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

S. Bai, P. Bambade, D. Wang, J. Gao, M. Woodley, M. Masuzawa

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, 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 ILC and CLIC linear collider projects, with the purpose to reach 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 measurements done in IHEP in the past and compared with more recent ones from KEK. Based on a sensitivity study, we report on the analysis of possible strategies to mitigate the effects of the measured multipoles. A suggestion is given which will benefit the ATF2 present commissioning to reach the nominal beam size, and also to facilitate the implementation of the reduced β optics in the future.

Key words ATF2, beam size, higher order multipoles, QEA magnets
PACS 29.27.Eg, 29.20.Ej

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, designed to reach a vertical 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). To achieve such a nanometer scale beam size, a number of optical parameters must be tuned experimentally to correct for imperfections in the beam line magnets and alignment. Such errors should not be too large for the tuning algorithm to work. In addition, the magnetic field in the magnets must respect tight tolerances on their higher order multipole content (sextupole, octupole, decapole, dodecapole,…), especially at some critical locations in the beam line.

There are seven dipoles, forty-three quadrupoles and five sextupoles installed in the ATF2 beam line, which consists of the extraction line (EXT) and the final focus line (FFS). Among the forty-three quadrupole magnets, twenty-seven are of the same type and are named QEA-D32T180 (hereafter referred to as QEA). They are part of a set of thirty-four magnets manufactured by IHEP, including also six magnets installed in the ATF damping ring and one kept as a spare [4]. Field measurements were conducted at IHEP, and later at KEK, to evaluate the multipole content of this set of magnets.

In this paper, the strength and tilt angle of the QEA magnet multipoles were reconstructed from the IHEP measurements and compared with recent KEK results. 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 the IP vertical beam size. Finally, a detailed study of possible mitigation strategies is presented for both the nominal and reduced β optics [5].

Table 1: Optical beam parameters at the IP for the nominal and reduced β optics

	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

2. Cross-check of IHEP and KEK measured QEA magnet multipoles

The QEA magnets were fabricated by IHEP in 2006, and shipped to KEK. The amplitudes of the multipole strengths and the rotation angles were measured at IHEP by the rotating long coil method. Similar measurements were later done at KEK as cross-check. Only the sextupole and octupole components were analyzed from these latter measurements, as it was shown that they are the most important ones for the IP vertical beam size [6].

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

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

where n is the harmonic measurement number (n=2 for a quadrupole). The multipole rotation angle with respect to main quadrupole component defines the multipole tilt angle in MAD [7]:

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

For a purely normal multipole, T_n is zero, otherwise a skew component of the multipole is also present. For our flat beams, the most harmful multipoles are the skew ones, because they can couple the large horizontal beam size into the small vertical one.

The multipole strength definition in MAD is shown below, integrated over the length of the magnet:

$$K_m L = \left(\frac{m!}{r^{m-1}} \right) \left(\frac{B_m L}{B_1 L} \right) K_1 L \qquad (3)$$

where m is the order of the multipole, corresponding to the harmonic measurement number n subtracting 1, with values in the range $0 \le m \le 9$. The measurements are conventionally referred to a radius r=0.01. $\frac{B_m L}{B_1 L}$ is the measured harmonic amplitude normalized to that of the quadrupole and $K_1 L$ is the quadrupole strength.

Good agreement was found between the absolute values of multipole strengths extracted from IHEP and KEK measurements using Formula (3) for all QEA magnets in the case of the sextupole component. On the other hand, for the octupole component, good agreement was only fond for the 25 first magnets in the batch. In addition, the calculation of the rotation angles using Formula (2) resulted in differences for a majority of magnets, see Figure 1.

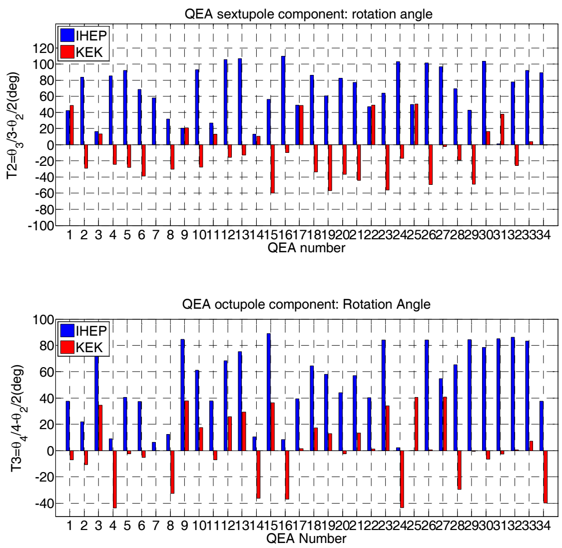


Figure 1: Comparison of rotation angles of QEA sextupole and octupole components extracted from IHEP and KEK measurements

An attempt was made to understand the differences in the rotation angles, as follows. For sextupoles and octupoles, the angles between the north and south poles are $\frac{2\pi}{6} = 60(\text{deg})$ and $\frac{2\pi}{8} = 45(\text{deg})$, respectively. Rotations with such angles result in polarity flips of the corresponding multipole (while twice these rotations will leave them unchanged). For each magnet, IHEP and KEK multipole rotation angle were compared after either adding or subtracting the north-south pole angle difference, to see whether or not agreement could be recovered.

a) If $T2_{IHEP} > 60$(deg), $T2_{KEK} = T2_{IHEP}$ -120(degree)

b) If $T2_{IHEP} < 60$(deg), $T2_{KEK} = \pm T2_{IHEP}$ (degree)

c) If $T3_{IHEP} > 0$, $T3_{KEK} = T3_{IHEP}$-45(degree)

d) If $T3_{IHEP} < 0$, $T3_{KEK} = T3_{IHEP}$+45(degree)

It was found that for the first twenty-five magnets in the batch, the observed rotation angle differences shown in Figure 1 could always be explained in terms of pure changes in polarity, see Figure 2. The origin of such inconsistencies in polarities is not understood, and several steps in the measurement procedure could be involved. For the last 9 magnets, differences remain in the reconstructed angles, for both sextupole and octupole components.

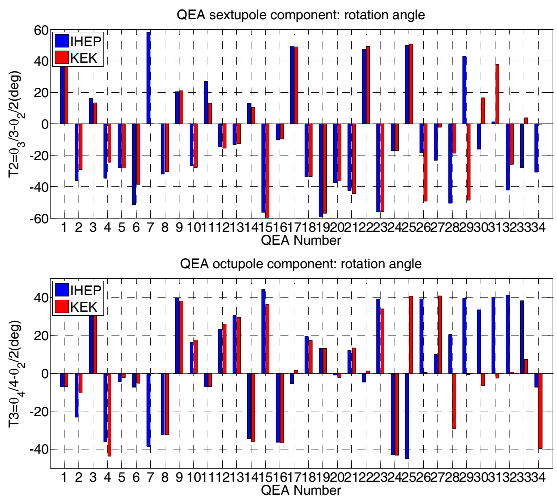


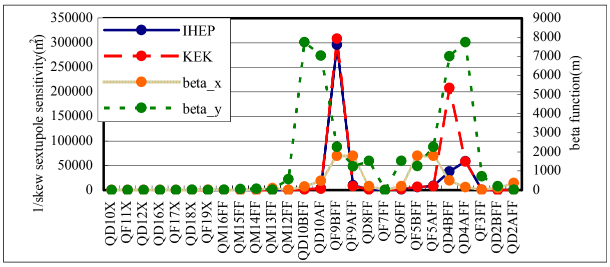
Figure 2: Rotation angles of QEA sextupole and octupole components after changes in polarities for IHEP magnets

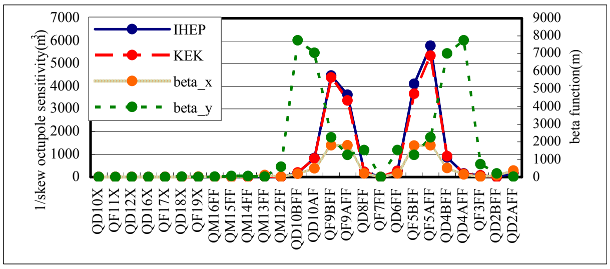
3. Skew multipole sensitivities

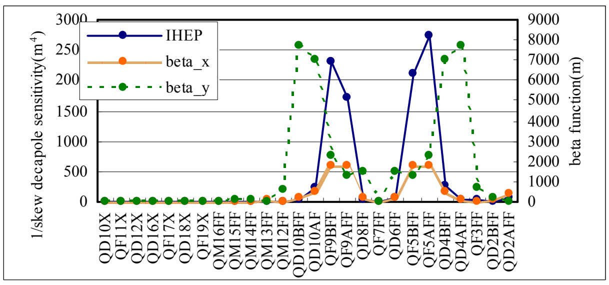
Since the rotation angles of the measured multipoles are not zero, both normal and skew components, computed as:

$$N_n \propto \cos(nT_n)$$
$$S_n \propto \sin(nT_n) \quad (4)$$

will influence the vertical beam size. 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 can be seen in Figure 3, the sensitivities follow the β functions. Magnets with large measured skew harmonic fraction and high optical sensitivity will have the largest effect on the IP beam size. They would be the ones to consider with highest priority in the context of an improvement program. Figure 4 illustrates the relation between the optical sensitivity and the measurements in terms of their ratio for the case of the skew sextupole component.







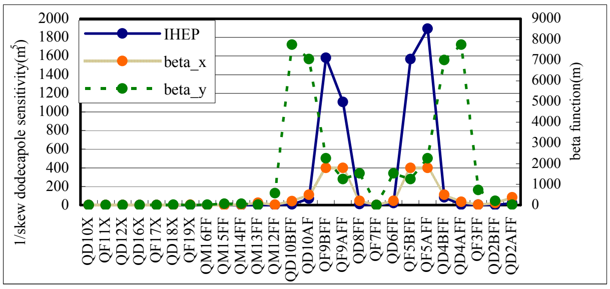


Figure 3: Skew sextupole, octupole, decapole and dodecapole optical sensitivity

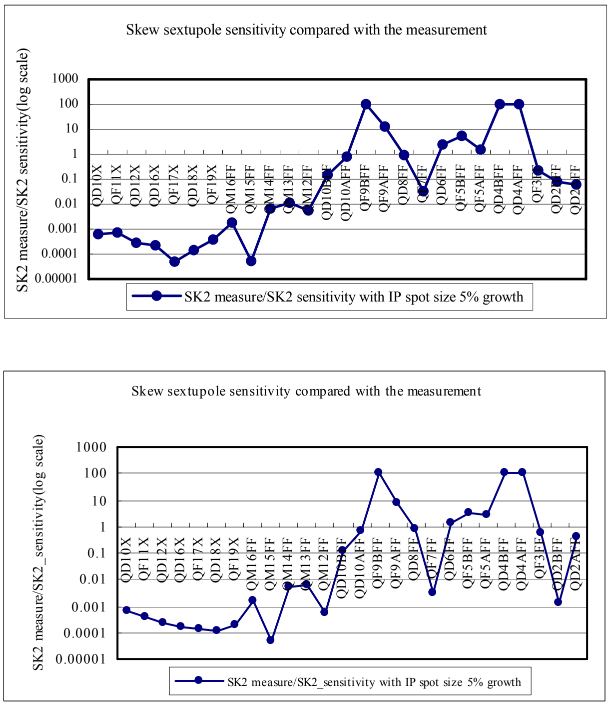


Figure 4: Ratio of optical sensitivity and IHEP (upper) or KEK (lower) measurements for the skew sextupole component

The largest values for both the optical sensitivities and measurement to sensitivity ratios are for the magnets QF9AFF, QF9BFF, QF5AFF, QF5BFF, QD4AFF, and QD4BFF in the final focus line. This suggests that these magnets should be improved, either directly or by swapping with higher quality magnets installed at locations with less optical sensitivity.

4. Mitigation strategies

4.1 IP beam size from tracking in the nominal optics

The analysis in Section 3 identified the six QEA magnets with the largest effects. Tracking simulations with 10000 input particles, using an energy spread σ_E=0.1%, were done for the nominal ATF2 optics, in three cases:

1. Including the measured sextupole and octupole components in all magnets,
2. Including the measured sextupole and octupole components in all magnets except in the six worst QEA ones and
3. Removing all multipoles.

For the first two cases, both IHEP and KEK measured multipoles were used for the QEA magnets, while for the Final Doublet quadrupoles QF1FF and QD0FF (the two quadrupoles at the end of the ATF2 beam line just before the IP), measurements from SLAC were used. The influence of the latter are significant since the β functions in ATF2 take their largest values in these final elements [8]. A project to replace QF1FF by a magnet with improved field quality is currently under consideration in the context of the proposed ultra-low β

IHEP / KEK	Multipoles in all ATF2 magnets	Multipoles in all ATF2 magnets except in the six worst QEA ones	Without multipoles
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
Gaussfit_σ_x(μm)	3.03 / 3.05	3.03 / 3.06	2.84
Gaussfit_σ_y(nm)	62.6 / 49.4	51.5 / 47.6	35.6

Table 2: Vertical beam size from tracking with IHEP and KEK sextupole and octupole component measurements for the nominal optics ($\beta_{x,y}$=4mm, 0.1mm at IP)

optics configuration[1].

Results for the above described cases are displayed in Table 2. The sextupoles used for chromaticity correction were refitted each time. The RMS beam size is the standard evaluation including the beams tails, while the Gauss fit method consists of fitting a Gaussian to the core of the particle distribution.

The beam size growth at the IP is more important using IHEP than KEK measurements. For the KEK case, removing the multipoles in the six worst QEA magnets does not provide a significant improvement.

4.2 Enlarging β_x and swapping magnets

Three approaches can be considered to mitigate the effects of multipoles in the ATF2 final focus optics:

1. Enlarging the horizontal β function
2. Swapping the worst QEA magnets with higher quality ones installed at less sensitive locations
3. Rebuilding the final doublet

Increasing β_x at the IP has the effect of lowering the beam size in the quadrupoles of the final focus, thus reducing the influence of their higher order skew field components. Although not a desirable solution since it departs from the nominal ATF2 optics and may moreover create less favorable conditions for the experimental tuning procedure, it can always be resorted to as an expedient to allow reaching a small σ_y in the presence of higher order multipoles.

Thus, improvements to the magnetic configuration of the ATF2 beam line should be evaluated in terms of their ability to minimize the need for such increased β_x values at the IP to achieve a given target value for vertical beam size. In the following, swapping the six identified worst QEA magnets for better quality ones installed elsewhere in the beam line is considered in this spirit. Two criteria were used for choosing "good" QEA magnets:

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

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

The explicit swapping assignment which was studied is shown below:

$$\begin{array}{lcl} \text{QM12FF} & \Leftrightarrow & \text{QF9BFF} \\ \text{QM13FF} & \Leftrightarrow & \text{QF9AFF} \\ \text{QM15FF} & \Leftrightarrow & \text{QD4BFF} \\ \text{QF19X} & \Leftrightarrow & \text{QF5BFF} \\ \text{QF17X} & \Leftrightarrow & \text{QF5AFF} \\ \text{QD10BFF} & \Leftrightarrow & \text{QD4AFF} \end{array} \quad (5)$$

Results obtained for the vertical beam size are shown in Figures 5 and 6 as a function of β_x for the IHEP and KEK measurements, with and without swapping QEA magnets according to (5), for both the nominal ($\beta_{x,y}$=4mm, 0.1mm at IP) and reduced β_y optics ($\beta_{x,y}$=4mm, 25µm at IP).

For the nominal optics, swapping the magnets does not appear to be necessary to achieve a vertical beam size smaller than about 50nm if we trust the more recent KEK measurements and evaluation, especially if a slightly larger than nominal value is used for β_x. (for instance, increasing it by 50%). A conservative approach covering also the possibility of larger effects, as seen for instance in the older IHEP measurements, consists in increasing β_x from 0.4cm up to between 1cm and 2cm.

On the other hand, for the reduced β_y optics, both swapping the magnets and improving the final doublet will be needed.

[1] Marin E. and Garcia H., "Tolerances for ATF3 QF1 from beam dynamics" and Vorozhtsov A., "A new QF1 magnet for ATF3", presented at the International Workshop on Future Linear Colliders in Granada, Spain, 2011-09-28.

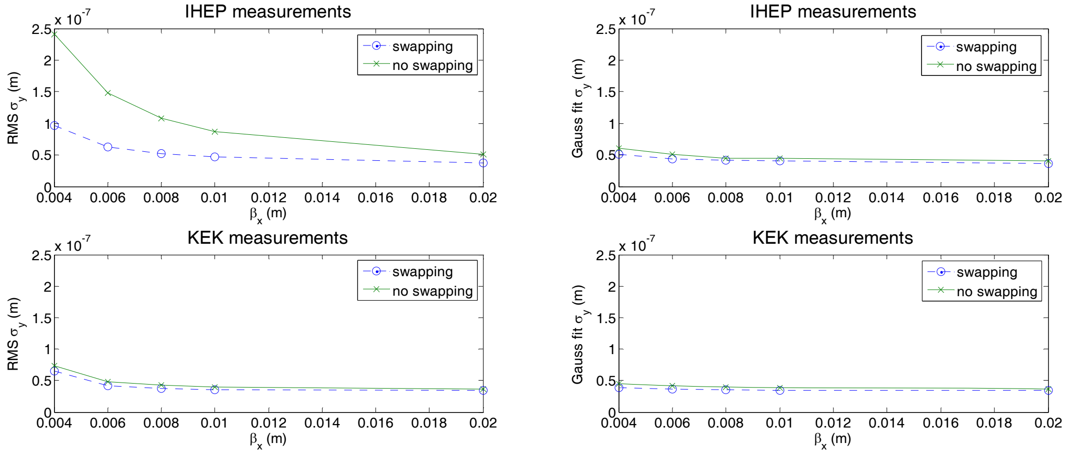


Figure 5: Vertical beam size enlarging β_x and swapping magnets (nominal optics with $\beta_y = 0.1$mm)

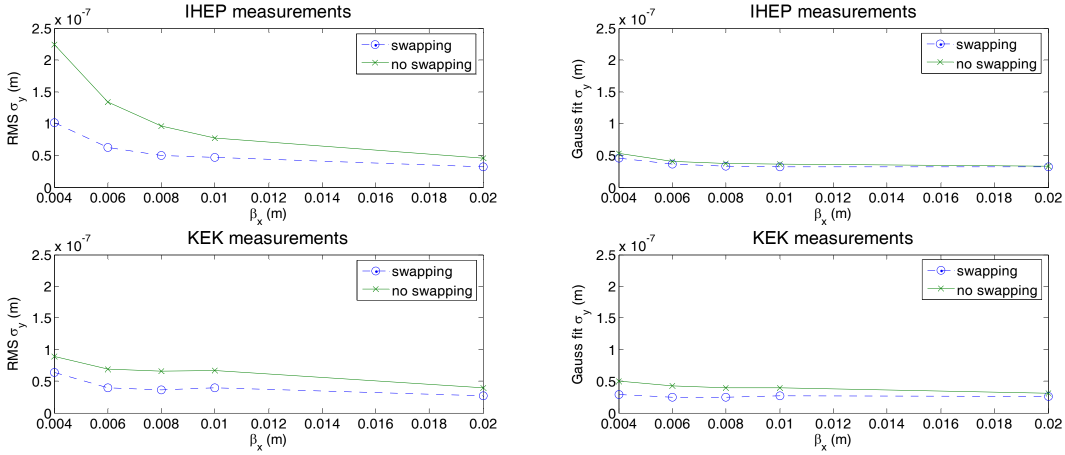


Figure 6: Vertical beam size enlarging β_x and swapping magnets (reduced β optics with $\beta_y = 0.025$mm)

5. Conclusions and prospects

The QEA magnet multipole strengths and rotation angles have been extracted from the past IHEP measurements and compared with similar more recent KEK results. Good agreement is found for twenty-five magnets out of thirty-four.

The most sensitive locations in the beam line for skew sextupole, octupole, decapole and dodecapole components have been specified. Unfortunately, several of the nine magnets for which IHEP and KEK measurements are inconsistent have typically large skew multipole magnitudes and are presently installed at sensitive locations in the final focus section. The six magnets which are the worst in this respect have been identified, and a proposal to swap them for better quality magnets, presently installed at less sensitive locations of ATF2, has been studied.

An additional way to mitigate the vertical beam size growth in the presence of skew multipoles in the quadrupoles, by enlarging the horizontal β function, was also considered.

It was found that for the nominal β_y optics, swapping the magnets is not required to achieve a close to 50nm vertical beam size. This is true especially if the more recent KEK measurements are used, while to cover also the case of the older IHEP measurements, increasing β_x from 0.4cm up to between 1cm and 2cm can be considered as a conservative approach.

For the reduced β_y optics, the field quality in the final doublet also influences the vertical beam size. In this case, both swapping and improving the final doublet are necessary irrespective of which of the KEK or IHEP measurements are trusted. The CERN group is now leading an effort in this direction, which will also involve further detailed checks of effects from the final doublet multipoles.

Acknowledgements

We acknowledge the support of the Agence Nationale de la Recherche of the French Ministry of Research (Programme Blanc, Project ATF2-IN2P3-KEK, contract, ANR-06-BLAN-0027), and the National Natural Science Foundation of China (NSFC, Project 11175192). And we acknowledge the support in part by the US Department of Energy under Contract DE-AC02-76SF00515.

References

[1] Grishanov B I et al. 2005, Report No. SLAC-R-771
[2] Bambade P. et al. Phys. Rev. ST Accel. Beams. 2010, 13:042801
[3] ILC RDR, ILC-Report-2007-001.
[4] Masuzawa M., Sugahara R. 2010, IEEE Transations on Applied Superconductivity, 20(3):1969 – 1972
[5] Tomas R. et al., PAC09 WE6PFP024.
[6] Cherrill S. 2010, Report No. SLAC-PUB-14339
[7] Iselin F.C. 1985, CERN LEP-TH No. 85-15.
[8] Marin E. et al., 2011, CERN-ATS-2011-122.