General Approach to 3-d Optimization of the Magnetic Design

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Overview

To 1st order the general consideration for the 3-d coil optimization are the same as for 2-d coil optimization

1. Minimizing field harmonics
2. Minimizing peak fields
3. Robust ends - Conductor layout and spacers

- This presentation will discuss the tricks/techniques for minimizing end harmonics and minimizing peak fields in the ends (also called the magnetic design)
- General criteria and guideline will be discussed on the layout of the individual turns (and blocks) in the ends. It is still optimized with the past experiences, practice windings, now aided with computer codes to minimize strain/deformation in the cable
- To first order, it is possible to decouple, the magnetic design (and end forces) from the detailed layout of the individual conductor, if certain discipline is followed.
- One should be able to accommodate minor tweaks later - even after the 1st winding

Basic Guidelines to be Expanded

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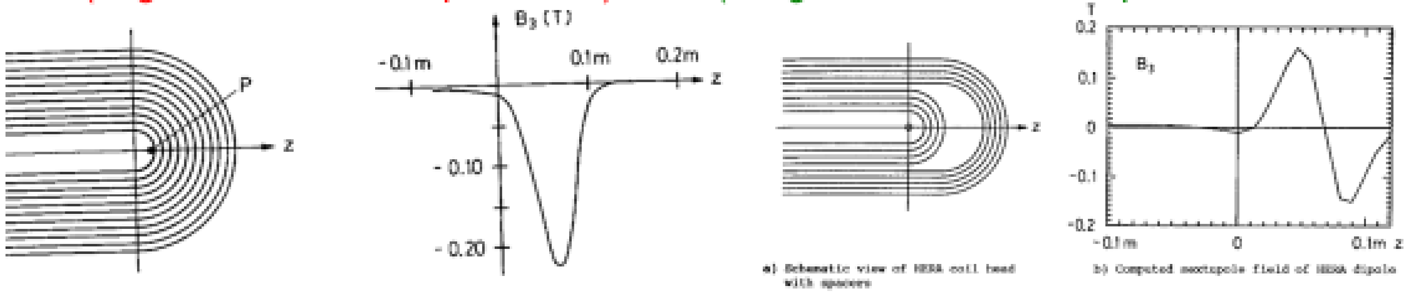
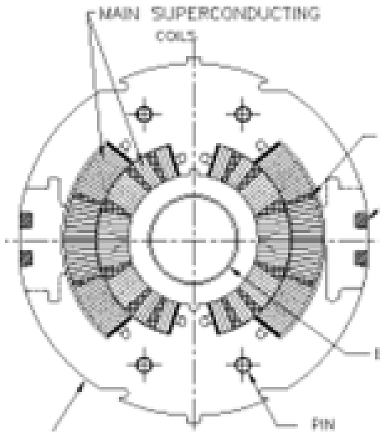
End Harmonic Optimization (conceptual)

Ends without spacer
(large harmonics and peak field)

Ends with spacer
(integrated harmonics & peak field reduced)





- End spacers increase the straight section length of some turns (turns at midplane go further out)
- Now consider the integral field generated by each turn. The harmonic component generated by a turn will depend on the angular location of it. The integral strength will depend on the length.
- A proper choice of end spacers can make integral end-harmonics small. However, note that the local values are large.
- Spacer also reduce the maximum value of field on the conductor (peak field) in the end.

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Optimize the design to add spacers at the strategic location

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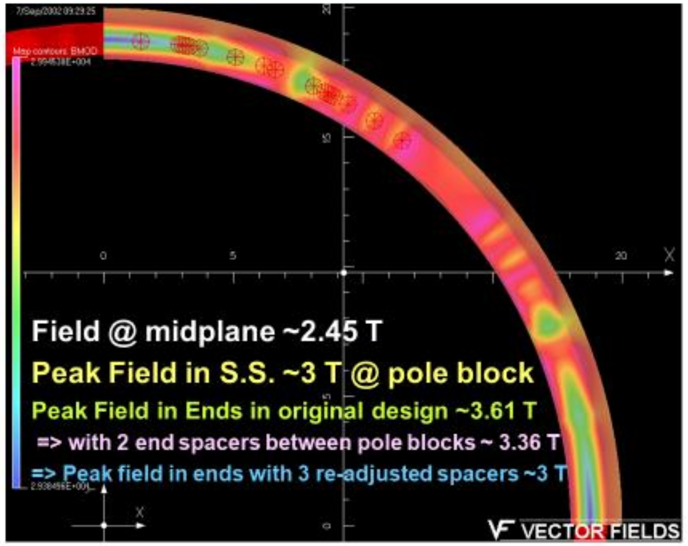
Peak Field Straight Section vs. Ends



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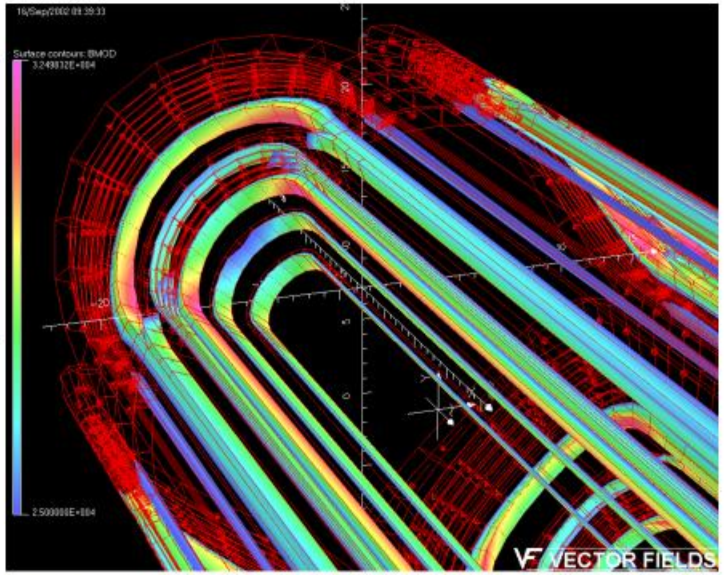
Ends with 3 Re-adjusted Spacers

Example (optimized):

Re-adjusted end spacer brings field in the ends down to S.S. level.



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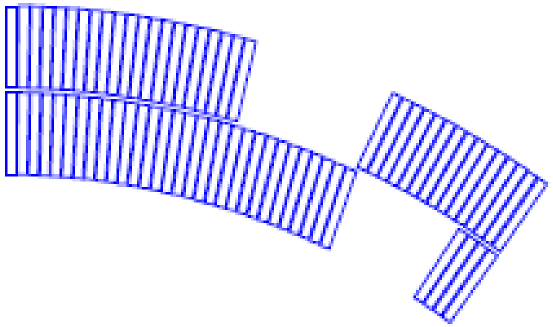
Minimization of Harmonics in the Ends

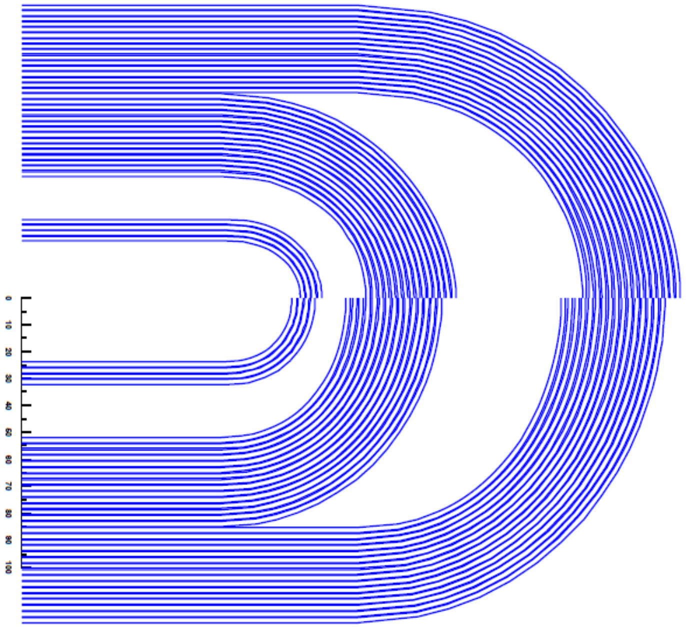


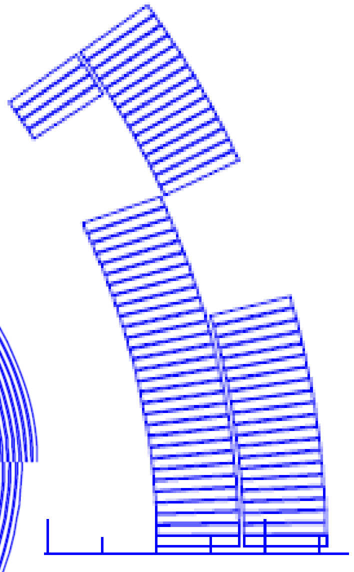
Quadrupole

for a line current located at (a, ϕ)

$$B_n \propto \left(\frac{R_0}{a}\right)^n \cos[(n)\phi]$$

- This means all harmonics (B_n) at the midplane (angle = 0) are positive
- All turn have to move from midplane to pole in the ends => means missing positive contribution. This means if done nothing, the integral harmonics will be negative
- We can't avoid the turning part; however, we can make turns with positive contribution longer to compensate for the negative
- Above expression determines the magnitude and sign of the contribution (depends on the angle)

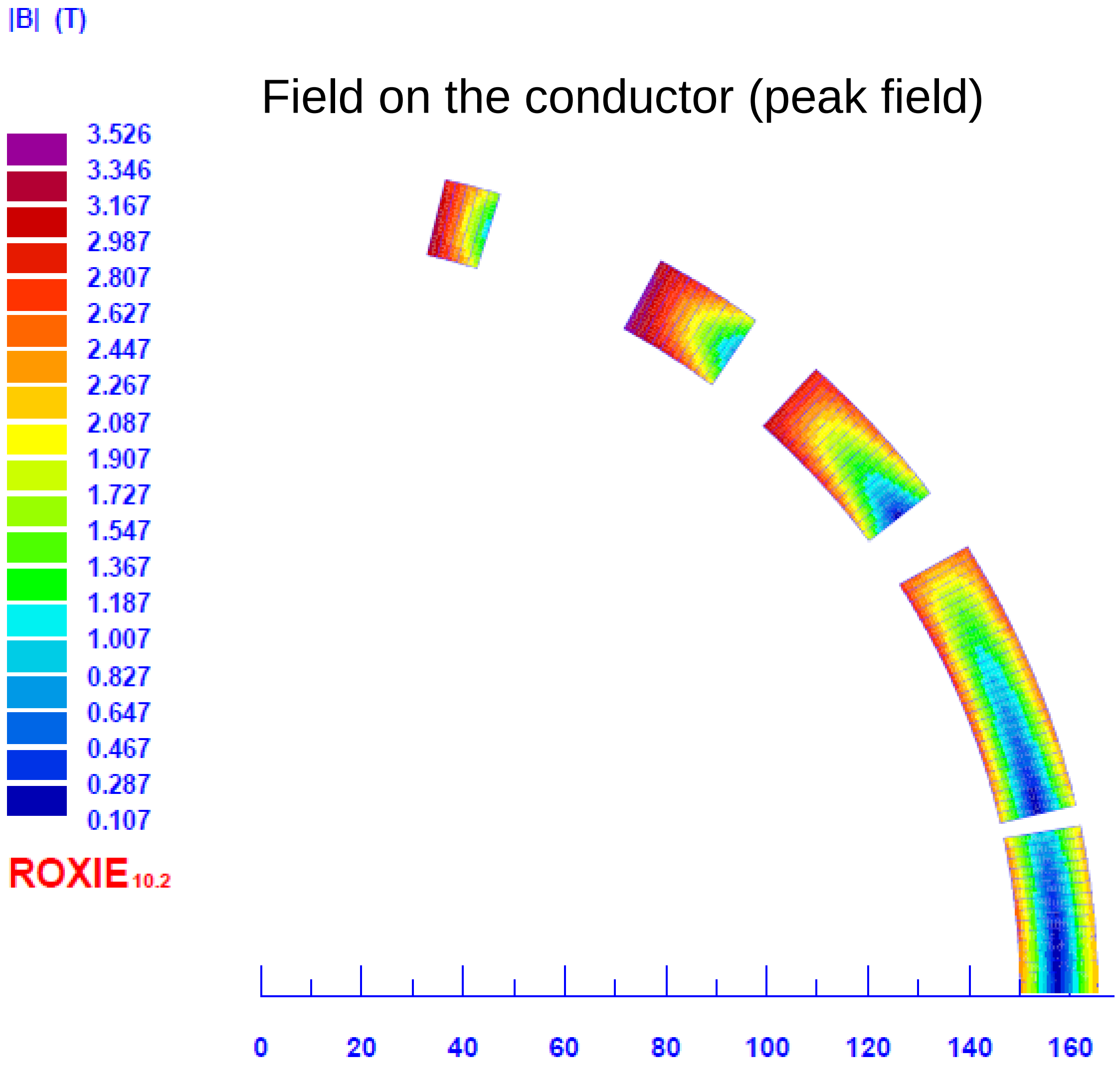




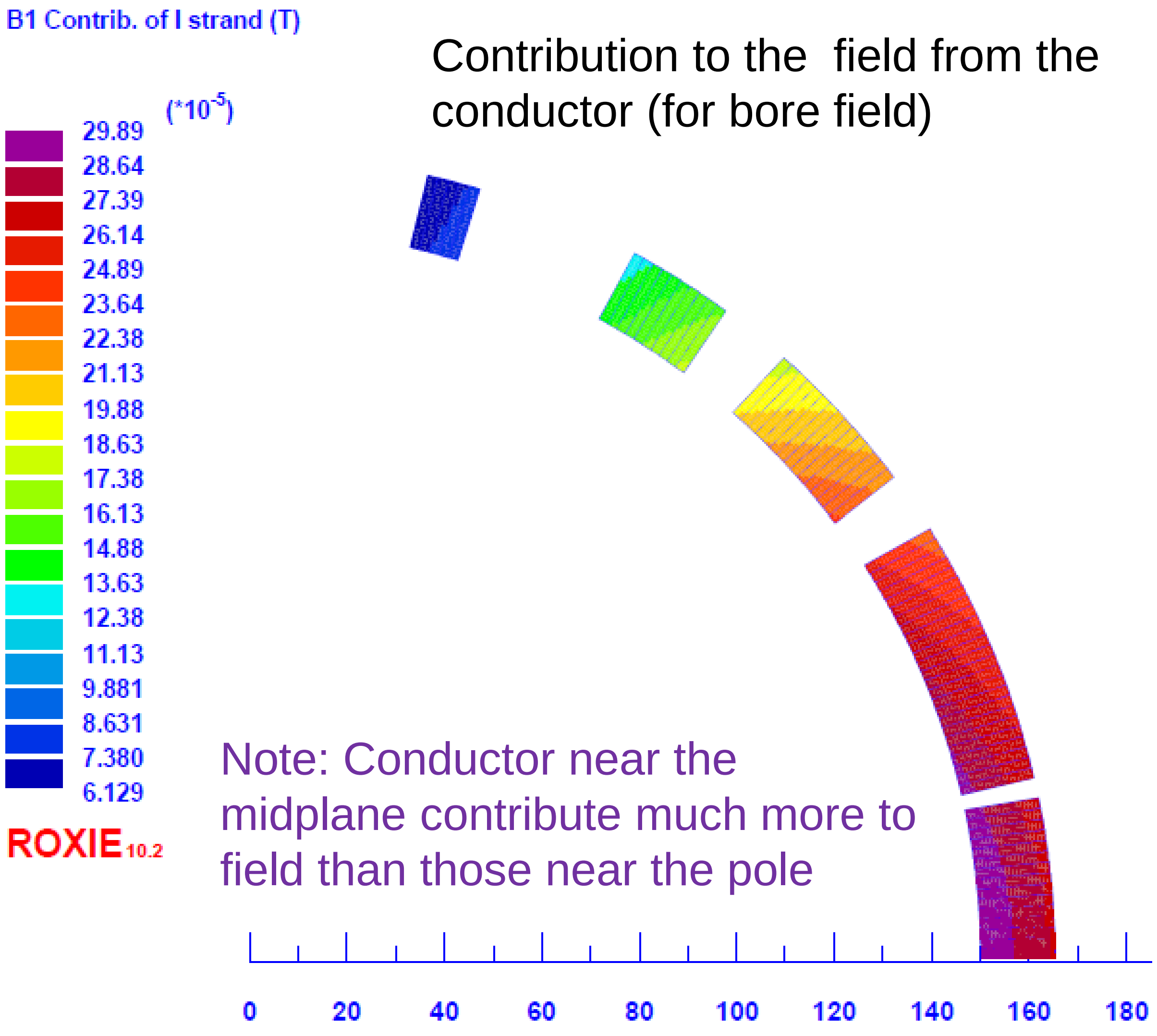
Note: The expression above is valid either for infinite long current or when it is integrated over entire field. However, overall guidance is still useful when used for a limited length

Peak Field and Contribution to the Field Harmonics

Field on the conductor (peak field)

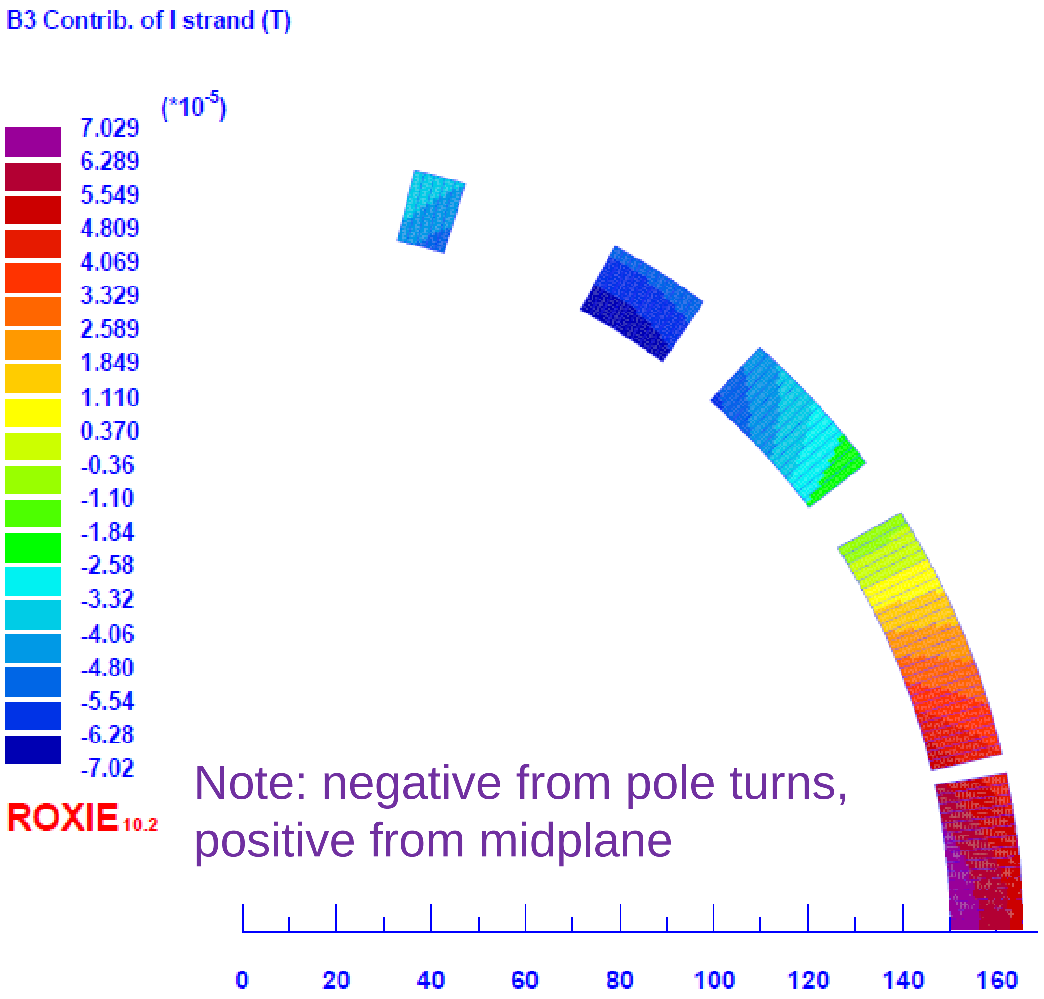


Contribution to the field from the conductor (for bore field)

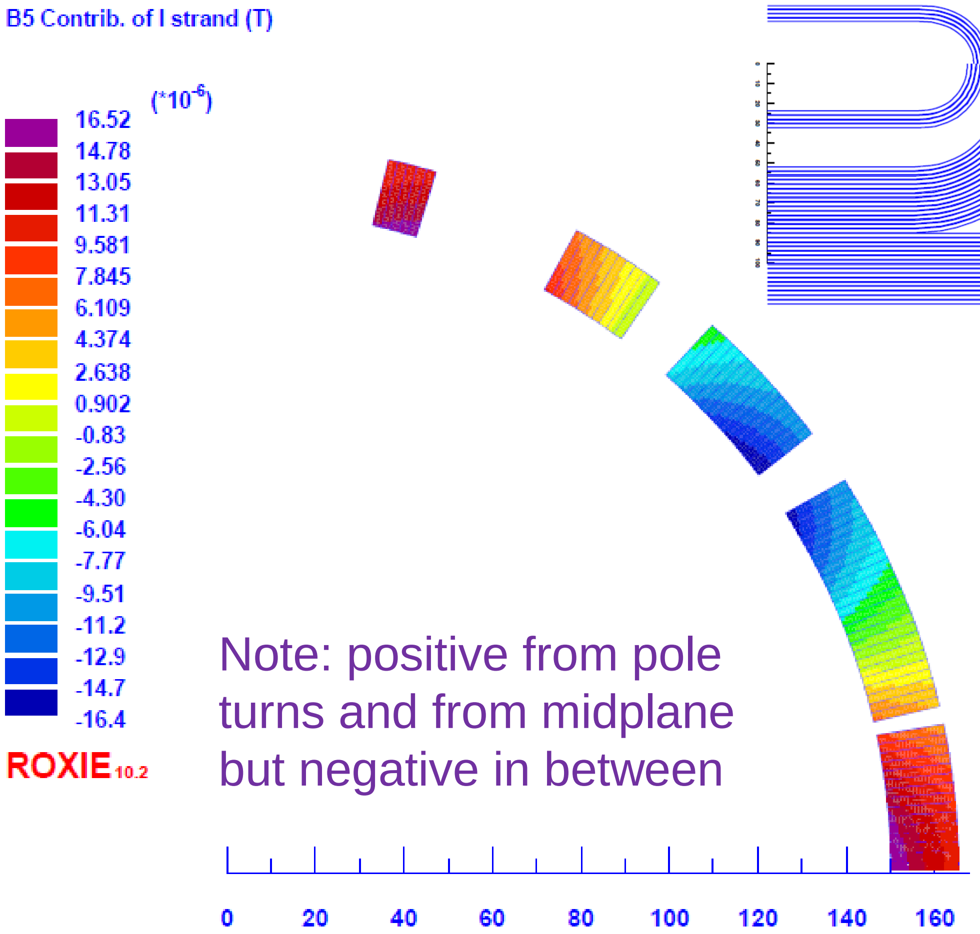


Note: Conductor near the midplane contribute much more to field than those near the pole

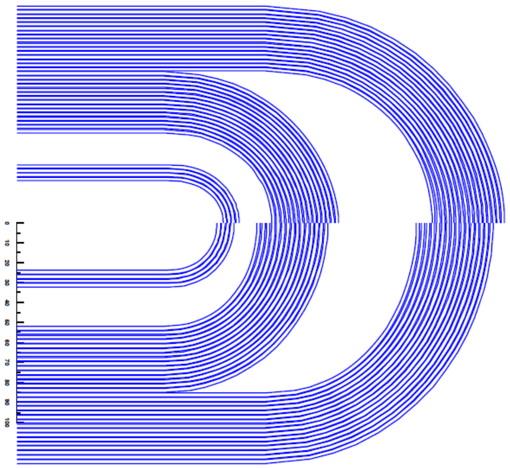
Contribution to the Field Harmonics (B3 and B5)



Note: negative from pole turns, positive from midplane

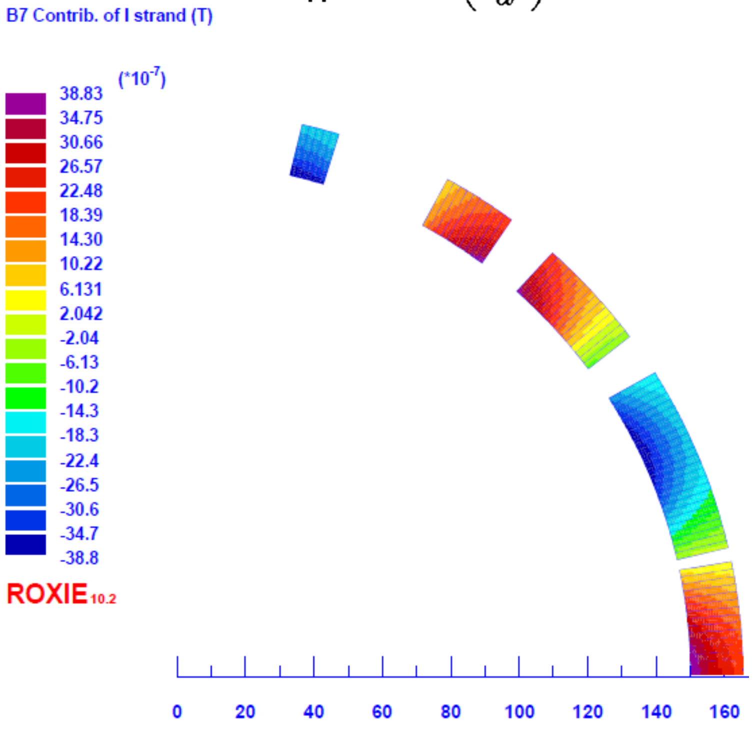


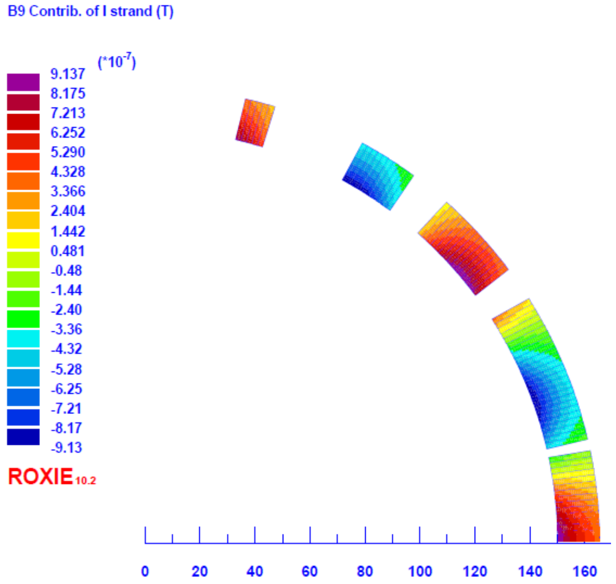
Note: positive from pole turns and from midplane but negative in between

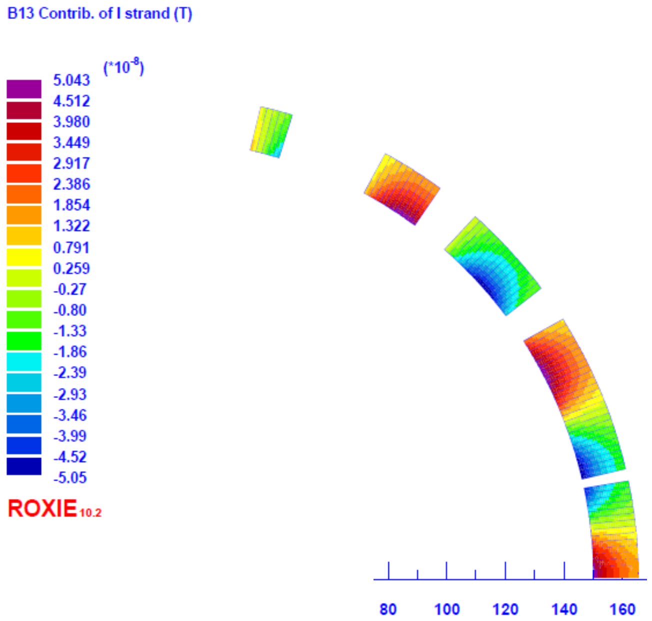


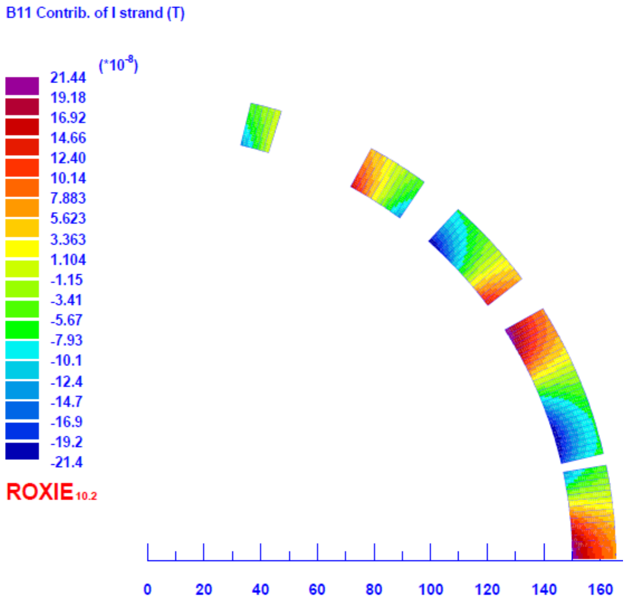
Contribution to the Field Harmonics (higher order)

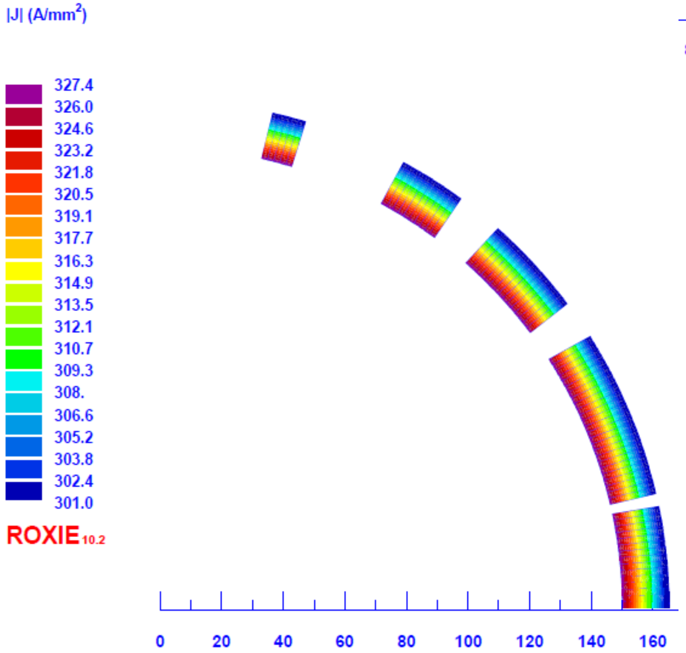
$$B_n \propto \left(\frac{R_0}{a}\right)^n \cos[(n)\phi]$$











Note: There are several positive and negative peaks for higher order harmonics. Obviously, we need to use computers to minimize all

Radial distribution of current (impact of keystone become important for higher order)

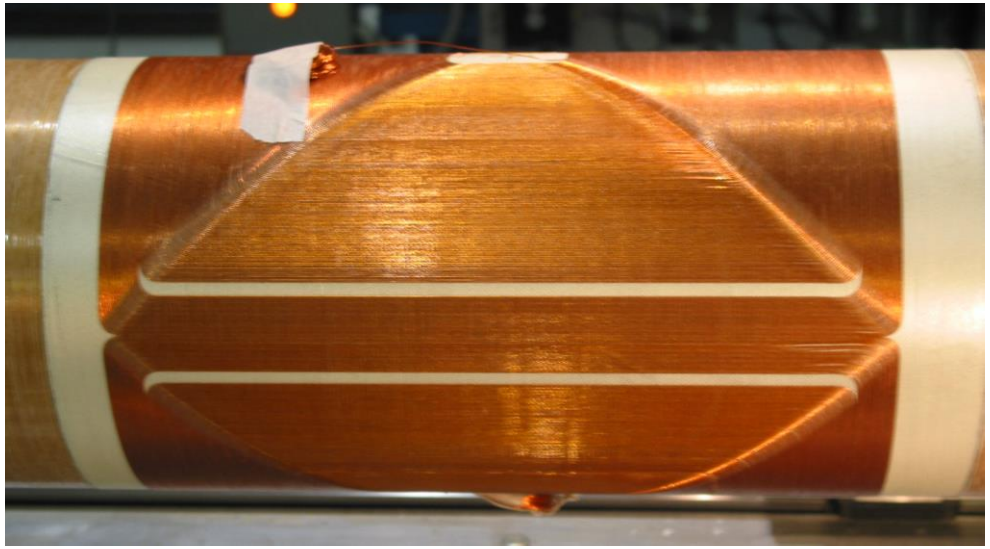
Strategies to Minimize End Harmonics Field harmonics (1)

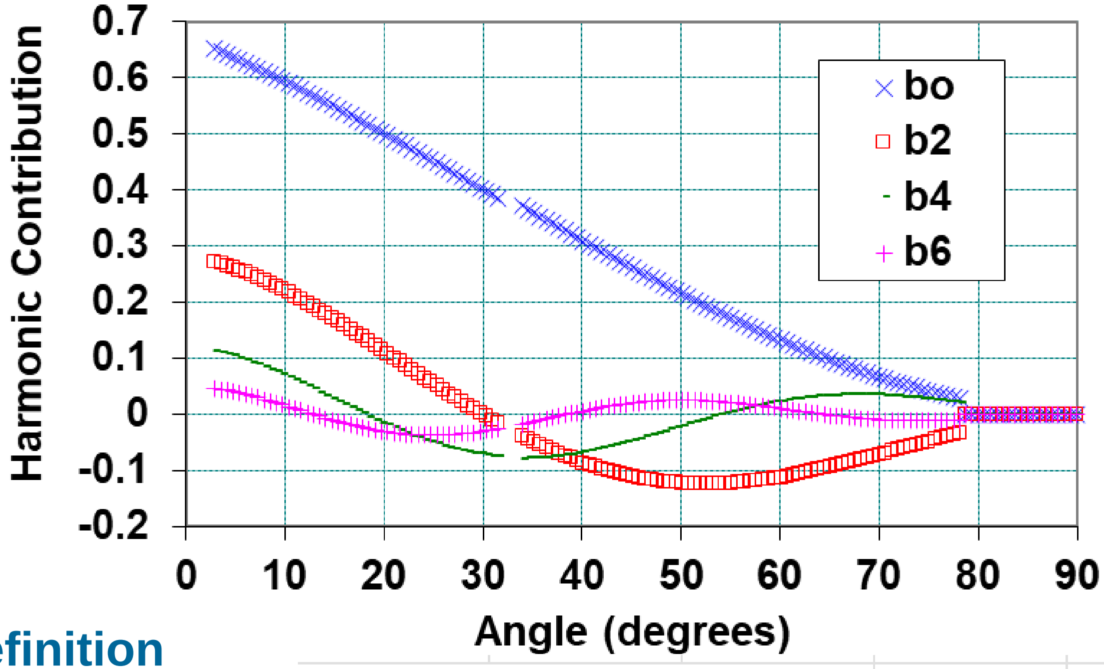
- Optimum integral design is an extreme example of the following strategy.
- Since the bending radius is small and turns at ends are perpendicular to the axis, the contribution from the turnover at end is small.
- Contribution for the end harmonics come primarily from different length of the turns.
- One can simply multiply harmonic by appropriate length and integrate them to zero.

for a line current located at (a, ϕ)

$$b_n = 10^4 \left(\frac{R_0}{a}\right)^n \quad cos\left[(n+1)\,\phi\right]$$

reference radius R_0



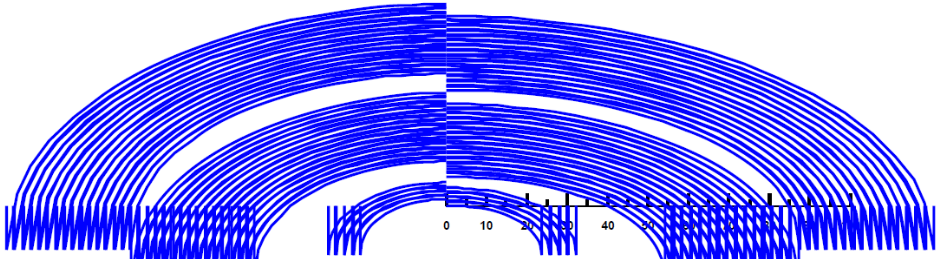


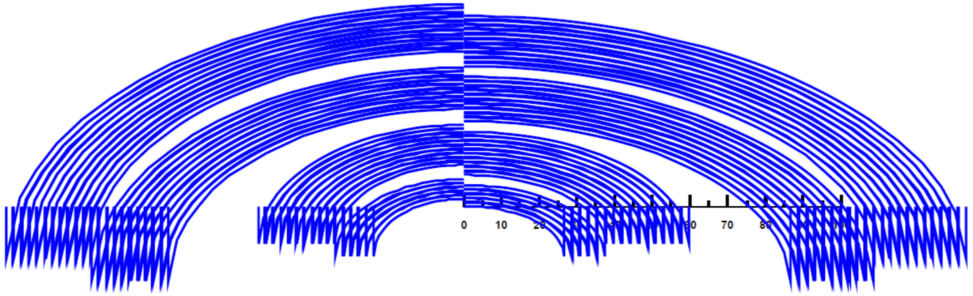
US definition
(b_2 is sextupole)

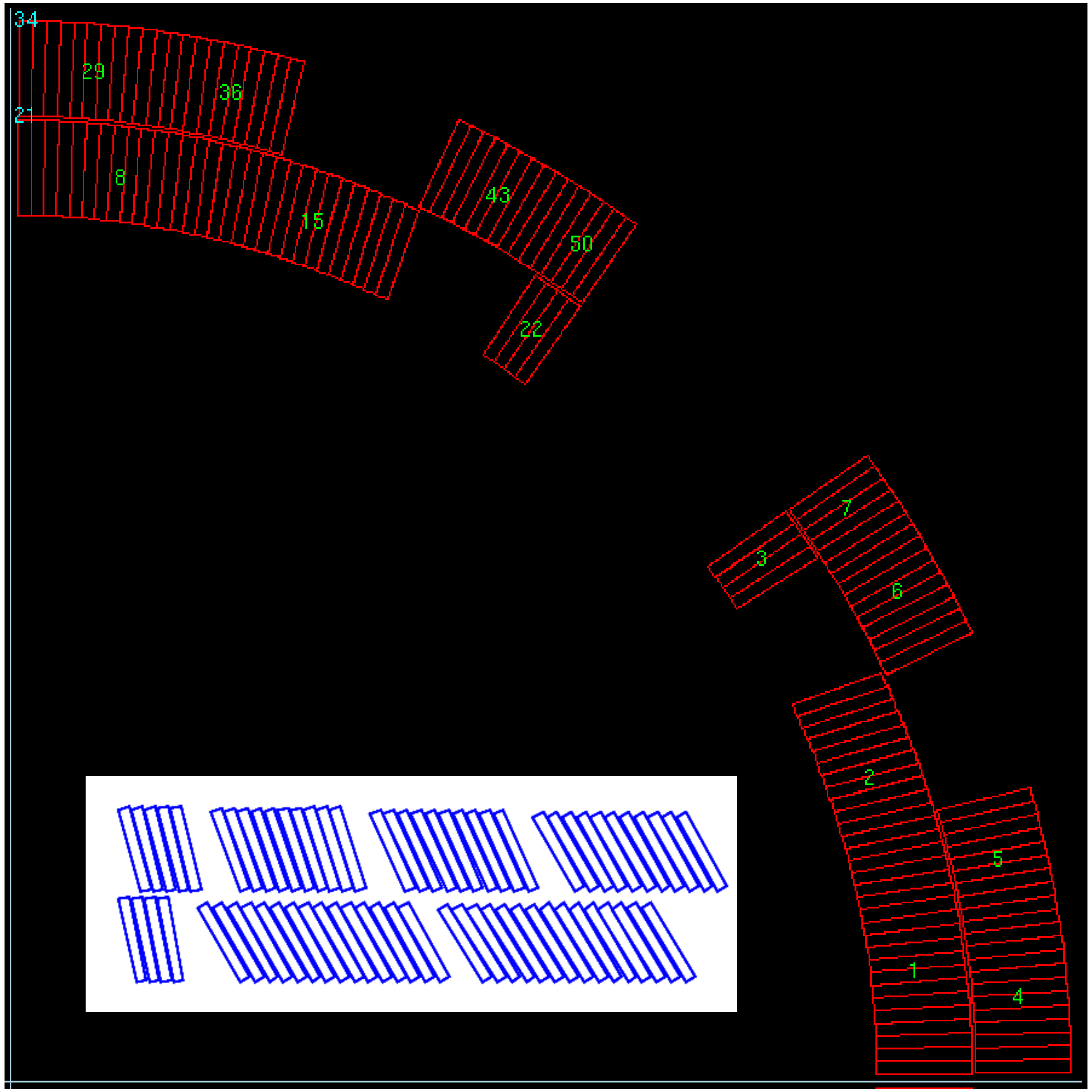
Bo (T.meter), bn (10^4)				
0.014939	-0.09299	-2.89085	-12.1232	-29.3454
37.3473	-0.00035	-0.0108	-0.04528	-0.1096
bo	b2	b4	b6	b8

Strategies to Minimize End Harmonics Field harmonics (2)

1. Decide strategically, if you need to break the SS blocks, and if yes, where?
2. Compute end harmonics from ~zero-length end
3. Compute contribution from say 10 mm increase in SS length of each block
4. Then by linear superimposition, one find out the initial value of spacers (simple excel will do)
5. Use ROXIE to do final optimization. This step can be skipped if you get good harmonics and low peak field (which will also determine the spacers) in the initial attempt itself

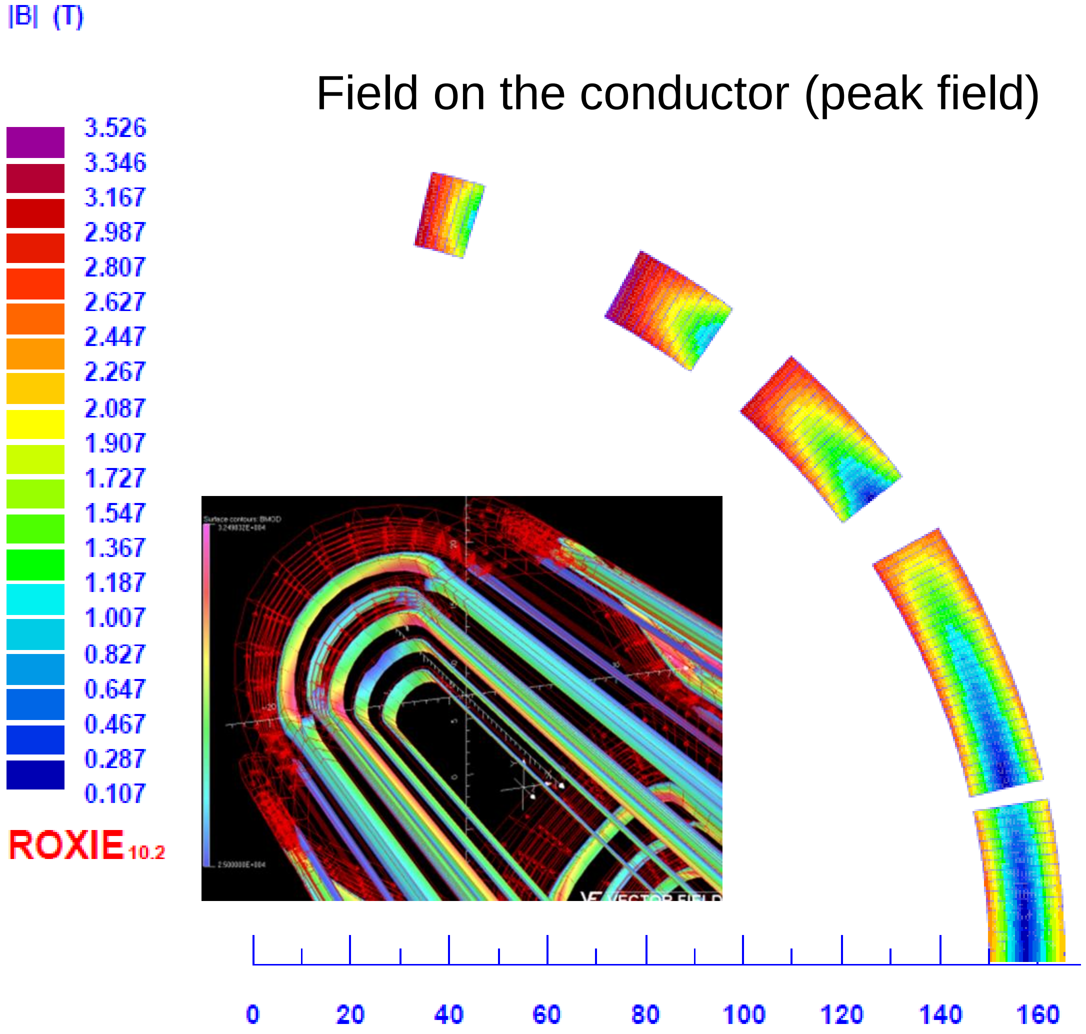






Minimization of Peak Fields in the Ends

- To first order, factors causing the peak fields in the ends are the same or similar as in the cross-section
- One gets a high peak field if a large number of turns are bunch-up at the pole and/or if pole angle is large
- Field on any block comes from two sources: (a) field of the block itself, and (b) field from the other block
- The field from the other block adds or subtracts depending on which side of the block you are
- For example, one side of the pole block will always add to the other side of the pole block. That's why pole angle shouldn't be too small. One can't avoid that in the ends as the turns have to come closer.
- Also, one block "sort of" shields nearby block. If the blocks are far away (see picture on right), lack of this shielding may result in higher peak field in the next. Same thing could happen in the ends, as well.



- ➢ Strategy to reduce peak field: # of turns in key blocks, strategic place and values of spacers
- ➢ In a two-layer coil, one can take advantage of end of one layer starting before the other
- ➢ One can also increase the yoke inner radius in the ends
- ➢ This needs to be done together with optimizing the field quality. Some iterations may be needed

Mechanical Layout

Cable Layout (path) in the Cosine theta Ends

- One major source of challenge in the cosine theta ends is the length of the cable between the path at inner radius and at outer radius when traversing from side to the other side. The difference is maximum for the midplane turn
- Rutherford cable can be starched a bit, can be deformed a bit also; but too much of that causes cable to degrade
- The cable is tilted to reduce the length at the outer side and increase at the inner side. A perfect constant perimeter end will have that.
- In reality, it can’t be done. The level of the complexity depends on the ratio of cable width to the coil radius.
- In optimizing ends, the change in tilt angle is made gradual, change in path length between the two sides is minimized from the centerline, sudden changes are avoided, and strain on cable is minimized.
- Some time we add extra spacers, to minimize bunching of a large number of turns to avoid making the block too soft