MAGNET REPAIR FOR 3-4 SECTOR

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Abstract

The incident in 3-4 sector has affected some 50 LHC main magnets, going beyond expectation. Our reserve of magnet will be barely sufficient (some 40 dipoles and 14 SSS, in some cases the reserve magnet types are not compatible with the one damaged). Furthermore the subsequent splice resistance measurements on other sectors have shown the necessity to replace other magnets. The plan and methods for assessing the damage that occurred to a cold mass and the decision on its substitution, rather than a simple revamping of the magnet itself, will be discussed. The question if the magnets in the sector are adequate for powering and beam operation will be addressed. The implementation of the changes and their traceability will be presented. Finally the spare situation, which includes the plan for repairing and testing of all damaged cold masses of sector 3-4 and the impact on it of the 3-4 incident, is discussed.

SPARE MAGNETS BEFORE INCIDENT

In 2004 an action to try to forecast the numbers of spare was launched in the AT department [1]. Meanwhile the magnet production was just entering the cruise velocity and was not even at 30% of finished cold masses, this relatively early decision was first triggered by expiration of spare options (at fixed price) in the components and in the main magnets contract. The main actions, based on risk analysis, educated guess by hardware owner on wear out and by financial constraints were, for the main magnets:

1) Activation of options for components and in some cases extension of the initial options. In particular for the SC cables it was decided the purchasing of spare cable for about 50 dipoles equivalent (the cable for dipoles is used also for main quadrupoles).
2) The order of 30 dipoles cold masses, in addition to the 16 that were already in the main contract to cope with losses during production;
3) The order of 8 quadrupoles cold masses (SSS), in addition to the 8 already in the contract;
4) The approval of the so called MAgnet Rescue facility (MAR), to be established by recovering of the best CERN-owned tooling from the various production line installed at the CMAs (Cold Mass Assemblers)

The MAR was intended to be able to repair the magnets such to maintain an adequate number of spares all along the life of the LHC. Based on consideration of a certain electrical weakness of our magnets a maximum number of 15 MBs were considered to be possibly damaged during hardware commissioning.

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The MAR has then evolved into MF (Magnet Facility) when new projects were approved throughout then new initiative of the so called White paper program [2].

However in 2007 the beginning of the construction of the MF was delayed to after the LHC commissioning because of budget and personnel restriction.

In Table 1 the 19th September situation of the dipoles and SSS (containing the Main Qaudrupoles) is reported.

Table 1: Status of MB and SSS cold mass spares at 19th September 2008

	Dipoles	**SSS (Quadrupole)**	**Comments**
Main Contracts	1248	400	
Lost in production	-1	-1	MB1005 limited by Sc cable fault. First SSS assembled as dummy SSS
Damaged String-2	-3	=	(SSS were proto)
Damaged from production or tunnel	-2	-1	MB2001,MB1055 and SSS080
Spare ordered	30	8	+2 bare MQ not assembled
Installed in LHC	1232	392	
Reserve available on 19th Septem-ber	40	13	All variants covered with at least 1 unit apart 1 SSS CM type (LQMSA/B)
Damaged or under investiga-tions	5	1	

However, for various reasons, the spare cold masses have not been tested and in most cases also not cryostated, with the plan to test them in 2008-2010 in a "test-cryostat" by cryostating and decryostating. The stage at which each cold mass (c.m.) was on 19th September 2008 is depicted in Fig. 1.

For dipoles the different variants are customized only just before installation (different preparation of corrector bus, beam screen orientation); the diode type (left or right

SPARES (and other) C.M. and CRYOMAGNETS GENERAL STATUS

STEPS	DIPOLE			
	TYPE A		TYPE B	
	QTY	ID	QTY	ID
COLD MASS (not cryostated, not tested)	11	2739 / 2868 / 2435 / 2436 / 2437 / 2438 / 2443 / 2444 / 2445 / 2446 / 2524	13	2399 / 2418 / 2421 / 2422 / 2428 / 2429 / 2431 / 2432 / 2433 / 2434 / 2440 / 2441 / 2442
CRYOSTATING DONE	3	2690 / 2439 / 1055 (sick magnet)	2	3383 / 2420
*COLD TEST DONE * waiting for PA*	4	2551* / 2598 / 2624* / 2790	3	2252* / 2427* / 2419*
STRIPPING DONE	0		0	
FIDUCIALISATION DONE	1	1011	1	2430
BEAM SCREEN INTEGRATED	2	2342 / 3413	1	1219
READY FOR TUNNEL	0		0	
TOTAL	21		20	

Legend
blue: diode L
red: diode R
black: no diode

STEPS	SSS					
	ARC		DS		MS	
	QTY	ID	QTY	ID	QTY	ID
COLD MASS (not cryostated, not tested)	12	005 / 055 / 072 / 243 / 277 / 279 / 344 / 364 / 367 / 369 / 372 / 080(leak under invest.)				
CRYOSTATING DONE	1	006 (under test in test-cryostat)	1	603		
*COLD TEST DONE * waiting for PA*	1	064*				
STRIPPING DONE						
FIDUCIALISATION DONE						
BEAM SCREEN & BPM INTEGRATED			1	523 (used for warm-up test)		
READY FOR TUNNEL						
TOTAL	14		2			

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Figure 1: Status of the Main Dipoles and Main Quadrupoles (SSS) at 1st October 2008, (situation at the incident).

connection) can be easily changed in a two days intervention. The only "hard" variant is type A or B because it implies different correctors and bus bar routing inside the c.m. envelope.

The variants are much more numerous for SSS, mainly linked to different types of correctors and of bus bars (Focusing/Defocusing, hydraulic restrictions for one SSS out of four); indeed for one type of ARC-SSS (LQMSA/LQMSB depending by diode polarity) there is no spare at all. The spare SSS includes also two that are prepared as dispersion suppression (series SSS500 and series 600) and cannot be used as ARC-SSS. The SSS cryostats present so many variants that, in conjunction with the variants of cold masses, preparation of the SSS is done only when the slot in the tunnel is known. In 2008, upon preparation of a simple "universal" cryostat, the test of all SSS was planned and just started in summer.

The MFs status at 18th September was:

- **SMI2** (Cryostating); functioning since June 2008, with two lines for cryostating/decryostating SSS (1 for arc and 1 for special SSS), one line for dipoles cryostating/decryostating and many benches for preparation/finishing and beam screening insertion.
- **Bldg.181**; it can cover all needs for cold mass finishing of special quadrupoles (series SSS600) and can be used to open end covers of dipoles. The vertical tower to be able to disassembly the SSS, recovered from ACCEL, will be assembled in spring/summer 2009. This will allow to repair SSS cold masses (but not MQ) and also to change corrector and bus bar types inside the cold mass; unfortunately today this is not possible, and for this reason some of the SSS to be changed in the damaged zone of the 3-4 Sector will not have the right correctors. A study [3] has shown that SSS cold mass cannot be open to change corrector in horizontal (liked is done for the series SSS600 that were assembled at CERN).
- **Bldg.180**; here the 5000 m^2 for the heart of the magnet repair and reconstruction facility , from coil winding to cold mass assembly, were made available - after agreement with PH - in summer 2008. The zone that is reserved for winding and collared zone is already under preparation and tooling installation (to be finished by end of 2009). The zone for cold mass assembly is being used for storage of cold mass out of the tunnel

and for the special line of de-cryostating (see later in the text).

- **SMA18**; completely emptied and renewed for the LHC celebration, is being used for storage of cryostated dipoles, diagnosis and intervention on the dipoles of 3-4 that can be re-used after cold test (see later in the paper) and for cold test preparation as well as for stripping (the part of preparation for tunnel).
- **Bldg.904**; it is used partially for storing SSS removed from S3-4 and for partial decryostating (QQS part).

MAGNETS IN THE D-ZONE

D-zone has been defined were the vacuum in the cryostat has been lost, either due to primary electrical arcs or because of leakage from the vacuum barrier or as consequence of puncturing of the helium enclosure due to secondary arc or of the displacement of the magnets. Actually, damages are more extended, however out of the D-zone the damage concerns mainly the beam screen that vacuum experts can be fix in situ.

The damaged zone, D-zone, is between Q19 and Q33 and the map of damaged is synthetically described by the diagram in Fig. 2.

The main features are:

1) J means presence of Jumper, VB of the vacuum barrier, and plugs stays for the hydraulic restrictions for the HEII passage among cold masses.

2) The **primary event was the arc developed in the connections between C24 and Q24**. The other electrical damages are induced by magnet displacement.

3) The color code try to give an idea of the damage, green indicating OK and red bad damage. A cold mass can be damaged electrically or mechanically (bus bar and end flanges) and also for reason of cleaning. In some cases; cold masses apparently OK were found badly contaminated by the soot.

4) The arrows are proportional to the displacement: the displacement of the cold mass is given with respect to its cryostat.

5) "elbow" arrows indicated damages on cold mass support, on QRL jumper.

There are 42 dipoles and 15 SSS in the D-zone, from Q19 till Q33. The magnet A34 was found with a damage wire inside the diode box, but this is probably not related to the incident. All magnets outside the D-zone were found electrically OK [4], not displaced and with no damage/dirtiness in the cold mass and in the cryostat.

ASSESSMENT OF DAMAGE AND CRITERIA FOR REPLACEMENT

A magnet can be: i) damaged at cold mass level; ii) not damaged but with minor damage to cryostat; iii) not damaged. The level of damages is assessed by visual inspection from outside (including cryostat integrity, cold mass end integrity upon opening the ICs), by electrical checks and by visual inspection inside cold bore and inside the end covers via endoscopy.

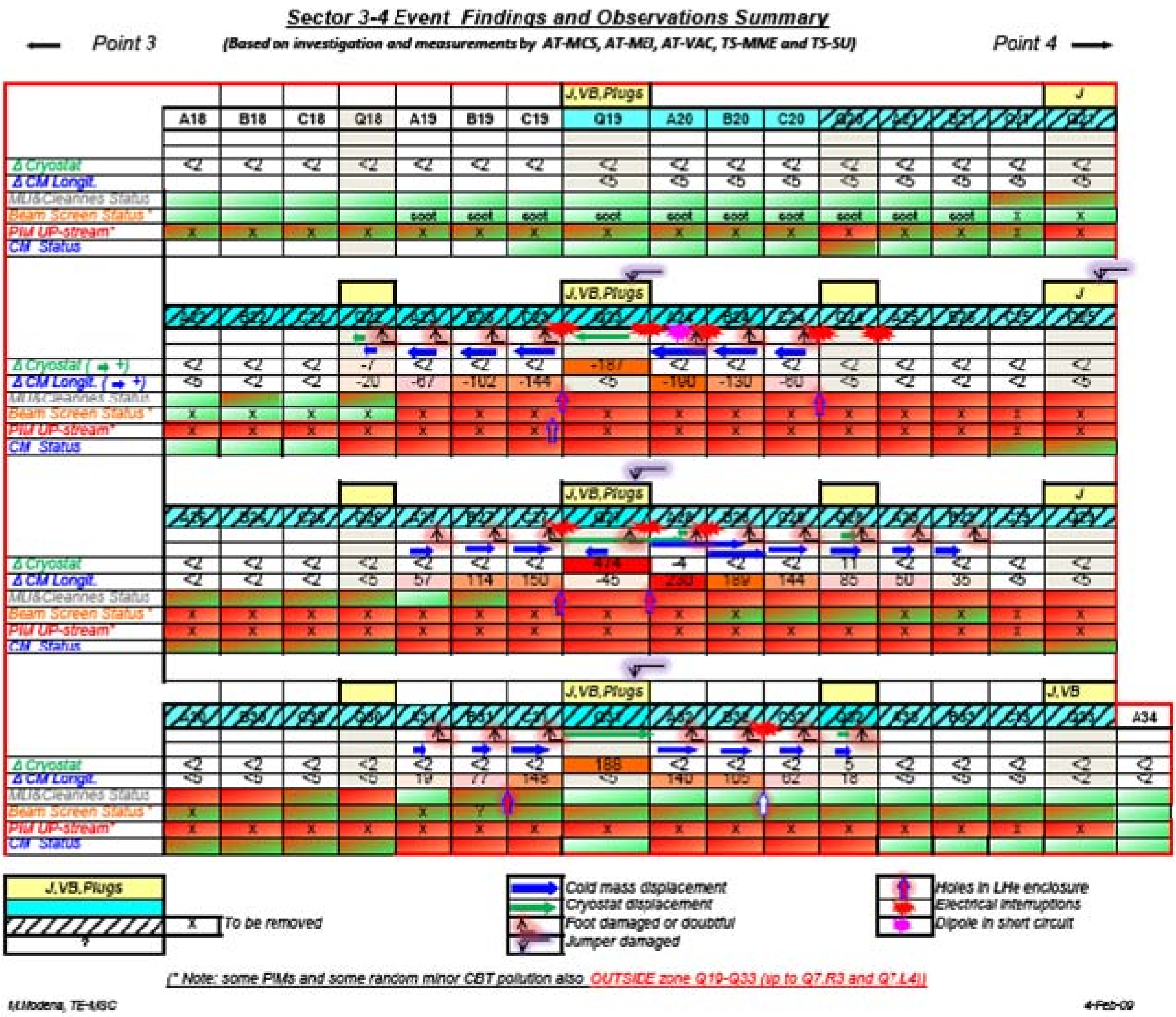

Figure 2: schematic with most of info on damaged magnets in sector 3-4. The D-zone is defined from Q19 to Q33. See text for details.

Here the action taken on each category.

1. *Cold mass removed and substituted when*:
   - 1st. Electrically damaged and/or
   - 2nd. Mechanically damaged and/or
   - 3rd. Bus-bar system damaged due to displacements and/or
   - 4th. Presence of soot inside the cold mass
2. *Magnets removed and re-used* (either without de-cryosting or after a partial decryostating to clean up the vessel, inspect support post and put in conformity of the multilayer superinsulation, especially true for SSS) if:
   - 1st. No electric damage or soot in the cold mass;
   - 2nd. No movements at rest: we estimate from a dynamic model that at max the displacement for such CM was < 50 mm well within the max elongation of the lyra (180 mm). For Q22 the displacement at rest is about 20 mm. We believe that it is safe and given the necessity of saving as much as SSS as we can (without of course taking undue risk) we have decided to keep it in this lot.
   - 3rd. No visual damage from endoscopy (except minor scratch or NCs on bus bar that are similar to other seen routinely in installed magnet).
   - 4th. Qualification after cold test
   - 5th. These magnets, although believed sane, are the nearest to the effectively damaged magnets; their removal, inspection and cold testing is a necessary measure of precaution.
3. *Magnets that stay in the tunnel*

These are magnets like category 2. that in addition are more far away from effectively damaged magnets. So we believe that, despite being in the D-zone they are safe, if the cold test of cat.2 magnets is successful.

This concern a small number of magnets in D-zone: Q19, A20, B20 and C20, at left of the epicenter of the event (C24-Q24). However this criteria applies also for the magnets at right, outside the D-zone: A34, B34 and so on are qualified by the fact cat.2 magnets of cell 33Left are good (to e verified at cold test).

There is an annoying finding: in many SSS cold mass has been found an unexpected wire bulging out in the end covers of the SSS. However this is believed to have been a leftover of a guiding wire used in the corrector cabling and that should not have any electrical function [9]. Electrical test are OK.

The final inventory in the D- zone is:

57 main magnets affected: 15 SSS and 42 Dipoles

53 removed (14 SSS and 39 Dipoles)

- *16 re-used* (9 Dipoles, almost intact, and 7 SSS, this one with larger re-vamping on the cryostat)

- *37 substituted with spare magnets* (30 Dipoles and 7 SSS)

4 left in the tunnel (Q19, A20, B20, C20)

In the inventory of substitution of magnets one has to add also the two Dipoles in sector 1-2 and 6-7 that will be changed because of bad splice. This makes 32 spare Dipoles in total to be installed in spring 2009.

LOGISTICS, WORKFLOW AND PLAN FOR 3-4 MAGNETS

The use of the magnet facilities has been already mentioned. It is worth to mention that another big effort has been done to have the cold test rate ramping up. For this aim from half February the 18 kW plant of point 18 will be again turned to the test facility. As early as October was announced that a crash program would allow preparing the magnets needed for 3-4 by end of March or April. A detailed plan was then studied and at half January, connecting the work in surface to slot in the tunnel: this plan, which has NO CONTINGENCY, is now the reference and it foreseen the descent of the last magnet by week 15, i.e. Friday 11 April. Actually today we have 2 weeks of delay on this because:

a) SSS is taking longer and the necessity to reinforce quality and checks is taking more time.
b) The "novelty" of bad splices inside the cold mass of the Dipoles is requiring more cryostating (so far at least four) and many more tests. In addition the uncertainty existing so far on SM18 datas (at least when splices are in the 20 nOhm range) requires re-testing of magnets for verifications. In conclusion today it seems likely to descend the last magnet well before the end of April. At present 5 dipoles are under splice investigation.

The choice of replacing as much as dipole cold mass as possible was taken for safety precaution and to optimize the time of the schedule: taking spare cold mass from the parking lot is considerably faster than try to assess the damage and then reconfigure the magnet for cold test, while the spare are already today in the test configuration.

From the point of view of the machine configuration and corrector magnet electrical circuitries, for Dipoles they will be exactly as before the incident, while for SSS the configuration will be in few cases different for lack of suitable spare SSS (at the moment we are sure to miss 2 MQS and 2 MO).

In the SSS replacement strategy BE-ABP has been involved closely throughout the MEB – Magnet Evaluation Board, and the following approach was adopted:

- Try to preserve MSCB (orbit corrector) and MQT/MQS/MO layout
- If not possible: preserve in priority MSCB respect to the MQT/MQS/MO corrector
- If more then one choice possible: sort MQ for minimize effect on beta-beating.

In total 4 SSS will have MQ correctors that will not be used; to accommodate this change the N-line cable and connection box mist be specially prepared with a new routing and special connection in N-line boxes.

PLAN TO RESTORE THE STOCK OF SPARE MAGNETS:

As soon as the magnet will be descended in the tunnel, the people working in the surface for magnet preparation will be divided in two groups: one group will help the works and QA in the IC works and the other one will immediately re-launch the set up of the magnet facility, in 181 for SSS and in 180 for dipoles, with the scope to be ready to repair magnets already in summer.

The magnets with a non-conforming splice in the end covers, the one of sector 1-2, the one from sector 6-7 and the ones coming from the reserve stock will be the first to be put in conformity since the work for this is relatively simple.

The Dipoles to be repaired coming from 3-4 are subdivided into three groups (starting from B because the group A is composed by the 9 magnets that are re-used in 3-4):

Group B) composed by magnets without apparent electrical fault and no displacement; the non-conformity regards mainly the presence of soot; 9 dipoles that will be treated starting from the ones farthest from the points of the arc, then going near to the source of damage. Careful inspection with eventual opening of the end covers to clean up will be carried out according to the scheme shown in Fig. 3.

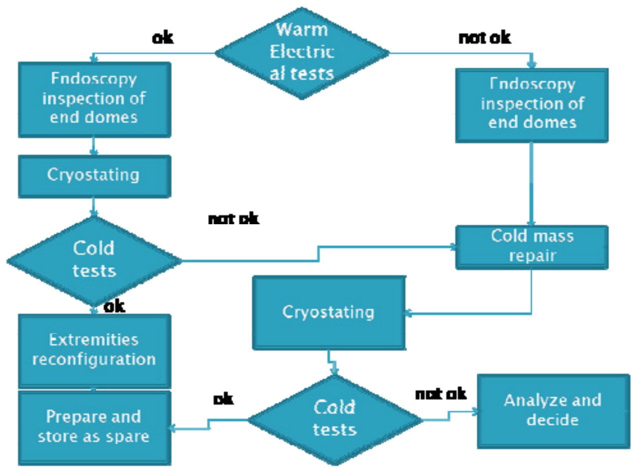

Figure 3: Flow chart of the repair and decision sequence for dipoles with minor damage (group B)

Group C) composed by 11 dipoles with displacement and OK upon electrical checks. These magnets as well will be treated from the less damaged to the most displaced. Careful attention will be put to the bus bars system violently solicited by large displacement. We think that all these magnets can be recovered without changing the bus bar because the point fix is much more robust than the connection itself, i.e. the this last as act as weak point. If this hypothesis will be true that means that bus bars can be put in conformity without opening the half shell, that requires much work, heavy tooling and considerable cost. The workflow of this group of magnets is reported in Fig 4.

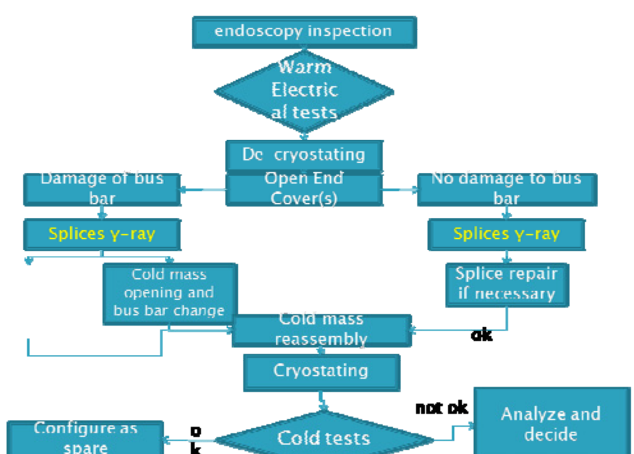

Figure 4: Flow chart of the repair and decision sequence for dipoles that displaced and with moderate damage (group C).

Group D) this is the group of electrically damaged magnets will be repaired as last. We have made the hypothesis, based on visual inspection and damage assessments that this subgroup may be divided into "easy" to repair, medium difficulty (i.e. when at least the coils can be recovered) and fully reconstructed. This last subgroup necessitate of the setting of the complete magnet facility and learning of long coil fabrication (something never done at CERN premises over the years of LHC R&D and prototyping). The workflow for these magnets is depicted in Fig. 5.

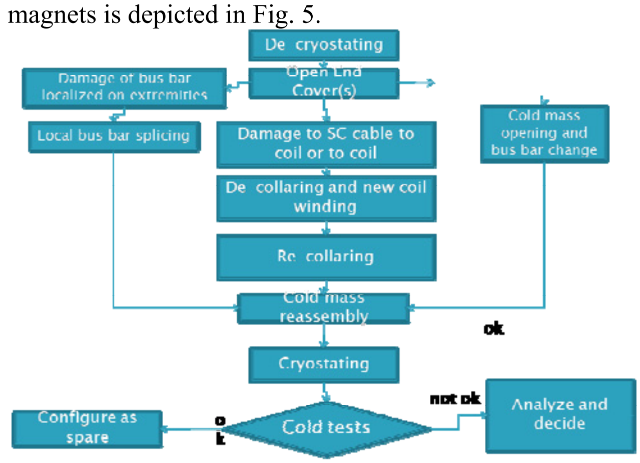

Figure 5: Flow chart of the repair and decision sequence for dipoles that displaced or not they have electrical faults, including arc originating the event (group D).

A preliminary time plan has been work out as shown in the table of Fig. 6. Almost all magnets can be recovered by end of 2010, in time for the shutdown 2010-11, which will allow to start the high energy run 2011 with the spare dipole stock almost all reconstitute.

Starting date	End date	Units/week	Magnet Group	Cumulative of repaired spare
Oct 2008	April 2009	2	New CM prepar.	(30)
May 2009	July 2009	Magnet facilities and tooling	==	==
		Reparation external splice		? (2 minimum)
September 2009	End November 2010	1	Group B	9
December 2009	Mid June 2010	0.5	Group C	20
June 2010	End of August 2010	0.5	Gr. D easy	23
September 2010	December 2010	1/month	Gr. D medium	27
January 2011	End 2011		Gr. D Rebuilt	30

Figure 6: table with first repair plan for dipoles

More complex is the treatment of SSS, given the fact that CERN has no direct experience in this type of assembly. Certain components are scarce, expensive and have long lead time of procurement (for example: the inertia tube and the bus bars) and must be recovered from disassembly itself. Later in 2009 the plan will be draw for SSS and eventual priority, with respect to the dipole repair plan, will be examined according to needs.

CONCLUSIONS

The incident of sector 3-4 has gone beyond our expectation in term of magnet damage. Despite this, the catastrophic scenario of not having dipoles or SSS (and especially MQs) not available has been avoided thanks to a considerable reserve of magnets constituted in 2005-06. We can face the needs of sector 3-4 and change directly – without waiting for repairing – a numbers of dipoles found defectives because of high resistance splices (so far two, one in 1-2 and one in 6-7). The fact of having launched in 2005-06 the concept of the Magnet Rescue facility allows us to quickly repair most of the damaged magnets. When we will restart the LHVC in autumn 2009 we will have still some 10 dipoles and 5 SSS as usable spare. By autumn 2010 (schedule of the next shut down) we will have reconstituted 90% or more of our reserve stock.

The reuse of a considerable number of magnets, 16, recycled form D-zone of 3-4 has been a necessary measure to avoid an even later restart of the accelerator and it has been validated by careful test. So far all the recycled magnets (about half) have successfully passed the cold test in SM18.

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