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SIMULATION STUDIES OF THE HELICAL SUPERCONDUCTING UNDULATOR INSTALLED AT APS*

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Abstract

A multi-year project at APS has resulted in construction of a helical superconducting undulator (HSCU) for installation in the ring. Before installation, simulation studies were done to ensure that APS performance will not be compromised. This paper describes the method used for calculating the HSCU's perturbation effects and the simulation results for both calculated and measured field map.

INTRODUCTION

APS has been developing superconducting undulators (SCU) for a number of years [1–4]. The newest device installed to the APS storage ring is a helical superconducting undulator (HSCU) [5,6]. The main parameters of the HSCU are given in Table 1, and its effects to beam had been studied earlier based on a theoretical field expansion [7]. As the development proceeded, a numerical field map [8] became available to us for doing a further beam physics assessment. Based on the simulation result, we confirmed that the device should not pose any negative effects on the machine performance, except for some non-vanishing field integrals which could either be compensated during the device tuning stage or corrected using local correctors after installation. The device was built and multipole components were measured [9] and provided to us for beam dynamics check again to assure there would be no surprising effects after installing the HSCU in the APS ring. In this paper, we summarize our simulation results and show that there is no concerns if the non-vanished field integrals are corrected properly. The HSCU was installed during the December 2017 shutdown, and smooth commissioning of HSCU in January 2018 confirmed our results.

Table 1: Main Parameters of the Helical SCU

Cryostat length	1.85 m
Magnetic length	1.2 m
Undulator period	31.5 mm
Undulator field $B_x = B_y$	0.4 T
Undulator parameter $K_x = K_y$	1.2
Magnetic bore diameter	31 mm
Full vacuum chamber gap	26 × 8 mm

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SIMULATION WITH CALCULATED FIELD MAP

After many struggles, the HSCU field map was calculated based on the the magnet design [8]. The on-axis field is shown in Fig. 1. The biggest concern from the calculated field was a possibility if coupling perturbation from the strong Bz field around the end poles. Thus, a detail beam dynamics simulation was performed based on this calculated field. As stated in the previous paper [7], the kickmap used for beam dynamics study was calculated by tracking particles through "FTABLE" [10] element in `elegant` [11]. By examining the calculated kickmap, non-vanished dipole and skew quadrupole components were revealed, as "HSCU0" shown in Fig. 2. Assuming this can be corrected by adding correction coils to HSCU, the required correction components are listed in Table 2. The on-axis kickmap after adding local correction is also shown in Fig. 2 as "HSCU".

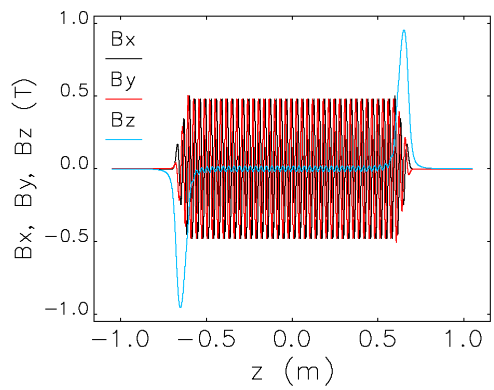

Figure 1: Calculated on-axis HSCU field.

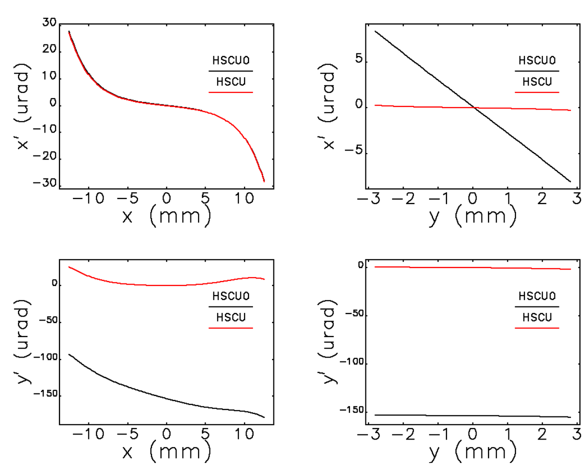

Figure 2: On-axis kickmap before (HSCU0) and after (HSCU) local correction.

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Table 2: Required HSCU Local Correction

Item	Value	units
I_{1x}	3.6×10^3	G-cm
I_{2x}	2.2×10^5	G-cm^2
I_{1y}	0	G-cm
I_{2y}	3.6×10^4	G-cm^2
B_0La_1 [a]	6.6×10^2	Gauss

[a] $\int(B_y + iB_x)dl = B_0L\sum_{n=0}^{\infty}(b_n + ia_n)(x+iy)^n$

Since this was the first helical device designed, built, and to be installed at APS, we wanted to understand the source of the kick map components shown in Fig. 2. Due to complexity of the mechanical design, even validity of the magnetic field simulation was not guaranteed. Non-zero kicks in general can be generated by real fields, in which case they could be measured after the device is built, or they can be generated by a combination of real fields and orbit wiggling inside the device, in which case they could not be measured using traditional measurement techniques. To find the source of the kicks, we calculated the field integral using the calculated field map at $y = 0$ plane vs x, then fitted a polynomial to the calculated integrals. Results are shown in Fig. 3. The fitted multipole strengths are very close to what was obtained from kickmap calculation results listed in Table 2, such like $I_{1x} = 3600$ G-cm vs. 3585 G-cm and $B_0La_1 = 660$ G vs 566 G. Thus, we conclude that the significant perturbation effects should be measurable after the device is built, and thus can be tuned to minimize the effects.

Machine performance, such as dynamic aperture (DA), which has direct effect on injection efficiency, and local momentum aperture (LMA), which has direct effect on beam lifetime, had been simulated also using the calculated kickmap. No performance degradation was found in the simulation results.

SIMULATION WITH MEASURED HSCU MULTIPOLES

Magnet measurement was performed after the HSCU was built and before the installation. There are dipole correction coils integrated with the device, so the on-axis first and second field integral could be corrected to zero. Thus, only measured multipoles as shown in Table 3 [9] were used for nonlinear beam dynamics simulation. One needs to remember that the magnetic field expression through multipoles used in magnet measurement results is as follows

$$B_y(x, meas) = B_0 + G * x + S * x^2 + O * x^3 + \ldots \quad (1)$$

while in `elegant` it is

$$B_y(x, simu) = B_0 + G * x + \frac{1}{2}S * x^2 + \frac{1}{6}O * x^3 + \ldots \quad (2)$$

It means that the Sextupole strength ($K2$) needed to be used in simulations is two times the measured number and the

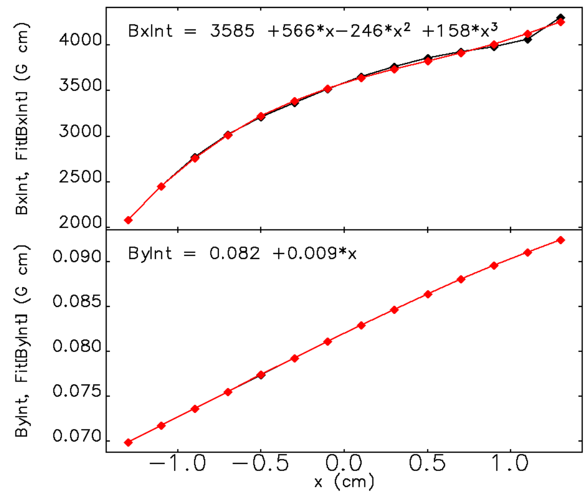

Figure 3: Calculated field integral vs x at $y = 0$ from field map. The fitted multipole components agree well with the kickmap calculation results, see Table 2. This means the major contribution to the calculated kickmap is the non-vanishing field integrals, and not the beam orbit wiggling inside the device.

Octupole strength ($K3$) is six times the measured number. With this in mind, we converted the measurement data to multipole strength used by `elegant`, split them in half and placed on both upstream and downstream ends of the HSCU.

There are two nominal optics [12] for daily APS operation, one has chromaticity of +4 in both planes for a lower single bunch operation mode, and another has a much higher chromaticity of +10 in both planes to accommodate for a special high single-bunch current (16 mA) operation mode. Simulations were done for lattices with both chromaticities. To make the simulation more robust, magnet errors (8 random sets) are also included. The error magnitudes are adjusted to give a roughly 1 to 2 percent of beta beat which is our regular achievement. Simulation study of DA and LMA was done for this bare error machine (without HSCU), which are noted as "NoWig04" and "NoWig10"; and machine with measured HSCU multipole errors, which are noted as "Wig04" and "Wig10" in Fig.4 and Fig.5. Results show minor impact from measured HSCU multipole errors. The calculated Touschek beam lifetime using the LMA are listed in Table 4. Note, to compare the multipole effect, the rf bucket limitation is set to 3%, which makes it irrelevant. In reality, we are limited by the available rf voltage, which is smaller than the calculated LMA in most part of the ring.

CONCLUSIONS

The HSCU is the first helical device installed in the APS storage ring. Due to it special field expansion, regular simulation tools don't work and we have to do direct particle tracking through the field. Using calculated field map, we found that the biggest perturbation comes from either a non-ideal field, or some limitation in the field calculation. The

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Table 3: Measured HSCU Multipole Components

Current (A)	Quad (G)	Sext (G/cm)	Oct (G/cm^2)	Skew Quad (G)	Skew Sext (G/cm)	Skew Oct (G/cm^2)
0	-26.2	-4.55	11.4	9.37	13.6	-1.32
100	233	-390	98.6	-98.2	-411	-82.1
200	-36.4	-682	257	28	-234	-178
300	-58.3	-923	416	24.2	-130	-190
400	1.81	-1100	457	-31.7	-5.44	-226
500	-6.28	-1230	529	-70.9	93.5	-238

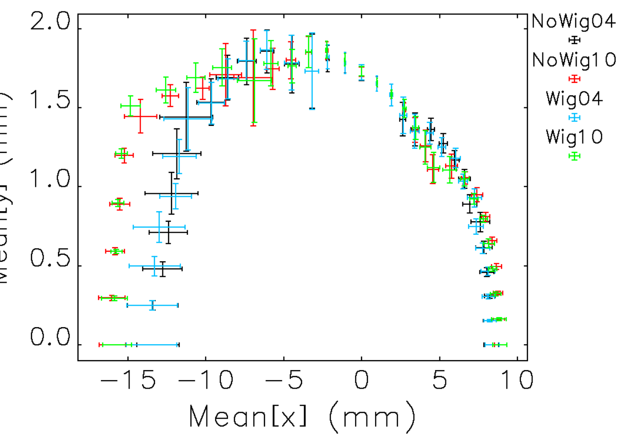

Figure 4: Calculated DA for error sets with (Wig04 and Wig10) and without (NoWig04 and NoWig10) measured HSCU multipole errors.

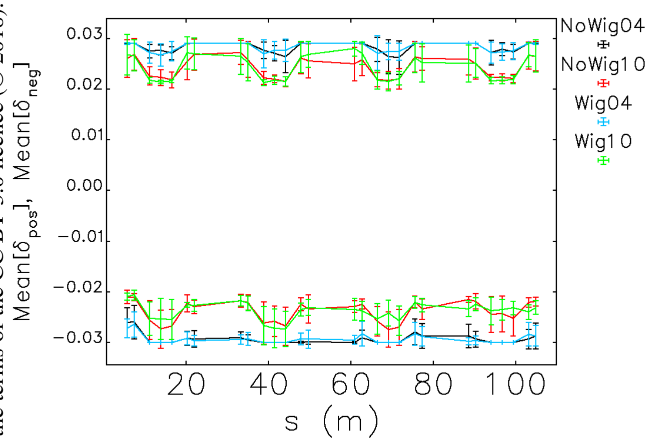

Figure 5: Calculated LMA for error sets with (Wig04 and Wig10) and without (NoWig04 and NoWig10) measured HSCU multipole errors.

perturbation terms should be possible to be measured and could be checked after device construction. By the end of last year, magnetic measurements of the HSCU were completed, and we confirmed that the perturbation was tolerable and the HSCU was allowed to be installed. The smooth commissioning of HSCU at the beginning of this year confirmed our simulation results.

Table 4: Calculated Beam Lifetime with and without Measured HSCU Multipoles

	Without HSCU multipoles	With HSCU multipoles
Min Life (h)	7.6	7.5
Median Life (h)	11.2	11.1
Max Life (h)	14.1	13.3

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