Super Conducting magnets for the SuperB Final Focus Doublet

Eugenio Paoloni INFN & Università di Pisa,
Simona Bettoni (CERN),
Marica Biagini, Pantaleo Raimondi(LNF),
Mike Sullivan (SLAC)

Talk outline

- Super*B:* a short introduction
  - The collider & its final focus
- Final focus requirements & Constraints
  - Specifications
  - Why unconventional solutions are required?
  - Possible solutions
  - Future activities

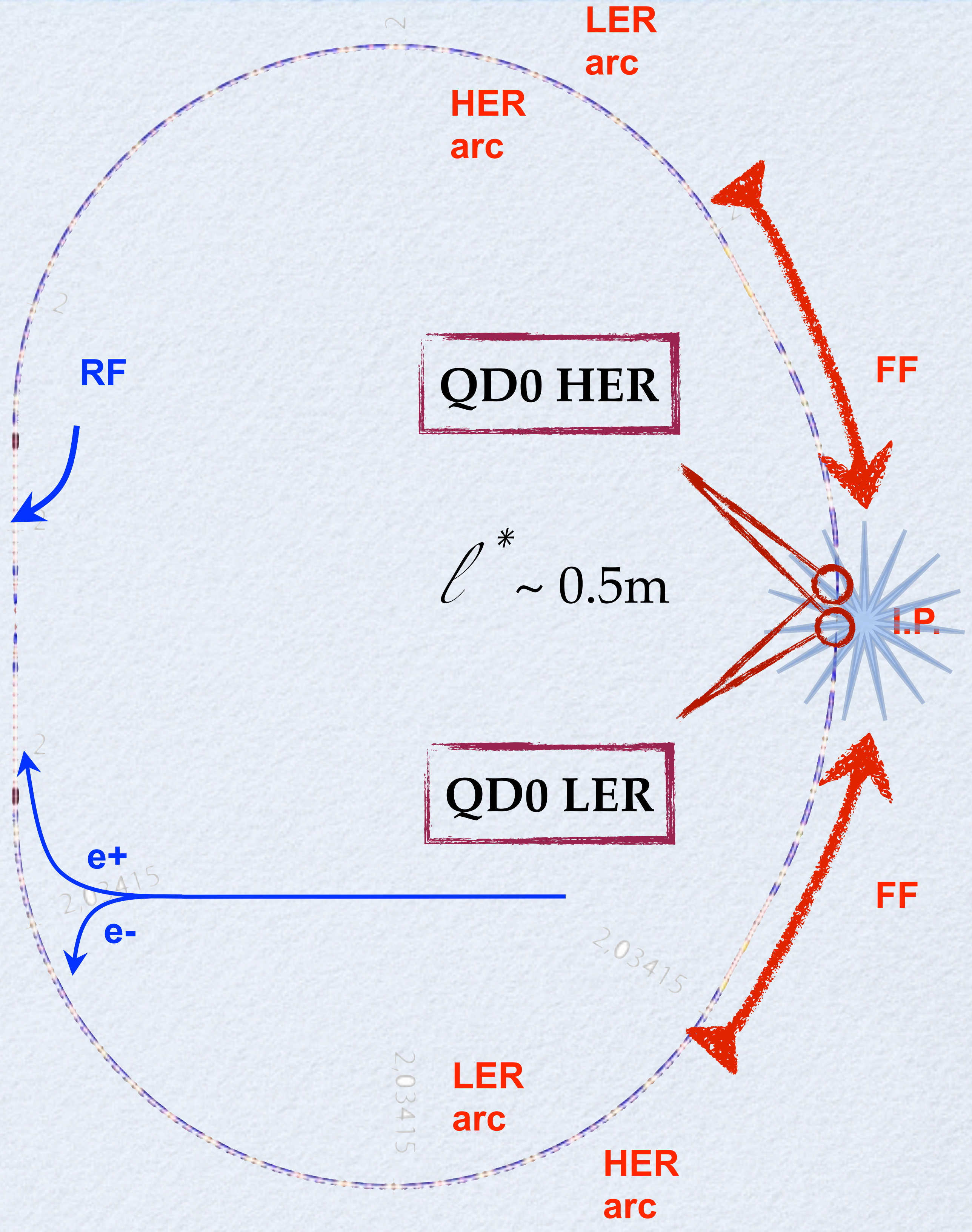
The collider

SuperB

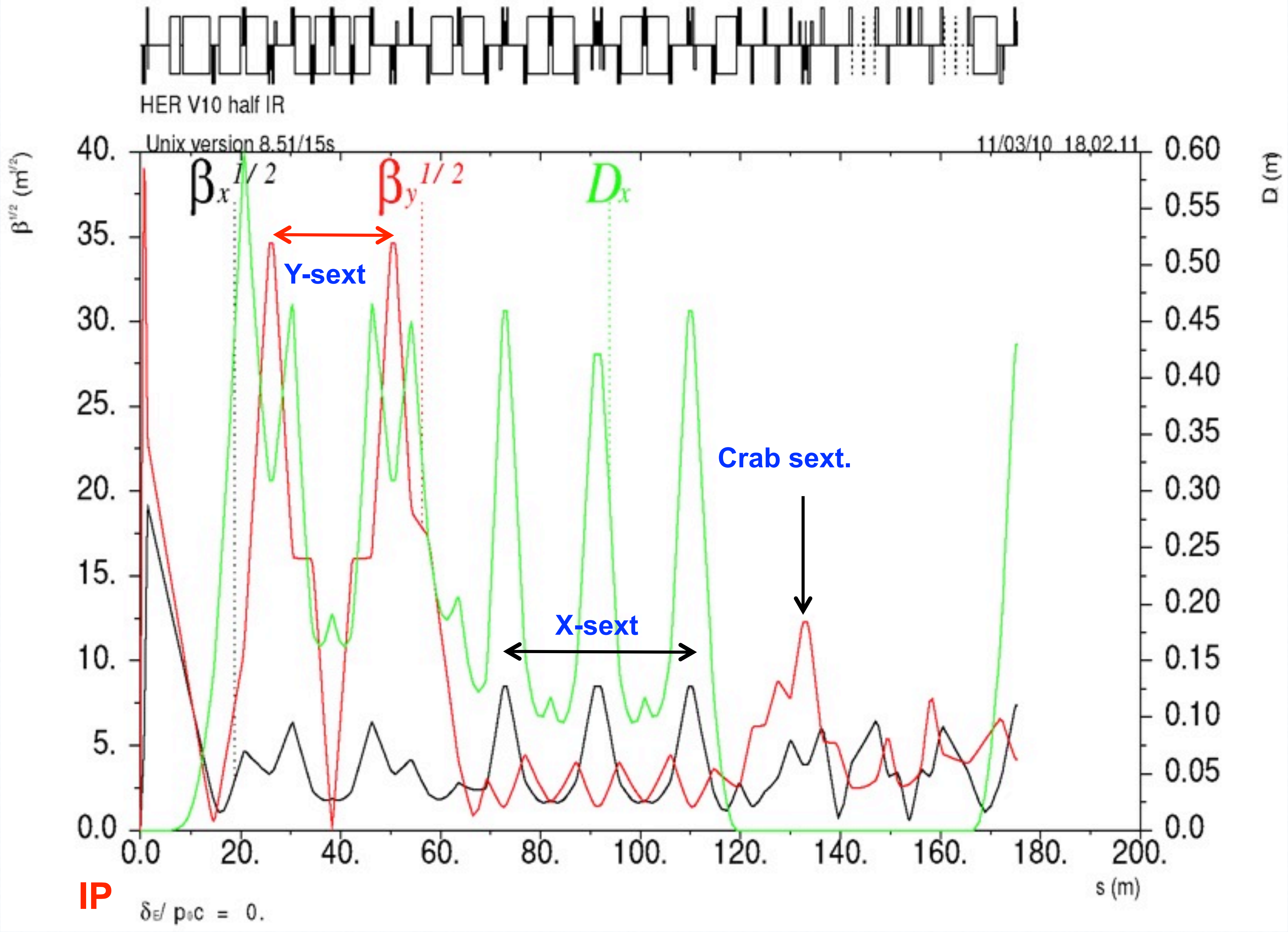
- Strong Physics case for building a new asymmetric e^+e^- collider @ the $\Upsilon(4S)$ peak aiming to reach 10^{36} cm^{-2}/s . (1 pb^{-1}/s)
- SuperB is one the flag ship programs of the Italian Ministry of the University & Research.
- SuperB is in the top priority list of the National Research Plan 2010-2013.
- Unfortunately the Sovereign debt crisis slowed down the funding and approval process of Super*B*.

Machine parameters

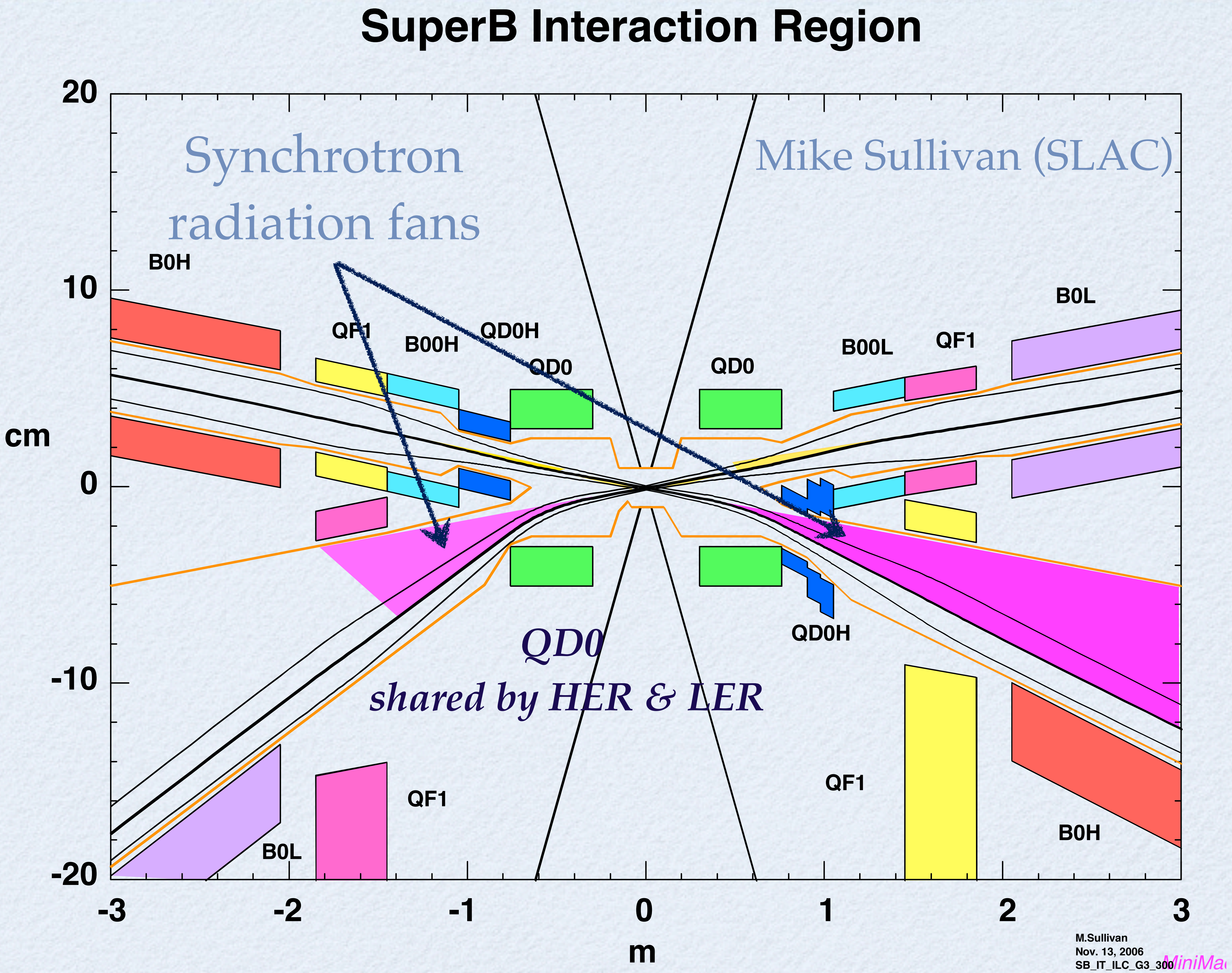
	Units	HER	LER
Release		Annecy March 2010	
Circumference	m	1258.4	
Frequency turn	Hz	2.38E+05	
# bunch		978	
Frequency collision	Hz	2.33E+08	
Full crossing angle	Rad	0.066	
Energy	GeV	6.7	4.18
Energy ratio		1.60	
β_x^*	cm	2.6	3.2
β_y^*	*cm*	*0.0252*	*0.0206*
coupling		0.0025	0.0025
ε_x	nm	2	2.4
ε_y	pm	0.005	0.006
Bunch length	cm	0.5	0.5
Current	A	1.892	2.410
# particles		5.08E+10	6.46E+10
σ_x	micron	7.21	8.76
σ_y	*micron*	*0.035*	*0.035*
Piwinsky angle		22.89	18.83
Horizontal tune shift	%	0.21	0.33
Vertical tune shift	%	9.78	9.78
Luminosity	*Hz/cm^2*	*1.02E+36*	



The final focus section



IR layout: Nov. 2006

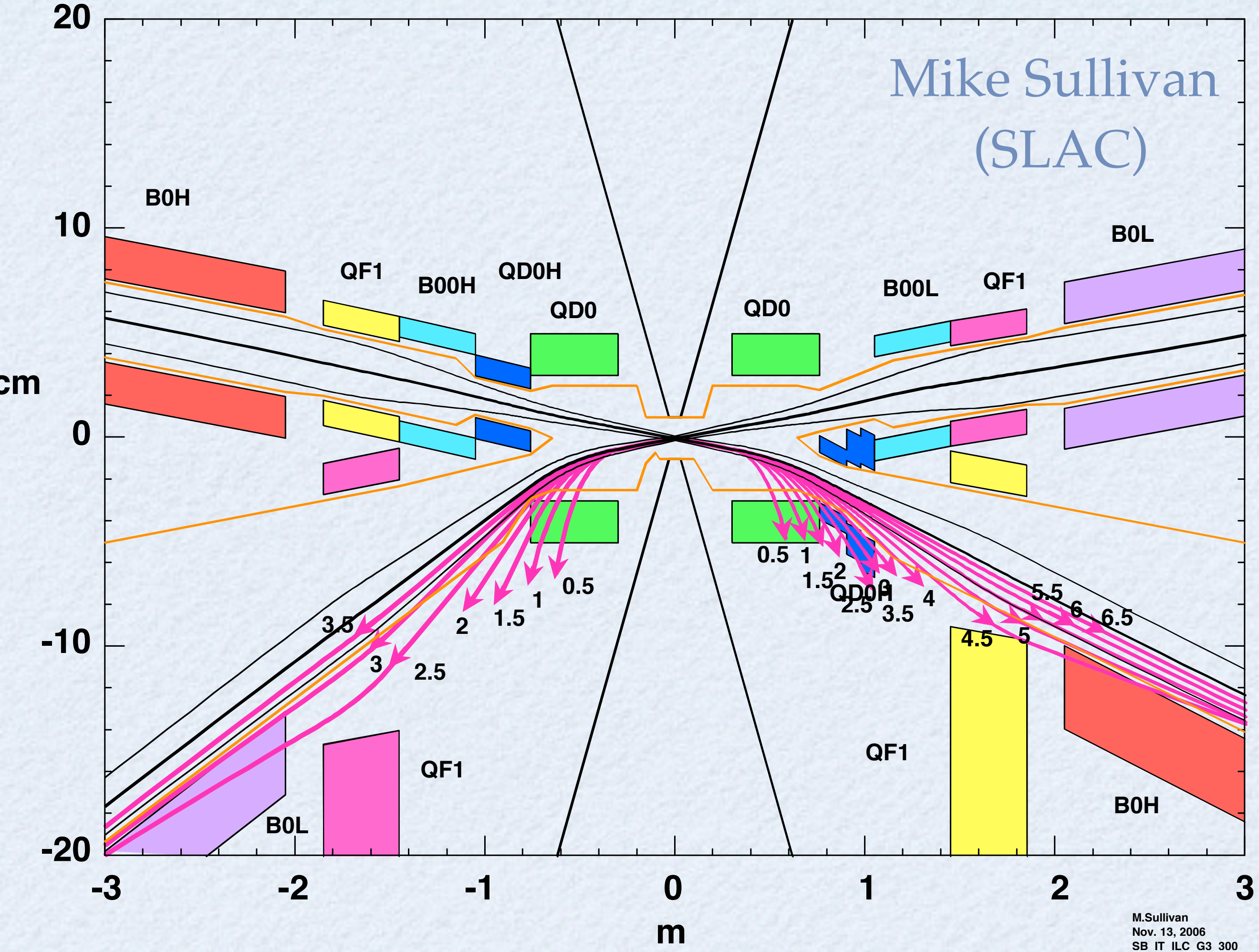


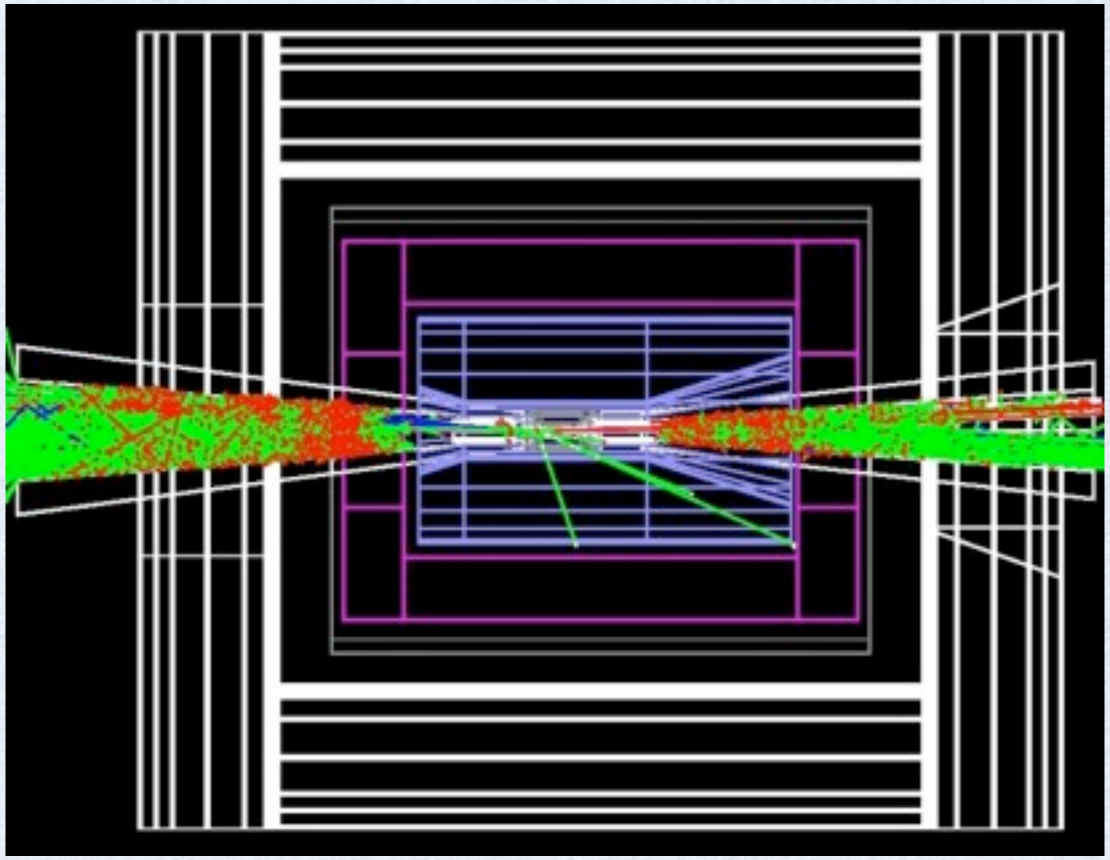
Synchrotron radiation fans

Mike Sullivan (SLAC)

QD0 shared by HER & LER

Radiative Bhabha background



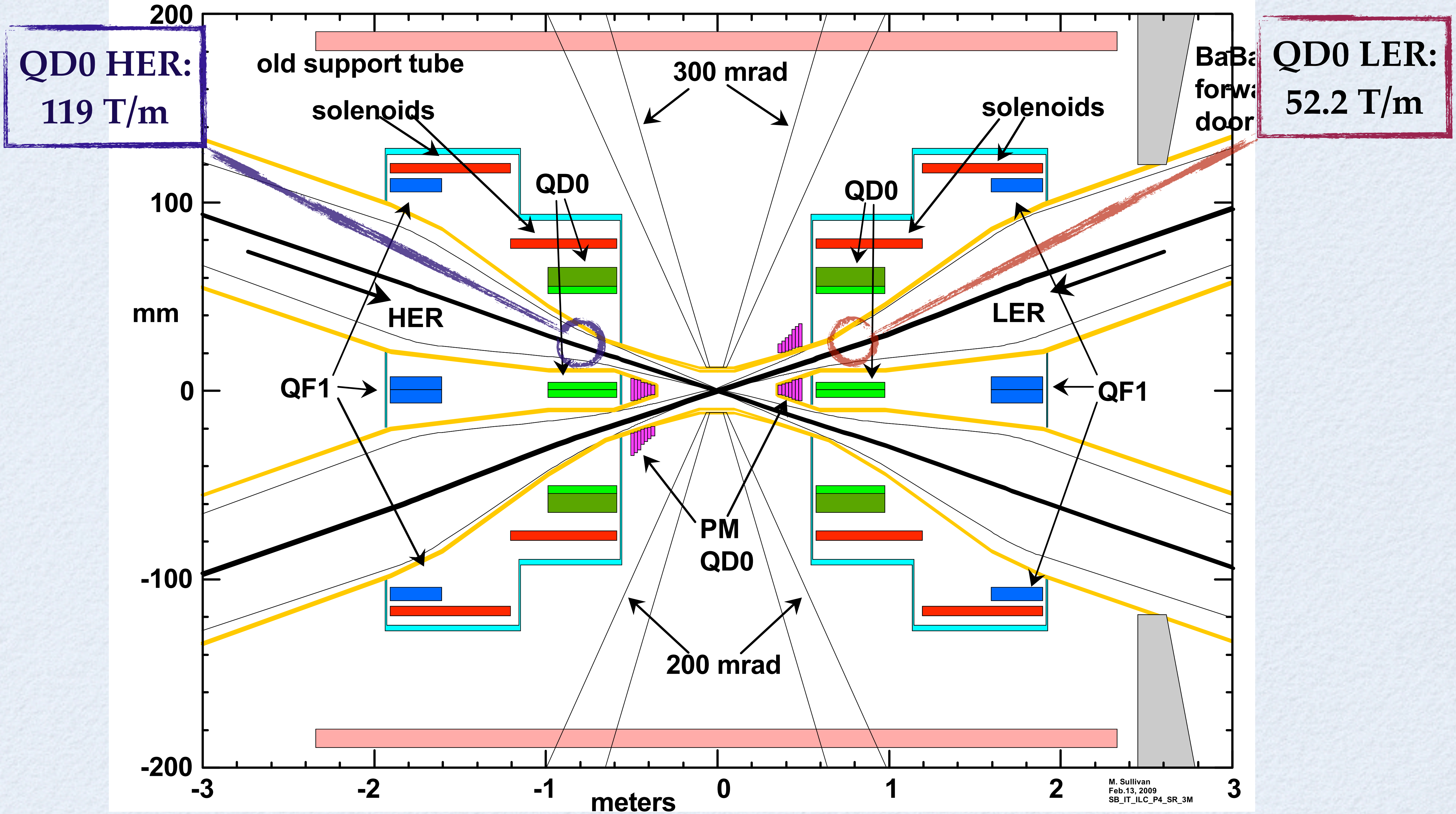


Geant 4 Background Simulation

- QD0 magnetic axis must be placed near the incoming beam lines to keep Syncrhotron radiation fans away from the detector.
- The QD0 becomes a spectrometer for the off-energy particles produced by Radiative Bhabha interactions.
- The resulting e.m. showers are a big problem for the detectors.

IR layout 2009

Inside the detector

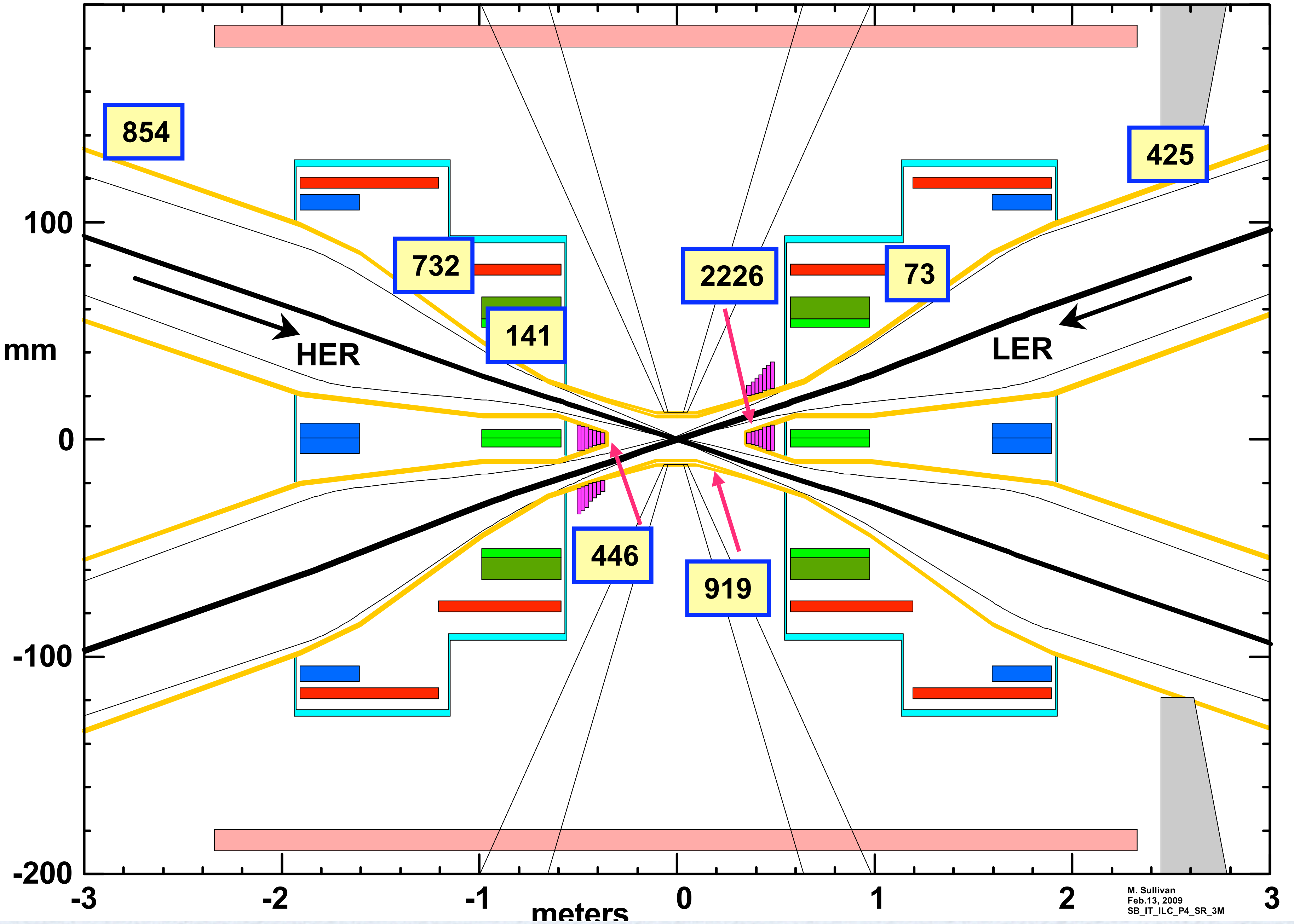


Mike Sullivan (SLAC)

Synchrotron radiation

Mike Sullivan (SLAC)

SR power (Watts)

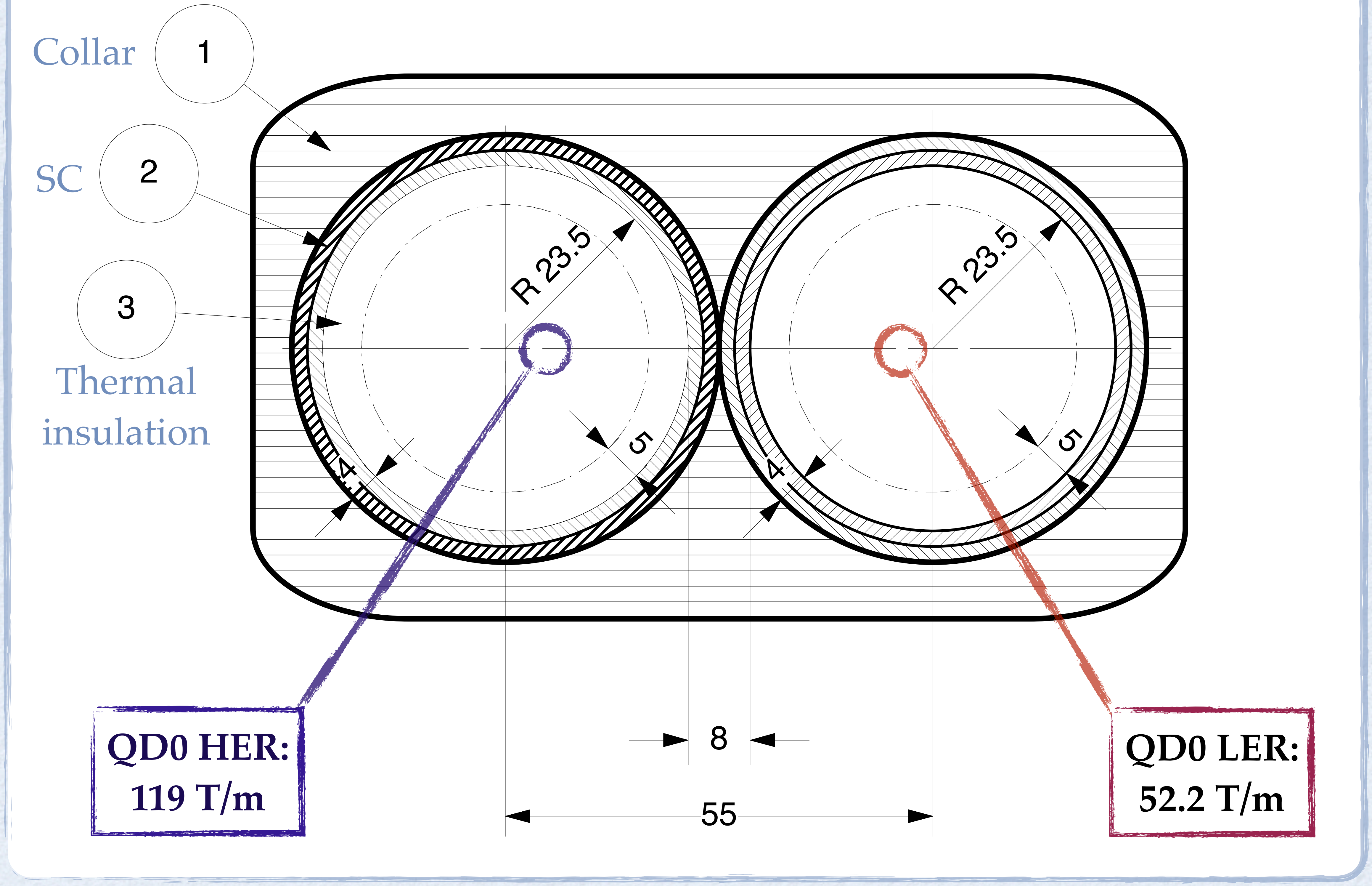


The cold bore option is not viable since the energy deposited by synchrotron radiation from the upstream dipoles is order of hundreds of Watts.

Main points

- Mechanical/Magnetic requirements
    - Gradients: ~ 120 T/m & 52.2 T/m
    - Field quality order of the 10^{-5} @ 10 mm
    - Radius of the mechanical aperture: ~ 23 mm
    - Available space for the SC windings: ~ 4 mm
- Operating temperature 1.9 K

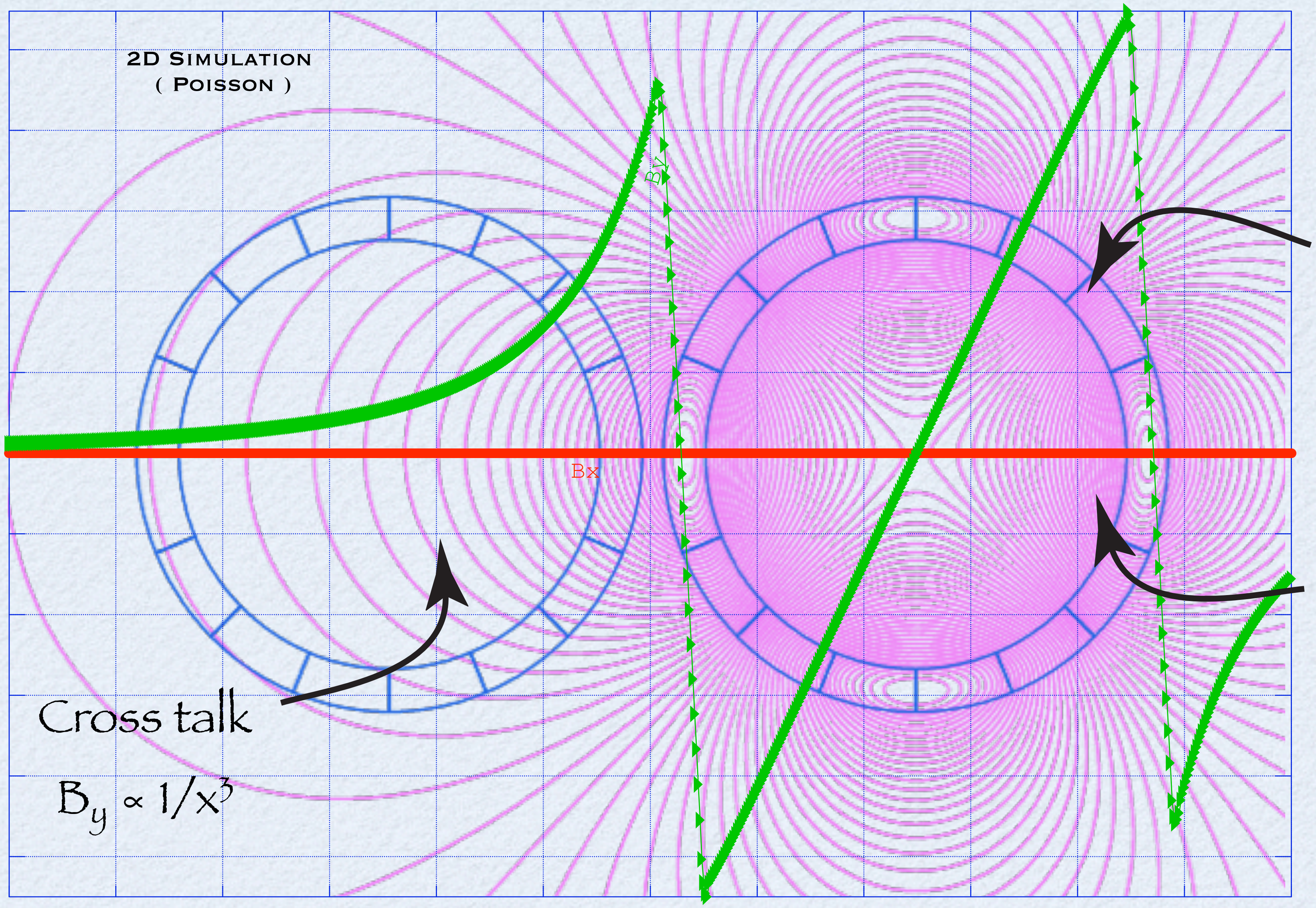
QD0: conceptual cross section



QD0 HER: 119 T/m

QD0 LER: 52.2 T/m

Cross talk.



SC windings

$J_z \propto \cos 2\varphi$

Quadrupolar field

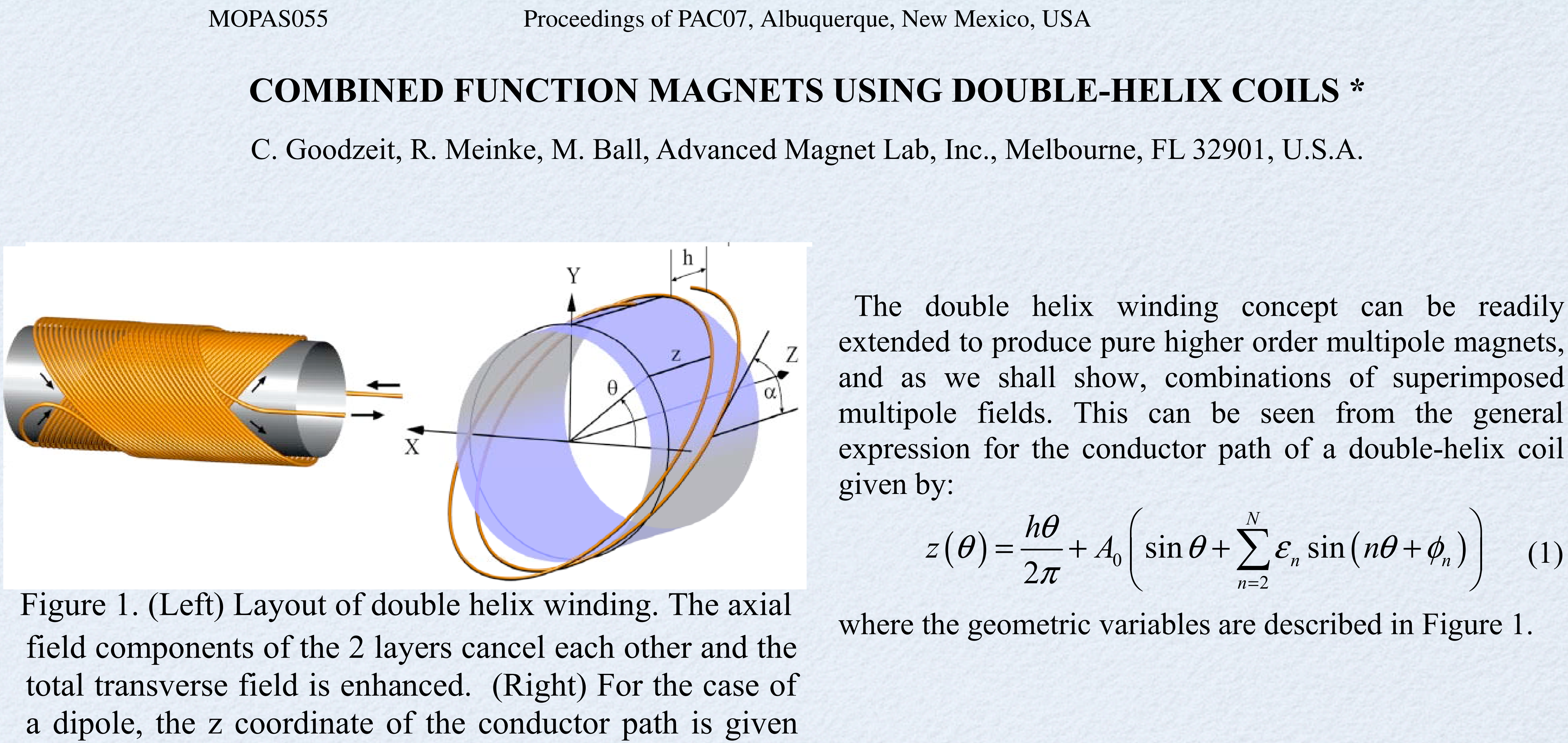
$B_y \propto x$

Cross talk

$B_y \propto 1/x^3$

- Only 8 mm for mechanical support and SC windings
- Field quality requested by Pantaleo: 10^{-5} @ 10 mm

AML docet:



MOPAS055 Proceedings of PAC07, Albuquerque, New Mexico, USA

COMBINED FUNCTION MAGNETS USING DOUBLE-HELIX COILS *

C. Goodzeit, R. Meinke, M. Ball, Advanced Magnet Lab, Inc., Melbourne, FL 32901, U.S.A.

Figure 1. (Left) Layout of double helix winding. The axial field components of the 2 layers cancel each other and the total transverse field is enhanced. (Right) For the case of a dipole, the z coordinate of the conductor path is given

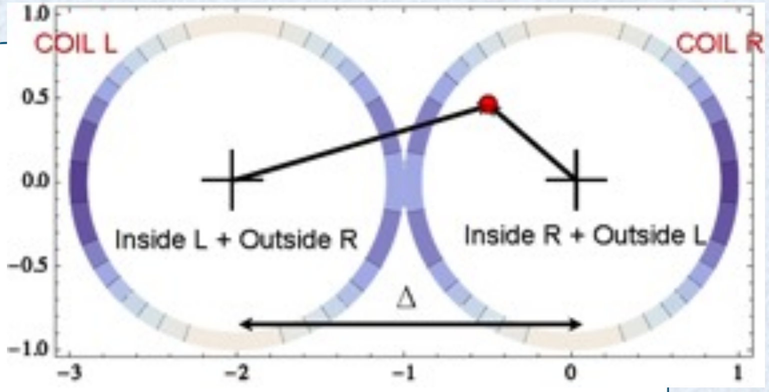
The double helix winding concept can be readily extended to produce pure higher order multipole magnets, and as we shall show, combinations of superimposed multipole fields. This can be seen from the general expression for the conductor path of a double-helix coil given by:

$$z(\theta) = \frac{h\theta}{2\pi} + A_0\left(\sin\theta + \sum_{n=2}^{N}\varepsilon_n \sin(n\theta + \phi_n)\right) \qquad (1)$$

where the geometric variables are described in Figure 1.

In simple words: given whatever a B_y field you need it is possible to design a coil to produce it.

Cross talk problem, algebraic solution



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

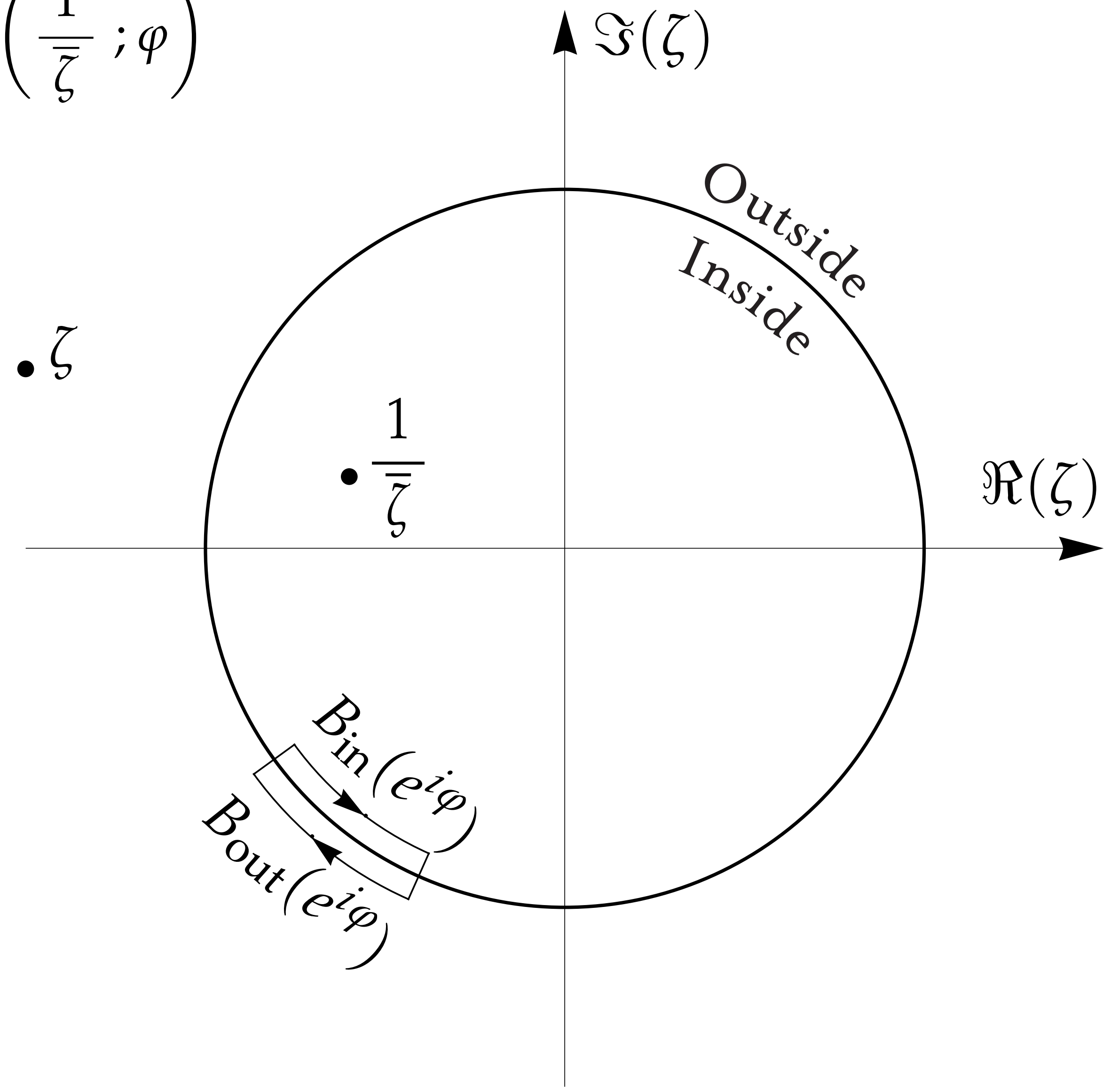
$$\boxed{B_{\text{out}}(\zeta) = -\frac{1}{\zeta^2}\overline{B}_{\text{in}}\left(\frac{1}{\overline{\zeta}}\right) + \frac{k}{\zeta}\int_0^{2\pi} j(\varphi)\,d\varphi}$$

Functional equation to solve:

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

Ampere law to determine the field source

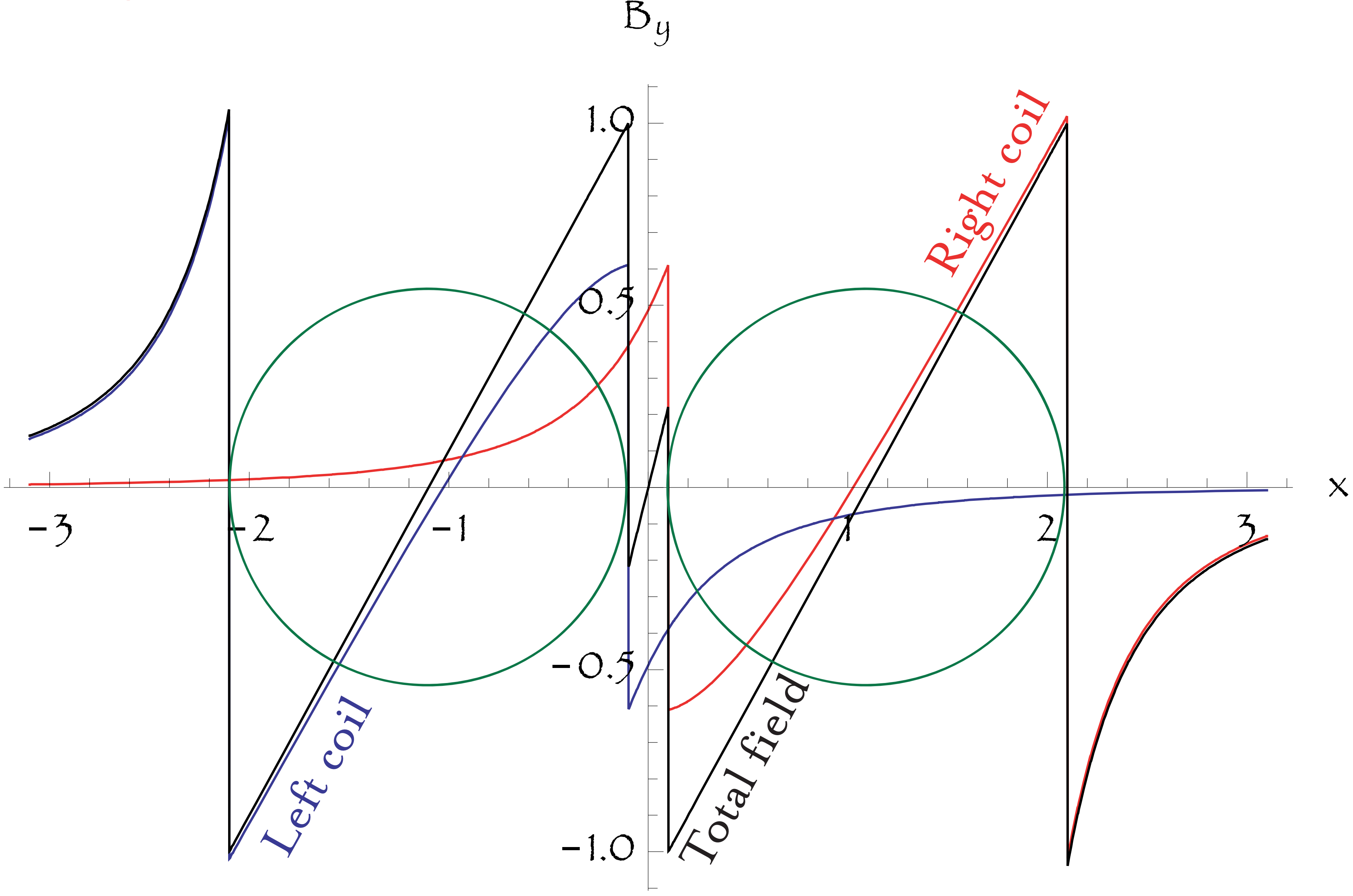
$$\boxed{j_z = \left[B_{\text{out}}(e^{i\varphi}) - B_{\text{in}}(e^{i\varphi})\right] e^{i\varphi}}$$



The field configuration

$B_y(x)$ generated by:

the right coil, the left coil, their sum



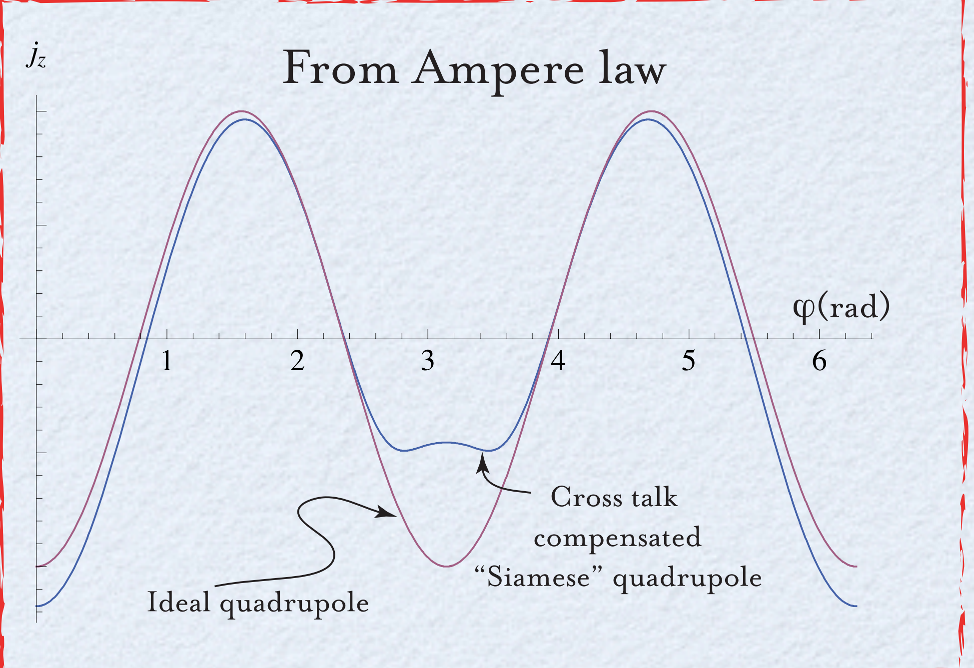
And the windings shape

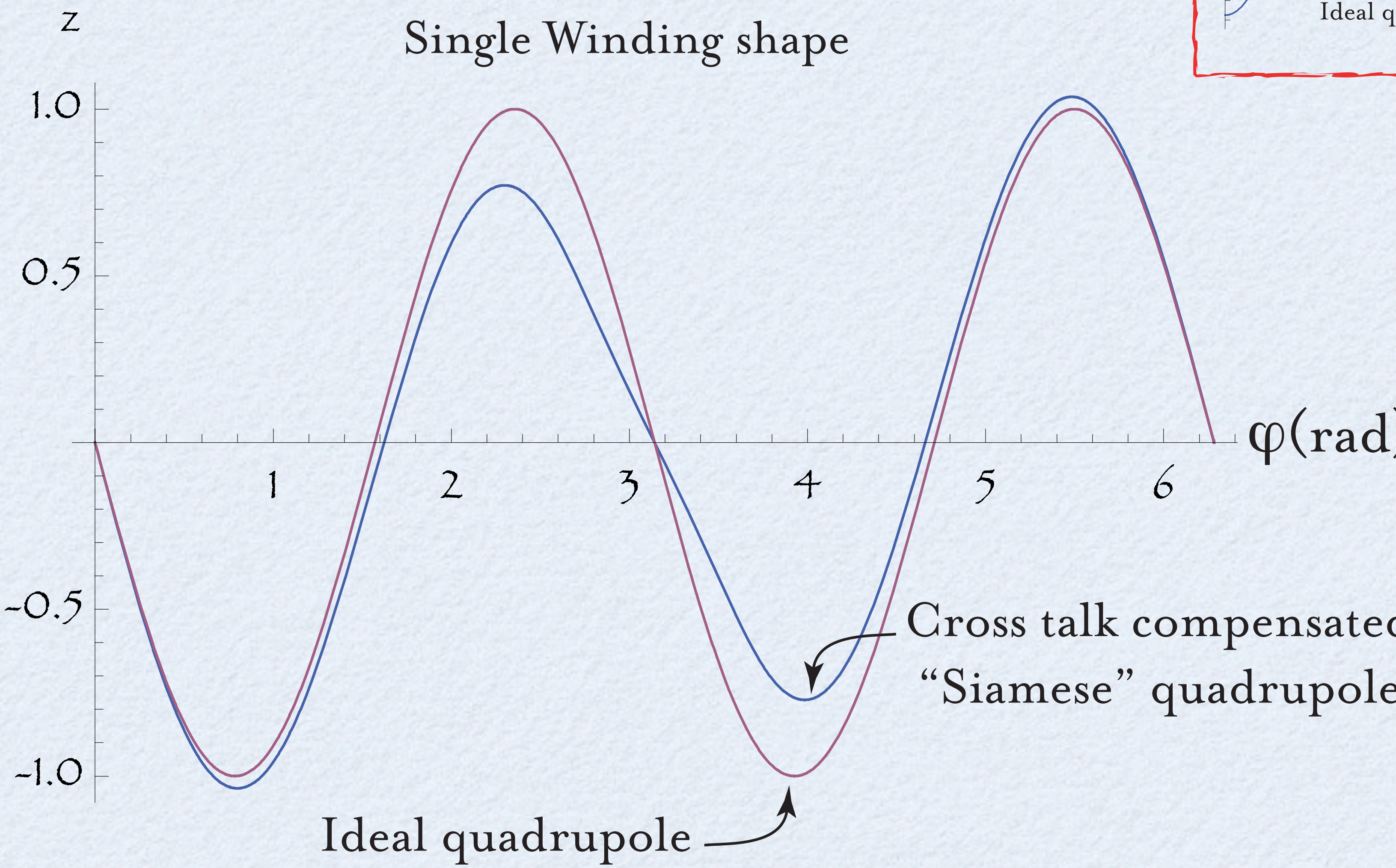
$$\dot{\mathbf{x}} = \mathbf{j}(\mathbf{x})$$

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

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

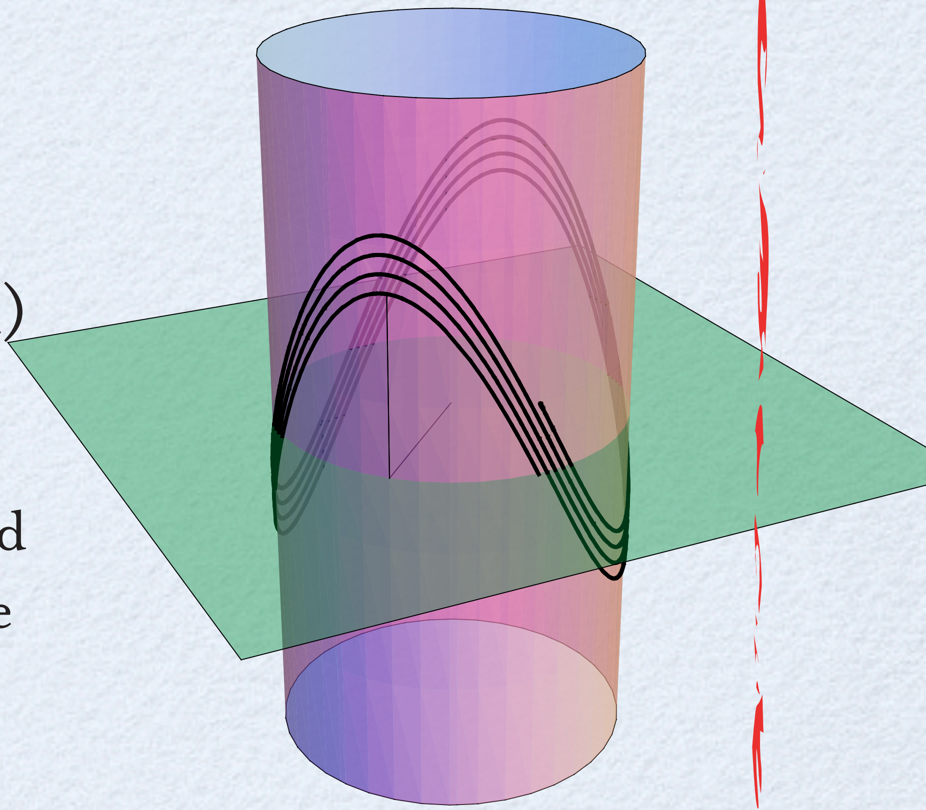
Counter rotating Solenoidal & Longitudinal field





Cross talk compensated "Siamese" quadrupole

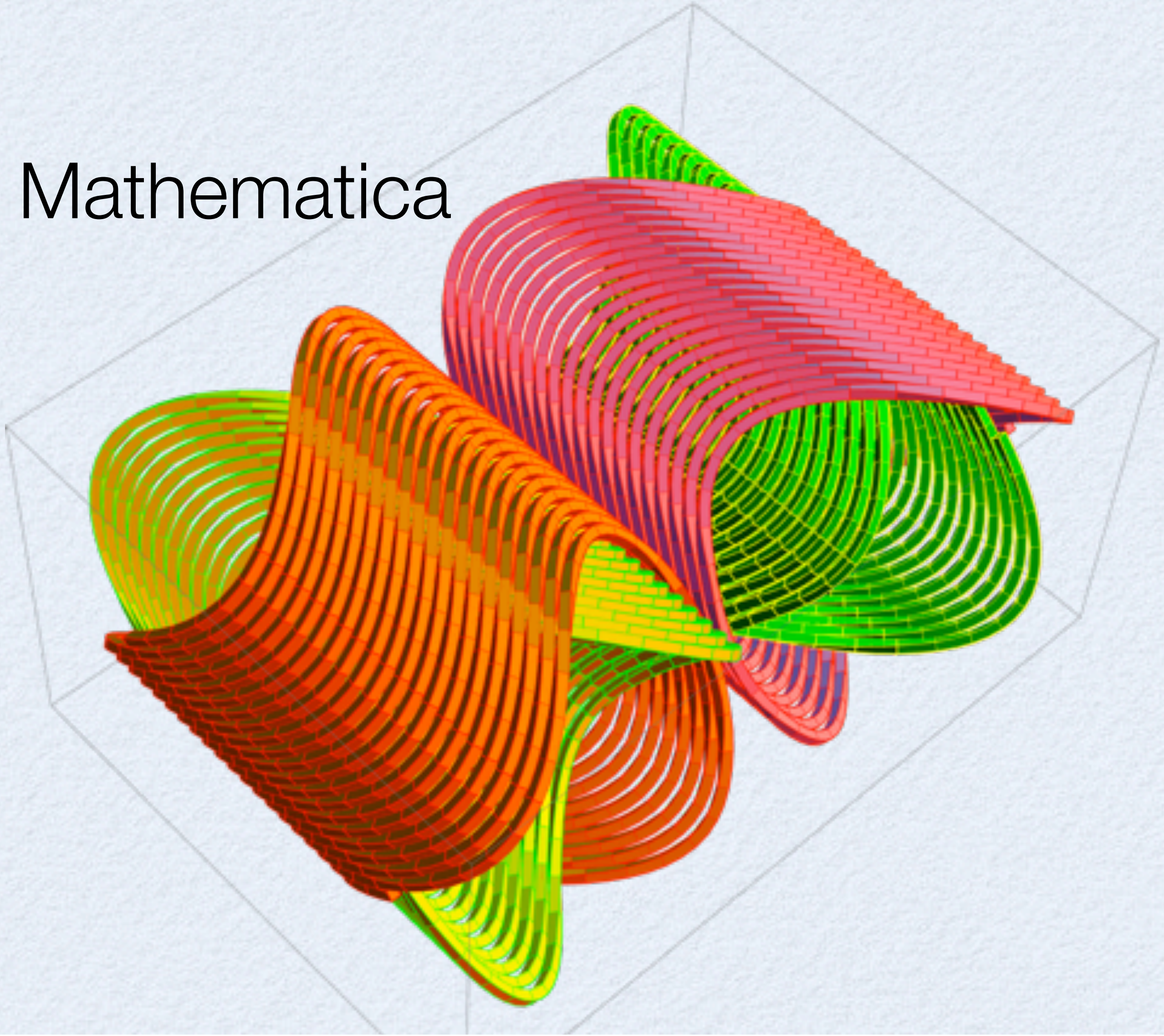
Ideal quadrupole

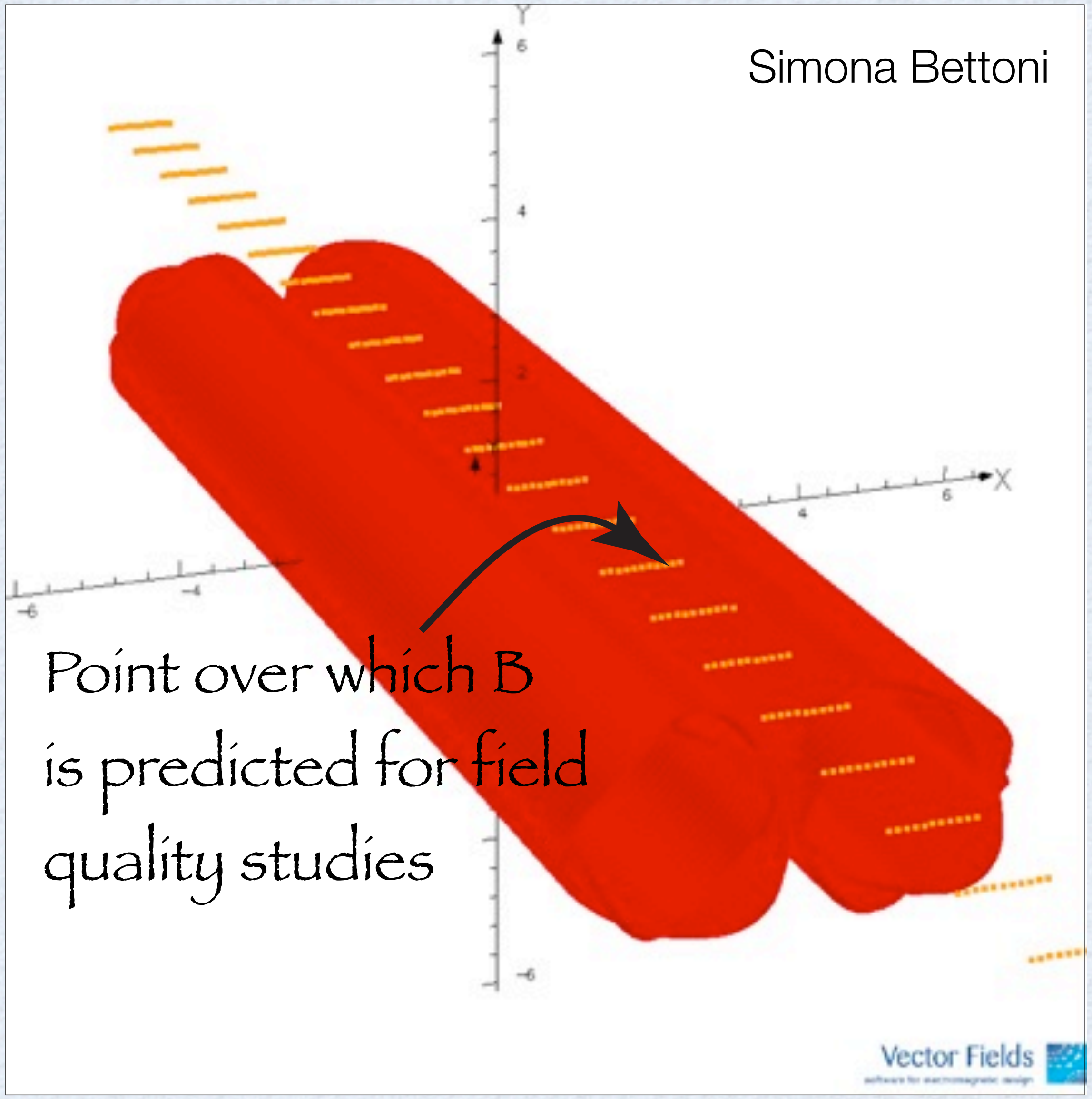


3D simulations: Tosca

- A 3D model is generated with Mathematica following the previous recipe
- The 3D model is simulated with Tosca
- Field quality and maximum field on conductors predicted

Mathematica

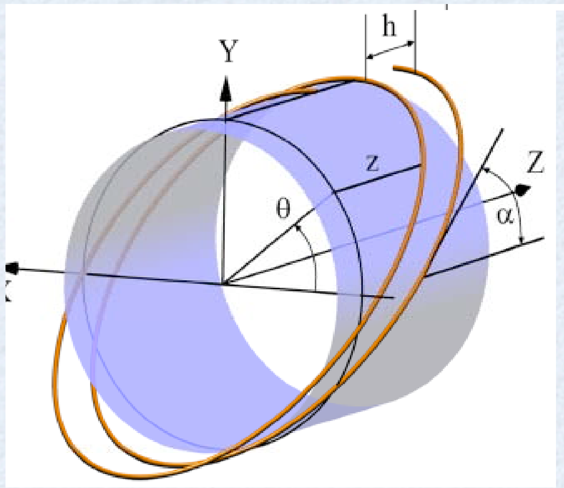


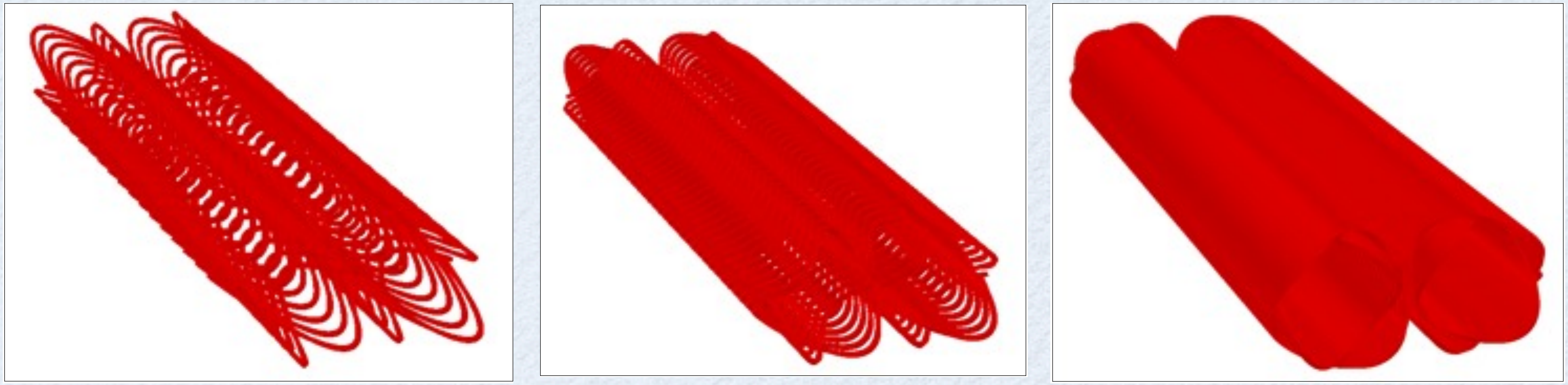


Simona Bettoni

Point over which B is predicted for field quality studies

Field quality optimization





Simona Bettoni

- We scan over α (the longitudinal scale of the modulation) and h (the step)

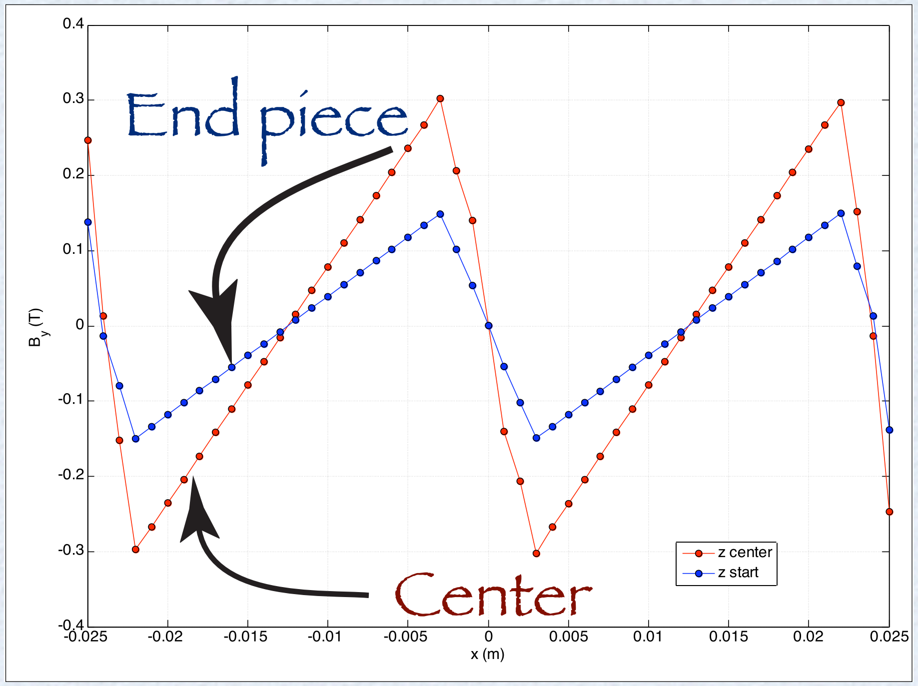
  keeping the gradient constant.

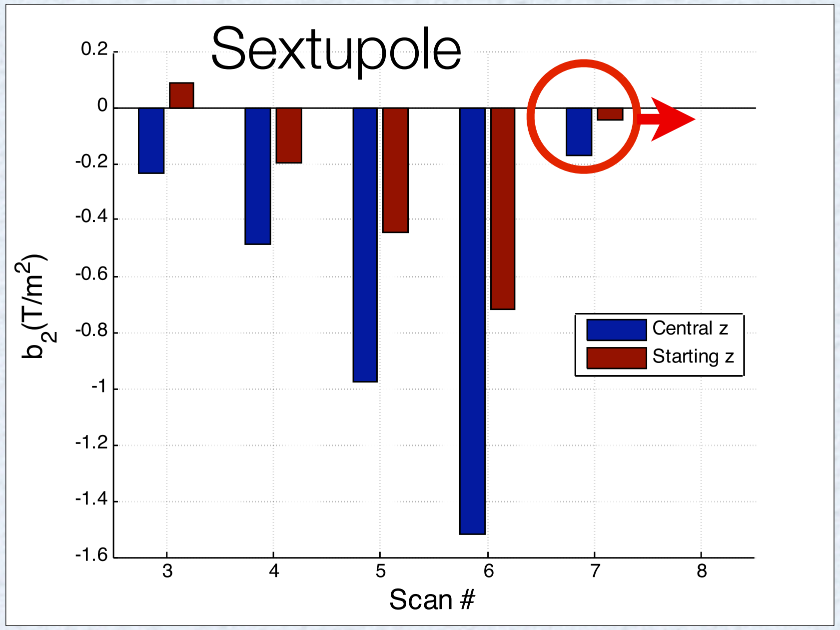
- From the field predicted by Tosca we evaluate the higher multipolar terms normalized to the quadrupole at tre reference radius

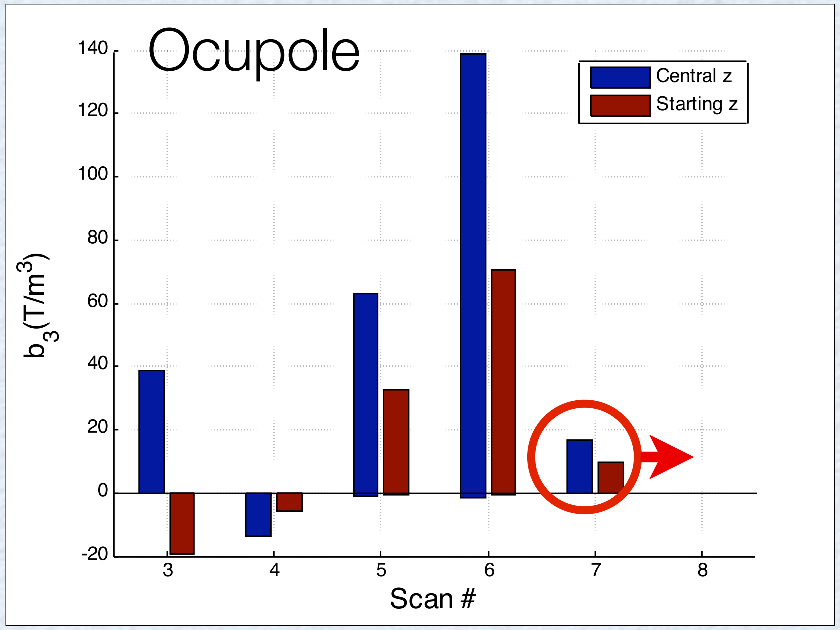
$$B_y(x - x_c, y = 0) = \sum_{k=0}^{\infty} b_k (x - x_c)^k$$

$$B_k \equiv \left. \frac{b_k (x - x_c)^k}{b_1 (x - x_c)} \right|_{x=\text{Ref. radius}}$$

Optimization results





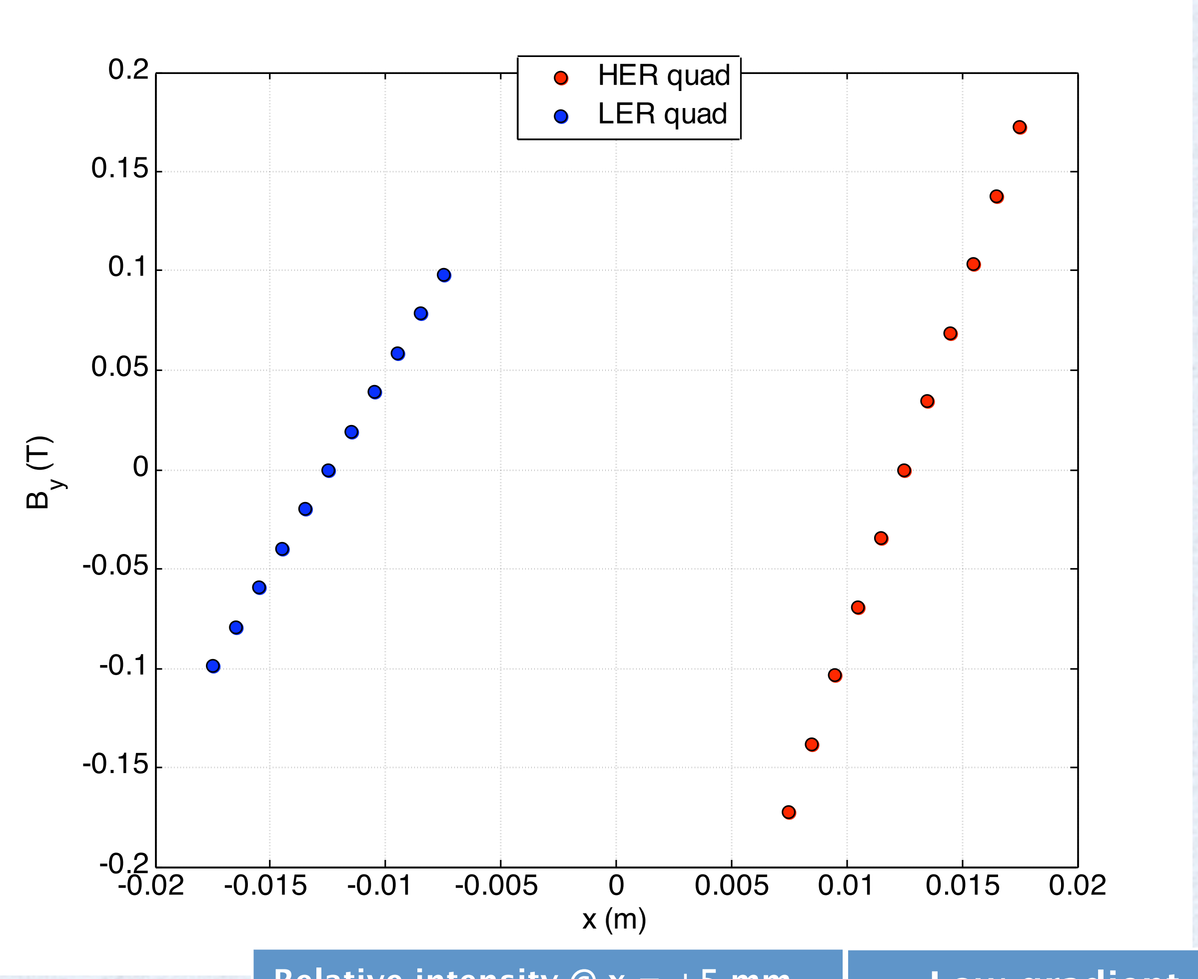


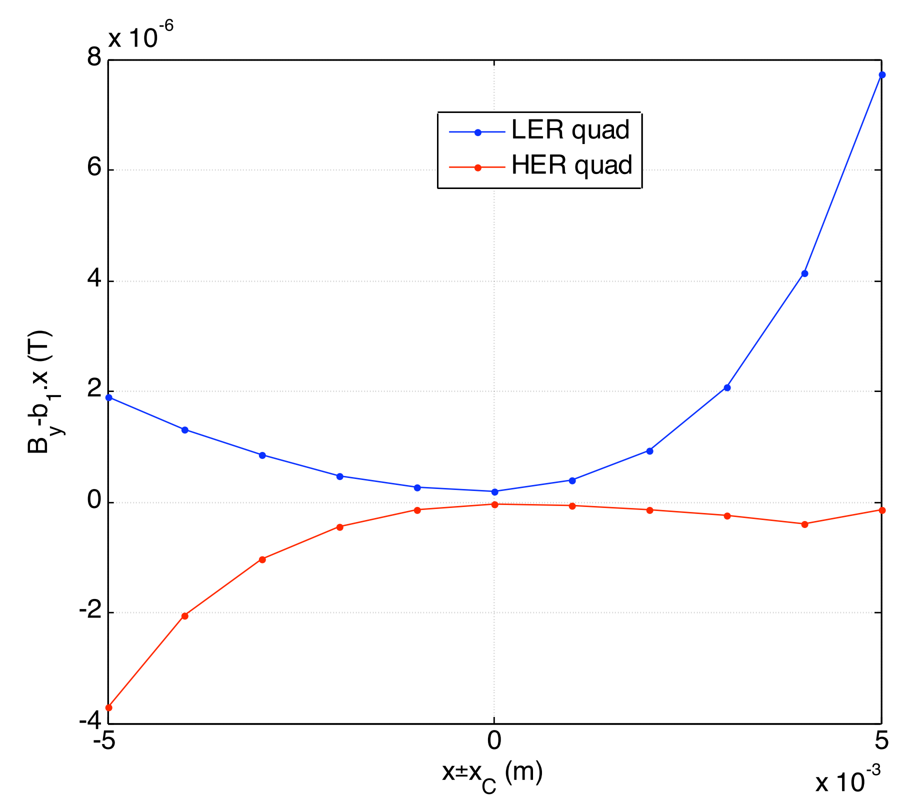
Simona Bettoni

Normalized multipoles @ x = ± 5 mm	Scan #4		Scan #7	
	center	extremity	center	extremity
B_2 (Sextupole)	$-7.74\ 10^{-5}$	$-6.28\ 10^{-5}$	$-2.72\ 10^{-5}$	$-1.36\ 10^{-5}$
B_3 (Octupole)	$-1.09\ 10^{-5}$	$-9.25\ 10^{-6}$	$-1.33\ 10^{-5}$	$-1.52\ 10^{-5}$

Asymmetric gradients

- The gradient needed for the LER in the latest design is smaller than the one needed for the HER. The gradients ratio is order of the energies ratio ~ 7/4 (still to be optimized)



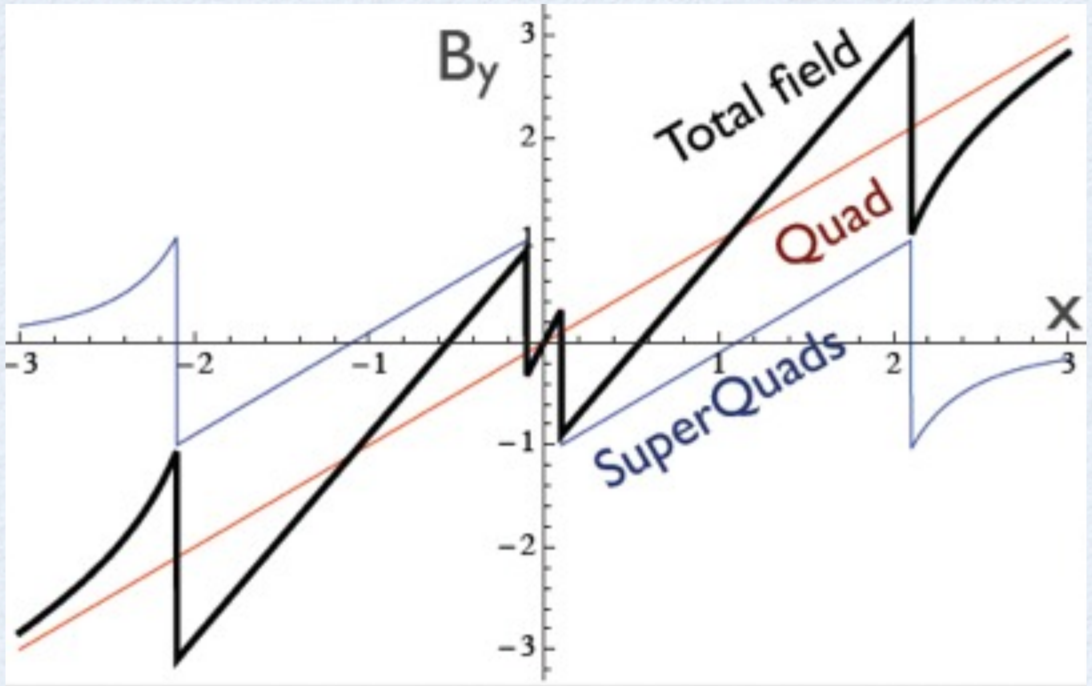


Simona Bettoni

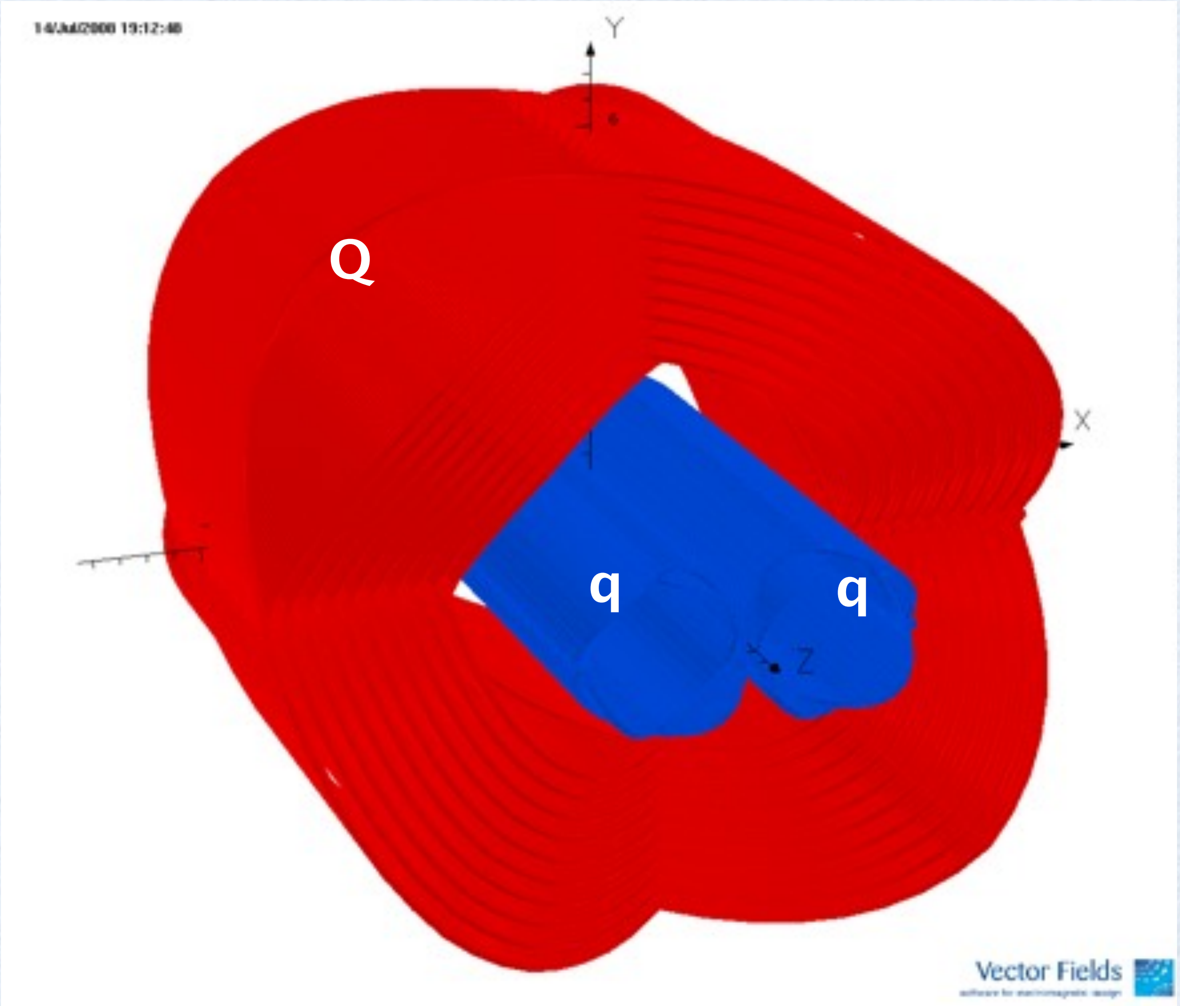
Relative intensity @ x = ±5 mm	Low gradient coil		High gradient coil	
	z center	z start	z center	z start
B_2	2.92E-05	3.00E-05	1.02E-05	1.22E-05
B_3	4.68E-05	4.71E-04	-1.10E-05	-7.43E-06

Margin to quench

- The high required gradients are not feasible with present SC wires in the small space available for the windings
- Simona's idea:



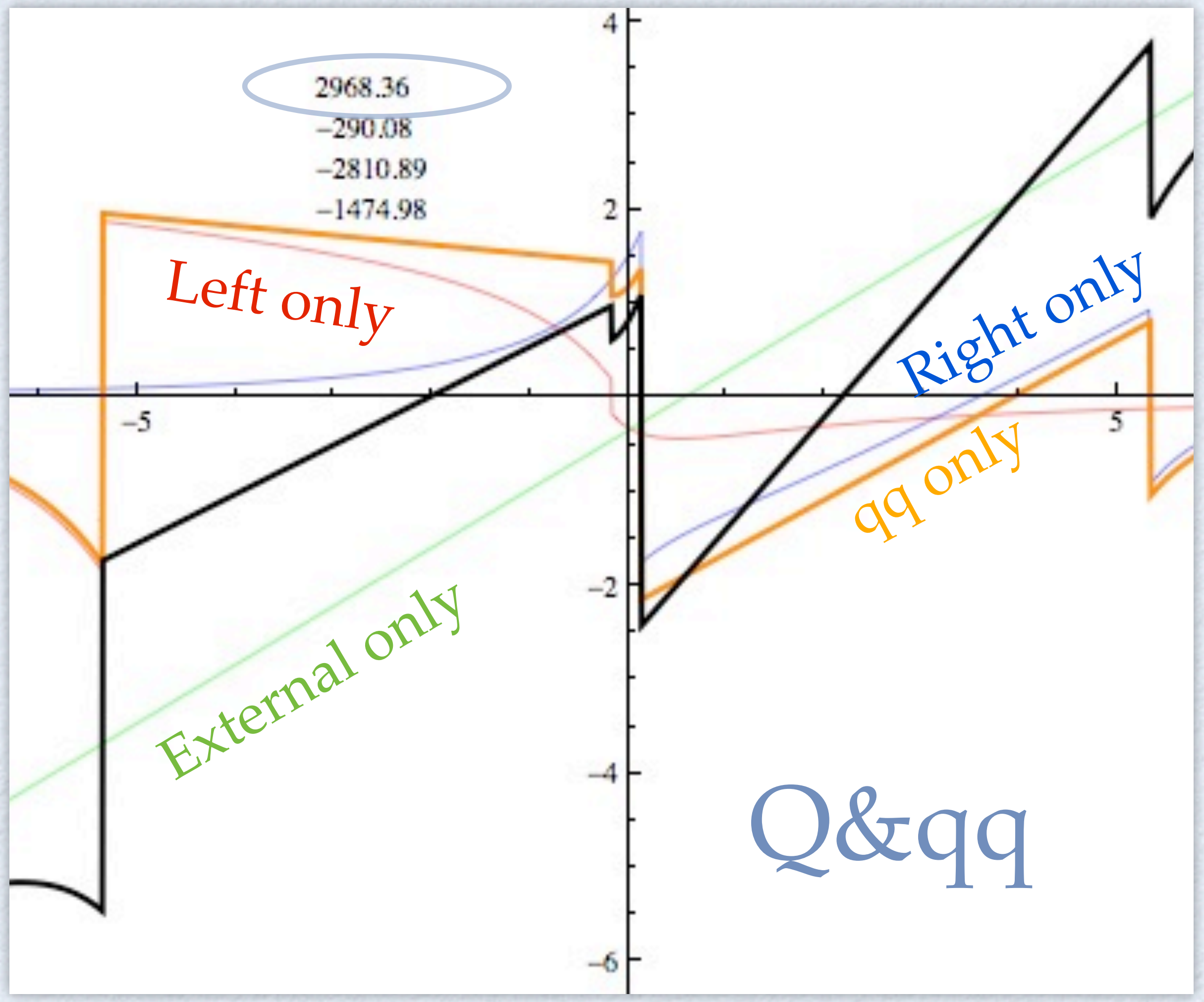
An external quadrupole can produce a big part of the field.

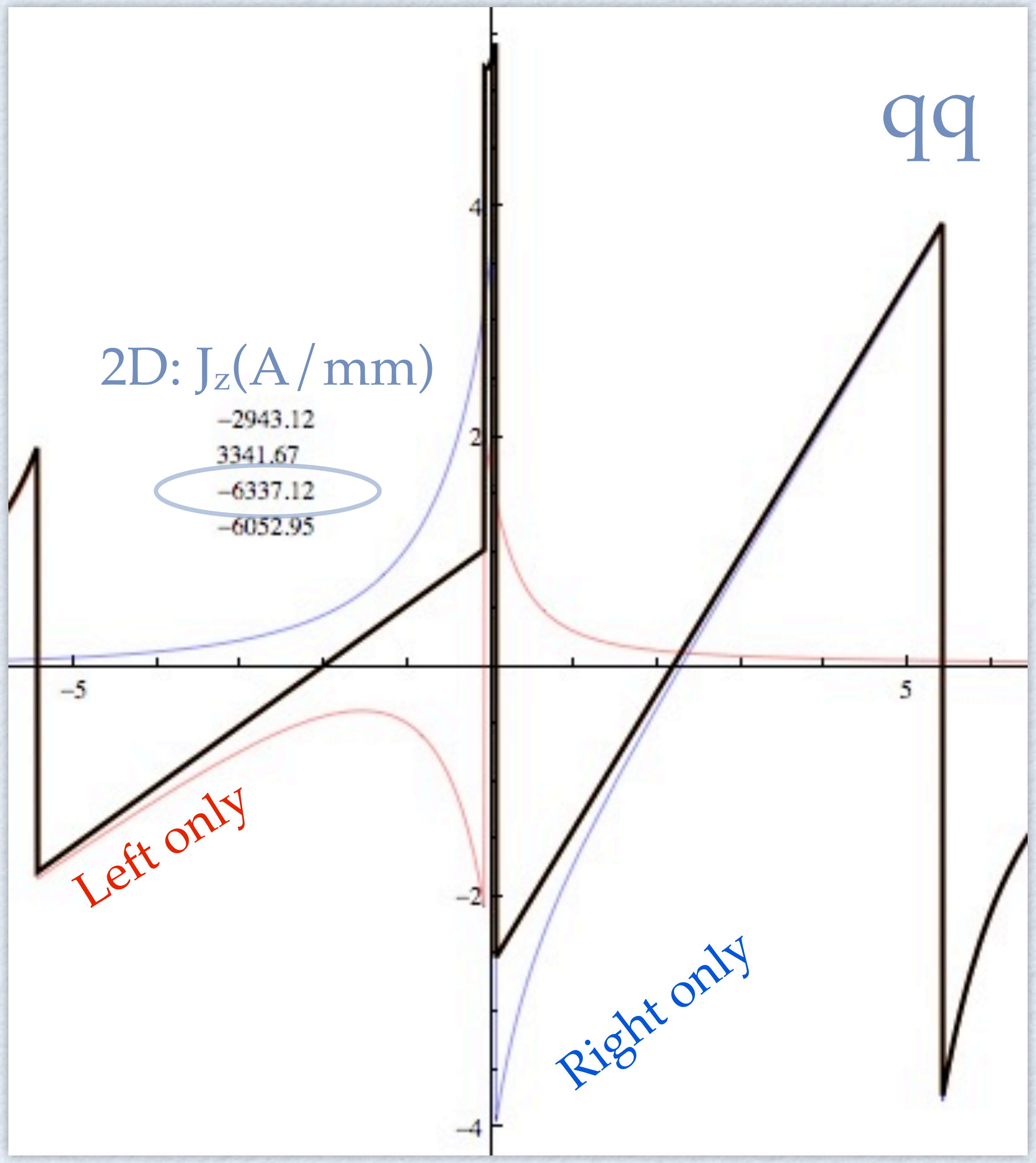


Configuration advantages

	HER	LER
Gradient (T/cm)	-1.191338	-0.5223842
Magnetic axis position (mm)	22.0	-20.0
Aperture (mm)	23.5	
Mechanical axis position (mm)	27.5	

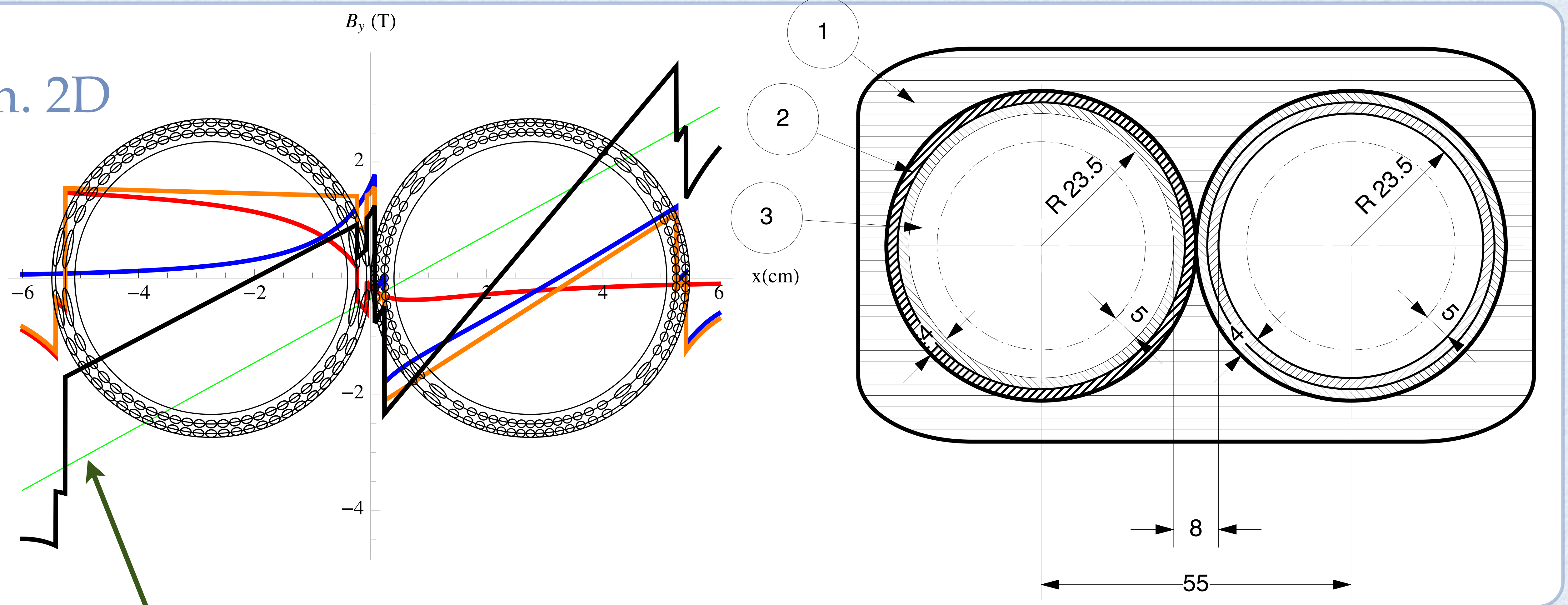
2D: J_z(A/mm)




2D: J_z(A/mm)

The present status

Sim. 2D



Extern field optimized to reduce the current density in the inner quadrupoles

G_{EXT} = 0.622 T/cm

External quad x-axis = 6 mm

Internal/external contribution to the gradient not optimized yet

Round NbTi wire

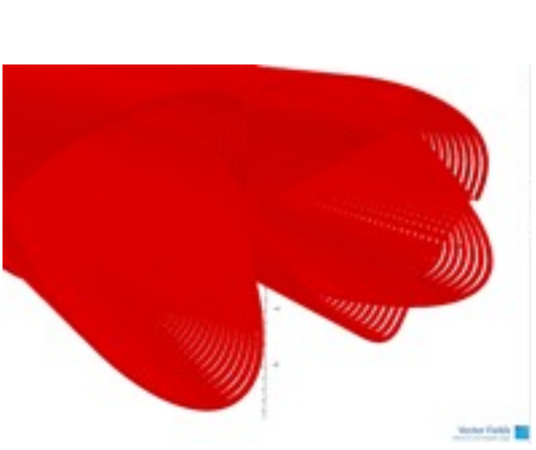
ϕ =1.3 mm

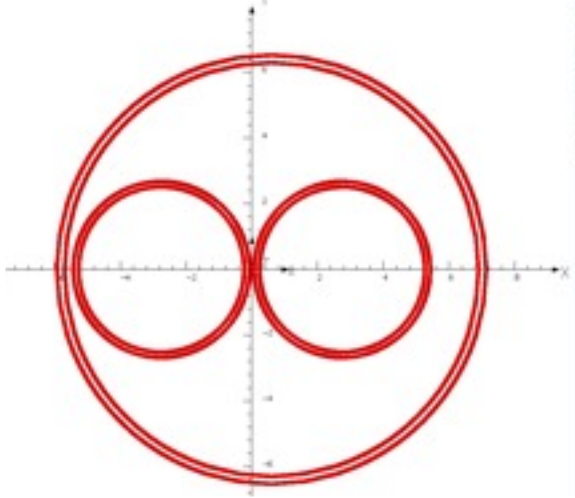
0.7mm for the mechanical support

$J_{Overall}$ = 1520 A/mm^2

3D Tosca max|B| = 5.5 T

3D simulation

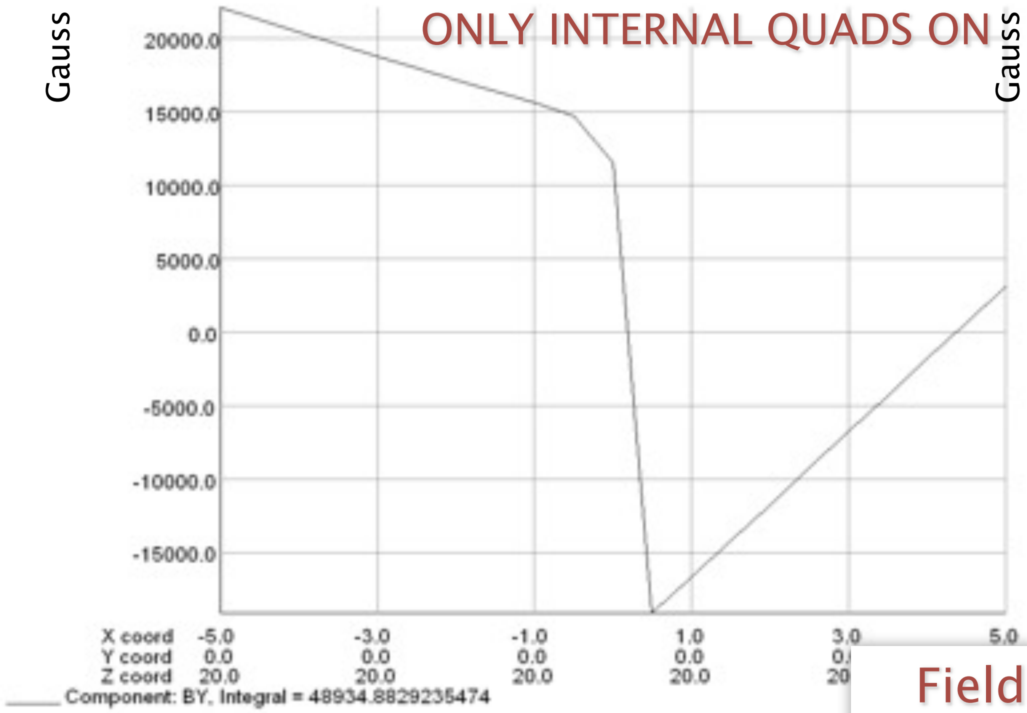


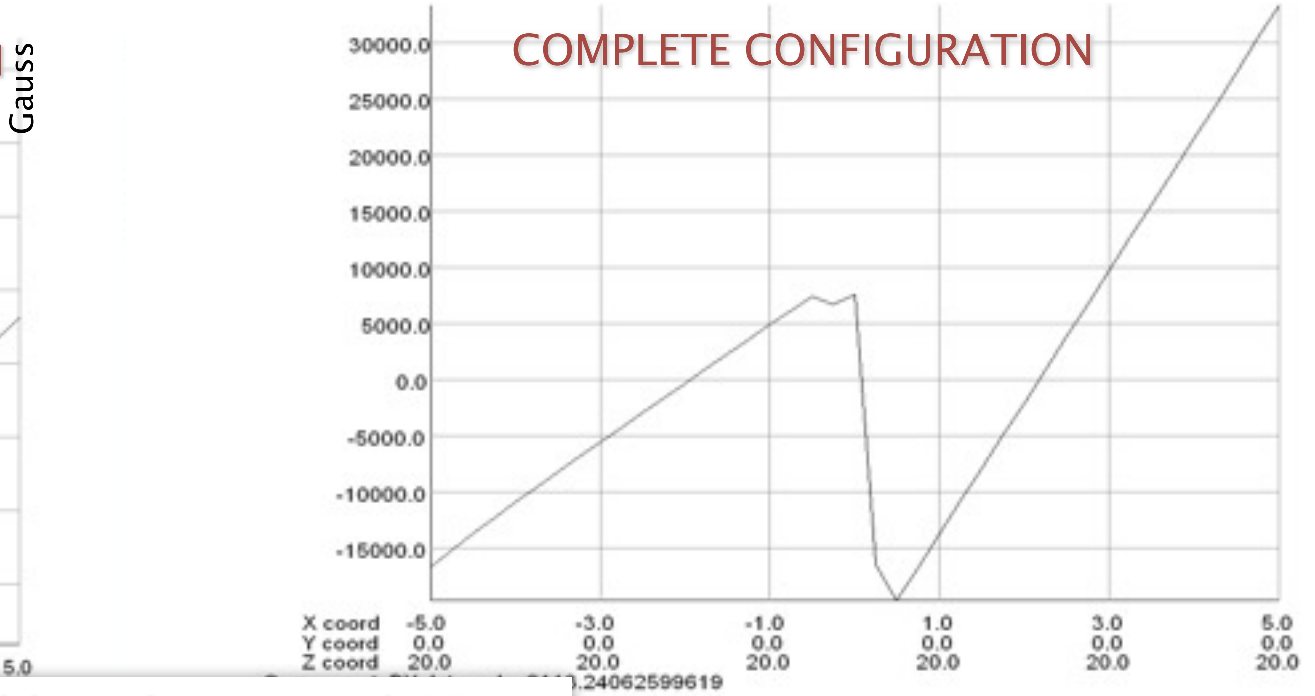


Cold mass space = 4 mm+4 mm

Used space (supports) = 2.6 mm +2.6 mm

$\Phi_{\text{wire (Bare)}}$ = 1.3 mm





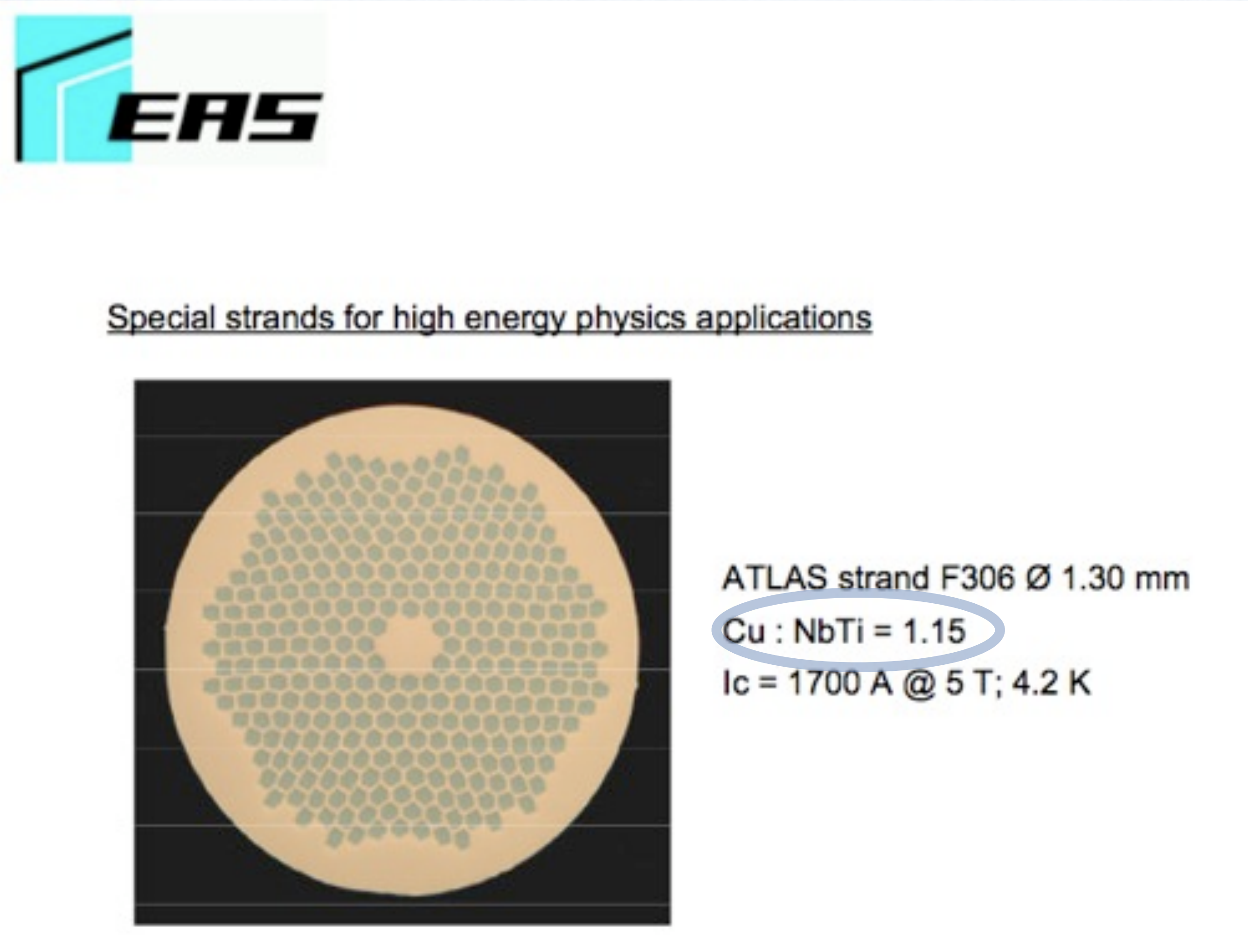
Field quality around 10^{-4}

(Scan not performed yet)

Margin to quench

Margin to quench @ 4.2 K still too small for commercially available NbTi SC.

1.9K seems viable.

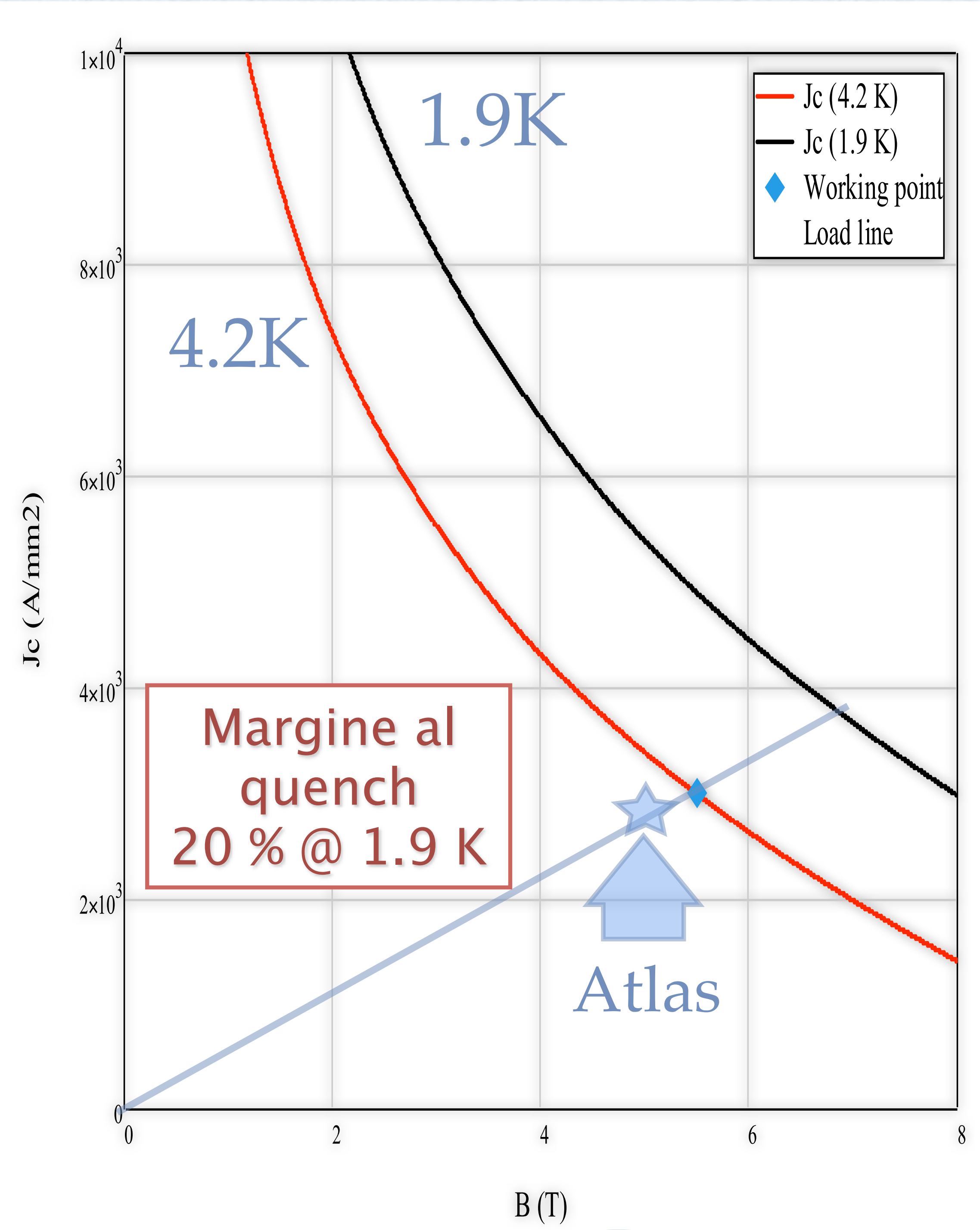


Special strands for high energy physics applications

ATLAS strand F306 Ø 1.30 mm

Cu : NbTi = 1.15

Ic = 1700 A @ 5 T; 4.2 K



Typical NbTi properties and Cu/SC ratio = 1 assumed.

Conclusions

- A promising solution to satisfy the challenging requirements of the quadrupoles of the final doublets of SuperB had been presented
- The cross talk compensation scheme is able (from 3D simulations) to meet the field quality requirements
- The configuration with an external conventional magnet + a twin compensated pair significantly increases the margin to quench

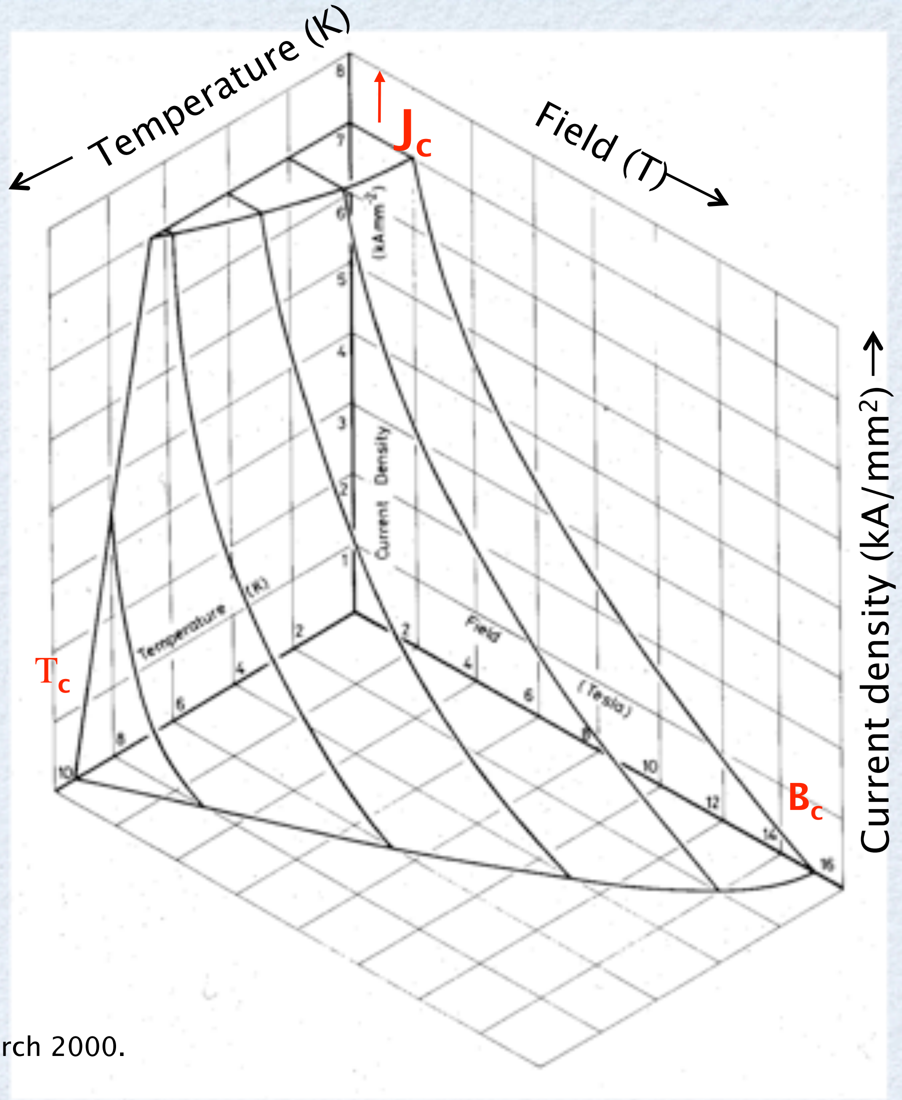
Grazie

Margin to quench NbTi

$$J \leq J_c \approx \frac{C_0}{B} \times b^{\alpha} \times (1-b)^{\beta} \times (1-t^{1.7})^{\gamma}$$

$$\begin{cases} b & \equiv \dfrac{B}{B_{c2}} \\ t & \equiv \dfrac{T}{T_{c20}} \\ B_{c2} & \equiv B_{c20} \times (1-t^{1.7})^{\gamma} \end{cases}$$

NbTi Parameters	
B_{c20} (T)	14.5
T_{C0} (K)	9.2
C_0 (kA T/mm^2)	23.8
α	0.57
β	0.9
γ	1.9



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