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Abstract

In fall 1994 the new heavy ion injector at CERN was brought into operation successfully and a lead beam of 2.9×10^7 *ions per pulse was accelerated in the SPS up to an energy of 157 GeV/u. The ion source, which was supplied by GANIL (France) was in operation almost continuously over a period of about one year and proved to be very reliable. It produces a current of more than 100* μA *of* Pb^{27+} *(after the first spectrometer) during the afterglow of the pulsed discharge. The current stays within 5% of the maximum value for a time of about 1 ms, which is more than required by the accelerators. Measurements of the charge state distribution, emittance and energy spread, which were made during this time window, are presented together with other operating data.*

Introduction

After the successful completion of the last light ion run in 1992, CERN's Linac I, which had been in operation for more than thirty years, was dismantled and replaced by a new heavy ion linac (Linac III) [1,2]. The various components of this new injector were supplied by five collaborating institutes.

The ECR ion source, was constructed and supplied by GANIL, France. The low energy beam transport system (LEBT), was contributed by INFN, Legnaro, who also designed and supplied the RFQ accelerator. The linac, which is a so called Interdigital-H (IH) accelerator, was developed at GSI, Darmstadt, who also supplied most of the RF systems. The filter line after the linear accelerators was contributed by INFN, Torino and the final debuncher is a construction of the IAP, University of Frankfurt [3].

The pulse length required by the synchrotrons at CERN is only 400-500µs with a repetition rate of 1 (or alternatively 10) Hz. Therefore CERN's accelerator complex is ideally suited for the application of the afterglow of the ECR discharge, which can produce ion pulses with durations ranging from a few hundred microseconds to several ms. Furthermore the afterglow is particularly well suited for the production of highly charged heavy ions (the species presently required at CERN is Pb^{27+}). The very successful application of the afterglow during the former operation with sulphur ions [4,5] and the good results obtained for lead ions at GANIL [6,7], gave great confidence, that the advantages of the afterglow could be utilized for CERN's heavy ion project.

Layout and Specifications

Fig. 1 gives an overview of the preinjector. The ion source, which is of the ECR4 type [8], is operated at a frequency of 14.5GHz; the maximum power available is 2kW. The source has c.w. capabilities, but was optimized for afterglow operation. The discharge is pulsed with a pulse length of 50ms and a repetition rate of 10Hz.

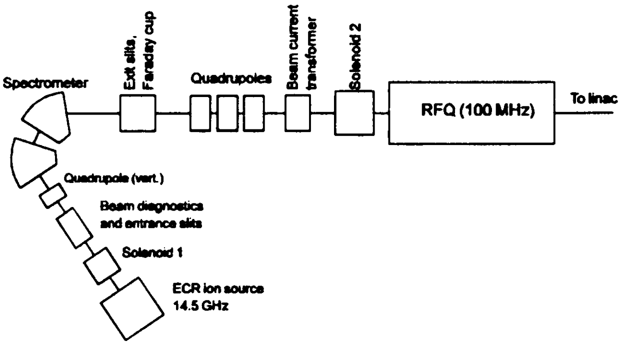

Fig.1. Low energy part of heavy ion injector

The RFQ requires an injection energy of 2.5keV/u, which leads to a preacceleration voltage around 20kV, depending on the charge state of lead. All components have been designed to accelerate Pb^{25+}. Presently charge state 27+ is preferred as this requires a lower RF level in the accelerators.

Oxygen is used as a carrier gas and isotopically pure lead 208 is evaporated into the plasma using a micro oven [7], which is situated inside the coaxial RF feed line.

The Pb-ion current originally specified in the design study [2], a figure of merit, on which all further (very optimistic) estimates in the accelerator chain were based, was 80μA of Pb^{27+} with a pulse duration of 600μs. In the design phase of the injector this current could be reached, however the duration was a critical parameter, as the position of the cutoff edge of the afterglow is usually not very stable.

The ion beam is extracted from an aperture of 13mm diam. with a single extraction electrode at ground potential. The extraction gap is 43mm. After a drift of approx. 1m the beam is focused onto the entrance slit of the spectrometer using a solenoid. The vertical matching to the spectrometer can be optimized by a single quadrupole. The spectrometer is a split pole dipole with a deflection angle of 135°. Higher order corrections, which are obtained by a special curvature of the inner edges of the poles, result in the very high resolution of $\Delta p/p = 0.003$. Its design is similar to that first installed at GSI's HLI [9].

After the spectrometer, the beam passes through an exit slit, which can be closed to ±3 mm without losses of the desired charge state losses. A Faraday cup with electrostatic- and additional magnetic secondary electron suppression is used to measure the ion current after the spectrometer. The radial symmetry of the beam is restored by a set of three independent quadrupoles and the final focusing into the RFQ is done by a second solenoid. The RFQ, which accelerates the beam from 2.5 to 250keV/u uses the four-rod principle, originally developed by A. Schempp [10]. The Legnaro design [11] used here employs four modulated vanes, which act as "rods" of the resonator.

The IH structure, designed by U. Ratzinger, GSI [12], accelerates the beam to 4.2MeV/u. At this energy the ion beam is stripped in a carbon foil to a distribution of charge states ranging from 49 to 57. A second spectrometer is then used to select charge state 53+ for the further acceleration in the synchrotrons.

Results

The originally specified 80μA of Pb^{27+} were reached soon after the installation of the source in Jan. 1993. After an extensive study of the parameter field, the performance could be further improved and currents of up to 140μA Pb^{27+} could be extracted during the afterglow under certain conditions. To classify the infinite range of possible operating conditions four operating regimes, mainly characterized by the magnetic field distribution were defined.

a) The "GANIL" or "standard" mode

In this case the currents in the two coils of the source lie around 1080/1020 A. The afterglow pulse (see Fig.2a) obtains a relatively flat top of a duration of up to 600μs, which is followed by a sharp cutoff edge. The maximum current obtained in this mode is 100μA. The beam current may fluctuate by a few percent from pulse to pulse and the position of the cutoff edge varies by a few tens of microseconds.

b) The "maximum" mode

The highest currents (up to 140μA, see Fig.2b) can be obtained at high magnetic fields (e.g., at 1100/1020A). The duration of the afterglow peak decreases to about 200μs and the stability is poor. This mode of operation does however give an indication of the potential for further improvements.

c) The "stable" mode

A third very distinct operating regime was found at very low magnetic fields (860/900A). In this mode of operation the afterglow has a completely smooth shape (see Fig.2c) as earlier predicted in ref. [5]. The current maximum is reached after a rise time of about 500 μs and is followed by a long tail with a decay time of several ms. The sharp cutoff edge, which is encountered in the other operating modes is probably due to breakdowns in the extraction system caused by the impinging beam, which in turn lead to instabilities in the plasma and disturb the further extraction process. Thus, if those breakdowns are reduced, which is evidently the case in this mode of operation, the pulse to pulse stability of the afterglow becomes extremely good: After some optimization it was possible to obtain a stability which was so good, that it was hardly possible to distinguish the continuously pulsing afterglow from a stored trace on a digital storage oscilloscope. This means that the pulse to pulse fluctuations are well below 1% of the total amplitude. Also the long term stability is greatly improved in this mode of operation. The ion current obtained in this mode are generally lower than in the the other cases, although 80 μA of Pb^{27+} can also be obtained.

d) "Operational" mode

During most of the running in phase of the accelerators and finally during the production run, the source was operated in a regime close to the stable mode but tending towards higher magnetic fields (900/940 A) and higher ion currents. In this mode the beginning of the afterglow is similar to that of the stable mode, but the sharp cutoff appears again after about 1ms (see Fig.2d). The maximum current obtained for this kind of operation was 100μA while the standard current in operation was 80-90μA.

Charge State Distribution

A special technique (decribed ref. [15]) was developed to measure the charge state distribution (CSD) during a given time window, maintaining the same beam otics for all charge states.

Fig.3 gives two examples of such a measurement, a) the CSD during the afterglow and b) - on a different scale - the CSD during the main discharge. The CSD during the afterglow peaks around charge state 26, which is overlapped by the intense O^{2+} peak. The distribution during the main pulse differs from this and a characteristic dip for charge state 25 is often observed.

Energy Spread and Voltage Stabilization

Due to the high resolution of the spectrometer and the limited acceptance of the RFQ in the radial plane, the energy stability during the afterglow is of great importance: A change in energy with time results in a displacement of the beam after the spectrometer and thereby causes a virtual growth of the emittance.

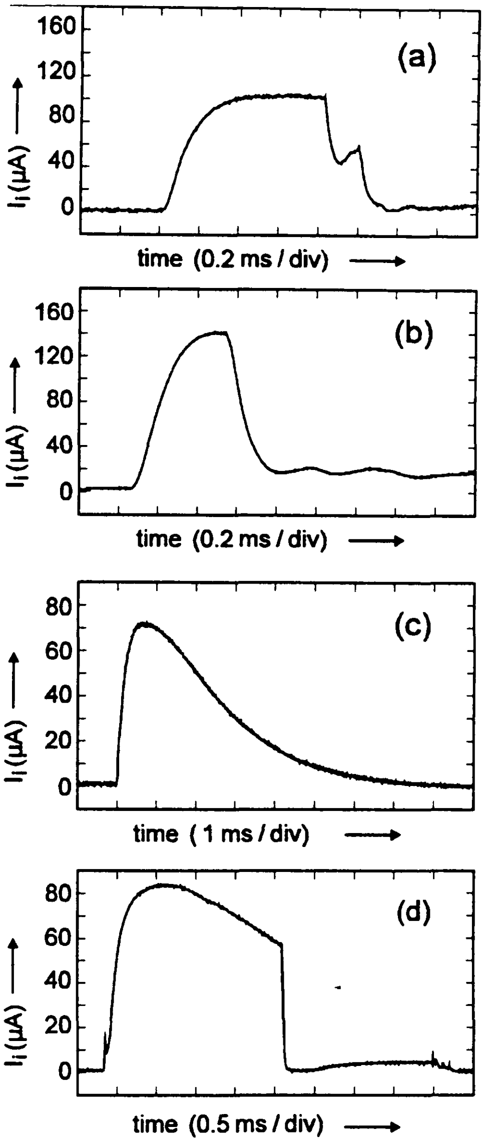

Fig.2. Comparison of different afterglow modes: a) "standard" mode, b) "max." mode c) "stable" mode and d) "operational" mode.

Apart from the energy distribution of the ions in the plasma, which is generally considered to be low for ECR ion sources, an energy variation can have two causes: Firstly the current drained from the HT supply varies greatly in pulsed operation, especially during the afterglow, where the total current leaving the source may increase by a factor of two. This then modulates the source potential. Secondly, if one assumes, that the afterglow is produced by ions trapped in a negative plasma potential as suggested by Shirkov [13], this potential will change during the course of the afterglow and thereby lead to a temporal energy variation.

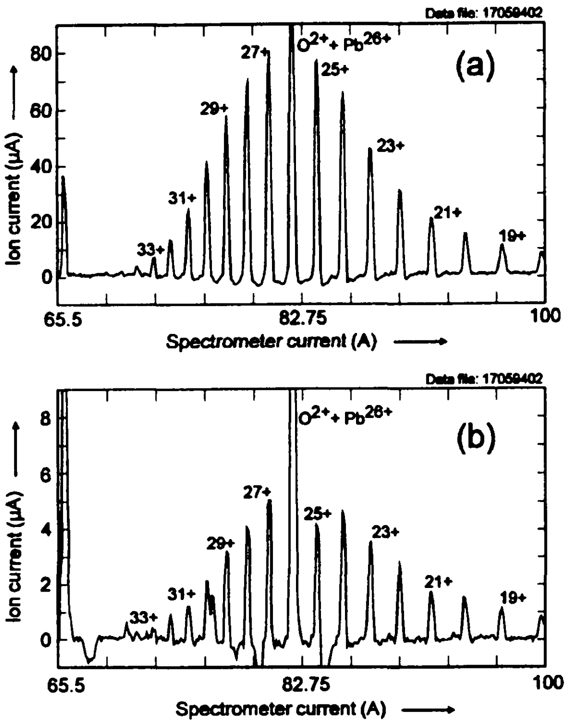

Fig. 3. Comparison of charge state distributions a) during afterglow and b) during main pulse (discharge optimized for afterglow).

The voltage variation was found to be about 300V at the beginning of the main pulse and an additional 50V negative with respect to the originally applied voltage during the afterglow. The time varying energy change could be measured using the high resolution spectrometer. Fig.4 shows a plot of momentum/time phase space, which was constructed from 100 stored oscilloscope traces. On fig.4a one sees a considerable distortion of this figure, which indicates a large change of momentum at the beginning of the pulse. After the installation of an electronic voltage stabilization, the change of energy with time disappeared almost completely as shown in Fig.4b, allowing an estimate of the energy spread obtained in the plasma: Using the full width of the peak with voltage stabilzation one arrives at a momentum spread of Δp/p of 0.005, from which spread of 50eV per charge can be calculated.

Emittance Measurements

A further uncertainty was the emittance of the beam during the afterglow. Earlier measurements had only been performed in c.w. operation. At CERN it was possible to measure the emittance during a time window of only 200µs using several hundred source pulses. The emittance was measured at the location of the RFQ entrance in both planes, using a slit and profile harp arrangement. It was found, that the emittance during the afterglow lies inside the required value of 200π mm mrad (see fig.5a). However, also some strong distortions of the emittance figure were found at certain LEBT settings (see fig. 5b). These distortions may be a result of an inhomogeneous plasma density at the outlet aperture, caused by the sextupole magnets. Furthermore spherical aberrations may be induced by the two solenoids. Nevertheless, the transmission through the RFQ was >90%, indicating, that the emittance lies well inside the acceptance of the RFQ. Detailed results of the LEBT investigations are found in [14].

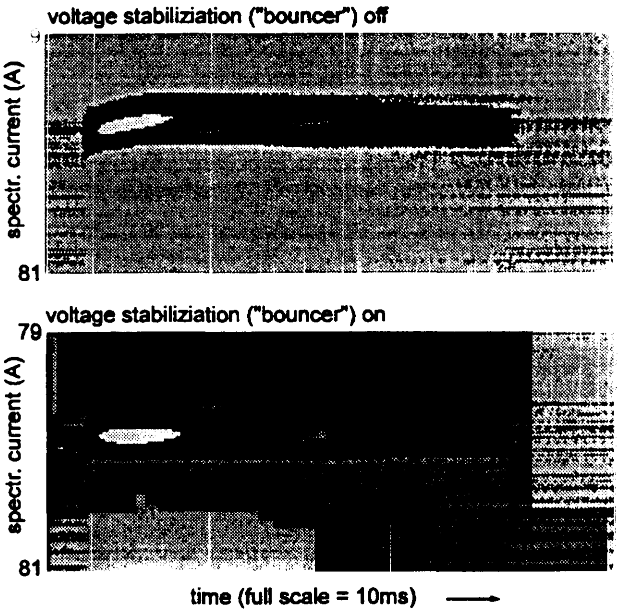

Fig. 4. Momentum/ time phase diagram of the Pb^{27+} beam during the afterglow

Long Term Operation

During the installation and setting up period of the injector, the source was operated almost continuously (24h per day) for almost one year, with short stops only for servicing. After the first injection into the booster synchrotron in June 1994 until the end of the year, there was virtually no deterioration of source performance and only minor readjustments were required per day. Thus the source proved to be extremely reliable also in long term operation.

Performance of the Lead Injector

The results of the 1994 ion run are summarized on fig.6: Although a maximum current of 140µA of Pb^{27+} can be reached, the stability was considered more important and a current of 80-90µA was adjusted during the production run. The highest current obtained at the exit of the RFQ was 80µA, the operational value being 70µA. The transmission through the IH linac was also very good and the current at its exit was 60µA. After stripping and filtering there remained a current of 25µA of Pb^{53+} for further acceleration.

The beam was transferred to the booster synchrotron (PSB) with almost no losses. The circular machines at CERN accelerate a total of four consecutive pulses from the linac during the PS supercycle of 16 seconds. Within those four pulses, the booster was able to accelerate 1.2×10^9 ions to 94Mev/u, the PS accelerated 7.5×10^8 ions to an energy of 4.2GeV/u and finally the SPS accelerated 2.9×10^8 fully stripped lead ions to an energy of 157GeV/u for fixed target experients.

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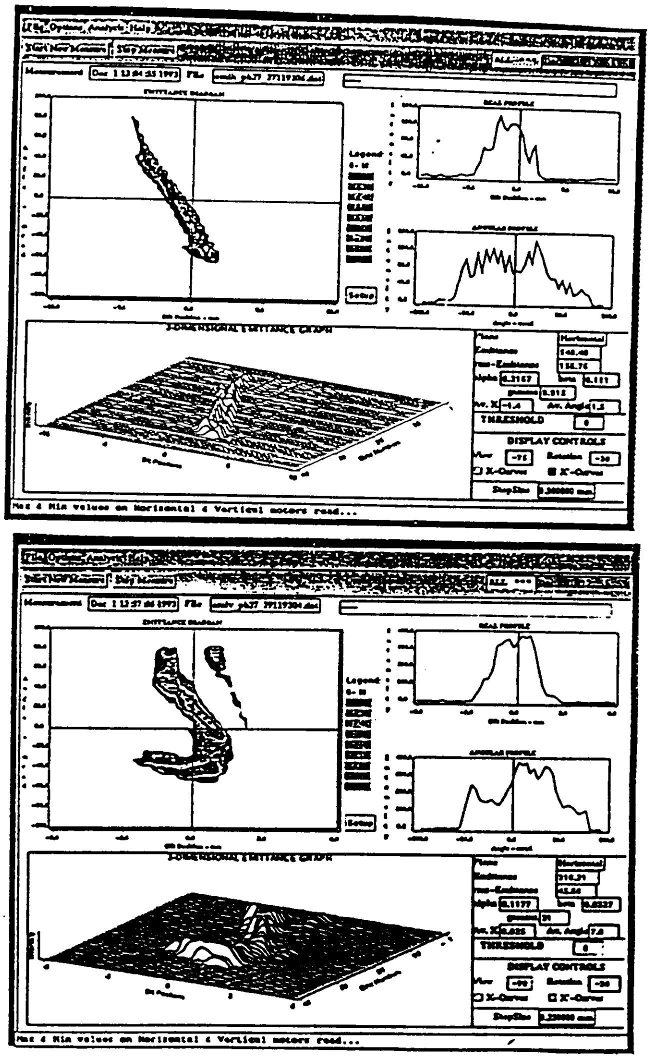

Fig. 5. Emittance measurements of the Pb27+ beam at the entrance of the RFQ.

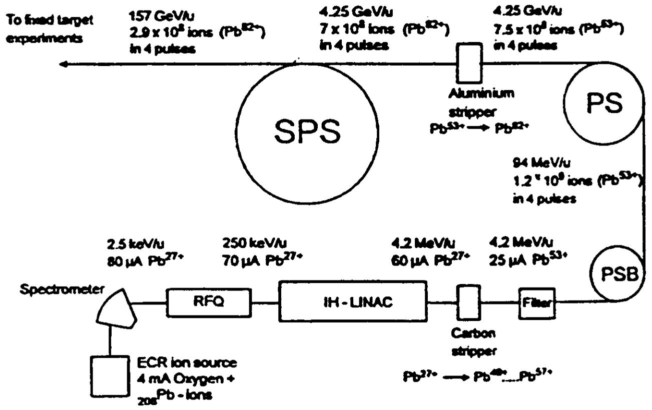

Fig.6. The heavy ion injector at CERN: Results of the 1994 lead ion run.