Design review for the LHC-BGI magnets

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Introduction

- The **Beam Gas Ionization** (BGI) monitor is a non-invasive instrument for **measuring transverse beam profiles**. Building on the success of BGI devices currently operational in the PS and tested in the SPS, the high potential of this technology has been well demonstrated. In the **2022** review, **BGI was selected as the baseline profile monitor** for the High Luminosity LHC (HL-LHC).
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- To meet the stringent operational requirements—achieving a transverse profile measurement accuracy within 2.5% and an emittance error below 5%—the **new Timepix-based** BGI requires a **magnetic field of 0.6T**. This marks a significant improvement over the older MCP-camera-based BGI, which operated at only 0.2T, making the reuse of existing magnets unfeasible.
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- With the increased magnetic field, operational considerations necessitate **an integrated B-field of zero** to maintain a closed orbit and avoid transverse offsets. To achieve this, **a triplet configuration** was chosen, consisting of one main magnet and two trims.
- Working within a constrained budget, the project has prioritized **cost optimization** by recycling **existing power converters**, **magnets**, and **infrastructure** wherever possible. Alternatives, including permanent magnets 3 in 1 magnet and MDX doublet configuration, were thoroughly evaluated before finalizing **the triplet configuration**, which requires a **new main magnet for each instrument.**
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- In total, **four instruments** will be deployed—one for each transverse plane of the two LHC beams—ensuring precise and reliable beam profile monitoring for the HL-LHC.

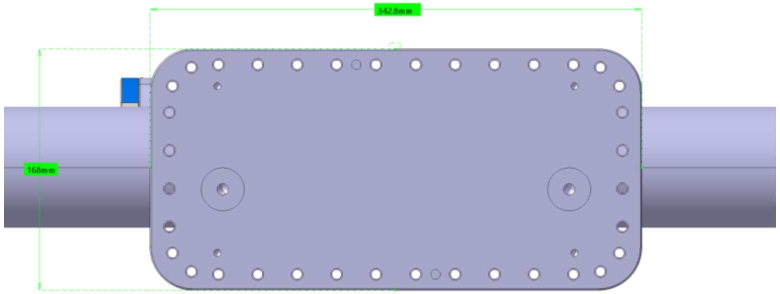
BGI-LHC Technical requirements

- 4 Beam Gas Ionization detectors in total are located in Point 5: **2 in 5R4, 2 in 5L4**.
- 2 configuration are used: One with a **horizontal** field and one with a **vertical** field per beam.
- A setup consist of 1 BGI magnet and 2 “field cancelling” trim magnets located 1 upstream and 1 downstream of the BGI magnet so they cancel the B field between the **three magnets together**. **The upstream and downstream magnets** provide each of them **half** of the **integrated B** field of the BGI magnet.
- The requested B Field in the detector gap is **0,6 T**, the Good Field Region is defined as a volume within the magnet center of X,Y,Z: 30 x 50 x 30 mm with Y offset of 1,5 mm.
- The field quality is defined as **DB/B <1 e^{-3}** in the defined volume above.
- The **magnet gap is 140** mm as a result of the instrument size and related vacuum chamber and assembly clearance (see Fig. 1, 2 and 3).
- The magnet design shall accommodates with the environment constraints defined by the machine layout, where basically the adjacent beam pipe and the QRL limits the transverse space (see fig. 4 to 7).
- **Easy access to the detector** is needed requesting the BGI magnet to be movable in the longitudinal axis of 210mm + clearance= minimum 300 mm.
- Operating power converter parameters:
  - BGI magnet converter: **600A, 40V**, 1 unit per BGI magnet, already available.
  - Trim magnets converters: 4 units available **of 125A and 125V**, presently in operation.
- Available cooling water: P=11 bars, DP 8 bars, inlet temp= 27 °C. (1/2” piping)

BGI-LHC Technical requirements

Designs overview

OPTION 4: LHC-BGI RECT INSTR & RECT CHAMBER ASSBLY - TPX3



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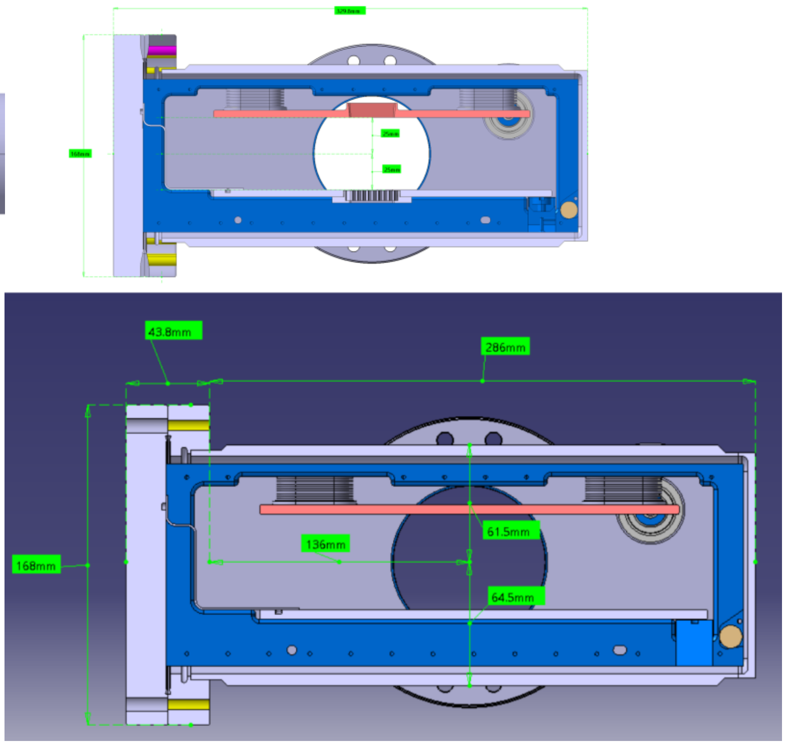
Detector: TPX3

Envelope ~ 180 mm x 352 mm x 355 mm

RF requirements:

- SPS-BGI type

Fig.1 instrument chamber size side view



Beam vertical offset +1,5 mm

Fig.2 & 3 instrument chamber size cross section

Magnet integration and layout

The configuration of the magnets is the following: **2 MDX magnets (in grey)** are set on each side of the **BGI magnet (in green)**. Identical distance between each magnet during operation is ensured for symmetry purposes. To **access** the instrument the BGI magnet is **slided longitudinaly** thanks to movable supporting devices recovered from the previous setup and to be adapted especially for the downstream MDX magnet.

5L4 configuration top view:

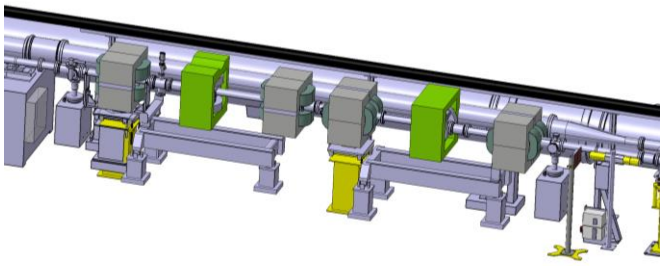


Fig.4 Operating configuration

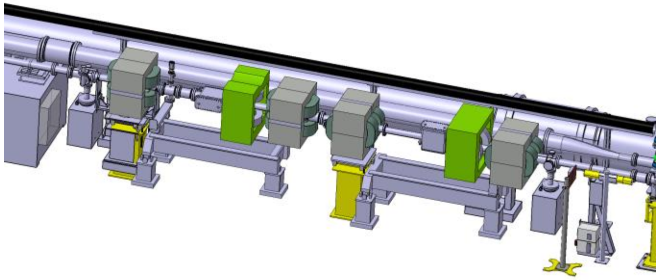


Fig.5 Instrument access configuration

5R4 configuration top view

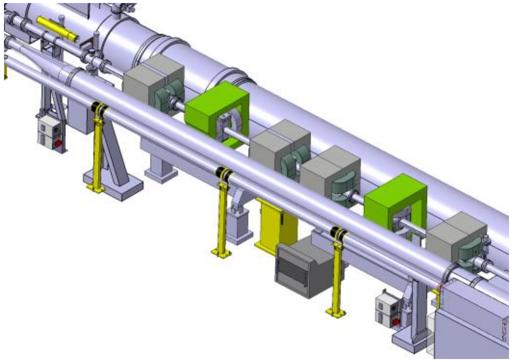


Fig.6 Operating configuration

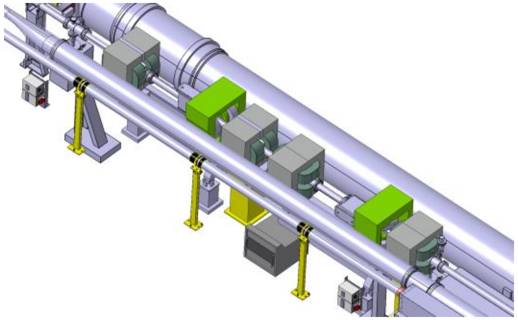


Fig.7 Instrument access configuration

Magnet integration and layout

The BGI **magnet yokes** are shaped so that they **do not interfer** with the adjacent equipment. It allows installation / removal with vertical lifting devices such as crane.

5L4 configuration top view:

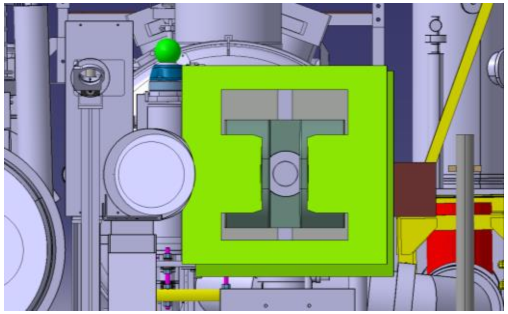


Fig.8 Horizontal field configuration

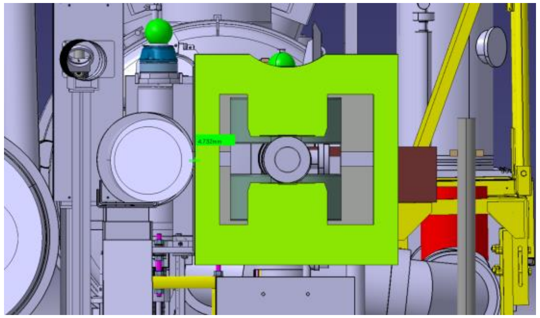


Fig.9 Vertical field configuration

5R4 configuration top view

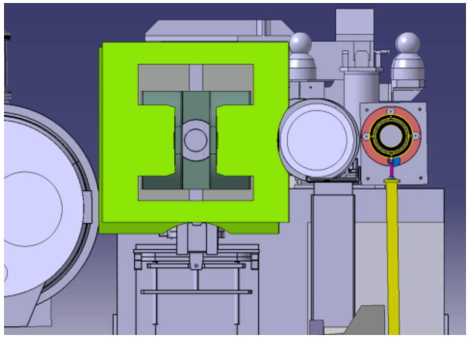


Fig. 10 Horizontal field configuration

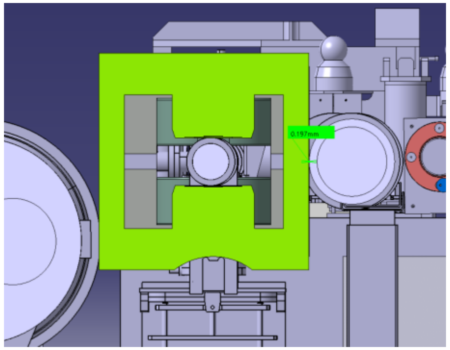


Fig.11 Vertical field configuration

BGI magnet design proposal

- The BGI magnet used to generate the B field to the beam instrumentation is **a H window solid yoke with cylindrical pole** shape made of ARMCO ©. The magnet design fits to the **4 configurations**. 2 ring like coils are used to optimize the electrical resistance w.r.t. the converter performances. The optimization of the **pole profile is tape**red on the last 30 mm and has a radius of 1000 mm on the pole tip corresponding to the best field homogeneity in the defined Good Field Region. **The pole offset is 4 mm** due to the R 1000 mm radius. **70562 amperes turns provides 0,6T** in the magnet gap at **485 amperes**. The **magnetic efficiency is 94,7%.** The return yokes are asymmetrical due to space constraints mainly due to the detector instrumentation supply and measurement cables.

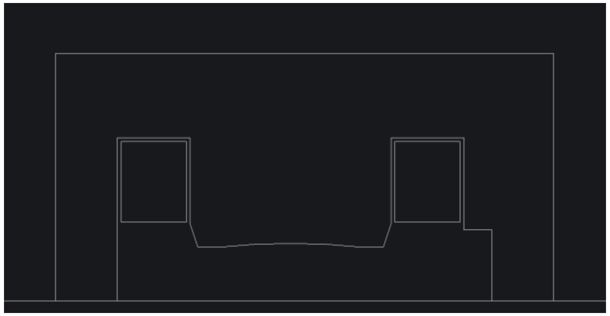


Fig.12 2D drawing with instrument integration

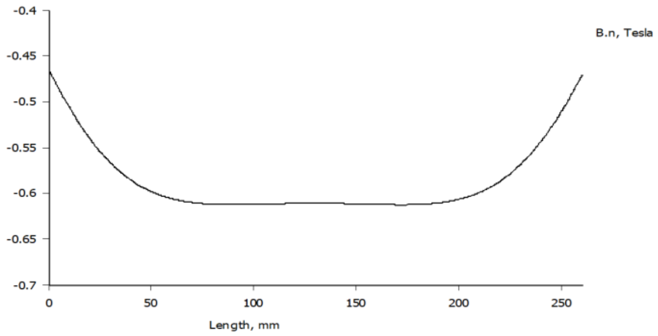


Fig.14 B field in transverse axis

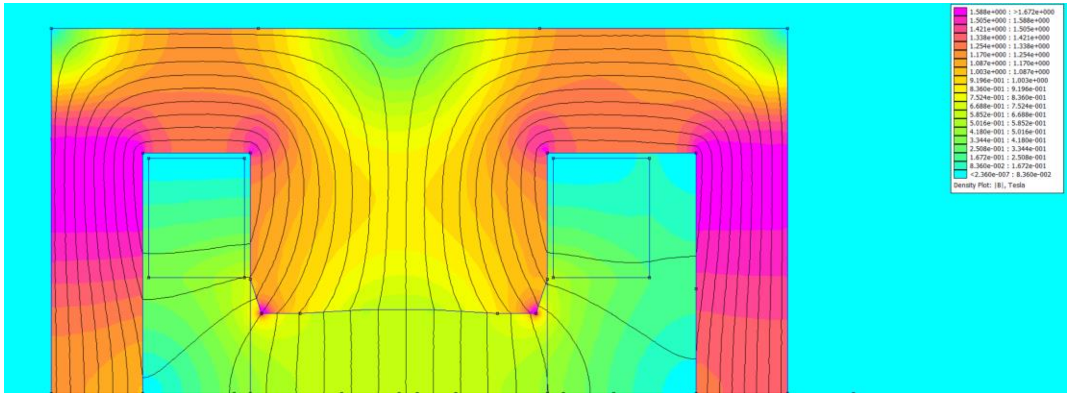


Fig.13 2D FEMM magnetic simulation

BGI magnet design proposal

- The pole **outer radius is 130 mm**. The **yoke length is larger** than the pole tip **by 60** mm en each side to reduce iron saturation by 120 mm. Small area on the yoke has a magnetic field of 1,6T (see Fig.17). The **field homogeneity** is dependent of the vertical position By (see Fig.16). The **optimization of the pole tip** with a **1000 mm radius** allowing the By field to **be 4 e^{-4} and 6,5 e^{-4} within the 1 e^{-3}** in the defined volume of x=30, y=56 (including the offset), z=30 mm.

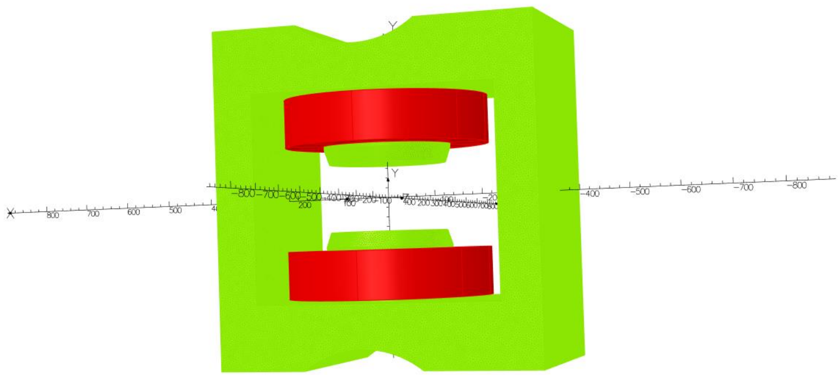


Fig.15 3D model of the BGI magnet

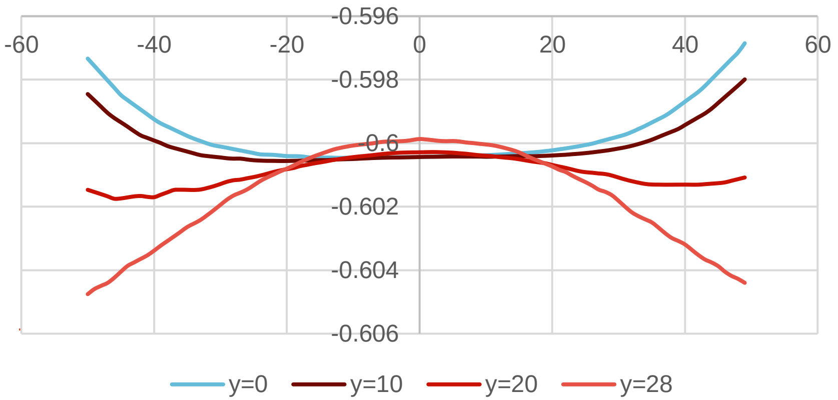


Fig.16 3D model of the BGI magnet

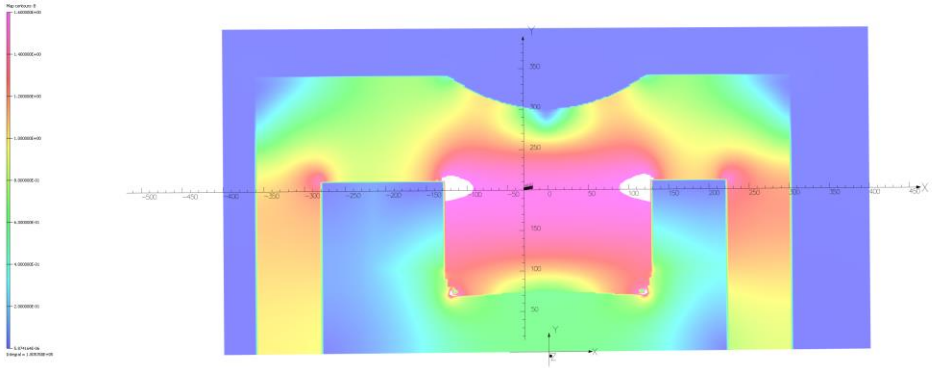


Fig.17 3D Field intensity in the yoke (transverse view)

BGI magnet performances

The following information stand for the non-symetrical yoke model:

The ∫ B.dl = 0,211 Tm at 0,6T.

Normalized harmonic values R=30 mm L= 2 m

Table 1: Harmonics

	Absolute values	Relative values
B1 [Tm]	0,214	
B2 [units]	0,033	3,08
B3 [units]	0,213	19,85
B4 [units]	4,98e-4	2.18E-03
B5 [units]	0,00269	-4.79E-01
B6 [units]	5,25e-5	-1.40E-04
B7 [units]	0,223e-3	-2.28E-01
B8 [units]	6,22e-5	3.60E-04

Table 2: Coils data

Coils data	
# of Turns/coil	72
Conductor size	10x10x4 mm
I density	5,66 A/mm^2
Cooling circuits	2/coil
Water velocity	2,5 m/s
Water flow/coil	7,5 l/min
Total dissipated power	9,19 kW
R magnet	0,039 Ω
Temperature increase	18 degC

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MDX magnet

- The MDX magnet is a **H type bending solid yoke magnet** with adjustable aperture. The integration of this magnet type **does not requires any yoke modification** appart from the supporting structure. In our case the **aperture is 100 mm** for a vacuum chamber of 85 mm outer diameter. The magnet yoke dimensions are 600 x 600 x 400 mm**. B field cancelling** by upstream and downstream MDX B field= 0,002120 Tm/A. 0,211 x 0,002120/2= **44,4 A** (30% lower than previous design with rectangular pole shape). Specific shim made experimentaly are designed. The connections are to be moved to the top of the magnet for the 5R4 location due to space constraints.

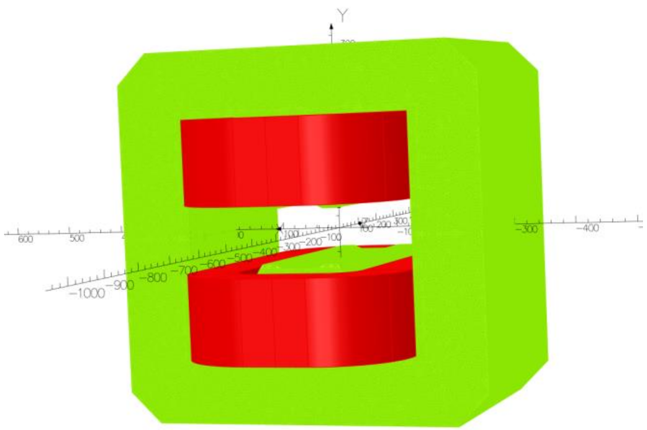

Fig.18: MDX magnetic model

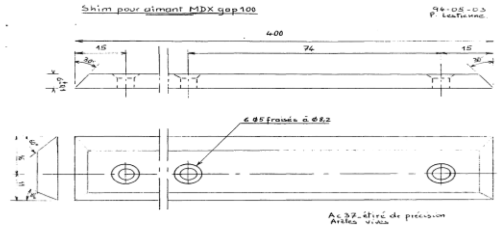

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Fig.19: 100 mm gap MDX magnetic shims

Table 3: Transfer function of the 100 mm gap MDX (archive)

I (Ampère)	$\int Bdz$ (Tm)	(T)B(o)	L eq (m)
0	0,00025	0,00030	-
40	0,09034	0,18239	0,4953
80	0,18049	0,36292	0,4973
120	0,27015	0,54371	0,4969
160	0,35834	0,72250	0,4960
200	0,44139	0,89340	0,4940
240	0,50585	1,03044	0,4909

MDX magnet performances

Table 4: Harmonics

	Absolute values	Relative values
B1 [Tm]	57.44	
B2 [units]	-5.48E-14	-9.54E-12
B3 [units]	0.115	2.00E+01
B4 [units]	-2.24E-14	-3.89E-12
B5 [units]	-0.268	-4.67E+01
B6 [units]	4.19E-15	7.30E-13
B7 [units]	0.05973	1.04E+01
B8 [units]	-2.13E-15	-3.71E-13

Table 5: Coils data

Coils data	
# of Turns/coil	180
Conductor size	6,5x6,5x3,5 mm
I density	1,4 A/mm^2
Cooling circuits	4/coil
Water velocity	2,35 m/s
Water flow/coil	710 l/min
Total dissipated power	0,38 kW
R magnet	0,1936 Ω
Temperature increase	0,5 degC

- The magnet configuration made of 2 MDX and one BGI generates a B field = 0 Tm when the operating current is set to self cancelling. The self cancelling effect is independent of the particle energy. For information the BGI magnets produces a beam deflection angle of 0,148 and 0,010 mrad at a Ek of 450 and 7000 GeV respectively.

Operating voltages

The following tables shows the total requested voltage per circuit. It includes the magnets and the supply cables.

Table 6: BGI magnet operating voltage

Total voltage drop of the BGI magnet + supply cables								
Magnet ID	BGIV.A5L4	BGICV.A5L4	BGIH.A5L4	BGICH.A5L4	BGIV.A5R4	BGICV.A5R4	BGIH.A5R4	BGICH.A5R4
Length PC to M [m]	64	73	62	70	64	73	59	67
Total cable length [m]	128	146	124	140	128	146	118	134
Cable cross section [mm2]	480	480	480	480	480	480	480	480
Rho copper	1,72E-08							
Cable R [ohm]	0,009	0,010	0,009	0,010	0,009	0,010	0,008	0,010
Operating voltage magnet + cables [V]	23,2	**23,9**	23,1	23,7	23,2	**23,9**	22,9	23,5

Table 7: MDX magnets operating voltage

Total voltage drop of 2 MDX magnets + supply cables								
Magnet ID	BGIV.A5L4	BGICV.A5L4	BGIH.A5L4	BGICH.A5L4	BGIV.A5R4	BGICV.A5R4	BGIH.A5R4	BGICH.A5R4
Length [m]	64	73	62	70	64	73	59	67
Total cable length [m]	128	146	124	140	128	146	118	134
Cable cross section [mm2]	95	95	95	95	95	95	95	95
Rho copper	1,72E-08							
Cable R [ohm]	0,046	0,053	0,045	0,051	0,046	0,053	0,043	0,049
Operating voltage magnet + cables [V]	36,0	**37,0**	35,8	36,6	36,0	**37,0**	35,4	36,3

The maximum operating voltage for the BGI 23.9V is well below the 40V limit,and for the 2 MDX 37V below the 125V.

The BGI operating current is 490 A for a I max of 600A, the MDX magnets connected in serie by two are operated at 44.4 A for a I max of 125A.

Cost / Planning

- The cost estimation for the procurement of the magnets is detailed as follow:
- One pre-serie magnet for magnetic measurements / optimization: 75 kCHF, lead time 9 months.
- Series production of three magnets: 150 kCHF Lead time 1 year if the magnets are similar to the pre-serie unit.
- One spare coil set: 20 kCHF
- Renovation and configuration (vertical versions) of 8 +2 spares MDX magnets: 100 kCHF
- Magnet support structures: BGI magnets table modification: 20 kCHF
- Supporting posts for MDX magnets: 12 kCHF
- Total: 377 kCHF

- Procurement lead time is 3 years from the design validation to commissioning.

Conclusions

- The magnetic model of the BGI-LHC magnets provides the requested B field of 0.6 Tesla with the required field quality of $10e^{-3}$ in the defined Good Field Region.
- The MDX magnet used as trim magnets operate as field canceling magnets and ensure the beam is set back to its orbit. As those magnets are available they reduce procurement costs.
- The magnets are compatible with the available space, the power and cooling constraints, using available power converters for all magnets and power cables for trims only.