TOWARDS AUTOMATED CAVITY FAILURE COMPENSATION IN THE SPIRAL2 SC LINAC

A. Plaçais*[1], F. Bouly[1], M. Di Giacomo[2], J.-M. Lagniel[2], A. Leduc[2],
G. Normand[2], A. Orduz[2], B. Yee-Rendon[3]
[1]Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, Grenoble, France
[2]GANIL, CEA/DRF-CNRS/IN2P3, Caen, France
[3]JAEA/J-PARC, Tokai, Japan

Abstract

RF systems in high-power particle accelerators such as SPIRAL2 are susceptible to failures, causing significant beam downtime. Cavity failure compensation can restore nominal beam conditions, but finding optimal settings is a complex challenge. This study adapts LightWin to SPIRAL2, implementing the NSGA-III algorithm for high-dimensional, constrained optimization. We demonstrate successful single-cavity-failure compensation, recovering nominal beam energy without longitudinal losses. These developments advance automation for SPIRAL2, but suboptimal transverse envelopes highlight the need for quadrupole retuning in LightWin.

CAVITY FAILURE COMPENSATION FOR HIGH AVAILABILITY

The SPIRAL2 superconducting (SC) linac is dedicated to accelerating intense ion beams, from protons to ions up to $A/Q = 7$ [1]. In this machine, RF cavity or associated system failures are a major source of beam interruption [2]. In case of RF failure, neighbouring cavities can be retuned to continue operation, sometimes even recovering nominal beam conditions. This cavity failure compensation has demonstrated practical feasibility on SNS [3] and SPIRAL2 [1, 4], and was applied during SPIRAL2 operation [5].

However, manually determining compensation settings is complex, time-consuming, and may be incompatible with operational constraints. To address this, we developed LightWin [6], an open-source tool for automatic cavity failure compensation. Originally designed for ADS linacs, where compensation is facilitated by specific design features, we are adapting LightWin to all linac types. In this study, we present our latest developments, enabling its operation on the SPIRAL2 SC linac, and perform a compensation study on a single cavity failure.

This paper is organized as follows. We first introduce the LightWin code and its parametrization. We then present the latest updates, focusing on optimization algorithms and SPIRAL2-specific challenges. Next, we showcase a compensation scenario and compare it to the settings from Ref. [5].

THE LightWin FRAMEWORK

Code Architecture and Features

LightWin [6] is an open-source tool for finding compensation settings, previously detailed in [7]. Written in Python, it provides beam dynamics and optimization tools, and is designed for use with any linac and cavity failure compensation strategy. Its main feature is automatic operation, enabling compensation settings to be found for any number of failure scenarios without intervention. This enables both rapid database creation for compensation settings and systematic comparison of multiple strategies across the same failure set. Its modular structure allows switching between different beam dynamics solvers and optimization algorithms. Here, we use two beam dynamics solvers: `Envelope1D`, an envelope longitudinal solver without space-charge effects, and `TraceWin`, which calls the reference code TraceWin to track the beam in 3D with multiparticle simulations, accounting for space-charge effects. All presented beam dynamics results were calculated with TraceWin, while compensation settings were found using LightWin. In LightWin, compensation is formulated as an optimization problem [8]:

$$\left.\begin{aligned}
&\text{Minimize}\, f_m(\mathbf{x}), && m = 1, 2, \cdots M && \text{(1a)}\\
&\text{subject to}\; g_j(\mathbf{x}) \geq 0, && j = 0, 1, \cdots J && \text{(1b)}\\
&\qquad x_i^{(L)} \leq x_i \leq x_i^{(U)}, && i = 1, 2, \cdots N && \text{(1c)}
\end{aligned}\right\}$$

where f_m are the M objective functions, g_j the J inequality constraints, and $\mathbf{x}$ the N-variable vector. Each variable x_i is bounded by $x_i^{(L)}$ and $x_i^{(U)}$. N, $\mathbf{x}^{(L)}$, and $\mathbf{x}^{(U)}$ define the design space. In our case, $N = 2n$, where n is the number of compensating cavities, each contributing two variables: electric field amplitude and phase.

Optimization for ADS Linacs

LightWin has been used for MINERVA [7, 9] and JAEA-ADS [7, 10, 11] SC linacs. These linacs, part of Accelerator-Driven Systems (ADS), cannot tolerate repeated or prolonged beam interruptions [12]. Their features facilitate failure compensation: very high longitudinal acceptance and cavities operable with accelerating fields E_{acc} above baseline [13, 14]. In our studies [7, 9–11], we could compensate single cavity failures with three to five compensating cavities.

We generally used the Downhill Simplex algorithm [15], best suited to single-objective, low-dimensional (*i.e.* few-variable) problems without constraints. The variable vector

---

* placais@lpsc.in2p3.fr

x consisted of each compensating cavity field map scaling factor k_e and synchronous phase ϕ_s. The limits for k_e were defined by the cavity and amplifier specifications. For ϕ_s, we imposed limits to keep it close to the baseline and between $-90°$ and $0°$. However, treating ϕ_s as a variable rather than a constraint increased calculation time, as the actual electric field phase ϕ_0 had to be determined at each iteration. This was necessary because Downhill Simplex did not support constraints, though it allowed setting limits on variables.

We defined three objective functions: the longitudinal mismatch factor M_z between baseline and compensated beams [10, 16], the beam kinetic energy difference ΔW_{kin} between baseline and compensated linacs, and the absolute beam phase difference $\Delta\phi_{\mathrm{abs}}$ between baseline and compensated linacs. All objectives were evaluated at the compensation zone exit, *i.e.* the last compensating cavity exit. When rephasing all downstream cavities was possible, we removed the beam phase objective [7]. This improved convergence and reduced demand on the cavities and associated amplifiers.

ADAPTING LightWin TO THE SPIRAL2 SC LINAC

The SPIRAL2 SC linac accelerates intense ion beams, from protons to ions with $A/Q \leq 7$. It comprises two superconducting sections, with cavity settings summarized in Table 1. Initially, increasing cavity gradients for compensation was not considered [17], so accelerating fields cannot be significantly increased. Reliability is increasingly important, as RF system failures are the main source of beam downtime [2]. In particular, the CMA11 cavity (11th of Section A) was removed in 2025 due to excessive pressure. Nominal beam energy and minimal losses were achieved after applying compensation settings [5].

Table 1: Cavity Settings in the SPIRAL2 SC Linac

Cavity parameters	Section A	Section B
Cavity type	QWR	QWR
f [MHz]	88.05	88.05
Cavities per cryomodule	1	2
Cryomodules	12	7
β_{opt}	0.07	0.12
$E_{\mathrm{acc}}@\beta_{opt}$ [MV m^{-1}] [a]	6.5	6.5
Max. E_{acc} [MV m^{-1}] [b]	8.0	8.0
Deuton W_{kin} range [MeV]	1.5 → 7.2	7.2 → 40

[a] CMA11, CMB01-02, CMB06-02, and CMB07-02 do not reach 6.5 MV m^{-1}.

[b] Additionally, CMA01, CMA03, CMA04, CMA05, CMA06, and CMB03-01 do not reach 8 MV m^{-1}. Maximum fields are reported in Fig. 1.

In this machine, E_{acc} margins are relatively low, limiting the additional energy we can provide to the bunch. In contrast to our previous studies with 15 MeV to 1.5 GeV proton beams, this study involves low β and W_{kin}, causing strong debunching between cavities. Consequently, we needed six to eight compensating cavities for a single cavity failure, compared to three to five in ADS studies. However, each additional cavity increases the design space dimensionality N, exponentially increasing the search complexity due to the curse of dimensionality. Since our usual algorithms (*e.g.*, Downhill Simplex or least-squares) often became trapped in unacceptable local minima, we implemented NSGA-III [18], which handles high dimensionality, multiple objectives, and constraints. A significant feature of NSGA-III is its support for constraints, unlike earlier algorithms such as Downhill Simplex. This allowed us to reformulate the optimization design space more naturally, improving the algorithm's convergence. The variables are k_e and ϕ_0. ϕ_s is now treated as a constraint rather than a bounded variable.

We used the same two first objective functions as our previous studies [7,9,10]: M_z and ΔW_{kin}. Note that $\Delta\phi_{\mathrm{abs}}$ is not part of the objectives; thus, all downstream cavities must be rephased. We rephase them to maintain their nominal ϕ_s and thus preserve their longitudinal acceptance.

Since we focus on longitudinal settings, we use our 1D envelope solver to find compensation settings, excluding transverse quantities from objectives and constraints. Once the settings are found, LightWin automatically instructs TraceWin to retune the steerers and perform the final multiparticle simulation. Practically, LightWin inserts the appropriate TraceWin commands (*i.e.* `STEERER`, `ADJUST_STEERER`) into a `DAT` file and requests TraceWin to perform the calculation.

EXAMPLE STUDY: FAILURE OF CMA11

We studied the CMA11 cavity failure, using well-established compensation settings from Ref. [5] for comparison. The beam is a 5 mA deuteron beam accelerated to 40 MeV. Using LightWin and the method from the previous section, we found compensation settings for this failure with three cavities upstream and four downstream. We compare the LightWin settings to those from Ref. [5], obtained with TraceWin and applied on the machine. The compensation strategy in Ref. [5] differed from that in this study: it used a *local-global* strategy [7] with fewer cavities around the failure, without recovering beam energy at the compensation zone exit. Instead, the beam was propagated with minimal losses and provided an additional energy boost using "booster" cavities at the linac exit, with four cavities upstream, one directly after the failure, and four at the linac exit.

Figure 1 shows the cavity parameters for the baseline, LightWin, and TraceWin settings [5]. The red line indicates the failed CMA11 cavity position. Marker sizes do not convey information; they ensure visibility when points overlap. Here, $k_e = 1$ corresponds to the nominal field $E_{\mathrm{acc}} = 6.5\,\mathrm{MV\,m^{-1}}$ at β_{opt}. Fig. 2 shows the transverse and longitudinal envelopes for the baseline and both compensation settings along the SC linac. The 0 m position corresponds to the first lattice of Section A. The red line indicates CMA11, and the grey area shows the compensation zone, spanning from the first to last compensating cavity.

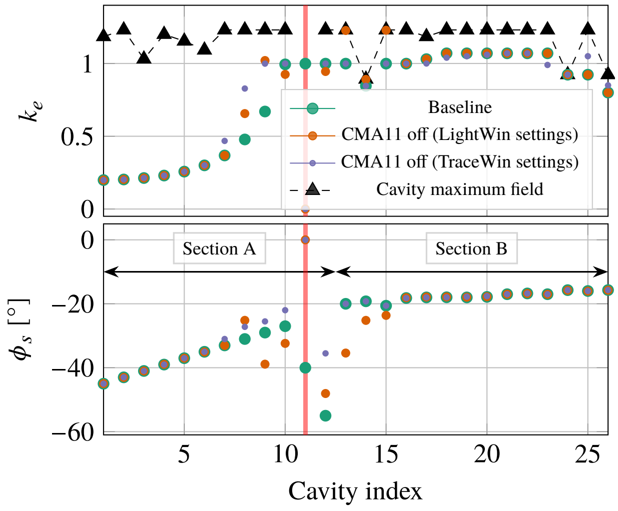

Figure 1: Cavity parameters for the baseline, LightWin, and TraceWin settings [5]. The red line outlines the failed cavity.

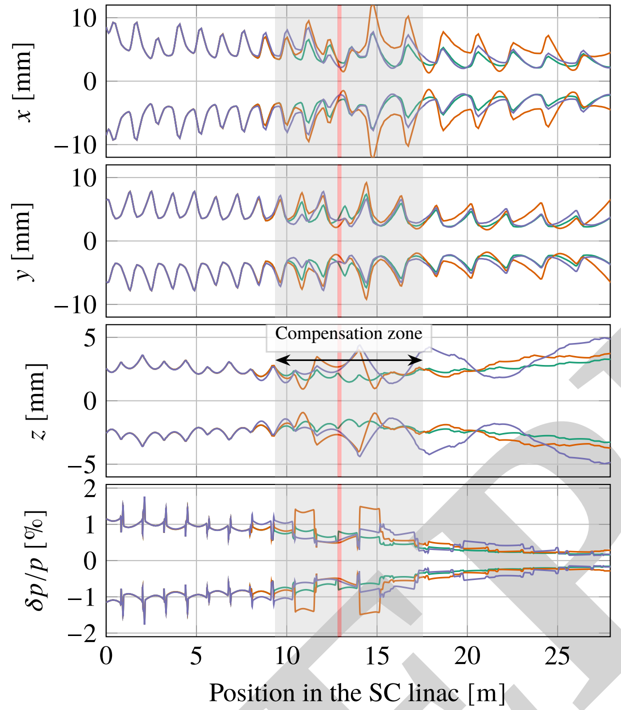

Figure 2: 3σ envelopes for the baseline, LightWin, and TraceWin settings [5]. Colors match those in Fig. 1. Envelopes were calculated with Partran from TraceWin. The red line indicates CMA11, and the grey area shows the compensation zone.

DISCUSSION

Our settings recover nominal beam energy without losses in the SC linac, using fewer compensating cavities than initially expected. The LightWin cavity settings (Fig. 1) are consistent and within allowed limits. In particular, k_e never exceeds any cavity's maximum field, and ϕ_s values remain close to the baseline. We also observed high longitudinal acceptance and no longitudinal losses. LightWin pushes several compensating cavities to their maximum allowed k_e, raising the question: could more compensating cavities bring beam parameters closer to nominal? Interestingly, Leduc *et al.*'s [5] ϕ_s values vary regularly from cavity to cavity, while LightWin's are more erratic–smoothing them might improve beam quality.

In the compensation zones, LightWin's longitudinal envelopes (Fig. 2) deviate slightly from the baseline but recover at the exit. However, LightWin's transverse envelopes differ significantly due to unretuned quadrupoles and transverse kicks from accelerating cavities, causing significant transverse acceptance reductions. As expected, the TraceWin settings with retuned quadrupoles achieved much better transverse envelopes [5]. Our previous ADS linac studies successfully found compensation settings without quadrupole retuning, which we now attribute to differences in beam conditions (particles, energy range, etc.) and design priorities: SPIRAL2 linacs are optimized for high acceleration efficiency, whereas ADS linacs prioritize fault tolerance (*e.g.*, derated operation). Additionally, breaking the periodicity at low energies and optical design factors (phase-advance, aperture size) further contribute to these differences. We are currently developing quadrupole retuning strategies: LightWin sets the optimization problem, but TraceWin performs the actual optimization by injecting commands into `DAT` files, as done for steerers. In the future, we will implement quadrupole retuning directly in LightWin.

Several observations suggest our optimization problem formulation is not yet optimal. The stochastic nature of NSGA-III means solutions vary between executions, and some are unacceptable. Additionally, we struggle to find solutions for complex scenarios, particularly full cryomodule failures. Finally, neglecting space-charge effects during optimization may not be optimal due to the low rigidity of the SPIRAL2 beam. Thus, we are implementing a 3D envelope beam dynamics solver with space-charge support, based on TraceWin [19] and pyACCEL [20].

CONCLUSION

This study successfully adapts LightWin to SPIRAL2, demonstrating effective longitudinal compensation for cavity failures and showing that the resulting settings are acceptable for single cavity failures. However, the compensation method parametrization is not yet optimal, so we plan systematic studies to identify the best approach. These studies will cover all cavity failures, as start and end failures may require different strategies. We also observed that, unlike in our previous studies, quadrupole retuning in the compensation zone is necessary to preserve transverse acceptance. This is another aspect we will address. Finally, we will develop improved beam dynamics solvers with space-charge modeling. These updates will advance automation of cavity failure compensation in the SPIRAL2 SC linac and adapt LightWin to any linac.

REFERENCES

[1] A. Orduz *et al.*, “SPIRAL2 operations and future plans”, in *Proc. LINAC’24*, Chicago, IL, USA, Aug. 2024, pp. 284–286. doi:10.18429/JACoW-LINAC2024-TUXA005

[2] R. Ferdinand *et al.*, “GANIL-SPIRAL2 facility - Recent achievements and upgrades”, presented at the 17th International Particle Accelerator Conf. (IPAC ’26), May 2026, paper MOI4M01, this conference.

[3] A. P. Shishlo and C. C. Peters, “Fully Automated Tuning and Recover of a High Power SCL”, in *Proc. LINAC’22*, Liverpool, UK, Aug. 2022, pp. 884–888. doi:10.18429/JACoW-LINAC2022-FR1AA06

[4] A. K. Orduz, M. D. Giacomo, J.-M. Lagniel, G. Normand, and D. U. Uriot, in *Proc. HB’23*, Geneva, Switzerland, Aug. 2024, pp. 106–111. doi:10.18429/JACoW-HB2023-TUA3I1

[5] A. Leduc *et al.*, “Cavity Failure Compensation Study in Spiral 2 LINAC: Simulation and Experimentation”, presented at the 17th International Particle Accelerator Conf. (IPAC ’26), May 2026, paper WEP5005, this conference.

[6] A. Plaçais, F. Bouly, J.-M. Lagniel, D. Uriot, and B. Yee-Rendon, LightWin, Nov. 2024. `https://github.com/AdrienPlacais/LightWin`

[7] A. Plaçais *et al.*, “Automatic retuning of superconducting linacs using LightWin”, in *Proc. LINAC’24*, Chicago, IL, USA, Aug. 2024, pp. 563–568. doi:10.18429/JACoW-LINAC2024-THXA001

[8] K. Deb, “Multi-Objective Optimization Using Evolutionary Algorithms: An Introduction”, in *Multi-objective Evolutionary Optimisation for Product Design and Manufacturing*, Springer, 2011. doi:10.1007/978-0-85729-652-8_1

[9] A. Plaçais and F. Bouly, “Cavity Failure Compensation Strategies in Superconducting Linacs”, in *Proc. LINAC’22*, Liverpool, UK, Aug. 2022, pp. 552–555. doi:10.18429/JACoW-LINAC2022-TUPORI04

[10] A. Plaçais, F. Bouly, and B. Yee-Rendon, “Development of a Tool for Cavity Failure Compensation in Superconducting Linacs: Progress and Comparative Study”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 4097–4100. doi:10.18429/JACoW-IPAC2023-THPA060

[11] B. Yee-Rendon *et al.*, “A systematic analysis of cavity compensations in the JAEA-ADS linac utilizing the LightWin tool”, presented at the 17th International Particle Accelerator Conf. (IPAC ’26), May 2026, paper WEP4621, this conference.

[12] B. Yee-Rendon, Y. Kondo, J. Tamura, K. Nakano, F. Maekawa, and S.-i. Meigo, “Beam dynamics studies for fast beam trip recovery of the Japan atomic energy agency accelerator-driven subcritical system”, *Phys. Rev. Accel. Beams*, vol. 25, no. 8, p. 80101, Aug. 2022. doi:10.1103/PhysRevAccelBeams.25.080101

[13] H. Podlech *et al.*, “The MYRRHA Project”, in *Proc. NAPAC’19*, Lansing, MI, USA, Sep. 2019, pp. 945–950. doi:10.18429/JACoW-NAPAC2019-THZBA2

[14] B. Yee-Rendon, Y. Kondo, F. Maekawa, S.-I. Meigo, and J. Tamura, “Design and beam dynamic studies of a 30-MW superconducting linac for an accelerator-driven subcritical system”, *Phys. Rev. Accel. Beams*, vol. 24, no. 12, p. 120101, Dec. 2021. doi:10.1103/PhysRevAccelBeams.24.120101

[15] P. Virtanen *et al.*, “SciPy 1.0: fundamental algorithms for scientific computing in Python”, *Nature Methods*, vol. 17, no. 3, pp. 261–272, Mar. 2020. doi:10.1038/s41592-019-0686-2

[16] T. P. Wangler, *Longitudinal Particle Dynamics*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2008. doi:10.1002/9783527623426.ch6

[17] J.-M. Lagniel, private communication, 2023.

[18] J. Blank and K. Deb, “Pymoo: Multi-Objective Optimization in Python”, *IEEE Access*, vol. 8, pp. 89497–89509, 2020. doi:10.1109/ACCESS.2020.2990567

[19] D. Uriot, N. Pichoff, and R. Duperrier, TraceWin, Université Paris-Saclay, CEA, Département des Accélérateurs, de la Cryogénie et du Magnétisme. `https://www.dacm-logiciels.fr/downloads`

[20] L. De Keukeleere, E. Tanke, J. Hustings, J. Van De Walle, and U. Dorda, “Benchmarking beam dynamics simulations for the MYRRHA Phase 1 accelerator”, presented at the 17th International Particle Accelerator Conf. (IPAC ’26), May 2026, paper WEP7154, this conference.