รายงานเชิงเทคนิค

(TECHNICAL REPORT)

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ชื่อฝ่าย Department	ฝ่ายปฏิบัติการเครื่องกำเนิดแสงสยาม 1
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คำสำคัญ Keyword	SPS-II, lattice design, low emittance ring, longitudinal gradient dipole

รายชื่อผู้ดำเนินโครงการและจัดทำรายงาน Name	ส่วนร่วมในการปฏิบัติงานในโครงการ Responsible tasks in the project
ดร. ฐาปกรณ์ ภู่ลำพงษ์	ทำการออกแบบ คำนวณ และเขียนรายงาน

Abstract

Siam Photon Source II, a 3 GeV medium size storage ring, was originally designed to provide both low emittance and high capacity. Thus, it offers both light source quality and BL quantity. The baseline design is rather conservative. The option considered the ability to build the machine in the country. Magnets specification is in a moderate range and not too aggressive. Double-Tripple Bend Achromat (DTBA) cell was modified from Diamond light source version. Only normal dipoles were used instead of longitudinal gradient dipole. In this study, the longitudinal gradient dipole option will be discussed for SPS-II. It is a possible upgrade option if required. The beam emittance was reduced by at least 30% and smaller beam stay clear was found.

คำค้น Keyword: SPS-II, Lattice design, Low emittance, Longitudinal gradient dipole

1. Introduction

Since 2016, SPS-II lattice design was started. There are many variations and developments of the lattice design. Requirements from engineer trying to make the machine easy to build and install were iteratively reviewed and implemented. The general lattice design challenges are depicted in Diagram 1. Magnet and vacuum group are the main contributors of the requirements. The basic design parameter that affects both groups is beam-stay-clear (BSC) which emerges from linear optic functions and beam emittance. Large BSC may limit the size of chamber and subsequently magnet's bore radius.

The Idea to reduce the BSC will ultimately ease the vacuum and magnet design. To reduce BSC, the global factor is the beam emittance. Since the beginning of the project, the lattice design took into account the simplest requirement possible. From the original Double-Trible Bend Achromat (DTBA) cell for Diamond-II, longitudinal gradient dipoles were replaced by normal dipoles. This is one of the reasons that SPS-II is not so aggressive in term of beam emittance. Thus, the option of longitudinal gradient dipole can be reconsidered. This will reduce the beam emittance down from 960 pm·rad to about 600 pm·rad or ~30% as shown in Figure 1.

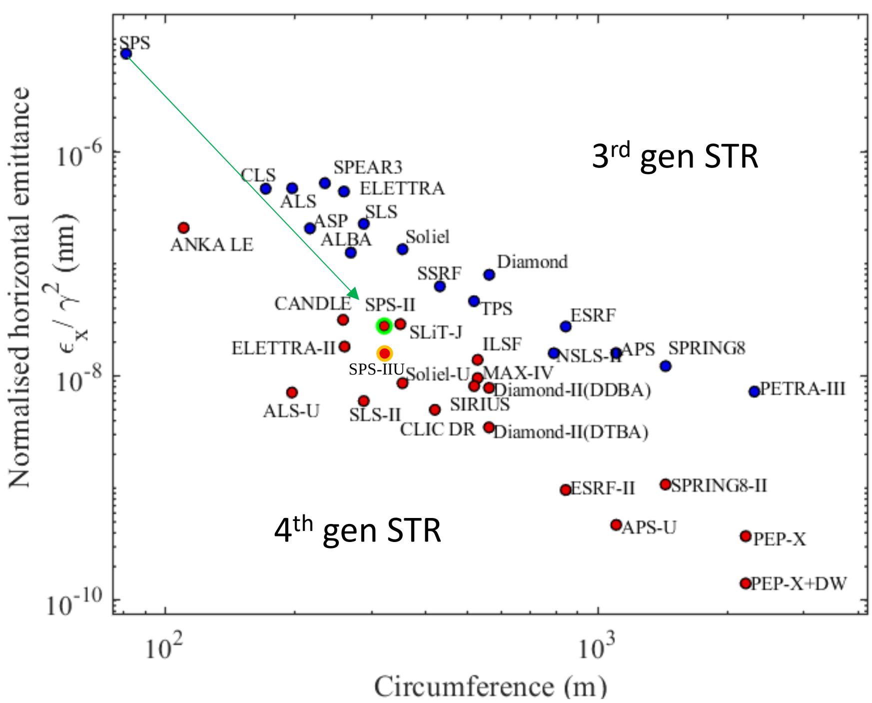
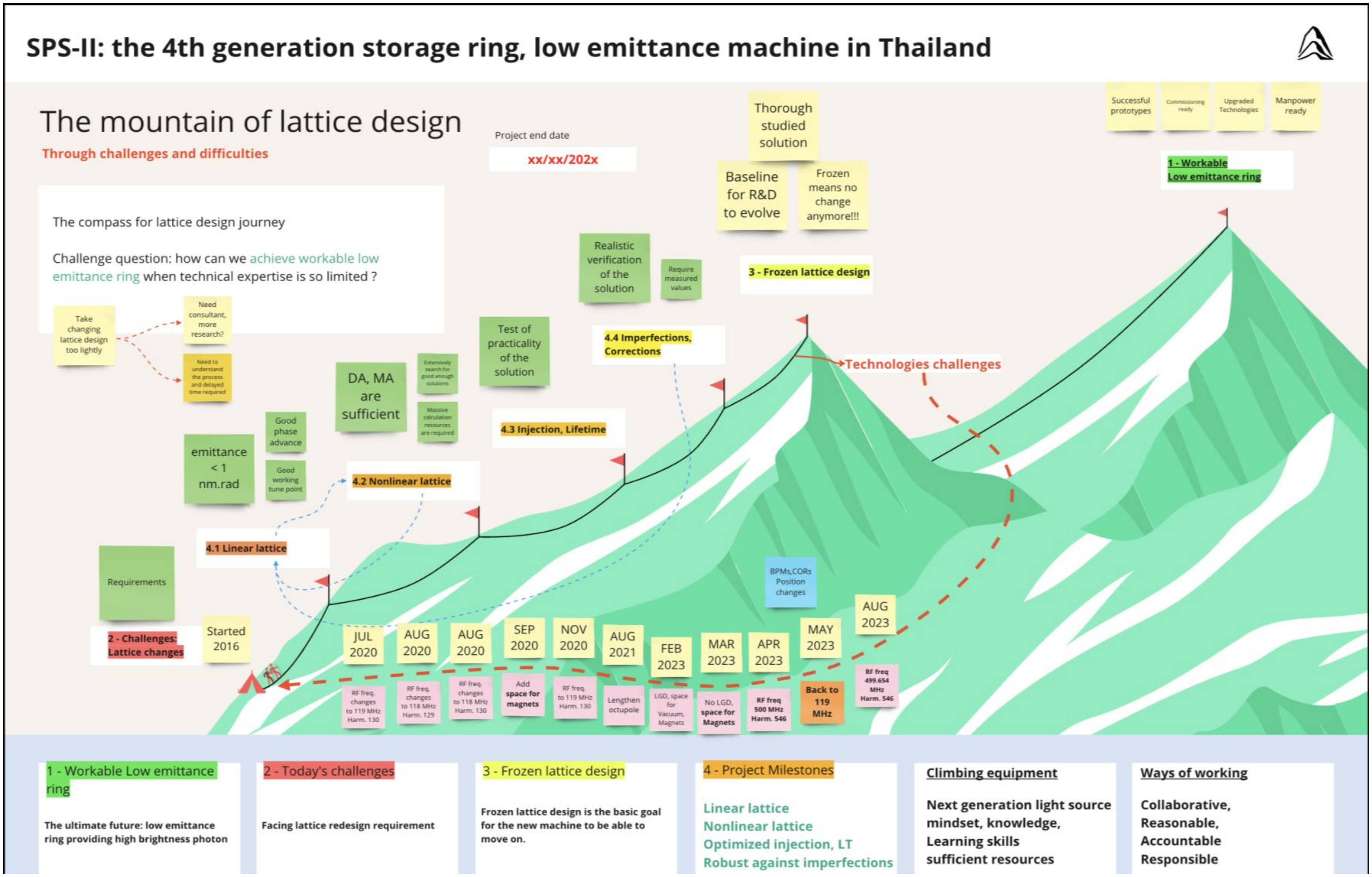


Figure 1 Normalised beam emittance comparison with respect to the ring circumference

Diagram 1 SPS-II lattice design challenges



This diagram shows the evolution of SPS-II lattice design. Many versions have been explored due to engineering challenges.

2. Study purpose

2.1 Feasibility study for longitudinal gradient dipoles (LGD) for SPS-II lattice design

2.2 Find a promising design solution as an option for SPS-II lower beam emittance which help also reduce the BSC as a whole.

3. Theory/Background

Undeniably, to determine the quality of a lattice, one of the most important parameters is horizontal beam emittance. Then to understand the source of the beam emittance, some mathematics need to be realized.

3.1 Beam emittance

By definition, beam emittance is the total area in phase space that is occupied by the beam. To clarify, phase space in horizontal plane is composed of position and angle (x, x') and similarly (y, y') for vertical plane. For electron machine, natural emittance considers only at the equilibrium stage when the effect of radiation damping (Figure 2) and quantum excitation (Figure 3) are equal.

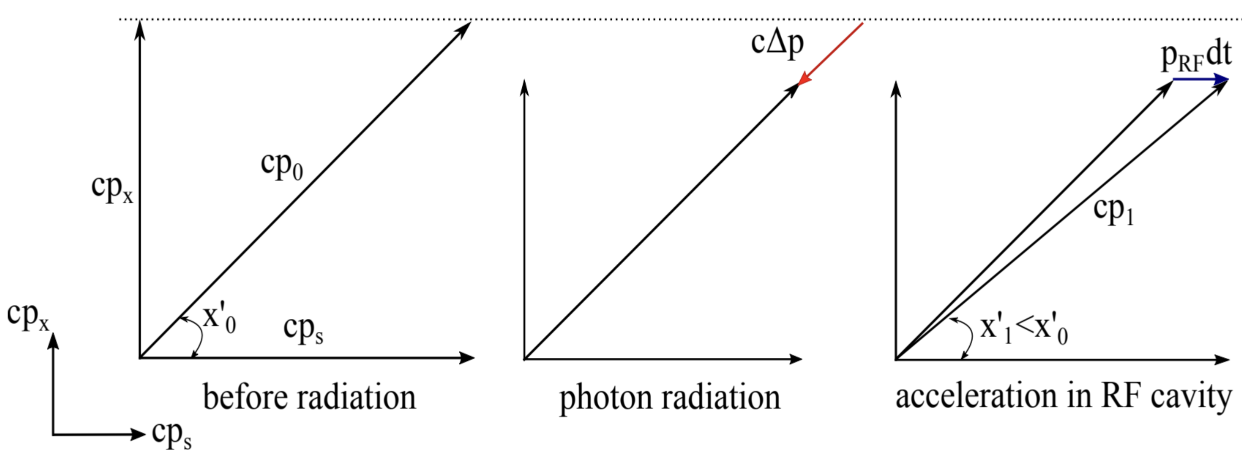


Figure 2 Radiation damping process: overall energy loss in every plane while energy restoration occurs only longitudinally resulting in transverse oscillation amplitude damping *[1]*.

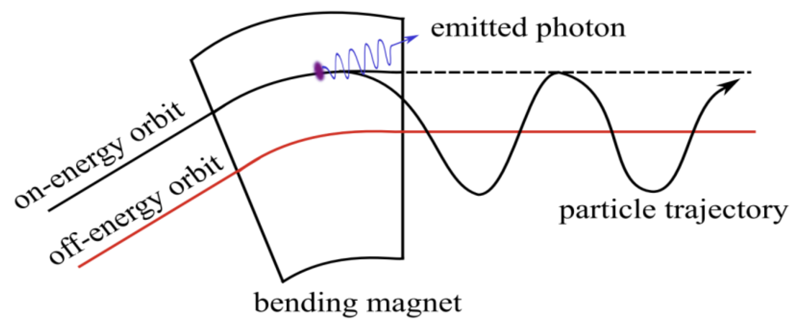


Figure 3 Quantum excitation process: an electron after photon emission (randomly) will oscillate around a new off-energy orbit with larger amplitude *[1]*.

If A(t) is the betatron oscillation amplitude as a function of time, equilibrium stage can be written as

$$\left\langle\frac{dA^2}{dt}\right\rangle_{damping} + \left\langle\frac{dA^2}{dt}\right\rangle_{excitation} = 0$$

Betatron oscillation invariant representing the electron beam can be written as

$$A^2 = \gamma x^2 + 2\alpha x x' + \beta x^2$$

The total beam invariant considering both effects is

$$< A^2 >_{tot} = \frac{1}{2} < \dot{N}_{ph} < u^2 > \mathcal{H} >_{tot}$$

Where $\dot{N}_{ph} < u^2 > = \frac{55}{24\sqrt{3}} < Pu_c >$, P is radiation power and u_c critical radiation energy. And dispersive invariant is defined as $\mathcal{H} = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta^2$.

From the RMS beam size $\sigma_x^2 = \frac{A^2\beta_x}{2}$, the equilibrium emittance can be written as

$$\varepsilon_x = \frac{\sigma_x^2}{\beta_x} = C_q \frac{\gamma^2}{J_x} \frac{< \mathcal{H}/\rho^3 >}{< 1/\rho^2 >}$$

Or in practical unit

$$\varepsilon_x[\text{nm·rad}] = 1470(E[\text{GeV}])^2 \frac{< \mathcal{H}/\rho^3 >}{J_x < 1/\rho^2 >}$$

In the equilibrium stage, phase space ellipse area is constant as shown in Figure 4. Thus, unlike beam size and divergence, emittance will not vary along the machine. This is convenient for emittance to be considered as a global parameter.

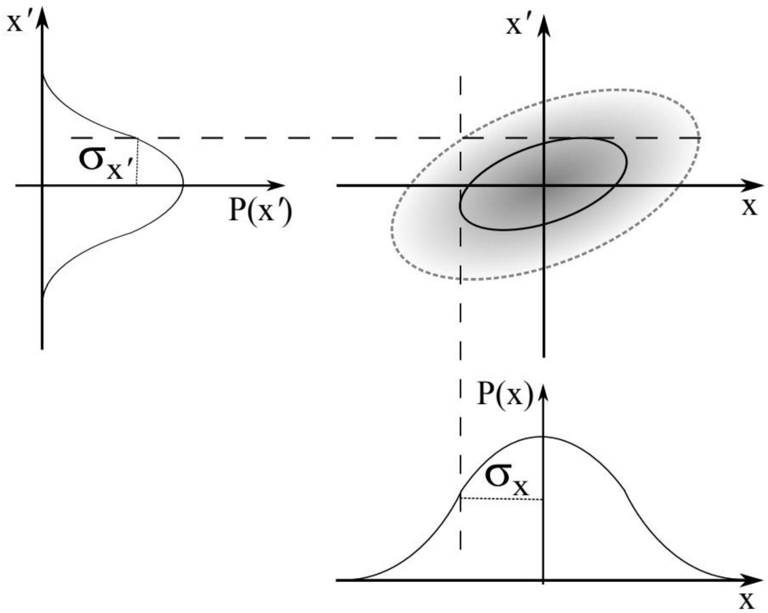


Figure 4 Electron density for a Gaussian distribution in horizontal phase space and projection on beam size and beam divergence *[1]*.

Dipole magnet is the main contributor for the beam emittance. To design a low emittance ring it is crucial to pay intense attention on the optic functions in the dipole magnet.

3.2 Longitudinal gradient dipole

Ideally, dipole field profile variation adjusted according to the twiss function can minimize the beam emittance by manipulating radiation integral I5. Longitudinal gradient dipole (LGD) is a finite number of sliced dipoles allowing each slice to be adjusted accordingly.

Suppose there are five slices of dipoles next to a non-dispersive straight section, magnetic field profile for each slice that can minimize the I5 term and emittance can be made as shown in Figure 5. To make it simple, large dipole field is in the position with the lowest dispersion function and vice versa.

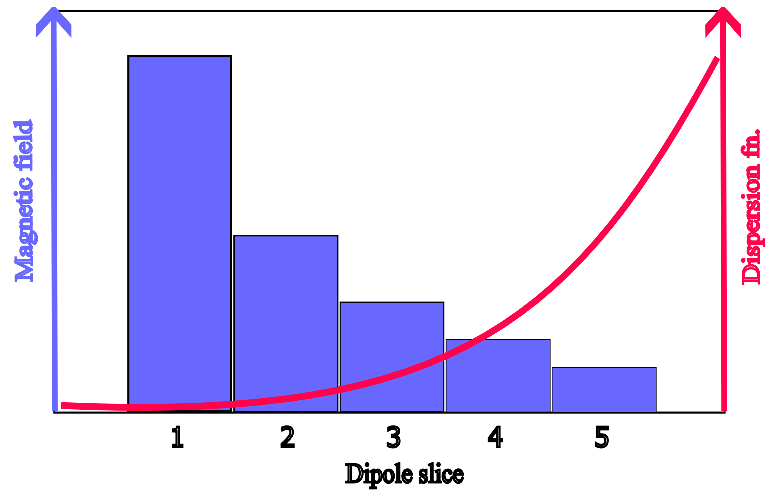


Figure 5 Magnetic field profile with respect to dispersion function in a LGD to reduce beam emittance.

With longitudinal gradient dipole it is possible to reduce beam emittance below TME with a uniform dipole. Strong dipole field can be expected at the low dispersion section which is possible to be employed as hard x-rays source.

3.3 Beam Stay Clear (BSC)

One of the important properties need to be considered when design a synchrotron machine is Beam Stay Clear (BSC) which defines the minimum boundary needed to be clear for the beam. BSC is then used to define the physical aperture or vacuum chamber and the minimum magnet bore radius and gap.

There are several ways to estimate the BSC of a machine. Size and possible movements of the beam from realistic scenarios will be discussed. Generally, two main events are associated with machine normal operation: to inject beam and to store beam. BSC can subsequently calculated from these two events and the minimum limit along the machine will be used as the total BSC to ensure the beam is clear from any possible objection.

For beam injection process, the horizontal BSC needed to be sufficient for beam injection can be defined as

$$X_{BSCinj}(s) = \left(\frac{\delta p}{p}\right)_i \eta_0(s) + \rho\sqrt{\frac{\beta_0(s)}{\beta_{0i}}} + x_{co}(s)$$

$$\rho = 6\sigma_i + T + 5\sigma_{0i}$$

where $(dp/p)_i$ is the momentum deviation of the injected beam, β_{0i} is the beta function at the end of the transport line connecting to the injection point. β_0 is the beta function of the stored beam. xco=4 mm is the closed orbit before correction. σ_i and σ_{0i}, are injected beam and stored beam size at injection point, respectively. T is the septum thickness.

The second factor to be taken into account is off-momentum effect when the stored beam has nonzero momentum distribution around the nominal value. This defines the BSC in both horizontal and vertical plane. BSC associated with the off-momentum particles for horizontal plane is defined as [2]

$$X_{BSCoff-p}(s) = \frac{\delta p}{p}(\sqrt{H_x(s)\beta_x(s)} + co_x)$$

where $H_x(s)$ is the horizontal invariant,

$\beta_x(s)$ is the horizontal beta function,

co_x is the maximum horizontal closed orbit after correction.

Similarly, for vertical plane, BSC is described as

$$Y_{BSCoff-p}(s) = \frac{\delta p}{p}(\sqrt{H_y^{eff}(s)\beta_y(s)} + co_y)$$

where $H_y^{eff} = H_y + \kappa H_x$ is vertical effective invariant,

κ is beam coupling constant,

co_y is the maximum vertical closed orbit after correction.

Longitudinal gradient dipole can generally reduce the beam emittance of the machine which also reduce the BSC. Thus, compared to the design without LGD, BSC will be globally reduced.

4. Methodology

There are two main steps in order to implement the longitudinal gradient dipole into the original solution. Firstly, proper longitudinal gradient field profile has to be determined and modelled correctly. Then optic function of the modified cell will be optimized to offer similar or better characteristic.

4.1 Longitudinal gradient dipole modelling

The longitudinal gradient dipole (LGD) magnetic field profile is crucial for minimizing the beam emittance while the total angle needed to be fixed to achieve 2π when all dipoles construct the whole ring. Practically, similar to other machines with LGD, the number of magnet slices is five for one meter length dipole. The maximum field for a slice is also limited by permanent magnet technology feasibility and the minimum gap. Stronger field requires more demanding magnet design: size, material and total cost. The maximum field is then limited at 1.8 T.

In Elegant [3] to model a longitudinal gradient dipole, individual slice was defined according to its field. Then the entrance and exit angle at each slice needed to be calculated correctly. There are four dipoles in DTBA cell that can be replaced by LGD. Economically, all four were design to have the same profile but may arrange differently depending on the dispersion function. Basically, a couple of dipoles in the dispersion bump has opposite field profile.

A couple of LGD, for example, in Elegant lattice file can be defined as

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For this LGD couple, the maximum dispersion in the dispersion bump is between DL1A and DL2B.

4.2 Optic functions matching

The requirements for optic functions are similar to the original DTBA cell without longitudinal gradient dipole. Small vertical beta function at the center of straight sections allows small source size at insertion devices. Dispersion function for long straight was matched to zero to ensure achromat condition. In the mid-straight, on the other hand, dispersion function was allowed to have a small value below 3 cm to allow low beam emittance while constraints the effect of IDs on the beam emittance and energy spread. Betatron tune, however; has to be larger due to stronger focusing for smaller beam emittance.

5. Results and Discussions

Four longitudinal gradient dipoles were modeled in the original SPS-II lattice. Proper optic functions were controlled and matched to be as close as the original as possible. The dipole field for each slice was also optimized to allow the smallest allowable beam emittance. The maximum dipole field is constrained at 1.8 T. The optimized longitudinal field profile is shown in Figure 6. The dipole field for each slice is listed in Table 1. The maximum dipole field is 1.74 T and the minimum field is 0.387 T

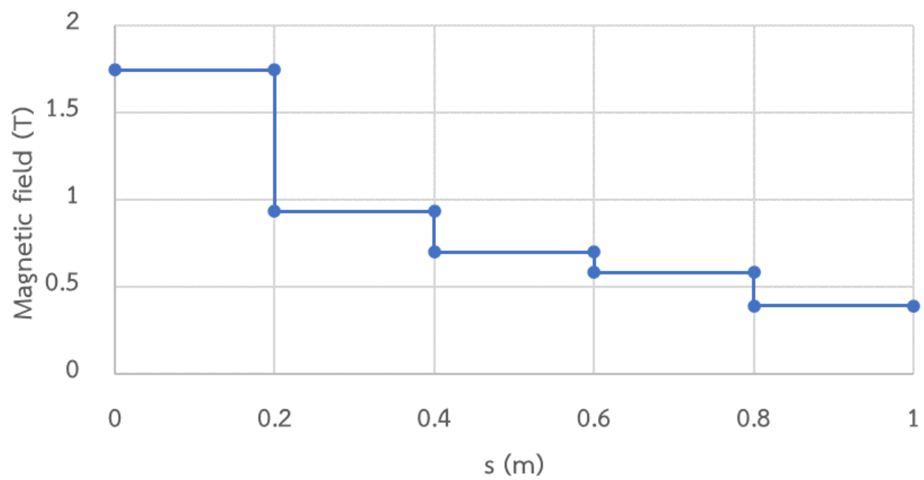

Figure 6 Longitudinal gradient dipole magnetic field profile.

Table 1 Longitudinal gradient dipole field for each slice

n Slice	S (m)	B (T)
1	0.2	1.743269
2	0.4	0.929743
3	0.6	0.697307
4	0.8	0.58109
5	1.0	0.387393

For optic functions, the maximum beta function is below 20 m. At the middle of the standard and short straights, the beta and dispersion functions are matched to be about the same as the nominal design without LGD as showed in Figure 7. Non-dispersive standard straight is preserved and low dispersion at the short straight below 3 cm is achieved. The dispersion bumps at the position of sextupoles are larger due to the LGD. This will benefit the design as the required sextupole strength for chromaticity correction is smaller with lead to lower non-linear terms.

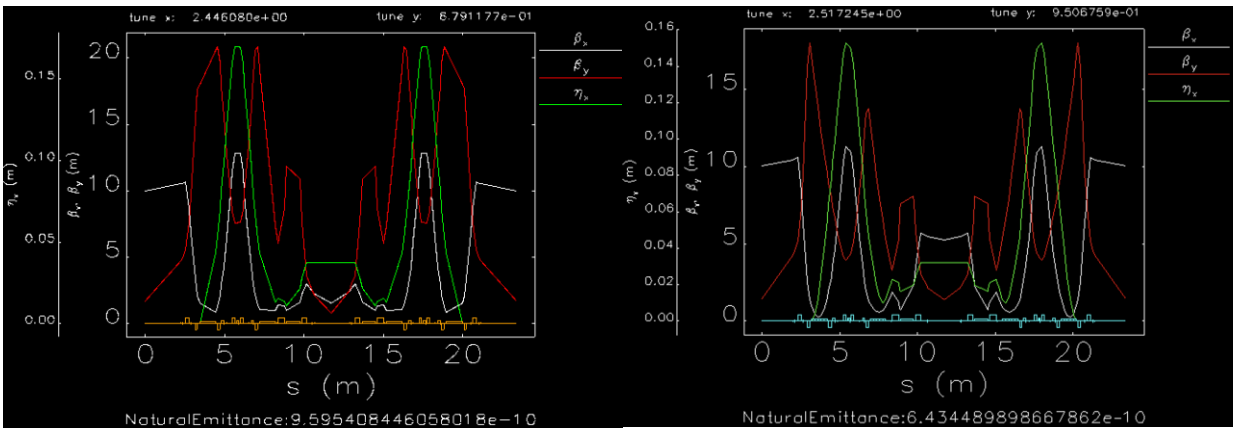

Figure 7 Optic functions for a DTBA cell: nominal (left) and with LGD (right).

The final beam emittance can be achieved is 0.64 nm.rad compared to that of the nominal of 0.96 nm.rad. As a result, about 33% emittance reduction can be reached with four LGD in the DTBA cell.

Smaller beam emittance provides overall smaller beam stay clear also. Figure 8 compares the horizontal beam stay clear of the original lattice and lattice with the LGD.

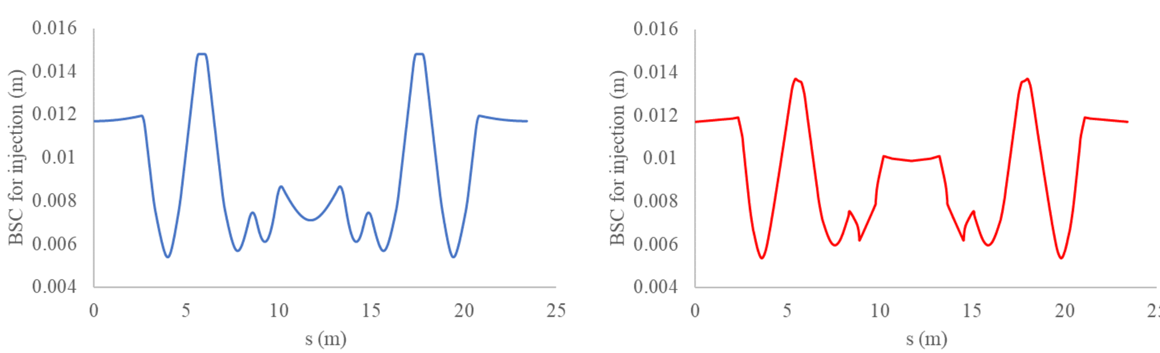

Figure 8 Horizontal beam stay clear for injection for nominal lattice (left) and lattice with LGD (right)

The maximum horizontal BSC for injection for the original solution is up to 14.8 mm while the version with LGD gives the maximum of 13.6 mm. More than 1 mm reduction is found.

6. Conclusion

- The feasibility study for longitudinal gradient dipole option in SPS-II was performed using Elegant.
- LGD was modelled with five slices and maximum field of 1.74 T. With four LGDs in the DTBA cell, the emittance can be reduced more than 30% compared to the nominal lattice.
- LGD can be made by permanent magnets and can reduce the total power consumption.
- The overall beam stay clear can be reduced due to smaller beam emittance.

7. User

- Accelerator physicists who involve in SPS-II machine project
- Accelerator Lattice designer
- Engineers

References

[1] T. Pulampong, "Ultra-low Emittance Lattice Design for Advanced," Oxford, 2015.

[2] H. Owen, "Proposed Storage Ring Beam Stay-Clear," 2001.

[3] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source, 2000.

[4] J. Varley and C. Coleman-Smith, "The Predicted aperture requirements for injection into the Diamond storage ring," 2001.

ภาคผนวก

Elegant lattice file

Elegant Lattice file: SPS2longit_01.new

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OF1D: KOCT,L=0.09,K3=-7189.693735416828,N_KICKS=40,SYNCH_RAD=1
QD2: KQUAD,L=0.162,K1=-6.476852272976219,N_KICKS=40,SYNCH_RAD=1
QD3: KQUAD,L=0.162,K1=-1.002425297640125e-14,N_KICKS=40,SYNCH_RAD=1
QD5: KQUAD,L=0.162,K1=-5.080555879191283,N_KICKS=40,SYNCH_RAD=1
QF1: KQUAD,L=0.215,K1=5.038489724742167,N_KICKS=40,SYNCH_RAD=1
QF41: KQUAD,L=0.162,K1=4.366894298121235,N_KICKS=40,SYNCH_RAD=1
QF42: KQUAD,L=0.162,K1=4.366894298121235,N_KICKS=40,SYNCH_RAD=1
QF4: KQUAD,L=0.162,K1=3.935065480974915,N_KICKS=40,SYNCH_RAD=1
QF6: KQUAD,L=0.412,K1=6.324701566609011,N_KICKS=40,SYNCH_RAD=1
QF8: KQUAD,L=0.328,K1=4.472154220929072,N_KICKS=40,SYNCH_RAD=1
SD1: KSEXT,L=0.14,K2=-215.6741080023876,N_KICKS=40
SD2: KSEXT,L=0.14,K2=-97.60262163913765,N_KICKS=40
SF2: KSEXT,L=0.07000000000000001,K2=150.4609120522425,N_KICKS=40
STR: KICKER
STR1: KICKER
STR2: KICKER
STR3: KICKER
STR4: KICKER
STR5: KICKER
FSTR1: KICKER
FSTR2: KICKER
GIR1: MARK
GIR2: MARK
GIR3: MARK
GIR4: MARK
DL1A: LINE=(DL1A_5,DL1A_4,DL1A_3,DL1A_2,DL1A_1)
DL2B: LINE=(DL2B_1,DL2B_2,DL2B_3,DL2B_4,DL2B_5)
DL2D: LINE=(DL2D_5,DL2D_4,DL2D_3,DL2D_2,DL2D_1)
DL1E: LINE=(DL1E_1,DL1E_2,DL1E_3,DL1E_4,DL1E_5)
C2: LINE=(DR_01,BPM_01,DR_90,FSTR1,DR_02,GIR1,QF1,DR_03,D05,STR1,DR_04,QD2,&
 DR_05,DL1A,DR_06,QD3,DR_07,SD1,STR3,DR_08,BPM_02,DR_09,QF4,DR_10,SF2,FPS,SF2,&
 STR5,DR_11,QF4,DR_12,OF1B,GIR1,DR_13,BPM_03,DR_14,GIR2,SD2,STR4,DR_15,QD5,&
 DR_16,DL2B,D025,DR_17,BPM_04,DR_18,QF6,DR_19,D02,DQ1,D02,DR_20,QF8,GIR2,DR_21,&
 STR2,D05,BPM_05,DR_23,CELLCENTER,DR_24,BPM_06,D05,STR2,DR_26,GIR3,QF8,DR_27,&
 D02,DQ1,D02,DR_28,QF6,DR_29,BPM_07,DR_30,D025,DL2D,DR_31,QD5,DR_32,SD2,STR4,&
 GIR3,DR_33,BPM_08,DR_34,GIR4,OF1D,DR_35,QF4,DR_36,SF2,FPS,SF2,STR5,DR_37,QF4,&
 DR_38,BPM_09,DR_39,SD1,STR3,DR_40,QD3,DR_41,DL1E,DR_42,QD2,DR_43,STR1,D05,&
 DR_44,QF1,GIR4,DR_45,FSTR1,DR_90,BPM_10,DR_46,IDMARKER,IDMARKER)
MAL: MALIGN,ON_PASS=0
M1: MALIGN,ON_PASS=0
W1: WATCH,FILENAME="%s.w1",MODE="centroid"
AP: RCOL,X_MAX=1
RFC: RFCA,VOLT=1500000,PHASE=157.3428826537241,FREQ=119000859.6588723,&
 CHANGE_T=1
RING: LINE=(MAL,14*C2,W1)
RINGRF: LINE=(MAL,RFC,14*C2,W1)
USE,C2
RETURN
```