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CAVITY FAILURE COMPENSATION STRATEGIES IN SUPERCONDUCTING LINACS

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Abstract

RF cavities in linear accelerators are subject to failure, preventing the beam from reaching it's nominal energy. This is particularly problematic for Accelerator Driven Systems (ADS), where the thermal fluctuations of the spallation target must be avoided and every fault shall be rapidly compensated for. In this study we present LightWin. This tool under development aims to create a database of the possible cavity failures and their associated compensation settings for a given accelerator. We apply it on the MYRRHA ADS, with a scenario including various faults distributed along the accelerator, and compare the settings found by LightWin to those found by the code TraceWin. We show that both tools find different compensation settings. We also outline the limitations of LightWin and explain the upcoming improvements.

INTRODUCTION

The efficiency, availability and reliability of particle accelerators is an important issue for high power linacs. In particular, accelerator-driven systems (ADS) have very stringent beam availability requirements. Their principal application is the transmutation of long-lived radioactive waste into shorter-lived fission products. To this end, they provide a continuous high-energy proton beam that subsequently produces a neutron flux thanks to a spallation target [1]. Repeated beam interruptions affect the ADS availability and sustainability: thermal stress, long restart procedures among others [2]. As an illustration, the Multi-purpose Hybrid Research reactor for High-tech Applications (MYRRHA) shall not exceed ten beam interruptions longer than three seconds per three-month operating cycle [3].

Consequently, such ADS machines require a robust linac design, to operate with margins and provide a large longitudinal acceptance. Mitigation strategies have been implemented to anticipate failure of RF cavities and their associated systems [4]. In such situations, the other cavities may be re-tuned to compensate for the malfunctioning ones [5]. The new tunings must achieve the same beam energy and must limit the increase in emittance. Plus, they must be set in a very short amount of time.

In the first Section, we introduce LightWin, a tool under development to rapidly find compensation settings. In the second Section, we present the results obtained by using LightWin to calculate multiple failure scenarios in the MYRRHA linac. The last Section is dedicated to the review of LightWin as well as to the compensation strategies and optimisation algorithm that should be implemented in the future.

PRESENTATION OF LIGHTWIN

Several beam dynamics codes enabling to find compensation settings already exist, such as TraceWin [6]. They have been used and validated by the accelerators community for several years. However, they are multi-purpose and thus are not particularly optimised for compensation. In addition, there is only a limited choice for numerical solvers and methods. Thus, we have been developing a tool called LightWin, dedicated to finding cavity failure compensation tunings and revising the work presented in [7]. It aims at providing precise retuning settings as fast as possible and is focused on the longitudinal bean dynamics description (envelope mode). It uses 1D RF field map and space charge effects are neglected as for now. LightWin uses the same linac description file format as TraceWin, and was designed to be used in combination with TraceWin for the 3D studies. LightWin is implemented in Python, and the most time-consuming routines are implemented in Cython.[1]

Computation of the beam and linac properties

The compensation process starts by the calculation of the energy and phase of the synchronous particle as well as of the longitudinal transfer matrix components, in absence of any fault (*nominal* linac).

Compensation zone

The second step is the set up of the compensation zone around every fault; it encompasses all the cavities to be retuned, all other cavities remaining untouched. It is the *local* compensation process – in the *global* compensation process, all the cavities after the faults are rephased. The global method should be less demanding in terms of RF power margins. However, it requires that a high number of cavities are rapidly rephased.

When two compensation zones overlap, the corresponding faults are fixed together. It corresponds in particular to the situation where a full cryomodule fails. When the scenario involves several faults, they are fixed in sequential manner starting from the linac entry. The choice of the number of compensating cavities per fault is up to the user. If a lattice period includes a least one compensating cavity, all other cavities of the lattice period will be compensating too. Fig. 1 represents the compensation zone strategy we adopted in this study.

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[1] https://cython.org

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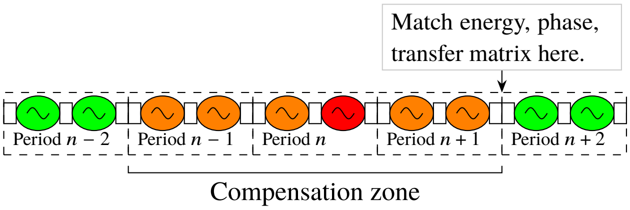

Figure 1: Scheme of a failed cavity (red) at the lattice period n. The $k = 5$ neighboring cavities (orange) compensate for the fault; cavity settings outside of the compensating zone remain in nominal tuning (green).

Optimisation process

The last step is the proper compensation. An optimisation algorithm is used to match the energy and phase of the synchronous particle as well as the longitudinal transfer matrix components at the end of the compensation zone. The variables are the entry phase and electric field of every compensating cavity.

From the mathematical point of view, finding a compensation setting is a multi-objective optimisation problem. The variables are the RF amplitude E_0 and the RF phase ϕ_0 of every compensating cavity. There is no bound on the phases, but lower and upper limits on the amplitude are given by the cavity technology, the multipacting limits and the maximum heat load that is acceptable for the cryomodules. We introduce constraints on the synchronous phase ϕ_s of each compensating cavity; lower limit is −90°. Upper limit was chosen 40 % above the nominal ϕ_s value to keep an acceptable longitudinal acceptance. The objectives are the phase and energy of the synchronous particle and the four components of the longitudinal transfer matrix, evaluated at the exit of the last compensating lattice period. The optimization is realized with a least-squares algorithm.

This whole process can be time-consuming. Hence it is provided that LightWin will pre-compute compensation settings for a variety of fault scenarios, creating a database of faults and of associated settings.

COMPARATIVE STUDY ON A MULTIPLE FAILURE SCENARIO

Presentation of the MYRRHA linac

This superconducting linac is designed to accelerates a 4 mA proton beam from 16.6 MeV to 600 MeV (maximum power of 2.4 MW). It contains three different types of cavities [3]:

- single spokes at 352.2 MHz in the first section (MINERVA) [8–12];
- double spokes at 352.2 MHz in the second;
- 5-cell elliptical cavities at 704.4 MHz in the third and last section.

Presentation of the fault scenario

The studied multiple failure scenario comprises a representative panel of the different faults that can occur [13]:

- Section 1:
  - a spoke at the beginning of the linac;
  - the penultimate single spoke;
- Section 2:
  - the second double spoke;
  - a double spoke in the middle of the section;
- Section 3:
  - the first elliptical cavity;
  - a full cryomodule (four cavities) in the middle of the section;
  - a cavity at the end of the linac.

In total, ten cavities are faulty.

Methodology

We calculated fault compensation settings with both LightWin and TraceWin codes and compared the results. We use the local compensation method and the maximum electric field norm is set to 30 % above the nominal electric field, following MYRRHA's design [3]. In LightWin study, synchronous particle is tracked with a fourth-order Runge-Kutta algorithm. The least-squares algorithm used for the optimisation is from SciPy library[2]; the convergence criterion has it's default value. TraceWin study requires much more time and dedication, as we have to manually hint the optimisation code with the synchronous phase and emittance that the beam should match. We realise this optimisation with the *Owner* algorithm.

Results

We represented in Fig. 2 the accelerating voltage and synchronous phase of the cavities for the nominal setting and for LightWin's and TraceWin's compensation settings. We can notice that the optimisation algorithms of LightWin and TraceWin converged towards different solutions. It means that several local optimum exist for every fault; finding the best among them is a fundamental issue.

We represented in Fig. 3 the difference of absolute phase between the nominal linac and the two fixed machines. Both tools managed to retrieve a null phase difference after every faults, which is a necessary condition for the beam to keep being synchronised with the following cavities. The only exception is the full cryomodule error in Section #3, where the absolute phase is not fully recovered with LightWin. However, it is compensated by the last failure compensation and the beam envelope remains well controlled.

DISCUSSION

LightWin enables automatic calculation of failure compensation, while for TraceWin the compensation required several manual adjustments. Still, there are several physics improvements that shall be implemented in LightWin. First of all, we try to match the four components of the longitudinal matrix; this could be reduced to three using the symplecticity properties of the transfer matrix. Alternatively, we

[2] https://scipy.org

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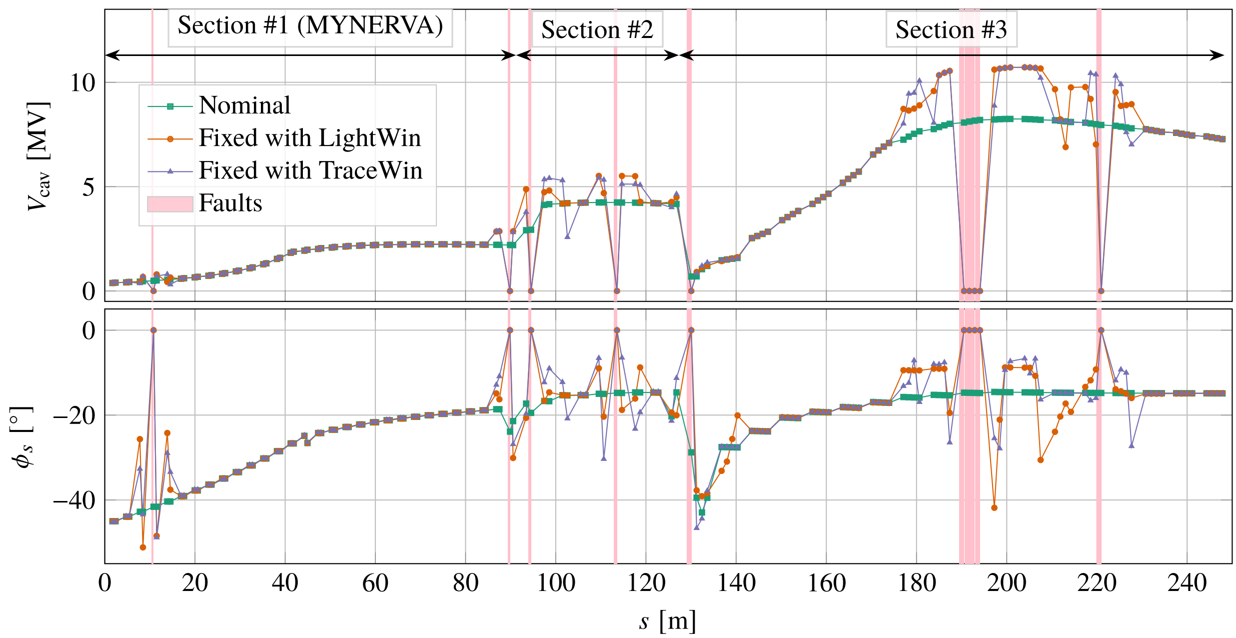

Figure 2: Accelerating voltage and synchronous phase of the cavities.

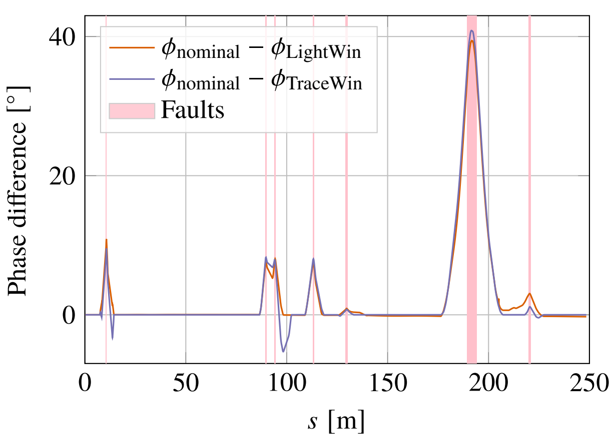

Figure 3: Error with the absolute nominal phase for LightWin and TraceWin.

could make a match on the Twiss parameters. Also, we introduced an arbitrary upper bound on the synchronous phases; it could be more relevant to adjust this bound for each cavity as function of the required longitudinal acceptance.

In Section #3, for the full cryomodule compensation, the LightWin solution did not fully match the required precision on the absolute phase. As a matter of a fact, the number of variables is too important for the least-squares algorithm. We could circumvent this problem by manually tuning the initial guess and bounds of the least-squares algorithm, but this approach is incompatible with the automatic creation of a database. A lot of different optimisation algorithms may suit our needs better and should be investigated: Downhill simplex, genetic algorithms, particle-swarm optimisation, Hooke and Jeeves, Rosenbrock.

Finally, the tool should enable to carry out systematic studies to calculate every single cavity failure scenario to provide a retuning database. LightWin should be adaptable to different linacs and enable to use different strategies, e.g. use more cavities with less or no margins on the accelerating field. It could also allow the rephasing of full linac sections.

CONCLUSIONS

In this paper, we presented our compensation tool, LightWin. We showed that it enables to automatically recalculate the cavity settings for a variety of failure scenarios. It is however still under development and several improvements should be implemented. In particular, the control of synchronous phases and longitudinal acceptance and other optimisation algorithm than the least-squares to explore the full space of parameters as to avoid local minima.

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