PSB Quadrupole

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TE-MSC-NCM

APPROVED by CONS

PSB Main Quadrupole Magnets

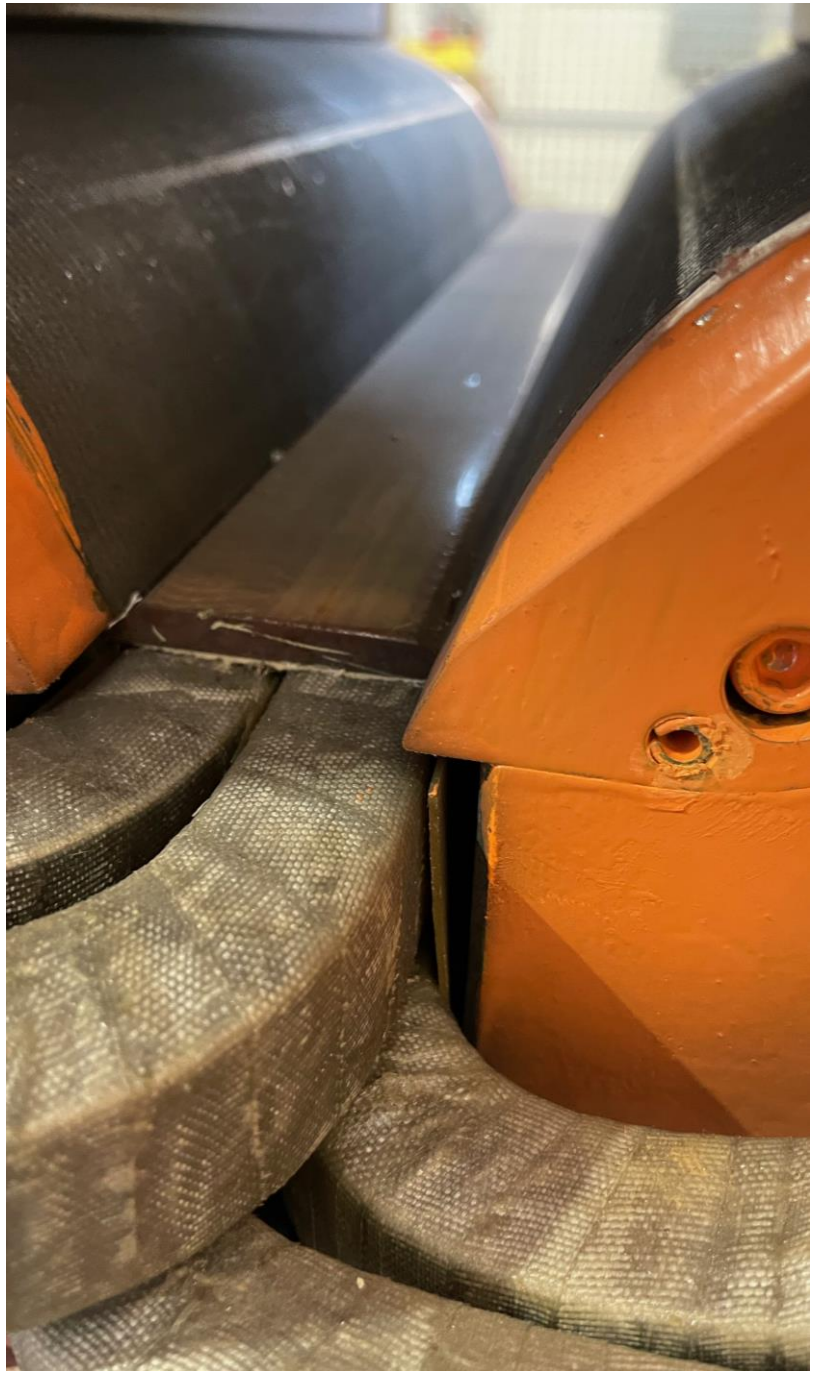
Design Code	Old Code	Installed	Spare	Description
PXMQNEC4WP	**QFO** left	**16**	**2***	Removed from the ring during the YETS 21/22, both spare magnets are under repair and have non-conformities linked to brazed joint*
PXMQNED4WP	**QFO** right	**16**	**1**	Certified Spare (was in operation for 40+ years)
PXMQNFA4WP	**QDE** left	**8**	**1**	Certified Spare (never installed)
PXMQNFJ4WP	**QDE** right	**8***	**1**	Certified Spare (never installed), magnet exchange during YETS22/23
		48		

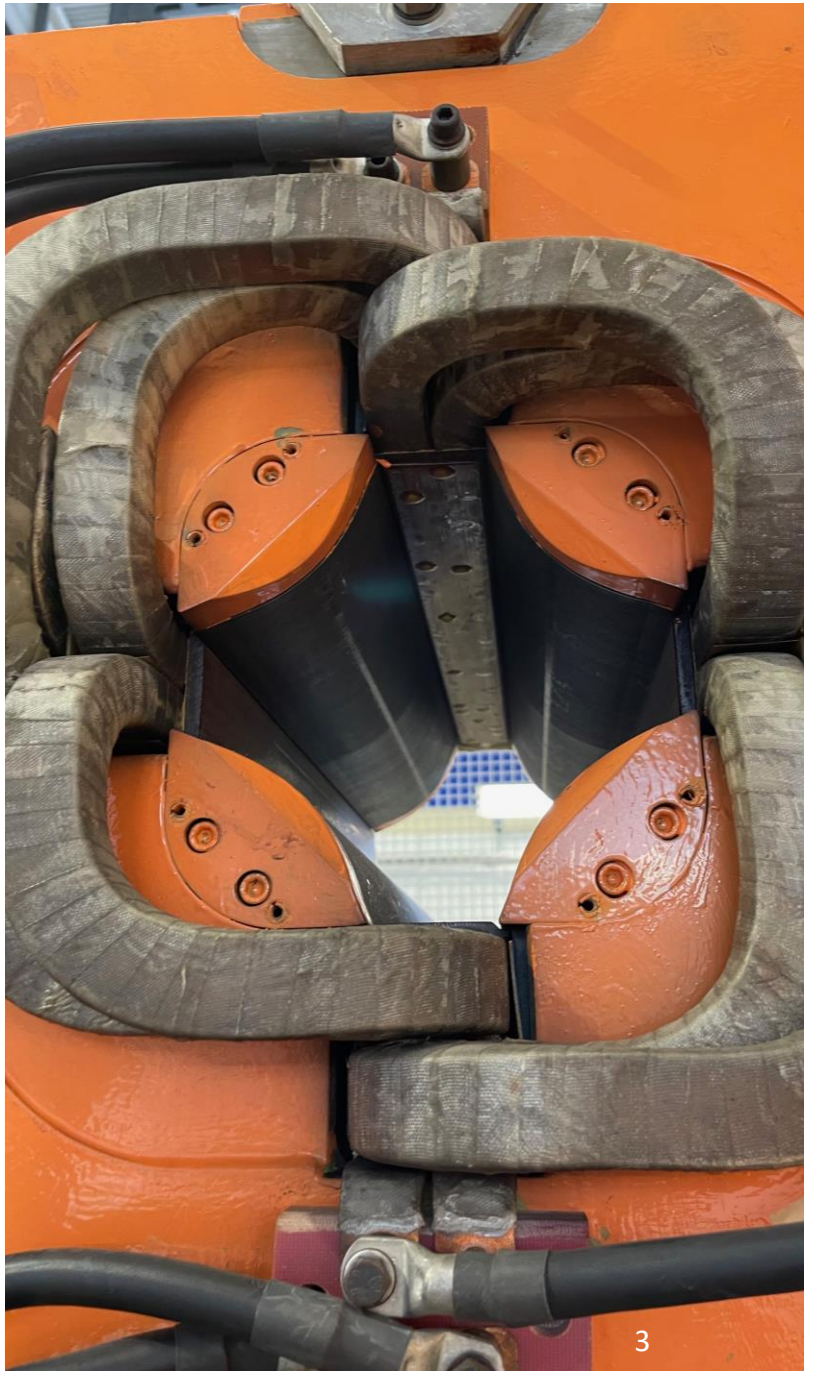
A Unique Construction!

- Single lamination (no split planes)
- Coil built-up turn by turn (~80 brazed joints/magnet)
- Mica/glass fiber insulation tape with the whole magnet resin impregnated (true VPI method based on autoclave, not available at CERN)
- Reliable operation over nearly 50 years

NO LEAKS UNTIL 2021, FIVE OCCURRED SINCE THEN!
Preliminary inspections indicate corrosion near brazed connections, presumably accelerated by the presence of Sulphur.

Corrective actions and renovation/new production under investigation by the mandated Task Force.





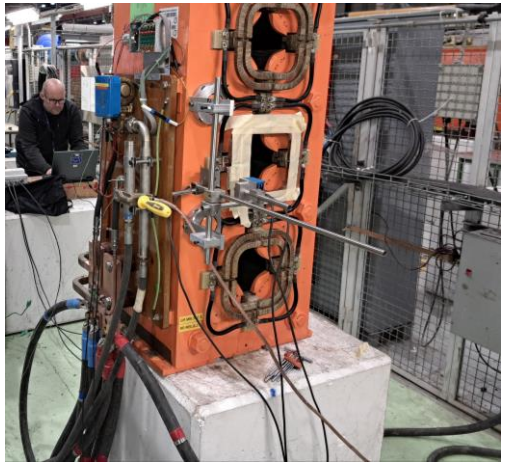
Is the origin of the faults understood?

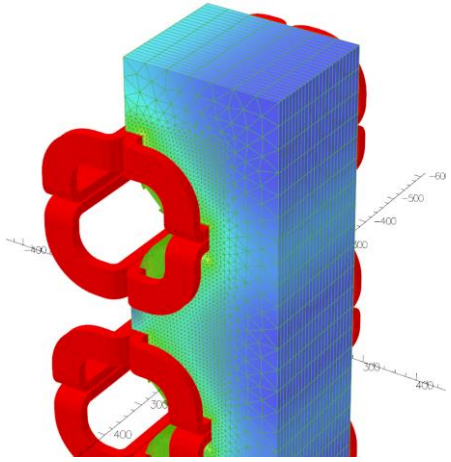
- Ultrasound (EN/MME) and endoscope (TE/MSC) inspections have not identified any erosion of the cooling channel or original brazed joints, further checks will be made on the QDE5 magnet once removed from the machine.

- SEM analysis (EN/MME) of the brazing confirms Ag-Cu-P brazing including traces of Cadmium material (which is a typical brazing filler to avoid flux).

- Simulations show a modest force (~250 N) on the coil and brazed joint, measurements on the spare (repaired QFO91) magnet show no movement during the magnetic cycle.

- Investigation will continue with the QDE5, but clear priority is to make the magnet operational.





Sulfide-Induced Corrosion of Copper-Silver-Phosphorus Brazed Joints in Welding Transformers

A source of moisture was traced to leaking brazed joints within the transformer's secondary winding

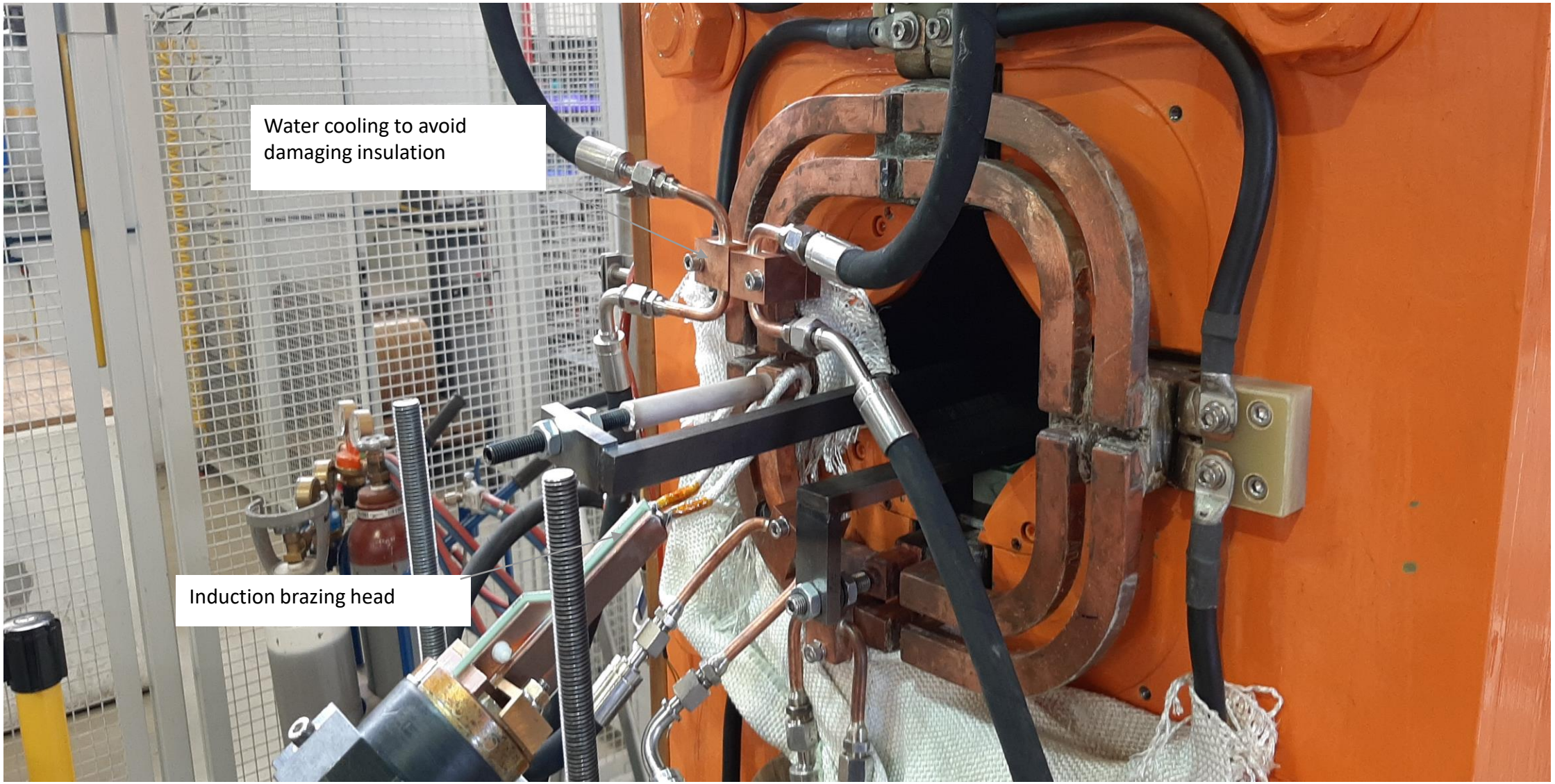
BY D. R. SIGLER, J. G. SCHROTH, Y. WANG, AND D. RADOVIC

- The corrosion consisted of **selective attack of copper within the braze metal as well as the adjoining copper tube and casting**.
- The existence of extensive copper sulfide scale in the winding and particularly at the brazed joint along with the presence of high phosphorus levels within the corrosion products suggests that **the corrosion mechanism was sulfide-induced corrosion that led to formation of phosphoric acid within the joint**.
- This **acid selectively attacked copper** either within the joint or adjacent to it.
- This **mechanism was reproduced in the laboratory** by exposing brazed joints to sulfide-contaminated deionized water at elevated temperature.

- **Copper phosphide phase is more noble than the copper phase** in Cu-P filler metals. Hence the more active copper will always tend to be attacked preferentially during galvanic corrosion.
- The selective attack of copper within and adjacent to copper phosphide joints is postulated to be caused by **sulfide-containing species in the water that form a sulfide scale** on the braze and copper component surfaces. Beneath the **sulfide scale, the local solute environment changes, which catalyses the formation of phosphoric acid in the braze joint**.

Transformer case: Cont…

- Closed-loop weld water systems are uniquely vulnerable to the action of sulfate-reducing bacteria (SRBs) that can grow in anaerobic environments. These bacteria can act to reduce innocuous sulfate ions into aggressive sulfide species that could promote the corrosion observed in transformers.
- The mechanism of sulfide-induced corrosion specifically for the braze alloys is not well understood, however, considerable work has been done to study the effects of sulfide on copper and copper-nickel alloys.
- As little as 10 ppb of sulfide can accelerate corrosion (Ref. 18).
- Once the sulfide scale is established on the metal surface, removing sulfide from the water does not return the corrosion rate back to that of sulfide-free metal in clean water, but rather the accelerated corrosion rate will remain.



Induction Brazing repair of the PSB QFO91 Quadrupole

Future Actions – Be Prepared!

In anticipation that future repairs are unsuccessful or not possible (ground or interturn shorts etc..), or the failure rate increases, it is proposed to already study and prepare to completely rebuild the magnets.

For this we propose a two-stage approach followed by the eventual renovation campaign:

Stage 1 – Study and dummy trials (~1 year & 170 kCHF)

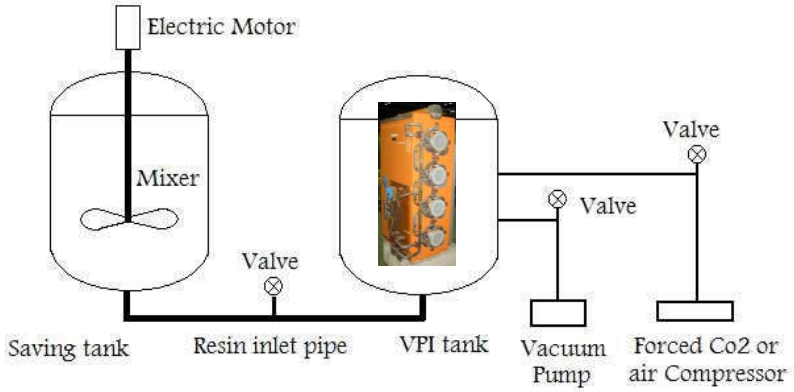
- Study current method and alternative method of impregnation;
- Order of raw material for dummy trials and to refurbish at least 6 magnets;
- Perform dummy assembly;
- By end of 2023, process validation and submission of full consolidation request.

Stage 2 – Consolidation request including series tooling and infrastructure (~1 year & 420 kCHF)

- Final definition and production of tooling;
- Part production;
- Infrastructure
  - VPI system
  - Curing oven

Renovation campaign of 6 magnets (~360 kCHF):

- FSU (0.6 per magnet)



Typical VPI System

Future Actions – Be Prepared!

	Estimated Cost (kCHF)	Estimated Date	Comment
STAGE 1			
Design office study	15	12/22 – 2/23	Operation Budget
Copper for 3 QD / 3 QF	54	06/23	" "
Copper forming (Dummy)	15	06/23 -09/23	" "
Insulation + Resin (3QD + 3 QF)	20	06/23	" "
Dummy ½ Yoke (2 apertures)	16	06/23	" "
Dummy Assembly (FSU)	30	09/23 – 12/23	" "
Impregnation of Dummy with industrial partner + validation	20	09/23 – 12/23	" "
Total	170		
STAGE 2			
Design Office, series tooling etc…	20	01/24 - 04/24	CONS Budget
Series tooling	30	from 01/24	" "
Copper forming (3 QD & 3 QF)	55	from 01/24	" "
Additional material for 6 magnets (Qstrip copper, shimming etc…)	30	from 01/24	" "
Infrastructure			
VPI System	250	Depending on Study	CONS Budget
Oven	40	Depending on Study	" "
Total	**420**		
Renovation Campaign of 6 magnets			
FSU (0.6 per magnet)	360	Depending on Study	Operation Budget
STAGE 1 + STAGE 2 + Renovation Campaign of 6 magnets*	**948**		

*Does not include the cost of exchanging the magnets in the machine, for example vacuum/transport/survey works.

In addition, other magnets such as the orbit correctors (PXMCCAAWAP) may need to be exchanged with the quadrupoles as is the case this YETS during the QDE5 replacement. A set of coils for each stack costs ~60 kCHF, for which our stock will soon be depleted.

Future Actions – Be Prepared!

We could soon face the situation where multiple failures can no longer be covered by the current spare situation or initial proposal to replace and renovate the magnets.

Along with the complete renovation campaign of the existing magnets, 0.6 MCHF + 0.6 FTE per magnet (stripping down the existing magnets and replacing the coils). Two more drastic solutions could be imagined:

- We propose to build 12 additional spares ~ 2.4* MCHF (4 of each QF left and right and 2 of each QD left and right).
- These magnets would need to be integrated into the machine as new designs and would probably need separate trim circuits to compensate the differences between the old and new yokes.
- A coffee discussion with OP has confirmed that this could be feasible but would need to be discuss with all involved.
- Eventually we will still need to rebuild all/most of the radioactive original magnets (0.3** FTE plus 25 kCHF per magnet) ~ 5.3 MCHF with the risk of significant downtime

- Maintaining the current magnets until say LS3, while in parallel building a complete new set of quadrupoles (32 QF and 16 QD plus 4 spares) ~10* MCHF

** Rough estimate of 200 kCHF per magnet*
*** One would assume that after the initial learning curve the renovation campaign would be optimized to ~3-4 months or less. The eventual vacuum, transport work remains the same and is not considered above.*