Mitigating the effects of higher order multipole fields in the magnets of the Accelerator Test Facility 2 at KEK*

BAI Sha(白莎)[1] P. Bambade[2] WANG Dou(王逗)[1] GAO Jie(高杰)[1]
M. Woodley[3] M. Masuzawa[4]

[1] Institute of High Energy Physics (IHEP), Beijing 100049, China
[2] LAL, Univ Paris-Sud, CNRS/IN2P3, Orsay, France
[3] SLAC, Menlo Park, California, USA
[4] KEK, Tsukuba, Ibaraki, Japan

Abstract: The ATF2 project is the final focus system prototype for the ILC and CLIC linear collider projects, with the purpose of reaching a 37nm vertical beam size at the interaction point. In the nanometer beam size regime, higher order multipoles in magnets become a crucial point for consideration. The strength and rotation angle of the ATF2 QEA magnets were reconstructed from the IHEP measurements and compared with the KEK ones to be identical. Based on the study of the skew multipoles sensitivity, we report on the analysis of the possible mitigation of the measured multipoles. A suggestion is given which will benefit the ATF2 present commissioning to reach the goal beam size, and also the reduced β optics in future.

Key words: ATF2, beam size, higher order multipoles, QEA magnets

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1 Introduction

The Accelerator Test Facility 2 (ATF2) [1, 2] is the test facility with an International Linear Collider (ILC) [3] type final focus line, to reach a final beam size of 37 nm at the optical focal point (hereafter referred to as IP, interaction point, by analogy to the linear collider collision point). When tuning the nanometer beam size, most of the variables should be within certain tolerances. The quality of the magnetic field of the magnets is one of the most important things. Especially when going down to the nanometer scale, higher order multipole fields (sextupole, octupole, decapole, dodecapole$\cdots$etc.) become a crucial point. There are 7 dipoles, 43 quadrupoles and 5 sextupoles which are installed in the ATF2 beam lines (extraction line (EXT) and final focus line (FFS)). Among the 43 quadrupole magnets, 27 magnets are of the same type and are named QEA-D32T180, QEA is its short form. Thirty-four QEA magnets were manufactured by IHEP, of which six are installed in the ATF damping ring and one is kept as a spare magnet [4]. In order to know the inherent multipoles of magnets, field measurement was conducted at IHEP, and later at KEK with only the sextupole and octupole for a cross-check.

Table 1. Beam parameters with nominal and reduced β optics at the IP.

	reduced β optics	nominal β optics
β_x/cm	0.4	0.4
β_y/cm	0.0025	0.01
σ_x/μm	2.80	2.80
σ_y/μm	0.020	0.034

In this paper, the strength and tilt angle of the QEA magnets were reconstructed from the IHEP measurement and compared with the KEK results in order to reach a consistence. An analysis of the sensitivity to the skew multipole components of QEA magnets – the most dangerous ones in the case of beams with very large x/y aspect ratios – is then reported, to identify which ones have the largest influence on

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the IP vertical beam size. Finally, a detailed study on possible mitigation of the measured multipoles in both nominal and reduced β optics [5] is described, in order to determine the possible alternative solutions.

2 Cross-check of QEA magnets' multipoles measurement between IHEP and KEK

The QEA magnets were fabricated by IHEP in 2006, and shipped to KEK. The amplitude for the multipole strength and rotation angle were measured up to the 36th pole by the rotating long coil method. While later at KEK, only the sextupoles and octupoles were measured for a cross-check, since the multipole magnet fields which affect the vertical beam size at the IP exist mainly in sextupoles and octupoles [6].

The amplitude of the multipole strength A_n is proportional to the sine of the multipole rotation angle $\frac{\theta_n}{n}$:

$$A_n \propto \sin(n\theta+\theta_n)=\sin\left(n\left(\theta+\frac{\theta_n}{n}\right)\right), \qquad (1)$$

where n is the harmonic measurement number, it is a quadrupole when n=2. So the multipole rotation angle with regard to a quadrupole is $\frac{\theta_n}{n}-\frac{\theta_2}{2}$, which is the multipole tilt angle T_n in MAD [7].

$$T_n=\frac{\theta_n}{n}-\frac{\theta_2}{2}. \qquad (2)$$

A normal multipole is defined when T_n is zero, otherwise it is a skew multipole. For our flat beams, the most harmful multipoles are the skew ones, because they can couple the large horizontal motion into the small vertical size.

The multipole strength definitions in MAD are shown below. It is the multipole coefficient integrated over the length of the multipole.

$$K_mL=\left(\frac{m!}{r^{m-1}}\right)\left(\frac{B_mL}{B_1L}\right)K_1L, \qquad (3)$$

where m is the multipole coefficient of order, which is the harmonic measurement number n subtracting 1, it may take the values $0\leqslant m\leqslant 9$, r=0.01 is the harmonic measurement radius, $\frac{B_mL}{B_1L}$ means the measured harmonic amplitude. K_1L is the quadrupole strength.

There is good agreement for the absolute values of the strengths between IHEP and KEK measurements using Formula (3). While for the rotation angles, some polarities are different. The rotation angles of the QEA sextupole and octupole component are calculated using Formula (2) and compared between the IHEP and KEK measured results, as shown in Fig. 1.

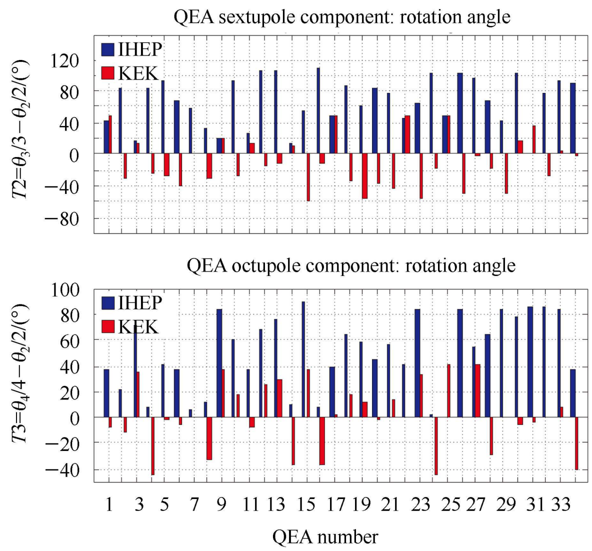

Fig. 1. The rotation angle of QEA sextupole and octupole component.

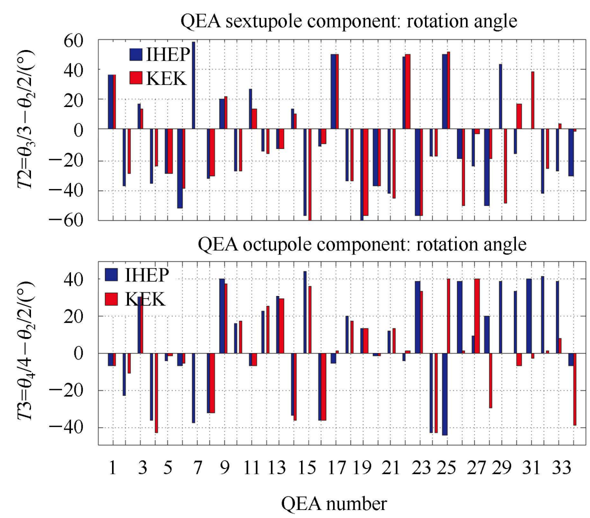

Fig. 2. The rotation angle of the QEA sextupole component after reconstruction.

As we know, for a sextupole, the angle between pole "N" and pole "S" is $\frac{2\pi}{6}=60°$. While for an octupole, the angle between pole "N" and ploe "S" is $\frac{2\pi}{8}=45°$. We reconstruct the IHEP rotation angles of the QEA sextupole and octupole component to be identical with each other.

a) If $T2_{\rm IHEP}>60°$, $T2_{\rm KEK}$=$T2_{\rm IHEP}$ $-120°$;

b) If $T2_{\rm IHEP}<60°$, $T2_{\rm KEK}=\pm\ T2_{\rm IHEP}$ °;

c) If $T3_{\rm IHEP}>0°$, $T3_{\rm KEK}$=$T3_{\rm IHEP}-45°$;

d) If $T3_{\rm IHEP}<0°$, $T3_{\rm KEK}$=$T3_{\rm IHEP}+45°$.

Some of the signs (polarity) have been changed during the reconstruction, both in the sextupole and octupole. There are many reasons for this; one of the most important issues may be the rotation direction during the measurement, clockwise or counterclockwise.

3 Skew multipole component sensitivity

Since the rotation angles of the measured multipole component are not zero, which is indeed the real situation, the multipole component not only has a normal branch, but also skew ones. This may make the vertical beam size at the IP become worse.

$$N_n \propto \cos(nT_n), \quad S_n \propto \sin(nT_n). \tag{4}$$

In all the 34 QEA magnets, some of the skew multipole components are very sensitive, which easily causes the IP spot size to increase. Here we determine the optical sensitivity for the skew components (the most harmful to the vertical beam size) of each magnet as the magnitude needed to increase the IP spot size by 5%. A small magnitude implies a high sensitivity. As you can see in Fig. 3, the sensitivities follow the β function. In this case, if the measured skew harmonic fraction is large, it indicates that the magnet should be improved. A ratio of the measured skew fraction and the relevant optical sensitivity on the skew multipole is shown in Fig. 4.

As you can see, the most sensitive QEA magnets are QF9AFF, QF9BFF, QF5AFF, QF5BFF, QD4AFF, and QD4BFF in the final focus line, which are the largest ones in Fig. 3 and Fig. 4. This suggests that these magnets should be improved, possibly by swapping with some of the best ones.

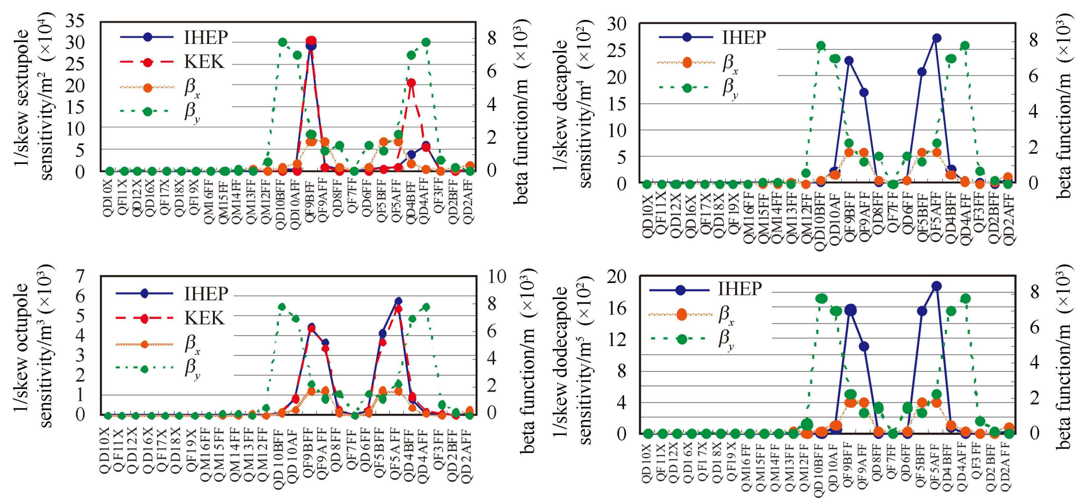

Fig. 3. Skew sextupole, octupole, decapole and dodecapole sensitivity.

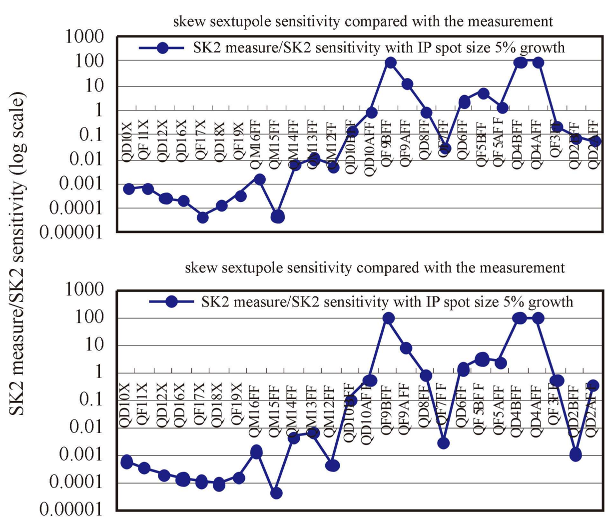

Fig. 4. Skew sextupole sensitivity compared with the measurement in both IHEP (upper) and KEK (lower) cases.

4 The cure on higher order magnetic multipoles

4.1 Tracking simulation studies and skew sextupole compensation

From the analysis in Section 3, the six most sensitive QEA magnets have been identified. An ideal solution is first to consider the comparison between the KEK and IHEP measurements, removing the six sensitive QEA magnets multipoles but including the final doublet multipoles (QF1FF and QD0FF, the two quadrupoles at the end of the ATF2 beam line just before the IP for strong focusing). Since the final doublet multipoles also have a large effect which is studied by CERN people [8], there is also a proposal

Table 2. Tracking simulations of IHEP and KEK measurements with only sextupole and octupole for the nominal optics ($\beta_{x,y}$=4 mm, 0.1 mm at the IP).

beam size	with QEA multipoles & FD multipoles ON		remove 6 most sensitive QEA multipoles & FD multipoles ON		without multipoles
	IHEP	KEK	IHEP	KEK	
RMS σ_x/μm	4.00	4.37	4.18	4.43	2.89
RMS σ_y/nm	246	85.2	82.2	84.9	36.6
Gauss fit σ_x/μm	3.03	3.05	3.03	3.06	2.84
Gauss fit σ_y/nm	62.6	49.4	51.5	47.6	35.6

by CERN to replace QF1FF by a newly built better quality magnet with lower multipoles[1,2].

Tracking simulations by inputting 10000 particles with energy spread σ_E=0.1%, have been done for the cases of IHEP and KEK definitions, meanwhile sextupoles are refitted for each $\beta_{x,y}$, considering all the cases mentioned above, which are shown in Table 2.

The RMS beam size is the standard evaluation in which the beams tails are fully considered in the calculation, while the Gauss fit method consists of fitting a Gaussian to the particle tracked histogram.

It seems that it is not enough to improve the beam size by just removing the six sensitive QEA magnets' multipoles. The effect seems very tiny. So we may need to resort to increasing slightly the horizontal β function.

4.2 Enlarging β_x and swapping magnets

We have now three ingredients in order to have a corrected final focus system optics which can reach the smallest possible σ_y even if we are not sure of the polarities of all the multipoles:

1) Improving / swapping QEA magnets;

2) Improving / rebuilding the final doublet;

3) Enlarging the horizontal β function.

In a practical way, we choose to swap six magnets among the QEA magnets, and the best ones from the point of view of two criteria:

a) Low absolute value of skew sextupole, octupole, decapole and dodecapole components;

b) Good agreement between KEK and IHEP measurements for the sextupole and octupole absolute values.

Depending on these two conditions, a swapping proposal is shown below:

$$\begin{array}{l} \text{QM12FF} \Longleftrightarrow \text{QF9BFF};\ \text{QM13FF} \Longleftrightarrow \text{QF9AFF} \\ \text{QM15FF} \Longleftrightarrow \text{QD4BFF};\ \text{QF19X} \Longleftrightarrow \text{QF5BFF} \\ \text{QF17X} \Longleftrightarrow \text{QF5AFF};\ \text{QD10BFF} \Longleftrightarrow \text{QD4AFF} \end{array} . \quad (5)$$

Increasing β_x at the IP, although not necessarily a desirable solution, may well be the only practical way to reach small σ_y at ATF2. The point is how much

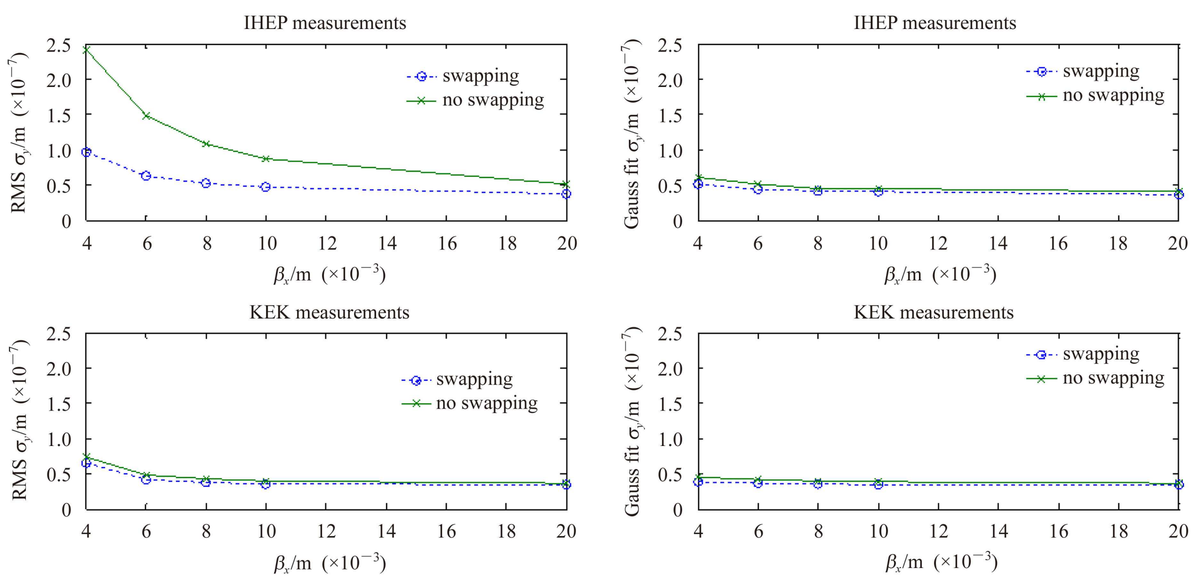

Fig. 5. Enlarging β_x- swapping magnets (β_y=0.1 mm).

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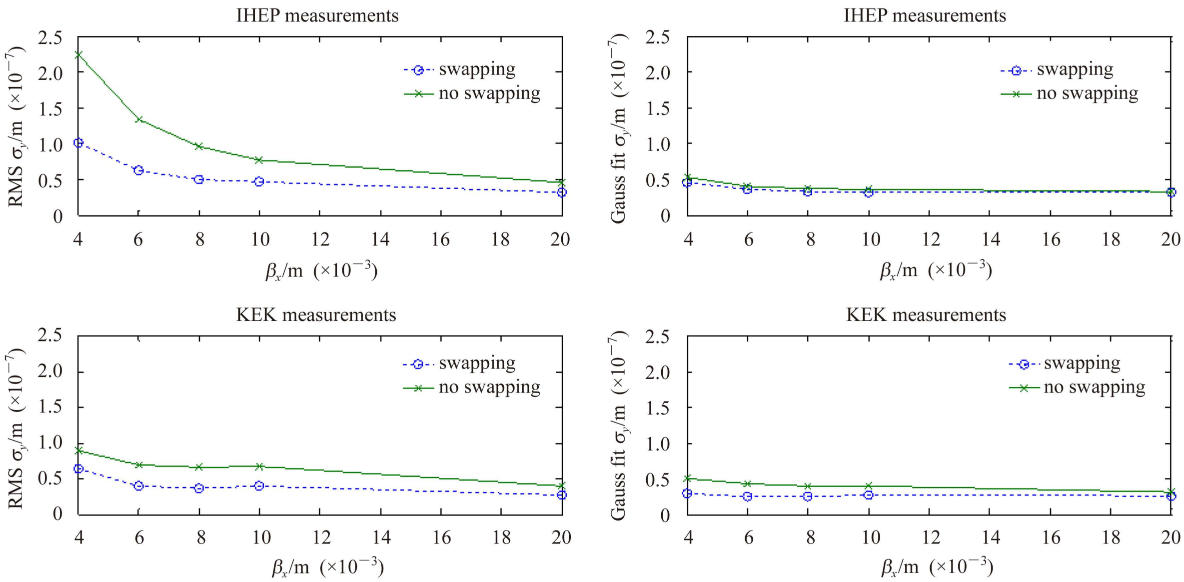

Fig. 6. Enlarging β_x- swapping magnets (β_y=0.025 mm).

we would need to increase β_x to enable a given value of σ_y, for example, nominal σ_y ($\beta_{x,y}$=4 mm, 0.1 mm at the IP), or smaller σ_y for the reduced (ultra-low) β optics ($\beta_{x,y}$= 4 mm, 25 μm at the IP), and if swapping some of the QEA magnets can make this easier, it is possible to reach a given σ_y without increasing β_x too much. σ_y as a function of β_x is shown in Fig. 5 and Fig. 6 with the swapping QEA magnets in (5) for both KEK and IHEP measurements.

For the nominal optics, swapping the magnets is not necessary if we trust the more recent KEK measurements and evaluation, especially when using a value slightly larger than the nominal value for β_x. For a conservative approach to mitigate also the possibility of larger effects, as seen for instance in the older IHEP measurements, increasing β_x from 0.4 cm to between 1 cm and 2 cm can be considered.

For the reduced β optics, both swapping magnets and improving the final doublet will be needed for both KEK and IHEP measurements, and also building a new QF1 at CERN should be very useful.

5 Conclusions and prospects

The QEA magnets' multipoles' rotation angles have been calculated based on the IHEP measuremental results, and also the consistentency with the KEK results. But we are not sure about some of the signs, and further studies would need to be pursued.

The most sensitive skew sextupole, octupole, decapole, dodecapole QEA magnets have been specified, in total 6 magnets in the final focus line, and this indicates which magnets could be improved, and a swapping proposal is given using some good ones which have a low absolute value of skew sextupole, octupole, decapole and dodecapole components.

After swapping the magnets, the IP vertical beam size is reduced a little bit, but it is still not enough. Enlarging the horizontal beta function becomes an effective way to mitigate the multipoles in the ATF2 QEA magnets. For the nominal optics, it is not necessary to swap, especially in the KEK measurements, while for the consideration of IHEP measurements, increasing β_x from 0.4 cm to between 1 cm and 2 cm can be a better choice. For the reduced β optics, since the final doublet has lots of influence on the beam size, swapping and improving the final doublet are also necessary in both KEK and IHEP measurements, and the CERN people may rebuild a new QF1. The present study should continue with more detailed checks upon the effects from the final doublet.

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