

# The CERN Heavy Ion Facility

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## Abstract

For the last few years CERN has been engaged in a collaboration with several outside institutes to accelerate lead ions. For this purpose, a new injector linac has been built and substantial upgrading in the existing circular machines undertaken. Present planning is to have a physics run before the end of 1994. This paper describes the state of the project and the first results with the injector chain.

## 1. INTRODUCTION

As a result of earlier tests, of production runs with deuterons and alpha particles, of a subsequent collaboration between LBL (Berkeley), GSI (Darmstadt) and CERN, a new collaboration to accelerate lead ions was decided between laboratories in France (GANIL), Italy (Legnaro, Torino, Padua), Germany (GSI, IAP, Frankfurt) and CERN. Financial contributions were received from Sweden and Switzerland. India helped with software and some hardware production, and the Czech Republic contributed some manpower.

This collaboration started formally with a meeting called by Prof. C. Rubbia, at that time Director-General of CERN, which took place on March 9, 1990. It was attended by representatives of most CERN Member States, an observer from the USA, spokesmen of the collaborations involved in the CERN ion programme and representatives from CERN. Subsequently, formal and informal agreements were concluded with the above-mentioned contributors. It was clear right from the beginning that CERN could not contribute a large amount of money to this project, which was estimated at about 30 MSFr. It was hoped that about two thirds could be contributed from outside, following the successful example of the LBL/GSI/CERN collaboration for the oxygen and sulphur ions. A proposal for a possible way to accelerate lead ions at CERN had been made already at the end of 1988 [1].

Similar to earlier attempts to accelerate ions, it is based on a minimum upgrade of our proton facility to cope also with ions [2,3]. It should be recalled that deuterons were accelerated in the CERN Linac 1 by simply feeding the duoplasmatron ion source with deuterium and using the linac in the so-called  $2\beta\lambda$  mode. Alpha particle acceleration was achieved by producing  $\text{He}^{1+}$  in the source (feeding it with helium), stripping at preinjector energy to  $\text{He}^{2+}$  and further acceleration like deuterons [4]. These two ions could be produced with a negligible amount of investment. For the oxygen and sulphur ions it was necessary to have a new source that could produce ions with a charge to mass ratio similar to deuterons. An ECR (Electron Cyclotron Resonance) source to produce  $\text{O}^{6+}$  and  $\text{S}^{12+}$  was chosen [5]. This required the Linac 1 to be pushed to 33% higher fields, which was the maximum that this machine could reasonably achieve. The O and S ions required already a

more substantial investment on the linac side but the following machines had, after stripping at the end of the Linac, deuteron-like particles and - apart from some RF gymnastics in the Booster - no more problems than with deuterons except for the considerably lower intensities [6]. There are no sources that could deliver, with reasonable intensities, heavier ions with a charge-to-mass ratio that could have been accepted by Linac 1. Therefore, it was clear that for really heavy ions a new Linac with an appropriate source would have to be built [7], and a careful optimisation process with several reiterations took place to come to a concept that tried to minimise the cost and nevertheless keep options open for improvements in the future [3,8].

## 2. THE SCOPE OF THE PROJECT

The project consisted of building a completely new Linac (Linac 3) with ion source, a LEBT (Low Energy Beam Transport), an RFQ (Radio-Frequency Quadrupole), a MEBT (Medium Energy Beam Transport), the IH (Interdigital H-structure) Linac and a beam analysing and filtering section [9] and substantial upgrading of the subsequent machines. The existing beam transport line to the PSB (Proton Synchrotron Booster) was modified to allow PPM (Pulse-to-Pulse Modulation) required for running with protons between ion pulses. Most of the linac is, starting right from the source, capable of running at 10 Hz, although initial operation with the Booster calls only for 1 Hz. A sketch of the whole layout is presented in Fig. 1.

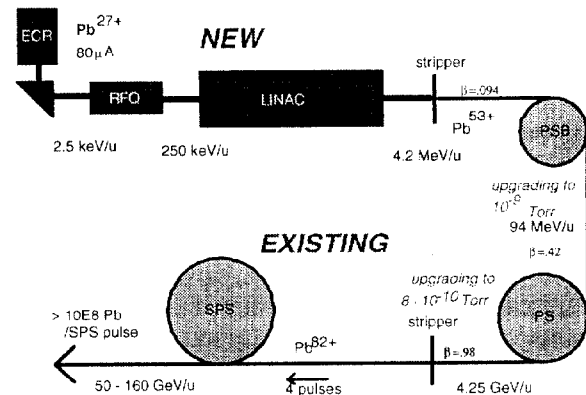


Figure 1. Layout of the CERN Heavy Ion Facility

A particular problem for completely or partially stripped heavy ions is the residual gas in the accelerators. The linac is not critical, because the time spent by the ions in this machine is very short; however, the PSB and the PS, where the ions stay for a longer time, have to have a reasonable vacuum. Figure 2 shows the transmission through the PSB

and the PS for  $Pb^{53+}$  as a function of the residual pressure and of the rate of increase of the magnet voltage.

## 2.1. The Linac

### 2.1.1 Source

Following the good experience with the oxygen and sulphur ion source an ECR (Electron Cyclotron Resonance) source has been selected to produce the lead ions. The source operates in the so-called afterglow mode [10] which was observed for the first time at Grenoble [11] in 1988 on the 16 GHz MINIMAFIOS source operating with oxygen and confirmed later on the ECR sources of GANIL and CERN. The afterglow is a sudden and brief increase of the beam intensity occurring just after the end of the UHF power pulse. Test runs showed that the source is capable of supplying 120  $\mu A$  of  $Ar^{12+}$  and 680  $\mu A$  of  $O^{6+}$ . Typically 80  $\mu A$  were achieved for  $Pb^{27+}$  during 600  $\mu s$ . For the time being this is our "favoured" charge state in spite of the fact that the source had been specified for a charge state of 28+; however, the rest of the linac was built to be able to cope even with 25+. The emittance is well within the specification of <100 mm mrad for 80% of the beam.

### 2.1.2 Low Energy Beam Transport (LEBT)

The LEBT [12] is the beam line connecting the source to the RFQ. Apart from matching the beam, the most important function of this line is a  $135^\circ$  spectrometer with a resolution of 3/1000. It is very similar to the one used for the LEBT of GSI for their high-charge state injector (HLI). The reason for the high resolution is the desire to separate even the different isotopes of natural lead and other heavy elements, although, we shall run initially on isotopically pure lead.

### 2.1.3 Radio-Frequency Quadrupole (RFQ) and Medium Beam Energy Transport (MEBT)

The first RF element in the chain runs, like the subsequent matching cavity and the first IH tank (and the debuncher after the Linac) at a frequency of 101.28 MHz. Input and output energies are 2.5 keV/u and 250 keV/u, respectively and the structure is a modified four-rod structure with a symmetric support [13,14].

The MEBT contains four quadrupoles and a four-gap longitudinal matching cavity.

### 2.1.4 IH Linac

The Linac consists of three tanks accelerating to 1.8, 3.0 and 4.2 MeV/u, respectively. Tanks 2 and 3 work at twice the frequency of the other RF elements: 202.56 MHz. Magnetic triplets are mounted inside Tank 1 (two) and between the tanks. The design of the tanks followed closely the design of the IH tank at GSI for the HLI injector [15,16]. The only significant source of radiation comes from x-rays of the tanks if they are at high RF levels. The radiation from the beam itself is negligible because of its low intensity and energy. To attenuate the x-rays an additional 5 mm lead shield is used on all three tanks.

### 2.1.5 High Energy Beam Transport (HEBT) and filter line

This line permits the measurement of the energy and with

a so-called "single pulse device" measurement to get an approximate measurement of the emittance. The layout of the first part of this line can cope with the beam as accelerated by the Linac (27+) and also after stripping. Stripping (to 53+) is being done in the usual manner with a carbon foil, which is placed very near to a transverse waist in order to minimise the transverse emittance blow-up and at a position where the bunches are still short, so that the increased energy spread due to straggling can be reduced by the debuncher placed further downstream in the line.

### 2.1.6 Controls

The Linac is controlled by several Unix-based workstations and several VME-bus based front end computers interconnected through an Ethernet LAN. These computers communicate through the TCP/IP protocol. Equipment access can be done directly through VME interface modules or via Mi1553 bus, GPIB or Camac. During the commissioning phase as well as for special applications and machine study sessions PCs running MS-DOS can be employed in addition to the workstations, allowing fast prototyping of procedures.

## 2.2. The Circular Machines

Although no major principal modifications were necessary on the circular accelerators, a large number of upgrades were needed either because of the low velocity of the ions, their low intensity, or because of charge exchange reactions with the residual gas. The transmission rates are shown in Fig. 2.

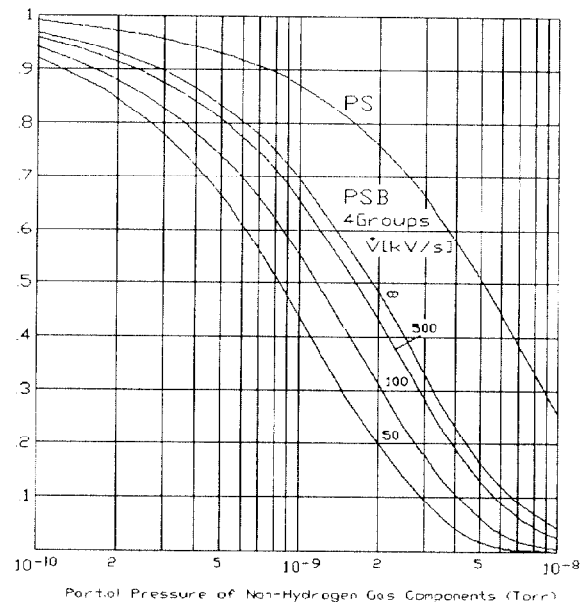


Figure 2. Transmission rates through PSB and PS

### 2.2.1 The Booster synchrotron and the injection line

The injection line has to operate with an increased magnetic rigidity of about 13%. Not all pulses will come from Linac 3, as Linac 2 (50 MeV proton Linac) will operate "simultaneously", i.e. in the "PPM" mode. For this reason PPM on the injection line is required. The vertical distributor, distributing one Linac pulse in "time sharing" to the four

Booster rings, which has to cope with 150  $\mu\text{s}$  for the proton beam could not have been easily upgraded. An additional distributor has been added to cope with the 600  $\mu\text{s}$  of the Pb beam.

The PSB itself has been upgraded by a general "clean-out" of the vacuum system together with a substantial increase of the pumping speed by means of a large additional number of titanium sublimation pumps. The existing ferrite of pulsed magnets has been replaced by new baked-out ferrite. The previous pressure of about  $1.9 \times 10^{-8}$  Torr is now around  $7 \times 10^{-9}$  Torr. This corresponds to  $1.6 \times 10^{-9}$  Torr non-hydrogen pressure and should allow a transmission of more than 50% through the PSB. Additional modifications concern the pulse length of the injection and ejection kicker magnets which had to be increased to 600  $\mu\text{s}$  at injection and had to be doubled for ejection (1245 ns revolution time per ring). A new digital beam control system has been added to decouple the functioning at the very different intensity levels which will allow open-loop acceleration of the Pb-ions. Acceleration will be done in a faster mode with an increased magnet voltage supplied from the main power converter. The short acceleration time is important to minimise the beam losses (particularly bad at low energies) due to charge exchange reactions.

Acceleration takes place up to an energy of 17.1 MeV/u on harmonic number 20 which is then changed by de- and re-bunching to harmonic number 10. Acceleration then continues up to 95.4 MeV/u. The change of harmonic number is necessary because of the limited RF voltage swing available.

New beam current transformers were installed which can cope with the very high-dynamic range between protons and ions. For ions a resolution of 2  $\mu\text{A}$  has been obtained.

### 2.2.2 Proton Synchrotron (PS)

As it is not possible to pulse the transport line between the Booster and the PS, the Pb beam has to be transferred with the same magnetic rigidity as the protons. The PS itself will have four ion cycles of 1.2 s within a supercycle of 19.2 s, thus allowing insertion of proton or  $e^+$  and  $e^-$  acceleration cycles. Injection of the PSB beam into the PS is done by recombining two PSB bunches into one PS bucket. The ion revolution time is 5  $\mu\text{s}$  instead of 2.5  $\mu\text{s}$  as for the protons. The injection kicker has hence been modified. For the ejection the existing equipment is adequate because the relativistic  $\beta$  is now (at 4.25 GeV/u) sufficiently close to 1. Two highly outgassing septa were redesigned and replaced. In the transfer line to the SPS a stripper foil (Ni or Cu) is installed to achieve the final stripping to  $\text{Pb}^{82+}$  with good efficiency.

### 2.2.3 The Super Proton Synchrotron (SPS)

Like all the other circular machines the SPS has to run in PPM mode, in particular as injector of leptons for LEP. The injection scheme for the lead ions follows closely the one used for oxygen and sulphur: Four batches of lead ions injected consecutively from the PS at 1.2 s intervals will be accelerated simultaneously. The relativistic  $\beta$  is 0.984 at injection and still not close enough to 1, which means that the frequency swing possible in the SPS travelling wave cavities is not

large enough. To avoid major rebuilds a novel scheme has been proposed [16], which makes use of the fact that four batches from the PS will not fill the whole ring of the SPS, but only about 10  $\mu\text{s}$  of the total revolution time of 23  $\mu\text{s}$ . The short filling time of the cavities (about 1  $\mu\text{s}$ ) makes it possible to readjust their phase during the beam-free period (if the "hole" is more than 2  $\mu\text{s}$  long). The cavities will hence operate at constant frequency and their phase will be readjusted after each revolution of the beam.

To allow operation with  $10^9$  to  $10^{10}$  charges required substantial upgrading of the beam monitors. Most improvements are due to improved electronics. For the beam profile monitors this was not possible: They are replaced by luminescent screen monitors which will be observed by highly sensitive cameras with subsequent electronic processing of the image. The servo control for the slow spill which has to work at extracted currents of about  $3 \times 10^{-11}$  A will use a thin scintillator placed in the beam path and observed by a photomultiplier. Its output will be used to control a quadrupole in the SPS ring which causes the spill-out.

In the external beam lines the amount of material which the beam has to cross has been reduced in order to lower beam losses [18]. Without modifications, losses of 30% (due to beam windows, air in target stations) would have been encountered. After modifications, losses of less than 10% are expected. In the secondary (in case of proton operation) beam lines, wire chambers placed in air between vacuum windows had been used as profile monitors. They are replaced by filament scintillation counters (FISCs) inside vacuum tanks.

## 3. THE PROJECT AS COMPARED TO THE "IDEAL ONE"

It was clear right from the beginning that the financial restrictions would not allow us to build a facility, which could be considered as a "maximum solution". The aim has been, as in the past for the oxygen and sulphur runs, to provide CERN with a facility, that would, for a reasonable amount of money, provide the interested physics community with a good tool to explore heavy ion physics at higher energies than had been available so far. A minimum of  $5 \times 10^7$  ions per SPS pulse had been requested for this purpose, although some of the experiments will most likely ask for more in the future. More particles could be obtained in several ways.

Another ECR ion source is proposed to achieve a factor two higher currents [19] with present day technologies (more expensive of course).

An EBIS source, that could provide lead ions with a charge state of 53+, would make stripping after the linac superfluous and could gain in this way a factor six in intensity.

A source (EBIS or laser ion source), which could provide the same number of particles in a shorter time (about 20  $\mu\text{s}$ ) would make monoturn injection into the PSB possible and hence gain about a factor two in intensity.

Improving the PSB vacuum to a value below  $10^{-10}$  Torr would again improve the intensity, but less than a factor two.

A linac, that could accelerate several adjacent charge states simultaneously to the same energy per nucleon could certainly

at least double the output current after the stripper foil. Most sources provide adjacent charge states with nearly the same intensity as the charge state with the highest intensity and the acceleration through the RFQ is not problematic. The Linac, of course, would not necessarily be an IH linac.

#### 4. PRESENT STATE OF THE PROJECT

The ion source has been operational for more than a year to the general satisfaction of the "users". Its stability is quite remarkable. The only (minor) problems have occurred so far with the electronics of the 14.5 GHz transmitter. The installation of the source was followed very quickly by the HEBT with the filter line. All other major components were installed end of last year (LEBT, Tanks 2 and 3, 202 MHz transmitters) or before April this year (Tank 1, 101 MHz transmitters and the RFQ with the matching section to the IH structure). Commissioning of the LEBT was done from the end of last year till April 1994. The RFQ running-in followed till mid-May largely helped by a Russian "BLVD" (bunch length and velocity detector) in a special temporary measuring line. For the installation of this line, tank 1 had been moved to the side. After its re-installation running-in with beam followed for one tank after the other being succeeded by transporting the beam through the filter line and joining the existing transport line for protons connecting Linac 2 with the Booster. Final measurements in the emittance and spectrometer lines just before the PSB took place on Saturday/Sunday June 11 and 12, 1994. First injection into the Booster was achieved as planned on June 15. Though intensity measurements were somewhat difficult for these extremely low currents (in the presence of high power RF equipment) the current is estimated to be slightly above 10  $\mu\text{A}$  of  $\text{Pb}^{53+}$  and emittances are close to the nominal figures. The energy spread (very important for a good capture in the Booster) could be reduced with the debuncher to below  $\pm 2$  keV/u.

##### 4.1 *What have we learned from the production and installation?*

###### *Experience with the collaborations*

Basically this experience had very positive aspects but required a lot of additional work on both sides. Any problems which have occurred could have happened also in a project under the sole responsibility of CERN.

###### *Information flow and standards*

For a good collaboration, exchange of information is extremely important. Money spent on travel seemed to be well invested. This did not only help the personal contacts, which are very important sometimes to understand the design philosophy and to appreciate the possibilities of a lab and its boundary conditions, but also to become familiar with the equipment at an early design stage, where useful discussions and modifications are still possible. These discussions have greatly helped to get standard CERN equipment incorporated where possible in order to ease the later maintenance that has to be done by CERN.

#### 5. SOME SPECIAL INSTRUMENTATION

Various beam measuring devices are installed or have been upgraded for ions.

One instrument, the so-called SEM (secondary emission monitor) using grids or wires, has shown its usefulness already not only for protons but also for light ions. It consists of a sort of harp made out of strips or wires with individual amplifiers to measure the secondary electron current that is emitted due to the impinging ions. The collected signals allow one to see the beam profile on a suitable display. Without them the oxygen and sulphur runs would have been almost impossible. Their extremely high sensitivity (down to a few nA per strip) made beam optimisation if not simple at least feasible. They are installed in the critical places from right after the source up to the transfer line after the PS.

Special mention should be made of the BLVD (Bunch Length and Velocity Detector) which was bought from the Institute of Nuclear Research in Moscow [20]. Its basic element is a very thin wire that is placed in the beam and which produces secondary electrons which are accelerated outwards and measured with a secondary emission multiplier. A RF deflector, synchronous with the Linac RF, are used to sweep the electron beam across the detector, hence resolving the time by different positions on the detector. As the bunch-to-bunch reproducibility should be quite good, integration over some time is possible and can be used to increase the sensitivity. This device cannot only measure the shape, but, by shifting the detector, also the velocity of the bunches, and hence the energy of the beam.

Another apparatus that proved its usefulness is a single pulse multislit emittance measurement system. The beam hits a plate with several slits followed by a scintillator screen. The picture on the screen is acquired by a triggered CCD camera and digitized. A special computer program is used to extract from these data the emittance profile.

#### 6. FIRST MEASUREMENTS

During initial running-in, source, LEBT, RFQ and IH seemed with the limited instrumentation available to be consistent with specifications.

At present it seems that the emittances at the end of the machine are somewhat larger than the design values.

As all accelerating, beam transport, beam measuring and control devices are now commissioned, a thorough review of the matching and acceleration from source to PSB can be made with emphasis on this emittance blow-up.

In the injection line currents of 15 and 10  $\mu\text{A}$  were measured and seem to indicate still some losses. Booster injection has confirmed the 10 (or more)  $\mu\text{A}$ :  $4 \times 10^9$  charges were injected into one ring during 100  $\mu\text{s}$ . The lifetime of the ions in the PSB vacuum is of the order of 30 ms, a factor 2 below the design value, but the TI-sublimation pumps are not yet operational.

#### 7. OUTLOOK: FUTURE IMPROVEMENTS AND LHC

As mentioned above increases in intensity are certainly within reach with present technologies. CERN's future LHC

(Large Hadron Collider) will need a substantial increase in luminosity than would be available with the present scheme. Several possibilities have been discussed [21,22]. The use of LEAR [23] with its e-cooling seems to be the most straightforward one. A laser ion source to replace the ECR may be also very promising [24].

## 8. ACKNOWLEDGEMENTS

Many thanks are due to all collaborating institutions. CERN having had little experience with ions has profited very much already in the design stage from their know-how.

Their motivated and experienced staff have greatly contributed to the success (so far) of our project. Last but not least, CERN staff has been implementing and running-in the equipment with a lot of enthusiasm and competence. A collaboration can only be as good as the collaborators are: I should like to thank them all for their skill and good will.

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