BEAM DYNAMICS SIMULATIONS AND MEASUREMENTS FOR THE LINAC PIAVE-ALPI

M. Comunian, C. Roncolato, E. Fagotti, F. Grespan,
A. Palmieri, A. Pisent, LNL-INFN, Legnaro (PD), Italy

Abstract

The layout of the LINAC PIAVE-ALPI is, from the point of beam dynamics, quite complex due the presence of RFQs, cavities, dipoles, magnets, etc. The normal LINAC operation for the final user is described, with the impact on the beam dynamics of the flexible use of the cavities to tune the required energy. The automatic tuning procedure of the TraceWIN [1] program is used for the simulation, and the comparison with the LINAC performance is reported.

INTRODUCTION

The ALPI (Acceleratore Lineare Per Ioni) accelerator is a flexible structure for the study of heavy ion for nuclear physics which is able to deliver ions from Si to U [2] with a final beam energy range from 6 up to 20 MeV/u. The facility consists of a series of 71 independently phased superconducting Quarter Wave Resonators (QWRs) accelerating cavities operating at two different frequencies, namely 80 and 160 MHz.

The accelerator is divided into three different sections (Table 1) according to the ion velocites. The operational frequency is 80 MHz for the Low Beta Section, whereas for the remaining sections it is at 160 MHz.

Table 1: ALPI Sections

Name	β_s	Type	# Cav.
Low Beta	0.047 / 0.055	Bulk Nb	4 / 12
Medium Beta	0.110	Sputtered Nb	44
High Beta	0.130	Sputtered Nb	8

The ALPI layout consists of two parallel lines of cryostats and magnets connected with a isochromatic and isochronous U-bend (Fig. 1). The cavities are arranged in groups of four in liquid helium cryostats operating at 4.2 K.

There are two options for the beam injection, accordingly to the element to be accelerated. The beams from Tandem are longitudinally focused at the entrance of the Low Beta section with a normal conducting 80 MHz QWR cavity, or at the entrance of the Medium Beta Section with a 160 MHz superconducting QWR when the ion velocity is high enough to achieve a TTF_n at least of 0.6.

The LINAC lattice consists of triplets followed by two cryostats equipped with a diagnostic box in between. There are two period lengths (4.06 m and 4.30 m at low and high energy) to compensate the increased beam rigidity.

The PIAVE injector [3] is composed of a ECR source, a preinjector, a three harmonic buncher, two SRFQ resonators housed in a single cryostat, eight QWRs housed in two cryostats (β_s equals to 0.047) and two beam transport and matching lines including two room temperature bunchers. The operational frequency is 80 MHz.

The profile of the ion velocity along PIAVE is kept constant for different ion species, so that the accelerating gradients and focusing magnets are rescaled with the A/Z (up to 7) ratio respect to a reference configuration.

The PIAVE-ALPI or Tandem-ALPI is a very flexible tool for acceleration of several ions at different final energies. However this flexibility needs a complete beam dynamics simulations in order to find the running configuration. The main goal is to have a set of accelerating gradients and phases for the cavities and the focusing strengths for the magnets.

In this paper two operational cases have been studied, namely a delivery of $^{76}Ge^{11+}$ with final energy of 540 MeV in the configuration of Tandem-ALPI (June 2010), and a delivery of $^{136}Xe^{26+}$ with 870 MeV using PIAVE-ALPI (May 2010). Both beams were delivered for the AGATA detector [4].

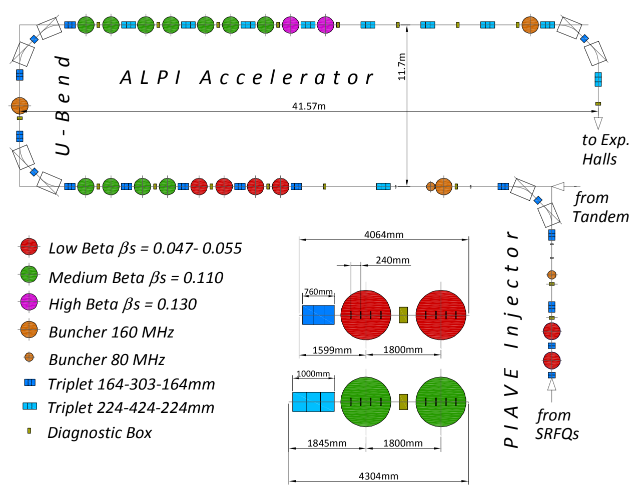

Figure 1: Layout of PIAVE-ALPI accelerator.

BEAM DYNAMICS SIMULATIONS

Typically the setup of the accelerator is done by using a spreadsheet program which carries out the first order longitudinal transport by using matrix calculations. The active cavities with a synchronous phase either +20° or -20° in order to keep the longitudinal RMS phase amplitude below 10° and reduce the transverse RF defocusing, whereas the fields are those make the maximum available performance. (Table 2). This computation gives a preliminary result about the final energy and prepares input files for TraceWIN, that is the program used for the full multiparticles simulation.

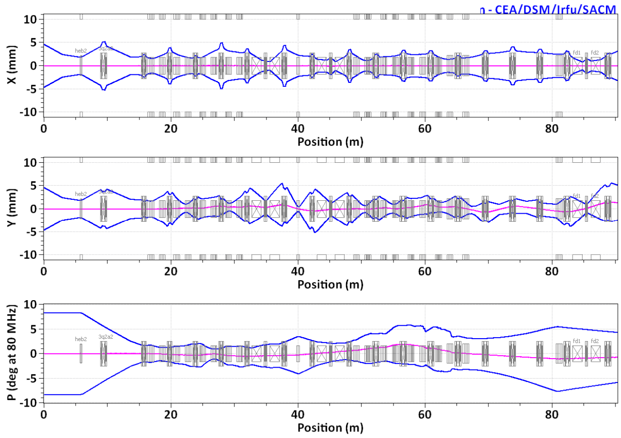

Figure 2: RMS beam envelopes for $^{76}Ge^{11+}$ (blue) and beam centre (magenta) simulated with QWRs' fields.

The advantages for using TraceWIN are the following:

- Possibility of using the QWR Fields Maps.
- Wide-ranging Matching Criteria.
- Full Graphics Output.
- Full Errors Study.

The calculated accelerator model does not take into account any statistical errors due to misalignments of the elements or amplitudes of the fields.

For each run two calculations with a different degree of approximation are done. The first one is the thin gap approximation, whereas the second one uses QWRs field maps. The cavities used in ALPI have been simulated with both HFSS and COMSOL, to generate the electric and magnetic fields for TraceWIN.

The input conditions for the simulations are a bunched beam perfect matched with the ALPI input with a quite large transverse RMS emittance of 0.1 mm-mrad normalized.

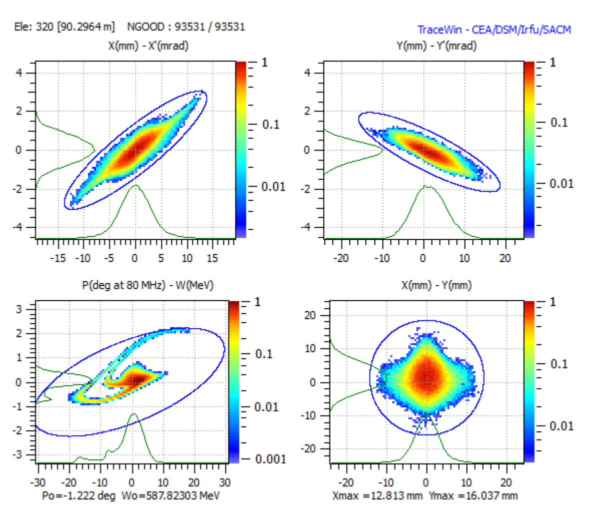

Figure 3: Phase spaces at ALPI exit for $^{76}Ge^{11+}$ simulated with QWRs' fields.

For the longitudinal RMS emittance, a value of 0.1 MeV-deg is set in TraceWIN when the beam comes from the PIAVE injector, whereas a larger value of 0.3 MeV-deg is used for the Tandem injector. This is a consequence of the single harmonic buncher system used.

The simulation starts either at entrance of ALPI or from the exit of SRFQs, when the beam injection is coming from the Tandem or PIAVE. In both cases, the end of the simulations are at end of ALPI, before the transfer line to the experimental halls.

The matching criteria used for the simulations are:

- Achromatic and isochronous line on the curve.
- Maximum gradient of 20 T/m for the magnets.
- Beam waist between the cryostats.
- Fields on the bunchers to get a longitudinal waist at the entrance of the next cryostat.
- Maximum beam size of 10 mm radius.

In this way the program calculates the magnet gradients and transports a bunch of particles up to the end (Fig. 2,3). The simulation with fieldmaps shows that the beam start oscillating vertically about ±1 mm all along the LINAC, due to the QWRs steering fields effects.

In both simulations a particle is lost when it hits the cavity or magnet bore, or if the particle is 180° or 20 MeV far away respect to the synchronous particle. In both case the increase in the transverse RMS emittance is about 30%. The transmissions found for $^{136}Xe^{26+}$ and $^{76}Ge^{11+}$ configurations are respectively 95% and 88%.

The exit longitudinal RMS emittance raises up to 5 times, in the case of $^{76}Ge^{11+}$ configuration and more than 15 times in the case of $^{136}Xe^{26+}$. The emittance calculations are restricted in the range of ±30° and ±10 MeV. The final longitudinal RMS emittance in both cases of about 1.5 ÷ 1.8 MeV-deg.

Table 2: Average Accelerating Gradients (MV/m)

Run	PIAVE	LB	MB	HB	# Cav
$^{76}Ge^{11+}$	n/a	3	4.2	n/a	62
$^{136}Xe^{26+}$	3	2.8	4.3	5.5	60

MEASUREMENTS RESULTS

From the two runs we collected some experimental data. First of all cavities' amplitudes and phases as well as magnets' gradients were stored and compared with the simulations (Fig. 4 and 5).

The chart in Fig. 4 describes the differences in percentage with respect to the experimental energies measured at the exit of each cavity with the dipoles of the LINAC. The curves show that experimental energy is lower than the simulated one of about 1%, and the two simulations results move apart starting from the Medium Beta Section. The reason is that the calculation of the TTF for the thin gaps made in the spreadsheets are carried out in linear approximation.

The simulated and experimental magnets' gradient sets are reported in Fig. 5. They show that the match is fair for the two simulations, apart for the end of the LINAC where the case with full QWRs fields makes use of lower strengths due to the steering effects. The differences with respect to the experimental gradients in the first part of the chart are due to the assumptions made on the SRFQs exit beam. In fact, the actual beam might have an off centre position. In the middle part the discrepancy can be connected with the misalignment of magnets and cavities, whereas in the last section the absence of cavities allows other possible transport solutions. In this case a transport with a larger beam size was used.

The current values measured from the Faraday Cups in the diagnostics boxes allow to calculate the actual transmission along the LINAC. The bunching efficiency of the three harmonic buncher of PIAVE is 57% for this run, and is not considered in Fig. 6. The comparison between simulations show larger losses for case with QWRs fields because of the steering effects. The losses start in the first part of the U bend due to the small vertical bore of the dipole magnets.

The experimental losses are far larger due to other effects that need further investigation

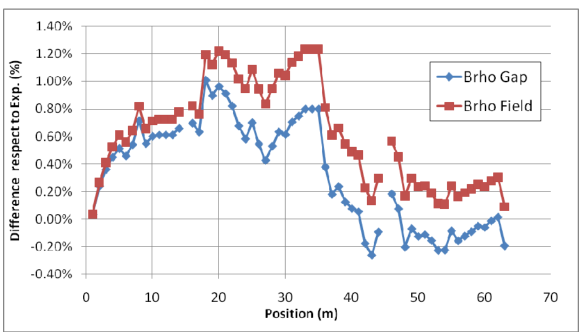

Figure 4: Energy difference respect to experimental for the $^{76}Ge^{11+}$.

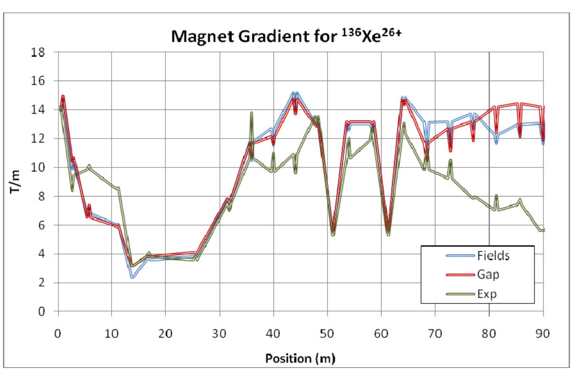

Figure 5: Comparison between simulated and experimental magnets' gradients.

CONCLUSIONS

Apart for the cases shown in this paper, all users' shifts of last year were analyzed with this method. The possibility to manage this multi parameters problem was well worked out with the connection of a spreadsheet program with TraceWIN. Not only could simulations be set up quickly, but also the comparison with the experimental set up was straightforward. The first aspects turned out to be extremely useful especially in the cavity setting. In case of a cavity failure during the experimental run, it is possible to propose an alternative solution with a new simulation in a short time.

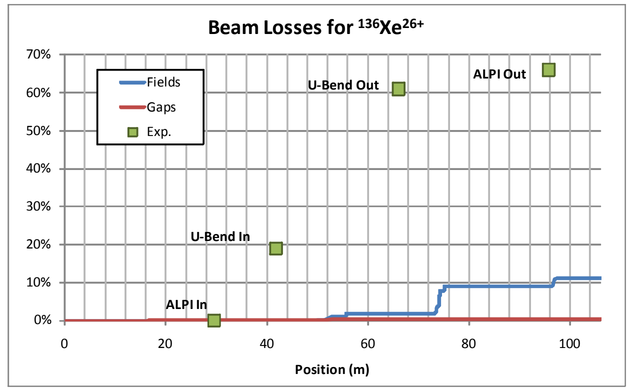

Figure 6: Beam Losses between begin and end of ALPI.

From the results presented in the previous charts, the comparison between thin gaps and full QWRs fields demonstrates that the non-linear effects are important and the second method should be applied.

The agreement between the experimental values and the simulations is unsatisfactory for a good setting and steering. More investigations are needed to understand in which way the real machine diverges from the simulated model. In any case, the LINAC simulated with fields sets a lower limit to the performance with respect to the thin gap approximation. In the next future, we will systematically collect data from the beam profile monitor in the diagnostic boxes for using the amplitude and center beam position in the simulations. Another important task will be the error study analysis of the LINAC to check the sensibility of the elements.

ACKNOWLEDGEMENTS

We are very grateful to D. Uriot for the help and support in the use of TraceWIN. We thank also D. Carlucci and operational group of LNL for the assistance during the shifts.

REFERENCES

[1] D. Uriot, “New Implement In TraceWIN/PARTRAN Codes: Integration In External Field Map”, PAC’03, Portland (USA), p. 3491.
[2] E. Fagotti et al., “Operational Experience in PIAVE ALPI Complex”, HIAT’09, Venice (I), p. 208.
[3] A. Pisent et al., “Result on the Beam Commissioning for the Superconducting RFQ...”, LINAC’06, Knoxville (USA), p. 227.
[4] A. Maj et al., "Preliminary results from the first AGATA demonstrator Experiment", LNL-INFN Ann. Rep. 2009, p. 6.