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PULSE TO PULSE MODULATION OF THE CERN PS COMPLEX

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Introduction and Summary

The CERN PS complex (CPS) comprises three accelerators in series: the 50 MeV Linac, the 800 MeV Booster (PSB) and the 28 GeV main synchrotron (PS). Since the beginning of May 1976 this complex has delivered beams to three main users: the 400 GeV SPS, the 30 GeV ISR and the 25 GeV PS experimental areas.

SPS

The PS beam is continuously transferred in one batch (=single transfer, i.e. one PS pulse),at 10 GeV/c but the intensity can vary between 2×10^{12}(0.5×10^{12}) and 10^{13} ppp , depending on SPS activities. SPS filling in two or three batches (i.e. taking two or three CPS pulses, ejected over correspondingly fewer turns[1]) may become operational in the future.

ISR

The transfer momentum can be adjusted between 11 GeV/c and 26 GeV/c depending on ISR requirements. The intensity requested is of the order of 3-4×10^{12}ppp, with high longitudinal and vertical densities. During the ISR injection setting-up, only three of the twenty PS bunches available are transferred, the remaining seventeen being used for 25 GeV physics. For ISR filling the whole beam is given to the ISR.

25 GeV Physics

Within a single pulse, there are usually two or three fast extracted bursts for bubble chambers, and the remainder is shared between bursts resulting from slow extraction, and an internal target, for counter experiments.

Supercycle

All these sometimes conflicting requirements have led us to the introduction of interleaved cycles, constituting a supercycle. Their duration can vary between 3.6 to about 10 seconds, according to the SPS cycles in use. A supercycle consists of 10 GeV/c "A" cycles devoted to the SPS, and of 26 GeV/c "B" or "C" cycles for ISR and 25 GeV physics. An example is given in Fig. 1. Extraction modes as well as beam properties, mainly intensity, have to be modulated from pulse to pulse; this is referred to as pulse to pulse modulation (PPM). In the following we will first describe the different possibilities which can be used to modulate intensity, their consequences on beam properties and the interest for the users. Then, we will describe the implementation at the hardware level and the operational facilities available.

Modulation of Beam Properties

The aim was to modulate beam properties in a clean way, that is to produce and accelerate as much as possible only the intensity useful to each user. To bring about this intensity modulation, one can, in principle, act on each of the three accelerators or on the various beam transfers.

Choice of Modulator

The first possibility is to use the Linac: the proton source, transmission through the 500 KeV transfer line, or RF trapping in the first Linac tank could be modulated. Up to now this was excluded, because the present Linac radio-frequency accelerating system is not able to handle pulse to pulse changes of the beam loading. The situation will be reviewed after the new Linac, presently under construction, has been put into operation.

In order to minimize induced radio-activity and component damage, we have excluded acting at high energy in the PSB or on the injection into the PS. This leaves the 50 MeV Linac-PSB transfer line, multiturn injection and acceleration up to 80 or 100 MeV in the PSB. Table 1 shows the main possibilities and their incidence on beam properties.

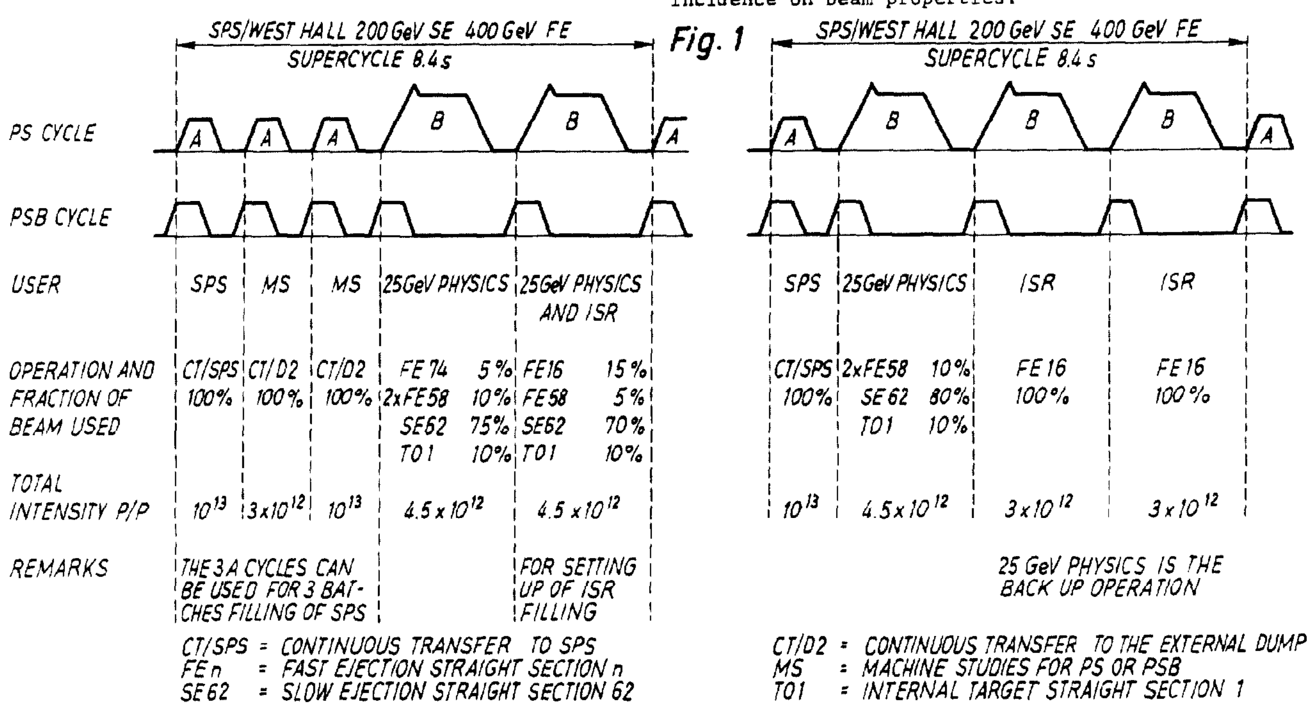

Fig. 1

TABLE 1

METHOD OF INTENSITY MODULATION

METHOD	REDUCTION FACTOR	MODIFICATION OF PROPERTIES IN RESPECT TO MAXIMUM INTENSITY					
		Emittances			Densities		
		ϵ_H	ϵ_V	ϵ_ℓ	ρ_H	ρ_V	ρ_ℓ
50 MeV Sieve	3 to 10	C	C	C	D	D	D
Horizontal scraping in 50 MeV line	1 to 5	D	C	C	I	D	D
Vertical scraping in 50 MeV line	1 to 5	C	D	C	D	I	D
Low RF trapping	1 to 5	C	C	D	D	D	I
RF spill out	1 to 3	C	C	D	D	D	I
Variation of turns injected into the PSB	1 to 5	D	C	C	C	D	D
Acceleration in 1 or 2 PSB rings	2 or 4	C	C	C	C	C	C
Horizontal scraping in the PSB	1 to 3	D	C	C	I	D	D
Vertical scraping in the PSB	1 to 3	C	D	C	D	I	D

I = increases , D = decreases , C = constant .

Relative Merits of Modulation Methods

Insertion of a sieve in the injection line is a simple way to obtain modulation by a factor three to five (ten). Transverse and longitudinal emittances remain relatively unchanged, as far as one can avoid space-charge effects. The low longitudinal and transversal densities obtained are unattractive for the ISR but can be very interesting for machine studies in the CPS or the SPS, or in case of search for a fault via beam behaviour, in one of the two machines. This method is however not suitable for standard operation, because of the impossibility to adjust the modulation factor and also the limited lifetime of the sieve mechanism.

Horizontal or vertical beam "scraping" in the transfer line. If done by mechanical scrapers, the lifetime is again a limiting factor. Moreover this process is very sensitive to beam position.

Variation of the multiturn injection process. The amount of beam injected in each of the four PSB rings is determined by the duration of the beam pulse from the Linac. This duration is controlled via the trigger time of the distributor fast magnet which switches the beam to the PSB rings. (The remaining beam is dumped in a clean way on a graphite block). It is a convenient method to modulate intensity by a factor of up to five. It produces an increase of horizontal emittance with intensity, but hardly of vertical emittance[2].

Acceleration in less than four PSB rings is a particular case of the variation of the multiturn injection process. Modulation by a factor 2 or 4 can be achieved, leaving the emittances unchanged. Unfortunately, this creates a strong structure at the PS revolution frequency. This is usually unattractive for 25 GeV physics and for the SPS. For the ISR it increases the filling time while decreasing the longitudinal stacking efficiency. Nevertheless, together with other methods, this permits to attain the highest modulation factors.

Low RF trapping and RF spill out. These two methods give the same kind of results, a reduced longitudinal emittance, with unchanged transversal emittances. Longitudinal density will be high, but may give rise to longitudinal instabilities in the PS.

Horizontal or Vertical scraping at low energy in the PSB. Horizontal scraping gives results comparable to those obtained by varying the number of turns injected, but in a less clean way. Vertical scraping will increase the average vertical density which is interesting for the ISR, but needs very good handling techniques for beams with very different emittances in the two transversal planes.

Priorities for implementation

Because of its flexibility, simplicity and cleanliness, we have chosen first to implement the modulation by the number of turns injected into the PSB. Preliminary tests were started in 1974, with a view to adjust the intensity between 10^{13} ppp for neutrino experiments to 3.10^{12} ppp for the ISR or other users. Other modes, in particular the sieve, horizontal and vertical scraping in the PSB and RF gymnastics are at various stages of progress.

Master Programmer

Usually in a supercycle there are at least four machine cycles. Up to four different beams may be needed for the SPS, the ISR or sharing between 25 GeV users. Moreover one cycle is sometimes used for machine studies. For each situation, specific control values or functions have to be transmitted to the hardware used for handling the beam in the transversal and longitudinal phase planes. For a given extraction, specific hardware has to be triggered. All these controls are programmed by means of logical levels distributed over program lines to all the CPS equipment rooms. Presently 50 program lines are used, six to specify the actual and next programmed machine cycle, ten as actual and next programmed intensity program lines and the remainder for ejections and targets.

The generation of all the program lines is achieved by a PDP 11/40 computer, working in real time[3]. It uses two classes of information: i) information for scheduled operations (ISR, SPS, etc.), with their planned intensities, and the stand-by instructions in case of failure of the programmed one; and ii) information directly coming from the process like present and next machine cycle, user's safety interlock status, ejection hardware status, refusal from ISR or SPS to accept the beam, and synchronisation pulses. All along the cycle these informations are monitored. In case of abnormal change, action is taken with a view to avoid unnecessary irradiation. According to the instant of decision within the cycle, the computer triggers a back-up operation or steers the beam onto an internal or external beam dump.

Implementation of PPM

Boundary Conditions

PSB and PS. The PS must deal with two kinds of problems which are different in principle: those related to the supercycle and those linked to the PPM of beam properties[4]. In practice both problems often concern the same equipment. The PSB machine cycle being fixed, the supercycle introduced only relatively minor problems due to irregular pulsing intervals. Hence PPM is the main problem[5]. In the following we will concentrate on the problems caused by the modulation of beam properties.

Space charge effects. For machines working in the low energy range, like the PSB and the PS in the first part of the acceleration cycle, intensity variation by a factor five will lead to strong variations in space charge dependent phenomena, and appropriate control of the accelerating system is used to cope with them.

Magnetic Elements

The situation of the controls and power supplies is very different at the PSB and at the PS. The PSB was designed (in 1967/70) for full computer control, but as a machine with essentially fixed operating con ditions. At this time, technical considerations led to the choice of a Varian 620 i computer as a centralized function generator. In contrast from the early sixties, the PS runs with pulse to pulse changes for high energy beam distribution, but with manual control. Starting in 1972, the conversion of magnetic corrections to programmed corrections and computer control was started. The evolution of technology led to the design of an autonomous new function generator (GFA). This context has led to choose two different ways to implement initially PPM in the PSB and the PS. The new CPS control computer system is expected to lead to a uniform technique.

PSB. To keep open a maximum of options and to limit interface modifications, a flexible software was developed, allowing to change from pulse to pulse about 50 control values taken from up to eight different sets. Within these limits, parameters to be modulated can be freely chosen , the particular choice depending on the tests which are performed. This software is installed in the IBM 1800 controlling the PSB. As the number of spare channels in the Varian is restricted, we have implemented, for only a few systems, the possibility to use two (three) different functions. The switching is directly controlled by the intensity program lines.

PS. The main magnet power supply regulation has been modified to fit this type of operation, giving to each user the same, or a better, field stability as before, with single identical consecutive cycles. The switch from rising field to flat-top is triggered by a pulse derived from the magnetic field; this allows a reproducibility of 1 Gauss on the flat-top. The control unit can produce three different magnetic cycles, and group them in a sequence of up to 12 magnetic cycles, the supercycle[6]. To solve the problem of magnetic corrections which are a function of the cycle and sometimes of the intensity, we have modified the GFA memory. It has been upgraded, to be able to contain 128 vectors instead of 32, which not only allows to store all the different elementary functions necessary within a supercycle, but also to activate each elementary function independently by means of the program lines[7]. This has solved the programming problem for all magnetic correction (and for RF voltage control).

Timing

The PSB and PS timing system has been modified to cope with PPM[8]. Especially the sequence control unit, which programs the Linac pulses allocation between the 50 MeV measurement lines and the PSB, has been totally rebuilt[9]. Up to 32 Linac pulses can be treated within a supercycle. Since 1976 a new timing system allows to use eight different sets of the number of turns injected in the PSB rings; it is directly controlled by the intensity program lines.

RF systems

In the PSB and PS the beam control dynamic range has been extended to cover a range of about 100 in intensity, avoiding any switching (and easing studies in which large losses occur during acceleration[10-11]). In the PSB the longitudinal stability is now handled by a longitudinal feedback, which is intensity independent[12]. In the PS case, we have solved presently the problem by programming the RF voltage according to cycle and intensity, to keep matched bunches.

Man- Process Interface

Beam Observation. Besides the electrodes for closed orbit and ν measurement, all the beam measuring systems have enough dynamic range to cover all intensities without switching. For the analog observation special trigger units have been built to synchronise the sweep of the scope with program lines, i.e. to select particular cycles.

Software for Digital Observation and Control: To allow work on a specific type of beam, the IBM 1800 software has been upgraded. One can work without any perturbation of the other operation modes[13].

Conclusions and Outlook

Having started at the end of 1973 for the main PS power supply and the end of 1974 for the other parts, the first stage of the PPM facilities were put into operation in February/March 1976, before the running-in of the SPS. The solutions adopted have proven their flexibility and reliability: we have been able to start delivering beam to the SPS without much inconvenience to the ISR and 25 GeV physics. Moreover, on spare pulses, we are able to prepare or even to perform machine studies in parallel with normal operation.

The present system suffers from the lack of homogeneity described and from a general lack of control computer power. The aim of the second stage is to remedy these shortcomings. This will be done in the framework of the new computer system, which is being implemented for the CPS. We will also continue to develop the complementary approach which is to make systems independent of cycle shape and intensity, as already done for the RF beam control systems.

The existing and new facilities will enable us, it is hoped, to meet all possible future challenges,ranging from PPM deceleration for electron cooling studies to maybe PPM change of type of ions accelerated.

Acknowledgements

The need for pulse to pulse modulation of beam properties and a supercycle was anticipated by the PS management, even before the users' requests were clearly formulated. This early start has allowed us to study and to select appropriately various methods and to implement the project effectively.

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