COMMISSIONING AND EXPERIENCE IN STRIPPING, FILTERING AND MEASURING THE 4.2 MEV/U LEAD ION BEAM AT CERN LINAC 3

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Abstract

The new CERN Heavy Ion Linac (Linac3) accelerates a Pb^{27+} beam to 4.2 MeV/u. The beam is then stripped to Pb^{53+} by a carbon foil, and, after stripping, a 12 m filter line prepares the beam for the injection into the Proton Synchrotron Booster (PSB). The filter line eliminates the unwanted charge states, checks the beam quality (energy, energy spread, transverse emittance and intensity), and finally transports the beam in the lines leading to the PSB.

The paper summarises the transverse beam dynamics of the line, and reports on its commissioning, especially focusing on the experiments that led to the stripper choice, and on the measurements performed with a specially developed single pulse multislit emittance device. The operational experience is also reported.

Introduction

At the end of Linac3, the Pb^{27+} ions are stripped to obtain a beam with a magnetic rigidity of 1.16 Tm, only 16% higher than the 50 MeV protons, which have in common with the ions (on pulse-to-pulse basis) the long transfer line and the injection into the PSB. This allows the use of the same magnetic elements for both particles. Optimum charge state and energy giving the required rigidity after stripping from Pb^{27+} have been determined as Pb^{53+} at 4.2 MeV/u [1].

A filter-stripper line (see Fig.1), 12 meters long, between the end of the linac and the shielding wall that separates Linac3 from the transport line to the PSB, is used to select and optimise for injection into the PSB the desired charge state after stripping, and to measure the parameters of the different lead ion beams (27^+ and 53^+ with the adjacent charge states). Measurements have to be performed independently from PSB operation, and on single pulse basis, to observe the ion beam stability. The design and realisation of the line has been done at CERN in collaboration with the INFN-Torino [2].

After the linac interdigital-H tanks, a quadrupole triplet focuses the beam on the stripper, then a four bending magnet sequence eliminates the unwanted charge states on a slit. At the end of the line, a debunching cavity (made at IAP-Frankfurt) minimises the energy spread for injection into the PSB. Longitudinal beam parameters are measured at the exit of the linac by a Bunch Length and Velocity Detector (BLVD), made at INP-Moscow [3], and by using the first bending magnet as a spectrometer. Horizontal and vertical emittances are measured in a straight line after the first bend with a single pulse emittance measurement device of the multislit type [4]. Five SEM-grids at different positions in the line allow the measurement of the horizontal and vertical beam position and profile, and two phase probes check the phase profile. Finally, beam currents for the different charge states are measured with two transformers, placed before and after the slit.
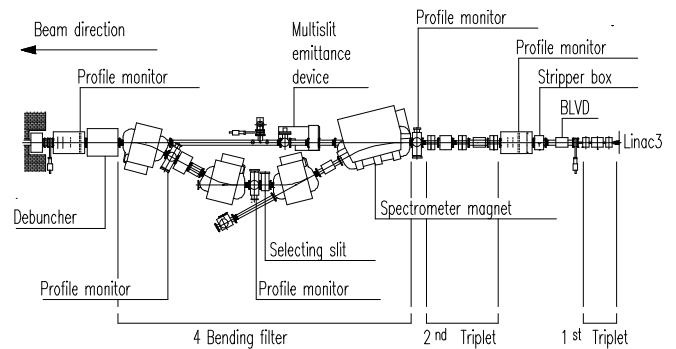

Figure 1. Layout of the filter - stripper line.

Beam Dynamics of the Filter-Stripper Line

The optics of the line have to take care of some critical points. First of all, position and transverse size of the beam should not exceed the foil dimensions (20 mm diameter) in the 100 mm long longitudinal region where the four stripper supports are located. Then, the filter resolution has to be considered, because the transverse width of the beam spot at the slit has to be smaller than the distance between two adjacent charge states. Moreover, the four bending magnets have to form an achromatic system with minimum emittance increase. The matching, done with the code TRACE-3D [5], is shown in Fig.2. It takes into account the emittance increase at the stripper, as well as the change of charge state.
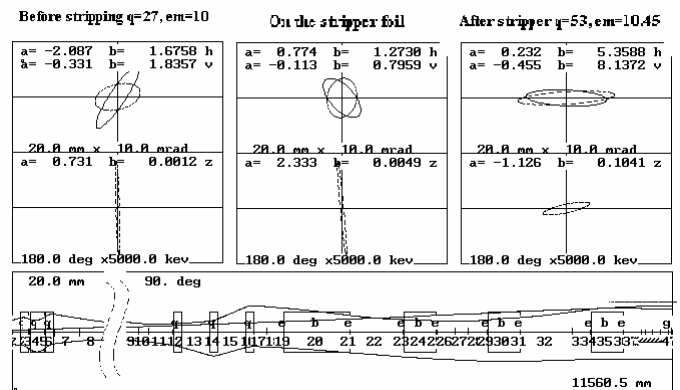

Fig. 2.Emittances in 3 positions and beam envelopes (TRACE-3D).

Stripper Measurements

The first stripping tests were done with carbon foils of surface density 100, 200, 300 and 400 µg/cm^2. Fig. 3 shows the corresponding charge state distributions measured after the spectrometer. They are all centred around 53$^+$, in excellent agreement with the predictions of Baron's formula[6].

This indicates that the equilibrium thickness is already reached with the 100 µg/cm^2 foils. Straggling is responsible for the larger energy spread across thicker foils. For Pb^{53+} and a 100 µg/cm^2 foil we measured an increase in energy spread of 11% (±33 against ±30 keV/u (2σ)) after stripping. This is acceptable for beam transport, since the energy spread for PSB injection is mainly defined by the debunching cavity. Therefore 100 µg/cm^2 (thickness of 0.5µm) has been kept as the nominal stripper surface density. The beam energy loss across this foil, measured at the spectrometer, is $\Delta W = (130 \pm 10)$ keV/u, in good agreement with the Firsov formula [7].
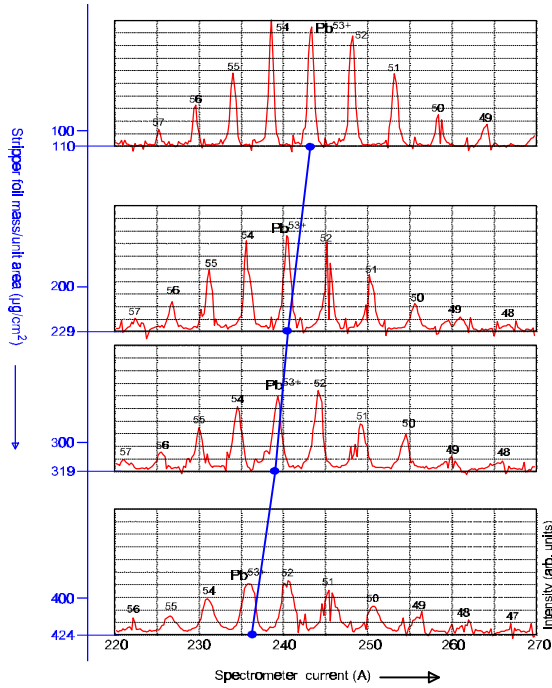

Figure 3. Charge state distribution after stripping for increasing stripper thickness.

The increase in beam divergence inside the stripper foil leads to an emittance growth that has been evaluated by measuring the increase in beam size at the SEM-grid after the stripper position, first without stripper, and then with two foils of increasing surface density. The measured data have been linearly fitted to the beam size calculated by TRACE-3D, taking as first input to the code the emittance and the Twiss parameters measured without the foil, and then emittances with increasing divergence at the stripper position. The result was a $\Delta\varepsilon/\varepsilon = (6 \pm 2)$ % for the nominal stripper thickness, larger than calculated, but smaller than the 10% foreseen in the design report [1].

A Model for Stripper Breaking

Since the first experiments, we noticed that foils thicker than 200 µg/cm^2 broke down after only a few minutes. For the 100 µg/cm^2 foils, direct observations through a quartz window showed that increasing the focusing on the stripper made the beam visible on the foil as a red spot. As the focusing was further increased the spot turned white and the foil broke. These observations can be explained by a calculation of the temperature T reached by the foil during the beam pulse. The energy that the beam loses inside the foil, as consequence of scattering with the foil atoms, goes first to heating of the foil material (only about 0.1% goes to the stripping of electrons), and then is dissipated by radiation from the small beam spot on the foil, the conductivity contribution through the 0.5 µm thickness being negligible. We can represent the three contributions with the equation:

$$\Delta W\, I \;=\; mc\, dT/dt + 2 e s\, S\, (T^4 - T_0^4) \quad,$$

i.e. the power produced by a beam of current I that loses the energy ΔW is equal to the sum of the increase in thermal energy of the stripper material (mc being its mass and specific heat) and of the radiated power, expressed by the Stefan-Boltzmann relation for the emission from a surface S. e is the emissivity (0.75 for Carbon) and s the Stefan-Boltzmann constant. The factor 2 takes into account the fact that energy is radiated from both sides of the foil. After a time usually shorter than the beam pulse length, T converges to the equilibrium temperature (T_0 can be neglected if $T \gg T_0$):

$$T \;=\; \left(\frac{\Delta W\, I}{2\, e\, s\, S} \right)^{\frac{1}{4}} \qquad (1).$$

The highest temperature is reached at the centre of the beam distribution, where the current density dI/dS is maximum. Considering a gaussian beam distribution in the transverse plane, dI/dS converges to $I/2\pi\langle x\rangle\langle y\rangle$, with I the total beam current and $\langle x\rangle\langle y\rangle$ the rms dimensions of the beam. Introducing this value into (1), one obtains the maximum stripper temperature as:

$$T_{max} = \left(\frac{\Delta W\, I}{4\, p\, e\, s\, \langle x\rangle\langle y\rangle} \right)^{\frac{1}{4}} \qquad (2).$$

Taking the Linac3 beam parameters, 80 µA of Pb^{27+} and 130 keV/u energy loss, for a round beam of rms radius r_{rms} we obtain the temperature as function of beam radius of Fig. 4. TRACE-3D calculations give r_{rms}=1.6mm, indicating that the temperature of the stripper of 100 µg/cm^2 comes close to the temperature of Carbon sublimation, 4100 K, assumed as the maximum that the foil can stand. Small reductions in beam size or imperfections in the foil would break it, while only a small increase in beam size brings the temperature down to a safe value. Since the energy loss ΔW is proportional to the foil thickness, thicker foils reach higher temperatures. The colours observed on the foil before breaking correspond well to the peak emission wavelength at the calculated temperatures. In conclusion, one has to find a compromise between the lifetime of the foil, requiring a large beam size,

and the minimisation of the emittance growth due to the increase in divergence, that instead requires a small beam size. This compromise has been found easily at Linac3 since emittance growth is not a very critical issue (large PSB acceptance), and foil lifetimes are now of the order of 2/3 months.

The formula (2), with the needed changes in the parameters, indicates as well that an Al_2O_3 stripper (melting T=2345 K, e=0.2), considered as an alternative to Carbon because it is easier to produce and more homogeneous in thickness, would not withstand the temperatures induced by the Linac3 beam.
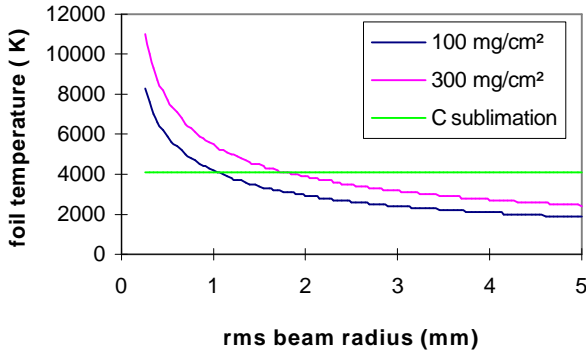
Figure 4. Linac3 stripper temperature from (1) as function of rms beam radius for two different Carbon foils.

Single Pulse Transverse Emittance Measurements

A single pulse emittance measuring device was required to check the pulse to pulse stability of the linac. We choose a multislit plate with a scintillator screen and CCD camera readout. Particles traversing the slits produce light on the scintillator and a special triggered CCD camera captures and digitises the image every 1.2sec, the repetition rate of the linac. Special software reconstructs the emittance from the digitised image and calculates the Twiss parameters [4].

Starting from nominal emittance values and orientations, preliminary simulations were needed to transport the beam to the multislit (see Fig.1). Final adjustments, especially with the steerers, were made by working experience.

CCDs' saturation was avoided using a fast exposure time (150 µs) and stopping down the iris. The scintillator, a CERN Cromox type 6 Al_2O_3 + 0.2% Cr_2O_3, showed linearity in our beam current range (up to 80 µA of Pb^{27+}) and no substantial degradation in performances in 30 hours operational time.

To obtain the Twiss parameters at Linac3 output we made backward TRACE-3D simulations taking as input the values measured at the detector and as output the Linac output parameters. We checked the measurement with different optics, confirming both the reliability of the device and the good pulse to pulse stability of the Linac. The multislit plate with 4 mm slit spacing and 0.2 mm slit width is a good compromise to obtain the best resolution.
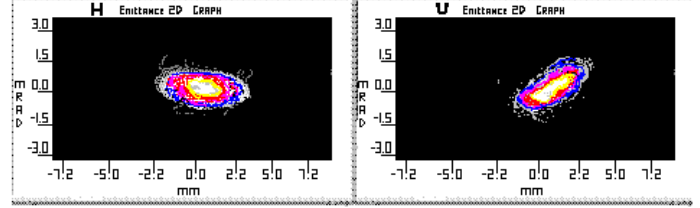

Figure 5. Emittance plots at detector position for Pb^{27+}.

An emittance plot at the detector position is shown in Fig. 5 and a summary of the measured values for Pb^{27+} is in Table 1. Measurements for Pb^{53+} are not very precise, since the detector is placed before the ion separation, nevertheless the total (4 x rms) horizontal emittance after stripping has been estimated to be ~10.5π mm mrad.

ε_x/π (unnorm.) mm mrad	ε_y/π (unnorm.) mm mrad	ΔW [keV], 2σ
9.7	9.9	±30

Table 1: Measured beam parameters at Linac3 output (Pb 27).

Conclusion

The matching of the line and the stripping were easier than foreseen, the best results being obtained with a 100µg/cm² carbon foil. The current transmission of the line is almost 100% (max. 80 µA of Pb^{53+}), and the beam quality is good for the injection to the PS Booster. The linac shows an excellent pulse-to-pulse stability.

Acknowledgements

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