CERN

Magnet ageing at CERN?

Antony Newborough on behalf of TE/MSC-NCM

Magnet ageing at CERN…

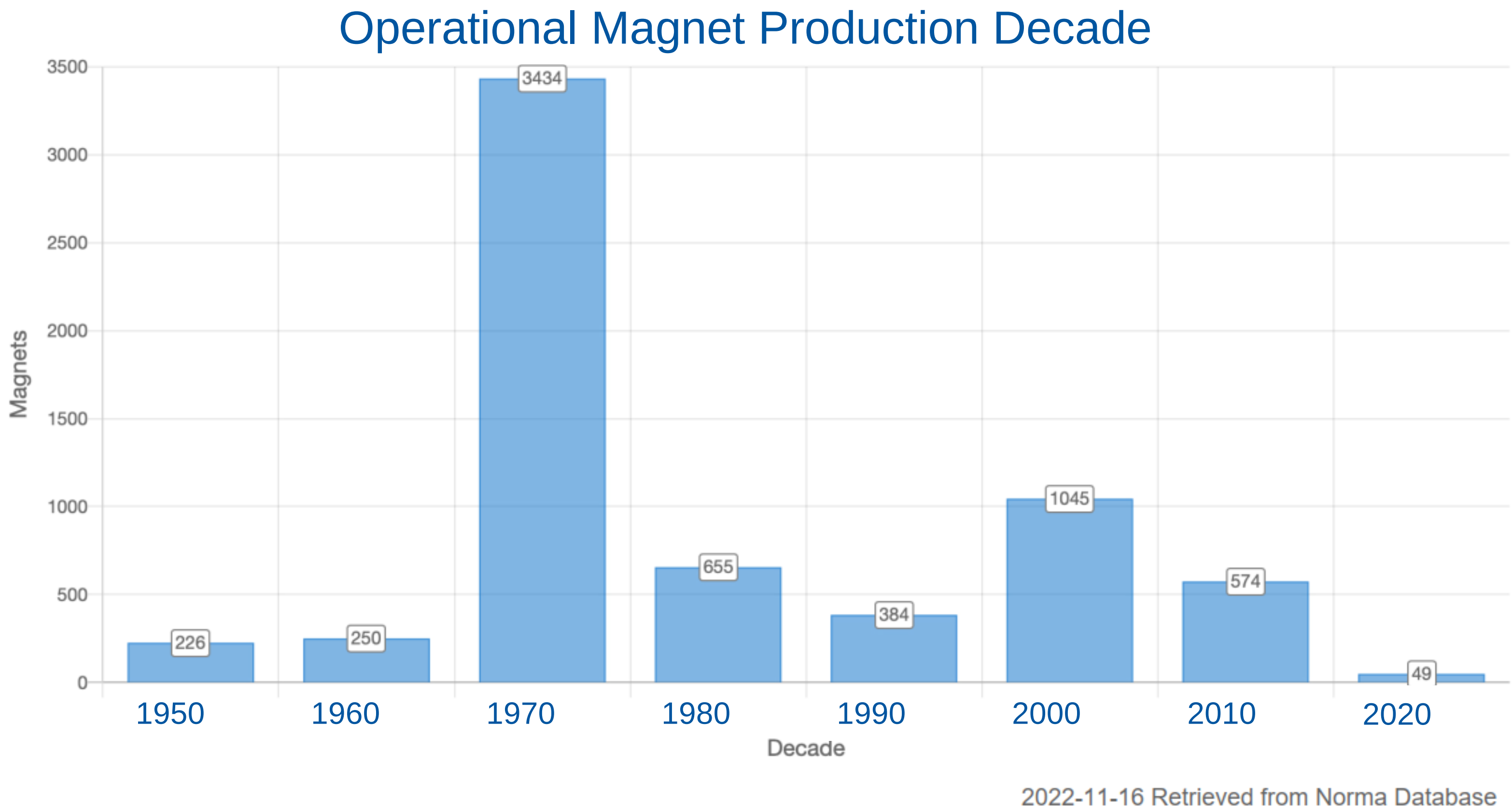
- Introduction:
  - Distribution of magnets by age;
  - Section mandate;
  - Risk assessment and consolidation actions.

- PSB magnet ageing:
  - PSB main quadrupole magnets
    - Evolution of the faults over the past 2 years;
    - Is the origin of the faults understood?
    - Actions put in place to minimize impact on operation;
    - Strategy for the future: spares? Consolidation project?
  - PSB main dipole magnets.

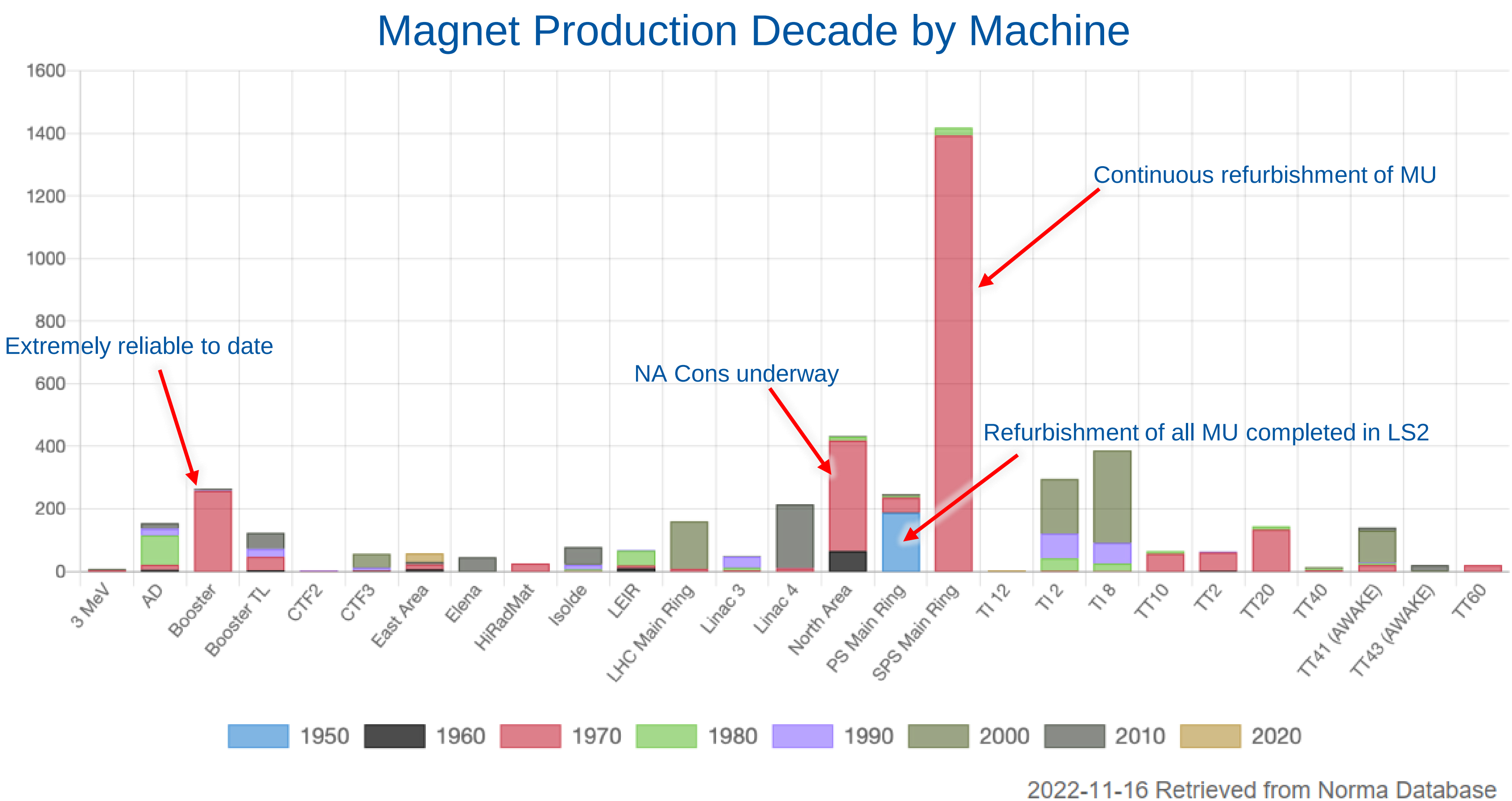
- AD target area magnet ageing:
  - Quadrupoles DI.QDE6010 & QFO6020
  - Bending magnets DI.BHZ6024 & 6025

- Conclusions

Magnet ageing at CERN…



Magnet ageing by machine…



Section Mandate:

Ensure the reliable operation of the NC magnet systems in the CERN accelerator complex until 2040

How we do this and more at the consolidation exercise:

https://edms.cern.ch/document/2787034

What we do…NCM Operation

- **Main activity is preventive/corrective maintenance of NC magnet systems:**
  - **Interventions and inspections** in the CERN accelerator complex
  - **Renovation** of (spare) magnets:
    - Disassembly
    - Replacement of coils
    - Repairs and upgrades of hydraulic circuits and instrumentation
    - Certification
  - **Fabrication** of new magnets (with industry and at CERN):
    - Coils
    - Magnet cores
  - **QA** – NORMA magnet database, risk analysis and spare inventory.

https://norma-db.web.cern.ch

What we do… Continuous maintenance

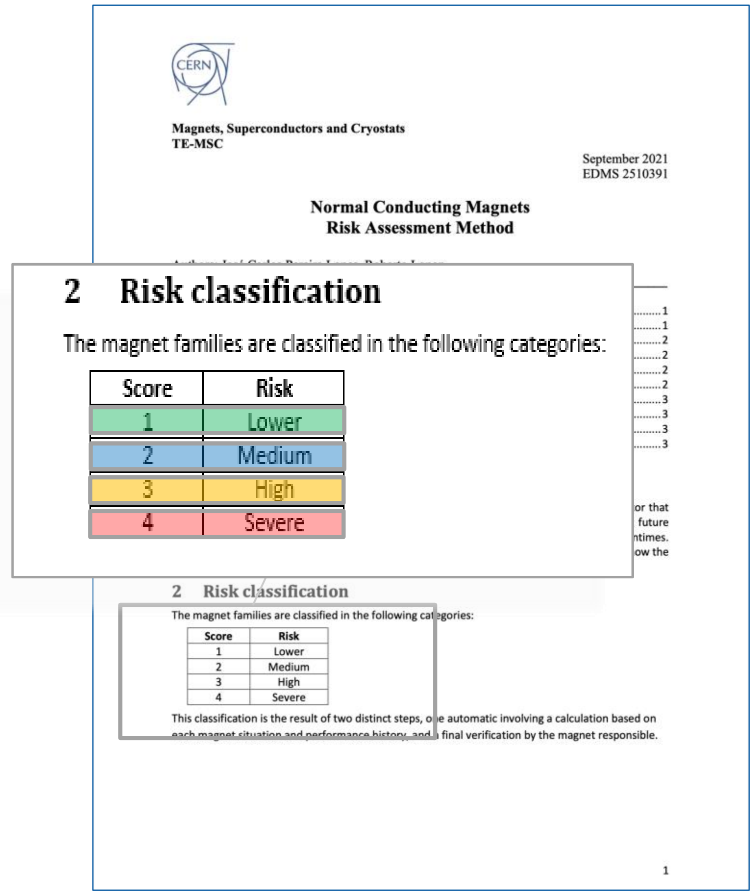
System	Magnet type	Total to renovate	No per year	man-w/magnet	man-w/year	FTE/year
SPS	Main dipoles MBA/MBB	746	10	6	60	1.30
SPS	Main quadrupoles QD/QF	216	5	8	40	0.87
SPS	Main quadrupoles QDA/QFA	18	1	10	10	0.22
AD	Main bend (6/24 remaining)	6	1	7	7	0.15
AD	Main QN (15/30 remaining)	15	2	5.5	11	0.24
PSB	Quad (Q130)	15	2	5.5	11	0.24
PSB	Correctors (type 1)	4	4	4	16	0.35
PS	Straight section magnets	15	5	6	30	0.65
PS	Bus bars	5	5	6	30	0.65
Linac3	Quadrupoles	2	1	6	6	0.13
Leir	Secondary magnets	2	1	6	6	0.13
n_Tof	Bending M100	3	1	8	8	0.17
3 MeV	Bending magnet	4	1	8	8	0.17
TT2	Spare quadrupoles	4	2	6	12	0.26
NA	Various "problematic families"	200	10	6	60	1.30
LHC	MSI/MSD	15	5	3	15	0.33
LHC	MQW	6	1	16	16	0.35

Highlighted in spare slides

Continuous maintenance performed in 2021

What we do…
Normal Conducting Magnets Risk Assessment

- **Goals**:
  - Minimise interruptions on CERN physics programs directly caused by the magnet systems
  - Prioritisation of consolidation and renovation activities to make the best use of our limited resources
  - Activity planning of NCM-workshops
  - Basis for the CONS-requests
- **Classification** of all NC magnet types by:
  - **spare situation and failure statistics**
  - **expected down-time in case of failure** requiring a replacement of the magnet
- **General Priority: Protons - Ions - Experimental**



Magnets, Superconductors and Cryostats
TE-MSC

September 2021
EDMS 2510391

Normal Conducting Magnets
Risk Assessment Method

2 Risk classification

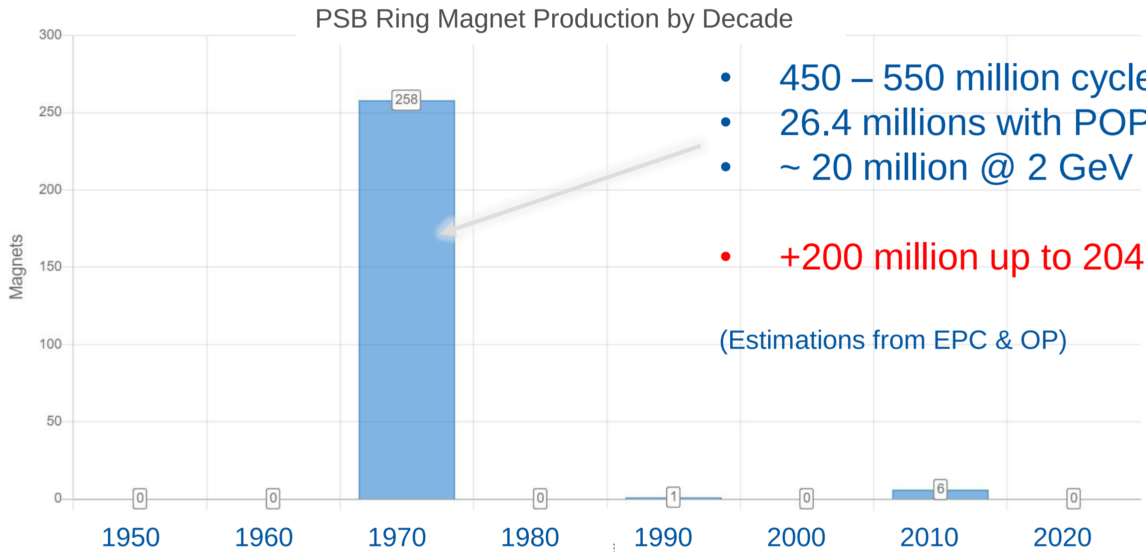
The magnet families are classified in the following categories:

Score	Risk
1	Lower
2	Medium
3	High
4	Severe

This classification is the result of two distinct steps, one automatic involving a calculation based on each magnet situation and performance history, and a final verification by the magnet responsible.

https://edms.cern.ch/document/2510391

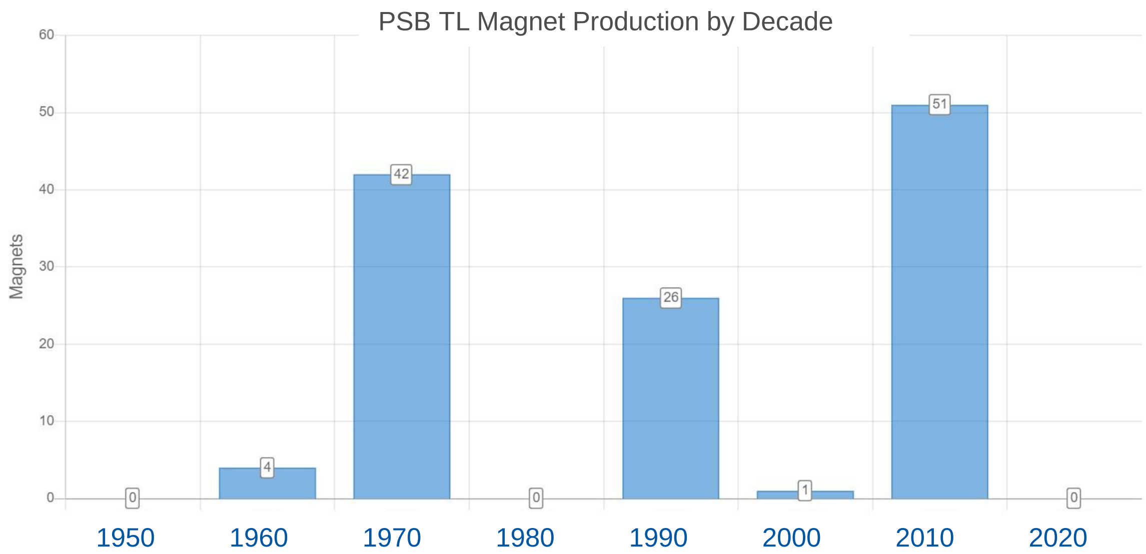
PSB magnet ageing

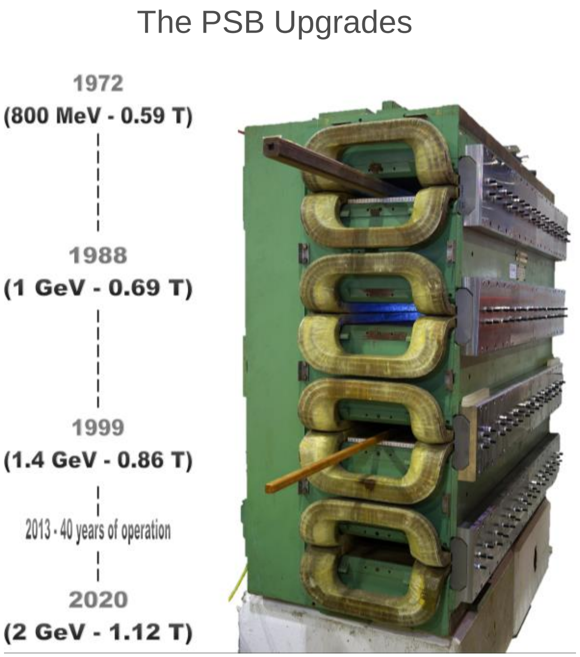


- 450 – 550 million cycles
- 26.4 millions with POPS-B and
- ~ 20 million @ 2 GeV

- +200 million up to 2040?

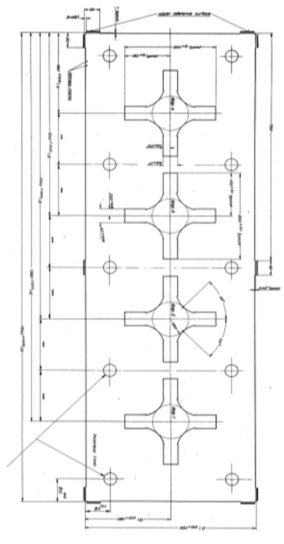
(Estimations from EPC & OP)

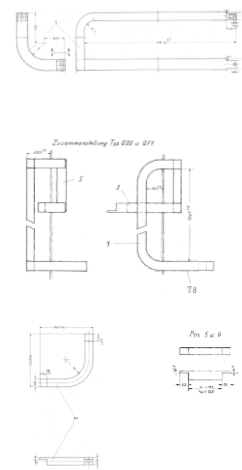




PSB quadrupole magnet ageing

REMINDER: Until 2021 the only PSB quadrupole exchange was due to a vacuum leak!





A Unique Construction!

- Single lamination (no means to open the magnet)
- Coil built-up turn by turn (~76 brazed connections per magnet, ~3650 in operation)
- Mica/glass fiber insulation tape with the whole magnet resin impregnated (true VPI method which CERN is not equipped)

ZERO LEAKS UNTIL 2021 AND THREE SINCE!

Design Code	Old Code	Installed	Spare	Comment
PXMQNEC4WP	QFO LEFT	16	2*	Removed from the ring during the YETS 21/22, both spare magnets have now been repaired and certified.
PXMQNED4WP	QFO RIGHT	16	1	Certified Spare (was in operation for 40+ years), to be installed in place of BR.QFO52 during YETS 22/23
PXMQNFA4WP	QDE left	8	1	Certified Spare (never installed)
PXMQNFJ4WP	QDE right	8*	1	Certified Spare (never installed) to be installed in place of BR.QDE5 during the YETS 22/23
		48	5	

PSB Quadrupole status

*Non-conformity reports:
https://edms.cern.ch/document/2664838
https://edms.cern.ch/document/2603476
https://edms.cern.ch/document/2779972

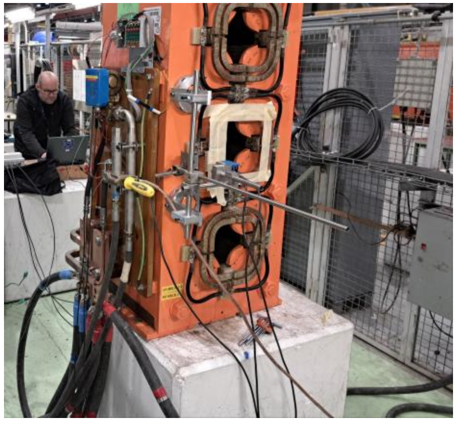
Is the origin of the faults understood?

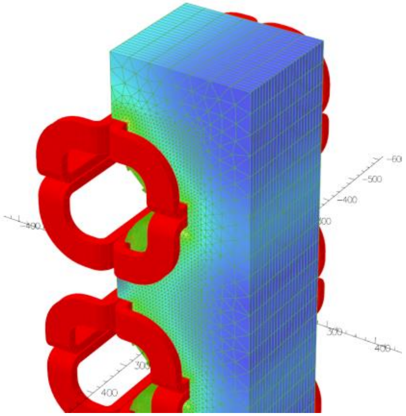
- Ultrasound (EN/MME) and endoscope (TE/MSC) inspections have not identified any erosion of the cooling channel or original brazed joints in either case, further checks will be made on the QDE5 magnet once removed from the machine.

- SEM analysis (EN/MME) of the brazing confirms a Copper / Silver / Phosphorus 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.





Inspections, measurements and simulations of the PSB Quadrupole Magnets

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:

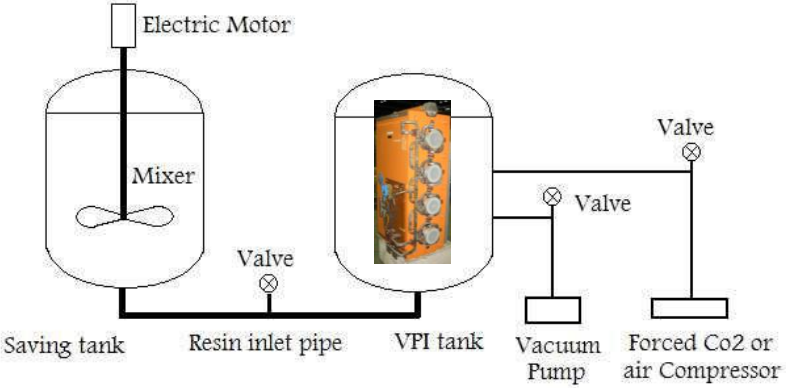
Stage 1 – Study and dummy trials (~1 year & 170 kCHF)

- 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.

PSB Dipole magnet ageing

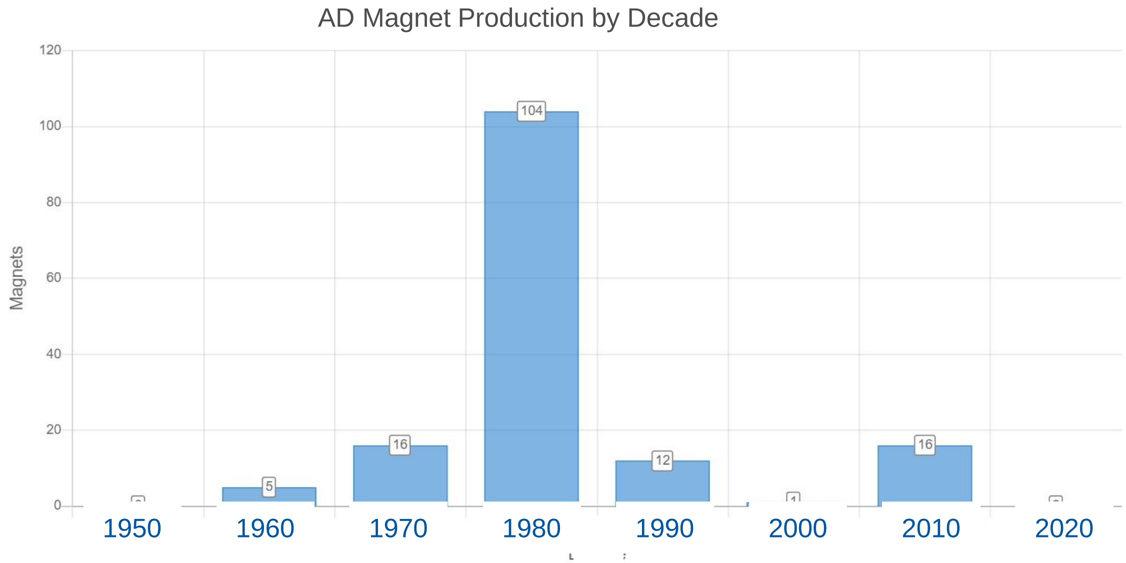
Design Code	Old Code	Installed	Spare	Comment
PXMBHGC4WP	BHZ	30+1	1	30 'normal' main bending magnet + 1 reference magnet + 1 spare + 1 complete set of coils
PXMBHGE4WP	BHZ INJ	1	1	'Special' injection magnet + 1 spare (Coils were upgraded for 2 GeV)
PXMBHGD4WP	BHZ EXT	1	1	'Special' extraction magnet + 1 spare (Coils were upgraded for 2 GeV)

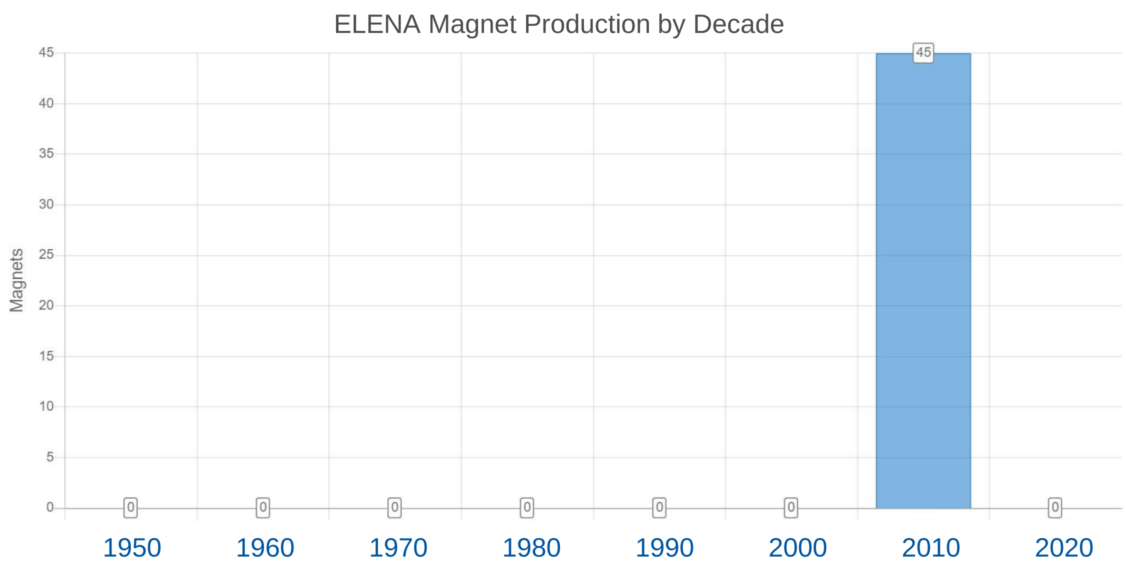
PSB bending magnet status

Very reliable magnet with no real downtime in 50 years of operation!

- Single lamination, upgraded with new closing plates to reduce saturation for 2 GeV operations, at the same time taking the advantage of improving the coil shimming;
- Includes ~35 hydraulic brazing (Silver/Phosphorous based) per magnet and more than 1100 in operation!
  - except for 1 internal brazing, all repairs could in theory be completed in-situ.
- Other than an issue with the new special injection and extraction trim coils, all other issues have been minor and are kept under control with regular maintenance work (revision of interlocks, changes of hoses etc.)
- If multipole failures did occur, we could soon use our 'original' spare coil stock and it may be prudent to consider ordering additional spares now that we have reached 50 years of operation, 1 - 2 years lead time.

AD magnet ageing





Continuous refurbishment campaign of main magnets are highlighted in the spare slides

AD target area magnet ageing – Quadrupoles DI.QDE6010 & QFO6020

- QDE6010, PXMQNFGFWP – 1990:
  - No direct spare magnet available, however the QFO6020 spare is compatible, and we are building spare coils, available end 2023

- QFO6020, PXMQNFHFWP – 1990:
  - Installed magnet has NC which could lead to failure in the coming years
    - https://edms.cern.ch/document/2720507/1
  - Spare magnet has NC and requires new coils – action is underway, available mid 2023
    - https://edms.cern.ch/document/2664817/1

- An alternative low current (4 kA > 400 A) solution is being studied (see spare slides)
  - ~2 years procure (still need to complete the ongoing coil manufacture);
  - ~380 kCHF for 2 + 1 spare, a common design is to be proposed for the two magnets;
  - funding maybe possible if we rescope the SY/EPC consolidation program.

- In the meantime, an effort (SY/EPC) to increase the lifetime by modifying the timing has now been made by reducing the number of pulses by up 80% (Pulsing ~10 times before beam compared to every 2.4 s in the 102 s cycle).

Existing PXMQNFHFWP design and spare coil production

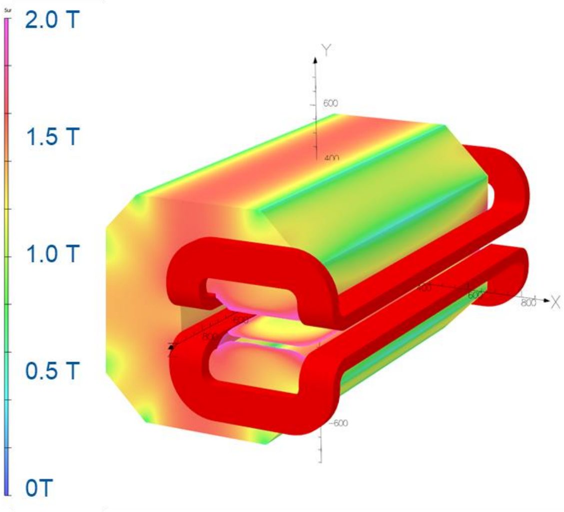
AD target area magnet ageing – Bending magnets DI.BHZ6024 & 6025 (PXMBHFECIP) - 1986

- Single turn ~70 kA magnet operated with a pulsed converter (5 kV) and local transform (18:1);
- Magnets have been exchanged several times over the last few decades;
- The current BHZ6025 has a NC and will be exchanged during the YETS22/23 for the new spare;
- After YETS 22/23 – Both spare magnets will have non-conformities and the need for an additional spare cannot be excluded (120 kCHF).

- An alternative low current (68 kA > 400 A) solution is being studied, see spare slides.
    - ~2 years procurement;
    - ~500 kCHF for 2 + 1 spares;
    - Funding maybe possible if we rescope the SY/EPC consolidation program.

- In the meantime, an effort (SY/EPC) to increase the lifetime by modifying the timing has now been made by reducing the number of pulses by up 80% (Pulsing ~10 times before beam compared to every 2.4 s in the 102 s cycle).

Existing PXMBHFECIP design



Low current alternatives

Magnet Ageing - Conclusions

Every year the heart of the accelerator complex is getting older. With no magical cream or elixir of life this isn't going to stop!

PSB Magnet Ageing:

- The PSB is one of the most solicitated machines in terms of magnetic cycles, ~500 million to date. Another 200+ million are needed to get to 2040.
- The magnets has been running without major faults for nearly 50 years, until the last 2 years where we have now seen 3 leaks on brazed connections.
- Even a small increase in failures (1 - 2% of 3650) could require to exchange/repair of all the quadrupole magnets in the machine!
- In the case that we run out of spares we could have to live with leaks for up to 2 years or suffer downtime.
- A study to be able to completely rebuild the quadrupole magnets is proposed, with stage 1 already underway. The total to refurbish 6 quadrupole magnets is estimated at ~1 MCHF.

Magnet Ageing - Conclusions

AD Target Area Magnet Ageing:

- The condition of the AD target area magnets has led to some recent (2021) downtime of the facility. Operation in 2023 must continue with nonconforming installed and spare magnets which require refurbishment.
- Along with the current refurbishment and coil production (MSC), a new timing has been implemented by EPC which should help arrive to LS3.
- An on-going study is being performed looking at the four most critical magnets just downstream from the AD target. If approved, a rescope of the EPC consolidation plan/budget could be performed to not only have new converters but also magnets for a similar cost.

Magnet Ageing - Conclusions

We must maintain and perhaps increase our current refurbishment and maintenance plans to ensure availability until 2040!

Questions?

www.cern.ch

SPARE SLIDES

Evolution of the faults over the past 2 years

BR.QFO161 PXMQNEC4WP-B2000030 – 06/21

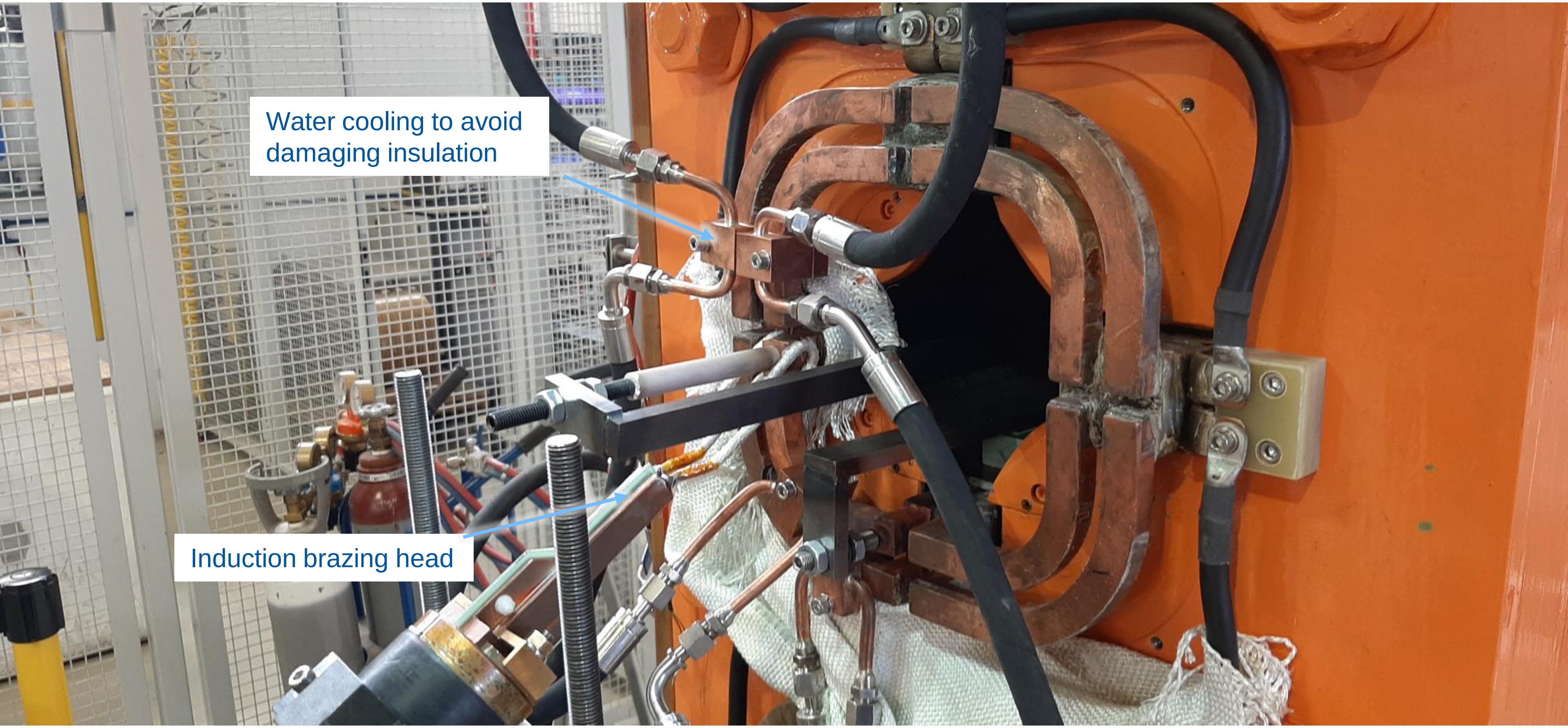
- https://edms.cern.ch/document/2603476
- Leaking brazed joint temporarily repaired in the machine with a soft brazing.
- Removed from the machine in YETS 21/22.
- Hard brazing replaced in the NCM workshop
- Weak insulation to ground ~ 50 MΩ requiring further repair!
- Vacuum bag impregnation to be studied.

BR.QFO91 PXMQNEC4WP-B2000017 – 11/21

- https://edms.cern.ch/document/2664838
- Leaking brazed joint discovered during the High Voltage test during the YETS 21/22.
- Removed from the machine in YETS 21/22.
- Repair has been completed and the magnet is now operational

BR.QDE5 PXMQNFJ4WP-B2000005 – 09/22

- https://edms.cern.ch/document/2779972/1
- Leak brazed joint similar to BR.QFO91
- Operation has continued diverting the water to the tunnel floor
- Magnet exchange planned during YETS22/23

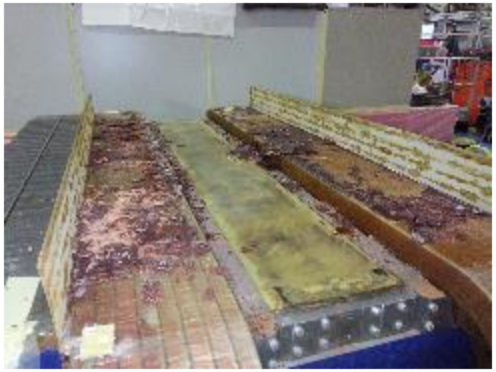


Induction Brazing repair of the PSB QFO91 Quadrupole

What we do… Continuous refurbishment AD Bending magnets, 1986

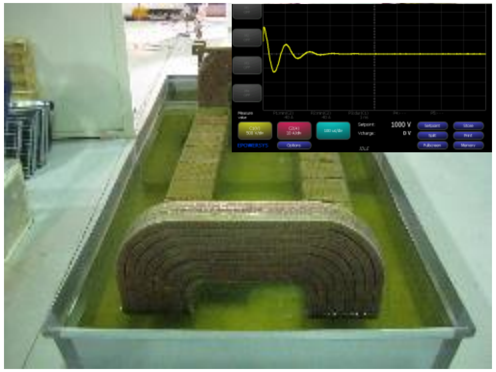
Min. 6 weeks per BHN magnet, max. 2 magnets in the workshop

Opening

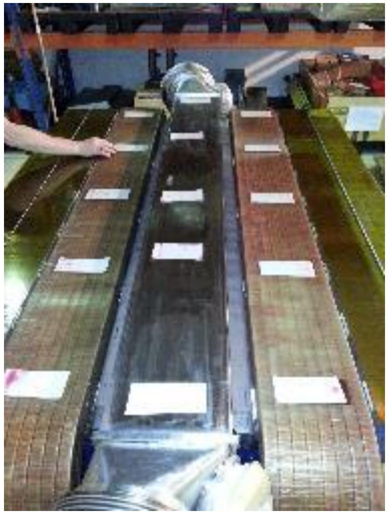


Cleaning

Handling



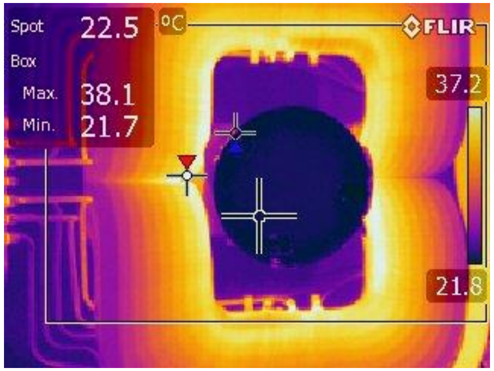
Testing



Measurement & Shimming

Assembly

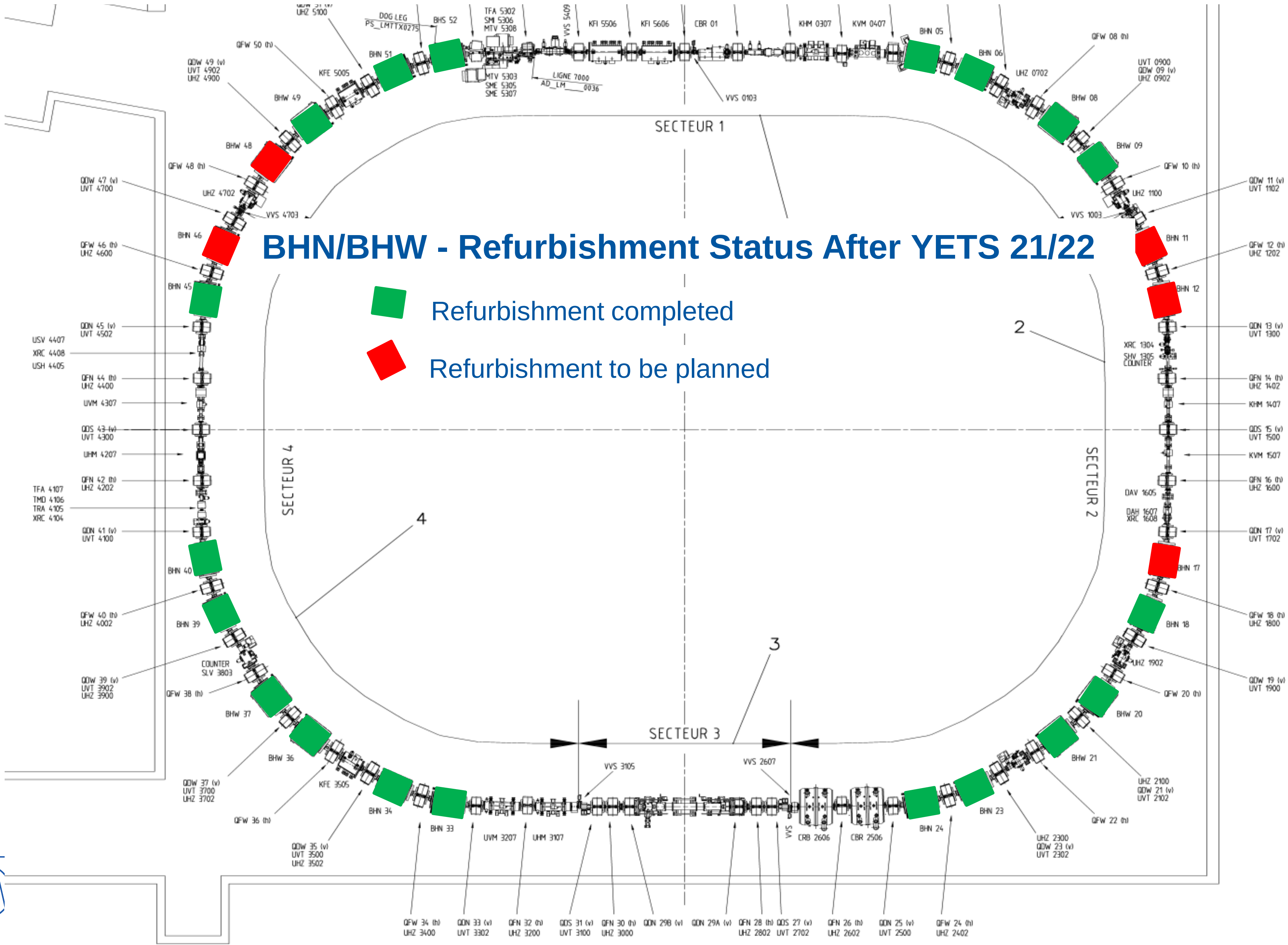
Closing



Certification

What we do… Continuous maintenance AD Bending magnets

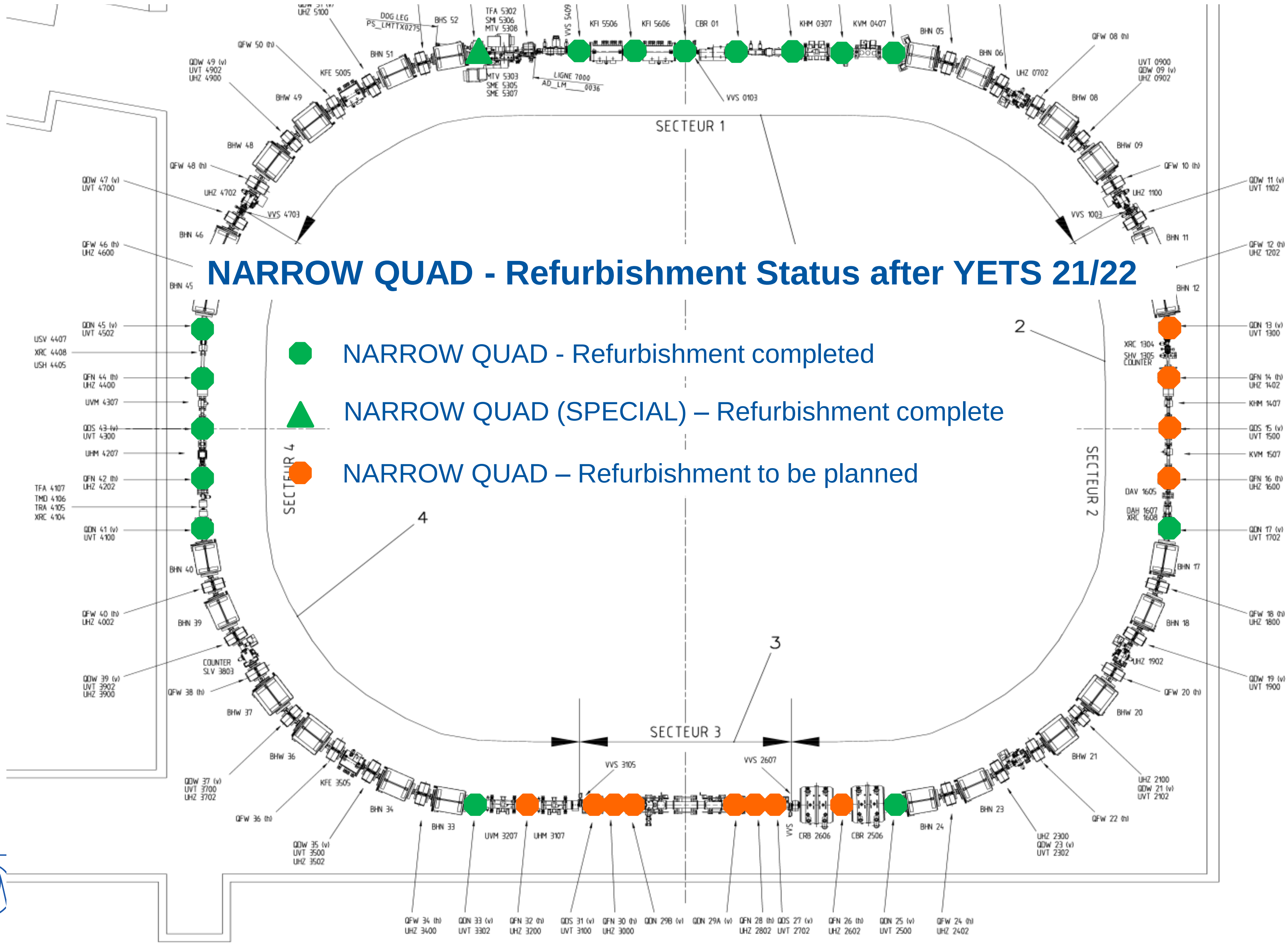
BHN/BHW - Refurbishment Status After YETS 21/22



Refurbishment completed

Refurbishment to be planned

What we do… Continuous maintenance AD Quadrupole magnets



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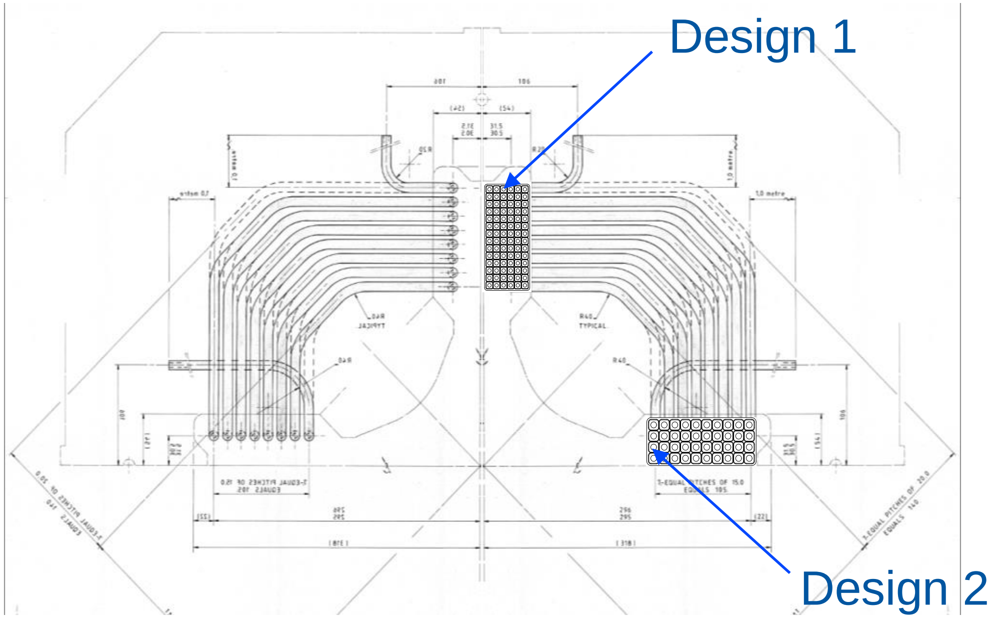
AD target area magnet ageing

- Alternative quadrupole magnets DI.QDE6010 PXMQNFGFWP & DI.QFO6020 PXMQNFHFWP continued…

New PXMQNFGFWP			
	Todays Design	Proposed Design 1	Proposed Design 2
Gradient, T/m*	8.9	8.9	8.9
Int Gradient, T*	8.1	8.1	8.1
Radius, m	0.095	0.095	0.095
Magnetic length, m	0.91	0.91	0.91
Iron Length, m	0.9	0.9	0.9
Current, A	4000	400	800
RMS current, A	75	36	72
Operation	5 pulses/102s	1 pulse/102s	1 pulse/102s
Max RMS current, A	-	200	275
Resistance, Ω	2.8E-02	0.487	0.15
Inductance, H	3.0E-03	0.3	0.075
Turns per pole, #	8	80	40
Cooling	Air**	Air**	Air**
Weight, t	5100	5400	5320

*Calculated, no mm data available - spare could be measured when repaired

** Hollow conductor is used allowing for higher RMS



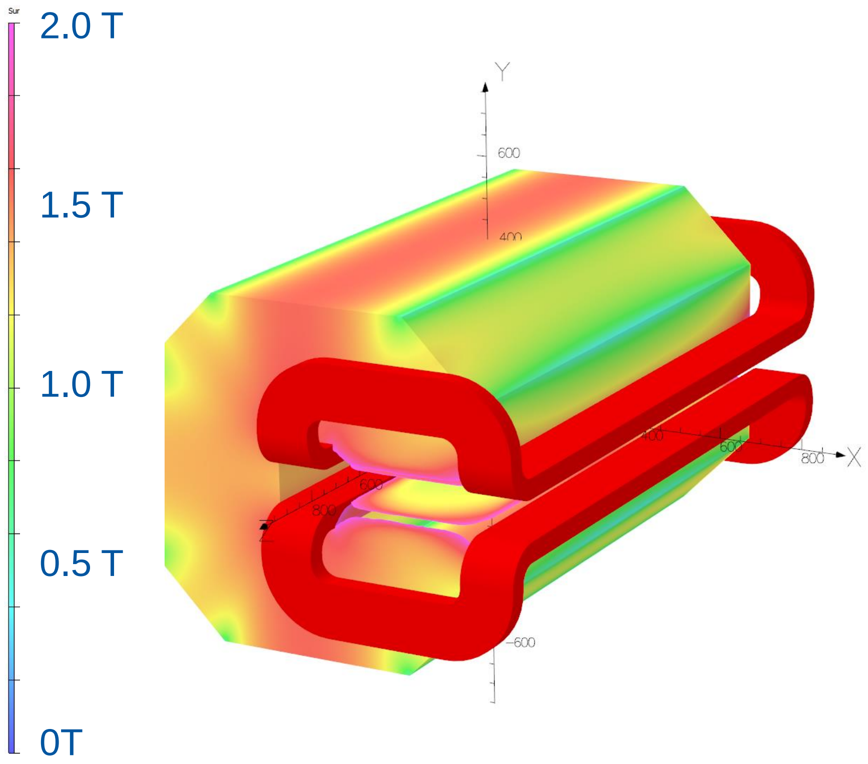
- Yokes (original yoke design)
  - Build 3 QF yokes (reduction in design), ~180 kCHF)
- Build 3 sets of coils (~180 kCHF)
- Assembly and tests, 4 weeks per magnet (23 kCHF)
- Total ~ 383 kCHF
- Availability LS3 (if we choose to maintain the yoke design)

See https://indico.cern.ch/event/1223365/

AD target area magnet ageing

- Alternative bending magnets DI.6024 & DI.6025
  PXMBHFECIP (https://norma-db.web.cern.ch/magnet/idcard/2616/)

New PXMBHFECIP		
	Todays Design	Proposed Design
Dipole field, T	0.92	0.97
Dipole Int/ field, Tm	1.464	1.464
Gap, m	0.088	0.088
Magnetic length, m	1.59	1.51
Aperture width, m	0.322	0.322
Iron Length, m	1.54	1.4
Current, A	68200	364
RMS current, A	1600	35
Operation	5 pulses/102s	1 pulse/102s
Max RMS current, A	-	200
Resistance, Ω	4.0E-05	0.4
Inductance, H	1.0E-05	0.32
Turns, #	1	2 * 96
Cooling	Air	Air
Weight, t	5.25	6.5
** Hollow conductor is used allowing for higher RMS		



See https://indico.cern.ch/event/1223365/