KEK MQX Field Error Analysis and Compensation

J. Wei

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Collider Accelerator Department
Brookhaven National Laboratory

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J. Wei, V. Ptitsin, N. Gelfand, T. Sen

$*$ Introduction

$*$ 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, $\|G_0\|$ [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]	$\pm7.3/\pm7.3$

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

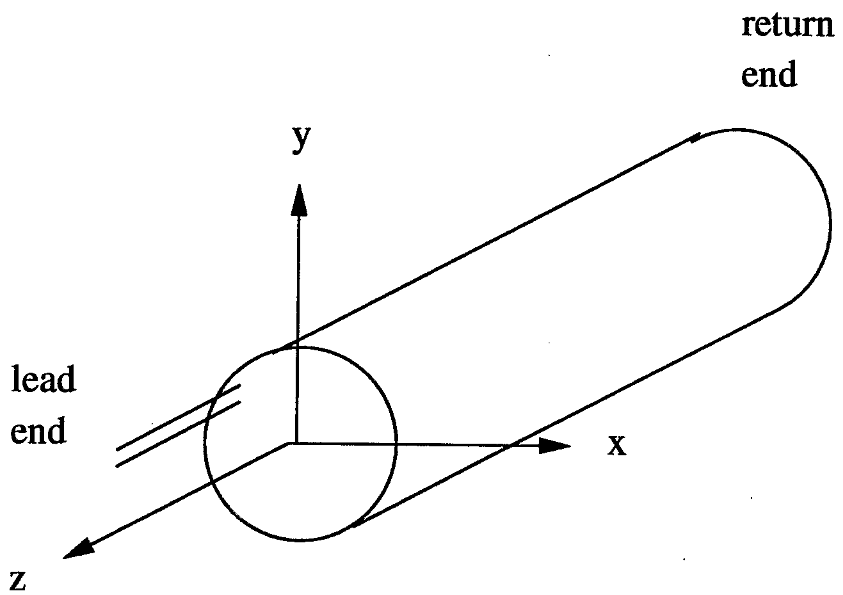
Assumptions:

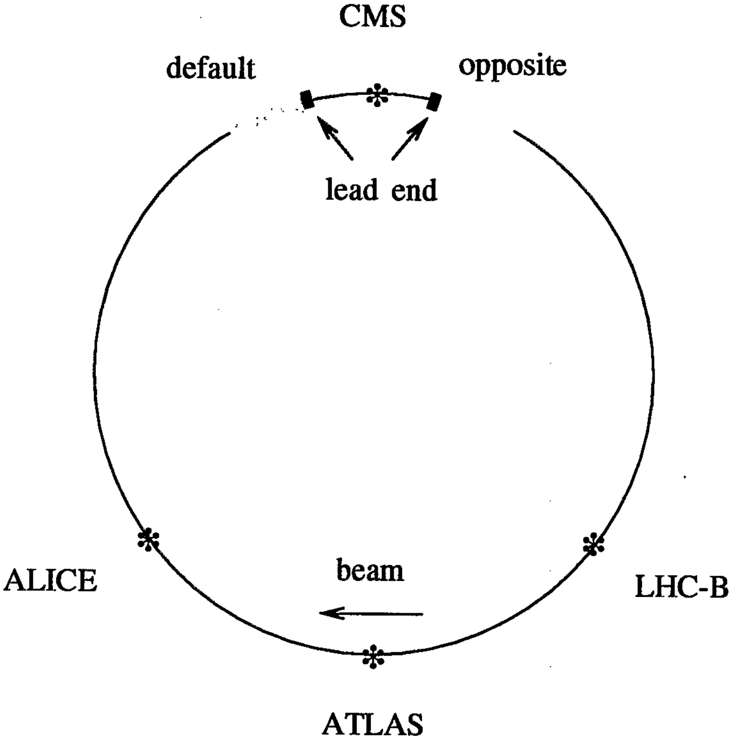
- Previous studies: FNAL v1.1 assumed for all four IPs
- "KEK case": KEK's at IP1 & 2; FNAL's at IP5 & 8
- LHC collision lattice version 5.1 with crossing angle
- magnetic error only; no beam-beam, no misalignment

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: $b_n \Rightarrow (-)^n \; b_n$; $a_n \Rightarrow (-)^{n+1} a_n$

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

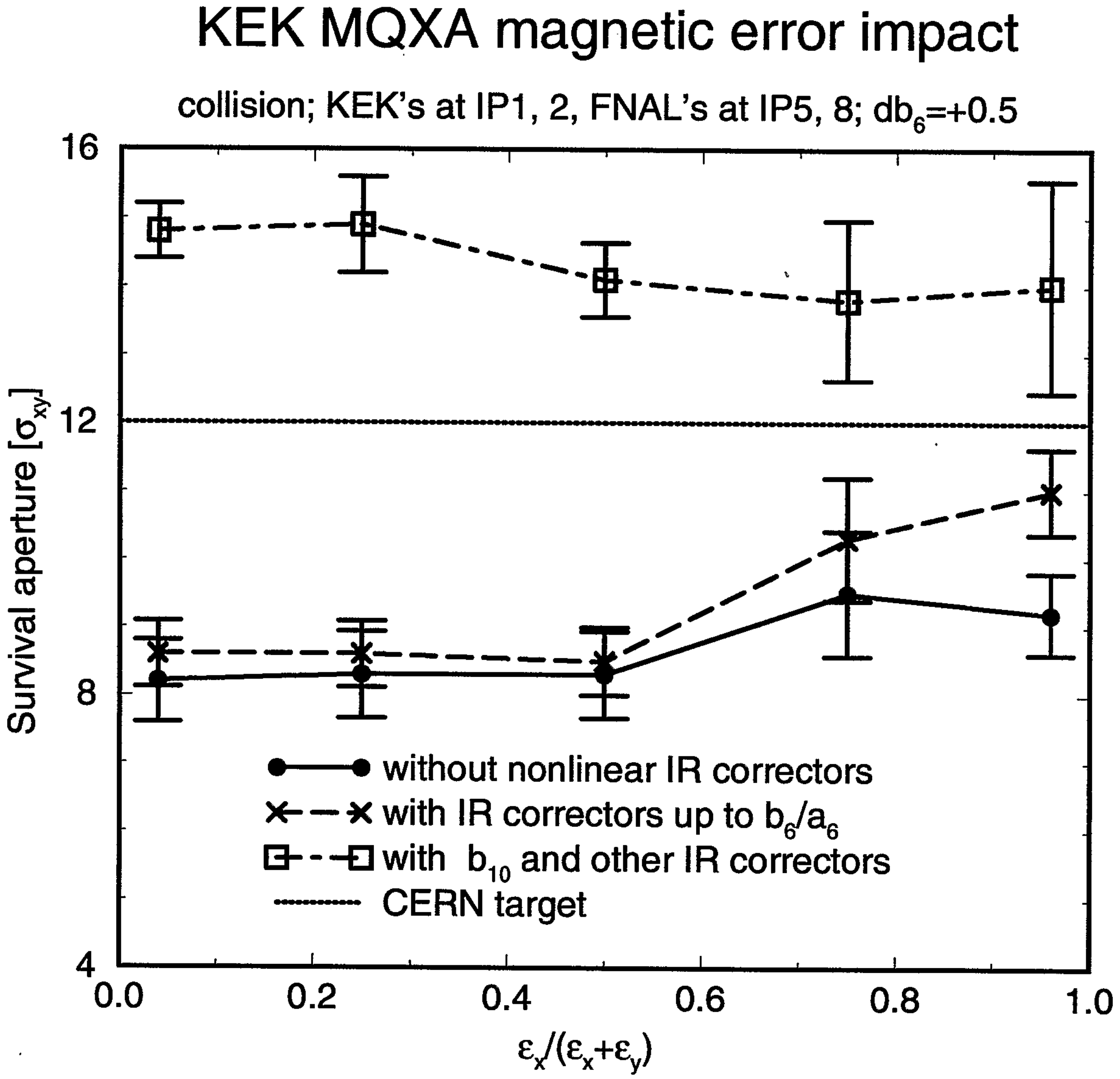
* Tracking Results

Effects of MQX field errors on dynamic aperture:

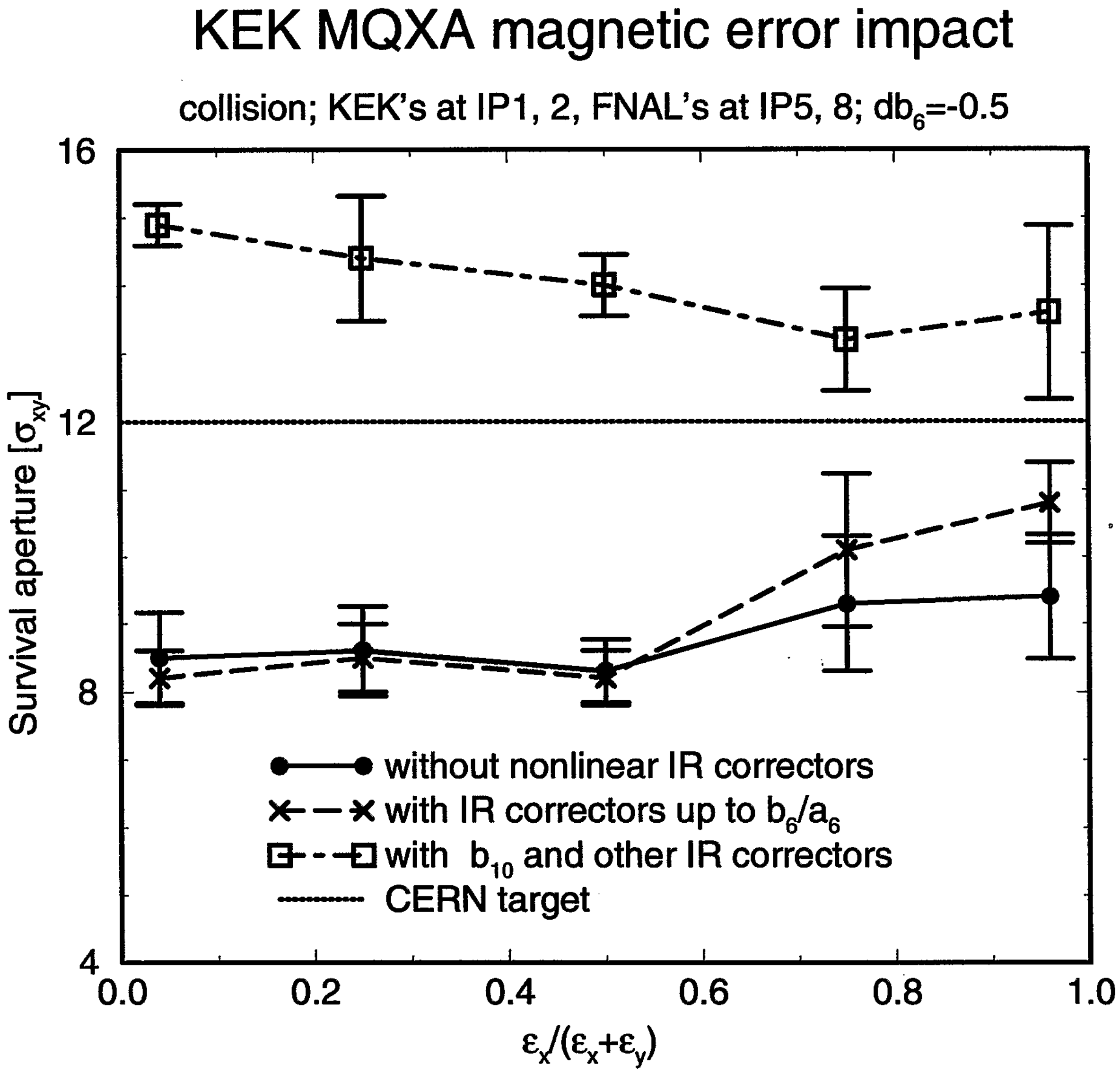
Case	DA [σ_{xy}] (mean±SD)	Min. DA [σ_{xy}]
FNAL:		
(10^3-turn)	10.7±1.7	8
KEK:		
v1.0	7.9±2.4	5
v1.0/1.1 without b_6 & b_{10}	11.4±2.2	8
v1.1	8.7±0.9	7
v1.1 with b_{10} at half strength	9.4±1.7	7
CERN target:		
(10^5-turn)	12	10

- 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

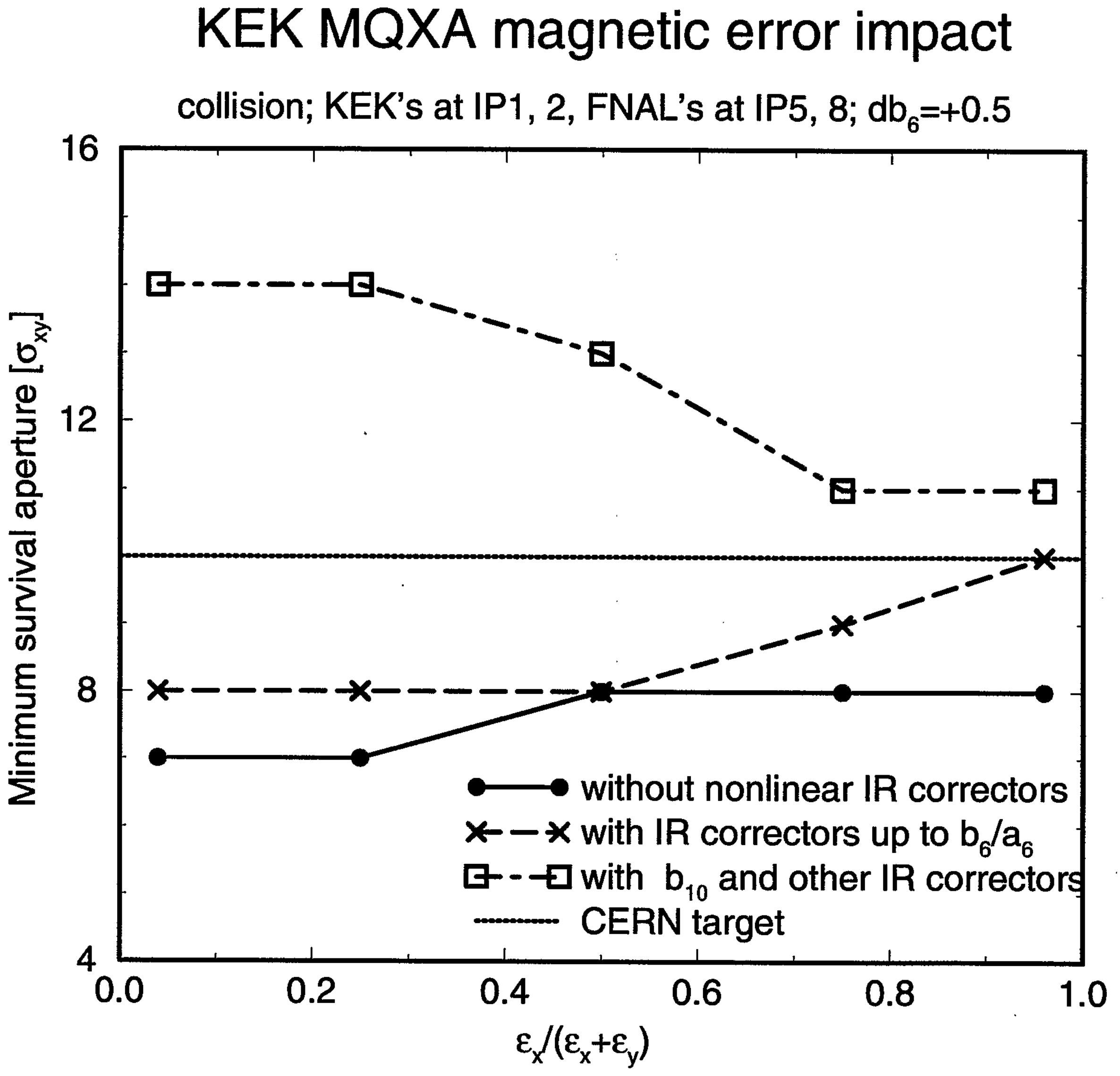
(Dynamic aperture mean & SD for $b_{6,sys} = 0.5$)



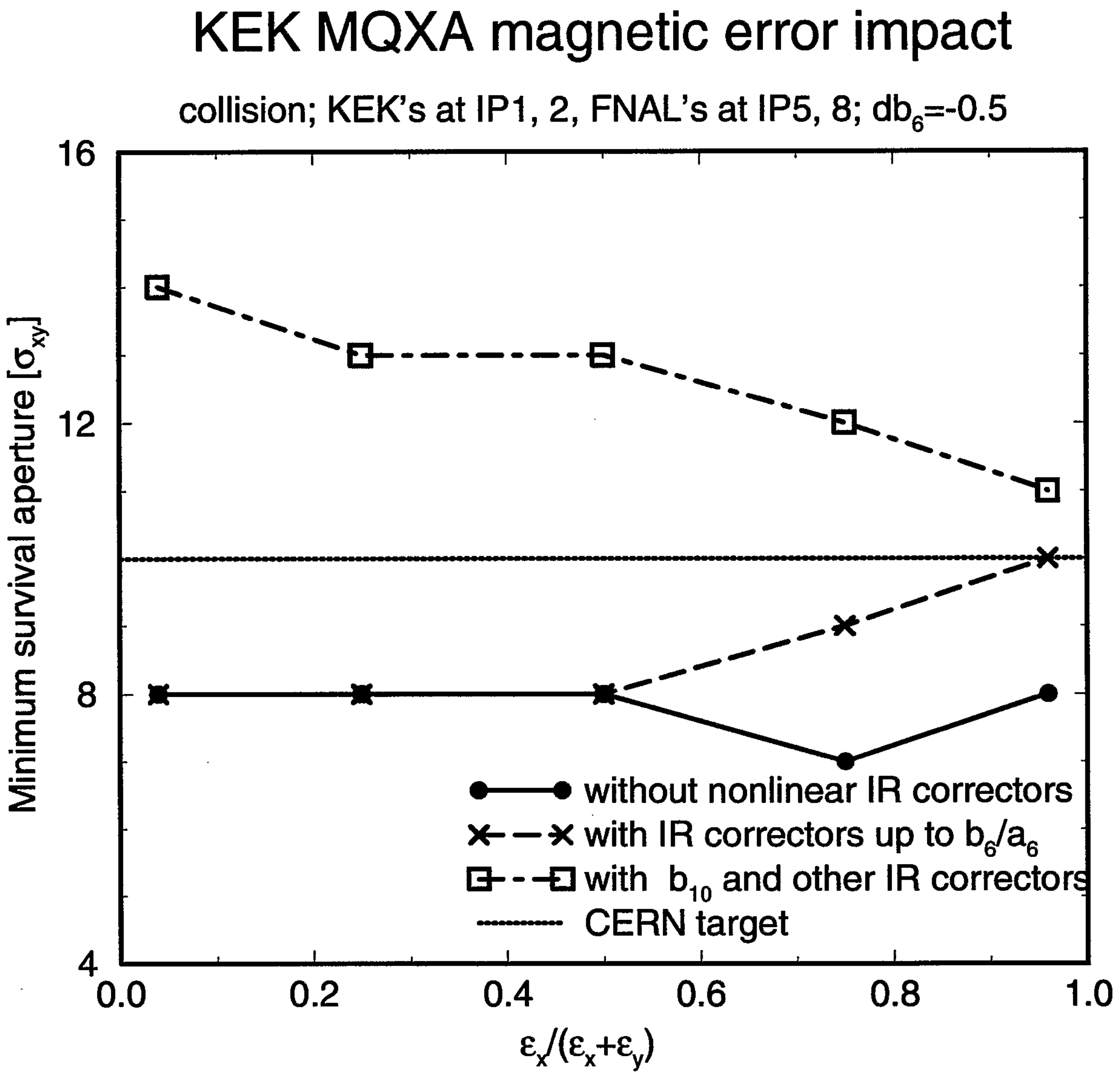
(Dynamic aperture mean & SD for $b_{6,sys} = -0.5$)



(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:

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

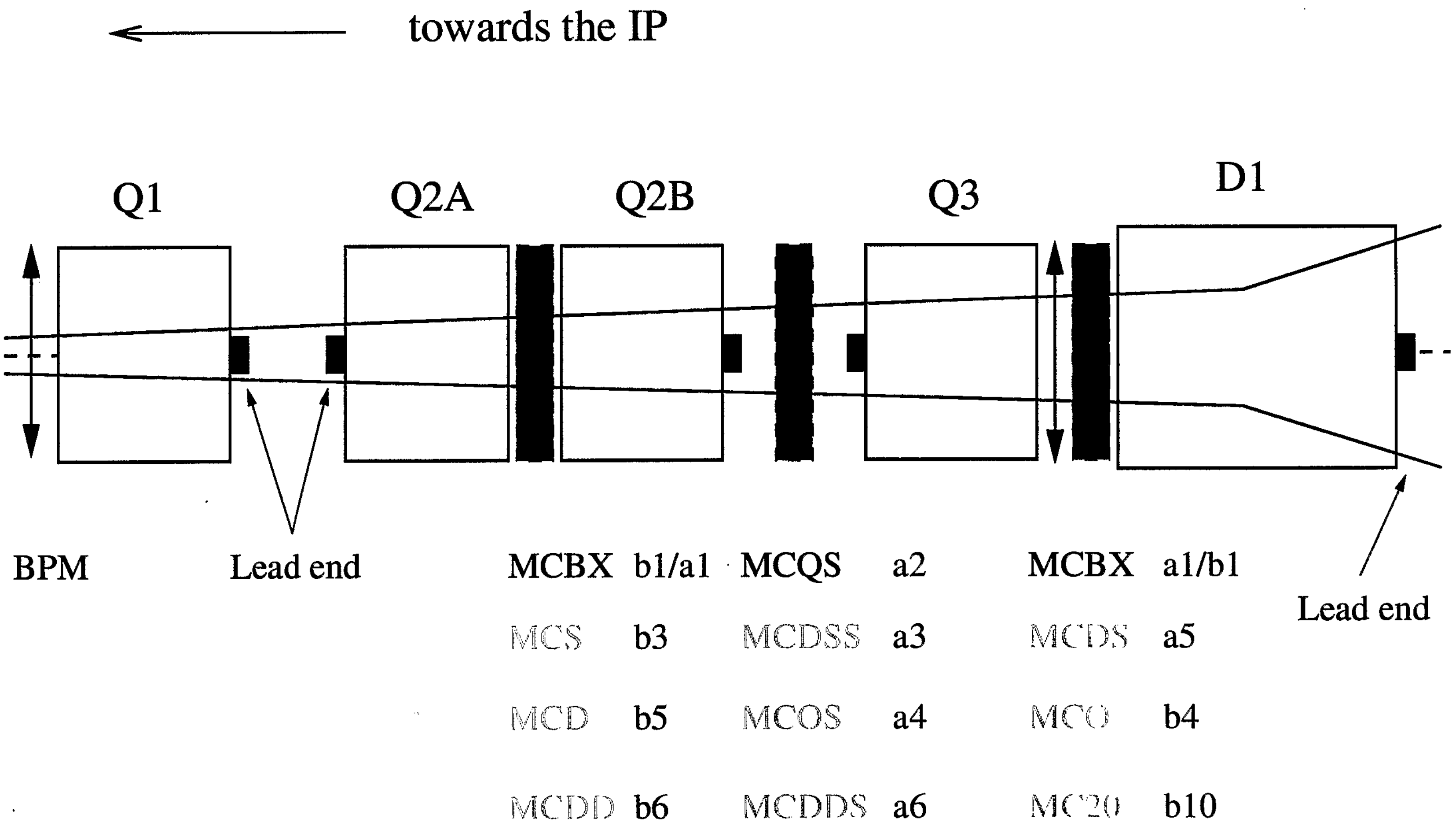
- to minimize both H and V kicks of the entire IP (two triplets)
- not to take into account the crossing-angle orbit offset
- works for both beams if the lattice is symmetric

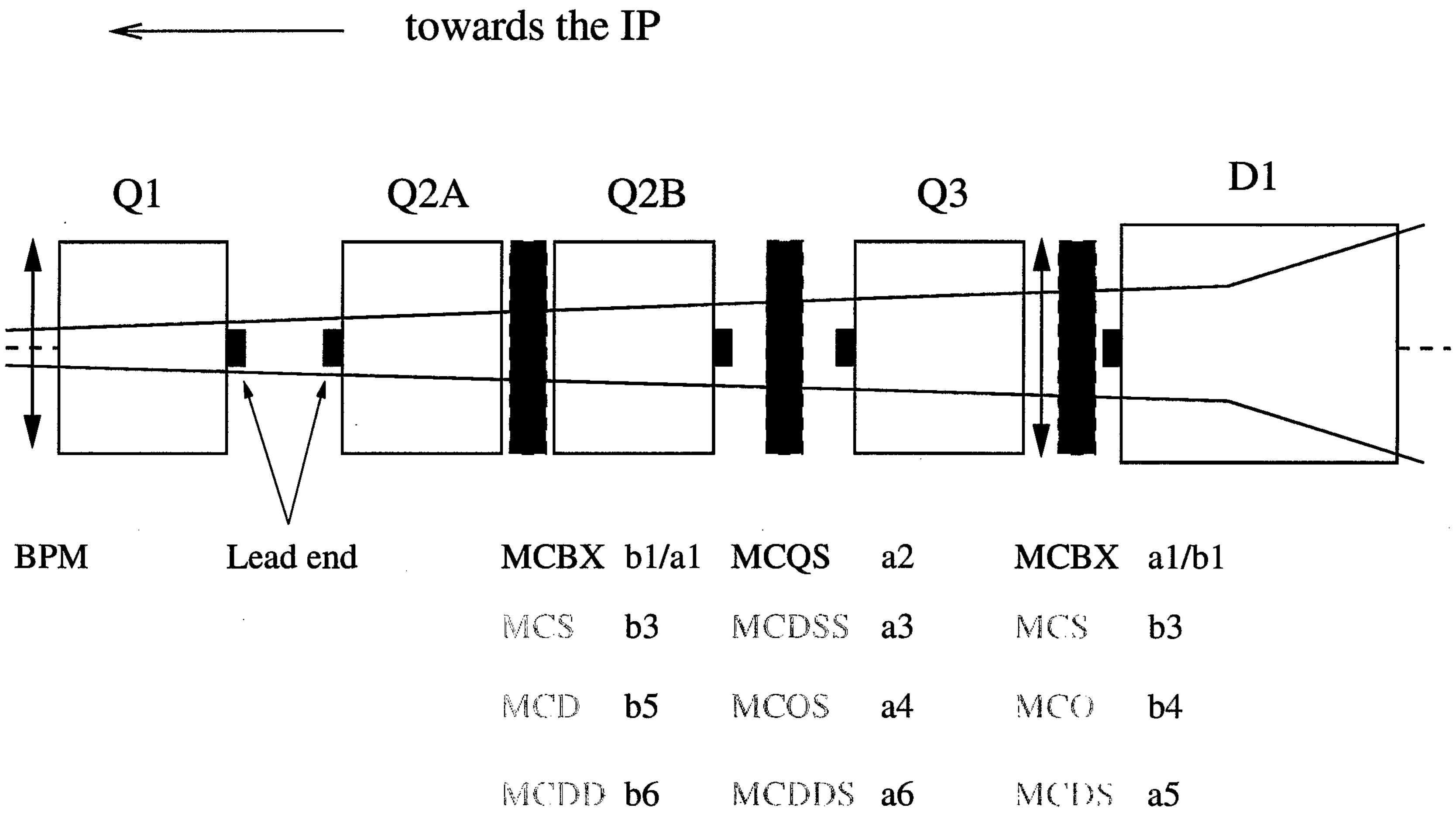
* Magnet Orientation Optimization

- 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
MCS b3
MCD b5
MCDD b6
MCQS a2
MCDSS a3
MCOS a4
MCDDS a6
MCBX a1/b1
MCDS a5
MCO b4
MC20 b10
Lead end


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

from A. Ijspeert

→ J. Wei

(Reg[illegible]

Designne.xls

(B_n mean + 6 × S.D.)

2-7-98

Program d:\excell\fields\nedesign:*** Design of a nested magnet ***A. Ijspeert, ~~28/10/94~~								Calculation takes account of 4.5 T from MCBX							
	Input parameters:		b6	b5	b3		a6	a4	a3		b10	a5	b4		
Magnet type		n	6	5	3		6	4	3		10	5	4		
Integrated gradient Bl/R^(n-1)	Tm/m^(n-1)	gl	4300000	60000	38		3900000	4200	88		6.3E+12	66000	2240		
Coil inner radius	mm	R1	37	41.5	44		37	40	43		37	41	43		
Coil outer radius	mm	R2	41	43.5	44.5		39.5	42.5	44.5		40.5	42.5	44.5		
NbTi crit. current at 5T and 4.2 K	A/mm2	jc	2600	2600	2600		2600	2600	2600		2600	2600	2600		
Bath temperature	K	T	1.9	1.9	1.9		1.9	1.9	1.9		1.9	1.9	1.9		
Copper/Supercond. ratio		r	1.6	1.6	1.6		1.6	1.6	1.6		1.6	1.6	1.6		
Filling fact.(*B/Bpeak evt.)		ff	0.6	0.6	0.6		0.6	0.6	0.6		0.6	0.6	0.6		
Working point load line		wp	0.4	0.4	0.4		0.4	0.4	0.4		0.4	0.4	0.4		
Nominal current	A	I	25	25	25		25	25	25		25	25	25		
	Output parameters:														
Current density NbTi	A/mm2	j	1464.39	1617	1810.6		1577.966	1559	1667		1547.306	1674.4	1670.4		
Field at R1	T	B	0.72929	0.4709	0.1431		0.537025	0.5692	0.3863		0.588928	0.3739	0.3806		
Gradient (B/R^n-1)	T/m^(n-1)	g	1.1E+07	158772	73.931		7744371	8893.8	208.94		4.53E+12	132302	4786.5		
Iron inner radius	mm	R3	200	200	200		200	200	200		200	200	200		
Iron outer radius	mm	R4	470	470	470		470	470	470		470	470	470		
Magnetic length	mm	Lm	408.859	377.9	513.99		503.5916	472.24	421.17		**1390.252**	498.86	467.98		
Coil length	mm	Lc	423.164	396.11	545.04		517.3727	494.48	452.22		1398.73	516.65	491.27		
Magnetic energy	J	W	142.965	49.509	8.8876		70.28301	106.05	55.592		280.3578	37.286	47.069		
Inductance	H	L	0.45749	0.1584	0.0284		0.224906	0.3393	0.1779		0.897145	0.1193	0.1506		
Number of turns/coil		N	367.855	265.59	129.02		242.9765	388.32	352.31		202.7507	202.62	264.77		
Wire cross-section (metal)	mm2	A	0.04439	0.0402	0.0359		0.041192	0.0417	0.039		0.042008	0.0388	0.0389		

@ 17 mm R.

using dipole
for a_2

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