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Heavy Ions in the CERN Accelerators

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Abstract

The history of heavy ion acceleration at CERN is presented. The basic schemes applied for the production of light and later on heavy ions at high energies are reviewed. Emphasis is put on the special technologies needed to make this endeavor a success.

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1 Deuterons, alphas and oxygen ions

Heavy Ions have by now quite a long history at CERN. With the acceleration of lead ions during almost a decade, CERN has shown the versatility of its accelerators. The "Heavy-Ion Facility Design Report" [1] gives an overview of the project and its history. Here we shall concentrate on the generalities and on some of special aspects of accelerator technology concerning heavy ions.

In the early days only protons were accelerated at CERN. First machine experiments to accelerate deuterons with the CERN 50 MeV proton linac (later called Linac 1) were carried out in 1964 [2] using the so-called $2\beta\lambda$ mode for acceleration, which could be almost achieved with the normal linac fields as for protons. Further successful operation of Linac 1 with deuterons prompted requests from the ISR user community first for deuterons and later for alpha particles. Deuterons were obtained with the conventional duoplasmatron source, supplied with deuterium gas instead of normal hydrogen. Alpha particles were produced by stripping a beam of He^{1+} ions after the pre-accelerator at an energy of 120 keV/u with a pulsed gas jet [3].

It was quite clear, from then onwards, that Linac 1 was in principle able to accelerate other fully stripped ions (at least up to calcium) as long as they could be provided at the input and as long as recombination losses due to the imperfect vacuum could be neglected.

The subsequent machines had no major difficulties, except for some RF gymnastics (such as the change of the harmonic number) and problems due to the lower intensity of the ion beams relative to the usual proton beams.

The next step towards heavier ions was a collaboration between GSI, LBNL and CERN [4,5], which provided a facility to accelerate oxygen ions. Some 100 μA of O^{6+} ions were produced in an Electron Cyclotron Resonance source (ECR, a device which uses a magnetic plasma confinement scheme, in which the electrons are heated by applying the appropriate rf frequency) source (built by R. Geller, CEA Grenoble) and acquired by GSI. The ions were initially accelerated with a RFQ (supplied by LBNL). GSI provided also beam transport elements in the low energy area.

A major problem in this set-up was the fact that these ions were not fully stripped, since no source could give reasonable intensities of O^{8+} . Linac 1, therefore, needed a 33 % increase in the RF accelerating fields as well as in the magnetic focusing fields because of the lower charge to mass ratio of the oxygen ions.

A key element proved to be the RF voltage holding capability, especially of the first linac tank. Special cleaning and bake-out procedures together with additional cryopumping and the use of a computer controlled RF conditioning program were needed to achieve this goal. The beam intensity at the end of the linac was in the range of 30 μA . Stripping by means of a carbon foil was done at the exit of the linac, yielding a fairly pure beam of O^{8+} .

Some drastic improvements were also required for the beam monitoring equipment in all the CERN machines to cope with this extremely low intensity.

Apart from the intensity this beam was similar to deuteron or alpha particle beams for the downstream machines. Part of the time the PS complex operated with higher intensity deuteron beams supplied by Linac 2, interlaced between oxygen ion pulses to allow the setting-up of the SPS. The intensities in the SPS were usually well above 10^{10} charges per pulse.

2 Sulphur ions and the separation from oxygen ions

For the acceleration of even heavier ions a new 14 GHz ECR ion source (again provided by GSI) resulted (1987) in a somewhat increased intensity for the oxygen beam accompanied by a large amount of S^{12+} ions. The majority of these ions was converted with the stripper foil at the end of the linac to a O^{8+} and S^{16+} beam and accelerated in the PS Booster (PSB).

In order to maximize the sulphur content the difference in energy loss per nucleon (proportional to Z^2/A , i.e. a factor 2) of the two types of ions when passing through a thin aluminum foil (3 μ m) was used in conjunction with a spectrometer. Typically, about 5% of S^{16+} beam content was measured.

This type of measurement was satisfactory for setting-up of the source, but it was not very useful for monitoring under normal operation, as it required stopping the beam going to the accelerators after the linac.

Since the O^{8+} and S^{16+} charge-to-mass ratios differ by only 5.4×10^{-4} , the two species are virtually indistinguishable by the accelerators after the source (RFQ, Linac 1, PSB) and the Linac, PSB and PS (up to transition energy) accelerated both beams equally well. For the setting up of Linac1, PSB and PS the additional oxygen beam was very valuable in order to solve instrumentation problems due to the low intensity.

However, as the experiments needed pure sulphur beam a special scheme for separating the two ion species and leaving only the desired sulphur beam was conceived [6]. At phase transition energy in the PS - about 6 GeV/nucleon (GeV/u) - this synchrotron becomes an extremely sensitive spectrometer. 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 SPS could be fed with a fairly intense oxygen beam for setting-up, and later with some 2×10^7 sulphur ions per PS cycle for supplying the experiments.

3 The lead ion project

With the fields increased by 33%, Linac 1 was really at the technological limit of its possibilities. Ions heavier than oxygen or sulphur, with the same charge to mass ratio are, with present day sources, only available at much lower intensities which would be insufficient for SPS operation and for most physics experiments. As the experiments requested even heavier ions the only way to achieve the intensities required implies accepting lower charge states and hence needed a complete replacement of Linac 1 and important modifications to the subsequent machines[1], as full stripping at the end of the linac was no longer possible. The following machines had then to deal with partially stripped ions with even lower velocities. This project exceeded CERN's financial possibilities and could only be realized without outside help. Offers to participate in this project had been made by several laboratories so that at a meeting on March 9, 1990, collaborations between the interested laboratories and CERN could be launched. With the presence of delegates from most member states, a US observer and spokesmen from the different heavy ion experiments it was possible to establish collaborations of several laboratories

IN2P3 (GANIL for the ECR-ion source), INFN (Legnaro for the low energy beam transport between source and linac, including a radio frequency quadrupole RFQ, Torino for the high energy transport and filter lines as well as beam measuring equipment for the Super Proton Synchrotron), GSI (for the linac, including some RF amplifiers), University of Frankfurt/IAP (for a debuncher), institutes from India (BARC VECC, CAT and TIFR) helped with vacuum equipment and controls software, and the Czech Republic provided support for the installation.

The ECR source and its afterglow mode

The source selected to produce Pb^{27+} ions was again of the ECR type. Ion currents from ECR sources at high charge states are fairly low. Only the invention of the afterglow made it possible to produce enough current to adjust the accelerators in an optimal way. The afterglow is based on switching off the rf driving the source and de-confining a large number of ions in high charge states, which can then be extracted. The interruption of the heating of the electrons by the rf power causes their rapid diffusion, and consequently causes a rapid de-confinement of the multicharged ions. [7,8]. Experiments made at GANIL [9,10] showed that this mode of operation was possible with a newly developed 14.5 GHz pulsed source built at GANIL in order to increase the output current, mainly for heavy elements (Pb, U). First results obtained with cw (continuous wave) operation used on the cyclotron machines were encouraging and subsequently pulsed operation was tried out, important for Linacs and synchrotrons.

The results in long pulsed operation were very encouraging: the currents were multiplied by a factor of 1.5 to 2 as expected and the charge state distribution was slightly shifted toward the higher charges. With a duty-cycle of 1/2 (to 1/3) and a repetition period equal to 100 ms (to 150 ms) a 30 μA beam of Pb^{28+} could be obtained (instead of Pb^{25+} in cw mode).

A very short beam pulse (0.5 to 1 ms) at the end of the rf pulse, corresponding to the “afterglow” effect results from an important flux to the wall of the chamber and a drastic increase in the extracted current. If the source parameters are then re-optimized on this current, the beam pulse during the rf pulse decreases and the highest current is produced at the end of the rf pulse, particularly for the multicharged ions.

Further optimization of this effect at CERN resulted in almost zero current during the “normal” operation of the source and currents of the order of 100 μA after stopping the rf power [11].

The IH structure for Linac3

For the linac itself a newly developed “IH” accelerating structure [12] was chosen instead of the classical Alvarez structure [13].

This very recently invented structure uses, in contrast to a conventional Alvarez linac a cavity with a transverse electric field. The longitudinal accelerating fields are generated by drift tubes which are alternately connected to the points of maximum rf fields. This structure has the advantage to support very high rf gradients and to accelerate with both half-sine waves of the rf – contrary to an Alvarez, which can use only the positive half-sine wave. The result is a very compact linac with a very high accelerating rate.

The IH Linac consists of three tanks accelerating from 0.25 to 4.2 MeV/u, Tank I at 101.28 MHz and Tanks 2 and 3 at 202.56 MHz, making a total length of only 8 m with an effective accelerating voltage of 33 MV. This linac design is an extension of the GSI ‘High charge state injector’ (HLI) [14] in which the beam dynamics concept of ‘combined zero degree synchronous particle sections’ is used.

The cavity operating in H mode, loaded by drift tubes, has the main accelerating field component on the axis. As RF defocusing is weak, there is no need for focusing within the thin-walled accelerating drift tubes, which leads to low capacitive loading i.e. high shunt impedance and modest RF power requirements. These drift tubes can stand exceptionally high fields, reducing the length of structure required. In tank 2 fields of 50 MV/m (3.5 times the Kilpatrick limit!) with local maxima of 75 MV/m were achieved [15].

Improvements to the other CERN machines

The upgrading of the vacuum in the PSB and PS was not an easy task. After stripping at the end of the Linac at energy of 4.2 MeV/u, Pb^{53+} is obtained as a dominant charge state. In order to obtain an acceptable transmission rate of better than 50% through both machines requires a partial pressure from the non-hydrogen gas components lower than 1×10^{-9} Torr in the PS and below 9×10^{-10} Torr in the PSB.

Installation of additional Titanium Sublimation Pumps and removal or special treatment of particularly outgassing equipment was needed [16].

The Super Proton Synchrotron (SPS) and the acceleration with a "non integer harmonic number"

Apart from instrumentation improvements one of the key issues was the fact that the SPS cavities, unlike those in the PSB and PS, were designed for a fixed frequency. At SPS injection, the revolution frequency of the lead ions with $\beta = 0.984$ is too low to allow acceleration in the usual mode, with a variable frequency proportional to the instantaneous revolution frequency of the beam, since the useful frequency range of the SPS cavities is only 0.5%. Fortunately, the latter are traveling-wave structures of which the filling time ($\sim 1 \mu\text{s}$) is much smaller than the revolution time ($23 \mu\text{s}$) of the particles. This feature opened up the possibility of a new method of acceleration in which the four PS batches occupy a total of about $10 \mu\text{s}$ while the other $13 \mu\text{s}$ are taken up by four holes, possibly of different lengths. Whenever a batch passes through the cavities, the latter are powered at a constant frequency with maximum accelerating voltage. During the passage of each hole or of one hole per revolution, the instantaneous frequency of the cavities is briefly changed so that the RF phase matches the arrival of the particles on their next passage through the cavities.

The result is acceleration with a "non-integer harmonic number". The first proposal at CERN was made already in a paper in 1975. The original idea was to use a phase shifter, in a closed loop, to supply the necessary phase jump [17]. Finally another very elegant alternative solution to this beam control electronics problem was proposed and implemented [18] This method obtained the phase jump in closed loop by modulating the frequency by means of a specialized Voltage Controlled Oscillator at multiples of the revolution frequency [19].

Each cycle of the SPS accelerates four batches of lead ions simultaneously, injected consecutively from the PS at 1.2 s intervals. This repetition time, which is standard for proton injection at 14 GeV/c into the SPS, limits the magnetic field on the flat top of the PS magnet cycle to a maximum value corresponding to a proton momentum of 20 GeV/c. In the PS the lead ions have a charge $Q = 53+$, but, since they are fully stripped in the beam transfer line after extraction from the PS, they have a charge $Q = Z = 82+$ in the SPS.

The peak intensities achieved in terms of charges accelerated in the SPS per cycle were for oxygen 8×10^9 and for sulphur 9×10^9 , both at an energy of usually 200 GeV/u and for lead 60×10^9 at an energy of up to 177 GeV/u.

Conclusion

Thanks to different new accelerator techniques the acceleration of lead ions at CERN was a success. Other ions were also accelerated, and a rich programme of heavy ion physics is foreseen for the LHC.

References:

- 1) D. Warner (ed) et al., CERN Heavy-Ion Facility Design Report, CERN 93-01, 1993.
- 2) T. Sluyters, A theoretical and experimental comparison of proton and deuteron acceleration in the CERN Linear Accelerator, CERN 64-22, 1964.
- 3) M. Bouthéon, R. Cappi, H. Haseroth, C.E. Hill and J.P. Koutchouk, Acceleration and stacking of alpha-particles in the CERN Linac, PS and TSR, Proc. 9th Particle Accelerator Conf., Washington, 1981 [Trans. Nucl. Sci. NS—28, 2049 (1981)].
- 4) N. Angert, J. Klabunde, B. Langenbeck, K. Leible, P. Spädtke, J. Struckmeier, B.H. Wolf, S. Abbott, D. Brodzik, R. Gough, D. Howard, H. Lancaster, J. Staples, H. Haseroth, C. Hill, P. Têtu, M. Weiss and R. Geller, A heavy-ion injector for CERN Linac 1, Proc. Linear Accelerator Conf., Seeheim, 1984, Ed. N. Angert (Report GSI—84—11, Darmstadt, 1984), p. 374.
- 5) H. Haseroth, C. Hill, P. Têtu, M. Weiss, B.H. Wolf, K. Leible, P. Spätke, J. Klabunde, B. Langenbeck, N. Angert, R.A. Gough, J. Staples, R. Caylor, D. Howard, R. MacGill and J. Tanabe, Ion acceleration in the CERN Linac 1, Linear Accelerator Conf., Stanford, Calif., 1986 (SLAC-Report-303, Stanford, Calif., 1986), p. 355.
- 6) N. Angert, E. Brouzet, R. Garoby, S. Hancock, H. Haseroth, C.E. Hill, K. Schindl and P. Têtu, Accelerating and separating mixed beams of ions with similar charge to mass ratio in the CERN PS complex, Proc. European Particle Accelerator Conf., Rome, 1988, Ed. S. Tazzari (World Scientific, Singapore, 1988), vol. 2, p. 1367.
- 7) P. Briand, R. Geller, G. Melin, Nucl. Instr. and Meth. A 294 (1990) 673
- 8) R. Geller, Proc. Conf. on Physics of Highly Charged Ions (Gießen), ed. E. Salzborn, P. H. Mokler and A. Müller; Berlin, Springer (1990) p. 117 and G. MELIN and al - Grenoble ECRIS Status - Journal de Physique - Colloque C1, tome 50- Janv. 1989
- 9) P. Sortais, P. Attal, M. Bisch, M.P. Bourgarel, R. Leherissier, J.Y. Pacquet; ECRIS Development at GANIL, mt. Conf. Ion Sources, Berkeley, 1989, Ed. I.G. Brown, Rev. Sci. Instr. 61, No. 1, Part. 11(1990) p. 288.
- 10) M. P. Bourgarel, P. Sortais, P. Attal, M. Bisch, P. Leherissier, J.Y. Pacquet, J.R. Rataud, C. Schmiechen, First Results of the 14.5 GHz GANIL ECR Ion Source with the CW and the Pulsed Operation Mode, 2nd EPAC, Nice, Vol. 1 (1990) p. 645.
- 11) M. P. Bourgarel, C. E. Hill, H. Haseroth, K. Langbein, E. Tanke, Proc. of the 12th Int. Workshop on ECR Ion Sources, RIKEN, INS-J182 (1995) 193
- 12) U. Ratzinger et al., The upgraded Munich linear heavy ion post accelerator, Particle Accelerator Conference, Washington, DC 1987 (IEEE Catalog No. 87CH2387-9), vol. 1, p. 367.
- 13) Computer design and dynamics of the quasi-Alvarez Linac / Lapostolle, P M; Tanke, E; Valéro, S; Vretenar, M; Warner, D J, CERN-PS-90-68-DI.- Geneva : CERN, Sep 1990
- 14) U. Ratzinger, 'The II-I-Structure and its Capability to Accelerate High Current Beams', Conf. Record of the 1991 IEEE PAC, San Francisco, 91CH3038-7, p. 567.
- 15) J. Broere et al, High Power Conditioning of the 202 MHz IH Tank 2 at the CERN LINAC 3, CERN-PS-98-050-RF, Geneva, Oct. 1998
- 16) Acceleration of lead ions in the CERN PS booster and the CERN PS, F. Blas, P. Bossard, R. Cappi, G. Cyvoct, R. Garoby, G. Gelato, H. Haseroth, E. Jensen, D.

Manglunki, K. Metzmacher, F. Pedersen, N. Rasmussen, K. Schindl, G.C. Schneider, H. Schönauer, L. Sermeus, M. Thivent, M. van Rooij, F. Völker, E. Wildner, CERN-PS-95-027 HI

- 17) C. Zettler, How to accelerate Deuterons and Heavier Particles in the SPS, CERN, LABII/RF/CZ/Note/75-32 (gives an untitled reference to K. W. Robinson, California Institute of Technology", Report CTSL-15)
- 18) D. Boussard, J.M. Brennan, T.P.R. Linnecar, Fixed Frequency Acceleration in the SPS, CERN SPS/89-49 (1989).
- 19) D. Boussard, T. Bohl, T. Linnecar, U. Wehrle, Non-integer Harmonic Number Acceleration of lead ions in the CERN SPS", PAC '95 Dallas, May 1995 and CERN-SL-95-22RF.