Istituto Nazionale di Fisica Nucleare

HB 2023

New techniques method for improving the performance of the ALPI Linac

Luca Bellan – INFN LNL

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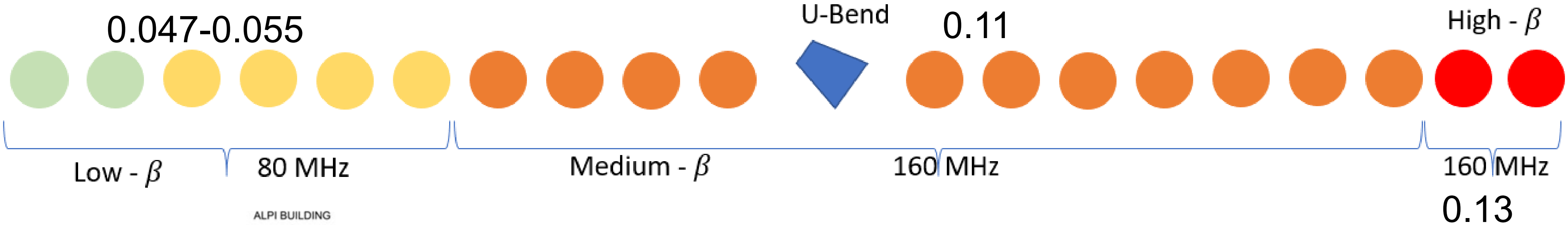
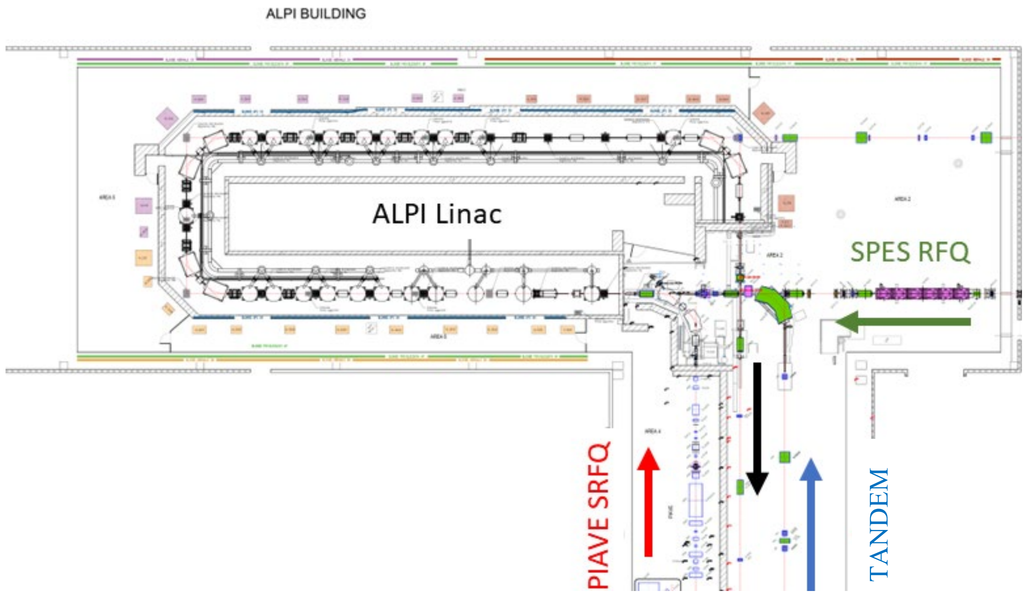
- Simulation study to increase longitudinal acceptance
- Towards the application on the real accelerator
- Results of the optimization of the full transverse optics on the real machine.
- Conclusions

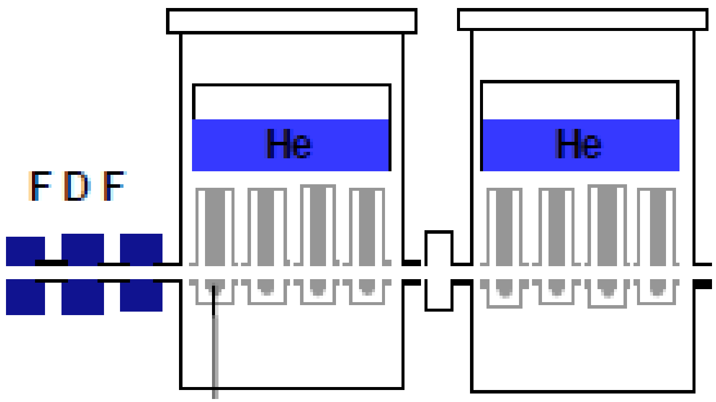
Tandem-ALPI-PIAVE facility





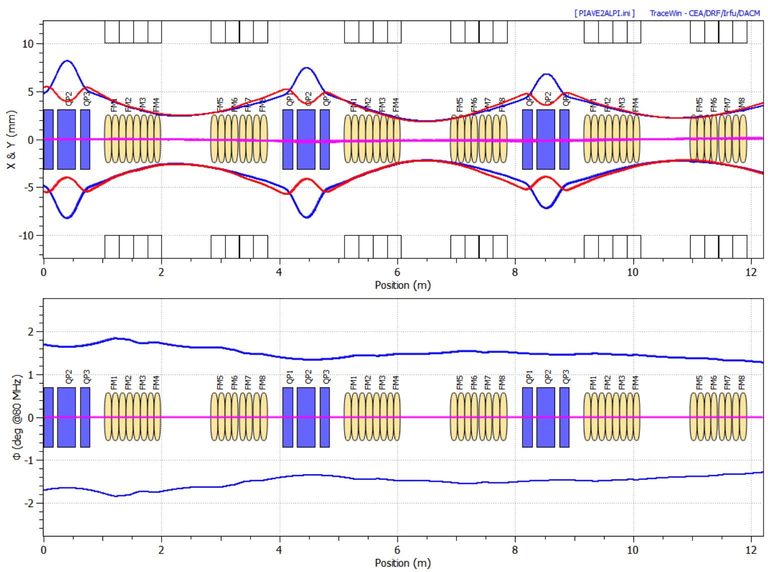
- Heavy ion CW Folded independent superconductive cavity linac.
- Design and built 80'-90' (One of the first prototypes in Europe)
- Three injectors: tandem, Super conductive RFQ, normal conductive RFQ (future)
- 82 Quarter Waves cavities at 4 K (80-160 MHz).
- 10 MeV/u energy output, from C to U

BD challenges



1 cryostat = 4 QW cavities

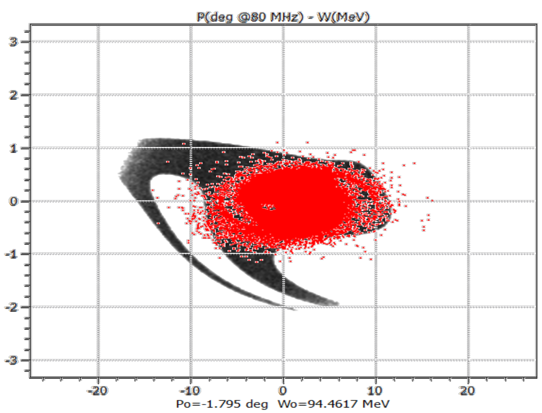
- Applied field problem (no space charge)
- **E_0 (5 MV/m) increased 4 times from the design**
- **20 mm diameter aperture** of the QW
- **Very long period (8 QW cavities per triplet)**
- Aggressive 0-current transverse phase advance (**120 deg**) makes the dynamics **sensible to the misalignments**, further enhanced by low beta
- **Transition between 0.055 and 0.11 cavities (with a frequency change) happens quite early in the linac**
- Small transverse acceptance
- Difficult benchmark with simulations



$$k_{l,0}^2 = \frac{2\pi q E_0(s) TTF sin[-\phi_s(s)]}{mc^2 \beta_s^2 \gamma_s^2 \lambda}$$

$$K_{RF} = \pi \frac{eE_a \sin\phi_0}{\beta^3 \gamma^3 mc^2 \lambda}$$

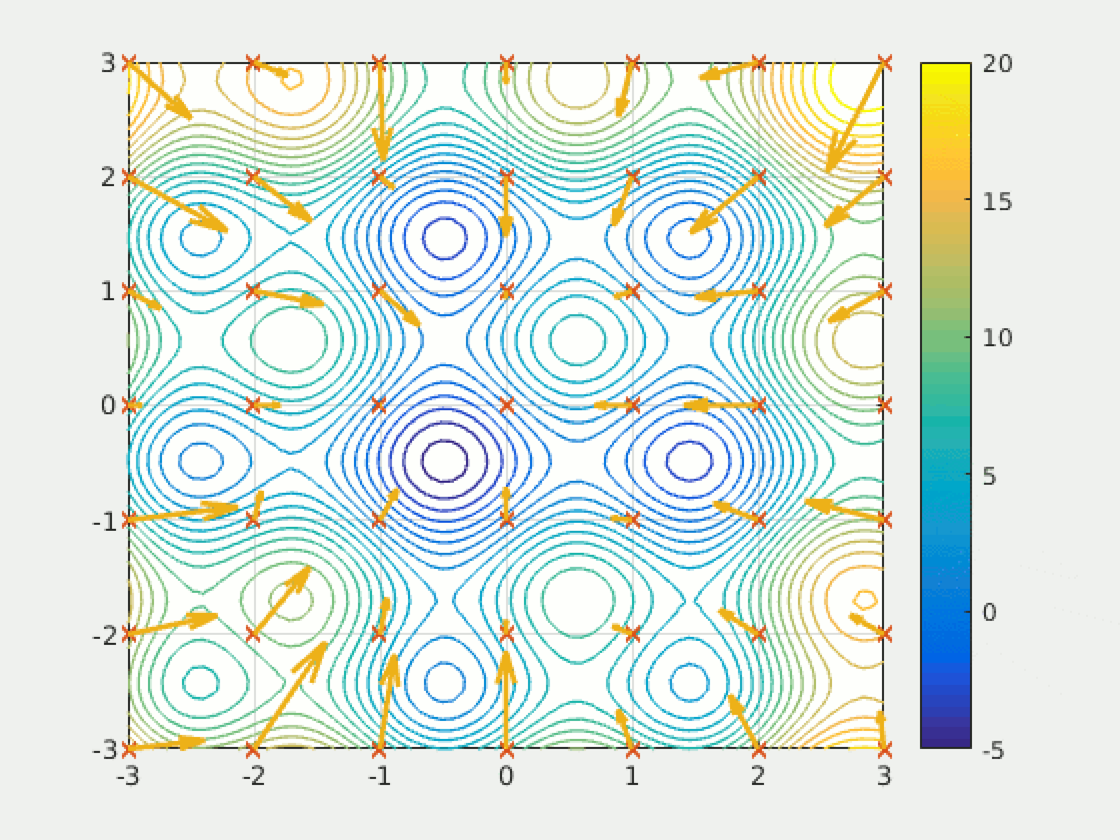
$$\Delta y' \sim \frac{2qeg \sin\phi}{\beta^2 \gamma A m_0 c^2} TTF \left[\beta c B_x \sin\left(\frac{\pi d}{\beta\lambda}\right) - E_y \cos\left(\frac{\pi d}{\beta\lambda}\right)\right]$$



→ Alternate Phase Focusing ±20 deg → APF Small acceptance

Let's try population-based algorithm, PSO (tried by CEA-Saclay for DONES superconductive linac)

PSO Algorithm details



- Algorithm based on information sharing between the swarm components
  - Direction of each particle depends on best maximum found along its path and the best maximum found by the whole ensemble of particles.
- Able to avoid local minima
- Fast search for minima in multidimensional scalar field.

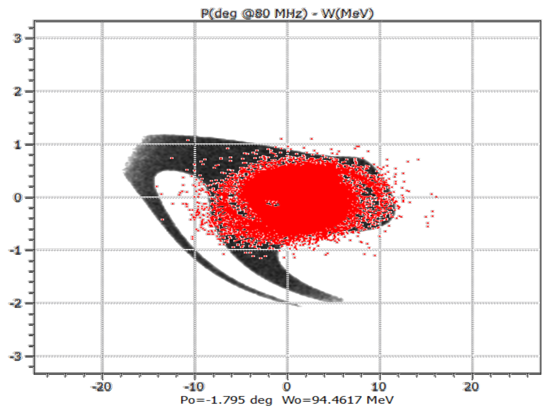
“Particle swarm optimization”, Wikipedia, 2023

$$\begin{cases} P_i^{s+1} = P_i^s + v_i^{s+1} \\ v_i^{s+1} = wv_i^s + c_1 r_1 (P_i^{\text{best}} - P_i^s) + c_2 r_2 (g^{\text{best}} - P_i^s) \end{cases}$$

Increment studies of the longitudinal acceptance

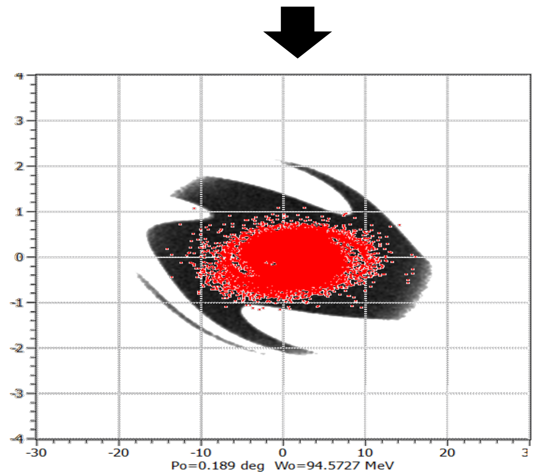
Applied to 82 cavity phases (± 90 range) to find new synchronous phases. Tested with input beam from normal conductive RFQ.

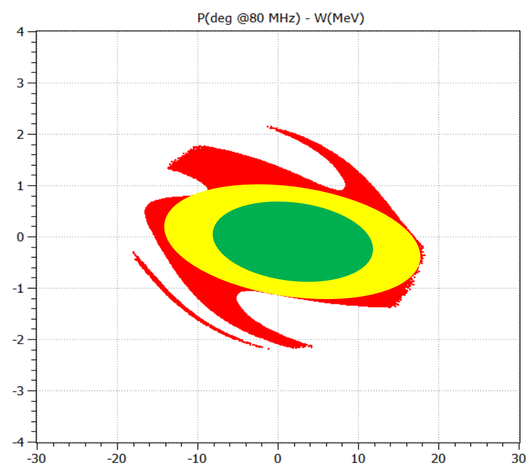
APF

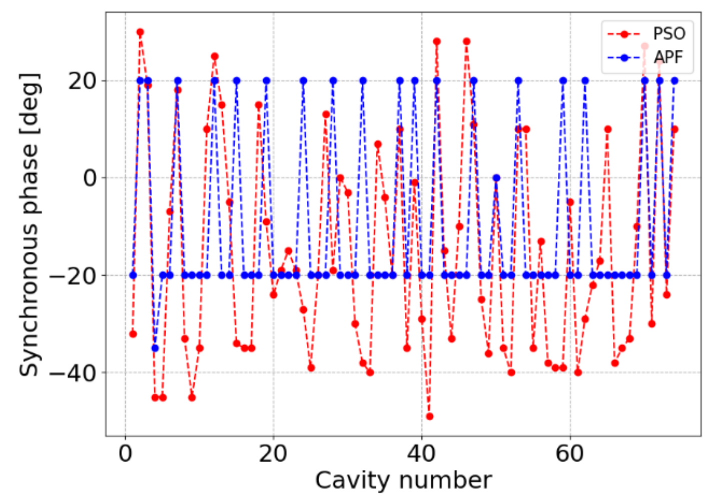


- Normal conductive longitudinal phase space is not well contained in the ALPI acceptance
- Increased usable acceptance (yellow)
- APF usable acceptance (green)
- Due to a larger average negative synchronous phase w.r. to APF, expected that the solution is more sensible to steering

PSO







[0] L. Bellan et al., "NEW TECHNIQUES FOR THE LNL SUPERCONDUCTIVE LINAC ALPI BEAM DYNAMICS SIMULATIONS AND COMMISSIONING", IPAC23', Italy, Venice. doi: 10.18429/JACoW-IPAC2023-TUODA3

From simulation to real accelerator

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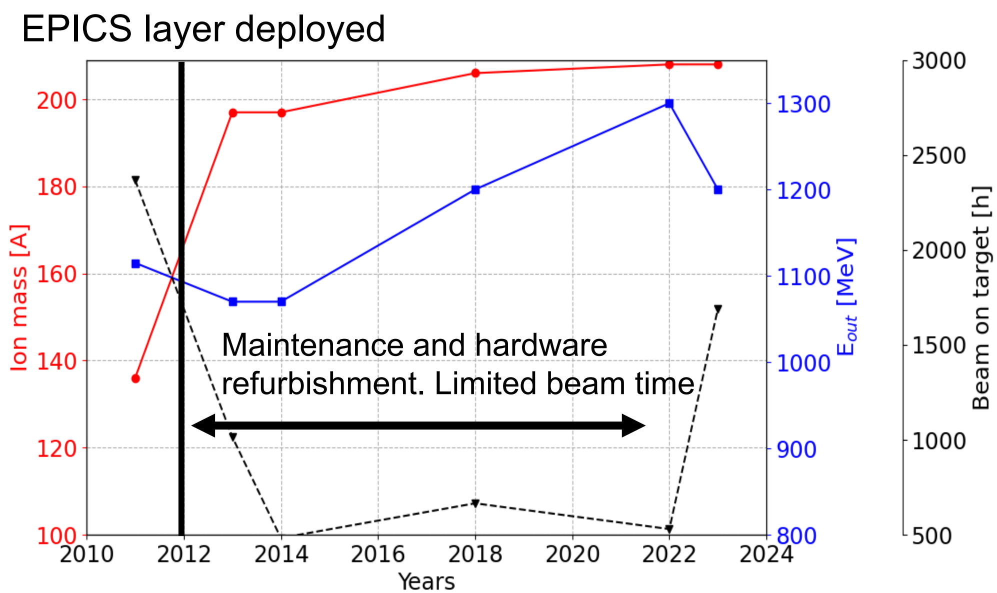
- **In the last years, several improvements on the linac increased dramatically its reliability**, allowing to allocate several days for accelerator experiments and machine studies.
  - We can practically speak of a second commissioning.
- The **EPICS layer** that allows to control the magnet power supplies from scripts has been deployed in 2012 (**pyEPICS**)
- In addition to the difficulties presented in the previous slides, there are some specific challenges related to the enormous number of cases (different A/q, different production mode, different input conditions, different cavity configurations (not scaled beta), different instabilities)



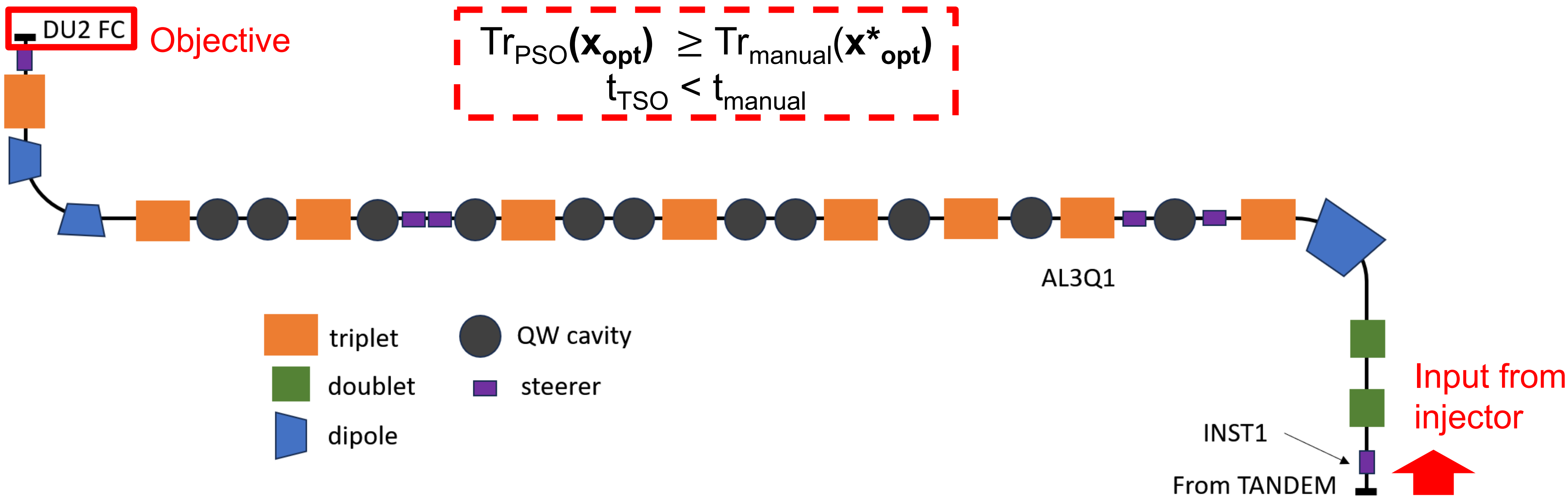
- We were looking at fast routine which can fit in the small amount of time given (**2 h**)
  - Full priority to the experiments
- Can adapt to multiple beam input parameters
  - 3 possible injectors with very different input conditions,
  - From C tu Pb ions. Further differences depending on the input conditions metal/gas compound.
  - Few and unreliable diagnostic

➡ Population based algorithms (TSO for ALPI project)

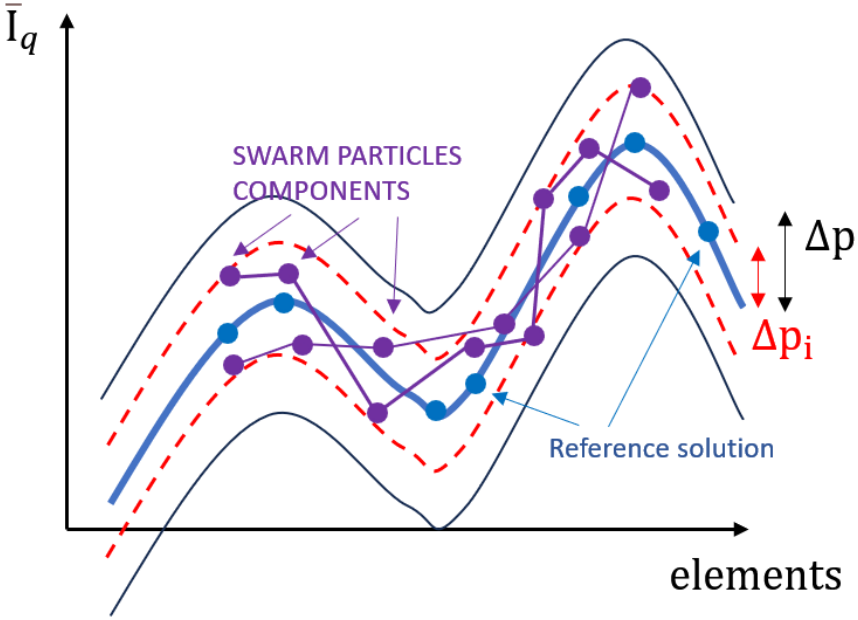
Whole optics experiment

- Whole optics set-up at the same time. **Objective function is the FC at the end of the line**:
  - 3 dipoles, 11 triplets and doublets, 6 steerers.
  - Cavities off and at ambient temperature (**beam pipe aperture reduced due to thermal dilatation of the cavity aperture**).
- 37 parameter space.
  - Order of magnitude differences in sensibilities between the different optic elements.
- Manual found solution (reference) (i.e. a set of PS settings for max transmission in FC)
  - Due to injector instability (TANDEM), **the reference solution, in one hour was not anymore applicable (0 current).**
  - 1 h estimated time before first order from injector instability. Source oscillations 30% in 1 min
  - A nightmare for testing the algorithm, but the perfect ground to study its robustness w.r. to the instabilities
- The steerer, quadrupoles and dipole field/gradient are expressed in % of the maximum current of the relative PS.

$$Tr_{PSO}(\mathbf{x_{opt}}) \geq Tr_{manual}(\mathbf{x^*_{opt}})$$
$$t_{TSO} < t_{manual}$$



Initial population and procedure



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

$$[\mathbf{p}_{min,s}, \mathbf{p}_{max,s}] = \mathbf{p}^* \pm \Delta\mathbf{p}_\mathrm{i} = \mathbf{p}^* \pm \Delta\mathbf{p}/n_S$$

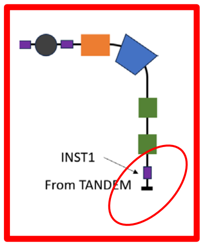
- $\mathbf{p}^*$ is the reference set. $\Delta\mathbf{p}$ components are the total variation range of each parameter
- $\Delta\mathbf{p}_\mathrm{i}$ contains the information on how far the initial population is deployed from the reference set
- n_S relates the initial position of the set w.r. to the total variation.

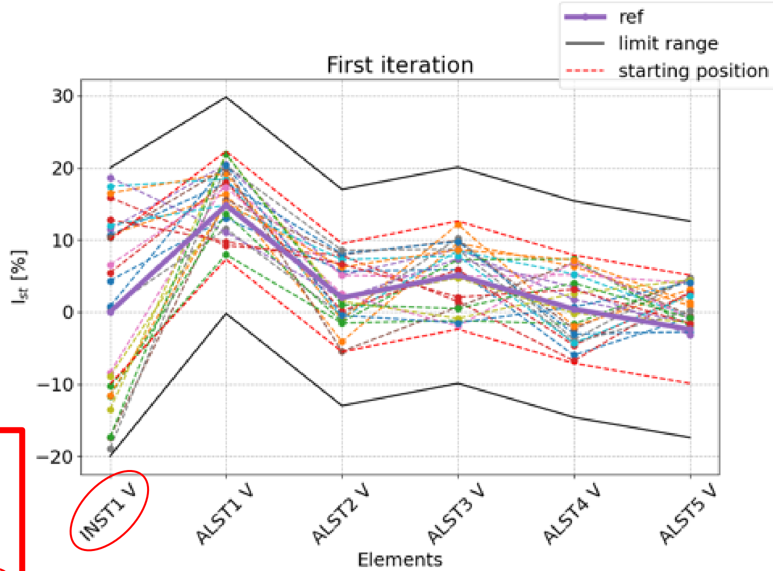
Optical lens	Δp [Tm, T/m, T]
Steerers	180% (250%)
Triplets/doublets	33%
Dipoles	0.03%

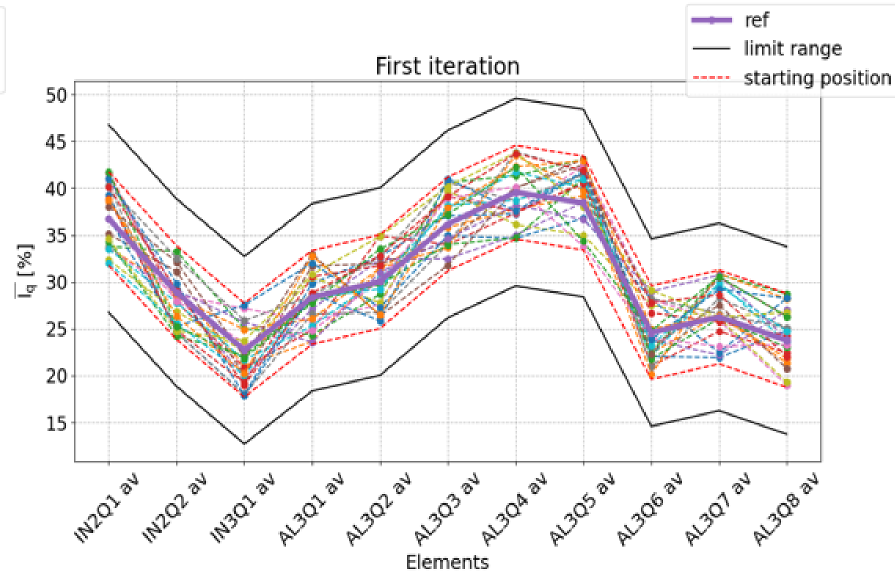
- $\mathrm{n_s}$ was gradually decreased
- $\Delta\mathbf{p}$ components gradually increased
- First steerer (after the injection) variation was increased up to 250% and its centre value put to 0%.
  - part of the instabilities coming from the injector were affecting the first order moment of the beam input.
- $\Delta\mathbf{p}$ components magnitude are such that a single variation of an element brought to 0 current at the FC
- **The initial positions led to 0 current on the initial iterations**

25 swarm components, 1.5 h of time

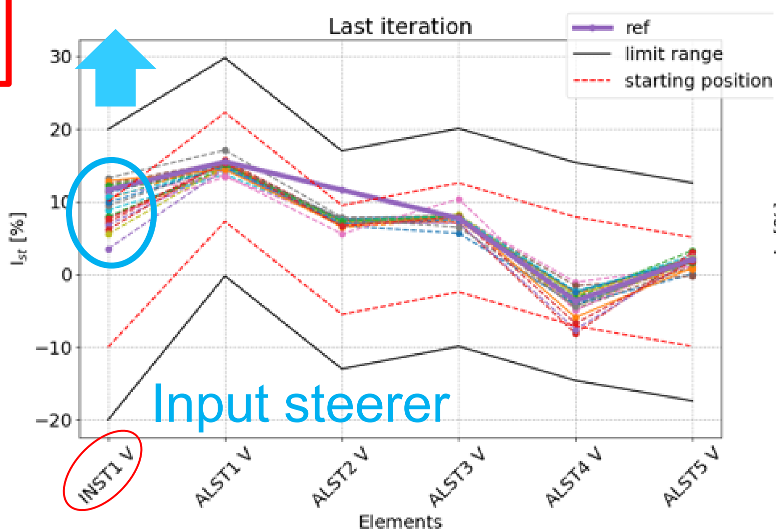
Results

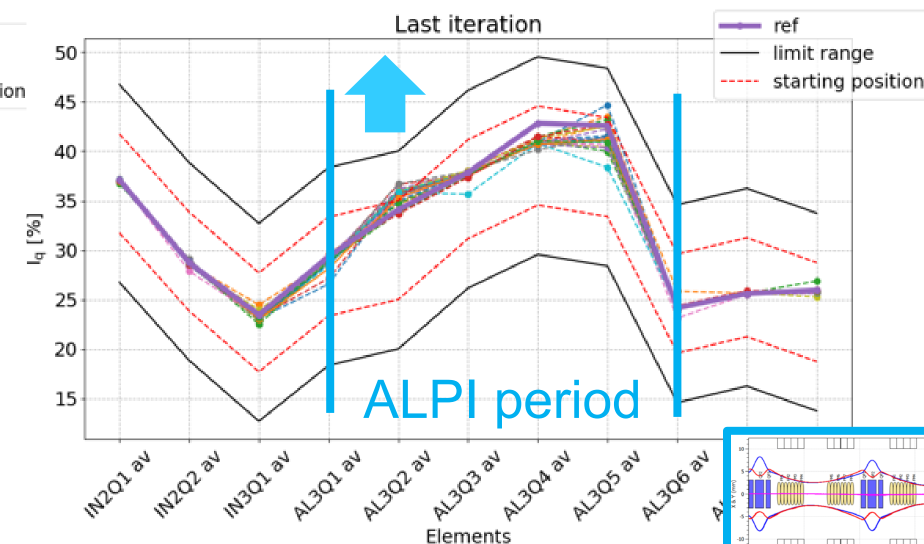


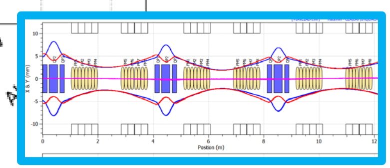




S T A R T







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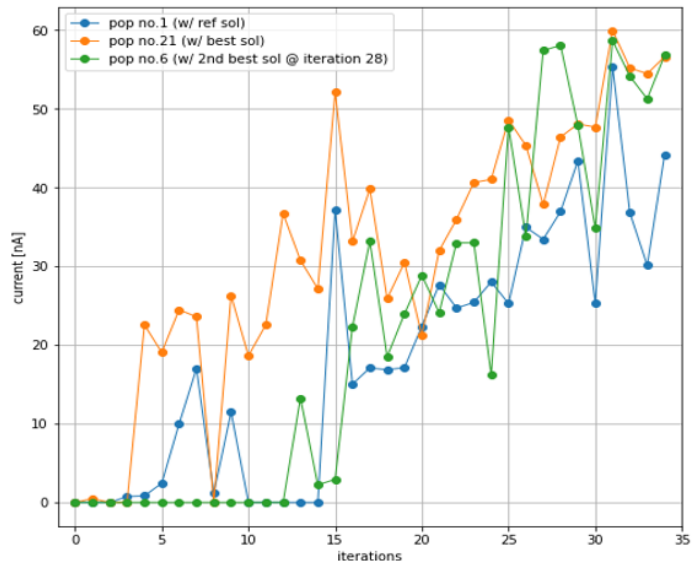
Analysis of the trends

Three components of the swarm

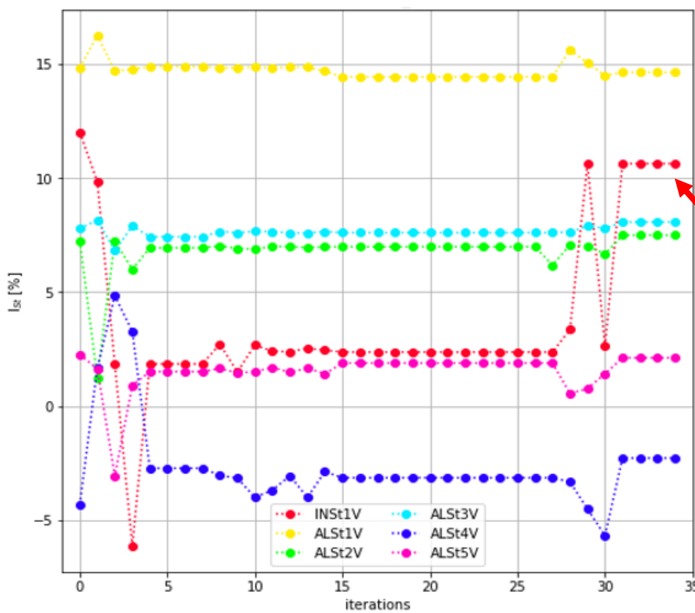
Trend of three components of the swarm



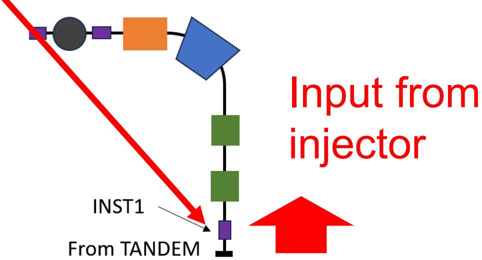
Three components evolution out of 25 w.r. to the iterations. On vertical axis it is registered the current at the FC

Steerers of best components

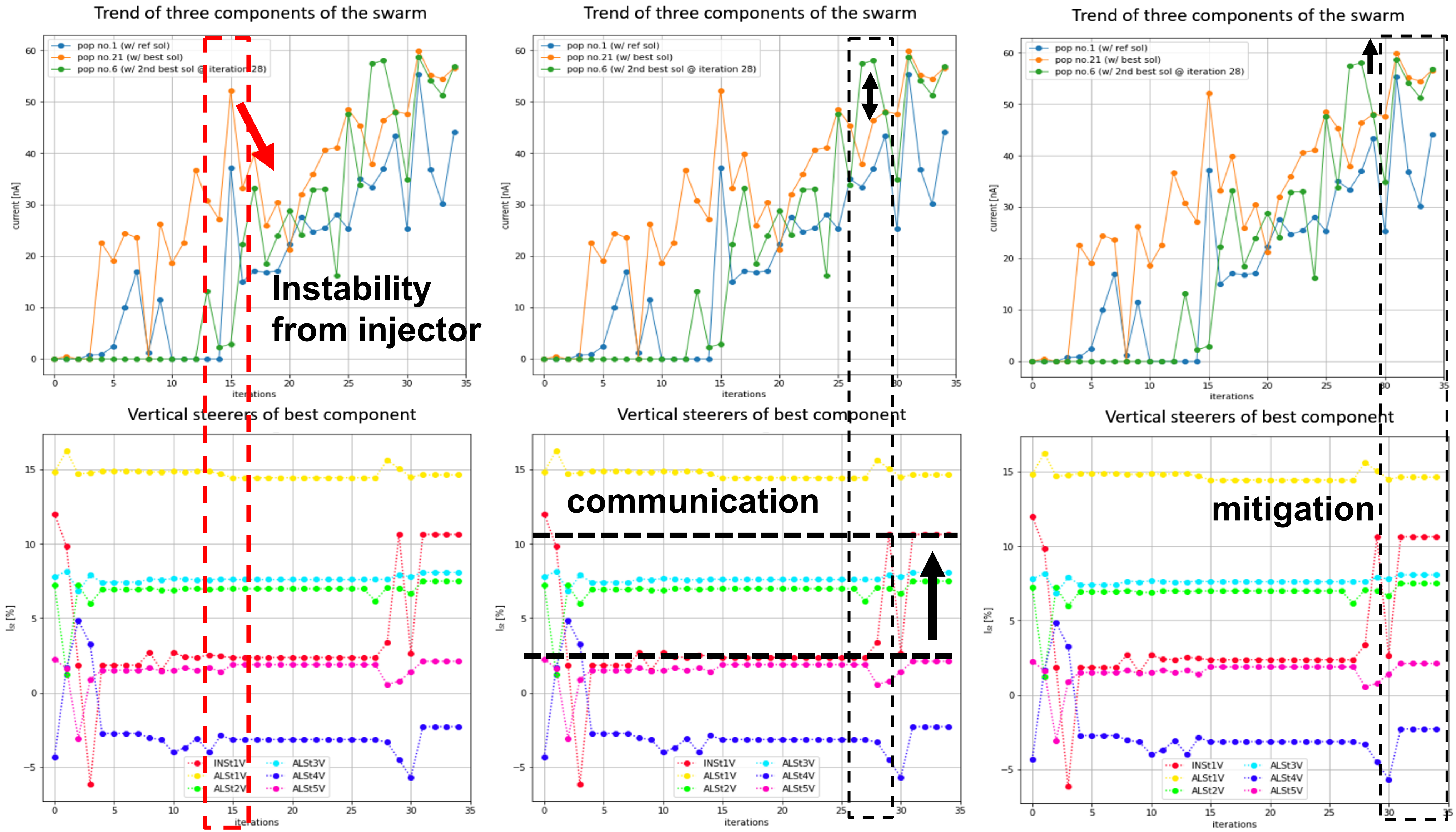
Vertical steerers of best component



Vertical steerer trend of the best component (orange) w.r. to the iterations. On the vertical axis it is recorded the PS value.



Instability mitigation



Conclusions and observations

- The method could handle:
  - optical instability from the injector which changes the first order moments
  - up to 30% beam current oscillations from the injector (source problems). Larger variations induce a failure in the setting

- **The routine increased the transmission in half time with respect manual optimization and it is operator independent**.

Parameter	Previous value	Manual	TSO
Transmission in DU2	0%	50%	55% (upper limit due to injector setting)
Time required	-	3 h	1.5 h (considering the instability)

- Future: application to the whole linac, also to synchronous phases. Possible inclusion of a reinforced learning and/or a NN in the routine.