RECENT INTENSITY INCREASE IN THE CERN ACCELERATOR CHAIN

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Abstract

Future requests for protons from the physics community at CERN, especially after the start-up of the CNGS experiments in 2006, can only be satisfied by a substantial increase in the SPS beam intensity per pulse. In September 2004 a three-week beam run was dedicated to high intensity; all accelerators in the chain were pushed to their limits to study intensity restrictions and find possible solutions. New record intensities were obtained in the accelerators of the PS & SPS Complex with this type of beam which is different from the nominal LHC beam. The challenges in producing this high-intensity beam are described, together with the measures needed to make it fully operational.

INTRODUCTION

The previous intensity record at CERN SPS, 4.8×10^{13} protons at 450 GeV/c, was obtained during high intensity operation for neutrino experiments in 1997. This intensity was reached after long and careful machine tuning in all the accelerators of the chain. Normal operation intensity was around 4.2×10^{13}. More recently the accelerators have been delivering $\sim 2.3 \times 10^{13}$ for fixed target (FT) physics at 400 GeV/c. In 2006, after the start-up of the "CERN Neutrino beam to Gran Sasso" (CNGS) programme [1], CERN must produce this FT beam with intensities of not less than 4.4×10^{13} [2]. In the meantime the CERN accelerator chain has been upgraded [3, 4], mainly in preparation for the high intensity LHC beam, but also for the CNGS beam, which has different parameters and production scheme, Table 1.

In September 2004 there was a special run with a high intensity FT beam to see the effect of the recent upgrades in the whole accelerator chain and to find the present intensity limitations and possible solutions for improving the machine performance for future high intensity operation. The results are presented below.

CNGS BEAM CHARACTERISTICS

In normal FT operation each of the four Booster rings is filled at 50 MeV from Linac2 with a current of 175 mA during 12 turns. Acceleration at harmonic h=1, with h=2 applied first for bunch flattening and then for splitting at top (kinetic) energy 1.4 GeV, allows injection of 8 bunches every 1.2 s into the PS. These bunches are accelerated in the PS first at harmonic h=8 and then, after splitting into two on the intermediate plateau with momentum 3.5 GeV/c, at h=16. On the flat top, 14 GeV/c, beam is debunched and then partially recaptured at 200 MHz – the frequency of the main RF system in the SPS. This beam, extracted from the PS in 5 turns, fills approximately half the SPS ring. After the second injection 1.2 s later the SPS ring is full and acceleration at h=4620 to 400 GeV/c completes the picture, Table 1. Unlike the LHC beam, this beam crosses transition energy, not only in the PS but also in the SPS.

Beam in the SPS		CNGS	LHC
injection P_s	GeV/c	14	26
extraction P_s	GeV/c	400	450
bunch spacing	ns	5	25
filling pattern		10/11	(3-4)/11
number of batches		2	3-4
bunches/batch		2100	72
intensity/bunch	10^{10}	1.05	11.5
total intensity	10^{13}	4.4	3.3
cycle length	s	6.0	21.6
transv. emit. at ext.	μm	<12	<3.5

Table 1: The CNGS and LHC nominal beam parameters.

UPGRADE OF ACCELERATORS

Since 1997, the year of the previous intensity record, all accelerators in the chain have been upgraded.

New working points in the transverse plane were established in the Booster (4.17, 4.23) and the PS. In the Booster acceleration at harmonic h=1 replaced the h=5 used in the past so that the coupled-bunch instabilities with 5 bunches in the ring have disappeared. Harmonic h=2 is used to decrease space charge effects and h=9 for controlled longitudinal emittance blow-up at high energy. Lowering the RF frequency required in turn significant effort to reduce the impedance created by the insulated vacuum flanges [3].

In the PS the injection energy was increased in 1999 from 1 GeV to 1.4 GeV to reduce space charge tune spread. Some equipment was aligned to decrease losses caused by reduced machine acceptance. The harmonic number was changed from h=20 to h=8. A fast single-bunch vertical instability observed near transition with bunch intensities above 3×10^{12} was cured by controlled longitudinal emittance blow-up using the RF system with h=458 [5].

In the SPS, measurements in 1997 on FT beam with intensity 4.1×10^{13} showed a ten times longitudinal emittance blow-up during acceleration caused by microwave instability. Shielding different elements, including kickers, septa and 800 pumping ports, allowed the microwave instability to be eliminated, at least up to nominal LHC intensities [3]. For FT beam some results of this campaign, are

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presented in Fig. 1. It can clearly be seen that emittance blow-up is significantly reduced for measurements done in 2004 with an intensity 25% higher than in 1997. Bunch length increase at the end of the cycle is due to a coupled-bunch instability which has a threshold decreasing with energy, but does not cause beam loss and can be cured by the 800 MHz RF system in bunch-shortening mode through the cycle [7]. The 800 MHz RF system will become operational for the LHC beam. The main 200 MHz TW RF system in the SPS now has new power couplers and one RF feedback system per cavity.

With the closing of LEP the equipment used for leptons was also removed from all machines during the long shutdown of 2000/2001. This includes a 114 MHz RF system in the PS and three RF systems (100 MHz, 200 MHz SW and 352 MHz) in the SPS. However some new equipment was installed for the LHC beam (13/20, 40, 80 MHz cavities in the PS, extraction kickers in the SPS).

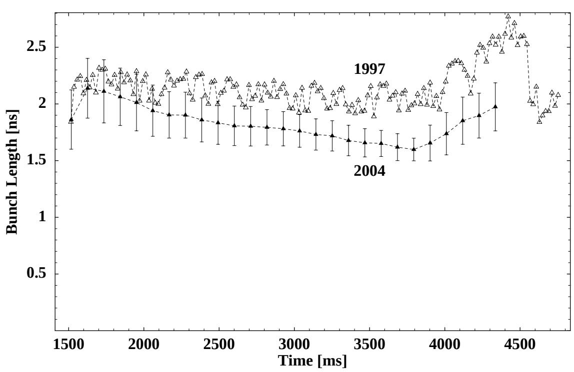

Figure 1: Bunch length evolution during the ramp starting from transition **before** (top trace) [6] and **after** (bottom trace, average for one batch) **impedance reduction in the SPS**. Voltage is around 7 MV in both cases. The total intensity is 4.1×10^{13} and 5.1×10^{13} correspondingly. Extraction at 400 GeV/c in 2004 and 450 GeV/c in 1997.

RESULTS OF THE HIGH INTENSITY RUN

Beam transmission

As a result of the recent upgrades a significant increase in intensity could be achieved in the three weeks, following some preliminary fine tuning in the PS. However some limitations which were discovered during this run should be removed before this beam can become really operational. Beam losses, especially at high energies in the PS and SPS, are the main concern.

Typical beam intensities in the different machines are shown in Table 2. For the **Booster**, the values are the sums of intensities in four rings, for example 3.84=0.99+1.02+0.89+0.94. As can be seen, even rings with the same optics behave slightly differently and the reason is not always clear. Ring 3 systematically has a smaller transverse emittance and intensity due to losses at injection. Realignment of all four rings is planned as a possible improvement. In the Booster 10% of beam loss occurs during the first 80 ms of acceleration when the beam is space-charge dominated. During this time the RF also requires fine adjustments. Implementation of all-digital beam control is foreseen for the future.

	Intensity/10^{13}		
Accelerator	injected	accelerated	extracted
Booster	4.3	3.84	3.65
PS	3.57	3.42	3.15
SPS 27.09.04	3.0x2	5.7 after tr.	-
SPS 03.10.04	2.9x2	5.5 after tr.	5.3

Table 2: Beam transmission through CERN accelerator chain for maximum achieved intensities.

No beam stability problems were seen in the **PS** for the normal scheme of operation, main intensity limitations coming from machine acceptance and the present 5-turn CT extraction. Injection losses around 6% could be improved by smaller injected emittances and machine alignment, which will be done in 2005. Implementation of novel techniques of beam extraction using beam capture in resonant islands should reduce losses at extraction from 9% to (2-3)% [8]. Running with high intensity beam also demonstrated that the required performance of the 10 MHz RF system in the PS is close to the limit: some equipment was broken or had to be changed. Preventive maintenance (new RF tubes, spare gap-relays) in the future should improve this situation, together with implementation of solid-state gap short-circuits. Transition crossing in the PS is almost loss-free; however the nature of continuous beam loss during the ramp ($\sim 3\%$) is not yet understood and needs further study. This run has also shown that measurements of intensity in the transfer lines Booster-PS and PS-SPS must be improved.

A new intensity record, 5.3×10^{13} at 400 GeV/c, was obtained in the **SPS**, but also with non-negligible beam losses, Fig. 2. At injection they are caused by vertical aperture limitations and are very sensitive to the vertical misalignment of the five turns extracted from the PS. One known bottleneck (beam dump absorber) will be removed in 2006. The nominal injection scheme with a constant capture voltage of 800 kV gives batches of triangular shape with an unacceptable number of ghost bunches in the kicker gap due to recapture of particles at the beginning of acceleration. The situation was partially improved during the run by ”quasi-adiabatic” capture of the first batch with a voltage step (0.8 MV increased to 2.5 MV); however this could not be applied to the second batch without additional losses from the first. The full solution requires new beam control for separate capture of each batch; possible due to the large bandwidth of the main 200 MHz TW RF system.

Transition crossing is a critical area in the SPS. The bunch length after transition is strongly modulated along the batch (see standard deviation bars in Fig. 1), in certain

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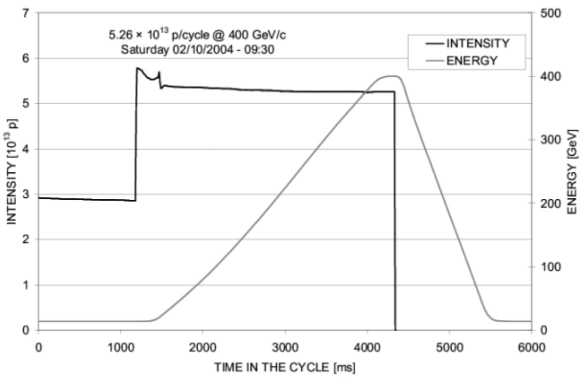

Figure 2: Beam transmission in the SPS at the end of the run. Transition crossing at $\gamma_t = 22.8$, t=1485 ms.

cases at ~ 1.3 MHz which corresponds to a minimum of 200 MHz RF feedback transfer functions [9]. This emittance modulation can explain the high voltage required after transition to reduce beam loss which results in more (but still acceptable) heating ($107°$ C) of extraction kickers (MKE) than hoped for [10]. Fast pulsed magnets with ferrite yokes are widely used in the SPS [11].

To avoid continuous beam loss at high energy, the one-turn-delay feedback was used during the whole ramp (unlike with FT beam). It was found that increased feedback gain improved transition crossing but created problems in the front porch. Variable gain is foreseen. We also plan an upgrade of the frequency range of the feedforward system which was not used this time and may also help.

The maximum record intensity was achieved in the PS a few days before the SPS could "digest" it (see Table 2) due to continuous beam losses after transition crossing preventing acceleration to top energy. The situation was improved on the last days of the run by adjusting the gain of the phase loop through the ramp.

A fast-growing electron cloud signal with clear dependence on beam intensity was observed in the SPS above 100 GeV/c (2.5 s) even with the conditioned machine. After a few hours' beam stop it also caused sparking of the Electrostatic Septa at the end of the cycle, perturbing normal FT beam in the following cycle.

PS-SPS transfer optimisation

A significant part of the September run was devoted to optimising the PS-SPS transfer. As a result of these studies the number of 200 MHz cavities in the PS used for rebunching at top energy, at present 8, will be reduced by a factor two. The necessity for debunching at top energy in the PS, which leads to microwave instability and absence of a kicker gap, was also under question. Beam transmission in the SPS and especially transition crossing is very sensitive to local particle density. For a debunched beam in the PS, beam losses in the SPS are less by $\sim 1\%$. This potential increase of loss with bunched beam could be compensated by reduced voltage at extraction in the PS, shown in these studies, and also by using a double harmonic RF system with h=8 and h=16 in bunch lengthening mode. Acceleration in the PS at h=8 without bunch splitting to h=16, which would allow the intermediate plateau in the acceleration cycle to be eliminated and the kicker gap to be increased, was also tested during this run. Strong coupled-bunch instabilities on the 3.5 GeV/c plateau and a single bunch longitudinal instability above transition observed in this situation could be cured by a one-turn-delay feedback, designed for another beam and requiring upgrade if to be used operationally.

SUMMARY

A new intensity record was obtained in the CERN accelerator chain. The relatively fast increase in intensity during the 2004 test is a result of recent accelerator upgrades. Further progress will be slower and require some hardware modifications. No fundamental intensity limitations were observed up to 5.3×10^{13}; however proposed improvements should be implemented before this intensity can become operational. On the contrary it was shown that operation with a nominal CNGS intensity of 4.4×10^{13} has a safety margin and should not have any serious problems. Due to the limited duration of the run not all possibilities were explored. Less reliable operation at high intensity demonstrated the need for preventive maintenance, which has been reduced at CERN for some years. Future work will concentrate on reduction of particle loss and the associated radiation problems which are the main concern for this high intensity beam.

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