Magnetic design studies for the final doublet of the Super*B*

(large crossing angle scheme)

S. Bettoni (CERN-AB/ABP) on behalf of the whole team

(S. Bettoni, M. E. Biagini, E. Paoloni, P. Raimondi, M. Sullivan)

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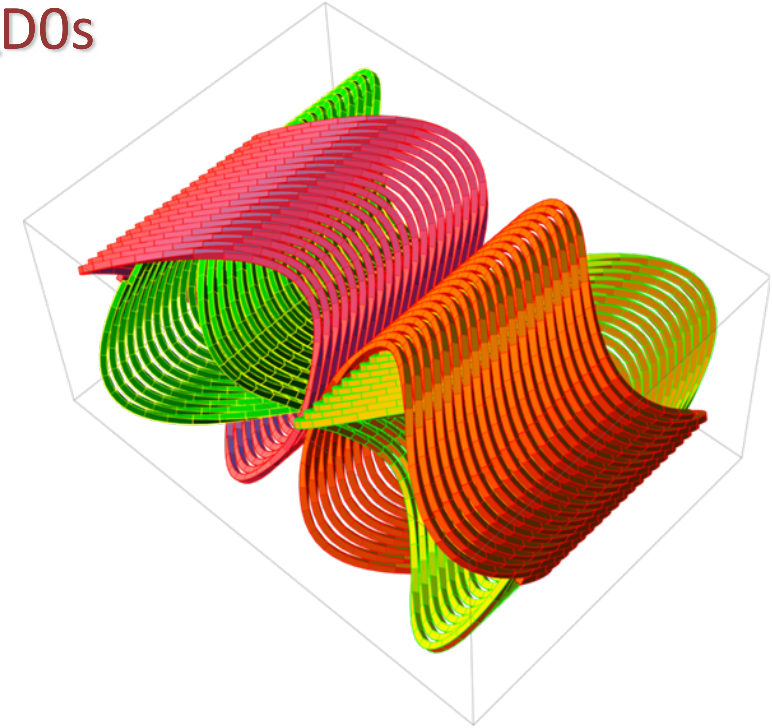
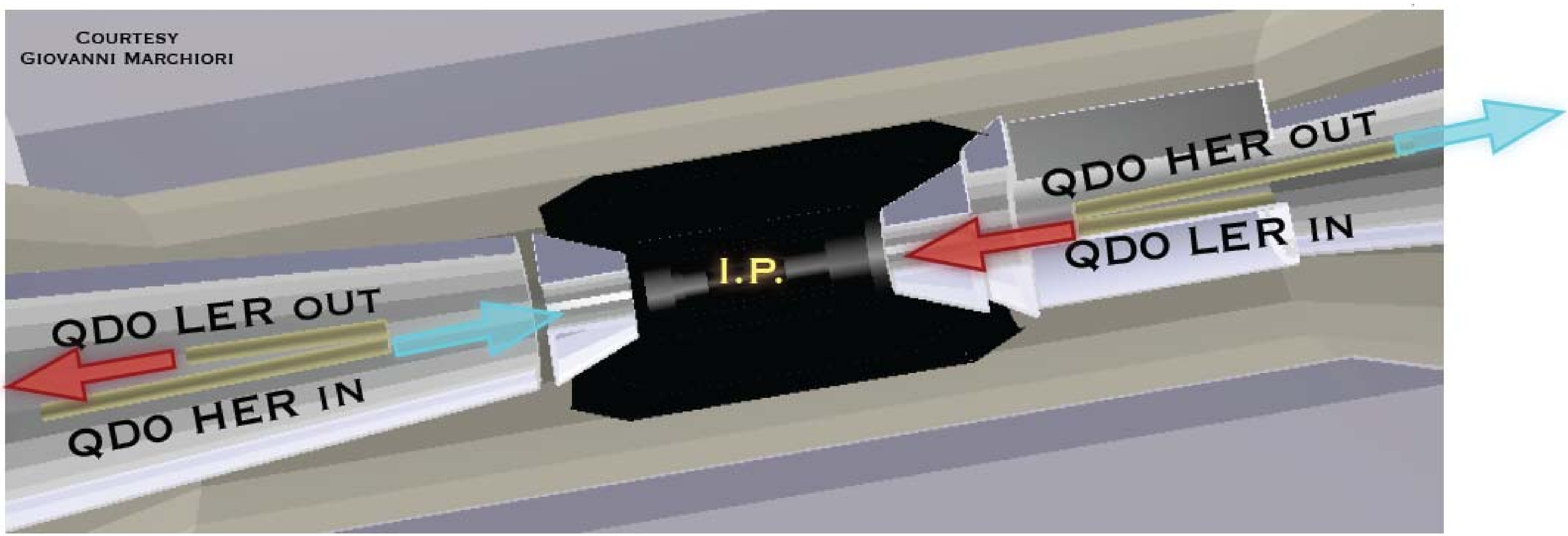
Outline

- Introduction
  - The final doublet of the large crossing angle scheme (Super*B* interaction region)
  - Possible options for the QD0s
- The cross talk between the Siamese QD0s
  - The 2D compensation algorithm
  - The 3D finite elements models
- Margin to quench parametric studies
- Conclusions

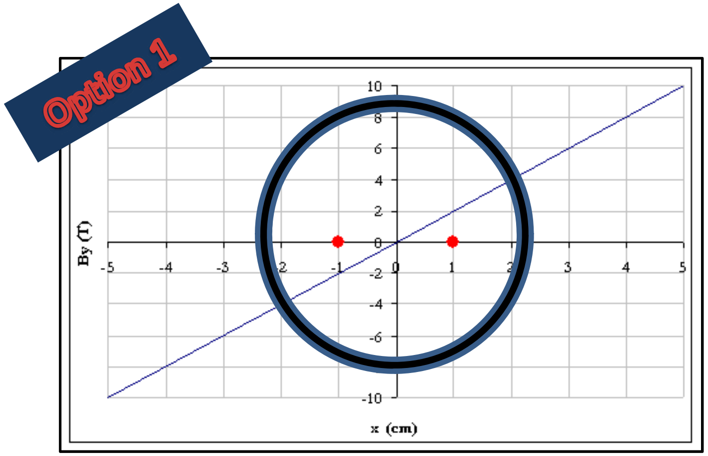


The IP region in the Super*B*

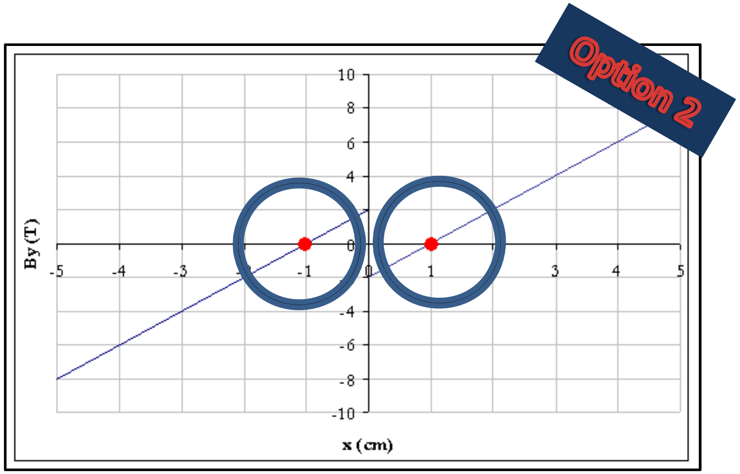


- Super*B* strategy to reach high luminosity (10^{36} $cm^{-2}s^{-1}$) relies on:
  - Strong final focusing (~166 T/m)
  - Large crossing angle (~2 x 25 mrad)
- Final doublet (QD0 + QF1)
  - Close to the IP to minimize chromaticity
  - Excellent field quality (order of 10^{-5})

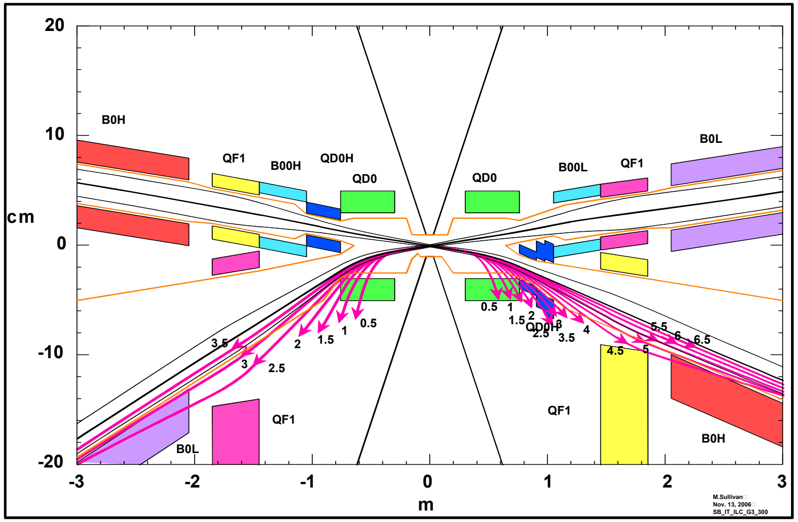
Possible options for the QD0

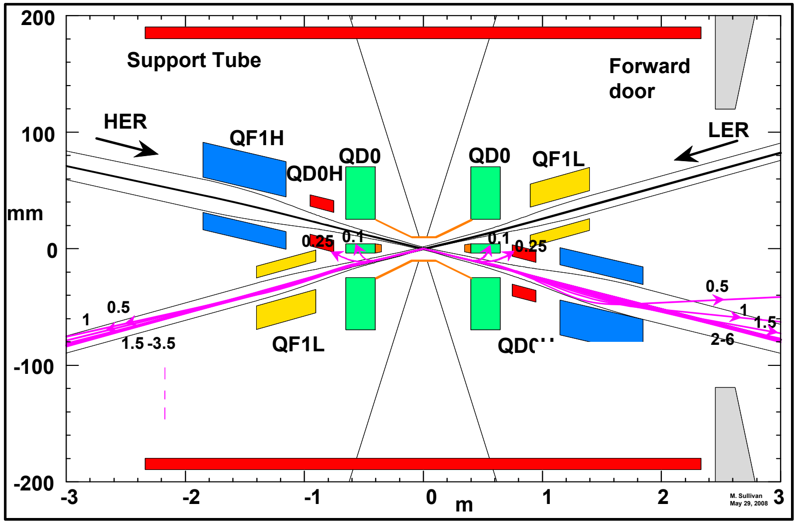


STRONG FINAL FOCUSING



LARGE INTEGRATED DIPOLE

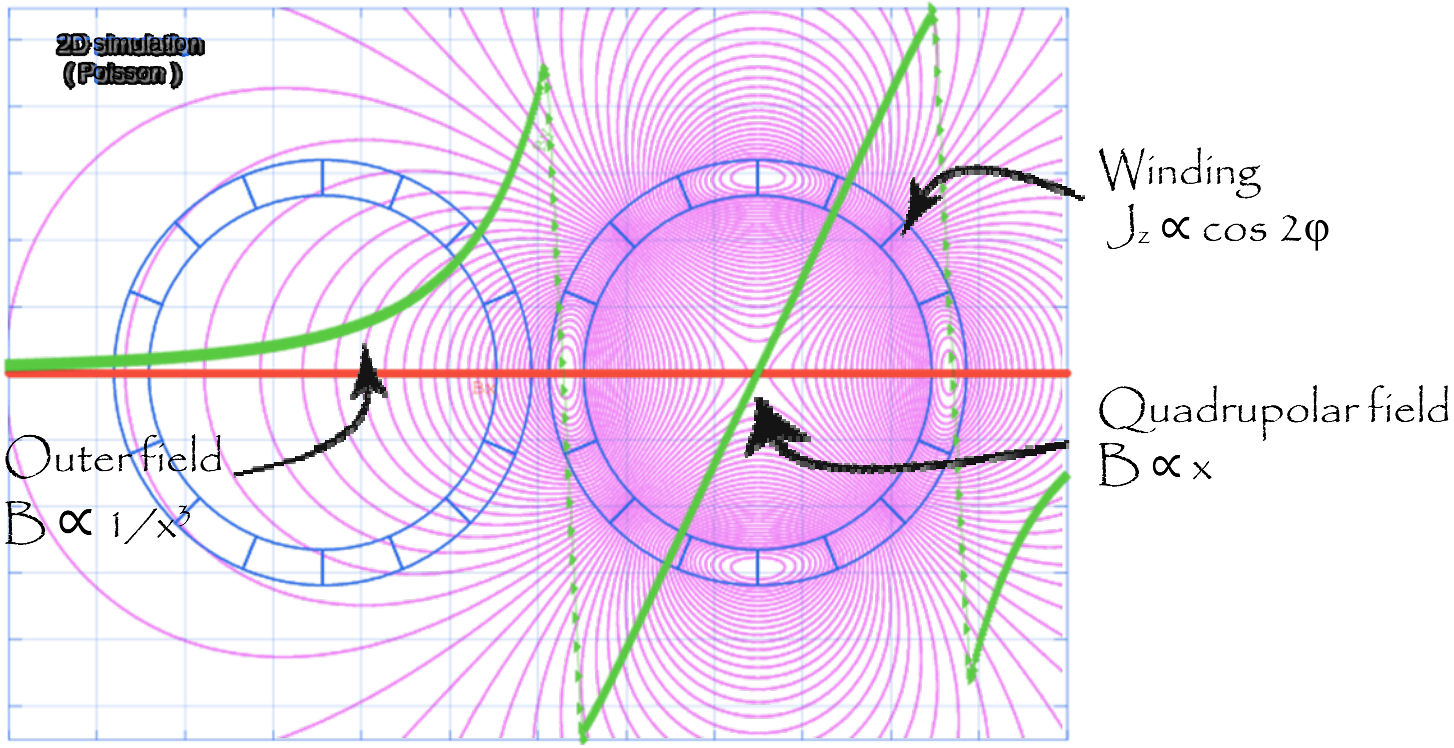




HUGE BACKGROUNDS

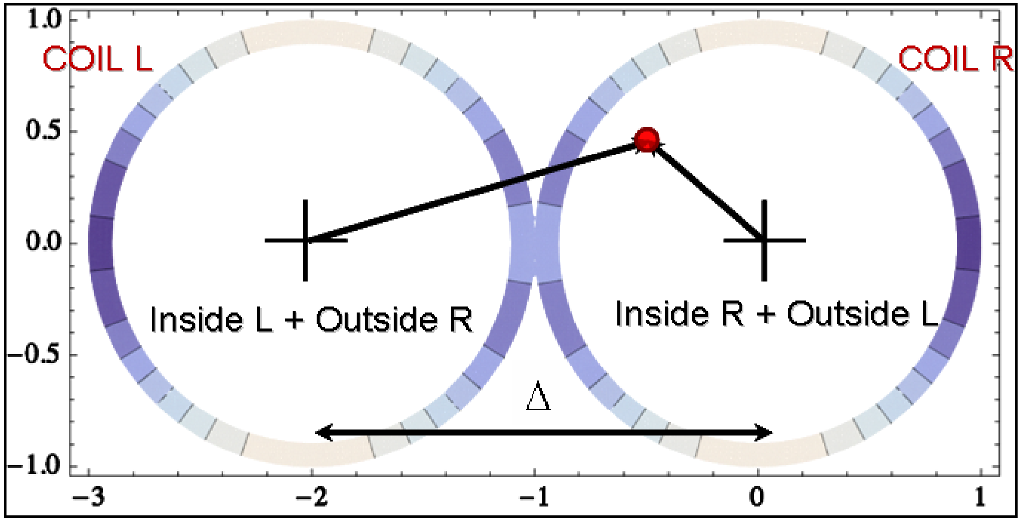
The cross talk

A cos (2 φ) magnet producing a quadrupolar field produces also a $1/x^3$ field outside...



- For the Super*B* IR: just ~0.5 cm for beam pipe + windings
  - Very challenging correct with more layers
  - Magnetic shielding

Any field you want



- Relationship between the inner and the outer fields

$$B_{\text{outside}}(z) = -\frac{1}{z^2}\bar{B}_{\text{inside}}(\frac{1}{\bar{z}}) + k\frac{1}{z}\int j(\varphi)d\varphi$$

- Impose the target fields as the sum inner fields

$$\begin{cases} B_{\text{R,in}}(z) + B_{\text{L,out}}(z+\Delta) & = z \\ B_{\text{L,in}}(z) + B_{\text{R,out}}(z-\Delta) & = \alpha z \end{cases}$$

Target fields

The cross talk compensation algorithm (2D)

2D complex notation:

$$\boxed{\begin{aligned}\zeta &\equiv x + i\,y\\ B &\equiv B_y + i\,B_x\end{aligned}} \qquad \boxed{B = k \int_0^{2\pi} d\varphi\, \frac{j_z(\varphi)}{\zeta - e^{i\varphi}}}$$

The algebraic relation:

$$\mathcal{G}(\zeta;\varphi) = \boxed{\frac{1}{\zeta - e^{i\varphi}} = \frac{1}{\zeta} - \frac{1}{\zeta^2}\frac{1}{\frac{1}{\zeta} - e^{-i\varphi}}} = \frac{1}{\zeta} - \frac{1}{\zeta^2}\overline{\mathcal{G}}\left(\frac{1}{\overline{\zeta}}\,;\varphi\right)$$

relates the outside B field with the inside B field

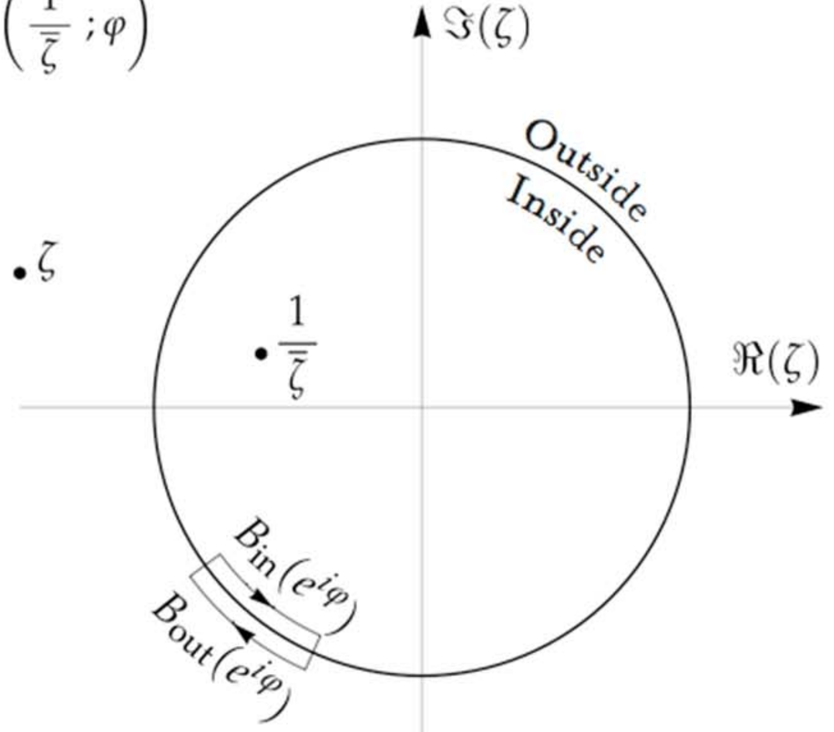
$$\boxed{B_{\text{out}}(\zeta) = -\frac{1}{\zeta^2}\overline{B}_{\text{in}}\left(\frac{1}{\overline{\zeta}}\right) + \frac{k}{\zeta}\int_0^{2\pi} j(\varphi)\,d\varphi}$$

Functional equation to solve:

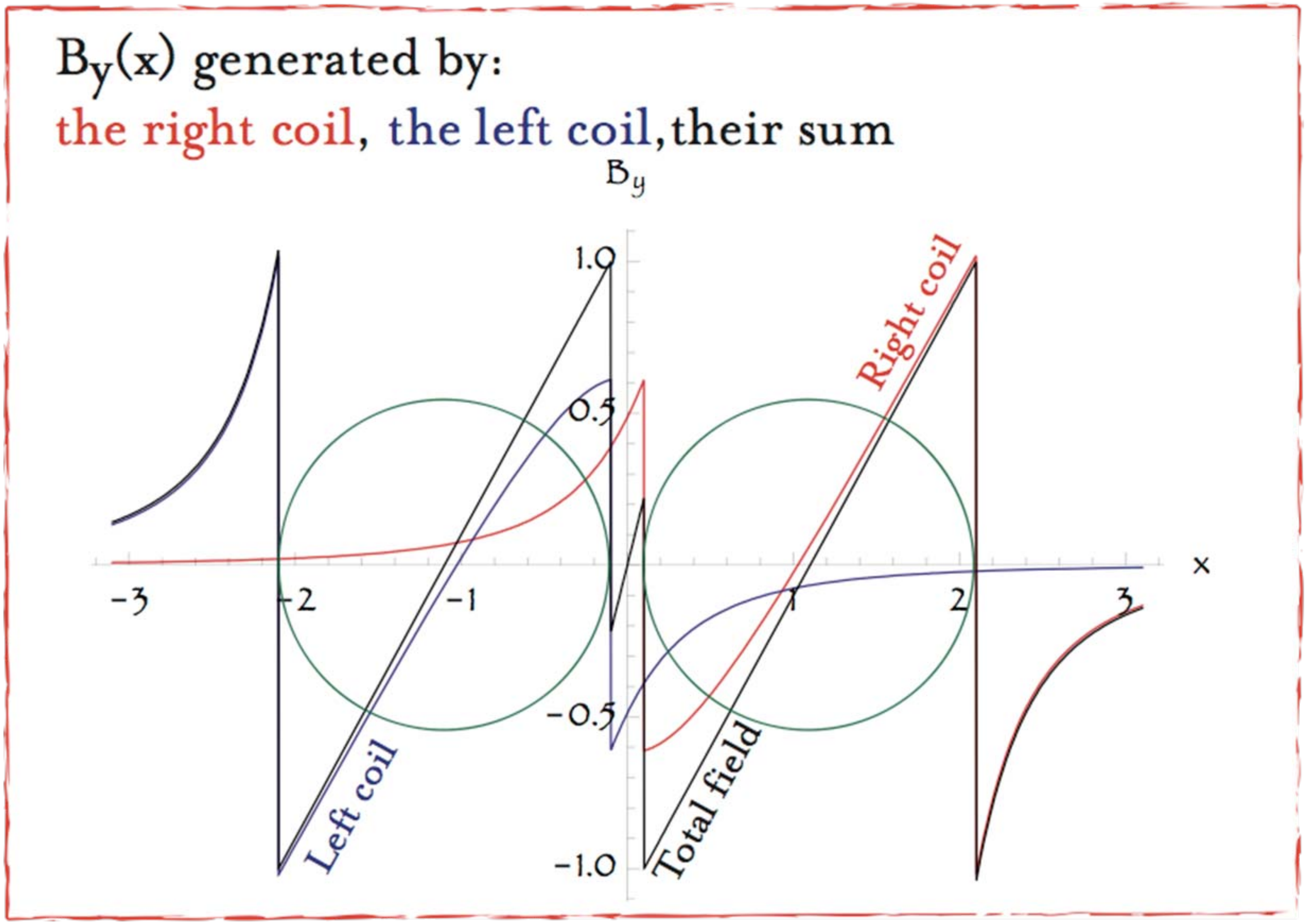
$$\begin{cases} B_{\text{R,in}}(\zeta) &= B_{\text{R,target}}(\zeta) + \overset{-B_{\text{R,out}}(\zeta+\Delta)}{\boxed{\frac{1}{(\zeta+\Delta)^2}\overline{B}_{\text{L,in}}\left(\frac{1}{\overline{\zeta}+\Delta}\right)}}\\ B_{\text{L,in}}(\zeta) &= B_{\text{L,target}}(\zeta) + \underset{-B_{\text{L,out}}(\zeta-\Delta)}{\boxed{\frac{1}{(\zeta-\Delta)^2}\overline{B}_{\text{R,in}}\left(\frac{1}{\overline{\zeta}-\Delta}\right)}}\end{cases}$$

Ampere law to determine the field source

$$\boxed{j_z = \left[B_{\text{out}}(e^{i\varphi}) - B_{\text{in}}(e^{i\varphi})\right] e^{i\varphi}}$$



How the algorithm works



$B_y(x)$ generated by:

the right coil, the left coil, their sum

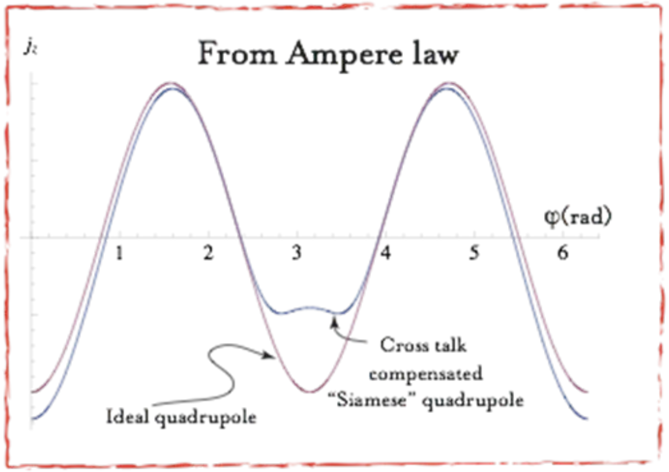
From 2D to 3D … from AML idea

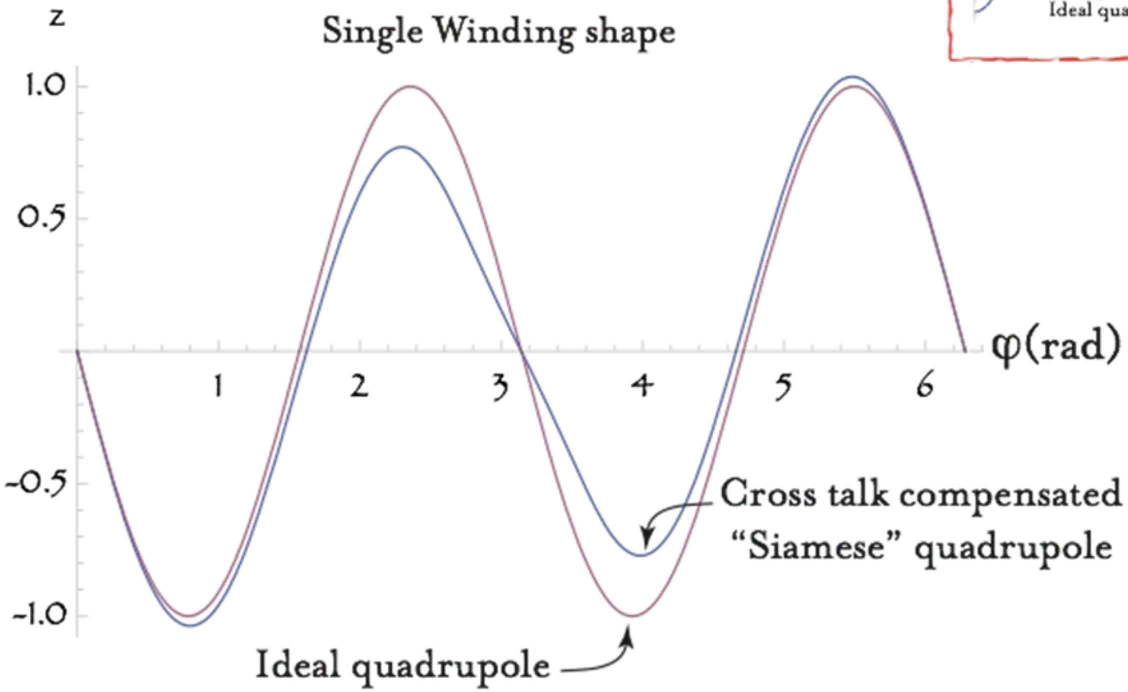
$$\dot{\mathbf{x}} = \mathbf{j}(\mathbf{x})$$

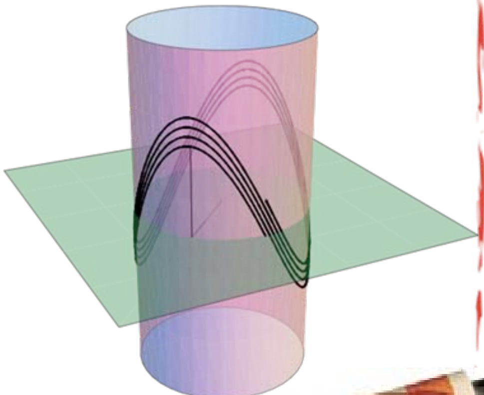
$$\mathbf{j} = \left[\hat{z} j_z(\varphi) - \hat{z}\frac{\Delta z}{2\pi} - \hat{\varphi}\right] \delta(r-1)$$

$$\mathbf{j} = \left[\hat{z} j_z(\varphi) + \hat{z}\frac{\Delta z}{2\pi} + \hat{\varphi}\right] \delta(r-1)$$

Counter rotating Solenoidal & Longitudinal field

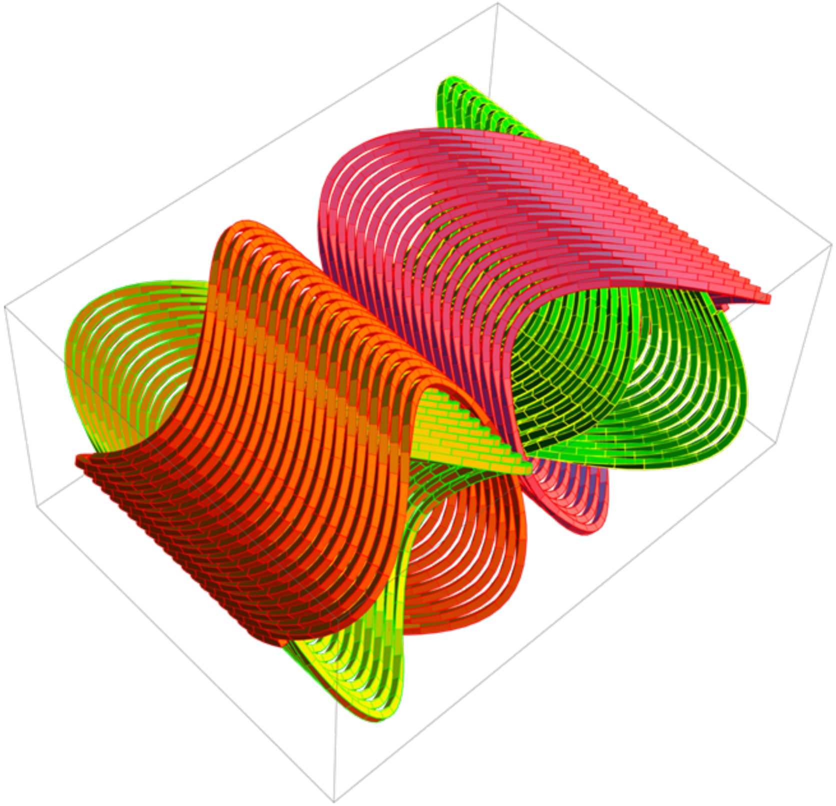


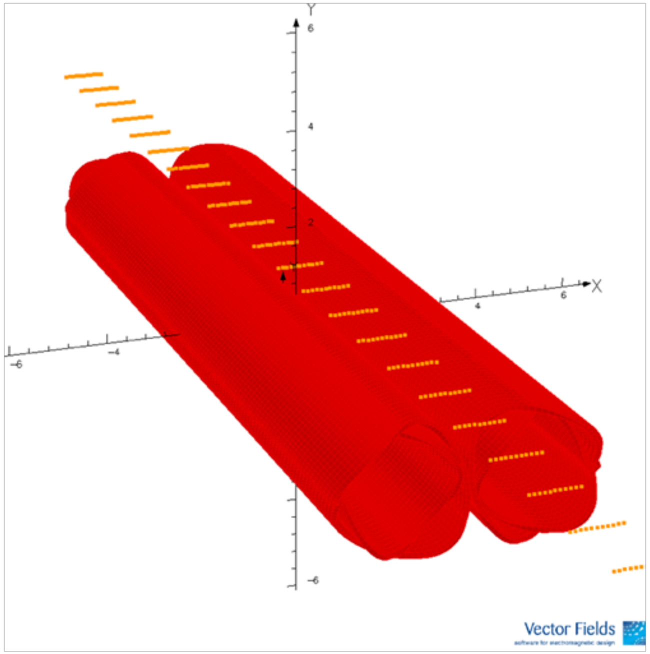




AML
Advanced Magnet Lab

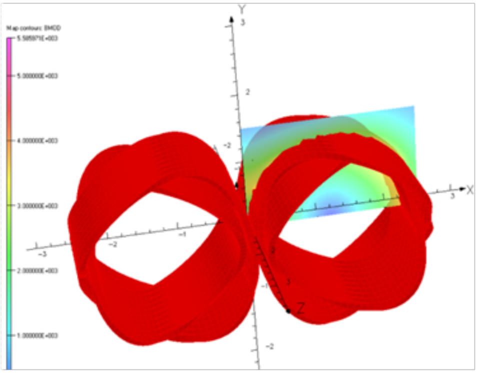
From the equations to the simulations: the 3D models





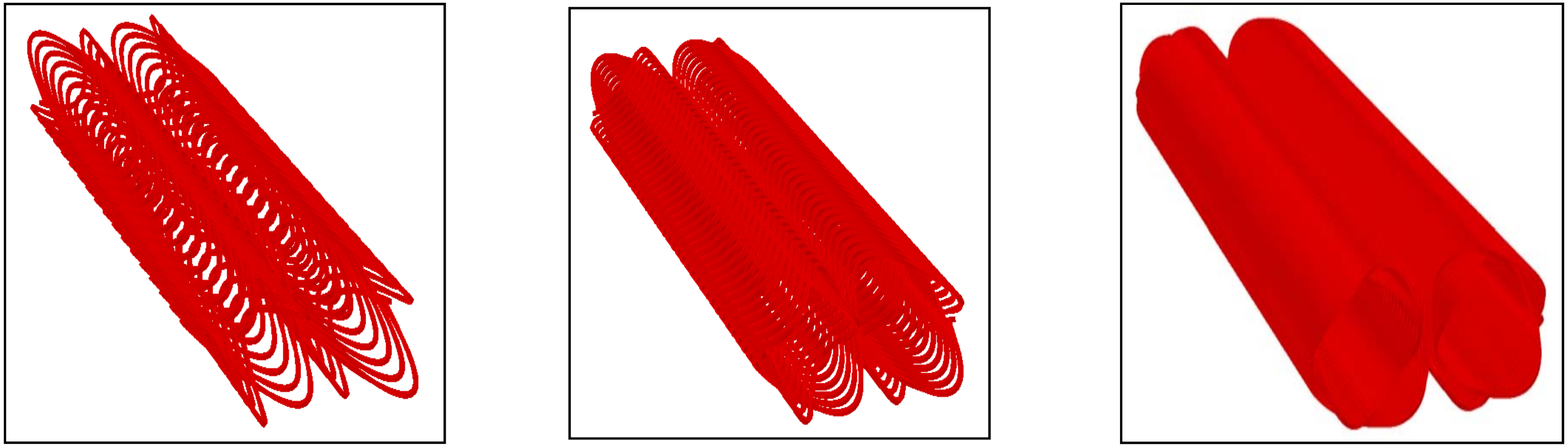
$$B_y(x-x_C,0,\bar{z})=\sum_{i=0}^{N} b_i (x-x_C)^i$$

$$\frac{B_i}{B1} \equiv \frac{b_i (x-x_C)^{i-1}}{b_1}$$



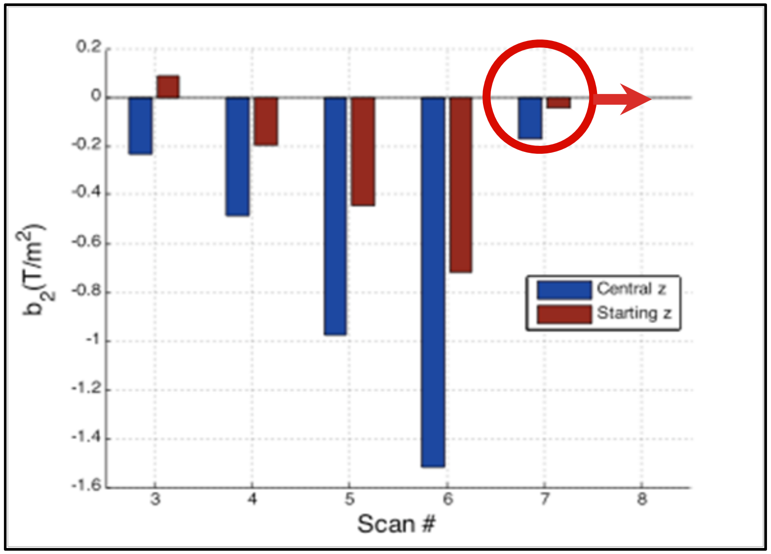
- 3D studies:
  - Quality field at several z
  - Maximum field on the conductor

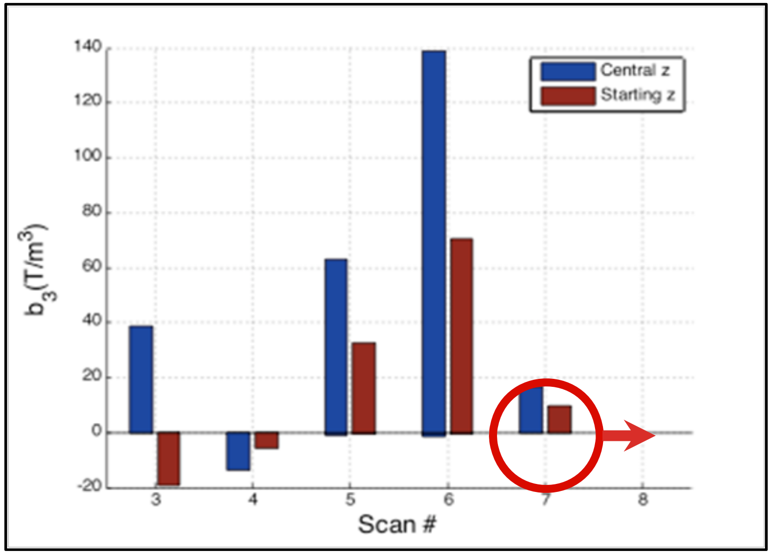
3D optimization



- Varied
  - The radius of curvature of the windings
  - The step of the windings
- To maximize
  - The field quality at the beginning/end of the windings
  - The ratio gradient/maximum field on the conductor

Results: the field quality





Relative intensity	Scan 4		Scan 7	
	z center	z start	z center	z start
B_2/B_1	-7.74E-05	-6.28E-05	-2.72E-05	-1.36E-05
B_3/B_1	-1.09E-05	-9.25E-06	1.33E-05	1.52E-05

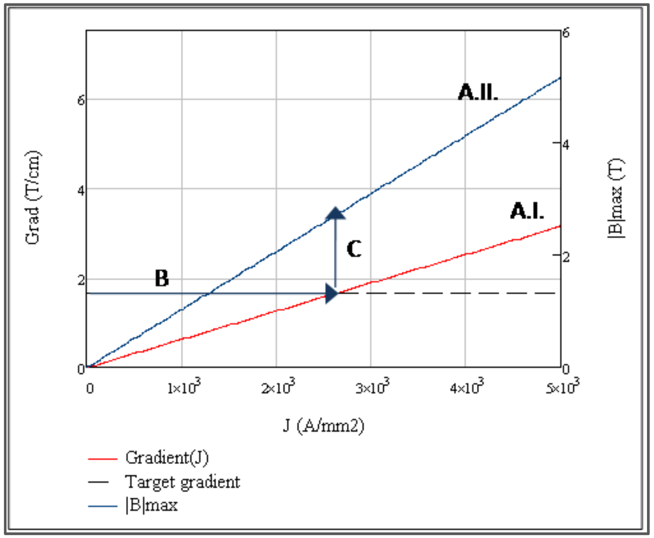
- The field quality doesn’t seem to be limited by the compensation algorithm

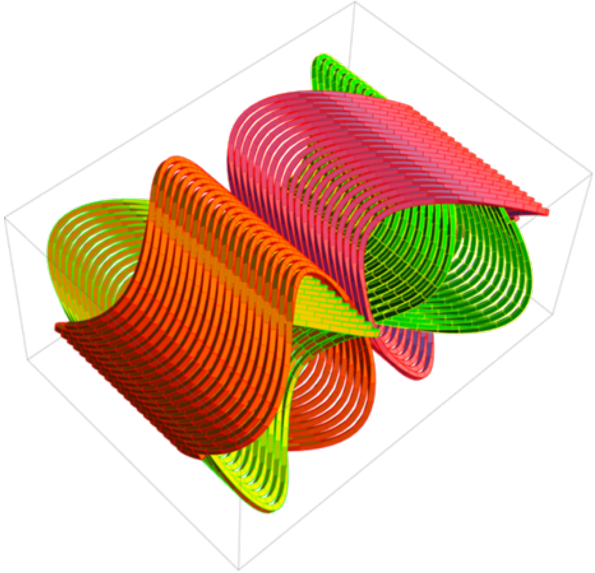
Results: the margin to quench

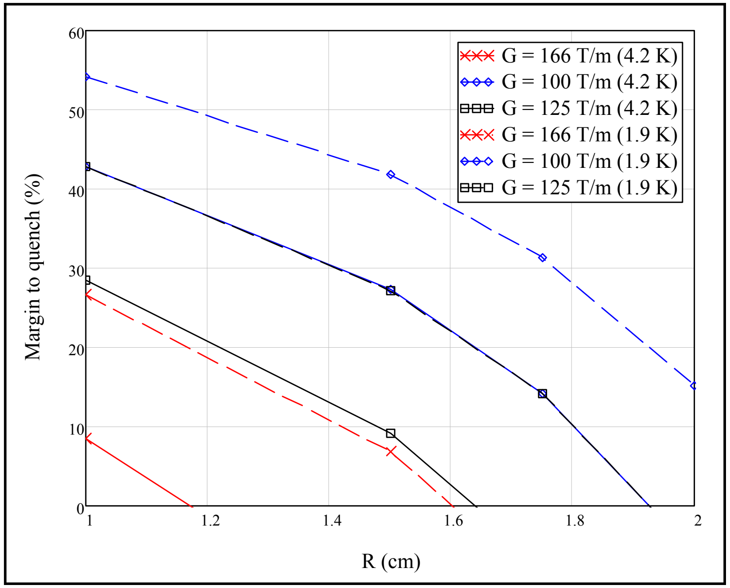
At a **FIXED** current density (500 A/mm^2) and wire dimensions (1 mm x 1 mm):

- Calculate:
  - I. The gradient as a function of J
  - II. The maximum field as a function of J
- Impose the target gradient and determine J
- Use A. II. to calculate the maximum field in the conductor
- Compare the found (Bmax,J) with the critical curve of NbTi at a fixed temperature

- NbTi* with Cu/SC = 1 assumed







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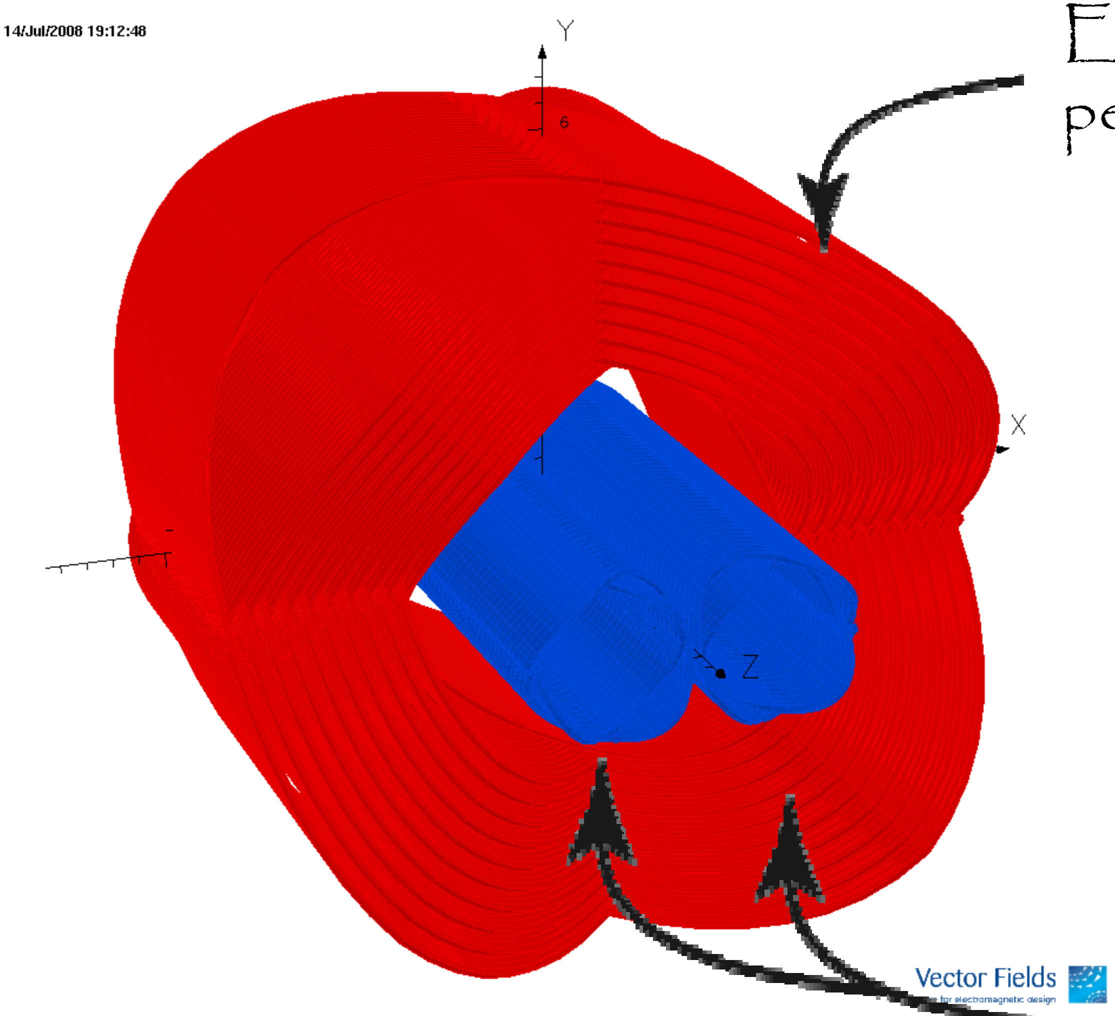
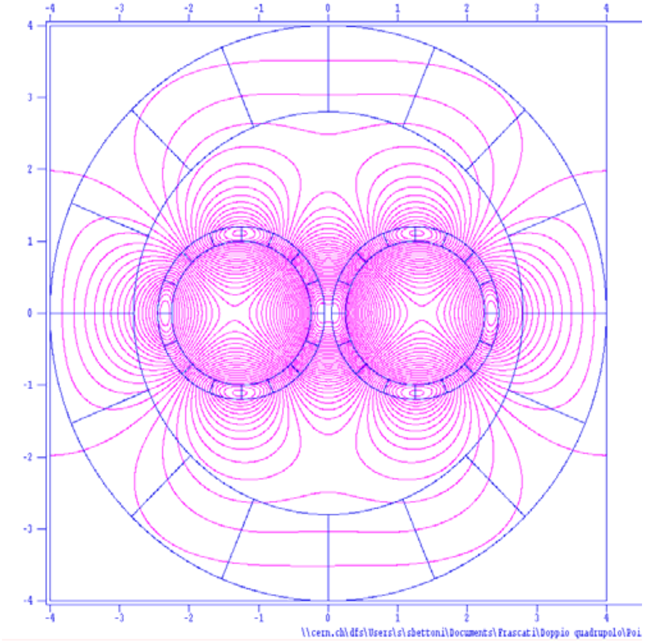
*L. Bottura, A practical fit for the critical surface of NbTi, IEEE Transactions on Applied Superconductivity, Vol. 10, no. 1, March 2000.

The nested quadrupoles configuration

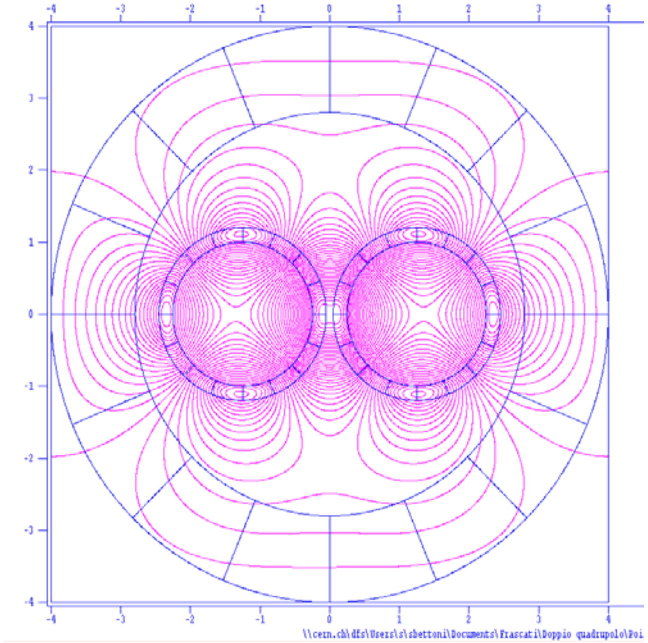


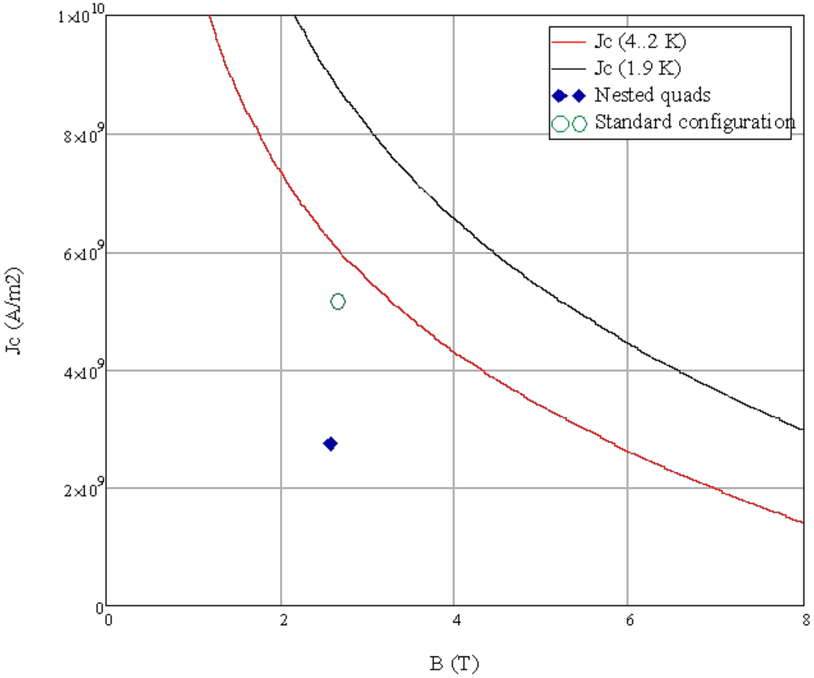
External helicoidal
perfect quadrupole

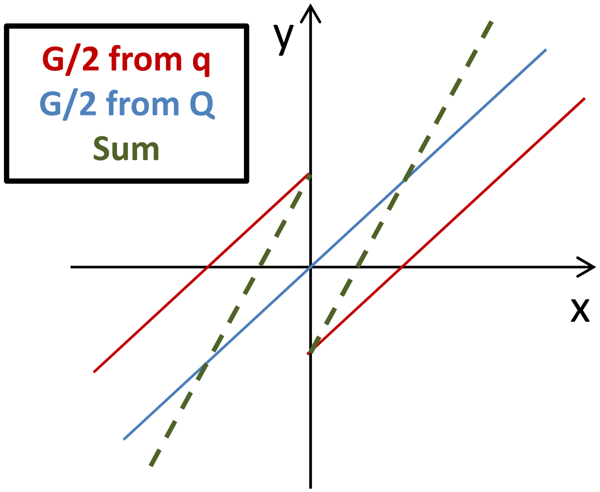


Internal helicoidal
Siamese twins quadrupole

How the configuration works







- Maximization of the mechanical aperture
- Magnetic axis shifted

G (T/m)	Margin to quench at 4.2 K	Margin to quench at 1.9 K	J overall
100	38.8 %	51.1 %	1041 A/mm^2
125	23.5 %	38.9 %	1302 A/mm^2
150	8.2 %	26.7 %	1562 A/mm^2

Conclusions

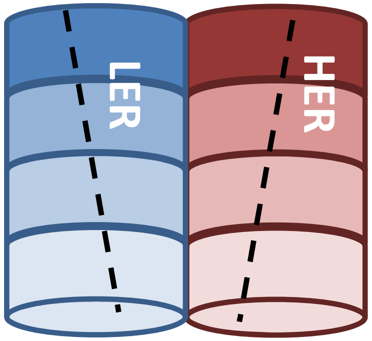
- Cross talk between the Super*B* final doublet is manageable
- This algorithm can be applied to obtain any pair of multipolar configuration
- 3D simulations:
  - The field quality seems to be not limited by the algorithm precision (assembly procedure accuracy)
  - Parametric (wire specifications and geometry) margin to quench studies have been performed
  - Nested quadrupoles configuration under study to maximize the mechanical aperture

? and/or !

QD0: possible scenarios under consideration

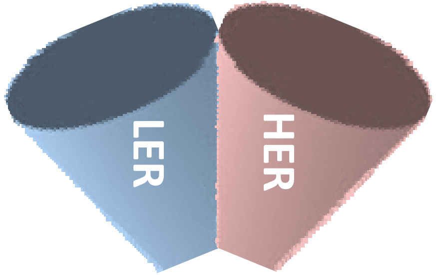
Option 1

Winding shape in such a way that the magnetic axis moves along z-axis



Option 2

Cone shape configuration



Option 3

Nested quadrupoles configuration