THE HEAVY ION LINAC FOR THE CERN LEAD ION FACILITY

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Abstract

The lead ion linear accelerator "Linac 3", its installation, RF conditioning, and beam commissioning, are described. Starting from the ECR source at 2.5 keV/u, lead ions are accelerated through several stages to 4.2 MeV/u. Since August 1993, 80 μAe of $^{208}Pb^{27+}$ ions have been used for tests at 2.5 keV/u, leading to a matched beam before the Radio Frequency Quadrupole. Commissioning of this RFQ in May 1994 established matched longitudinal and transverse emittances, at the input of the Interdigital-H (IH) accelerator. The latter accelerated in three stages to 4.2 MeV/u, with the operating parameters set by detailed measurements. At the output of the IH, the beam was stripped to obtain Pb^{53+} ions. Matching into the Proton Synchrotron Booster (PSB) was achieved on 15 June 1994.

Introduction

The CERN Heavy-Ion Facility has been presented several times; in particular [1], the 1993 design report gives a detailed account of the history, design, mechanical aspects and parameters, mostly concerning "Linac 3", an entirely new construction made in collaboration with outside institutions. Referring to Fig. 1 the parts contributed were: IP by GANIL; ITL, IAQ and ITM by Legnaro; IA1, IA2, and IA3 by GSI; ITF by Torino. In addition, GSI provided the high power RF systems, Frankfurt (IAP) the debuncher, India software effort, the Czech Republic some manpower, and Sweden and Switzerland financial contributions. The collaborations were very active recently in the equipment installation and in the testing of the beam performance. This present paper describes the beam commissioning, and refers to previous reports [1,2,3] and other papers at this conference [4,5,6,7] for further aspects and details.

The installation of Linac 3 and beam commissioning were dictated by a "milestone" date, the 15 June 1994, for first injection of the Pb^{53+} beam into the PSB. In fact a heavy-ion physics run in November 1994 will follow closely the commissioning of the synchrotrons, PSB, PS and SPS. The beam commissioning above 250 keV/u started in May, compressing the initial proving tests for the beam acceleration, transport and instrumentation, into six weeks.

Linac 3: Main Design Features and Instrumentation

The layout emphasizing the beam instrumentation is given in fig. 1. Systems are given both their traditional names and the CERN PS nomenclature [1], which is also used for the measuring instruments.

The Accelerator from Source to Debuncher

The Injection System (IP) This consists of a 14.5 GHz Electron Cyclotron Resonance (ECR) ion source delivering 80 μAe of lead ions, $^{208}Pb^{27+}$, in the pulsed afterglow mode to produce a stable pulse several ms long. Acceleration to 2.5 keV/u is made by operating the source at 19.2 kV. At the source output are some mA of ions mainly of the support gas, oxygen, and charge states around Pb^{27+}. The performance of the source is assessed by separating the species in the low energy beam transport, ITL.

Low Energy Beam Transport (LEBT, ITL) [4] This line has a spectrometer arrangement in its first part providing a mass resolution of 1/300 at an image slit. It comprises solenoid focusing on to an object aperture, then a

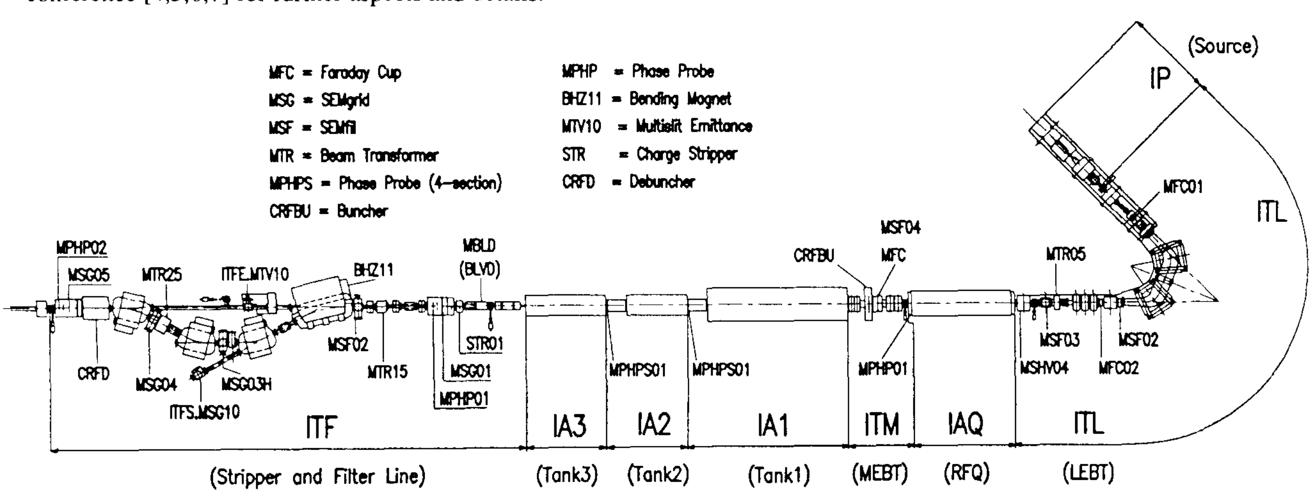

Fig. 1 Layout of Linac 3 showing positions of beam monitors.

quadrupole lens followed by two 67.5^0 bending magnets. Then the beam is transported using a quadrupole triplet so that it has circular symmetry at the solenoid that focuses to a small matched waist in the RFQ (IAQ). The low energy beam transport section, ITL, also contains beam measuring equipment: two Faraday cups, a transformer, and two sets of horizontal and vertical SEMgrids, for profile measurements. Defining slits and two sets of steering magnets are available.

Radio Frequency Quadrupole (RFQ, IAQ) [5] The RFQ operates at 101.3 MHz, has four rod-like vanes and accelerates from 2.5 keV/u to 250 keV/u in about 2.5 m. After beam preparation and energy boosting in 0.8m (to about 20 keV/u), the energy increases linearly over the final 1.7m. At the input the beam is at a waist 1.9 mm x 80 mrad (0.35 mm mrad normalized emittance) whereas the acceptance is 0.8 mm mrad. A four-sector iris at the input, monitors the beam position and limits the aperture. The nominal output beam has a longitudinal emittance of 28 deg keV/u (ΔW = 2.8 kev/u) and an ideal transverse emittance of 0.40 mm mrad, 4-rms, normalised.

Medium Energy Beam Transport (ITM) [6] The RFQ output beam must be matched into the IH structure (IA1) which requires a convergent beam closely fitting the acceptance in all planes. With one buncher, the length of the ITM, 1.65 m, is dictated by the longitudinal matching. Two pairs of quadrupoles transform the rather different H and V parameters to a larger convergent beam at the input of IA1. One constraint is the buncher aperture diameter of 28 mm. Two pairs of steering dipoles are available and the beam monitoring provided is a Faraday cup and profile monitors for the H and V planes (SEMgrids).

IH Linac (IA1, IA2 and IA3) This linac has three cavities accelerating to 1.8 MeV/u (IA1 at 101.3 MHz), to 3.1 MeV/u and to 4.2 MeV/u (IA2 and IA3 at 202.56 MHz). The design extends that used at GSI and incorporates "combined zero-degree synchronous-particle sections" [7]. For a cavity with the H-mode loaded by small axial drift tubes, this principle allows separation into five sections (three in IA1) between which quadrupole focusing triplets are mounted. There are effectively 32.9 MV over 99 gaps in 8.1 m overall length. The acceptance is closely matched to the RFQ emittances implying critical adjust-ments of the RF field and phase for acceptable longitudinal characteristics. The triplets maintain round cross-sections at the five beam waists. As the cavity separations are just sufficient to house the quadrupole triplets there are neither vacuum valves nor standard beam monitors there, but the triplets incorporate steering windings and four-sector phase probes are installed in the input flanges of IA2 and IA3.

Stripper, Filter and Transfer at 4.2 MeV/u (ITF) In this region measurements are made on the overall performance. Nevertheless, the beam optics functions are essential i.e. stripping to charge states around Pb^{53+} separation of the required state, and the transfer and matching of a "debunched" beam in ITH towards the PSB. ITF has a quadrupole triplet at the IA3 output to focus the beam on the stripper foil, followed by three pulsed quadrupoles before the bending magnet (BHZ11) which can handle the more rigid Pb^{27+} ions. The three weaker magnets in the filter each give 500 mrad deflection, and a beam waist is produced at the debuncher (11 m from IA3). There are four pairs of steering dipoles, two before the spectrometer.

The correct operation of the line concerning beam alignment and profiles, requires five sets of SEMgrids, with one set in the spectrometer to measure energy spread. Three sets of apertures are used as object slit for the spectrometer, as beam defining slits in the filter and before the multi-slit emittance device, respectively. During the running-in, the Bunch Length and Velocity Detector (BLVD) has been mounted after the triplet at the IA3 output. Two beam transformers are essential for optimisation during operation, and there are two phase probes, one near each end of this line.

Beam Instrumentation

Strong emphasis was put on beam monitoring for commissioning and operation. The problems with Linac 3 concern low currents (<100 μAe) in a 600 μs pulse at 1 Hz, with possible RF noise, and low energy, high charge states favouring secondary electron production. At low energy, extra emittance measurement devices and the BLVD were installed temporarily for measurements and calibrations.

Beam Current Linac 3 has three Faraday cups and three beam transformers. Both types suffer from noise, the transformers acutely, and are liable to errors from secondary electrons, which are suppressed on the Faraday cups by suitable biasing (600 V) or by a magnetic field. At 2.5 keV/u and 250 keV/u, Faraday cups can give repeatable indications; however transformers are non-destructive.

Profile Measurements Transverse beam profiles in both H and V planes can be measured at ten places along Linac 3. Secondary emission grids (SEMgrids or SEMfils) consisting of metallic ribbons or wires suitably spaced (like a miniature harp) give signals proportional to the impinging current thus registering the transverse distribution. One SEMgrid is used in the 4.2 MeV/u spectrometer. The software required depends on the application, with the mean beam position and its rms width as basic parameters.

Emittance Measurements There are two dedicated instruments, the first being a slit and collector assembly used on previous linacs. It moves in steps across the beam with a collector like a SEMgrid. The software produces profiles in position and angle, a "mountain " display, an equidensity contour emittance plot and rms emittance parameters (fig. 2). This was installed for commissioning at 2.5 keV/u (ITL) and 250 keV/u (RFQ and ITM).

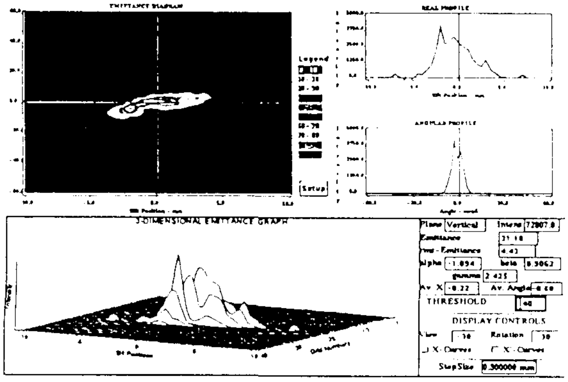

Fig. 2 Emittance measurement at 250 keV/u showing profiles, a "mountain" display and an equidensity contour plot.

The second system is a multi-slit arrangement [8] with 0.3 mm slits spaced by 6 mm followed by a fluorescent screen observed by a video camera equipped with CCD readout. To each slit corresponds a profile measurement, and emittance can be derived with acceptable resolution and displayed as equi-density profiles. This special device for Linac 3 was compared with the previous instrument at 2.5 keV/u and 250 keV/u, before use at 4.2 MeV/u.

Phase Probes There are three standard capacitive phase probes installed, one after IAQ and the others in ITF. Due to the low velocity (β= 0.023), the former probe has a rise-time of > 3 ns which gives a qualitative, differentiated indication of the bunch form. The other probes have about 1 ns rise-time, and may be used for velocity studies.

Two four-sector probes at the inputs of IA2 and IA3 respectively, allow measurements of beam phase, phase spread (qualitatively), and vertical and horizontal position.

Bunch Length and Velocity Detector (BLVD) This bunch shape analyser, from INR Troitsk, was applied to the 250 keV commissioning when the velocity measurement was first used [3]. Secondary electrons with the time structure of the impinging beam are produced from a fine tungsten wire. This electron beam is analysed via deflector plates at 202.5 MHz followed by a multi-channel detector. With a time resolution of 10 ps, bunch shape and fine velocity measurements were made at 250 keV and later, at 1.8 MeV/u, 3.1 MeV/u and particularly 4.2 MeV/u.

Preparations for Beam Commissioning

Installation

The ECR source, previously tested at GANIL, was installed around Christmas 1992. To test the source, the ITL spectrometer was available during July 1993. Most of the ITF elements were in place by July 1993 with completion in May 1994. The accelerating structures, were delivered and installed in reverse order of requirement; IA2 and IA3 in December 1993, IA1 in February 1994 (all by GSI) and the RFQ (IAQ) by Legnaro in April 1994.

RF Experience

Low Power Field Measurements These were important for the RFQ and the IH tanks where checks on frequency, Q, tuner range, feed-loop match and monitoring-loop coupling were made for all cavities.

On delivery of IA2 and IA3 the GSI results of the field measurements in the gaps (28 and 30 respectively) were confirmed using different apparatus and analyses. Similarly for IA1, the more critical field distribution was adjusted according to dynamics computations and beam measurements [7]. RFQ measurements done at Legnaro were repeated and the field symmetry (<5% error) was confirmed. The four-gap buncher was checked at CERN [6].

RF Conditioning Of the six cavities conditioned only two (IA2, IA3) were the same type. For the ITM buncher and for the ITF debuncher, the relatively low power, 2.5 kW, with variable pulse rate and length allowed a quick initial conditioning. However the buncher would not accept power reliably with ion pumps on, nor when beam was lost nearby. This has recently been solved by deflecting the long, low-current pulse before the after-glow pulse. Conditioning of the RFQ cavity at 101 MHz was straightforward, taking less than two days.

The 202.56 MHz cavities typically required a day at low power before accepting a few kW. Then the power could be steadily increased and the tanks' surfaces degassed with the RF until passing, after a few days, the operating levels corresponding to Pb^{25+} acceleration, i.e. 430 kW and 400 kW respectively. There was similar behaviour at 101.3 MHz when conditioning IA1 to 260 kW.

Beam Commissioning Along Linac 3

Guiding Principles

As there were four designing institutes, the sequential commissioning aimed to meet the specification of each part before working on the whole linac. Certain characteristics only become evident with the complete accelerator and its beam instrumentation operating reliably, then iterative optimisation gave further improvements. The aim was to meet the beam specifications for the PSB injection for beam current (implying >90 % transmission per system), transverse emittance and energy spread. This was substantially achieved .

Source (IP) and Low Energy Beam Transport (ITL) The ITL spectrometer is the diagnostic tool for identifying charge states from the ECR source. From mid-July 1993, oxygen, argon, krypton and xenon were tried with the latter showing a complicated spectrum requiring resolution of charge states from Xe^{22+} to Xe^{26+}, and isotopes ^{129}Xe, ^{131}Xe and ^{132}Xe. With lead the preferred state, $^{208}Pb^{27+}$, has slightly more current, 80 μAe, than the neighbouring states. A resolution, dm/m < 1/300, was demonstrated and the perturbing effect of droop on the HT supply corrected. The beam energy, 2.5 keV/u, matches the RFQ requirements, and the accelerator RF defines a 600 μs stable pulse (at 4.2 MeV/u) from the full after-glow pulse.

Other proving tests on ITL took place up to March 1994 [4]. As well as commissioning beam monitors, the main aim was to produce a match in both transverse planes at the RFQ input. This was achieved by measurements and TRACE2D computations along ITL, with the single slit emittance device at the output, and SEMgrid measurements (MSGHV03). Calibration of the ITL beam monitors was made so that, with the RFQ in place, the matched beam could still be set up.

RFQ (IAQ) and Medium Energy Beam Transport (ITM) For commissioning the RFQ, the ITM beam transport, matching and beam monitors were used with a temporary measuring line comprising the BLVD, the single slit emittance device and the multi-slit emittance device in the position of IA1 input. With the short time available, from 3 to 13 May, a wide range of beam measurements and equipment tests was achieved [5, 6] e.g. the BLVD was used for the first time with low energy ions for velocity, phase, phase spread and longitudinal emittance measurements. [3].

A small beam current was accelerated by the RFQ on 29 April and detected with the phase probe (CRFPH). With ITM completely mounted, 65 μA was measured in the Faraday cup (MFC) on 3 May. The aim was to produce a matched beam at the input of IA1, and to calibrate the quadrupoles, the buncher and the SEMgrids. It was possible with the BLVD to calibrate the RF levels, to set the relative phases between the RFQ and the buncher (CRFBU) and to measure the beam velocity, nominally 0.02316c at 250 keV/u [3]. In addition the buncher phase was used to vary the beam energy by a few keV/u in a controlled way. The longitudinal emittance could also be deduced, with the expected range around 40 deg keV/u being found.

Transverse matching required iterative cycles of emittance and profile measurements, coupled with TRACE3D computations. The single quadrupole calibration did not fit the doublet combinations in ITM so calibrations were done via the measured beam parameters compared to computations. Good results were achieved with the multi-slit emittance device at 250 keV/u, after preliminary results at 2.5 keV/u [8].

IH Linac, Cavities IA1, IA2 and IA3 On 24 May the systematic transfer and acceleration up to 4.2 MeV/u was started by passing the optimally bunched 250 keV/u beam through the unpowered cavities to test the calibration and alignment of the four triplets. The beam retained sufficient bunch structure to test the phase/position monitors in the intertanks and in ITF.

According to computations and GSI experience, IA1 would be the most critical of the cavites concerning RF level and phase for good acceleration conditions. The nominal level was set from the low power RF measurements and the expected sensitivity to level and phase obtained for the phase probe signal. Measurements at 1.8 MeV/u to obtain the operating levels precisely, used the spectrometer and the BLVD, which indicated the need for readjustment of the field distribution by the cavity tuners. Initially, much of the time available was devoted to beam monitor commissioning.

For IA2, beam was accelerated on 26 May to the nominal 3.04 MeV/u (measured on the BLVD) with the expected RF settings. The frequency change from 101 MHz in IA1 to 202 MHz in IA2 caused no difficulties.

After 4.2 MeV/u had been obtained from IA3, the RF levels in all cavities were reviewed, using as criteria the energy, energy spread and phase spread measured on the ITF spectrometer (fig. 3) and the BLVD. Systematic variations of parameters gave results in the expected range.

Transverse measurements were made, deducing emittances from SEMgrid profiles with systematic quadrupole changes. Reasonable agreement was obtained with the multi-slit emittance results transferred backwards with TRACE. This was important when matching the 4.2 MeV/u beam to the PSB via the transport line, ITH.

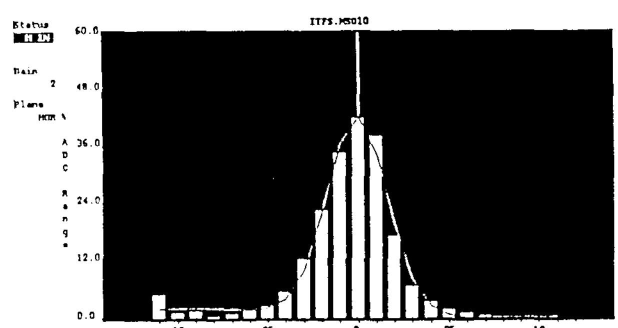

Fig. 3 Energy and energy spread measurements for Pb^{27+} at 4.2 MeV/u: (10 keV/u per channel)

Stripping and Beam Transport in ITF Few measurements were necessary to confirm the basic operation of the charge stripper. Observing the current on the central SEMgrid wire (MSGH10) in the ITF spectrometer, the charge states around Pb^{53+} were identified by changing the current in the bending magnet, BHZ11, (see fig.4). The thinnest carbon foil of the four variants installed, 100 μg/cm^2 , gave the best beam and had a lifetime of several hundred hours.

The beam transport through four bending magnets to the debuncher cavity (CRFD) was straightforward using two steering dipoles and three SEMgrids.

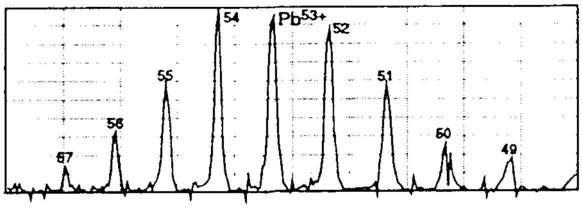

Fig. 4 Charge state distribution of lead ion beam after stripping.

Beam Transfer, Emittance and Energy Spread Before the PSB Beam transfer beyond ITF is in existing beam lines, ITH and LTB, (also used for 50 MeV protons). This was difficult, requiring sensitive adjustments of steering and focusing, and working sometimes at one pulse/15 s due to the proton programme. All CERN hadron linacs have used the lines near the PSB to check beam emittance and matching (LBE), and energy spread (LBS). This spectrometer was used to set the debuncher phase and amplitude. Initially 0.08 % , the energy dispersion is now near the 0.05 % requested (fig. 5). Emittances were initially about 20 mm mrad (4-rms), double those required, but both planes now approach 10 mm mrad, unnormalised (fig. 5).

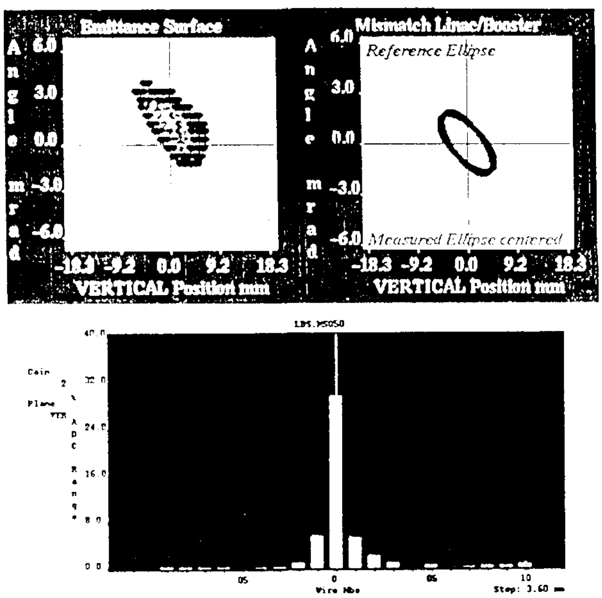

Fig. 5 Above: Emittance and beam matching in LBE (near PSB)
Below: Energy spread for Pb^{53+} beam in LBS, (2 keV/u / ch)

A requirement for the period after 15 June was a stable reproducible beam for the Proton Sychrotron Booster (PSB) tests. This was achieved in parallel with commissioning of the auxilliary systems e.g. RF and controls. Recently, the parameter settings were restudied by measuring the stripped beam in ITF.MTR15, and varying the focusing in ITM and the four triplets in the linac, giving improvements in beam current and quality. The sensitive parameters were the first triplets (in IA1); this might indicate transverse mis-matching between ITM and IA1.

A summary of the recent measured performance is given in Table 1.

TABLE 1
Measured Performance of Linac 3

Region of Linac 3	ITL	ITM	ITF	ITF	LBE/LBS
Ion and Charge State	Pb^{27+}	Pb^{27+}	Pb^{27+}	Pb^{53+}	Pb^{53+}
Energy (keV/u)	2.67	250	4280	4200	4200
Current (μAe)	80	70	60	22	22
$E_{H,n}$ mm mrad, 4rms	0.24	0.32	$1.2^{\$}$	-	$1.6^{\$}$
$E_{V,n}$ mm mrad, 4rms	0.24	0.38	$1.1^{\$}$	-	1.2
$\Delta\phi$ (deg $^{\#}$) 2 rms	-	13-20	2.5-4	-	-
ΔW (keV/u) 2 rms	-	5-8	23-25	-	2.5

\# At 101 Mhz $ Typical values, minima 20 % lower

Acknowledgements

I would like to thank the many people who have helped to bring Linac 3 to an operational state in particular the members of the Linac 3 Running-In Team (L3RIC) including members from outside CERN, whose work, especially since May 1994, is reported here. We have relied on the willing efforts of HI group, and of the support groups (PS division, CERN and outside institutions) which were involved in the installation and commissioning of the accelerator hardware and the ancillary systems.

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