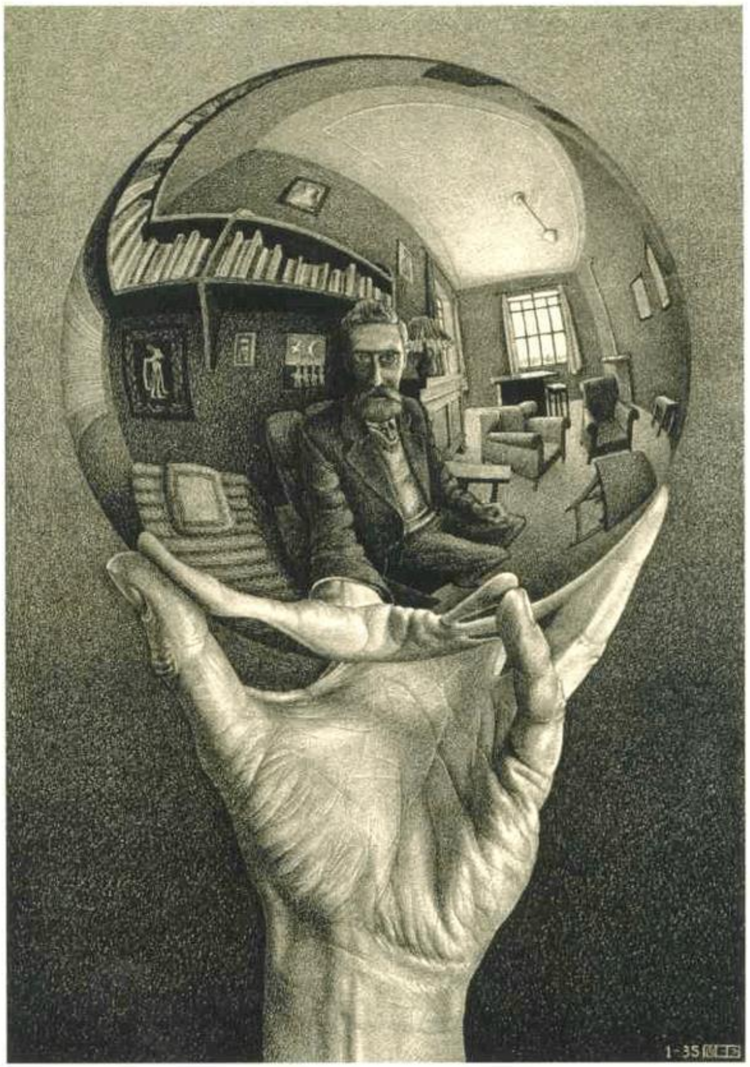
What could stop us,when and how long?

As far as magnets are concerned


M.C. Escher, “Hand with a Reflecting Sphere”, 1935

L. Bottura

Review of LHC & Injector Upgrade Plans Workshop (RLIUP)

Archamps, October 2013

Outline

- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

I will not cover the injectors (see talk from Katy)
I will not cover the arcs (but advocate diagnostic)
I will not cover cooling limits in the present triplet

Outline

- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Sc magnets failure modes

Operational

- Ice blocks causing overpressure

Manufacturing QA

- Joint installation without solder
- Shorts (chips, slivers, debris)
- Mechanical abrasion of insulation

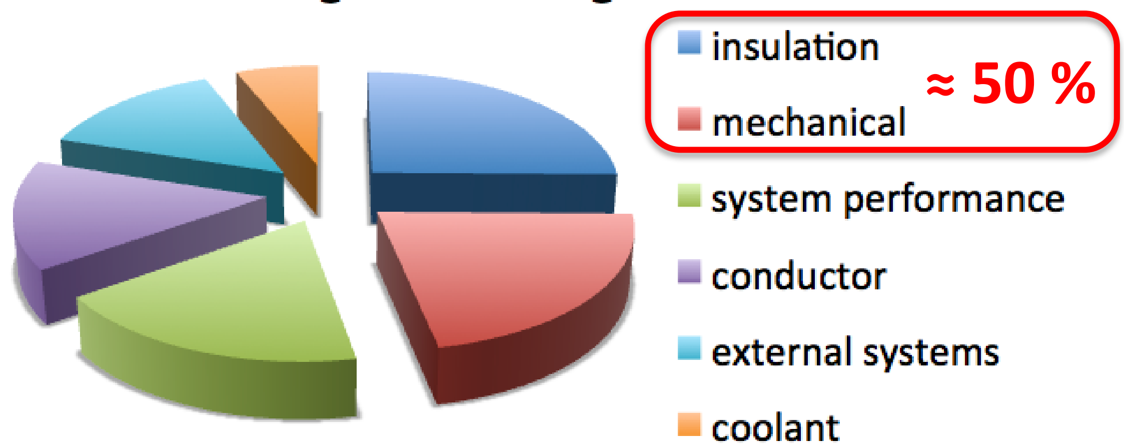
Reliability

- Power supplies/switch control failure

Structural

J.H. Schultz, in Engineering Superconductivity, J. Wiley & Sons, 2001

Origins of SC magnet failures



Y. Iwasa, Case Studies in Superconducting Magnets, Plenum Press, 1994.

Table 1.0: CLASSIFICATION OF FAILURES

		# entries
1.0 MECHANICAL SUPPORT RELATED		
1.1 unantisipated stress distribution		3
1.2 excessive motion		11
1.3 structural failure		4
1.4 mechanical componant failure		2
1.5 loose parts		2
1.6 support link failure		2
1.7 heat shield mechanical failure		1
Subtotal	25	
2.0 CONDUCTOR RELATED		
2.1 conductor damage		1
2.1.1 conductor breakage		0
2.1.2 resistive conductor		1
2.1.3 overheating of conductor		3
2.1.4 conductor burnout		1
2.2 joint failure		2
2.3 lead burnout		10
Subtotal	17	
3.0 INSULATION RELATED		
3.1 insulation mechanical failure		2
3.2 insulation electrical failure		
3.2.1 ground fault		12
3.2.2 terminal fault		0
3.2.3 interpancake fault		4
3.2.4 turn-to-turn fault		5
3.2.5 lead electrical fault		3
3.2.6 I&C fault		3
Subtotal	29	
COOLANT RELATED		
4.1 coolant leak		3
4.2 loss of coolant		3
4.3 flow unbalance		1
Subtotal	7	
EXTERNAL SYSTEMS RELATED		
5.1 bus mechanical fault		10
5.2 bus electrical fault		2
5.3 dump resistor fault		4
5.4 power supply fault		0
Subtotal	16	
SYSTEM PERFORMANCE RELATED		
6.1 poor stablity		2
6.2 premature quench		8
6.3 charge rate sensitvity		1
6.4 field error		1
6.5 vacuum leak		5
6.6 loss of vacuum		4
Subtotal	21	
TOTAL	115	

D.B. Montgomery, Review of Fusion Magnets System Problems, Proc. 13^{th} IEEE Symp. Fus. Eng., 27, 1989

Potential causes of failures in the LHC

- Mechanical fatigue on coil, structure, busses:
  - Powering cycles: 10^4 per magnet
  - Thermal cycles: a few for the LHC
- Singular events and associated thermal and electrical stress:
  - Quenches: order of 10 per magnet
  - Heater discharges (triggers): order of 10 per magnet
- Radiation and associated degradation of mechanical and electrical strength:
  - Magnet in the triplet region (Point 1 and Point 5)
  - Magnets in the collimators region (Point 7)

Outline

- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Electrical NC's in the LHC SC magnets

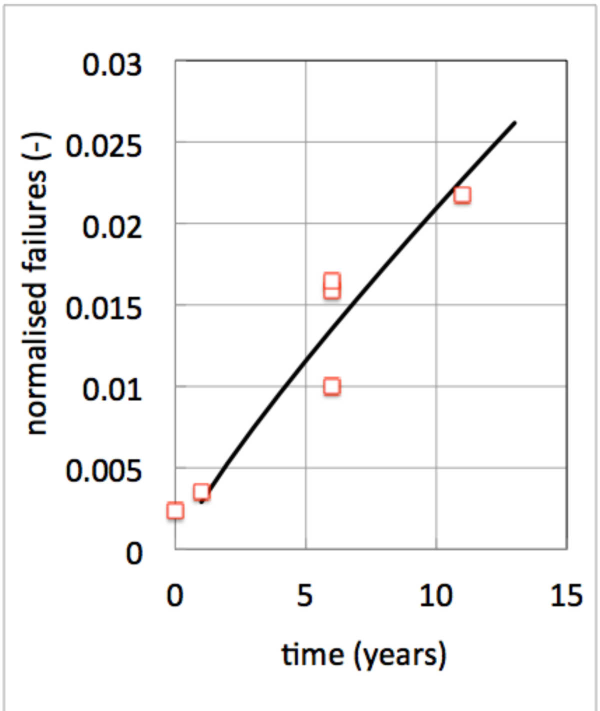
- To date (M. Bednarek, LSC 31.05.2013) we have 35 NC's pending
- Limiting to the cold part, 12 were known before LS1, 7 were identified during the LS1 ELQA
- Magnet exchanged so far
  - 2007: 1 dipole (suspected developing interturn short)
  - 2008: 2 dipoles for high internal resistance
  - 2013: 15 dipoles and 3 quadrupoles, of which
    - 13 dipoles for electrical issues (high internal resistance, 4+1 QH issues, 1 dielectric strength),
    - 1 quadrupole for failure of the orbit corrector
  - 2018 (?): at least 8 dipoles and 3 quadrupoles, of which
    - all dipoles and 1 quadrupole for high internal resistance
    - a number "TBD" for other issues "TBD" (e.g. re-training ?)

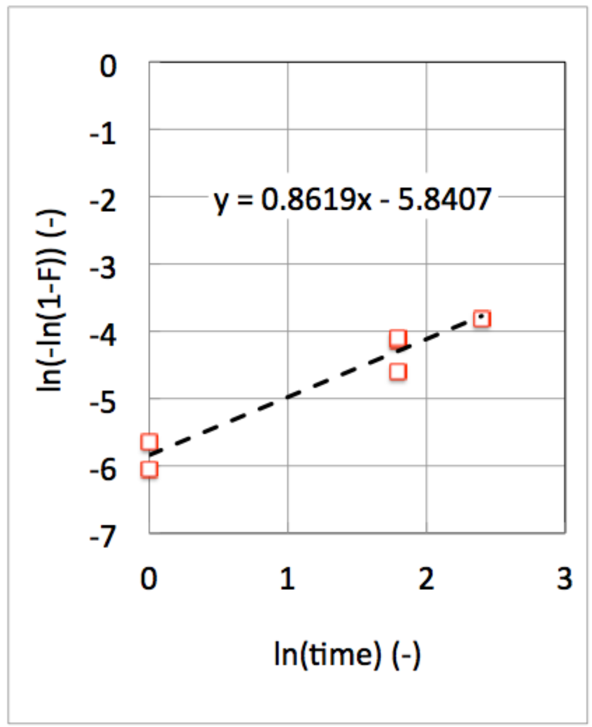
Warning: we have not pushed the LHC yet

Expected MTBF of SC magnets

Weibull analysis of magnet electrical failure probability

year	phase	MB	reason	MQ	reason	correctors	reason	years	cumulated failures	normalised failures	weibull F	weibull x
2007	commissioning	1	potential short ? (1055)			3	RCO.A78B2, RCO.A81B2, RSS.A34B1	0	4	0.002352941	-6.050911543	0
2008	34 repair	2						1	6	0.003529412	-5.644856754	0
2013	LS1	8	internal resistance	1	MCBY corrector	2	RQTF.A81B1, RCBH31.R7B1	6	17	0.01	-4.600149227	1.791759469
2013		5	quench heater issues	1	LQXAA.1R1	4	triplet correctors	6	27	0.015882353	-4.134552429	1.791759469
2013		1	dielectric strength					6	28	0.016470588	-4.097886644	1.791759469
2018	LS2	8	internal resistance	1	internal resistance			11	37	0.021764706	-3.816483268	2.397895273



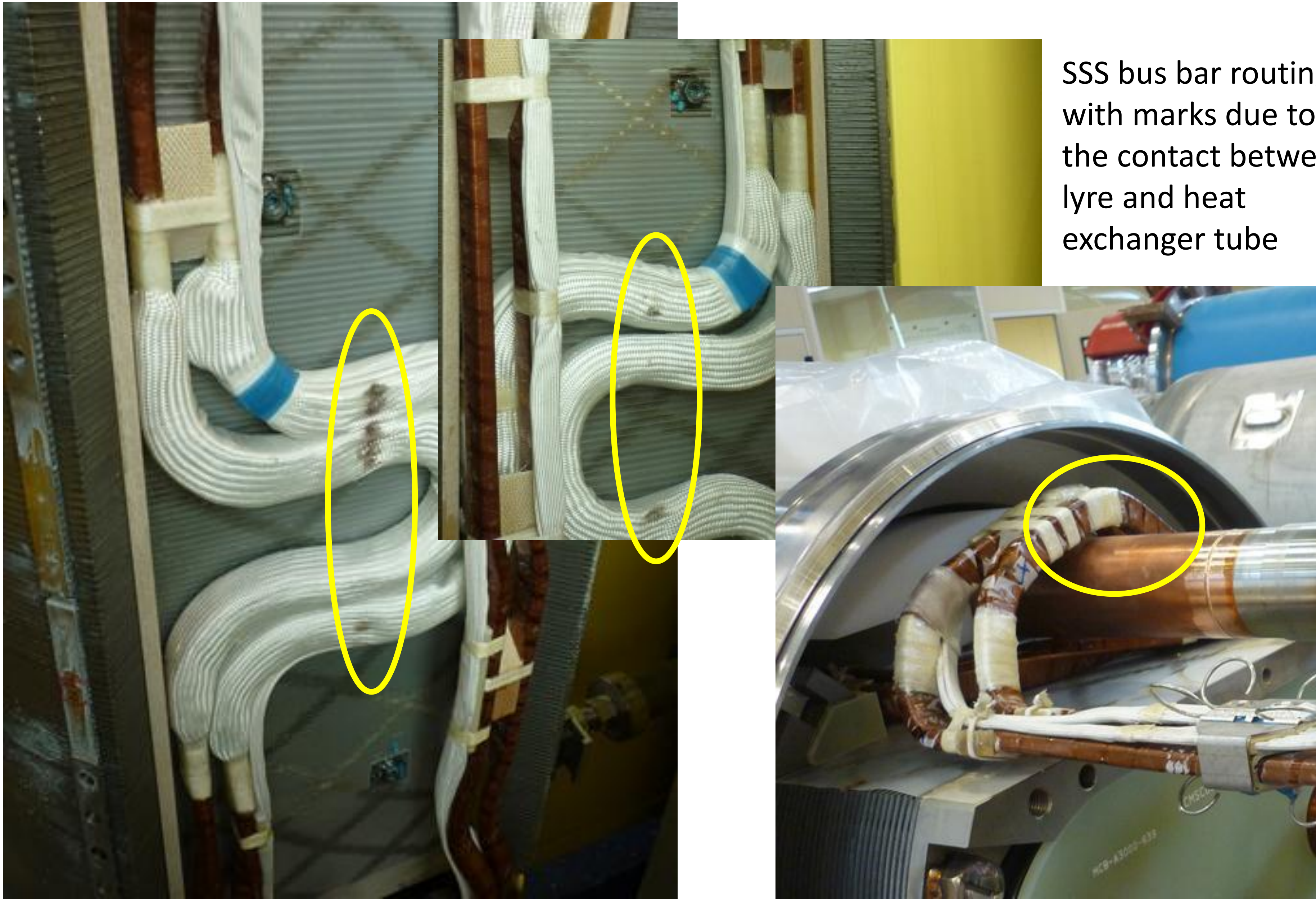


k	0.8619
k ln(lambda)	5.8407
lambda	877.0291

time (years)	F (-)	rate (1/year)	MTBF (years)
1	0.0029	0.00251	399
2	0.00527	0.00228	439
3	0.00746	0.00215	465
4	0.00956	0.00207	483
5	0.01157	0.00201	498
6	0.01353	0.00196	511
7	0.01543	0.00191	522
8	0.0173	0.00188	532
9	0.01913	0.00185	541
10	0.02093	0.00182	549
11	0.0227	0.0018	556
12	0.02445	0.00178	563
13	0.02617	0.00176	569

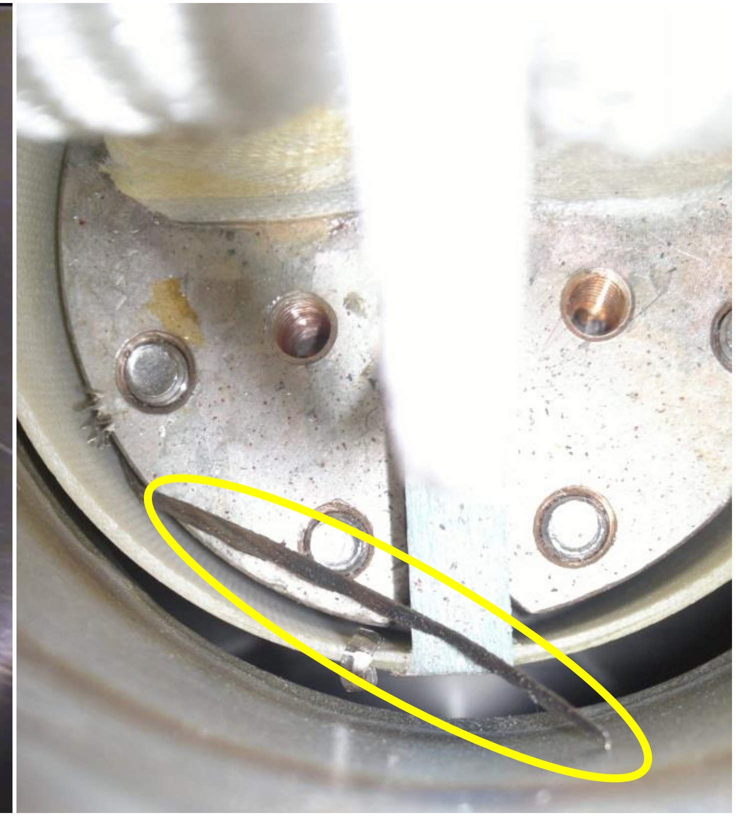
Expected MTBF of 400 to 500 years, translates in a range of 3…4 magnets electrical NC’s per year

Delicate details – 1/2



SSS bus bar routing with marks due to the contact between lyre and heat exchanger tube

Delicate details – 2/2



Contact between MB circuit bus bars and MCS corrector

Chip causing a short between the *half moon* and the diode

The LHC, as all electrical machines, will most likely experience electrical faults. This is true for the whole CERN accelerator complex, **and is normal**

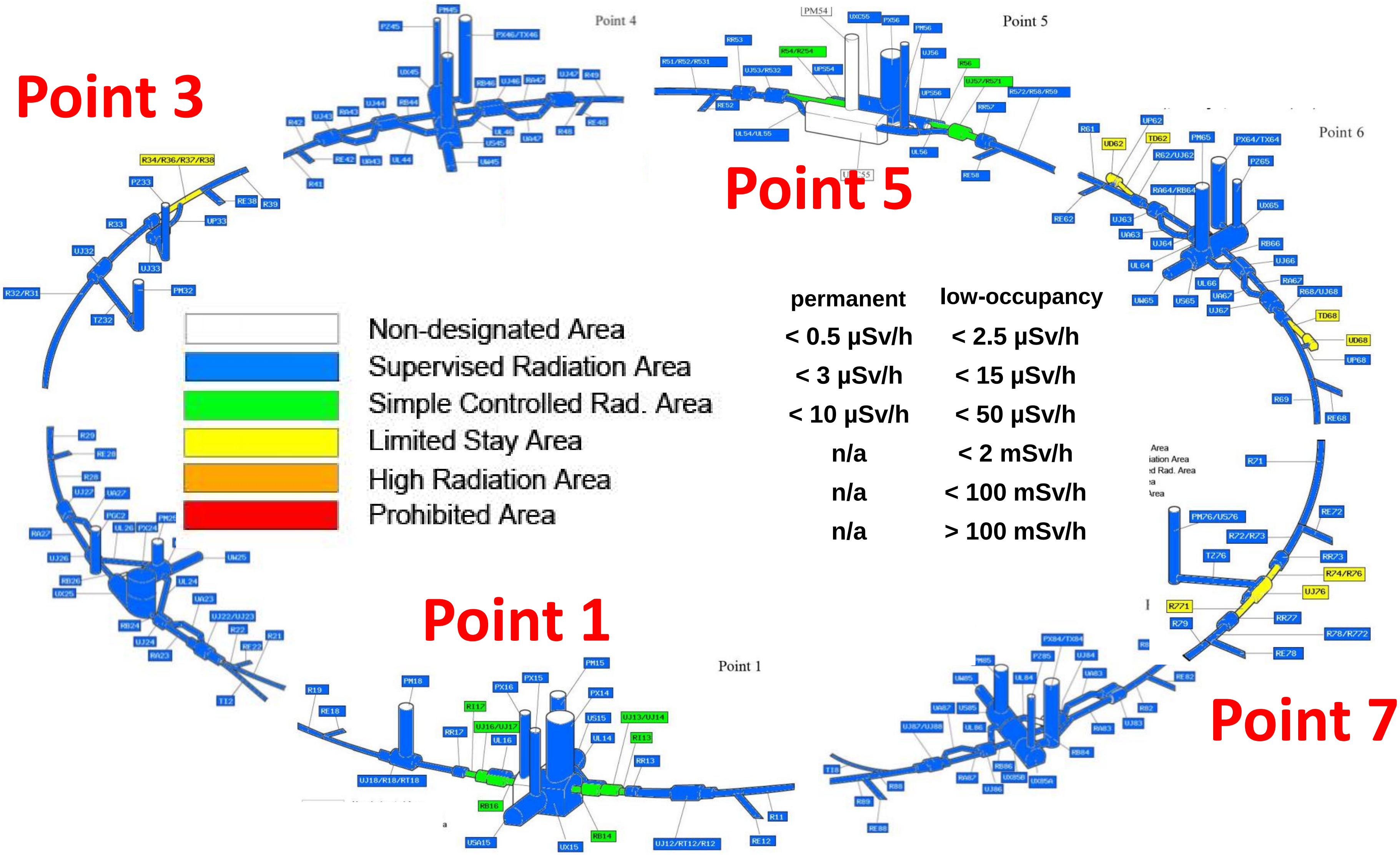
Summary – SC electromechanics

- An MTBF of 400…500 years has been estimated(1) for the LHC superconducting magnets
- This translates in approximately 3…4 magnet electrical NC's per year of operation, and at least 10…15 magnets exchanges every long shutdown(2)
- A proposal was made to adapt the main ring spare policy at the ACC Consolidation Day: procure NbTi wire, magnetic steel, build MQ's (https://indico.cern.ch/conferenceDisplay.py?confId=266926)
- Given the estimated MTBF, the probability of electrical failure of one of the triplet magnets within the next 10 years of operation is 3 %, i.e. 1 magnet

Outline

- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Radiation – where ? Today



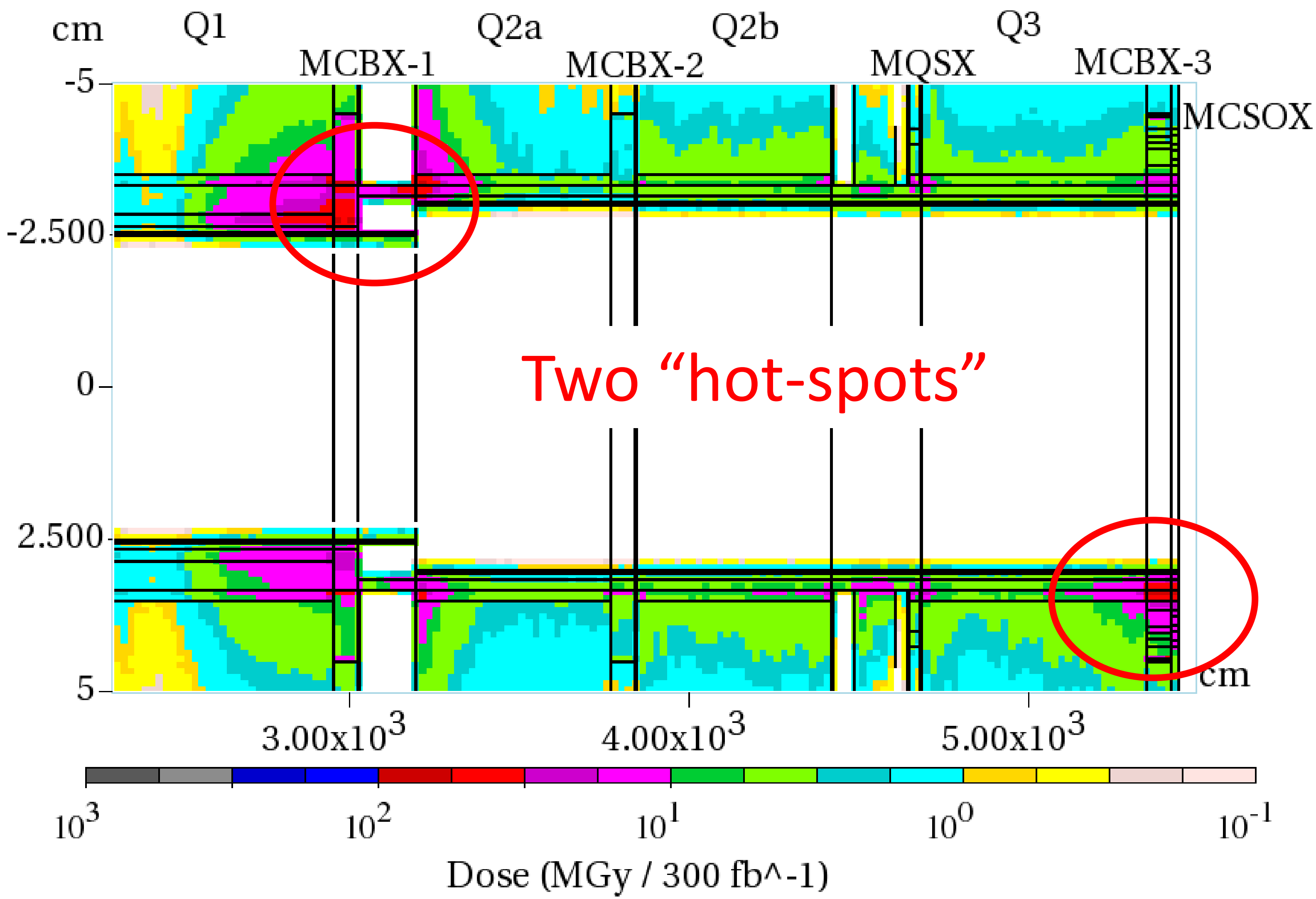
S. Roesler, The Panorama of the Future Radioactive Zones from Now to 2020, May 2013

https://indico.cern.ch/conferenceDisplay.py?confId=233480

Outline

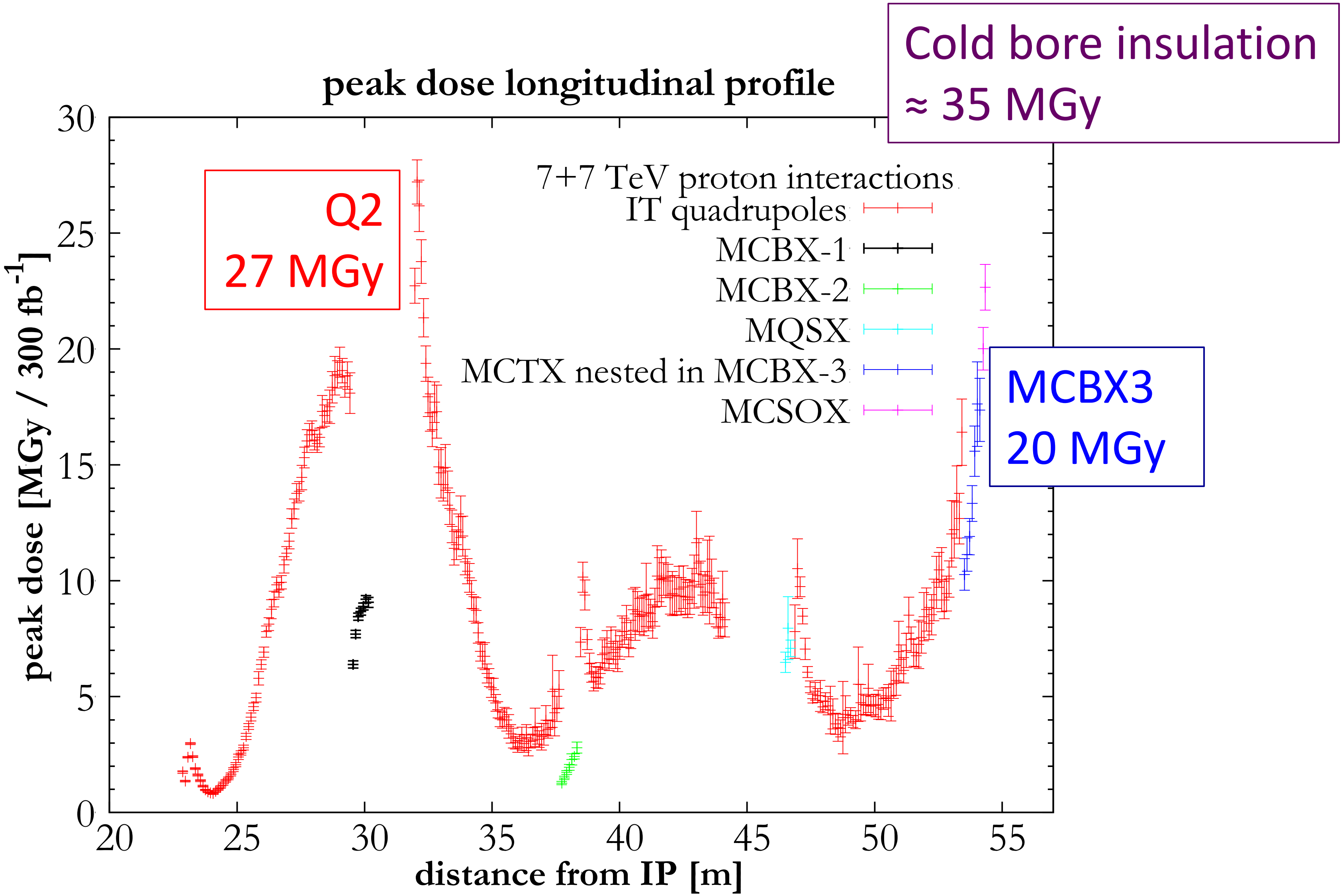
- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Radiation dose in the present triplet (300 fb^{-1})



F. Cerutti, et al., WP10: Energy Deposition and Radiation Damage in Triplet Magnets, April 2013
https://indico.fnal.gov/conferenceDisplay.py?confId=6164

Radiation dose in the present triplet (300 fb^{-1})



F. Cerutti, et al., WP10: Energy Deposition and Radiation Damage in Triplet Magnets, April 2013

https://indico.fnal.gov/conferenceDisplay.py?confId=6164

In the gizzards of the triplet

- Q2 (MQXB)
  - Conductor insulation: 50 (150) μm Kapton
  - Coil insulation: 400 μm Kapton
  - Ground insulation: 450 μm Kapton
  - G11R end spacers

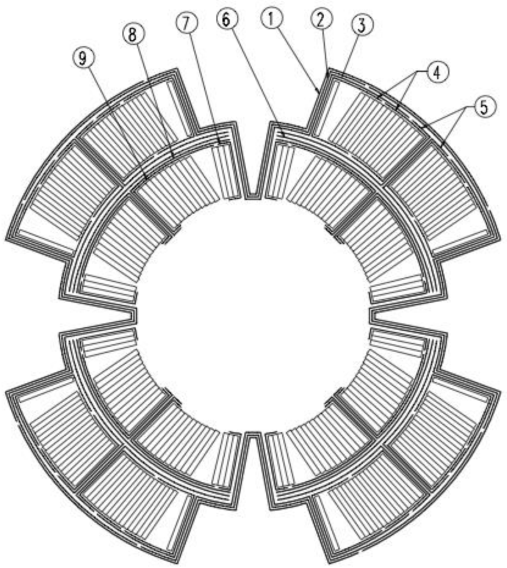
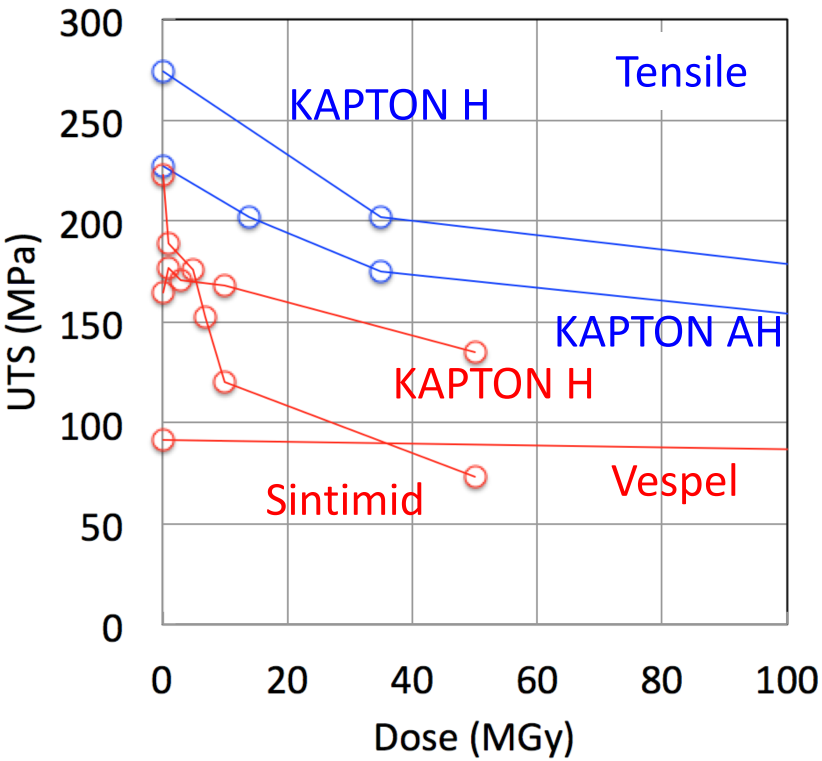
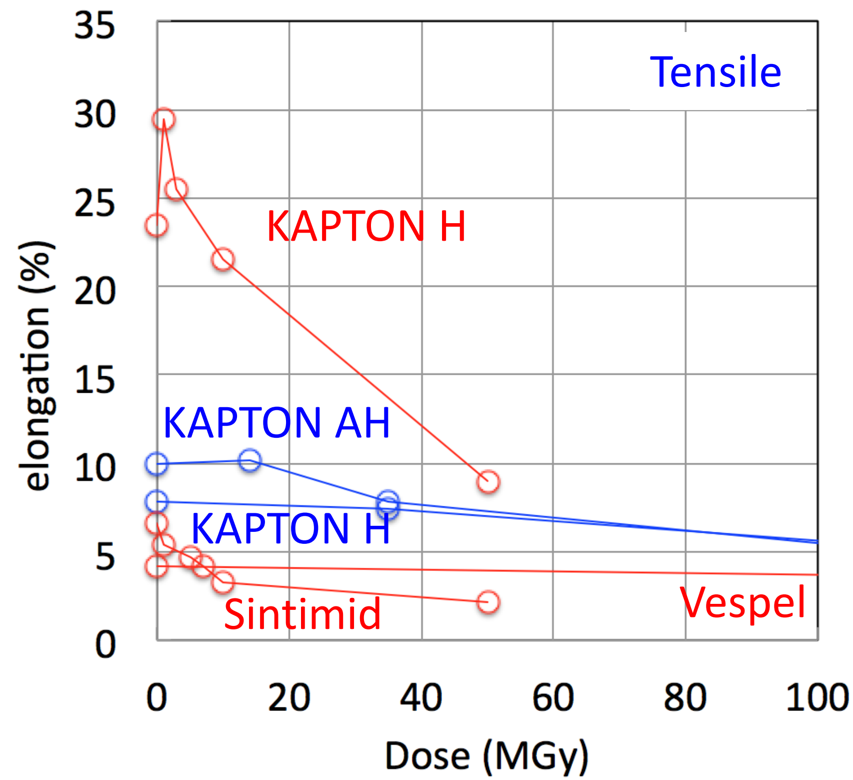


Fig. II.1.2.2-4. HGQ coil insulation system: 1,2,3 – pole ground wrap; 4, 7, 9 – coil caps; 5, 8 – parting plane layers; 6 – quench heater.

- MCBX
  - Multi-wire cable, each layer potted with epoxy resin
  - Two layers potted (glued) in the final coil with epoxy resin

Material limits – Polyimide

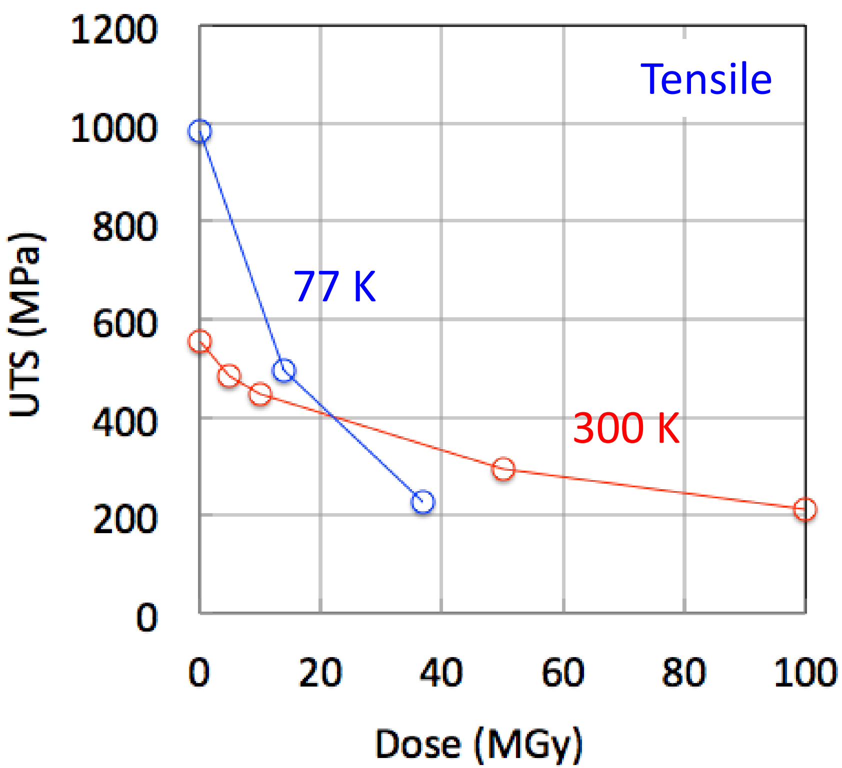


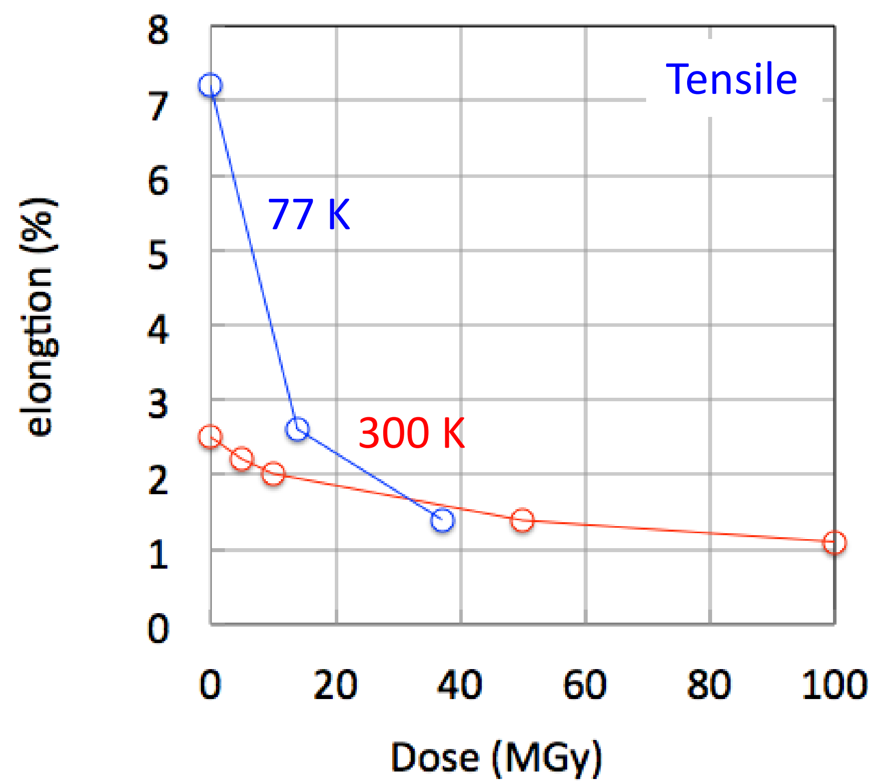


Significant degradation at ≈ 50 MGy

E.R.Long, S.A.T. Long, NASA Technical Paper 2429, 1985
D.J.T. Hill, Radiat. Phys. Chem., 48 (5), 533-537, 1996
M. Tavlet, et al., Compilation of Radiation Damage Data, CERN 98-01, 1998

Material limits – G11

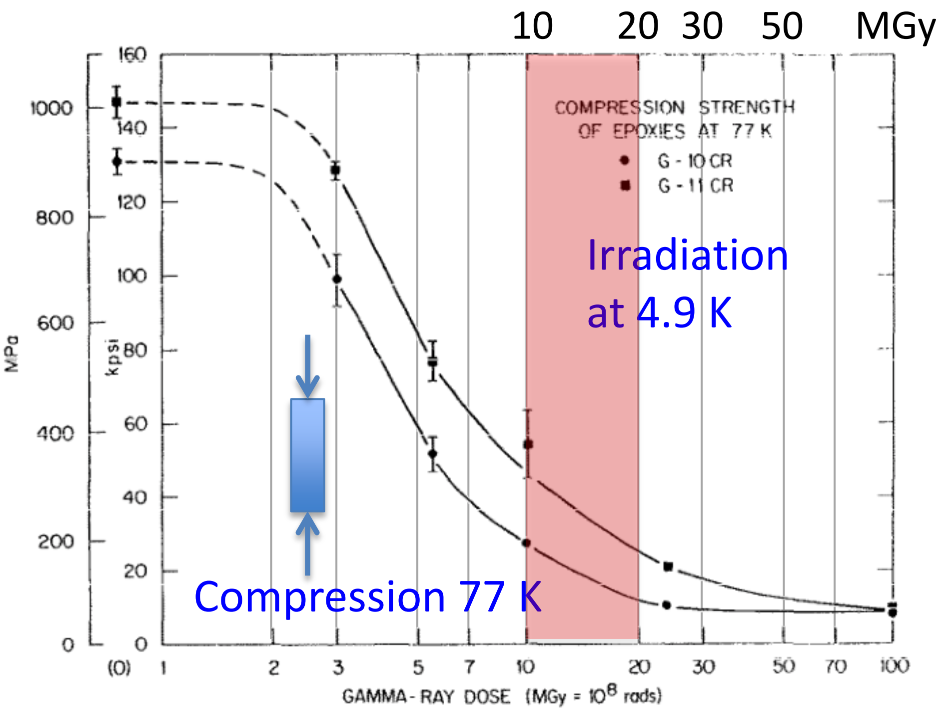


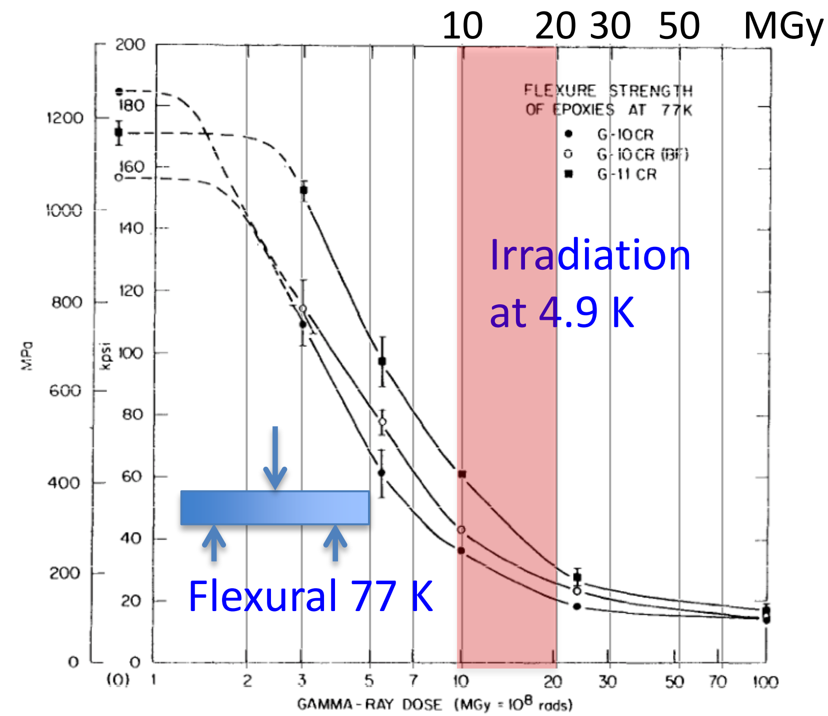


Significant loss of strength and elongation at dose above 30 MGy

M. Tavlet, et al., Compilation of Radiation Damage Data, CERN 98-01, 1998

Material limits – G11

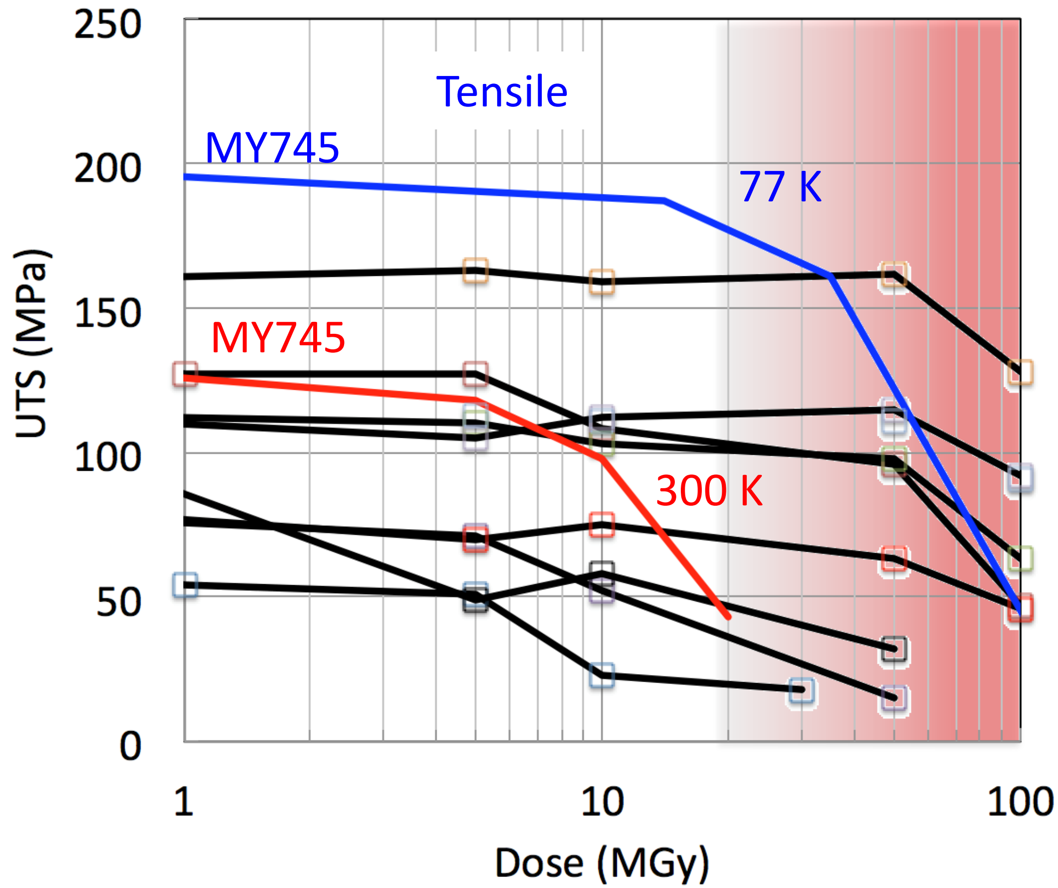




The degradation is caused by loss of bonding in the epoxy component at 10…20 MGy

R.R. Colman, C.E. Klabunde, The Strength of G-10CR and G-11CR epoxies after Irradiation at 5 K by Gamma Rays, J. Nucl. Mat., 113, 268-272, 1983

Material limits – Thermosetting resins



Complex situation, significant loss of strength (50% at cold) at dose above 50 MGy

M. Tavlet, et al., Compilation of Radiation Damage Data, CERN 98-01, 1998

Summary on triplet magnets

- Expected dose by LS3 (300 fb^{-1}) with 50 % uncertainty[(3)]
  - Range of 27 [18…40] MGy in the Q2
  - Range of 20 [13…30] MGy in the MCBX
- Bonding strength (shear) of epoxies is strongly degraded (80 %) above 20 MGy
- Fracture strength of insulating materials degrades by about 50 % in the range of 20 MGy (G11) to 50 MGy (epoxies, kapton)
- Insulations (polyimide) become brittle above 50 MGy
- Triplet magnets may experience mechanically-induced insulation failure in the range of 300 fb^{-1} (LS3 ± 1 year)
  - Premature quenches (cracks in end spacers)
  - Insulation degradation (monitor on line[(4)])
  - Mechanical failure (nested coils in MCBX)

Is this a surprise ?

- J. Kerby, M. Lamm, “INNER TRIPLET QUADRUPOLE MQXB”, LHC-LQX-ES-0002 rev 1.1, EDMS 256806, 2001:
  - Projected maximum acceptable dose of the triplet magnets of 20 MGy (based on G11 spacers)
  - Expected lifetime of 7 years at 10^{34} 1/cm^2 s (200 days operation, 50 % lumi time, dose calculation by N. Mokhov)
  - Compensatory measures included, as described in N.V. Mokhov, I.L. Rakhno, J.S. Kerby, J.B. Strait, “Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions”, LHC Project Report 633, 2003
  - Note: additional limits from the functional specification

Item	*Value*
Number of Thermal Cycles	25
Number of Powering Cycles	12,000
Number of Quenches	10

  - Note: the functional specification proposed magnet swaps among points…
- R. Ostojic, 2009: […] *on the lifetime of the LHC triplet* […] *That is the reason I quoted the radiation hardness of the present triplet as “about 400 fb^{-1}”*

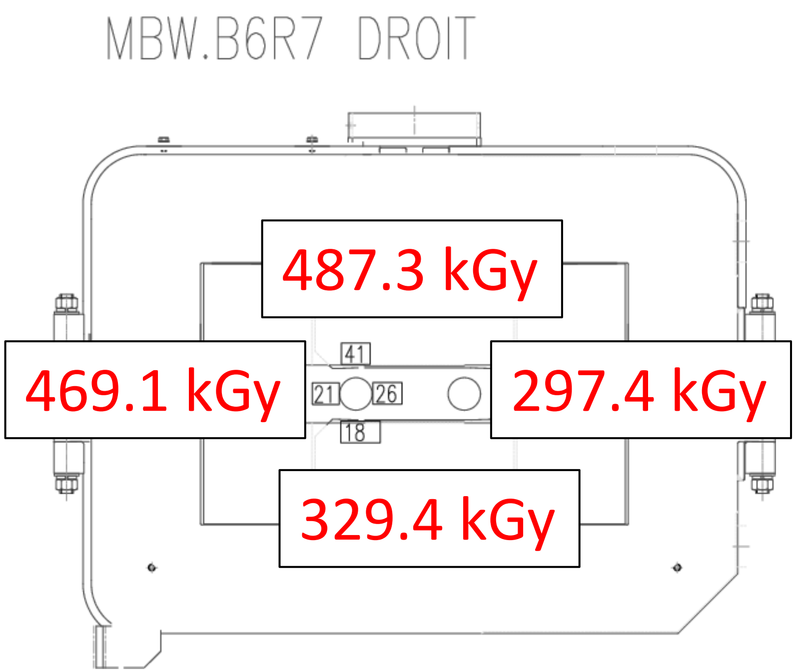
A limit in the range of 300 fb^{-1} (with the present evaluation) is hence **consistent with previous analyses**

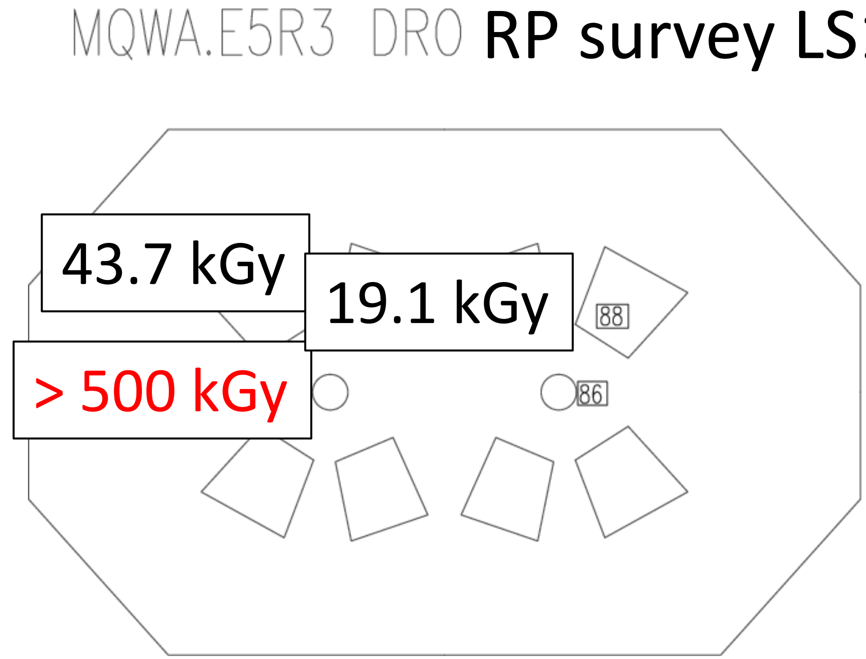
Outline

- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Dose in the MBW and MQW

RP survey LS1





Dose esimates at 300 fb^{-1} (MGy)

	IR7 right	IR7 left	IR3 right	IR3 left
MQW	**86**	29	9	18
MBW	**87**	43	3.8	7.6

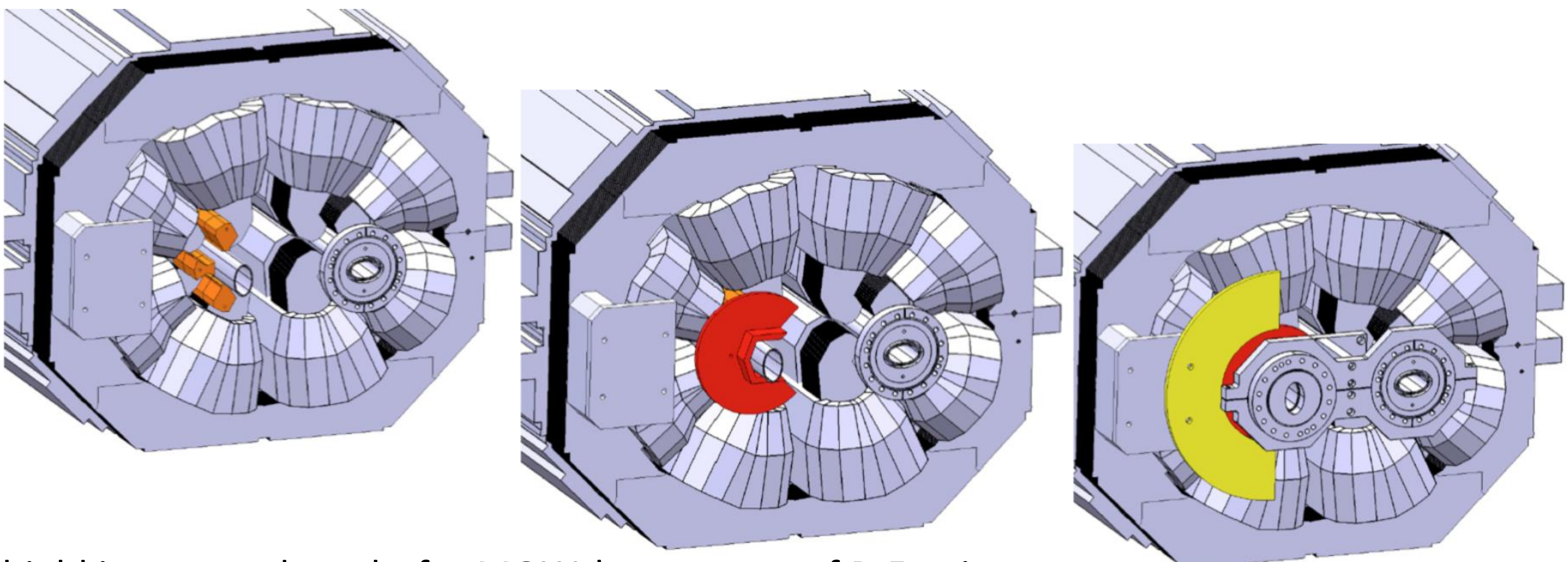
P. Fessia, MBW-MQW in the LHC, Considerations on expected life and available options, 2013

Summary on warm magnets

- Expected dose by LS3 (300 fb^{-1})
  - Range of 80….90 MGy in the MBW and MQW
- Limits for the epoxies used are in the range of 50 MGy for MQW and 70 MGy for MBW
- Actions have been proposed and approved (TETM67 8/10/2013, LSC24 11/10/2013) to avoid insulation failure in the period LS2 to LS3
- Mitigation and preparation work is planned (and *mandatory*) during LS1

Compensatory measures

- Shield (W inserts and masks)
- Remove magnets (change optics, insert absorber, simplify powering, *add redundancy*)
- Build rad-hard replacements for the longer term



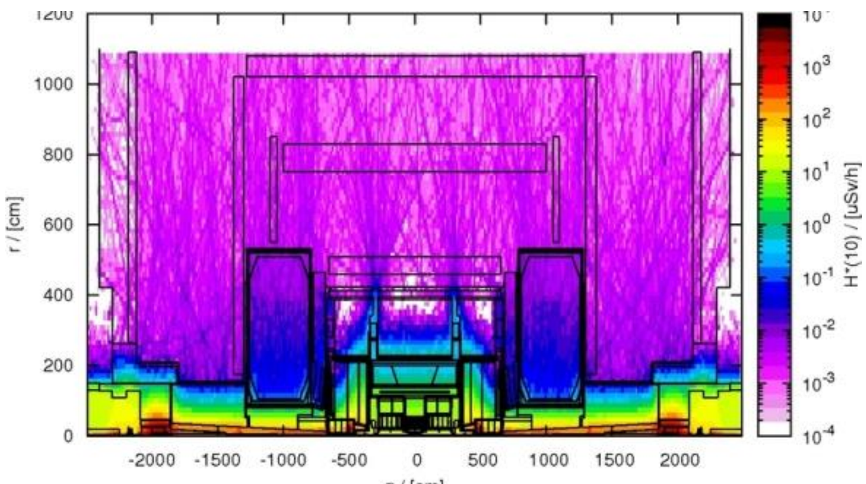
Shield inserts and masks for MQW, by courtesy of P. Fessia

Outline

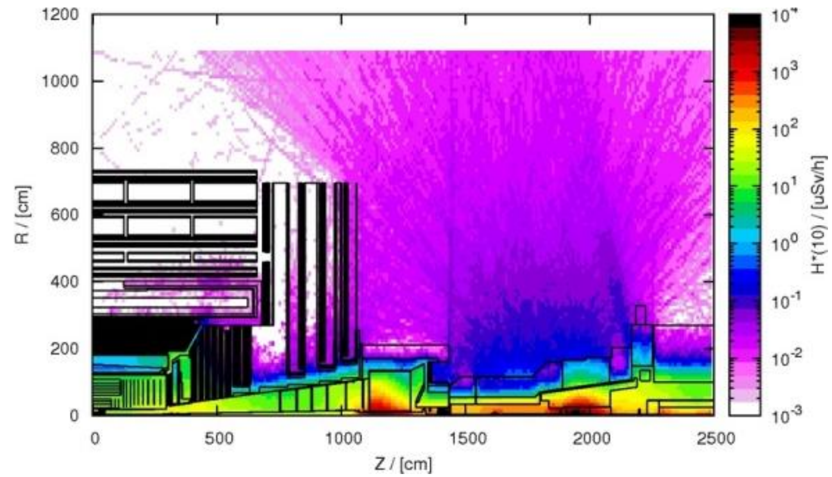
- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Radiation map – LS1 after 1 week

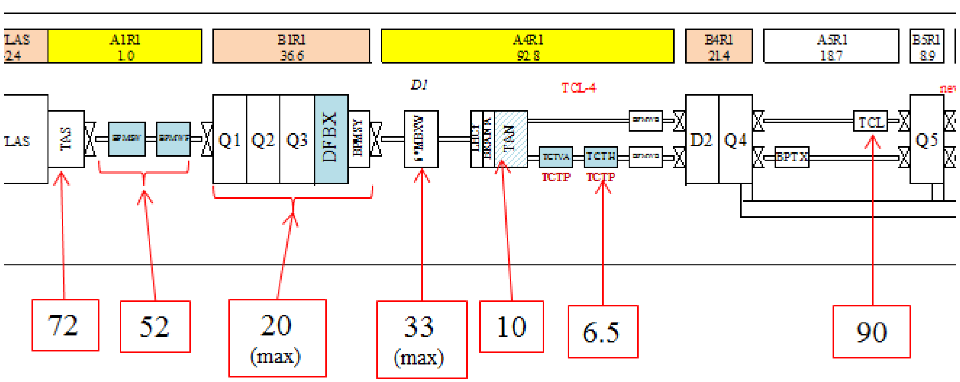
- Point 1

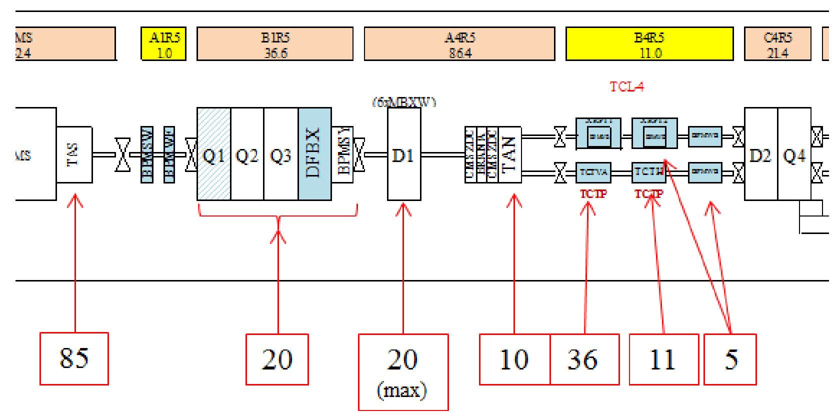


- Point 5



Ambient dose equivalent rates in µSv/h at 40cm measured on Dec 17, 2012 (last "good" fill on Dec 5)



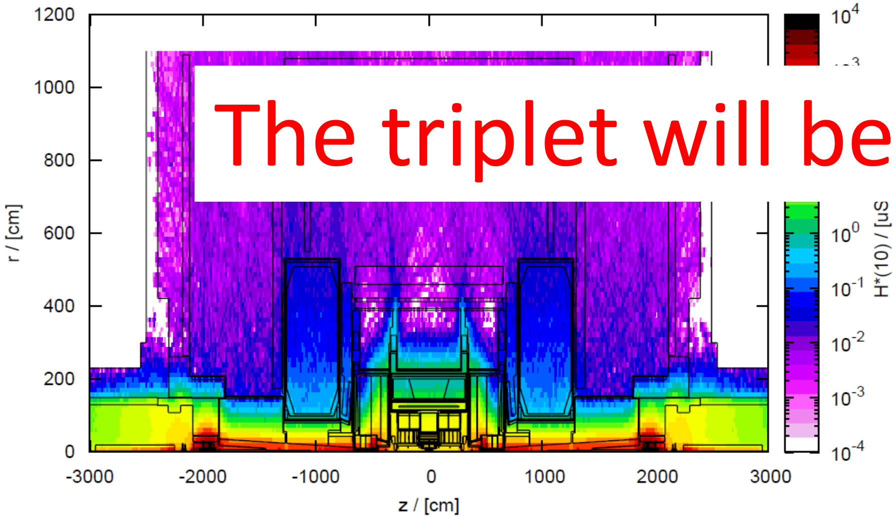


S. Roesler, The Panorama of the Future Radioactive Zones from Now to 2020, May 2013

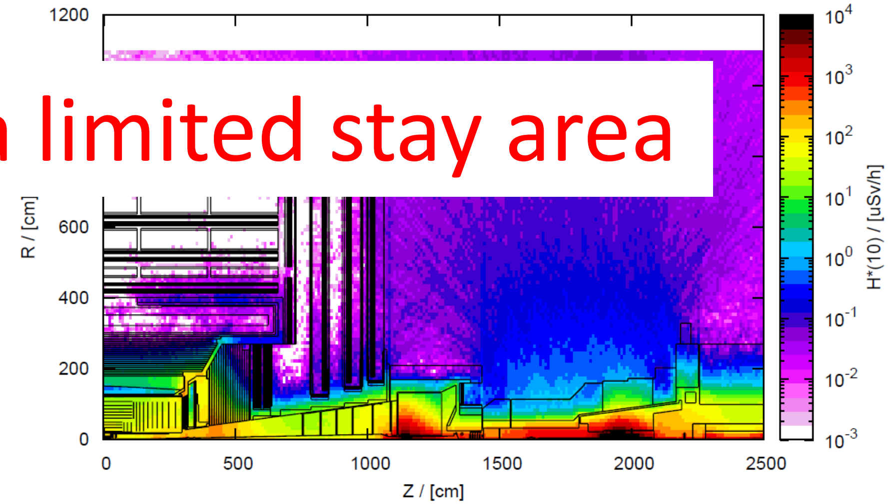
https://indico.cern.ch/conferenceDisplay.py?confId=233480

Radiation map – LS3 after 4 months

- Point 1

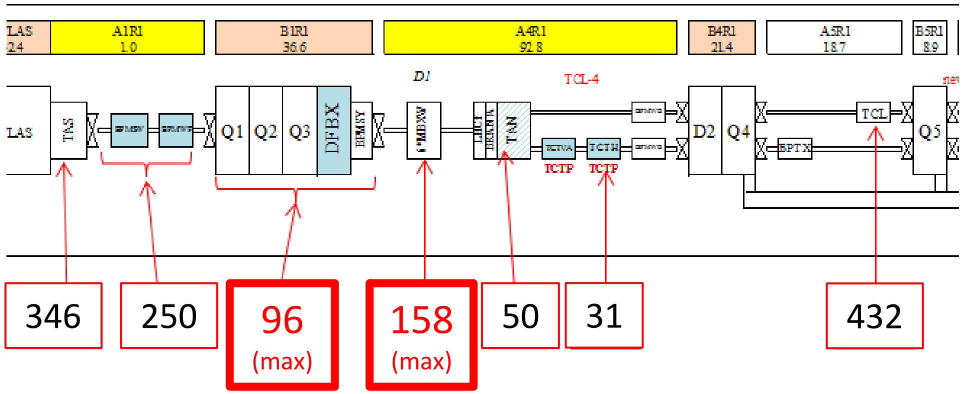


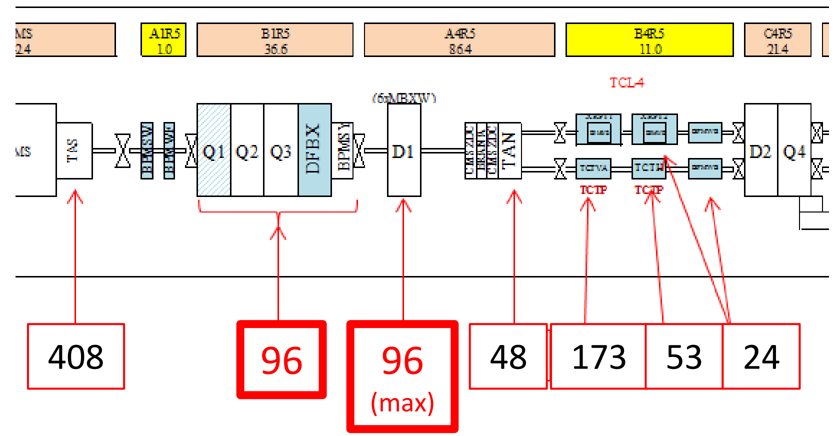
- Point 5



The triplet will be a limited stay area

Ambient dose equivalent rates in µSv/h at 40cm extrpolated from measurements after LS1

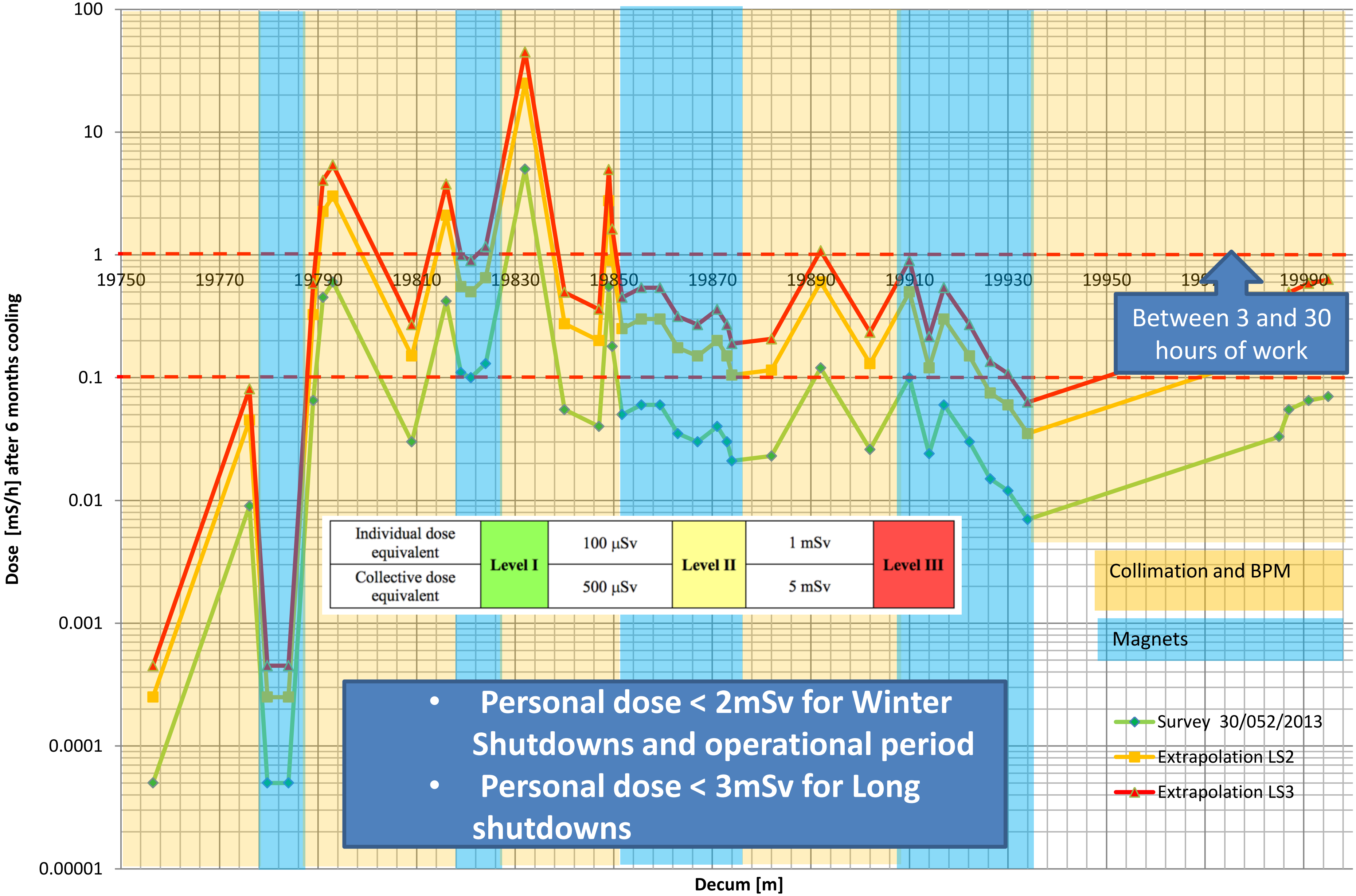




S. Roesler, The Panorama of the Future Radioactive Zones from Now to 2020, May 2013

https://indico.cern.ch/conferenceDisplay.py?confId=233480

7L extrapolation of dose to LS2 and LS3



P. Fessia, MBW-MQW in the LHC, Considerations on expected life and available options, 2013

Issues of personal dose – actions

- Access and work in the triplet and collimator area will be subject to ALARA-level III rules
- Measures must be taken to reduce intervention time by:
  - Adopting rad-hard designs for magnet replacements, with *robustness* improved by factors (3…5)
  - Adding redundancy when and where possible (tolerate failures of single elements)
  - Reducing/facilitating/accelerating manual operations for disconnection, removal, installation, reconnection, and introducing “remote handling” concepts
- This work needs to be prepared in LS2, and executed in LS3 (at the latest) to make further exploitation of the LHC a success

Outline

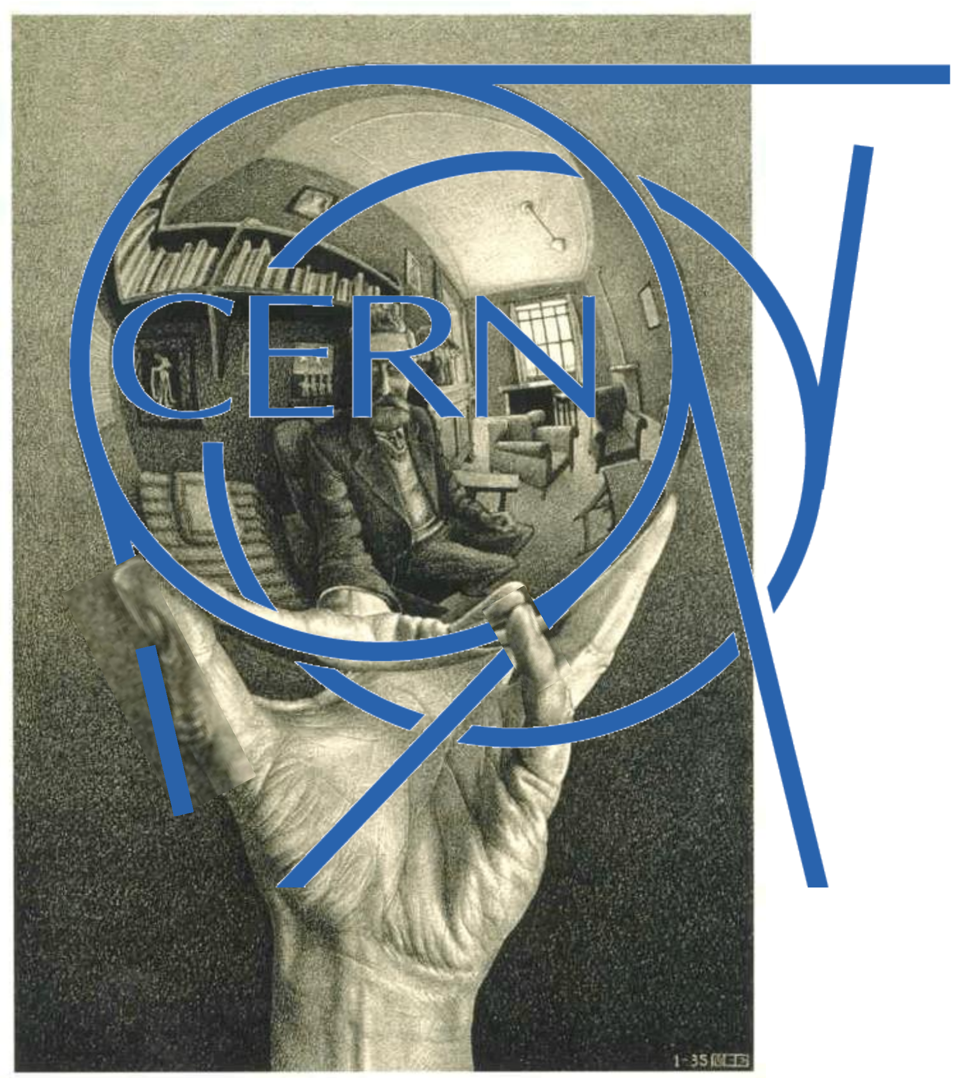
- Magnet failure modes
- Electrical/mechanical failures
- Effect of radiation
  - Magnets in the triplet region
  - Magnets in the collimators region
- Personal dose
- A summary and required actions

Summary

- On the time scale of LS3, and provided the present operation scenario scales as discussed, we should expect aging-related and/or radiation induced failures in
  - The triplet magnets (Q2, MCBX) at Points 1 and 5
  - Warm magnets in the collimation region of Point 7
- By that time, a magnet exchange in the triplet may require ≈1 year (4…6 months cooling time, 6…8 months of work, scenario TBD)
- The situation for the warm magnets is less dramatic (few units concerned), provided the area is prepared

A *must-do* plan

- During LS1
  - Protect most exposed warm magnets in the collimator area (4 MBW + 4 MQW)
  - Survey the triplet to prepare for repair in the following period (LS1-LS2)
- Between LS1 and LS2
  - Design modifications to collimator area for long term operation after LS3
  - Work out a baseline for triplet replacement after LS2, and design triplet modification for long term operation after LS3
- During LS2
  - Shield warm magnets in the collimator area (6 MBW + 29 MQW)
  - Prepare triplet area and tools for works in LS3
- During LS3
  - Preventive triplet exchange (?)
  - Modify hardware layout and (possibly) machine operation parameter of critical radiation exposed areas


CERN

Notes and *caveats*

1. The estimation is based on the infancy of hardware and operation, and before reaching full electro-mechanical stress conditions
2. This is obviously consistent with the present work (LS1, 18 cryo-magnets) and plans (LS2, in excess of 10 cryo-magnets)
3. According to benchmarking and expectations by F. Cerutti, (CERN EN-STI)
4. I strongly advocate for the development of hardware and procedures for the on-line monitoring of the dielectric strength of the LHC
5. A number of effects, such as ion irradiation (see next slides) may cause localised degradation, which is difficult to quantify today

The ion case

Figure 12 refers to the results of an experiment recently carried out in the frame of a common scientific activity between CERN and GSI to understand the difference of electrical damage produced, at given absorbed doses, by different ionizing radiation on polyimide tapes. The effect of heavy-ion radiation on the dielectric strength is noticeable already at very low radiation doses.

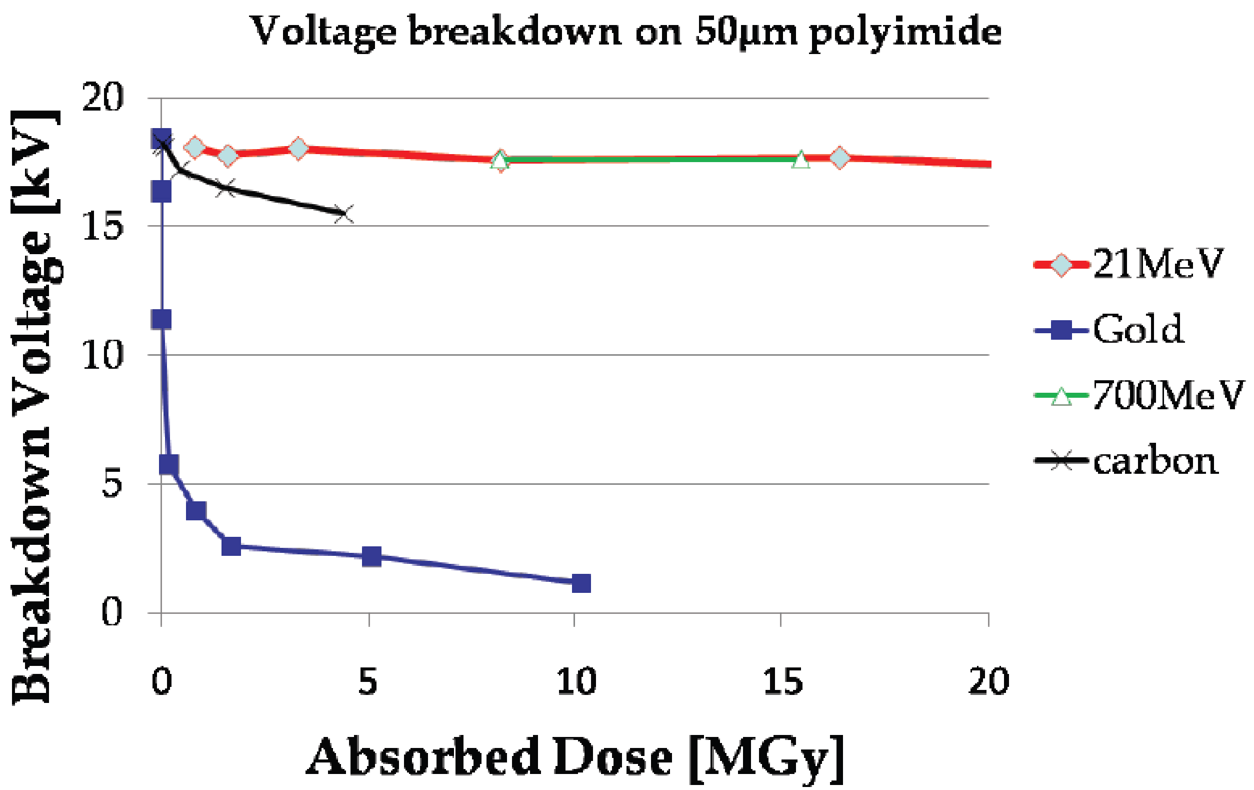


Fig. 12: Dielectric strength of irradiated polyimide [courtesy R. Lopez, CERN, and T. Seidl, GSI]

By courtesy of P. Fessia, CERN TE-MSC

Observation of heavy-ion tracks in polyimide by means of high-resolution scanning electron microscopy

Sameer Abu Saleh, Yehuda Eyal *

Department of Chemistry, Technion – Israel Institute of Technology, Haifa 32000, Israel

S.A. Saleh, Y. Eyal / Nucl. Instr. and Meth. in Phys. Res. B 208 (2003) 137–142 139

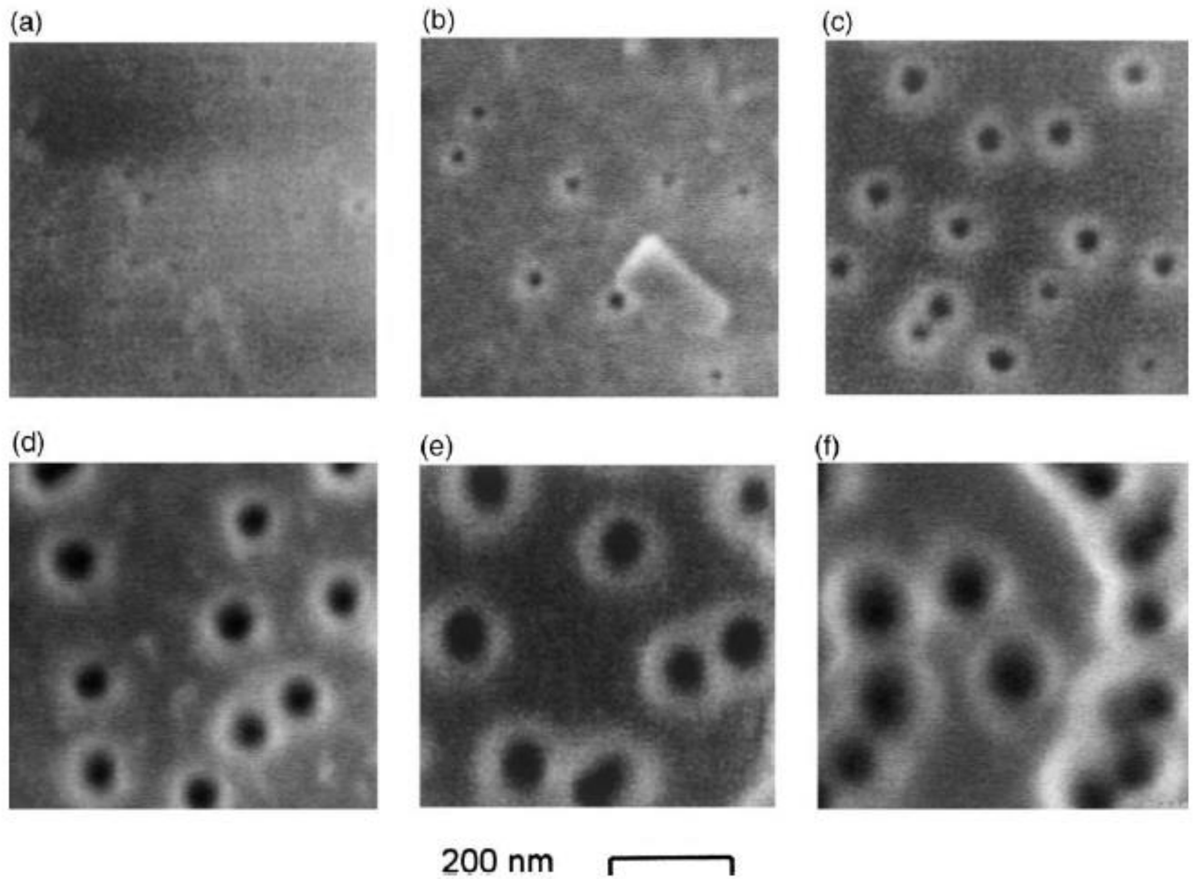


Fig. 1. HRSEM images of etched ^{238}U-ion tracks in polyimide. The etching times of the samples displayed in panels (a), (b), (c), (d), (e) and (f) were 40 s and 1, 2, 3, 4 and 5 min, respectively.

By courtesy of P. Fessia, CERN TE-MSC