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Design of radiation hard spare units for the orbit corrector dipoles of LHC

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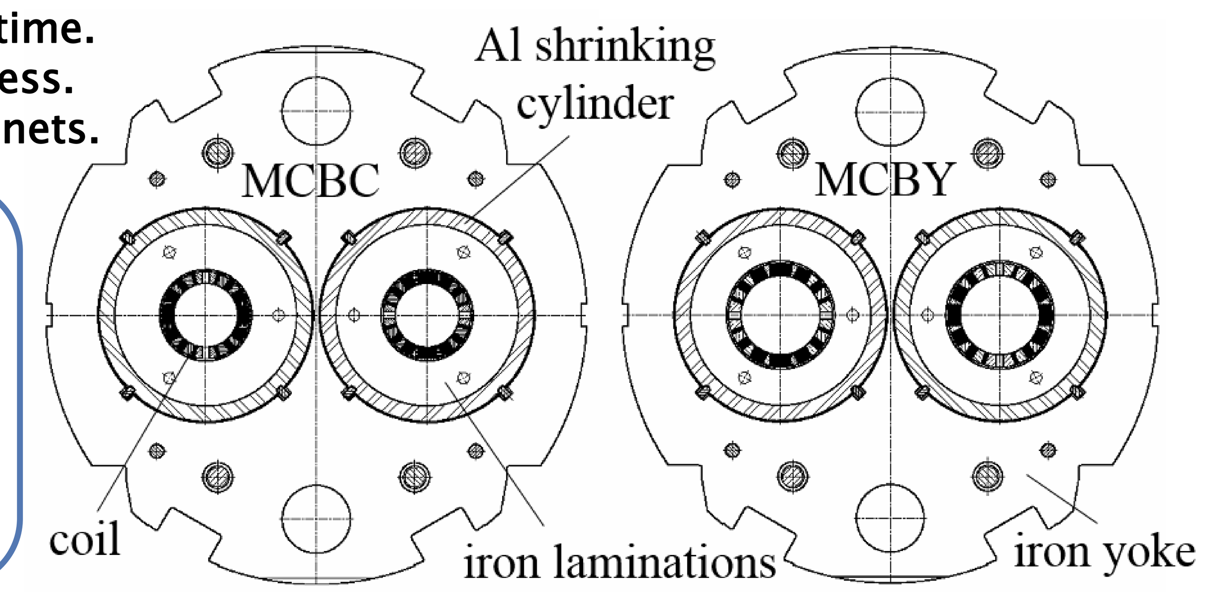
Context

Due to the HL-LHC upgrade, the Nb-Ti orbit corrector dipoles (MCBC and MCBY) will receive significantly increased gamma radiation doses, i.e. up to 20 MGy over the HL-LHC lifetime. These magnets, essential to the LHC operation, were not designed to withstand such doses; we have thus started a gamma radiation campaign to determine their radiation hardness. In addition, since the available spare magnets are limited in number and not radiation resistant, we have also designed radiation hard versions of the present MCBC and MCBY magnets.

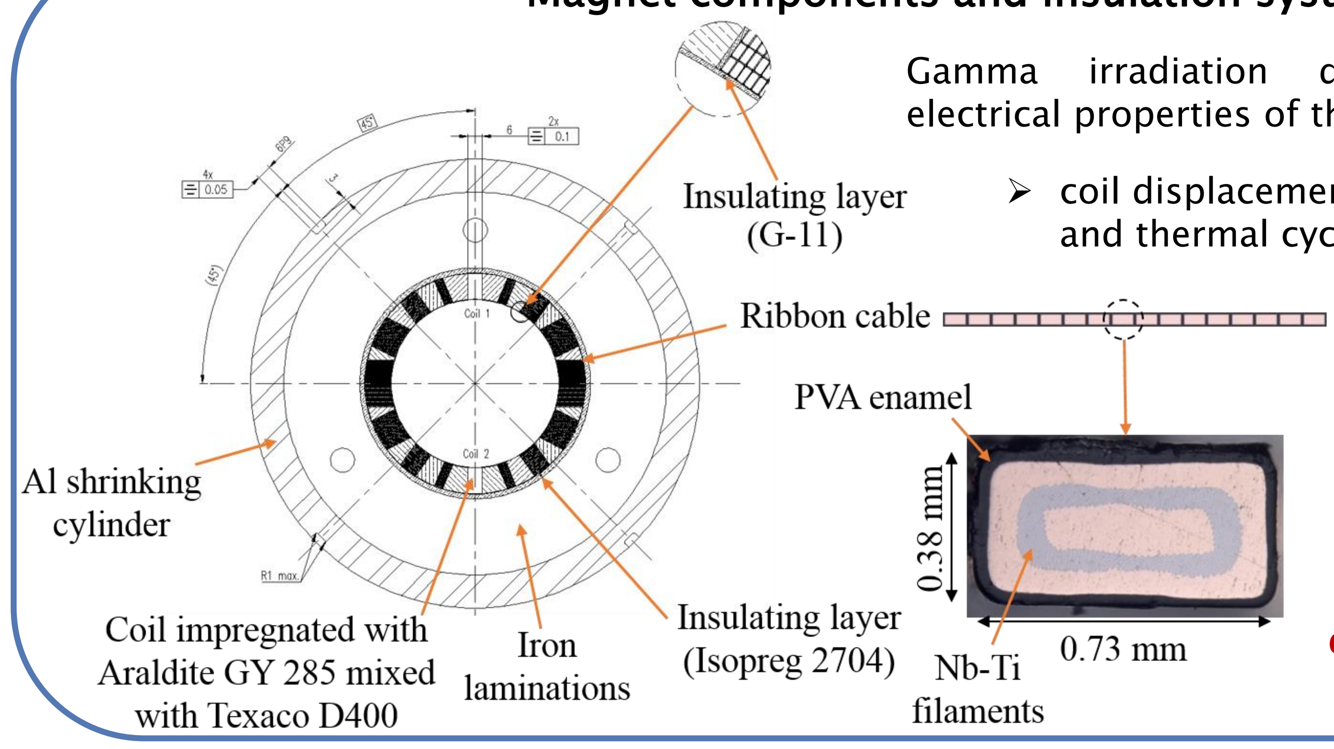
	Coil bore diameter	Overall length	Magnetic length	Operating temperature	Nominal current	Nominal bore field	Peak field on conductor	Percentage along load line	Self-inductance	Stored energy
MCBC	56 mm	1100 mm	904 mm	1.9/4.5 K	100/74 A	3.11/2.33 T	3.65/2.68 T	58.1/58.3 %	2.84 H	14.2/7.8 kJ
MCBY	70 mm	1100 mm	899 mm	4.5 K	72 A	2.5 T	2.96 T	60.0 %	5.27 H	13.7 kJ

Number of MCBC / MCBY magnets		Integrated luminosity at the end of HL-LHC in 2038	
		2850 fb^{-1} (nominal)	4300 fb^{-1} (ultimate)
Gamma dose	1 MGy	20 / 12	20 / 12
	5 MGy	6 / 0	20 / 12
	10 MGy	6 / 0	6 / 0
	20 MGy	0 / 0	2 / 0



Gamma radiation hardness of present magnets

Magnet components and insulation systems



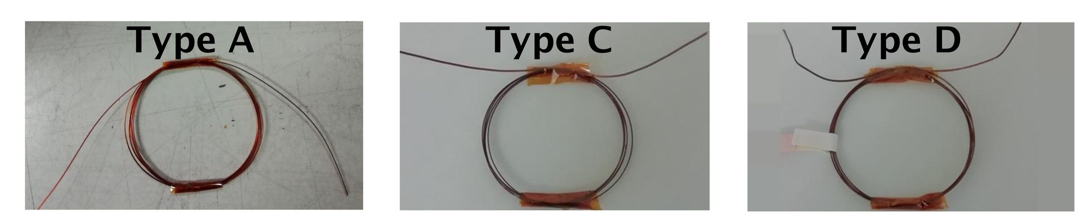
Gamma irradiation degrades mechanical and electrical properties of the organic materials

- coil displacement during operation, powering and thermal cycles
- quench triggering
- electrical arcing
- field quality deterioration

→ Gamma radiation can damage the coil and degrade magnet performances

Gamma irradiation campaign

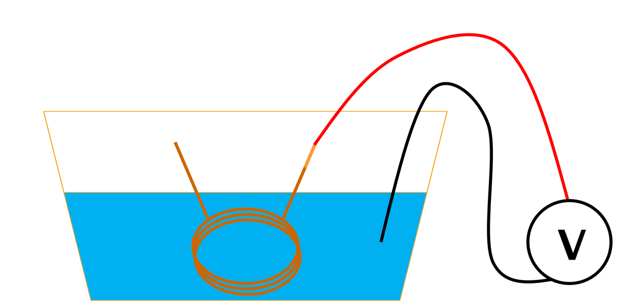
Gamma irradiation with ^{60}Co source at BGS facilities (Germany)



LHC spare wire (PVA enamel) | Supercon Inc wire (polyimide) | Type C + Araldite 2011 (ribbon glue)

Average breakdown voltage after irradiation	Type A	Type C	Type D
0 MGy	1.5 kV	3.2 kV	4.1 kV
1 MGy	2.4 kV	–	–
2.5 MGy	<10 V	2.8 kV	4.2 kV
5 MGy	–	3.8 kV	2.9 kV

Breakdown voltage tests after irradiation of LHC spare wire (A) and candidate wire (C, D), all samples withstood 1 kV before irradiation



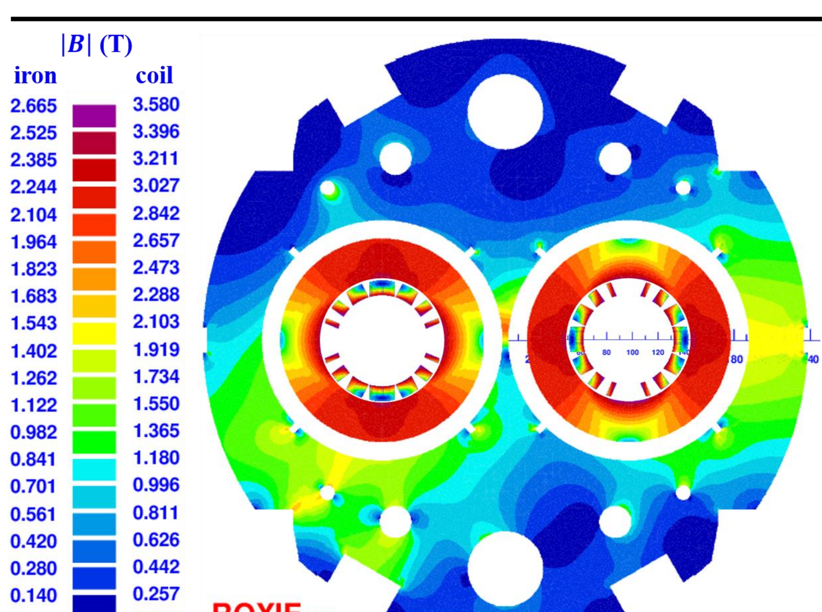
→ LHC spare wire resists between 1 and 2.5 MGy
→ Candidate wire resists more than 5 MGy
→ Tests performed under conservative conditions

Upcoming gamma radiation campaign:

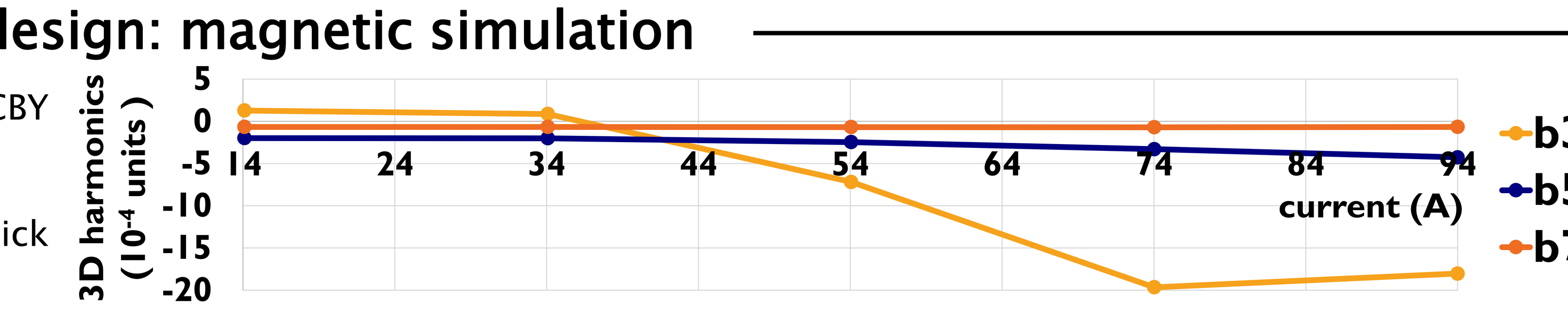
- Ribbon cables irradiated under more representative conditions (impregnation and He atmosphere)
- Additional samples to test the other magnet components: cuts of old pre-series MCBC coil and Isopreg 2704
- Irradiation up to 2.5, 5 and 10 MGy
- Post-irradiation breakdown voltage and mechanical tests will be performed

→ will help to better estimate the radiation hardness of the present magnets

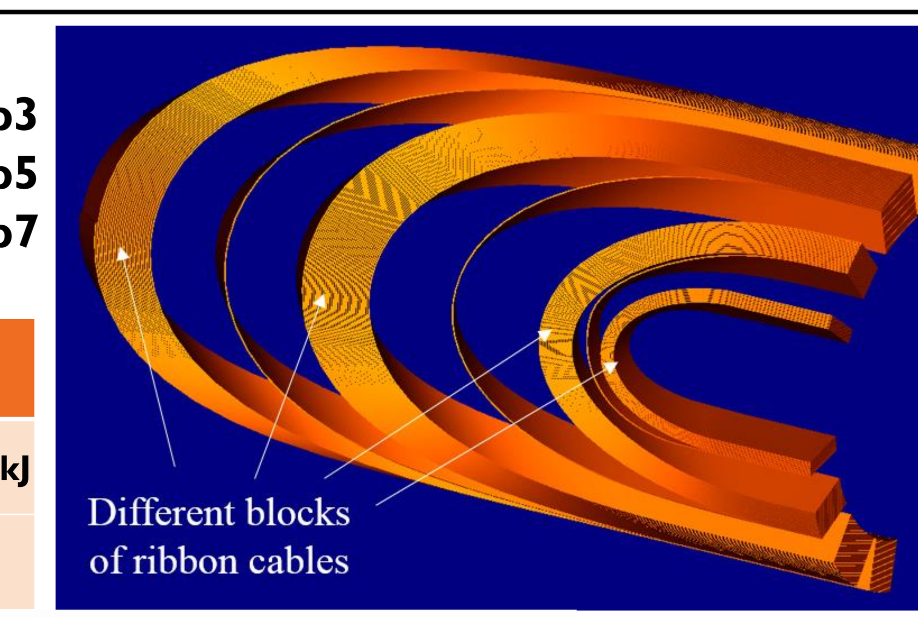
Radiation hard design: magnetic simulation



- Common design (based on MCBY) for the radiation hard spare units of MCBC and MCBY magnets to reduce the manufacturing cost (called MCBYR and MCBY* respectively)
- Compared to MCBC, the larger aperture of MCBYR allows to place a 7mm-thick tungsten shield to increase the protection against radiation
- Re-optimization of the coil ends with present ROXIE algorithm to control the cable mechanical strain in the coil ends and the magnetic field quality along the magnet

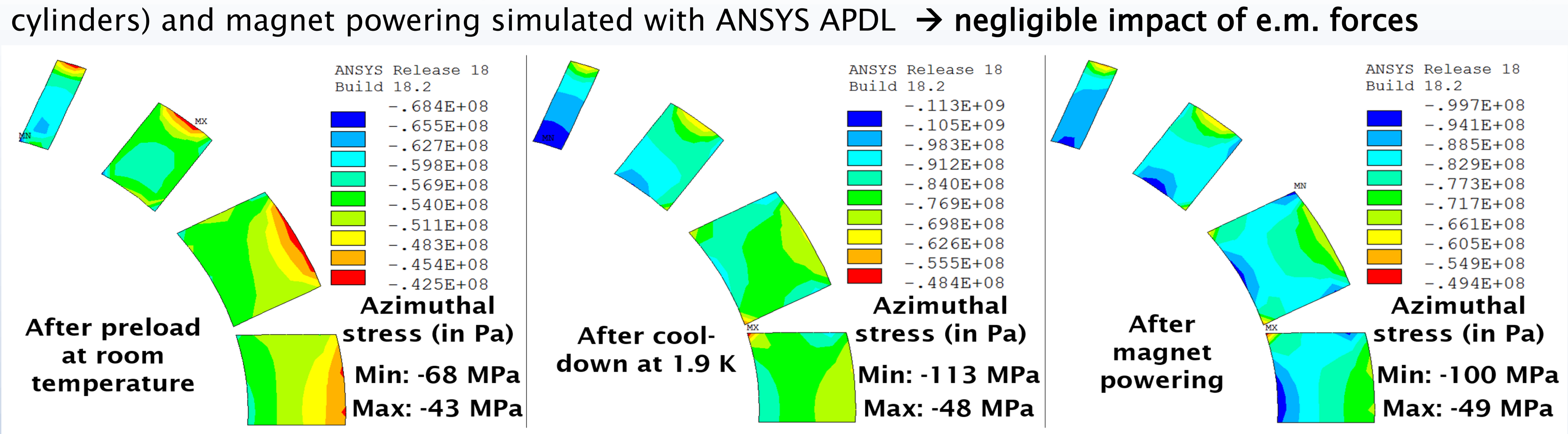


	Coil bore diameter	Overall length	Magnetic length	Operating temperature	Nominal current	Nominal bore field	Peak field on conductor	Percentage along load line	Self-inductance	Stored energy
MCBYR	70 mm	1100 mm	880 mm	1.9/4.5 K	94/70 A	3.18/2.35 T	3.63/2.69 T	56.23/57.37 %	4.69/4.87 H	20.7/11.9 kJ
MCBY*	70 mm	1100 mm	880 mm	4.5 K	74 A	2.56 T	2.92 T	61.76 %	4.86 H	13.3 kJ



Mechanical simulation

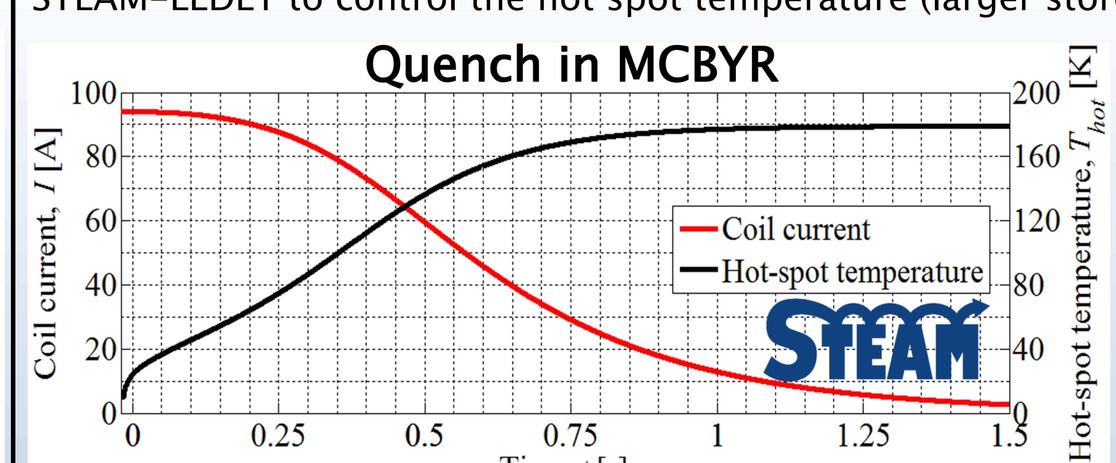
Azimuthal stress in **MCBY** after preload (scissors laminations), cool-down at 1.9 K (aluminum shrinking cylinders) and magnet powering simulated with ANSYS APDL → **negligible impact of e.m. forces**



→ Stress levels will still be within acceptable limits for MCBYR and MCBY*

Quench simulation

2D quench simulation of **MCBYR** with 80mΩ crowbar resistance performed with STEAM-LEDET to control the hot spot temperature (larger stored energy than MCBY)



- Longitudinal quench propagation velocity taken into account to evaluate the resistive growth
- Adiabatic hot spot temperature ~180 K

→ Quench protection scheme suitable for MCBYR and MCBY*

Alternative CCT design

A Canted Cosine Theta (CCT) design, similar to MCBRD, with a 500A polyimide-insulated conductor has been developed

- mechanically robust and radiation hard
- cost reduction for a few units
- individual quench protection system needed (larger stored energy)
- conductor development to reach MCBYR nominal current required

3D printed coil support models

Conclusion

We have presented the results of a radiation test campaign on LHC wire and candidate materials for wires for MCBC and MCBY magnets.
We have started a wider radiation campaign to determine the gamma dose that these magnets can safely absorb to anticipate the number of units that will need to be replaced.
In parallel, we have designed radiation hard spare versions of the MCBC and MCBY magnets involving technology modifications (polyimide, tungsten shield) with respect to their original designs.
In addition, we have performed integration, mechanical and quench protection studies that have confirmed the viability of these designs in the same technological environment than the present MCBC and MCBY magnets installed in LHC.