EXPERIENCE WITH STRIPPING CARBON FOILS IN ALPI SUPER-CONDUCTING ACCELERATOR

P. A. Posocco*, Consorzio RFX, Padova, and INFN/LNL, Legnaro, ITALY
D. Carlucci, A. Pisent, M. Poggi, INFN/LNL, Legnaro, ITALY

Abstract

The super-conducting linac ALPI, injected either by a XTU tandem or by the s-c RFQ of PIAVE, is composed by 3 cryostats of bulk-Nb cavities ($\beta_o = 0.056$) and 13 cryostats of Nb-sputtered-on-Cu cavities ($\beta_o = 0.11$ and $\beta_o = 0.13$), for a total of 64 cavities and an equivalent voltage of 35 MV. The linac is build up in two branches connected by an achromatic and isochronous U-bend. In January 2007 a stripping station equipped with carbon foils of different thickness was placed after 6 cryostats, before the U-bend, to test the feasibility of acceleration and transport of a charge enhanced beam. The study was performed with 4 different beams (Ca, Ar, Zr and Xe) and a complete data analysis has been carried out.

INTRODUCTION

ALPI (Acceleratore Lineare Per Ioni) [1] is a super-conducting linac running since 1995 at LNL, Legnaro. The structure of this booster (see Fig. 1) is comprised of two branches (low and high-energy branch) connected by an achromatic and isochronous U-bend. There are three families of cavities, 12 $\beta_o = 0.056$ of bulk Nb, 44 $\beta_o = 0.11$ and 8 $\beta_o = 0.13$ of Nb-sputtered-on-Cu, 4 cavities in each cryostat. At present the low-β cryostats reach an average accelerating field of 3.5 MV/m, the medium-β 4.2 MV/m and the high-β 5.5 MV/m, resulting in a total available voltage of 48 MV [2]. The effective voltage reaches ∼ 35 MV due to a careful beam dynamics optimization.

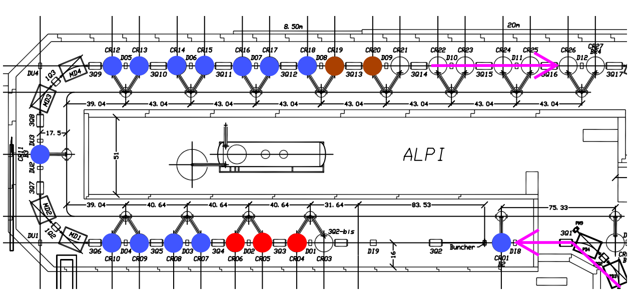


Figure 1: ALPI plan. The beam coming from PIAVE injector passes through the low-β (in red), medium-β (blu) and high-β (brown) cryostats.

The linac period is made by one triplet and 2 cryostats with a diagnostics box (profile monitor and Faraday cup) in between. In January 2007 it was decided to place a stripper station in the center of the low-energy branch period, at the both transverse and longitudinal focal point in order to reduce undesired emittance growths. Hence, the diagnostics box DO4 was modified to held the device.

The position along the accelerator was chosen to optimize the overall energy gain: the energy before the stripping is about 3 MeV/A, enough to enhance the charge state by 50% for the medium/high mass ions (see Fig. 2), and the remaining accelerating voltage is 2/3 of the total voltage. This means that the final energy of the stripped beam is 20 ∼ 30% higher than the unstripped one.

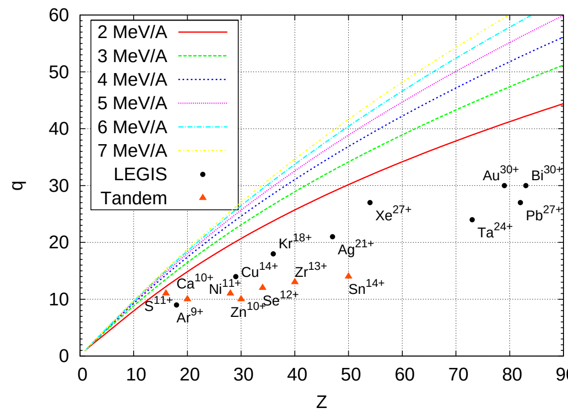


Figure 2: Most probable charge state from stripper as function of Z and energy compared to some examples of available ions out of LNL Tandem injector or foreseen for the new LEGnaro ecrIS (LEGIS).

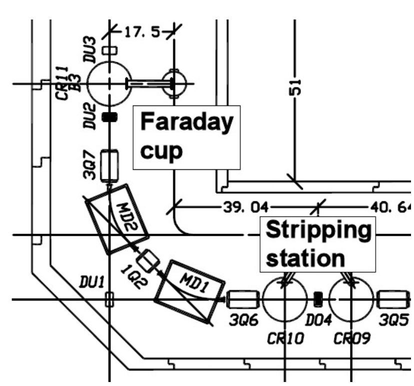
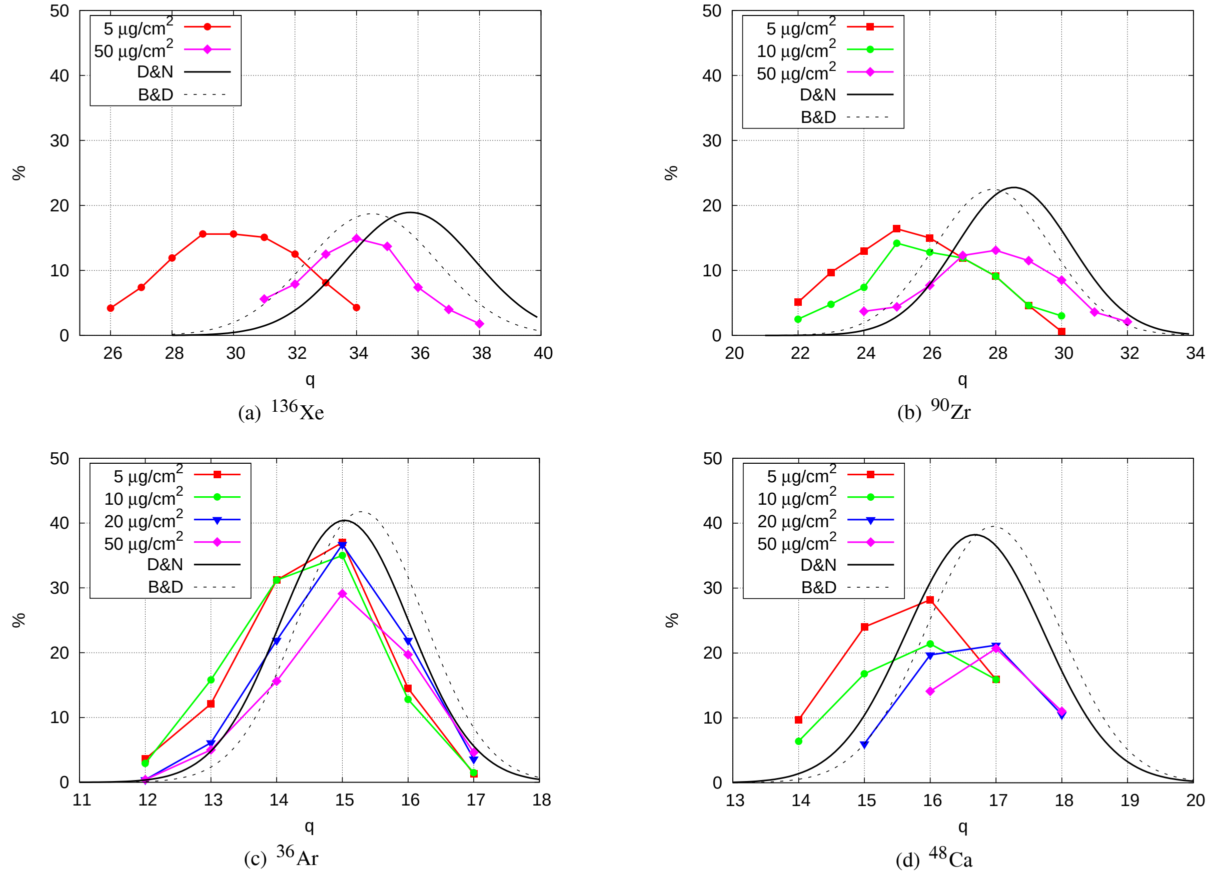


Figure 3: ALPI layout around the stripper station. The beam focalized in the diagnostic box D04 is stripped and then selected by the two dipoles MD1 and MD2.

* piero.antonio.posocco@lnl.infn.it



(a) ^{136}Xe (b) ^{90}Zr (c) ^{36}Ar (d) ^{48}Ca

Figure 4: Stripping probability as function of the target thickness. Semi-empirical formulas predictions are added as comparison. The data are normalized on the beam current before stripping.

EXPERIMENTAL SET-UP

The stripper station foresees a carousel equipped with a hundred stripper foil of various thickness values (5-10-20-50 µg/cm^2) preceded by a collimator, which ensures a proper beam focusing at the foil plane. The system is remote-controlled via PC. Downstream the stripper station the beam is focalized by 3Q6 triplet and bent by MD1 and MD2, whose magnetic field is measured by a Tesla-meter with a precision of $1/10^6$. The beam passes through 3Q7 triplet (set to off) and is then monitored relatively to its position and current in the diagnostics box DU2, in the middle of the U-bend. This way, the first half of the U-bend acts as a spectrometer. The overall scheme is shown in Fig. 3.

The procedure consists in recording dipole field and current of both the collimated unstripped beam and of the different stripped charge states, which are selected by the dipoles. The procedure is repeated for the different foil thicknesses.

STRIPPING DATA ANALYSIS

If $N(q)$ is the number of ions having charge state q after being stripped, the charge state fraction is defined by $P(q) = N(q)/\sum_q N(q)$. Figure 4 shows the evolution of the charge state fractions for ^{90}Zr, ^{48}Ca (from Tandem) and ^{136}Xe, ^{36}Ar (from PIAVE) as a function of the carbon target thickness t. As the thickness is increased, the $P(q)$ curve moves towards higher charge states. The equilibrium thickness t_∞ is reached when the average charge state $\bar{q} = \sum_q P(q)$ stops raising.

The $\bar{q}$ as function of t (Fig. 5) can be fitted by

$$\bar{q}(t) = q_0 + (\bar{q}_\infty - q_0)\ e^{-\frac{t}{k}}, \quad (1)$$

where q_0 is the charge of the beam before stripping and $\bar{q}_\infty$ is the most probable charge state for t_∞. This formula, already used in [3], is misleading because the beam loses part of its energy as it passes through the foil, resulting in a drop of $\bar{q}$ for $t >> t_\infty$. Nevertheless, for low thickness it is very useful and it is easy to get the $\bar{q}_\infty$. From the fit it possible to obtain an estimate of the t_∞ as well. Assuming that $t_\infty \simeq 5\ k$, the results are reported in Tab. 1.

Equilibrium distributions may be approximately represented by a normal distribution,

$$P(q) = \frac{1}{d\sqrt{2\pi}} \exp\left(-\frac{(q-\bar{q}_\infty)^2}{2d^2}\right)$$

with $d^2 = \sum_q (q-\bar{q}_\infty)^2 P(q) - 1/12$.

A large collection of data from stripping experiments was analyzed by H. D. Betz in [4]. In particular he summarizes all the semi-empirical formulas for $\bar{q}_\infty$ and d published up to that time, listing them by stripper material, Z of the ions and energy range. Among those, only two fit the conditions for the present experiment (Carbon foils, medium/high Z, E ∼ 3 MeV/A): Dmitriev and Nikolaev (D&N) and Baron and Delaunay (B&D). The predictions by these formulas (Tab. 1) match both the maximum $\bar{q}$ found in the data distributions and the $\bar{q}_\infty$ from the fit.

Concerning the beam energy loss through the stripper, the data in Fig. 6 are linearly fitted by

$$\Delta E(t) = \delta E + \Delta E/\Delta x \cdot t, \qquad (2)$$

where ΔE/Δx is the stopping power and δE is the error on the beam energy before stripping (see Tab. 1). For all the four beams, the former perfectly matches the value calculated via SRIM program [5]. On the contrary, the latter is not compatible with zero: a systematic error was clearly committed in the energy measurement, probably due to a slight misalignment of the beam line. The problem will be investigated promptly.

CONCLUSIONS

- $^{136}Xe^{34+}$ was easily transported to the experiment: the final energy reached 1.1 GeV (8.1 MeV/A), 20% more of the energy of the unstripped beam (923 MeV). The beam current on target was greater than 1 pnA, but the transmission in the ALPI high-energy branch was limited to 50%, probably due to an unexpected longitudinal emittance growth. A better control over the longitudinal focusing at the foil plane is therefore mandatory.

- $^{90}Zr^{28+}$ was transported only up to half of the high-energy branch. Due to the low current of the selected charge state (< 1 pnA), the cavity setting was extremely difficult and the right synchronous phase setting could not be guaranteed.

Table 1: Data analysis. The equilibrium thickness is in [µg/cm²], energy in [MeV/A] and the stopping power in [keV/µg/cm²].

	$^{136}Xe^{23+}$	$^{90}Zr^{13+}$	$^{36}Ar^{8+}$	$^{48}Ca^{9+}$
E	2.475	2.614	3.206	3.487
max $\bar{q}$	33.9 ± 0.4	27.9 ± 0.7	15.0 ± 0.4	16.9 ± 0.3
D&N	35.8	28.5	15.0	16.7
B&D	34.5	27.9	15.3	17.0
$\bar{q}_\infty$	33.9	27.9 ± 0.7	14.8 ± 0.1	16.6 ± 0.2
t_∞	24	13 ± 3	9 ± 3	15 ± 3
ΔE/Δx	78.8	62 ± 6	18 ± 3	22 ± 6
SRIM	82.9	58.1	19.4	22.7
δE (‰)	8.6	4.6 ± 0.8	7.7 ± 0.5	2.1 ± 1.5

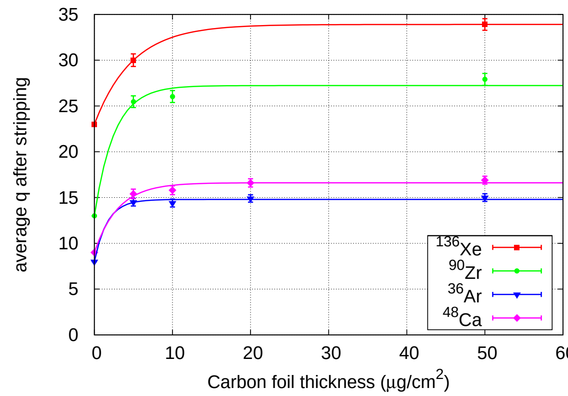


Figure 5: Beam average charge $\bar{q} = \sum_q P(q)$ as a function of target thickness. Fit by Eq. 1.

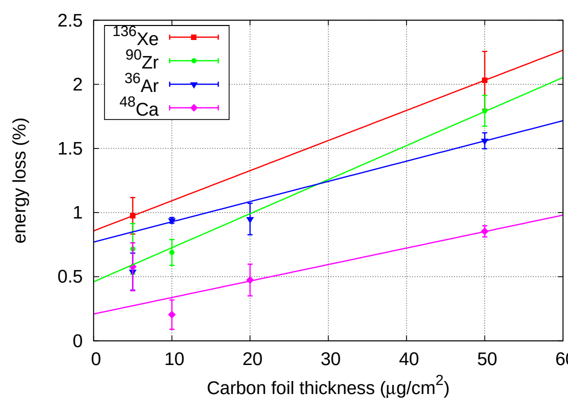


Figure 6: Beam energy loss as a function of the target thickness. Fit by Eq. 2.

- $^{36}Ar^{15+}$ was transported to the experiment with some troubles due the failure of the last cryostat before the stripper station. The final energy reached 450 MeV, whereas the energy without stripping was 300 MeV. The lack of the four cavities did not allow to focus longitudinally the beam at the foil plain and the transmission of the high-energy branch was extremely low (20%).

- $^{48}Ca^{17+}$ was not transported since the current was too low for the synchronous phase setting.

The acceleration was successful only for the beams coming from PIAVE thanks to the high current provided by the ECRIS ion source. The low-energy branch beam dynamics must be carefully optimized to obtain a strong longitudinal focusing at the foil plane.

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