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PRELIMINARY HARDWARE IMPLEMENTATION OF COMPENSATION MECHANISM OF SUPERCONDUCTING CAVITY FAILURE IN C-ADS LINAC

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Abstract

For the proton linear accelerators used in applications such as C-ADS, due to the nature of the operation, it is essential to have beam failures at the rate several orders of magnitude lower than usual performance of similar accelerators. In order to achieve this extremely high 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. The hardware implementation of the mechanism poses high challenges due to the extremely tight timing constraints, high logic complexity, and mostly important, high flexibility and short turnaround time due to varying operation contexts. We will explore the hardware implementation of the scheme using fast electronic devices and Field Programmable Gate Array (FPGA). In order to achieve the goals of short recovery time and flexibility in compensation algorithms, an advanced hardware design methodology including high-level synthesis will be used.

INTRODUCTION

The Chinese ADS (C-ADS) project is aimed to solve the nuclear waste problem and the resource problem for nuclear power plants in China. To C-ADS linac, which is a high power proton accelerator, unexpected beam trips may lead to the serious change of temperature and thermal stress in the reactor core, and eventually result in the permanent damage of facilities. Therefore, the extremely high reliability and availability for C-ADS linac was proposed [1, 2], as shown in Table 1.To reach such an ambitious goal, it is clear that reliability-oriented design practices need to be followed from the early design stage [3]. In particular: (1) a high degree of redundancy needs to be planned in critical areas. (2) “Strong design” is needed. (3) fault-tolerance capabilities have to be considered. This paper will focus on the concept of fault-tolerance, and present the preliminary hardware implementation of the compensation mechanism of the superconducting cavity failures in C-ADS linac.

Table 1: Specifications of C-ADS Proton Linac

Parameters	Design	
Particle	proton	
Energy	1.5	GeV
Current	10	mA
Beam Power	15	MW
RF Frequency	(162.5)/325/650	MHz
Duty Factor	100	%
Beam Loss	<1	%
Beam Trips/Year	<25000	1s<t≤10
	<2500	10s<t≤5min
	<25	t>5min

THE COMPENSATION MECHANISM

The compensation methods of superconducting cavity failures can be divided into global compensation method and local compensation one [3]. The global compensation means that all the cavities downstream of fault cavity attend the compensation, while the local compensation is related to the elements neighbouring the failing cavity. The global compensation has lower demand of the performance of each cavity, but it needs all cavities act at the same time, which means the RF control should be extremely accurate. By contrast, the local compensation has the advantage of involving a small number of elements, yet the performance margin of the elements must be larger.

The representative compensation work may be found on SNS, which adopts the global compensation. When the cavities fail, the machine will look up the database to find the data of compensation and then readjust the parameters of the working cavities. The whole process may take a few minutes, which is too long for C-ADS linac. In this paper, we tried another way to achieve the compensation by the hardware implementation of the scheme using fast electronic devices and Field Programmable Gate Array (FPGA). The preliminary compensation diagram of the injector I of C-ADS, which is a 10MeV proton linac, is shown in Fig.1.

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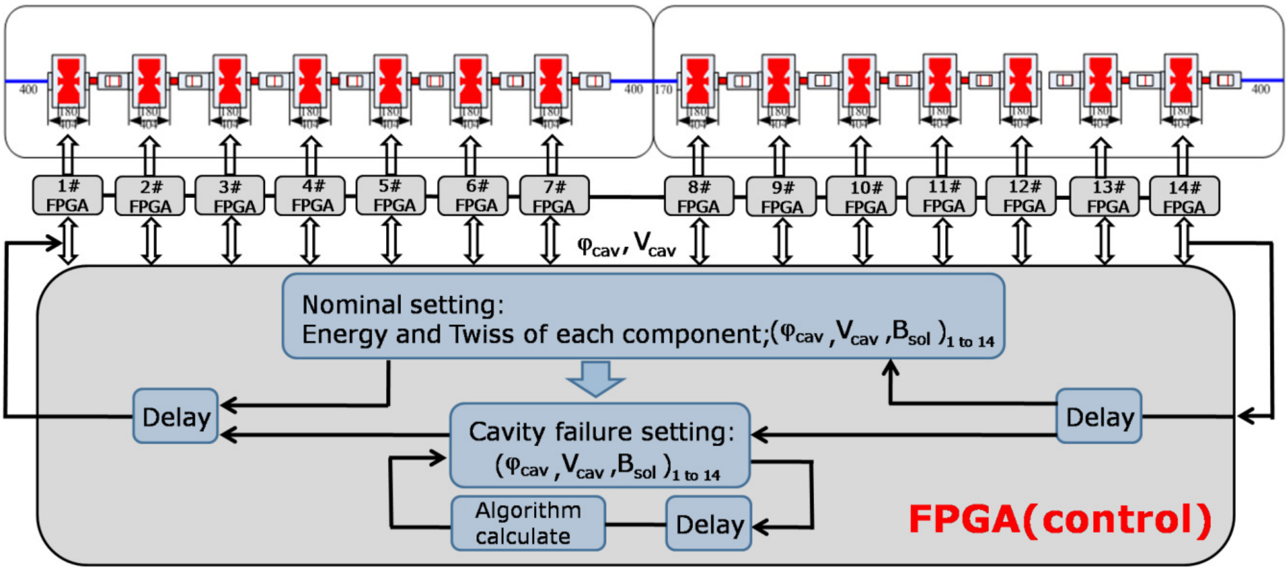

Figure 1: Diagram of the hardware compensation in C-ADS.

The advantage of FPGA is its parallel processing. After we build the model of each element, the top FPGA will combine some kinds of algorithm, such as genetic algorithm, to get the optimal solution according to the model. The whole process of compensation will be limited in tens of microseconds, supposing the model and algorithm are excellent enough. It is very helpful for the speed of accomplishing the whole compensation.

THE MODEL OF ENERGY AND TRANSFER MATRIX WITHOUT SPACE CHARGE

FPGA is consisted of lots of logic gate. The easiest way to get the result of algorithm is to use addition, subtraction, multiplication. So, we choose linear basis function models [4], as shown in Eq. 1.

$$\mathrm{y}(\mathrm{x},\mathrm{w}) = w_0 + \sum_{j=1}^{M-1} w_j \phi_j(x) . \tag{1}$$

$\phi_j(x)$ are known as basis functions, which can be fixed as nonlinear functions. We take the energy 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 $\phi_j(x)$. Through fitting the data of Tracewin code by Matlab, we get the equation of gain. Confidence intervals of ten coefficients are stated at 95% confidence level, as shown in Table 2, where x is known as normalized kinetic energy at the range of 4.4 MeV to 7.7 MeV, y is normalized synchronous phase at the range of -60 degree to -22 degree, z is normalized E_{peak} at the range of 13.75 MV/m to 35.75 MV/m. All the coefficients are at the scope of confidence intervals. At the same time, the R^2 statistic is 0.9996 from Matlab, which means the model fits the samples very well. For null hypothesis of H_0, $\beta_9 = \beta_8 = .. \beta_0 = 0$ at the significance level of $\alpha = 0.05$. We get the critical value $F_\alpha(9,790) \approx F_\alpha(9,\infty) = 1.88$ from F distributions, which is much smaller than $F = 238850.65$, the value of F statistic from Matlab. H_0 should be rejected, which means the regression equation is significant.

Table 2: Coefficient Confidence Intervals

Term	Coefficient	Confidence interval
x^2	-0.3493	[-0.366,-0.333]
y^2	-0.08843	[-0.0909,-0.0860]
z^2	0.002166	[0.000230,0.00400]
xy	0.06705	[0.0614,0.0727]
yz	0.2058	[0.204,0.208]
xz	0.1179	[0.113,0.123]
x	0.3893	[0.372,0.406]
y	0.1855	[0.182,0.189]
z	0.1910	[0.188,0.194]
constant	0.03768	[0.033,0.0420]

Besides the energy gain, the model of transfer matrix without space charge is also built. In the model, we first choose the structure of "drift + gap + drift" to be equivalent to the cavity, and it may be easier to prove the

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top algorithm. We take the term of s21 in the longitudinal transfer matrix of the gap as an example. By analyzing the residual of eight hundred groups of observed value and fitted value, we get the residual case order plot, as shown in Fig.2. The red lines are abnormal data, which appear at the edge of independent variable. They can be removed by the way of setting active area of independent variable.

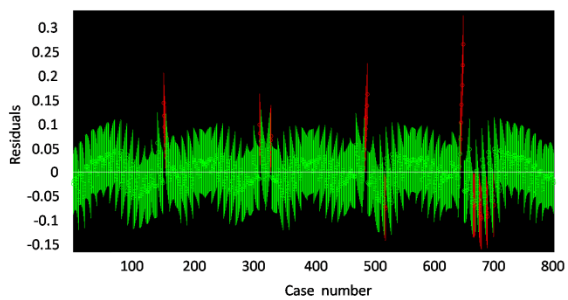

Figure 2: Residual plot of s21 term of gap's transfer matrix.

The way of building model can not only simplify the algorithm operating in the FPGA, but also realize the work of compensation on the real facility, which can test and prove the whole system of compensation.

THE PRELIMINARY RESULT OF HARDWARE SIMULATION

There are two methods to realize the compensation of major component. The first is to look up the database to find the data of compensation which was already calculated. All the data that need to change include Eacc and synchronous phase of each cavity and the magnetic field strength of each solenoid. All the data of 14 cavities and solenoids are stored in the ROM of FPGA, which can be quickly got.

The second is to build the model to realize the compensation online, which can update the important parameters of each major component without breaks. We can get the result of building the whole injector with 14 Spoke012 cavities which is equivalent to the structure of "drift + gap + drift". Take the longitudinal beta as an example, which is shown in Fig.3.

The first picture is picked from Tracewin. The lattice is close to the real structure of Injector I. Its envelopes are shown in the first picture. At the same time, the lattice has been translated into mathematical model in Matlab and tested on FPGA, as shown in the next two pictures. The error of beta between TRACEWIN and the result of fitting by polynomial at last element is 0.36%. Among all the beta of the entrance or exit of all elements, the maximum error is 5%. Meanwhile, the energy error after the last element is 0.32%. In conclusion, the polynomial is successfully equivalent to the result of beam dynamics simulation both in transfer matrix and energy. That is wonderful for us to realize the compensation by FPGA.

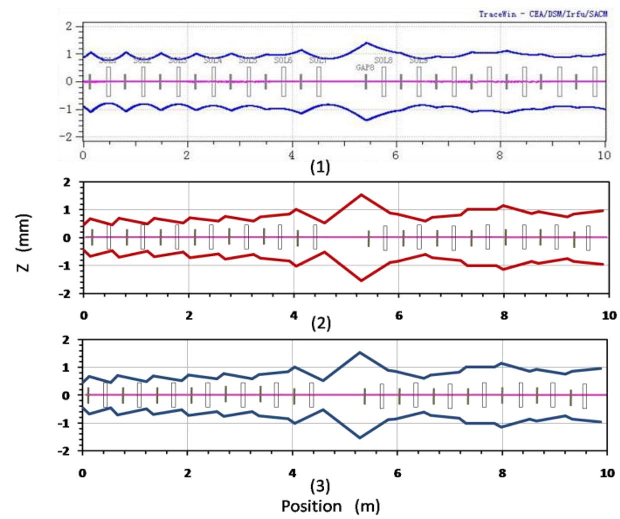

Figure 3: The envelopes of TRACEWIN (the upper picture), the broken line graph of beta in MATLAB (the middle picture) and the broken line graph of beta by hardware simulation (the down picture).

The longitudinal transfer matrix and energy of 14 periods has been changed into Verilog code. All the ports and timing sequence has been tested. When the clock is under 200MHz, the calculation of longitudinal Twiss parameters and energy of one period takes about 54 ns, which means all the process of compensation is hopeful to limit in tens of microseconds.

CONCLUSIONS

The model of energy and transfer matrix has been built by combining Tracewin and Matlab. It is efficient to reflect the influence of the major component to the beam. Through debugging the FPGA, we check the partial function of building model and testing algorithm. Yet, there is still a lot of work underway, such as the algorithm of compensation that will be realized in FPGA, the verification of horizontal transfer matrix by FPGA. The most important point is to take the space charge into account, whose process will become more complicated.

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