LEAD ION BEAM EMITTANCE AND TRANSMISSION STUDIES IN THE PS-SPS COMPLEX AT CERN

G. Arduini, R. Bailey, T. Bohl, H. Burkhardt, R. Cappi, C. Carter, K. Cornelis, M. Dach, G. de Rijk, A. Faugier, G. Ferioli, H. Jakob, M. Jonker, D. Manglunki, G. Martini, M. Martini, J.P. Riunaud, C. Scheidenberger*, B. Vandorpe, L. Vos, M. Zanolli

CERN, Geneva, Switzerland, *GSI, Darmstadt, Germany

Abstract

In the Lead Ion Facility at CERN [1] Pb^{53+} ion beams are accelerated up to a kinetic energy of 4.2 GeV/u in the CERN PS, extracted and stripped to Pb^{82+} in the transfer line from PS to SPS where they are injected and accelerated up to 157 GeV/u. The stripping efficiency, emittance growth and energy loss in Al strippers of different thicknesses have been measured and they are in good agreement with the theoretical values. The results of these measurements and considerations on the PS-SPS transmission efficiency are presented.

1 INTRODUCTION

The stripper used in the 1995 lead ion run was a 1 mm thick Al foil. Charge-distribution studies with heavy ions at moderate relativistic energies [2][3] have shown that materials with medium atomic numbers deliver the highest fractions of bare ions since the ratios of the ionisation and electron-capture cross-sections are largest in these materials. Al and Cu strippers induce about the same emittance blow-up for the same stripping efficiency.

Al was finally chosen for mechanical reasons as the stripper has to move in and out in a short time (~ 0.7 s) on every ion cycle because the same line is also used to transfer p^+ and e^+ beams. A magnetic coupling mechanism has been designed to avoid moving bellows and therefore to guarantee operation without failure for more than 2 million pulses per year. The choice of the stripper location had to take into account the existing optics and the available mechanical space. The actual values of the β functions at the stripper are β_H = 20 m and β_V = 16 m.

The measurements of the stripping efficiency, transverse emittance blow-up and energy loss were performed to choose the optimum stripper thickness leading to the highest PS-SPS transmission for Pb^{82+} ions.

2 MEASUREMENT DESCRIPTION

2.1 Stripping efficiency

The beam after the stripper could be observed using a luminescent screen and a camera. Two distinct spots, corresponding to Pb^{81+} and Pb^{82+} could be distinguished in a dispersive section in the transfer line. The stripping efficiency was calculated from the intensity of the two spots and the error estimated from non-linearities of the camera.

2.2 Emittance blow-up

Emittance was measured with two sets of three SEM grids in each plane, one is located at extraction from the PS (before the stripper) and the other in proximity of the injection point in the SPS (after the stripper).

2.3 Energy loss

The energy loss was evaluated from a velocity measurement performed in two steps, using Pb^{82+} ions (stripper in) in the first and Pb^{53+} ions (stripper out) in the second step:

1) The average ion velocity $v = 2\pi(R_o+\Delta R)f$ was determined by measuring the revolution frequency f and the average radial beam position ΔR. The average SPS radius R_o = 1100.0093 ± 0.00015 m had been previously measured [4].
2) The magnetic fields of all the magnets in the section of the transfer line following the stripper and of the main magnets (dipoles and quadrupoles) in the SPS ring were increased by a factor 82/53 and Pb^{53+} was injected.

2.4 Transmission efficiency

The intensity of the lead ion beam was measured with high sensitivity beam current transformers: one of them is installed in the PS ring, five in the transfer line (two before and three after the stripper) and one in the SPS.

3 EXPERIMENTAL RESULTS AND COMPARISON WITH THEORETICAL PREDICTIONS

The results of the measurements for three different Al strippers 0.5, 0.8 and 1.0 mm thick, respectively, are reported in this section.

3.1 Stripping efficiency

The measured fractions of bare ions after the stripper are listed in Tab. 1.

Stripper thickness [mm]	Bare ion fraction [%]	$\Delta\varepsilon_H$ [π mm mrad]	$\Delta\varepsilon_V$ [π mm mrad]	$\Delta T/T$ [%]
0.5	83 ± 5	0.43 ± 0.21	0.214 ± 0.049	0.164 ± 0.011
0.8	96 ± 2	0.56 ± 0.19	0.427 ± 0.054	0.291 ± 0.011
1	98 ± 1	0.73 ± 0.16	0.550 ± 0.083	0.369 ± 0.013

Table 1: Measured bare ion fraction, emittance blow-up and relative kinetic energy loss vs. Al stripper thickness.

Fig. 1 shows that there is a good agreement between measured and predicted bare ion yields [2].

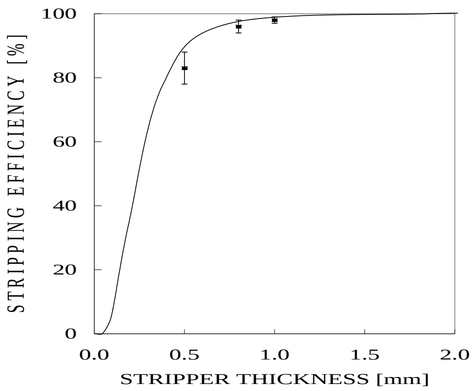

Figure 1: Measured yield of bare ions after the Al stripper vs. stripper thickness. The solid line represents the theoretical prediction according to Ref. [2].

3.2 Emittance blow-up

As the vertical physical acceptance of the SPS was comparable to the emittance of the injected lead ion beam, the transverse emittance blow-up was another important parameter to be studied. The emittance blow-up $\Delta\varepsilon$ is defined here as the increase in the emittance of the beam as a consequence of the multiple scattering in the stripper and it is given by:

$$\Delta\varepsilon_{H,V} = 4\beta_{H,V}\,\theta_o^{\,2}$$

where $\beta_{H,V}$ is the Twiss function at the stripper and θ_o is the r.m.s. projected scattering angle given by (in the range $10^{-3} < x/X_o < 100$) [5]:

$$\theta_o\,[\mathrm{rad}] = 13.6\, z\, (\beta p)^{-1}\, (x/X_o)^{1/2}\, [1 + 0.038 \ln(x/X_o)\,]$$

where p [MeV/c], βc and z are the momentum, velocity and charge number (assumed to be 82) of the ion and x/X_o is the stripper thickness in radiation lengths (for Al $X_o = 89$ mm).

The horizontal and vertical emittances of the unstripped beam measured at the two mentioned locations in the transfer line are in good agreement (within 10 %) and amount to 1.8 and 1.6 π mm mrad, in the horizontal and vertical plane, respectively. These values refer to a 2σ-contour in the beam transverse phase space.

In Figs. 2 and 3 the measured horizontal and vertical emittance blow-ups for the different stripper thicknesses are compared with the expected values.

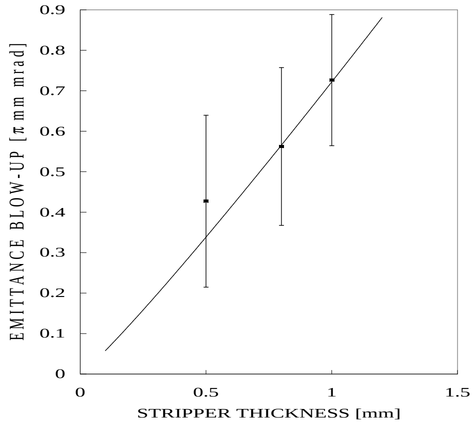

Figure: 2 Horizontal emittance blow-up vs. thickness for an Al stripper. The solid line represents the theoretical behaviour for $\beta_H = 20$ m at the stripper.

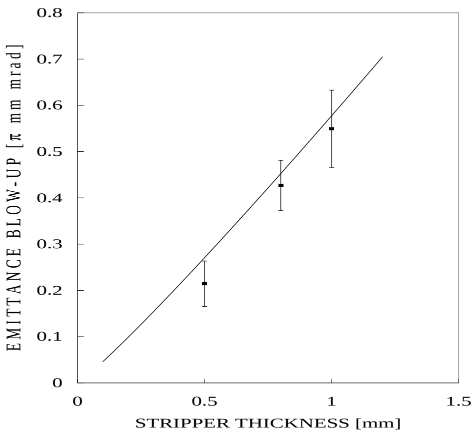

Figure 3: Vertical emittance blow-up vs. thickness for an Al stripper. The solid line represents the theoretical behaviour for $\beta_V = 16$ m at the stripper.

3.3 Energy loss

The mean energy loss of bare ions can be calculated from the relativistic Bethe formula [6]. However, recent experimental [7] and theoretical [8] investigations show that this formula correctly applies only to light nuclei and that the energy loss of the lead ions penetrating the stripper is expected to be increased by 12 % with respect to the Bethe formula. This result fits well to the measured data as shown in Fig. 4.

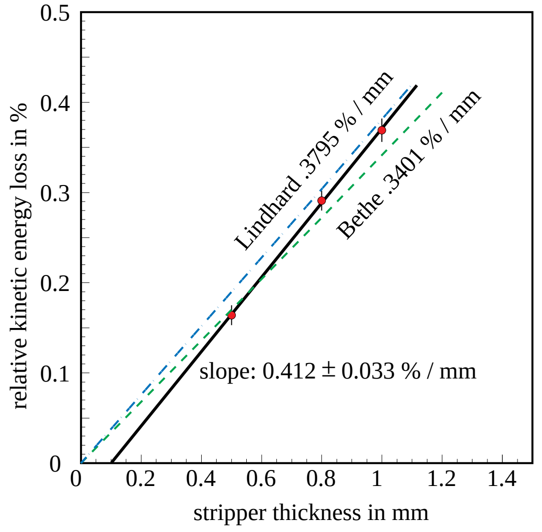

Figure 4: Measured relative kinetic energy loss (data points) in Al vs. stripper thickness compared with theoretical predictions according to Refs. [6] and [8] (dashed lines). The linear fit to the experimental data is also shown (solid line).

For the 0.5 mm thick stripper the expected energy loss is overestimated because the calculation was carried out assuming that charge-state equilibrium is reached in a surface layer of negligible thickness as compared to that of the stripper. However, in the experiment the charge state of the incident ions was much smaller than the mean charge state in equilibrium thus leading to a slightly smaller energy loss.

3.4 PS-SPS transmission

The optimum stripper thickness is determined as a compromise between the concurrent requirements of good stripping efficiency, limited emittance blow-up in order to minimise injection losses and mechanical reliability.

The vertical physical SPS acceptance, measured to be about 2 π mm mrad, limits the injection efficiency to approximately 80 % for a 1 mm thick stripper. The injection efficiency has been measured as a function of the vertical emittance of the injected beam, varied by scraping in PS. The injection efficiency was found to decrease with increasing beam emittance as expected assuming a bivariant gaussian distribution in the transverse phase space and a vertical physical acceptance of about 2 π mm mrad.

On the basis of the good agreement between the presented experimental results and theoretical models an estimate of the PS-SPS transmission vs. stripper thickness was calculated and is presented in Fig. 5. The product of the PS extraction efficiency and of the transfer line transmission was measured to be η = 80.1 ± 3.2 % with the 1 mm thick stripper and assumed to be independent of the stripper thickness.

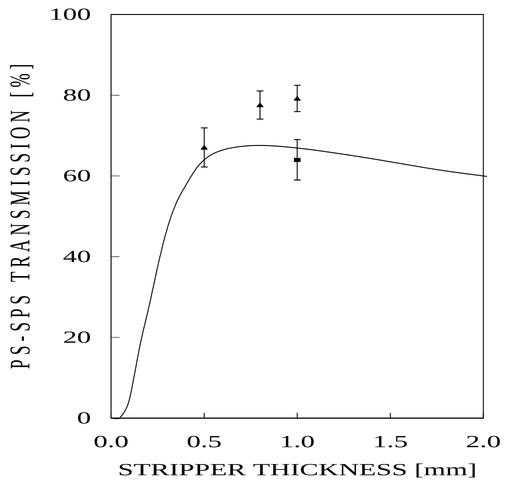

Figure 5: Estimate of PS-SPS transmission vs. stripper thickness (solid line). The measured transmission for the 1 mm thick stripper (square) and the measured stripping efficiencies multiplied by η for the 0.5, 0.8 and 1 mm thick strippers (triangles) are also shown.

4 CONCLUSIONS

The measurements performed during the 1995 lead ion run allowed to verify the consistency of the emittance data obtained by PS and SPS and to determine the stripping efficiency, emittance blow-up and energy loss with Al strippers of different thicknesses. The results of these measurements are in good agreement with theoretical expectations and they show that, considering the SPS vertical aperture, the optimum stripper thickness is about 1 mm. This was the stripper thickness used during the 1995 run.

REFERENCES

[1] D. Warner, ed., 'CERN Heavy-Ion Facility Design Report', CERN 93-01.

[2] R. Anholt, W.E. Meyerhof et al., Phys Rev. A36, 1586 (1987) and references therein.

[3] C. Scheidenberger, H. Geissel at al., Nucl. Instr. Meth. B90, 36 (1994).

[4] T.P.R. Linnecar, Private Communication.

[5] Particle Data Group, 'Review of Particle Properties', Phys. Rev. D50, 1253 (1994).

[6] U. Fano, Ann. Rev. Nucl. Sci. 13, 1 (1963).

[7] C. Scheidenberger, H. Geissel at al., Phys. Rev. Lett. 73, 50 (1994).

[8] J. Lindhard and A.H. Sorensen, Phys. Rev. A53, 2443 (1996).