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SIMILAR CHARGE TO MASS RATIO IN THE CERN PS COMPLEX

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Summary

In autumn 1987, sulphur 32 ions were accelerated by the CERN machines to a world record energy of 6.4 TeV. An Electron Cyclotron Resonance source produces sulphur ions as a 5 per cent "contamination" of an oxygen ion beam. As their charge-to-mass ratios differ by only 5.4×10^{-4} , the two species are not distinguishable by the downstream accelerators (RFQ, Linac 1, PSB), though measurable in a specially equipped spectrometer line. In this way, enough current is available for controlled acceleration at low beta in the PSB. However, at phase transition energy in the PS - about 6 GeV/nucleon (GeV/u) - this synchrotron becomes an extremely fine spectrometer, with sulphur 16+ ions being driven inwards, and oxygen 8+ outwards. This can be used for separating the beams by manipulating the low-level radio-frequency system at transition, so that either oxygen or sulphur is selected. Indeed, the PS could be fed with a fairly intense oxygen beam for setting-up, and later with some 2E7 sulphur ions per PS cycle. The required RF manipulations, the present understanding on beam dynamics at transition, as well as diagnostic techniques for determining the amount of sulphur are presented.

Introduction

The 1987 physics period with 200 GeV/u sulphur ions delivered by the SPS enabled the experimenters (North and West areas) to repeat their measurements, taken one year earlier with O^{8+} ions, with heavier projectile nuclei. The overall layout of the accelerators [Ref. 1] involved in the ion programme [Ref. 2, 3] is once more described here for convenience (Fig. 1). A new E.C.R. source delivered a mixture of S^{12+}/O^{6+} ions (5.6 keV/u). A 200 MHz RFQ took the beam to 140 keV/u, followed by Linac 1 (200 MHz Alvarez) which operated in the 2 β -mode and required a 33% increase in accelerating and focusing fields in order to match the charge-to-mass ratio (Q/A) of 3/8. The S^{12+}/O^{6+} leaving Linac 1 with 11.8 MeV/u, were stripped to S^{16+}/O^{8+} , and only at this stage did a measurement of the sulphur content indispensable for proper source adjustment - prove easible. Typically, 1.5 μ A of S^{16+} in 30 μ A of

mixture were found. Four Booster rings were filled with this beam, captured on $h = 10$, with a harmonic change ($10 \rightarrow 5$) during acceleration [Ref. 4]. Sixteen (out of twenty) bunches were transferred to the PS at a magnetic rigidity corresponding to 815 MeV protons (i.e. 258.6 MeV/u). The PS accelerated this beam on the usual $h = 20$ to transition (~ 6 GeV/u) where the two species, virtually undistinguishable until this stage, occupied different radial orbits and could be separated by RF gymnastics. Four batches of S^{16+} or O^{8+} (whichever was selected at transition), were sent to the SPS and stacked on a 10 GeV/u flat bottom, captured and accelerated to 200 GeV/u, at which they were resonantly extracted on a 4.4 sec flat top. During the 4-week sulphur period, the PS complex profited from those cycles not employed for SPS filling to provide protons for the East Hall, antiprotons for LEAR, and to prepare leptons for the SPS.

ECR ion source producing mixed beams

For sulphur, a new 14.5 GHz E.C.R. source [Ref. 5] (Fig. 3) was installed in place of the oxygen source (10 GHz). As oxygen ions were still required for tuning the downstream machines, oxygen and hydrogen sulphide were used as source gases. The tiny difference in Q/A between O^{6+} and S^{12+} made monitoring of the sulphur content problematic at the source output. The technique described below proved to be the most effective way of measuring the S^{12+} percentage. Certain source settings, whilst giving a good sulphur yield, gave rise to severe beam intensity instabilities which exacerbated the problems in adjusting accelerators further down the chain. Eventually, a compromise was found between sulphur intensity and overall beam stability. These proved to be critically dependent on the source gas settings and drifts in the gas handling system required regular source parameter adjustment to meet ion and beam stability criteria. Long-term memory effects in the plasma chamber also produce drifts in intensity, especially after vacuum failures. Fig. 2a shows the beam entering the RFQ. Only 100 μ s of this beam was subsequently accelerated in the Linac.

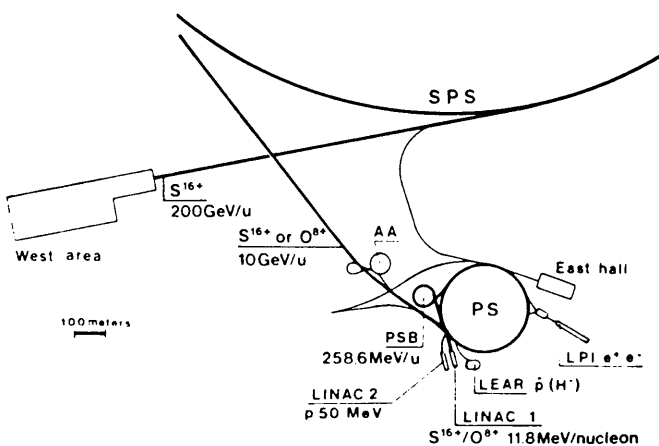


Fig. 1 : The CERN PS-SPS complex and those parts involved in the ion programme (bold lines)

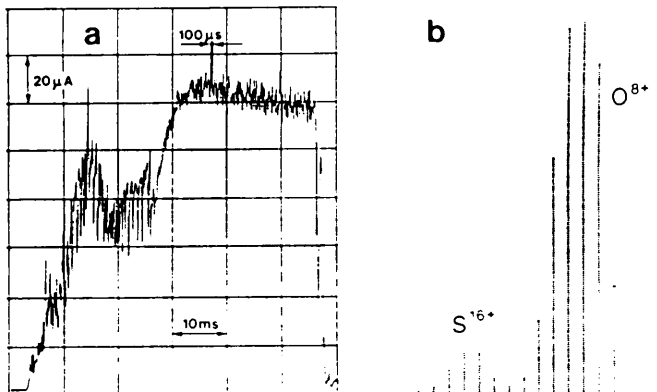


Fig. 2 : (a) S^{12+}/O^{6+} mixed beam current delivered by the E.C.R. source. (b) Monitoring the S^{16+}/O^{8+} ratio with a SEMgrid after the mixture's passage through a degrader and a spectrometer

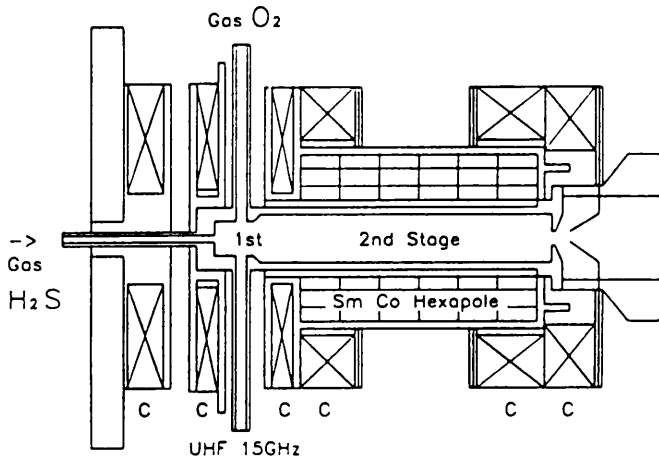


Fig.3 : Upgraded E.C.R. source for S^{12+}/O^{6+} production, with increased UHF (10 → 14.5 GHz) and magnetic field (0.36 → 0.54 T)

Analysis of the S^{12+}/O^{6+} ratio out of Linac

A (destructive) system downstream of the Linac enabled separation of the two species after the foil used for stripping S^{12+} to S^{16+} and O^{6+} to O^{8+} . The different energy losses per nucleon (proportional to Z^2/A , i.e. a factor 2) of the two types of ion when passing through a thin aluminium foil (3 μm) was used as the basis of the measurement. A spectrometer separated the two beams which could then be observed on a SEMgrid. Beam separation was optimised by varying the angle of the foil relative to the beam. The optics adopted minimised the effects of scattering in the foil (small beam dimensions) and imaged the beam on the SEMgrid using a quadrupole triplet such that the horizontal transfer matrix was of the form (a1 0 / a3 a4). The energy resolution of the spectrometer is 26 keV/u per SEMgrid strip. Fig. 2b shows the two separated beams. In estimating the relative percentages of the two ions, account should be taken of the S^{15+} , S^{14+} , O^{7+} and O^{6+} created during the passage through the thin foil as well as the different yields in the SEMgrid according to ion type. Typically, about 5% of S^{16+} beam content was measured.

Acceleration and Separation of Mixed Ion Beams in the PS

Acceleration using a RF frequency program. The same hardware which was developed for the oxygen run of 1986 [Ref. 2] is used to capture and to accelerate the sixteen bunches. It comprises a dedicated RF beam control which relies solely on the accuracy of its frequency program to determine the radial position of the beam. No attempt is made to control the beam by processing the very low-level signal from a beam position pick-up. An AC-coupled phase loop damps coherent dipolar oscillations. The position of the beam relative to the central orbit varies with the accuracy of the frequency program according to the relationship

$$\frac{\Delta R}{R} = - \frac{\gamma^2}{\gamma_{tr}^2 - \gamma^2} \frac{\Delta f}{f}$$

Hence, near transition, this imposes a severe constraint on the accuracy of the frequency program if the beam is to be kept inside the vacuum chamber. In 1986, the problem was eased by employing a gamma-transition jump. For reasons explained below, this was not the case in 1987 but the quality of the

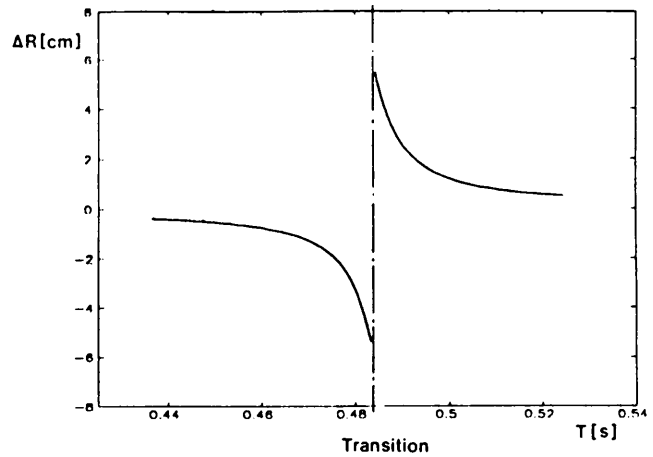


Fig.4 : Radial position of sulphur with respect to oxygen near PS transition energy. Note that ΔR stays finite [Ref. 6]

frequency program proved adequate, presumably because the acceleration rate is ultimately controlled - via the phase loop - by the phase program. Computer simulations are being performed to investigate this behaviour in detail [Ref. 6].

Mixed ion beams. For a given RF frequency applied to a machine containing a beam comprising two ion species whose Q/A ratios are very similar, there coexist two families of buckets. The relative radial distance between the bucket centres of the different species is

$$\frac{\Delta R}{R} = - \frac{1}{\gamma_{tr}^2 - \gamma^2} \frac{\Delta(Q/A)}{(Q/A)}$$

The synchronous phase, however, is nearly the same for both species. Consequently, each single bunch observed by a longitudinal pick-up is the superposition of two different ones. The relative difference in charge-to-mass ratio for S^{16+}/O^{8+} ions is a mere 0.0537% but such a mixture separates into two distinct beams near transition. Fig. 4 shows how the radial distance between the beams evolves during acceleration; in the adiabatic limit they would become infinitely far apart at transition. The reason for suppressing the gamma-transition jump is to maximize the separation of the two beams.

RF selection of ion species. Various schemes have been proposed to exploit the above-mentioned behaviour [Ref. 7]. Operationally, the method is as follows : (i) The phase loop is kept closed throughout the cycle; (ii) a frequency program which maintains sulphur near the central orbit is used. The beam control acts on the centre of charge of the mixture and so it is dominated by the oxygen ions (~ 8.10⁹ charges) until these are eliminated, only then does it "see" the sulphur (~ 4.10⁹ charges); (iii) the oxygen ions are removed by perturbing the accelerating phase during a 30ms period beginning 40 ms before transition. This drives the oxygen to the outside until it is lost on the vacuum chamber (Fig. 5 a); (iv) the sulphur ions alone cross transition under the influence of a beam control which is specific to sulphur. This ensures the reproducibility of the characteristics of the resultant beam at high energy. Fig. 5b shows, on an expanded time-scale, the radial position of the centre of charge of the beams and the accelerating phase during the RF manipulations near transition. One sees the centre of gravity of both beams being driven to the outside under the influence of the

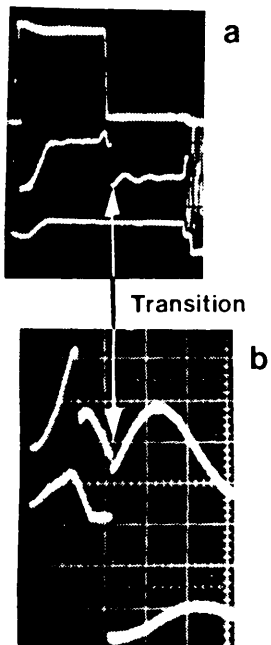


Fig. 5: RF manipulations near PS transition in order to separate the ion species (here: oxygen beam driven to the outside and removed): (a) beam current (upper trace) with the tiny sulphur beam left, phase bump (middle trace) and dB/dt (lower trace); (100 ms/DIV) (b) expanded time scale, radial position (upper trace) and phase bump (lower trace) near transition (20 ms/DIV)

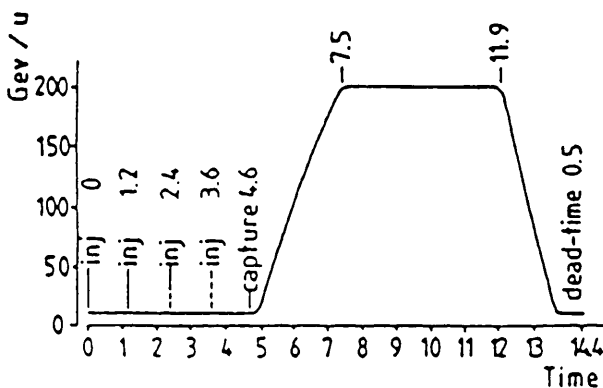


Fig. 7 : SPS ion cycle with flat bottom for accumulation of four PS batches, and flat top for resonant extraction of ions to West and North Experimental Areas

downstream accelerators. In this way, the four consecutive PS batches were better equalized and the overall transmission efficiency between PS and SPS was increased from 25% to about 55%. The result was an available sulphur intensity of about $6-8 \cdot 10^9$ charges at 200 GeV/u in the SPS with all four PS batches in the $3-4 \cdot 10^9$ charges range. A peak intensity of more than 10^9 charges was reached at 200 GeV/u, a factor ten or so less than the corresponding 1986 oxygen figures. Beam was delivered by simultaneous shared slow extractions to the West and North experimental areas (effective spill time about 70%)(Fig. 7).

Outlook

The present Linac 1 limits the charge-to-mass ratio of ions that can be accelerated to 0.375. Lower charge states are not possible due to the voltage holding capabilities of the Alvarez cavities. Heavier ions with this Q/A are only available from present day ion sources with very low intensities, too low for our machines. The possibility of mixing low intensity heavy ion beams with higher intensity light ion beams of about the same charge to mass ratio - as presented in this paper for S^{16}/O^8 - is probably limited to $\Delta(Q/A) < 0.1\%$. Calcium and sulphur are about the only other pair satisfying this condition. Acceleration of heavier ions like, for example, lead can only be achieved with much more powerful ion sources and special accelerating structures which can cope with lower charge-to-mass ratios than our present Linac 1. Relevant studies are in progress.

References

- [1] W.C. Middelkoop, 1986, Int. Acc. Conference, Novosibirsk, USSR
- [2] E. Brouzet, W.C. Middelkoop, Proc. 1987 US Part. Acc. Conference, Washington, USA, p. 50
- [3] H. Haseroth et al., Proc. 1986 Linear Acc. Conference, Stanford, USA, SLAC-Report-303, 1986
- [4] C. Carter et al., Proc. 1987 US Part. Acc. Conference, Washington, USA, p. 526
- [5] R. Geller, private communication
- [6] S. Hancock, "Modelling the acceleration and separation of ion mixtures in the PS", to be published
- [7] W. Hardt, private communication
- [8] V. Agoritsas, private communication

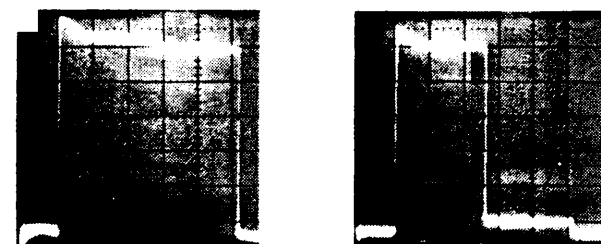


Fig. 6 : Beam current in PS showing separation of oxygen from sulphur near transition. Left: elimination of sulphur. Right: elimination of oxygen. - $2 \cdot 10^9$ charges/DIV, 100 msec/DIV

phase perturbation; the oxygen ions reach the vacuum chamber first, where they are lost, producing a discontinuity in the radial position trace. A complementary process was also set up which allowed the preferential selection of oxygen ions at the expense of the sulphur. It was, in fact, optimized first and the resulting oxygen beam was routinely available for SPS adjustments.

Diagnosics at PS extraction

The RF techniques described above gave complementary losses just before transition: about 95% when eliminating O^8 ions and 5% for S^{16} ions (Fig. 6) in good agreement with the measurements of the linac output. To check the beam quality at the PS output, a counting experiment was set up in a PS ejection line to measure the ion content of the beam slowly extracted at 12 GeV/u. A pulse height analyser, fed by a thin scintillation counter, saw the whole spectrum of the pulses and provided a video display averaged over several ejected bursts [Ref. 8]. As expected, both the sulphur and the oxygen beams proved to be very pure.

Performance

At the beginning of the physics run, the source parameters were adjusted principally to optimize the sulphur percentage. This led to unstable beams. After a few days, the source parameters were retrimmed to give less sulphur output but with increased stability, easing beam adjustments in the