# PERFORMANCE OF THE PS AND SPS ACCELERATOR COMPLEX WITH OXYGEN IONS

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## Abstract

Among the multiple modes of operation of the PS and SPS, CERN has implemented a limited exploratory program of experiments with fully stripped oxygen ions which can be accelerated to an energy of up to 225 GeV per nucleon (GeV/u). In September 1986, for the first time, a beam of $2.10^8$ oxygen ions was accelerated to 200 GeV/u, i.e. 3.2 TeV per ion, extracted and transferred to an experimental area. Towards the end of 1986, five major and 8 smaller experiments among which five emulsion exposures, were taking data at 60 and 200 GeV/u during a successful 17 day period. A second run, possibly with sulphur ions, is foreseen for October 1987.

This paper describes the acceleration of oxygen ions from an ECR source through successively an RFQ linac to 140 keV/u, a linac to 11.4 MeV/u, the booster synchrotron (PSB) to 261 MeV/u, the proton synchrotron (PS) to 10 GeV/u and the super proton synchrotron (SPS) up to 225 GeV/u. The performance of the accelerators in providing oxygen ion beams of 60 and 200 GeV/u to the experiments is discussed.

## Introduction

At CERN, acceleration of ions other than protons to energies higher than 1 GeV/u has previously remained limited to deuterons and α particles. Although the first deuterons were accelerated in the 50 MeV Linac I as early as 1964, it took until 1976 before they were injected and accelerated in the PS and subsequently transferred and stacked in the ISR at 15.5 GeV/u per beam [1]. As from 1980, low intensity α particle beams were stored in the ISR [2], with a three-time intensity increase in 1983 when passing through the Booster [3].

Several studies on the possibilities of accelerating heavier ions in the CERN machines were made from 1975 to 1977 [4,5]. In 1980 a first ion physics experiment was proposed at the PS [6]. A subsequent study [7] showed that the mass range accessible for ion acceleration in the PS complex is restricted by conditions such as the maximum accelerating field sustained by Linac I and the lower current limits for controlling and monitoring the circular accelerators.

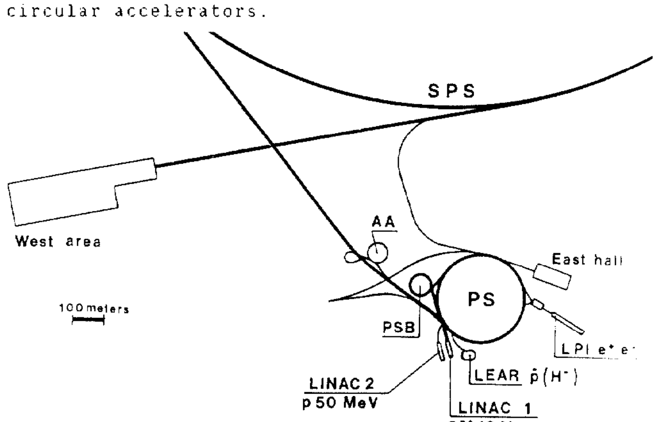



Fig. 1. Layout of the accelerator complex for the $^{16}O$ beam. The North Area with its beam transfer line (not shown) is located 120° clockwise around the SPS from the transfer line to the West Area. AA, LEAR and LPI are not involved.

Due to the evolution in physics considerations the required ion energies shifted to values attainable in the SPS and led to the decision to implement the present oxygen ion program [8] by using the Linac I-PSB-PS-SPS chain while leaving free the Linac II-PSB-PS chain for other uses such as delivering a deuteron beam for diagnostic purposes. Fig. 1 shows a general view of the accelerators involved.

## Acceleration in the injector and Linac I

The minimum requirement of the oxygen project, as far as the Linac is concerned, is to provide a sufficient number of fully stripped oxygen ions to the downstream accelerators for beam control and diagnostics needs. This sets a lower limit of 10 μA per pulse every 1.2 s at the Linac I exit.

The oxygen injector [9] shown in fig. 2 consists of an electron cyclotron resonance (ECR) source [10], a low energy beam transport system (LEBT) for charge and mass analysis, a radio-frequency quadrupole (RFQ) accelerator [11] and two rebuncher cavities [12]. The ion source and transport elements before the RFQ have been provided by GSI, Darmstadt, and the RFQ by LBL, Berkeley. A 60° inflector magnet between the two bunchers permits the injection of proton or $H^-$ bunches from a separate injector.

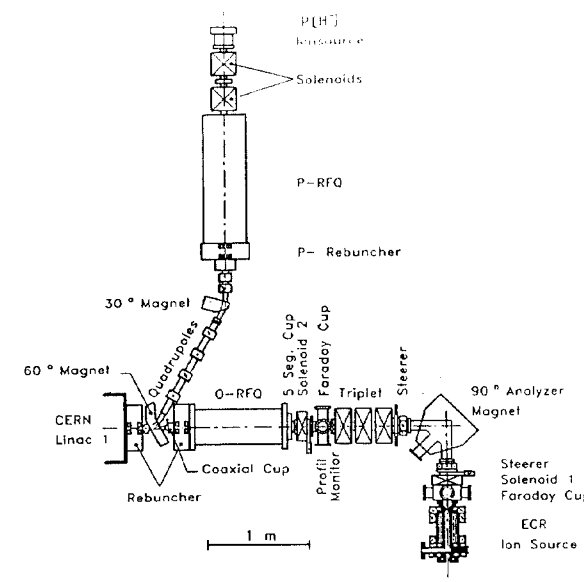



Fig. 2. Proton and oxygen injector for CERN Linac I.

The ECR source provides about 100 μA $O^{6+}$ ion beam at 5.6 keV/u; a pulse duration of 30 ms (fig. 3) is needed for the formation of the highly charged ion states in plasma. A 200 μs slice of this beam is accelerated to 139.5 keV/u by the RFQ (fig. 4).

Subsequently, the $O^{6+}$ beam is accelerated by Linac I in the 2βλ mode with a 33% increase in electric and magnetic fields compared to those for proton acceleration. Stripping to $O^{8+}$ is done with good efficiency at the end of Linac I by a 1 μm carbon foil. Next, the $O^{8+}$ beam with a pulse duration of some 100 μs is sent to the PSB at an energy of 11.4 MeV/u with an energy spread of ± 0.1%. The beam intensity was typically 15 to 30 μA, varying within the pulse and from pulse to pulse due to the fluctuations at the source exit (fig. 5). In spite of the complexity of the source and the extreme working conditions of the old Linac, this preinjector complex proved to be quite reproducible and reliable.

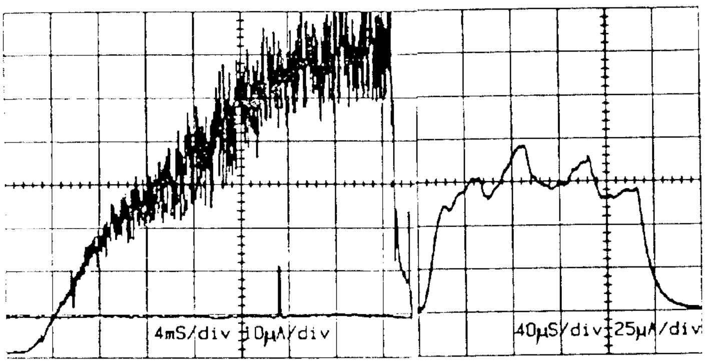
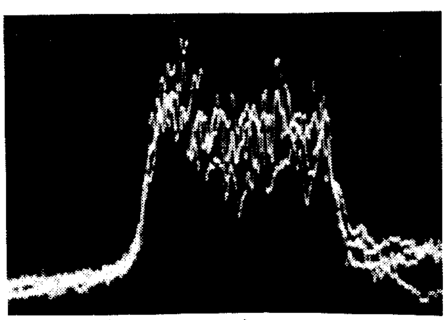



Fig. 3. $O^{6+}$ beam from source. | Fig. 4. $O^{6+}$ beam from RFQ.

To achieve these performances, several hardware and instrumentation problems had to be solved. The first Linac cavity had to be protected against vacuum pollution to prevent excessive recombination of the $O^{6+}$ ions and its conditioning, which needed computer control, proved to be very difficult. Two beam lines, for measuring the energy spread and the emittances, down to a current of 0.5 µA with a resolution of $0.25 \times 10^{-3}$ in Δp/p, proved to be indispensable diagnostics tools. Monitoring in the transfer line was only possible with sensitive SEM grids with a minimum resolution of 20 nA [13].



25 µA

100µs

Fig. 5. The $O^{8+}$ beam in LI-PSB line; 4 pulses superimposed.

Acceleration in the PSB

The $O^{8+}$ beam with the above characteristics is injected into the four PSB rings, filling 7.5 turns by betatron stacking in each ring. An adiabatic RF capture is applied on harmonic 10 (3 MHz) instead of harmonic 5 normally used for protons, because of the limitation in the RF frequency range. The 10 bunches, with an initial bunch area of 0.04 eVs, are accelerated to 47.8 MeV/u (RF frequency of 6 MHz) where the harmonic number is changed from 10 to 5 by a debunching-rebunching process on a 50 ms intermediate magnetic flat-top. These 5 bunches are then accelerated to 261 MeV/u corresponding to the standard PS injection field. Fig. 6 illustrates this acceleration.

20 ms/div.

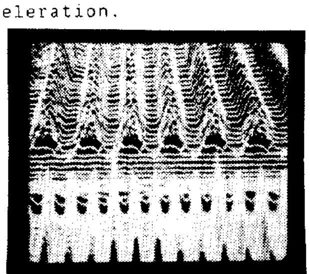


Fig. 6. PSB acceleration including the debunching, rebunching process (h=10 → 5). The scans start at 140 ms after injection.

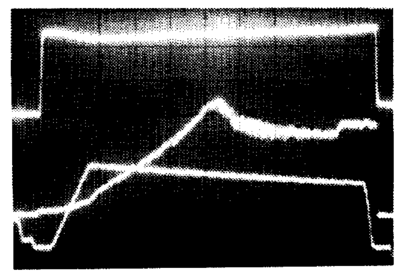
200 ns/div.

Due to limitations in the pulse lengths of the extraction and recombination kickers, only four bunches per ring can be extracted and transferred to the PS. The overall efficiency "entry PS/entry PSB" was typically about 32%. A total intensity of 3 to $6 \times 10^{9}$ charges, depending on the strong Linac beam structure, was delivered in 16 bunches of 0.15 eVs each.

Several hardware modifications, mainly on RF low level electronics and beam instrumentation [14] were carried out to adapt the PSB to the very low intensity beams as well as to the extensive RF gymnastics required. The beam control loops acting on beam phase and mean radial position have been improved to handle these very low intensities in a pulse sharing mode with cycles having intensities of up to $10^{13}$ protons/ring.

Acceleration in the PS

The 16 $O^{8+}$ bunches from the PSB are injected and captured in the PS on a magnetic flat-bottom, then accelerated to 10 GeV/u within a cycle of standard duration of 1.2 s. Fast extraction sends these 16 bunches, of about 0.2 eVs each, towards the SPS. Transmission efficiency through the PS was practically 100%, as shown on fig. 7.



50 ms/div

Fig. 7. Signals from the beam current transformer (top), and the wide-band PU, as well as dB/dt (bottom) during one PS cycle.

To fit the SPS requirements on the Δp/p of the extracted beam, an RF gymnastic is applied prior to extraction; in this way, the extracted bunch length could be adjusted from 10 ns (without rotation) down to 4 ns. Four 1.2 s PS cycles were dedicated to this operation during the 14.4 s SPS cycle, allowing on request the transfer of 1 to 4 consecutive beams of up to $6.10^{9}$ charges each on the SPS injection flat-bottom. In addition, in the Linac II-PSB-PS chain, a deuteron beam of similar characteristics but with an intensity adjustable from $10^{10}$ to $2.10^{11}$ charges, was always available for adjustments of the SPS.

To cope with the low intensities involved and to allow parallel running with the high intensity operations, a dedicated RF beam control has been built, optimised for low intensity acceleration ($10^{8}$ to $2.10^{11}$ charges) and able to handle any type of ion in a cycle-to-cycle sharing mode. As in the SPS this system does not use a radial loop, but relies instead on an accurate frequency program to control the beam position. This avoids the use of very low level beam position PU signals and opens the way to open loop acceleration foreseen in the future for mixed beam acceleration. A phase loop was incorporated to damp coherent dipolar oscillations, using a high quality non-resonant PU and large dynamic range electronics (80 db).

For beam monitoring, the already existing PS beam current transformer has been adapted to these low intensities (fig. 7) with a resolution of $\pm 10^{8}$ charges. In the beam transfer lines, an improved type of scintillator screens and a new type of vidicon proved to be very successful.

## Acceleration in the SPS

Ions with q/A = 0.5 can be accelerated in the SPS to a maximum energy of 225 GeV/u, i.e. the equivalent of 450 GeV protons. A typical SPS cycle is shown in Fig. 8. The duration of the flat-bottom permits the injection of up to 4 batches of ions transferred from the PS. The injection energy has been chosen at 10 GeV/u because it is the minimum energy compatible with the bandwidth of the travelling wave structure of the SPS cavities without change of harmonic number during the cycle and the maximum energy which permits a 1.2 s duration for the PS cycle.

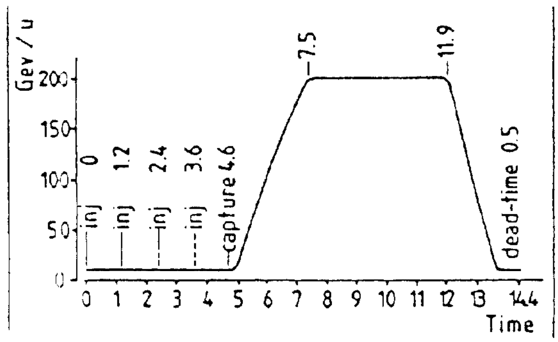



Fig. 8. SPS cycle of 14.4 s. duration for the acceleration of $^{16}O^{8+}$ ions to 200 GeV/u with 4 batch injection and a flat-top length of 4.4 s.

The four PS batches of 1.65 μs duration with about $5\times10^{8}$ ions/batch are injected equidistantly around the circumference of the SPS. The beam is distributed around the ring through debunching during at least 1 s, about 3 times the time constant for this process assuming a momentum spread $\Delta p/p = \pm10^{-3}$. Thereafter, the ions are captured by the RF system. The total accelerated intensity was typically $\geq 10^{9}$ oxygen ions per SPS cycle.

As in the PS, rather than using the radial loop for the control of the RF frequency during acceleration, which would imply the use of a pick-up with a critical beam intensity threshold, the radial beam position is controlled through a frequency loop with a fine RF frequency program designed to cover the entire energy range from 10 to 225 GeV/u. The allowable error in frequency at transition for no particle loss is $\pm6\times10^{-8}$ of the fundamental frequency. A sensitive resonant phase pick-up has allowed capture and acceleration of beam intensities down to $10^{7}$ charges [15].

The minimum intensity needed for reliable operation is mainly determined by the SPS because of its 11 times larger circumference as compared to that of the PS. The available intensity of the oxygen beam is below the threshold for observation of the closed orbit. The operation in the SPS, including extraction, is therefore optimized with the deuteron beam coming from Linac II-PSB-PS and the oxygen beam is accelerated with minimum instrumentation.

## Extraction and beam transfer from the SPS

The experiments required oxygen beams at 60 and 200 GeV/u with, at each energy, simultaneously shared slow extraction to the West and North experimental areas. The choice of 200 GeV/u rather than 225 GeV/u was for taking advantage of the longer flat-top of 4.4 s instead of 2.8 s for the latter energy. The cycle for 60 GeV/u is merely a truncated version of that shown in Fig. 8 and has a flat-top duration of 7.4 s. The beam sharing ratio can be adjusted from 0.1 to 0.9 through a change of the radial position of the circulating beam with respect to that of the electrostatic septa in the two extraction channels by means of local closed orbit bumps. The effective spill time of the slow extracted ion beams at 60 and 200 GeV/u, for low frequency intensity modulation of up to 1kHz, was 50 to 70% of the flat-top duration with the RF turned off during the flat-top. Through a combination of conventional resonant extraction and stochastic resonant extraction [16,17], the effective spill time improved to about 75% at 60 GeV/u and to 95% at 200 GeV/u.

Four out of the five major experiments were located in open experimental areas, of which one in the West Area and three in the Hall EHN1 of the North Area. The intensity in each beam line in these areas must be limited to $\leq 10^{6}$ ions per pulse due to the absence of sufficient shielding. The fifth experiment was installed in the shielded Hall ECN3 of the North Area. This latter experiment could therefore receive a high intensity beam of $\geq 10^{8}$ oxygen ions. Five of the 8 smaller experiments, those which involve emulsion exposures, were also done in the West and the others in the North Area.

The beam intensities per SPS cycle requested for the different experiments varied from $10^{4}$ ions for some of the emulsion exposures to $10^{8}$ ions for the experiment in ECN3. All experiments are installed at the end of beam lines normally used for the fixed target physics program with protons. The simultaneously shared extractions were adjusted for extracting 90% of the circulating beam to the North and the remainder to the West Area. The beam transfer to the West did not involved beam splitting, but the beam to the North Area was divided twice by means of splitter magnets into 3 different beams [18]. The very low intensities for emulsion exposures were created by kicking the beam out of the transfer line about 50 ms after the start of extraction. The contamination by nuclear fragments of the core of the beams at the end of the transfer lines was less than 2% [19].

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