

RF UPGRADE PROGRAM IN LHC INJECTORS AND LHC MACHINE

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Abstract

The main themes of the RF upgrade program are: the Linac4 project, the LLRF-upgrade and the study of a tuning-free wide-band system for PSB, the upgrade of the SPS 800 MHz amplifiers and beam controls and the upgrade of the transverse dampers of the LHC. Whilst LHC Splice Consolidation is certainly the top priority for LS1, some necessary RF consolidation and upgrade is necessary to assure the LHC performance for the next 3-year run period. This includes 1) necessary maintenance and consolidation work that could not fit the shorter technical stops during the last years, 2) the upgrade of the SPS 200 MHz system from presently 4 to 6 cavities and possibly 3) the replacement of one LHC cavity module. On the longer term, the LHC luminosity upgrade requires crab cavities, for which some preparatory work in SPS Coldex must be scheduled during LS1.

INTRODUCTION

Winter Technical Stops (WTS) were relatively short over the last years, shorter than traditional winter shut-downs. Some important maintenance work does not fit those WTS and thus had to be postponed and re-scheduled to LS1; a couple of near-miss incidents clearly indicate that some systems are operated close to their limits. One example is the HV power supply of the SPS 200 MHz system, which already exploded in 1997 with major impact and which recently again had serious problems; luckily this could be discovered and fixed, but it could have caused a similar, major incident. The likelihood of this type of incident can be reduced only by correct preventive maintenance. In particular in view of a planned long operation period following LS1, the thorough maintenance of our systems during LS1 is of primordial importance in order to assure the reliable and the safe operation of our systems.

LINAC 4

The Linac 4 project has made good progress during 2011: the klystrons are ordered, the RFQ brazing difficulties now seem solved, the 3 MeV test stand is in operation and continuously upgraded, the DTL drift tubes are now in production, the fabrication of the CCDTL structures in Novosibirsk is finished and the PIMS discs are being machined in Poland. The Linac4 project has to keep its momentum to progress correctly to allow commissioning at 50 MeV (possibly at 160 MeV) in 2014. Even if the final connection to the PSB is scheduled only for LS2 (2018), the commissioning of Linac4 at intermediate energy with protons is important in order to be ready if ageing Linac2 fails beyond possible repair.

PSB

LLRF upgrade

The PSB LLRF upgrade is part of a major modernisation program towards modular, versatile and modern LLRF systems for all CERN synchrotrons, following a common philosophy and methodology; the present PSB LLRF program takes advantage of experience gained with LHC and LEIR; it will soon demonstrate its versatility since it will have to operate both with the traditional ferrite cavities and the modern wide-band FINEMET® cavity system now under study.

The LLRF upgrade is based on digital technology with direct RF sampling, digital signal processing and direct digital synthesis. DSPs and FPGAs allow very flexible and powerful, firmware-upgradable systems. These systems allow the inclusion of practically all control loops (phase, radial, synchronisation, polar, tuning ...) with all parameters fully controllable in PPM, using standard protocols to interface with controls and diagnostics.

After initial successful beam tests in one PSB ring and prototype hardware in 2011, the new LLRF hardware will be tested in ring 4 in 2012. The production of the hardware for all rings is planned for 2013 and 2014, such that the full deployment of the upgraded system can be commissioned with beam directly after LS1.

RF Power upgrade

There are presently 4 RF systems in the PSB: the C02 (0.6 ... 1.8 MHz), the C04 (1.2 ... 3.8 MHz), the C16 (6 ... 16 MHz) and the transverse damper system. While the C02 was designed and built in 1996 as dedicated system for the LHC, the C04 harmonic system (the former $h=5$ system) clearly limits the intensity of the Booster. The upgrade program thus concentrates on this system, while all other systems receive moderate upgrades concerning obsolete sub-systems and protocols (G64, interlocks, protections, modernized power supplies, filament supply stabilizers etc.)

The upgrade of the C04 system follows a double strategy: a wideband, FINEMET® based system is being designed and tested that could eventually replace both the C02 and C04 systems. Since this system is based on new concept that has to be fully validated with all PSB beams, the remaining risk must be mitigated. For this reason, the upgrade of the final amplifiers for existing C04 system is studied in parallel. This power upgrade is the fall-back solution which would not be implemented if the modern FINEMET® system is fully validated.

FINEMET® is a magnetic alloy that allows design of wideband RF systems. The concept has first been invented and developed at KEK and is at the heart of the J-PARC facility. At CERN, it has been successfully

implemented for the LEIR RF system. The PSB however has to deal with substantially larger beam current (2E13 protons per ring) and the voltage requirements impose a relatively large number of gaps, which increases the impedance presented to the beam and requires special attention.

The potential advantages of this system however seem to outweigh the risks: 1) it would be possible to instantaneously cover the full frequency range of the C02 and C04 systems (0.5 ... 4 MHz) allowing for multi-

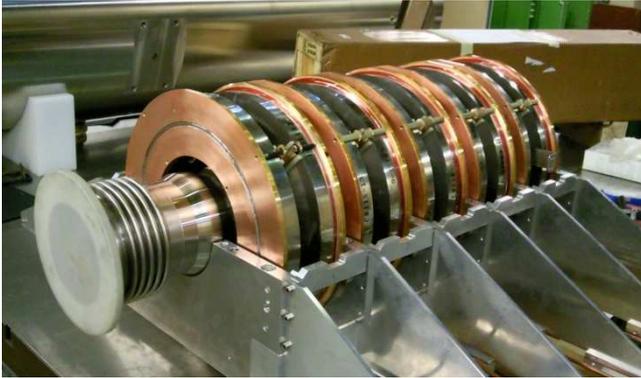


Figure 1: The five-cell prototype FINEMET® system.

harmonic operation, 2) with a single gap with two FINEMET® rings constituting one 0.7 kV cell, the system is fully modular, 3) it uses solid-state amplifiers, mounted directly on each cell allowing for fast RF feedback to electronically reduce impedance, 4) the large

instantaneous bandwidth makes tuning and large tuning power supplies unnecessary and 5) the modularity allows for increased RF voltage and for “hot spares”, thus increasing reliability.

A five-cell prototype FINEMET® system (Fig. 1) has recently been built and installed in section 6L1, ring 4. It will be tested with beam and with the new digital LLRF system (see above) during 2012. If successful, the next step will be the construction of a full, 13 cell system for ring 4, which will allow full qualification. The installation of this system is planned through LS1 with beam commissioning directly afterwards. The full production for the systems for the remaining rings would follow in 2015 and 2016 with possible installation during LS2, after which the existing C02 and C04 systems could be recovered.

PS

Upgrades and consolidation work in the PS are summarized in Table 1. The on-going LLRF studies and the subsequently planned upgrade to full digital beam control are part of the same strategy mentioned above under the PSB LLRF upgrade. The implementation of the 1-turn delay feedback is on-going; equally the fast tuners for the 80 MHz (and 40 MHz) systems, which will become essential for operation of protons and Pb ions during the same supercycle.

Table 1: PS consolidation and upgrade program

Activity	Schedule	Status
LLRF Studies	05/2011 – 06/2012	active
Digital beam control upgrade	06/2014 – 06/2018	planned
1-Turn delay feedback	01/2012 – 12/2014	active
Prototype commissioning	03/2012 – 06/2012	active
Installation on all cavities	LS1	planned
HLRF studies	05/2011 – 12/2012	active
Preparation for Ar ions	LS1	planned
10 MHz system renovation	12/2012 – 06/2018	planned
PS Longitudinal damper	01/2012 – 06/2014	planned
Install prototype in PS	LS1	planned
Coupled bunch feedback. LLRF	01/2012 – 12/2015	planned
40/80 MHz feedback renovation	06/2012 – 06/2017	planned
Fast tuner for 80 MHz system	01/2012 – 12/2015	active
Install prototype in PS	LS1	planned
C201 C206 consolidation	01/2013 – 03/2014	planned

SPS

LLRF upgrade

The SPS LLRF system upgrades to hand in hand with the power upgrades described below in order to assure and improve beam stability. Elements of this upgrade are: a complete 800 MHz LLRF overhaul, new frequency programs, implementation of prototypes for the 200 MHz LLRF system, the upgrade of the MMI controls from G64

to VME style and the preparation of the SPS LLRF for the light ion run.

The 200 MHz power upgrade

Since 1980, when the SPS became a proton-antiproton collider, there have been four 200 MHz travelling wave cavities, two 4-section and two 5-section cavities. In travelling wave structures, the beam loading at higher beam current will reduce the forward travelling power such that the effective accelerating voltage is significantly reduced – for “full beam loading” e.g., the forward travelling power is reduced to zero at the downstream end

and the accelerating voltage is approximately halved; to reduce this effect of beam loading, a larger number of shorter cavities is advantageous. Fig. 2 below demonstrates how the total accelerating voltage is reduced with beam currents for the four (black), five (pink) and six cavities (blue).

The upgrade plan is to build four 3-section cavities from the 10 sections of the existing 5-section cavities plus two of the existing spare sections. This would allow having a total of six cavities from LS2, two 4-section cavities and four 3-section cavities.

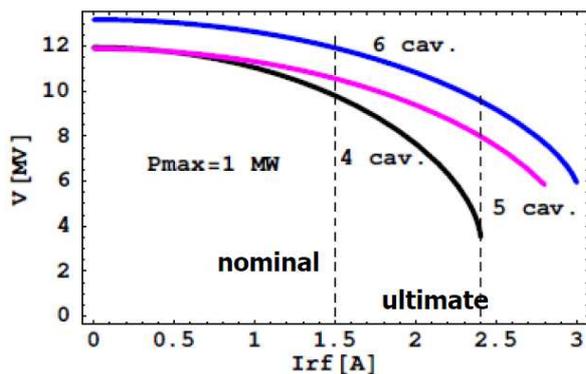


Figure 2: SPS accelerating voltage vs. beam current for different numbers of cavities (more, shorter cavities lead to less effect of beam loading).

This upgrade of course implies the increase of RF power by 50%, and different options for the new RF power amplifiers are presently under study, including a full solid-state solution, a conventional tetrode based solution or even more unconventional IOT final stages. In either case this will be a major installation that will require a new surface building between BA3 and BB3 – the new building “BAF3” is presently being studied. The construction is planned for 2013/2014. With the decision on the amplifier solution imminent in 2012, construction of the amplifiers with industry could start later in 2012 for delivery and installation in BAF3 in 2015 and commissioning in 2016. With these approximate time lines in mind, it is clear that the necessary re-arrangement of accelerating structures in LSS3 in the SPS tunnel can only take place during LS2.

The 800 MHz system upgrade

The proton beams for the LHC are intense and unless careful precautions are taken they become unstable in the SPS. One of the most important systems in the SPS used to keep the beams stable and of the highest quality is the 800 MHz RF system. The present system is very old and has become very unreliable.

For the upgrade, we decided to order IOT (Inductive Output Tube) based, turn-key transmitter systems. In 2011, after successful Factory Acceptance Test, we received our first pre-series transmitter. Endurance tests at CERN however revealed a weakness – the *maximum* time between failures was only 168 h and not good enough for our reliability demands! Careful analysis revealed

however that all of the many observed trips happened between 4 AM and 7 PM – a clear indication that the problem was high sensitivity to industrial noise (in sufficient EMC) and not due to the IOT concept. The system could be fully qualified and the series was ordered later in 2012. The revised schedule now foresees delivery of the series of 8 transmitters in the middle of 2013 and commissioning in the second half of 2013.

SPS Transverse Damper upgrade

Even if the re-arrangement of 200 MHz cavities in LSS3 will take place only during LS2, some preparation work is planned during LS1, notably the relocation of pick-up and kicker elements of the SPS transverse damper system. The high bandwidth transverse damper system, presently under study jointly with US-LARP, will have some new pick-ups installed in LSS3. Also some limited consolidation work on the transverse damper elements in BA2 is presently under discussion with BE-BI.

Preparation of Coldex area for CC tests

In the framework of HL-LHC, the RF group is committed to the study and initial tests of crab cavities, which are required in LHC to compensate for luminosity loss with a substantial crossing angle. With the planning for installation of the final crab cavities in the LHC upstream and downstream of the IPs only in LS3 and their final construction in the years just preceding this, initial validation tests of crab cavities are required before LS2. In order not to tamper with LHC physics, the SPS was chosen as ideal test bed for crab cavities. A well suited area in the SPS was identified to be BA4 where presently the Coldex is installed. During LS1, it is planned to prepare this area for first crab cavity tests in 2015. It was agreed with TE-CRG that the existing cryoplant (TCF20) will be upgraded to 2 K liquefaction mode.

LHC

400 MHz ACS

The LHC main RF system (ACS) consists of four superconducting modules of four single-cell cavities each. This system has been working relatively reliably during 2011; one module (M1B2) however contains one cavity (#3) which is limited to 1.2 MV instead of the nominal 2 MV. It should be noted that *all* cavity related trips during 2011 occurred in this module. It is planned to replace module M1B2 with the spare module during LS1. To this end, the existing spare module will have to be re-tested during summer 2012. This change is a major intervention that requires careful planning and follow-up.

400 MHz Klystrons and modulators

The 400 MHz high power klystrons suffer from a power limitation from a wrongly designed collector; these collectors are progressively replaced by the supplier. Half of the 16 existing klystrons have already been upgraded –

the remaining 8 will be upgraded during LS1. This is however not a limitation for present LHC operation.

The planned upgrades follow from analysis of the 2011 LHC RF fault statistics: most trips were caused by a klystron heater fault or a crowbar event, followed by cavity trips and arc detector triggers. The klystron heater faults are due the use of old and unreliable LEP hardware (DCCTs) and due to degrading spring contacts in the HV voltage connectors – both were improved during the 2012 WTS. The crowbar system, protecting the klystron from over-currents, uses thyratrons, which require very careful adjustment; a solid state replacement using a thyristor-stack instead of the thyatron is presently under study. The presently used arc detectors are equally inherited old LEP equipment, not optimized for LHC use. They suffer from radiation induced opacity of the optical fibres and have frequent false trips triggered by secondary showers directly from the beam; new fibre-less “shower head” arc detectors have been designed and initial measurement results are very encouraging [2]. A combination of 4 redundant detectors with improved trigger logic allows minimizing spurious trips.

ADT

The upgrade of the LHC transverse damper system (ADT) is aiming at reducing noise for the 7 TeV run. This will be reached by upgrading to better RF cables and the

use of additional pick-ups. Also will the reliably be improved by adding a HV switch to the power supplies that will automatically disconnect a faulty amplifier.

CONCLUSIONS

The table below summarizes the on-going and planned RF consolidation and upgrade program in the LHC and its injectors. The program is very demanding but necessary to assure performance and reliable operation.

ACKNOWLEDGMENTS

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	2011	2012	2013	2014	2015	2016	2017	2018	2019
LHC			LS1: Splice Consolid., Collimation IR3					LS2: Collimation, CC preparation	
Injectors								L4 Connection, PSB -> 2 GeV	
LHC work									
LHC klystron collector ug.		4	8 remaining						
Thyatron ug/replacement									
Replace module M1B2		verify spare	Swap with spare						
ADT			ug. cabling, PU						
Linac 4	IS/Services Installation	Acc. Installation	Commissioning						
PSB RF Power upgrade									
Finemet 5-cell, 6L1R4	Design-install	Beam tests							
Full system 6L1R4			Build,install	Beam tests					
Full system all rings					Design, build, install				
PSB LLRF upgrade									
Prototype hardware	Beam tests								
New hardware		Beam tests R4	Series production	All rings					
Linac4 connection					interlock system, ring synchro				
SPS 200 MHz upgrade									
RF hardware		Studies/tendering	Hardware construction/test			Equipment installation			
Tunnel LSS3			AEWB, BPWA, WP&K				Rearrange cavities		
Building BA3/BB3		Authorizations	Construction	Services		Equipment installation			
LHC Crab Cavity									
Technology Validation	Technology validation			Technical Design				Construction	
Beam Tests					SPS		LHC IR4		
LHC P4 cryo upgrade					possible?				
Preparation (Coldex)			Prepare Coldex & CC cryo						
Injectors Consolidation									
PS C201-C206			Renovation						
PS C10			Renovation (1-turn delay FB, fast FB, driver, gap relays, long. damper, coupled bunch FB, ...)						
SPS TWC800			Renovation						
SPSTransverse Damper			ug. PU, kicker, PS						