THE CPS IMPROVEMENTS 1965-1973
AN ASSESSMENT

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Summary

In 1965, plans were made to increase the beam intensity delivered by the CPS by a factor of ten or more. The first stage, involving a new power supply for the main magnet and more than doubling the cycle repetition rate, was completed in 1968. In the second stage, which is now essentially complete, the major items was the construction of an 800 MeV slow-cycling booster injector. Many other modifications were included. The Linac current had to be increased by an order of magnitude to supply the Booster, and the higher beam intensities required a more powerful RF accelerating system. Besides the 800 MeV injection elements, quadrupole lenses were installed to avoid longitudinal dilution at transition, and multipoles to counteract instabilities. In addition, the chamber vacuum was improved by a factor of ten, shielding and radiation resistance increased where necessary, and beam-equipment interaction reduced. Adequate instrumentation and control facilities had to be provided, and the efficiency of fast and slow extraction systems improved. Perturbations due to various collective phenomena had to be overcome.

The performance obtained during the first physics runs is reported.

1. Introduction

After a few years of operation, the CPS had reached a maximum intensity of 1 Tp/pulse* and, in view of space-charge effects, a further factor of two seemed the most that could be expected. The motor-generator set supplying the main magnet limited the duty cycle to a typical value of 10% at 19 GeV/c (200 ms flat-top with a 2 s repetition time) and even less at higher energies (100 ms flat-top every 3 s at 24 GeV/c). The experimental facilities comprised two halls, with a total area of 4000 m^2, fed by internal targets and a single fast extraction channel.

In 1964, an improvement programme was launched with the object of increasing the average accelerated beam intensity by a factor of 10 to 15[1]. This was to be achieved in two stages :

i) raising the repetition rate to gain a factor of 2 or 3, depending on energy and flat-top length, by constructing a new magnet power supply;

ii) raising the injection energy (factor $\sim$ 5 in intensity per pulse). Two possible methods were investigated in detail; a 200 MeV Linac[2] and a 600 MeV twin slow cycling booster synchrotron[3]. A comparative study[4] showed that although both schemes could produce the required intensity increase, the higher space-charge limit of the booster allowed a greater potential for future development. Further studies finally led to an 800 MeV booster with 4 superposed rings[5]. In addition to the new injector, this part of the programme involved a number of complementary improvements to the 50 MeV Linac and the main proton synchrotron, which are detailed below.

The programme was balanced by a comparable expansion of experimental areas and facilities (West Hall with the Omega spectrometer and the Big European Bubble Chamber (BEBC) and neutrino facility with Gargamelle), which took place simultaneously.

2. Main Magnet Power Supply

The new power supply[6] was designed to more than double the duty cycle.

The magnet voltage was increased from 5.4 to 10.8 kV, which approximately halved the rise and fall times of the magnetic field. In order to avoid increasing the maximum voltage to ground, limited by the winding insulation, a second rectifier set was inserted in the middle of the magnet circuit, with the output voltages of both rectifier sets symmetrical to ground. Keeping the same maximum current (6400 A) as before, the higher magnet voltage implies a higher peak power, namely 95 MVA in place of 46 MVA.

The increase in duty cycle raises the average power and the losses in the magnet. Mean power rose from 18 to 46 MVA and power dissipation in the magnet from 1.6 to 3 MW. The magnet cooling system had to be adapted to the new conditions.

The new power supply has a more flexible control system, which provides a wider choice of magnet cycles, including the possibility of two "flat-tops" at different energies. The distribution of accelerated protons between users is thereby simplified; a common example of such a complex cycle is : acceleration to 26.3 GeV/c, ejection of 4 bunches to ISR, deceleration to 24 GeV/c, then slow extraction shared with an internal target over a 400 ms burst.

The reduction obtained in the ripple voltage (20 V peak to peak instead of 100) and the better reproducibility of the magnet field ($4\ 10^{-4}$) are important factors in producing a satisfactory slow extracted beam.

Reliability has proved to be very good (2 h downtime per 1000 hours of operation in 1973).

An important additional implication was the need to increase the mean power and the rate of rise of the auxiliary power supplies. These modifications were carried out progressively, and still continue today, as each auxiliary sub-system proves to be a bottle-neck for an increase in the machine overall efficiency and has, in its turn, to be matched to the main power supply capability or modified to improve the control of beam dynamics effects.

3. Linac

Since the original 50 MeV Linac had also to serve as injector for the new Booster synchrotron, its performance required substantial improvement. This involved increasing the pulse length to 100 μs, for multiturn injection up to 15 turns; more current (100 mA) within a specified emittance and energy spread (30 π mm mrad

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* Tp = 10^{12} protons (Teraproton).

and ± 150 keV); and a higher repetition rate (2 s^{-1}) so that alternate pulses could be sent down a pair of new beam measuring lines. Besides increasing the duty cycle of several components (ion source, pre-accelerator, pulsed quadrupoles, etc.), a major problem was cavity beam loading and its compensation. This was tackled by installing for each of the three tanks an additional RF amplifier using more powerful tubes. However, the beam loading compensation is very difficult to adjust with adequate stability for long pulses at peak intensity, and it has been necessary to limit the beam to 50 mA, to achieve stable operation and reproducible beam quality.

4. 800 MeV Injection System

After injection at 50 MeV from the Linac and acceleration in the Booster, the 800 MeV beam is injected into the PS over one turn, and the bunches are trapped directly in synchronized buckets. The injection system together with the associated beam observation devices and low energy magnetic corrections is described elsewhere[7]. An incoming beam within the specified characteristics is trapped with barely detectable losses.

5. Accelerating System

The reduction of the magnetic field rise time also implies an increase of the energy gain per turn, and it was initially intended to achieve this with a set of three additional narrow-band second-harmonic cavities[8]. These would have been switched on 80 ms after injection when a remaining frequency swing of only 10% was needed to reach top energy. Although prototype units were developed and successfully tested with the beam, the project was dropped when, during the second stage of the improvement programme, it became clear that the whole RF system would have to be rebuilt.

An additional requirement was the desire to be able to trap the 20 Booster bunches in 10 of the PS buckets as a means of increasing the ISR luminosity. After investigating several alternatives[9], it was decided to build a new acceleration system capable of coping both with the faster rate of rise brought about by the new magnet power supply (section 2) and the higher beam intensity.

The new RF system[10] comprises ten units spaced around the ring. Each unit has two identical ferrite-tuned cavity resonators, working over the frequency range 2.5 - 10 MHz, providing a peak accelerating voltage of 2 x 10 kV. The available power output is 90 kW per unit, which is adequate, under the worst conditions, for an intensity of 1.5 Tp per PS bucket. The pair of resonators is connected in parallel, which simplifies tuning current control and allows a larger tolerance for the power tube output capacitance. The accelerating gaps are short-circuited by vacuum relays at the end of the acceleration phase of the cycle, so that they show a low impedance to the beam and re-bunching is avoided.

The power amplifier is a neutralized 70 kW tetrode, operating with grounded cathode in class B. It is housed in the cavity compartment to provide isolation between the varying cavity impedance and the feed cable, and is built as a plug-in assembly for rapid exchange; the rest of the system is in the centre of the ring where it is always accessible. All sub-assemblies are easily interchangeable and, apart from the final stages, fully transistorized.

The beam control system has also been replaced to meet the more stringent operational requirements (automatic phase programme, adapted pick-up sensitivity, beam-derived frequency programme, synchronization with the Booster, single bunch acceleration).

6. Vacuum System

It has long been known that residual gas could be a source of beam instabilities, and therefore set a lower limit on ultimate performance than simple gas scattering effects would indicate. Furthermore, the prospect of increased radiation damage, and therefore reduced reliability of vacuum seals made of organic materials, was an additional reason for redesigning the vacuum system[11].

The 82 oil diffusion pump groups have been replaced by about 130 sputter-ion pumps (200 or 400 ℓ/s pumping speed according to the local load) and 14 turbomolecular pump groups (260 ℓ/s) for pumping down to the 10^{-5} Torr range. All the rubber seals have been replaced by metallic types, and new bellows-sealed valves installed.

The completion of this project has reduced the mean pressure by a factor of ten, namely from 2-3 10^{-6} Torr down to 2-3 10^{-7} Torr. Recent beam dynamics experiments[12] have shown that at the intensity level of 2 Tp/p a return to the old pressure level immediately lowered the intensity by 50%. It should also be noted that, in spite of the longer pump down time, the time lost due to vacuum system faults has gone down from 20 h to 10 h per 1000 h of operation.

7. Extraction Systems

Efficient sharing of accelerated protons between an increasing number of users demanded the development of new extraction systems and components. Limitation of the intensity permissible on internal targets, to avoid both overheating of the target head and radiation damage to adjacent components, places a premium upon methods of slow extraction which can simultaneously share the beam without unduly increasing losses. A resonant extraction system of this kind is now in operation[13]. Generally, the use of higher intensities implies the necessity for improvements in extraction efficiency.

This problem has been tackled in two ways; firstly, by the development of extraction system components with wider apertures for the same deflecting power; secondly, by the use of devices ahead of the extractor magnet which enhance the separation of the protons-to-be-ejected whilst providing the minimum obstruction in the machine aperture (septa). Brief descriptions of these components follow.

i) A Full Aperture Kicker (FAK), to replace the plunging partial aperture devices which could only handle beam of pre-booster dimensions.
The new system consists of 9 ferrite transmission line magnet modules of 15 Ohm characteristic impedance. With a pulse voltage of 40 kV (80 kV on the pulse generator), the flux density in the 53 mm gap is 630 Gauss and the total kick strength at 26 GeV/c gives a displacement of 19 mm at the septum extractor magnet location with a 55 ns (10 to 90%) rise time. These parameters have been chosen taking into consideration the expected larger transverse emittance and the longer bunch length of the high intensity beam. The system was commissioned in 1973 and has performed well up to

26 GeV/c (nearly 100% efficiency) with the maximum beam injected so far (6 Tp/p).

ii) Electrostatic septum deflector as first stage of the slow extraction beam channels[15].
This unit has a 0.1 mm molybdenum foil grounded anode (the septum) with an anodized aluminium cathode. Field strengths of 100 to 110 kV/cm are currently achieved over a 10 to 20 mm gap. No adverse effects are observed when the proton beam hits the septum even at 6 Tp/p, but it is necessary to avoid grazing the cathode.
Among the major difficulties was the effect of secondary ions, which had to be screened off to avoid excessive sparking, and electromagnetic coupling of the septum with the beam, which had to be damped to avoid exciting strong beam oscillations.
The successful operation of the electrostatic septum was the main factor in reducing slow extraction losses to 3-5%[16].

iii) As intermediate element in the slow extraction channel, a 1.5 mm thick septum magnet[17], capable of giving a 1.5 mrad deflection (0.115 T at 24 GeV/c), was built and installed, and has been operating reliably for two years.

iv) Large aperture septum extractor magnets are being developed to accommodate the bigger beams. A vertical aperture of 30 mm (instead of 15-20 mm) is now necessary. For slow extraction, the 10% duty cycle initially specified had to be raised to 30% to match the capability of the new main magnet power supply (section 2).
The 30x50mm aperture magnet for fast and slow extraction from a long straight section has three 76 cm modules with 6 and 9 mm septa giving 30 mrad deflection (0.9 and 1.3 T at 26 GeV/c); although performing electrically and magnetically as intended, it has suffered from several mechanical failures (water/vacuum seals and has had to be modified.
Large aperture magnets for fast extraction from a short straight section[19] (30 x 45 mm aperture with a 19 mrad deflection at 26 GeV/c given by 1.8 T) are being built and will be installed this year. Because of their vertical dimensions, these new models can no longer fit between the upper and lower main magnet coils, and therefore have to be significantly shorter (105 instead of 140 cm).

8. Corrections for Beam Quality Preservation

The low-energy corrections are discussed elsewhere[7], as well as the γ-transition jump system to avert longitudinal blow-up when passing through transition[20] energy.

At energies above transition, two types of correction are used :

i) programmed octupoles increase the spread in betatron frequencies in order to avoid the vertical head-tail instability. This effect is discussed in another paper[21]. It is expected to become stronger with increasing intensity. More powerful and more compact lenses (to fit into the restricted straight section space) have been built[22].

ii) the RF voltage is carefully programmed to provide enough Landau damping to suppress longitudinal instabilities[23].

In addition it is intended to install pulsed sextupoles in the near future, in order to program chromaticity and thus reduce the growth rate of the head-tail instability. The use of pulsed quadrupoles to correct the betatron tune dynamically during acceleration is also planned.

Extensive research into the coupling characteristics of various machine components which might interact with the beam is being conducted[24].

9. Instrumentation and Controls

The CPS instrumentation has been a key element in understanding beam behaviour and in obtaining rather rapidly the performance summarized in section 11 below. The main techniques used in the PS ring and for extraction systems have been reviewed elsewhere[25]. The special devices developed for the injection of the Booster beam are described in ref. 7.

In parallel with the improvements to the major components of the CPS, a control system centered around an IBM 1800 has been built up. This computer system serves the Booster and many sub-systems of the Linac and PS. Computer driven consoles with interactive control are used by the operating staff in the Main Control Room[26].

A multi-computer system is being built around several intercommunicating PDP-11/45[27], to facilitate operation under the even more demanding future conditions.

10. Radiation Problems and Beam Dumping

Although the proportion of accelerated protons wasted has been steadily reduced by increasing efficiency in their distribution, the increase in intensity has nevertheless created problems because of radiation damage; the higher levels of induced activity render "in situ" maintenance more difficult.

Most of the organic materials near the beam have been replaced by metal, ceramic or oxide-coated components, designed for faster servicing and quicker exchange. The major source of concern was the main PS magnet[28]. Several units have already had to be replaced, the weak points being the adhesive holding the laminations together and the poleface windings. The magnet blocks can be mechanically clamped, but the poleface windings will have to be replaced by a new version. An evaluation of the situation in the experimental areas of the CPS with regard to induced activity and radiation damage has also been made[29].

The roof shielding above targets was reinforced, and the earth shielding over the remainder of the ring increased to the structural load limit. An evaluation of the effects of various modes of operation on site radiation has been made, and this is one of the criteria used in establishing long-term programmes. There is a continued effort to keep down unnecessary losses.

In the operation of an accelerator such as the CPS, a certain amount of beam dumping is inevitable. This occurs, for example, during beam studies, or when one part of a complex distribution cycle has to be temporarily suppressed.

The CPS lattice makes it very difficult to design an efficient general purpose fast dumping system, capable of absorbing the total expected intensity (10 Tp/p) for several hours, as has been done for newer machines such as the ISR, NAL or the SPS.

The policy[30] is therefore to use the external beam channels as often as possible for this purpose, and to provide a dump in each of them. Nevertheless, internal dumping cannot altogether be avoided. Internal dump targets, capable of localizing the losses in a limited region of the machine and of withstanding the thermal stresses caused by the higher intensity are being designed, and the feasibility of a fast dumping kicker is being investigated.

11. Performance

The peak intensity reached so far, as a result of the improvement programme, is over 6 Tp/pulse at 26 GeV/c. A much more important outcome is that the PS has been operating stably for regular scheduled high energy physics runs, at 26 GeV/c with 5 to 6 Tp/p at a 2 s repetition time. The beam was extracted by the full-aperture kicker system with losses barely above the threshold level of the beam loss monitoring system.

A longitudinal emittance of 9 mrad* (in units of RF radians x $\Delta p/m_0c$) was maintained at 6 Tp/p from trapping at 800 MeV up to transfer to the ISR at 26 GeV/c, thanks to the γ-transition jump system. With the octupole corrections and the programming of the RF voltage along the cycle, all the harmful instabilities can be kept under control.

There is still some transverse mismatch and dilution during the first phase of acceleration due to the (not yet quite optimum) matching of the Booster-PS transfer line, to differences between the beam from the four PSB rings, and to the present somewhat limited flexibility of the low field corrections.

There are no measurable injection losses when the PSB beam is reduced to the specified emittance (E_V = 12 π mm mrad; E_H = 33 π mm mrad at the CPS entrance),i.e. during machine studies , but when it is not collimated, injection losses of about 10% have been observed.

It is not planned to use high intensity beam for "counter physics" experiments until the East experimental area is re-arranged in 1975[31] but slow extraction has been tested, and, although not optimized, showed losses of only 7 to 10%.

The PS beam is at present distributed over some 20'000 m^2 of experimental areas, and to the ISR. Later, the machine will also act as injector for the 400 GeV SPS under construction nearby.

Typical cycles in current use have a 2.5 s repetition time, with fast extraction at 26 GeV/c for the ISR and bubble chambers, followed by a 500 ms flat-top at 24 GeV/c for counter experiments.

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* 1 rad = 15.6 eVs for the CPS.

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