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Local compensation–rematch for major element failures in superconducting linacs with very high reliability and low beam loss

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ABSTRACT

In order to achieve the extremely high reliability and availability in superconducting linacs required by some applications such as in accelerator-driven systems (ADS), a fault tolerance design is usually pursued. With the example of the China-ADS main linac, the failure effects of key elements such as RF cavities and focusing elements in different locations along the linac have been studied and the schemes of compensation by means of the local compensation–rematch method have been proposed. For cavity failures, by adjusting the settings of the neighboring cavities and focusing elements one can make sure that the Twiss parameters and beam energy are recovered to the nominal ones at the matching point. For solenoid failures in the low energy section, a novel method by using a neighbor cavity with reverse phase is used to maintain simultaneous acceleration and focusing in both the transverse and longitudinal phase planes. For quadrupole failures in the warm transitions in the high energy section, triplet focusing structure is adopted which can be converted locally into a doublet focusing in case of one quadrupole failure and the rematch method is proven very effective. With macro-particle simulations by TraceWin, it is found that the normalized rms emittance has no obvious growth and the halo emittance has modest growth after applying the local compensation–rematch in the cases mentioned above. In addition, a self-made code based on MATLAB has been developed to double check the simulations by TraceWin for the local compensation and rematch method.

1. Introduction

Extremely high reliability and availability are considered to be the most important characteristics for the beam application in an Accelerator-Driven Subcritical System (ADS). This has to be guaranteed by special design methods in the driver linac. Besides all the hardware will be operated with conservative performance and redundancy, it is also important to have fault-tolerant capabilities in the physics design [1,2]. However, 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 addition, for linacs with a beam power of a few megawatts or even higher, very low beam loss rate is required. This means that all the factors which may lead to potential beam losses should be controlled very strictly. Generally, one must control the growth in fractional or halo beam emittance along with the linac very strictly. Both global and local compensation methods were proposed to tackle cavity failures in superconducting linacs [3], with the latter being considered to suitable for meeting the very high reliability in ADS linacs. In this article, the local compensation–rematch method is further developed to deal with the failures of two kinds of major components: superconducting RF cavities (also as SC cavities) and transverse focusing elements including superconducting solenoids and room-temperature quadrupoles. It aims to shorten the beam-off time for readjusting the linac and the growth in halo emittance when performing such compensation and rematch.

The C-ADS (or 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 the sustainable development of nuclear power in China. With its long-term planning spanning until about 2040, the project will be conducted in three major phases: R&D Phase, Experimental Facility Phase and Demo Transmutation Facility Phase. The proton driver is based on

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a superconducting proton linac working in the CW mode [4–6]. The local compensation–rematch method is applied to the main linac of C-ADS to show its effectiveness. The layout of the C-ADS linac is shown in Fig. 1. The main parameters for each section of the linac are given in Table 1.

2. Local compensation–rematch for RF cavity failures

Several factors may cause the failures of RF cavities, which concern 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, particularly in low energy sections where the beam is not highly relativistic. The reason is that the phase slip caused by the change in beam velocity will make the beam center phase to exceed the longitudinal acceptance of the downstream acceleration section. At SNS, it is the usual operation to adjust some downstream SC cavities when one cavity fails [7]. However, it takes some minutes to make the adjustment and the beam should be switched off during the tuning. For the C-ADS, the beam-off time for the tuning should be controlled within a few seconds as required by the reactor design. Another major difference from the SNS where it deals only with the cavities working at energy higher than 186 MeV so that the compensation–rematch is not very difficult and the so-called global compensation method can work well. However, one has to deal with the cavity failures from very low energy at C-ADS. The best way to deal with this kind of failures is to readjust the setting of the neighboring cavities to regain the nominal beam velocity, and to rematch the transverse and longitudinal focusing at the same time as the RF cavities also affect the focusing [2]. By doing so, only a few local elements are involved in the compensation that can shorten the beam-off time. Another advantage of the local compensation method over the global compensation method is that it can avoid the resetting errors in the downstream elements. Therefore, the local compensation–rematch method for any failure of the cavities in the main linac will be applied at C-ADS. To achieve this goal, the design has made least 30% redundancy in the nominal field level to all the cavities. In this way, more cavity failures in different locations at the same time can be compensated independently and efficiently [2,5,9], which is also an important aspect in ADS applications. In addition, the failures of focusing elements including superconducting solenoids and room-temperature quadrupoles can be also re-matched locally.

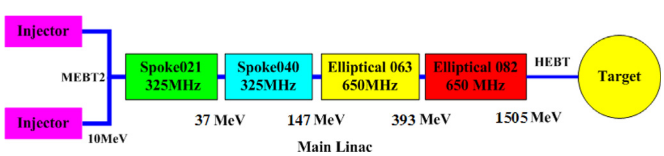

Fig. 1. Schematic of the C-ADS driver linac.

In this study, to make the local compensation–rematch method convincing, detailed multiparticle simulations including space charge by using TraceWin [8] have been carried out. In most cases, an initial 6D water-bag distribution and full 3-dimensional field maps for the cavities have been used to study the dynamic behaviors of the beam, including rms features and fractional emittances of the beam.

2.1. Local compensation–rematch for cavity failure in the Spoke021 section

As mentioned above, cavity failure may lead to beam loss, especially in the low energy section. Taking a 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. 2. Here one periodical cell is composed of one cavity, one solenoid and the second cavity. One buncher (Cav-1 in the figure) in the MEBT2 [9] which is the same cavity type as Spoke021, together with the three neighboring cavities are used for the energy compensation. In addition, they and the four neighboring solenoids together are used for the rematch in the phase spaces.

If nothing is done for the cavity failure, the large phase slip (about 77° at the entrance of the first cavity of the next cell) will lead to large beam loss and the accelerator operation should be interrupted immediately, as shown in Fig. 3 and Fig. 4. The large power losses occur at the downstream of the failed cavity.

Table 1
Main parameters of the proton driver linac.

	RFQ	Spoke012	Spoke21	Spoke040	Ellip063	Ellip082	Total
Energy (MeV)	3.2	10	37	147	393	1505	1505
Cavity number	1	14	36	60	42	100	252
Focusing structure		RS	RSR	R^2SR^2	R^3FDF	R^5FDF	
Section leng. (m)	4.8	10.006	39.024	57.84	84.336	191.8	
CM number		2	6	15	14	20	57
Synch. phase		−35 to −25	−42 to −30	−27 to −22	−20 to −18	−15 to −14	

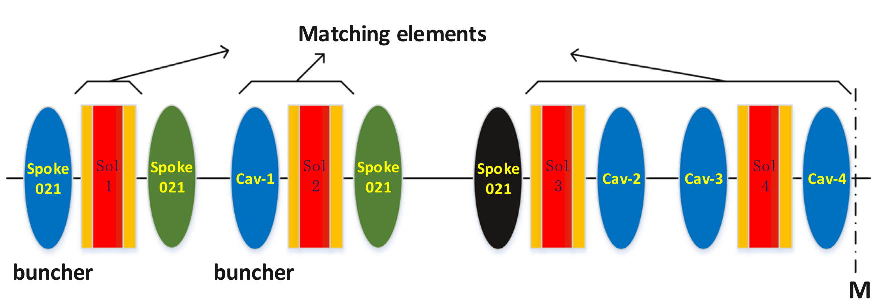

Fig. 2. Local compensation–rematch for the failure of the first cavity in the Spoke021 section. The ellipses stand for cavities, the rectangular for solenoids, the green ellipse for the back-up buncher cavity, the black ellipse for the failed cavity; *M* stands for the matching point. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)