ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUODA3

NEW TECHNIQUES FOR THE LNL SUPERCONDUCTIVE LINAC ALPI BEAM DYNAMICS SIMULATIONS AND COMMISSIONING

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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 the re-acceleration of the radioactive ion beams for the SPES (Selective Production of Exotic Species) project. The linac was designed in 90' with the available techniques and it was one of the peak technologies of this kind in Europe at those times. However, the improvements on the cavity fields increased the real-estate gain and the energy output, at the price of lattice periodicity and non-linear RF defocusing. This fact turned out to be troublesome for the operations and delayed the nominal transmission achievement. In this paper we will present the innovative results obtained with swarm intelligence algorithms, in simulations and commissioning. In particular, the increment of the longitudinal acceptance for RIB (Radioactive Ion Beams) acceleration, managing 84 independent cavity phases, 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 cavity linac ALPI [1]. The final output energies are shown in Fig. 1 for the stable ion beams (around 10 MeV/u) and the output current are generally around 100 nA. The ion species supplied span from protons up to ^{208}Pb ion. The whole heavy ion complex is commonly called TAP (TANDEM ALPI PIAVE). At the state of the art, the maximum transmission ever reached was 20% with respect to 54% (design).

THE INJECTORS

ALPI has two injectors for stable ions: the electrostatic accelerator TANDEM type which accelerates light ions; and the PIAVE superconductive RFQ [2], which exploit the transition section between the normal-conductive part and the superconductive part immediately after the source platform. The RFQ output energy is 587.5 keV/u. Third injector, is composed by a normal conductive internal bunching RFQ [3]. that will be used for both RIB and stable ions, will enter in service in the next years. This SPES RFQ was design in such a way to reduce the longitudinal emittance output and to increase the injection energy into ALPI to 727 keV/u, in order to cope with the low longitudinal acceptance of the machine.

THE SUPERCONDUCTIVE LINAC ALPI

The linac is composed by 20 cryostats which house four Quarter Wave Cavities each. Each cavity must independently tune with the beam at the beginning of each ion specific run. 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 field was designed to achieve 3 MV/m with a diameter bore of 10 mm aperture. 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).

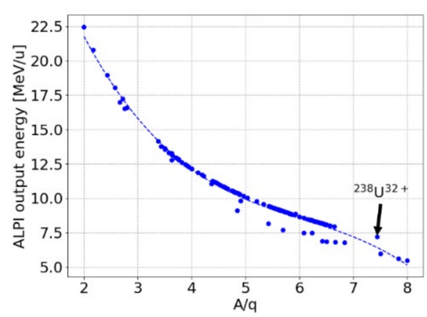

Figure 1: Output energies for heavy ions accelerator facility TANDEM-ALPI-LINAC.

During the lates decade, the technology of the superconductive cavities boosted the accelerating field of the cavities up to 1.5 - 2 times the previous value of 3 MV/m. In this way, it was increased massively the real estate gain, but at the cost of the transmission. Three main effects (for $\gamma\sim 1$, low energy ions) contribute to this loss from the beam dynamics point of view:

1. $K_{rf}\sim\frac{q}{m}E_{acc}\frac{\sin(-\phi_s)}{\beta^2}$ transverse defocusing force from RF cavities. (1)
2. $k_{rf,l}^2\sim\frac{q}{m}E_{acc}\frac{\sin(-\phi_s)}{\beta^3}$, the longitudinal phase advance can become easily instable, being closer to 160 deg with already 2 MV/m. (2)

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3. $\Delta y' \sim \frac{q}{m}\frac{\sin(-\phi_s)}{\beta^2} \mathrm{TTF}\, f(B_{acc,x}, E_{acc,y})$, steering effect of QW described in [4]. (3)

In order to counteract all those phenomena, particularly strong at the low beta regime, it was decided to use the technique of Alternate Phase Focusing [5] with ± 20 deg synchronous phase. In this way the longitudinal phase advance dropped below 120 deg, mitigating the defocusing force and managing the steering and defocusing effects. However, this type of solution reduced the longitudinal acceptance of ALPI which is an important parameter for the RIB acceleration facility and the overall robustness of the dynamics.

SWARM INTELLIGENCE FOR INCREASING LONGITUDINAL ACCEPTANCE

The SPES RFQ output emittance is $\varepsilon_{rms,l} = 0.69$ deg MeV which increases up to 28.4 deg MeV when we consider the emittance of the 100% of particles.

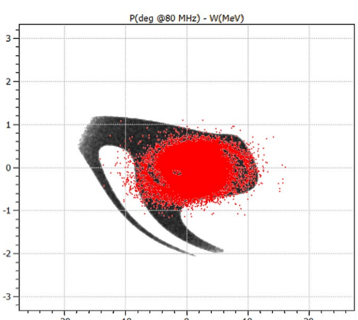

Figure 2: ALPI input beam longitudinal phase space from SPES RFQ (red) and ALPI acceptance (black).

As can be seen by Fig. 2, the SPES RFQ beam is barely contained by the ALPI acceptance making ALPI extremely sensitive to any input energy/phase difference. In general, having a larger acceptance is important to have a robust dynamic. In our case, it is even more due to the “blind tuning” technique for RIB ions. To increase the longitudinal acceptance ALPI, we chose to use the Particle Swarm Optimization to tune the linac [6]. The choice depends on two very important considerations: first, we do not know where the optimum synchronous phase set is; second, we needed an algorithm able to optimize a function that lives in $\mathbb{R}^{84}$. The optimization should not only find a larger acceptance, but also needed to preserve as much as possible the real-estate gain. The latter consideration is automatically ensured by the small transverse acceptance of ALPI (caused by the10 mm radius cavities), which drives for a highest possible energy.

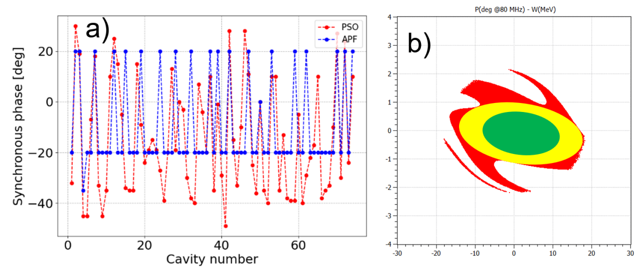

Figure 3: a) synchronous phase of the accelerating cavities. Blue: APF. Red: the PSO results. b) Acceptance after swarm optimization. Blue: APF; Yellow: usable acceptance after PSO. Red PSO full acceptance.

Therefore, it was possible to optimize both parameters looking at the transmission of a very large longitudinal emittance input beam (a factor of 20 with respect the SPES input beam). Through the Pymoo python module [7] and Tracewin [8], we parallelized the algorithm through 80 CPU’s, using a 3000 elements swarm and 100 iterations. Each cavity could choose in a range between ± 90 deg of synchronous phase. The transverse optics was optimized for each component of the swarm, before function evaluation, through TraceWin Simplex method. The results can be seen in Fig. 3: a) shows the synchronous phases along the linac for APF (blue) and PSO (red); b) shows the resulted acceptance (red) after PSO with the usable acceptance (yellow). For comparison, it is reported also the usable acceptance for APF (green). It resulted doubled with respect to the APF. The application of this method to the maximum A/q reduced the output energy of -4.4% with respect the APF, however it is still above the project objectives.

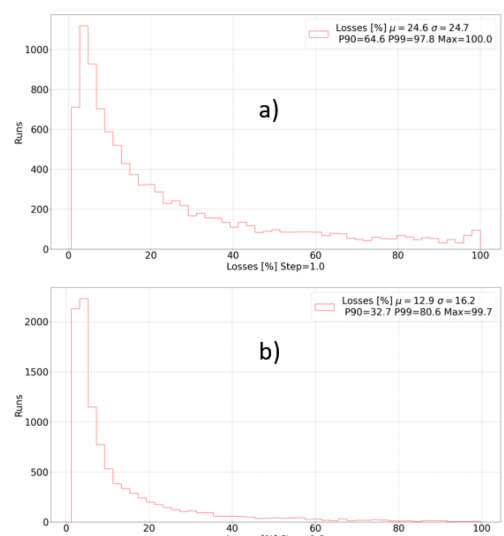

Figure 4: a) error study losses distribution for the PSO case. b) Error study losses distribution for the APF case.

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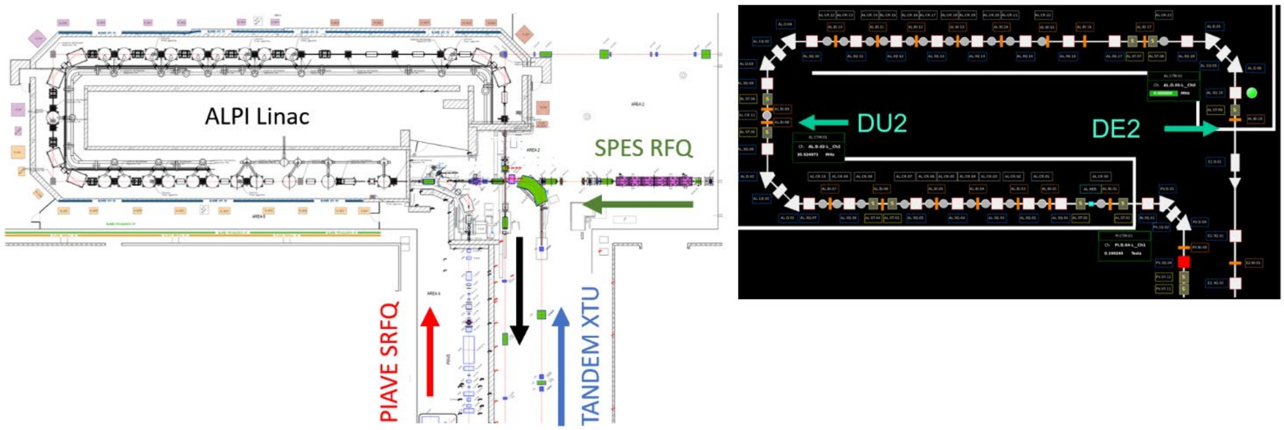

Figure 5: LEFT: Stable heavy ion accelerator facility overview: the three injectors and the directions of the beam lines are shown. Tandem in blue, PIAVE in red and SPES RFQ in green. The outgoing beam direction to the experimental hall is in black. RIGHT: control system view of the ALPI acceleration section. Position of the involved Faraday Cups

A 10000 cases error study involving the misalignment of cavities and elements (uniformly distributed) was performed (see Fig. 4) to evaluate the stability of the solution. We discovered that the PSO solution is more susceptible to the misalignment errors than the APF solution.

This agrees with the resulted synchronous phases obtained from PSO (Fig. 3-a). The average synchronous phases within the 77 cavities we get -10 deg in case of APF and -18 deg in case of PSO as shown in Fig. 3. because the effects of Eq. (2) and Eq. (3) the overall average steering effect resulted larger in the new solution; therefore, a good steering procedure is required.

SWARM INTELLIGENCE FOR STEERING ON REAL MACHINE

TAP facility is equipped with several diagnostic stations with beam profiles and Faraday Cups with (10 mm diameter), albeit the first ones are not aligned and suffers from several bugs. Another consideration is that the cryostats have a residual off-axis alignment of the order of mm which, coupled with the small apertures, makes the on-axis orbit not to be the best solution for transmission. As a matter of fact, the quadrupole shunting techniques for steering resulted partially effective in dealing with the steering effect. For such reason we decided to apply the PSO (called Transport Swarm Optimization, TSO) to the steering procedure, pointing to specific locations directly to the FC on the real machine. This procedure was possible to implement on the real machine due to the last years implementation of the EPICS [9,10] layer on the TAP facility. It allows, within many features, to control the PVs of the power supply (PS) and the diagnostic outputs directly form python scripts. Figure 4 right, shows the layout in control room of the ALPI linac: the diagnostic stations with the involved FCs are shown, as well as the position of the cryostats (the circles), the steeres (the grey squares with an "S" in the middle). In this framework, the function to optimize lives in $\mathbb{R}^{36}$. From simulation results, it would require 100 of swarm components and 40 iterations to converge. The time taken from the algorithm on the real machine is given by two sources: from computational point of view, we could not parallelize the process; from hardware point of view, we had a problem with the steerer PS that limits the velocity of steerer set. During the 2022 and 2023 we tested the proof of principle of this new technique on Tandem-ALPI and ALPI-PIAVE steerer lines. Table 1 shows the results in transmissions (FCs shown on Fig. 5).

Table 1: Result of TSO study, transmissions with respect the manual and the "No set" cases are shown

Line	No set	Manual	TSO
PIAVE ALPI (up to after the SRFQ)	3%	53%	58%
TANDEM ALPI (up to DE2)	1%	24%	35%

We compared the results of the TSO in two situations: with respect steerers at 0 strength (No set) and with respect the manual optimization. The swarm population started uniformly distributed between the PSs limits. As a matter of fact, the test had to be depowered using a low population number 40 and just 20 iterations. The total time taken is 1 h – 1.5 h instead of 15 minutes expected due to the problem of the steerer PSs. Despite that, with these first results, the TSO proved to be able to match and improve the transmission in both cases.

CONCLUSIONS

TAP facility in the last decade received numerous upgrades (hardware's and software) to boost its performances [11,12,13,14,15]. One of the parts to be improved is given by its beam dynamics. Several new implementations [16] are ongoing to improve the performances. In this paper we tried to address the transmission performances with innovative methods both from the simulation point of view and on the real machine point of view. We obtained a new set of cavities with double usable area for longitudinal acceptance. We were able to set up the steerers of the ALPI linac via the TSO program. In future we will increase the number of elements automatically set such as dipoles and triplets in order to reach a fully automatic optimization.

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