US-LHC Tele-Video
December 7, 1998

KEK MQX Field Error Analysis & Compensation

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- ∗ Tracking Results
- ∗ Compensation Schemes
- ∗ Discussions

$*$ Introduction

- KEK IR quads (MQXA) have significant systematic error b_{10}
- Aside from b_{10}, KEK quads have similar errors as FNAL quads

Questions:

* What is the impact of KEK quad field errors?

* What compensation schemes can be used to minimize the impact?

* How much corrector strengths are needed and are they achievable?

LHC IR Parameters at proton collision (7 TeV)

(Version 5.1 from CERN SL/AP)

Betatron tunes (H/V)	63.31/59.32
Synchrotron tune	0.00212
Chromaticity (H/V)	2/2
β^*, IP1, 5, 2, 8 (H/V) [m]	0.5/0.5, 0.5/0.5, 15/10, 13/15
$\Phi/2$, IP1, 5, 2, 8 (H/V) [μr]	0/150, 150/0, 0/-150, 0/-150
Parallel sept., IP2, 8 [mm]	(H) 0.75, 0.75
Parasitic sept., IP1, 5, 2, 8 [σ_{xy}]	$>$ 7.3, 7.3, 17, 18
Quad gradient, $\lvert G_0 \rvert$ [T/m]	200
Coil i.d., MQX/D1,2 [mm]	70/80
Length, Q1,3/Q2A,B/D1,2 [m]	6.3/5.5/9.45
Max. β [m]	4705
rms emittance, ϵ_N [m·r]	3.75×10^{-6}
rms momentum dev., σ_p	1.1×10^{-4}
Max. rms beam size, σ_{xy} [mm]	1.5
Max. orbit offset (H/V) [mm]	±7.3/±7.3

Reference MQXB (FNAL) errors at collision: (v 2.0; $R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
3	0.0	0.3	0.8	0.0	0.3	0.8
4	0.0	0.2	0.8	0.0	0.2	0.8
5	0.0	0.2	0.3	0.0	0.2	0.3
6	0.0	0.6	0.6	0.0	0.05	0.1
7	0.0	0.06	0.06	0.0	0.04	0.06
8	0.0	0.05	0.05	0.0	0.03	0.04
9	0.0	0.03	0.03	0.0	0.02	0.02
10	0.0	0.03	0.03	0.0	0.02	0.03
LE	[unit·m]		(Length=0.41 m)			
2	0.0	0.0	0.0	16.4	0.0	0.0
6	0.82	0.82	0.31	0.0	0.21	0.06
10	-0.08	0.08	0.04	0.0	0.04	0.04
RE	[unit·m]		(Length=0.33 m)			
6	0.0	0.41	0.31	0.0	0.0	0.0
10	-0.08	0.08	0.04	0.0	0.0	0.0

Reference MQXA (KEK) errors at collision: (v 1.1; $R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
3	0.0	0.51	1.0	0.0	0.51	1.0
4	0.0	0.29	0.57	0.0	0.29	0.57
5	0.0	0.19	0.38	0.0	0.19	0.38
6	0.0	0.5	0.19	0.0	0.10	0.19
7	0.0	0.05	0.06	0.0	0.05	0.06
8	0.0	0.02	0.03	0.0	0.02	0.03
9	0.0	0.01	0.01	0.0	0.01	0.01
10	-1.0	0.1	0.01	0.0	0.01	0.01
LE	[unit·m]		(Length=0.45 m)			
2	0.0	0.0	0.0	13.4	0.0	0.0
6	2.28	0.0	0.0	0.07	0.0	0.0
10	-0.17	0.0	0.0	-0.02	0.0	0.0
RE	[unit·m]					
6	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0

Reference MQXA (KEK) errors at collision: (v 1.0; $R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
3	0.0	0.51	1.0	0.0	0.51	1.0
4	0.0	0.29	0.57	0.0	0.29	0.57
5	0.0	0.19	0.38	0.0	0.19	0.38
6	1.25	0.10	0.19	0.0	0.10	0.19
7	0.0	0.05	0.06	0.0	0.05	0.06
8	0.0	0.02	0.03	0.0	0.02	0.03
9	0.0	0.01	0.01	0.0	0.01	0.01
10	-0.89	0.01	0.01	0.0	0.01	0.01
LE	[unit·m]		(Length=0.45 m)			
2	0.0	0.0	0.0	13.4	0.0	0.0
6	2.28	0.0	0.0	0.07	0.0	0.0
10	-0.17	0.0	0.0	-0.02	0.0	0.0
RE	[unit·m]					
6	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0

Reference MQXB (FNAL) errors at collision: (v 1.1; $R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
3	0.0	0.34	0.85	0.0	0.34	0.85
4	0.0	0.26	0.87	0.0	0.26	0.87
5	0.0	0.20	0.34	0.0	0.20	0.34
6	0.0	0.17	0.25	0.0	0.17	0.25
7	0.0	0.14	0.11	0.0	0.14	0.11
8	0.0	0.10	0.07	0.0	0.10	0.07
9	0.0	0.08	0.07	0.0	0.08	0.07
10	0.0	0.06	0.03	0.0	0.06	0.03
LE	[unit·m]		(Length=0.41 m)			
2	0.0	0.0	0.0	16.0	0.0	0.0
6	2.3	0.0	0.0	0.07	0.0	0.0
10	-0.09	0.0	0.0	-0.03	0.0	0.0
RE	[unit·m]		(Length=0.33 m)			
6	0.39	0.0	0.0	0.0	0.0	0.0
10	-0.07	0.0	0.0	0.0	0.0	0.0

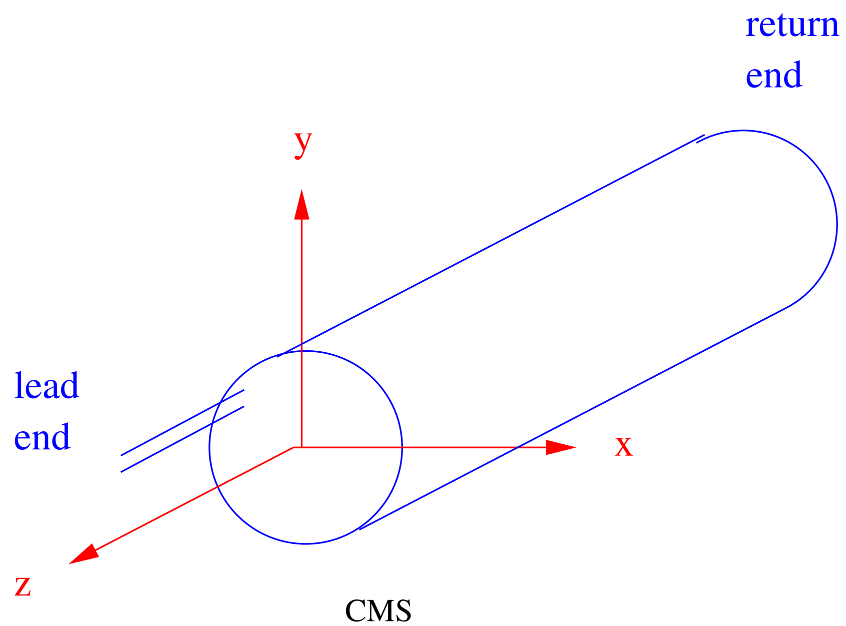
Assumptions:

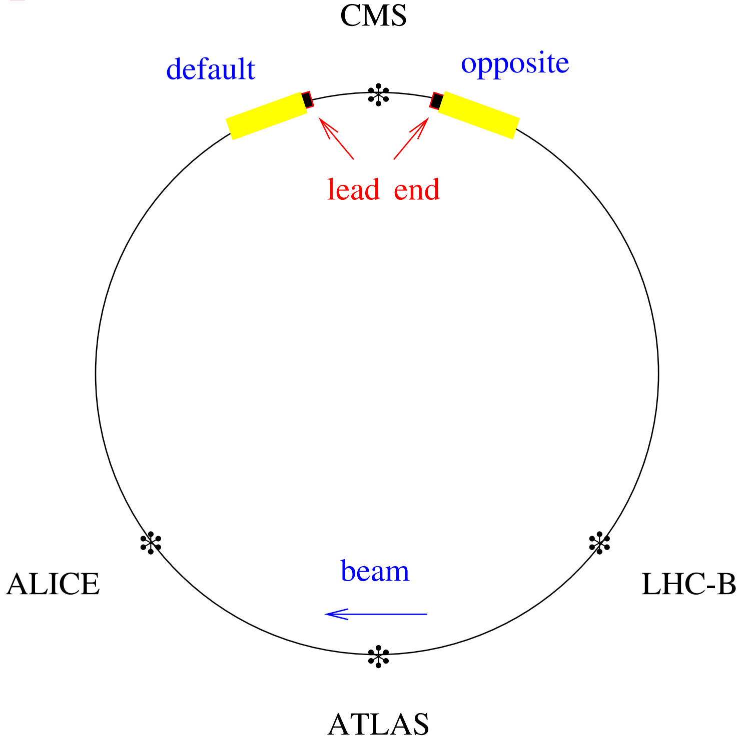
- Previous studies: FNAL v1.1 assumed for all four IPs
- "KEK case": KEK's at IP1 & 2; FNAL's at IP5 & 8
- LHC collision lattice version 5.1 with crossing angle
- magnetic error only; no beam-beam, no misalignment

Tracking conditions:

- 10 seeds & 100 seeds, 3σ cut on random errors; full positive or negative $d(b_n)$ & $d(a_n)$
- 5 initial x/y direction
- Refit to the nominal machine operating point ($Q_x = 63.31$, $Q_y = 59.32$, $\xi_x = \xi_y = 2$)
- Comparing with 10^3-turn tracking, 10^5-turn tracking further reduces mean and min. DA by about $0.5\sigma_{xy}$
- Physical aperture limitation: 60 mm for MQX
- multipole sign reversal according to magnet orientation
- ends separated, treated as lumped kicks
- body divided into 8 pieces for β variation

Multipole measurement conventions:





Multipole transformation for ‘‘opposite’’ orientation magnets:

quadrupole: $b_n => (-)^n\, b_n$; $a_n => (-)^{n+1} a_n$

dipole: $b_n => (-)^{n+1} b_n$; $a_n => (-)^n\, a_n$

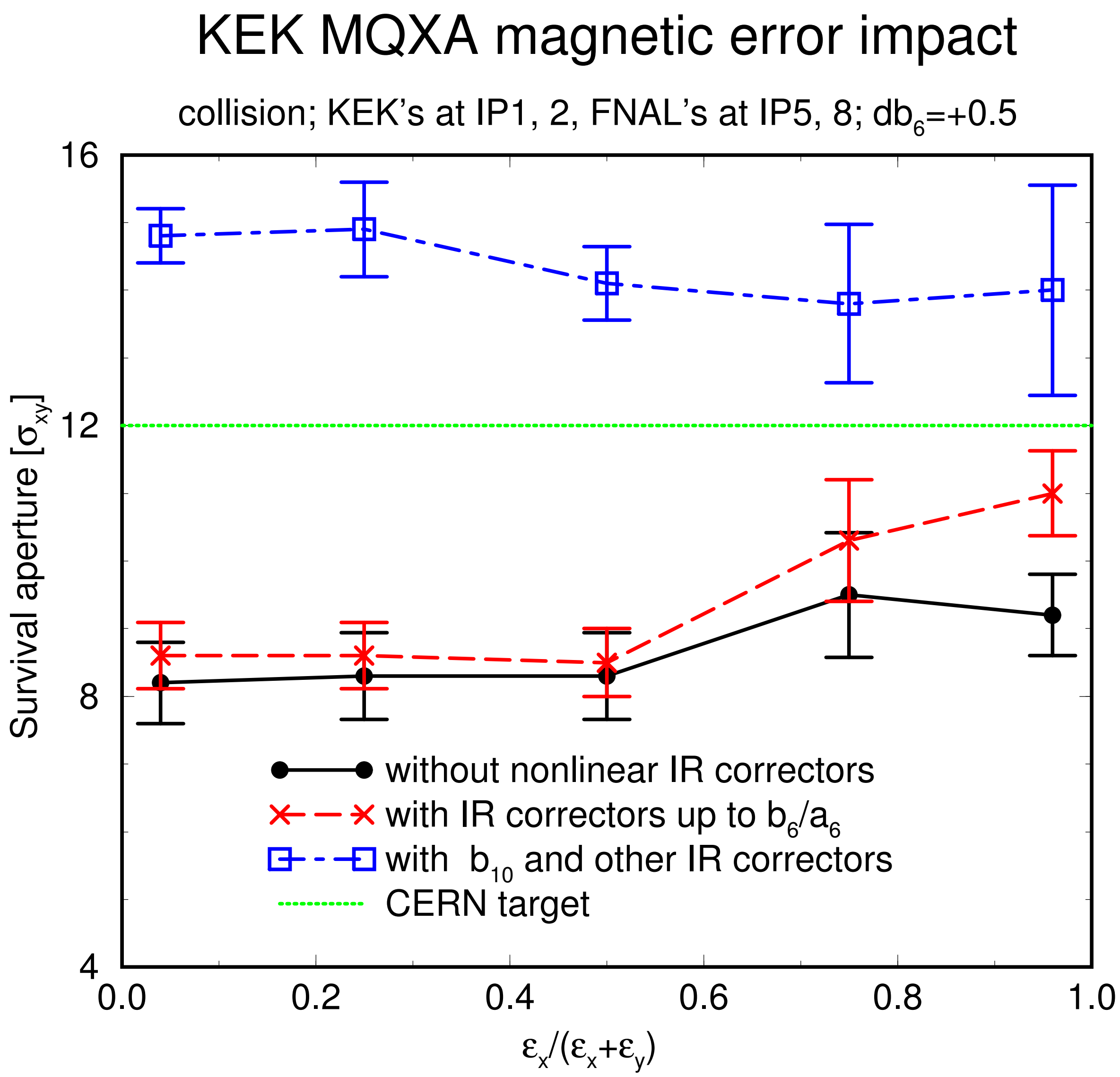
$*$ Tracking Results

Effects of MQX field errors on dynamic aperture:

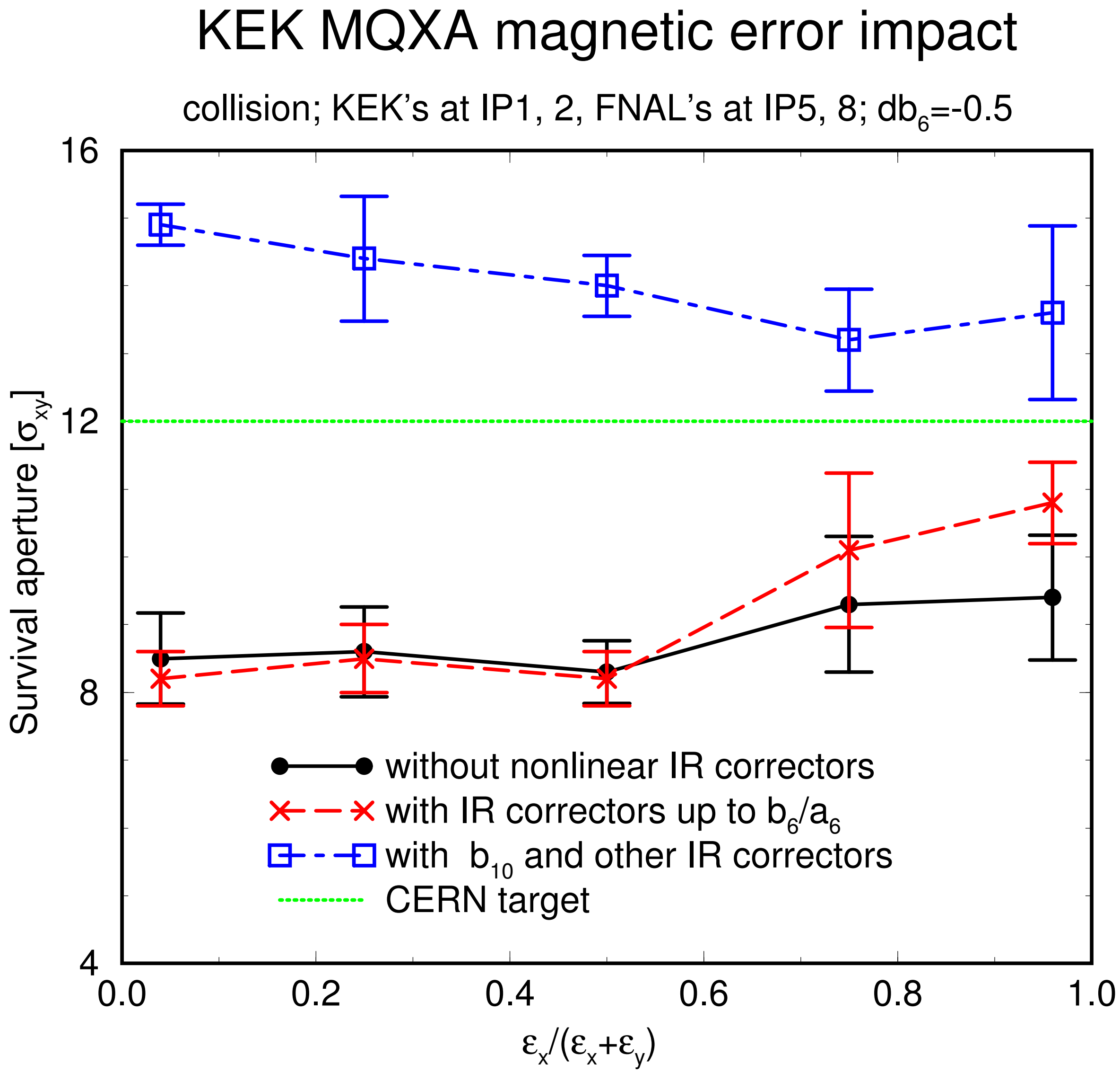
Case	DA $[\sigma_{xy}]$ (mean±SD)	Min. DA $[\sigma_{xy}]$
FNAL:		
(10^3-turn)	10.7±1.7	8
KEK:		
v1.0	7.9±2.4	5
v1.0/1.1 without b_6 & b_{10}	11.4±2.2	8
v1.1	8.7±0.9	7
v1.1 with b_{10} at half strength	9.4±1.7	7
CERN target:		
(10^5-turn)	12	10

- KEK (10^5-turn) v1.1: 8.2±0.9 σ_{xy} 6.5σ_{xy}
- With either FNAL v1.0 or v2.0, the KEK error impact is the same

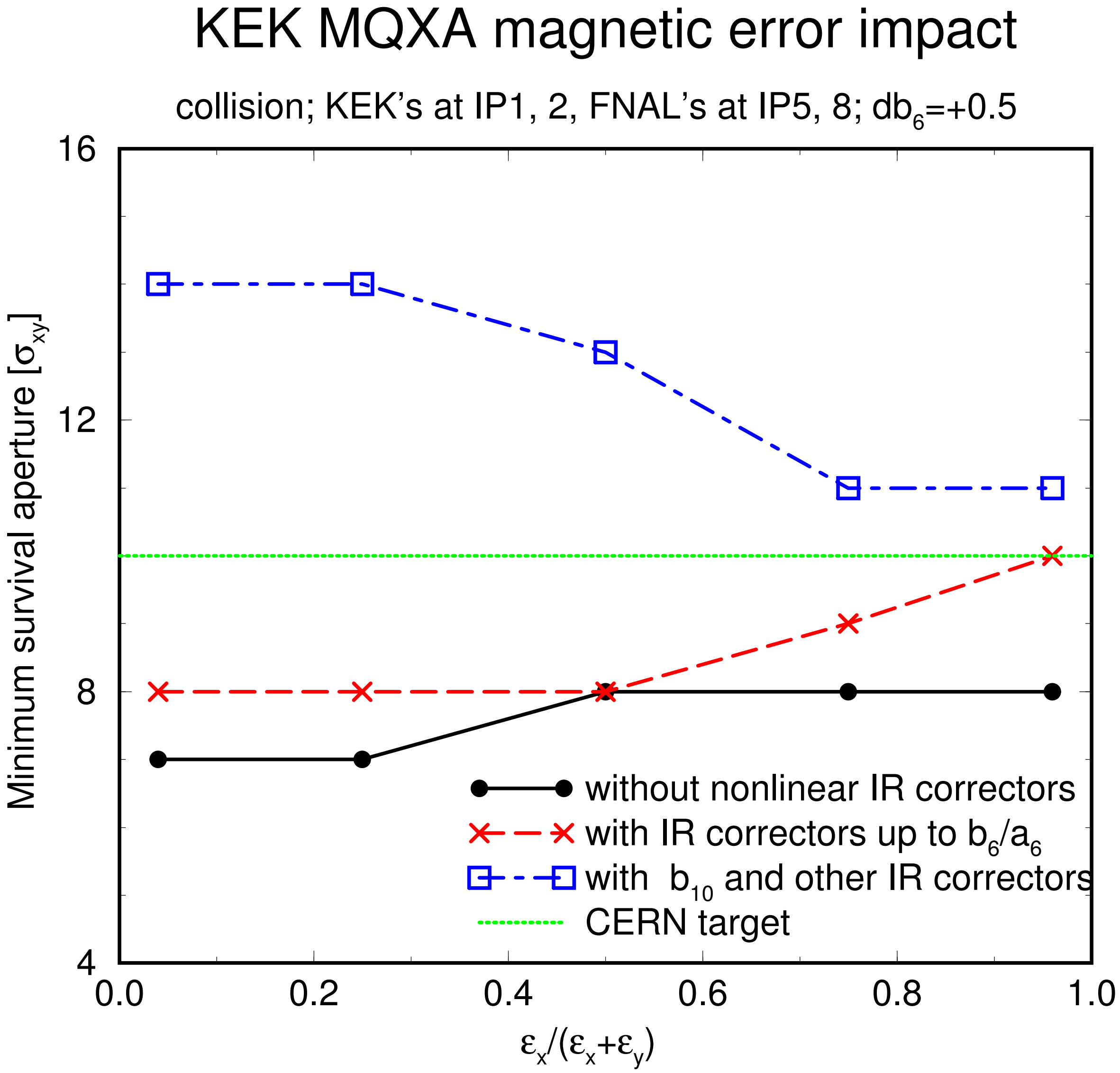
(Dynamic aperture mean & SD for $b_{6,sys} = 0.5$)



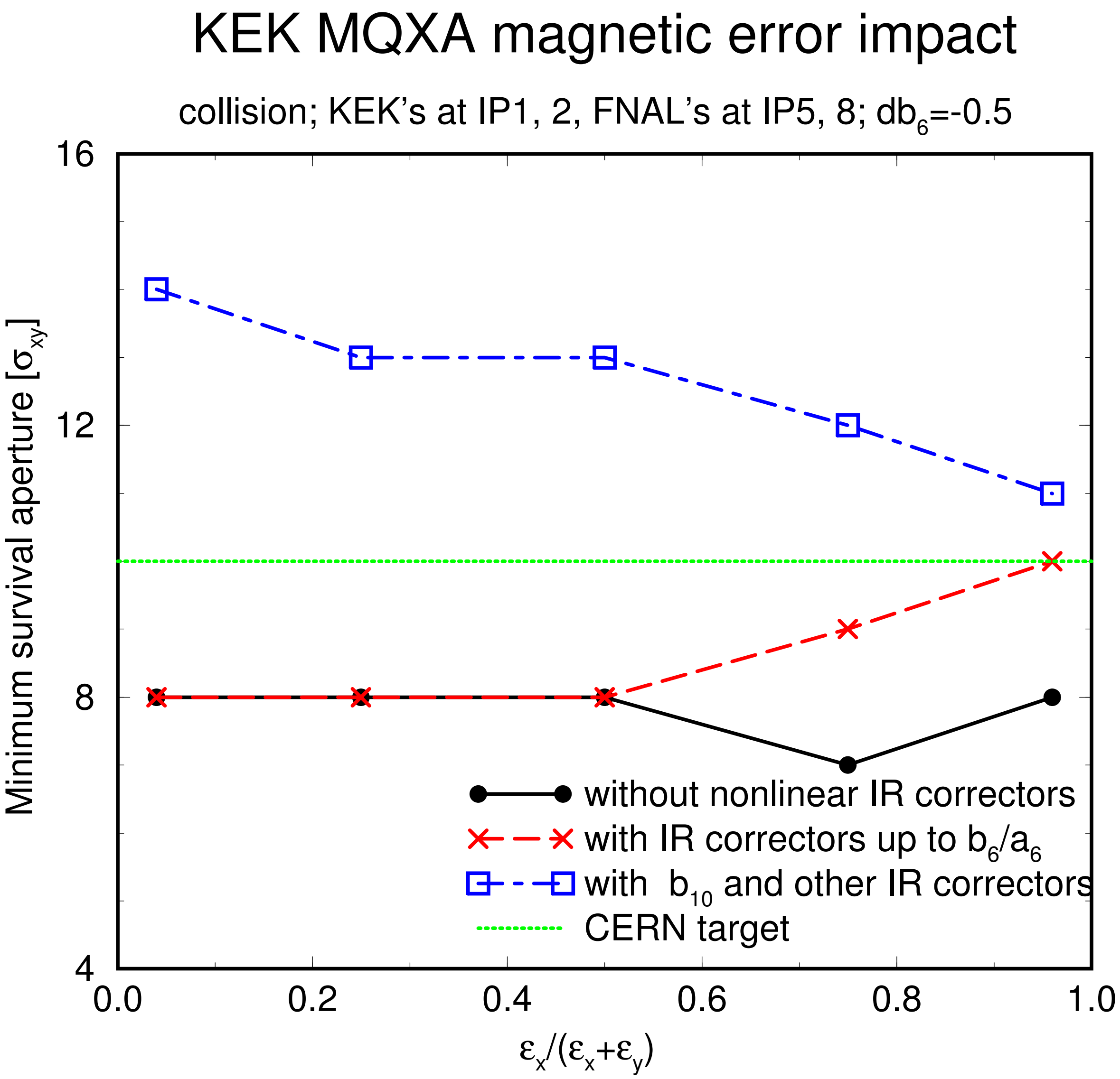
(Dynamic aperture mean & SD for $b_{6,sys} = -0.5$)



(Minimum dynamic aperture for $b_{6,sys} = 0.5$)



(Minimum dynamic aperture for $b_{6,sys} = -0.5$)



$*$ Compensation Schemes

Figure of merit for IR local correction:

$$\int_L dl\beta_z^{n/2} B_0 b_n + (-)^n \int_R dl\beta_z^{n/2} B_0 b_n, \quad z = x, y \qquad (1)$$

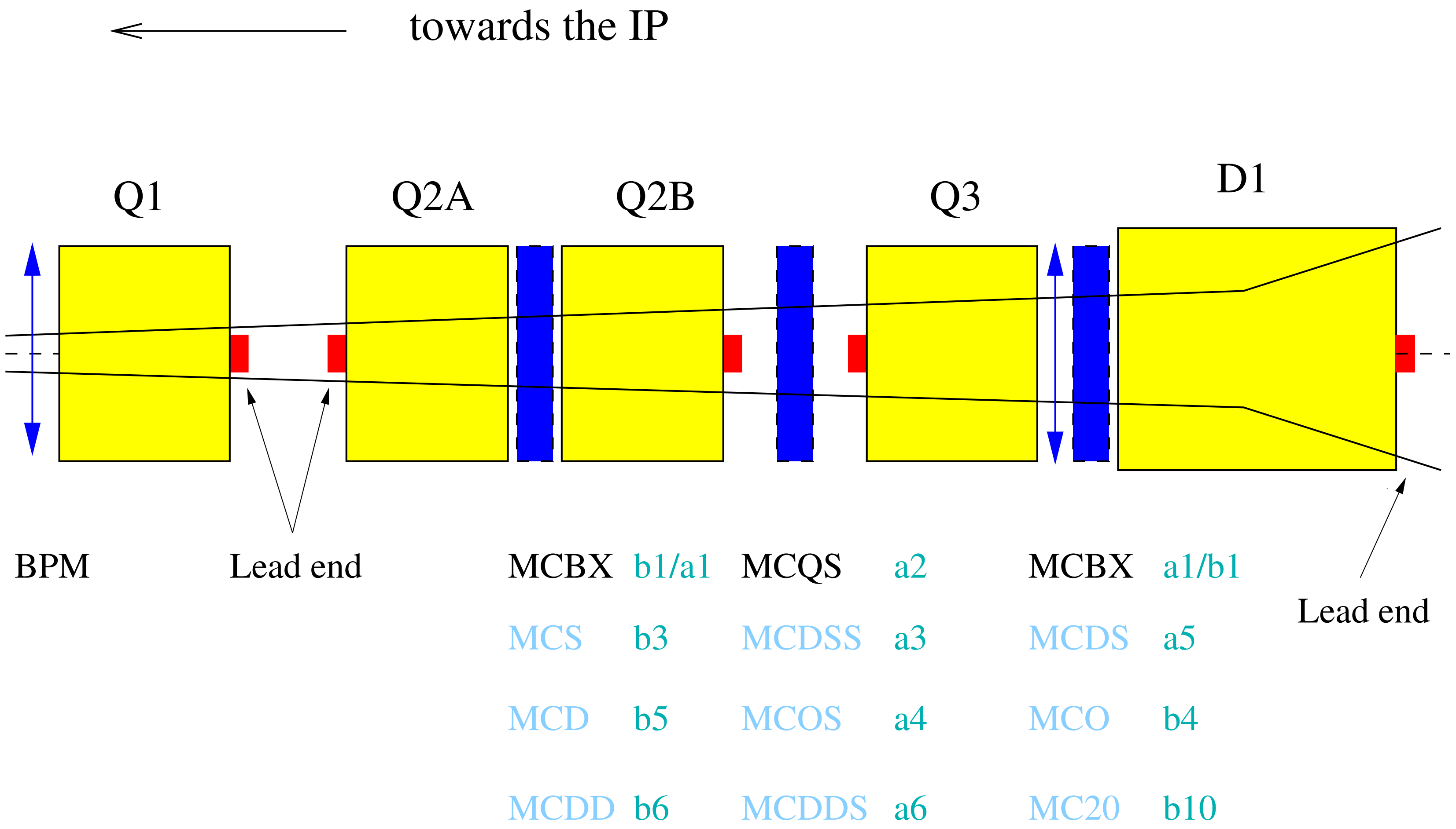
- to minimize both H and V kicks of the entire IP (two triplets)
- not to take into account the crossing-angle orbit offset
- works for both beams if the lattice is symmetric

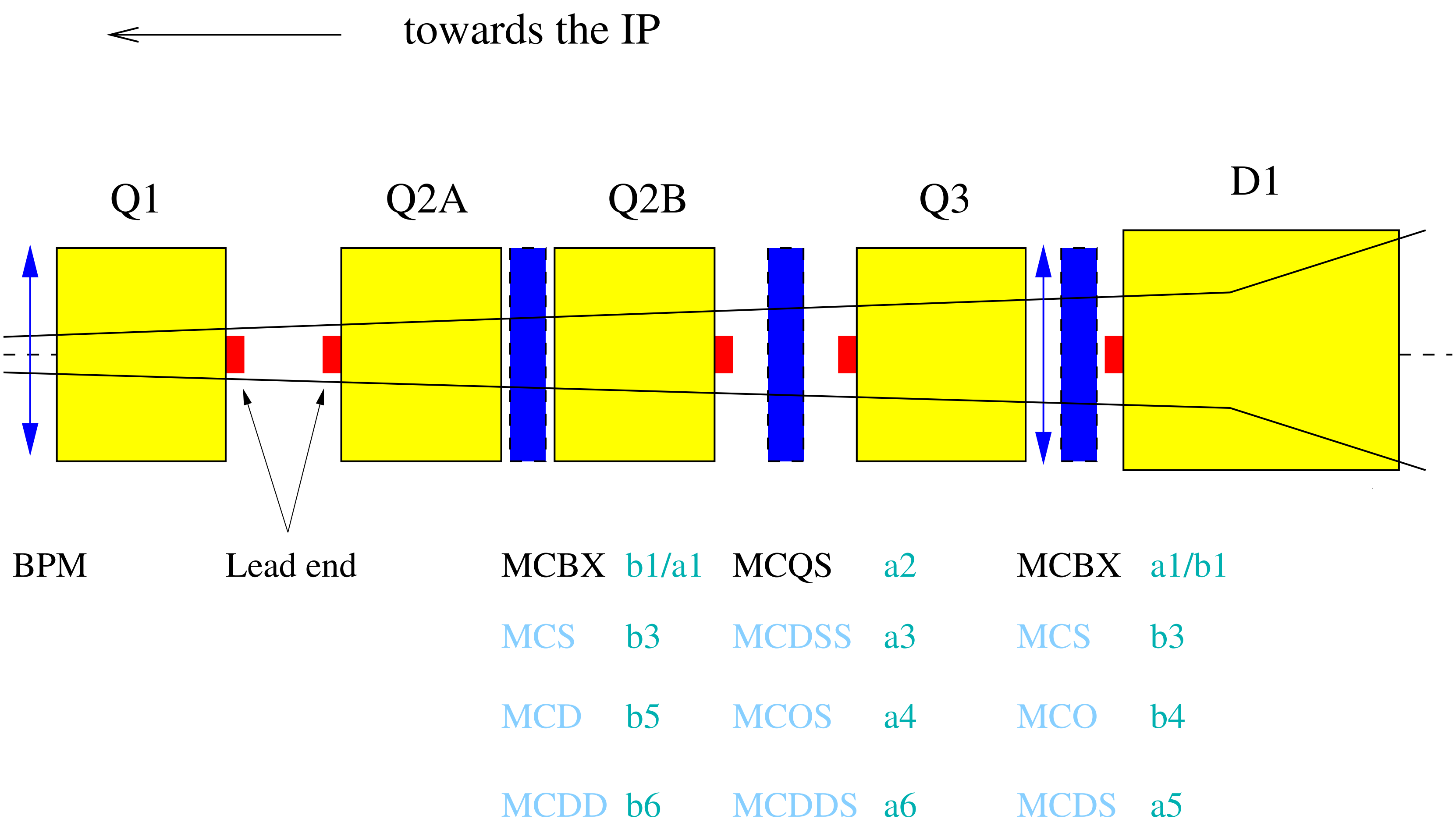
* Magnet Orientation Optimization

- cancelling MQX lead-end b_6 among F and D quads
- benefit not significant for b_{10} due to high β power dependence

* IR Correctors

- based on bench multipole measurements (assuming 5$\%$ rms error)
- limited by space and available strengths


towards the IP
Q1
Q2A
Q2B
Q3
D1
BPM
Lead end
MCBX b1/a1
MCQS a2
MCBX a1/b1
Lead end
MCS b3
MCDSS a3
MCDS a5
MCD b5
MCOS a4
MCO b4
MCDD b6
MCDDS a6
MC20 b10



MCBX	b1/a1	MCQS	a2	MCBX	a1/b1
MCS	b3	MCDSS	a3	MCS	b3
MCD	b5	MCOS	a4	MCO	b4
MCDD	b6	MCDDS	a6	MCDS	a5

Comparison of IR correction efficiency

(FNAL v1.1)

Case	DA (σ_{xy})	Min. DA	$\Delta\nu_{max}$ (10^{-3})	layers
0	10.7±1.7	$8\sigma_{xy}$	1.9±1.1	0
1	10.7±1.3	$9\sigma_{xy}$	2.1±1.0	1
2	12.5±1.9	$9\sigma_{xy}$	1.9±1.5	1
3	13.3±1.6	$10\sigma_{xy}$	1.0±0.7	2
4	13.6±1.5	$11\sigma_{xy}$	0.5±0.3	3
5	14.1±1.5	$11\sigma_{xy}$	0.5±0.4	3

case 0: b_1, a_1, a_2
case 1: case 0 plus b_3, a_3, b_4
case 2: case 0 plus b_6, b_6, a_6
case 3: case 0 plus b_3, b_4, b_6, a_3, a_4, a_6
case 4: case 0 plus b_3, b_4, b_5, b_6, b_6, a_3, a_4, a_5, a_6
case 5: case 0 plus b_3, b_4, b_5, b_6, b_{10}, a_3, a_4, a_5, a_6

- nonlinear corrections are activated in IP1 and 5 only.
- assume 10% rms measurement error.
- for zero measurement error, add $\sim 0.5\sigma_{xy}$
- numbers of layers are for nonlinear multipoles ($n \geq 3$)

IR corrector strength used for compensation:

(FNAL v1.1)

order	Integrated strength [unit·m]	Field B_n at 17 mm (mean ± SD) [T]	Field B_n at 17 mm (mean + 6 SD) [T]
b_3	5.6 ± 4.5	0.0038 ± 0.0031	0.022
a_3	13.0 ± 10.5	0.0088 ± 0.0071	0.051
b_4	7.0 ± 4.1	0.0048 ± 0.0028	0.022
a_4	10.8 ± 8.3	0.0073 ± 0.0056	0.041
b_5	2.3 ± 2.0	0.0016 ± 0.0014	0.010
a_5	2.4 ± 2.3	0.0016 ± 0.0016	0.011
b_6	5.4 ± 1.9	0.0038 ± 0.0013	0.012
a_6	3.5 ± 3.1	0.0024 ± 0.0021	0.011
b_{10}	0.5 ± 0.3	0.00034 ± 0.00020	0.0015

Note:

- assume $L_m = 0.5$ m magnetic length
- bi-polar, individually powered

IR corrector strength used for compensation:

(KEK v1.1)

order	Integrated strength [unit·m]	Field B_n at 17 mm (mean ± SD) [T]	Field B_n at 17 mm (mean + 6 SD) [T]
b_{10}	21 ± 2	0.014 ± 0.001	0.015

Note:

- assume $L_m = 0.5$ m magnetic length
- bi-polar, individually powered
- for $n \leq 6$, the FNAL (mean + 6 SD) value is adequate

Is this b_{10} strength achievable?

- According to A. Ijspert, in 3-layer (nonlinear) configuration all except b_{10} can be made
- The b_{10} needed for KEK is 28 times achievable value

Comparison of IR correction efficiency

(KEK v1.1)

Case	DA (σ_{xy})	Min. DA	layers
0	8.7±0.9	$7\sigma_{xy}$	0
1	9.4±1.2	$8\sigma_{xy}$	3
2	14.3±1.1	$11\sigma_{xy}$	3

case 0: b_1, a_1, a_2
case 1: case 0 plus b_3, b_3, b_4, b_5, b_6, a_3, a_4, a_5, a_6
case 2: case 0 plus b_3, b_4, b_5, b_6, b_{10}, a_3, a_4, a_5, a_6

- nonlinear corrections are activated in IP1 and 5 only.
- assume 5% rms measurement error.
- numbers of layers are for nonlinear multipoles ($n \geq 3$)

$\ast$ Discussions

- Comparing with FNAL quads, KEK quad field error further reduces DA by about $2\sigma_{xy}$

- KEK field error gives DA (mean ± SD: $8.2 \pm 0.9\ \sigma_{xy}$; min. $6.5\sigma_{xy}$) about $4\sigma_{xy}$ lower than the CERN target (mean $12\sigma_{xy}$, min. $10\sigma_{xy}$)

- Leading impact is from b_{10}; secondly from b_6

- Local corrections using multipoles not higher than b_6/a_6 gives limited improvement ($\sim 1\sigma_{xy}$); b_{10} correctors are needed to meet the target

- Local corrections with b_{10} can meet the target; needed b_{10} strength is 0.015 [T] at 17 [mm] (L=0.5 [m]), or integrated gradient BL/R^9 at 6.3×10^{13} [T/m^8] — 28 times achievable value in a 3-layer (nonlinear) configuration

- Global map/resonance correction may improve situation in the absence of b_{10} correctors, but the operation is likely to be challenging and less robust in practice