire laser is 10 kHz, the average flux from the "satellite" beam as it pass through the two 3.5 m EPU48 in the long straight is about $3x10^7$ photons/s per 0.1% bandwidth at 1 keV photon energy. For two 2.134 m IU22 in-vacuum undulators in the long straight, the average flux is about $2.5x10^6$ photons/s per 0.1% bandwidth at 10 keV photon energy. Temporal dilution of the "satellite" bunch as it travels from the modulator wiggler to the radiator is the quadratic sum of the laser pulse duration, the time slippage of electron with respect to optical pulse, the contribution due to betatron oscillation and energy dispersion [6]. The estimated values of temporal dilution are listed in Table 2. It should be noted that the contribution of energy dispersion to temporal dilution of "satellite" bunch is calculated with natural energy spread of TPS. It is actually depend of the width of the collimator we use for beam selection.

Table 2: Estimation of the durations of the "satellite" bunch at the centre of 12 m long straight section with modulator at locations "A", "B" and "C".

Location of modulator	A	B	C
Laser pulse duration (fs)	50	50	50
Slippage (fs)	48	48	48
Betatron oscillation (fs)	1.88	1.90	--
Energy dispersion (fs)	44.1	39.9	--
Final bunch length (fs)	82.17	79.99	--

CONCLUSIONS

Our preliminary study of the TPS laser-slicing source with a W250 modulator wiggler in 7 m medium straight section (location "A" or "B") and with radiators in downstream straight sections appears to be a feasible way to generate 100 fs soft or hard x-rays with photon flux as high as $\sim1x10^7$ photons/s/0/1% BW depending on the total length of the undulator we use. Impact of the modulator wiggler to TPS performances has been evaluated and the side effects are shown to be insignificant. However, the lattice parameters are subject to change in a real machine, the flexibility of this scheme needed to be studied in details. In order to improve average photon flux from the satellite bunches, it is desirable to increase laser repetition frequency. The dependence of radiation intensity from beam halo on laser repetition frequency, however, implies a significant reduction of signal-to-noise ratio. But according to the analysis of Streun [13], as in the SOLEIL's situation, a signal-to-noise ratio at 10 kHz laser rep.-rate is still acceptable.

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