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AUTOMATIC RETUNING OF SUPERCONDUCTING LINACS USING LightWin

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Abstract

Reliability is an important feature for high-power particle accelerators. A significant proportion of beam trips come from the failure of superconducting accelerating cavities or their associated systems. Failure compensation is a technique that can limit the impact of these failures and therefore increase beam availability. Finding ideal compensation settings is, however, a difficult challenge that involves beam dynamics and multi-objective optimization, and which raises very different issues according to the linac under study. In this study, we present the LightWin tool to automatically find compensation settings in linacs. We study different compensation strategies on the MINERVA superconducting linac and present our first results on the SPIRAL2 superconducting linac.

CAVITY FAILURE COMPENSATION FOR HIGH AVAILABILITY

In order to advance the frontiers of particle physics and develop new applications, hadron accelerators are being driven towards increasing mean beam power. This tendency gives rise to numerous issues concerning accelerator design. These systems are expensive, making it important to maximize beam availability. To increase the RF-to-beam efficiency, reach higher accelerating fields, and optimize operation costs, the accelerating systems generally utilize superconducting (SC) technologies. However, these systems involve more subsystems which increase the failure risk.

Failure of cavities or their associated systems is a significant source of beam trips. Therefore, a promising solution to increase beam availability lies in cavity failure compensation. When a cavity failure is detected, the cavity is quickly detuned, and neighboring or all RF cavities are retuned. This can help maintain the beam and, in some cases, restore nominal beam conditions.

This method has already been applied successfully [1–3]. However, finding compensation settings for a given failure scenario can be complex and time-consuming. Additionally, this method is relatively new, and best practices for compensation are not well established. Furthermore, the failure compensation strategy may differ from one machine to another. This strategy depends on the linac design characteristics (*e.g.*, longitudinal acceptance) and its purpose

(type of beam and reduced velocity). Margins – foreseen by design, especially on the accelerating gradient – will also ease the application of the failure compensation scheme.

This is generally the case for Accelerator-Driven Systems (ADS). They are nuclear fission reactors driven by a stable proton beam. The beam impacts a spallation target, producing neutrons and interacting with the sub-critical nuclear core. Every prolonged interruption of the beam creates thermal constraints on the reactor structure. These interruptions also necessitate lengthy restart procedures, further reducing plant availability [4]. Thus, ADS feature a fault-tolerance design based on redundancy. The cavities are operated derated to their maximum capabilities, and the longitudinal acceptance of the linac is maximized by design. The requirements may differ from one project to another, but generally one should be able to recover the beam after a failure in a few seconds [5].

Considering the importance of reliability studies, the dedicated ReFiL (Reliability and fast Failure compensation methods in RF superconducting Linacs) project was launched at CNRS – IN2P3. Its objectives are to develop new RF failure mitigation techniques and assess the causes of longitudinal acceptance reduction – in particular, non-linear effects and parametric resonances in high gradient linacs [6]. The initiative currently involves the LPSC Grenoble, IJCLab Orsay and GANIL Caen French laboratories.

In the first section, we introduce the LightWin code and provide general implementation details. LightWin is a beam dynamics code developed for finding compensation settings in SC linacs. The goal is to provide a tool that can adapt to any linac to study different compensation strategies. The following sections present examples of studies and working perspectives for different linacs. The second section is dedicated to a systematic study on MINERVA. In the third section, we present the specific challenges of the SPIRAL2 SC linac, as well as the initial settings we found for a cavity failure in the low- β section.

LightWin

LightWin is an open-source code we developed for finding compensation settings [7–9]. It is mainly written in Python. It was designed with the ultimate goal of being usable on any linac, with any cavity failure compensation strategy. Its main feature is that it operates automatically, meaning it can find compensation settings for any number of failure

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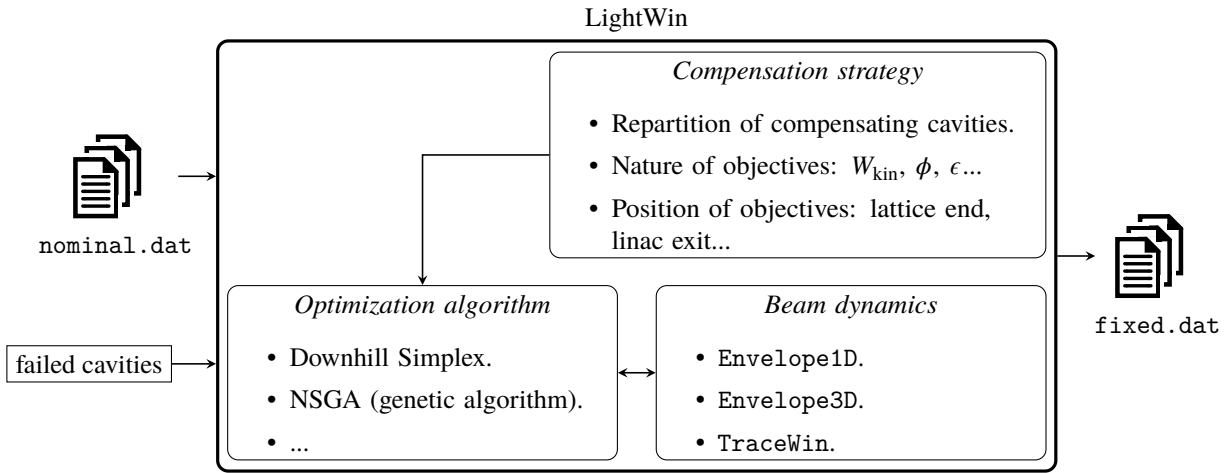


Figure 1: Simplified structure of LightWin.

scenarios without requiring intervention. This serves two purposes. Firstly, it significantly aids in creating a database to enable the rapid application of compensation settings. Secondly, it allows for the systematic comparison of several compensation strategies across the same set of failures.

We represented in Fig. 1 the simplified structure of LightWin. The input and output .dat files describing the structure of the linac follow the same syntax as the files used by the beam dynamics reference code TraceWin [10]. The optimization algorithm, parametrized by the compensation strategy, calls the beam dynamics tool with different settings until the converge criterion are met. In the following, we present how these three main blocks are parametrized for this study.

Beam Dynamics

Finding compensation settings is an optimization process that requires a significant amount of beam dynamics calculations. The rapidity of those calculations is crucial. For the optimization, we propagate the beam envelope beam in the longitudinal phase-space and neglect space-charge effects. These simplifications allow LightWin to be very fast; we found it accurate enough to describe beams primarily influenced by longitudinal dynamics.

Once the compensation settings are determined, the compensation model is tested using multiparticle simulations with space-charge effects to evaluate the performance in a more realistic scenario. The emittances, beam power losses, cavity parameters that we present in this study were all obtained with a multiparticle TraceWin simulation.

Optimization Algorithm and Compensation Strategy

In the following studies, we perform the optimizations with the Downhill simplex algorithm [11, 12]. We found it to be fast and reliable when the number of compensating cavities is relatively low, *i.e.*, between 1 and 8 cavities. On a modern laptop (11th Gen Intel i7-11850H @ 4.8 GHz), finding settings for a failure compensated by four cavities

typically takes a few tenths of seconds. For a cryomodule compensated by eight cavities, it takes 10 min to 20 min.

Variables Typically, the variables in this problem are the amplitude and phase of each compensating cavity's electric field. The bounds on the amplitude are given by the cavities' specifications. We try to keep the beam focused in the longitudinal phase space and the longitudinal acceptance as high as possible. To that end, we maintain the synchronous phase of the accelerating cavities between -90° and $\phi_s^{\text{base}} + 30\%$. ϕ_s^{base} is the synchronous phase of the cavity in the baseline design. The synchronous phase ϕ_s is defined by:

$$\Delta W_{\text{kin}} = V_{\text{cav}} \cos \phi_s \quad (1)$$

where ΔW_{kin} is the kinetic energy gained by the synchronous particle in the cavity and V_{cav} is the accelerating potential. Since the Downhill Simplex algorithm does not support constraints, we must reformulate the problem to respect the synchronous phase boundaries. We observed that the best approach was to replace the phase variable with a synchronous phase variable, bounded between -90° and $\phi_s^{\text{base}} + 30\%$. This involves more operations, but greatly facilitates the convergence of the optimization algorithm.

Objectives The optimization objectives are defined to restore a beam as close as possible to the baseline beam. The first objective to minimize is the longitudinal mismatch factor $M_{z\delta}$ at the exit of the compensation zone. The mismatch factor quantifies the difference between the emittances of two beams [9, 13, 14]. The second objective to minimize is the difference in beam kinetic energy between the baseline and retuned linacs at the exit of the compensation zone.

In this work, contrary to our previous studies [8, 9], we do not recover the absolute phase of the beam at the exit of the compensation zone. This approach is less constraining for compensating cavities and facilitates the convergence of the optimization algorithm. However, it necessitates rephasing all downstream cavities to maintain synchronicity between

the beam and RF fields, a method we refer to as "local-global" compensation method. One of LightWin's key advantages is its flexibility in switching between different compensation strategies. Specifically, the tool supports the local-global method, the local method (where only a few cavities near the failure are retuned), and the global method (where all downstream cavities are retuned).

MINERVA STUDY

MYRRHA-ADS and SC linac

The MYRRHA-ADS project is led by the SCK CEN laboratory in Mol, Belgium. Its objective is to build an ADS based on a 4 mA, 600 MW CW (Continuous Wave) SC proton linac. The phase I of the project, called MINERVA, consist in building and operating the first section of the linac in an ADS-like configuration. It will accelerate a 4 mA proton beam from 17 MeV to 100 MeV, with the first beam expected by the end of 2027 [15]. The cavity parameters for this first section are detailed in Table 1.

Table 1: Cavity Parameters in MINERVA

Cavity parameters	MINERVA
Cavity type	Single spoke
f [MHz]	352.2
Cavities per cryomodule	2
Cryomodules	30
$E_{\text{acc}} @ \beta_{\text{opt}}$ [MV m ⁻¹]	7.0
E_{acc} possible values [MV m ⁻¹]	9.1 (+30%)
Range of ϕ_s [°]	-37 → -18

As the linac produces a beam for an ADS, it must meet stringent reliability constraints. Specifically, there should be fewer than 10 failures longer than 3 s per 3 month operating cycle. Additionally, beam losses in the SC linac should not exceed 1 W m⁻¹ [5]. This is achievable due to high longitudinal acceptance and derated cavities and amplifiers; the accelerating field can be increased by up to 30% over nominal tuning.

Single Cavity Failure Systematic Study

There are 60 cavities in the MINERVA linac. We conducted a systematic study to find compensation settings for each cavity failure using the "local-global" compensation method described in the previous section. We selected two compensating lattices per failure, in addition to the working cavity in the same lattice as the failed one. The compensation scheme is shown in Fig. 2. Green cavities are not retuned. The red cavity is failed, and the failure is compensated by the orange cavities. All downstream cavities, in yellow, are rephased.

For every failure compensation case, the beam energy was successfully recovered at the linac exit with acceptable beam properties. We conducted multiparticle TraceWin simulations for each scenario and observed that particle losses were moderate. Figure 3 shows the maximum linear

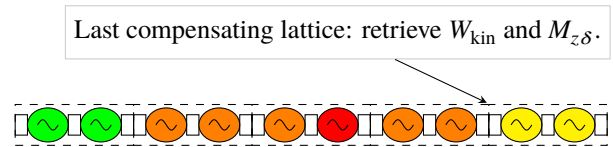


Figure 2: Scheme of the compensation strategy chosen for the MINERVA study. Green cavities are nominal. Failed cavities are in red. Orange represent retuned cavities. In yellow, the cavities that are only rephased.

losses in the SC linac for each failure. The losses remained below 1 W m⁻¹ in all cases, except for cases #20 and #30, where the losses were still within reasonable limits.

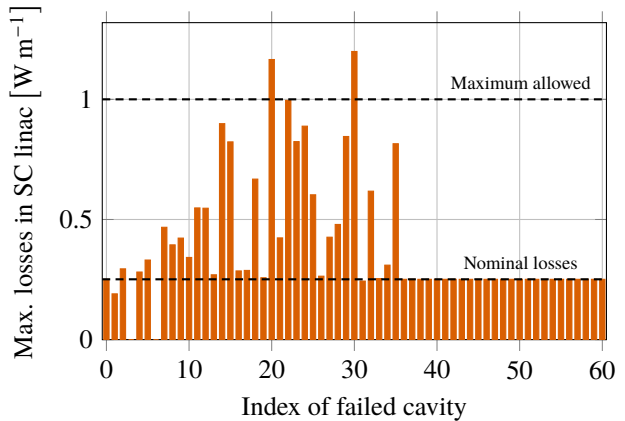
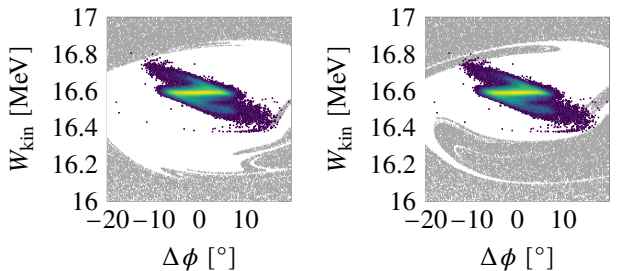


Figure 3: Maximum linear losses for every cavity failure, after compensation.

The highest total power loss was 9.0 W, occurring with a failure in cavity #14, which we found to be representative. Figure 4 shows the longitudinal acceptance of the SC linac in the nominal case and after compensation of cavity #14. Additionally, it displays the particle distribution in the longitudinal phase-space at the SC linac entrance. The particle distributions in the longitudinal phase-space at the exit of the SC linac are illustrated in Fig. 5.



(a) Nominal tuning. (b) Compensation of #14 failure.

Figure 4: Longitudinal acceptance of the MINERVA SC linac with the input beam distribution in the $[\Delta\phi, W_{\text{kin}}]$ phase space.

As shown in Fig. 5, compensating the failure led to a moderate increase in filamentation. This effect is already

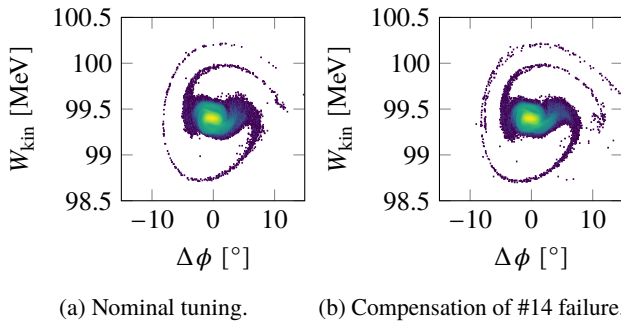


Figure 5: Longitudinal emittance at the exit of the MINERVA SC linac.

significant in the nominal case due to a relatively large beam halo at the linac entrance. Furthermore, as depicted in Fig. 4, the compensation settings led to a reduction in longitudinal acceptance, excluding some halo particles. These particles will be lost in the longitudinal phase space and due to improper acceleration and physical aperture, they are also progressively lost in the transverse plane. This process can take several lattices period to manifest explaining why Fig. 3 shows minimal power losses in the second half of MINERVA. In some cases this could lead to additional losses in the transfer line downstream of the MINERVA linac.

This study underscores the importance of designing a linac with a maximized acceptance to safely apply retuning procedures, as previously highlighted in [16–18]. Additionally, it emphasizes the critical role of tuning the injector and associated transfer line to provide a beam as compact as possible (with minimized halo) at the SC linac input, particularly for failure compensation at low- β . Such losses were not observed in previous studies conducted on higher energy sections [9] or in multiple failure compensation scenarios using “less realistic” Gaussian beam distributions [8].

SPIRAL2 SC LINAC APPLICATIONS

Presentation of the SC linac

SPIRAL2 (*Système de Production d’Ions RAdioactifs en Ligne de 2^{ème} génération*, 2nd generation radioactive ion production linear system) is a SC linac located in Caen, France [3]. It is designed to accelerate intense ion beams with A/Q ranging from 1 to 7, which can be utilized in various experimental facilities for nuclear physics and applied research. Currently, accelerated particles are mainly D^+ and $^4He^{2+}$ with energies ranging from 7 to 20 MeV A^{-1} . First linac tuning with $^{18}O^{6+}$ and $^{40}Ar^{14+}$ were carried out [3].

The linac is composed of two superconducting sections, with the corresponding cavity settings summarized in Table 2.

Initially, increasing the cavities gradients to compensate for a failure was not considered [19]. Additionally, due to the strong debunching effect [3], global compensation was found to be the most effective retuning strategy. As shown in Fig. 6, all cavities downstream of the failure are

Table 2: 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
$E_{acc} @ \beta_{opt}$ [MV m^{-1}]	6.5	6.5
E_{acc} possible values [MV m^{-1}]	6.5 \rightarrow 8.0	5.8 \rightarrow 8.0

retuned, along with two upstream cavities. From a mathematical point of view, this represents a complex optimization problem with a very high number of variables. Moreover, given the non-negligible effect of the RF cavities’ field on the transverse beam dynamics, it is also necessary to retune some quadrupoles. These challenges require significant adaptations in LightWin to consistently retrieve compensation settings for SPIRAL2. At the time of writing, these improvements are still being implemented in the code.

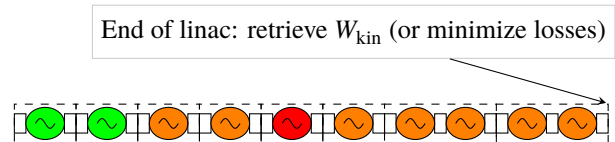


Figure 6: Illustration of the global compensation strategy. All the downstream cavities as well as two upstream cavities (orange) participate in the compensation of the failed cavity (red). First cavities of the SC linac remain untouched (green).

Compensation Settings

Several cavity failures have already occurred during operation [2, 3]. The failed cavities were located in the high- β section (section B), where the beam is relatively rigid. The SC linac could be operated by retuning all downstream cavities, although the output energy was reduced.

Compensating for failures in the low- β section (section A) presents a more significant challenge. In this section, the beam is extremely soft and space-charge effects cannot be neglected. Plus, there is substantial debunching between the cavities [3]. In the following, we focus on compensating the CMA06 cavity, the sixth cavity in the section A. At this position, the beam experiences moderate debunching, making it an ideal candidate for initial low- β compensation trials.

At the end of 2023, we deliberately turned off CMA06 and rephased all cavities downstream of the failure to preserve the longitudinal acceptance. This approach allowed us to successfully propagate a 900 μA $^4He^{2+}$ beam to the end of the linac [3]. However, the final energy was reduced from 80 MeV to 64 MeV, and additional 140 W of losses were calculated. Measured losses were under 1 W m^{-1} .

Ongoing Studies

Since then, operational experience has shown that the cavities gradients can be increased (see Table 2) to apply failure compensation. Based on this insight, we propose new compensation settings utilizing these updated margins, which enable the recovery of the final beam energy without introducing additional losses in the machine. Figure 7 illustrates the compensation settings alongside the nominal ones for delivering a D^+ 40 MeV in both cases. The position of CMA06 is highlighted with a red vertical line. We found the

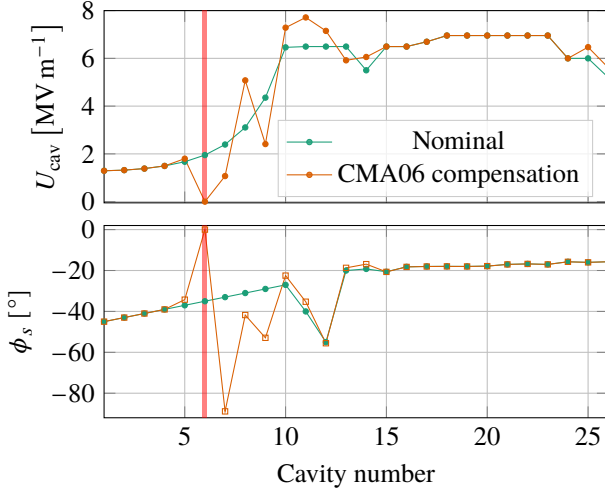


Figure 7: Cavity settings for the CMA06 compensation. Position of the failure is indicated by the red vertical line. U_{cav} is the electric field applied to the cavity.

settings cavity per cavity, to preserve beam matching from one lattice period to the next and maintain the longitudinal acceptance as large as possible. To achieve this, the cavity immediately downstream of the failed one (CMA07) was operated in quasi-buncher mode. The lack of acceleration was smoothly mitigated by rephasing the rest of the linac. The final energy adjustment was made by increasing the gradient of the last two cavities in section B.

We illustrated in Fig. 8 the longitudinal acceptance of the SC linac in both the nominal case and after CMA06 compensation. As observed in the MINERVA study, the longitudinal acceptance is reduced, leading to the loss of some halo particles. However, the losses are moderate, amounting to an additional 3.2 W distributed along the linac. Figure 9 illustrates the longitudinal emittances at the exit of the SC linac. No significant distortion is observed, and emittance growth is minimized without any noticeable filamentation effect. A dedicated experimental campaign is planned for the end of 2024, during which we will attempt to implement these compensation settings.

CONCLUSIONS

Enhancing the reliability and beam availability of SC linacs is an increasingly important challenge, driven by rising

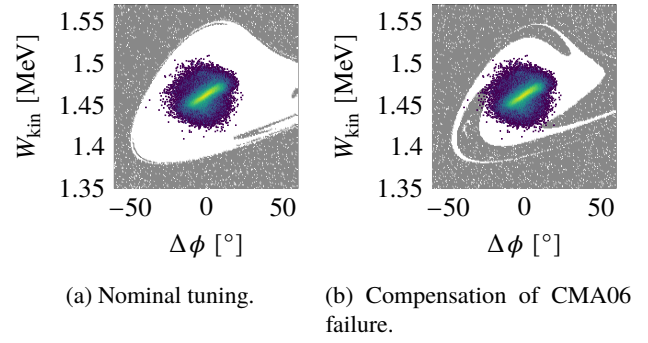


Figure 8: Longitudinal acceptance of the SPIRAL2 SC linac with the input beam distribution in the $[\Delta\phi, W_{\text{kin}}]$ phase space.

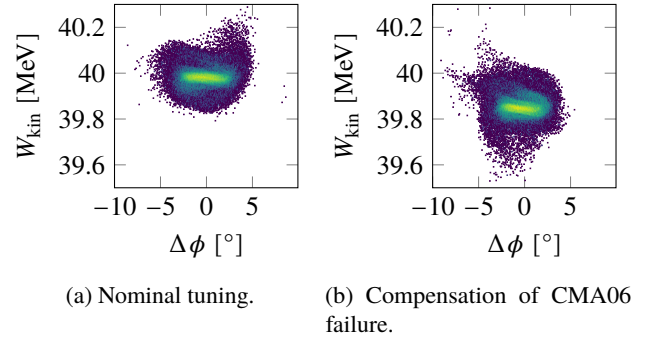


Figure 9: Longitudinal emittance at the exit of the SPIRAL2 SC linac.

machine costs and the need for cost-effectiveness. In this paper, we explored compensation strategies in two SC linacs.

For the MINERVA SC linac, which is part of the MYRRHA-ADS project, we conducted a systematic study using the open-source tool LightWin [7]. We successfully identified compensation settings for all single cavity failures, with losses consistently remaining below or close to the 1 W m^{-1} threshold.

In addition, we found compensation settings for the CMA06 cavity, a low- β cavity in the SPIRAL2 SC linac, specifically for a deuteron beam configuration. We were able to restore the nominal beam energy at the linac exit with minimal losses. An experimental campaign is scheduled for November 2024 to test these settings on the actual machine.

A key challenge identified in both studies is the reduction in longitudinal acceptance. This reduction leads to the exclusion of some halo particles, which are then not properly accelerated, resulting in longitudinal losses. To address this, we will continue refining compensation methods within LightWin to better preserve longitudinal acceptance. Additionally, we plan to implement new beam dynamics tools that account for space-charge effects, enabling more accurate modeling of the SPIRAL2 beam. Finally, we aim to develop new optimization algorithms to manage scenarios with a larger number of compensating cavities, such as full cryomodule or global compensation strategies.

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