PRESENT AND FUTURE PERFORMANCE OF THE CERN PS ACCELERATOR COMPLEX

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Introduction /1..3/

Over the past ten years the performance of the CPS accelerator complex [50 MeV Linac, 800 MeV Booster Synchrotron (PSB) and 25 GeV Proton Synchrotron (PS)] has undergone a continuous process of improvement, in order to meet the demands of new applications for its output beams and increasingly stringent quality requirements. The earlier stages were largely directed towards obtaining higher intensity and density; emphasis is now shifting towards increasing flexibility in multiple-service operation.

Throughout this time, the requirements of particle physics have been constantly evolving. The ISR began to store protons supplied by the PS in 1971, and in 1976 the first beams were sent to the SPS, whilst "25 GeV" experimental physics continued in the PS area. The ISR has shown some interest in deuteron beams, which they have successfully stored. For the future, apart from supplying higher intensity to the SPS, there is the possibility of light ion acceleration for other experiments, and considerable interest in the production of antiproton beams.

First requirements for higher average intensities were met by a new main magnet power supply capable of higher repetition rates, and by the provision of extracted beams of primary protons from which many experiments could run simultaneously. Between 1968 and 1974, beams of better quality and higher density became available through the development of the new RF accelerating system, the gamma jump for crossing transition energy, the coming into service of the Booster as injector to the PS, and careful compensation of stop-bands in both machines. To supply the SPS, the "Continuous Transfer" extraction system was developed, and to meet the individual requirements of different user programmes on successive cycles, the pulse-to-pulse programming of many parameters has been brought into routine operation.

For the future, a reduction in cycling time and the introduction of the new linac, accompanied by modifications to the beam transfer system, will provide higher intensity for the SPS, whilst acceleration with 200 MHz RF will help to overcome the problems encountered in debunching and re-bunching. Manipulations with the RF system can be used to obtain a higher linear bunch density for new colliding beam experiments.

This paper outlines the stages by which present performance standards were attained and work going on towards reaching the ultimate limits.

1. Evolution of accelerator performance /4..6/

Since 1974 the Booster synchrotron has been operational as injector to the PS, and beam quality through the three accelerators has been greatly improved. The machines appear to be well matched, since intensity limits found at several different points are virtually identical ($\sim$ 1.8 - 2.0 $\times 10^{13}$ protons per pulse). Table 1 below shows forecasts made in the past on the basis of existing knowledge and compares them with the results obtained.

Table 1 : Measured and predicted intensity and emittances of the PS internal beam

	Status 1970-1972	1972 forecasts for 1975	Status 3) 1974	Status 5) 1976-1977	1977 forecasts for 1980
N (10^{12} ppp) 1)	1.5-2	5-10	5	10	15-20
ε_H^* ($\pi\ 10^{-6}$ rad.m) 2)	30	30-60	60	60	60-75
ε_V^* ($\pi\ 10^{-6}$ rad.m) 2)	15	15-30	30	30	30-40
A_{RF} (10^{-3} rad)	10	20-30	10	18-25 4)	25-30

1) Proton per pulse

2) Normalised emittances = $\beta\gamma$ x surface comprising 95% of the particles (to avoid assumptions on beam distribution). They are larger than the 2σ figure used elsewhere, by a factor 1.5 for Gaussian distributions.

3) Obtained at 10 GeV/c, 10^{13} ppp obtained at 26 GeV/c with larger emittances.

4) Depending on controlled blow-up.

5) At 10 and 26 GeV/c.

2. Present performance /7..16/

Characteristics of current performance at critical stages of the acceleration process are summarized in Tables 2 and 3.

Table 2 : Linac performance

	Present Linac	New Linac (Specifications)		
I (mA)	86	150	100	70
ε_o ($\pi\ 10^{-6}$ rad.m) 1)	8	12.5	8.3	6
ΔE (keV)	±150 2)	±230	±150	±115
Duration (μs) 3)	80	70	160	200

1) $\varepsilon_o = N_{total} \Big/ \left(\frac{dN}{d\varepsilon}\right)_{origin}$

2) adjustable with debunchers

3) useful length (for good trapping efficiency)

Table 3 : Present optimum performance in normal operation

	PSB		Transfer PSB/PS	PS				CT [5] (→ SPS)	FE (→ ISR)
	50 MeV [1]	800 MeV	800 MeV [2]	800 MeV [3]	1 GeV [4]	10 GeV/c	26 GeV/c	10 GeV/c	26 GeV/c
N (10^{13} ppp)	1.4	1.33	1.27	1.20	1.05	1	1	0.9-1	1
ϵ_H^* (π 10^{-6} rad.m)	40	45	55	60	55-60	60	60	30	60
ϵ_V^* (π 10^{-6} rad.m)	18	20	25	30	25-30	30	30	30	30
A_{RF} (10^{-3} rad)	7	10	10	10	20 [6]	20 [6]	20 [6]	20 [6]	20 [6]

1) after multiturn "skew" injection (efficiency 42%) , RF capture (efficiency 80%) and fast blow-up
2) after recombination of the four PSB beams
3) after capture and dilution due to mismatching
4) after controlled longitudinal dilution on a 1 GeV plateau
5) 10 turn "continuous transfer", without phase plane exchange in the PS-SPS transfer line
6) adjustable from 18 to 25 mrad, by using 200 MHz RF on the 1 GeV plateau.

The principal means employed to obtain this performance are outlined below.

a) Improvements in quality and stability of the Linac beam for optimum use of the available pulse-length during 13-turn injection into the PSB. Further amelioration was obtained by using the "skew" injection method.

b) An almost complete suppression of slow transverse beam blow-up at 10^{13} ppp, from 50 MeV to 26 GeV/c, resulting from the following measures:
   - dynamic control of betatron tune,
   - careful dynamic compensation of second order resonances in the PS and third order in both machines,
   - reduction of transverse space charge by diminishing longitudinal densities,
   - improvement of the matching between PSB and PS and optimum employment of PS acceptance during the injection process.

c) Suppression of transverse instabilities by Landau damping with octupole lenses in both machines and control of chromaticity by the pole-face windings in the PS.

d) Damping of longitudinal instabilities by:
   - beam loading compensation,
   - active feedback for dipolar and quadrupolar modes in the PSB,
   - Landau damping by careful RF voltage programming in the PS (full buckets).

   In addition controlled emittance blow-up is produced on a 1 GeV field plateau using a 200 MHz cavity synchronized to the bunch frequency. Stable crossing of transition with diluted bunches (20 mrad) is much easier.

3. Studies to define performance limitations /17-18/

Table 4 lists studies related to hardware development necessary to reach

Table 4 : Present and future studies of performance limitations

	Limiting phenomena	Studies and development	
		Completed	In Progress
Linac	Brightness : $I_o/\varepsilon_o > 12 \frac{\text{mA}}{\pi\ 10^{-6}\ \text{rad.m}}$	Improved beam loading compensation	New Linac
	Momentum spread and bunch length at given intensity	Double frequency debunchers	
PSB			
Injection	Acceptance (ε_H/I, ε_V/I)	Skew multiturn	
Transverse capture	Space charge detuning (ε_H/I, ε_V/I)		Working point at injection
RF capture	Beam loading	Lower Q in cavities (modulator)	Optimisation of adiabatic capture
Acceleration	Transverse blow-up	Dynamic working point Use of multipoles	Systematic resonance $3Q_V = 16$
	Transverse instabilities	Use of octupoles	Transverse feedback
	Longitudinal instabilities	Longitudinal feedback	Bunch dilution by "shaking"
Recombination and Transfer	Acceptance	Improved optics and better control with the use of the measurement line	Compensation of mismatch between rings
PS			
Inflexion optics	Acceptance Mismatching	Improved injection kicker and measuring device Better matching	Injection with large horizontal emittance
Transverse low energy	Space-charge de-tuning		Improved dynamic stop-band compensation
RF capture	Beam loading	Compensation on cavities	Servo-loops on cavities
Acceleration	Longitudinal instabilities	Dilution using 200 MHz on 1 GeV plateau	Feedback? Further dilution(implications for 200 MHz system)
	Transition (25 mrad)	"Super" Gamma jump	
	Transverse instabilities	3-circuit PFW system Octupoles	Final PFW system (5 separate circuits)
Continuous Transfer	SPS limit intensity/ε_V		More powerful fast bumpers Multibatch filling

the potential maximum beam intensity (per accelerated pulse). The maximum expected from the present Linac is approximately 1.5×10^{13} ppp, but it is hoped to raise this to about 2×10^{13} ppp with the new Linac.

4. Beam utilization /19..23/

Accelerated beam is supplied to individual users on successive cycles, and accelerator parameters are altered from one cycle to another so as to provide each with the beam properties required.

The ISR have recently been provided with longitudinally-diluted bunches, which are less prone to microwave instabilities and hence allow higher-efficiency stacking, resulting in new records for stored-beam intensity (41.6 A) and density (1.25 A/mm).

Apart from supplying the SPS with more protons per PS pulse, its beam intensity can also be increased by using more than one pulse to fill the ring. Double-batch filling has worked successfully, and a five-batch technique is being

Table 5 : Present and estimated ultimate intensity limits for SPS

	Characteristics	Single Pulse Filling			Multibatch Filling			
		Present	Improved	Limit 3)	Present		Limit	
PS	N (10^{13} p per PS pulse)	1	1-1.2	1.8	0.3-1		0.5-1.8	
	ε_H^* (π 10^{-6} rad.m)	60	60	70	30-60		30-70	
	ε_V^* (π 10^{-6} rad.m)	30	30	35	18-30		15-35	
Transfer to SPS	No. turns CT	10	10	10	5	2 5)	5	2 5)
	No. PS pulses	1	1	1	2	5	2	5
	N (10^{13} p per SPS pulses 4)	0.9	0.9-1.1	1.6	0.5-1.8	1.3-4.5 6)	0.9-3.2	2.2-8(?)
	ε_H^* (π 10^{-6} rad.m) 1)	30	15 2)	18	18-35	30-60	15-35	30-70
	ε_V^* (π 10^{-6} rad.m) 1)	30	30	35	18-30	18-30	15-35	15-35

1) **Emittances after continuous transfer, without phase plane exchange [which can be effected when interesting ($\varepsilon_H^* < \varepsilon_V^*$) to reduce ε_V^* in SPS]**

2) **Short term improvement of CT, not applicable to multibatch filling (end 1977)**

3) **Ultimate limit on intensity**

4) **Assumed 90% total efficiency ejection + transfer**

5) **Mixed ejection : 1 turn beam shaving + 1 turn fast ejection**

6) **Not possible until completion of new, more powerful, fast bumpers.**

actively developed; other possibilities under consideration use three or ten pulses. The scheme includes a reduction of PS cycling time (for 10 GeV/c from 1.2 s to 0.65 s); possible effects on machine performance are being examined, but are expected to be rather small. Table 5 shows the expected performance of two- and five-pulse versions compared with single-pulse transfer. The figures depend upon imposed constraints - for example, vertical emittance in SPS limited to about $\varepsilon_V^* = 15\pi\ 10^{-6}$ rad.m, or maximum intensity required within its design normalised acceptance of 30 and 60(π 10^{-6} rad.m) respectively in the vertical and horizontal planes.

Another factor limiting SPS intensity at present is the debunching-rebunching process necessitated by the different accelerating frequencies in the two machines (9.5 MHz and 200 MHz). This is now carried out in the SPS after injection at 10 GeV/c but, because of microwave instabilities, it would be better done at low energy in the PS where the instability threshold is much higher; transfer would then become a direct bunch-to-bucket process. The design of a 200 MHz accelerating system for the PS has been undertaken, and preliminary studies appear to show that the optimum energy for the frequency change will be in the region of 1 GeV; the RF voltage required for trapping depends upon energy by way of two factors, namely bucket area and blow-up during the debunching-rebunching process. Further experiments will be needed to estimate more accurately the longitudinal beam characteristics, which have therefore not been included in the table. In the meantime, an improvement in the present situation is being sought by further increasing longitudinal emittance in the PS.

5. New applications /24..28/

a) High linear-density bunches. These are needed for antiproton production at 26 GeV/c (to be followed by "cooling" and $p\bar{p}$ collisions in the SPS). A combination of two techniques is envisaged to produce high-linear density bunches containing at least 2×10^{12} protons per bunch and less than 15 ns long. This involves, firstly, vertical superposition of bunches coming from two pairs of Booster rings to make 10 PS bunches. Limits are set by the vertical acceptance of the PS inflexion system and by the increased space charge at low energy. Experiments have already produced 10^{12} ppb at low energy. Secondly, RF manipulations are required in the PS to transform these 10 bunches into 5 short bunches, either by:

- capture at high energy of two bunches in a bucket at half the usual accelerating frequency and ejection after a quarter synchrotron oscillation, when the two bunches are superimposed,
- or by changing the harmonic number on a low-energy field plateau and accelerating the 10 PS bunches in 5 buckets at half the usual frequency. The production of short bunches is achieved by a jump to unstable phase, with return to the stable point prior to ejection,
- or by direct injection from two pairs of PSB rings set at slightly different energies into two sets of five buckets in the PS, and RF combination.

b) Very short bunches. Studies have started on production and extraction of 20 short bunches (about 5 ns) with an intensity of 7×10^{12} p, required to provide the SPS with a proton beam suitable for electron-proton collisions ("CHEEP" project).

c) Beams for "cooling" experiments. Cooling studies directed towards storage of $\bar{p}$ beams require the ejection of one or two bunches in a range of momentum extending below the PS injection energy of 800 MeV, requiring the development of techniques for deceleration. Experimental studies have determined the limits stemming from transverse space-charge effects and from the acceptance of the extraction system (designed for high energies). It is estimated that bunches of 10^{10} protons can be ejected at 50 MeV, and up to 2×10^{11} ppb in the higher energy range as far as 2.1 GeV/c. A cycle interleaved between those used for normal operation will be employed, leaving regular transfer to the SPS undisturbed.

d) Acceleration of deuterons and light ions. Deuterons have been successfully accelerated on several occasions and supplied to the ISR. Overall performance was very satisfactory; in the best case a 12 mA, 100 μs pulse from the Linac, with normal beam quality, gave 3×10^{12} deuterons at injection into the PS, and 6.5×10^{11} were accelerated to 24 GeV/c (12 GeV/c per nucleon); the loss was due to space-charge limits. This gave a stored beam in the ISR of about 9 A. The acceleration of other light ions is being studied; a prototype source to produce fully-stripped ions is under construction.

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ДИСКУССИЯ

A.van Steenbergen: Do you have an explanation for the large transverse emittance blow up due to the "skew mode" of injection into the Booster. What would the vertical emittance be in the booster if you did not use this mode of beam stacking?

P.Lefèvre: A multi-turn injected high intensity beam with the vertical emittance of about the linac emittance would never fit into the space between the working point $Q_v \sim 5.32$ and the integer resonance $Q_v = 5$, Laslett Q-shift is too large. It seems that the beam blow up starts already during injection and continues until the increased vertical emittance corresponds to a maximum Laslett Q-shift that fits into the mentioned free space, Skew injection results in a higher injection efficiency; the corresponding vertical emittance blow up is rather marginal as compared to the initial one.

Studies are presently under way to improve the injection working point.