SYNCHROTRON LIGHT MONITOR SYSTEM FOR NSLS-II

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Abstract

A visible synchrotron light diagnostic beam line has been designed at the NSLS2 storage ring, using the dipole radiation. The 'cold-finger' configuration has been selected to block the central x-rays. Beam power on the first mirror is less than 1W, no water cooling is required for the in-vacuum mirror. The beam line layout and major applications will be discussed in this paper. Two vacuum ports are reserved in the NSLS2 booster ring to monitor the transverse profile as well as bunch length measurement during ramping. There will be a synchrotron light port in the BTS transport line to observe the injection beam behavior during top-up operation.

INTRODUCTION

The ultra high brightness NSLS-II storage ring is under construction at Brookhaven National Laboratory. It will have 3GeV, 500mA electron beam circulating in the 792m ring, with very low emittance (0.9nm.rad horizontal and 8pm.rad vertical). The ring is composed of 30 DBA cells with 15 fold symmetric. Three damping wigglers will be installed in long straight sections 8, 18 and 28 to lower the emittance [1]. While electrons pass through the bending magnet, synchrotron radiation will be generated covering a wide spectrum. There are other insertion devices in the storage ring which will generate shorter wavelength radiation as well. Since the NSLS-II visible diagnostic beam line will use the radiations from bending magnet, we will discuss the dipole radiation only in this paper.

Synchrotron radiation has been widely used as diagnostic tool to measure the transverse and longitudinal profile. Three synchrotron light beam lines dedicated for diagnostics are under design and construction for the NSLS-II storage ring: two x-ray pin-hole camera beam lines with the source points from Cell 24 BM_A (first bending in the DBA cell) and Cell25 three-pole wiggler; the third beam line is using visible part of radiation from Cell 30 BM_B (second bending magnet from the cell). Pinhole beam lines designs can be found in the paper. [2] Our paper focuses on the design of the visible beam line. Synchrotron light monitors along the injector chain will be discussed as well.

Table 1 lists major parameters related to the NSLS2 storage ring

Parameter	Value	Unit	Comment
General machine parameters			
E	3	GeV	Energy
f_{rf}	499.68	MHz	RF freq.
h	1320		har. #
f_{rev}	378.55	kHz	
T_{rev}	2.64	μs	
C	791.96	m	
I	500	mA	
ε_x	0.9	nm.rad	with 3 DW
ε_y	0.008	nm.rad	
σ_E/E	0.09%		with 3 DW
Bending magnet parameters			
ρ	25.02	m	bending radius
B	0.4	Tesla	
E_c	2.4	keV	
λ_c	0.52	nm	
Bunch length related			
Vc	3.1	MV	
U0	287	keV	bend loss
	674	keV	total loss with 3DW
α	3.63E-4		
fs	3.32	kHz	
σ_t	15.66	ps	RMS bunch length
Beam size related			
β_x	2.7763	m	
β_y	19.5252	m	
η_x	0.1370	m	
σ_x	133.05	μm	
σ_y	12.50	μm	

SOURCE POINT

NSLS-II ring has 30 DBA cells, each cell has two bending magnets which bend the electron beam 6-deg each. Synchrotron radiation extracted from the beginning of bending magnets, with horizontal opening angle 0 to 4.25mrad. The nominal source point for user's beam line is 2.125mrad +/- 1.5mrad. To use the same extraction configuration is highly desired for the visible diagnostic beam line. Synchrotron radiation from the dipole has natural open angle depending on the radiation wavelength. With longer wavelength, the synchrotron radiation from dipole will have larger natural open angle. See Equation (1). For the 500nm green light, which will be used on the optic table for various measurements, the natural opening angle is ~1.2mrad. To avoid the bending magnet edge radiation, the diagnostic beam line horizontal aperture was selected from 1.25mrad to 4.25mrad. Edge radiation has been investigated and 1.25mrad is large enough to avoid the edge radiations at visible light range. On the other hand, edge radiations can be a useful diagnostic tool. We keep the option to move the aperture to intercept these kinds of radiations.

$$\theta_{SR\_\sigma\_rms} \approx 0.4097\left(\frac{\lambda}{R}\right)^{1/3}$$
$$\theta_{SR\_\pi\_rms} \approx 0.5497\left(\frac{\lambda}{R}\right)^{1/3} \quad (1)$$
$$\theta_{SR\_rms} \approx 0.4488\left(\frac{\lambda}{R}\right)^{1/3}$$

Equation (1) listed the natural open angle of σ and π modes as well as total effect of bending magnet radiations. R is the bending radius, λ is radiation wavelength. Longer wavelength radiation will have larger natural open angle.

Several possible source points have been evaluated. The horizontal beam size will be around 100 microns or larger if the source point location has some dispersion. The visible beam line will be able to measure the horizontal beam size of 100 microns. From the measured beam size at dispersion location, it's easy to extract the beam energy spread. This gives a supplementary method to measure the energy spread to pinhole camera. Vertical beam size in the NSLS2 will be ~10 microns, which will be dominated by diffraction resolution of visible light. We can rely on the pinhole for vertical beam size measurement. At the visible beam line we plan to test the double-slit interferometer [3] and pi-mode beam size measurement [4].

Cell 30 straight section will be occupied by the injection system. There is no user's beam line from that straight. Thus Cell 30 BM_B is selected to be the source of visible synchrotron radiation light beam line. Since the source point is located just after the injection, it gives the advantage to measure the injected beam during commissioning and machine studies. Cell 30 is heavily shielding area where there is much higher radiation compared to rest of the ring. The beam line can be moved to RF cavity sections if radiation safety is a concern.

Figure 1 shows the schematic layout of visible diagnostic beam line with racks shown on the mezzanine floor. The synchrotron light monitor (SLM) lab will be outside the tunnel to conduct the measurements/studies, with optical table of 3m *1.5m. It's hard to fit the lab on the mezzanine floor as preferred. The current design is to locate the SLM lab on the experiment floor, using the beam line port from Cell 30 ID, where no user's beam line exists.

Total power within 3mrad horizontal fan will be ~70W. After the cold finger, the power on to the first mirror is about 0.5W, since most of the power near the central plane is blocked by cold finger. Vacuum window and mirrors will further filter the UV radiations, typical power into the SLM lab is around several mW level.

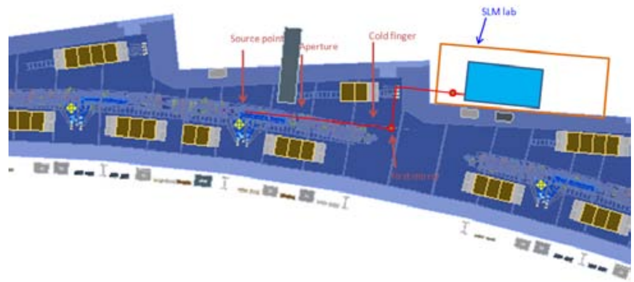

Figure 1, layout of visible synchrotron diagnostic beam line of NSLS2 storage ring.

Crotch absorber and fixed mask will define the SLM aperture to +/-1.5mrad horizontally and +/-3.5mrad vertically. Size of the open aperture is determined by the measurement resolution and light intensity. There are more discussion about the system resolution in the following sections. The first mirror will be about 7-meters away from the source point. Beam height inside the tunnel is 1.2m and 1.4m on the experiment floor, proper vertical elevation is necessary to bring the light on to the optical table.

FIRST MIRROR

The first mirror in the visible diagnostic beam line is essential to reflect the light outside the vacuum. The surface of the mirror must have minimum deformation with high head load. The flatness should be less than 1/10 of measurement wavelength. Basically there are three approaches for the first mirror design, as shown in Figure 2.

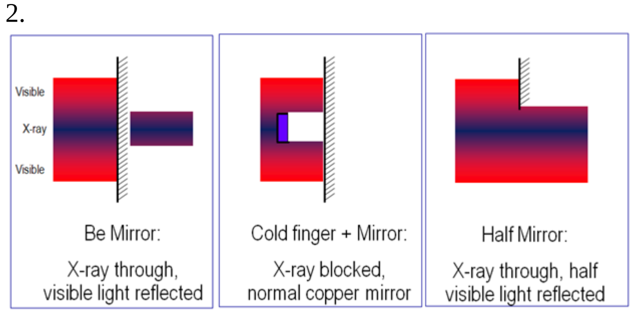

Figure 2, first mirror configurations in the visible diagnostic beam line.

The first option will adopt mirror made from low atomic mass material (like Beryllium). X-ray will pass through the mirror while visible part of the radiation will be reflected from the polished surface. Although the mirror material has small atomic mass, the mirror will suffer from heating problem and deformation at high current. Besides, toxic Beryllium is not easy to handle. The second type of mirror configuration combines a stick absorber and mirror. The thin absorber was called 'cold' finger which blocks the central part of the radiation, most of the central part has shorter wavelength radiation. By selecting appropriate open angle of the cold finger, the power onto the mirror could be very small (several Watt or even less than 1W). The mirror could be made from SiC or copper. No water cooling is needed due to low power shining on the mirror. We plan to have retractable cold finger which could be moved out the beam while beam current is low. The cold finger could track the electron beam vertical position as well. For the NSLS2 SLM beam line, we will adopt this configuration. Temperature sensors will be attached to the mirror, monitoring any potential heating issues.

The third type of configuration uses half mirror to intercept only top (or bottom) half of long wavelength radiation. Central x-ray will not illuminate the mirror. The advantage of this configuration is central x-ray cone can still be used by users' experiment or other diagnostic purpose (like bunch purity monitor using x-ray APD). Compared to the cold finger configuration, half mirror loses half of the intensity. In some measurements like monitoring injected beam profile, more photons are needed. Besides these three widely-used configurations, other approaches might exist but with difficulties. For example: one can use two half mirrors to intercept the top and bottom radiation. The difficulty is hard to align two half mirrors in the same plane. Or we can cut a slit in the mirror to let the x-ray pass through the slit, the difficulty is there is always a round corner near the slit edge. Some may add a fork shape to block the slit edge before the mirror, which increases the complicity.

A finite element analysis simulation has been done to estimate the thermal load effect on the first mirror. With 500mA stored beam and all the 3mrad horizontal open aperture radiation fan incident on the mirror (Glidcop material, 100mm*100mm*25mm size), with radiation cooling only, the highest temperature of the mirror will be 274 ºC [5]. In other words, the mirror is still safe without water cooling even the cold finger was moved out the beam by accident.

MEASUREMENT ERRORS

The visible diagnostic beam line spatial resolution is contributed from several factors, including the depth-of-field error, curvature error and diffraction error etc. Chromatic error can be minimized by using band pass filter before the camera. For some applications, we may need polarizer.

Depth-of-field error

As illustrated in Figure 3, slit with horizontal open angle +/- θ_x will accept the radiation from a curvature with length of $2R\theta_x$, where R is bending radius. Besides the open angle of the slit, synchrotron radiation itself has natural opening angle. With lower frequency (longer wavelength) radiation, the natural open angle is bigger, see Eq (1). In another words, even if the slit open angle is 0, there still is synchrotron light coming through due to the natural open angle of synchrotron radiation. With visible light, which is typically much longer than critical wavelength, the open angle is ~ 1mrad.

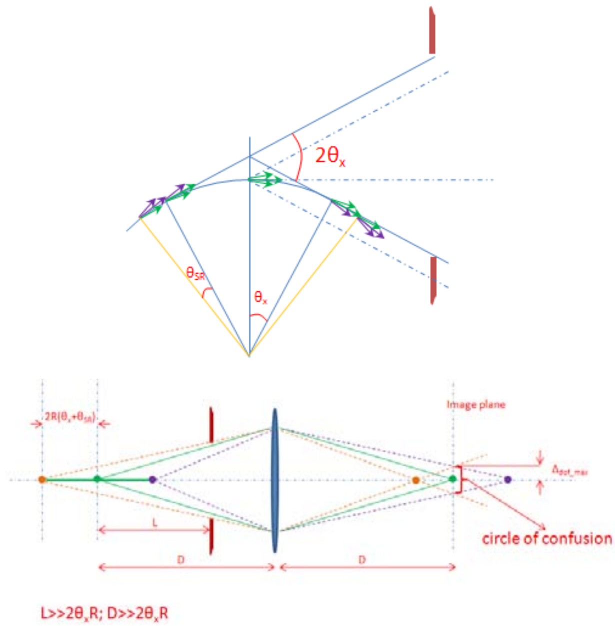

Figure 3, depth-of-field error

In Figure 3, including the synchrotron radiation natural open angle, light within +/- (θ_x + θ_{SR}) will pass through the slit and reach to the CCD camera. With 1:1 image onto the CCD, even if the transverse beam size were 0, some finite size area on the image plane will be illuminated. This area is called "circle of confusion", radius of this circle is defined as depth-of-field error. With simple math, one can get the radius:

$$\Delta_{dof\_\max} \approx R\theta_x\left(\theta_x + \theta_{SR}\right) \quad (2)$$

Assume the light in the circle-of-confusion is uniformly distributed, then RMS value of depth-of-field error can be written as:

$$\Delta_{dof\_rms} = \frac{\Delta_{dof\_\max}}{\sqrt{6}} \quad (3)$$

For the NSLS-II storage ring SLM beamline: bending magnet radius R = 25m; detecting wavelength λ = 500nm; slit horizontal open angle (half) θ_x = 1.5mrad; synchrotron radiation natural open angle $\theta_{SR} \sim 0.45(\lambda/R)^{1/3}$ = 1.2 mrad (for 500nm light). We calculate the depth-of-field error: Δ_{dof_max} ~ 101 um and Δ_{dof_rms} ~ 41 um. This value may be still over estimated. The distribution in circle-of-confusion could be Gaussian like instead of uniform. Depth-of-field error applies to both planes (horizontal and vertical).

Curvature error

Since the SLM source is coming from the bending magnet, the curvature of the electron beam contributes an error term that limits the horizontal resolution. Curvature error can be calculated as:

$$\Delta_{cur\_\max} = \frac{R}{\cos\theta_x} - R \approx \frac{R\theta_x^2}{2} \qquad (5)$$

$$\Delta_{cur\_rms} = \sqrt{\frac{1}{2\theta_x}\int_{-\theta_x}^{\theta_x}\left(\frac{Rx^2}{2}\right)^2 dx} = \frac{R}{2}\sqrt{\frac{2\theta_x^5}{5}\frac{1}{2\theta_x}}$$

$$= \frac{R\theta_x^2}{2}\frac{1}{\sqrt{5}} = \frac{\Delta_{cur\_\max}}{\sqrt{5}} \qquad (6)$$

Again for the NSLS-II diagnostic beam line, with bending radius 25m and 1.5mrad horizontal open angle, we get Δ_{cur_max} ~ 28um, Δ_{cur_rms} ~ 13um. Curvature error applies to horizontal plane only.

Diffraction error

Any image system with aperture will have a diffraction error. Contrary to the depth-of-field and curvature error, diffraction error increases while the aperture decreases. With horizontal slit opening angle θ_x and synchrotron radiaiton natural open angle θ_{SR} , a rough estimate of diffraction error:

$$\Delta_{diff} = \begin{cases} 0.5\dfrac{\lambda}{\theta_x} & if \quad \theta_x < \theta_{SR} \\ 0.5\dfrac{\lambda}{\theta_{SR}} & if \quad \theta_x \geq \theta_{SR} \end{cases} \qquad (7)$$

The diffraction error from Eq (7) is far too big, for the NSLS2 SLM beamline. With bending radius R = 25m, measuring wavelength λ = 500nm and horizontal open angle θ_x = 1.5mrad, one gets Δ_{diff_rms} ~ 167 um.

It's worth to note that Eq (7) only stands for uniform illuminated slit (or circular iris, which has diffraction error 0.61λ/θ). However, this is not the case for synchrotron radiation. Hoffmann has quantitative treated the issue using Fraunhofer diffraction. RMS of diffraction error can be expressed as (for σ-mode only) [6]:

$$\Delta_{diff} = 0.21\left(\lambda^2 R\right)^{1/3} \qquad (8)$$

Diffraction resolution improves with shorter wavelength and with smaller bending radius. Larger machines typically have larger bending magnet radius. For NSLS2 the bending radius R=25m, which is much bigger compared to other median energy light sources. Special magnet with strong bending (smaller R) could help to improve the resolution. One could use UV light instead of visible, which could improve the diffraction resolution by 20-30%. The problem using UV is safety concerns, and not so many optic components available in the market. It seems not worth to do that way.

Notice that Eq (8) is correct for $\theta_x > \theta_{SR}$. Besides, if there is cold finger or slit in the beam line to let the x-ray through, that changes the E-field. Diffraction error should be calculated again. CLS has done detailed analysis for their diagnostic beam line using half mirror [7]. Anyway, Eq (8) gives very close estimate of diffraction error.

For the NSLS-II beamline, with bending radius R = 25m, measuring wavelength λ = 500nm, the RMS diffraction error from Eq. (8) is Δ_{diff_rms} ~ 39 um. Diffraction error applies to both planes (horizontal and vertical).

From above analysis, total measurement errors from the NSLS2 beam line can be estimated. With horizontal 1.5mrad and vertical 3mrad opening and wavelength of 500nm, measurement errors for both planes are close to 58um. With this resolution, it's possible to measure the horizontal beam size (σ_x ~100um). Vertical beam size is buried in the measurement errors.

APPLICATIONS

After the first mirror and vacuum window, synchrotron light will be steered to the end station where experiments will be carried on. We will have a 3m*1.5m optic table in the SLM shed. Major measurements using the visible light include: streak camera to measure the bunch length and longitudinal profile; fast gated camera to measure the transverse profile of single bunch in single turn; other applications like FleaCCD to monitor the profile, interferometer to measure the vertical beam size, synchrotron radiation fluctuation to measure the bunch length, bunch purity measurement using MCP-PMT etc.

Layout of the possible setups on the optic table are shown in Figure 4,

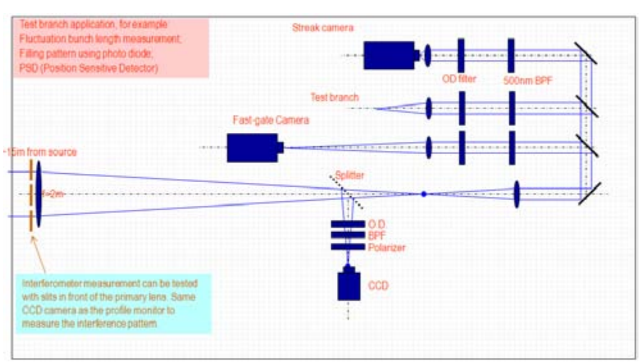

Figure 4, optic table setups in the SLM end station

Streak camera will measure the bunch length, synchronous phase and longitudinal profile at various machine conditions to get machine parameters such as: broadband impedance, microwave instability threshold, beam loading, injection transient etc. Intensified CCD camera with 2ns minimum gate will be used to measure the transverse profile of every individual bunch. This is especially important for the injection beam tuning and characterization. Beam size blowup along the bunch train due to wake field could be measured from the gated camera as well. Other tests/measurements applicable at the end station include the double slit interferometer to measure the vertical beam size, photon counting using multichannel plate photon multiplier (MCP-PMT) to measure the bunch purity, position sensitive detector to measure the beam central position, pockels cell to measure the bunch-to-bunch motion etc.

INJECTOR SLM

NSLS-II injector consists of 200MeV LINAC, the LINAC to booster transport line (LTB), 200MeV to 3GeV booster and booster to storage ring transport line (BTS). The LINAC will be a turn-key machine from vendors, while the booster will be semi turn-key system. Synchrotron light from the booster ring and BTS are useful diagnostic tools as non-interceptive method. Two synchrotron light ports are required in the booster ring and one port in the BTS is under consideration.

It's highly desired to measure the booster transverse profile and bunch length during the energy ramping. There are two light ports in the booster. One of them will be used for transverse profile monitoring. This monitor will be located inside the booster tunnel with minimum optic lens. Light from the other port will be guided outside the tunnel and onto the optic table, where streak camera bunch length measurements and other monitoring system can be setup. It's very interesting to have a synchrotron light profile monitor in the BTS during top-up operation. With that one can monitor the real-time injection bunches. It will be very helpful during the top-up injection.

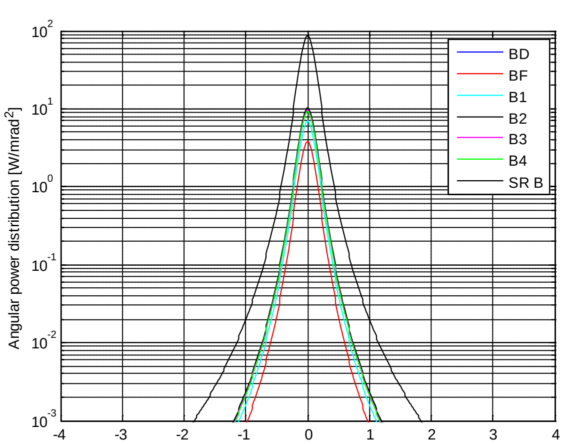

Figure 5, synchrotron radiation power angular distribution.

There are two types of combined function dipole magnets in the booster ring – defocusing dipole (BD) and focusing dipole (BF). There are 8 BD and 7 BF in one quarter of the booster lattice, with 32 and 28 for the whole booster ring. In the BTS transport line, there are two types of dipoles as well. One type of them is close to the booster extraction and storage ring injection point. These are not suitable for diagnostics due to very limited space. The other type has 4 dipoles with 1.3m length each, named B1, B2, B3 and B4 in the BTS. B2 will switch the beam to storage ring or beam dumper. We calculated the dipole radiation power based on the magnet specifications. Figure 5 shows the power angular distribution in these magnets. Peak power in the booster dipole is less than 10W/mrad^2 with 20mA circulating beam. Compared to 500mA storage ring, where the peak power is 88W/mrad^2.

SUMMARY

Visible diagnostic beam line has been designed at the NSLS-II storage ring. Various applications have been defined to characterize the 1nm.rad machine. Measurement resolution has been estimated. Synchrotron light ports in the booster ring and BTS have been proposed.

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