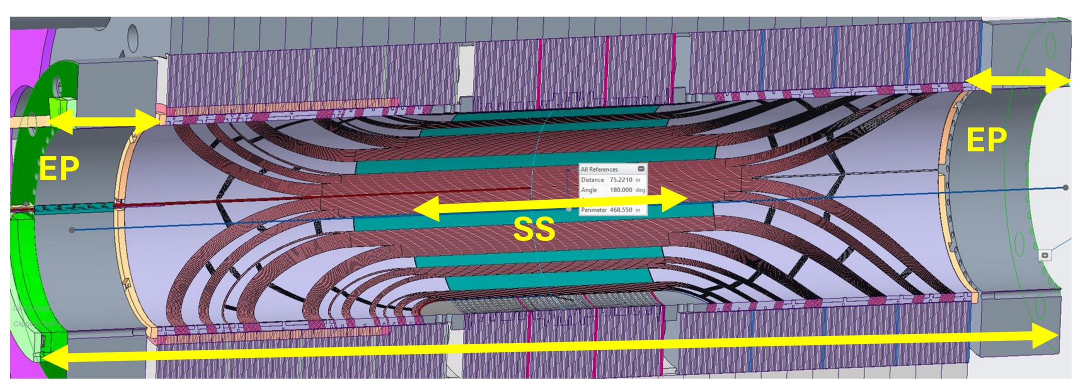
BROOKHAVEN
NATIONAL LABORATORY
Superconducting
Magnet Division

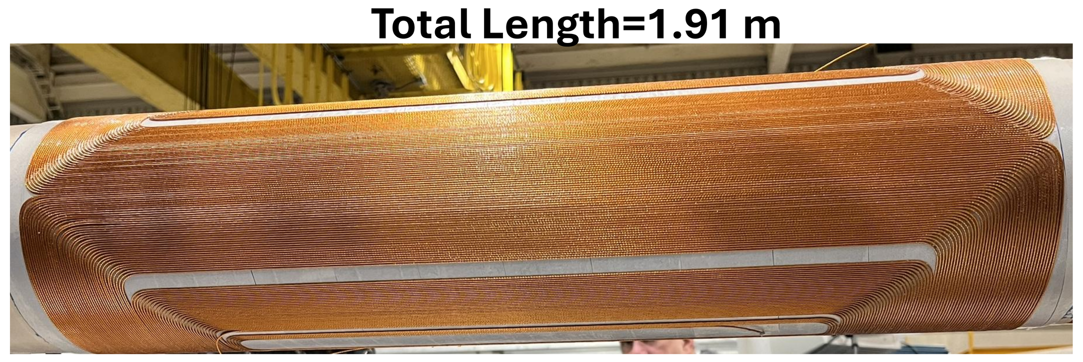
Optimum Integral Design for EIC Dipole B1pF/B1ApF -Ramesh Gupta, BNL

Abstract- The Optimum Integral Design (OID) with Direct Wind (DW) technology offers a unique value engineering opportunity for the Interaction Region (IR) dipoles B1pF and B1ApF of the Electron Ion Collider (EIC). The current design of these magnets is based on the conventional cosine theta configuration using Rutherford cable. As compared to most accelerator magnets, B1ApF has a small coil length (1500 mm) to coil aperture (370 mm) ratio (4.2). The relative benefit of the Optimum Integral Design is significant in such short magnets since it minimizes the loss in effective magnetic length due to ends.

COMPARISON BETWEEN DESIGN OPTIONS

B1ApF based on the Rutherford Cable





Optimum Integral Direct Wind Design

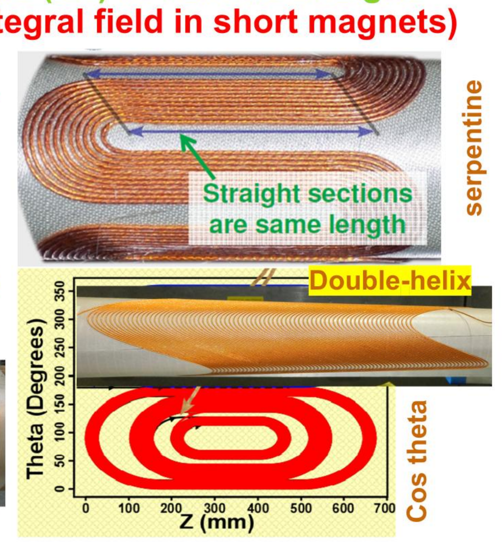
Compare the length of Straight Section (SS)

The present design of B1ApF is based on the cable magnet. It has a small Straight Section (SS). Moreover, End Plates (EP), needed to restrain the axial Lorentz forces take a significant space of the available slot-length.

In a direct-wind optimum integral dipole, the end plates will not be needed and the midplane turns (which create the maximum field) can extend the full length.

Length of the Straight Sections (SS) in Various Designs
(length of SS determines the integral field in short magnets)

- *Space for turns in the Ends must be at least as much as that used in the arc of the straight section (usually more).*
- *Thus, straight section will have ~1/3 of the length in a cos theta dipole or in a serpentine. It's worse in double-helix.*
- *In the optimum integral design, straight section length is the full coil length.*



Optimum Integral

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OPTIMUM INTEGRAL DESIGN

Optimum Integral Design – What is new and why is it important?

Conventional End Designs:
- Conventional ends take large space (~2X coil ID in dipole)
- Field per unit length in ends is ~1/2 of that in the body => relative loss in field integral is significant in short magnets

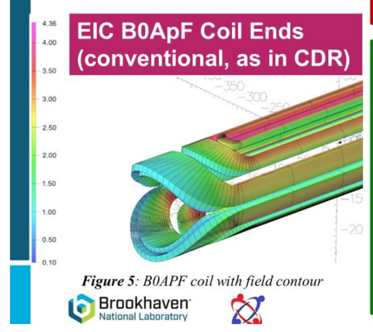
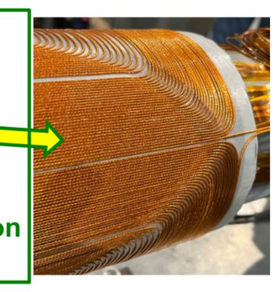


Figure 5: B0APF coil with field contour

Optimum Integral Design:
- End turns at midplane runs full length of the coil => almost no loss in space due to Ends
- Gain in magnetic length => about a coil diameter in dipole.
- This could be a significant fraction of total length in short magnets.



Basic Principle of the Optimum Integral Design

Modulation of the current in the straight section (SS) of the conventional designs:

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

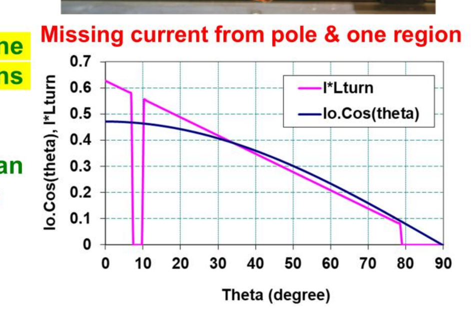
...and then ends are optimized separately.

Contribution to field from the ends is small and field integral is primarily determined by the length of the SS.

In the optimum integral design, turns at midplane extend full length, while the length of other turns decreases with the angle.

Cos theta azimuthal distribution is obtained in an integral sense, i.e., not in "$I(\theta)$", but in "$I(\theta).L(\theta)$":

$$I(\theta)\,.\,L(\theta) = I_o\,.\, L_i(\theta) \propto I_o\,.\,L_o\,.\,\cos(n\theta)$$



Conventional Design Approach

A two-step process:

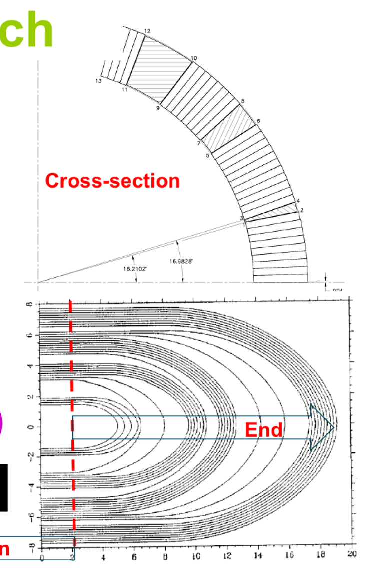
Step 1: Optimize coil cross-section to obtain cosine theta like distribution:

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

Step 2: Optimized ends for harmonics

(also, optimize both for low peak fields)

Each step limits the maximum integral field



Optimum Integral Magnet Design Approach

Optimize cross-section and ends together to obtain an integrated cosine theta distribution

$$I(\theta)\,.L(\theta) = I_o\,.\, L_i(\theta) \propto I_o\,.\,L_o\,.\,\cos(n\theta)$$

For no wedges or end spacer, function varies linearly ==> Modulate it to cos theta

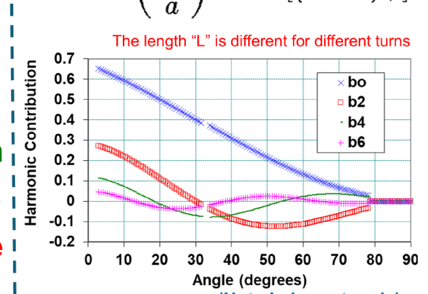
➢ Full-length midplane turn defines the length of the magnet

Essentially no loss due to magnet ends

Integral harmonics:

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

The length "L" is different for different turns



Integral harmonics can be optimized with EXCEL

A computer program, IntegralOpt, has been developed to optimize a coil pattern. It works fast as it directly computes integral harmonics from line current (rather first compute field and then harmonics). It also creates files for OPERA3d & RAT models and winding pattern.

First Optimum Integral Magnet: AGS Corrector (2004)

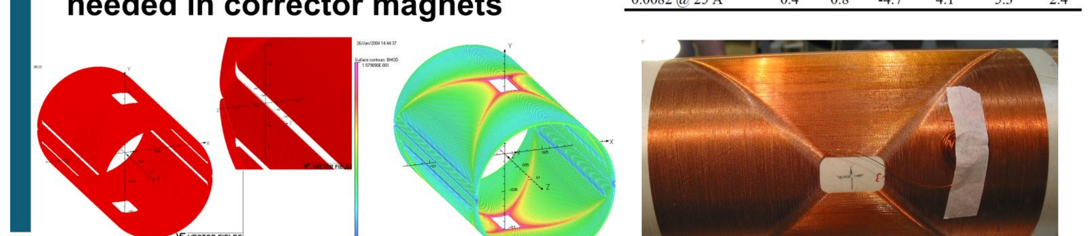
➢ Note: Almost the full use of available azimuthal and axial space by the conductor (very high fill factor).

➢ Some space is needed for the leads at the pole.

➢ That, and a small azimuthal spacer was sufficient to obtain field quality needed in corrector magnets

COMPUTED INTEGRAL FIELD HARMONICS IN THE AGS CORRECTOR DIPOLE DESIGN AT A REFERENCE RADIUS OF 60 MM. THE COIL RADIUS IS 90.8 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4

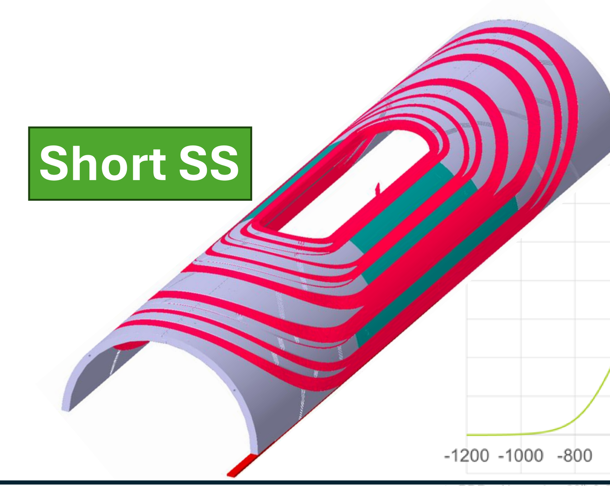


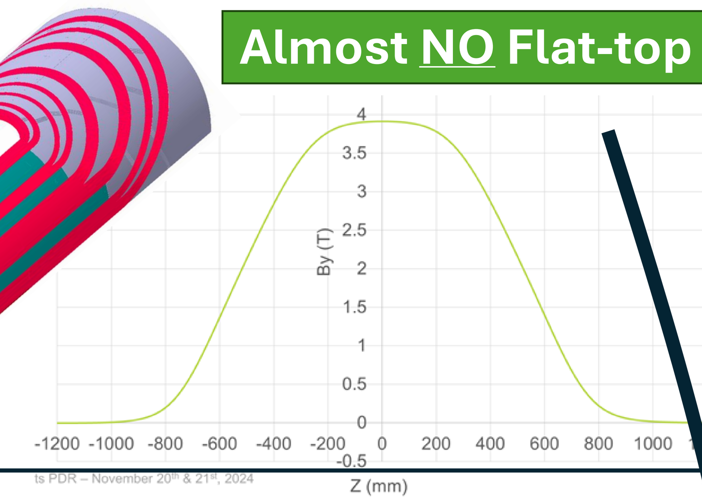
R. Gupta – "Optimum Integral Design for Optimizing Fields in Short Magnets (ASC2004)

OPTIMUM INTEGRAL B1aPF

GOAL: Examine the benefit of replacing cable magnet (current design) with a direct wind optimum integral dipole.

Design Parameters of the Cable Magnet:
- Coil id: 370 mm
- Coil length: 1,540 mm
- Length/Aperture: 4.2
- Field at the center: 3.91 T
- Integral field: 4.05 T.m
- Magnetic length: 1.039 m
- Design current: 13,400 A
- Operating Temperature: 1.92K

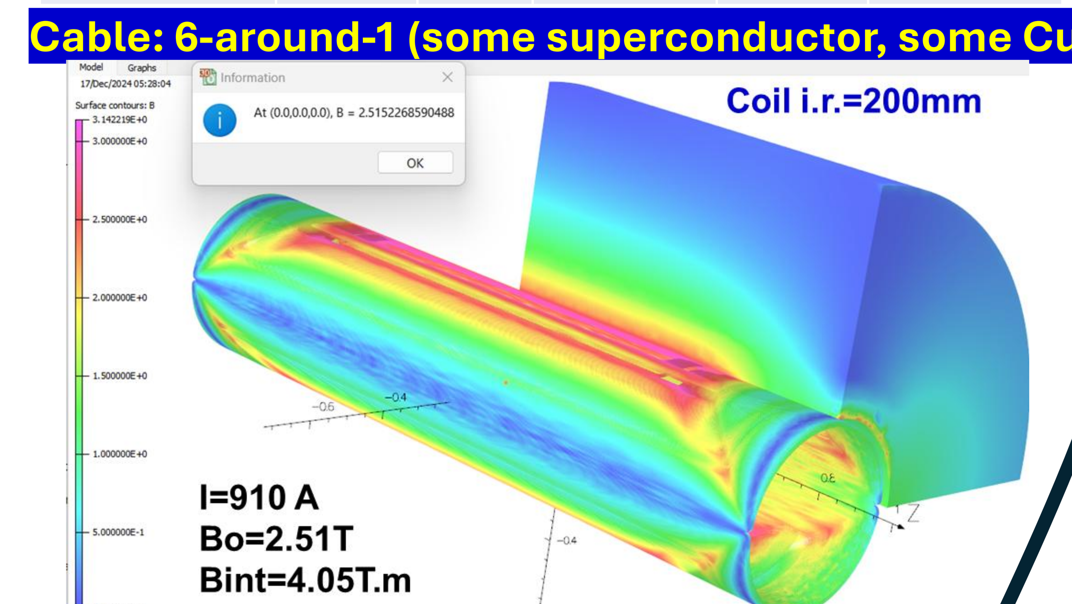


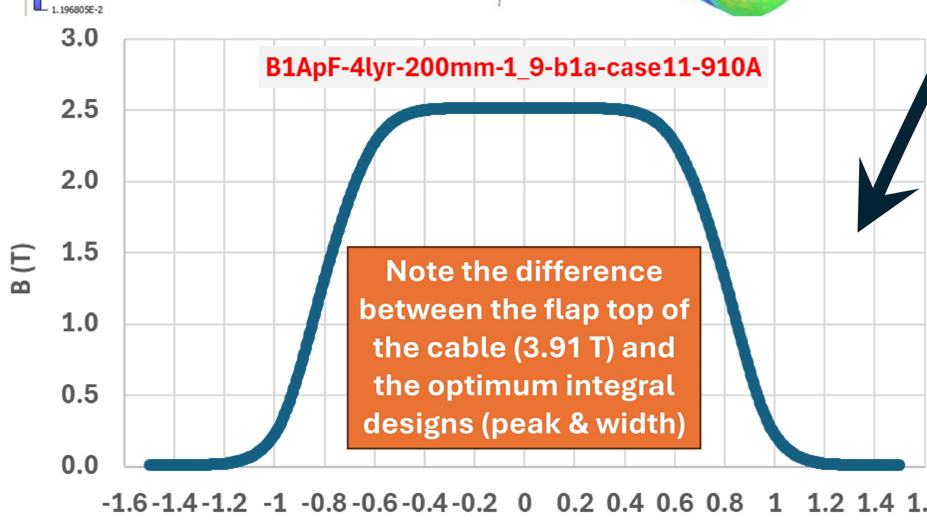


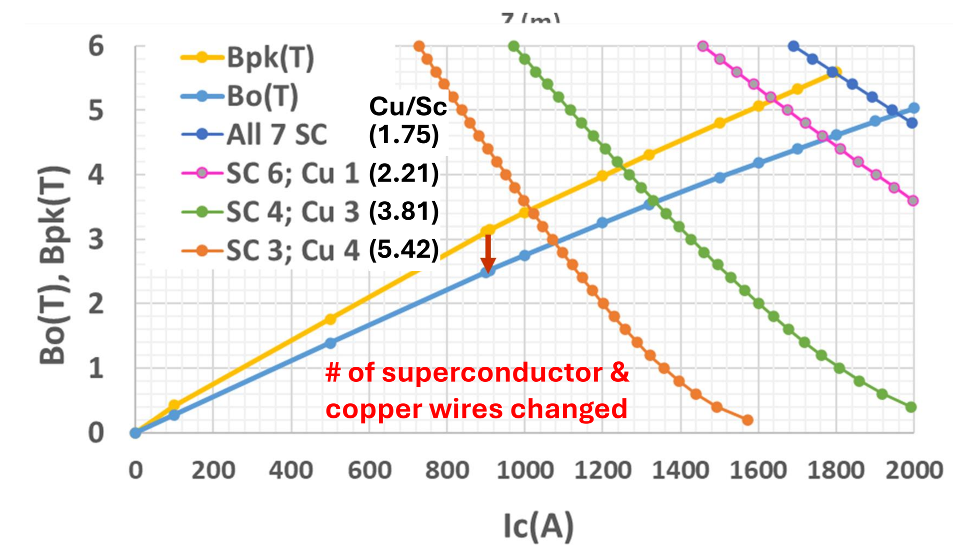
OPTIMUM INTEGRAL 4-LAYER DIRECT WIND

Wire	Dia (mm)	Cu:NC	Min Ic (7T,4.2K) A	Jc(7T,4.2K) A/mm²	Scaled Jc (5T,4.2K) A/mm²
Direct wind type 1*	0.47	1.60	105	1574	2675

Cable: 6-around-1 (some superconductor, some Cu)







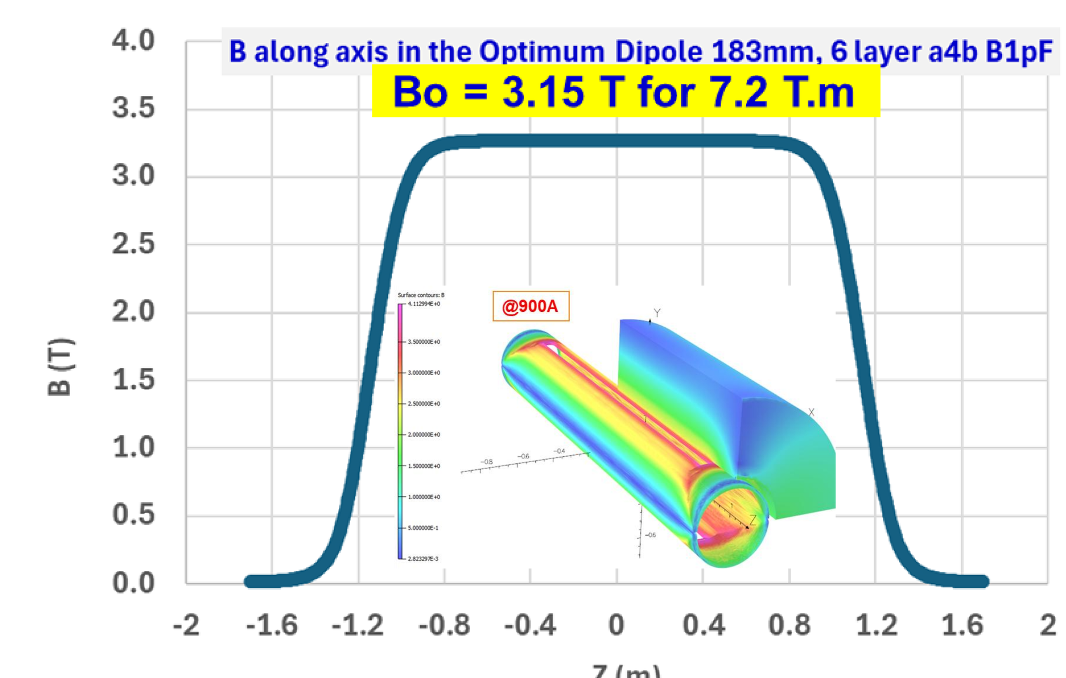
Looks attractive as the required field goes down from 3.9 T to 2.5 T. As such the integral field can be achieved by a 2-layer design. 4-layer design gives more options for quench protection.

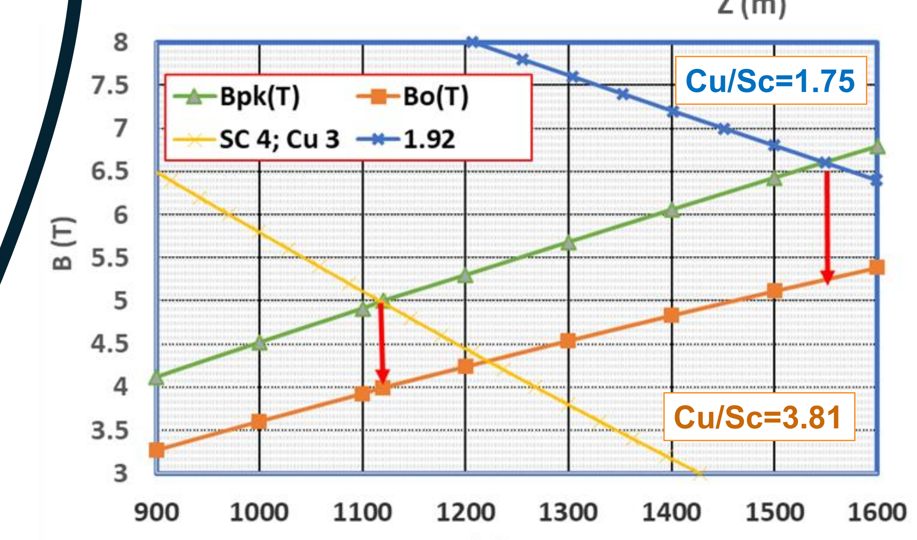
OPTIMUM INTEGRAL B1PF/B1aPF

GOAL: Replace EIC IR cable magnets B1pF and B1ApF (current designed with different apertures, fields and lengths) by two magnets with the design for both.

Furthermore, a direct wind option will bring more savings in cost and schedule.

Initial optimum integral 6-layer design:
- Coil id: 363 mm
- Coil length: 2,500 mm
- Length/Aperture: 6.9
- Number of layers: 6
- Field at the center: 3.2 T
- Integral field: 7.2 T.m
- Magnetic length: 2.248 mm
- Design current: 885 A
- Wire diameter: 0.47 mm
- Cable: 6-around-1 (not all Superconductor)
- Temperature: 1.92 K



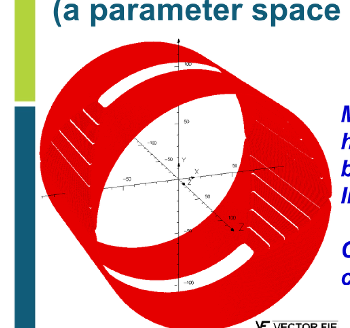


Replacing some SC wires by Cu wire in 6-around-1 cable helps in quench protection at the expense of margin.

Margin (all SC): 78% => 4 SC and 3 Cu: 28% (still heathy)

SUMMARY

Optimum Integral Design Opens a New Parameter Space
(a parameter space not considered practical for s.c. magnets before)



Model of a short length, high field quality dipole based on the Optimum Integral Design.

Coil length 175 mm; coil diameter 200 mm.

(a design example with no spacers in the end)

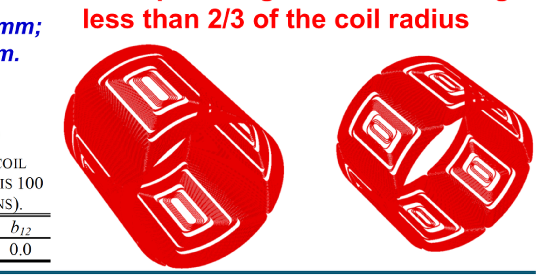
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

➢ High field quality dipoles with coil length less than the coil diameter

➢ Quadrupole magnets with coil length less than the coil radius

➢ Sextupole magnets with coil length less than 2/3 of the coil radius



Direct wind, optimum integral design offers a good value engineering option for EIC IR magnets B1ApF and B1pF. Optimum integral reduces the field required by increasing the magnetic length and direct wind technology reduces the cost and schedule for one off magnets.