Permanent Magnet Final Quad

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Permanent Magnet Study Short History

2002~2005 First R&D program for FFQ

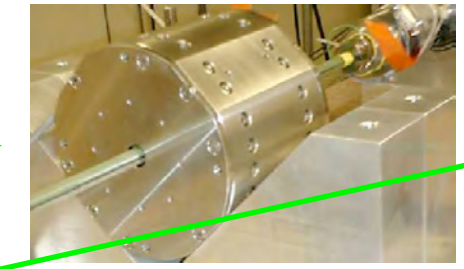
Permanent Magnet Quadrupole for Final Focus Lens in a Linear Collider

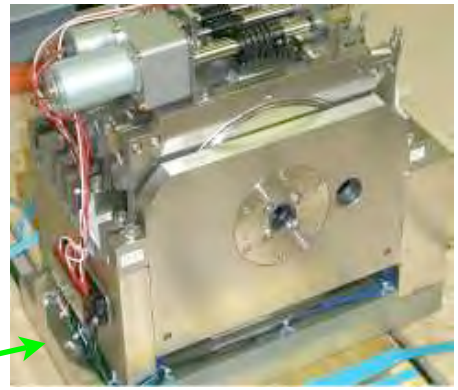
2002 Fixed strength PMQ

2003 Adjustable PMQ (double ring)

2004 Measurement and fine tuning

2005 Higher gradient at small bore





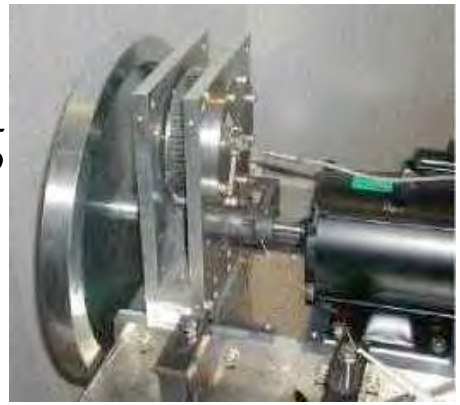
2006~2009 Second R&D program

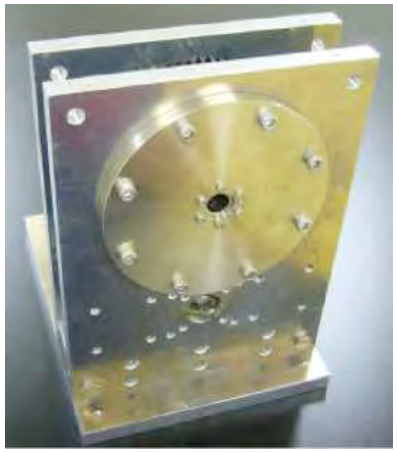
Development and Application of PMQ for Linear Collider and Neutron optics

2006 Half scale Model of Rapid Cycling Sextupole

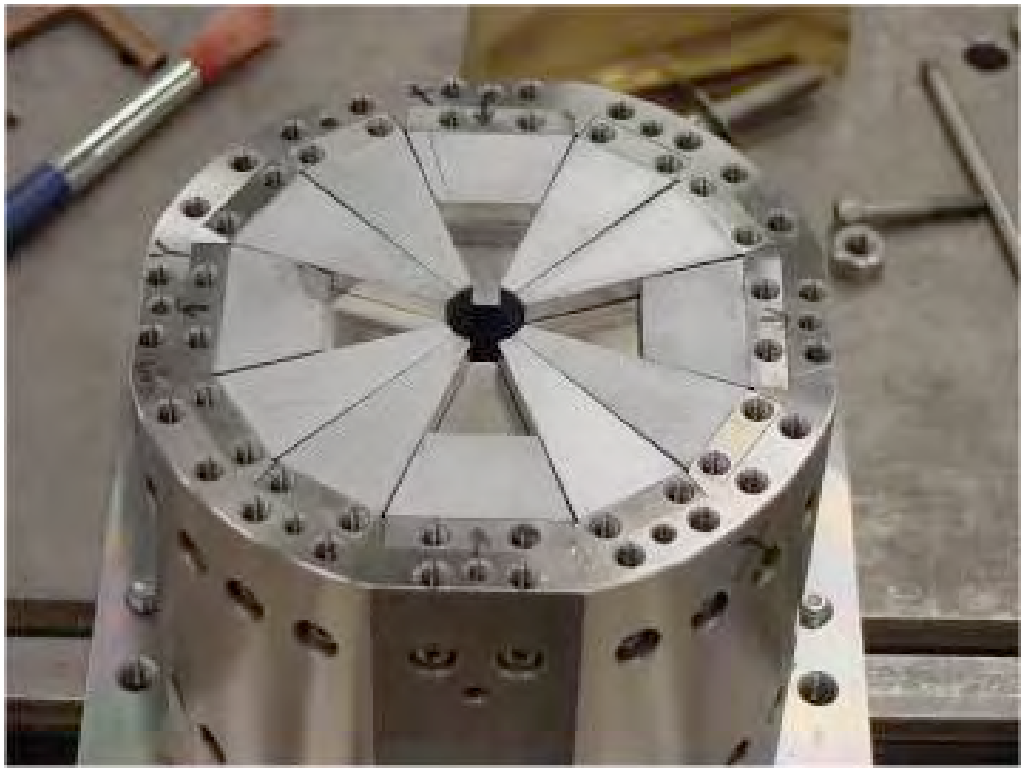
2007~Adjustable PMQ（2nd model）

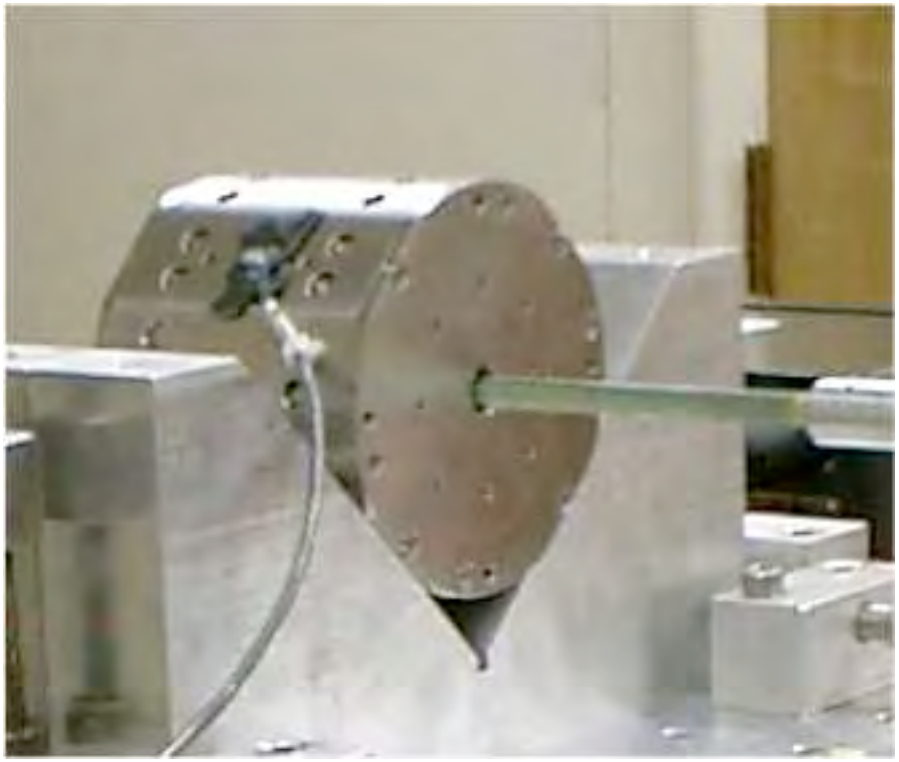
2008 ...





First prototype (fixed field)





Prototype PMQ

Measurement at SLAC

Bore: ø14, OD ø130, L100, GL=28.5T
(290T/m)

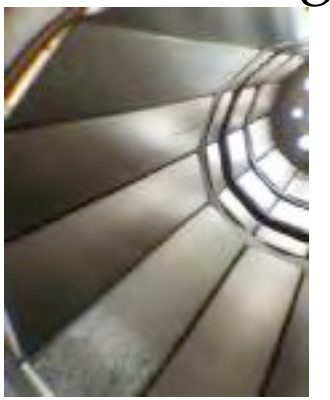
The 20mr Variable FFQ Magnet

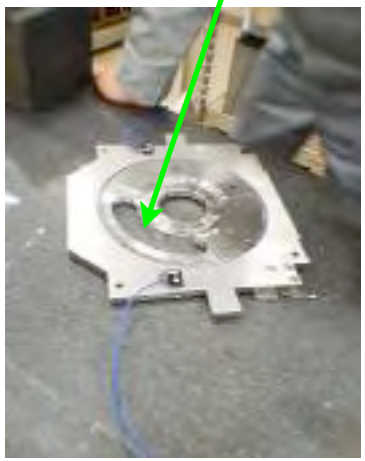
Bore radius	1cm
Inner ring radii	In 1cm out 3cm
Outer ring radii	In 3.3cm out 5cm
Outer ring section length Physical length	1cm, 2cm, 4cm, 8cm 23cm
Pole material	Permendur
Magnet material (inner ring)	NEOMAX38AH
Magnet material (outer ring)	NEOMAX44H
Integrated gradient (strongest)	24.2T
Integrated gradient (weakest)	3.47T
Int. gradient step size	1.4T

Inside View of Outer Ring

Extra beam hole

Inner Ring

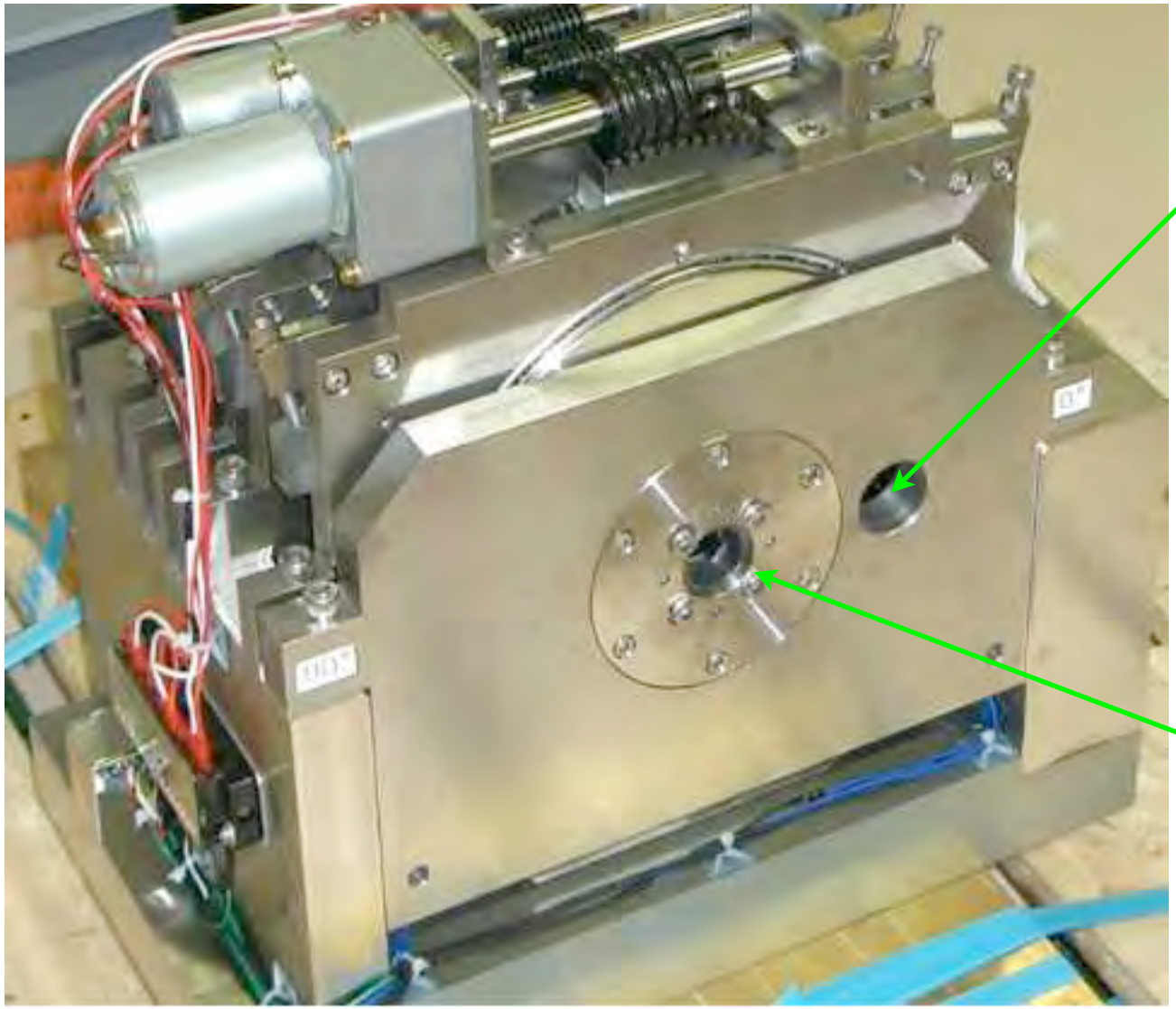




Base plate

Before assembly

The 20mr Variable FFQ Magnet



hole for outgoing beam

hole for incoming beam

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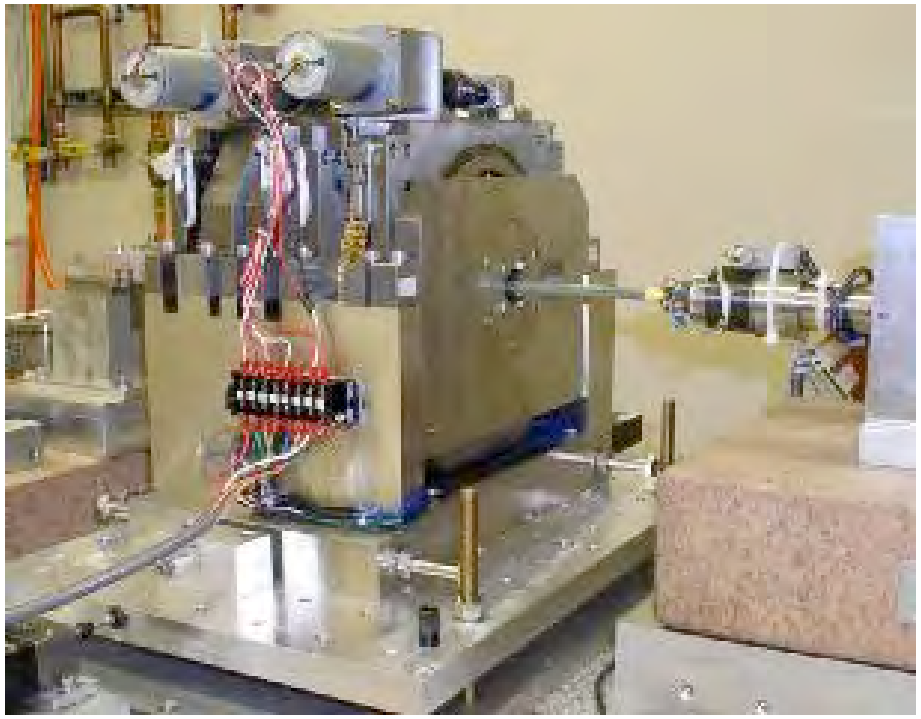
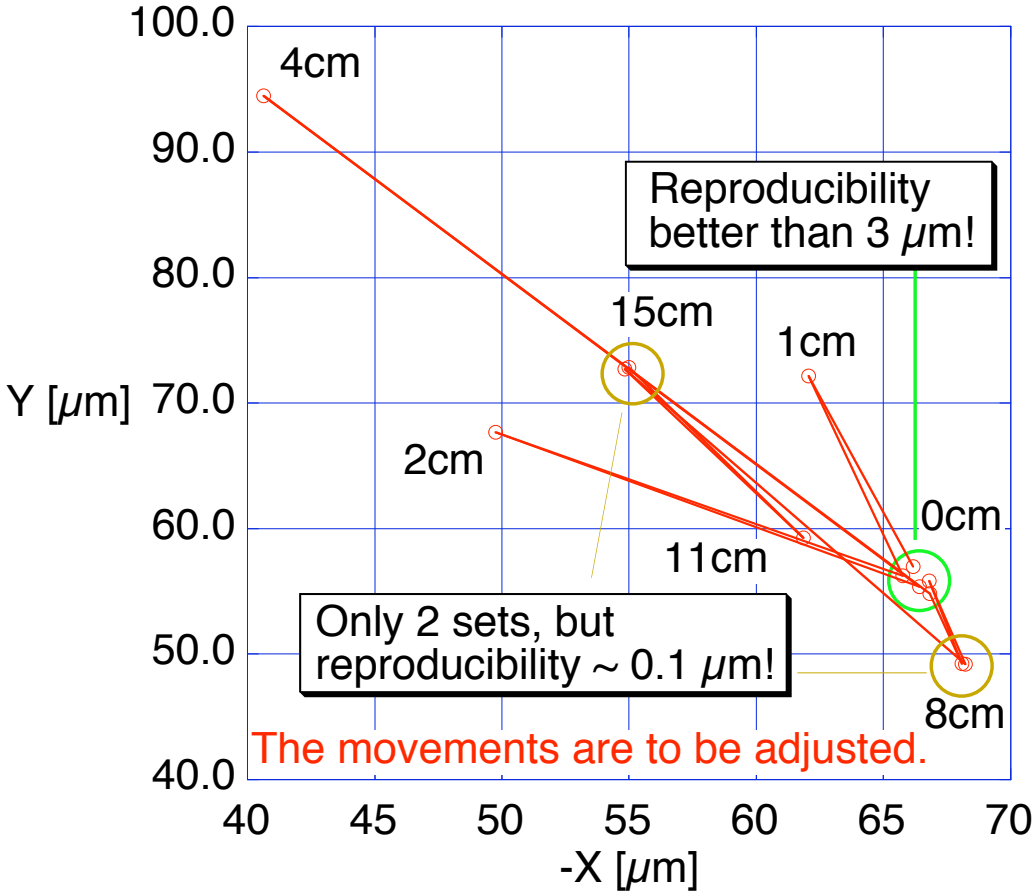
Magnetic Center Movement





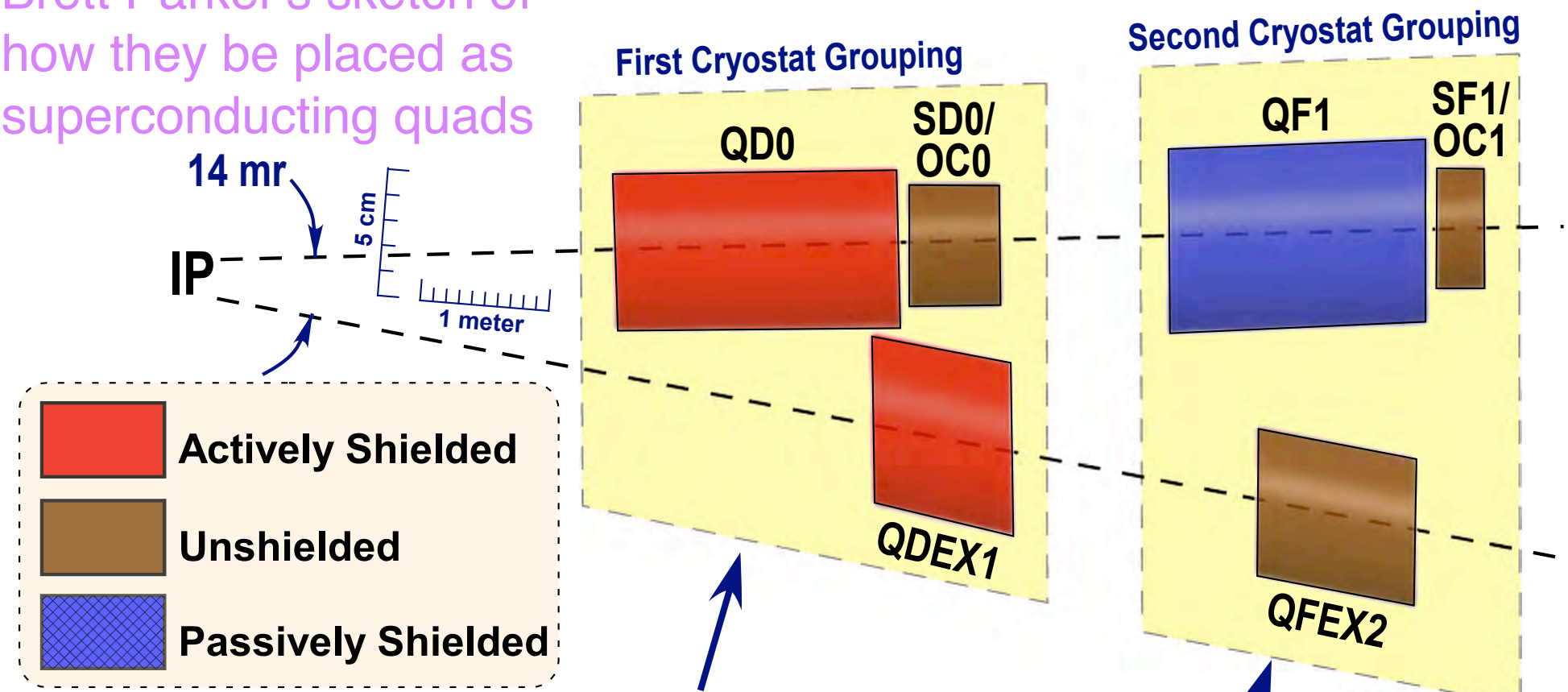
The cm values show the Switched-On-Length

The center moves several μm for 20% strength change.

See http://accelconf.web.cern.ch/AccelConf/l04/PAPERS/TUP81.PDF (LINAC'04)

Post Valencia 14 mr Magnet Layout Compatible with Push-Pull

Brett Parker's sketch of how they be placed as superconducting quads

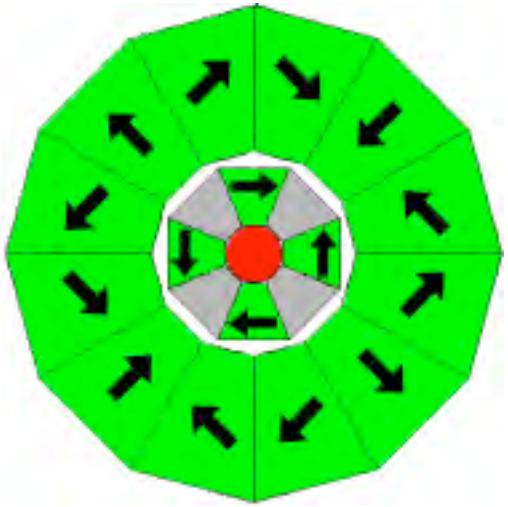


One of these magnet groups is needed in both ends of each detector (move with experiment, not shared).

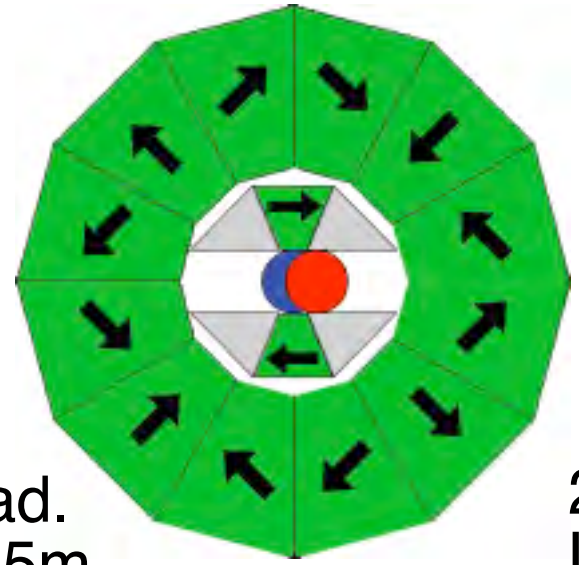
One of these magnet groups is needed on each side of the common push-pull IR hall (fixed position, experiments share).

For actively shielded coils the shield is run in series with the main quadrupole current but with a trim circuit shunt power supply for fine adjustment.

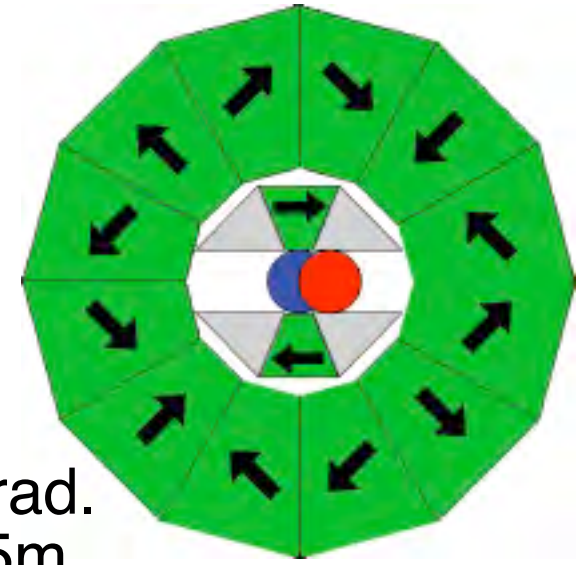
Configurations for Various Crossing Angles



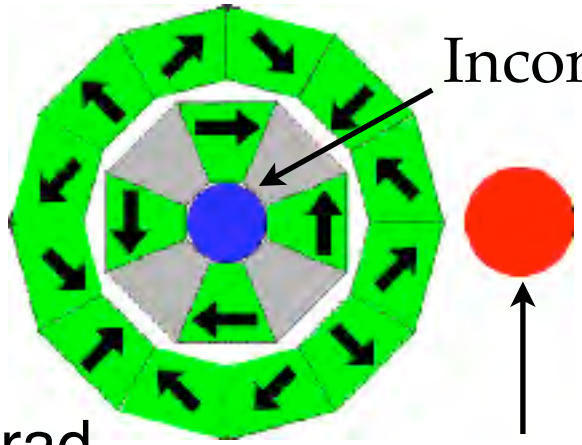
0 mrad.
(Head-On)



2 mrad.
L*=3.5m



2 mrad.
L*=5m



20 mrad.
L*=3.5m

Table II PMQ parameters for various crossing angles.

Crossing angle [mrad]	0	2	20
Outer Diam. [mm]	180	180	100
Max. Gradient [T/m]	18 0	130	120
Min. Gradient [T/m]	-20	-60	8

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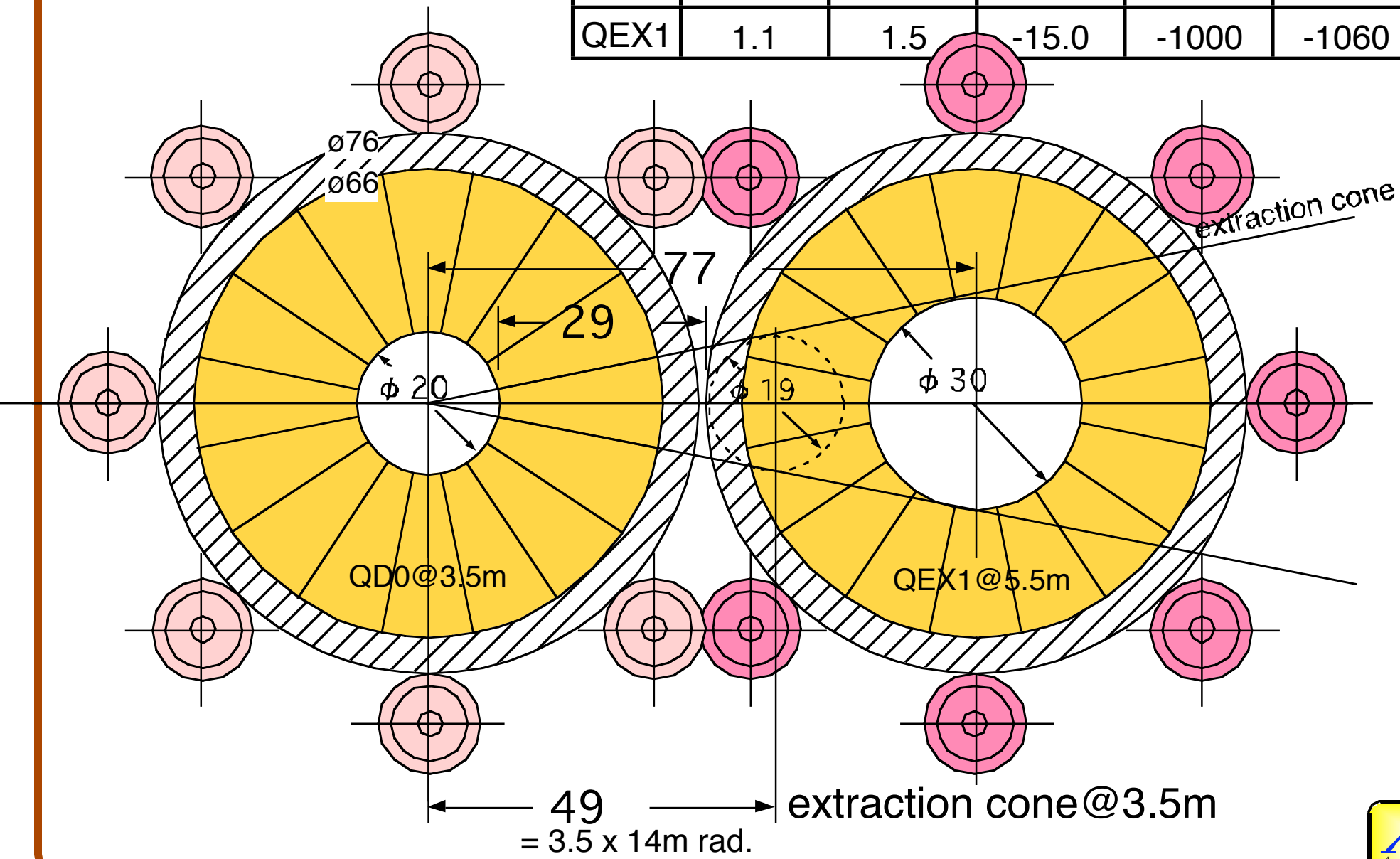
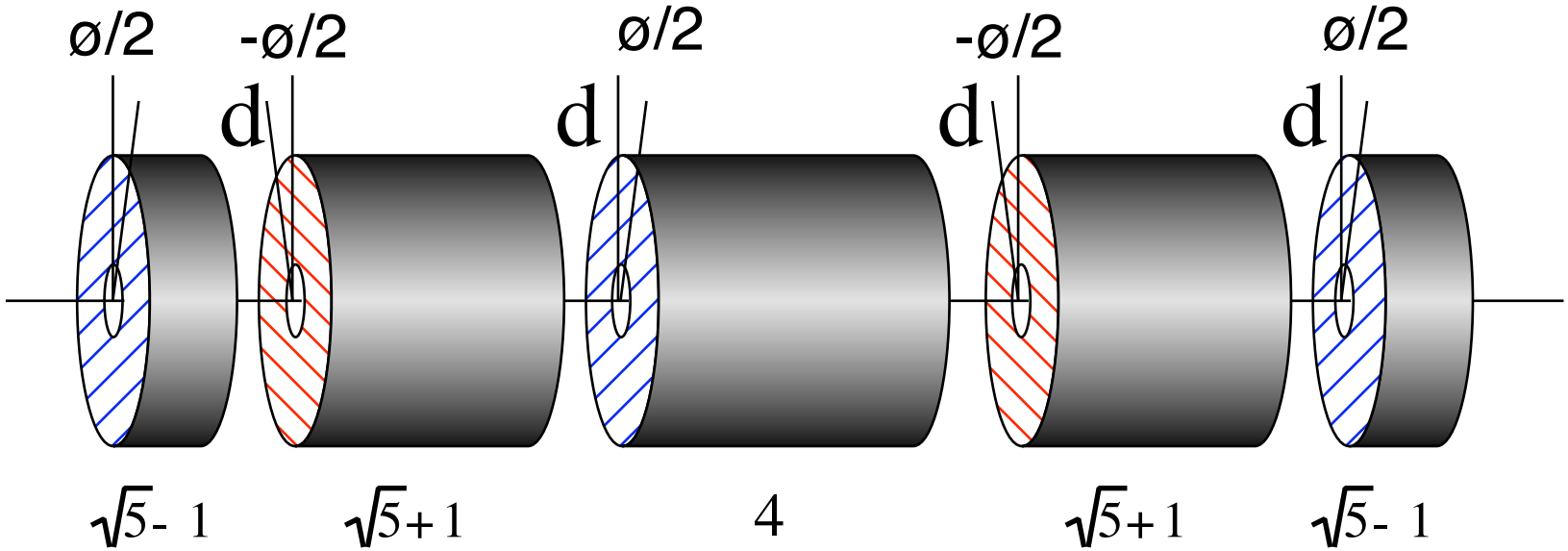
14mr option

	Eff.L [m]	R [cm]	kG	kG/m	GL [kG]
QF1	2.0	1	8	803	1605
QD0	2.2	1	-14.2	-1416	-3116
QEX1	1.1	1.5	-15.0	-1000	-1060



Gluckstern's skewless variable PMQ



$$M = R \bullet M2 \bullet R^{-2} \bullet M1 \bullet R^{2} \bullet M0 \bullet R^{-2} \bullet M1 \bullet R^{2} \bullet M2 \bullet R^{-1}$$

4x4 matrix: $M=\begin{pmatrix} Mxx & O^5 \\ O^5 & Myy \end{pmatrix}$ when d=0.

R.L. Gluckstern and R.F. Holsinger: Adjustable Strength REC Quadrupoles, IEEE Trans. Nucl. Sci., Vol. NS-30, NO. 4, August 1983, http://epaper.kek.jp/p83/PDF/PAC1983_3326.PDF

$$M0=\begin{pmatrix} \mathrm{Cos}[el\,k] & \frac{\mathrm{Sin}[el\,k]}{k} & 0 & 0 \\ -k\,\mathrm{Sin}[el\,k] & \mathrm{Cos}[el\,k] & 0 & 0 \\ 0 & 0 & \mathrm{Cosh}[el\,k] & \frac{\mathrm{Sinh}[el\,k]}{k} \\ 0 & 0 & k\,\mathrm{Sinh}[el\,k] & \mathrm{Cosh}[el\,k] \end{pmatrix}$$

$$kL \rightarrow \Gamma$$

$$k = \frac{G}{B\rho}$$

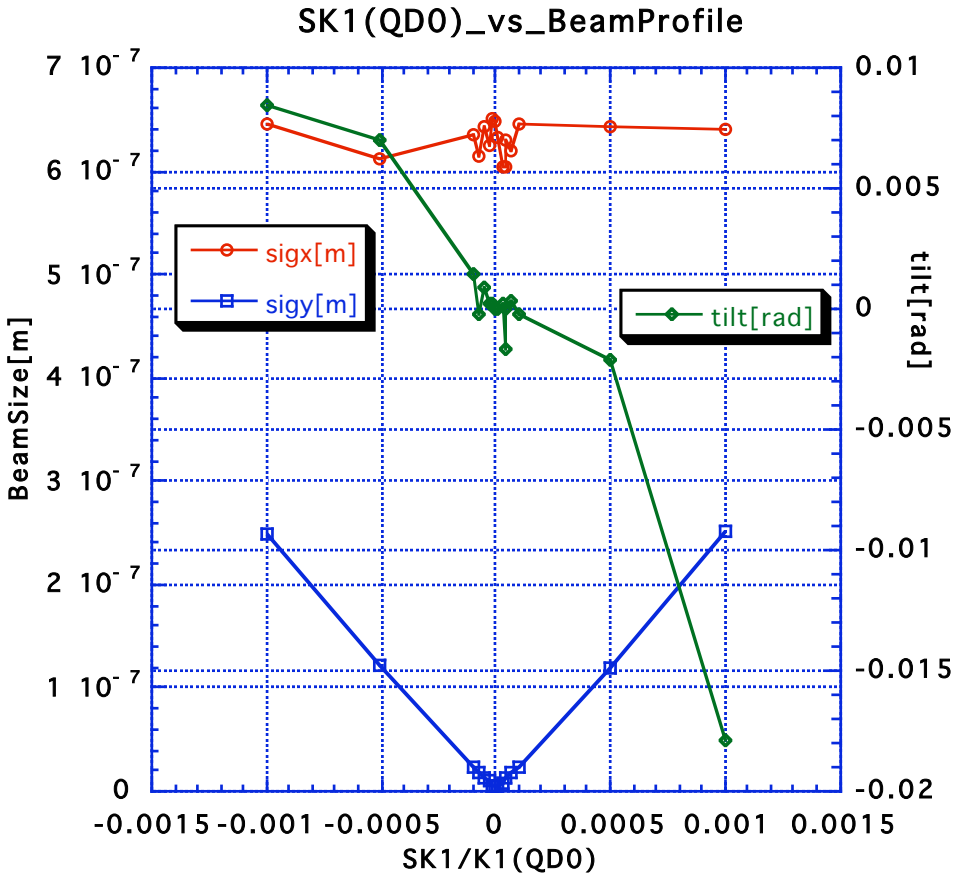
$$M = R \bullet M2 \bullet R^{-2} \bullet M1 \bullet R^{2} \bullet M0 \bullet R^{-2} \bullet M1 \bullet R^{2} \bullet M2 \bullet R^{-1}$$

$$M = \begin{pmatrix} Mxx & Mxy \\ Myx & Myy \end{pmatrix} \quad Mxy = \begin{pmatrix} Mxy_{1,1} & f(k,L,d,\alpha) \\ Mxy_{2,1} & Mxy2,2 \end{pmatrix} \cdots L0 = \alpha L$$

$$\text{Solve}: \quad f(k,L,d,\alpha) \approx \sum_{n=0,4} \frac{d^n}{d\alpha^n} f(k,L,d) \frac{\alpha^n}{n!} = 0$$

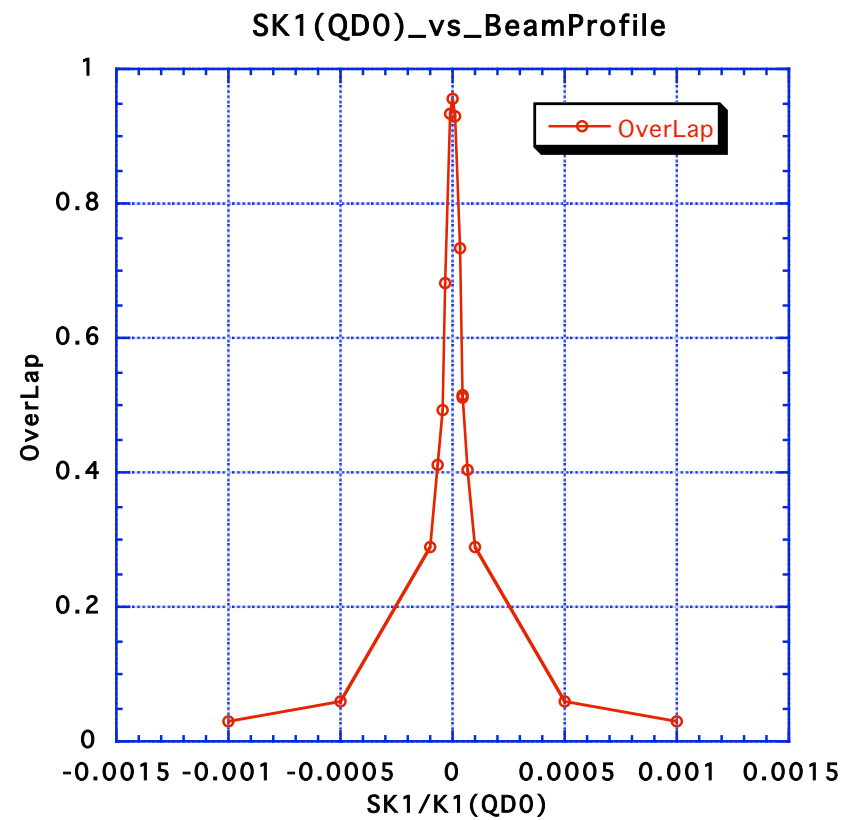
$$\alpha = -458.949,\ -1.01896,\ 0.318954,\ 460.003$$

Effect of Skew Component of QD0



Deck used: ilc2006b.ebds1

OverLap is defined by the integration of the product of two Gaussian distribution; w/wo skew error. (Center is assumed to be the same.)
The distribution is constructed with <xx>, <yy> and <xy>.



Beam profile is defined by tracking with 1000 particles. Accuracy can be seen in the fig.

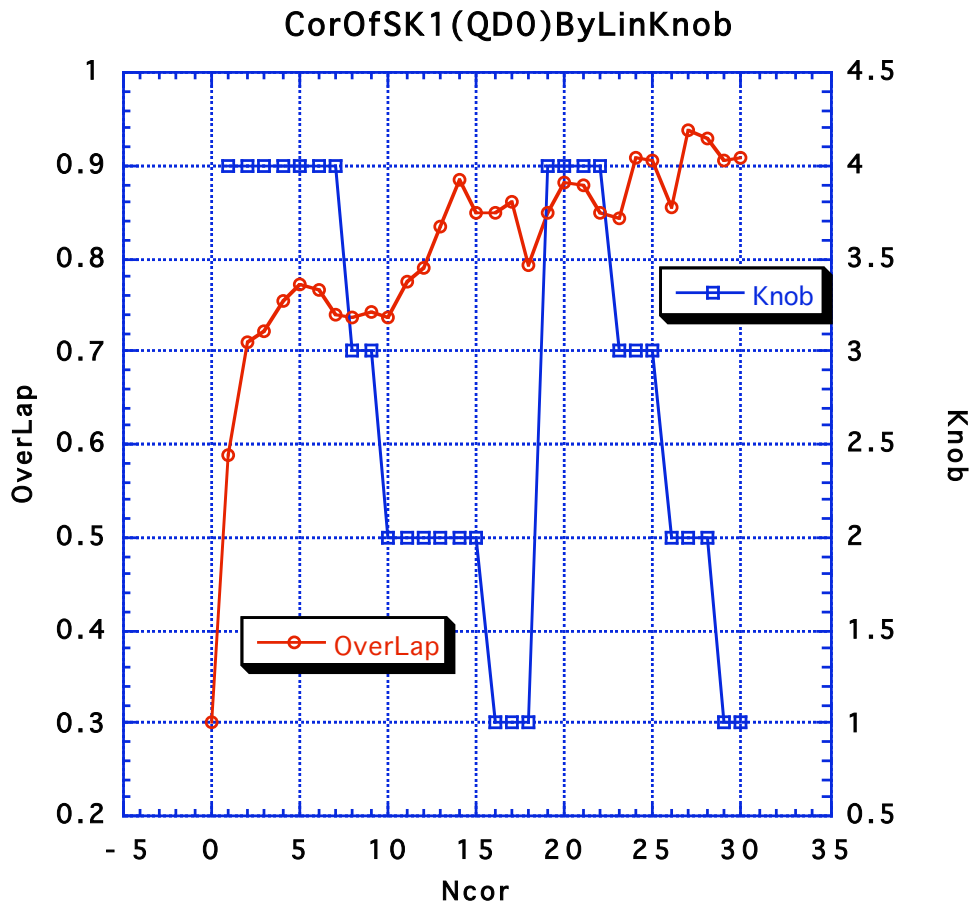
When luminosity is assumed to be proportional to the OverLap, SK1/K1≈<1e-5 is required for L/L0>≈0.93

by S. Kuroda

Correction with Linear Knob

Since the OverLap seems to be affected more by σy, correction with WaistY, PEY, R1 and R2 knobs were tried.

Case with SK1/K1=1e-4



Knob:
1(WaistY)
2(PEY)
3(R1)
4(R2)

Final Position of SX Mover

SX name	DX[m]	DY[m]
SD4	4.73748e-12	-7.96327795e-7
SF1	1.00814e-7	3.975626e-5
SD0	1.65113e-7	1.862614e-5

Max. movement is about 40um for SF1 DY.

Luminosity can be recovered upto ≈93%.

by S. Kuroda

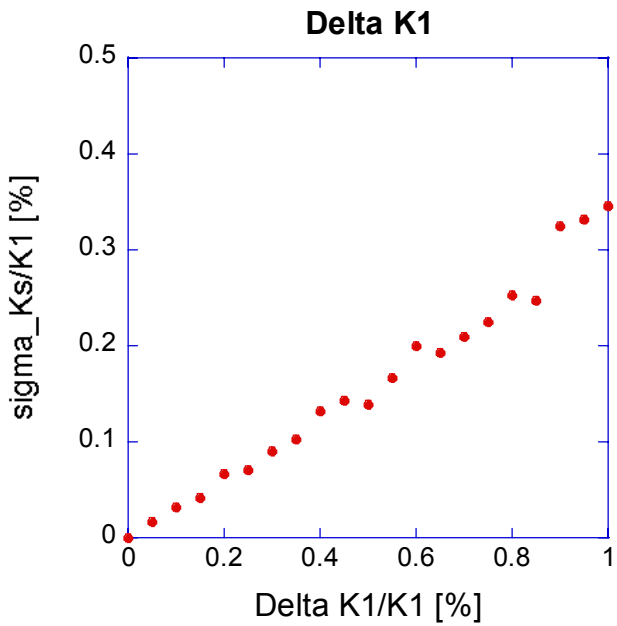
Magnet Error Estimation

Simulation Condition

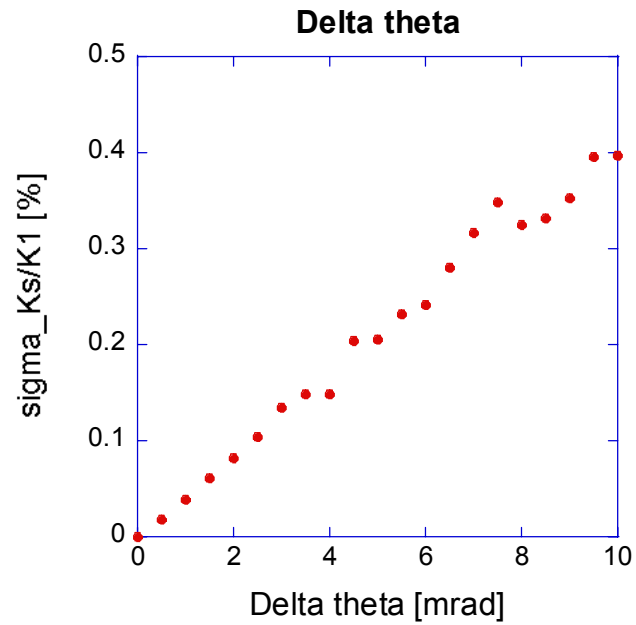
L1 = 0.0637909
L2 = 0.0500000
L3 = 0.0181046
D = 0.0100000

Beam Energy 250GeV
G = 140 T/m
theta = 30 degrees (K1 = 0.16793 [1/m])

100 random seeds for each point



0.31% @ sigma_Ks/K1 = 0.1%



2.4mrad @ sigma_Ks/K1 = 0.1%

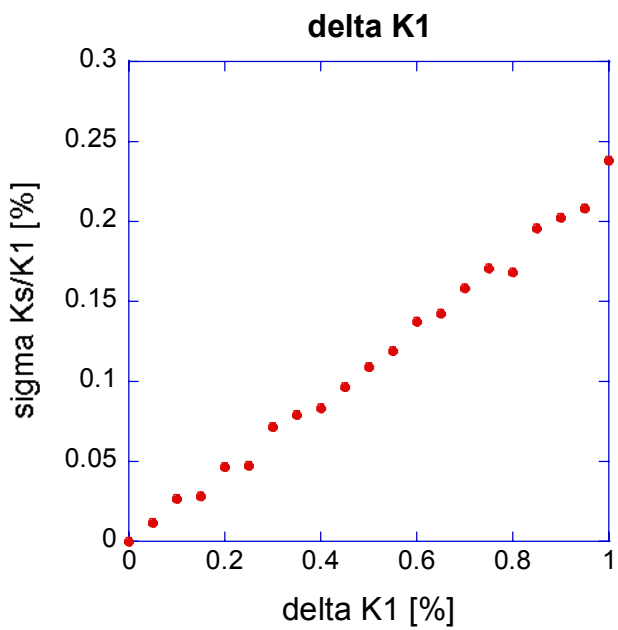
by T.Okugi

Magnet Error Estimation (triplet)

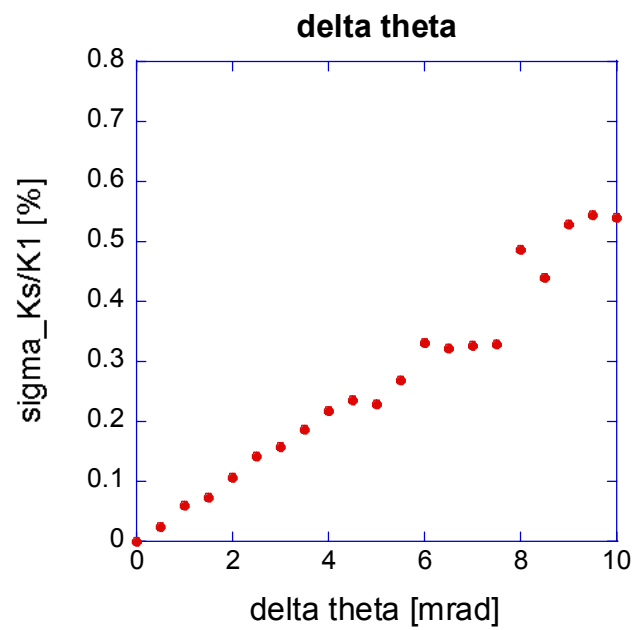
Simulation Condition

L1 = 0.1000000 Beam Energy 250GeV
L2 = 0.0500000 G = 140 T/m
D = 0.0100000 theta = 30 degrees (K1 = 0.16796 [1/m])

100 random seeds for each point



0.45% @ sigma_Ks/K1 = 0.1%



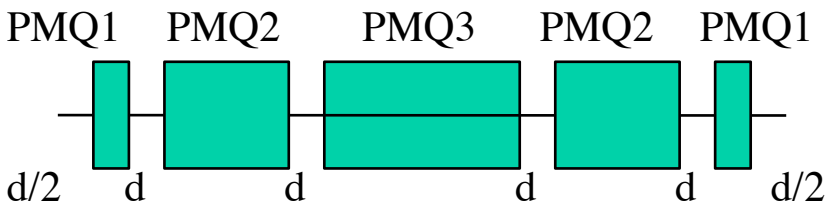
1.9mrad @ sigma_Ks/K1 = 0.1%

by T.Okugi

Final Focus Optics with Permanent Q

Permanent Mgnet

Unit of magnet



Dimensions
L[PMQ1]=a, L[PMQ2]=b, L[PMQ3]=c
a:b:c:=1.81046: 5: 6.37909 (Iwashita)
2a+2b+c=20cm
1cm Drift space between Q (d=1cm)

Qs are rotated by θ(PMQ1,3) and - θ(PMQ2) to adjust K1.

Permanent QD0

As QD0, 12 units of magnet are used.
Total length is 301cm including half drift spaces at both sides.

Installation of Permanent QD0

Starting with 'ilc2006b.ilcbds1'(14mrad version)
Since the original QD0 is of 2.2m length, adjustment of drift space is required to keep the total length unchanged.

D1B(QF1-SD0) L : 1.35 → 0.945m
D0 (L*) L : 3.51 → 3.105m

by S. Kuroda

Procedure of Fine Tuning for Optics with Permanent Q

Starting with 'ilc2006b.ilcbds1'(14mrad version), permanent QD0 is installed.

1. Linear Optics Matching

Since the permanent QD0 changed not only α^* and β^* but also η^*, we need to adjust some Q in dispersion region(FF section). QF1 is chosen as that knob because there is no change of transfer matrices between SXs upstream.

Variables for the matching:

K1 of QM(matching Q) and QF1

θ of PMQ(Fixed field gradient of 140T/m is assumed)

Matching requirement:

$\alpha x=\alpha y=0$, $\beta x=0.021$m, $\beta y=400$um, $\eta x=0$ at IP

Final θ of PMQ is 6.58 degree.

2. Off-Momentum Matching

Since the FF optics downstream of QF1 has been changed, we need to re-optimize K2 of SXs.

3. Fine Tuning of K2 of SXs looking at the beam size at IP.

QNAME	K1[1/m]	
	before	after
QM16	-0.00876	-0.00829
QM15	-0.00200	0.00128
QM14	0.00898	0.0156
QM13A	-0.0110	0.0117
QM13B	0.0423	0.0429
QM12	-0.0190	-0.0321
QM11	0.0179	0.0201
QF1	0.0963	0.0994

SXNAME	K2[1/m^2]	
	before	after
SF6	0.843	0.888
SF5	-0.217	-0.188
SD4	1.65	1.68
SF1	-1.09	-1.26
SD0	2.32	2.51

Final beam size obtained: $\sigma x/\sigma y=656$ / 5.44nm for $\gamma\varepsilon x/\gamma\varepsilon y=9.2e-6/3.4e-8$m and $\sigma\delta=6e-4$.

(636 / 5.25nm for original design)

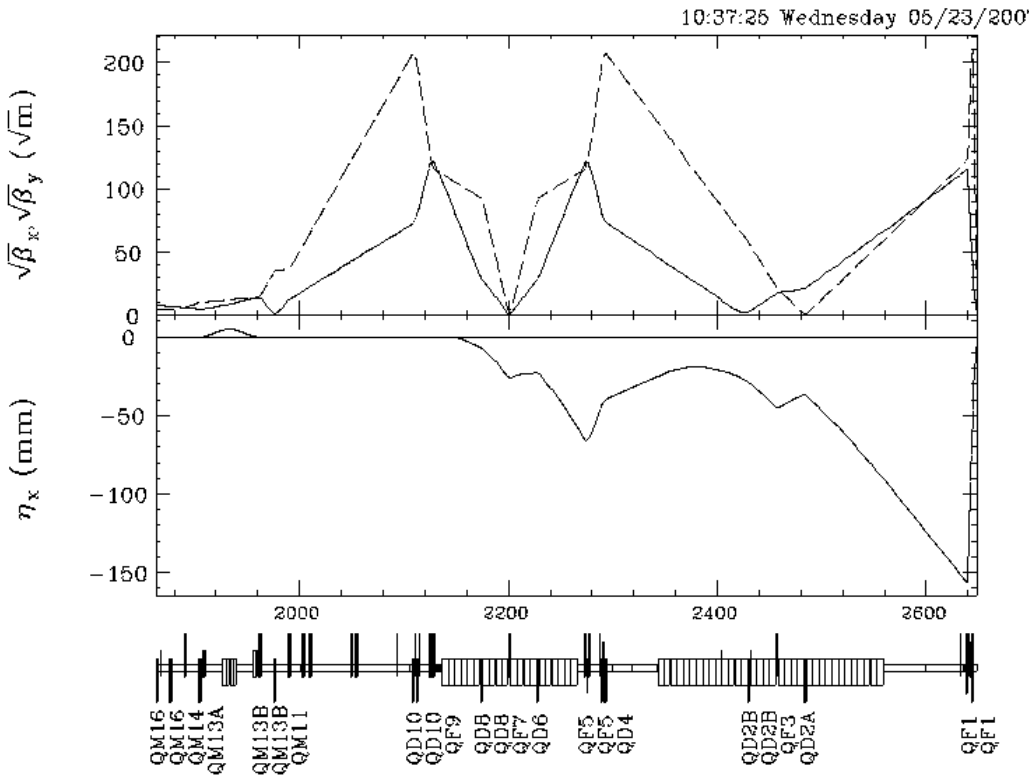
	DP				
	-6e-4	-3e-4	0	3e-4	6e-4
αx	-0.0372	-0.0184	-3.22e-7	0.0180	0.0357
βx	0.0210	.0210	0.0210	0.0210	00210
αy	0.252	0.124	7.82e-6	-0.120	-0.236
βy	4.19e-4	4.03e-4	4.00e-4	4.09e-4	4.30e-4
ηx	7.48e-6	3.62e-6	6.16e-11	-3.37e-6	-6.50e-6

Strength of SF1&SD0 must be checked.

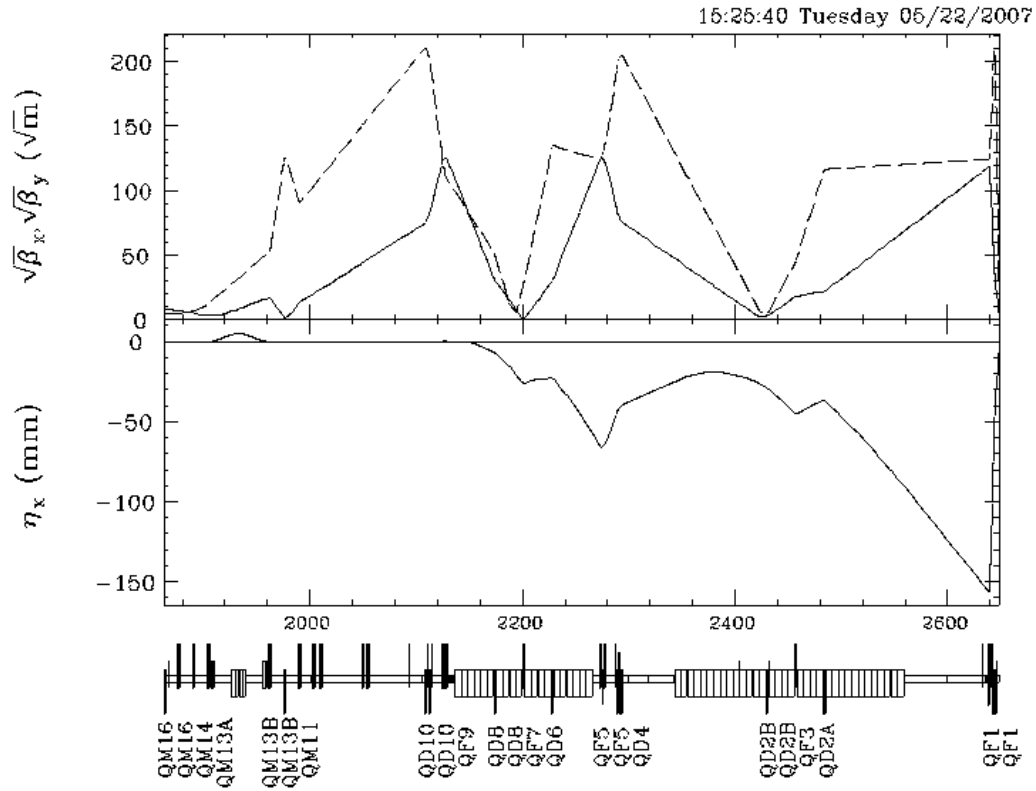
by S. Kuroda

Optics with Permanent Q

Original optics



Optics with permanent QD0



Optics with permanent QD0 is somewhat ugly.

Need to restore symmetry around the B section of s ≈ 2200m?

Optimization is not perfect(e.g. Octupole magnets were not touched...).

Need someone to complete the design.

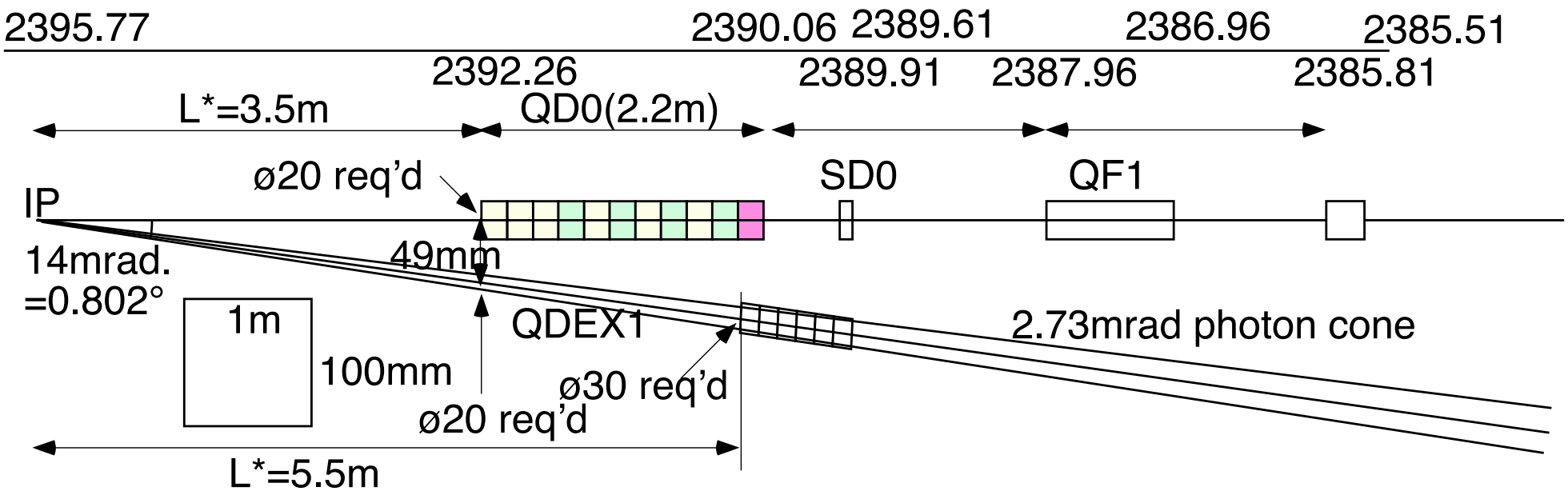
deck file is available at SAD computer:

'/users/kuroda/sad/jlc/ilc2006b.ebds1ForPMQ'

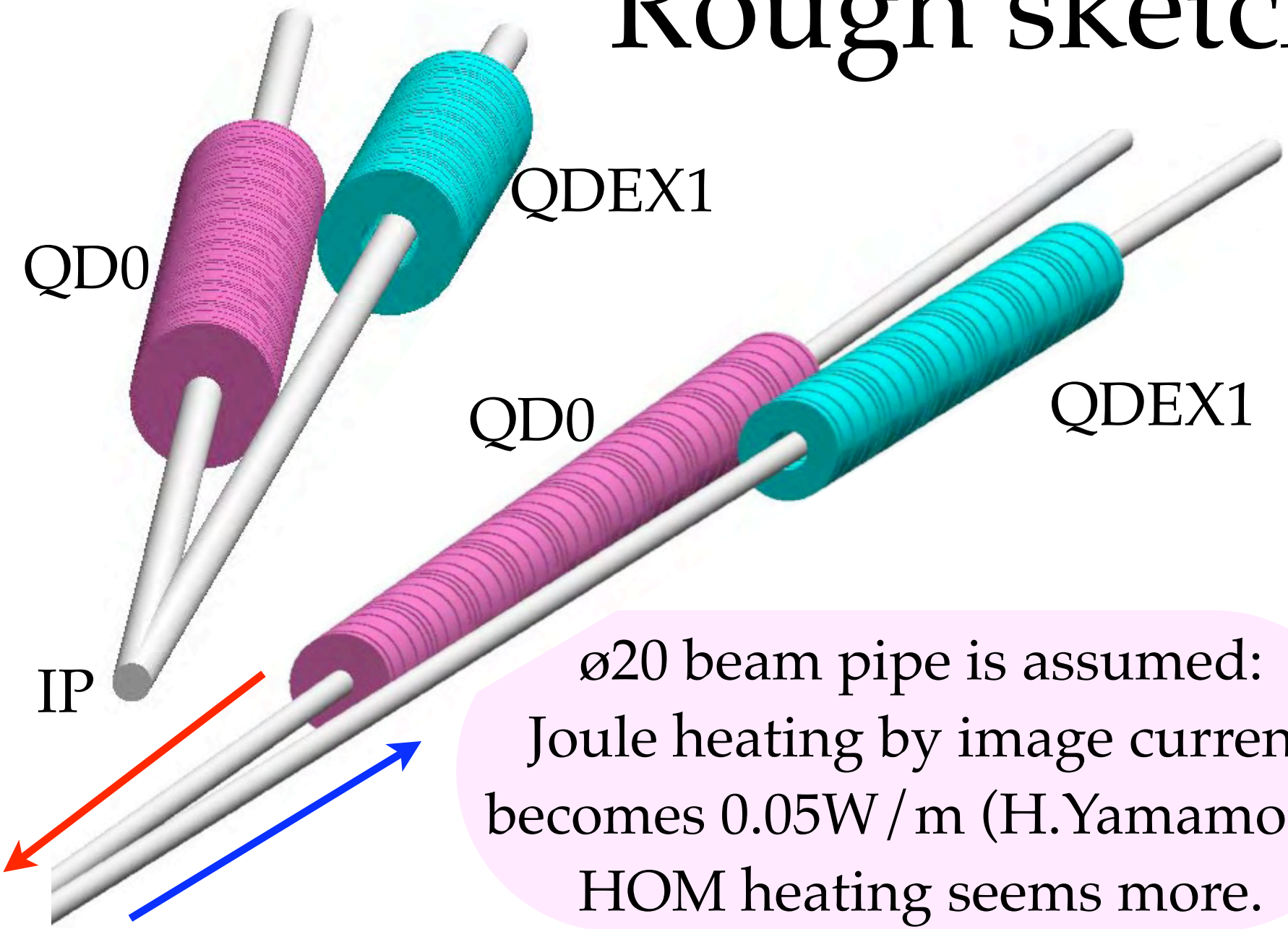
by S. Kuroda

Single Ring Train Configuration

	Eff.L [m]	R [cm]	kG	kG/m	GL [kG]
QF1	2.0	1	8	803	1605
QD0	2.2	1	-14.2	-1416	-3116
QEX1	1.1	1.5	-15.0	-1000	-1060



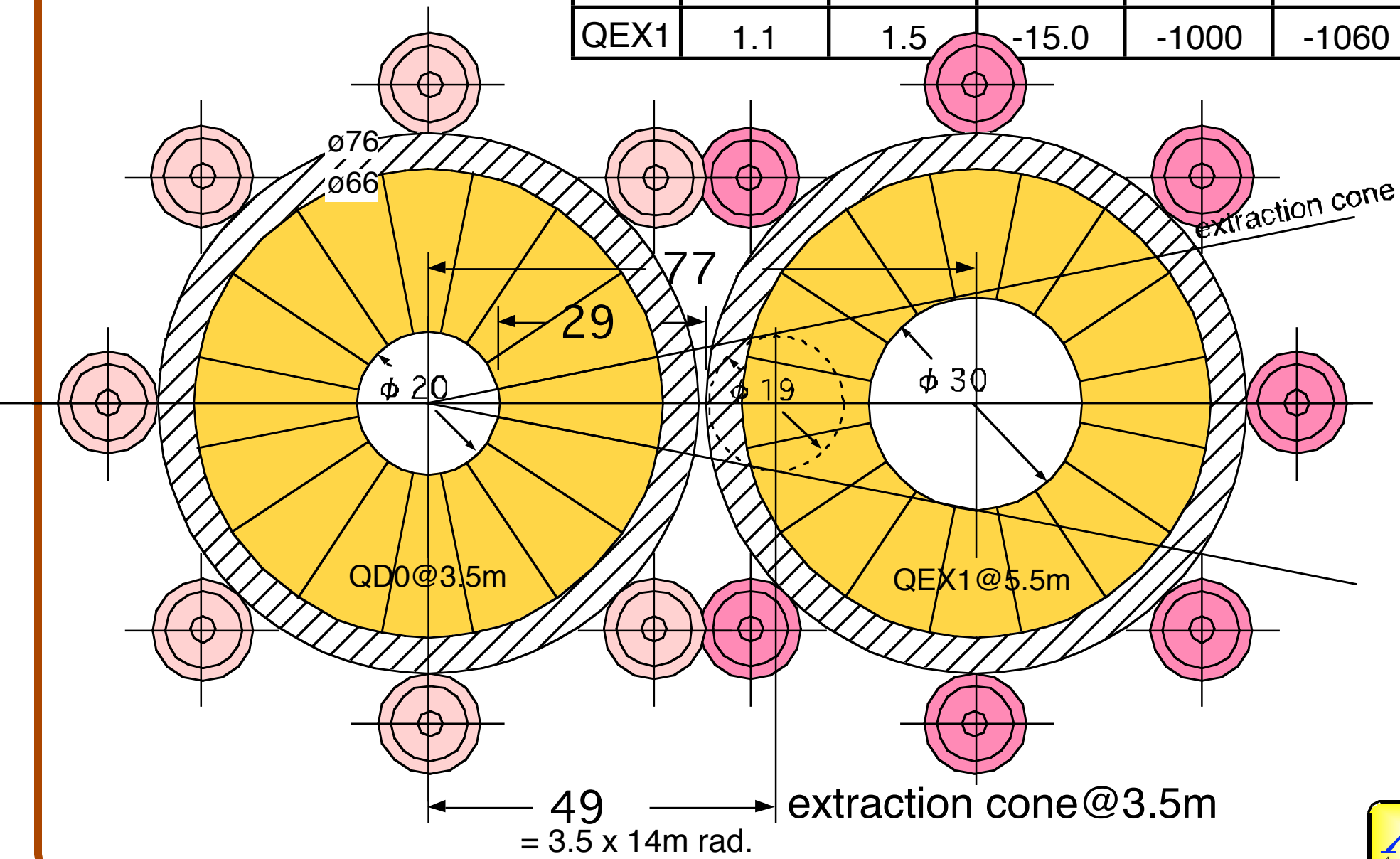
Rough sketch



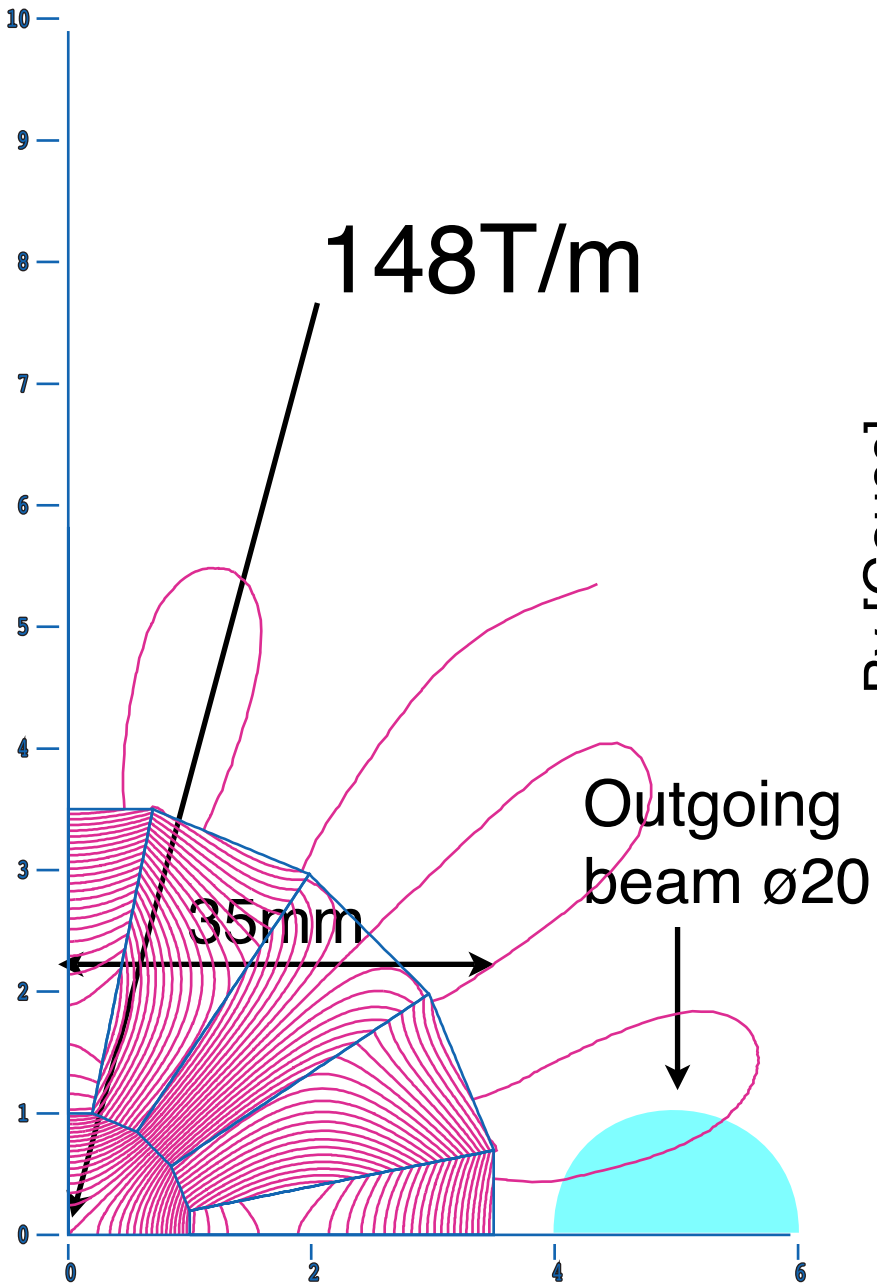
ø20 beam pipe is assumed:
Joule heating by image current
becomes 0.05W/m (H.Yamamoto)
HOM heating seems more.

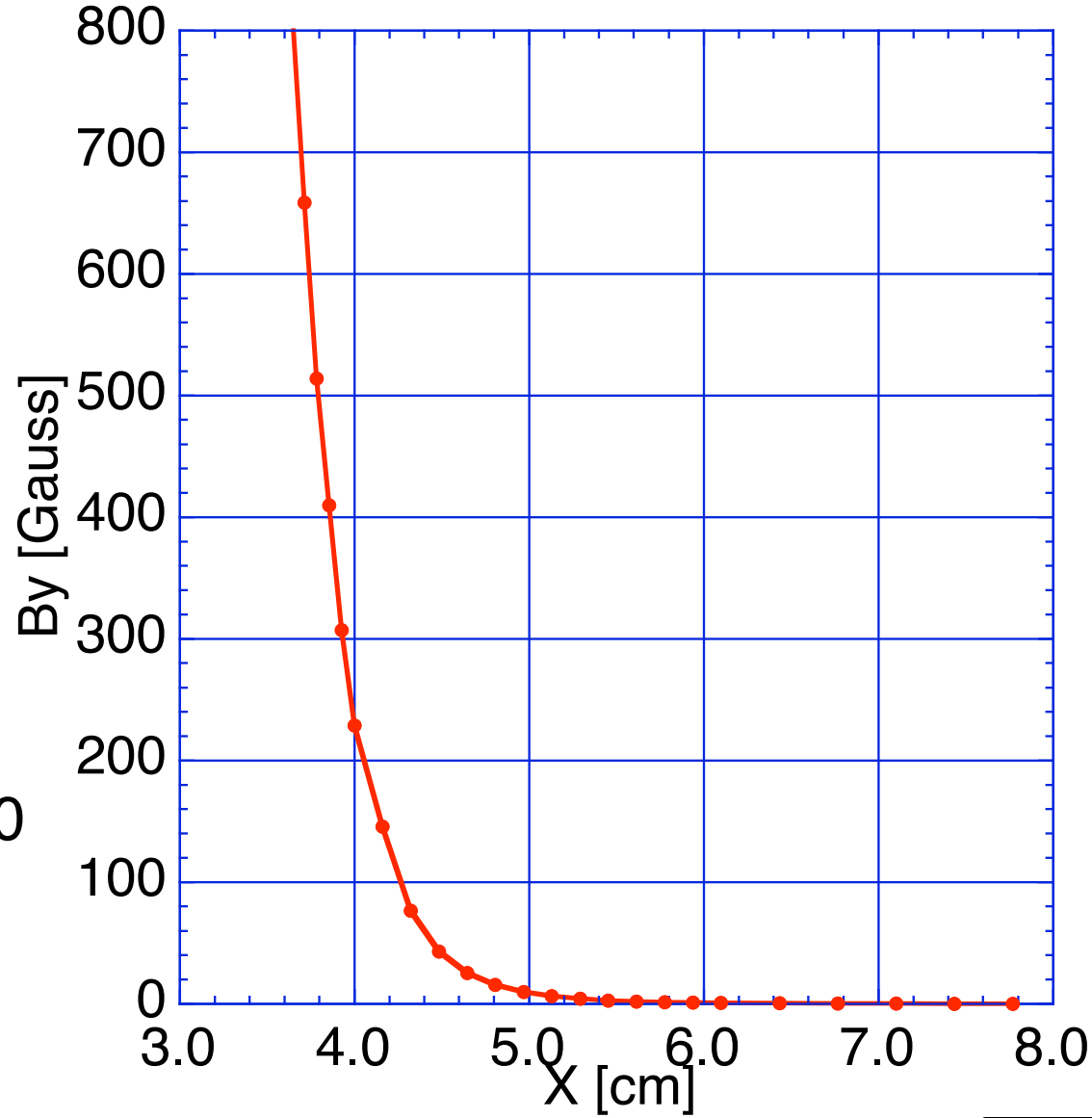
14mr option

	Eff.L [m]	R [cm]	kG	kG/m	GL [kG]
QF1	2.0	1	8	803	1605
QD0	2.2	1	-14.2	-1416	-3116
QEX1	1.1	1.5	-15.0	-1000	-1060

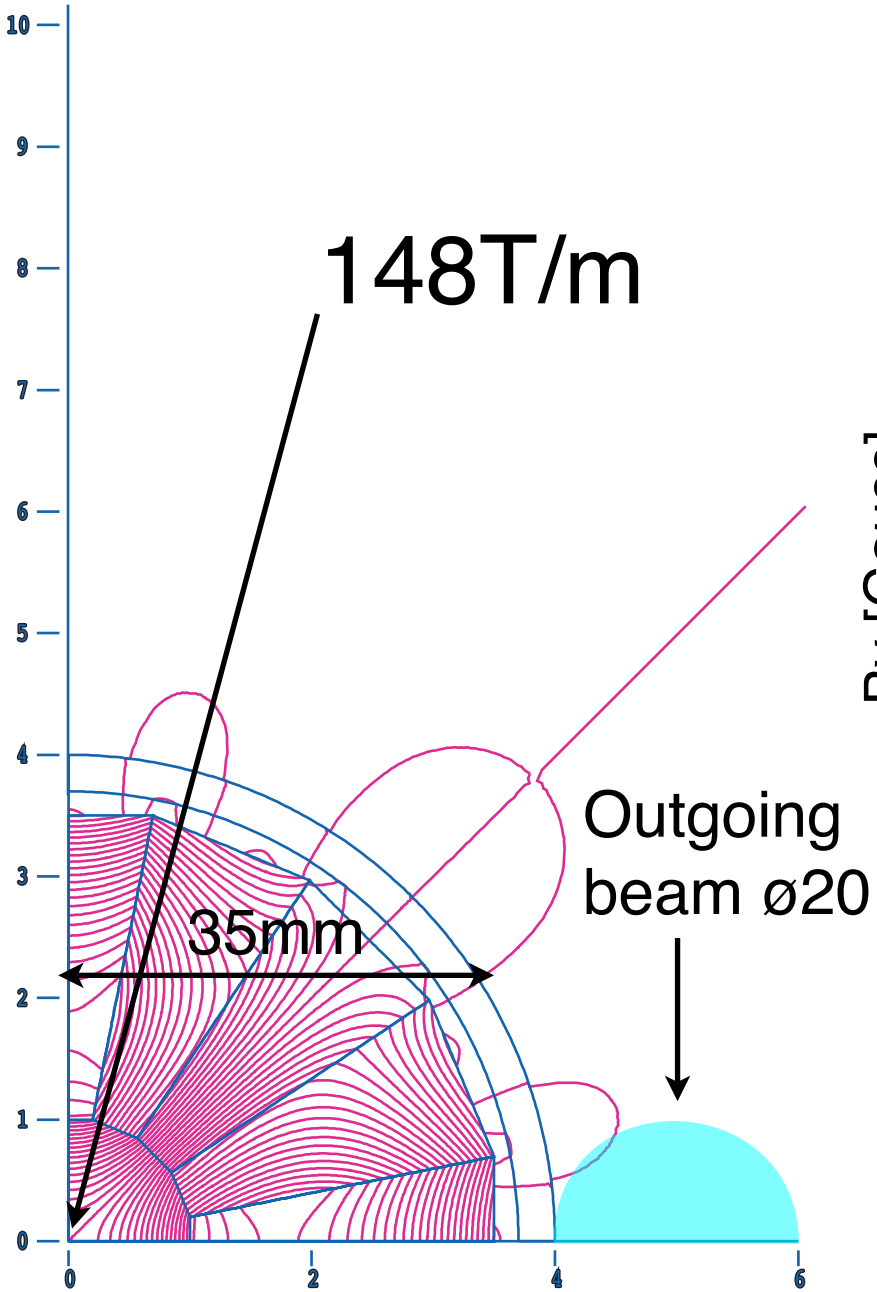


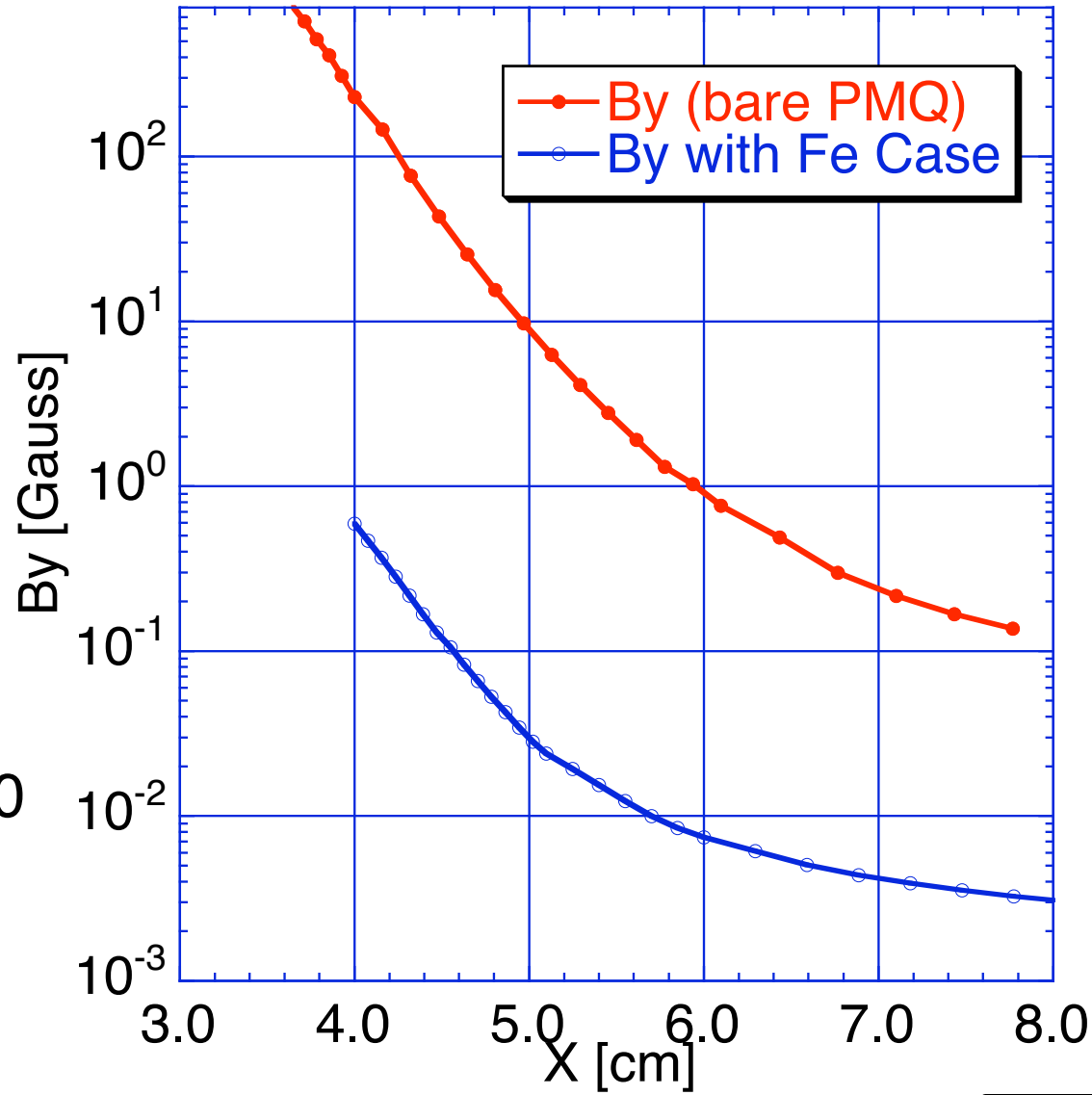
Alternative configuration: A Simple PMQ



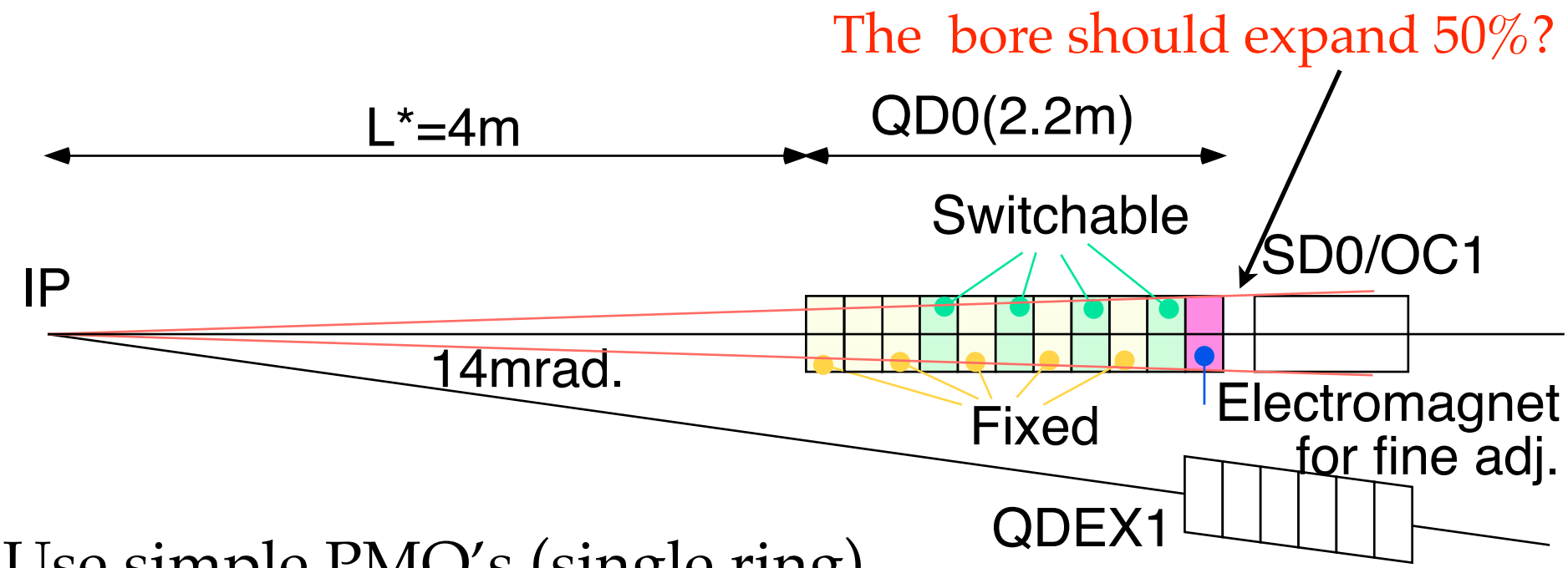


Alternative configuration: A Simple PMQ





A Possible Configuration with Simple PMQ



- Use simple PMQ's (single ring).
- 20% strength will be achieved by flipping 40% PMQ's.
- The step size can be reduced by subdividing the PMQ's.
- Fine adjustment by electromagnet.
- The center shift should be investigated for this config.
- ø20mm bore enough all along the 2.2m QD0?

Summary

- 1st variable PMQ was based on double-ring structure (for 20mr) and evaluated.
- 2nd one (for 14mr) will have **5-ring-singlet structure** whose skew effect can be canceled with appropriate ratios in lengths.
- The strength can be changed **continuously**.
- The **stray flux** outside PMQ can be small.
- PM only structure **withstands higher external field**.
- There is **no vibration source** in PMQ.
- Image current heating of beam pipe has to be study.
- A prototype will be fabricated this FY.

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