BROOKHAVEN
NATIONAL LABORATORY

BNL-94858-2011-CP

Short Pulse Generation by Laser Slicing at NSLSII

L.H. Yu, A. Blednykh, W. Guo, S. Krinsky, Y. Li, T. Shaftan, O. Tchoubar, G.M. Wang, F. Willeke, L. Yang

Presented at the 2011 Particle Accelerator Conference (PAC'11)
New York, NY
March 28-April 1, 2011

March 2011

Photon Sciences Directorate

Brookhaven National Laboratory

U.S. Department of Energy
DOE - Office of Science

DISCLAIMER

SHORT PULSE GENERATION BY LASER SLICING AT NSLSII*

L.H. Yu, A. Blednykh, W. Guo, S. Krinsky, Y. Li, T. Shaftan,
O. Tchoubar, G. M.Wang, F. Willeke, L. Yang , BNL, Upton, NY11973, U.S.A.

Abstract

We discuss an upgrade R&D project for NSLSII to generate sub-pico-second short x-ray pulses using laser slicing. We discuss its basic parameters and present a specific example for a viable design and its performance. Since the installation of the laser slicing system into the storage ring will break the symmetry of the lattice, we demonstrate it is possible to recover the dynamical aperture to the original design goal of the ring.

There is a rapid growth of ultrafast user community interested in science using sub-pico-second x-ray pulses [1-4]. In BNL's Short Pulse Workshop [5], the discussion from users shows clearly the need for a sub-pico-second pulse source using laser slicing method. In the proposal submitted following this workshop [6], NSLS team proposed both hard x-ray and soft x-ray beamlines using laser slicing pulses (Fig.1). Hence there is clearly a need to consider the R&D efforts of laser slicing short pulse generation at NSLSII to meet these goals.

LASER SLICING METHOD

The method is first proposed by Zholents and Zolotarev [7]. To illustrate the basic principle of the scheme, we use the modulator and the EPU49 in Fig.1 as a soft-x-ray short pulse source and illustrate it in

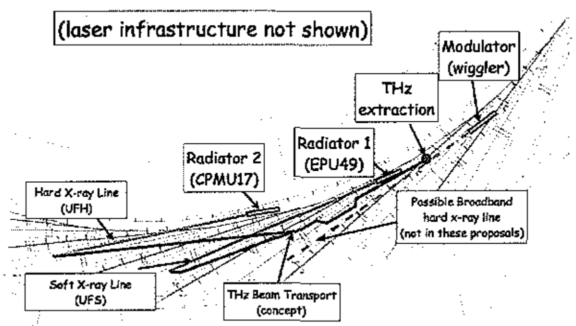

Fig.1 The Soft and Hard X-ray ultrafast beamlines

Fig.2.

In the long straight section, the electron bunch of 30 ps long and laser pulse of 50 fs long interact in a wiggler (the modulator), in part of bunch (50 fs long) electrons are modulated, a part of these electron are modulated to 20MeV. The storage ring lattice is designed to have dispersion in the short straight section next to the long straight section with the modulator.

*Work supported by DOE contract DE-AC02-98CH10886.

Hence when the electron bunch enters the radiator EPU49 in the short straight section, the modulated part of the electrons is separated from the most of the electrons in the bunch (the core). Due to the dispersion in the radiator, the radiation of the modulated electrons can be separated from the core electrons since they have different centroid and direction.

System Parameters and Performance

Laser wavelength and pulse length.

Since we need short pulse, Ti-Sapphire laser is a clear choice with wavelength at λ_L = 800nm and pulse length of

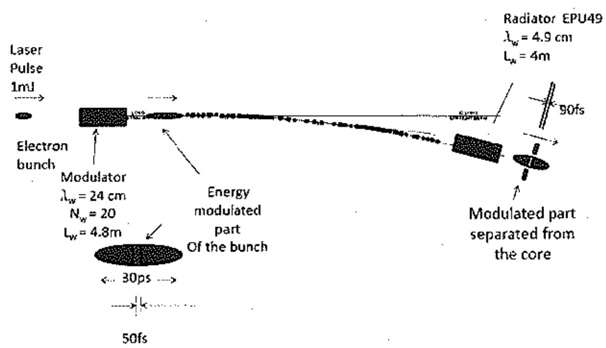

Figure 2. Illustration of laser slicing method

τ_L=50fs is available with high power. Since the period is λ_L /c=2.6 fs, the number of period in the pulse is N_L=20.

Modulator period and length.

With electron beam energy E_0=3GeV we have for λ_w =24cm, K=21.5 with peak field at B_w =0.96 Tesla. Wiggler period number N_w =20, so the slippage is $N_w \lambda_L$ /c=50fs. Hence the pulse length from an electron is 50 fs. We take N_w=N_L=20. Then the wiggler length is L_w=N_w λ_w =20×24cm=4.8m.

Energy modulation, wiggler Length and laser Rayleigh Range.

From the FEL equation for the energy modulation and the relation between laser Rayleigh range L_R and beam waist we find that to maximize the energy modulation we need to match the Rayleigh range with wiggler length so that $L_w \cong 2.8 L_R$. For laser energy $A_L = 1mJ$ we find that, $(\Delta E)_{max} \cong 20MeV$. We have the ratio to energy spread as $p = (\Delta E / E_0)/(\sigma_\gamma / \gamma) = 7.3$, with energy spread σ_γ / γ=0.9 %,

Separation from beam core in the Radiator

For simplicity, here we only consider the separation of coordinates of the modulated beam from the core. The photon beam size $\sigma_{xT} = 84\,\mu$m from the modulated electrons is a convolution of natural beam size determined by beta function, the dispersion beam size, and the photon beam size determined by diffraction limit. Take the dispersion D_x =6.5cm, the separation from the core is $\Delta x = D_x\,(\Delta E)_{max} / E_0 = 440\mu$m. This leads to $\Delta x / \sigma_{xT} = 440\mu m/84\,\mu m = 5.1$

Experiences from other lab require the separation ratio larger than 5, so we need dispersion ~6.5cm . For soft x-rays beamline, because the larger divergence angle of the soft x-rays radiation, a mixed coordinate and angle separation gives better separation. Based on experiences from SOLEIL [4] it is estimated to have dispersion η=4.8cm, η'=25mrad. Optimization of a mixed coordinate and angle separation will be carried out later.

Flux of short pulses

The fraction η of the modulated electrons fall within the observation window in one optical period is found to be 0.14. Thus for the whole bunch the fraction is $\eta\, \tau_L / \tau_b = 0.14{\times}50\,\text{fs}/30\,\text{ps} \cong 2.3{\times}10^{-4}$. Photon flux from EPU49 for 500mA core current is S=2×10^{15} photons/s/0.1%BW at 1.4 keV. Assume 1000 bunches in the ring , with revolution period 2.63 μs, the photon flux per pulse for core bunch current 0.5mA is S ×2.63 μs /1000=5.3 ×10^{6} photons/0.1%BW . With the fraction $2.3{\times}10^{-4}$, the short pulse photon flux per pulse is then 1300 photons/0.1%BW. Assume repetition rate of f_L=1kHz, the short pulse photon flux is then 1.3 ×10^{6} photons/0.1%BW.

Short pulse flux for camshaft bunch of 5 mA

If we use camshaft bunch with current of 5mA, the bunch lengthening is expected to reach 55ps instead of 15ps [8], the peak current is expected by extrapolation to increase by a factor 10×15/55=2.7. Hence the photon flux per pulse is 1300×2.7=3500 photons/0.1%BW.

Repetition Rate and energy spread

When the repetition rate f_L of the laser increases, the energy spread increases. Estimated by random walk, the energy spread squared is found to be proportional to the repetition rate with growth rate $f_L p^2 \tau_L / \tau_b / 2 = 48/s$, where p=7.5 is the ratio of energy modulation over initial energy spread, as calculate before. With radiation damping rate 80/s we expect the energy spread increase due to the modulation is not very large. However if we increase the repetition rate to 10 kHz, to avoid the energy spread increase, we may need to use 10 camshaft bunches.

Pulse duration in short straight section

In the transport process between the modulator and the radiator, the short pulse length is expected to increase by R_{56} due to the finite energy spread, contribution from R_{51} and R_{52} is negligible. For a lattice without dispersion in the straight sections we find $R_{56} = 9.6$ mm. With energy spread $9{\times}10^{-4}$, the spread of the path length is $\Delta\ell = 9\,\mu$m, and pulse length stretch is $2\ \Delta\ell / c \cong 60$ fs. The pulse of the modulated electrons is a convolution of the laser pulse length and the slippage length (see subsection 2 above), both 50 fs, so its length without the stretch is $\sqrt{2}\,\tau_L = 70$ fs. With the stretch, the total output pulse length is 91 fs. A reduction of R_{56} in the lattice design with dispersion will be able to reduce the pulse stretch. In a first attempt as shown in the following, in a lattice with the desired dispersion we are able to reduce R_{56} to 4.8mm from 9.6 mm. Thus the total output pulse length is found to be76fs.

Laser input and exit port and Rayleigh

Exit port is used for initial laser alignment. The position and size of the laser input and exit port will affect the design of the vacuum chamber in the long straight section. Use the Rayleigh range formula, we find beam waist $w = 660\mu$m. At the photon shutter positioned at L=18.5m, we find the laser beam size 7.2mm. The current photon shutter widow size is about 3-4mm, hence we may need to modify the photon shutter for the experiment, unless we can find a method to initially align the laser with only a part of the laser spot.

Lattice with dispersion at short straight section

The NSLSII lattice is designed without dispersion in the straight sections. The introduction of dispersion in the radiator in one of the many short straight sections requires a modification and will break the symmetry of the ring. Furthermore, since it is desired to have both soft and hard x-ray beamlines, we need to modify the next long straight section to have dispersion, thus generate distortion to three sections among all the 30 sections. This distortion of the lattice has to be corrected both linearly and non-linearly and need extensive works. In addition, to optimize the separation of modulated beam from the core, there is a need for optimization of a mix between coordinate and angular separation. This in turn requires a dispersion with a slope in the straight section of the radiator.

As a first step we study the effect of introducing a dispersion with η=4.8cm, η'=25 mrad into the short straight section immediately following the long straight section where the modulator is located (figure 3). For this lattice both horizontal and vertical tune between the two centers of the long straight section remain the same as without dispersion, the beta functions change is minimized. The horizontal and vertical beta function in the radiator are β_x=1.7m, β_y=1.26m, near their original values without dispersion. Maximum horizontal and vertical beta functions are both 30 m. Figure 3 shows the second half of the super-cell (26m-52m) is significantly different from the first half, breaking the symmetry.

After sextupole optimization of the lattice, the tune footprint and frequency map is shown in figure 4 and 5 respectively. We introduced 30μm misalignment errors and 0.5mrad roll errors for all quads and sextupoles, and carried out orbit correction. The dynamic aperture at ±2.5% momentum deviation reaches the design goal of±10mm. This result demonstrates that the distortion due to the introduction of dispersion into one of the straight sections can be corrected.

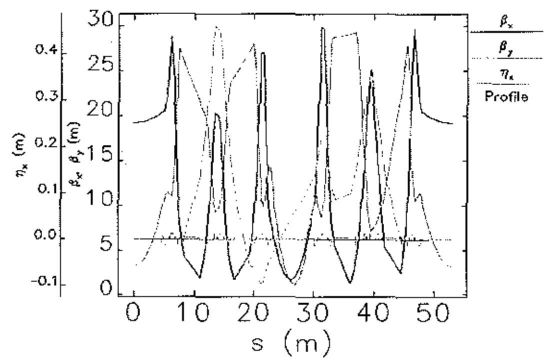

Figure 3. Lattice with dispersion and slope in straight section

To minimize the stretch of bunch length, we tried both negative and positive dispersion, and found that while the negative one increases R_{56} , the positive dispersion with positive slope reduces it. The result shows it is reduced from 9.6mm to 4.8 mm. This reduces the stretched pulse length from the early estimated 91 fs to 76 fs.

The emittance of the test lattice increases to 2.1 nm from 2 nm, a modest increase. The emittance increase due to the presence of dispersion in the radiator is estimated to be less than 0.3% and is negligible.

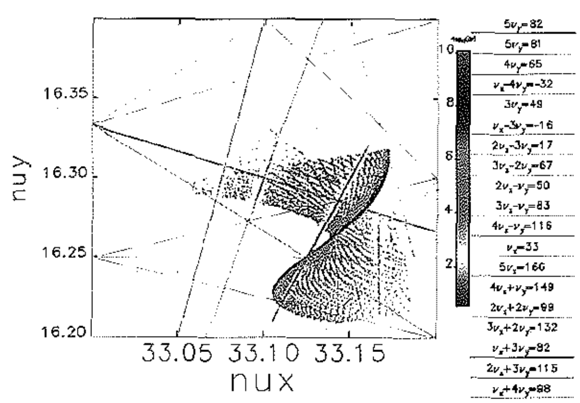

Figure 4. The tune footprint

REQUIRED R&D EFFORT

Further improved design of non-symmetric dispersion with dispersion in several straight sections requires iteration of linear and non-linear optimization including the reduction of R_{56} .

The modulator has longer period than damping wiggler. Whether it may serve as a damping wiggler require study.

The development of laser system requires high repetition rate and short pulses synchronized with the pump-probe experiments.

The Laser input and exit port requires extensive works of modification of the vacuum chamber and may present a technical challenge because the large laser beam size and the crowded area at the exit port.

Collaboration with ultrafast beamline R&D on the scheme of separation of short pulse from the core affects the design of lattice.

Diagnostic system, in particular the THz beamline in the dipole immediately following the modulator beamline requires study for the alignment and synchronization for the short pulse generation.

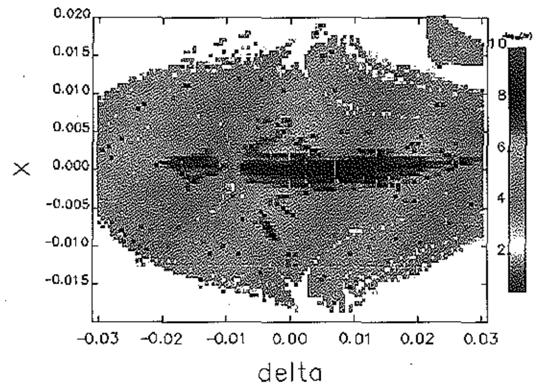

Figure 5. The frequency map for x vs. momentum

References

1. R. W. Schoenlein, "Generation of Femtosecond Pulses of Synchrotron Radiation", SCIENCE .2237, VOL 287 24
2. S.Khan, H.A. Durr, "Femtosecond synchrotron radiation pulses at BESSYII", p.701, Proceedings of EPAC 2002, Paris, France
3. Gerhard Ingold*, et. al., "Towards pump-probe resonant X-ray diffraction at femtosecond undulator sources", 223 (2008) 292–306, Z. Kristallogr.
4. A. Nadji, et.al., "FEMTO-SECOND ELECTRON BEAM SLICING PROJECT AT SOLEIL", 2330, Proceedings of EPAC 2004, Lucerne, Switzerland
5. Darío Arena, Ultrafast Science Workshop, May 27, 2010, Brookhaven National Laboratory
6. Darío Arena, Rob Crowell and the UFS / UFH Proposal Team, UFS[†] & UHF[††] Beamlines: Opportunities for Ultrafast Science at NSLS-II, Brookhaven National Laboratory, 19 July 2010
7. A. Zholents and M. Zoloterev, PRL.76 (1996),912.
8. SLSII Preliminary Design Report