5th FCC Physics Workshop
Liverpool, February 10th 2022

The quadrupole QDO for the SuperB interaction region

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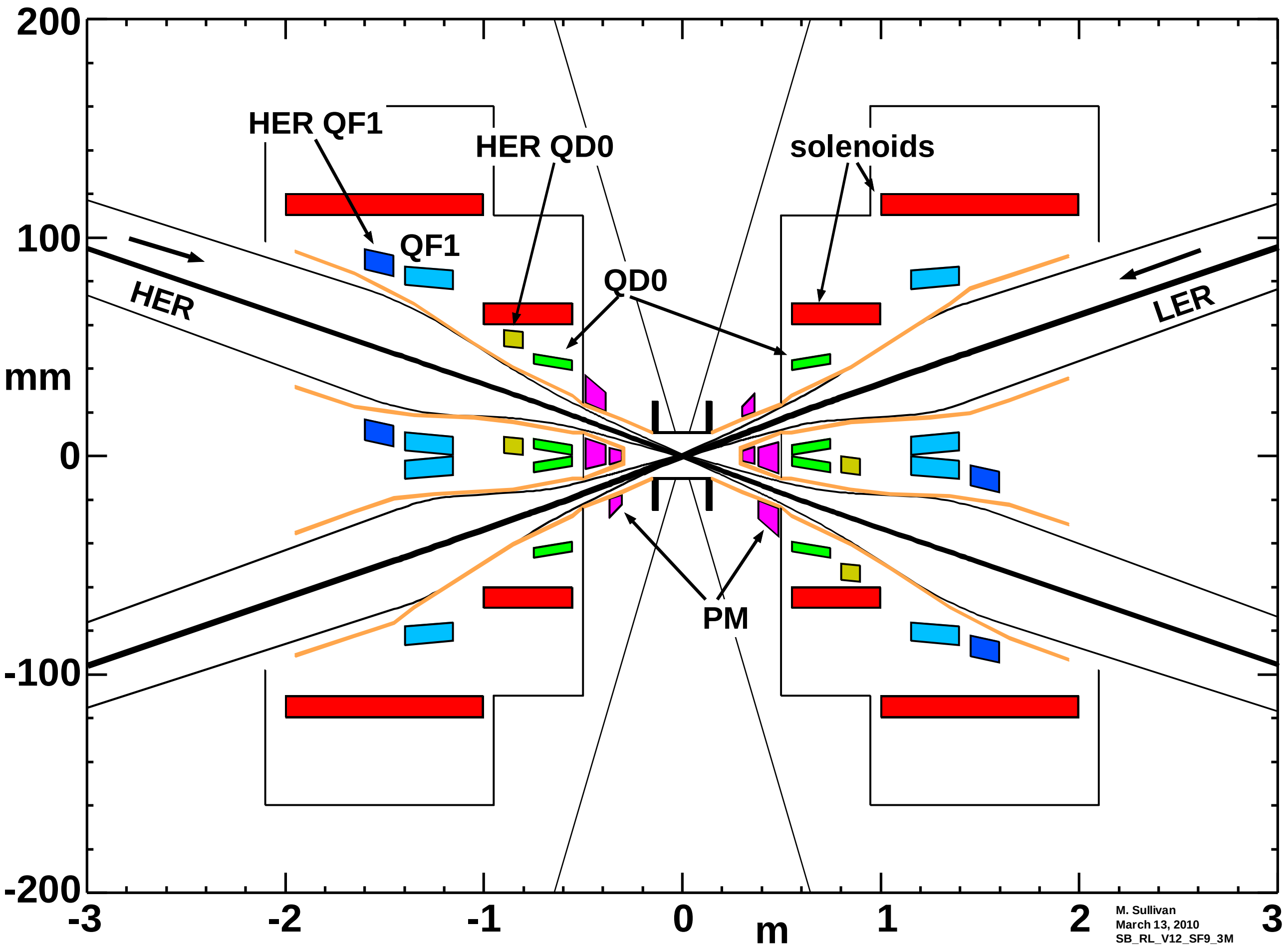
SuperB: a 10^{36} cm^{-2} s^{-1} accelerator

- SuperB was an **international enterprise** aiming at the construction of a very high luminosity (10^{36} cm^{-2} s^{-1}) asymmetric e^+e^- Flavor Factory to be built near the INFN National Laboratory of Frascati.
- The project started around 2001 and **it was cancelled** by the Italian government on 27 November 2012.
- In the collider scheme, a crucial role was played by the **quadrupole doublets QDO/QF1** which were to be placed close to the interaction region and were designed to generate gradients close to **100 T/m**.
- A **Conceptual Design Report**, signed by 85 Institutions was published in March 2007 (arXiv:0709.0451 [hep-ex]).

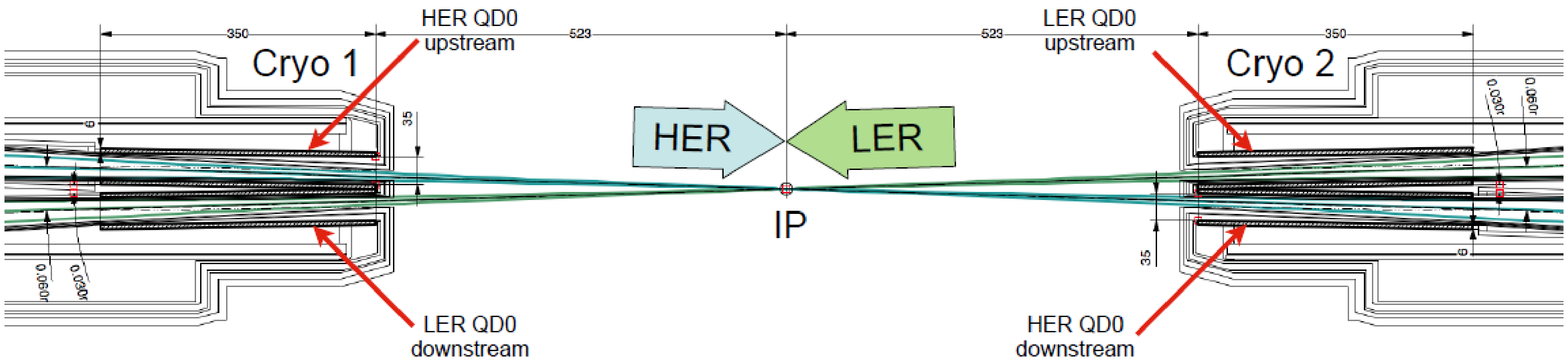
SuperB Interaction Region

- The small beta functions require the final focus magnets to be as close to the interaction point (IP) as possible in order to keep the maximum beta values as low as possible and minimize the chromaticity generated in the final focus.
- The first quadrupole magnet (QDO) **starts ~0.5 m away from the IP** and its radial dimension and offset limits the detector **acceptance** to about **300 mrad** in the forward and backward direction.



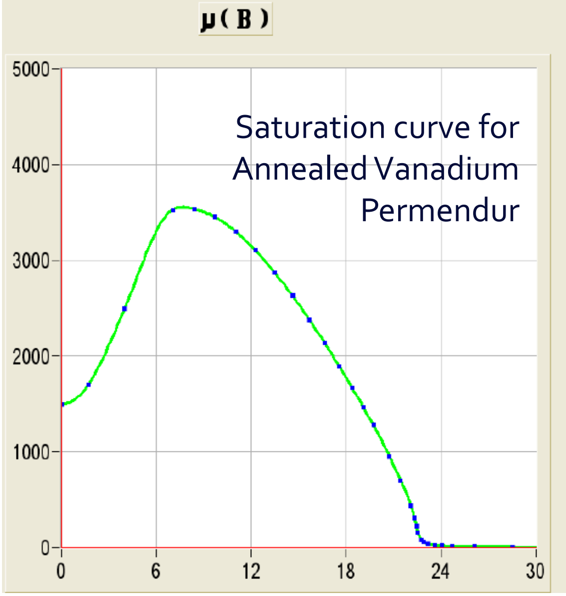
Magnet design details

	QDO	QDOH	QF1	QF1H
IP face (m)	0.52	0.90	1.25	1.70
Length (m)	0.3	0.15	0.4	0.25
Axis offset (mm)	0.5	–	4	–
Angle wrt beam (mrad)	30	0	27	1
G (T/m)	95.6	70.6	40.8	38.1
Aperture (mm)	35	50	73	78



Iron core «siberian» design for QDO

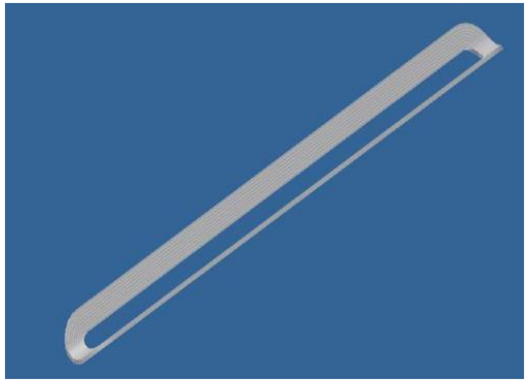
- Pros:
  - Easy SC coils
  - Iron yoke (Vanadium Permendur) helps in reducing cross-talk and fringe field, enhances the magnetic field gradient and reduces the current

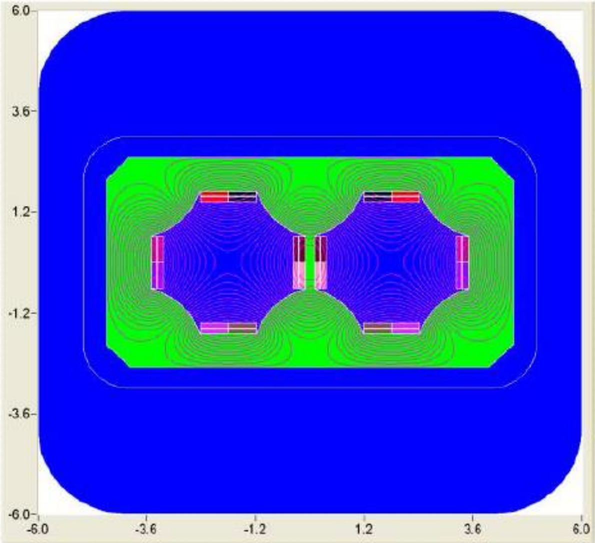


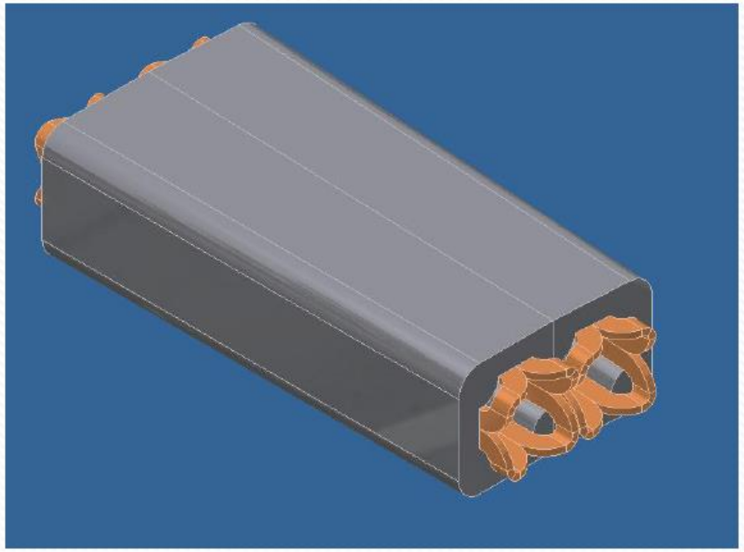
Spline

B	μ	μH'
0.000	1500.00	1.00
2.727	2017.42	0.51
5.455	3110.34	0.30
8.182	3545.62	1.10
10.909	3315.85	1.45
13.636	2841.54	1.99
16.364	2207.15	2.90
19.091	1464.02	4.86
21.818	566.38	18.00
24.545	12.25	12.21
27.273	5.77	5.77
30.000	4.03	4.03

- Cons:
  - Complicated structure to fit it in the allowed space







Courtesy I.Okunev

https://agenda.infn.it/event/2303/contributions/40596/attachments/28291/33098/IR_C-tau_Okunev.pdf

Air core CCT design for QDO

- Nominal parametric description

$$\gamma_1 = \begin{cases} r_1 \cos\theta \\ r_1 \sin\theta \\ \frac{h\theta}{2\pi} + A_1 \sin 2\theta \end{cases} \qquad \gamma_2 = \begin{cases} r_2 \cos\theta \\ r_2 \sin\theta \\ \frac{h\theta}{2\pi} - A_2 \sin 2\theta \end{cases}$$

$$A_1 = \frac{1}{2}\left(\frac{r_1}{\tan\beta} - \frac{h}{2\pi}\right) \text{ and } A_2 = \frac{1}{2}\left(\frac{r_2}{\tan\beta} - \frac{h}{2\pi}\right)$$

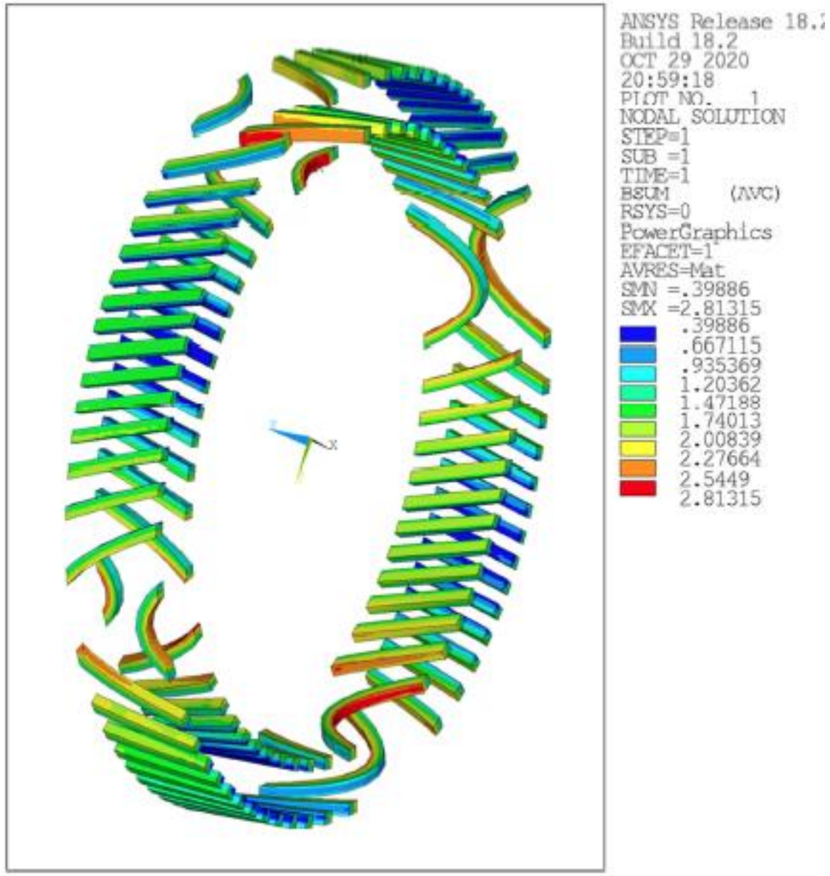
- Gradient

$$G = \frac{\mu_0 I}{h}\left(\frac{A_1}{r_1^2} + \frac{A_2}{r_2^2}\right)$$

$$G \sim \frac{\mu_0 I}{2h\tan(\beta)}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

QDO characteristics	
Aperture	35 mm
Inner radius (r_1)	19.565 mm
Outer radius (r_2)	23.065 mm
Pitch (h)	6.4 mm
Number of turns	48
Bare conductor diameter	1.28 mm
Insulation thickness	0.125 mm
Gradient	95.6 T/m
Current	2626 A
Tilt angle (θ)	14.1°
Magnetic length	300 mm
Stored energy	2.06 J/mm

Electromagnetic FE analysis of QDO periodic cell (T)



More information in S.Farinon *et al.*, DOI: 10.1109/TASC.2021.3053346

Cross talk: the compensation algorithm

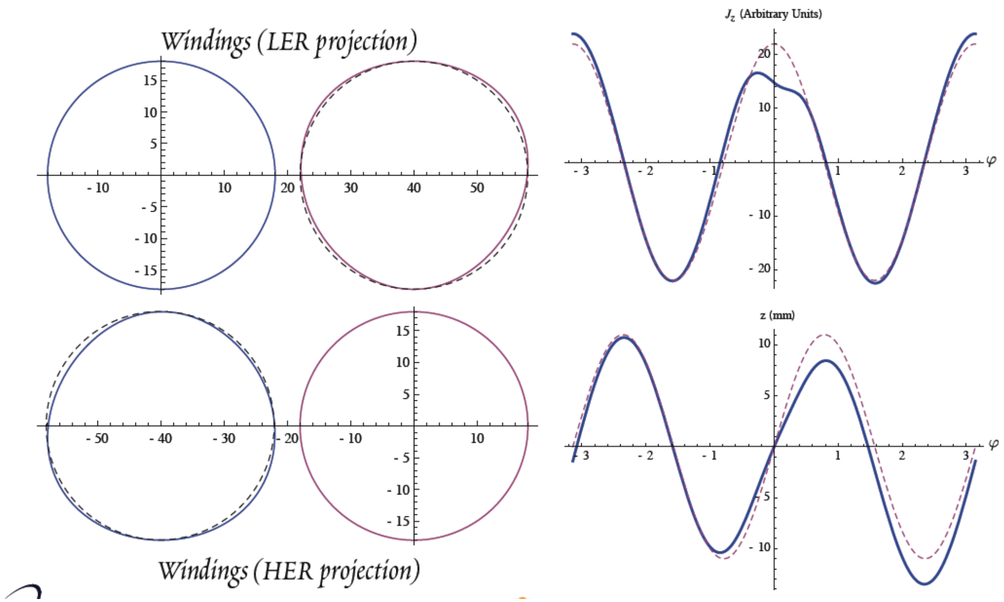
1. Determine the winding shape (for each winding) such that B(z) is the desired one using the Biot & Savart law (i.e. neglecting the wire thickness)

$$\vec{\mathbf{B}}(\vec{\mathbf{r}}) = I\frac{\mu_0}{4\pi}\int \frac{\vec{\mathbf{w}}'(l)\times(\vec{\mathbf{r}}-\vec{\mathbf{w}}(l))}{\left|\vec{\mathbf{r}}-\vec{\mathbf{w}}(l)\right|^3}\,dl$$

2. $\vec{\mathbf{w}}(l)$ gives the position of the center of the SC wires as a function of some continuous parameters l and I is the current flowing in the wire. From this expression one can obtain for $\vec{\mathbf{B}}(\vec{\mathbf{r}})$

$$\vec{\mathbf{B}}(\vec{\mathbf{r}}) = I\frac{\mu_0}{2\pi}\int \frac{\vec{\mathbf{w}}'_{\parallel}(l)\times(\vec{\mathbf{r}}-\vec{\mathbf{w}}(l))+\vec{\mathbf{w}}'_{\perp}(l)\times(\vec{\mathbf{r}}_{\perp}-\vec{\mathbf{w}}_{\perp}(l))}{\left|\vec{\mathbf{r}}_{\perp}-\vec{\mathbf{w}}_{\perp}(l)\right|^2}\,dl$$

3. Parametrize $\vec{\mathbf{w}}(l)$ as an interpolating polynomial controlled by N key points sliding along the support cylinder. Determine the position of these N points in such a way that $B(z)$ is the desired one on the reference circumference



Courtesy E.Paoloni
https://agenda.infn.it/event/4442/contributions/53040/attachments/38027/44719/Frascati_Dec_2011.pdf

The NbTi wire

- The **NbTi multifilamentary wire** which was preliminarily chosen is the strand of the CMS conductor (bare diameter 1.28 mm, Cu/SC ratio is 1.1) produced by Luvata

$$J_{eng} = \frac{I}{\pi r_{wire}^2} \sim 2000 \text{ A/mm}^2$$

A value incredibly high!
(in LHC dipole J_{eng}~400 A/mm²)

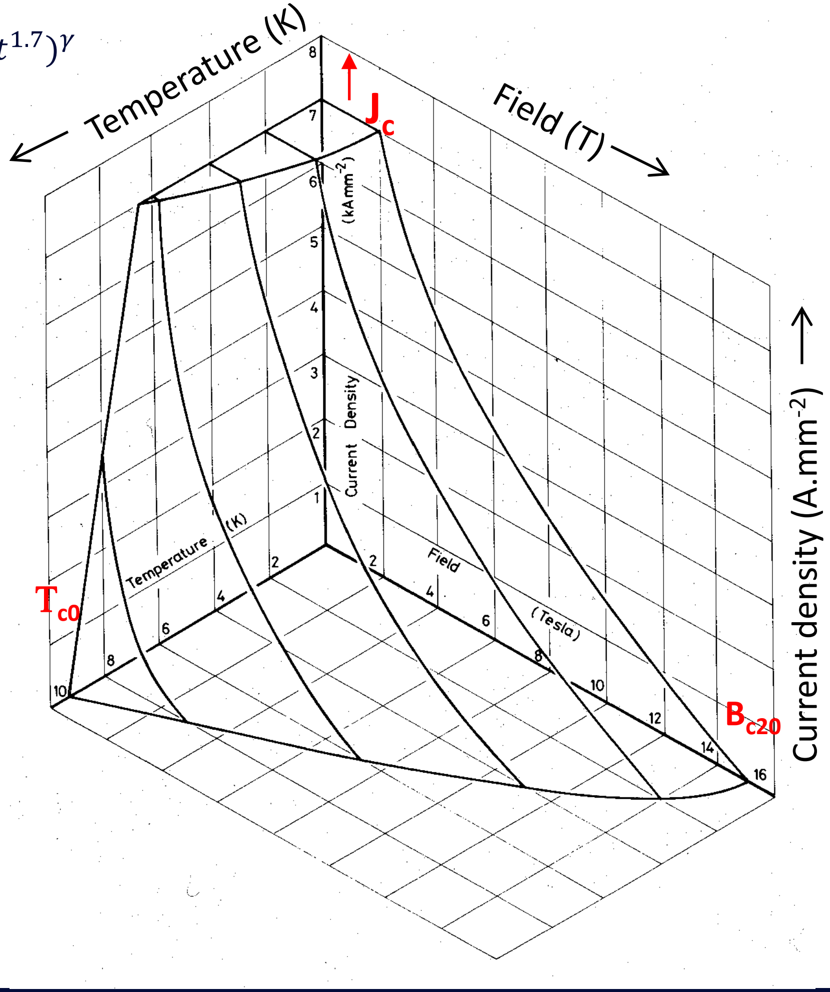
➡ Protection is critical

- The **NbTi critical surface** parameterization

$$J_c = \frac{C_0 J_{ref}}{B} \cdot b^{\alpha} \cdot (1-b)^{\beta} \cdot (1-t^{1.7})^{\gamma}$$

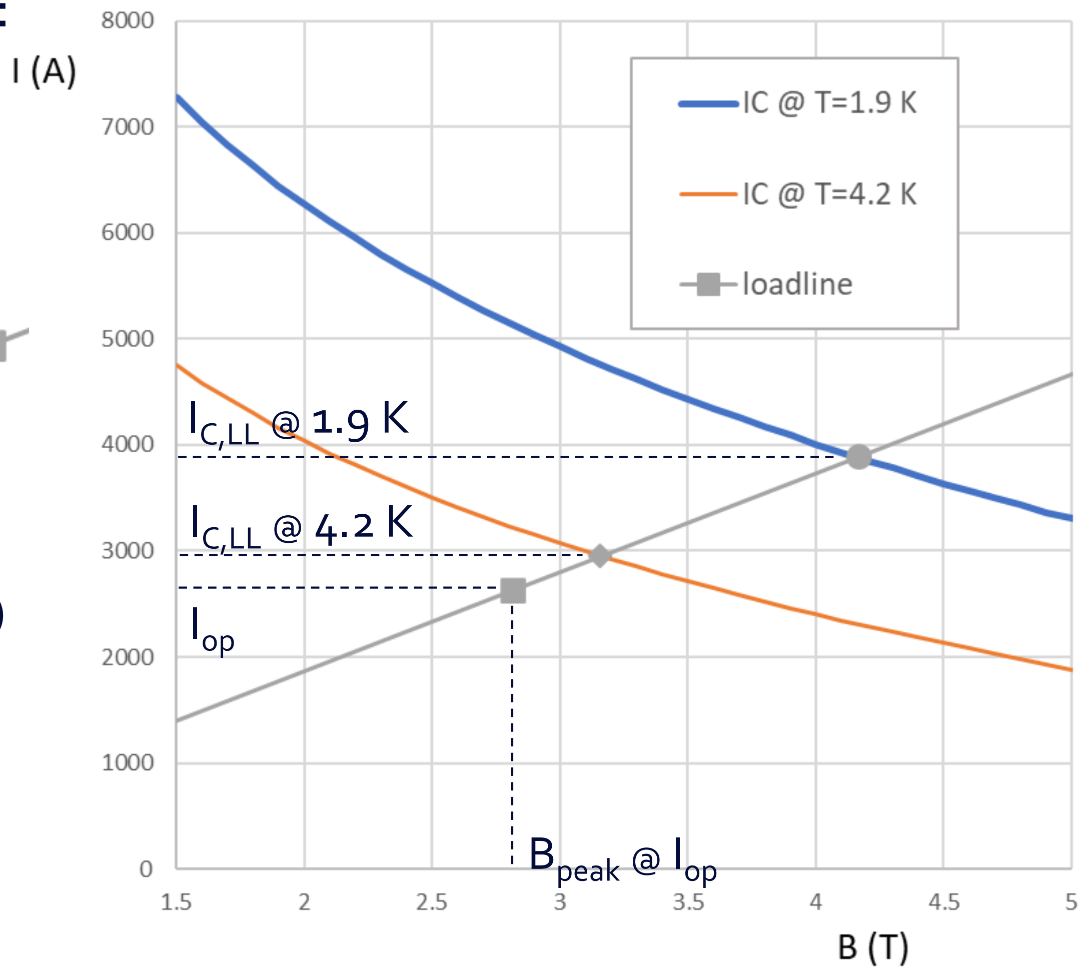
$$\begin{cases} B_{c2} = B_{c20} \cdot (1-t^{1.7}) \\ t \equiv \dfrac{T}{T_{c0}} \\ b \equiv \dfrac{B}{B_{c2}} \end{cases}$$

Parameters	
B_{c20}	14.5 T
T_{c0}	9.2 K
C_0	31.4 T
J_{ref} (4.2K, 5T)	3000 (A/mm²)
α	0.57
β	0.9
γ	1.9



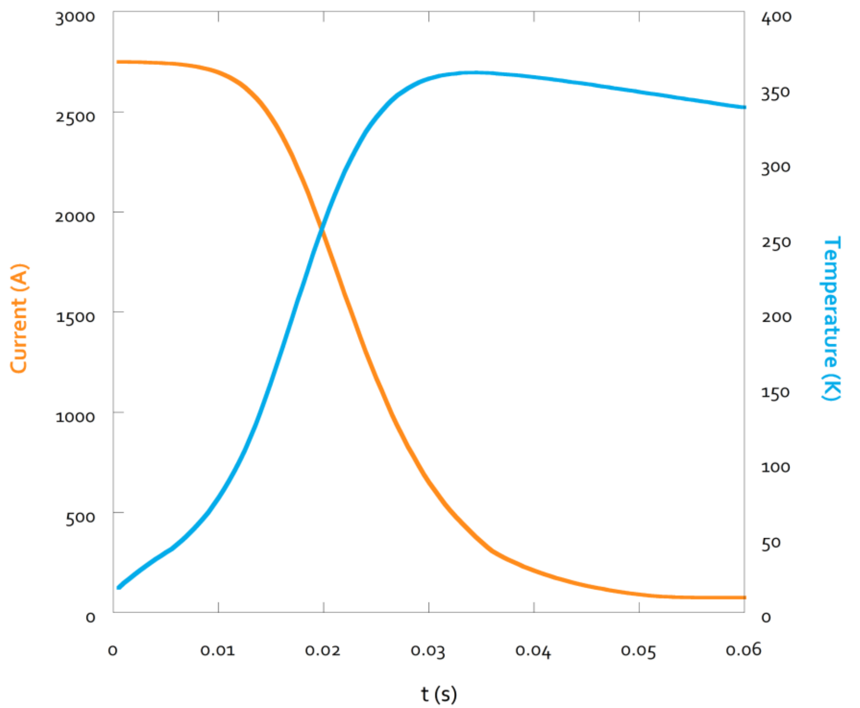
QDO working point and temperature margin

- An important concept for SC magnet is the loadline:
  - It represents the peak field at the conductors as function of the supplied current
  - In absence of permeable material (iron yoke), it is a straight line
  - B_{peak} at nominal current identifies the working point
  - $1 - \frac{I_{op}}{I_{C,LL}}$ is the **margin on the loadline**
- In our case B_{peak}=2.8 T and I=2626 A, then:
  - At T=4.2 K the margin on the loadline is 11% (too low!!)
  - At T=1.9 K the margin on the loadline is 33%
- The corresponding temperature margin are:
  - ΔT=0.6 K at T=4.2 K
  - ΔT=2.9 K at T=1.9 K



Potential quench issues

- Given the very high current density and low current and temperature margins, we hypothesized possible quench problems
- Very simple 1D quench analysis indicated possible hot spot temperature of 350 K, at the limit of safe operating conditions
- The heating effect of eddy currents in the mandrels (quench back effect) and persistent current was difficult to estimate reliably
- ➡ we decided to manufacture a model



current decay (orange) and temperature of the hottest point (blue) for a quench that starts at a given position and propagates to both sides

The quadrupole model

- To maximize the technical feasibility of the model, especially with regard to mandrel fabrication and winding, we landed on the following parameters:

Model characteristics	
Aperture	50 mm
Inner radius (r_1)	28.165 mm
Outer radius (r_2)	32.665 mm
Pitch (h)	8.5 mm
Number of turns	60
Bare conductor diameter	1.28 mm
Insulation thickness	0.125 mm
Gradient	50.4T/m
Current	2600 A
Tilt angle (θ)	14°
Physical length	919.5 mm
Stored Energy	2.46 J/mm

→ larger aperture (easier mandrel manufacturing and winding)

→ larger pitch (so that the minimum thickness of the “ribs” is $\gtrsim$ 0.5 mm)

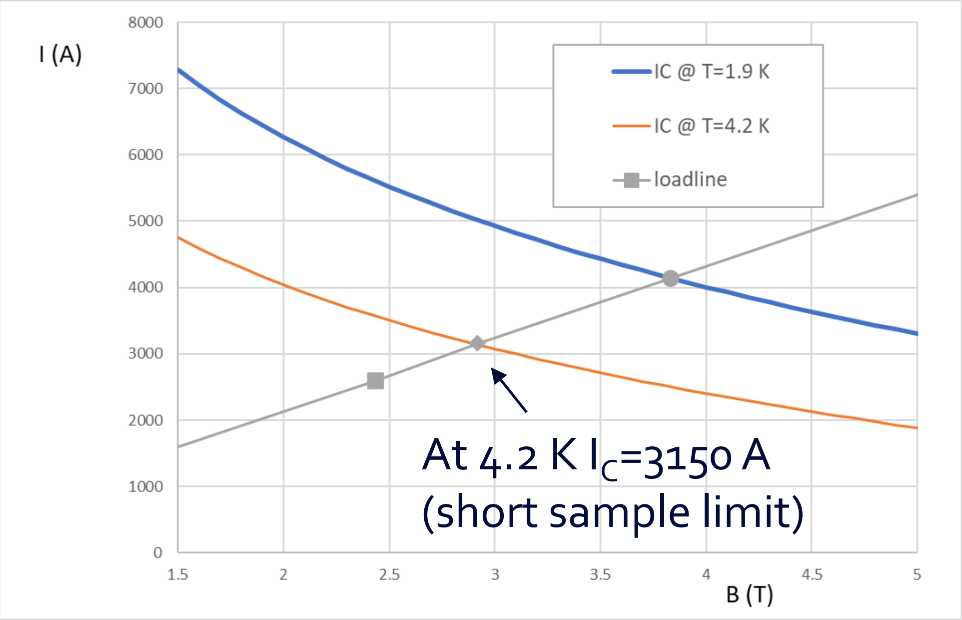
→ lower gradient (to reduce total stored energy)

→ same current (and same wire) to get that same (large) current density

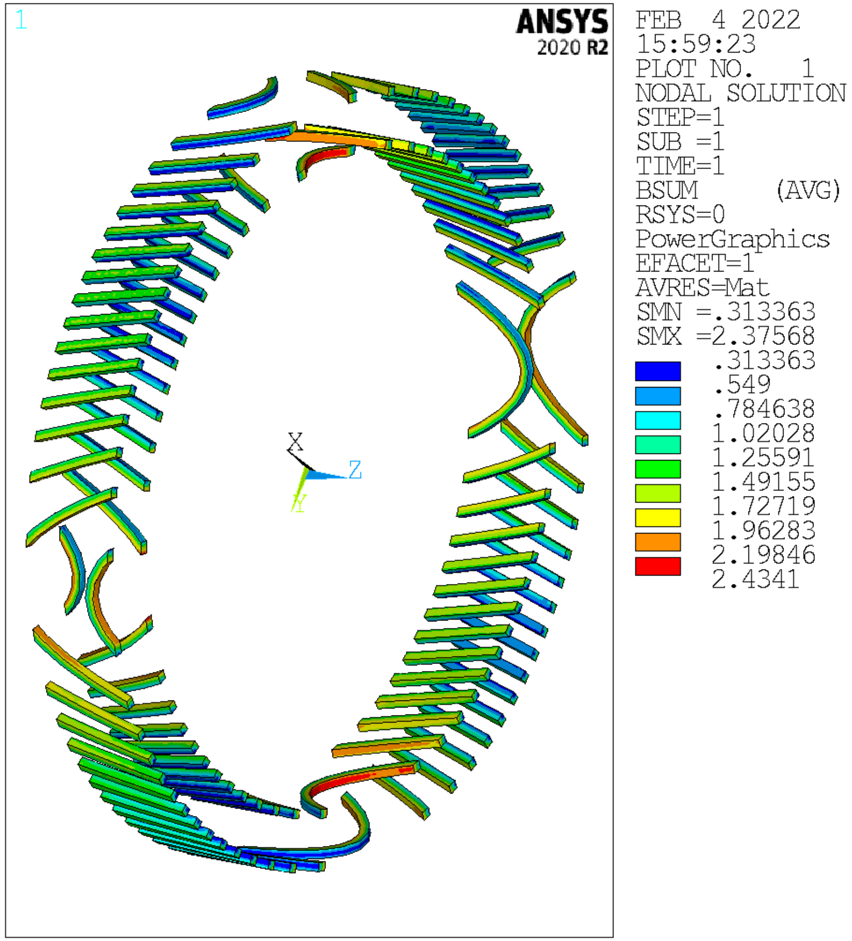
Quadrupole model margins

- Peak field of the quadrupole model is 2.43 T, leading to the following margins:
  - At T=4.2 K the margin on the loadline is 17% (still low)
  - At T=1.9 K the margin on the loadline is 37%

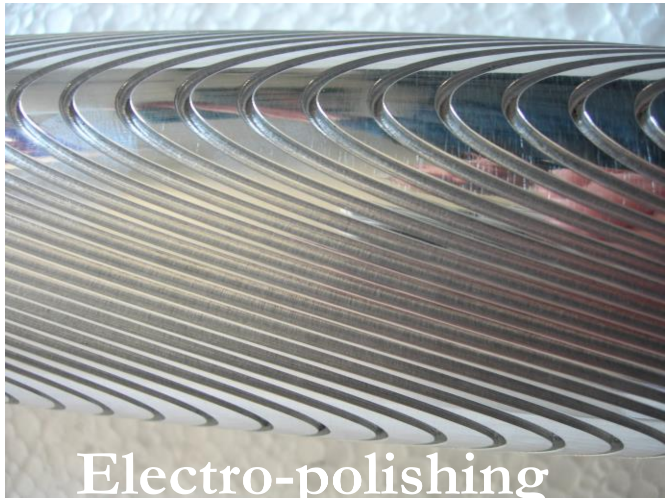
  - At T=4.2 K the temperature margin is 0.9 K
  - At T=4.2 K the temperature margin is 3.2 K

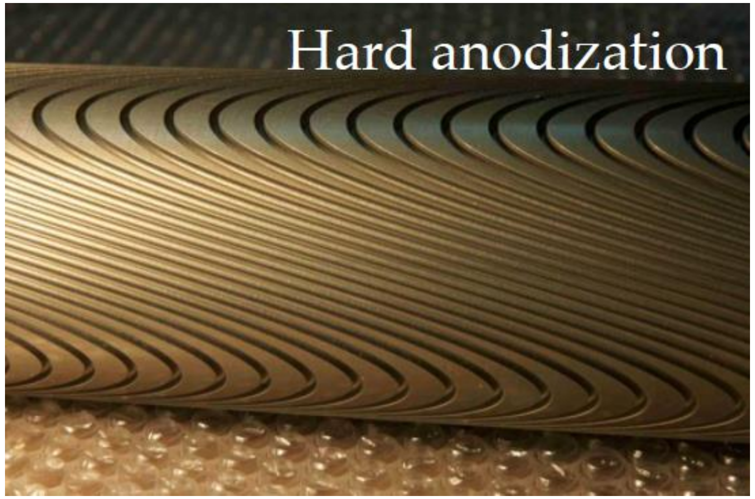


Electromagnetic FE analysis of quad model (T)

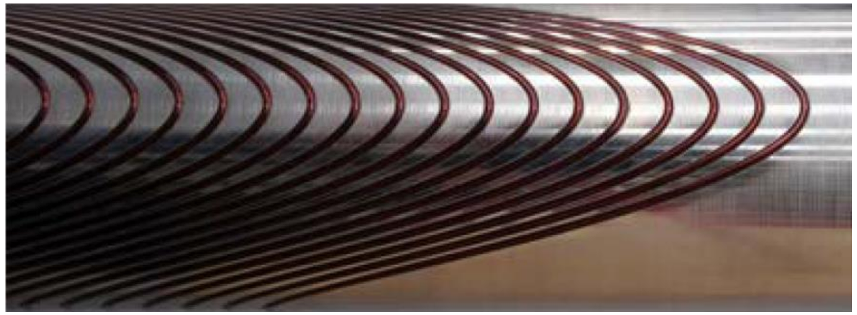


Mandrel manufacturing





- Al alloy 6063 had been chosen for its high thermal and electric conductivity at cryogenics temperature
- The grooves on the support cylinders were milled with a 4 axis CNC machine, then electro polished and anodized
- The NbTi wire was insulated with a polyester braid, deposited on the groove and kept in place by a layer of glass tape
- The two cylinders were then precisely coupled and epoxy impregnated

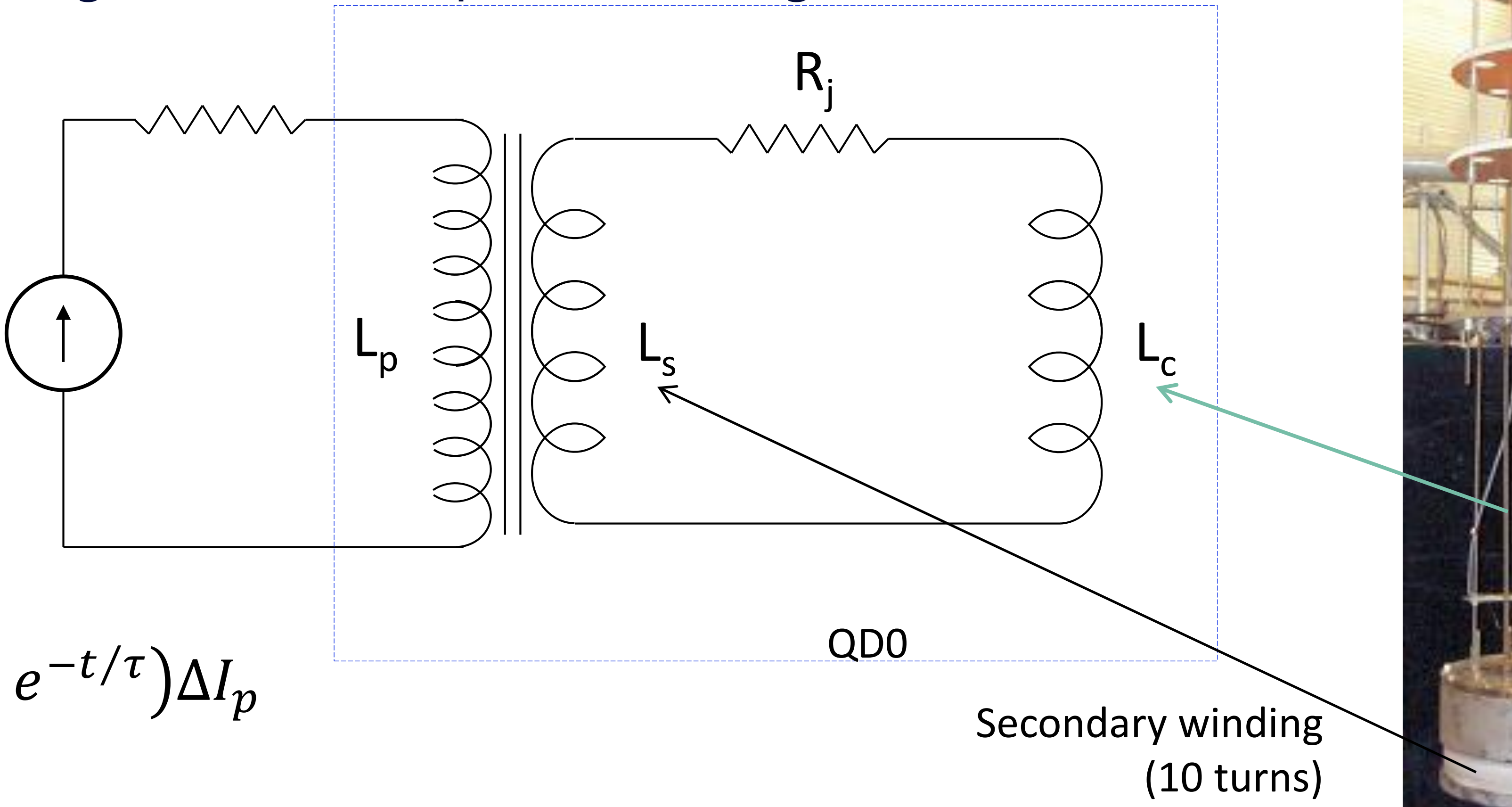


The supporting cylinder were manufactured at INFN-Pisa

The magnet was manufactured by ASG Superconductors Genova

Cold test of the quadrupole model

- The quadrupole is charged with the superconducting transformer
  - $L_p = 6.4$ H
  - $L_c = 670$ μH
  - $L_s = 90$ μH



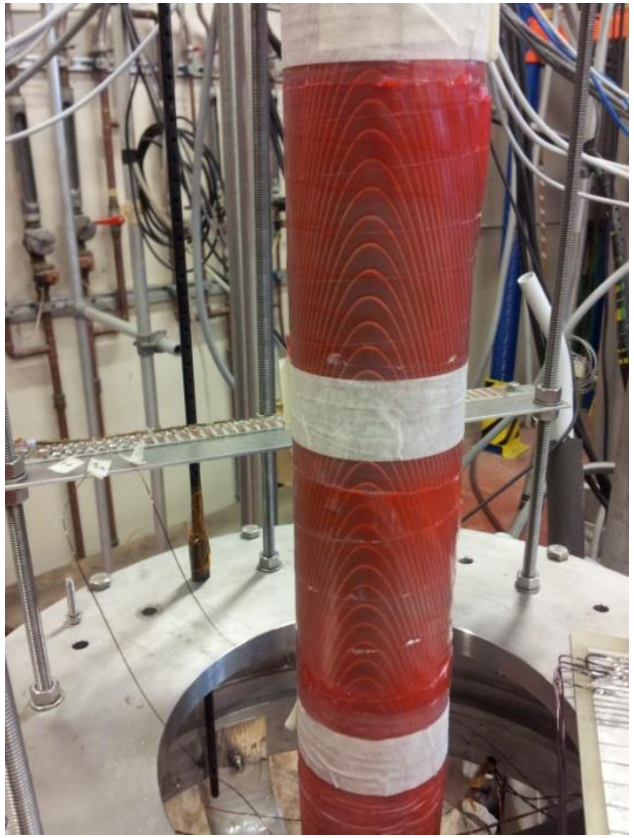
$$I_s = \frac{M}{L_s + L_c}\frac{\tau}{t}\left(1 - e^{-t/\tau}\right)\Delta I_p$$

Courtesy of R.Musenich

https://agenda.infn.it/event/4107/contributions/50233/attachments/35496/41902/Test_of_QD0.pptx

The test of the quadrupole model

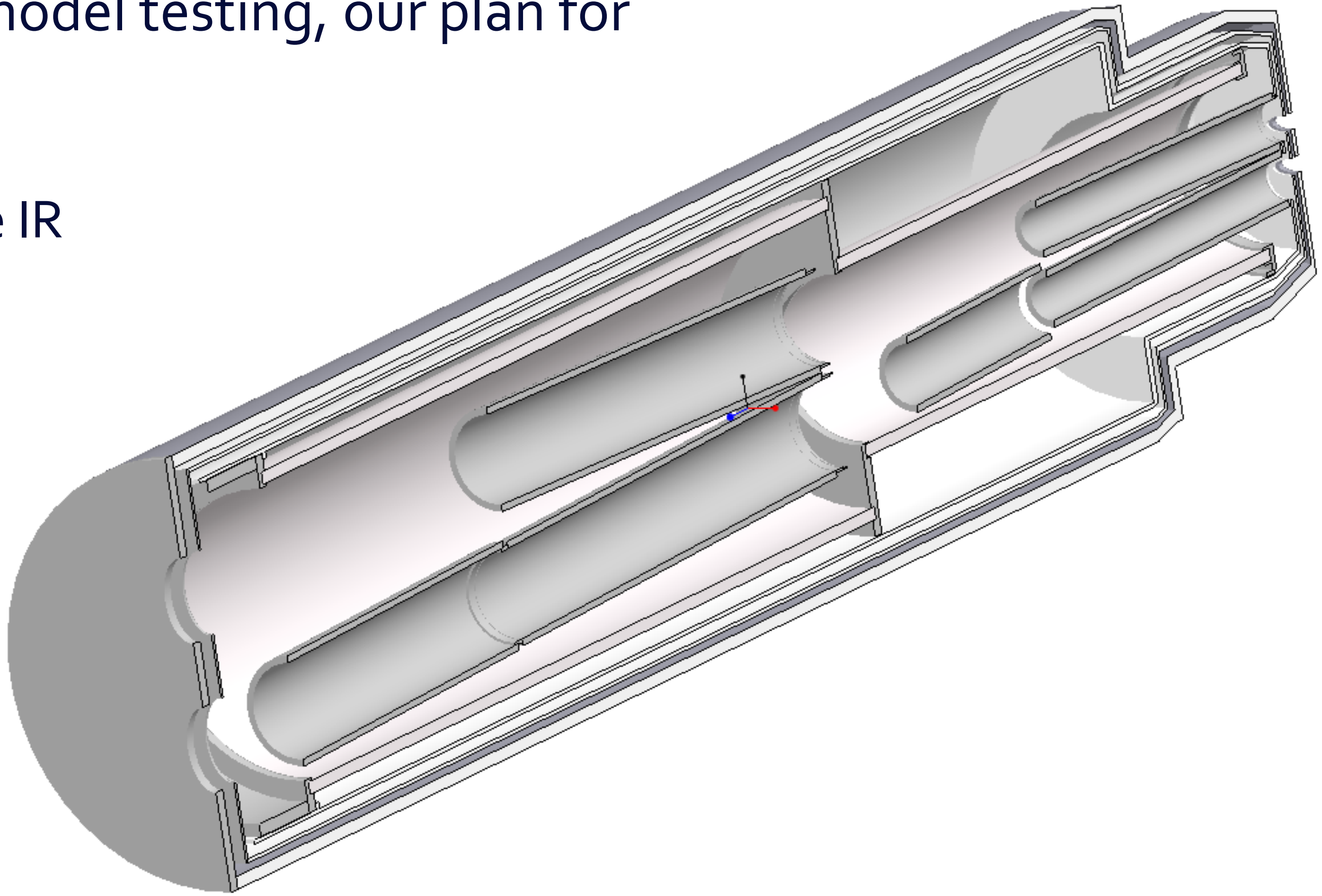
- The model was tested on Jan. 2012 @ 4.2 K in our laboratory (INFN-Genova) using the facility Ma.Ri.S.A.
- The measured magnet performances were better than expected:
  - after a few quenches, it reached 2830 A, i.e. **90% of the short sample limit**
  - After the quench, the quadrupole quickly restores the superconducting state and can be charged again
  - the magnet looks to be **self-protected** with no need of a quench detection activating a protection system



More information in F.Bosi *et al.*, DOI: 10.1109/TASC.2012.2231716

Where we were when the project was cancelled

- Given the promising results of model testing, our plan for the next future was to:
  - build a prototype of QDO
  - design the structure of the entire IR

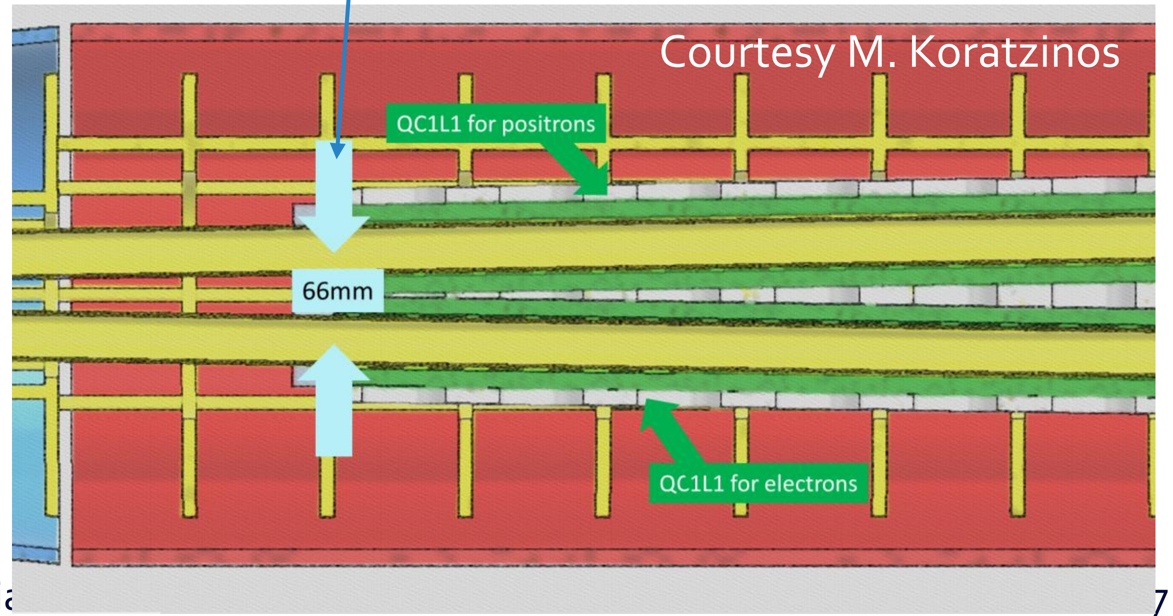


First sketch of the cryostat (370 mm OD). The suspension system (not yet studied) shall be design to hold high axial forces (4 t)

SuperB vs FCC-ee MDI region

- The dimensions and space availability of QC1L1 are very challenging but not unrealistic
- CCTs are the only viable solution
- Compared to QDO, wound with a single wire, it is a great idea to take advantage of the experience of G.Kirby's work in winding multiple wires in the same groove → reduce the current/strand
- **Quench analysis/considerations are necessary**
- **A cold test is fundamental for consolidating the design**

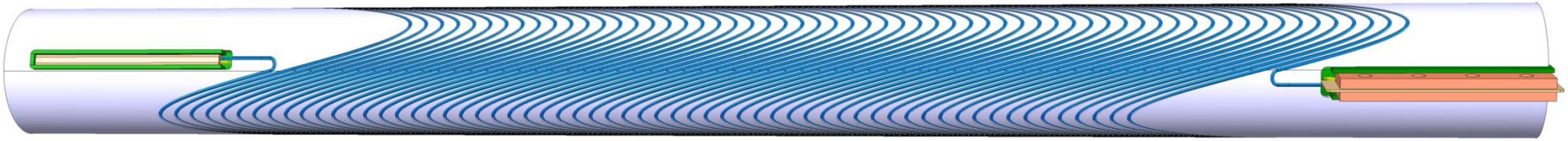
	QC1L1	QDO	QDO model
Aperture (mm)	40	35	50
Beam distance at IP face (mm)	66	63	–
Available thk for magnet (mm)	13	14	–



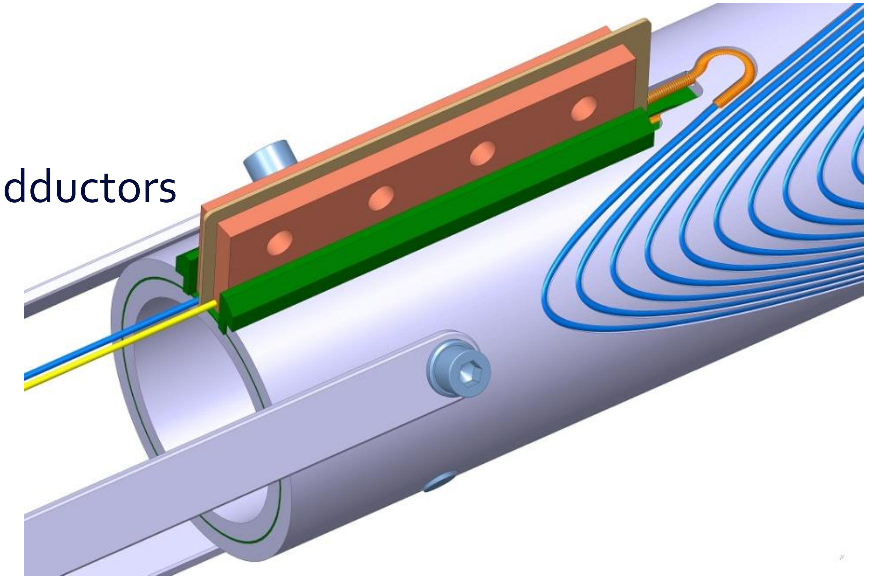
THANK FOR YOUR ATTENTION

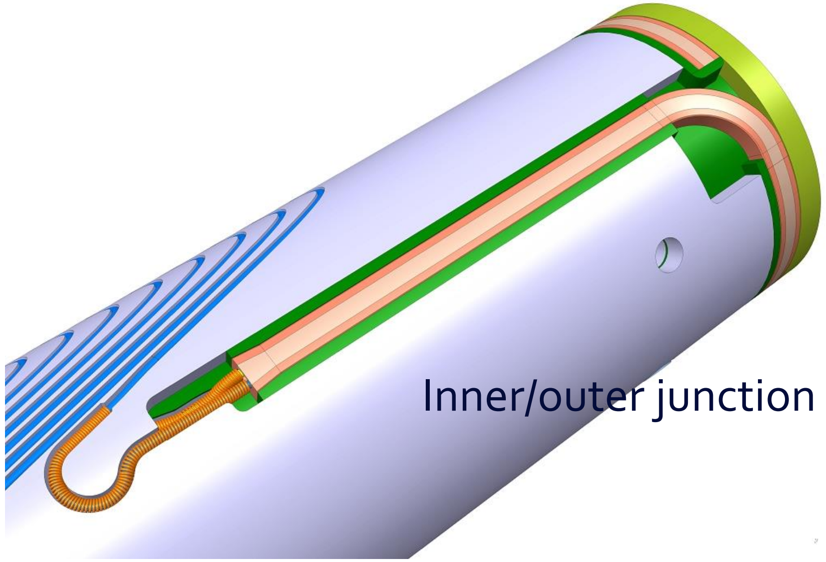
SPARES

The quadrupole model



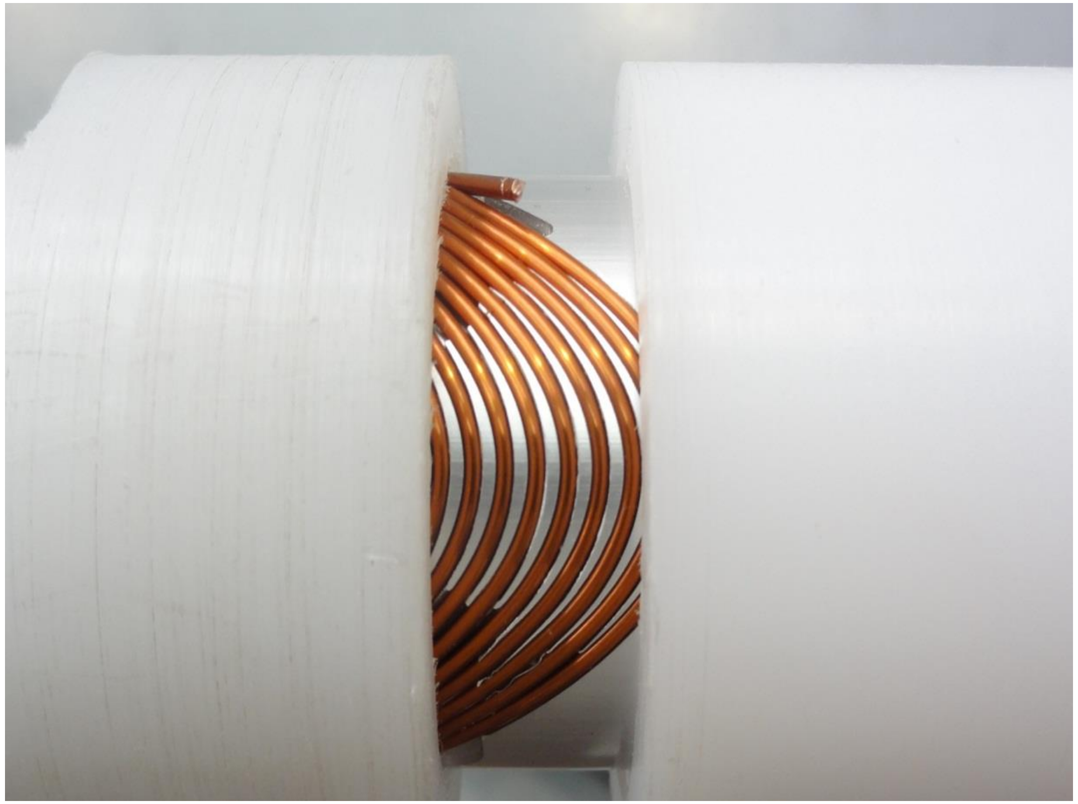
to current adductors

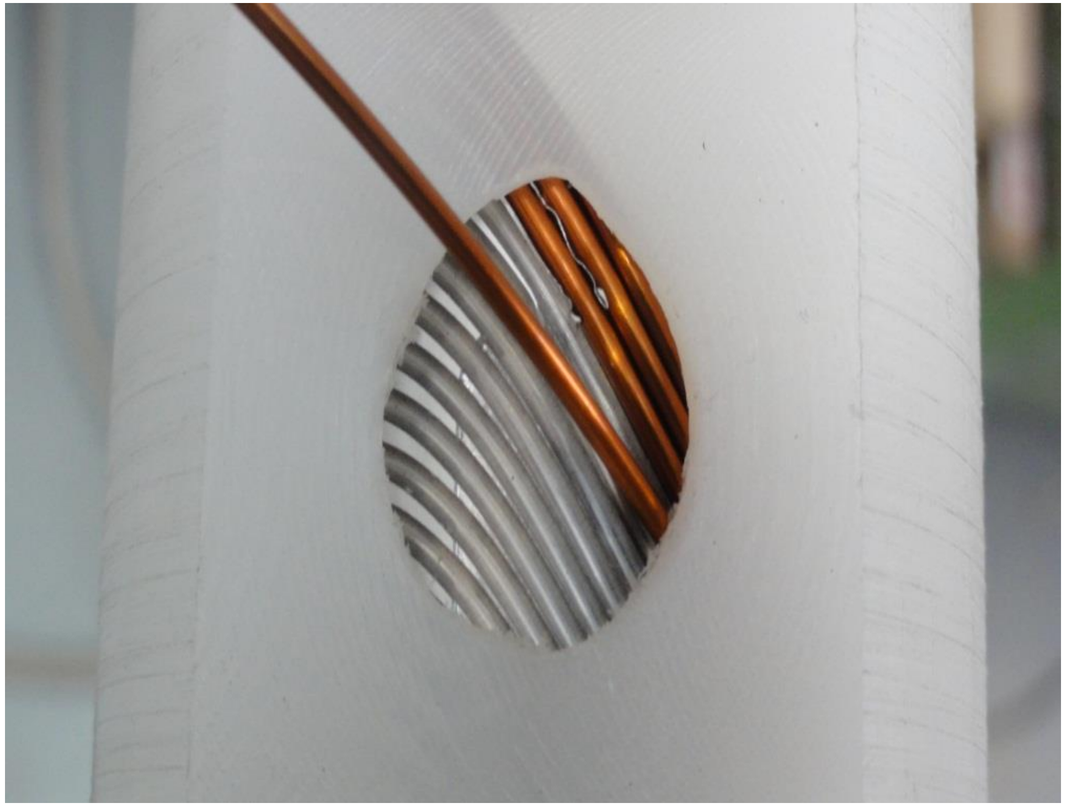




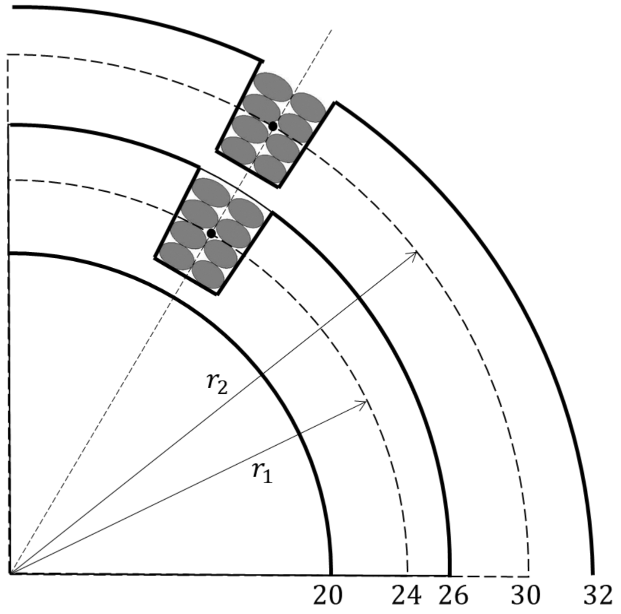
Winding test @ ASG Superconductors

- Too thin «ribs» create winding problems





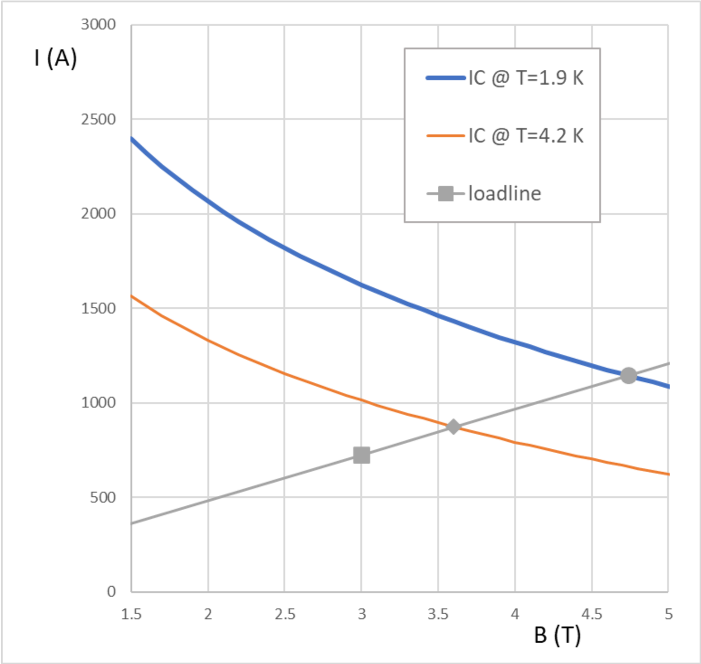
QC1L1-like quadrupole



$$G = \frac{\mu_0 I}{h}\left(\frac{A_1}{r_1^2} + \frac{A_2}{r_2^2}\right) = 93\ \text{T/m}$$

QC1L1-like quadrupole characteristics	
Aperture	40 mm
Inner radius (r_1)	24 mm
Outer radius (r_2)	30 mm
Pitch (h)	5 mm
Current	725x8=5800 A
Tilt angle (θ)	30°
Peak field	3 T

Strand characteristics	
Φ	0.825 mm
$R_{\text{cu-non Cu}}$	1.9
I_C(4.2K, 5T)	620 A



- At T=4.2 K the margin on the loadline is 17%
- At T=1.9 K the margin on the loadline is 37%
- At T=4.2 K the temperature margin is 0.95 K
- At T=4.2 K the temperature margin is 3.25 K

➡ Same as QDO model

Possible alternative design

4101604 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 22, NO. 3, JUNE 2012

BNL Direct Wind Superconducting Magnets

Brett Parker, Michael Anerella, John Escallier, Arup Ghosh, Animesh Jain, Andrew Marone, Joseph Muratore, and Peter Wanderer, *Member, IEEE*

***Abstract*—BNL developed Direct Wind magnet technology is used to create a variety of complex multi-functional multi-layer superconducting coil structures without the need for creating custom production tooling and fixturing for each new project. Our Direct Wind process naturally integrates prestress into the coil structure so external coil collars and yokes are not needed; the final coil package transverse size can then be very compact. Direct Wind magnets are produced with very good field quality via corrections applied during the course of coil winding. The HERA-II and BEPC-II Interaction Region (IR) magnet, J-PARC corrector and Alpha antihydrogen magnetic trap magnets and our BTeV corrector magnet design are discussed here along with a full length ILC IR prototype magnet presently in production and the coils that were wound for an ATF2 upgrade at KEK. A new IR septum magnet design concept for a 6.2 T combined-function IR magnet for eRHIC, a future RHIC upgrade, is introduced here.**

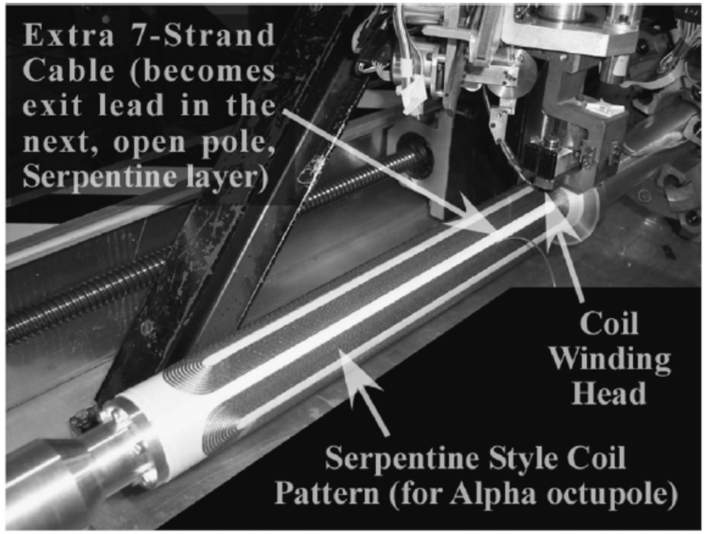


Fig. 1. BNL direct wind production of a serpentine style octupole coil.