RESEARCH ON COMPENSATION OF SUPERCONDUCTING CAVITY FAILURES IN C-ADS INJECTOR-I*

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Abstract

For the proton accelerators such as the China Accelerator Driven subcritical System(C-ADS), it is essential and difficult to achieve extremely high performance reliability requirement. In order to achieve this performance reliability requirement, in addition to hardware improvement, a failure tolerant design is mandatory. A compensation mechanism to cope with hardware failure, mainly RF failures of superconducting cavities, will be in place in order to maintain the high uptime, short recovery time and extremely low frequency of beam loss. This paper proposes an innovative and challenging way for compensation and rematch of cavity failure with the hardware implementation of the scheme using fast electronic devices and Field Programmable Gate Arrays (FPGAs). A method combined building an equivalent model for the FPGA with an improved genetic algorithm has been developed. Results based on the model and algorithm are compared with TRACEWIN simulation to show the precision and correctness of the mechanism.

INTRODUCTION

C-ADS aims to build a superconducting linac with beam energy of 1.5 GeV and beam current of 10 mA [1, 2]. In order to reach the reliability requirement, a fault-tolerance capability has to be considered, which requires some main components to allow compensation and rematch.

The traditional compensation and rematch methods are based on the simulation software for beam dynamics, like TRACEWIN [3, 4]. During the calculations of compensation and rematch for each component, a lot of work needs to be prepared by humans, and it is easy to make mistakes during data processing. This paper gives an alternative method, with calculation done in FPGAs to deal with cavity failure [5]. FPGAs have higher arithmetic computing speed to make instantaneous compensation and rematch possible. Meanwhile, good portability and repeatability is another advantage compared with traditional human work.

EQUIVALENT MODEL

The diagram of the operating principle of FPGA-method is shown in Fig.1. Firstly, upper FPGAs which are responsible for finding the optimal solutions should calculate the objective parameter according to the nominal setting. When lower FPGAs transport abnormal signal, the upper FPGAs will repeatedly re-calculate the whole process by high-level algorithm until the optimal solutions satisfy the objective function. At last, the modified setting for key elements will transport to lower FPGAs by hardware interfaces.

FPGA is consisted of lots of logic gate. The easiest way to get the result of algorithm is to use addition, subtraction, multiplication. Because of this, we choose linear basis function models, as shown in Eq.1

$$y(x,\omega) = \omega_0 + \sum_{j=1}^{M-1} \omega_j \varphi_j(x) . \quad (1)$$

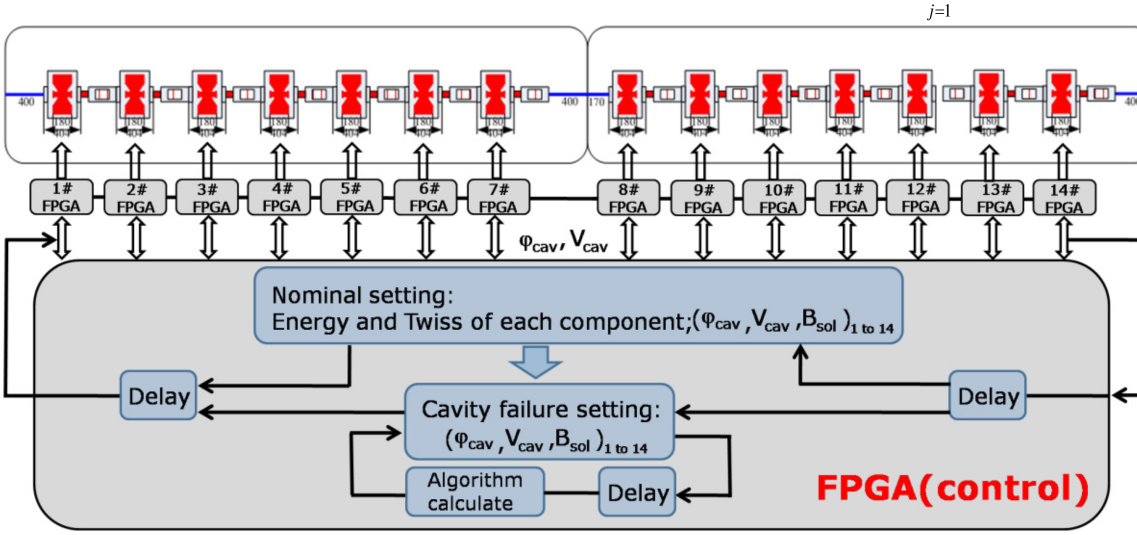

Figure 1: Diagram of the hardware compensation and rematch in C-ADS Injector-I

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$\phi_j(x)$ are known as basis functions, which can be fixed as nonlinear functions. We take the gain as an example. Gain is related to the kinetic energy, synchronous phase and Eacc. Here we choose second-order term to take the place of $\phi_j(x)$. Besides the gain, the model of transfer matrix with space charge is also built. In the model, we first choose the structure of "drift + gap + drift" to be equivalent to the cavity. This way can not only simplify the algorithm operating in the FPGA, but also make the work of compensation on the real facility so that the whole system of compensation may be tested and proved.

Concerning the linear space charge, the components should be divided into short slices for which space charge can be dealt with as a thin lens inserting into each slice [6]. The space-charge transfer matrix may apply on a distance Δs, shown in Eq.2.

$$R_{ce} = \left[\begin{array}{cc|cc|cc} 1 & 0 & 0 & 0 & 0 & 0 \\ F_x\Delta s & 1 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & F_y\Delta s & 1 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \gamma F_z\Delta s & 1 \end{array}\right] \quad (2)$$

where F_x, F_y, F_z can be expressed as

$$F_x = \frac{3qI\lambda(1-f)}{20\sqrt{5}\pi\varepsilon_0 mc^3\gamma^3\beta^2(a_x+a_y)a_z a_x} \quad (3)$$

$$F_y = \frac{3qI\lambda(1-f)}{20\sqrt{5}\pi\varepsilon_0 mc^3\gamma^3\beta^2(a_x+a_y)a_z a_y} \quad (4)$$

$$F_z = \frac{3qI\lambda(1-f)}{20\sqrt{5}\pi\varepsilon_0 mc^3\gamma^2\beta^2 a_x a_y a_z} \quad (5)$$

Similarly, all the elements in space-charge matrix can use polynomial equivalent. However, there are too many variables in equation, so the method of separating the item on beam energy and those on beam sizes is applied.

GENETIC ALGORITHM

Cavity failures bring about not only loss of energy but also mismatching which eventually leads to beam loss. How to re-adjust the parameters and complete the compensation and rematch can be treated as a problem of finding optimal solution, which can be solved by combining the equivalent model with some algorithms. Genetic algorithm [7] is a good choice to get near-optimal solutions by iteration. A flowchart for the genetic algorithm applied to an FPGA is shown in Fig. 2.

During the whole genetic algorithm, some classical methods are used in all kinds of modules, such as binary coding, "roulette wheel" selection operator, two-point intersection, multipoint mutation and linear feedback shift register in random-number processing.

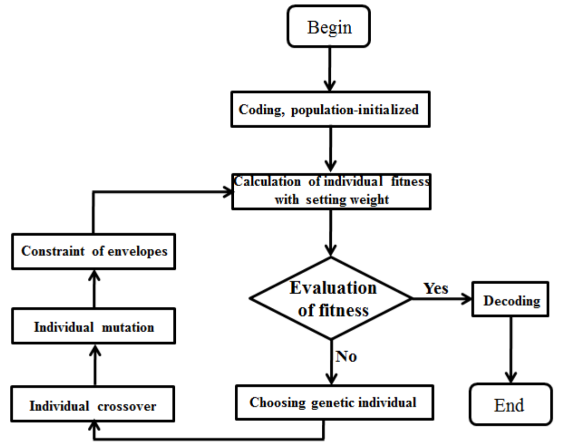

Figure 2: Flowchart for the genetic algorithm applied in the compensation and rematch.

Under the control of top module, all the hardware system work together, shown in Fig.3.

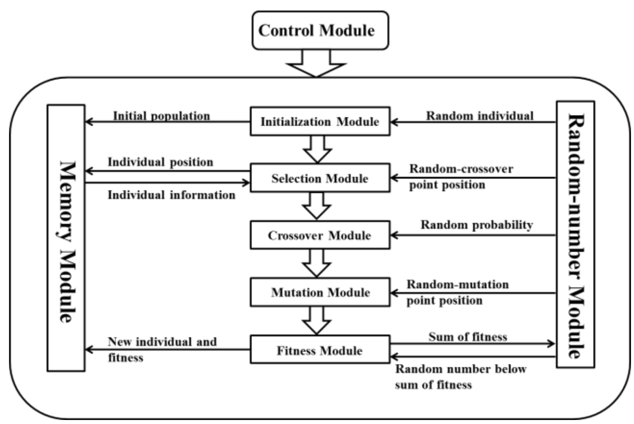

Figure 3: Function module of hardware genetic algorithm.

TRACEWIN VERIFICATION

In order to verify the feasibility of the hardware compensation and rematch, this paper uses TRACEWIN to test the optimization result with the above-mentioned model and algorithm. Cavity' failure compensation in Injector-I is illustrated as follows.

Injector-I is the head of C-ADS linac, which is based on an ECR ion source, a LEBT, a 325MHz RFQ, a MEBT1 and a superconducting section with 14 cavities and 14 solenoids in two cryomodules.

Due to the difficulty of compensation and rematch in low energy, we take a superconducting cavity failure in the eleventh period whose energy has already reached about 8 MeV as an example. The neighbouring four cavities are used to realize the compensation and rematch, as shown in Fig.4.

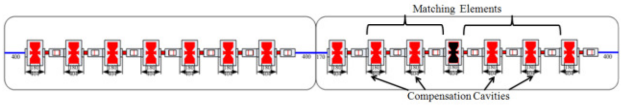

Figure 4: Local compensation and rematch of Spoke012-11# failure in C-ADS Injector-I.

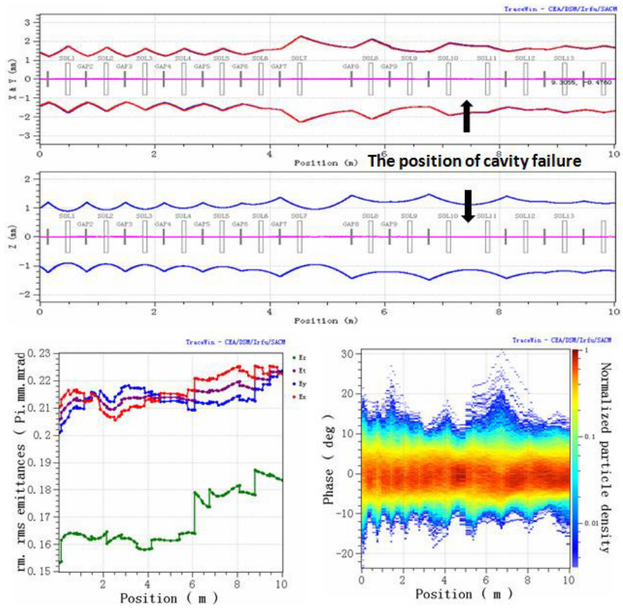

Figure 5: Results verified by TRACEWIN.

Using the compensated parameters calculated by FPGAs, we simulated the lattice of Injector-I again and the results are shown in Fig.5. The horizontal and longitudinal envelops can be controlled in ±3mm and ±2mm respectively. Meanwhile, the growth of longitudinal and horizontal emittance show about 15% and 5%. There is no greater jitter in the longitudinal phase. The mismatch factor [8] and the relative error are shown in Table 1.

Table 1: Twiss Parameters at the Matching Point with Spoke012-11# Failure in Injector-I

Twiss	nominal	After compensation and rematch	Mismatch Factor
Beta-x	1.9548	1.9548	3.72%
Alpha-x	0.5476	0.4683	
Beta-y	1.9856	1.9687	3.94%
Alpha-y	0.5599	0.4787	
Beta-z	1.2822	1.3623	3.90%
Alpha-z	-0.3446	-0.3181	

TIME NEEDED FOR CALCULATION

Taking no account of the space charge effect, the time of calculating horizontal and longitudinal lattice for Injector-I are 695 ns and 270 ns respectively, with FPGAs operated at 200 MHz clock. When the space charge effect is considered, the coupling of horizontal and longitudinal will show up, and the time of calculating the lattice for Injector-I is up to 392 us. Yet, this is still much shorter than the time needed by TRACEWIN simulation, which is typically ~1s.

CONCLUSIONS

The method based on fast electronic circuit and FPGAs hardware for local compensation and rematch of superconducting cavity has been investigated. Compared with the traditional method, this method has the advantages of faster operating speed, easier hardware interaction, better portability and repeatability. Combined polynomial modelling with hardware genetic algorithm, optimal solutions for compensation and rematch can be efficiently found. And, the compensation and rematch result of C-ADS Injector-I has been verified by TRACEWIN

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