LOCAL COMPENSATION-REMATCH FOR MAJOR ELEMENT FAILURES IN THE C-ADS ACCELERATOR

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Abstract

In order to achieve the required reliability and availability for the C-ADS accelerator, a fault tolerance design is pursued. The effects of cavity failure in different locations have been studied and the schemes of compensation by means of local compensation have been investigated. After one cavity failure, by adjusting the settings of the neighbouring cavities and the focusing elements we can make sure that the Twiss parameters and energy are approximately recovered to that of the nominal ones at the matching point. We find that the normalized RMS emittance and emittances including 99.9%and 100% particles have no obvious growth after applying the compensation with the RMS rematch in each section of the main linac. However, the compensation with the TraceWin code doesn't consider the phase change during the cavity resetting. A code based on MATLAB is under developing to compensate the arrival time at the matching point, and shows its effectiveness.

INTRODUCTION

The extremely high reliability and availability are considered to be the most important characteristics for the C-ADS accelerator [1]. Besides all the hardware is operated with conservative performance and redundancy, it is also important to have fault-tolerant capabilities in the physics design [2, 3]. Anyway, no matter how we improve the hardware's reliability performance, it should be expected to meet some failures of important devices with a much lower frequency. The accelerator design has to deal with these situations. In the following, we will discuss how to compensate the failures of two kinds of major components: superconducting resonators and transverse focusing elements including solenoids and quadrupoles.

LOCAL COMPENSATION FOR RF CAVITY FAILURES

Several factors may cause the failures of RF cavities: RF power source, coupler, LLRF, cavity mechanic tuning, etc. If a cavity fails and nothing is done, the whole or part of the beam may be lost in the downstream linac. The reason is that the phase slip caused by the velocity change will make the beam center phase to exceed the longitudinal acceptance of the downstream acceleration section. The best way to deal with this kind of failures is to readjust the setting of the neighbouring cavities to regain the nominal velocity, and to rematch the transverse focusing at the same time as the RF cavities also affect the transverse focusing. At SNS, it is the usual operation to adjust some downstream SC cavities when one fails. However, it takes some minutes to make the adjustment and the beam should be cut off during the tuning. For C-ADS, the beam stop time should be controlled within a few seconds and it is better to make the compensation by just involving only a few neighbouring cavities. In this way, more cavity failures in different locations can be compensated independently and efficiently [4].

Compensation in the Spoke021 Section

As mentioned above, the cavity failure may lead to beam loss especially in the low energy section. Taking the cavity failure in the Spoke021 section as an example, the local compensation method for the failure of the first cavity in the Spoke021 section is shown in Fig.1, two bunchers in the MEBT2 [5]are used to rematch, and they can be adjusted together with the other neighbouring cavities.

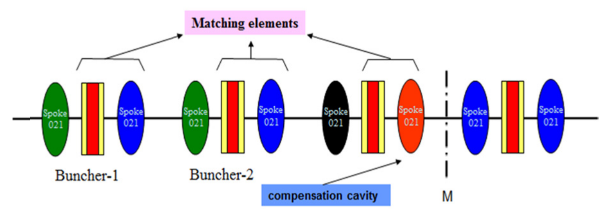

Figure 1: Local compensation method (The blue ellipses stand for cavity, the red squares for solenoids, the black ellipse for the failed cavity, the orange ellipse for major compensation cavity and M stands for the matching point).

If nothing is done for the cavity failure, the large phase slip will lead to beam loss and phase oscillation in both transverse and longitudinal planes (see Fig. 2).

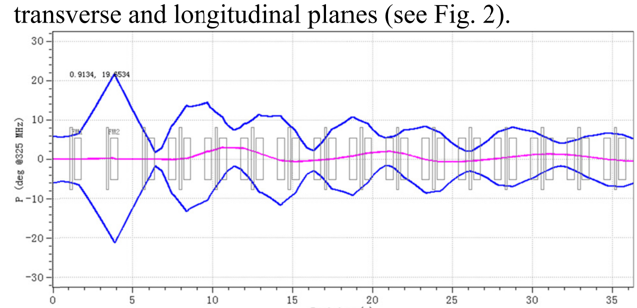

Figure 2: Longitudinal envelope evolution after the cavity failure.

Meanwhile, the beam halo emittance growths are evident in both the longitudinal and transverse planes, as shown in Fig. 3. As the field of the first cavity is quite low, about 0.66 of the nominal value due to the limitation of 90° phase advance in the longitudinal plane, we can compensate the failure by changing the voltage of the second cavity in the same cell and the synchronous phase of the bunchers in MEBT2 from -90° to -70° (see Table 1).

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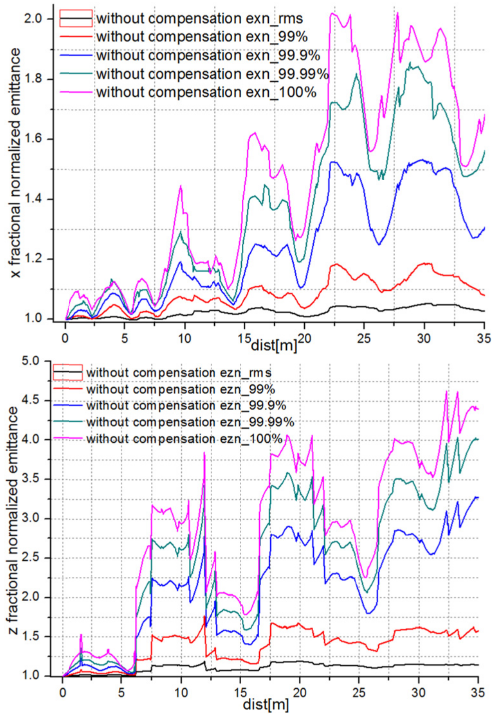

Figure 3: the emittance evolutions without compensation after the cavity failure.

Table 1: Parameters of the Cavities and the Solenoids for Local Compensation-Rematch

Element	**Cavity-1**	**Cavity-2**	**Cavity-3**
Initial RF phase	-90°	-90°	-30°
After rematch	-65.9°	-72.3°	-33.9°
Element	**Solenoid-1**	**Solenoid-2**	**Solenoid-3**
Initial field / T	2.5	2.5	2.47
After rematch / T	2.64	2.51	2.38

In this way, only little adjustments for the neighbouring cavities and solenoids are needed and the beam energy and the Twiss parameters can be recovered at the matching point "M". The Twiss parameters at the matching point "M" after rematch are shown in Table 2, with comparison to the initial ones.

Table 2: Twiss Parameters at the Matching Point after the Local Compensation-Rematch

Twiss parameter	**Alpha x**	**Beta x / m**	**Alpha y**
Initial	0.4031	2.4414	0.3882
After rematch	0.384	2.446	0.4089
Twiss parameter	**Beta y / m**	**Alpha z**	**Beta z / m**
Initial	2.1851	0.3048	17.6833
After rematch	2.1739	0.3065	17.7659

After the compensation and rematch with the rms beam, the normalized rms emittance growths at the end of Spoke021 section are 0.86% and 1.24% in the two transverse planes and 1.8% in the longitudinal plane, which keeps very smooth along the downstream part of the Spoke021 section and the halo emittance growths are also not evident, as shown in Fig. 4.

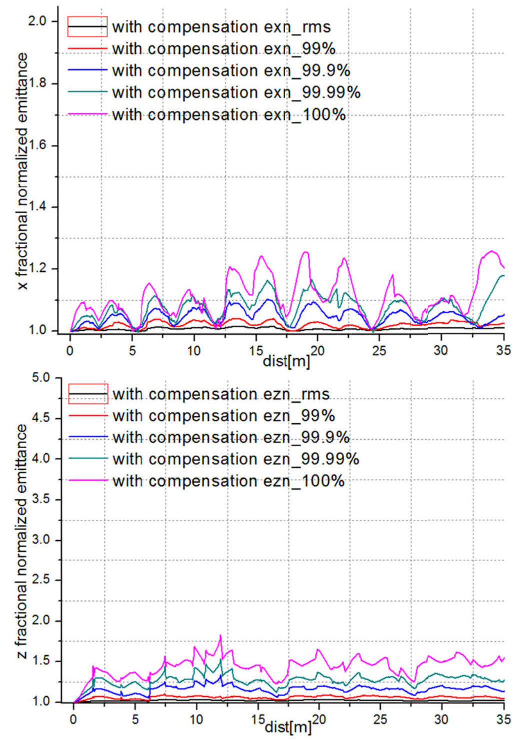

Figure 4: The emittance evolutions with compensation.

The local compensation-rematch for the other cavity failure in other part of the Spoke021 section is similar.

REMATCH FOR TRANSVERSE FOCUSING ELEMENT FAILURES

Usually transverse focusing element failures occur less frequent than RF cavities, but it is still very important due to the very strict requirement on reliability of the main linac. Rematch is also needed to reduce the emittance growths due to the failures. However, the rematches for SC solenoid and quadrupole failures are very different.

Rematch for SC Solenoid Failures

Solenoid failures may be one of the most difficult situations for rematch, especially in the low energy sections. As there is only one solenoid in one cell for transverse focusing, once the solenoid fails, the beam size in the cell or downstream cells will become much larger. We take the failure of a solenoid in the middle part of the Spoke021 section as an example, as shown in Fig. 5.

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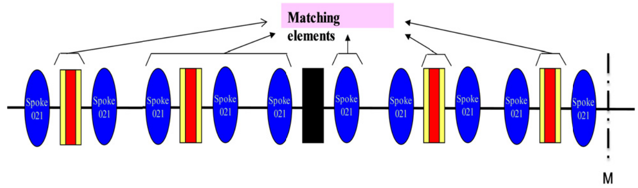

Figure 5: Rematch method for a solenoid failure in the middle part of the Spoke021 section.

As the transverse phase advance per period is very large here, the rematch only with the solenoids in the neighbouring cells does not give rematch results. We study a new method by including the neighbouring cavities into the rematch. Especially, we change the synchronous phase of the second cavity in the previous cell from negative to positive. This means that we obtain transverse focusing and longitudinal defocusing at the cavity while keeping the acceleration. The original focusing structure of DFD in the transverse planes and FDF in the longitudinal planes becomes FD and DF. The local rematch goal at the matching point can be achieved. The parameters of the involving cavities and SC solenoids before and after the rematch for the failure of an SC solenoid in the middle part of the Spoke021 section are shown in Table 3.

Table 3: Parameters of the Cavities and the Solenoids for the Rematch of a Solenoid Failure in the Spoke021 Section

Cavity Number	**1**	**2**	**3**	**4**	
Initial RF phase	-33°	-33°	-33°	-33°	
After rematch	-33.9°	40.5°	-48°	-30.7°	
Initial voltage / MV	1.24	1.26	1.35	1.37	
After rematch / MV	2.1	0.92	1.64	0.46	
Solenoid Number	**1**	**2**	**3**	**4**	**5**
Initial field / T	3.21	3.34	3.48	3.56	3.5
After rematch / T	4.08	3.64	-----	3.63	2.6

The Twiss parameters at the matching point "M" after rematch are shown in Table 4.

Table 4: Twiss Parameters at the Matching Point for the Rematch of a Solenoid Failure in the Spoke021 Section

Twiss parameter	**Alpha x**	**Beta x / m**	**Alpha y**
Initial	-0.02	2.35	0.03
After rematch	-0.03	2.83	0.03
Twiss parameter	**Beta y / m**	**Alpha z**	**Beta z / m**
Initial	2.28	0.09	17.63
After rematch	1.88	0.07	17.57

After the rematch, the normalized rms emittance growths at the end of Spoke021 section are 6.97% , 7.47% in the two transverse planes and 7.4% in the longitudinal plane, which is considered not so good but perhaps acceptable. The halo emittance growths are evident in both longitudinal and transverse planes (see Fig. 6), further optimization will be pursued.

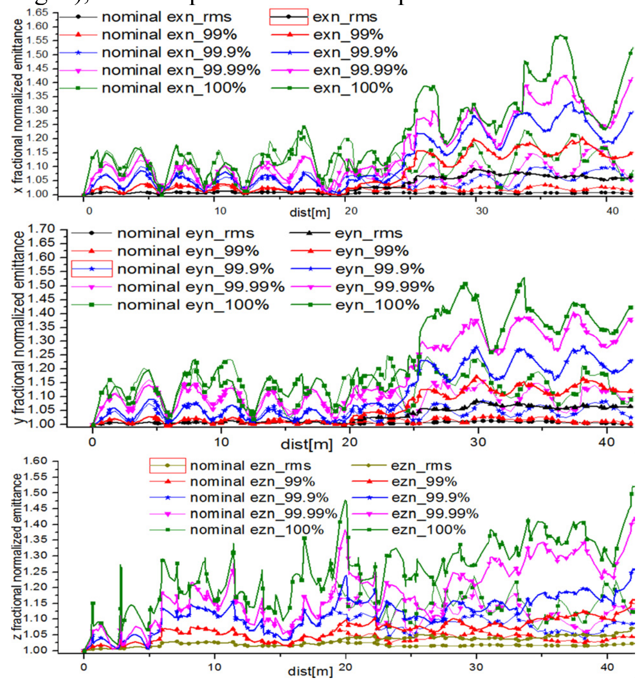

Figure 6: Halo emittance evolutions after applying the local rematch to the failure of a solenoid in the middle part of the Spoke021 section.

We have also studied the SC solenoid failures in the Spoke040 section. As the energy grows, the rematch becomes easier than that at lower energy, and only SC solenoids in the neighbouring cell can achieve the matching goal. The halo emittance growths are not evident in both the longitudinal and transverse planes.

Rematch for Quadrupole Magnet Failures

The rematch method for the failures of the quadrupole magnets in the high energy section (Ellip063 and Ellip082 section) has also been studied. For example, a quadrupole magnet failure in the middle of the triplet-cell structure in the middle part of Ellip082 section, as shown in Fig. 7.

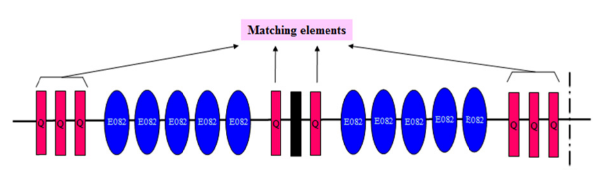

Figure 7: rematch method of the quadrupole failure in the middle part of the Ellip082 section.

We have adopted a triplet-based lattice, and triplet-cell focusing structure has advantage over doublet-cell structure in the rematch of the failure of a quadrupole magnet: when one of the three quadrupole fails, the two others can be easily transformed into a doublet to rematch the rms beam at the matching point with little mismatching. Besides, as the rematch in the periods of smaller phase advance (the high energy section) is more

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effective than the one in the periods of larger phase advance, slight readjustments in the two neighbouring triplets can help make almost a perfect rematch. The parameters of the involved quadrupoles before and after the rematch for the failure of a quadrupole in the middle part of the Ellip082 section are shown in Table 5.

Table 5: Parameters of the Rematch Quadrupoles for the Rematch of a Quadrupole Failure in the Ellip082 Section

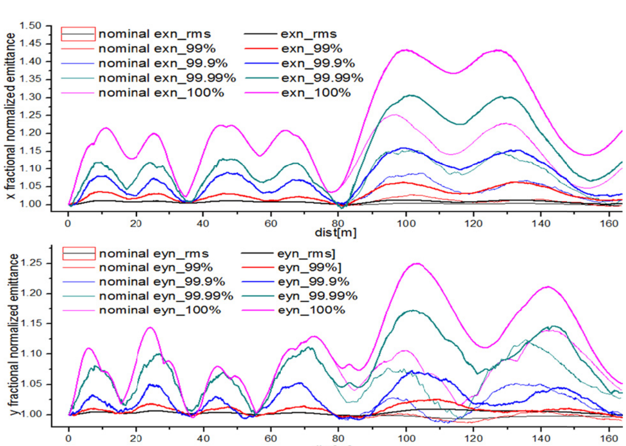
Cavity Number	1	2	3	4
Initial gradient T/m	7.73	-15.24	7.73	7.54
After rematch gradient T/m	7.57	-16.12	5.39	10.54
Cavity Number	**5**	**6**	**7**	**8**
Initial gradient T/m	7.54	7.35	-14.55	7.35
After rematch gradient T/m	-10.22	7.0	-14.3	6.64

The Twiss parameters at the matching point "M" after rematch are shown in Table 6.

Table 6: Twiss Parameters at the Matching Point for the Rematch of a Quadrupole Failure in the Ellip082 Section

Twiss parameter	Alpha x	Beta x / m	Alpha y
Initial	0.69	35.75	0.33
After rematch	0.71	36.17	0.34
Twiss parameter	**Beta y / m**	**Alpha z**	**Beta z / m**
Initial	26.12	0.16	39.0
After rematch	25.72	0.16	39.0

Unlike the case of solenoid failures in the low energy section, there is no need to put the neighbouring cavities in the rematch. After the rematch method is applied, the normalized rms emittance growths keep very smooth along the downstream part of the Ellip082 section. However, the phase advance has the discontinuity in the period where the quadrupole magnet failed and the halo emittance growths are evident especially in the two transverse planes, as shown in Fig. 8.



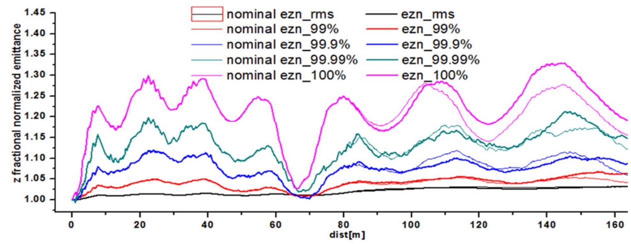


Figure 8: Emittance evolutions after applying the rematch method to a quadrupole failure in the middle part of the ellip082 section with comparison to the nominal one.

MORE STUDY ON COMPENSATION-REMATCH

All the local compensation-rematch study results above are based on the simulations with the TraceWin code. With the code, the energy loss due to a cavity failure can be correctly compensated. The rematch on both cavity and transverse focusing element failures can be achieved. However, the compensation for the arrival moment at the matching point is not correct because the code fits the RF phases for the downstream cavities automatically without taking into account the energy change due to the failed cavity. This does not fully meet the requirement for the local compensation-rematch method. This means that the phases for all the downstream cavities should be readjusted.

To solve this problem above, we have made a dedicated code-LOCCOM with MATLAB to search for the fully local compensation schemes. With the cose, we can carry out the compensation-rematch in two steps: first, it is easy to find a good setting of the compensation cavities to achieve the matching in the beam energy and the arrival time of the reference particle at the matching point; second, the phase space matching in all the three phase planes is performed at the matching point by using the cavities and the neighbouring transverse focusing elements. In the second step, the combination of the voltage and the phase of a cavity can be taken as one focusing parameter when the energy gain is kept unchanged during the optimization. Several iterations of the Step 1 to Step 2 loop are needed to obtain a satisfactory compensation-rematch scheme.

We study a cavity failure in the middle part of the Spoke021 section (see Fig. 9).

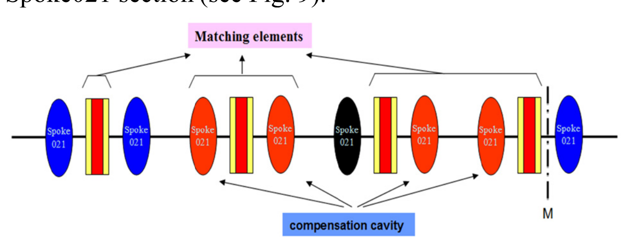


Figure 9: Local compensation method with LOCCOM.

The obtained parameters for the matching elements with LOCCOM are put into TraceWin to check the compensation-rematch effect. We find that the Twiss

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parameters remain matched (see Table 7) at the matching point after the compensation of both energy loss and phase difference.

Table 7: Twiss Parameters of the Matching Point

Twiss parameter	**Alpha x**	**Beta x / m**	**Alpha y**
Initial	-0.61	29.96	-0.46
After rematch	-0.60	29.72	-0.46
Twiss parameter	**Beta y / m**	**Alpha z**	**Beta z / m**
Initial	18.62	0.19	47.09
After rematch	18.47	0.19	47.70

The result above is based on zero current which means the space charge effect has not been considered. Further development by including the space charge for the code is under way.

CONCLUSIONS

The local compensation-rematch method has been studied and developed for the C-ADS accelerator. It is efficient to keep the good beam quality in case of failures of both cavity and focusing elements. With the rms beam emittance kept little changed after applying the method, the growth in the halo emittance is evident but still under control. The compensation-rematch is easier at the section of higher energy or smaller phase advance per cell. Triplet cells are advantageous in the rematch, as it can be transformed into doublet cell when one of the three elements fails. This method can also be applied to the rematch of solenoid failures by using positive phase for one of the cavities in the same cell.

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