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► To cite this version:

A Plaçais, Frédéric Bouly, B. Yee-Rendon. Development of a tool for cavity failure compensation in superconducting linacs: progress and comparative study. 14th International Particle Accelerator Conference (IPAC23), May 2023, Venice, Italy. pp.4097-4100, 10.18429/JACoW-IPAC2023-THPA060 . hal-04306983

HAL Id: hal-04306983

<https://hal.science/hal-04306983>

Submitted on 25 Nov 2023

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DEVELOPMENT OF A TOOL FOR CAVITY FAILURE COMPENSATION IN SUPERCONDUCTING LINACS: PROGRESS AND COMPARATIVE STUDY

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Abstract

Reliability in high power hadron accelerators is a major issue, in particular for Accelerator-Driven Systems (ADS). In these devices, thermal fluctuations in the fission reactor must be avoided. A significant number of breakdowns are caused by the failure of accelerating cavities or by their associated systems. The cavities neighboring a fault can be retuned to compensate it and avoid extended beam interruptions. In this paper, we use a fully automated tool called LightWin to find compensation settings for a set of errors in a section of the superconducting linac of the Japan Atomic Energy Agency ADS project. LightWin models longitudinal beam dynamics, and does not take space charge effects into account. Hence, we inject LightWin compensation settings into TraceWin to perform multiparticle simulations. We compare the resulting beam optics to those found in a previous study with TraceWin only. We find that they are similar.

INTRODUCTION

High power accelerator operation requires high availability and reliability. Accelerator-Driven Systems (ADS) must fulfill extreme reliability requirements, since any beam interruption creates thermal stress on the spallation target and the reactor structure [1]. As an illustration, the Japan Atomic Energy Agency (JAEA) ADS maximum frequency of beam trips longer than 5 min was set to 42 per year [2]. This is why ADS linacs adopt a fault-tolerant design [3], with a specifically high acceptance. In particular and to enable failure compensation, superconducting rf (SRF) cavities are operated with a derated accelerating field E_{acc} regarding their maximum capacities. Finding the *ideal* compensation settings is a long and tedious work, which is not compatible with the ADS availability requirements.

We therefore developed LightWin, a beam dynamics code dedicated to finding compensation settings and benchmarked it against TraceWin [4]. It is automatic, which allows for a systematic study of every relatable fault scenario for a given linac. We already showed that it could find compensation settings for the MYRRHA ADS [5]. For the sake of rapidity, we made strong assumptions when developing LightWin. Only longitudinal dynamics are implemented; space-charge effects are neglected; the only particle that is tracked is the synchronous particle.

The objective of this study is to test the robustness of LightWin on the JAEA-ADS linac. We also want to verify if our modelling of beam dynamics is precise enough for this

accelerator. As a matter of fact, it accelerates a continuous-wave (CW) 20 mA beam and neglecting the space-charge effects seems to be a bold approximation. We use the work of B. Yee-Rendon *et al.* [6], who found compensation settings for several faults distributed along the JAEA-ADS linac with TraceWin only. We use LightWin to find compensation settings corresponding to some of these faults and compare them to the previous study.

COMPENSATION STUDY PROCEDURE

The JAEA-ADS is an ADS under development, which we represented in Fig. 1 [7]. A 30 MW CW superconducting proton linac produces neutrons by spallation on a lead-bismuth eutectic target. In order to maximise the beam availability and for compensation purposes, SRF cavities can increase their accelerating field E_{acc} by up to 20 %.

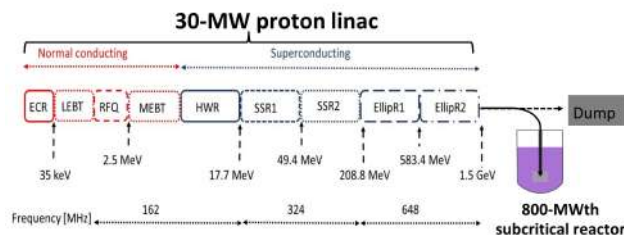


Figure 1: Schematic of the JAEA-ADS [8].

In this study, we analyzed the last eight periods of the last section of this ADS, which are periods 108 to 116. They encompass cavities 254 to 293, and accelerate the proton beam from 940 MeV to 1.5 GeV. Each period contains five cavities, which are five-cell elliptical resonators at 648 MHz.

In a previous study, B. Yee-Rendon *et al.* [6] studied various cavity and quadrupole errors distributed along the SC linac. They found compensation settings with the help of TraceWin. It allows one to retune elements of the linac in order to reach the target beam values. A lot of operations are manual – such as setting the compensating elements or the position of the matching – which is time-consuming and error-prone.

In this study, we use the envelope longitudinal dynamics code LightWin. It retunes the norm and the phase or synchronous phase of the field in the compensating cavities. We implemented several optimisation algorithms, including a least-squares method [9]. The optimisation objectives can be the difference of any beam optics parameter between the

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baseline and the retuned designs: kinetic energy, absolute phase, transfer matrix components, emittances, Twiss parameters, envelopes, cavity parameters. It can finally be set to the longitudinal mismatch factor [10, 11], also defined in the appendix.

The full automatic workflow is the following:

1. Choose faulty cavity and take associated compensation scheme from Ref. [6].
2. Using LightWin, compute the propagation of the beam in the compensation zone until optimum is reached.
3. Then, recompute the propagation of the beam up to the end of the linac.
4. Implement the retuning settings into TraceWin and perform the multiparticle study, including space-charge effects.
5. Evaluate the beam optics difference between the baseline and the retuned cases, at the end of the linac.

The objective functions, evaluated at the end of the compensation zone, are: (i) difference of kinetic energy between baseline and retuned designs; (ii) difference of absolute phase between baseline and retuned designs; (iii) longitudinal mismatch factor M . The retuned accelerating fields cannot increase by more than 20 % with respect to the baseline design. The maximum variation of the synchronous phase is kept below 50 %. The compensation scheme is a k -out-of- n method, where n errors are compensated by $k = 5n$ cavities. For the TraceWin simulation, we use one million of macro-particles, with the same distribution as B. Yee-Rendon *et al.* Employing the outputs of this simulation, we compute the relative variation of RMS emittance with the nominal settings and the mismatch factor. Both are evaluated in the longitudinal and transverse planes, at the exit of the SC linac.

SINGLE CAVITY ERROR STUDIES

We studied the single cavity errors #257 to #293 – the compensation schemes of errors #254, 255 and 256 fall out of the scope of this study as they involve cavities in the 107th period. A summary of the beam optics is given in Table 1. We also reported the beam optics that B. Yee-Rendon *et al.* found; we highlighted the cases where their optics were better than this study's. From a general point of view, we achieved slightly lower variations of emittances and mismatch factors. No losses were observed in any of the cases.

As an example, we represented in Fig. 2 the beam envelopes of the retuned linac for error #289 in the transverse, phase and energy planes. For this error, there are two upstream and three downstream compensating cavities. Fig. 3 shows the baseline and retuned cavity setting for this case. Our accelerating fields in all the compensating cavities are increased by 20 %. Synchronous phases from this study remain very close to the baseline design. It is noteworthy that

the compensation settings from Ref. [6] are relatively different. Their retuned accelerating fields and thus their energy consumption are lower. However, their retuned synchronous phases are much higher than ours, which affects more the longitudinal acceptance.

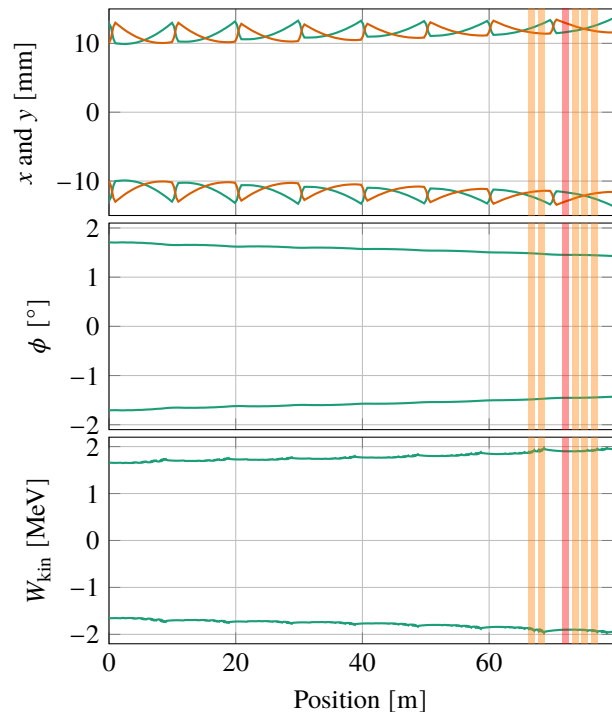


Figure 2: 6σ envelopes of the compensation scheme for the cavity #289 versus the position in the SC linac. 0 m corresponds to the position of the entry of the 108th period. Orange vertical lines show the position of compensating cavities; red vertical line shows position of failed cavity.

FULL CRYOMODULE ERROR STUDY

In Ref. [6], the FullPerV case is a scenario where the last cryomodule is entirely down. Similarly to the single cavity errors, authors compensated it with a k -out-of- n scheme – hence there are twenty-five compensating cavities. We reported in Table 1 the beam optics corresponding to this scenario, and are shown in Fig. 4 the envelopes in the transverse and longitudinal planes. As the failed cavities are at the very end of the linac, keeping the synchronicity of the beam is not necessary, and LightWin does not optimize the phase difference with the baseline. It explains why the longitudinal mismatch factor is important. Though, no losses were observed and these settings are acceptable.

CONCLUSION

In this paper, we studied several failure scenarios in the JAEA-ADS linac. We focused on a fraction of the last section, accelerating the proton beam from 940 MeV to 1.5 GeV. We found that the compensation settings that we obtained with our dedicated tool, LightWin, were acceptable. The main advantage is that it is automatic, allowing to make systematic studies on a wide range of scenarios.

Table 1: Beam optics performance for this study. “LW” stands for LightWin and “TW” for TraceWin. TraceWin results are taken from Ref. [6]. We outlined in red the beam optics that were better with TraceWin than with LightWin.

Faulty cavity	$\Delta\varepsilon/\varepsilon_0$ [%]				M			
	Transverse		Longitudinal		Transverse		Longitudinal	
	LW	TW	LW	TW	LW	TW	LW	TW
257	0.42	1.07	-1.11	1.52	0.03	0.02	0.10	0.09
258	0.11	0.88	-0.27	1.02	0.01	0.01	0.02	0.09
289	-0.01	0.09	-0.10	0.13	0.00	0.01	0.00	0.04
290	-0.06	-0.17	0.10	0.25	0.00	0.03	0.01	0.08
291	0.12	0.04	-0.03	0.13	0.01	0.03	0.03	0.09
292	-0.09	0.04	0.10	0.25	0.01	0.03	0.02	0.09
293	-0.02	0.21	0.17	0.25	0.01	0.03	0.02	0.09
289–293	0.18	1.78	-0.29	-1.27	0.13	0.02	0.35	0.06

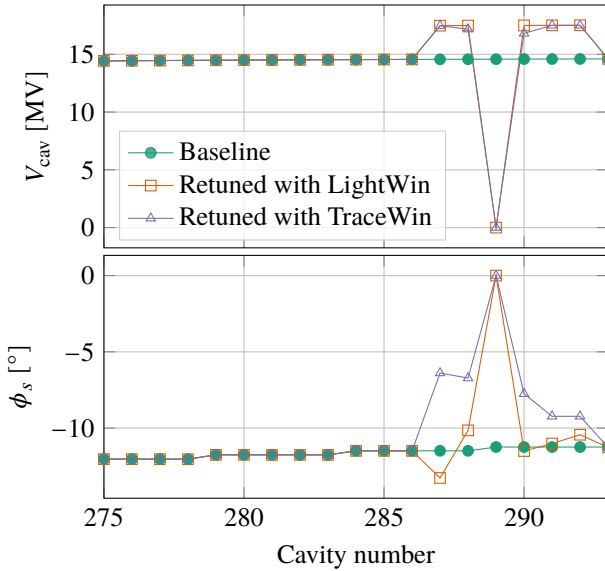


Figure 3: Accelerating potential and synchronous phase of the baseline and retuned settings when the cavity #289 is down. “Retuned with TraceWin results” are taken from Ref. [6].

In the future, we will continue to test the robustness LightWin against different scenarios. In particular, the low-energy section of the JAEA-ADS linac, where the space charge effects will be more important. We will also tune the genetic optimisation algorithms that we already implemented, as they are more adapted to this kind of multi-objective problem with a significant number of variables.

APPENDIX

The mismatch factor M_u between two ellipses of same emittances $\varepsilon_{u,1} = \varepsilon_{u,2}$ is defined as [10, 11]:

$$M_u = \sqrt{\frac{1}{2} \left(R + \sqrt{R^2 - 4} \right)} - 1 \quad (1)$$

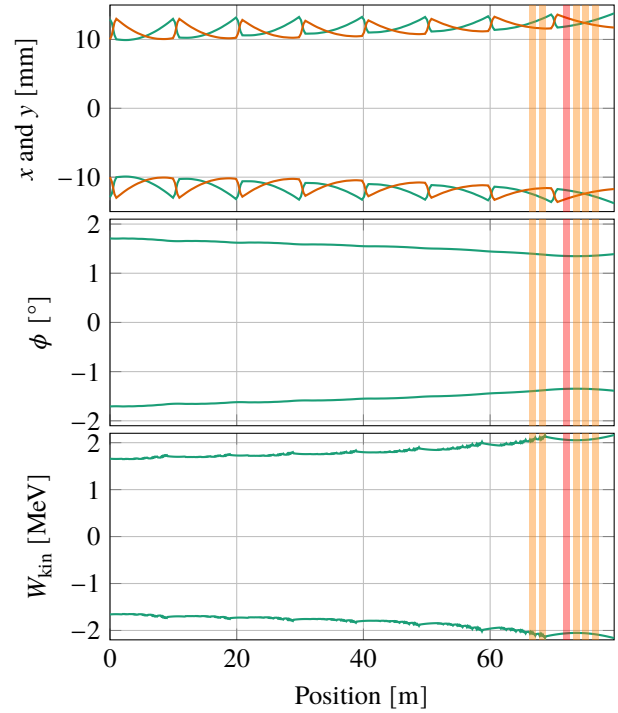


Figure 4: 6σ envelopes of the compensation scheme for the FullPerV scenario versus the position in the SC linac. 0 m corresponds to the position of the entry of the 108th period. Orange vertical lines show the position of compensating cavities; red vertical lines show position of failed cavities.

where

$$\begin{cases} \varepsilon_{u,1}(s) = \gamma_{u,1}(s)u^2 + 2\alpha_{u,1}(s)uu' + \beta_{u,1}(s)u'^2 & (2a) \\ \varepsilon_{u,2}(s) = \gamma_{u,2}(s)u^2 + 2\alpha_{u,2}(s)uu' + \beta_{u,2}(s)u'^2 & (2b) \\ R = \beta_{u,1}(s)\gamma_{u,2}(s) + \beta_{u,2}(s)\gamma_{u,1}(s) - 2\alpha_{u,1}(s)\alpha_{u,2}(s) & (2c) \end{cases}$$

and $u = x, y$ or z .

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