METHOD DEVELOPMENT FOR CAVITY FAILURE COMPENSATION IN A SUPERCONDUCTING LINAC

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Abstract

Reliability is a major challenge within the perspective of improving the performances, the costs and sustainability of high power hadrons accelerators. The requirements are even more stringent in the case of Accelerator Driven systems (ADS) such as the MYRRHA (Multi-purpose Hybrid Research reactor for High-tech Applications) demonstrator. In this purpose, this ADS accelerator design is based on a redundant and fault-tolerant scheme to enable rapid mitigation of a cavity failure. The adopted strategy is to apply local compensation: a failed cavity is compensated by several neighbouring cavities. Beam dynamics studies and method developments to apply such a failure compensation scheme are presented.

INTRODUCTION

In a global context of energy conservation, the optimisation of MegaWatt class accelerators performances to maximise their efficiency, reliability and therefore beam availability, while controlling costs (construction and operation), is becoming more and more challenging. These reliability requirements are even more stringent in the case of Accelerator Driven systems (ADS). As an example, for the MYRRHA (Multi-purpose Hybrid Research reactor for High-tech Applications) ADS demonstrator [1, 2], the actual availability limit is set to a maximum of 10 beam interruptions (longer than 3 seconds) over a 3-month operating cycle. In this purpose, the design of this high power (600 MeV, 4 mA CW) superconducting (SC) linac is based on a redundant and fault-tolerant scheme to enable rapid mitigation of a cavity failure [3-5]. The adopted strategy is to apply local compensation: the failure of a cavity is compensated by several neighbouring cavities.

A method (and a tool) is developed. It would enable to calculate the SC cavity settings to apply this local compensation scheme. Here, the MYRRHA SC linac is taken as reference example, since it has been designed in this purpose.

LOCAL FAULT-COMPENSATION SCHEME & FEASIBILITY

The MYRRHA SC linac (17-600 MeV), will be composed of 3 cavity families: single (section #1) and double spoke (section #2) cavities at 352.2 MHz and 5-cells elliptical cavities at 704.4 MHz (section #3). In nominal conditions the cavities are operated "de-rated": with an accelerating gradient ~30 % below their maximum capabilities [4]. The planned fault-compensation scheme is described by Fig. 1. If a cavity cannot be used anymore, it will be compensated by 4 of its closest neighbours. The new settings have to be applied in less than 3 seconds. Therefore, the new cavity settings will be calculated in advance and stored in a database where a maximum of failure scenarios is considered.

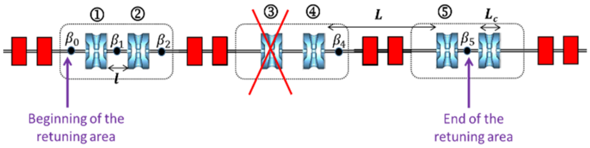

Figure 1: Fault-compensation scheme for the failure of a cavity (the failed one is cavity #3).

The retuning feasibility was assessed: for the beam dynamics and on the technological point of view (RF power margins, requirement for fast cold tuner) [6, 7]. Multiple failure scenario have been calculated [6], using the TraceWin code [8] and its optimisation algorithms. A multiple failures compensation example is illustrated by Fig. 2: 1 failed cavity in section #1, 1 failed cryomodule in section #2 (i.e 2 adjacent cavities), 1 failed cavity in section #3.

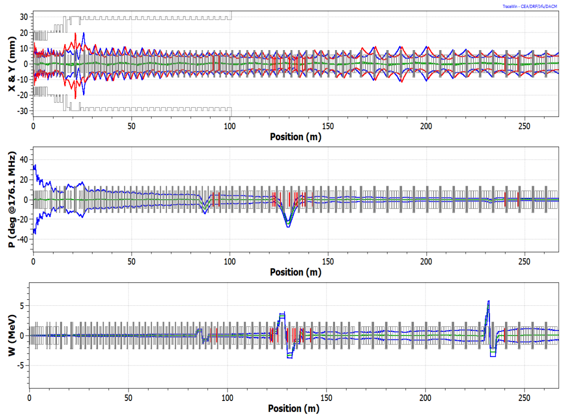

Figure 2: Beam envelopes (4σ, mulitparticle tracking) with several failures compensations.

Although it was shown that it is possible to calculate the failure compensation settings, this approach has some limitations, such as the calculation time. When coupled with errors studies, in some cases the retuning could create beam losses higher than the 1W/m limit. Indeed, the phase advance law is sometimes strongly affected creating some emittance growth and the longitudinal acceptance is also decreased [6]. In addition, this method is using diagnostics as defined in TraceWin that could not always be implemented on the real machine.

Therefore, a new approach has been developed in order to be "less aggressive" for the beam and to better control the lattices parameters. The final goal being to dispose of a

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reliable tool that enables to automatically calculate any failure compensation case.

METHOD DEVELOPMENT

The first developments of the method have been based on solving the local failure mitigation of one cavity, described by Fig. 1.

To calculate the new cavities settings, it was therefore chosen to use a simplified model: first order transfer matrix, only in the longitudinal plane, are considered. Indeed, in this first order approach only the cavities are retuned and the transverse focussing effect of these cavities is neglected [9, 10].

Then the retuning algorithm is based on 3 main criteria.

1st Criterion

The transfer matrix (M_{Tot}), in the longitudinal phase space, of the retuned area must be the same in both conditions: nominal and fault compensation.

So,

$$M^R_{Tot} = M_{Tot}, \tag{1}$$

by writing every parameters in the retuning case with a superscripts case " ^{R} ".

And, in a first approximation, with the assumption Δβ/β<<1, one can consider a cavity transfer matrix as [10]:

$$\begin{bmatrix}\Delta\phi \\ \Delta\phi'\end{bmatrix}_{Out} = \begin{bmatrix} Cos(k.L_c) & \frac{1}{k}\,Sin(k.L_c) \\ -\,k\ Sin(k.L_c) & Cos(k.L_c)\end{bmatrix} \begin{bmatrix}\Delta\phi \\ \Delta\phi'\end{bmatrix}_{In} \tag{2}$$

With $\Delta\phi$ the phase excursion of the particle and $\Delta\phi' = d\Delta\phi/dz$. L_c is the cavity length and k is the synchrotron phase advance, written as:

$$k = \sqrt{\frac{\omega_{RF}}{m_0\, c^3\, \beta^3\, \gamma^3}\; q\, E_{acc}\ sin(\phi_s)} \tag{3}$$

with ω_{RF} the RF pulsation and q the charge. β and γ are the reduced velocity and the Lorentz factor. In the case of Fig. 1, solving the Eq. (1) consists in finding the phase advance of the 4 retuned cavities: $k^R_1, k^R_2, k^R_4, k^R_5$. Then, once the k^R_i factors are determined, it should be possible to deduce the new accelerating field (E_{acc}) and the new synchronous phase (ϕ_s) for each cavity, by considering the following criteria.

2nd Criterion

The energy gain over the retuned area must remain the same.

By writing ΔW_i the energy gain in the ith cavity it equates as:

$$\Delta W_1 + \Delta W_2 + \Delta W_3 + \Delta W_4 + \Delta W_5 = \\ \Delta W^R_1 + \Delta W^R_2 + \Delta W^R_3 + \Delta W^R_4 \tag{4}$$

And ΔW_i depends on E_{acc_i} and the ϕ_{s_i} of the cavity

$$W_i = q\, E_{acc\_i}\, L_{acc}\ Cos(\phi_{s\_i}) \tag{5}$$

with the definition of L_{acc} :

$$L_{acc} = N_{gap}\, \beta_{opt}\, \lambda/2 \tag{6}$$

N_{gap} is the number of accelerating gaps in the cavity, β_{opt} is the reduced velocity for which the acceleration is optimal and λ is the RF wavelength, $\lambda = c/f_{RF}$.

3rd Criterion

The time of flight, T_{Tot}, must remain the same than in nominal conditions. So that the beam remains synchronised with the RF field in the cavities placed downstream the retuning area. Within the assumption that the time of flight of the bunch passing through the ith cavity is:

$$T_i = \frac{L_C}{\frac{(\beta_{i-1}+\beta_i).c}{2}} \tag{7}$$

Considering the input reduced velocity β_{i-1} and the output reduced velocity β_i for the ith cavity, one can obtain the following equation:

$$c.T_{Tot} = \frac{l}{\beta^R_1} + \frac{L}{\beta^R_4} + \frac{(L + L_C + l)}{\beta^R_2} \\ +2\, L_C \left[\frac{1}{\beta_0+\beta^R_1} + \frac{1}{\beta^R_1+\beta^R_2} + \frac{1}{\beta^R_2+\beta^R_4} + \frac{1}{\beta^R_4+\beta_5}\right] \tag{8}$$

ALGORITHM AND EXAMPLE

Based on these criterions, an algorithm has been established. It calculates the new transfer matrix of the 4 compensation cavities. Then the new energy gain ΔW^R_i per cavity is determined. The new values of E_{acc} and ϕ_s of each cavity is calculated according to Eqs. (3) and (5). Finally, the found solution is "injected" in the TraceWin model-which includes cavity field maps - for fine tuning.

To illustrate the effect of the method one example is discussed hereafter. The multiple failures case of Fig. 2 is considered. Results obtained with two different approaches to calculate the compensation of the first failed cavity (at ~80 m) are compared.

- The 1st approach is the one presented in [6]: the retuning calculations were directly carried out with the TraceWin code.
- The 2nd approach is done with the method previously exposed in this section.

1st Approach: Direct Calculation with TraceWin

The zero current phase advance and the emittances evolutions (10^5 macro-particle tracking) calculated with this first approach are plotted on Fig. 3. A subsequent emittance growth is observed due to the several retuning

In TraceWin, for each of the compensation cavities some margins are set to adjust the field amplitude and the RF phase. In some cases, these margins had to be modified from one optimization to another to guide the code to converge to an acceptable and realistic solution: energy gain per cavity equally distributed, synchronous phase below ~15°, etc. This led to a quite long simulation time since one optimisation may take several minutes. Once a solution is found acceptable, the transport is checked with a multiparticle tracking simulation.

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Energy and phase diagnostics are used at the end of the retuning area and in the following lattice periods. The goal being to recover the same energy and phase at the end of the retuning area. In addition, the code is forced to recover (as best as possible) the same Twiss and emittance parameters than in nominal conditions, with a highest priority for the longitudinal plane.

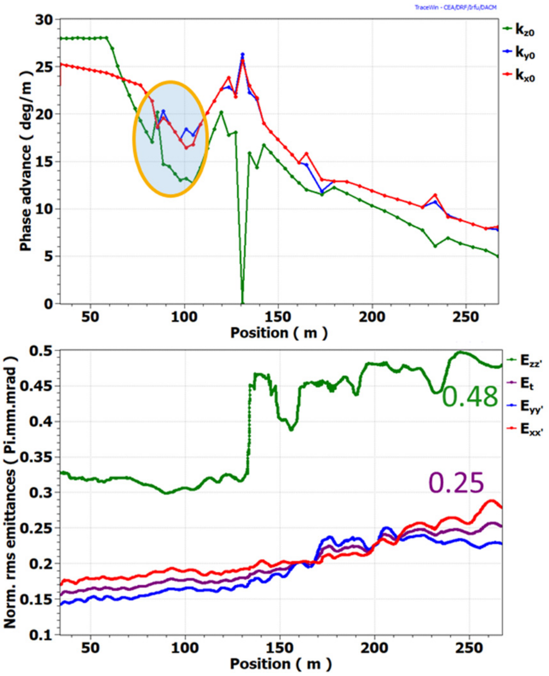

Figure 3: Zero current phase advance and emittance evolution calculated with 1st approach.

2nd Approach: With Optimisation Algorithm

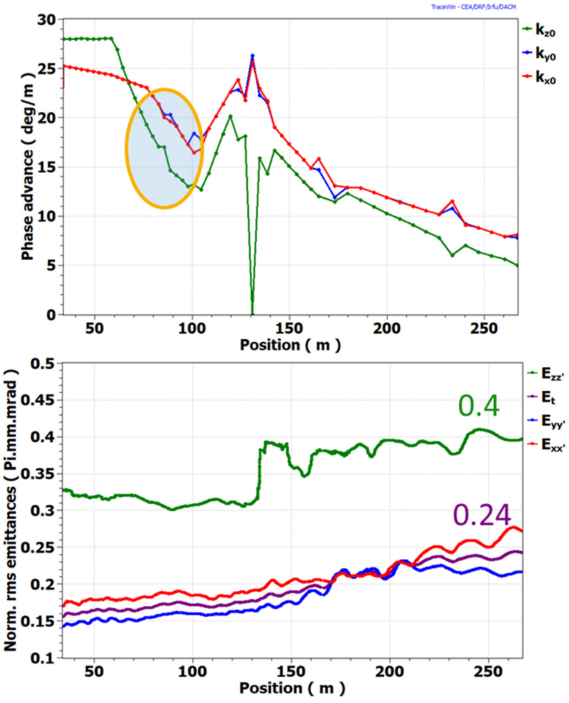

Figure 4: Zero current phase advance and emittance evolution calculated with 2nd approach.

The zero current phase advance and the emittances evolutions (105 macro-particle tracking) calculated with the optimisation algorithm are plotted on Fig. 4. It provides one solution for the new cavities set points. This solution is then implemented in TraceWin by putting small margins of variation for each of the parameters: typically ± 2% for the cavity voltage and ± 1° for the RF phase. This fine tuning is done by using energy and phase diagnostics and the Twiss parameters in the longitudinal phase space is also checked. Actually, the main purpose of this fine optimisation was to verify that the calculation, done with the tuning algorithm, was indeed producing a coherent solution for the beam dynamics transport.

In comparison with the previous method, the abrupt phase advance variations in the retuning area are smoothed, and the emittance growth is decreased providing a safer beam transport.

FINAL REMARKS

A method to apply failure compensation in the superconducting linac has been developed and proposed. The obtained results so far tend to prove that the method enables a better control of the beam dynamics in the retuned linac: the goal being to keep the longitudinal acceptance in as large as possible and to minimize the emittance growth.

Nevertheless, many improvements are still required to dispose of a reliable tool that enables to calculate every failure compensation scenario. First, regarding the adopted methodology and the definition of the retuning area: it will probably be more relevant to take into account full lattice periods, instead of stopping just after the last retuned cavity. In this way the phase advance per lattice will be used as convergence criterion for the algorithm. In addition, a strong effort has to be made to fully automatize the algorithm calculation and the convergence limits. In this purpose the use of machine learning techniques or metaheuristics may help. The limits of the simplified cavity model must also be assessed, especially at low β.

To prove the robustness of the procedure, the method will have to be tested on a maximum number of possible scenarios: failure of each cavity and of each cryomodule. A strong effort has to be made to develop a tool that enables to automatize these calculations and that can be adaptable to different SC linacs.

Finally, regarding the ADS case: multiple failures compensation will have to be explored in more details. In interaction with these studies, the development of a reliability model of the linac – as done in [11] – is of great relevance. Considering the actual developments on RF technologies - such as solid state amplifier- the failures occurrence may decrease. This would confirm, or reassess, the minimum number of cavities needed to compensate a failure; and perhaps to relax the constraints on the beam dynamics and the cavity performances.

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