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NEW TECHNIQUES METHOD FOR IMPROVING THE PERFORMANCE OF THE ALPI LINAC

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Abstract

The superconductive quarter wave cavities hadron linac ALPI is the final acceleration stage at the Legnaro National Laboratories. It can accelerate heavy ions from carbon to uranium up to 10 MeV/u for nuclear and applied physics experiments. It is also planned to use it for re-acceleration of the radioactive ion beams for the SPES (Selective Production of Exotic Species) project. In this article we will present the innovative results obtained with swarm intelligence algorithms, in simulations and measurements. In particular, the increment of the longitudinal acceptance for RIB (Radioactive Ion Beams) acceleration, and beam orbit correction without the beam first order measurements will be discussed.

INTRODUCTION

The CW heavy ion accelerator facility at Legnaro is composed by two main sections: the injectors and the superconductive independent linac ALPI [1]. The final output energies are for the stable ion beams around 10 MeV/u and the output current are generally around 100 nA. The ion species supplied span from carbon ions up to ^{208}Pb ion. The whole heavy ion complex is commonly called TAP (TANDEM ALPI PIAVE). In this paper we will presents the second part of the tests.

THE SUPERCONDUCTIVE LINAC ALPI AND RECENT RESULTS

The linac is composed by 20 cryostats which house four Quarter Wave Cavities each. Each cavity must independently tune with the beam during the runs. The ALPI linac was one of the first prototype in Europe, designed and built between the 80'-90' and for this reason exploited many innovative techniques at that time. At the design stage the superconductive cavities accelerating filed was designed to achieve 3 MV/m with a diameter bore of 20 mm diameter. To maximize the real estate of the machine, the period of ALPI was designed with one triplet for transverse focusing and 2 cryostats (8 cavities). The design of the cavities, the accelerating field improvements, and the lattice design force a very aggressive transverse focusing, which result in a phase advance, of about 120 deg (see Fig. 1). Such phase advance, beside reducing the overall transverse acceptance, it is also sensible to beam misalignment. Another important fact to consider is that the transverse position of the cavities suffers of an error around 1 mm when cooled down, while, when they are at room temperature, the error can reach several mm, closing the further the aperture. This was the situation when we tested the presented results of the algorithm.

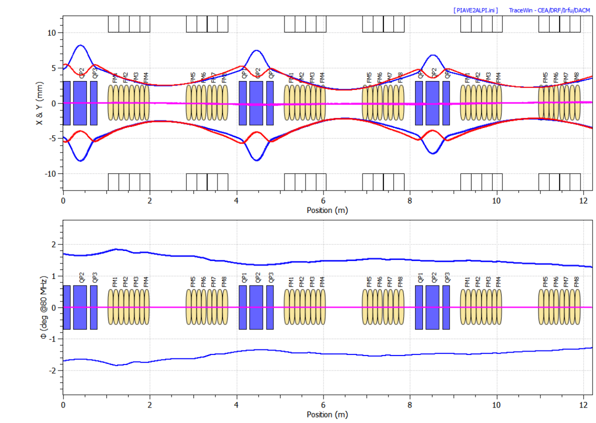

Figure 1: ALPI lattice beam envelopes, with $\sigma_0 = 120$ deg.

In a recent paper [2], we applied the PSO techniques [3] to increase the longitudinal acceptance of the linac. We obtained a double increase of the longitudinal acceptance (see Fig. 2).

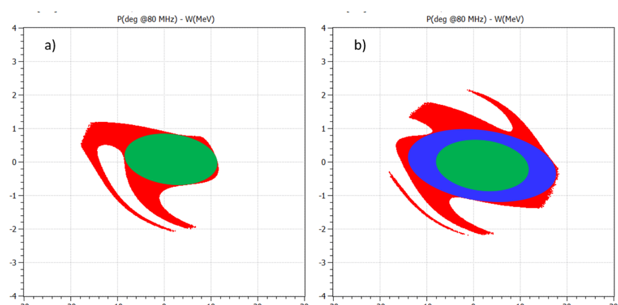

Figure 2: a) green acceptance ellipse calculated over the ALPI alternate gradient acceptance. b) acceptance increase after swarm optimization.

However, this solution required an effective steering procedure, which worsen the situation given by σ_0. Because the steering is very troublesome in ALPI, as explained in Ref. [2], we proposed a different steering which look at the transmission directly. We verified it in simulations and then we applied on the ALPI linac obtaining an increase of transmission from 24% (manual setting) to 35% (automatic setting).

Figure 3 illustrates the layout of the accelerator facility.

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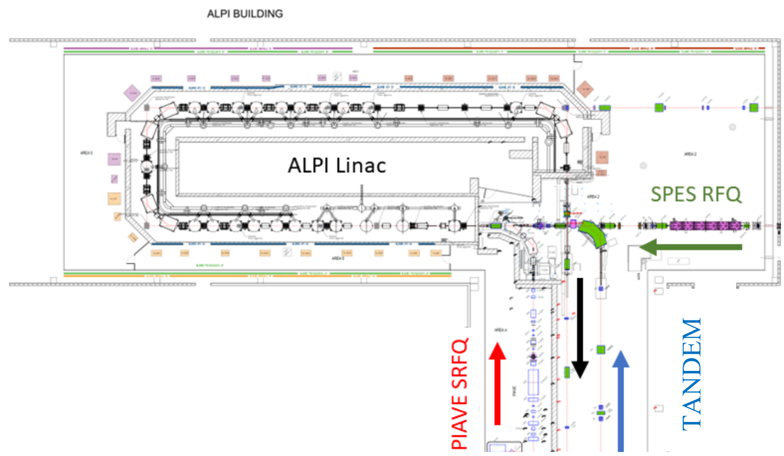

Figure 3: Stable heavy ion accelerator facility overview: the three injectors and the direction of the beam lines are shown.

IMPLEMENTATION IN THE REAL ACCELERATOR

The application of these methods is possible on the real machine due to the last years implementation of the EPICS layer on the TAP facility. It allows, within the many features, to control the PVs of the power supply (PS) and the diagnostic outputs directly from the python scripts. The name of the project is TSO for ALPI (Transport Swarm Optimization for ALPI). The main bottle neck found during the previous experiments [2] is the time taken PSs to reach the required value by TSO. As a matter of fact, the tests had to be depowered down both in term of number of swarm components and iterations, in order to reduce the time required (of a factor of four). However, thanks to the good preliminary results obtained with the steerer tests, we decided to expand the procedure to all the transverse optics, composed by steerer and quadrupole strengths, dipole fields.

TRANSVERSE OPTICS OPTIMIZATION

We performed the test with the beam 32S9+ @ 135 MeV from TANDEM (1.05 Tm rigidity and 130 nA current) in a coasting beam transport through ALPI, up to the half of the line (due to maintenance operation on the other second half), which terminates with a FC (see Fig. 4).

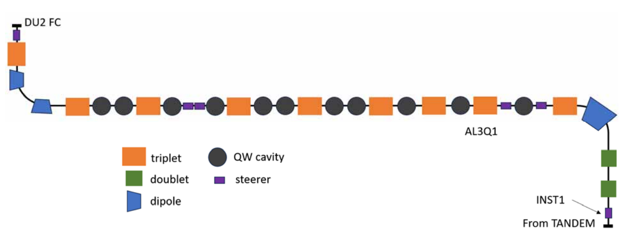

Figure 4: sketch of the experimental line used for the tests. The important elements are shown such as the quadrupoles, the steerers and the cavities.

The entire line is composed by two doublets, nine triplets, three dipoles and six HV steerers. From the TANDEM exit all diagnostics, quadrupoles, dipoles and steerers were controllable by EPICS. The electrostatic lens and steerers of the injector, instead, were not under control of the EPICS layer. At the beginning the beam was transported up to the DU2 in the standard manual in three hours. It was possible to achieve a transmission of 50% from Tandem exit. The working environment was quite troublesome due to the instability of the machine. Then, a general optimization which also involved the negative sputtering ion source, the TANDEM electrostatic lens and the linac, after 4 ours, brought the transmission up to 90%. The transverse optics set (which includes the steerers, the dipoles and the quadrupole from TANDEM exit) was recorded. However, at the start of the experiment, three hour later, due to the machine instabilities, the transmission with the reference set gave zero in DU2. After an adjustment of the ALPI transverse optics, we were able to retrieve at least 35% transmission. We recorded then the solution and called it reference solution. It was decided then to start the experiment from this situation. The reference solution was used to build up the population distribution at the initial iteration. We defined a variation range parameter $\Delta\mathbf{p}$ which defines the variation of the parameters such as:

$$[\mathbf{p}_{min}, \mathbf{p}_{max}] = \mathbf{p}^* \pm \Delta\mathbf{p}, \quad (1)$$

where $\mathbf{p}^* \in \mathbb{R}^n$ components are the values of the lens/steerers/dipoles of the reference solution. n is the number of parameters involved in the study, in this specific case 37. Then, we defined the initial deposition parameter (which impacts on the starting position at 0^{th} iteration of the population), $\Delta\mathbf{p}_i=\Delta\mathbf{p}/n_s$ such that:

$$[\mathbf{p}_{min,s}, \mathbf{p}_{max,s}] = \mathbf{p}^* \pm \Delta\mathbf{p}_i = \mathbf{p}^* \pm \Delta\mathbf{p}/n_S. \quad (2)$$

In such a way that $[\mathbf{p}_{min,s}, \mathbf{p}_{max,s}] \subset [\mathbf{p}_{min}, \mathbf{p}_{max}]$. The objective achieved was to control, via the n_s parameter, the distance of the components of the swarm with respect to the reference.

Figure 5 illustrates the concept described above.

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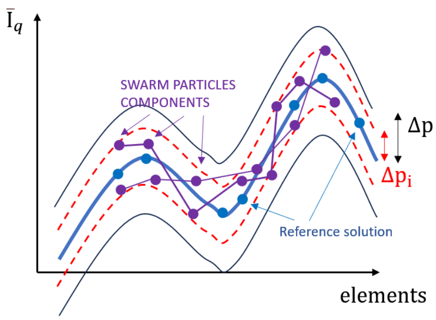

Figure 5: Sketch of the strategy for the initial distribution of the population. The initial positions (red), the full variation range (black), the reference solution (blue) and an example of swarm component (violet) are shown.

On the first trials, we supplied directly to the swarm a component with the reference set. Therefore, at the first iteration, while all the other component of the swarm resulted in 0 transmission (due to the initial randomize values) at DU2 FC, the reference solution showed a non-zero transmission. The individual and social coefficient were found to be most effective with 0.5 and 2 respectively. Therefore, a strong social behaviour pulled the swarm close to the reference solution on these initial iterations. However, after some time, we decided to modify the initial steerer of the reference solution setting it to 0 (killing the transmission of the reference set), and we doubled its variation range, just for the initial steerer (INST1V and INST1H). The reason for that is that we noticed that in our linac, the initial conditions (mainly the first order moments) were not stable at all, therefore we allowed more freedom to the algorithm to choose the proper initial steerer values. Moreover, we wanted to test the ability of the TSO to find out a non-zero solution form an all 0 currents swarm, in the initial iteration. That said, at the last experiment we were able to reach such order of variations:

- Average variation of triplets gradients (w.r. to reference solution) of about 33%
- Dipole 0.03% w.r. the reference solution
- Initial steerer current INST1 $\pm$250% w.r. the stronger steerer value for such beam in ALPI. The other steerers could vary of about $\pm$180% w.r. to their values.
- $n_s = 2$ but the initial steerer.

As far as the hyperparameter of the PSO, we set:

- the initial velocities v_i as random.
- The initial $c_1 = 0.5$, $c_2 = 2.0$, modified then during the execution of the algorithm.
- Swarm component 25.
- Time given for execution 1.5 h.

It is very important to mention that a full range variation (as specified above) of any element of the line with respect the reference solution, was able to decrease the transmission down to 0. Another interesting point refers to the bending magnets: the dipoles in ALPI have a quite large effect of hysteresis. In particular the injection dipole has a 1.6 meter bending radius with an average field of 0.7 T. The small variation used in the last test, around 0.03%, could literally move the beam position completely out of frame but it kept the hysteresis effect under control. However, a variation of 0.09% (it was checked) led instead to a too large effect of hysteresis that invalidate the procedure. Figure 4 shows the convergence of the algorithm after the 1.5 h. It is interesting to notice the presence of a flat top between 400th and 700th calculation. We will come back later, but we can anticipate that something inside the machine was changing its behaviour while the procedure was ongoing.

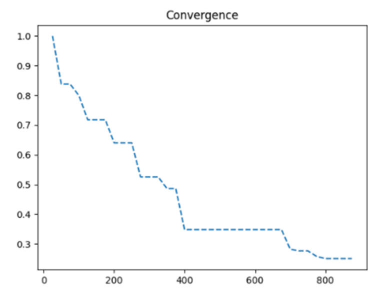

Figure 6: Convergence plot of the TSO in the final test.

The following plot shows the initial and final population distribution of the steerers (Fig. 6) and quadrupoles (Fig. 7).

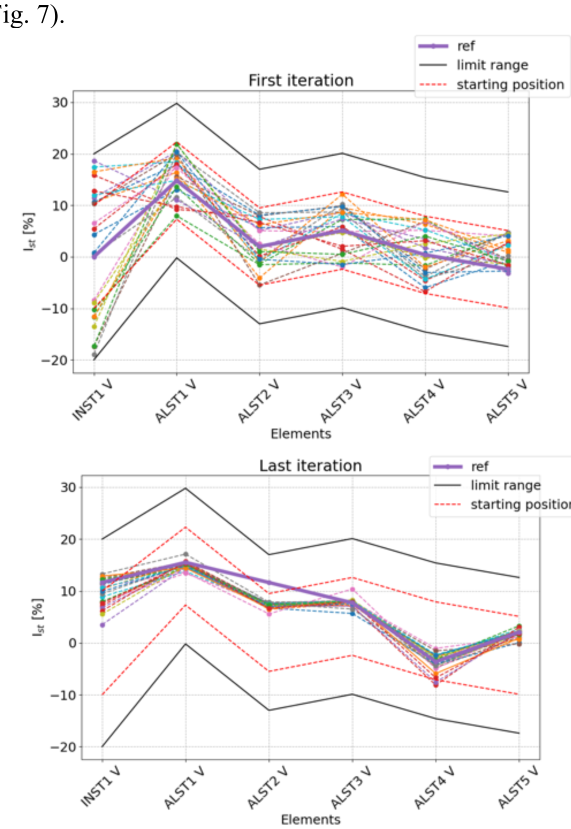

Figure 7: First and last iteration of the population distribution. Steerer strengths (abscissa) in power supply notation.

The vertical axis reports the current from the power supply of the lenses. The scheme of the plots follows Fig. 5. It is interesting to note the result in the final iteration of Fig. 6: not all the values stay within the initial deposition boundaries and the initial steerer (vertical component) shows a quite large change from its starting value.

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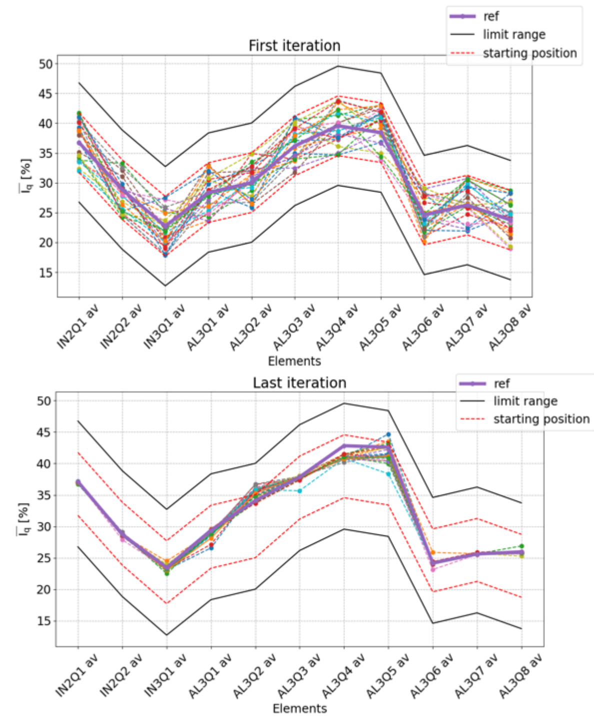

Figure 8: First and last iteration of the population distribution. Quadrupoles gradient (abscissa) in power supply notation.

In Fig. 8, the final population, after AL3Q1 (start of the periodic lattice of ALPI), presents larger gradients with respect to the reference solution, meaning that the algorithm was improving the beam transport. As a matter of fact, the steering problem causes, in the manual procedure, to a decrease of quadrupole gradients in the periodic section of the linac, to reduce the effect of the large phase advance. The algorithm was able to manage steering while correctly increasing the phase advance. As far as the flat top seen by Fig. 5 after 400th calculation (15 iteration): from Fig. 9, which shows three components of the swarm (the best one, the reference and a control one) it is possible to see that after 0.5 h (15 iteration) the algorithm was going to find its maximum (upper plot). However, an event happened, and the best candidate swarm component (orange one) showed suddenly low current values. Then after some search, the swarm could find out the new set that retrieves and improves the transmission thanks to the information supplied by the other components (such as shown by the control component green). In order to understand what changed, we looked at all the lens values of the best and control components through the iterations. The lower plot of Fig. 8 shows the vertical steerer values of the best component w.r. to the iterations. From the analysis, the current was retrieved after the event at 15th iteration by increasing the vertical steerer strength of the initial steerer INST1 (red line, 26 iteration). Therefore, the event at 15 iteration was caused by a variation of the vertical first moment of the beam coming from TANDEM. The information was given by the other components of the swarm that efficiently communicates the variation to be performed.

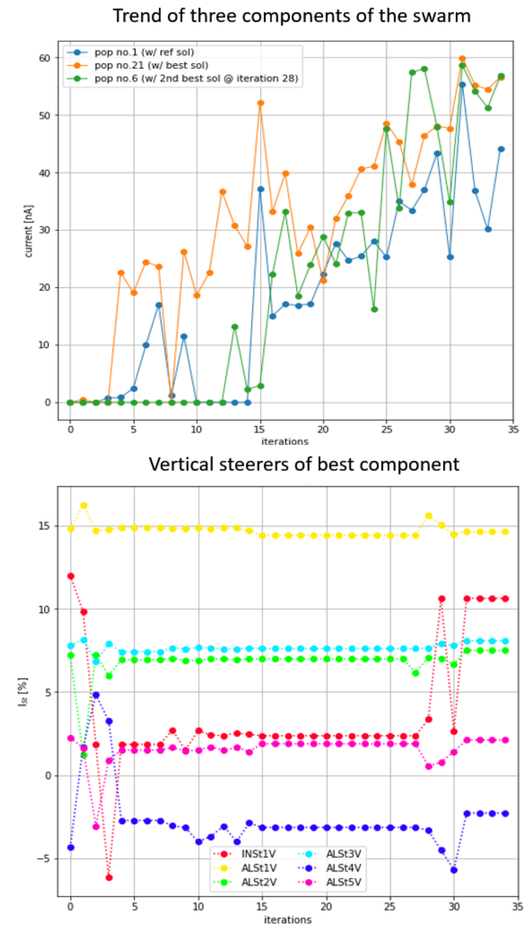

Figure 9: Upper plot: three swarm components, best (orange), control (green) and reference (blue) current at DU2 FC, w.r.t. the iterations. Lower plot: vertical steerer strengths in PS notation of the best solution w.r.t. the iterations.

CONCLUSION

In this paper we presented the tests of the optimization algorithm in the ALPI accelerator environment. Table 1 summarizes the results:

Table 1: Result of TSO Study

Line	Previous Value	Manual	TSO
Transmission	0%	50%	55%
Time required	-	3 h	1.5 h

The algorithm was able to mitigate the initial conditions change, modifying the optics in a meaningful way, proving its robustness w.r. to the optical instabilities. We will now extend the procedure to the whole linac optics, including the cavity phases of the accelerator.

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