# High Order Corrector Magnets Status


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Presented by Giovanni Volpini



HiLumi General Meeting, CERN,  30 Oct 2015

# Summary

1. Magnet features & Sextupole Manufacture Status
2. The magnet protection
3. A parallel development

# MAGIX & INFN participation to HL-LHC

MAGIX

| MAGIX | | |
|---|---|---|
| **WP1** | CORRAL | Design, construction and test of the five prototypes of the corrector magnets for the HL interaction regions of HiLUMI |
| **WP2** | PADS | 2D & 3D engineering design of the D2 magnets |
| **WP3** | SCOW-2G | Development of HTS coil for application to detectors and accelerators |
| **WP4** | SAFFO | Low-loss SC development for application to AC magnets |

**MAGIX** is a INFN-funded research project, whose goal is to develop superconducting technologies for application to future accelerator magnets.
It includes four WP's, two of which are relevant to HL-LHC 2014-2017

## CERN-INFN Collaboration Agreement

CERN endorses MAGIX WP1 & WP2 deliverables and milestones through the collaboration agreement KE2291/TE/HL-LHC

**1**


Done in two copies in the English language on:
Date: 25 GIU. 2014
Date: 17 JUIL. 2014
Instituto Nazionale di Fisica Nucleare (INFN)
Prof. Fernando Ferroni
President
The European Organisation for Nuclear Research (CERN)
Prof. Rolf-Dieter Heuer
Director-General
T. Lagrange
Head of Finance, Procurement and Knowledge Transfer Department
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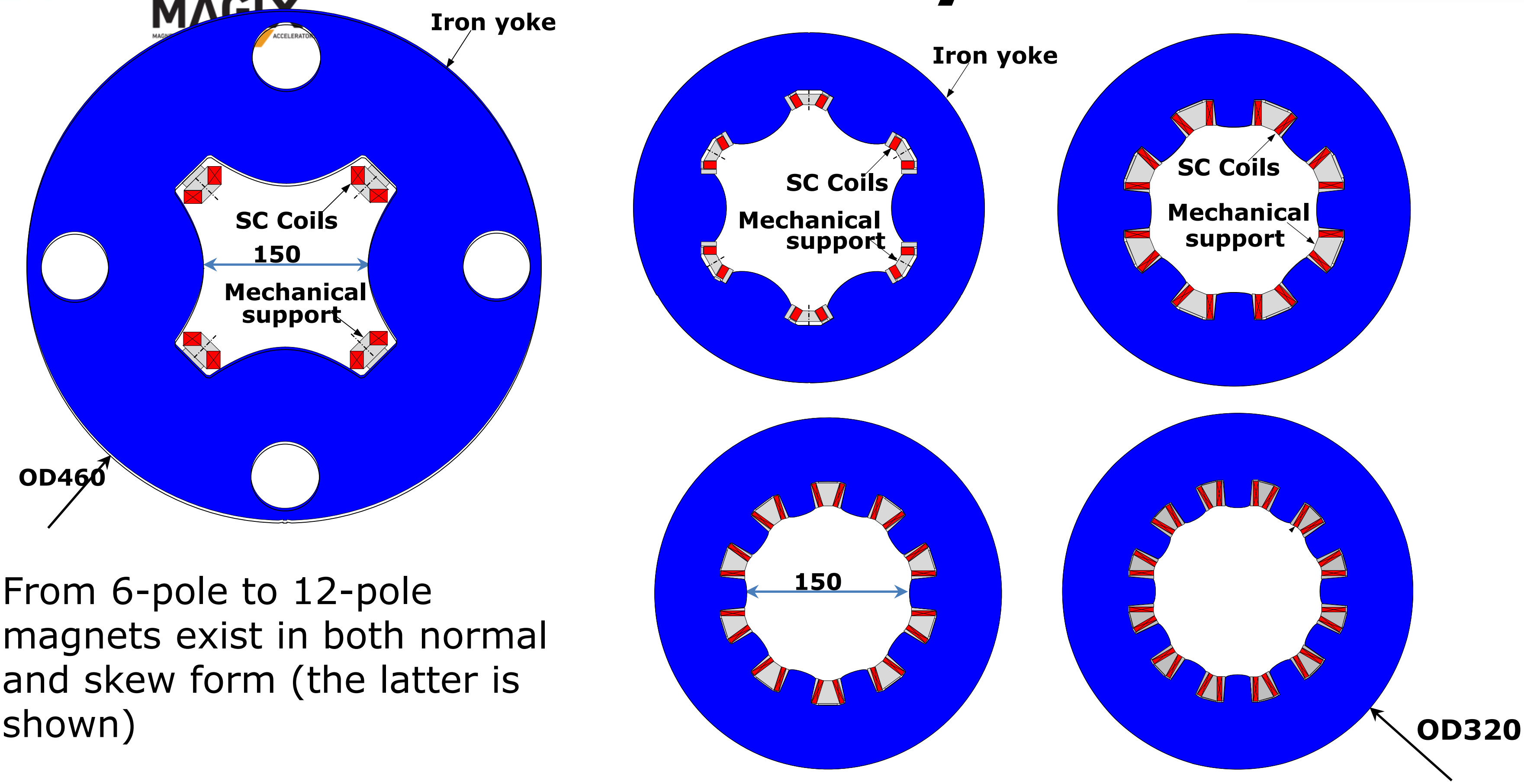
**2**

INFN already involved in FP7-HiLumi (**UE-HILUMI**, GrV)
*WP2 beam dynamics, LNF*
*WP3 magnets, MI-LASA*
*WP6 cold powering, MI-LASA*

# Corrector magnet inventory




From 6-pole to 12-pole magnets exist in both normal and skew form (the latter is shown)

*The superferric design was chosen for ease of construction, compact shape, modularity, following the good performance of earlier corrector prototype magnets developed by CIEMAT (Spain).*

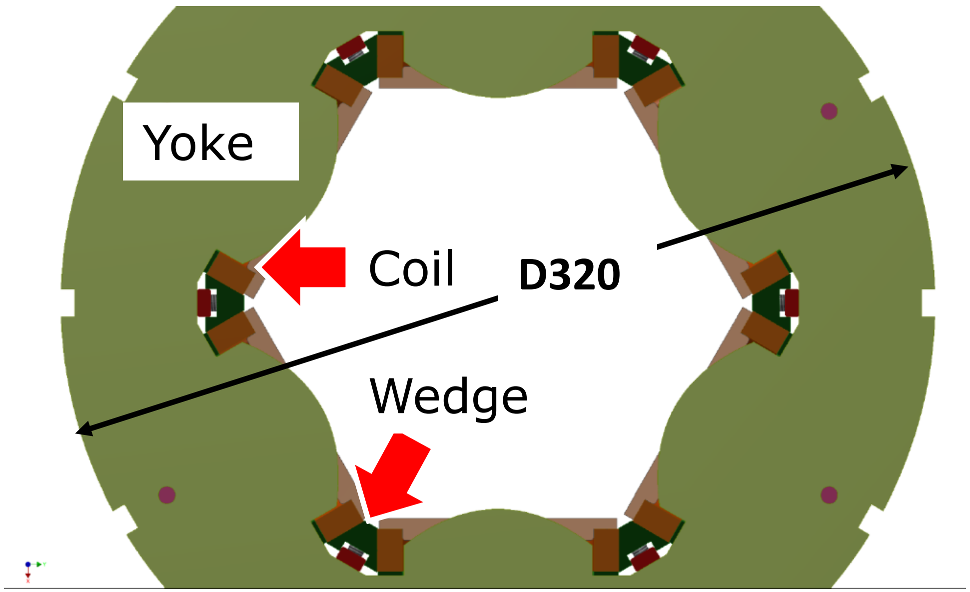
# LHC vs. HL-LHC corrector magnet comparison chart

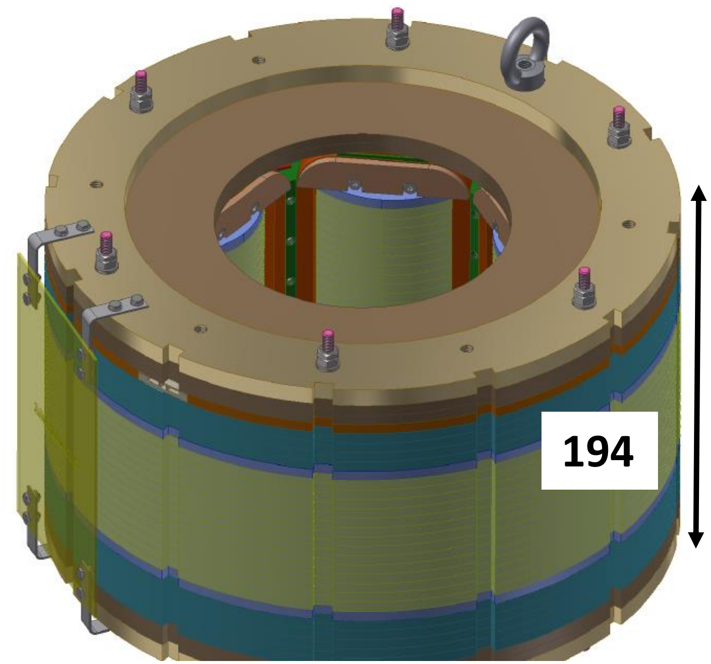
MAGIX

| Order | Type | LHC | | | | | | HL-LHC | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Aperture | Stored energy | Operating Current | Inductance | Aperture | Stored energy | Operating Current | Integrated field at r=50 mm | Magnetic Length | Differential Inductance @ Iop |
| | | | | mm | [J] | [A] | [mH] | [mm] | [kJ] | [A] | [T.m] | [m] | [H] |
| **2** | S | MQSX | | 70 | 2,116 | 550 | 14 | 150 | 24.57 | 182 | 1.00 | 0.807 | 1.247 |
| **3** | N | MCSX | MCSTX | 70 | 39 | 100 | 4.7 | 150 | 1.28 | 132 | 0.06 | 0.111 | 0.118 |
| **3** | S | MCSSX | MCSOX | 70 | 6 | 50 | 7.8 | 150 | 1.28 | 132 | 0.06 | 0.111 | 0.118 |
| **4** | N | MCOX | | 70 | 16 | 100 | 4.4 | 150 | 1.41 | 120 | 0.04 | 0.087 | 0.152 |
| **4** | S | MCOSX | | 70 | 22 | 100 | 3.2 | 150 | 1.41 | 120 | 0.04 | 0.087 | 0.152 |
| **5** | N | | | | | | | 150 | 1.39 | 139 | 0.03 | 0.095 | 0.107 |
| **5** | S | | | | | | | 150 | 1.39 | 139 | 0.03 | 0.095 | 0.107 |
| **6** | N | MCTX | MCSTX | 70 | 94 | 80 | 29.2 | 150 | 4.35 | 167 | 0.086 | 0.430 | 0.229 |
| **6** | S | | | | | | | 150 | 0.92 | 163 | 0.017 | 0.089 | 0.052 |

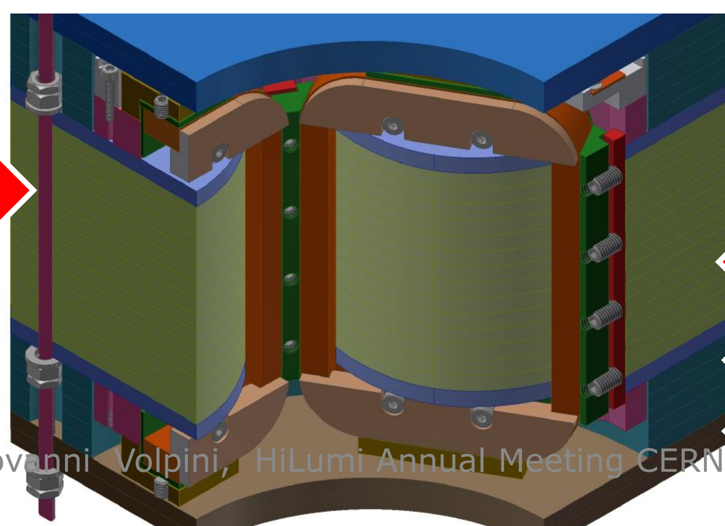
Rev 9 July 2014 187/II

# Sextupole layout

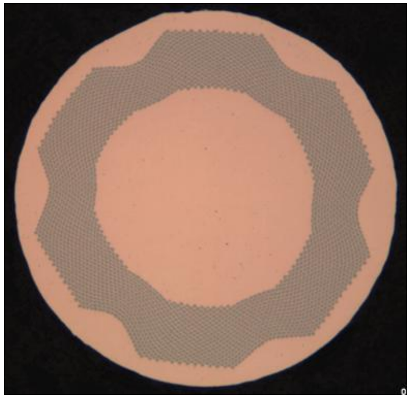


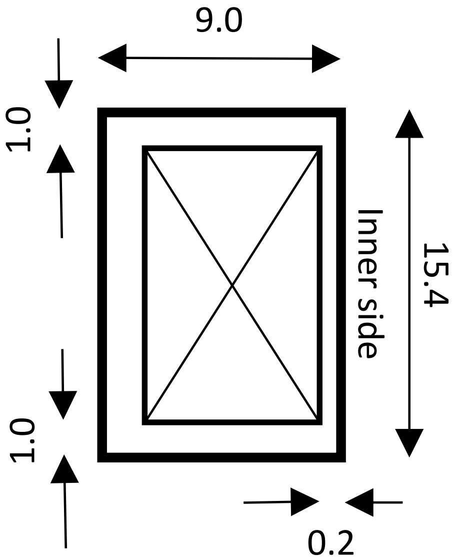

5.8 mm thick iron laminations, machined by EDM



# Coil Design



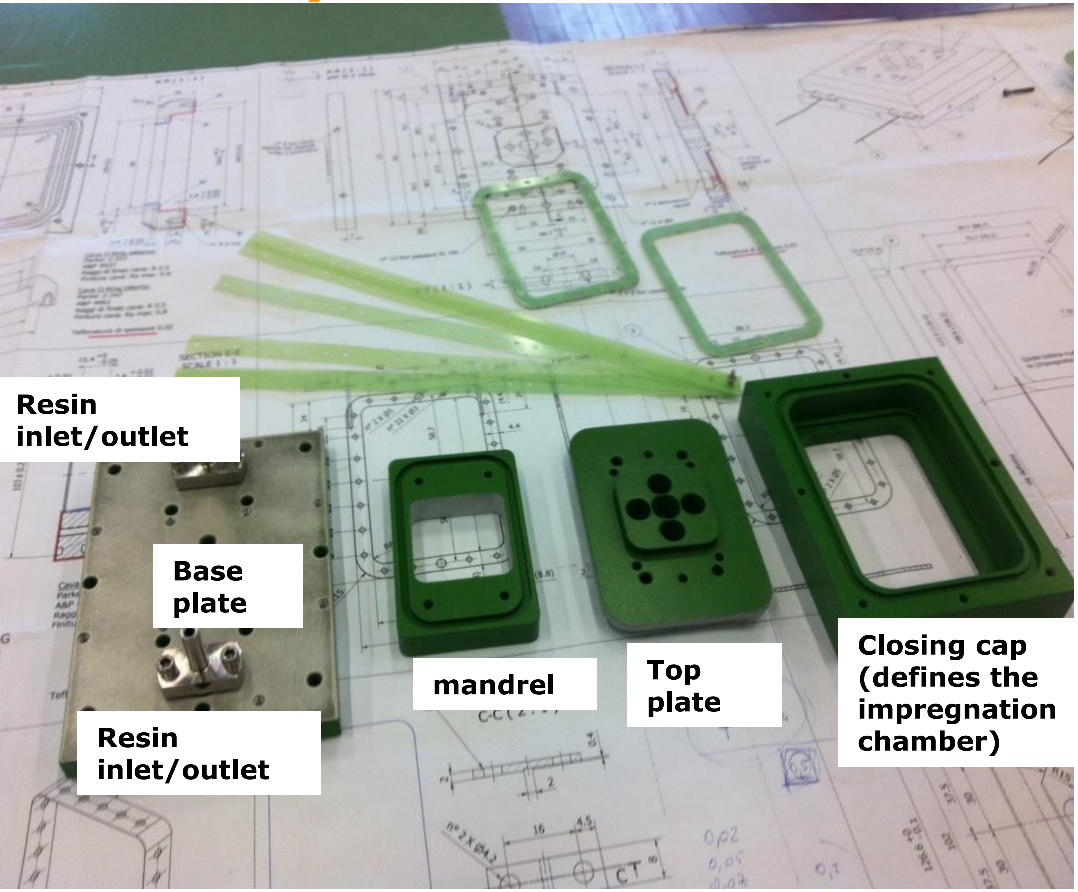
**Bruker-EAS**
**NbTi for Fusion application**
**Fine filaments ITER PF wire**
**Wire type 2**
Cu:NbTi ≈ 2.30
Number of filaments 3282
Filament diameter≈ 8 μm @ 0.73 mm
Two wire diameters: **0.5** and **0.7 mm**
S2-glass insulation.

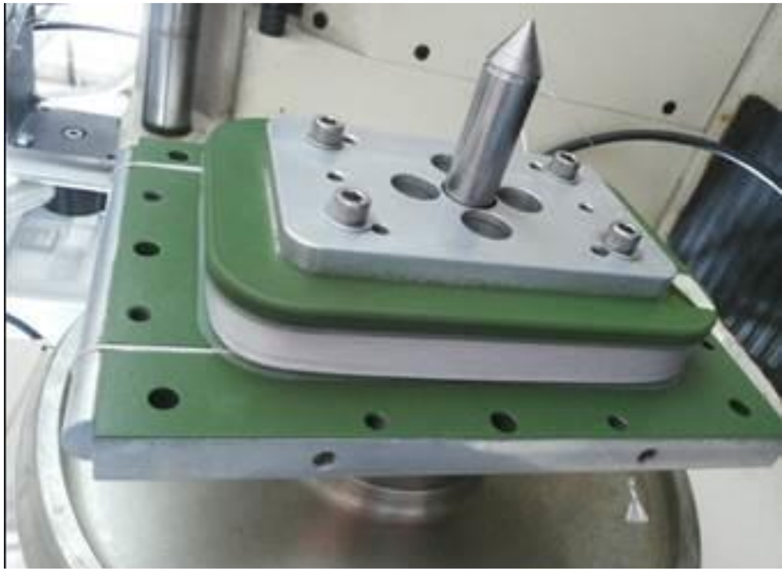


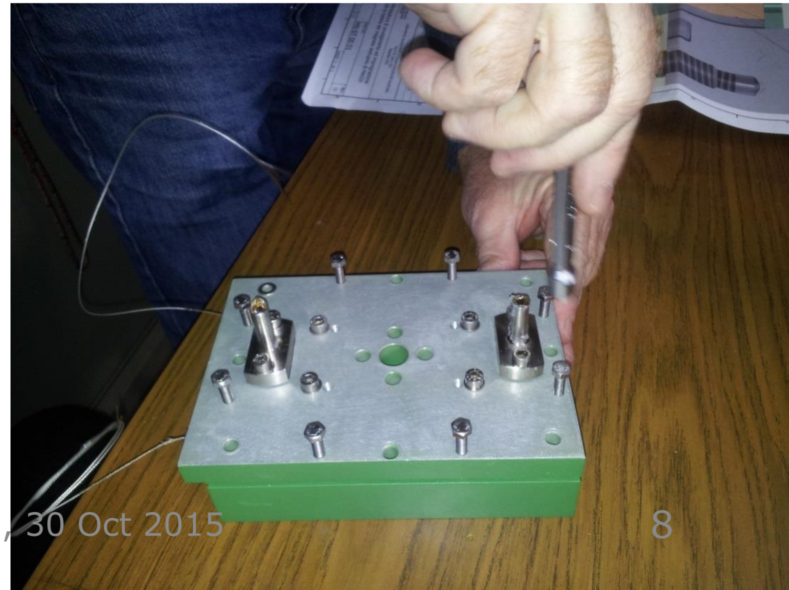

**Insulation scheme:**
-wire w/ S2 glass 0.14 mm thick (on diameter)
-ground insulation:
G11, 2 mm thick plates on both sides of the coil, including the wire exits
G11 thin, flexible layer on the inner wall of the coil;
S2 tape on the outer wall

***To identify a new, radiation resistant, material for the ground insulation***

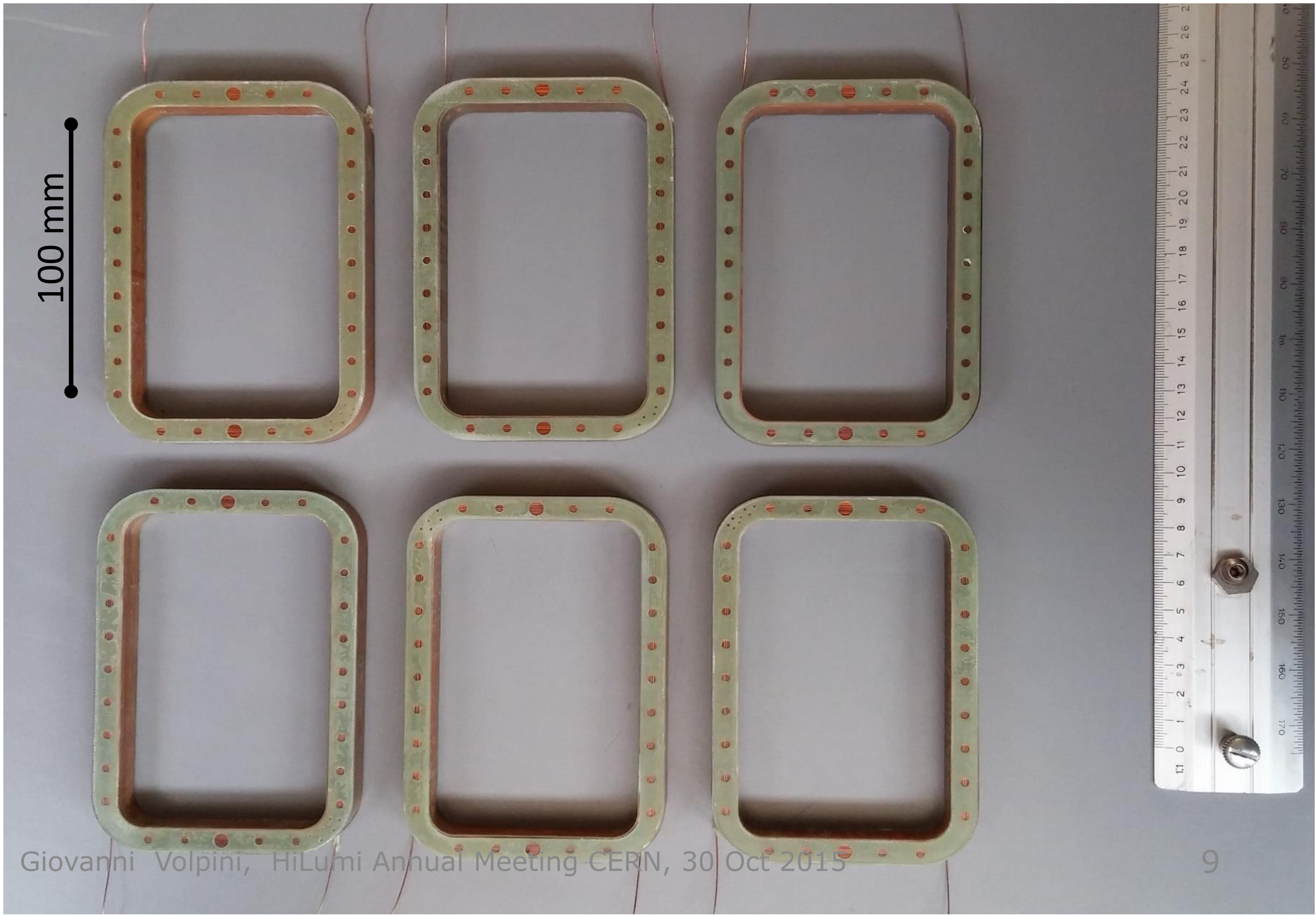
# Coil winding & impregnation



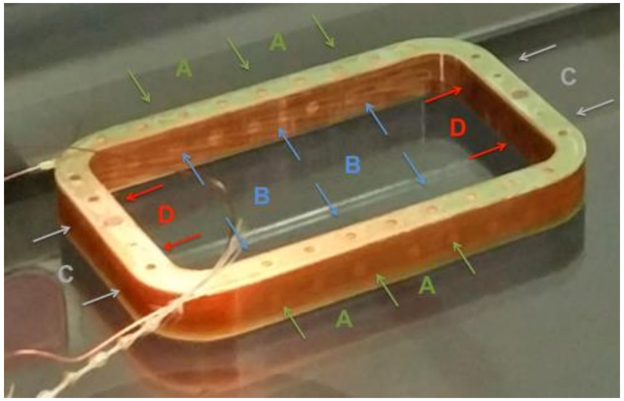


# Sextupole Coils Manufacture



# Coil Assessment

| | All coils [mm] | Mould 1 [mm] | Mould 2 [mm] |
|---|---|---|---|
| **A** | 88.64±0.16 | 88.76±0.07 | 88.50±0.10 |
| **B** | 70.28±0.05 | 70.31±0.04 | 70.24±0.02 |
| **C** | 132.48±0.17 | 132.58±0.09 | 132.35±0.16 |
| **D** | 114.07±0.11 | 114.08±0.12 | 114.06±0.13 |




| | | Mean Value | Minimum & Maximum | Standard deviation |
|---|---|---|---|---|
| **Ground insulation @ 5 kV** | TΩ | 1.5 | 0.8-2.0 | |
| **Coil Resistance @ 19.2 °C** | Ω | 9.982 | 9.973-9.987 | 0.007 |
| **Coil Inductance** | mH | 8.587 | 8.570-8.613 | 0.05 |

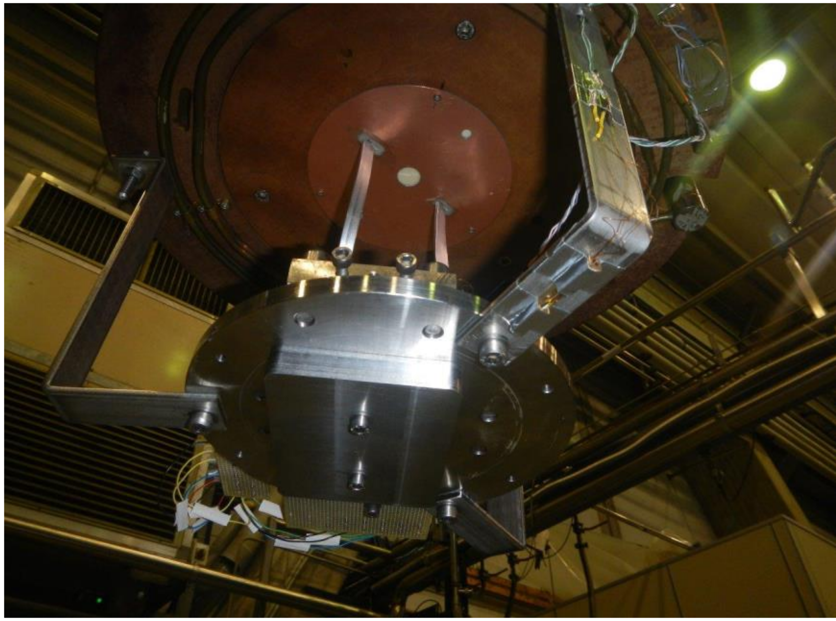
Coil manufacture tolerances defined.
Teflon coating not suitable for this application (high wearing)
New releasing agent tested and selected.
QC plan being established.

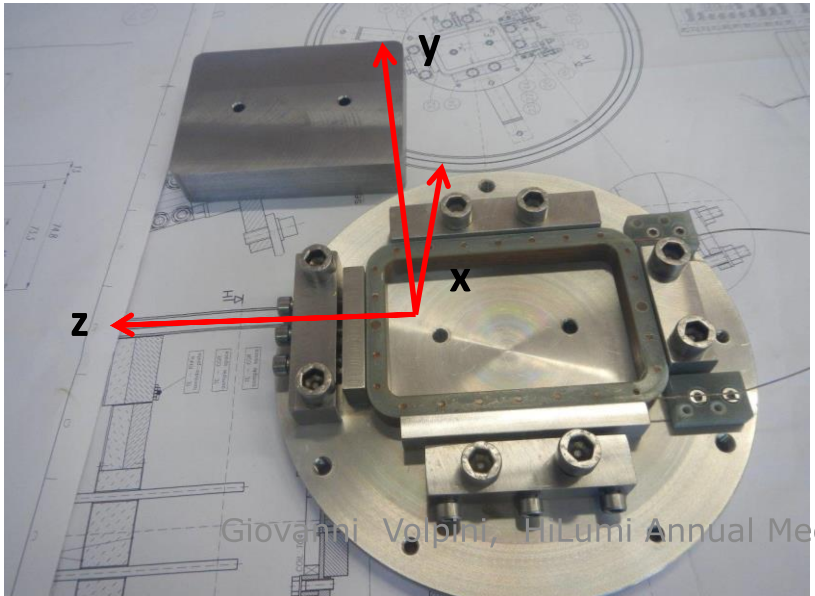
# Single Coil Sample Holder

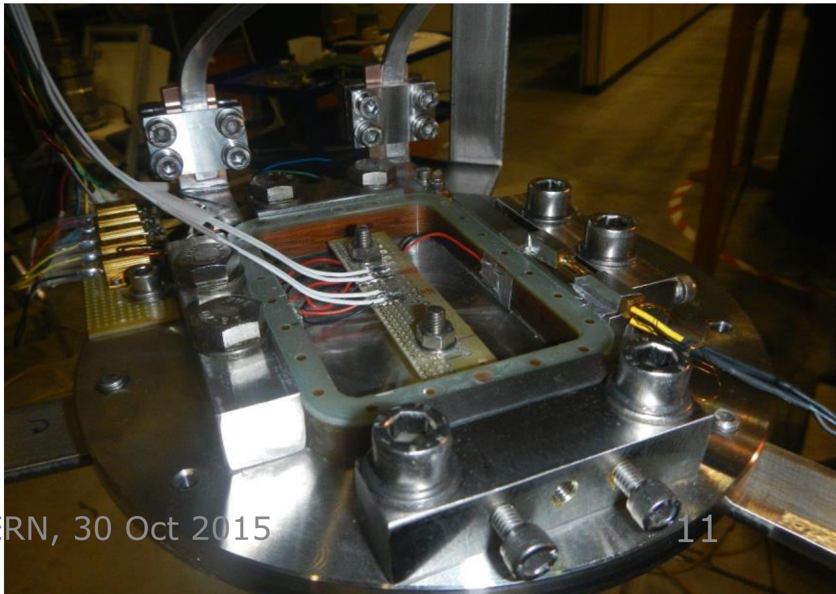
Goals:

1) To test a coil in "realistic" conditions to identify major faults in the design/assembly;

2) To commission the "small" magnet test station, to be used to test sextupole, octupole and decapole





# Test results

**First test at 4.2 K**
Current increased by steps at 0.3 A/s. Quench induced with heaters at 90, 160, 200 and 220 A. Ramp up to 260 A (no quench induced at this current value by choice). **No spontaneous quench occurred.**

**Test at subcooled LHe**
Significant heat load in the bath prevents from reaching a temperature lower than 2.5 K. Main reason is the thermal shield, whose temperature decreases very slowly. Current ramp up to quench.

**Four training quenches** occurred at
295 A (2.56±0.04 K) or 80% of the s.s. at this *T*
318 A (2.60±0.04 K) or 87% "
329 A (2.72±0.05 K) or 91% "
325 A (2.85±0.06 K) or 91% "

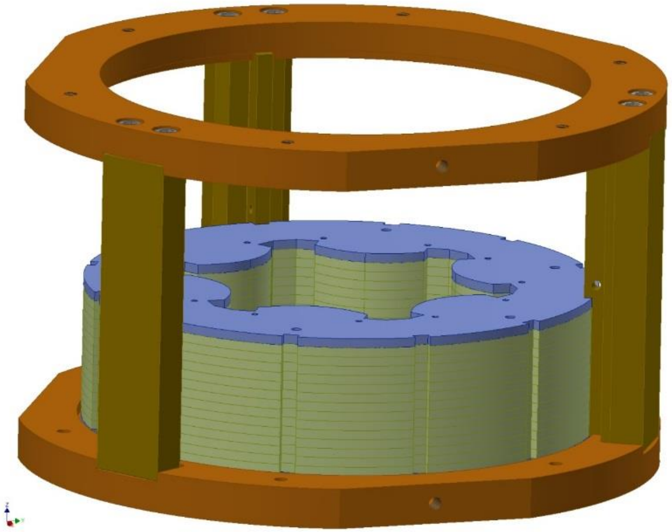
***The magnet operates at 40% on the load line***

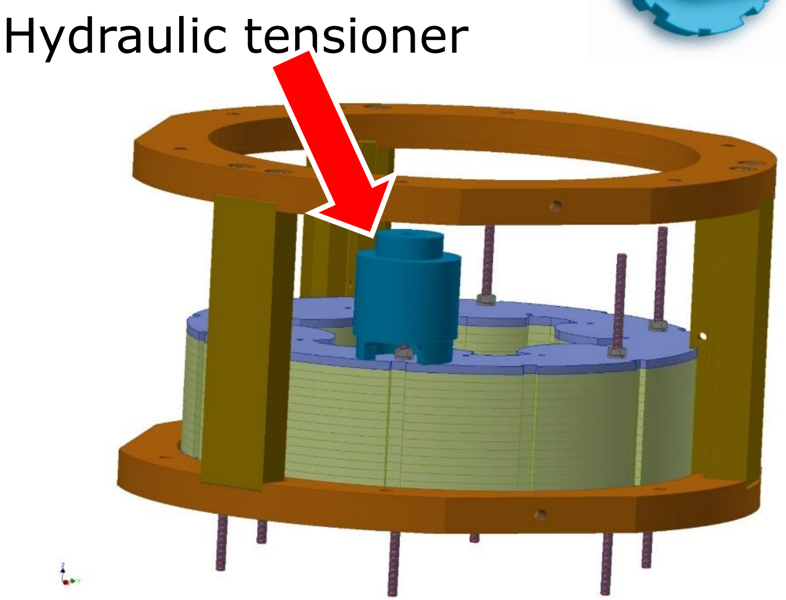
**Training at 4.2 K**
Current ramp up to quench at 0.3 A/s
First quench at 280 A, then repeated increasing the ramp rate up to 5.7 A/s (limited by power supply in this configuration). In total **14 quenches at 280 A** , or 95% of the s.s. limit.

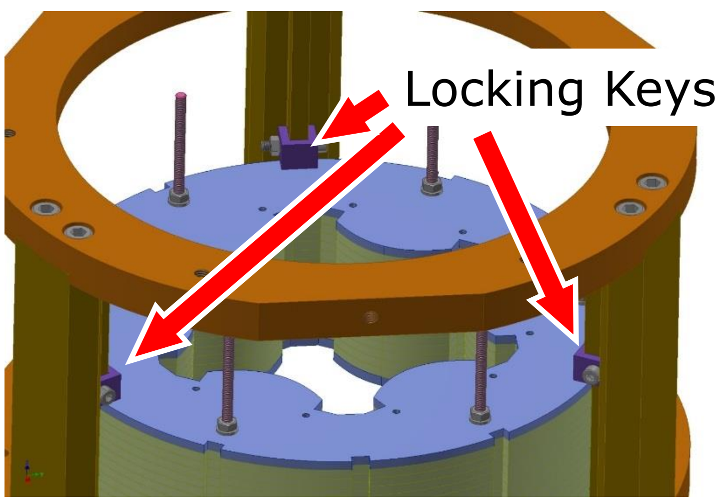
**E.M. Forces**
A magnetic plate creates along the normal of the coil plane an e.m. force pattern more resembling to that experienced by a coil during its operation inside the magnet.

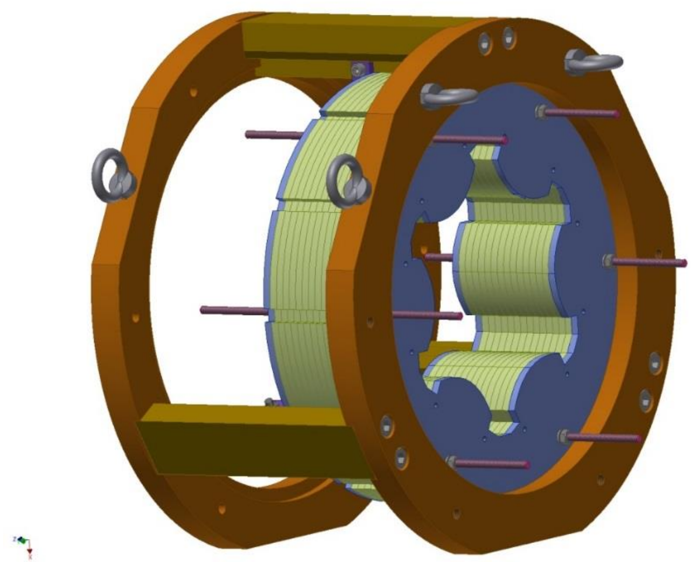
| | | | |
|---|---|---|---|
| Fx (normal to the coil plane, half coil) | 2.9 kN @ Iop, | here reached at about | 300 A |
| Fy (normal to long axis, half coil) | 1.5 kN @ Iop, | " | 250 A |
| Fz (normal to long axis, half coil) | 0.6 kN @ Iop, | " | 180 A |

# Assembly sequence: I

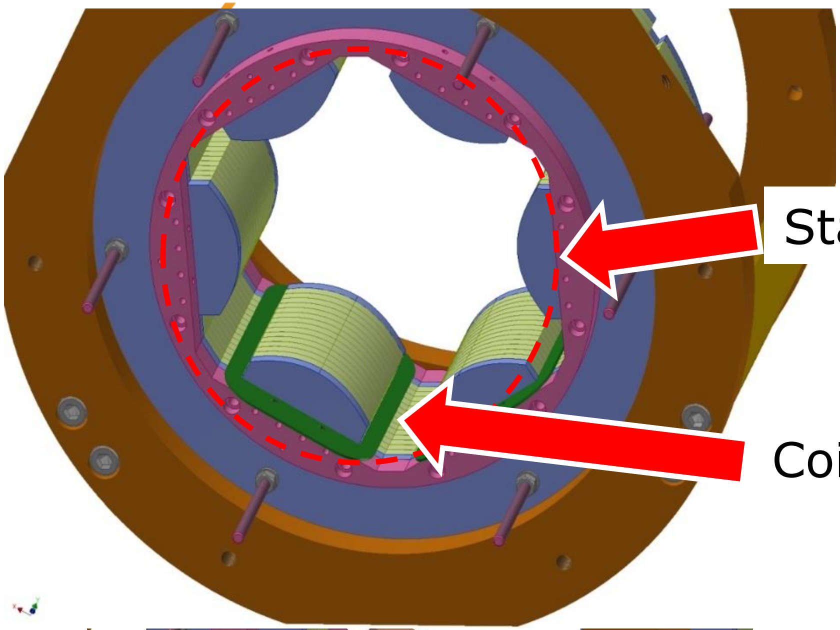


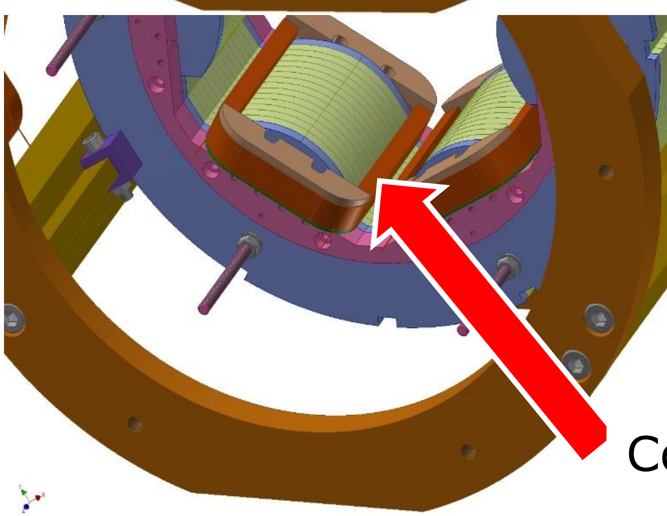


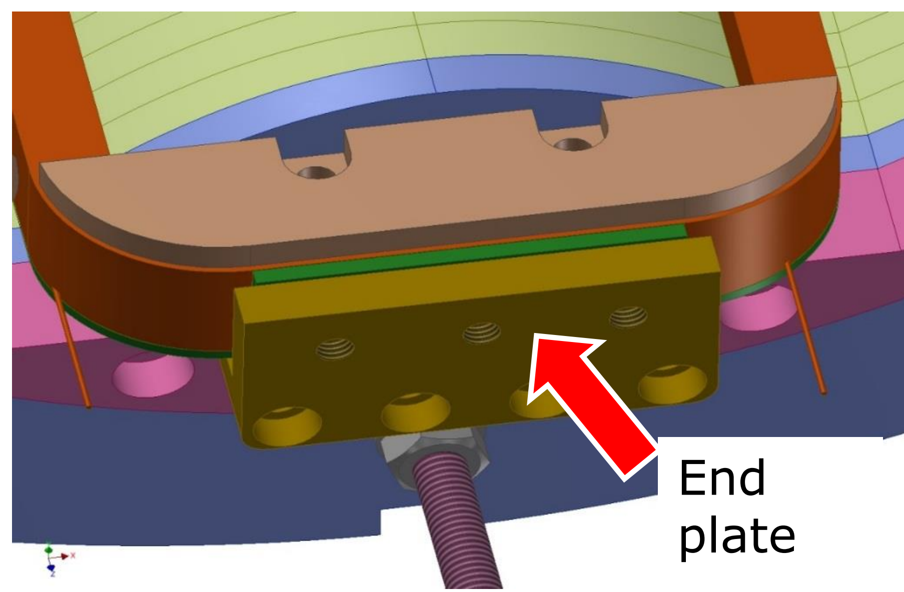



# Assembly sequence: II



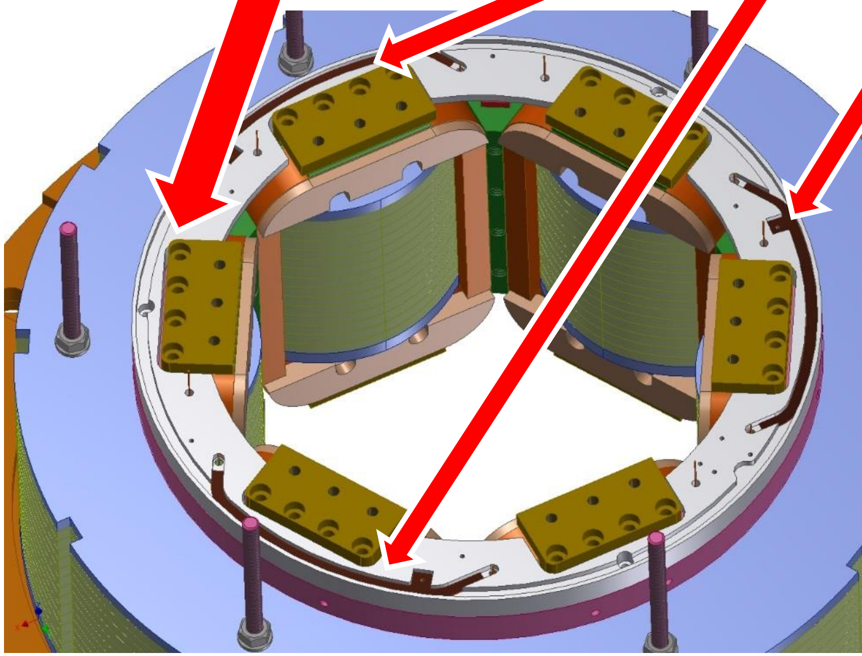



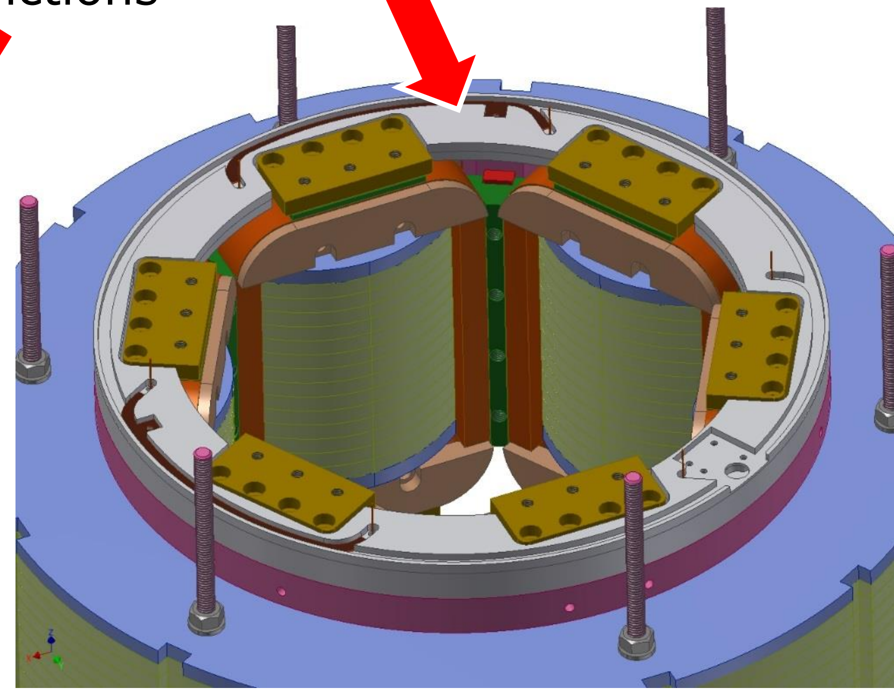
# Assembly sequence: III

Duratron plate #1

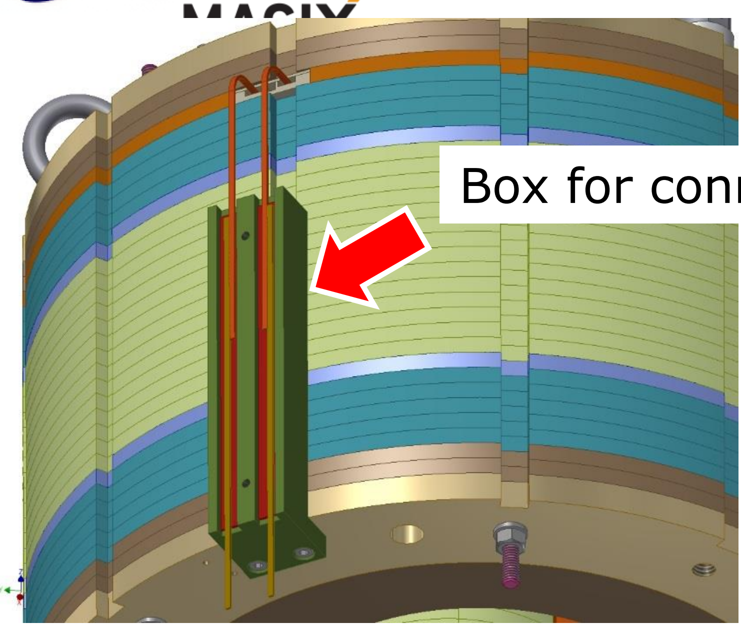
Duratron plate #2

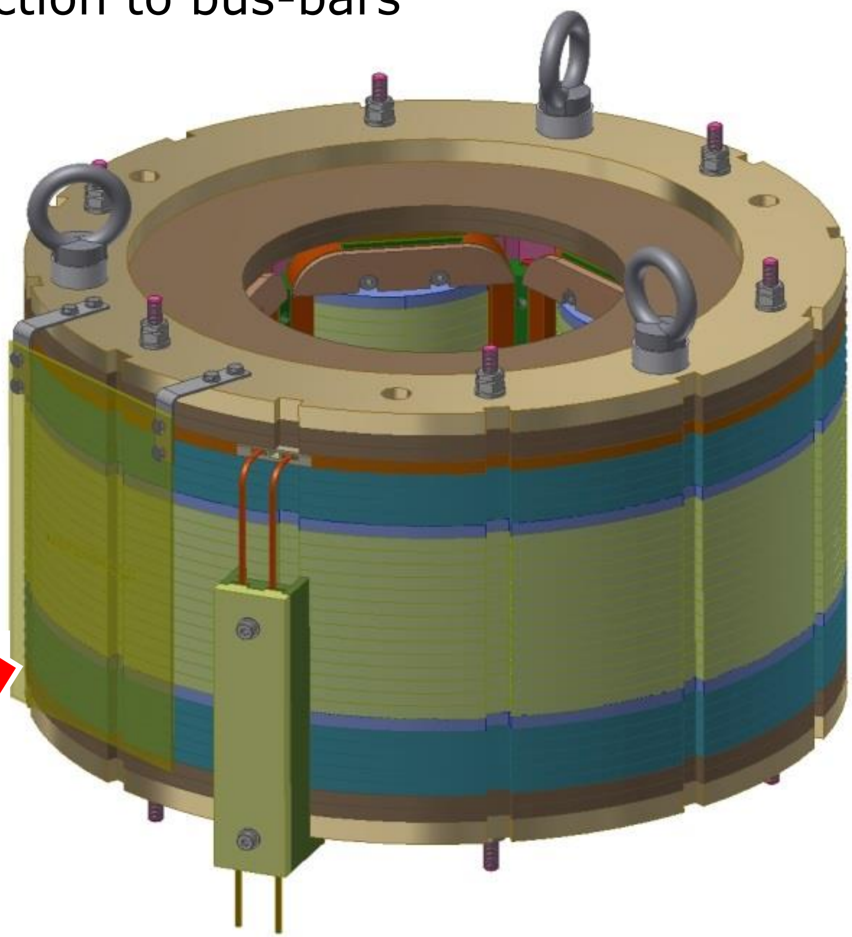
1-mm thick Cu traces for coil-to-coil junctions





# Assembly sequence: IV



Voltage signal board with current-limiting resistances

1. Magnet features & Sextupole Manufacture Status

2. The magnet protection

3. A parallel development

# Magnet Protection general considerations

We assumed a «traditional», conservative, approach for the magnet protection. Present CS's are based on this.
-energy extraction on an external resistor dump assumed, following a quench detection;
-$V_{dump}$ fixed at 300 V;
-No quench heater.

Cost & space issues led to some suggestions (which I could not refuse…):
i Rely as much as possible to PC crowbar, limiting voltage to 50 V;
ii Try to match operating currents to exsisting PC's, (180-130 A to less than 120 A, including some margin)

Workplan

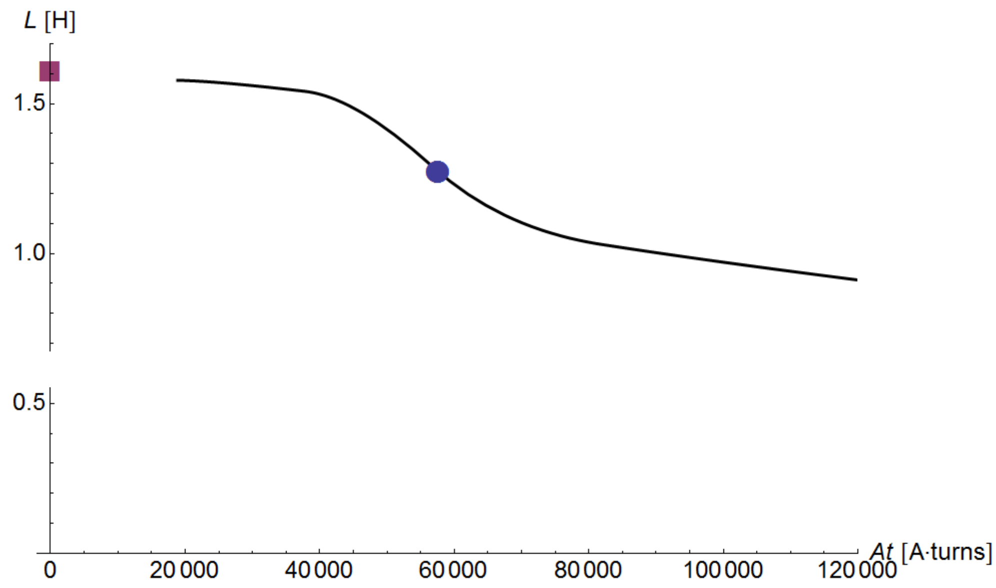
- Verify whether the 4-pole (most critical) in its present design can be protected in a passive way;
- Perform a partial redesign, lowering the operating current below 120A. This leads to an increase of the inductance and making protection more critical. Passive protection is verified again.

# Magnet Protection model assumptions

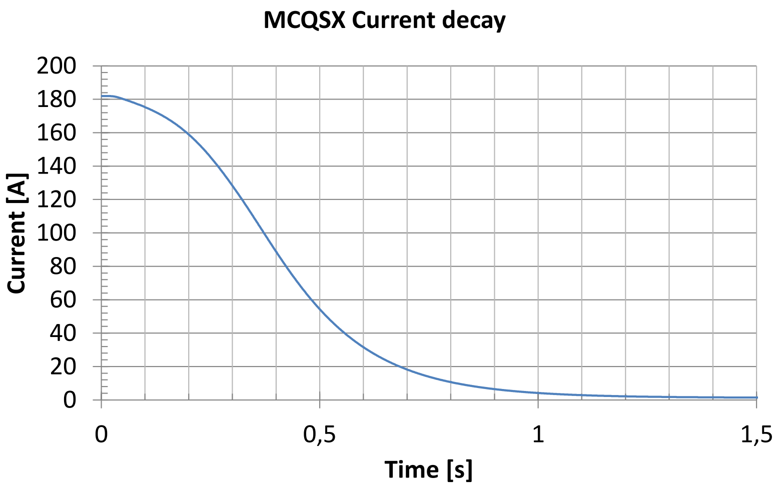
Quench simulations with QLASA were performed, with following assumptions:

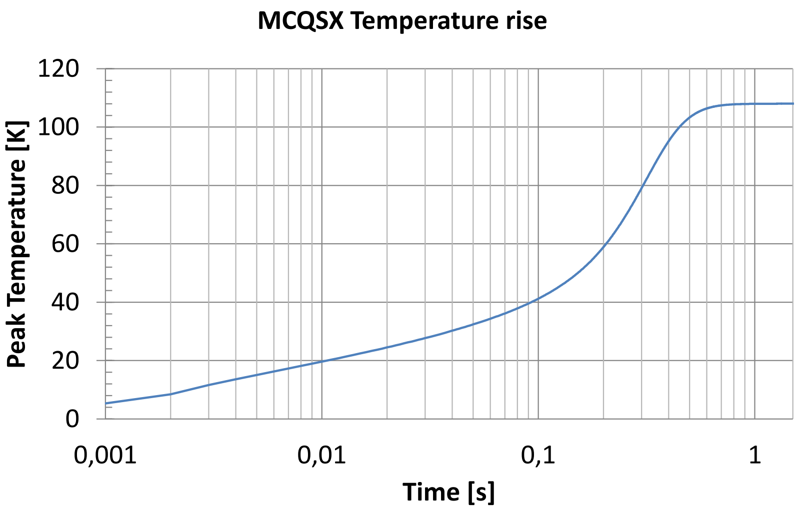
We assume that the PC has an output voltage compliance of 12 V; when this is reached, we do not trip the PC, which continues to provide a fixed voltage. This is justified later, and allows to drop any hypothesis on the reaction time.

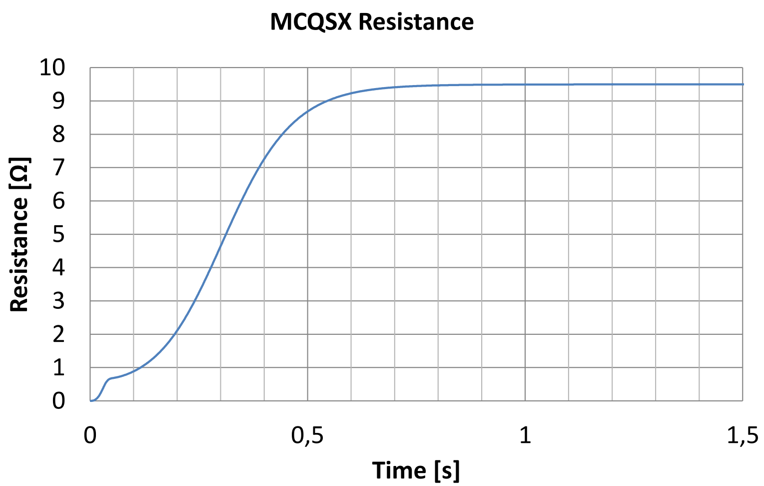
Current dependent inductance.

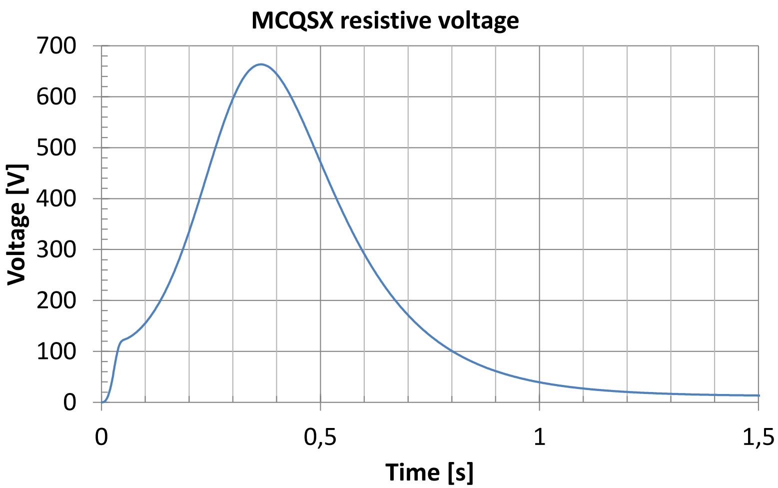


# Magnet Protection the Quadrupole case



# Magnet Protection the Quadrupole case II

| | | QLASA $v_q$ finite PC at VL=12V | $v_q$ infinite No external dump | $v_q$ infinite External dump with Vmax=300V | $v_q$ infinite External dump with Vmax=50V |
|---|---|---|---|---|---|
| Peak temperature | K | 108 | 98 | 74 | 94 |
| Energy dumped into coil vs. stored energy | - | 103% | 100% | 50% | 90% |
| Final resistance | Ω | 9.5 | 8.7 | 4.4 | 7.9 |
| Max voltage between a coil (internal) end and ground | V | 507 | 490 | 340 | 420 |

We are close to the case of infinite quench velocity ($v_q$), one whole coil is quenched

# Magnet Protection Conclusions

Quadrupole seems, in its present design, well protected simply limiting the PC output voltage. Energy extraction with 300V would help, but it is not necessary. Little use of a 50 V dump.

To be confirmed with the new, low current, design.

Other magnets should be less critical, but this too must be confirmed

*Caveat artifex!*
*This result depends on a computed longitudinal and transverse quench propagation speed.*
*To be cross-checked with experimental results*

# Updated Design

The CS magnet designs are now revised to set the maximum operating current below 120 A, to comply with the exsisting power converters.

For the magnets from sextupole to dodecapole we will simply increase the number of the turns, modifying the iron shape to have more room, and keeping the same 0.5 mm dia wire. The load line margin becomes larger than 60%.

For the quadrupole, we could consider to use either the 0.5 mm wire, or the 0.575 mm dia wire manufactured by Luvata Pori, already procured at LASA (but to be insulated).

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# $MgB_2$ development

The pursuit of new solutions based on innovative superconducting materials and/or design solutions, would represent an interesting scientific added value

We are working on an innovative solution, first proposed in '74 by Malychev, that we call *Round Coil Superferric Magnet* (RCSM)

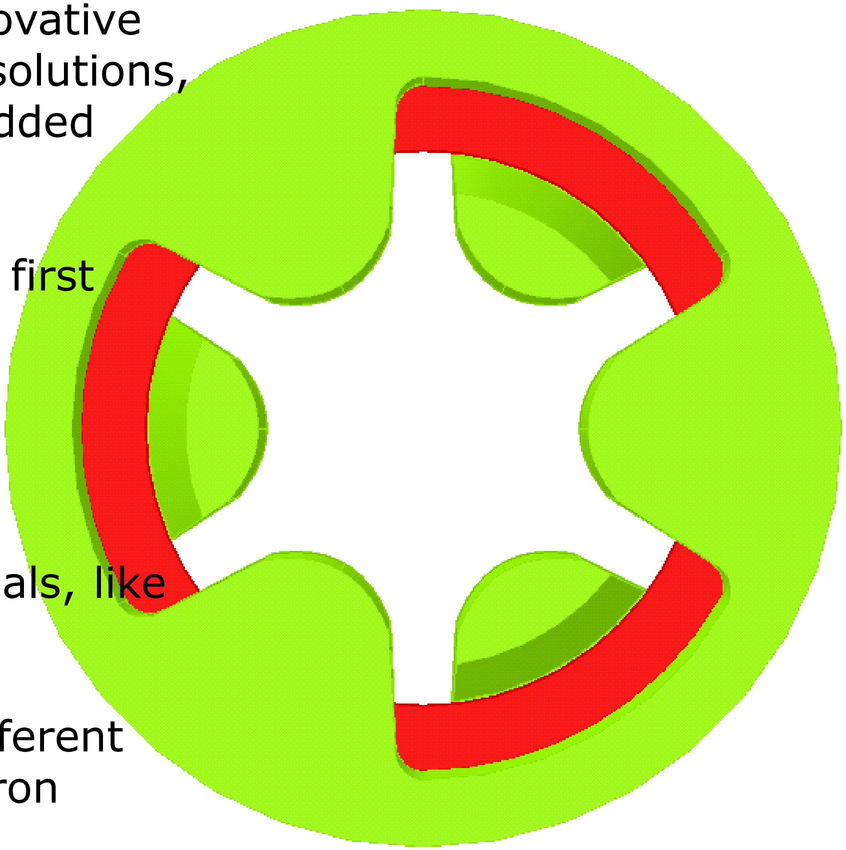
Simple, circular coil shape, cost effective.

Expecially suited to strain-sensitive materials, like $MgB_2$

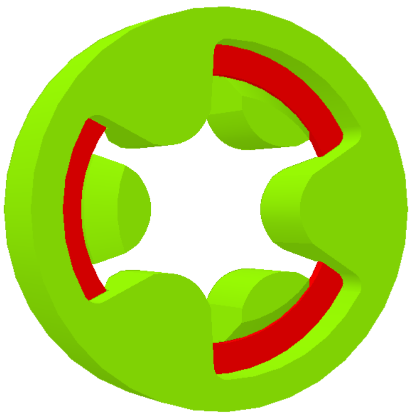
We consider a sextupole configuration; different multipoles may be realized replacing the iron

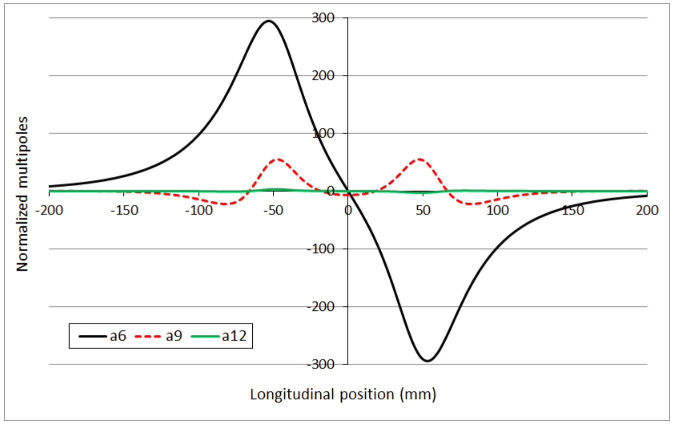
Preliminary design in progress.

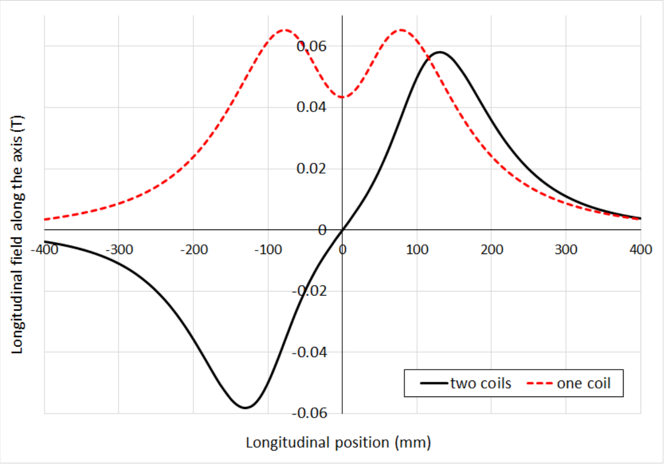
Work done at CERN with **Juho Rysti**

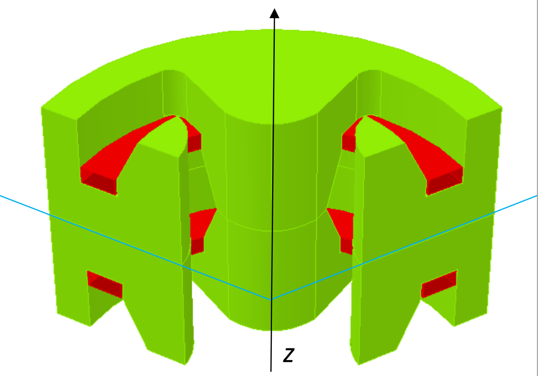


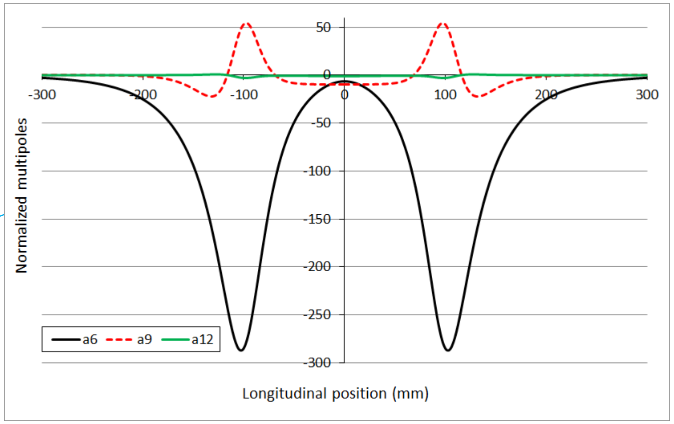
# Harmonic Properties



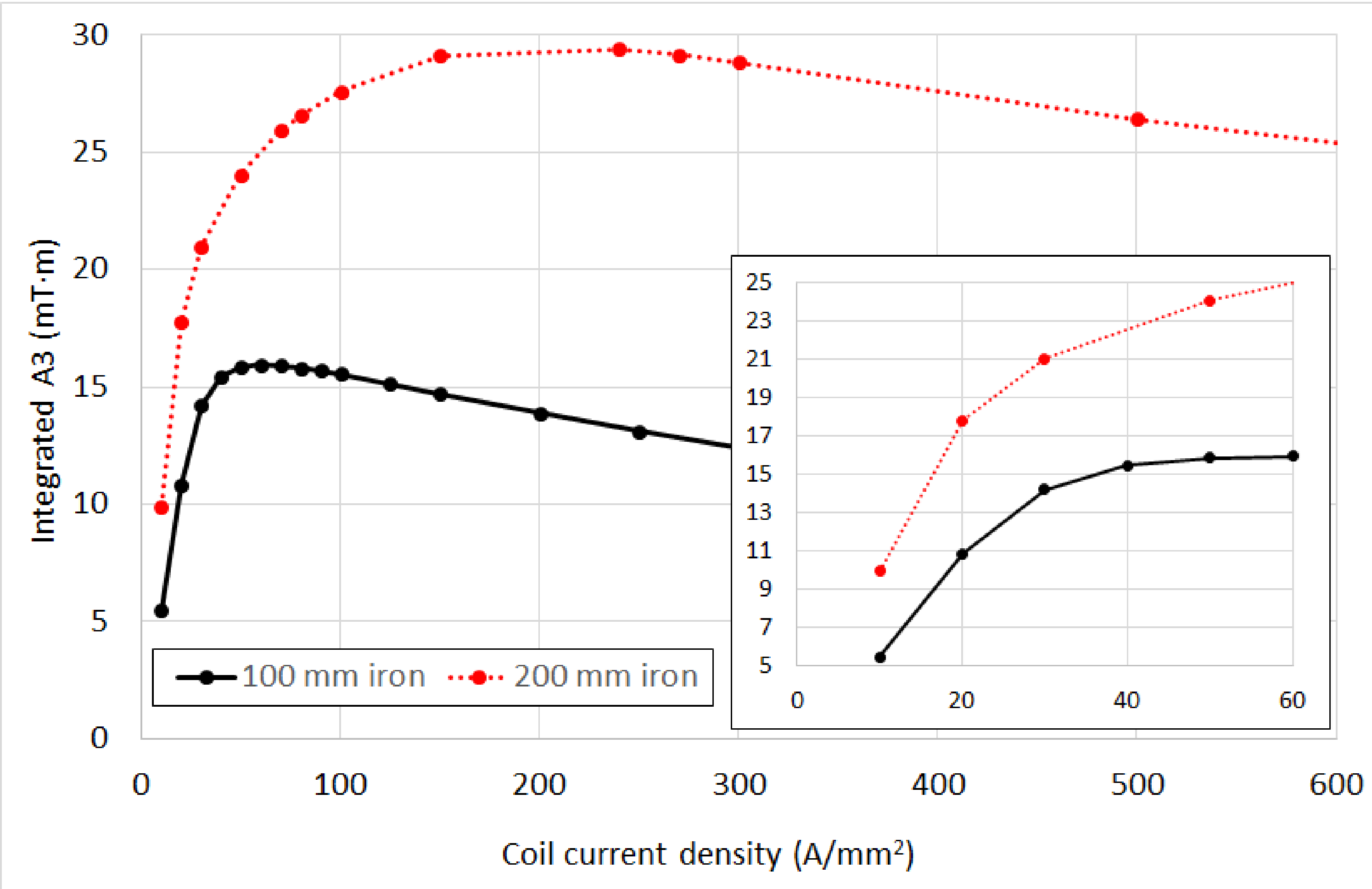


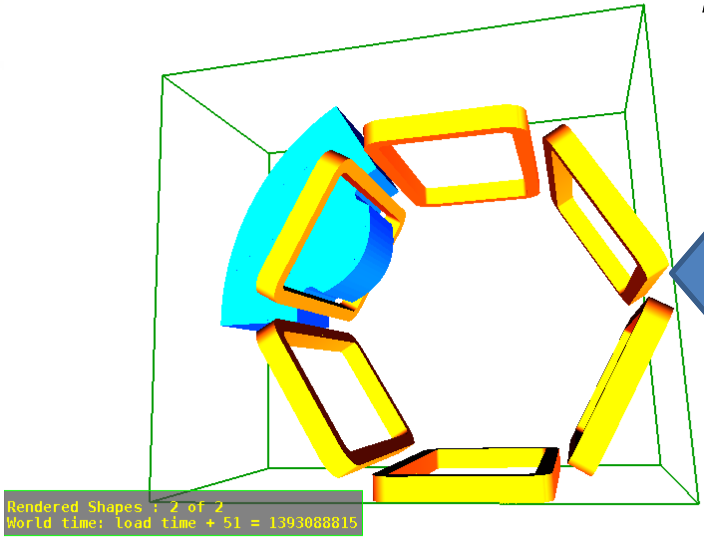



# Saturation Effect



# The End

# A rule (symmetry) changer



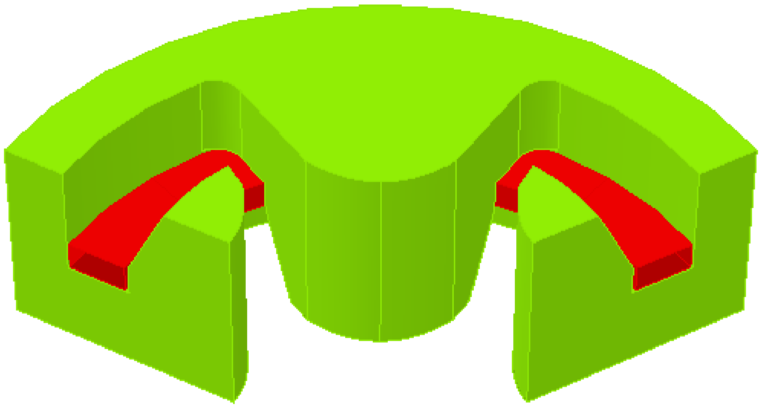

No matter how a sextupole magnet is done, it is invariant by a 120 degree rotation.

A 60 degree exchanges the "north" and "south" poles; if we reverse the current direction as well, the field is globally unchanged!

A RCSM is invariant by 120 degree rotation.

A rotation by 60°, amounts to a "mirroring" w.r.t. a plane normal at *z*-axis, at *z*=0. No change in current.

No overall mirror symmetry.



This difference of the symmetries has profound consequences on the harmonics properties: a "traditional" layout has no even ("forbidden") harmonics, and no net solenoidal field; a RCSM has also even harmonics, that vanish when integrated from -∞ to +∞, and a net solenoidal field. More complex configurations may suppress the latter, at the price of net even harmonics.

# Old & Older

196 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010

## A Novel Design of Iron Dominated Superconducting Multipole Magnets With Circular Coils

Vladimir Kashikhin

*Abstract*—Linear accelerators based on superconducting magnet technology use a large number of relatively weak superconducting quadrupoles. In this case an iron dominated quadrupole is the most cost effective solution. The field quality in this magnet is defined by iron poles; the magnet air gap is minimal as are coil ampere-turns. Nevertheless, it has long racetrack type coils, which must be rigid and fixed by a mechanical structure to provide the needed mechanical stability. The novel concept of using circular superconducting coils in such a quadrupole type is described, with a discussion of quadrupole parameters, and results of 3D magnetic designs. Variants of short and long sectional quadrupoles and multipoles are presented.

*Index Terms*—Accelerator magnets, coils, iron, magnetic fields, superconducting magnets.

I. INTRODUCTION

SEVERAL Linear Accelerators based on superconducting technology now are under design and construction [1]–[3]. These machines use various superconducting magnets to provide particle beam steering and focusing. The main beam focusing element is a superconducting quadrupole mounted inside a cryomodule between SCRF cavities [4]–[6].

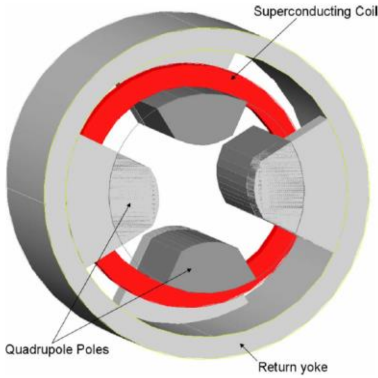



Fig. 1. Iron dominated quadrupole with circular coil.

(9) VV

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Государственный комитет Совета Министров СССР по делам изобретений и открытий

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Заявитель —

МНОГОПОЛЮСНАЯ

1

Изобретение относится к устройствам для магнитной фокусировки заряженных частиц, в частности к квадрупольным и многополюсным магнитным линзам.

Известны квадрупольные и многополюсные линзы, содержащие полюса гиперболического или цилиндрического профиля, магнитопровод и обмотки, расположенные на каждом полюсе.

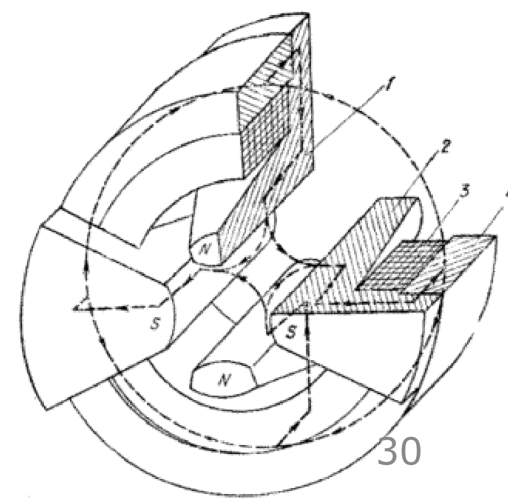
Известные линзы сложны по конструкции, так как число их обмоток равно числу полюсов. Особые трудности возникают при выполнении таких линз со сверхпроводящими обмотками.

Целью изобретения является упрощение конструкции линзы.

Предложенная магнитная линза отличается тем, что она имеет одну обмотку независимо от числа полюсов, расположенную коаксиально магнитопроводу, причем ось обмотки совпадает с осью линзы, а полюса выполнены в виде Г-образных тел, попеременно с разных сторон закрепленных на магнитопроводе.

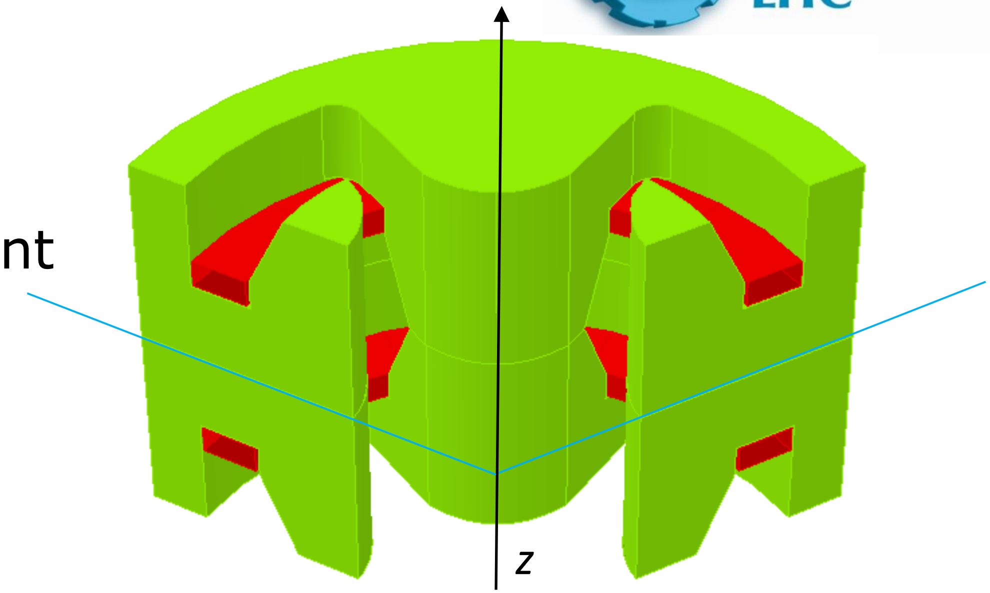
На фиг. 1 показана предложенная линза; на фиг. 2 и 3 — конструкции из предложенных линз.

Линза содержит северный [illegible] южный 2 полюса, обмотку 3, магнитопровод 4. Ось обмотки 3 совпадает с осью линзы, обмотка расположена коаксиально магнитопроводу 4. Полюса 1 и 2 выполнены съемными в виде Г-



# *Two coils*

- Two magnets with mirror orientation, and reversed current (**RCSM2**).

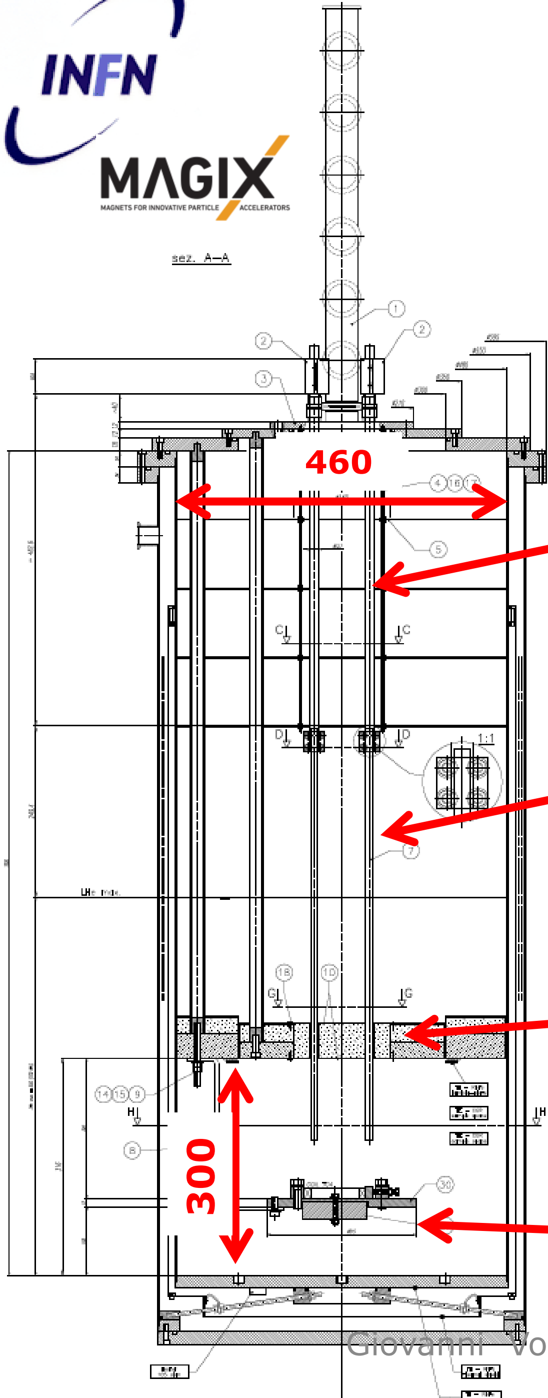



It possesses reflection symmetry w.r.t. a plane normal to *z*-axis, but –surprisingly- it has no other symmetry (apart from 120° for sextupole).

Therefore $\int_{-\infty}^{+\infty} B_z dz = 0$ <u>so not net z-component</u>

But it turns out that its <u>harmonic content is very high</u>, lacking those symmetries which "cancel" specific harmonics.

# Test Station

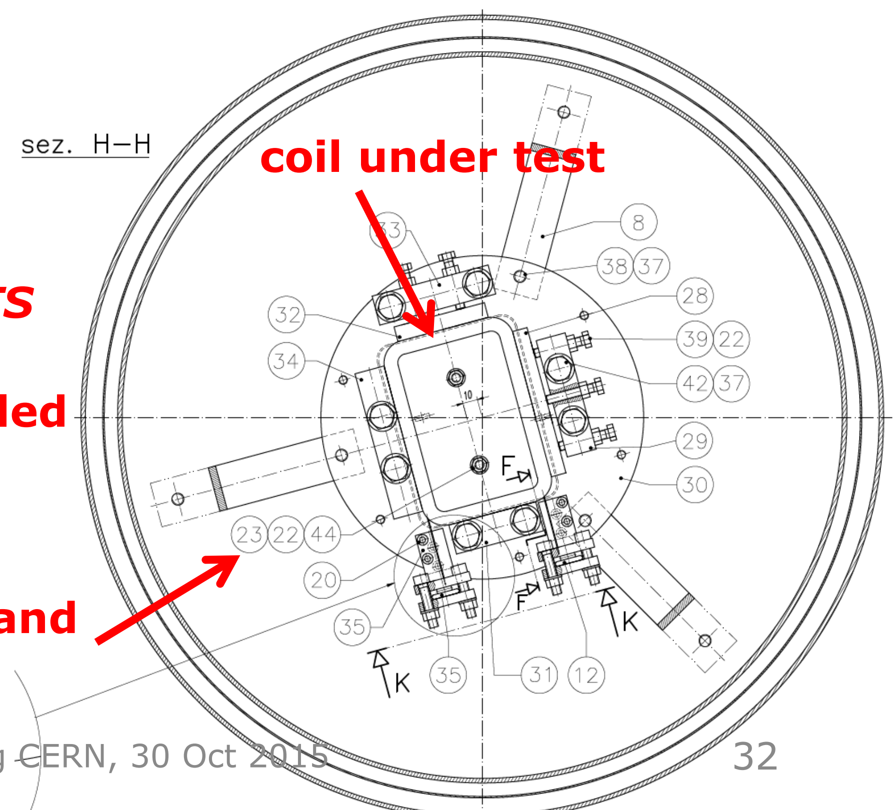



**500 A current leads**

**SC bus-bars**
**Al-clad NbTi SC**
**cable from *Mu2e TS***

**λ-plate for subcooled**
**LHe operation**

**Single coil test stand**
**(later 6-pole …)**



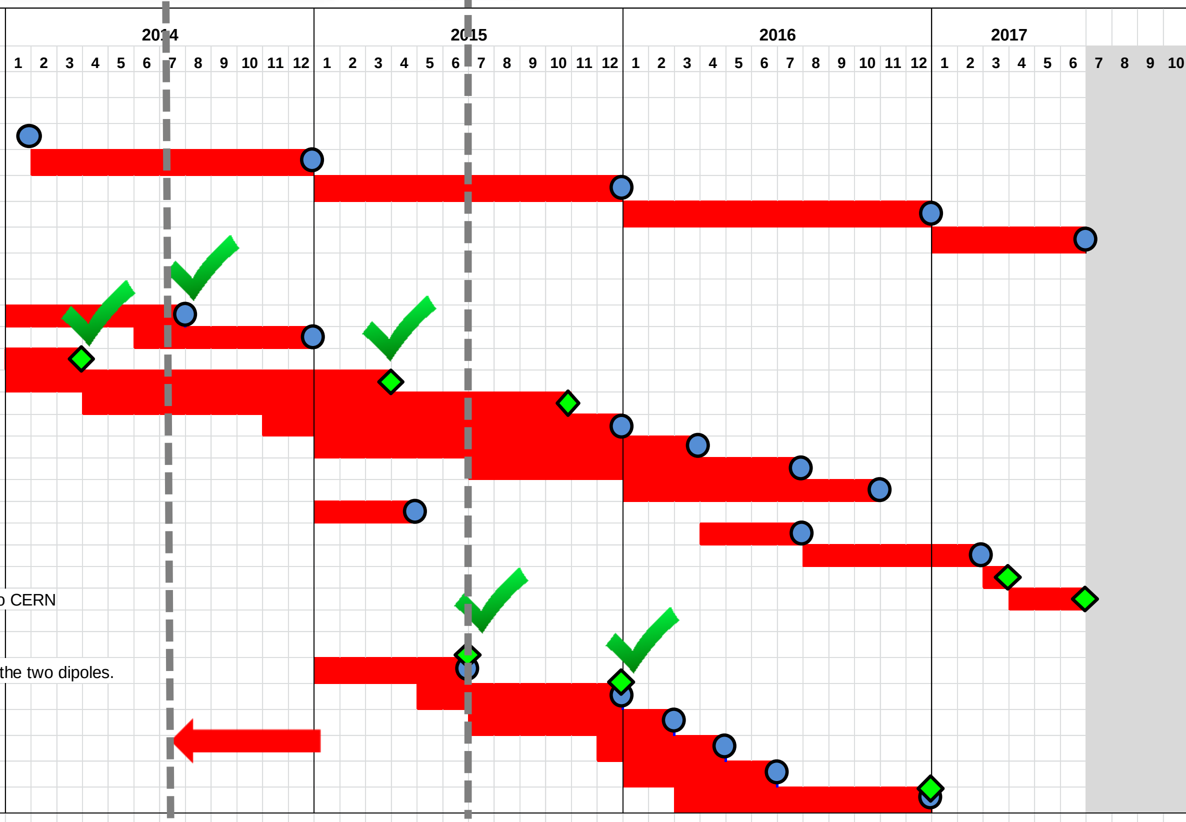
# Schedule

MAGIX — MAGNETS FOR INNOVATIVE PARTICLE ACCELERATORS


## *HiLumi-MAGIX schedule*

*v. February 2014*

| | | | | | |
|---|---|---|---|---|---|
| **WP0** | | | | | **Project Management** |
| | **M 0.1** | | Feb 2014 | | Kick-off meeting with specification transfer |
| | **M 0.2** | | Dec 2014 | | 1st year activity monitoring |
| | **M 0.3** | | Dec 2015 | | 2nd year activity monitoring |
| | **M 0.4** | | Dec 2016 | | 3rd year activity monitoring |
| | **M 0.5** | | Jun 2017 | | 4th year activity monitoring |
| **WP1** | | | | | **CORRAL** |
| | **M 1.1** | | Jul 2014 | | Sextupol engineering design. |
| | **M 1.2** | | Dec 2014 | | Sextupol construction. |
| | | **D 1.1a** | Mar 2014 | * | Preliminary 2D design of the five magnet types |
| | | **D 1.1b** | Mar 2015 | * | Preliminary 3D design of the five magnet types |
| | | **D 1.2** | Oct 2016 | | Executive design of the five magnet types |
| | **M 1.3** | | Dec 2015 | ** | MgB2 quadrupole design. |
| | **M 1.4a** | | Mar 2016 | *** | Octupole and decapole construction |
| | **M 1.4b** | | Jul 2016 | *** | Quadrupole and dodecapole construction |
| | **M 1.5** | | Oct 2016 | | MgB2 quadrupole construction |
| | **M 1.6a** | | Apr 2015 | **** | Test of the sextupole |
| | **M 1.6b** | | July 2016 | **** | Test of the octupole and decapole |
| | **M 1.6c** | | Feb 2017 | **** | Test of the dodecapole and quadrupole |
| | | **D 1.3** | Mar 2017 | | Corrector magnet test report |
| | | **D 1.4** | June 2017 | | Corrector magnets final check, packing and transport to CERN |
| **WP2** | | | | | **PADS** |
| | **M 2.1** | **D 2.1** | June 2015 | | 2D magnetic design to minimize the cross talk between the two dipoles. |
| | **M 2.2** | **D 2.2** | Dec 2015 | | 2D mechanical design. |
| | **M 2.3** | | Feb 2016 | | 3D magnetic design including the coil ends. |
| | **M 2.4** | | Apr 2016 | | Quench preliminary analysis. |
| | **M 2.5** | | Jun 2016 | | 3D mechanical design with the axial pre-load study. |
| | **M 2.6** | **D 2.3** | Dec 2016 | | Final Engineering design. |



***Notes***

* These two deliverables are grouped in one in the MAGIX project

** Note the change of scope wrt to the MAGIX project

*** These two milestones are grouped in one in the MAGIX project

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***Explanation***

**Activity**

**Milestone**

**Deliverable**