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UPGRADING THE CERN PS BOOSTER FOR SPS MULTI-PULSE FILLING AND ANTIPROTON PRODUCTION

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Summary and Introduction

New demands of PS users, notably regarding an increase of SPS intensity and $\bar{p}$ production for the accumulator ring (AA), are being met through an improvement programme involving most of the PSB systems. Progress is reported under the headings (i) doubling the PSB repetition rate for SPS multi-pulse filling[1,2]; (ii) vertical recombination of beams from 2 x 2 rings[3]; (iii) conversion of the computer controls[4]; and (iv) measures to consolidate peak performance and to go beyond[5].

The programme required substantial modifications of PSB magnets and their power supplies as well as of timing and beam observation equipment, a capacity increase of the air cooling (and heating) system, and connection to a new computer interface carried out during a four-months' shutdown. The provision of transverse damping systems[6] (being installed) as well as of h = 10 cavities[7] (under construction) are the major developments required for raising the beam intensity towards 3.10^{13} protons per pulse. All these PSB improvements are described and first results of commissioning are discussed briefly.

Doubling the Repetition Rate for SPS Multi-pulse Filling

RF bunch area. The transfer, without decreasing significantly the SPS repetition rate, of three beam batches, or even five, instead of the present two batches, calls for reducing the PSB cycle time from 1.2 to 0.65 s. The PSB magnet field rise then takes 0.3 s (instead of 0.6s) (Fig. 1) between injection (0.125 T) and ejection (0.592 T) field levels; a resulting doubling of $\dot{B}$ would imply a larger stable phase angle ϕ_s and hence a reduction in the RF bucket area. With the normal cycle and constant RF voltage (12 kV), the longitudinal acceptance goes through a minimum near injection ($\sim$ 8 mrad including the reduction due to space-charge) and becomes much larger ($\sim$ 25 mrad) near 800 MeV. A B(t) function has been calculated[8] such that the bucket size can be kept at the present level (Fig. 2) for up to 5.10^{12} pp ring (> 4.10^{12} experimentally). $\dot{B}$ increases progressively from the present 0.8 T/s(ϕ_s = 5°) near injection to a maximum of 3 T/s(ϕ_s = 20°); this latter value of $\dot{B}$ does not lead to a supply voltage exceeding the magnet voltage rating because of the small magnet inductance.

The upgraded main magnet power supply[9,10], directly connected to the 18 kV mains, consists of four rectifier groups, each of them including two separate, phase-shifted 6-phase thyristor bridges (Fig. 3). It underwent major modifications in order to (i) cope with faster and irregular cycle repetition rates as well as larger $\dot{B}$ while keeping the mains voltage ripple at acceptable levels; (ii) minimize the reactive power variations at the 18 kV mains; and (iii) enable the key parameters to be controlled by computer.

This upgrading involved (i) introduction of sequential operation of four rectifier groups (which include freewheeling thyristors, greatly reducing the reactive power drawn from the mains); (ii) provision of a 6 MVA reactive power compensator[10] consisting of AC thyristor controllers connected to the phase-shifted secondaries of two separate transformers - the current of single-phase linear inductors is modulated, via a regulation circuit, such as to minimize fast variations of the 6 kV bus-bar voltage and to keep the total reactive power drawn from the mains roughly constant -; (iii) additions to the AC filter to have 6 tuned LC circuits in order to reduce harmonics 5, 7, 11, 13, 18, 24; (iv) provision of remote control of the cycle shape: flat bottom current I_1, reference function dU/dt (= Ld^2I/dt^2) up to a given dI/dt, flat top current I_2; and (v) means for coping with a sequence consisting of "fast", "normal" and "special" cycles (the latter required for parasite machine studies on flat tops of different energies).

A refined regulation system, consisting of current and voltage loops, ensures the generation of any magnet cycle (including the one matched to constant bucket up to 0.4 T) within the specified reproducibility of 2.10^{-4} of I_2 right after switch-on.

The "$\int$Bdl" and "Q-strips" correction windings are used for fine adjustment, per PSB ring, of respectively the total bending power and the betatron tunes. The former are indispensable for providing beams, from four rings, with equal energy, accelerating frequency, and horizontal positions; the latter is required for adjusting individually the dynamic (= time-varying) working point to suit the stop-band situation in each ring. In order to allow a somewhat independent optimization of the working point during multiturn injection and RF trapping respectively, a Q-change of $\Delta Q_{max} \sim 0.10$/ms was specified.

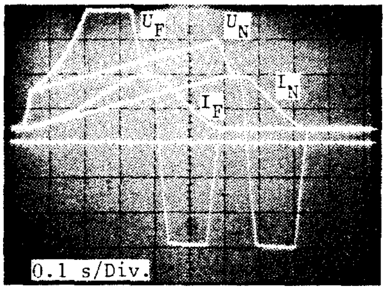

Fig. 1 - Normal and Fast magnet cycles: current (I) (1.4 kA/Div) and voltage (U) (0.7 kV/Div).

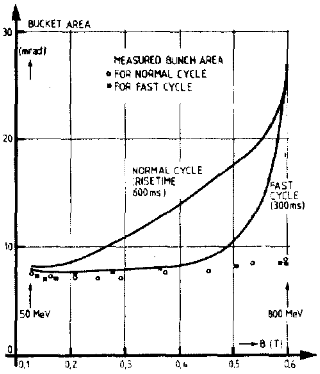

Fig. 2 - Bucket area (computed, full line) and bunch area (measured, dots) for normal and fast magnet cycles (N = 4.10^{12} pp ring).

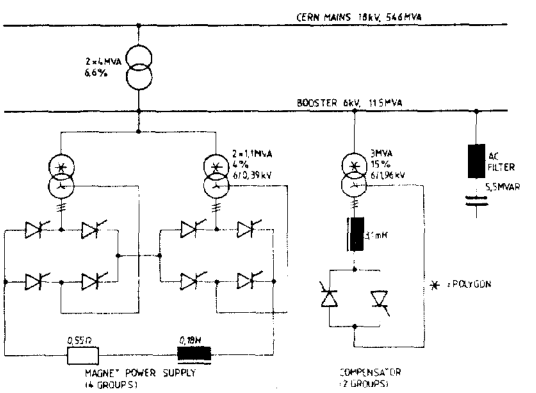

Fig. 3 - The upgraded main magnet power supply with reactive power compensator and AC filter.

TABLE 1 - Characteristics of New PSB Magnet Power Supplies

	∫Bdl	Q-strips	Pulsed dipoles	Pulsed septa
Number	4	8	55	5
Peak (r.m.s.) current [A]	50 (40)	100 (80)	10 or 20	3000-20000**
Max. $\dot{I}$ [kA/s]	0.25	20*	-	-
Current stability	10^{-3}	10^{-3}	10^{-3}	10^{-4}
Peak output voltage [V]	200	100	250 or 500	1000/40-20**

*) $\dot{I}$ required for $dQ/dt \gtrsim 0.10$/ms.**)On secondary of matching transformer

The corresponding 12 supplies[11] had to be replaced (Table 1) because of the faster pulse repetition rate and the higher induced voltage (the correction windings are magnetically coupled to the main power supply). Their design is based on a 12-phase rectifier and an optimized LCR filter yielding fast response and low ripple voltage across a transistor regulator, largely independent of the output current. A current regulation loop provides optimum tracking and fast response in spite of the unusually large dI/dt and the spikes induced by the main supply. The polarity can be changed (from cycle to cycle for the Q-strips supplies) by a thyristor bridge.

The pulsed power supplies for steering dipoles and for septum magnets[12] (Table 1) had to be replaced essentially because of the increased repetition rate. About 50 steering dipoles of six different types are fed by modular capacitor discharge supplies equipped with series transistor regulators for stabilizing flat top currents. These supplies can deliver reproducibly currents changing in amplitude and polarity from cycle to cycle, at irregular repetition times down to 0.65 s. The supplies for the septum magnets are of comparable though higher performance design (Fig. 4). Lengthening of the pulse top to 200 μs is provided by a third harmonic circuit in series with the storage capacitor; the resulting double-peaked top is flattened (Fig. 5) by a parallel active filter. A further servo-loop yields constant and reproducible values of U_C and hence flat top currents for all modes of operation. The various pulsed septa are fed via different matching transformers.

The capacity and reliability of the closed circuit air cooling system was increased by replacing two of the four compressor units by more powerful ones and linking the various cold water circuits via a 30 m^3 thermally insulated water storage tank. After other transformations heat freed in the refrigeration process is used for heating of buildings.

The timing system underwent redesign[13]: (i) conversion to computer control, including pulse-to-pulse modulation of several time intervals, with automatic provision of manually preset default values in case of unavailability of the computer data link; (ii) provision of two sets of timing signals (because with fast cycling, pre-injection operations for the "next" cycle overlap with actions to be taken for the "present" cycle);(iii) reduction of the B pulse train resolution from 0.1 to 1 gauss, to cope with the fourfold increase of $\dot{B}$ during the fast magnet cycle.

All systems needed for SPS multi-pulse filling have been shown to perform up to specifications, also with fast magnet cycles and beam.

Vertical Addition of 2 x 2 Rings in the 800 MeV Booster-PS Line for $\bar{p}$ Production

Rather than ejecting beams from rings 3, 4, 2, 1 one after the other ("20-bunch mode"), ring 3 is ejected at the same time as ring 2, and ring 4 together with ring 1. Beams are recombined vertically by a double septum magnet (Fig. 6), yielding 10 bunches with a line density improved by a factor 2 (∿ 1.7 experimentally because of unavoidable losses), at the expense of a vertical emittance increase by a factor three[3]. Obviously, beam steering and matching for this "10-bunch mode" differ from the ordinary settings; the settings of four steering magnets, one kicker magnet and the double septum magnet, as well as of four quadrupoles have to be modulated from cycle to cyle. In order to cope with the pulsed currents, the solid-core steering dipoles were replaced by laminated ones. The double septum magnet is a window frame device with opposite fields on either side of the 1 mm thick current septum (zero mechanical stress) made from a Cu-Be alloy. The current connections are placed at the central part of the coil, thereby enabling one to design the magnet ends for minimum fringe field effects (Fig. 6). The magnetic circuit is made up of Mn-Zn ferrite blocks held by an Al frame. The nominal current is 3125 A (deflection ∿ 2.6 mrad), the effective length 40 cm; positioning is by remote control.

Six electrostatic beam position monitors have been added in the 800 MeV recombination and transfer line, and nine replaced, to enable the 10-bunch mode to be set up with sufficient precision. Their design is based on high electrode capacitance (700 pF, 3 mm thick ceramic cylinders silver plated on both outer and inner surfaces), and 1 MΩ impedance differential amplifiers to achieve wide band-width (300 Hz to 50 MHz), the 300 Hz eliminating the need for base-line restitution during the beam passage time of 2.5 μs. The digitizing is performed by fast gated integrators, one for each signal, allowing measurement of the trajectory through the 800 MeV lines for any selected bunch (of 60 ns duration). With the aid of a remotely commutable gain the system can measure down to ± 0.5 mm for a range of intensities from 2.10^{11} to 2.10^{12} pp bunch.

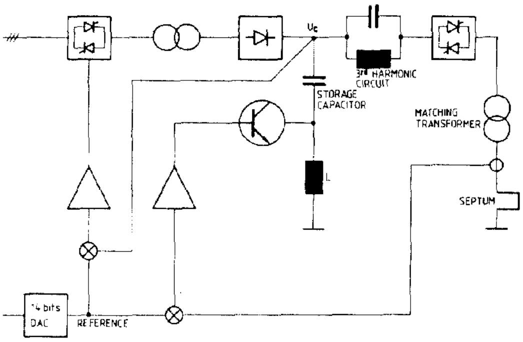

Fig. 4 - Pulsed power supply for injection septa and 10-bunch mode double septum magnet for vertical deflection.

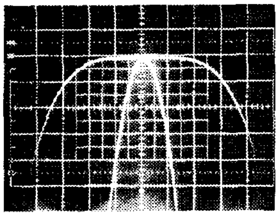

Fig. 5 - Flat top of septum magnet current and fundamental sinewave. 0.1 ms/Div.

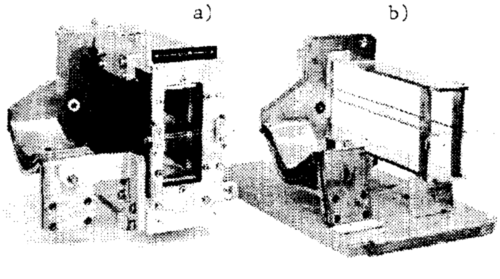

Fig. 6 - "Vertical" double septum magnet
a) complete magnet
b) coil.

During recent AA tests, the vertical addition scheme has been successfully put into operation for $\bar{p}$ production, usually in cycle-to-cycle beam sharing with 20-bunch mode users.

Conversion of the Computer Controls

The faster PSB cycles, the ever increasing requests for modulating settings from pulse to pulse, as well as the obsolescence of the IBM 1800 control system were the major reasons for this conversion, as a first slice of the project for equipping the CERN PS with a NORD-CAMAC system[4]. Standardized interface hardware, including local intelligence to cope with the real time tasks of pulse-to-pulse modulation and measurement data buffering, were connected to the partially readapted PSB systems during the four months' shutdown. This was followed by elaborate tests, made feasible by the provision of local user-oriented microcomputer test facilities[14]. A five-week period with beam was scheduled for testing the chain: control room console - computer network - serial CAMAC - interface - equipment; this concentrated effort of all persons concerned, including machine physicists and operators, allowed the PSB to resume its function as PS injector according to schedule, with debugging and tests continuing in parallel[15]. Improvements seen already by the users: design matched to operation[16], low beam down time due to rather reliable hardware particularly in the interface (local memories), new facilities for super-cycle programming[17], and better data presentation for beam diagnostics. Being completed and/or improved: application programs, global parameter setting facilities, a credible "alarm" (equipment and beam status surveillance) program, speed and reliability of touch panel tree manipulations for accessing parameters, console up-time, documentation for fully familiarizing the accelerator operators with the new controls. The overall performance of the new system should surpass the old one in 1981.

PSB Performance: Status and Potential Improvements

While continuing its role as reliable injector[18] for the PS, extensive machine studies and substantial hardware investments enabled the PSB to deliver routinely, at the expense of somewhat enlarged transverse emittances, 2.10^{13} ppp[19], twice the design intensity. The incoherent space charge tune shifts ($\Delta Q_H \sim 0.25$, $\Delta Q_V \sim 0.40$), still the limiting factor, are proportional to the peak line density and inversely proportional to transverse emittances. As was demonstrated, the former may be modified usefully by an h = 10 cavity (fundamental: h = 5), the latter by removal of aperture restrictions and properly shaping the transverse proton distribution. Harmonic 10 cavities[7], essentially following the h = 5 design, are being built; removal of aperture restrictions in the PSB as well as in the 800 MeV PSB-PS transfer line are on their way. Transverse instabilities will be damped by a wide-band feedback system[6]. These together with a few other developments[5], notably improvement of the linac beam brilliance, beam loading compensation, refined beam diagnostics, and full use of the PS acceptance (horizontal 50 π, vertical 30 π) could raise the PS performance limit to $\sim 3.10^{13}$ ppp in the coming years (see Fig. 7 for the evolution of constraints to PSB intensity).

Two Booster rings accelerating this type of beam will yield a line density comparable to the one obtained by vertical addition of 2 x 2 rings at present intensity ($\sim 5.10^{10}$ p/m) while virtually eliminating the beam losses at 800 MeV inherent in the 10-bunch mode. Alternatively, the measures described will render the present peak intensity more readily attainable while reducing beam losses and machine irradiation.

Acknowledgements

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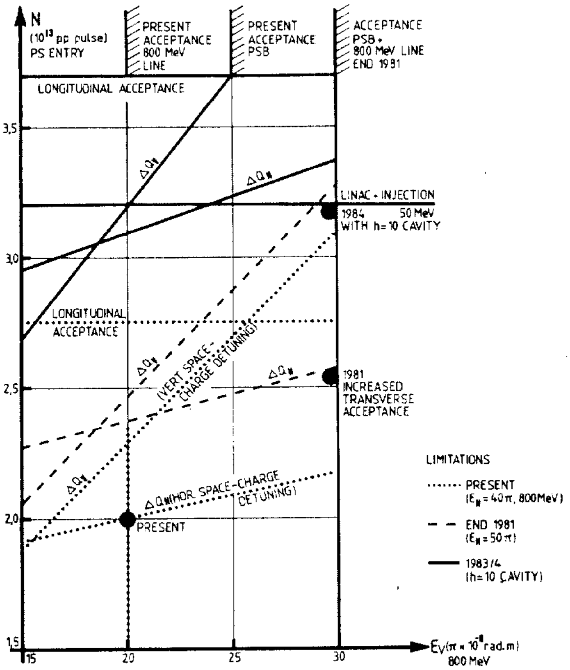

Fig. 7 - Machine parameters limiting PSB intensity at present and after future improvements. Intensities at PS entrance (800 MeV).