Compensation-rematch for the major components of C-ADS injector-I *

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Abstract: The China-ADS project is a strategic plan launched by the Chinese Academy of Sciences to solve the nuclear waste problem and the resource problem for nuclear power in China. Under its long-term plan, it will last until about 2040. In order to achieve the extremely high reliability and availability required for the C-ADS accelerator, a fault tolerant strategy has been implanted. The failure effects of key elements such as the RF cavities and focusing elements in different locations of the injector-I part have been studied and schemes of compensation based on the local compensation-rematch method have been proposed. In addition, error analysis has been carried out to check the reliability of this method compared with the uncompensated situation, and it is found to be very effective. As the injector-I testing facility is coming into operation, it is possible to check and improve the compensation-rematch method with the beam testing experiment before the main linac operation.

Key words: C-ADS, high reliability, compensation-rematch, injector-I

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1 Introduction

The China Accelerator Driven subcritical System (C-ADS) project is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear energy in China. The C-ADS accelerator complex is a large continuous wave (CW) proton linac with 10 mA beam current and about 1.5 GeV final beam energy. Except for the radio frequency quadrupole (RFQ), all the accelerators are superconducting structures [1]. The layout of the linac is shown in Fig. 1.

The linac consists of two major parts: the two injectors and the main linac section. There are two different schemes for the injector section. Injector-I is based on a 325 MHz RFQ and superconducting Spoke012 cavities and solenoids housed in two cryomodules. The nominal design for the injector-I is shown in Fig. 2 and the normalized rms emittance at the exit of RFQ is 0.2 mm·mrad and 0.17 mm·mrad in both transverse and longitudinal planes [2].

For the superconducting section of injector-I, several reasons may cause failures of the RF cavities and solenoids, which are related to the RF power source, coupler, LLRF, cavity mechanical tuning, etc. Taking the first cavity failure in the first cryomodule as an example, if it fails, the large phase slip will lead to large beam loss in the downstream section and the accelerator operation should be interrupted immediately. From the simulation of multiparticle tracking with TraceWin code (version 2.6.3.5) [3], we see large phase dispersion due to the change in the focusing, as shown in Fig. 3.

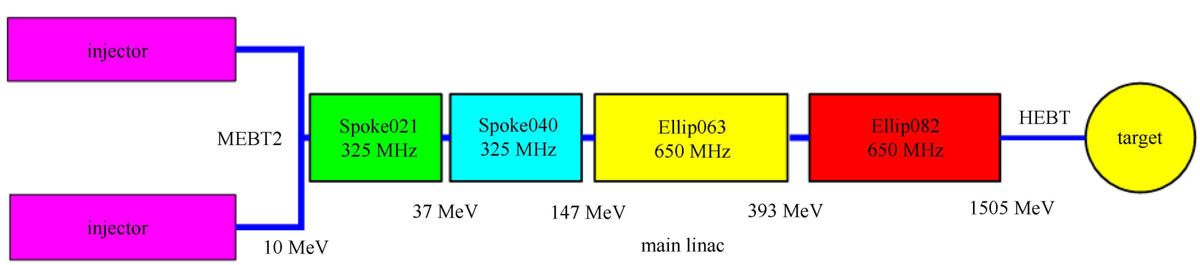

Fig. 1. (color online) layout of the C-ADS driver accelerator.

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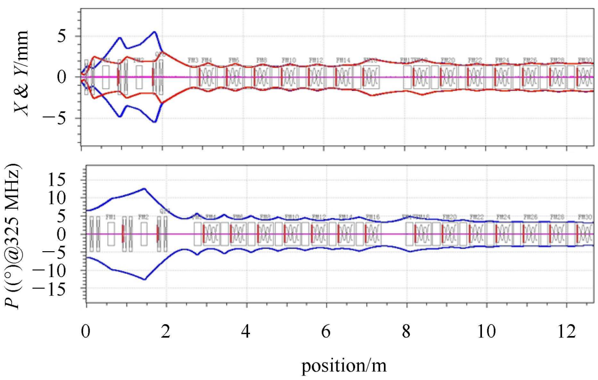

Fig. 2. (color online) Envelopes of both transverse and longitudinal planes evolution in injector-I.

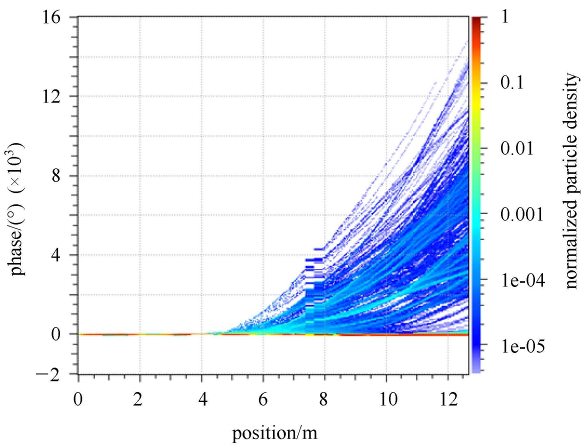

Fig. 3. (color online) Longitudinal envelope evolution after the first cavity failure in the superconducting section of injector-I.

In order to get over such problems, a fault tolerant design is usually pursued for each accelerator [4]. The local compensation-rematch method has been proposed to achieve a fault-tolerance design in the main linac [5]. For the injector section, the failure of each key component has more important impact to the beam quality, thus a two-injector scheme with one as a hot-spare to the operational one is designed, which is shown in Fig.1 However, for the test stand of the injector-I, there are also needs to do compensation-rematch practices. One reason is that one can check and improve the compensation-rematch method with hardware performance; and the other is that it can maintain the beam commissioning even in the cases of key component failures.

2 Local compensation rematch for cavity failure in injector-I

As the field level is normalized to the nominal RF voltage of 27.5 MV/m for the Spoke012 cavity in injector-I and the nominal solenoid field level is 4.5 T, and the available RF field level is 30% higher or with a field level of 1.3, the initial design fields of the Spoke012 cavities are set to a field level of about 1.1. As there is large redundancy for all the Spoke012 cavities, it is not difficult to keep the energy gain and the Twiss parameters recovering at the matching point "M" downstream, therefore, we divide the power loss into three kinds for both cavity and solenoid failures with the error analysis: beyond 10 W/m, between 1 and 10 W/m, and below 1 W/m. The detailed simulation results are shown below.

2.1 Cavity failure power loss over 10 W/m

As mentioned above, cavity failures may lead to large beam losses. If a cavity fails and nothing is done, the beam loss will be more severe for the upstream cavity failures. With the multiparticle tracking simulation, we find the power loss of the first six cavity failures is above 10 W/m. Taking the second cavity failure in the first cryomodule as an example, if nothing is done for the cavity failure, the envelope vibration is very evident and the power loss is about 300 W/m (see Fig. 4). However,

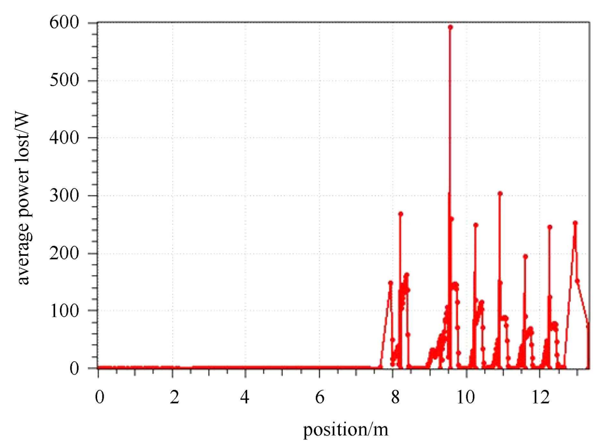

Fig. 4. (color online) Average power loss for the second cavity failure without compensation and rematch.

Table 1. Twiss parameters at the matching point after applying local compensation-rematch.

twiss parameter	alpha-x	beta-x/m	alpha-y	beta-y/m	alpha-z	beta-z/m
nominal case	0.76	1.12	0.74	1.08	−0.43	0.84
after compensation and rematch	0.75	1.11	0.74	1.09	−0.43	0.84
mismatch factor M	0.53%		0.16%		0	

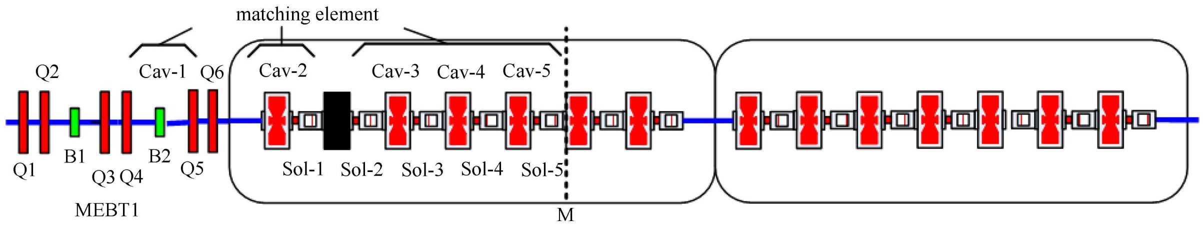

Fig. 5. (color online) Local compensation-rematch for the failure of the second cavity in the superconducting section of injector-I.

the situation will be much better if compensation-rematch is applied. The compensation method for the failure is shown in Fig. 5. The buncher in the MEBT1 [6] and the neighboring four cavities and five solenoids are involved for the compensation and rematch. The Twiss parameters at the matching point after the rematch compared with the nominal parameters are given in Table 1, and the parameters for the cavities and solenoids before and after the compensation-rematch are shown in Table 2.

Table 2. Parameters of the matching cavities and solenoids for the local compensation-rematch in the superconducting section of injector-I.

element	Cav-1	Cav-2	Cav-3	Cav-4	Cav-5
initial field level	1.01	1.1	1.1	1.1	1.1
after rematch	1.3	0.80	0.76	1.13	1.21
element	Sol-1	Sol-2	Sol-3	Sol-4	Sol-5
initial field level	0.82	0.83	0.83	0.83	0.82
after rematch	0.57	0.75	0.99	0.90	0.77

The mismatch factor M is defined to represent the change in the emittance ellipse, which also means the growth in the effective emittance due to mismatch [7]. The mismatch not only introduces envelope oscillations in the downstream linac but also leads to realistic emittance growth due to the space charge and nonlinear fields. Therefore it is very important to obtain a small mismatch factor. After the compensation and rematch, the field level factor for the cavities involved can be increased up to 1.3, keeping the maximum peak surface field below 35 MV/m. Besides, error analysis has been carried out to check the reliability of the method, and the static and dynamic tolerances of each error type are given in reference [8]. All the errors are included with 1000 linacs which represent different error settings. With all static and dynamic errors included, one can still control the residual orbit errors quite well with correction, the power density probability is controlled and the average power is lower than 1 W/m (see Fig. 6).

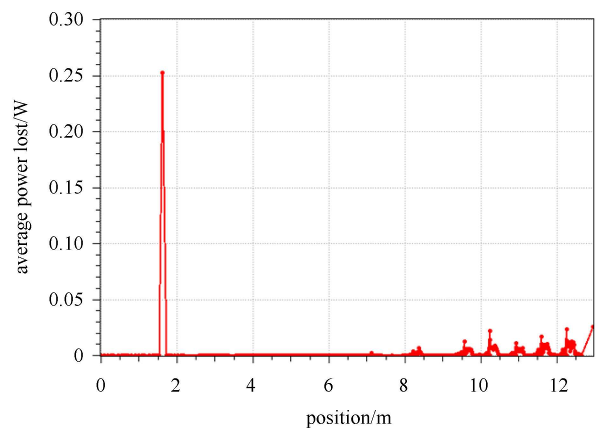

Fig. 6. (color online) Average power loss for the second cavity failure in the superconducting section of injector-I after compensation and rematch.

2.2 Cavity failure power loss between 1 and 10 W/m

As the energy increases, the power loss will be not be so big after cavity failure without any compensation. From the multiparticle tracking result, we find only the seventh cavity failure power loss is about 5 W/m

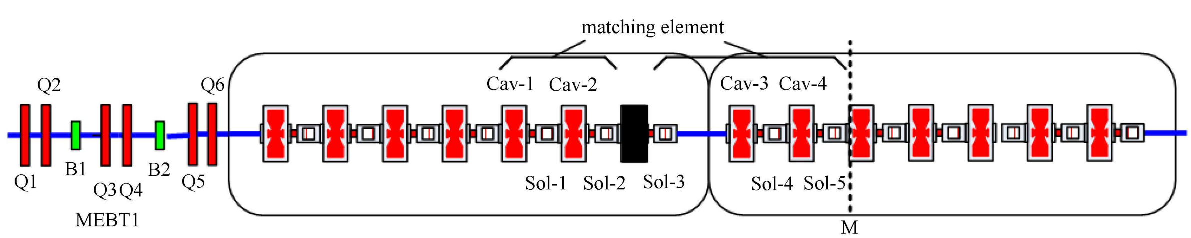

Fig. 7. (color online) Compensation-rematch for failure of the seventh cavity in the superconducting section of injector-I.

Table 3. Twiss parameters at the matching point after applying local compensation-rematch.

twiss parameter	alpha-x	beta-x/m	alpha-y	beta-y/m	alpha-z	beta-z/m
nominal case	0.61	1.45	0.60	1.43	−0.32	1.05
after compensation and rematch	0.60	1.45	0.60	1.45	−0.31	1.05
mismatch factor M	0.5%		0.22%		0.5%	

(between 1 to 10 W/m). The compensation method for the failure can be seen in Fig. 7.

As the picture shows, the cavities and solenoids in the second cryomodule are also used. The distance between the two cryomodules, which is about 580 mm, breaks the nominal lattice period. The field level of the first cavity and the second solenoid which are involved should go down to 0.44 and 0.48 respectively, which keeps the beam passing through smoothly. The optimization results for the Twiss parameters at the matching point are given in Table 3.

With the help of the neighboring cavities and solenoids, we can obtain a good compensation and rematch by optimization. In addition, the error analysis has also been carried out and the average power is less than 1 W/m, which proves that the method is feasible.

2.3 Cavity failure power loss below 1 W/m

To check the method further, we also considered the situation with the power loss below 1 W/m. The tracking result shows if the cavity fails and nothing is done, only the average power loss of the eighth cavity failure at the beginning of the second cryomodule is about 0.005 W/m (less than 1 W/m), and the others downstream are all 0 W/m even with error included. The compensation-rematch method is similar to that for the seventh failed cavity; the cavities and solenoids used are in the two different cryomodules, the mismatch factor is less than 1% and the average power is 0 W/m.

The compensation and rematch method for the Spoke012 cavity in different lattice periods has also been studied. Similar to the three kinds of power loss condition, the phase advance per cell becomes smaller as the energy increases, and the compensation and rematch becomes much easier. Thus, the method is viable for all the cavity failures except the first cell.

3 Rematch for solenoid failures in injector I

Solenoid failures should not happen frequently compared with RF cavity failures, but the rematch methods for the SC solenoid is very different, especially in the low energy section. As there is only one solenoid in each period for transverse focusing, once the solenoid fails, the larger distance between the two cells will lead to a big beam size, which will result in beam loss. Like the cavity, we divide beam power loss into two kinds: greater than 10 W/m and less than 10 W/m.

3.1 Solenoid failure power loss over 10 W/m

Unlike with cavity failure, beam power loss does not decrease regularly along with the linac. We find the power loss of the second and seventh cavity failures is above 10 W/m. Taking the seventh solenoid failure (at the end of the first cryomodule) as an example, if nothing is done, the average beam power loss is 150 W/m which is greater than 10 W/m after the error analysis without rematch. The envelope and power loss are shown in Fig. 8.

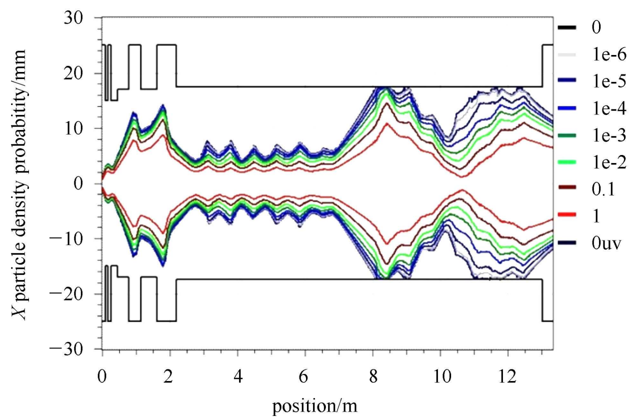

Fig. 8. (color online) Envelope evolution for the seventh solenoid failure in the superconducting section of injector-I without rematch.

To solve the problem, the cavities are used in the rematch. The rematch method has been divided into two steps: firstly, keeping the energy gain the same as the nominal section at the matching point; secondly, matching the Twiss parameters approaching to the initial value. The local rematch for the seventh solenoid is shown in Fig. 9.

As Fig. 9 shows, the large gap between the two cryomodules besides the distance of the two cells will lead to great beam loss compared to that of the first solenoid failure, therefore, the five cavities and solenoids nearby are involved in the rematch. The key step in the rematch is to decrease the field level of the cavities and solenoids to keep the focusing structure of Defocusing-Focusing-Defocusing (DFD) in the transverse planes from Sol-3 to Sol-4, which prevents the beam size from expanding. As expected, with the help of the cavities, the problem of rematch for such a large gap has been solved. The

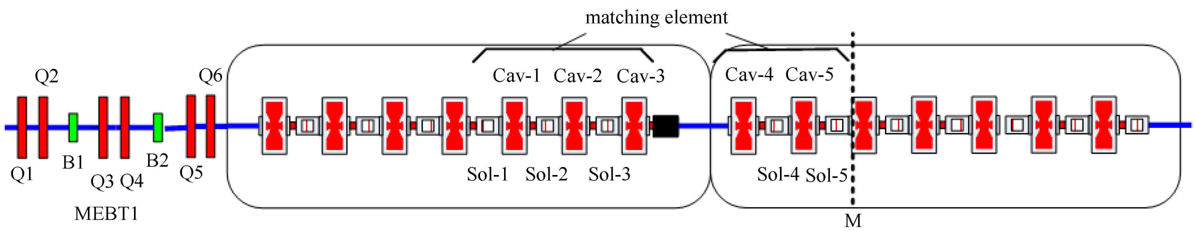

Fig. 9. (color online) Rematch for the failure of the seventh solenoid in the superconducting section of injector-I.

Table 4. Parameters of the matching cavities and solenoids for rematch in the superconducting section of the injector-I.

element	Cav-1	Cav-2	Cav-3	Cav-4	Cav-5
initial field level	1.1	0.89	0.83	0.67	0.60
after rematch	1.41	0.54	0.78	0.52	0.37
element	Sol-1	Sol-2	Sol-3	Sol-4	Sol-5
initial field level	0.83	0.82	0.57	0.80	0.53
after rematch	0.61	0.71	0.76	0.83	0.33

parameters for the cavities and solenoids before and after the rematch are shown in Table 4. The mismatch factor can be controlled below 1% in both transversal and longitudinal planes.

After the rematch, all static and dynamic errors are taken into the consideration (1000 linacs with errors) and the simulation is shown in Fig. 10. From the result, we see the beam power loss has decreased to less than 1 W/m with error correction.

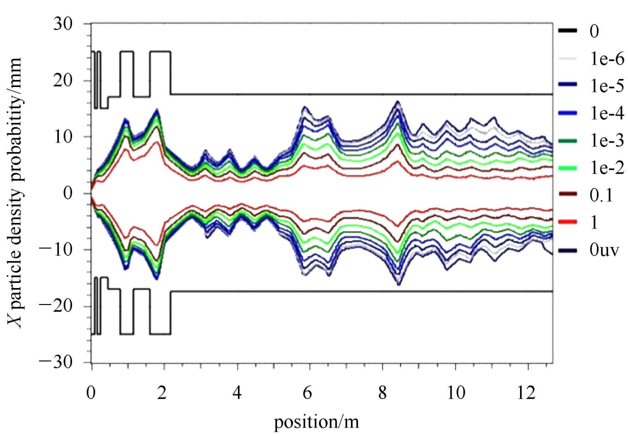

Fig. 10. (color online) Envelope evolution for the seventh solenoid failure in the superconducting section of injector-I after rematch.

3.2 Solenoid failure power loss below 10 W/m

To check the rematch method further, the rematch for the average power loss below 10 W/m has also been studied. The power loss of the first and fifth solenoids is between 1 and 10 W/m, the others are below 1 W/m. Taking the fifth solenoid failure in the first cryomodule as an example, as it is nearly at the middle of the first cryomodule, the field levels of the cavities and solenoids involved in the rematch do not change significantly, which keeps equal energy gain and Twiss parameters matching at the matching point. After careful optimization and multiparticle tracking with error analysis, the beam power loss decreases to below 1 W/m. The parameters for the cavities and solenoids before and after the rematch are shown in Table 5.

Table 5. Parameters of the matching cavities and solenoids for rematch in the superconducting section of the injector-I.

element	Cav-1	Cav-2	Cav-3
initial field level	1.1	1.1	0.89
after rematch	1.02	1.0	0.92
element	Cav-4	Cav-5	Cav-6
initial field level	0.83	0.67	0.60
after rematch	0.87	0.79	0.62
element	Sol-1	Sol-2	Sol-3
initial field level	0.83	0.83	0.57
after rematch	0.70	0.87	0.66
element	Sol-4	Sol-5	Sol-6
initial field level	0.82	0.80	0.53
after rematch	0.77	0.74	0.52

In addition, we studied the failure of the third solenoid and found the average power loss below 1 W/m without any rematch. With the help of the five cavities and four solenoids nearby, the rematch result is perfect. There is no power loss after the multiparticle tracking with error analysis.

4 Discussions and conclusions

To achieve the requirements of high reliability and low beam loss for the C-ADS accelerator, the compensation rematch method has been proposed. As the testing apparatus is coming into operation, it is possible to check and improve the compensation-rematch method with the beam testing experiment before the main linac operation. For the cavity failure, it is possible to achieve compensation and rematching at the matching point except for the first cavity failure. For the solenoid failure, the rematch can be achieved at the matching point with the help of the neighboring cavities. From the simulation of the multiparticle tracking with error analysis, all the power loss can be controlled down to 1 W/m, which ensures the feasibility of this method.

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References

1 LI Z H, CHENG P, GENG H P et al. Phys. Rev. ST Accel. Beams, 2013, **16**: 080101
2 YAN F LI Z H, MENG C et al. Chinese Physics C, 2014, **38**(2): 027
3 http://irfu.cea.fr/Sacm/en/logiciels/index3.php
4 Biarrotte J L, Novati M, Pierini P et al. Proceedings of European Particle Accelerator Conference, 2004. 1282
5 SUN B, YAN F, LI Z H et al. Proceedings of HB'12, 2012. 2102
6 LI Z H, MENG C, GENG H P et al. Proceedings of IPAC'13, 2013. 3863
7 TANG J Y. Nuclear Instruments and Methods in Physics Research A 2008, **595**: 561
8 MENG C, LI Z H, TANG J Y et al. Proceedings of IPAC'13, 2013. 3866