Open Midplane Dipoles and Crab Cavity Quadrupoles

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Contents

Open Midplane Dipoles:

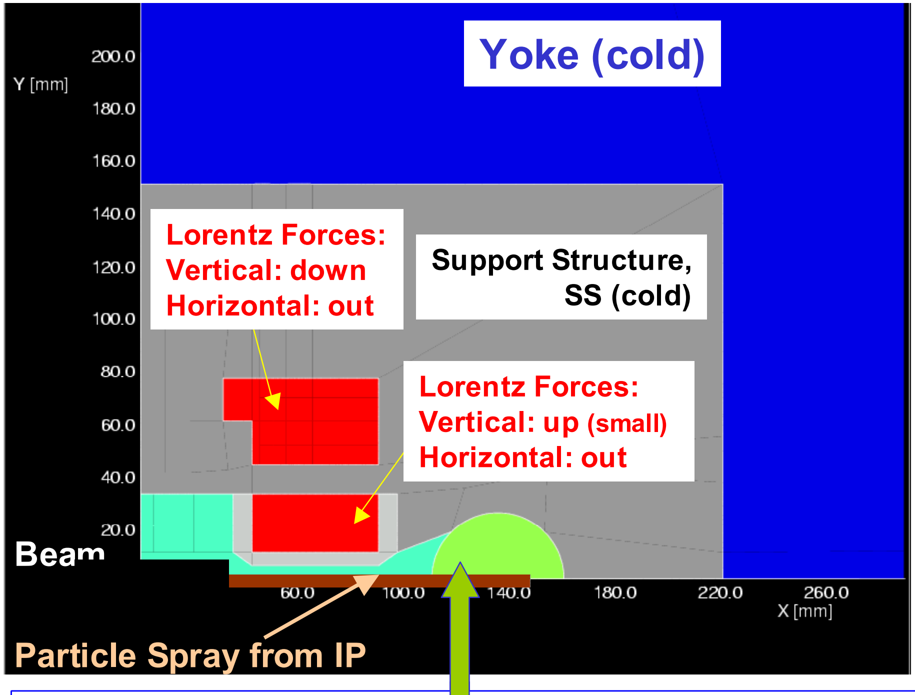
- Achievable Fields in Open Midplane Dipole Designs made with
  - ⊗ Nb_3Sn
  - ⊗ NbTi
  - ⊗ Hybrid (HTS + Nb3Sn)
- Advantage, Challenges, R&D and Cost Consideration

Quadrupoles Designs for Crab Cavity Optics:

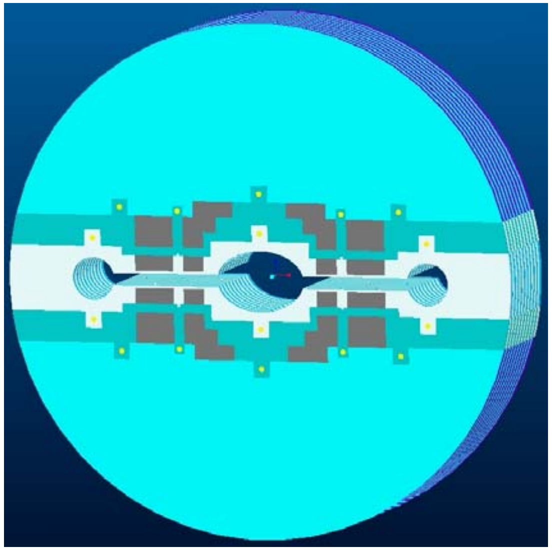
- Three possible options
  - ⊗Nb_3Sn
  - ⊗ NbTi
- Challenges

A True Open Midplane Design

By *Open Midplane*, we mean truly *Open Midplane*:



Particle spray from IP (mostly at midplane), passes through an open region to a warm (~80 K) absorber sufficiently away from the coil without hitting any structure at the midplane.



A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

Earlier designs did not work so well because the secondary showers from the other structure at the midplane deposited a large amount of energy on the superconducting coils.

Energy Deposition Summary (Nikolai Mokhov 04/05)

SUMMARY

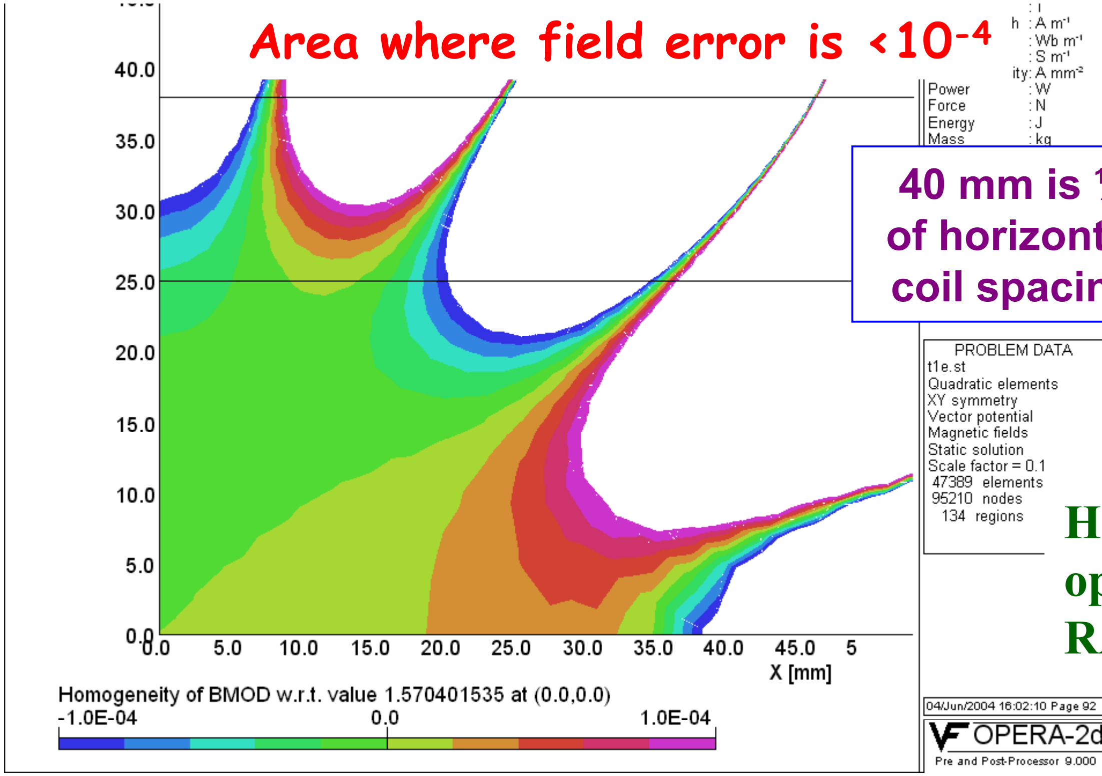
- The open midplane dipole is very attractive option for the LARP dipole-first IR at $\mathcal{L} = 10^{35}$. The design accommodates large vertical forces, has desired field quality of 10^{-4} along the beam path and is technology independent.
- After several iterations with the BNL group over last two years, we have arrived at the design that – being more compact than original designs – satisfies magnetic field, mechanical and energy deposition constraints.
- We propose to split the dipole in two pieces, 1.5-m D1A and 8.5-m D1B, with a 1.5-m long TAS2 absorber in between.
- With such a design, peak power density in SC coils is below the quench limit with a safety margin, heat load to D1 is drastically reduced, and other radiation issues are mitigated. This is a natural two-stage way for the dipole design and manufacturing.

Fermilab

N. Mokhov

Field Harmonics and Relative Field Errors in an Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:



Harmonics optimized by RACE2dOPT

(Beam @ x=+/- 36 mm at far end)

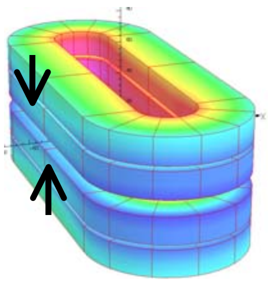
(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

Field errors should be minimized for actual beam trajectory & beam size.
It was sort of done when the design concept was being optimized by hand.
Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.
However, the design as such looks good and should be adequate.

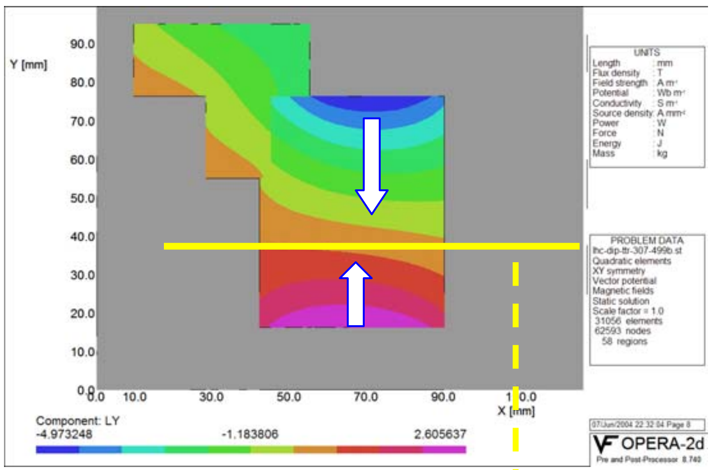
Design Optimized For Lorentz Forces



In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils.

- **Special design concept is developed to deal with this**

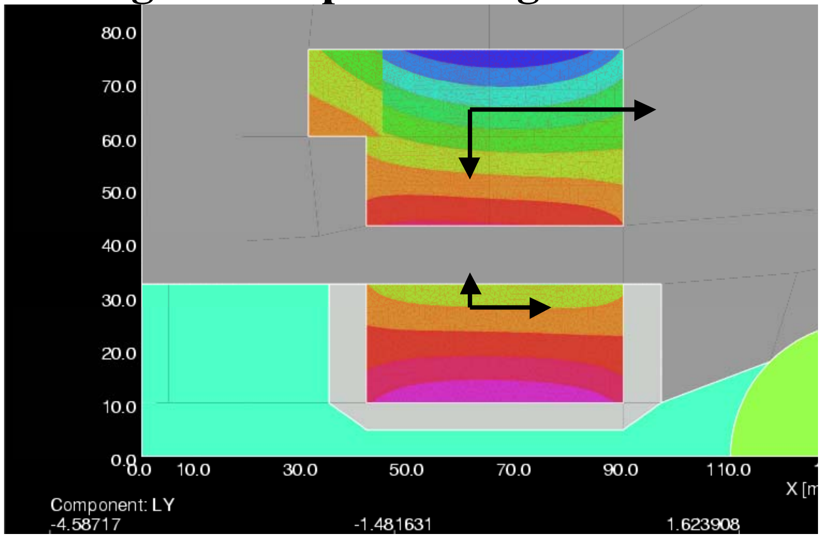
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to navigate Lorentz forces



Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

LARP Midplane Design Iterations

Nb_3Sn designs investigated as a part of LARP:

Please see PAC05 Paper for details

	A	B	C	D	E	F
H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40
V/H	0.39	0.15	0.31	0.25	0.43	0.33
B_o(T)	13.6	13.6	13.6	13.6	15	13.6
B_{ss}(T)	15	15	15	14.5	16	15
J_c(A/mm^2)	2500	3000	3000	3000	3000	3000
Cu/Sc	1	1,1.8	0.85	0.85	0.85	1
A(cm^2)	161	198	215	148	151	125
R_i(mm)	135	400	400	320	300	300
R_o(mm)	470	800	1000	700	700	700
E(MJ/m)	2.2	4.8	9.2	5.2	4.1	4.8
F_x(MN/m)	9.6	10.1	12.3	9.5	10.4	9.6
F_y(MN/m)	-3.0	-6.8	-8.7	-7.0	-5.1	-5.4

Open Midplane Designs With Niobium Titanum (NbTi)

H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40

NbTi Open Midplane Dipoles with above apertures could be designed so that at 1.8 K, they operate at a field of ~ 8 T (quench field ~9.5 T).

Open Midplane Designs With High Temperature Superconductors (HTS)

H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40

- In such applications, HTS makes most sense when it is used in a hybrid design with Nb_3Sn coils.
- Such magnets, in principle, could be designed to operate at a very high field (16 Tesla and above).
- Another advantage of HTS is that it could tolerate a large amount of energy deposition. In a hybrid design, HTS will be used in lower and inner coils - the places where the heat load and peak fields are relatively high (and HTS is most advantageous).

Magnet Size, Conductor Uses, Magnet Cost, Risk and R&D in Open Midplane Dipole

Magnet Size:

Many designs have shown that overall dimensions of *"Open Midplane Dipole"* is similar to conventional *"Cosine Theta Dipole"*.

Conductor Uses:

***"Open Midplane Design"* uses significantly more conductor (20%-50%) than conventional *"Cosine Theta Design"* with no midplane gap.**

Magnet Cost:

For small number of high tech magnets, the magnet cost is primarily determined by the R&D program, rather than the cost of conductor.

Risk:

This is a new design and hence expect a larger risk associated with it. The risk also depends on the type of conductor used, etc.

R&D Program:

The risk can be minimized by a step-by-step systematic R&D program (see earlier presentations). Expect a longer R&D program, however, intermediate results will be available in a systematic and cost-effective R&D program.

IR Quads for Crab Cavity Optics

- In *"crab cavity optics"*, the two beams have a large crossing angle - nominal 8 mrad (other variants use 2-8 mrad), as compared to 0.225 mrad in LHC.
- This means that IR should be consisted of two side-by-side quadrupoles.
- Required gradient is 200 T/m; field quality must be very good.
- Since, the separation between two beams is not large enough for two separate quads (184 mm minimum), the two coils must be placed in a common yoke, at least for Q1.

Courtesy:
Rama Calaga &
Rogelio Tomas

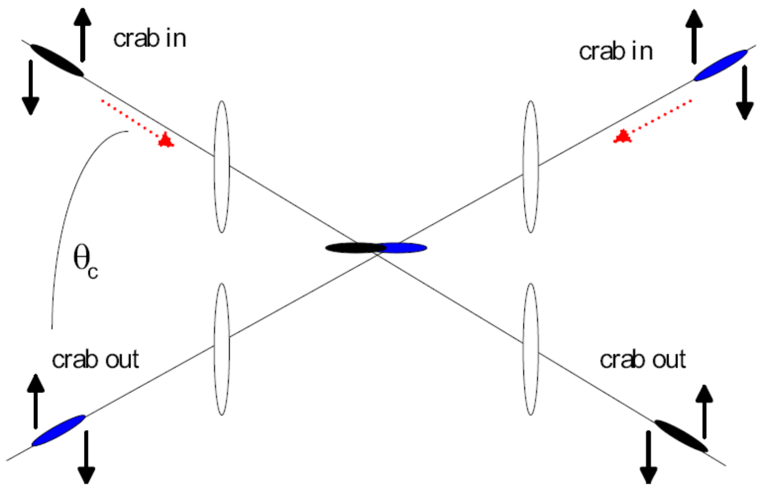
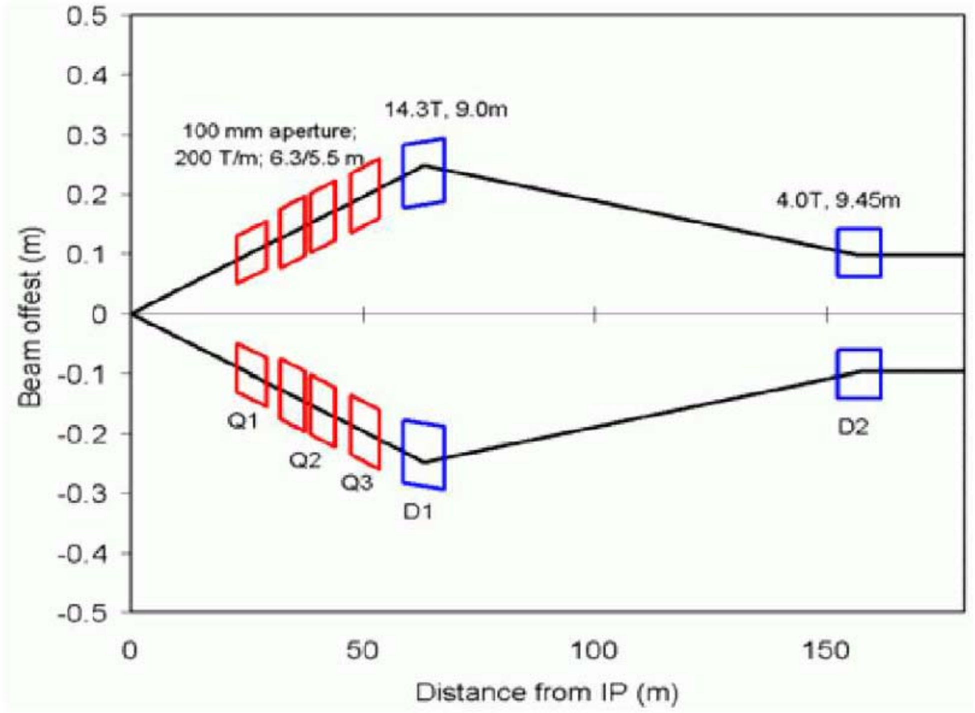


Figure 4: The crab crossing principle. Incoming bunches are tilted by transverse deflecting mode crab cavities on the extremities of the IR so that they collide head-on. The tilt is removed on exit by another set of RF cavities [2].



Design Considerations for Quads for Crab Cavity Optics

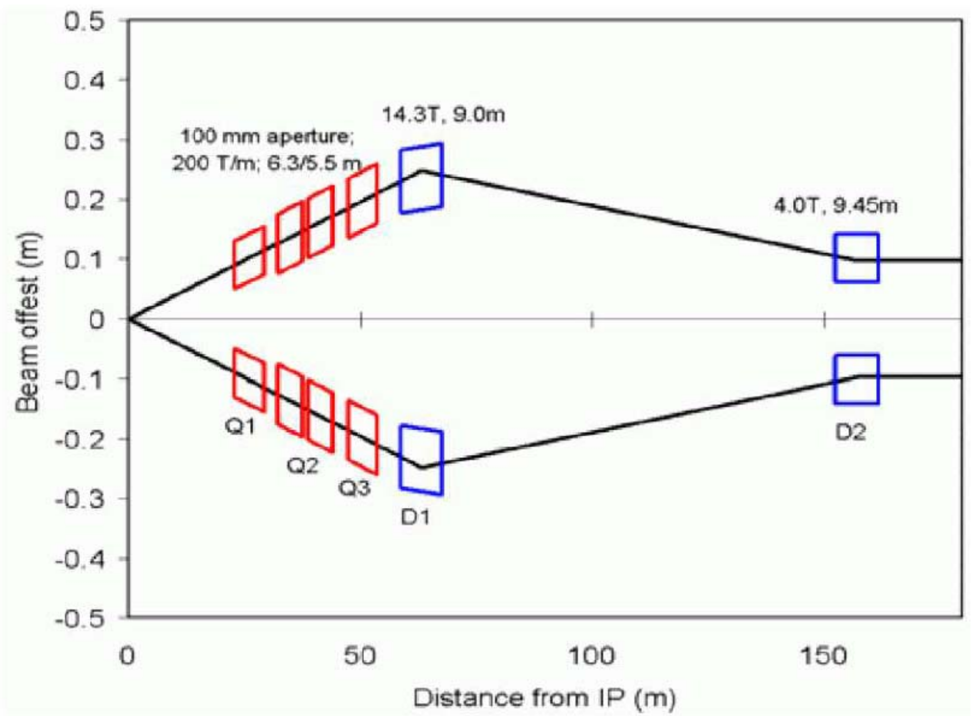
Because of large crossing angle, the separation between the two counter-rotating beam changes significantly as beam passes through these quadrupoles : Difference in beam separation between the entrance and exit end of Q1-Q3 is ~45-55 mm.

<u>This offers three different options:</u>

(1) Two side-by-side quads that are parallel and the change in separation is accommodated in aperture.

(2) Two side-by-side non-parallel quads whose magnet axis are aligned to the beam axis (see picture on right).

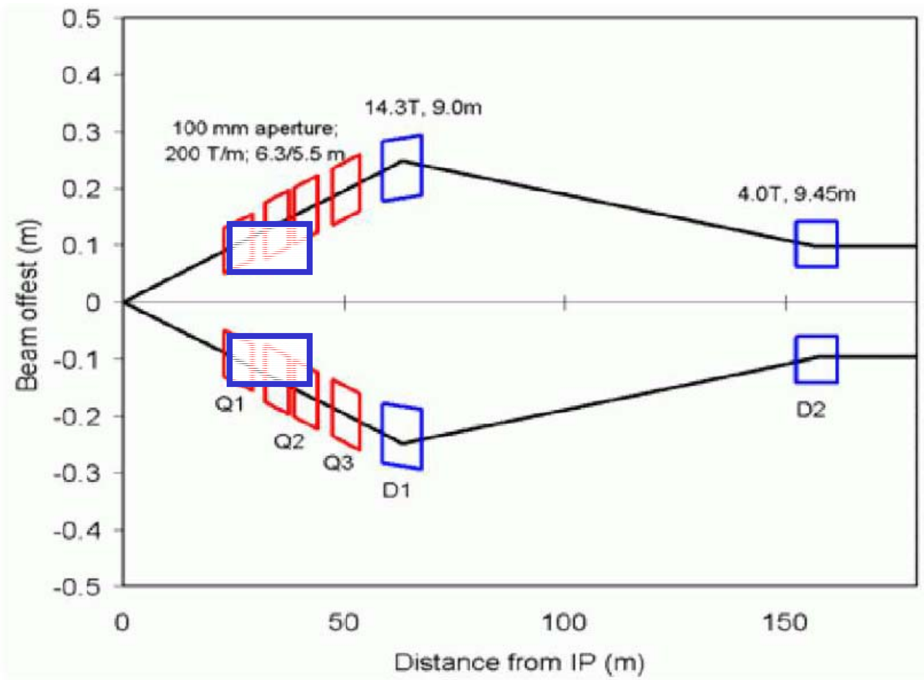
(3) Two side-by-side quads that are staggered such that each quad has a field free region for another beam.



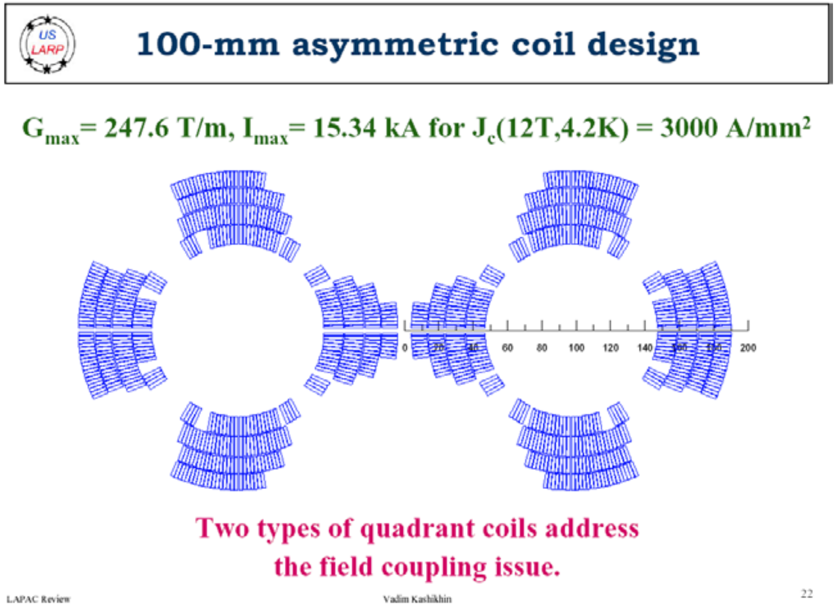
Each option is examined briefly in subsequent slides.

Larger Aperture Parallel Quads (Option 1)

- This is the case when non-parallel, counter-rotating beam pass through the aperture of two side by side quads laid out parallel to each other.
- In this case, in order to accommodate the separating beams, the aperture of each quad must be increased by ~25 mm (half of ~45-50 mm).
- Aperture: ~100 mm, Gradient: 200 T/m =>>> Magnets should use Nb_3Sn technology.
- Because the separation is small, the cross-talk must be carefully minimized by design to obtain required good field quality. Mechanical structure needs to be carefully examined.

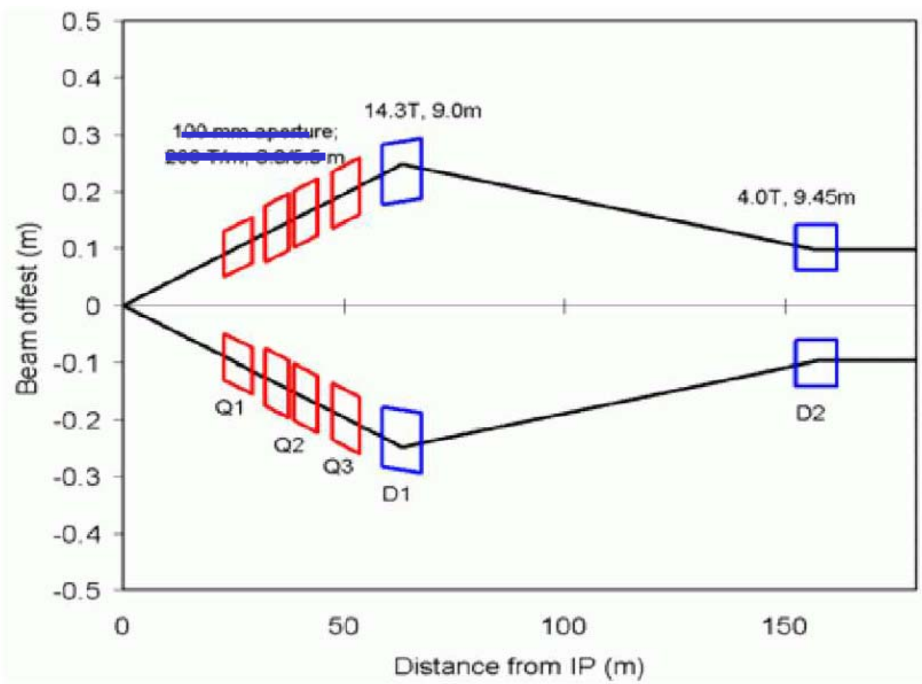


Courtesy: V. Kashikin, FNAL



Smaller Aperture Non-parallel Quads (Option 2)

- **In this case quadrupole axis is aligned to the non-parallel beam axis.**
- **Therefore the aperture requirements are lower (by ~30% as per Rogelio Tomas).**
- **200 T/m, 70 mm aperture can be (has been) made with NbTi. (Is 70 mm OK?)**
- **However, this scenario poses significant challenges in magnetic and mechanical design.**



- **Since the two side-by-side Q1 quads are close, the cross talk between the two will be large. (Out of 184 mm spacing, 70 mm goes for aperture, ~90 mm for two coils, thus leaving ~24 mm space in between).**
- **One can come up with a 2-in-1 magnet and coil cross-section to keep cross talk low for one separation. However, since the separation changes by a large amount (~50 mm) axially, to keep cross talk small, the cross-section may have to change too.**
- **More work is needed but it appears that 3-d magnetic and mechanical design of the non-parallel structure will be challenging.**

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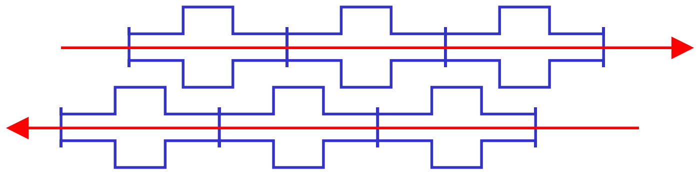
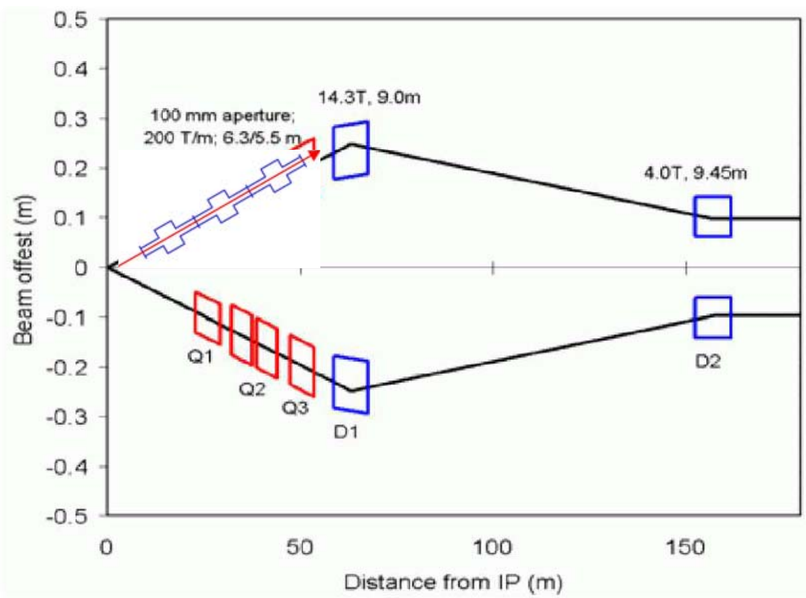
Smaller Aperture Staggered Quads (Option 3)

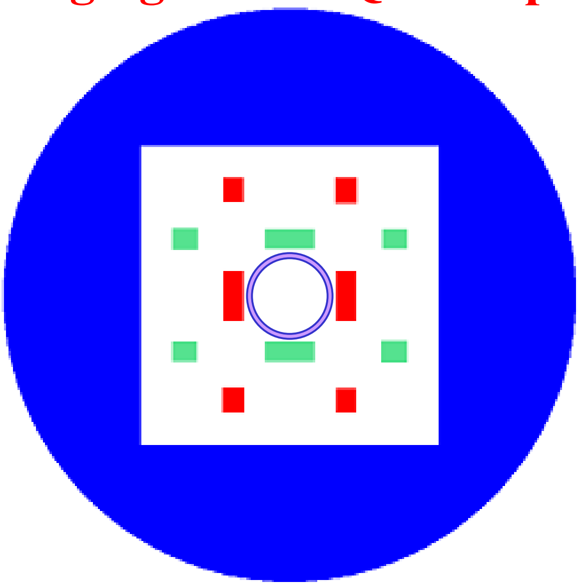




- The third option is to staggered focussing for the two counter rotating beams.
- This means that at the critical location, we have high gradient quad on one side (for one beam) and field free region on the other side (for the other beam).
- This will allow two beams to come closer since the field free region takes much less space than a quadrupole magnet.
- Staggering may just be needed for Q1. Moreover, a better solution may be possible if new optics and magnet designs are optimized together.
- This will work provided if a field free region can be found just outside the coil.

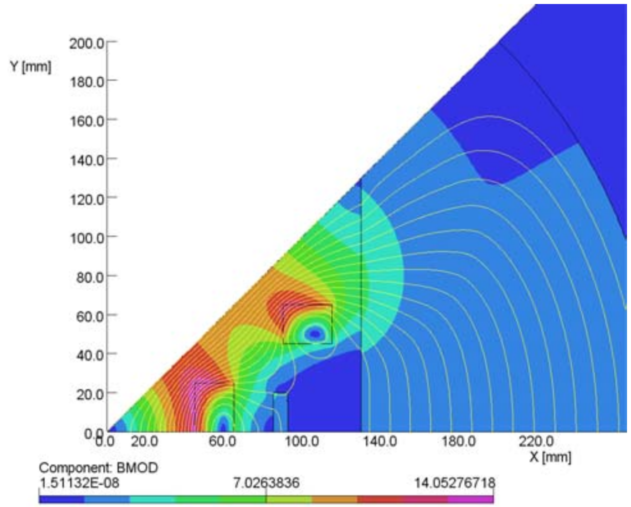
Modular Design for Crab Cavity

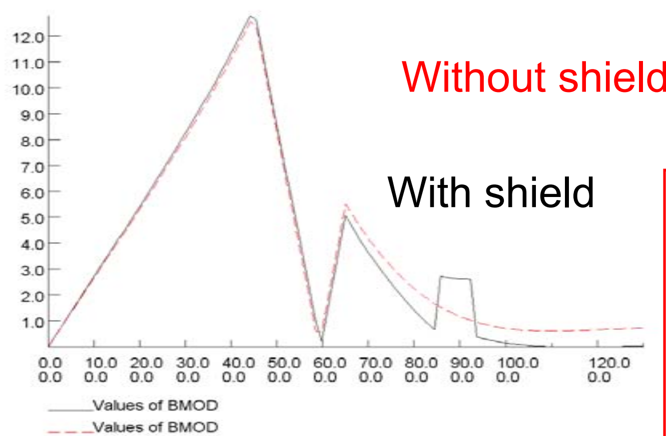
A racetrack design for high gradient Quadrupole



(Details in ASC06 Paper)

Steve Peggs noticed that the design naturally leaves a field free space that can be used by another beam in crab cavity optics.





Field harmonics optimized with RACE2DOPT for 90 mm aperture coil at 30 mm reference radius (2/3 of coil radius).

Harmonic	Value
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

NOTE:

The 2-d harmonics (given in 10^{-4} units) are essentially zero.

These 70 mm aperture magnets can be easily made with NbTi. They use twice the conductor, but that should be acceptable for a few critical magnets.

Summary

Various options for open midplane dipole and crab cavity quadrupole have been examined

- **Variation in magnet aperture**
- **Variation in magnet designs (cosine theta and racetrack)**
- **Variation in conductor type (NbTi, Nb3Sn and HTS)**

Both of these options require more design work and then R&D to prove that the design challenges can be met.