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Abstract

Siam photon source has been improving both its machine and light sources. Though the storage ring has accommodated IDs at its full capacity, the idea add one more ID still emerged. In-vacuum wiggler (IWW) as a prototype of the new SPS-II machine has been designed and planed for assembly. Thus feasibility study to install such ID in the existing storage ring is required. IWW was modeled with kick map element into the SPS storage ring for particles tracking simulation. IWW was placed (off-center) next to SWLS which was positioned in the middle of the straight. Then both dynamic aperture (DA) and momentum apertures (MA) were investigated to assess the effects in both transverse and longitudinal planes. Due to the position of IWW is off-center, distortion effect is strong at minimum gap of 15 mm. The DA is not sufficient for beam injection and lower lifetime is expected from smaller MA. However the DA at fully opened gap of 120 mm, slight reduction of DA and MA can be found. As a result, IWW shows obviously strong effects on the performance of the storage ring. It will definitely introduce difficulties and risks to operate the storage ring at its required quality. IWW installation is then not recommended.

Keyword: IWW, Wigglers, Storage ring

Contents

1	Introduction	3
2	Purposes	4
3	Theory of Wigglers effects	4
3.1	Linear effect	5
3.2	Radiation Integral	6
3.3	Horizontal Emittance Increase	6
3.4	Energy Spread Increase	7
3.5	Radiation Damping	7
3.6	Momentum aperture and Beam Lifetime	7
3.7	Dynamic Aperture	8
4	Study of IVW effects	8
4.1	IVW modeling	8
4.2	IVW effect	13
5	Results	14
5.1	Bare ring	14
5.2	IVW at fully opened gap	14
5.3	IVW at fully closed gap	15
6	Conclusion	18
7	Users	18
A	Matlab script for kick map conversion	20

1 Introduction

Siam Photon Source (SPS) has been operating for more than twenty years. SPS is the only machine providing high quality synchrotron light to the users in Thailand. SPS has undergone many improvements to promote beam stability and quality. In term of photon production, at full capacity, four insertion devices (IDs) were installed to enable hard-xray and higher brightness. Undulator U60, 2.2 T Multipole Wiggler (MPW), 6.4 T Superconducting Wavelength Shifter (SWLS) and 3.5 T Superconducting Multipole Wiggler (SCMW) fully occupies all four straight sections. Ultimately, MPW was installed off-center in the injection straight sacrificing storage ring symmetry leading to strong perturbation on the beam optic and reduce dynamic aperture (DA). Unable to inject the beam with the MPW gap closed, machine operation has been suffered from the MPW strong effects.

The development of a new In-vacuum wiggler (IVW) as a prototype for the IDs to be used in the new 3GeV machine SPS-II seeks the opportunity to add one more ID to the existing SPS storage ring. IVW will be installed in the same straight as SWLS which already occupied the center of the straight as shown in figure 1. Thus IVW is positioned off-center. The specification of the IVW can be summarized in table 1. To prevent unwanted scenario as for the MPW case [1], effects of the IVW on the storage ring need to be realised.

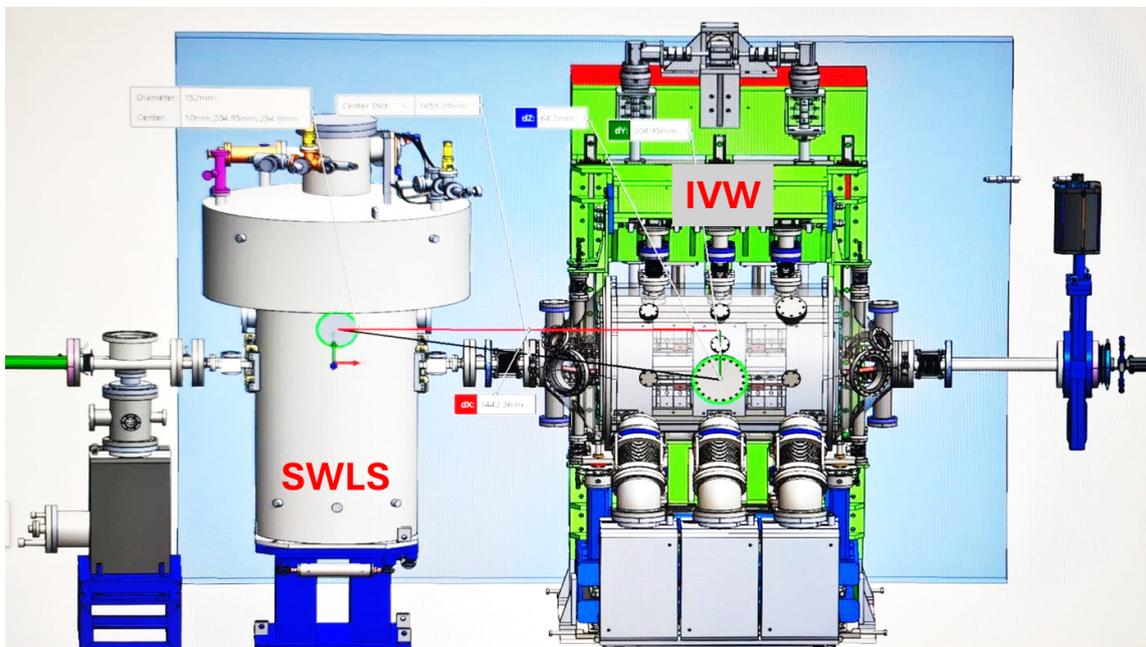


Figure 1: IVW installation layout

Table 1: IWW specifications

Parameters	Value	Unit
Magnet structure	Hybrid	
Peak field on axis (magnetic gap 15 mm)	1.9	Tesla
Operating vacuum gap	14.8	mm
Wake field shield on magnet surface	0.1	mm
Operating magnetic gap	15	mm
Minimum magnetic gap	5	mm
Maximum magnetic gap	120	mm
Magnetic period length of the ID	230	mm
Number of full-strength poles	5	
Length the ID for the regular period	575	mm
Number of regular periods	2.5	
Total length of the ID	795	mm
K value (magnetic gap 15 mm)	40.79832	
Effective magnetic field	1.2	Tesla
Effective K value	25.91258	
Total power	0.2837	kW
Critical energy	1819	eV
Magnetic force at magnetic gap 5 mm	24	kN
Magnetic force at magnetic gap 15 mm	16	kN
RF transition tapers	CuBe	
Field roll off 0.1 % at gap of 15 mm	±4	mm

2 Purposes

1. to model IWW for beam dynamics simulation.
2. to study the effect of IWW on the storage ring at fully opened gap of 120 mm
3. to study the effect of IWW on the storage ring at fully closed gap of 15 mm

3 Theory of Wignlers effects

A wiggler is an insertion device in an electron storage ring used to generate high-intensity, broad-spectrum synchrotron radiation. The wiggler can affect the storage ring locally and parameters globally.

3.1 Linear effect

A wiggler can be treated as a thin kick element. Vertically, a wiggler behaves as a quadrupole whose average focusing parameter can be expressed as [2]

$$K_z = \left\langle \frac{1}{\rho^2} \right\rangle \quad (1)$$

where ρ is the bending radius of the wiggler. The transfer matrix can then be written generally as

$$M_{eff} = \begin{pmatrix} \cos \theta^* & \beta^* \sin \theta^* \\ -\sin \theta^* / \beta^* & \cos \theta^* \end{pmatrix} \quad (2)$$

where

$$\cos \theta^* = \cos \theta + \frac{\theta \sin \theta}{2}, \quad (3)$$

$$\beta^* = L \left(\frac{1}{\theta^2} - \frac{\cot \theta}{\theta} - \frac{1}{4} \right)^{1/2}, \quad (4)$$

and $\theta = \sqrt{KL}$, $\beta = \frac{1}{\sqrt{K}} = \frac{L}{\theta}$.

With the wiggler, M_{eff} will perturb the storage ring transfer matrix by multiplication and result in betatron tune shift from modified phase advance μ_w which can be written as

$$\cos \mu_w = \cos \mu \cos \theta^* - \frac{\sin \mu \sin \theta^*}{2} \left(\gamma \beta^* + \frac{\beta}{\beta^*} \right), \quad (5)$$

where μ is unperturbed phase advance.

Using thin lens approximation the transfer matrix become

$$M_{eff} = \begin{pmatrix} 1 & \theta^2 L / 12 \\ -\theta^2 / L & 1 \end{pmatrix} \quad (6)$$

And betatron tune shift can then be

$$\Delta Q = \frac{KL\beta}{4\pi} \left(1 + \frac{L^2}{12\beta^2} \right) \quad (7)$$

Beta-beating can also be written as

$$\frac{\Delta\beta}{\beta} = \frac{KL\beta}{2\sin \mu} \left(1 - \frac{L^2}{12\beta^2} \right) \quad (8)$$

It is obvious that the effect of a wiggler is proportional to its peak strength and length.

3.2 Radiation Integral

A wiggler with the length L and can contribute to synchrotron radiation integral as follows:

$$\Delta I_1 = \oint \frac{D}{\rho} = \int \frac{\cos^2(k_0 s)}{\rho_0^2 k_0^2} = \frac{L}{2\rho_0^2 k_0^2} \quad (9)$$

$$\Delta I_2 = \oint \frac{1}{\rho^2} = \int \frac{\cos^2(k_0 s)}{\rho_0^2} = \frac{L}{2\rho_0^2} \quad (10)$$

$$\Delta I_3 = \oint \frac{1}{|\rho^3|} = \int \frac{|\cos^3(k_0 s)|}{\rho_0^3} = 4 \frac{L}{3\pi\rho_0^3} \quad (11)$$

$$\Delta I_4 = \oint \frac{D}{\rho^3} - \frac{2kD}{\rho} = - \int \frac{\cos^4(k_0 s)}{\rho_0^4 k_0^2} + 2 \int \frac{\sin^2(k_0 s) \cos^2(k_0 s)}{\rho_0^4 k_0^2} = - \frac{L}{8\rho_0^4 k_0^2} \quad (12)$$

$$\Delta I_5 = \oint \frac{H}{|\rho^3|} \quad (13)$$

where $H = \gamma D^2 + 2\alpha DD' + \beta D'^2$

These integrals play a very important role of controlling electron beam parameters. In case of SPS-I, naturally large dispersion in the straight can be found and wiggler generated dispersion can be neglected. Approximation can be made for

$$\Delta I_5 \approx \frac{4}{3\pi} \frac{\langle H \rangle L}{\rho_0^3} \quad (14)$$

and momentum compaction factor

$$\Delta\alpha_p = \frac{\Delta I_1}{L_{tot}} = \frac{L}{L_{tot}} \frac{1}{2\rho_0^2 k_0^2} \quad (15)$$

3.3 Horizontal Emittance Increase

The horizontal emittance ϵ_x in a storage ring is affected by the presence of a wiggler. A wiggler placed in a dispersive straight can introduced unwanted emittance growth. The increase in emittance can be estimated by considering the equilibrium emittance contribution from the wiggler. Generally, the horizontal beam emittance is given by:

$$\epsilon_x = \frac{C_q \gamma^2 \langle H \rangle}{J_x \rho_0} \quad (16)$$

where:

- $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{m_e c} \approx 3.83 \times 10^{-13} \text{ m}$ is a constant,
- γ is the relativistic Lorentz factor,
- $\langle H \rangle$ is the average of the H-function over one period of the lattice,
- J_x is the horizontal damping partition number,
- ρ_0 is the bending radius of the dipole magnets.

With a wiggler, the horizontal emittance becomes:

$$\epsilon_x = \frac{C_q \gamma^2 \left(\langle H \rangle_{\text{ring}} + \langle H \rangle_{\text{wiggler}} \right)}{J_x \left(\rho_0^{-1} + \rho_{\text{wiggler}}^{-1} \right)} \quad (17)$$

3.4 Energy Spread Increase

The energy spread σ_E is also influenced by the wiggler. The energy spread is given by:

$$\left(\frac{\sigma_E}{E}\right)^2 = C_q \gamma^2 \frac{I_3}{2I_2 + I_4} \quad (18)$$

The effect of a wiggler on the energy spread can be written as

$$\left(\frac{\sigma'_E}{\sigma_E}\right)^2 = \frac{1 + \Delta I_3/I_3}{1 + \frac{2\Delta I_2 + \Delta I_4}{2I_2 + I_4}} \quad (19)$$

$$\sigma_E^2 = \frac{C_q \gamma^2}{J_\epsilon} \left(\frac{1}{\rho_0} + \frac{N_w}{\rho_w} \right) \quad (20)$$

where:

- J_ϵ is the energy damping partition number,
- N_w is the number of wiggler periods,
- ρ_w is the bending radius of the wiggler.

3.5 Radiation Damping

The radiation damping times τ_x , τ_y , and τ_s for the horizontal, vertical, and longitudinal planes, respectively, are affected by the wiggler. The damping times are given by:

$$\tau_i = \frac{2T_0 E}{J_i U_0} \quad (21)$$

where:

- T_0 is the revolution period,
- E is the beam energy,
- U_0 is the energy loss per turn,
- J_i is the damping partition number for plane i (x , y , s).

The presence of a wiggler increases U_0 , thereby decreasing the damping times.

3.6 Momentum aperture and Beam Lifetime

The beam lifetime τ_b can be affected by changes in beam emittance, energy spread and momentum aperture caused by the wiggler. Generally a wiggler can introduce non-linearity to the ring and reduce the momentum aperture of the ring. Touscheck lifetime can be expressed as:

$$\tau_b^{-1} = \frac{r_e^2 I_b}{8\pi e \gamma^3 \sigma_s} \oint_C \frac{F\left(\left[\frac{\delta_{acc}(s)}{\gamma \sigma_{x'}(s)}\right]^2\right)}{\sigma_x(s) \sigma_{x'}(s) \sigma_z(s) \delta_{acc}^2} ds \quad (22)$$

where r_e is the classical electron radius, σ_s the bunch length, I_b the bunch current. $\sigma_x(s)$ and $\sigma_z(s)$ the rms horizontal and vertical beam sizes. c is the vacuum velocity of light, e the electron charge, and γ the relativistic Lorentz factor of the beam and

$$F(x) = \int_0^1 \left(\frac{1}{u} - \frac{1}{2} \ln \frac{1}{u} - 1 \right) \exp\left(-\frac{x}{u}\right) du. \quad (23)$$

Reduced momentum acceptance can reduce the beam Touscheck lifetime.

3.7 Dynamic Aperture

The dynamic aperture, which is the region in phase space where stable particle motion occurs, can be reduced by the wiggler. The precise impact is complex and depends on the detailed design of the storage ring and the wiggler. Wigglers significantly affect storage ring performance by introducing strong non-linearity to the ring. At large amplitude, nonlinear field components kick the beam much stronger, depending on its order, and lead to particle loss. As a consequence, stable region of the beam to survive shrinks leading to beam injection difficulty and lower lifetime.

In addition, a wiggler installation which break symmetry of the ring can even affect the ring in a bad way.

4 Study of IVW effects

4.1 IVW modeling

To simulate the effect of the IVW, particle tracking is required. Elegant [3] is the well-known simulation code in the accelerator community world-wide. Kick map [4] can be used to represent IDs in the storage ring model. UKICKMAP, an undulator kick map, is an element accepting kick map as an input. It is basically a thin kick element to simulate the effect from the ID. Data from Radia can be conveniently taken. Integrated field along the beam axis for various transverse position can be used to generate a kick map. The kick map contains both horizontal and vertical kick factor in the unit of T²m². Tables of kick angle for various position on transverse grid of horizontal and vertical plane was provided. The boundary given from the received data is ± 100 mm and ± 7 mm for horizontal and vertical plane respectively. The data was converted to SDDS [5] format using Matlab script (in the Appendix) to be compatible with Elegant for particle tracking. The kick map for IVW at fully opened gap at 120 mm and fully closed gap at 15 mm were generated to make a comparison of the IVW effect at different gap. Figure 2 shows the

kick map of the IVW at 120 mm gap. The maximum kick angle is about $\pm 6 \times 10^{-5}$ T²m² and $\pm 5 \times 10^{-5}$ T²m² in horizontal and vertical plane respectively. The generated kick at fully opened gap is small but not negligible. Noticeably, the kick around the center part appears to be close to linear pattern.

Similarly, figure 3 shows the kick map of the IVW at 15 mm gap. Compared to the kick at the fully opened gap, much stronger kick can be seen. The maximum kick peaks at about $\pm 4 \times 10^{-2}$ T²m² for both planes. The kick maps clearly show large non-linearity. As a consequent, strong effect of the IVW at the minimum gap can be expected.

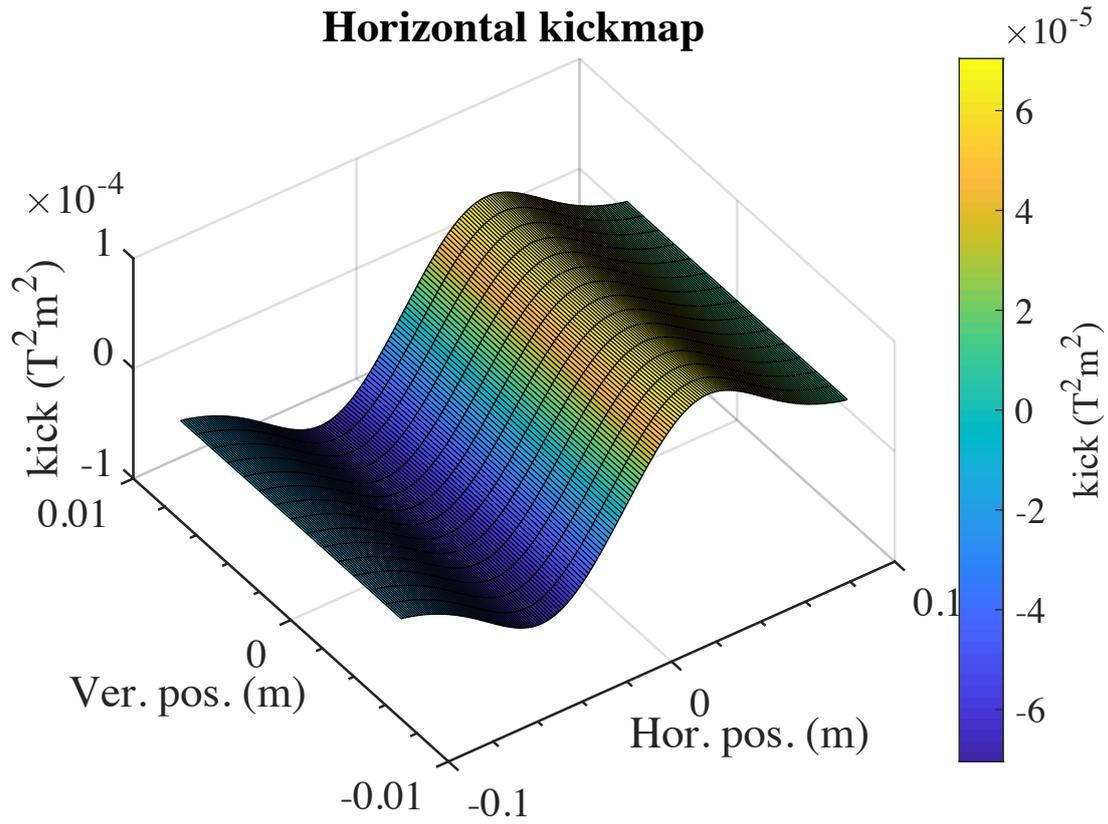
After the kick maps were converted into SDDS format, 2D map can be plotted using sddsplot as shown in figure 4. The kick map conversion steps from raw data to SDDS file to be used by Elegant is summarized in figure 5. It is worth noting that the data in the SDDS kick map file assumed the data of x varies fastest. This can be accomplished with the command:

```
sddssort -column=y,increasing -column=x,increasing input1.sdds input2.sdds
```

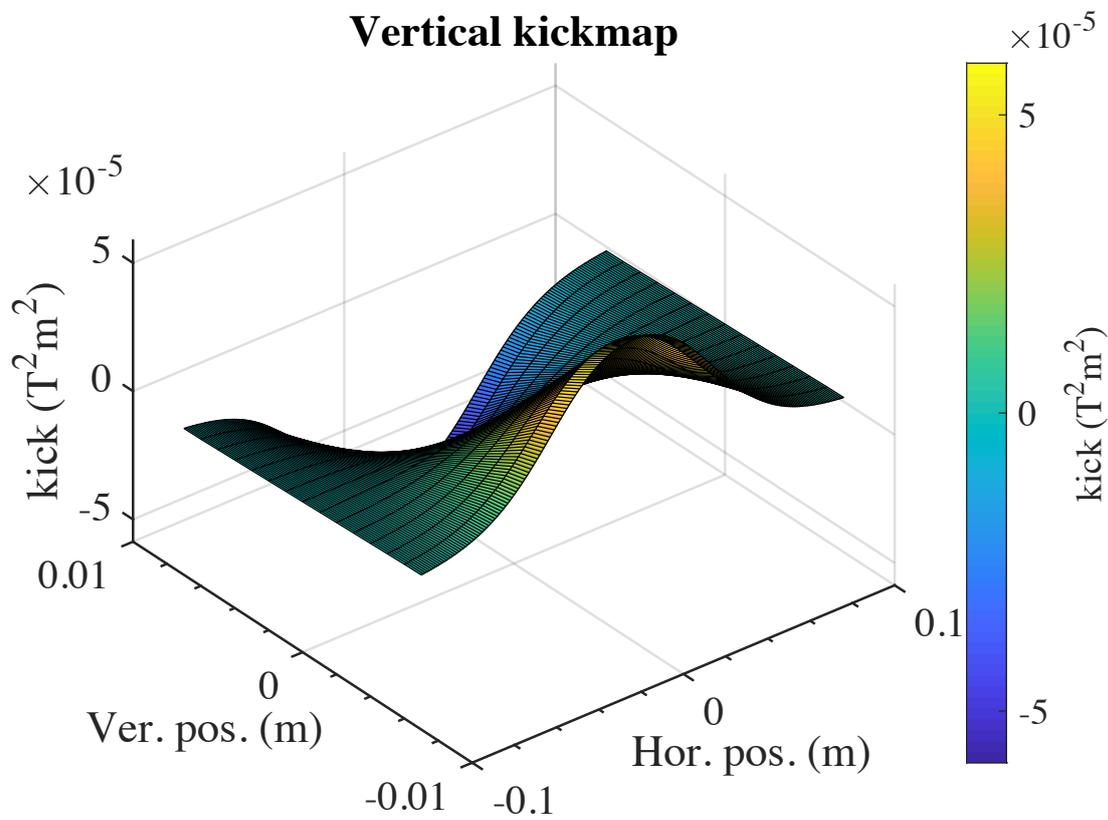
IVW modeling in SPS After obtaining the generated kickmap in the compatible SDDS format, It is required to simply indicate the file name in the UKICKMAP element in the elegant lattice file. The SPS lattice file was prepared with the exact position of the IVW just next to the SWLS’s position in the downstream direction. As the SWLS was placed in the middle of the straight, thus IVW is to be installed off-centered. Elegant ‘s element line with IVW can be written as follows

```
SPERIOD4:line=(DIVWU,IVW,DIVWD,CORH,D02,BPM,D03,QF1,D04,&
CORV,D05,QD2,D06, B01,D07,BPM,D08,QF3,D09,SF,D10,CORH,&
DBmp01Up,Bmp01,DBmp01Dwn,CORV,D2X,SD,D13,QD4R,SS4M,QD4L,&
D14,SD,D5X,BPM,D6X,CORH,D17,SF,D18,QF38_MPW,D19,BPM,D20,&
B02,D21,QD28_MPW,D22,CORV,D23,QF18_MPW,D24,BPM,D25,CORH,&
DInjUp,Inj,DInjDwn)
```

To simplify the simulation, the only ID in the storage ring is IVW in order to investigate its effect individually.

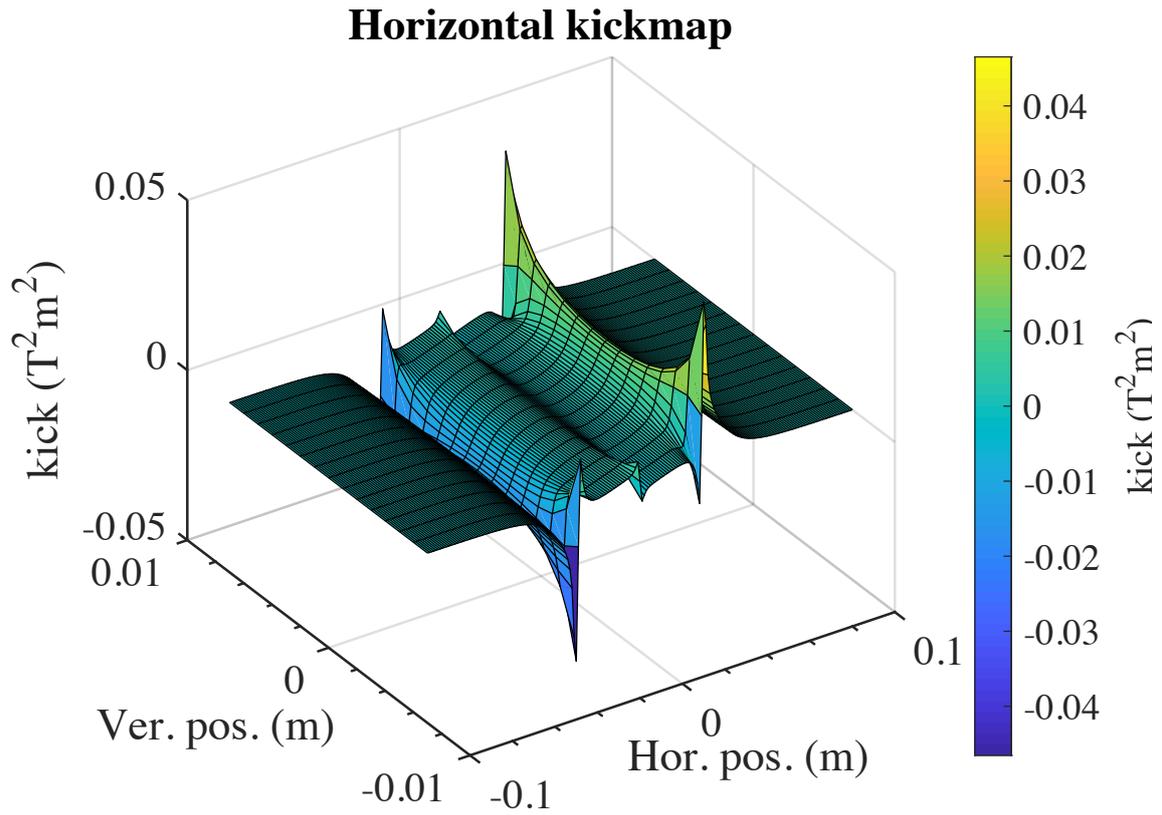


(a)

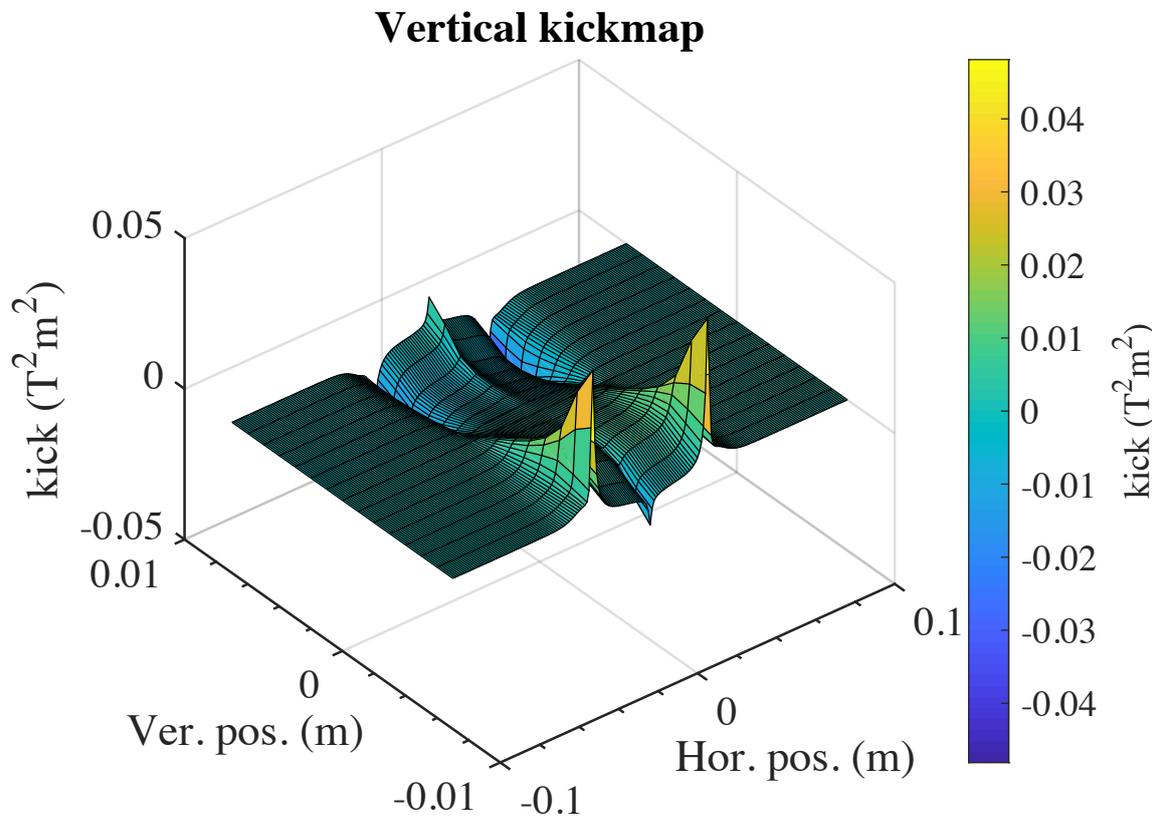


(b)

Figure 2: Kick map for IVW at 120 mm gap (a) Horizontal (b) Vertical

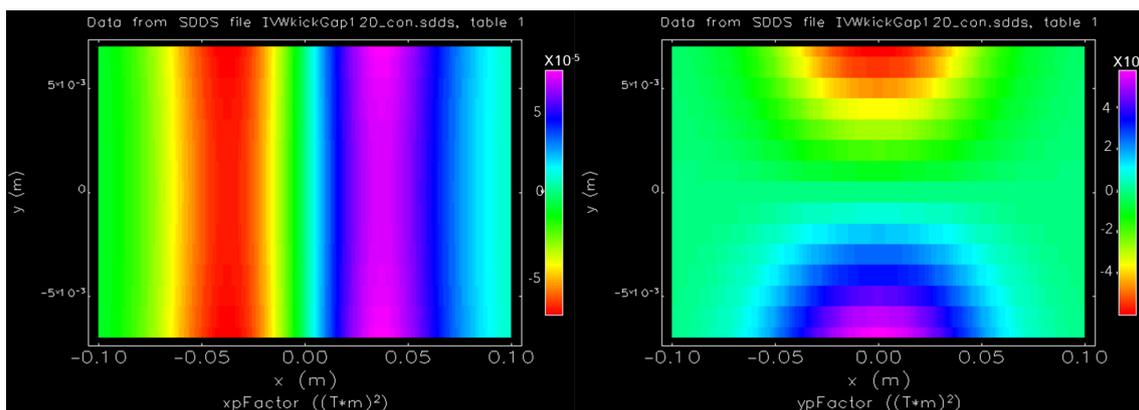


(a)

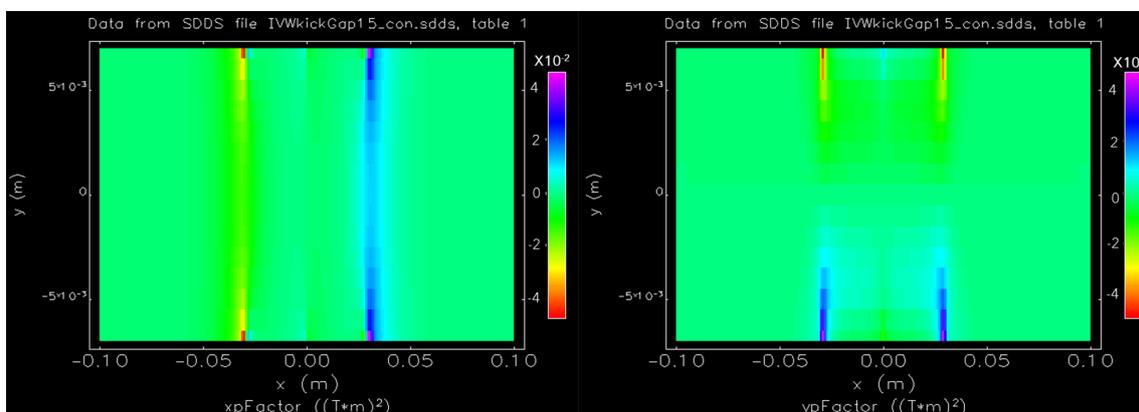


(b)

Figure 3: Kick map for IVW at 15 mm gap (a) Horizontal (b) Vertical



(a)



(b)

Figure 4: Elegant kick map for IVW (a) at 120 mm gap (b) at 15 mm gap

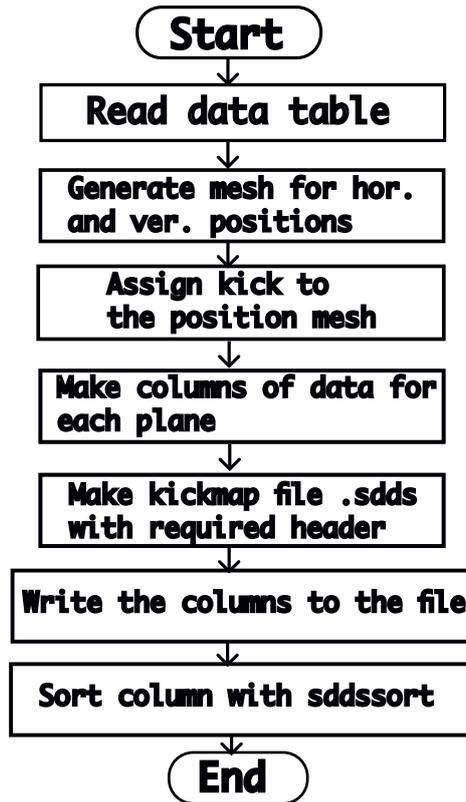


Figure 5: Kick map conversion steps

4.2 IVW effect

Fundamental linear effect can be observed from twiss function distortion from the ideal case. Beam emittance and tune shift can be assessed from the linear lattice calculation.

To study the non-linear effect of the IVW, particle tracking through the element along the ring multipole turns is required. Two main particle tracking procedures are dynamic aperture and momentum aperture tracking to assess the effect in both transverse and longitudinal planes. For dynamic aperture, frequency map analysis tracking was utilized. A grid of horizontal and vertical position was generated. Then tracking started for several turns and diffusion ($d = \log(\Delta\nu_x^2 + \Delta\nu_y^2)$) was calculated from tune difference for each point.

IVW conditions for investigation are at fully opened gap of 120 mm and fully closed gap of 15 mm. To make comparison with the ring without the IVW, particle tracking with ideal bare ring was performed.

All the studies considered ideal case without any error or misalignment to investigate the effect of the IVW solely. In all case, chromaticity was corrected to be 3 in both planes prior any particle tracking.

5 Results

5.1 Bare ring

Twiss functions for the bare ring can be depicted in figure 6. It is a ring with four typical Double-Bend Achromat (DBA) cells with dispersion function leak in the straight to minimize the beam emittance. The horizontal emittance is about 60 nm·rad and good symmetry can be clearly seen here.

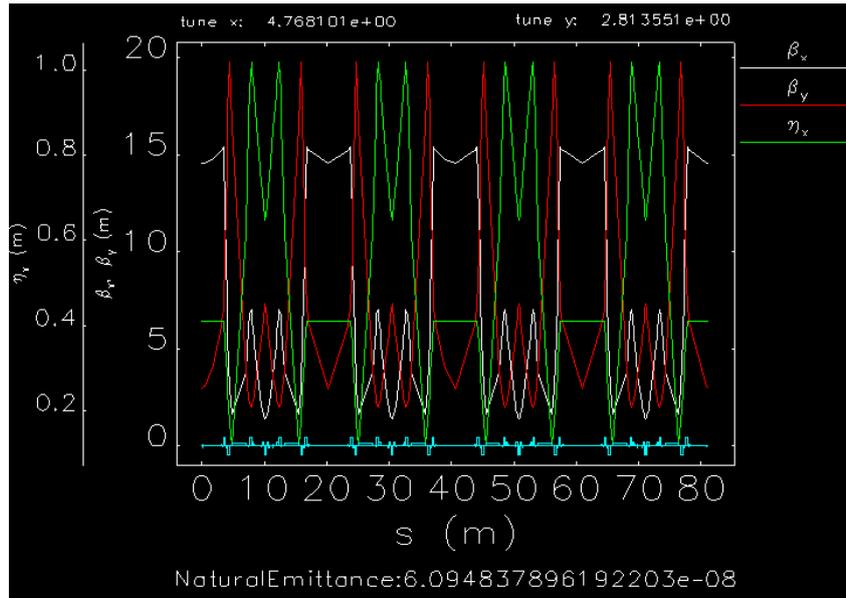


Figure 6: Twiss functions of the storage ring(bare ring)

Frequency map analysis (FMA) representing the transverse dynamic aperture (x-y) was studied. As shown in figure 7, the FMA of the bare ring can accommodate the beam oscillation upto about ± 60 mm. The tune footprint of the tracked particles is plotted in the tune diagram. The DA can accommodate comfortably the injected beam with injection offset at -42 mm. This will be used as a benchmark to study the effect of the IVW in the ring.

5.2 IVW at fully opened gap

Minimum effect can be expected from IVW at fully opened gap. At 120 mm small kick angle produced may still affect the beam. For twiss functions, figure 8 shows only small change. Symmetry optic functions are still preserved with almost no effect on the beam emittance.

For dynamic aperture, figure 9 shows the FMA of the ring with IVW at fully opened gap. Clearly, smaller DA in vertical plane was seen because of its limitation of the vertical physical aperture to ± 7.5 mm. For horizontal plane, slight reduction can also be

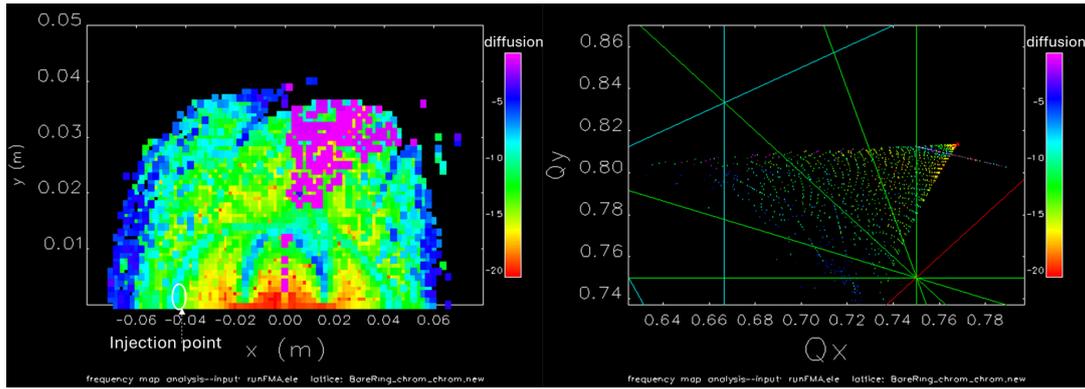


Figure 7: Dynamic aperture of the storage ring (bare ring)

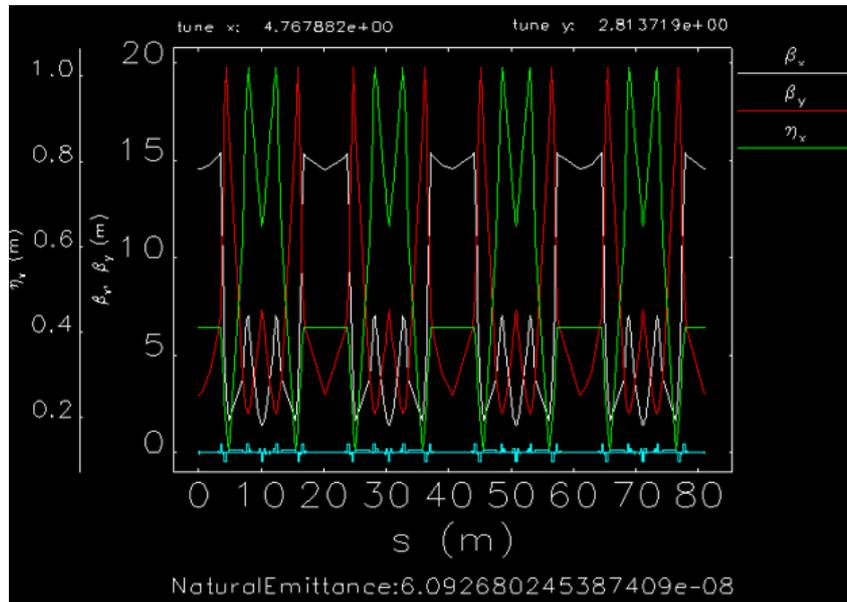


Figure 8: Twiss functions of the storage ring with IVW at 120 mm gap

observed. Moreover, the tune footprint shows only narrower painting in the tune space compared to that of the bare ring case.

5.3 IVW at fully closed gap

For IVW operation, minimum gap at 15 mm will be used. Linear optic of the ring with IVW at minimum gap shows strong perturbation as shown in figure 10. Asymmetry was introduced for all twiss functions: horizontal and vertical beta functions and dispersion function. Higher dispersion function and larger beam emittance were found. This definitely deteriorate the photon source quality. It is worth mentioning that to correct the asymmetry effect of the IVW, more quadrupole power supplies are required. Individually adjustable quadrupoles in the straight section up and down stream the IVW are needed.

For beam injection, dynamic aperture as shown in figure ?? highlights a very limited

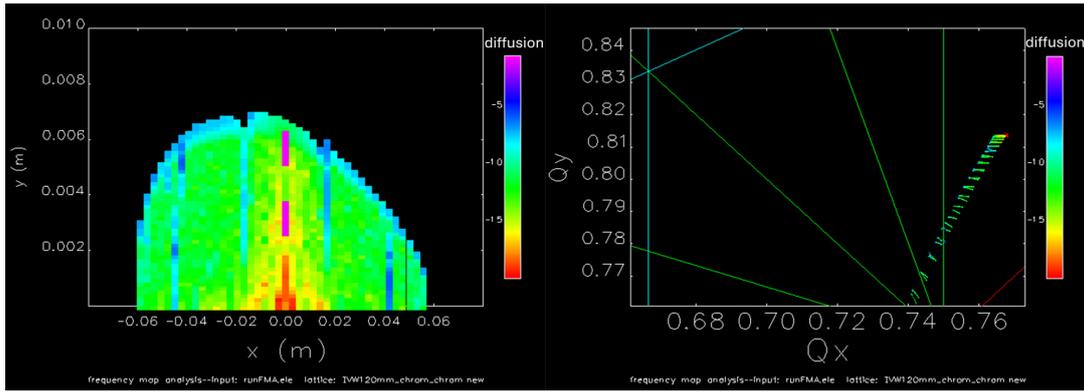


Figure 9: Dynamic aperture of the storage ring with IVW at 120 mm gap

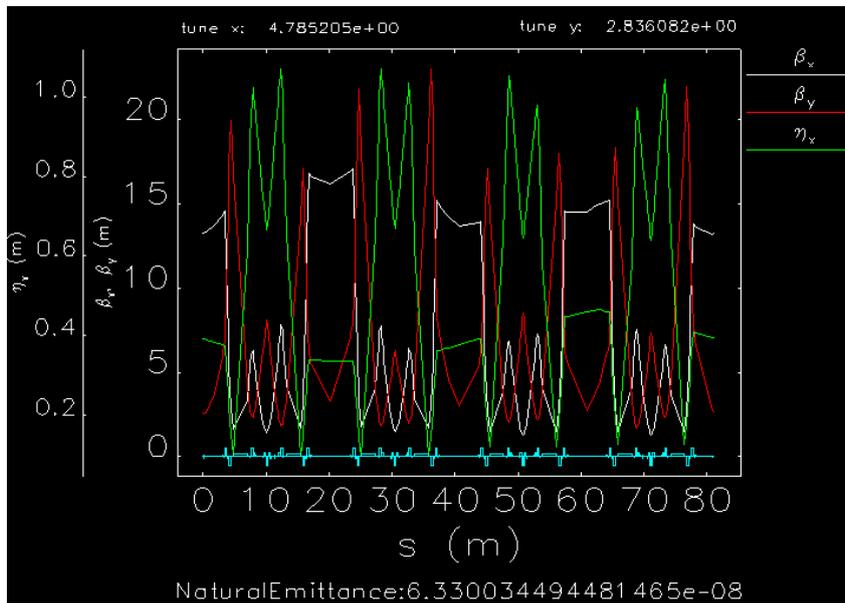


Figure 10: Twiss functions of the storage ring with IVW at 15 mm gap

stable area for the beam below ± 40 mm. While the required injection point is at -43 mm, it is as a result impossible. Both vertical and horizontal planes shrink dramatically indicating strong effect of the IVW at minimum gap.

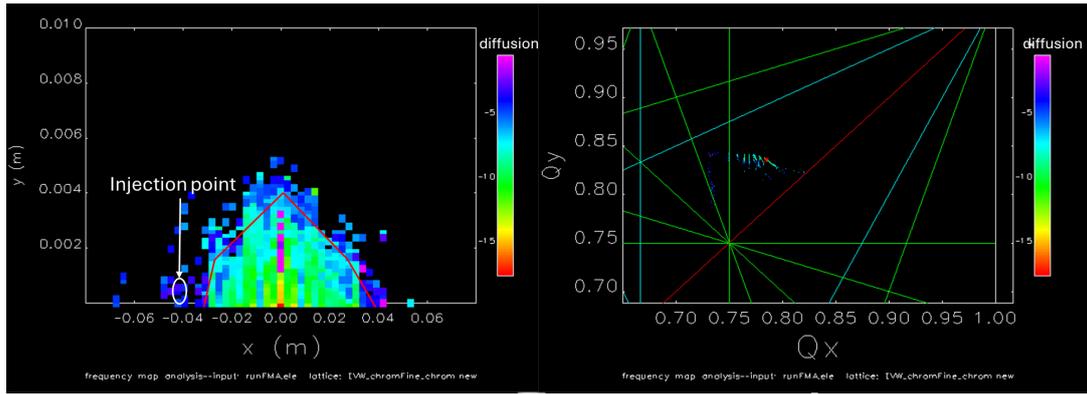


Figure 11: Dynamic aperture of the storage ring with IVW at 15 mm gap

Table 2: Beam parameters comparison.

Parameters	Bare ring	Ring+IVW 15 mm	Ring+IVW 120 mm
Beam energy [GeV]	1.2	1.2	1.2
Tune : h/v	4.7681/ 2.8135	4.7852/ 2.8361	4.768/ 2.814
Emittance: h/v[nm·rad]	60.95	63.30	60.93
Energy spread (rms)	6.039E-04	6.039E-04	6.039E-04
Momentum compaction	1.814E-02	1.810E-02	1.814E-02

To understand the effect of the IVW at different gap more clearly, table 2 summarizes the beam parameters. At fully opened gap, IVW affect the betatron tune slightly. At fully closed gap, on the other hand; stronger effect can be observed. Figure 12 compares the DA and MA for the bare ring, the ring with IVW at 120 mm gap and the ring with IVW at 15 mm gap. Dynamic aperture of the ring reduced significantly by the effect of IVW at smaller gap. Similarly, momentum aperture is also decreased compared to the bare ring case especially on the positive energy side.

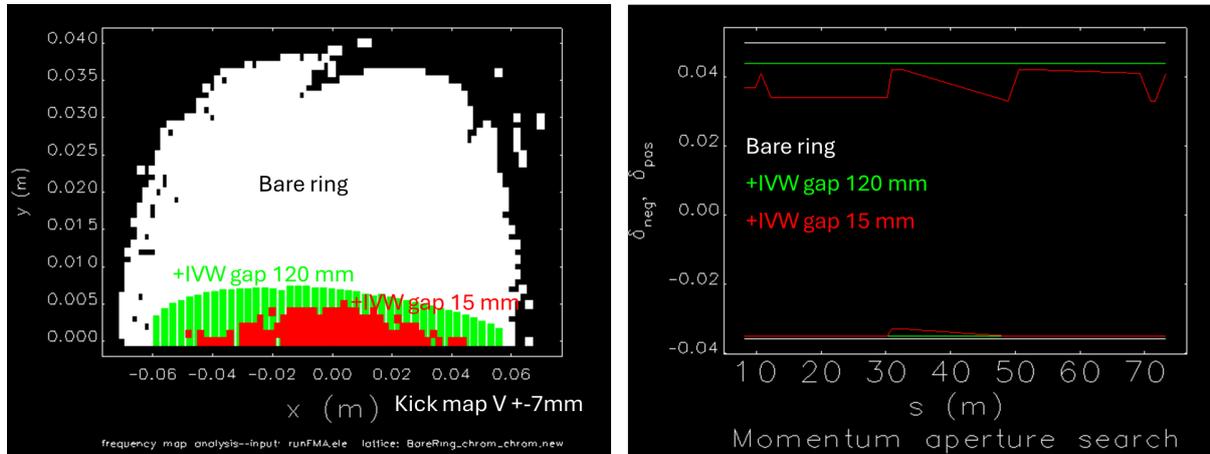


Figure 12: Dynamic aperture (left) and momentum aperture (right) comparison for bare ring (white), ring+IVW 120mm gap (green) and ring+IVW 15mm gap (red)

6 Conclusion

Obviously, it can be concluded that IVW at minimum gap of 15 mm affects the performance of the storage ring dramatically. It introduces asymmetry and strong non-linearity to the ring. No injection is allowed and lower beam lifetime can be expected. Thus, it is no recommended to install the IVW in the storage ring.

Lesson should be learned from the previous example when 2.2 T MPW was installed off-center in the injection straight and no beam injection can be done with minimum gap. Already machine operation has suffered from the MPW effect. Operation points for beam injection and beam store have to be made for each operation mode (7 modes). MPW gap closing strongly affects the beam orbit and dynamic of the storage ring.

IVW in the storage ring poses serious risks and complexity to machine operation and performance as a whole.

7 Users

1. Accelerator physicists
2. Operation engineers and machine operators
3. Insertion devices designers

References

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A Matlab script for kick map conversion

reakKickmap_IVU.m

```
%% read radia kickmap file and prepare variables
%% input file
[baseName, folder] =uigetfile('*','select xls file');
fName=fullfile(folder, baseName);
% fp=fopen(radiaName,'r');
format long;
%% get data from file
kmap_x = readmatrix(fName,'Sheet','Hkick');
kmap_y = readmatrix(fName,'Sheet','Vkick');
x0=[-100e-3:1e-3:100e-3];
y0=[-7e-3:1e-3:7e-3];
x=x0';
y=fliplr(y0);
y=y';
%% make correct matrix dimension
%construct
xx= repmat(x(:,1),1,length(y));
yy= repmat(y(:,1),1,length(x));
yy=fliplr(yy');
xx=xx';
yy=yy';
xu=reshape(xx,length(x)*length(y),1);
yu=reshape(yy,length(x)*length(y),1);
kmap_xu=reshape(kmap_x,length(x)*length(y),1);
kmap_yu=reshape(fliplr(kmap_y),length(x)*length(y),1);
%% Visualization
figure;
surf(xx,yy,kmap_x);
c = colorbar;
c.Label.String = 'kick (T^2m^2)';
title('Horizontal kickmap');
figure;
surf(xx,yy,kmap_y);
c = colorbar;
c.Label.String = 'kick (T^2m^2)';
title('Vertical kickmap');
```

A script to do the whole process `genKickmap_IVU.m`

```

%%kickmap gen
%% read radia kickmap and construct variables
clear;
readKickmap_IVU;
%use variable from readKickmap.m
[dummy,name]=fileparts(fName);
kmName=sprintf('%s_con.sdds',name)
fp1=fopen(kmName,'w');
%% make sdds file header
fprintf(fp1,'SDDS1\n');
%fprintf(fp1,'%parameter name=yc, units=m, type=double, &end\n');
fprintf(fp1,'%parameter name=NumberCombined, description="Number of files
    combined to make this file", type=long, &end\n');
fprintf(fp1,'%column name=x, units=m, type=double, &end\n');
fprintf(fp1,'%column name=xpFactor, units="(T*m)$a2$n", type=double, &end\
    n');
fprintf(fp1,'%column name=ypFactor, units="(T*m)$a2$n", type=double, &end\
    n');
fprintf(fp1,'%column name=y, units=m, type=double, &end\n');
fprintf(fp1,'%data mode=ascii, &end\n');
fprintf(fp1,'%! page number 1\n');
%fprintf(fp1,'1.2000000000000000e-002\n');
fprintf(fp1,'1\n');
fprintf(fp1,' %d\n',length(x)*length(y));
%%kickmap data
for j=1:length(xu)
fprintf(fp1,'%f %f %f %f\n',xu(j,1),kmap_xu(j,1),kmap_yu(j,1),yu(j,1));
end

fclose(fp1);
%% need for correct sorting format
comm0=['sddsort ',kmName,' -col=y,incr -col=x,incr'];
system(comm0)

```