Here is a grand summary, reverse chronological order of various design options for superconducting final focus magnets that can accommodate various crossing angle scenarios including gamma-gamma requirements. For completeness I am including the email explanation sent with each file before each set of figures.

An outline of this document is given on the next page. Note that this is very much a work in progress and one should be careful about taking some of the earliest ideas out of context (i.e. as more understanding of realistic design constraints evolved).

At the SLAC ILC workshop my understanding of the FF requirements underwent a complete turnabout in that before the workshop we had a readily achiveable superconducting magnet design, compatible with 20 mr total crossing angle, with the main uncertainty being how to guarantee nm position stability. With the adoption of the cold linac bunch structure plus active feedback it has been claimed that the stability requirement is relaxed two order of magnitude to 100 nm but then the question was turned around to be how far the magnet design can be pushed to accommodate a desire to reduce the crossing angle.

For a related problem, determining the minimum x-ing angle geometry for gamma-gamma, there is an additional constraint that the spent electron beams cannot exit though regions of "high field" since they include energies all the way down to 8 GeV.

The following is a snapshot of some investigations, really brainstorming, to map out some limits as to what is possible. Preliminary indications are that it may reasonably be possible to go down to about 12 mr x-ing for e+e- and close to 20 mr for gamma-gamma. Some more exotic speculations on single aperture double field quadrupoles to go down close to 6 mr are also presented but these approaches bring practical limits in achievable field quality.

Brett Parker (parker@bnl.gov) 2-Nov-04

#1: pg 3-10 Final gamma-gamma concept with exterior compensation, (Comments sent with gamma_quad_new.pdf)

#2: pg 11-13 First gamma-gamma concept with close in, non-linear (sextupole) compensation (Comments sent with gamma_comp.pdf

#3: pg 14-15 Compensating outbound beam kick (Comments sent with skew.pdf)

#4: pg 16-24 Optimized x-ing angle solution (Comments sent with three_layer.pdf)

#5: pg 25-31 Later generalization to double field quadrupole having equal gradients at the two beam locations by using octupole-like symmetry (Comments sent with obq_26oct04.pdf)

#6: pg 32-42 Semi-realistic double field quadrupole that has opposite gradients at the two beam locations using sextupole-like symmetry (Comments sent with dfq_21oct04.pdf)

#7: pg 43-49 Original Proposal from SLAC ILC Workshop: SpecialMagnets3.pdf

Note: The original figures are not from PowerPoint (Canvas 9.0 is the graphic design program that I use); however, from Canvas I can easily export a specific figure in a variety of formats, jpeg, being one that is particularly convenient. B. Parker 2-Nov-04

Comments sent with gamma_quad_new.pdf (7 pages)

>
> Hi Brett,
>
> This work indeed is very interesting and can open more possibilities.
>
> Rather than (or in addition to) forwarding this your message,
> would it be possible if you would put together several slides,
> which would summarize also your earlier messages and all your
> recent results that you came up with in the last two weeks?
>
> These slides then could be sent to the persons preparing the
> Final doublet talk and the Gamma-gamma talk at ILC meeting.
>
> Thank you!
>
> Best regards
>   Andrei
>

Ok, I‘ll put together a summary but it may be a day or so before I get it done. Hopefully this is acceptable?

The main point of this email is to report on some final work I did at home this weekend on improving my gamma-gamma solution. It occurred to me that if we do not use a strong sextupole magnet in the compensation coil (i.e. to really null out the field over a larger region) then there is not much penalty in making the compensation coil large enough that the inner quad fits inside it (as I proposed for the normal final focus).

This gets rid of more structure between the incoming and outgoing beams so maybe the x-ing angle could again be brought down to 20 mr. This is what I have done with the attached pdf file.

The attached file has two cross sections. The first near the IP and the second a larger coil for use at the IP away end. With a combination of an external quadrupole coil plus dipole coil I can set the field to zero at two locations (here chosen to be the center of the inner quad and the nominal point defined by the 20 mr x-ing angle). Note the coordinate system is always with respect to the main quad center.

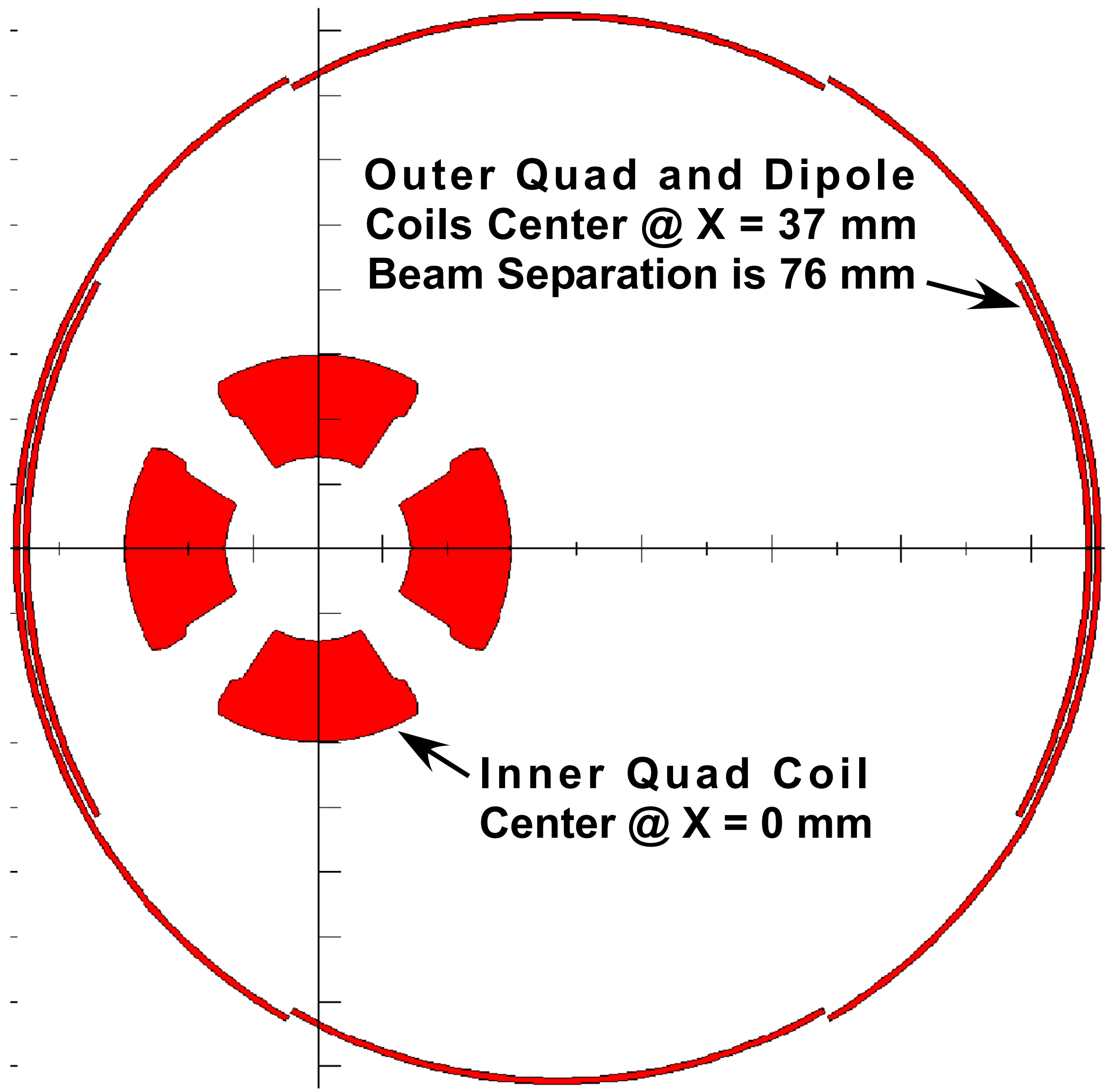
Constraining the zero crossings does not leave me with freedom to zero out the gradient seen by the extracted beam but the gradient starts out fairly small 4.4 T/m and drops to 0.8 T/m by the end of the 2 m long magnet.

If we relax the zero constraint for the main quad, either by giving it a slight horizontal tilt or adding one more small diameter dipole corrector just around the main beam pipe, then it is possible to zero our or even reverse the gradient at the extracted beam location.

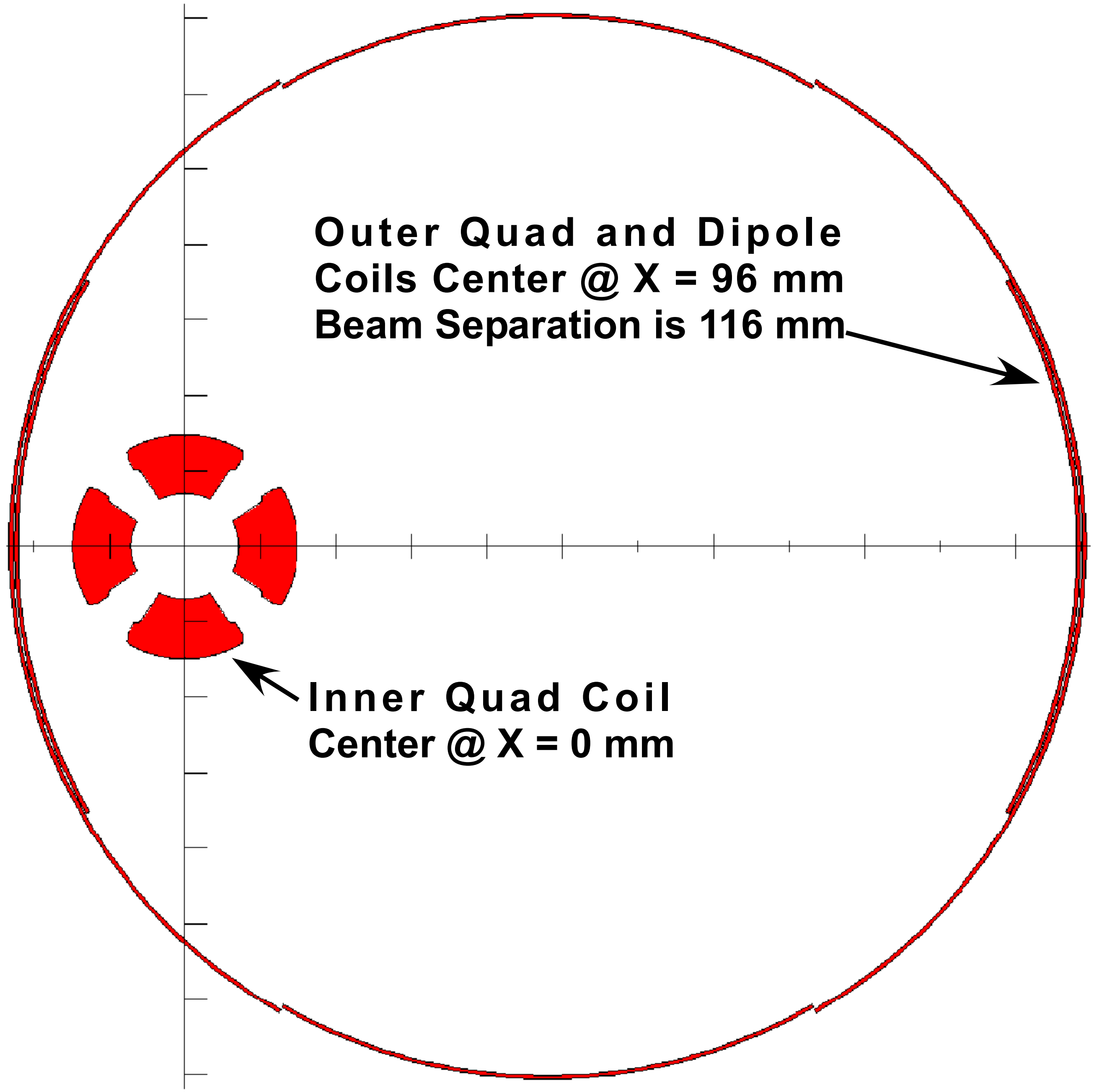
My personally favored solution would be to under compensate at the IP end and over compensate at the IP away end so that we end up with a weak quadrupole doublet that hopefully can be used to help contain 8 GeV beam while leaving high energy particles unaffected. A subtle point is that if this solution uses dipole distributions of opposite polarity along the magnet then the net torque to the cold mass due to interaction with the solenoidal field can be reduced.

I still worry that low energy particles may tend to follow the detector solenoidal field rather than the 20 mr outgoing beam direction so realistic tracking would be required decide upon a final optimum solution. Once we get the tapered coil option working in out Serpentine coil winding code (right now has small bug with tapered magnets) I can do 3D calculations and with rather modest effort can then provide coarse grained 3D field maps.

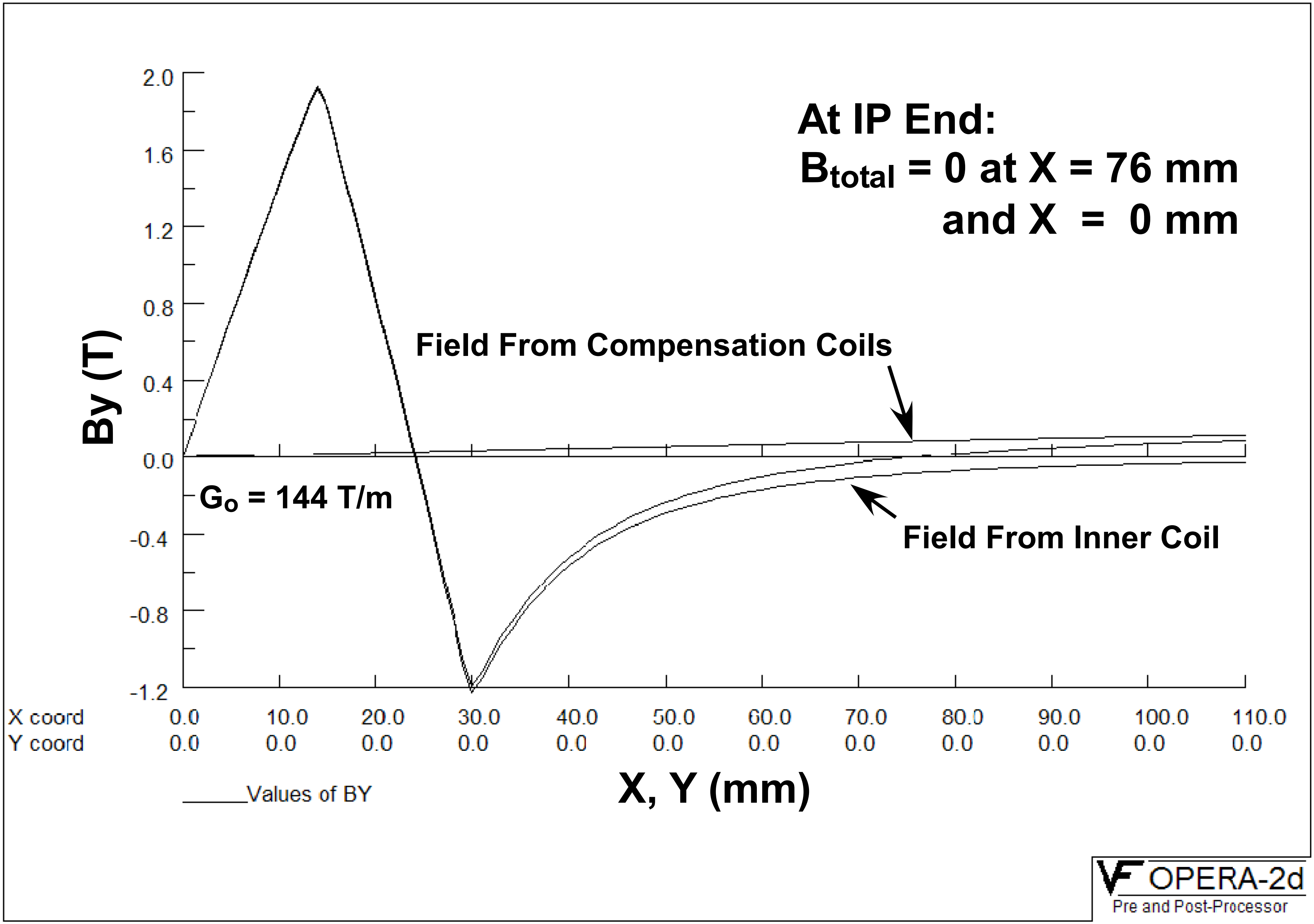
QD0 Coil Overlaid with Compensation Coils at IP End



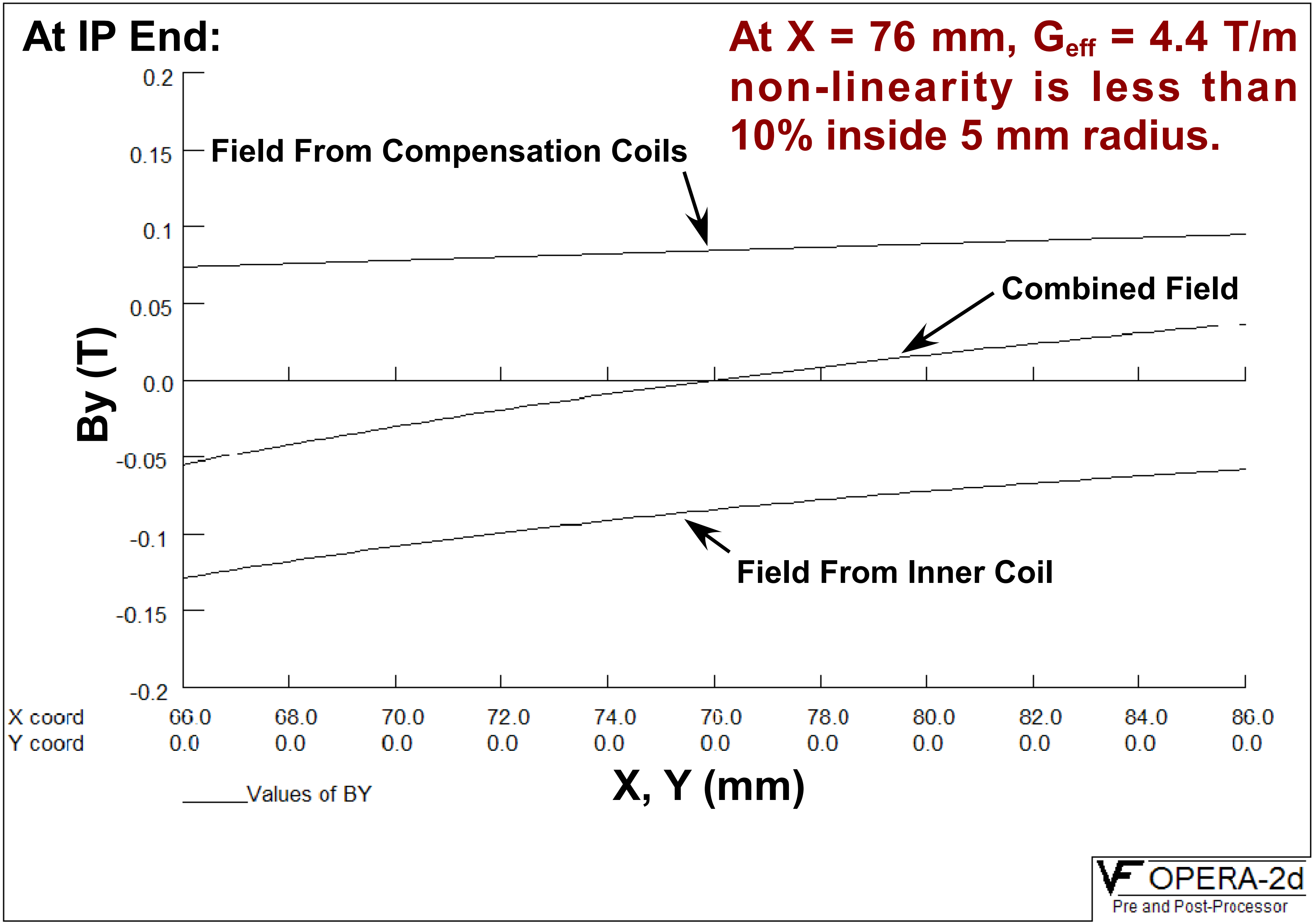
QD0 Coil Overlaid with Compensation Coils at End Away From IP



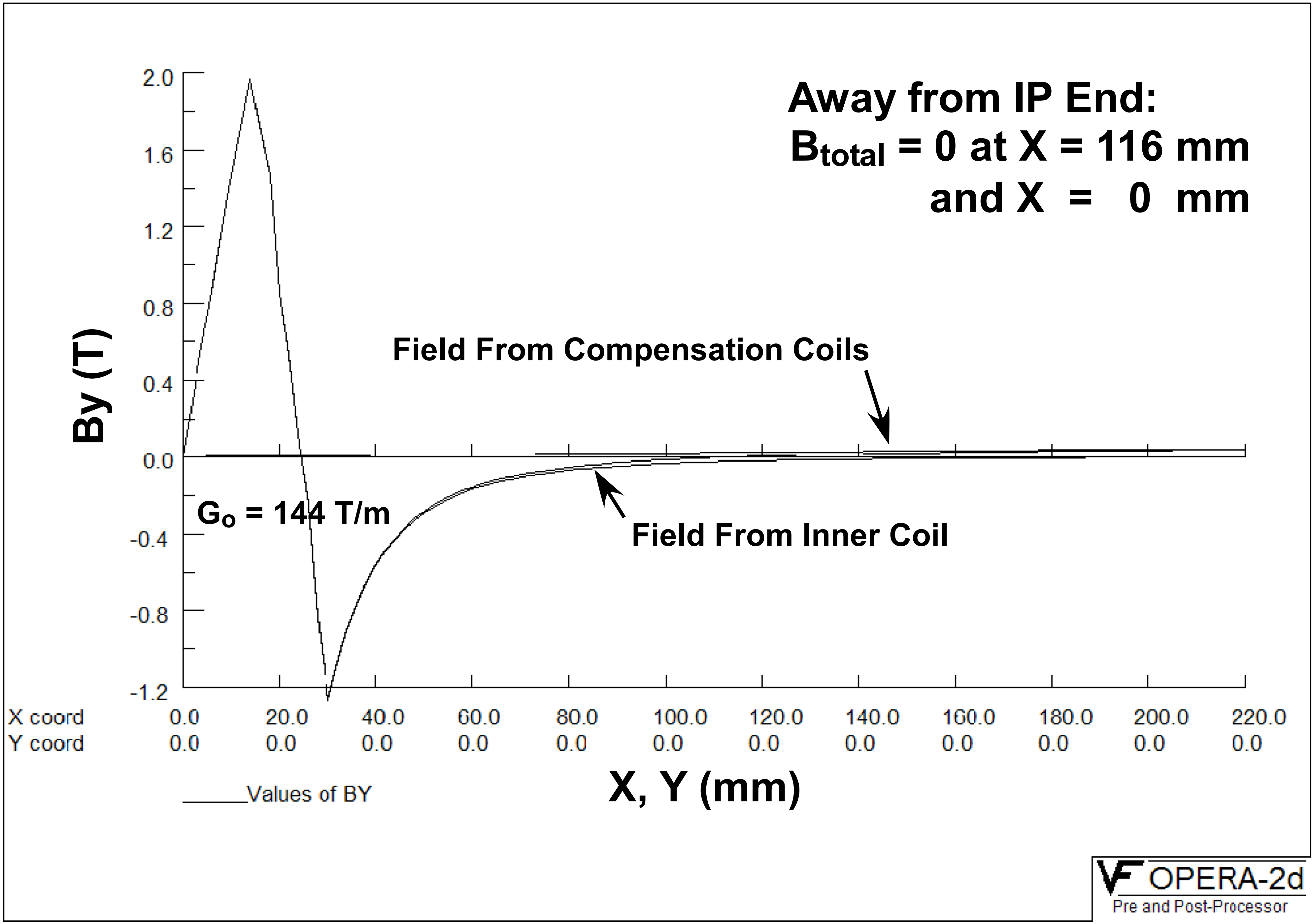
Vertical Field Component, By, on Axis vs. Horizontal Position, X



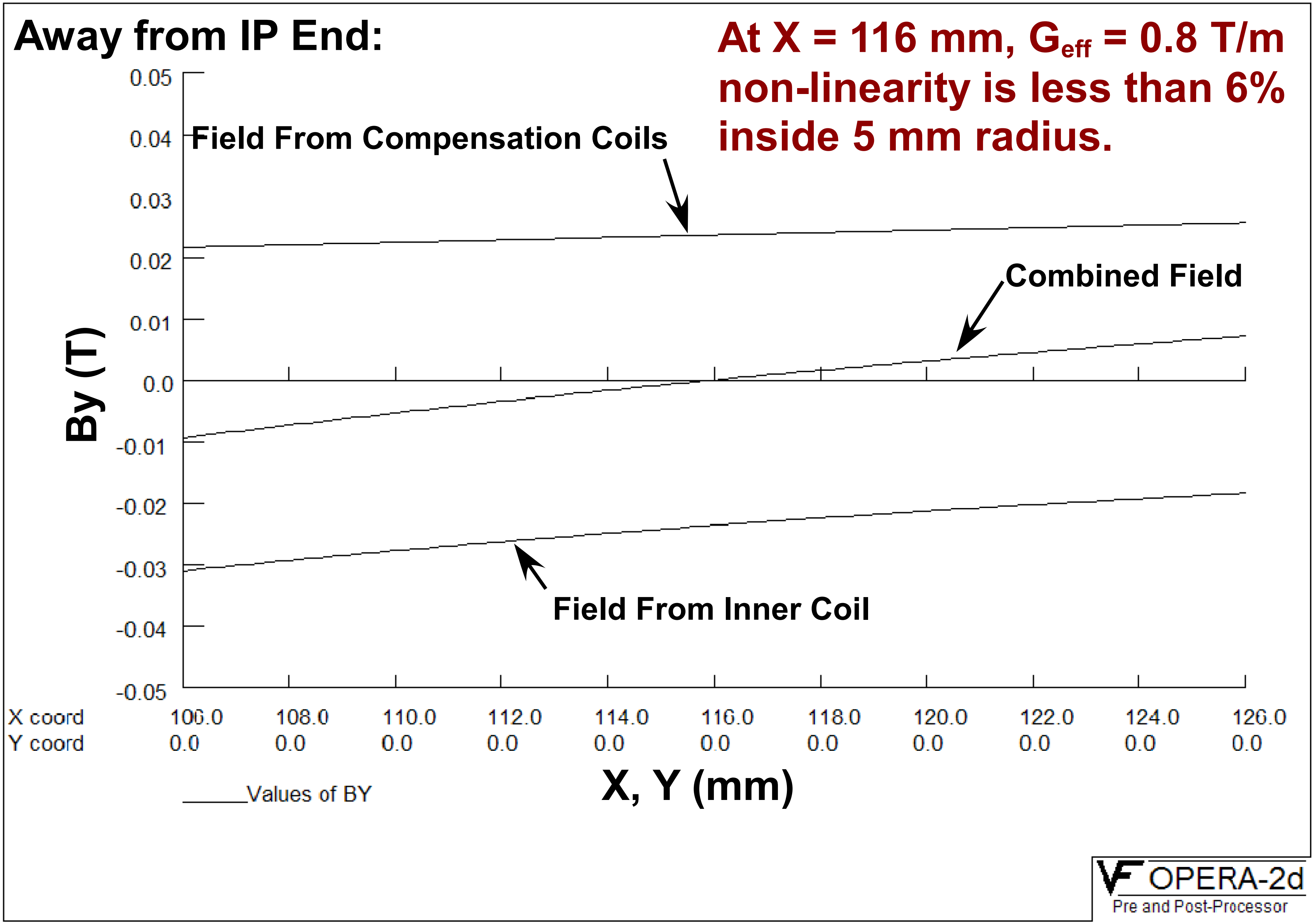
Vertical Field Component, By, on Axis vs. Horizontal Position, X



Vertical Field Component, By, on Axis vs. Horizontal Position, X



Vertical Field Component, By, on Axis vs. Horizontal Position, X



With this exercise we try to make B=0 at the incoming and outgoing beam locations for 20 mr total x-ing angle. For a given correction coil offset this constraint fixes the gradient and dipole field of the correction coils. Still we find that the local gradient at the outbound beam center goes from 4.4 to 0.8 T/m [Note for comparison 144 T/m x (8 GeV / 250 GeV) = 4.6 T/m]. If needed this gradient can be reduced further either by allowing the incoming beam to be offset in the beam pipe or adding an additional dipole corrector around the incoming beam pipe. It is also possible to reverse the gradient at the downstream end so the outgoing beam sees effectively a weak quadrupole doublet.

The corrections fields are fairly small so the correction coils will not be too hard to make. There is a net very-weak horizontal force between the inner and outer coils.

Final coil optimization should take into account particle tracking to minimize losses on the extracted beam line. In particular the detector solenoid may tend cause low momentum particles to stay at smaller X than the value expected from the x-ing angle geometry; so it may then be better to shift the field zero crossing to smaller X (?).

Comments sent with gamma_comp.pdf (2 pages)

While I am thinking about how small a beam separation is possible for using a superconducting final focus magnet, I though that I might also take a shot doing the same for gamma-gamma. For this exercise I assume:

- o the same inner coil as for my previous work ,
- o 20 mr crossing angle which with L*=3.8 m means 76 mm nominal beam separation,
- o 10 mr opening cone for the outgoing beam,
- o and close to zero field over a region centered at the outgoing beam.

The last point is accomplished via a compensation coil that has dipole, quadrupole and sextupole coil windings. For this exercise I looked at the on axis fringe field at 66, 76 and 86 mm and created magnets with sufficient strength to zero the field at these three locations.

The result, that almost works, is shown in the attached pdf file. The final coils overlap slightly so 20 mr looks still to be a bit too tight but something like 22 mr (or increasing L*) probably does go. Especially since increasing the separation means that the fringe field we have to compensate starts out even smaller in magnitude. Since my best QD0 design works with 12 mr e+e- crossing angle, adding a 10 mr keep away zone, resulting in a 22 mr minimum, is probably not such a surprise.

The sextupole and qudrupole field strengths for the compensator magnet are such that they can each be made from four single wire conductor layers; while the dipole only needs two wire layers. Note that as we go further from the IP the beam separation increases and the fringe field goes down.

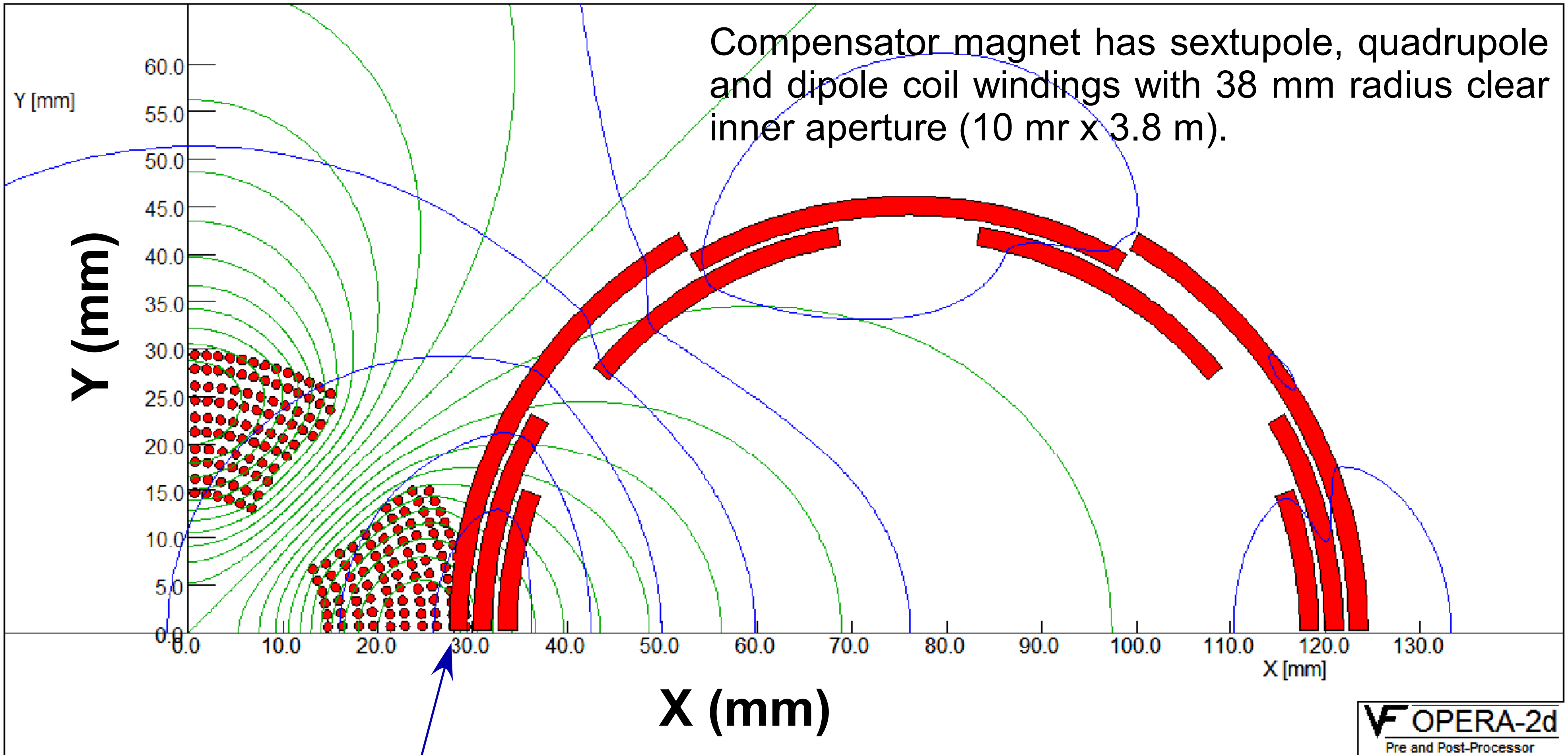
But since the required aperture also increases the coil radius also gets pushed out further and the correction field naturally goes down. Now optimizing the precise design of a tapered corrector magnet to do the best job on average along its length will take a bit of work but does not seem to me to be an insurmountable problem. In any event the degree of compensation that is finally achieved should probably be compared with the residual effect of spraying particles at such a large range of energies and angles across the solenoidal field lines.

Jeff in your talk you said that no optics (i.e. focusing) is permitted but there are optics effects to consider even if we do not add extra focusing simply due to the beam divergence from the IP and the detector solenoid. If we worry most about containing the low energy tail then it seems to me that at least a little bit of focusing may prove helpful in getting these particles to a final beam absorber. The highest energy charged particles will of course effectively ignore a weak field. So maybe there is some room for optimization here?

I final thing I had worried about was the effect of the compensator magnet back on the main electron beam but its fringe field (coming mainly from the weak dipole) is pretty low, 0.082 T, and in a 144 T/m quadrupole corresponds to a 0.6 mm shift of the center. There is also a small change in local gradient which can be compensated for by changing the current in the main coil. Higher order terms are small. If we go to 22 mr crossing angle, rather that the 20 mr I have calculated, then the fringe field drops another 25% and the impact back at the main beam location is even smaller.

So my tentative conclusion is that we do not need 35 mr crossing for gamma-gamma but 22 mr may be enough to be able to meet the requirements I heard at the last ILC workshop at SLAC. While a serious solution will require serious work (using proper harmonics for field optimization, tapered magnets, 3D fields in order to calculate end effects etc.) for the KEK meeting you might want to consider using 22 (or even safer 25 mr) for your gamma-gamma geometry discussions.

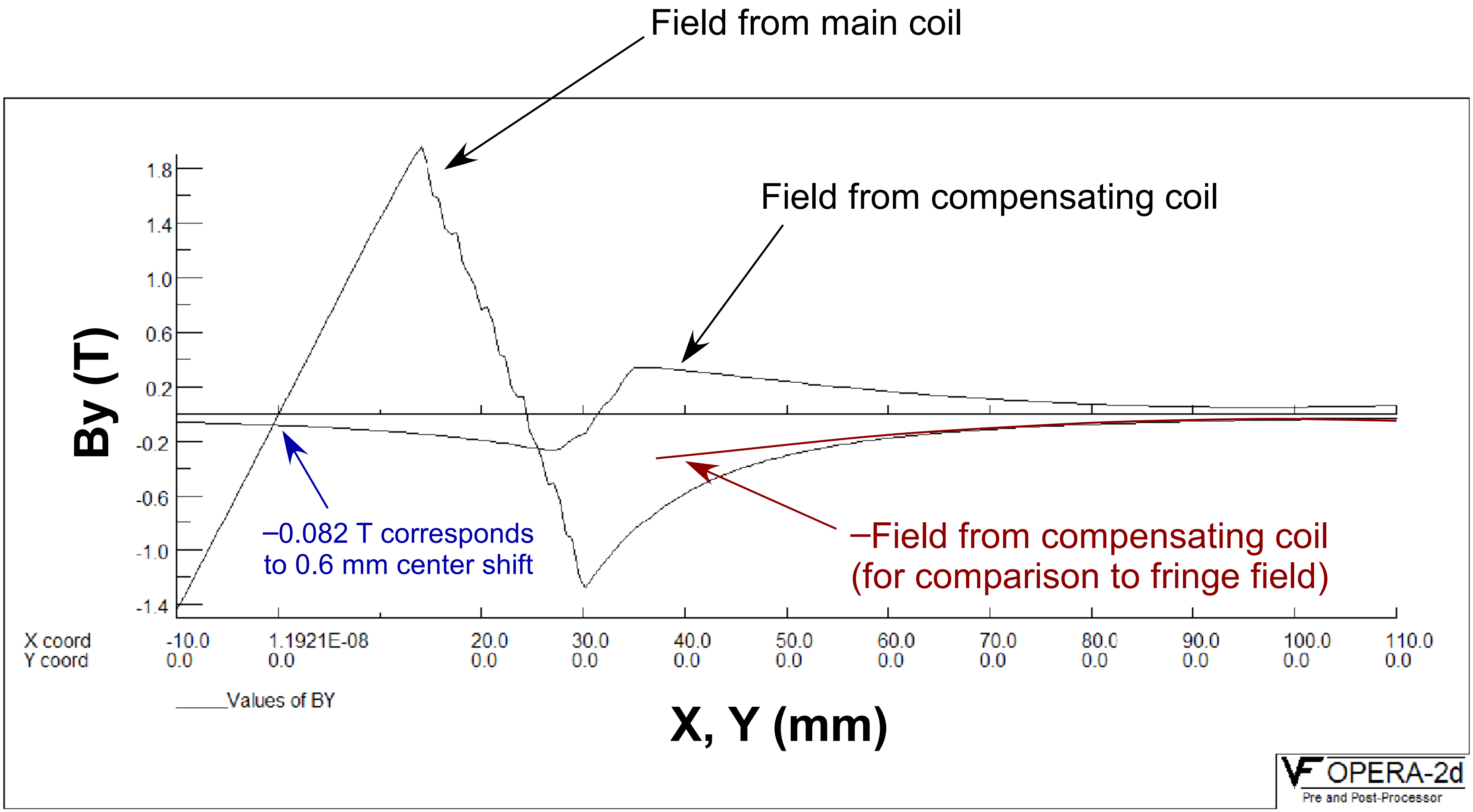
QD0 Quadrupole Coil Overlaid with Compensation Coils



Found that dipole coil can be made half as thick as shown.

Zero Field Point is at X = 76 mm (i.e. 3.8 m x 20 mr)

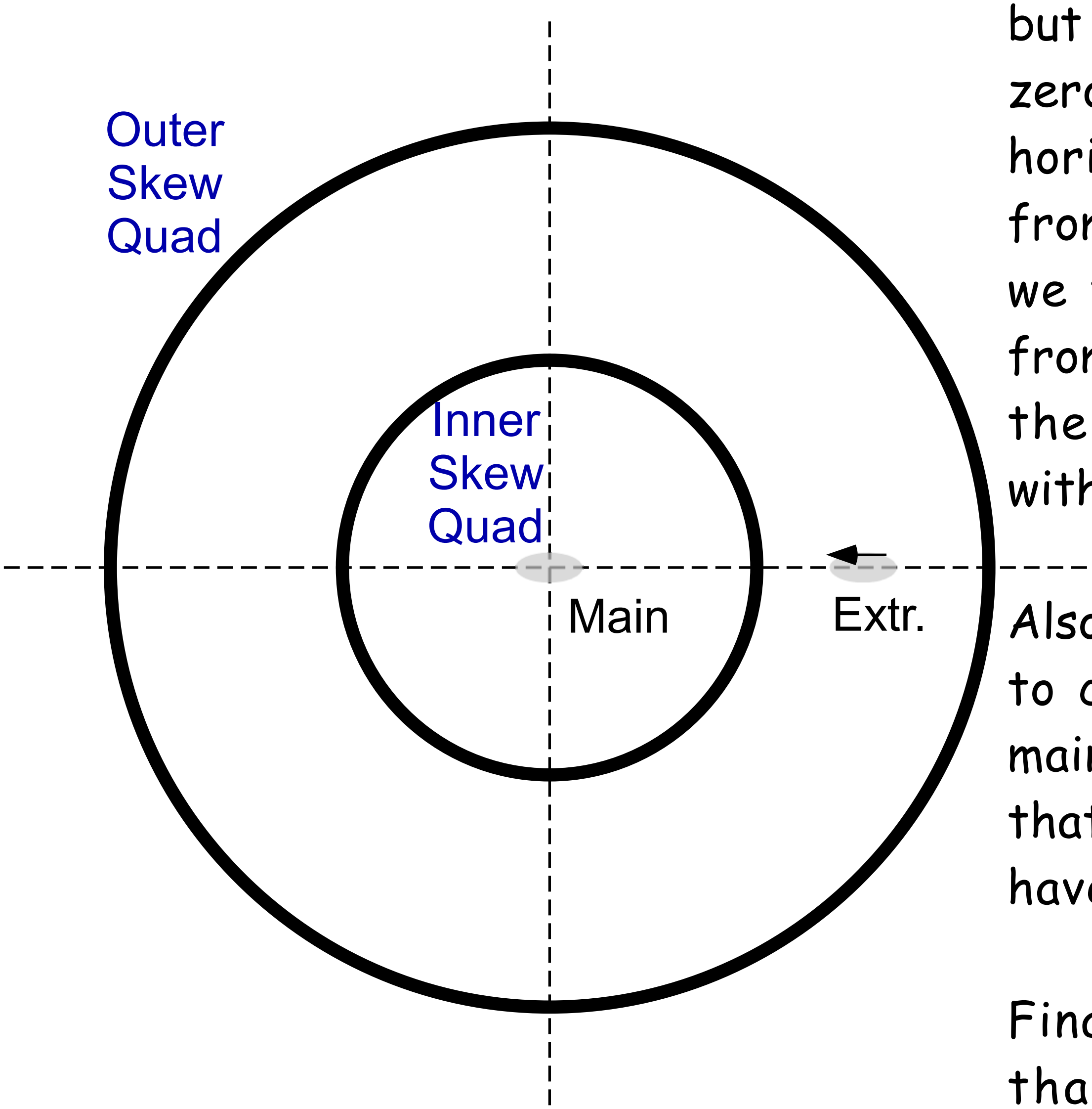
Vertical Field Component, By, on Axis vs. Horizontal Position, X



Comments sent with skew.pdf (1 page)

Hello Andrei,

This is a follow up to my last email. If we do decide to add another layer of quadrupole coils as I proposed earlier, then there is something nice that could be done to help minimize the kick given to the extracted beam. My idea is outlined in the attached pdf file. Please let me know what you think. - Brett



Proposal: Add two weak skew-quadrupoles of opposite gradient. Then the main beam not only does not see a horizontal field but there is no skew field even away from zero. But the extracted beam will see a horizontal field component (fringe field from inner adds slightly in this case). If we then superimpose a horizontal field from DID we should be able to minimize the kick given to the extracted beam without having to mess up the main beam.

Also having such coils available allows us to correct for field angle rolls for the main beam if we remove the constraint that the two skew quadrupole gradients have to be equal in magnitude.

Finally not using a skew dipole means that there are no torques from the detector solenoid to worry about.

Comments sent with three_layer.pdf (6 pages)

At the time of the ILC workshop at SLAC we were asked how small a crossing angle was reasonable that goes with our compact superconducting magnet design. Since then we have explored some single aperture options that might enable reaching quite small x-ing angles but their coil layout is at best “challenging.” Also Animesh has shown that there are general limits to the field quality that is achievable at both beam locations if we do not put at least some conductor between the beams. If very small, say less than 10 mr total x-ing angle is really needed, there are still some “racetrack style” coil options, similar to what Ramesh Gupta and I have looked at for the VLHC, that could be explored.

But with this email I would like to introduce a concept that is only a small addition to our present design but would allow going down significantly in beam separation. This proposal also has the advantage of giving a modest field gradient for the outgoing beam and thus may be helpful for designing the extraction beamline.

Introduction

Since we are led (see previous emails) anyway to consider placing some conductor between the two beam apertures why not just start with the present coil design which already has undergone some degree of optimization? That is open up the cryostat so that the extracted beam is allowed to pass just (i.e. with 10 mm clearance) outside the cold mass. Well without some compensation of the fringe field the extracted beam would see fields close to 0.6 T at this location.

As discussed previously putting an “anti-quadrupole,” a quadrupole of opposite sign, outside the main coils is a way to handle this, but for E_beam = 250 GeV and G = 144 T/m over a 2 cm aperture the coil parameters are beyond what at least I am presently comfortable with.

The basic problem is that the shield quadrupole while canceling the fringe field also robs gradient from the center. The efficiency of the shield quadrupole goes as its radius to the fourth power and we guess that for beam separations of at least 80 mm or more this path may ultimately prove viable (i.e. this is a scenario for a gamma-gamma FF where they really want zero field outside).

But we can also consider putting an extra coil at a larger radius than the region of interest. In this case we can use a quadrupole of the same polarity as the inner one since the fringe field from the inner coils is in the opposite direction. This is the essential point of the
present proposal.

Adding another larger radius coils does the following good things:

- Gives a zero crossing that can be easily tuned to be where we want it to be,
- Adds to instead of subtracting from the central gradient.
- Provides a gradient, that is of the correct sign but reduced in magnitude compared to the central gradient, starting at the same L* as QD0. This gradient should be useful for optimizing the extraction beam line.

Sample Proposal for Reduced Crossing Angle

The attached pdf file shows an example that was optimized for 50 mm beam separation. Note for reference: a total crossing angle of 13 mr at L* = 3.85 mm yields 50.05 mm but you can obviously scale to your favorite combination of L* and x-ing angle.

The proposed coil goes from 64 to 68 mm in radius and has an average current density low enough that it could be made from single strand wire. Doing this coil from single strand wire then gives a lot of flexibility for coil layout. In particular as the extracted beam moves further away (Z) from the IP the beam separation increases and the fringe field from the inner coil drops. Both can be accommodated by letting the outer coil radius increase as we go away from the IP and while I have not yet designed a full coil for this application we were quite successful
making tapered magnets for HERA-II. With our new Serpentine winding technique and especially using single strand wire, where I can afford to use several layers for optimization, I'm confident that a workable solution can be found.

We see that for the proposed 50 mm beam separation and maintaining 144 T/m at the center we get about 40 T/m gradient for the extracted beam. The field quality seen by the extracted beam is relatively poor, about 6% nonlinearity at 2 mm radius compared to an ideal 60 parts per million at the same radius for the main aperture. This comes about because we are subtracting a linear function from a 1/r**3 dependence.

If field quality for the extracted beam becomes an important issue (so far nobody has studied impact of inner coils fringe field on the extracted beam) we could presumably budget a little bit extra radial space in order to place a thin correction coil around the extraction line beam pipe. A relatively weak, small radius and high-order corrector would have only a small impact on field quality in the main aperture. Even if we do not deem it important to improve the field quality for the extracted beam, we may want to add a small
skew-dipole (vertically bending) for the extracted beam to compensate the momentum dependent kick from crossing the solenoidal field lines at an angle.

[A second approach that now becomes possible is to co-wind with the outer coil a weak skew-quadrupole. This could be optimized along side the DID to compensate the solenoid kicks since a skew quadrupole would give different magnitude horizontal fields at the two beam locations.

One down side for this proposal is that the cryostat now must be enlarged and the beam pipe interface at each end gets more complicated; however, there is also an opportunity here. Away from the extracted beam location there are now regions with significant transverse field that can be well correlated to the field at the magnet center. Thus if we make further cryostat penetrations we can find locations to monitor the magnetic field where no beam goes and I would think this could be useful for stabilizing the magnet.

Final Comments

The proposal for adding another quadrupole coil outside the extracted beam should be even easier for the present 20 mr crossing angle scheme as there looks to be space for the extra "plumbing." The 13 mr solution shown in the attached file looks to me to be a bit tight but for a final design I would certainly reoptimize the central coils and could probably gain a bit more radial space. Also since we have more space to return cryogens in the outer shell some of the space that is taken up in the present coil layout becomes available for use.

So taking things further the minimum separation could probably be reduced
slightly so 12 mr may be possible. I think though that going below 10 mr is still problematic in any reasonable scenario.

I hope that between this and my previous emails on double field quadrupoles you now have the information you need for the KEK ILC meeting to have informed discussions on crossing angle options. As I said at the SLAC ILC meeting there are superconducting magnet designs that can accommodate zero and 20 mr crossing angles and for intermediate angles we now have some options to explore.

If 20 mr is deemed to be too large, I would recommend falling back to about 15 mr and using an extra qudrupole coil as proposed above. The superconducting magnet design parameters should be reasonable for this case and such a crossing angle is still big enough to do some good further away from the IP where we still have to separate other components, detector halls etc. I would also recommend, if possible to have the second FF magnet, QF1, placed outside the detector field (if possible) so that we can incorporate magnetic materials in its design.

Example Showing Reduced X-ing Angle with Present Design

Scenario: Beam separation is 50 mm (IP end)

10 mm radius clear aperture at both beam locations

With L* = 3.85 m we then have...

±6.5 mm x-ing angle (≈ 13 mr total)

L_{mag} = 2 m (≈ ±38 mm for beams away from IP)

G = 144 T/m for inner coil (main beam)

G ≈ 40 T/m at 50 mm offset location (extracted beam, IP end)

B_{peak} = 2.65 T

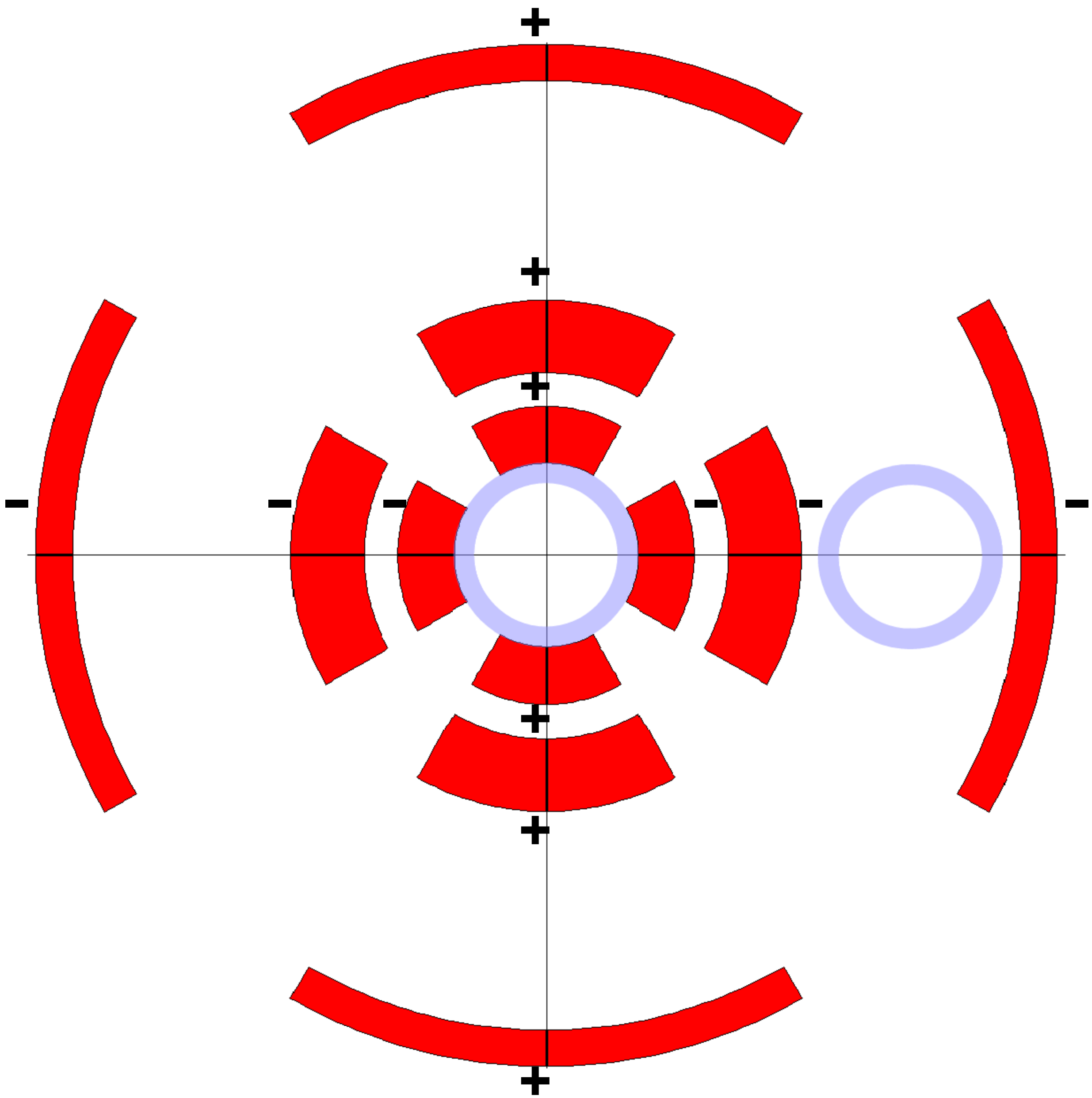
Inner coil set is taken from present compact quad design.

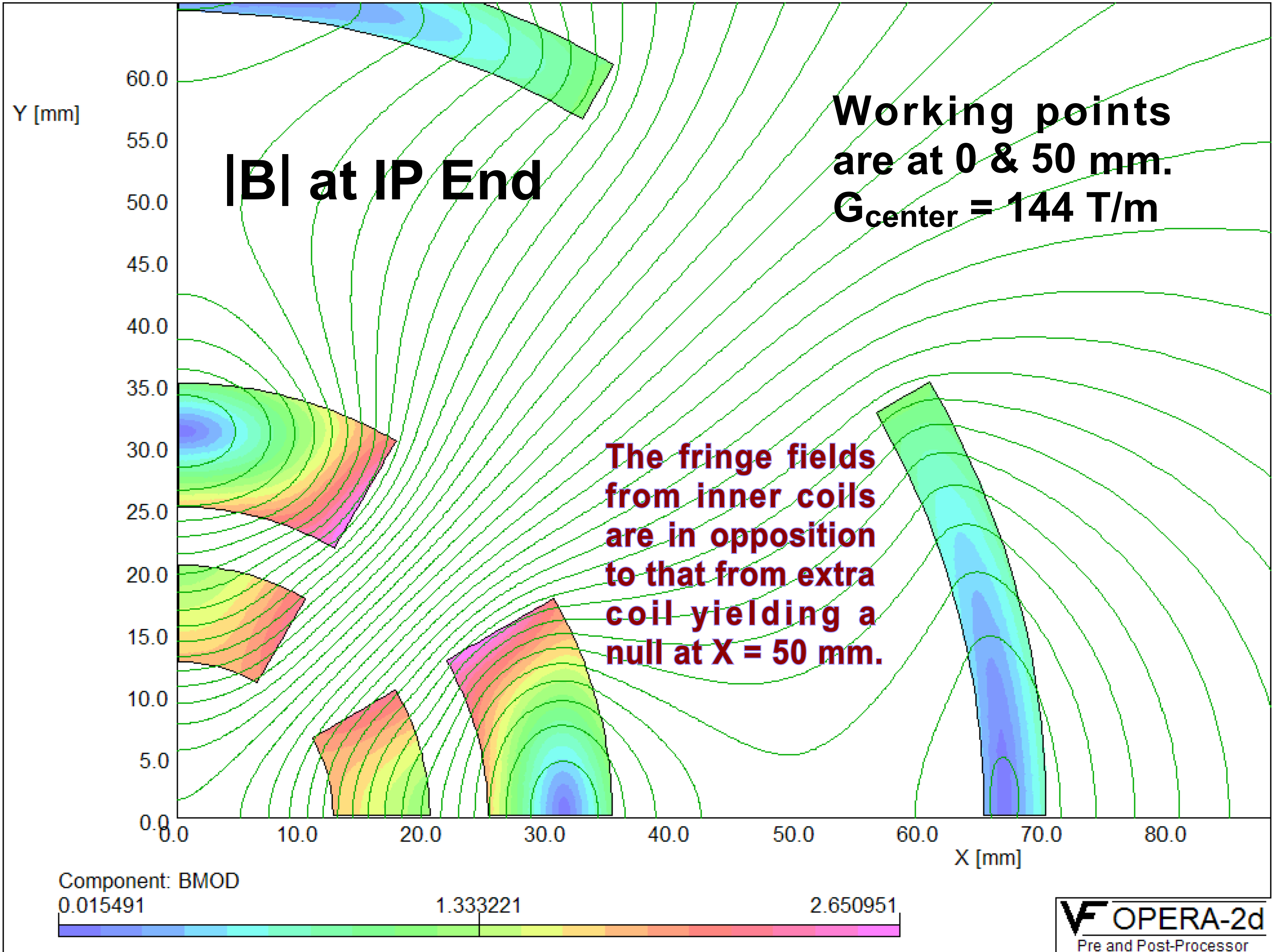
Outer coil tapers to provide extraction line aperture and to match fall off of external field with radius from inner coils.

Trick: Adding one more quadrupole coil set, with the same polarity as the inner coil, permits extracted beam to pass through a region of reduced field rather than the 0.6 T that otherwise would be present so close to the inner coil.

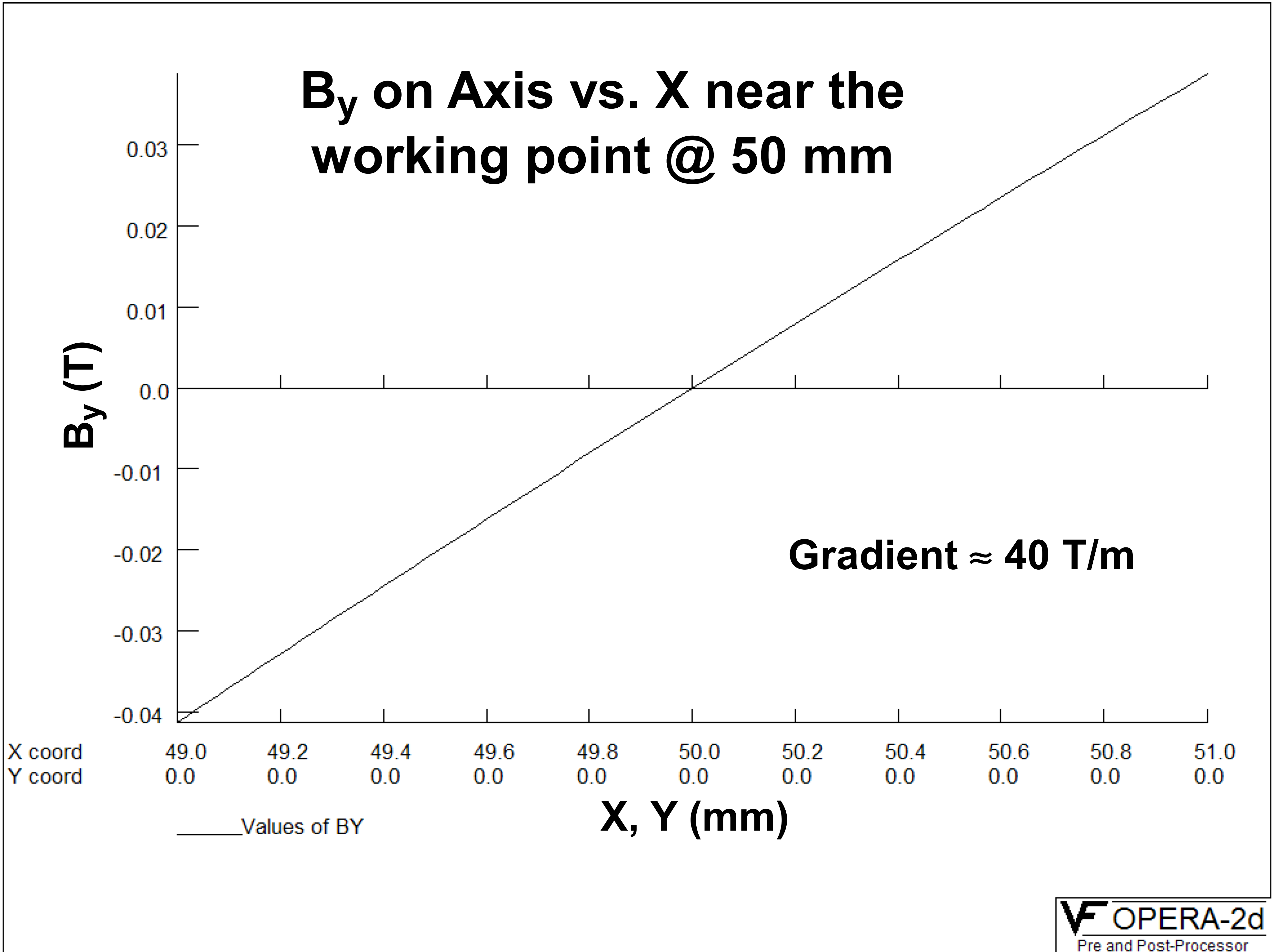
The outer coil adds to the gradient in the inner aperture and thus provides extra operating margin.

Cross Section at IP End with 50 mm Beam Separation

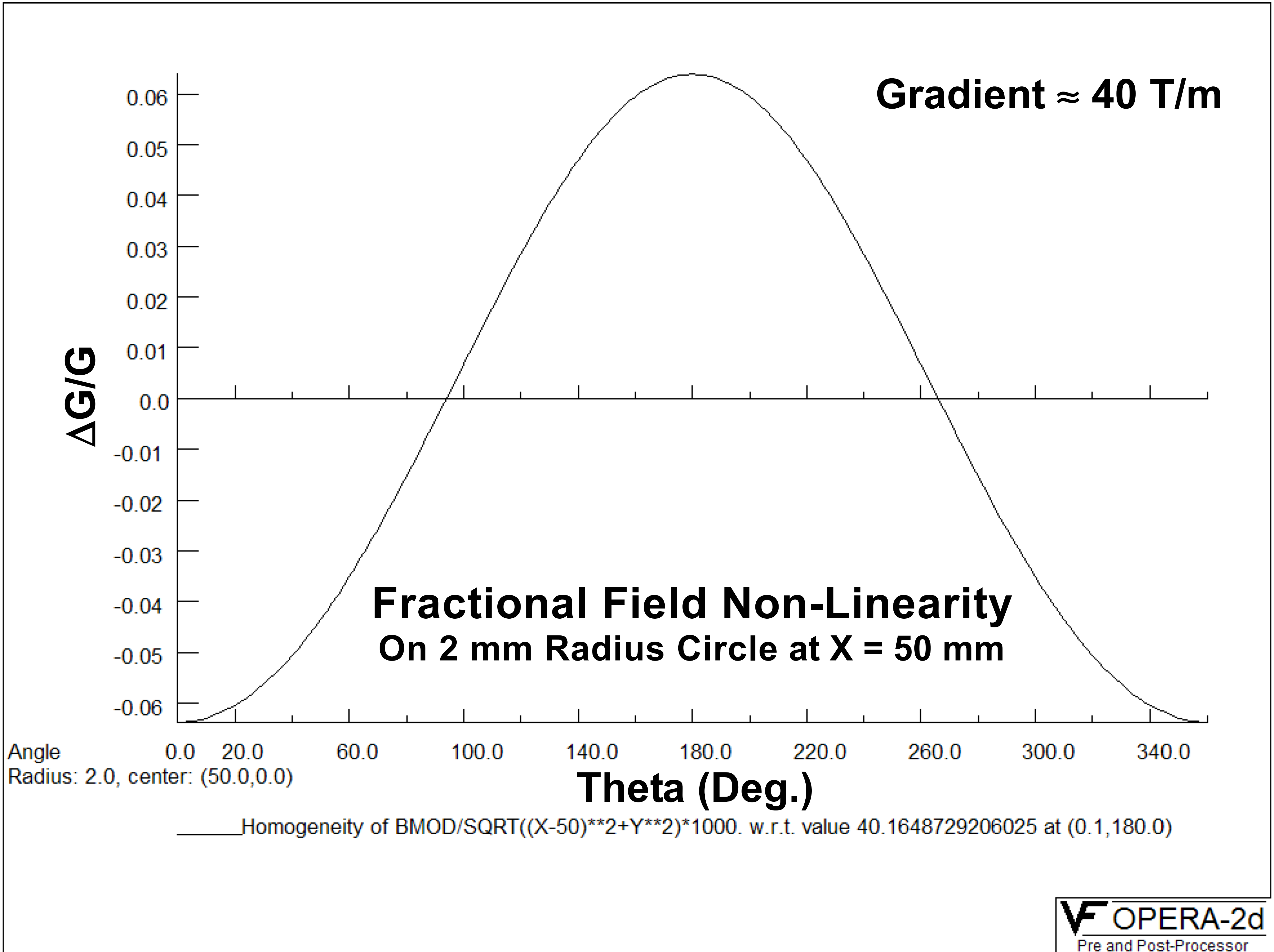


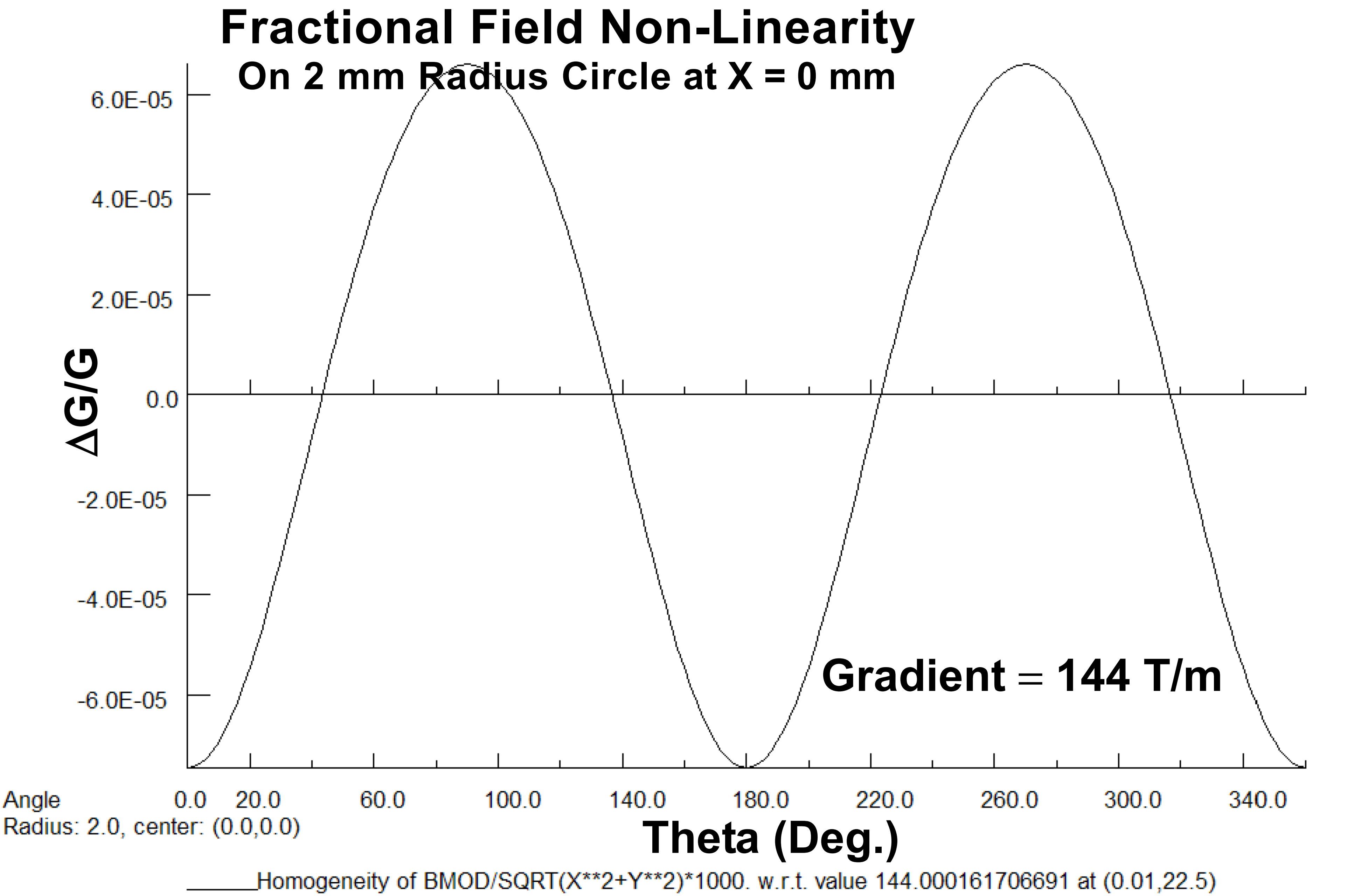


|B| at IP End
Working points are at 0 & 50 mm.
Gcenter = 144 T/m
The fringe fields from inner coils are in opposition to that from extra coil yielding a null at X = 50 mm.
Y [mm]
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
X [mm]
Component: BMOD
0.015491
1.333221
2.650951
OPERA-2d
Pre and Post-Processor



By on Axis vs. X near the working point @ 50 mm
0.03
0.02
0.01
0.0
-0.01
-0.02
-0.03
-0.04
By (T)
Gradient ≈ 40 T/m
X coord 49.0 49.2 49.4 49.6 49.8 50.0 50.2 50.4 50.6 50.8 51.0
Y coord 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
X, Y (mm)
Values of BY
OPERA-2d
Pre and Post-Processor


Gradient ≈ 40 T/m
0.06
0.05
0.04
0.03
0.02
0.01
0.0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
ΔG/G
Fractional Field Non-Linearity
On 2 mm Radius Circle at X = 50 mm
Angle
Radius: 2.0, center: (50.0,0.0)
0.0 20.0 60.0 100.0 140.0 180.0 220.0 260.0 300.0 340.0
Theta (Deg.)
Homogeneity of BMOD/SQRT((X-50)**2+Y**2)*1000. w.r.t. value 40.1648729206025 at (0.1,180.0)
OPERA-2d
Pre and Post-Processor



Note: Gradient in central aperture is more uniform by almost three orders of magnitude if we ignore both systematic and random construction errors.

OPERA-2d
Pre and Post-Processor

Comments sent with obq_26oct04.cvx (6 pages)

We have made more progress in understanding what is possible to achieve with a septumless superconducting quadrupole with multiple zero points. In particular Animesh has done a fair amount of theoretical work and has worked out general expressions for the expected harmonic content at the two working points as a function of beam separation and field reference radius if the gradients are equal in magnitude but opposite in sign (sextupole like symmetric solution) or if the gradients are equal (octupole like anti-symmetry solution) and he is close to having a general solution that allows one to specify arbitrary gradients at the two locations.

Attached to this email is a particular solution that illustrates what the inner coil might look like for 10 mr total crossing angle and the same gradient at the two field points. Note for the same gradient case we need more space between the beams in order to fit an additional conductor pack.

So the good news is that Animesh has shown that the field uniformity that can be achieved is (except for a numerical factor that depends upon the choice of harmonic terms to optimize) a function of the beam separation and field reference radius. This is also the bad news; there is a natural scale for the field non-uniformity that just depends upon the beam separation and reference radius. That is we cannot expect to make the field arbitrarily good without putting at least some conductor between the two beams.

For the +/- gradient (sextupole like) solution discussed last week, with r_ref = 5 mm and beams at +/- 12 mm the practical limit seems to be abut 1.5% if we keep good field for both beams. For the equal gradient case the field has to have another zero crossing (i.e. there are higher order terms) and for the same beam separation the field non-uniformity is quite a bit worse. In fact it does not look to be possible to simultaneously zero both the sextupole and octupole terms for the equal gradient case. In Animesh's code we choose to zero the sextupole term and live with the octupole since the octupole term vanishes faster as one reduces the reference radius.

So Andrei, once we have a general calculation for the field harmonics I assume you can incorporate these non-linearities into your optics and can then tell what the impact is if any is on luminosity, operations etc.? Remember the above it the only approach I have thought of to be able to access intermediate size total crossing angles (1 - 15 mr total crossing angle) with a single bore magnet. So we might be able to rule out this whole class of single-aperture x-ing angle solutions if it turns out that even a single pass collision cannot work with such large optics nonlinearies.

The thing is if we are then forced to put some conductor between the beams, I'm pretty confident that we can rule out total crossing angles below about 10 mr due to the space the conductor will occupy.

Example of an Octupole Based Multi-Field Quadrupole

Scenario: ±5 mm x-ing angle (10 mr total)

L^* = 3.6 mr (±18 mm for beams near IP)

L_{mag} = 2 m (±28 mm for beams away from IP)

10 mm radius clear aperture at both beam locations

Minimum 2.5 mm thick support tube (beam pipe)

G = 140 T/m (same sign at both locations)

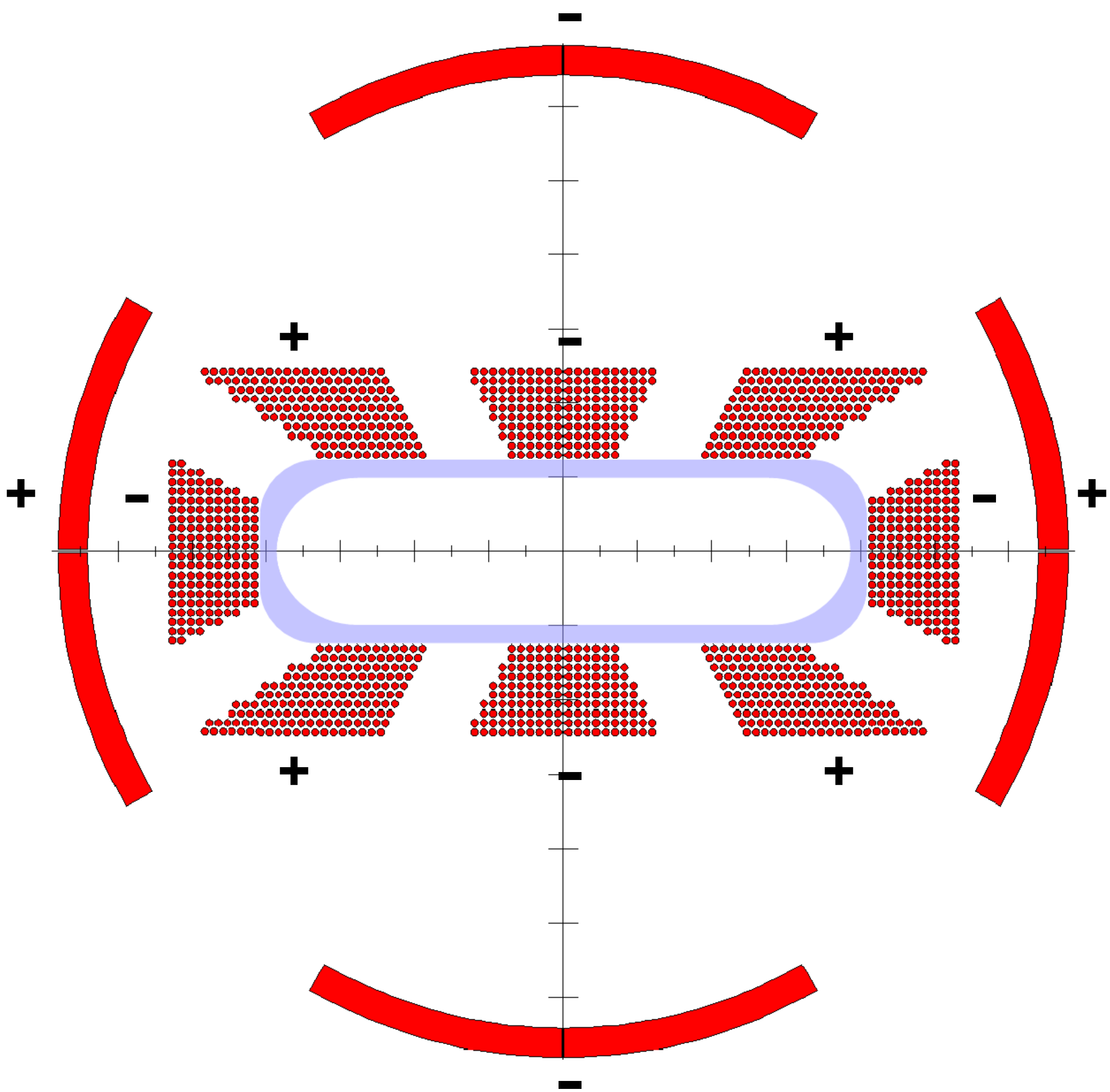
B_{peak} = 2.86 T

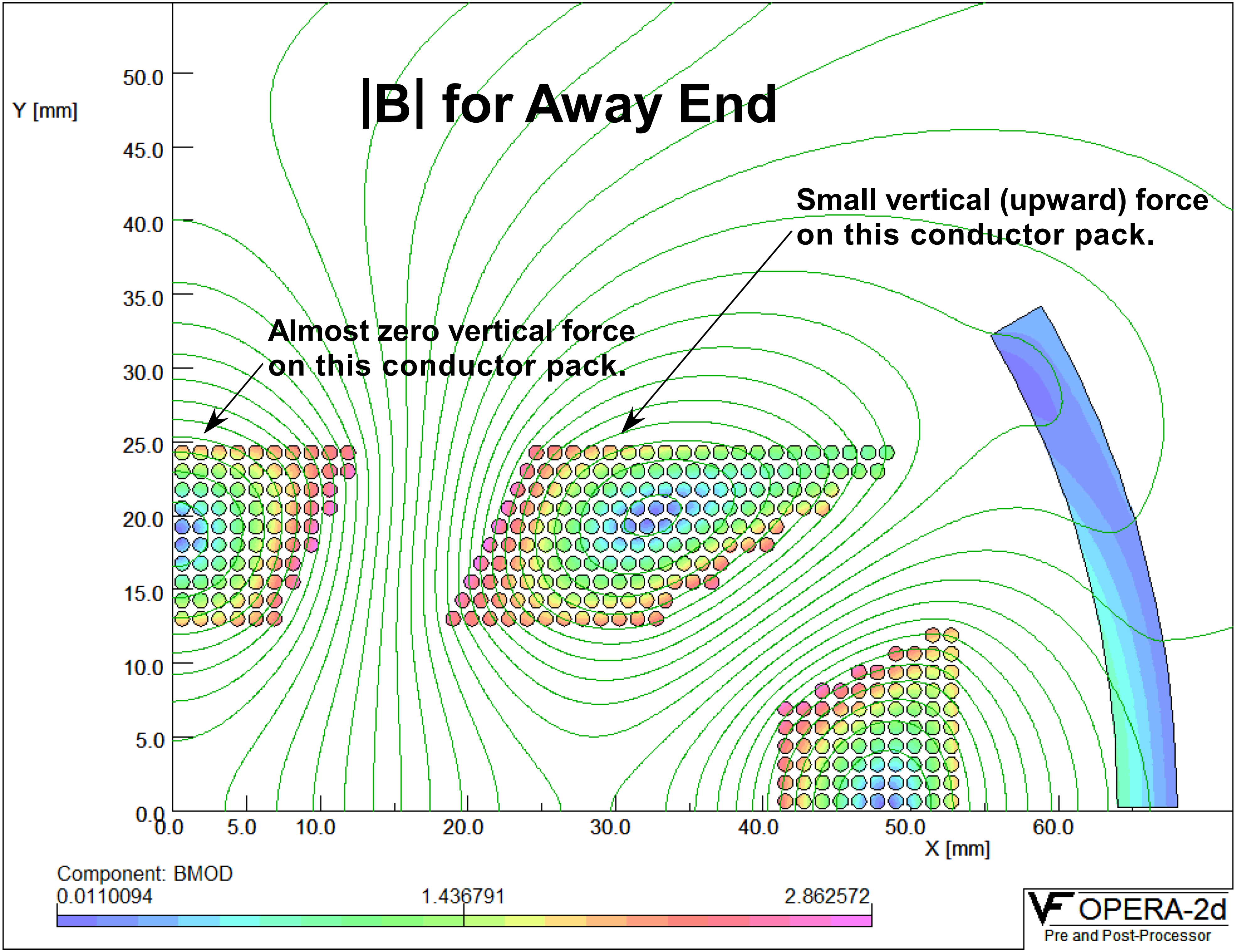
Inner coil is flattened octupole

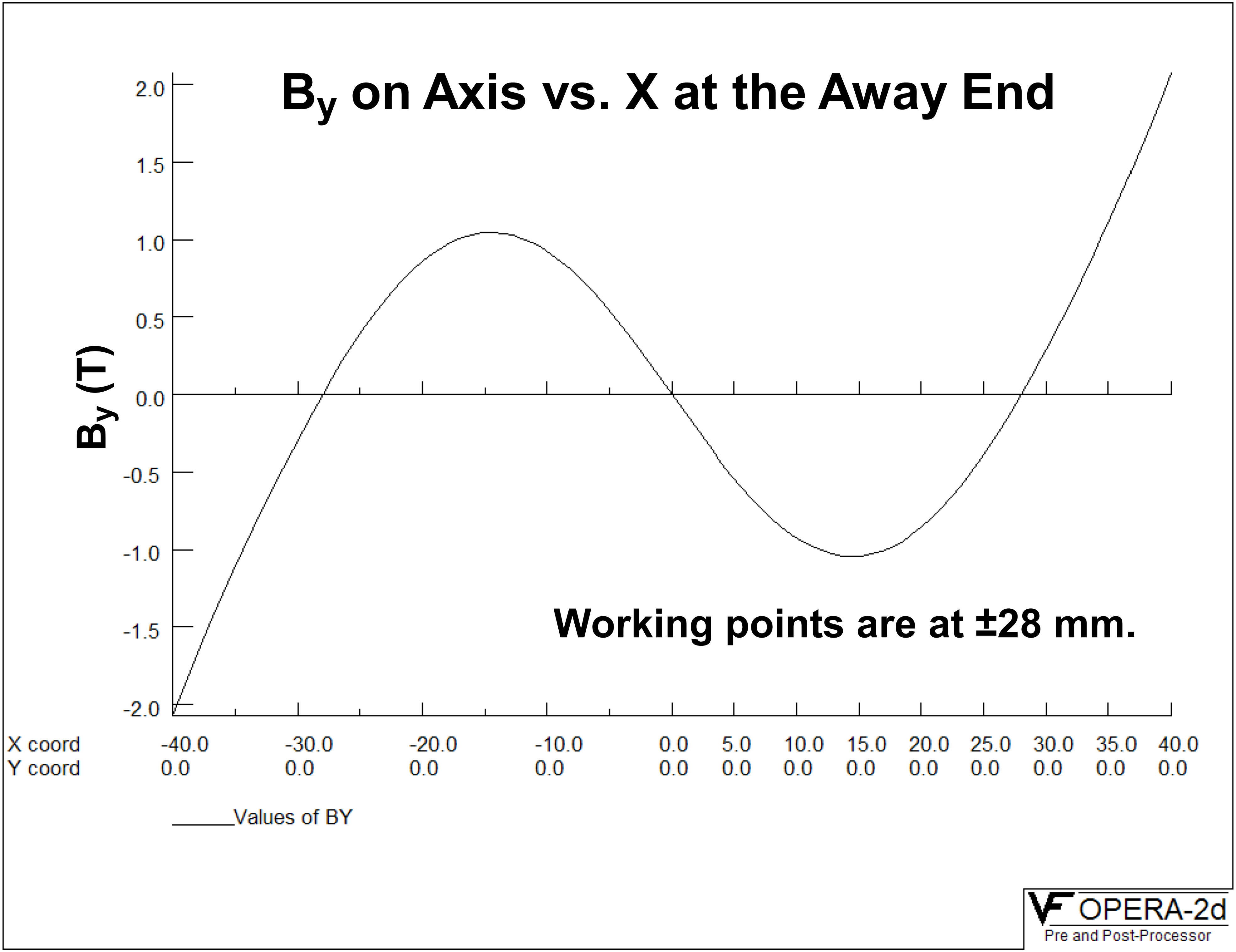
Outer coil is weak quadrupole to adjust zero crossing

Use Serpentine style winding patterns

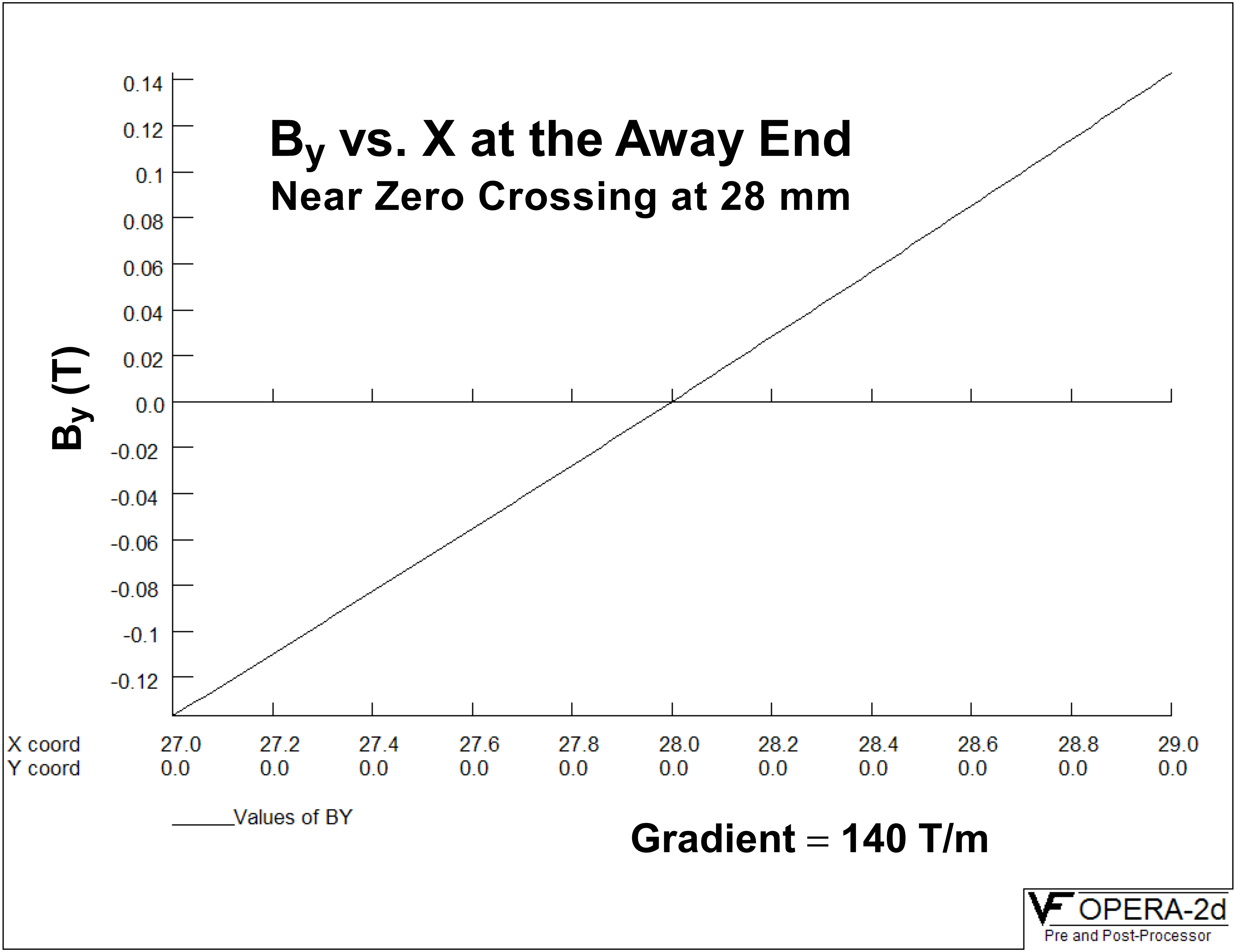
Cross Section at IP End with Beam offsets = ±28 mm



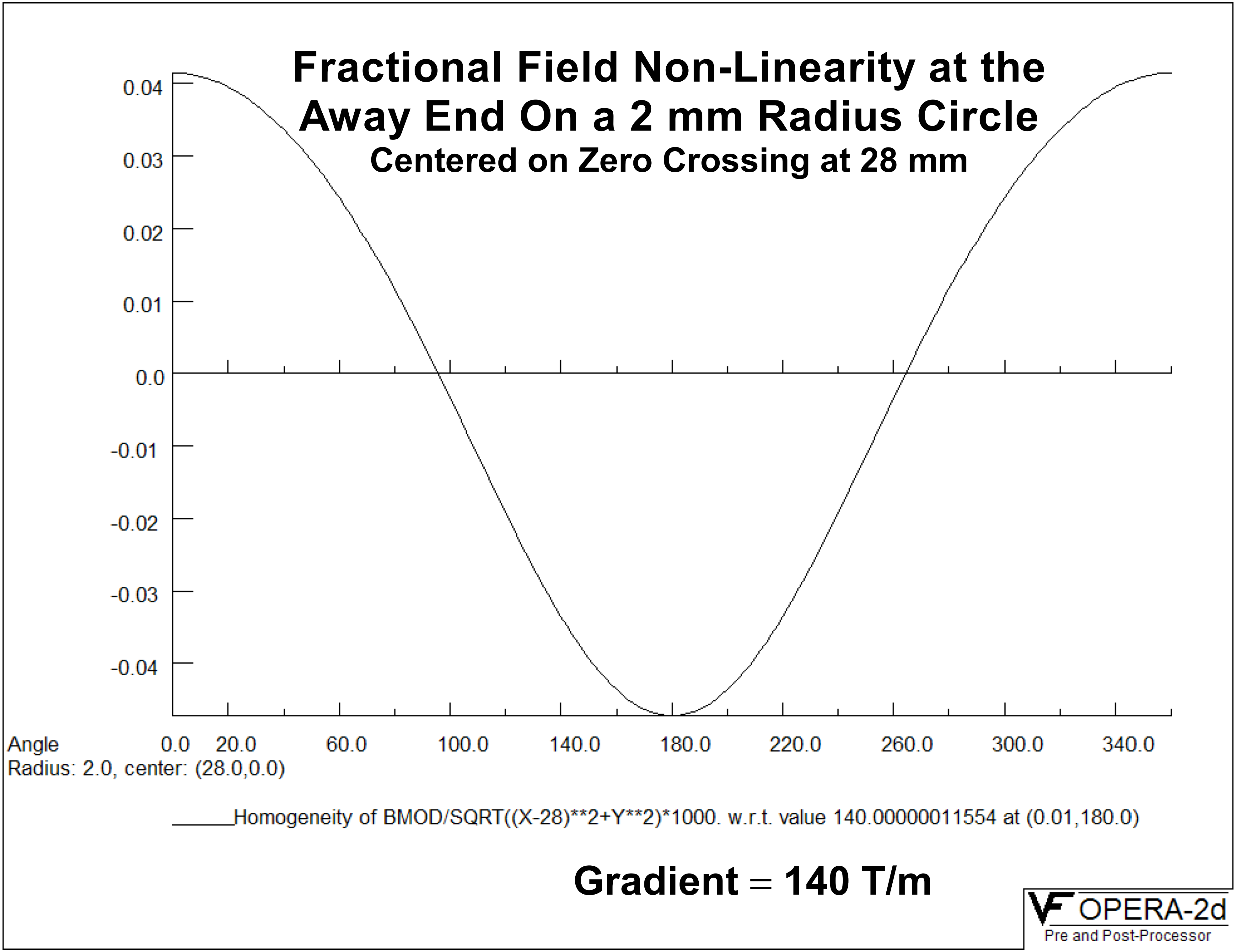

|B| for Away End
Y [mm]
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
X [mm]
Almost zero vertical force
on this conductor pack.
Small vertical (upward) force
on this conductor pack.
Component: BMOD
0.0110094
1.436791
2.862572
OPERA-2d
Pre and Post-Processor



By on Axis vs. X at the Away End
By (T)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Working points are at ±28 mm.
X coord -40.0 -30.0 -20.0 -10.0 0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0
Y coord 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
Values of BY
OPERA-2d
Pre and Post-Processor



B_y vs. X at the Away End
Near Zero Crossing at 28 mm
B_y (T)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
X coord 27.0 27.2 27.4 27.6 27.8 28.0 28.2 28.4 28.6 28.8 29.0
Y coord 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
Values of BY
Gradient = 140 T/m
OPERA-2d
Pre and Post-Processor



Fractional Field Non-Linearity at the
Away End On a 2 mm Radius Circle
Centered on Zero Crossing at 28 mm
0.04
0.03
0.02
0.01
0.0
-0.01
-0.02
-0.03
-0.04
Angle
0.0 20.0 60.0 100.0 140.0 180.0 220.0 260.0 300.0 340.0
Radius: 2.0, center: (28.0,0.0)
Homogeneity of BMOD/SQRT((X-28)**2+Y**2)*1000. w.r.t. value 140.00000011554 at (0.01,180.0)
Gradient = 140 T/m
OPERA-2d
Pre and Post-Processor

Comments sent with dfq_21oct04.pdf (8 pages)

During the last two days I have work on developing the double field quadrupole, DFQ, design we discussed last week and actually have made more progress than I had expected given that the original idea came from 4 am sleepless musings.

The DFQ parameter goals are:

- o Accommodate 7 mr total crossing angle
- o L* = 3.5 m (beam separation 24.5 mm at IP end)
- o Lmag = 2.0 m (beam separation 38.5 mm end away from iP)
- o Gradient about 144 T/m (equal in magnitude but opposite in sign for incoming/outgoing beams).
- o At least 10 mm (radius) clear aperture for both beams
- o While winding assumes some upgrade of out winding machine, the coil patterns are compatible with the Serpentine winding technique and the conductor is kept the same as we have used before.
- o Magnet should have enough operating margin to work in a 3 T solenoidal background field.
- o Field uniformity at the level of 0.1% at 5 mm reference radius (initially for both beams).

While this magnet is certainly challenging, so far we have not found any show stoppers and it looks like this may give us a new tool for considering modest x-ing angle geometries in the range 6 - 10 mr total crossing angle. The proposed magnet is shown in the attached pdf file and a description of the design along with issues that had to be addressed now follows along with a discussion of the results.

Design Issues

The design has an inner superconducting coil that is optimized to give as much gradient as possible at the offset beam locations surrounded by a much weaker outer coil that is used to improve the field linearity. The inner coil is essentially a "mashed sextupole" that gives mainly a combination of sextupole and dipole field to create two zero field points with close to the correct horizontal separation. At present the outer coil only contributes a dipole field that is used to fine tune the field zero crossing points.

Note that the inner coil cross sections differ at the magnet ends in order to accommodate the additional 14 mm beam separation that occurs over the 2 m magnet length. The main difference at the two locations is that the coil packs spread apart horizontally but maintain a constant vertical clearance. This avoids having a drop in gradient that would be expected if the coil were to be spread vertically also at the cost of a somewhat unfavorable (mechanically) support tube shape. An optimum design will probably spread the coil vertically but then bring in additional turns along the length of the magnet. Such an optimization is beyond the scope of the present study which is focused on a proof of principle.

Originally I thought that I would have to write an optimization code to determine the conductor layout but once I started my hand optimization I soon discovered that simply packing as much conductor as possible consistent with keeping to the lowest possible peak field pretty much fixed the number of turns in each layer. Since spacer gaps robbed turns from the pack, the main freedom I found was to slide the turns back/forth in each layer over the beam.

The midplane coil pack is completely determined from tight packing according to the total number of turns and in order to do this coil with a simple Serpentine style wind the number of turns in each layer above/below the beam is the same as that for the midplane pack.

Discussion

While there is not much freedom left to optimize the inner coil pattern to improve its field harmonics it is possible to add correction windings to the outer coil in order to do this. In fact Animesh Jain has derived formula for what needs to be done in terms of harmonic correction at the outer coil in order to linearize the field to a given level and up to a given harmonic at the two offset beam locations. In general odd harmonic numbers B1, B3, B5 ... (dipole, sextupole, ten-pole etc.) affect the +/- offset locations the same while even harmonics, quadrupole, octopole etc., will cause a difference at the two locations. So if we want to have good harmonics for both beams we must restrict the terms used but if we are willing to let the outgoing beam suffer more (as it certainly must with the KEK FF magnetic pole design) then we can do a better job.

For a given beam offset, Delta_X, and field harmonic reference radius, R_ref, the degree of unavoidable non-linearity scales as:

(R_ref / Delta_X) ** p

where p depends upon the order of multipolarity for correction. According Animesh's calculation, since I did not include even a sextupole corrector, the best I could have expected for 12 mm offset and 5 mm reference radius was about 10% non-linearity over the full 5 mm radius circle.

In fact my hand optimization is already pretty close to this, meaning that there is not a whole lot of point in messing with the inner coil much more if the only point is to improve field uniformity. Rather I should next work on adding appropriate correction layers to the outer coil. Since this can be done in a deterministic manner, there is no need to wait to make an optimization code (existing codes for designing correctors are sufficient) and hopefully it is just a matter of turning the crank to get an answer.

In principle it should be possible to correct the field down to the desired 0.1% level at 5 mm radius but I have not started to do this yet (wanting to give you all a heads-up on the preliminary results). Of course until I do this I cannot say how ugly the outer coil becomes or what it does to the existing peak field at the inner coil, but we can still be hopeful at this point.

Note this is the only path I can possibly imagine to access intermediate scale x-ing angles with reasonable magnet technology. A traditional single bore quadrupole is presumably limited because it is only possible to bring one beam along a low field beam path. i.e. even a 2 mr total crossing angle implies 0.002 rad x 144 T/m x 3.5 m = 1.0 T field that the outgoing disrupted beam has to get through.

On the other hand the compact quadrupole design, that is similar in size to the permanent magnet solution, is only comfortable with the present 20 mr crossing angle. If the design is “pushed a bit” we might consider bringing this down to of order 15 mr but even if this magnet can be made there is a down side to moving very far in this direction. As I reported back in June ’02, with the present scheme the extracted beam passing outside the cryostat sees as much as 200 Gauss transverse field as it goes closest to the IP end of the quadrupole coil. A simple thing to do to get the beams closer is to enlarge the cryostat to include both beams and then let the extracted beam line pass just skimming by the cold mass. But since the external field scales as 1/separation**3 the field goes up rapidly. I would guess that for an optimized design the field would go up to something like 400 - 500 Gauss. Of course this happens over only a short length so it may still be tolerable; its just that things will become very interesting trying to make a compact quadrupole solution work much below 15 mr!

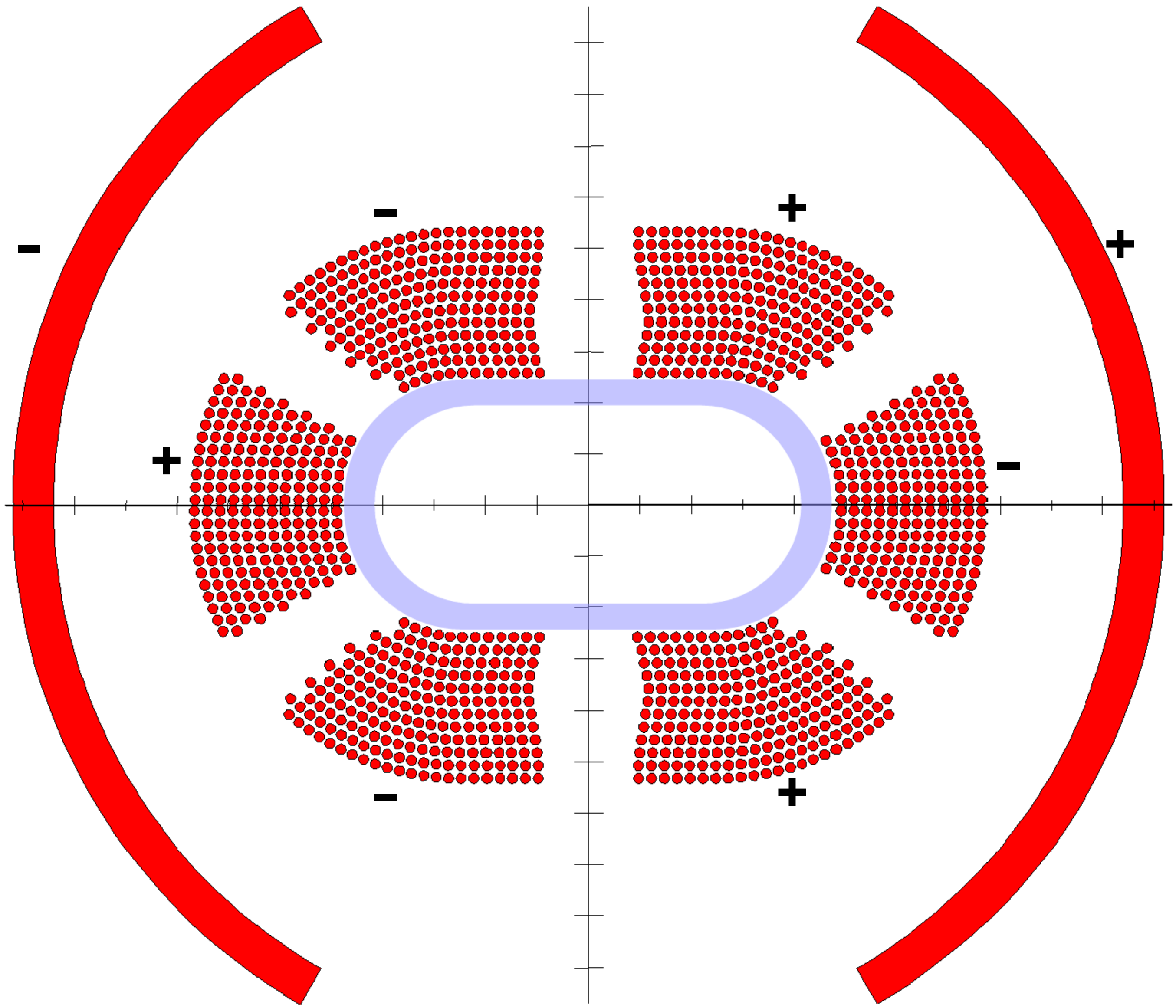
A final comment about the DFQ.... Note that a the proposed DFQ itself has a natural range of x-ing angles it can accommodate. With too small a beam separation (relative to the desired linear field region) it becomes very hard to keep the field linear without also killing the gradient. I also expect that too large a beam separation will force me to have to open up the coil pack so much vertically (issue is to have enough structure to keep the coil from collapsing) that while I can make very linear fields the achievable gradient will again suffer.

While I do not yet have a study to back this up, my gut feeling is that for the L* = 3.5 m and 10 mm radius clear aperture, x-ing angles of between about 6 to 10 (maybe 12) mr might be doable. An important input parameter for this work is the degree of non-linearity that is allowable [Maybe someone could do a quick estimate of this!]. The beam is small enough that it will always effectively see a linearized field. The issue (I think) is that if we move the IP spot around much the incoming beam samples regions that differ in gradient and therefore in effective focal length (plus some aberrations). If we can come up with a scheme to keep the incoming beams really "fixed" or if we have enough simple knobs to make optics corrections then maybe this is not such a problem. Getting the linearity down an order of magnitude to 1% at 5 mm reference radius may not be too hard but to get it below 0.1% we already know will require going to some fairly high order correctors. So quantifying this number with beam studies is important for the feasibility of the DFQ.

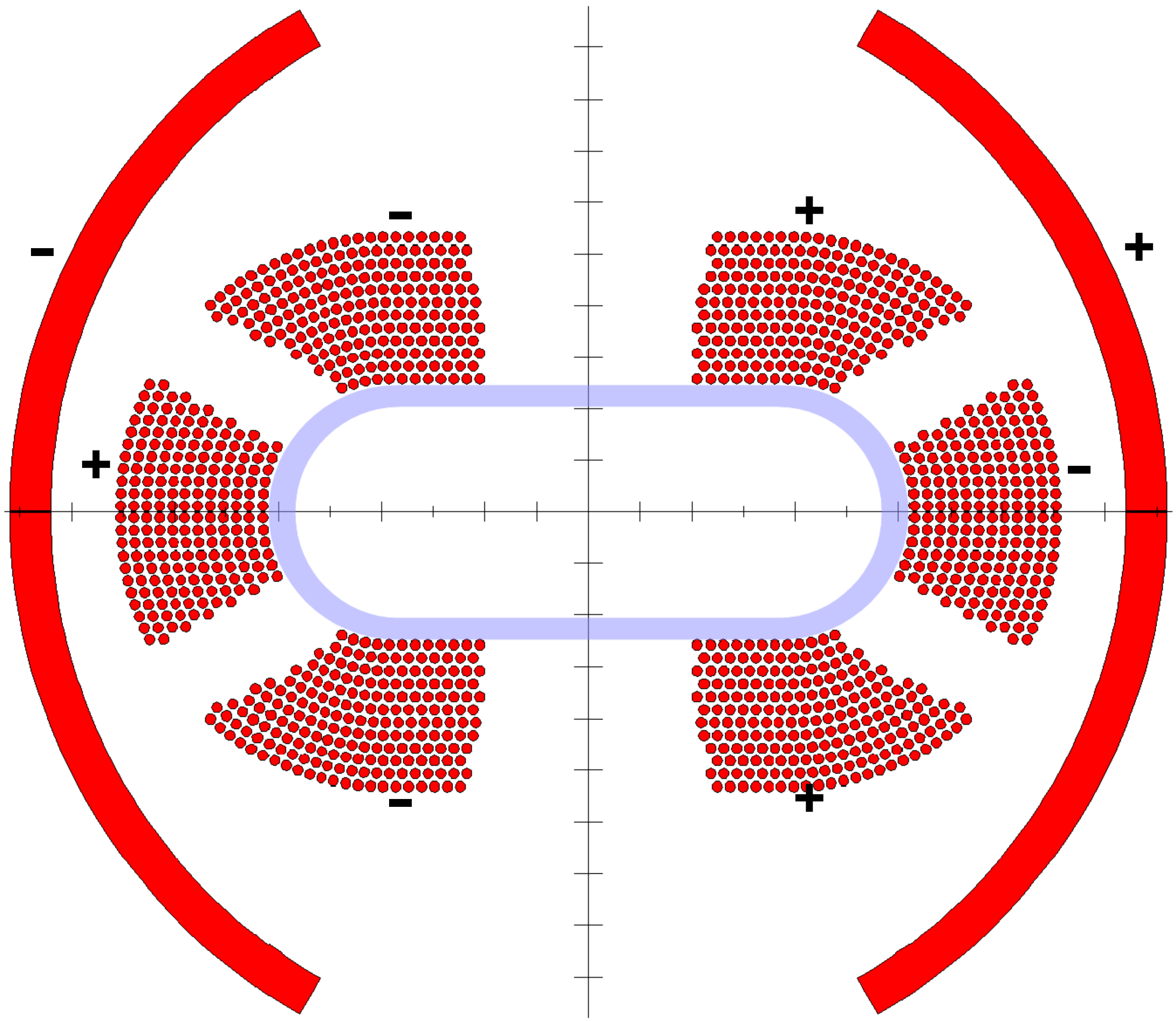
Note as usual the possible crossing angle scales roughly with L* though for fixed beam separation the magnet will be physically easiest for the combination
of largest L* and smallest x-ing angle (at least until we know how much
L* drives goodness of field).

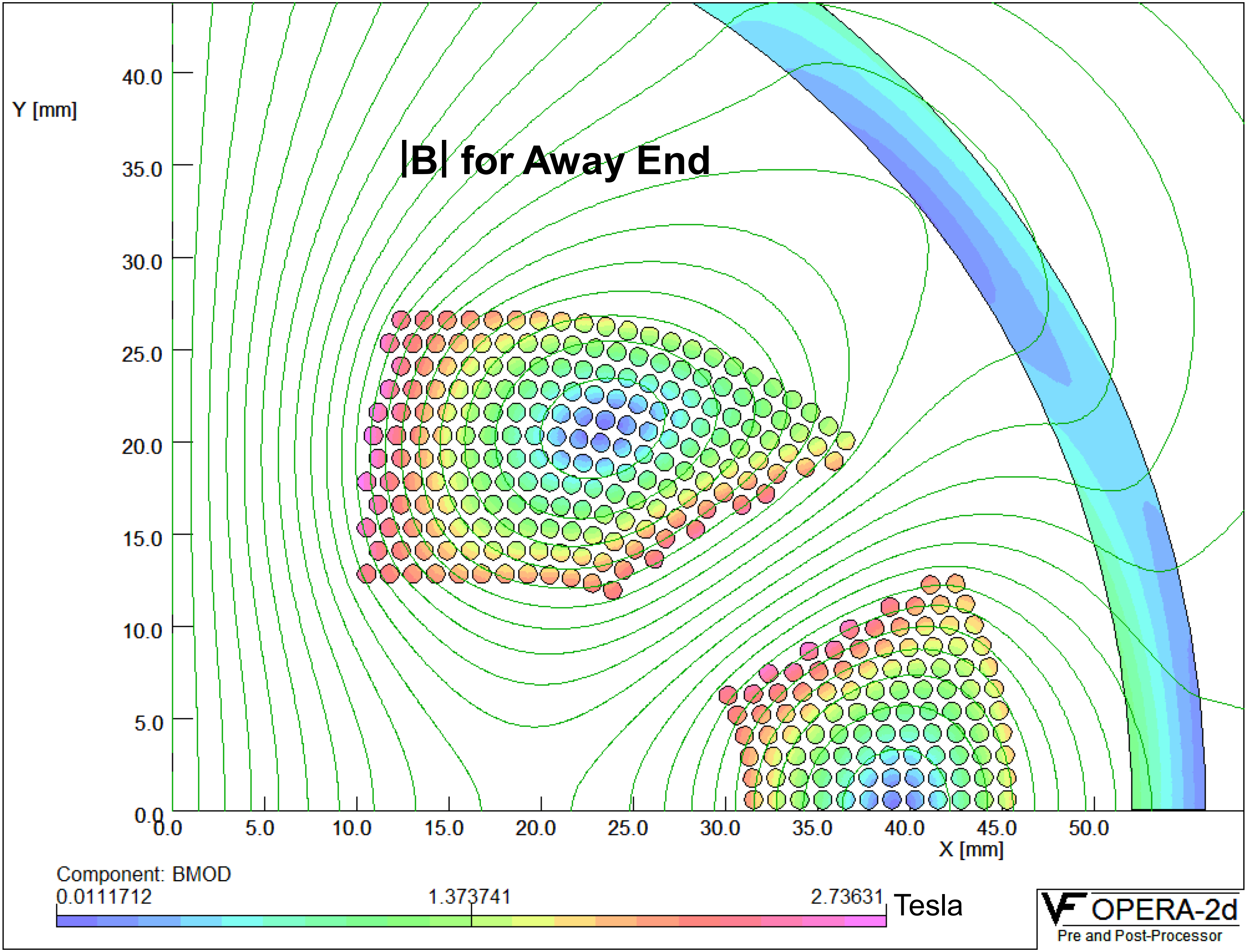
Hopefully you will find this work useful in assessing feasibility for intermediate crossing angle options and can use this information as a basis for ILC discussions at KEK.

Cross Section at IP End with Beam offsets = ±12.25 mm

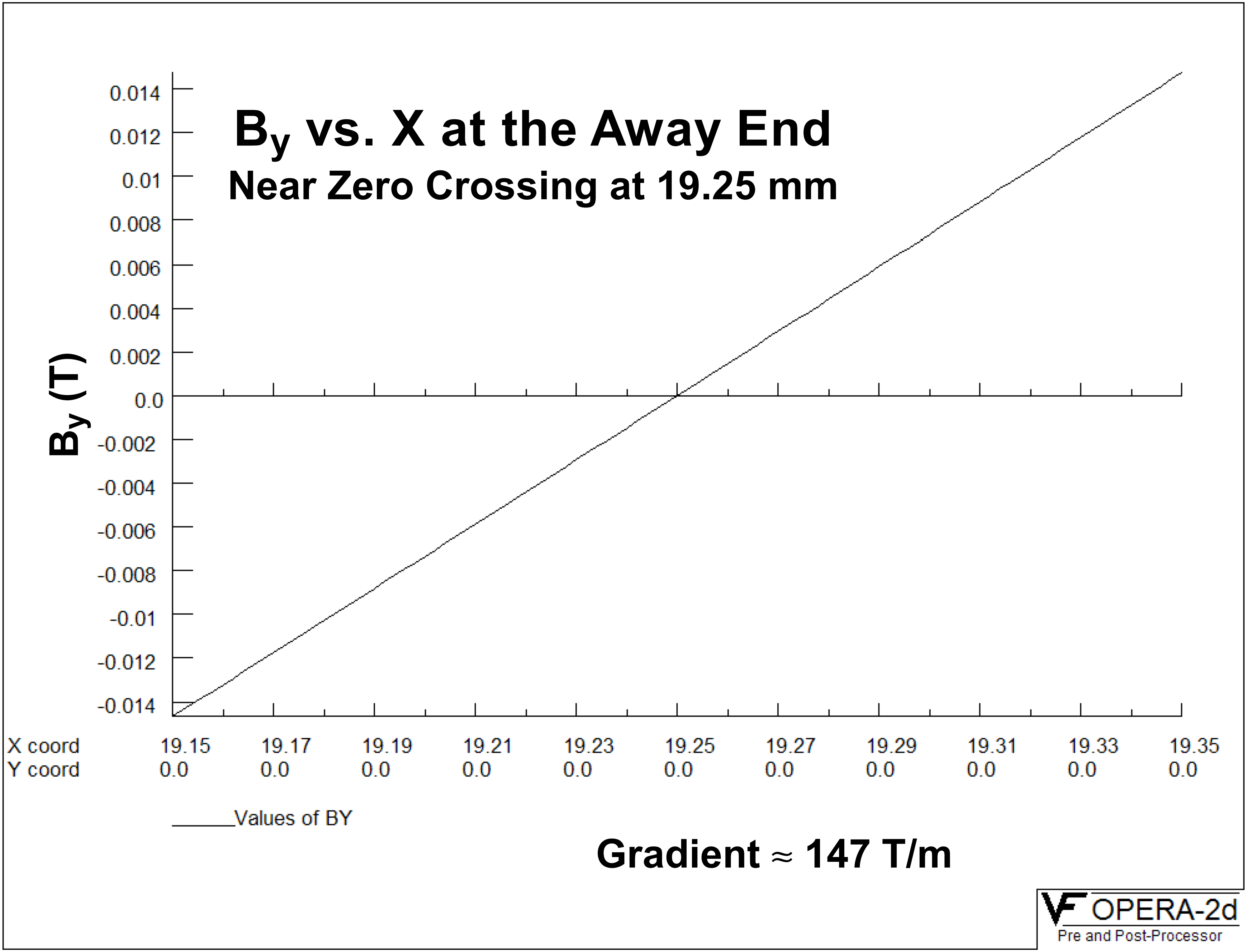


Cross Section for End Away from IP with Beam offsets = ±19.25 mm

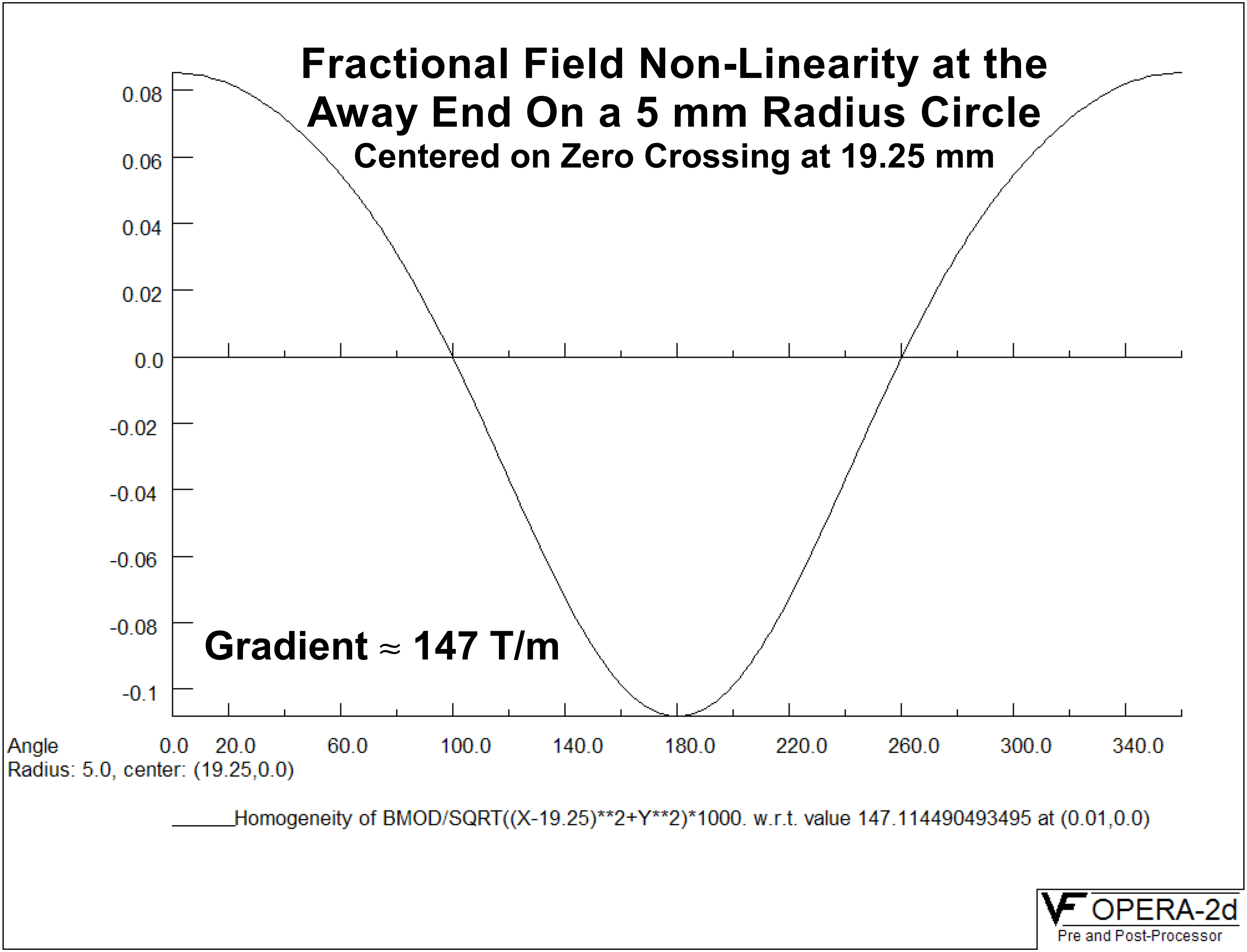


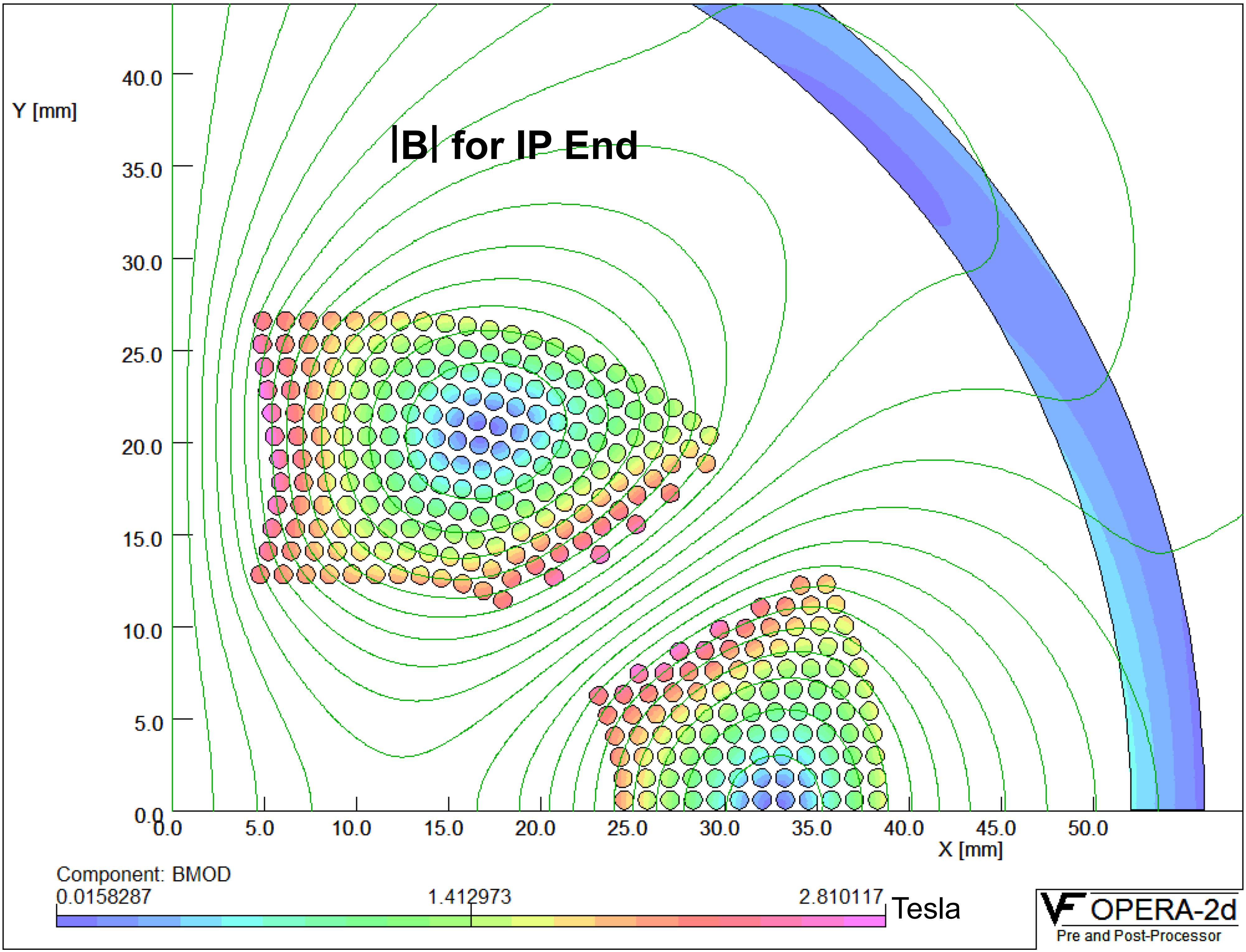


|B| for Away End
Y [mm]
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
X [mm]
Component: BMOD
0.0111712
1.373741
2.73631
Tesla
OPERA-2d
Pre and Post-Processor

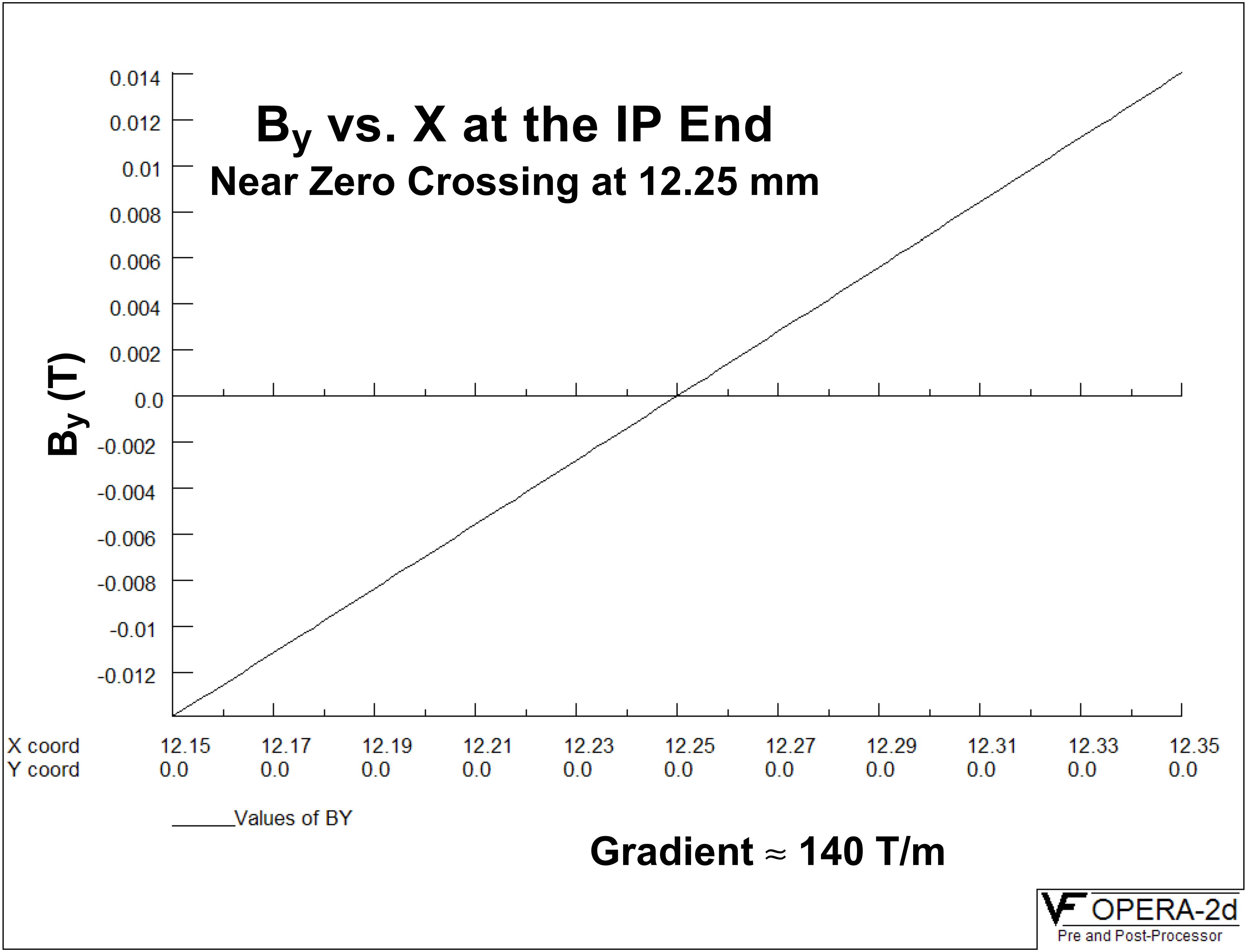


B_y vs. X at the Away End
Near Zero Crossing at 19.25 mm
B_y (T)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0.0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
X coord 19.15 19.17 19.19 19.21 19.23 19.25 19.27 19.29 19.31 19.33 19.35
Y coord 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
Values of BY
Gradient ≈ 147 T/m
OPERA-2d
Pre and Post-Processor

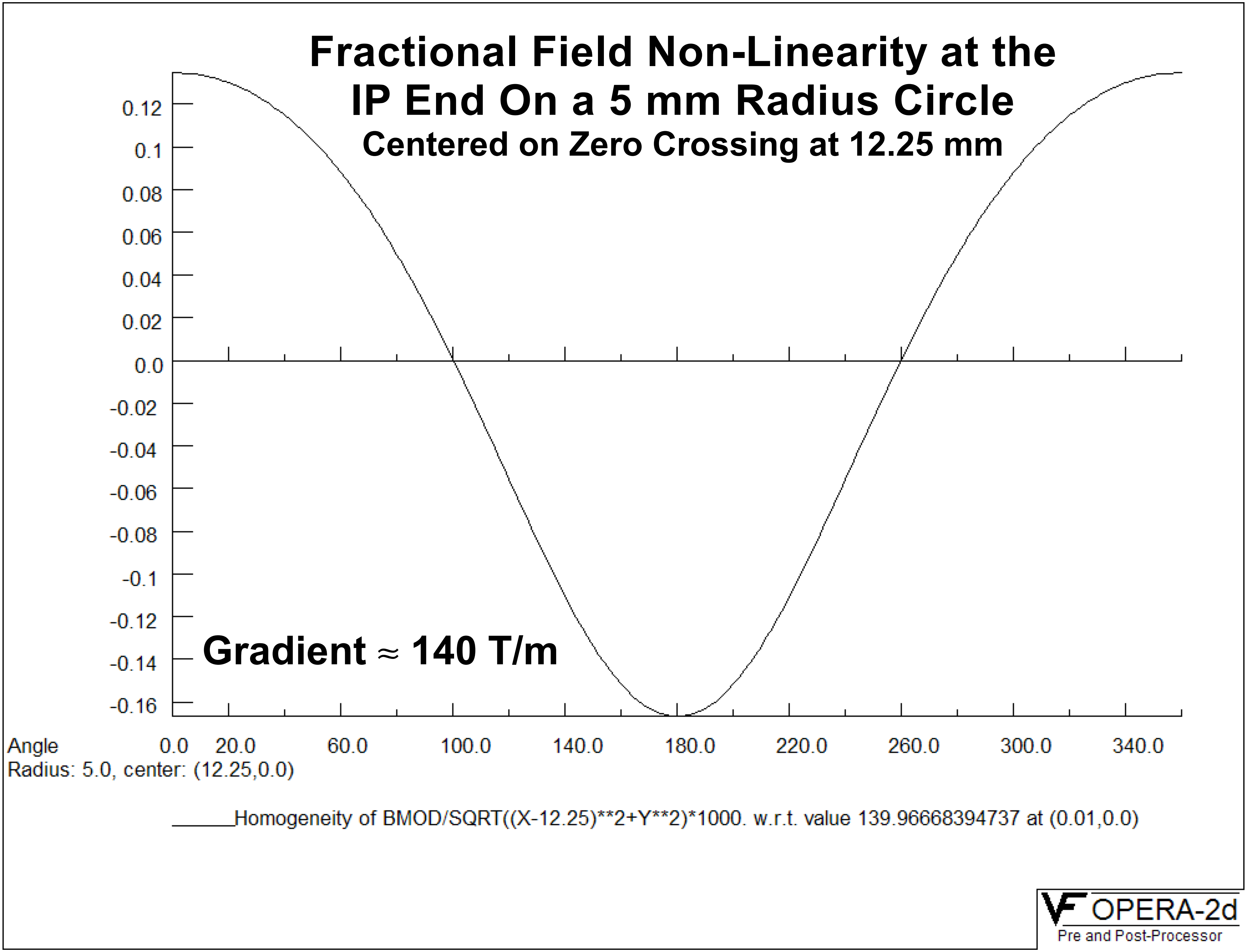

Fractional Field Non-Linearity at the
Away End On a 5 mm Radius Circle
Centered on Zero Crossing at 19.25 mm
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.1
Gradient ≈ 147 T/m
Angle
0.0
20.0
60.0
100.0
140.0
180.0
220.0
260.0
300.0
340.0
Radius: 5.0, center: (19.25,0.0)
Homogeneity of BMOD/SQRT((X-19.25)**2+Y**2)*1000. w.r.t. value 147.114490493495 at (0.01,0.0)
OPERA-2d
Pre and Post-Processor



|B| for IP End
Y [mm]
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
X [mm]
Component: BMOD
0.0158287
1.412973
2.810117
Tesla
OPERA-2d
Pre and Post-Processor



B$_y$ vs. X at the IP End
Near Zero Crossing at 12.25 mm
B$_y$ (T)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0.0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
X coord 12.15 12.17 12.19 12.21 12.23 12.25 12.27 12.29 12.31 12.33 12.35
Y coord 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
Values of BY
Gradient ≈ 140 T/m
OPERA-2d
Pre and Post-Processor



Fractional Field Non-Linearity at the
IP End On a 5 mm Radius Circle
Centered on Zero Crossing at 12.25 mm
0.12
0.1
0.08
0.06
0.04
0.02
0.0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
Gradient ≈ 140 T/m
Angle
0.0
20.0
60.0
100.0
140.0
180.0
220.0
260.0
300.0
340.0
Radius: 5.0, center: (12.25,0.0)
Homogeneity of BMOD/SQRT((X-12.25)**2+Y**2)*1000. w.r.t. value 139.96668394737 at (0.01,0.0)
OPERA-2d
Pre and Post-Processor

Original Proposal: SpecialMagnets3.pdf (6 pages)

At 4 in the morning tried using a simple conductor shape that could easily be hand optimized to see if idea for having “septumless” double aperture magnets made any sense at all.

Was able to achieve useful magnitude gradients without going to rediculous current densities.

Found solutions with fairly large but maybe not fatal field non-linearities.

Clearly have to use realistic conductor in model and optimize to see how much improvement in field quality is possible.

For now ignore mechanical issues associated with wide flat beam pipe and coil forces.

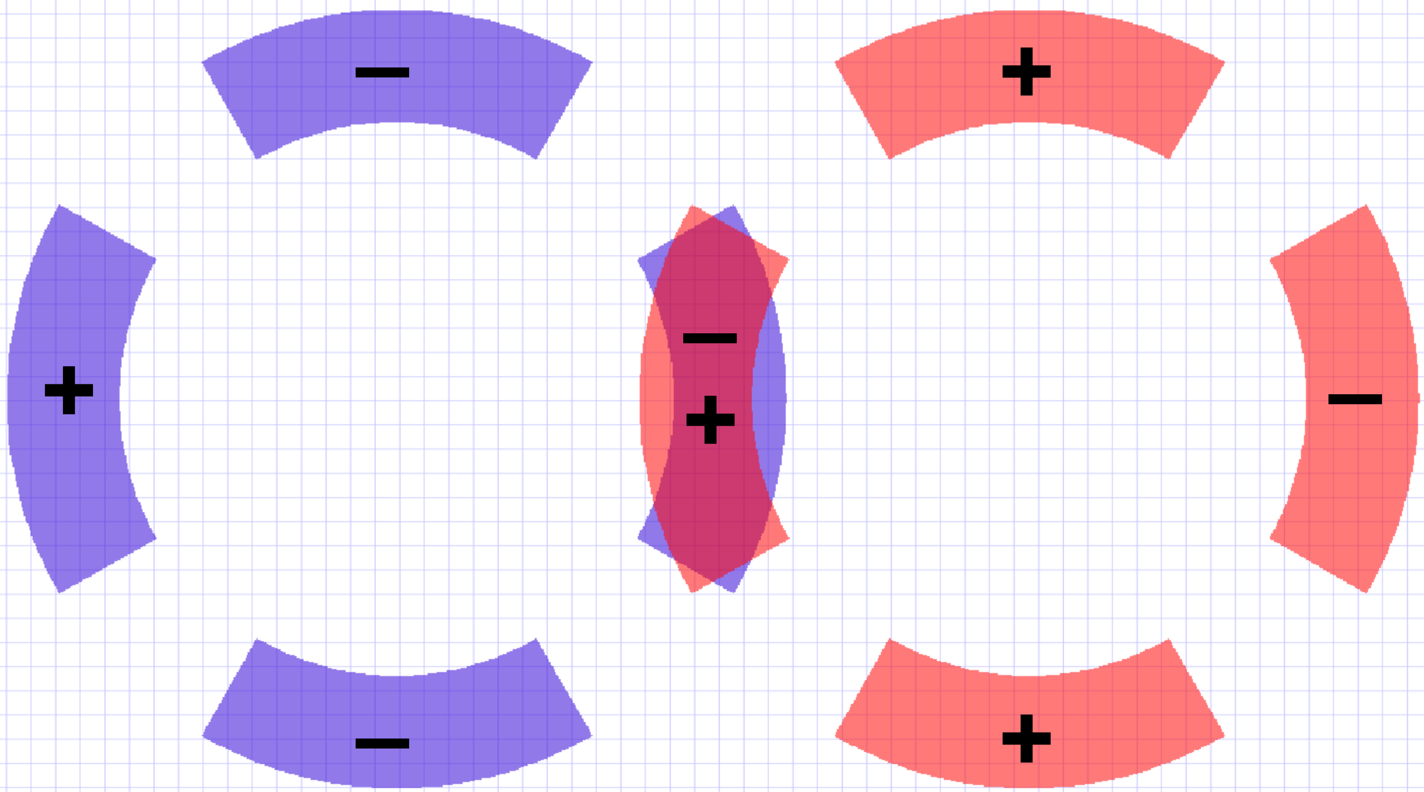
It turned out that Animesh Jain was able from general principles to derive expressions for field quality that depend upon beam geometry and the order and number of field harmonic terms that are used.

Also placing an external coil around flat inner coil package in some cases reduced net force between coil pack on opposite side of beam.

Special ILC BDS Magnets: And Now for Something Completely Different...

Presented by
Brett Parker, BNL-SMD

First Overlap Two Quadrupoles With Opposite Polarities.

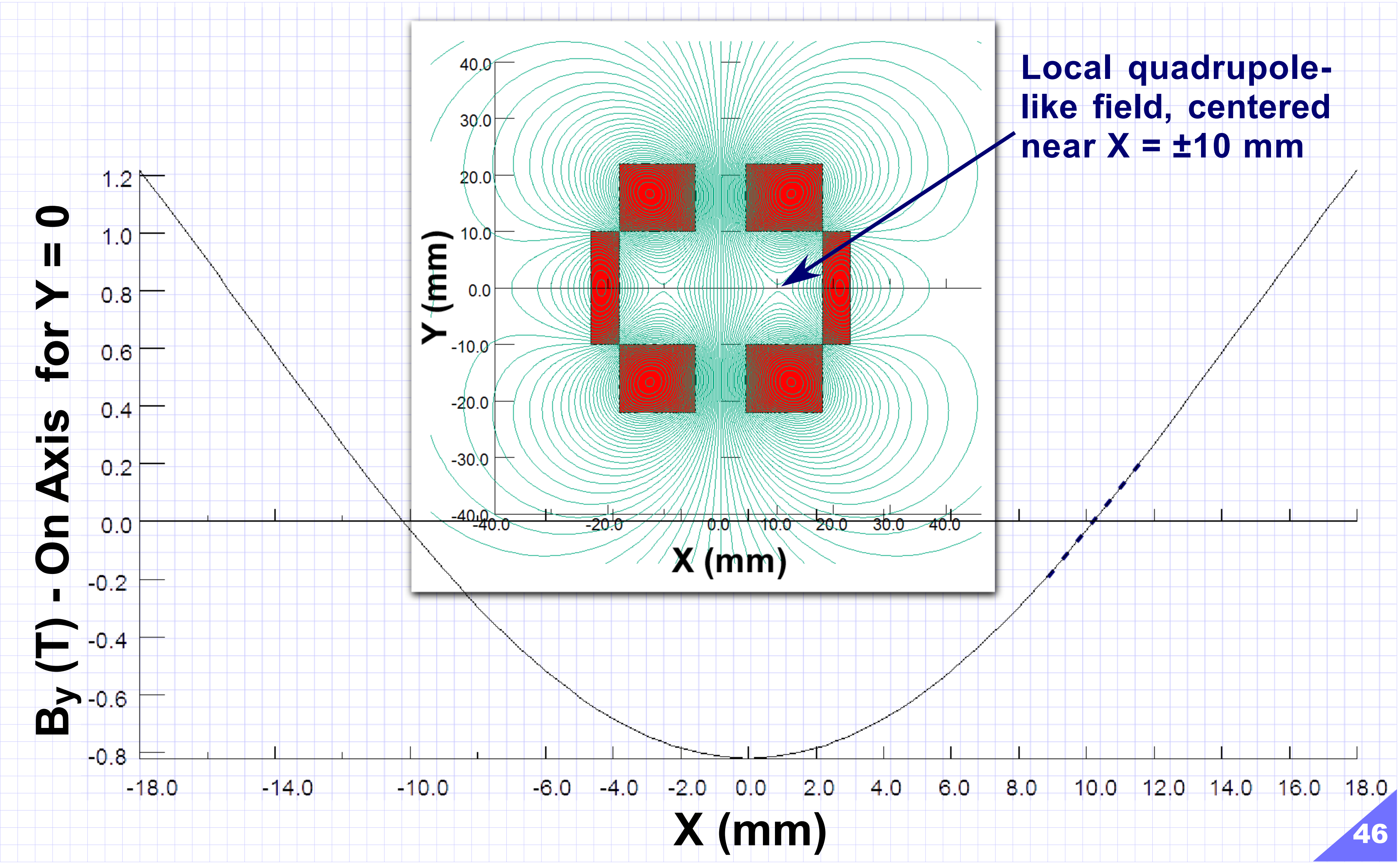


International Linear Collider

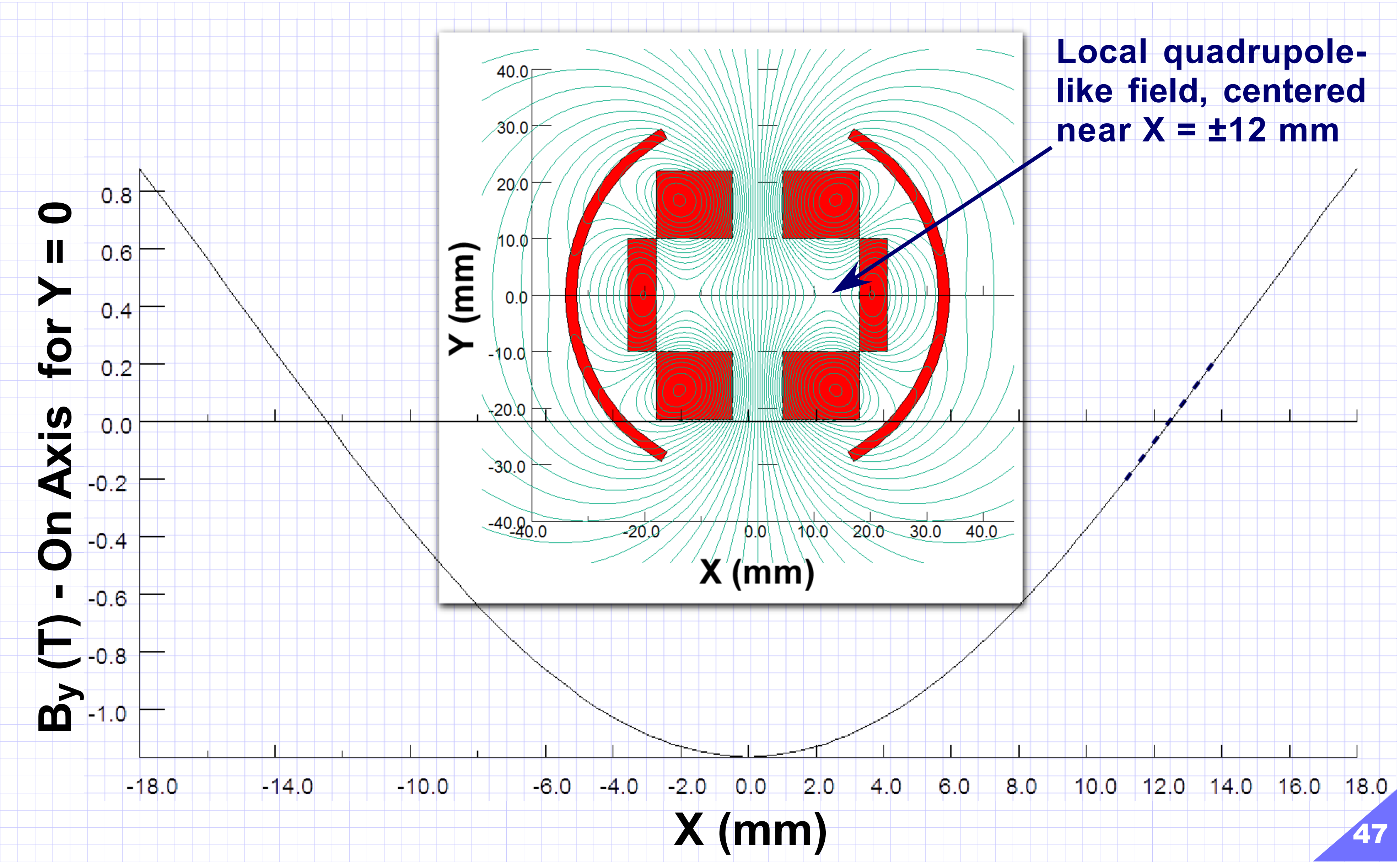
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Wipe Out Conductors That Cancel & Optimize Zero Crossings.

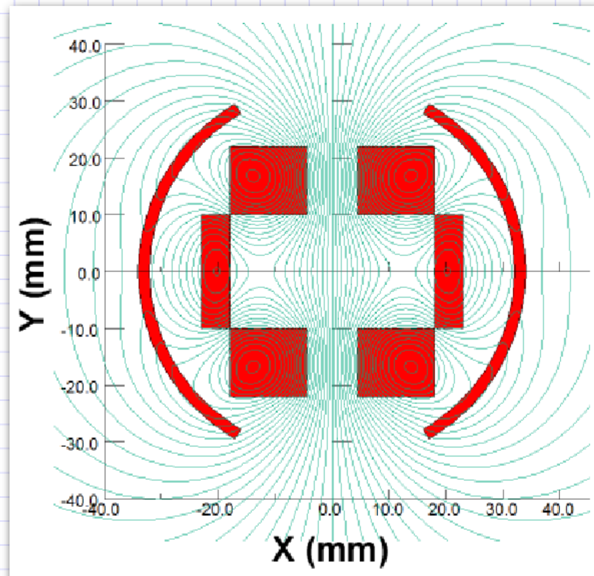


Then Add Dipole Coil to Move Zero Crossings Further Apart.

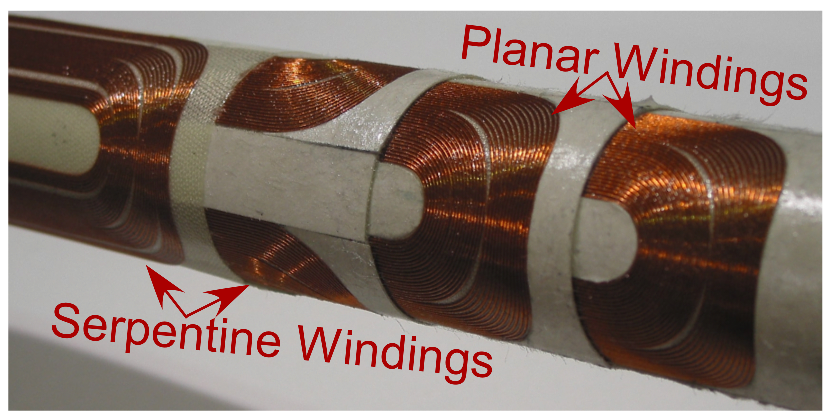


Tailor Longitudinal Distribution to Match Desired Crossing Angle.

- Overlap dipole coils with different lengths for $B_o(z)$.
- Can also play with varying inner coil dimensions (taper) as function of z.



We have already wound coils on tapered support tubes (HERA-II)



Winding Test Pattern

Some Final Observations.

- Trick is basically adding a longitudinally varying dipole field atop a funny looking sextupole to get two regions with opposite quadrupole gradients.
- Single pass nature hopefully means that field harmonics do not have to be perfect?
- Use computer to optimize Serpentine winding path to ensure constructible coil & reasonable integral harmonics (Panofsky style quad coils used for hand optimization).
- If we try the same trick but overlay dipole and quadrupole coils rather than two quads, it may be possible to get focusing inside magnet but near null outside for 35 mr crossing angle requested for $\gamma\gamma$.