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PARTICLE SWARM OPTIMIZATION TECHNIQUES FOR AUTOMATIC BEAM TRANSPORT AT THE LNL SUPERCONDUCTING LINAC ACCELERATORS

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Abstract

The superconductive quarter wave cavities hadron Linac ALPI is the final acceleration stage at the Legnaro National Laboratories and it is going to be used as re-acceleration line of the radioactive ion beams for the SPES (Selective Production of Exotic Species) project. The Linac was designed in '90s with the available techniques and it was one of the peak technologies of this kind in Europe at those times, controls included. In the last decade, controls related to all the functional systems composing the accelerator have been ungraded to an EPICS-based solution. This upgrade has given us the opportunity to design and test new possible solutions for automatic beam transport. The work described in this paper is based on the experience and results (in terms of time, costs, and manpower) obtained using Particle Swarm Optimization (PSO) techniques for beam transport optimization applied to the ALPI accelerator. Due to the flexibility and robustness of this method, this tool will be extended to other parts of the facility.

LINAC DESCRIPTION

The Legnaro CW heavy ion accelerator facility is divided into two main sections: the injectors and the superconducting independent cavity Linac, known as ALPI (Acceleratore Lineare Per Ioni) [1]. Stable ion beams achieve a final output energy of about 10 MeV/u (for stable ion beams), accompanied by an average output current of roughly 100 nA. The provided ion species provided can span in a range from protons to 208Pb ions. The entire heavy ion complex is commonly denoted as TAP (Tandem-Alpi-Piave).

ALPI utilizes two injectors for stable ions: a TANDEM-type electrostatic accelerator responsible for light ion acceleration, and the PIAVE superconductive RFQ (Radio Frequency Quadrupole) [2]. The latter exploits the transition section between the normal-conductive and superconductive parts immediately after the source platform. The RFQ achieves an output energy of 587.5 keV/u.

The ALPI Linac is constructed from a series of 20 cryostats, each accommodating four Quarter Wave (QW) Cavities. These cavities necessitate individual tuning at the commencement of each ion-specific run. A pioneering European prototype developed during the 1980s and 1990s, the ALPI Linac incorporated several innovative techniques characteristic of its era. During the design phase, particular emphasis was placed on achieving a superconductive cavity acceleration field of 3 MV/m, facilitated by a 10 mm aperture diameter. In a strategic optimization of spatial resources, the ALPI period was meticulously configured to cover a transverse focusing triplet and 2 cryostats, collectively housing 8 cavities. In the latter decade, advancements in superconductive cavity technology propelled the accelerating field of the cavities to 1.5 - 2 times the previous value of 3 MV/m.

In this approach, the energy output was significantly increased, although this was achieved at the expense of transmission efficiency, which is caused by 3 main effects: the transverse defocusing force from RF cavities, the longitudinal phase advance that can become unstable in particular conditions, and the steering effect of the QW. To counteract these phenomena (particularly pronounced within the low beta regime), Alternate Phase Focusing technique was implemented, using a ±20-degree synchronous phase. This adjustment led to a reduction in the longitudinal phase advance to below 120 degrees, thereby mitigating the defocusing force and managing the steering and defocusing effects. However, this solution did decrease the longitudinal acceptance of ALPI, which holds significance for the RIB acceleration facility and the overall stability of the dynamics.

THE TRANSPORT SWARM OPTIMIZATION APPLICATION

In general, possessing a greater acceptance holds considerable significance in maintaining a robust dynamic. With the objective of enhancing the longitudinal acceptance of ALPI, Particle Swarm Optimization algorithm was chosen for Linac fine tuning.

The TAP facility is equipped with diagnostic stations containing beam profiles and Faraday Cups with a 10 mm diameter. However, these initial stations are misaligned and face various issues. Additionally, the cryostats have a significant off-axis alignment, around a few millimeters, which combined with the small apertures, makes the transverse optics optimization troublesome. Standard optics techniques such as the quadrupole shunting for steering have been only partial partially successful in dealing with the problem, at the price of a time-consuming tuning. To address this and to proceed to a more automatic setting of the accelerator, a dedicated python application called Transport Swarm Optimization (TSO) and based on Particle Swarm Optimization (PSO) algorithm was implemented to maximize beam transport through and automatic setting of the transverse optics.

Particle Swarm Optimization Algorithm

PSO is a computational technique inspired by the behavior of birds or fish flocking together [3]. In PSO, a group of potential solutions (called particles) collaboratively searches for the best solution to a problem. Each particle

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adjusts its position in the solution space based on its own experience and the experience of other particles in the group. Over time, particles converge toward the best solution by sharing information and adapting their positions.

Different approaches and algorithms could be used to test e optimize the problem, but considering the type of problem the TSO try to solve, PSO was choose because of the several advantages and peculiarities provided by the algorithm [4]:

- Population-based approach: PSO maintains a population of candidate solutions called particles, which move through the search space to find optimal solutions. This allows for exploration of multiple regions simultaneously and increases the chances of finding global optima.
- Social interaction: PSO incorporates social interaction among particles to guide their movement towards better solutions. Considering as particle each steering system, the collection of objects adjusts its position based on its own best solution (personal best) and the best solution found by any particle in the population (global best). This cooperative behavior helps in exploiting promising areas of the search space, keeping in mind the correlation effects between devices.
- Simplicity and ease of implementation: it has a simple concept and requires fewer parameters compared to other optimization algorithms like Genetic Algorithms or Simulated Annealing. This simplicity makes it easier to implement and tune for different problem domains.
- Convergence speed: PSO tends to converge quickly towards optimal solutions due to its ability to exploit good regions in the search space efficiently while exploring new areas as well, especially for single objective function.
- Lack of gradient information: unlike some other optimization algorithms that rely on gradient information, PSO does not require any derivative information, which is difficult data to define in a complex system like a particle accelerator.
- No need for algorithm training: the large differences of the several input conditions from the different injectors makes troublesome to cover all training cases required by a neural network: ions (from C to U), accelerator lines (TANDEM, PIAVE, ALPI, etc.), 74 cavities (which has a different effect depending on the beam input and field) require several datasets for training the algorithm, with an important impact in the operational time.

Python pymoo (*Python Multi-Objective Optimization*) framework [5] was chosen to develop the TSO application using PSO algorithm.

TSO Application Description

The beam transport control system for ALPI-PIAVE line, along with diagnostics system, is based on EPICS framework [6-8]; due to the APIs provided by EPICS, the TSO application can be easily interfaced and integrated into the distributed control architecture as an EPICS client application. For this reason, pyepics [9] was used as interface to the EPICS environment.

As consequence, the first version of the application is a CLI python script based on the pymoo, pyepics and asyncio packages to evaluate the preliminary design and perform the first tests.

The minimum set of parameters used to proper configure the PSO problem (implemented as python class by pymoo) is indicated in Table 1, while:

- the list of steerers/lens is required to define the dimension of the problem ($\mathbb{R}^n$) and describe the initial conditions;
- the Faraday Cup current measurement is demanded for the PSO objective function ($\mathbb{R}^n \rightarrow \mathbb{R}$).

As consequence, beam transport optimization challenge can be managed as a single-objective optimization problem. The results coming from the usage of this first version of the application will be shown in the next section.

Table 1: Minimum Set of Parameters Required to Run TSO

Parameter	Description
Population size	the size of the swarm being used for PSO
Number of iterations	overall number of function evaluations used to define a termination criterion to stop the optimization procedure
List of devices	ordered dictionary of steerers power supplies used by the PSO to control the beam transport
List of starting conditions	starting position and boundaries for devices' EPICS PVs
Target parameters	Info related to faraday cup used by PSO to evaluate the optime point

A second version of the TSO was developed with the aim to detach configuration parameters from the code and extend the functionalities in term of:

- Plant description: dedicated python classes were defined to manage different kind of devices (lens, diagnostics, etc.), extending the original set. In addition, JSON files are used to initialize objects related to the plant. This approach let developer easily extend the type of objects manageable with the application while users had the possibility to describe the entire facility without touching the code.
- Configuration parameters extension: because of the experience matured during the first tests, additional configuration for PSO where required. For this reason, further parameters were added (i.e., termination criterion options or starting condition definitions for new kind of devices).

These new features were partially tested but further verification will be done in the next months.

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USE OF TSO WITH THE REAL MACHINE AND PRELIMINARY RESULTS

In general, the TSO application can be applied to a heterogeneous range of devices. However, for the initial set of tests aimed at validating the usage of the PSO algorithm and debugging the logic, it was employed to optimize the accelerator's steering procedure by directing the process towards specific positions on the machine's Faraday Cups.

First tests were used to estimate optimization times, in order to compare manual and automatic optimization tuning starting. For these tests, TANDEM-ALPI and PIAVE-ALPI were used and limitation on steering setpoint values, using a subset of the full range window. Different population size and number of iterations were used with TSO and the results in terms of transmission obtained are shown in Table 2. During the tests, the current of the tandem continuously oscillated, and consequently, the steering also varied. Despite this situation, we were able to observe how the algorithm still managed to handle the state of instability and find points of improved transmission.

A second set of tests were performed introducing the optimization of quadrupoles and dipoles. In addition, an average estimation for faraday cup current measurement was required to compensate oscillations coming from the source and the noise observed in the acquisition chain and a finer way to estimate starting conditions and setpoint variations for the PSO was used.

Table 2: Transmission — Comparation Between TSO and Manual Tuning

Parameter	Exec. Time	Transmission	
		Automatic Opt. (TSO)	Manual Opt.
Iterations: **10** Population size: **20** Diag. target: **DU2**	30 min	56%	41%
Iterations: **15** Population size: **30** Diag. target: **DE2**	1 h	30,3%	24%
Iterations: **20** Population size: **40** Diag. target: **DE2**	2h	35%	24.5%

Several promising results were obtained, as confirmation of the validity of the algorithm and the application. One of the most interesting analysed was the TSO's ability to adapt to changes in machine conditions was observed. Figure 1 shows the trends of three components of the swarm related to steering devices as the iterations and current change (current at the Faraday Cup) concerning three components of the swarm: as visible in the graph, around iteration 15 the system was approaching a maximum. However, some changes to the machine occurred after iteration 16: the control component (green line) began to assume higher current values differently from before. In particular, around iterations 26-27, it reached a new maximum. At this point, the control component communicated the new parameters to the swarm to transmit the current correctly. With this new information, the population's best member retrieved high current values, correcting its parameters compared to the control solution. It's possible to observe and deduce the event that changed the optimum's position by examining the currents in the best solution in relation to the iteration trend.

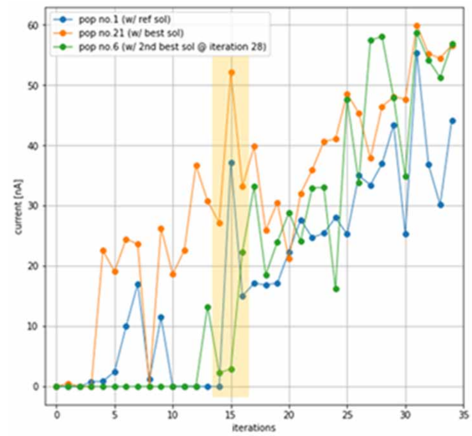

Figure 1: TSO adaption effect after machine condition changes (trends related to steering devices).

FURTHER DEVELOPMENTS

Based on the results coming from the tests performed, different actions were chosen to achieve logic optimization, execution time minimization, software architecture standardization and improvement. For logic and execution time, part of the code is under upgrade. In parallel to this task, particular modifications and upgrades were identified in the facility (i.e., steering system power supplies firmware upgrade, diagnostic noise suppression, etc.). For software standardization and improvement, one of the goals is to extend the application from a CLI program to a web application: the application architecture adopted and the usage of particular technologies such as JSON and python let us easily implement a web version of the program. Framework like Flask od Django can be valid candidates for this task.

CONCLUSION

The TSO application has proven its effectiveness in improving the longitudinal acceptance of ALPI by enhancing beam transport control. Using the PSO algorithm, TSO addresses challenges arising from misaligned diagnostic stations and suboptimal steering performance. PSO's cooperative behaviour, simplicity, and lack of gradient information requirements make it a suitable choice.

TSO's initial version was used for testing, demonstrating adaptability to changing conditions and achieving improved transmission.

Further developments aim to optimize logic, reduce execution time, and standardize the software architecture, including transitioning to a web application.

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