EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 98-022 (RF)

BEAMS IN THE CERN PS COMPLEX AFTER THE RF UPGRADES FOR LHC

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6th European Particle Accelerator Conference (EPAC98), June 22 - 26, 1998, Stockholm, Sweden

Geneva, Switzerland
14 August 1998

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1 INTRODUCTION

A substantial upgrade of the CERN PS Complex (Linac 2, PSB, PS) is necessary to achieve the requirements of the LHC in terms of beam brilliance (intensity/transverse emittance) and of longitudinal bunch characteristics (25 ns spacing, 4 ns length) before transfer to the SPS [1, 2, 3]. The major part of this upgrade, particularly concerning RF equipment, has been implemented during the '97-'98 winter shut down. The PSB is now equipped with the low-frequency RF systems listed in Table 1 [4] (1 cavity/ring/system) which permit acceleration of a single proton bunch per ring.

Table 1: PSB RF systems for the LHC era

System	**Frequency** (MHz)	**Vp** (kV)	**Purpose**
C02	0.6 - 1.8	8 kV	Acceleration (h=1)
C04	1.2 - 3.9	8 kV	Bunch shaping, splitting, and acceleration (h=2)
C16	6 - 17	6 kV	Blow-up

In the PS, the two new RF systems described in Table 2 have been added for rebunching at 40 MHz (at 26 GeV) and bunch compression [5].

Table 2: New RF systems in the PS for the LHC era

System	**Frequency** (MHz)	**Nb. of cavities**	**Vp / cavity** (kV)
C40	40.050	1	300 kV
C80	80.100	2	300 kV

All modes of operation of the PSB and PS RF were changed to be adapted to and to profit from, these modifications [6]. Commissioning took place during a four-week start-up in March '98 with the primary goal of re-establishing the beams needed by physics in '98, and especially the very demanding high-intensity beams for neutrino experiments. Second priority was given to the LHC-type beams to be delivered to the SPS later this year.

2 MAIN MODES OF OPERATION

2.1 For LHC-type beams

Transverse space charge detuning at low energy, both in the PSB and in the PS, is the mechanism limiting beam brilliance in the PS injectors' complex. The LHC specifications are met in the PSB by halving the intensity per pulse, accelerating one bunch per ring and filling the PS in two batches [1]. In the PS, the injection energy is increased from 1 to 1.4 GeV (kinetic), which reduces the tune shift by a factor 1.5 [2].

The RF mode of operation is the following:

- one bunch per ring is adiabatically captured on h=1 at T=50 MeV in the PSB, and h=2 is applied for bunch shaping to reduce transverse detuning. Acceleration then takes place and phase-modulated h=9 is added at high energy for controlled longitudinal emittance blow-up.
- each bunch is transferred at T=1.4 GeV into a matched bucket on h=8 in the PS. Two PSB cycles are necessary to fill the PS entirely (Fig. 1b).
- acceleration proceeds on h=8 up to 3.5 GeV/c, where splitting is done, doubling the number of bunches to be accelerated further on h=16.
- at 26 GeV/c the beam is adiabatically debunched and rebunched on h=84 (40 MHz). By pulsing the 40 MHz and 80 MHz systems, bunch rotation is triggered and ejection takes place when the bunches are shortest.

2.2 For the present physics programme

To meet the needs of on-going neutrino experiments, the PS must operate at the highest beam intensity with single-batch injection. Consequently, bunch splitting is applied at the end of acceleration in the PSB and the resulting four pairs of bunches are transferred to fill the 8 buckets available in the PS evenly (Fig. 1a). The gymnastics described in Section 2.1 are then applied, except that rebunching is done on h=420 (200 MHz) at 14 GeV/c.

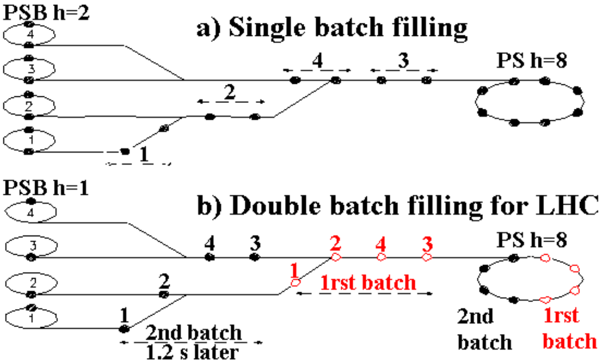

Figure 1 : (a) PS single and (b) double batch filling schemes.

To supply the lead ions beams for fixed-target physics in SPS, the new PSB RF systems will be used to simplify operation in that machine in the following manner:

- four bunches per ring are captured on h=4 with system C02 (Table 1) at T=4.2 MeV/u in the PSB. Beam is then accelerated on h=4 until 24.3 MeV/u when system C04 starts and system C02 is stopped.
- at 96.8 MeV/u, the 16 bunches from the 4 PSB rings are transferred into h=16 buckets in the PS.
- acceleration proceeds in the PS up to 5.09 GeV/u when the beam is ejected and passes through a stripping foil before entering the SPS.

3 PSB STATUS

3.1 PSB modifications

In addition to, and because of, the extensive changes made to the high-power RF system [4], the beam controls have been completely rebuilt to provide the capability to operate according to the new modes. Based on the standard architecture for "digital" beam controls in the PS division [7], they rely on direct digital synthesizers controlled by an accurate real-time measurement of the magnetic field in the dipole magnets to precisely position the beam in the vacuum chamber. Ten new NIM electronic modules have been developed and ~140 units have been built.

An important benefit of the harmonic numbers now in use is that the coupled bunch instabilities, which existed when 5 bunches were accelerated in each ring, have disappeared. The corresponding damping system is no longer needed, which simplifies the lay-out and noticeably eases setting-up for high beam intensity.

For stability reasons, dual-harmonic operation remains based on the previous principle, where the RF on the h=2 cavity (C04) is phase-locked onto the first harmonic of the beam current (rather than onto the RF of the h=1 cavity) [8].

3.2 PSB performance

The four-week commissioning period in March '98 was plagued by a large number of mundane problems not directly related to the recent upgrades (e.g. delays due to late installation of devices, wrong scaling factor in the Q control supplies, metal parts inside the PS vacuum chamber). As far as the new equipment is concerned, the running-in progressed correctly. Each PSB ring could be adjusted separately for operation up to the highest beam intensity ($9x10^{12}$ protons per pulse (ppp)), and the expected improvements were observed in terms of stability of the dual-harmonic operation and of duty factor for high beam intensity.

The beam proved more stable in every respect and even the quadrupolar mode damping system did not need to be re-installed. But performance degraded and serious difficulties were encountered when trying to accelerate high beam intensity simultaneously in several rings. This was due to equipment perturbed by the much lower frequency of the beam-induced signals (the maximum of the beam spectrum now spans 0.6 to 1.8 MHz instead of 3 to 8 MHz when h=5 was in use). The impedance across each of the 180 (per ring) DC-isolated vacuum flanges unfortunately peaks at ~10 Ω around 1MHz, so that a large fraction of the beam image current is likely to circulate through the many cables connected to devices in the ring. Filters had to be installed in many different equipments to circumvent the problem. The final solution will be applied during the next shutdown, when all clamps connecting the flanges will be modified.

Nevertheless the physics beams were delivered on time, and present performance is comparable to '97:

- peak intensity for each single ring: $9x10^{12}$ ppp
- maximum total intensity in four rings: $3.3x10^{13}$ ppp (for ISOLDE, without splitting)
- maximum total intensity for SPS: $3x10^{13}$ ppp

Figure 2 illustrates the end of the cycle for neutrino physics, when splitting and blow-up take place after dual-harmonic acceleration (as described in Section 2.2).

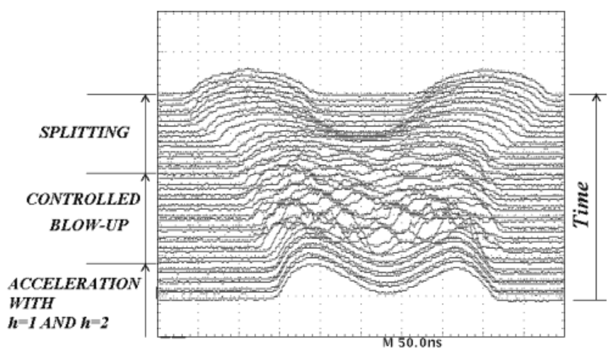

Figure 2 : Splitting and blow-up at the end of acceleration in the PSB ($3x10^{12}$ protons).

Setting-up for lead ions will take place in June and September ‘98 to prepare for the physics run starting in October.

4 PS STATUS

4.1 PS Modifications

The high power systems listed in Table 2 are available as planned since the end of the recent shutdown. The 80 MHz systems were installed this year [5], while the 40 MHz one has been in place since ’97. Because of the new RF harmonics used in the PSB, all PS beam controls had to be rebuilt. This opportunity was used to modernise and simplify lay-outs extensively. Routine operation now involves acceleration on h=8 first and later, after bunch splitting, at 3.5 GeV/c, on h=16.

4.2 Performance for the present physics beams

The adjustment of the beam controls progressed as foreseen, and the bunch splitting gymnastics proved very stable up to the highest intensity. The only unexpected difficulty in the longitudinal phase plane is a coupled bunch instability (n=6) before splitting on the 3.5 GeV/c flat-top which was cured by re-using decommissioned equipment from the PSB.

The steady increase in intensity has been slightly slowed down by problems of the beam instrumentation having to cope with the new harmonic numbers and by more classical difficulties in the optimisation of the working point. However, the beams planned until now for physics were delivered on time and the ‘98 record intensity for the SPS has reached 2.7×10^{13} ppp.

Figure 3 shows signals during a typical high intensity cycle for the SPS (2.4×10^{13} ppp). The peak beam pick-up signal is free of oscillations, which proves longitudinal stability, and few losses are observed during the acceleration cycle.

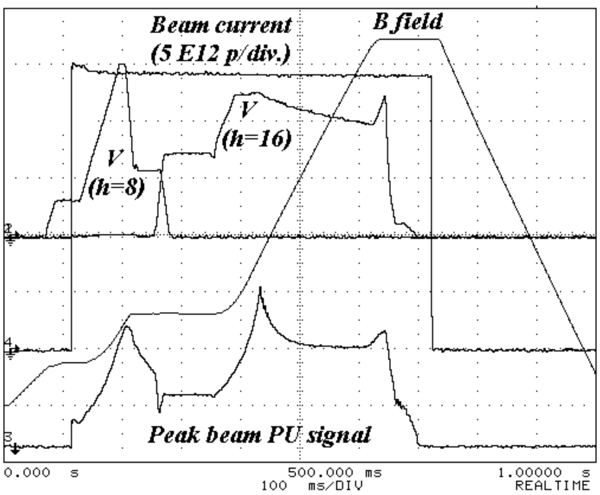

Figure 3: Full PS acceleration cycle for SPS.

4.3 Preliminary tests of the LHC-type beam

The beams required by physics in ’98 do not involve the new 40 and 80 MHz equipment. Nevertheless some tests have already been done with the following results:

- the impedance of these cavities is properly reduced by RF feedback and HOM dampers, since no disturbance has been observed on any beam,
- the systems are able to follow the specified programmes up to the nominal intensity (10^{13} ppp)
- the expected longitudinal characteristics of the 40 MHz bunches have not yet been achieved (ε_l~0.5 instead of 0.35 eVs). More work is required to understand and improve the situation.

5 CONCLUSIONS

The RF systems planned for the LHC era in the PS Complex are now installed and working. The proof has been made that the high-intensity beams for physics can be delivered with such a configuration at the same level of performance as before. The next operational beams for ’98 (Pb^{53+} for SPS and protons for AD) and the LHC-type beams are being actively prepared. Double batch operation will only be tried after the shutdown ’98-’99, when the transfer energy will be brought up to 1.4 GeV.

6 ACKNOWLEDGEMENTS

These achievements would have been impossible without the assistance of many specialists from all support groups as well as the dedication of supervisors and technicians from the main control room.

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