ERROR ANALYSIS AND CORRECTION SCHEME IN C-ADS INJECTOR-I*

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Abstract

C-ADS Injector-I is a 10-mA 10-MeV CW proton linac. It uses a 3.2-MeV normal conducting 4-Vane RFQ and 12 superconducting single-spoke cavities. According to the detailed sensitivity analysis of alignment and RF errors, the error tolerance of both static and dynamic ones for Injector-I is presented. The simulation results show that with the errors there are beam losses, the residual orbit is too large, which will produce significant emittance growth, so that the correction is necessary for Injector-I. After detailed numerical studies, a correction scheme and monitor distributions are proposed. After correction the rms residual orbit can be controlled within 0.4 mm and RMS emittance growth can be controlled within 10%, but it still has 1.7×10^{-6} beam loss, which comes from the RF errors and small longitudinal acceptance. To minimize beam loss, the causes of beam loss have been studied and a short period Injector-I lattice with larger longitudinal acceptance have been designed with good error tolerance performance. According to detailed analysis and simulations, as a consequence, longitudinal emittance control and longitudinal distribution control as well as large longitudinal acceptance are the key to minimize beam losses and emittance growth in low energy section.

INTRUDUCTION

The C-ADS project is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China [1]. For the C-ADS accelerator that is a CW proton linac, it uses superconducting acceleration structures except the RFQs. The C-ADS linac consists of two injectors and a main linac section, as shown in Fig.1.

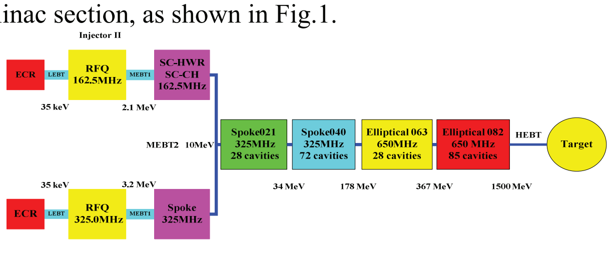

Figure 1: Layout of the C-ADS driver accelerator.

Two identical injectors will be operated in the mode of one as the hot-spare of the other. However, two different injector schemes are shown in Fig.1, and this means that in the early developing phase two different approaches of injector will be developed in parallel by two different teams. C-ADS Injector-I [1] is a 10-mA 10-MeV CW proton linac. It uses a 3.2-MeV normal conducting 4-Vane RFQ and 12 superconducting single-Spoke cavities. This paper will report error analysis and correction scheme in Injector-I including MEBT-1 and spoke cavity section.

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SIMULATIONS CONSIDERING DIFFERENT SOURCES OF ERROR

All the devices having electromagnetic field influence over the beam have installation errors including translational errors and rotation errors, and also field errors. We can classify the possible sources of error into four groups [2]:

- Translational errors: affect all the elements of the accelerator system.
- Rotation errors (pitch/yaw/roll): affect all the elements of the accelerator system.
- Field errors: affect the field level as well as the phase of an accelerating cavity and the field of magnets.
- BPM uncertainty: affect the correction effects

As RMS residual orbit reflects beam loss and emittance growth to some extent [1], it can be considered a criterion to evaluate the influence of errors without correction schemes. The sensibilities of different static errors in Injector-I, such as solenoid displacements, solenoid rotations, spoke cavity displacements, and spoke cavity rotations have been studied.

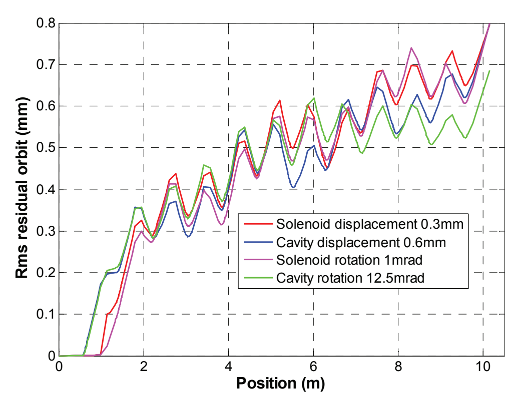

Figure 2: Comparison on rms residual orbit among different error types in Injector-I.

It is found that the rms residual orbit is approximately proportional to the magnitudes of four errors. The sensitivity comparison is shown in Fig.2, which shows the downward importance for the errors: solenoid rotation, solenoid displacement, spoke cavity displacement and spoke cavity rotation. About the rms emittance growth, the spoke cavity displacements have the most important influence and the RF errors have also significant influence. Following the preliminary error study and technical feasibilities, Table 1 shows the initial error definitions for the error studies [3-6].

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Table 1: Amplitudes of Errors Used For Error Studies

Error	Tolerance	
	Static	Dynamic
cold element displacement	±1mm	±10μm
warm element displacement	±0.1mm	±2μm
element rotation	±2mrad	±0.02mrad
BPM uncertainty	±0.1mm	---
Magnetic gradient	±0.5%	±0.05%
RF amplitude fluctuation	±1%	±0.5%
RF phase fluctuation	±1°	±0.5°

CORRECTION SCHEME

The simulation results show that it has beam loss with errors and the residual orbit is too large, so the correction scheme of Injector-I is necessary. In this study, only the spoke cavity section is included for studying the correction scheme. According to the lattice design, a pair of corrector and BPM in each period is responsible for the orbit correction. The correction scheme relies on the steering coils attached to solenoids and the beam position monitors between spoke cavity and solenoid, as shown in Fig.3. This one-to-one correction scheme maintains the RMS residual beam orbit below 0.4 mm while keeping the maximum deviation below 1 mm and RMS emittance growth below 10%, as shown in Fig.4.

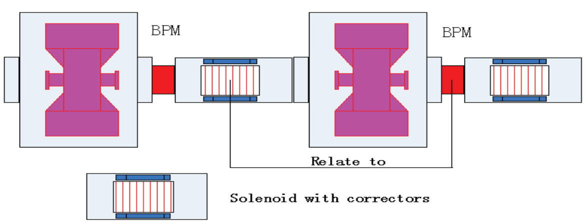

Figure 3: The schematic diagram of correction scheme.

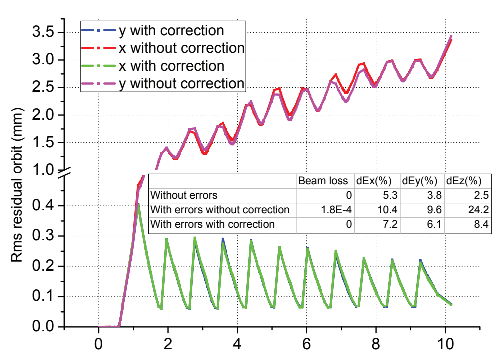

Figure 4: Residual RMS orbit, emittance growth and beam loss with all nominal errors included in the spoke section.

SIMULATION RESULTS WITH ERRORS

In order to study the effect of errors along Injector-I, Monte-Carlo simulations have been carried out by tracking 9.9×10^4 particles with the simulated RFQ exit distribution through 1000 different linacs, each with different random errors. From the simulation results, one can see that the correction scheme works well. However, there are beam losses of about 1.7×10^{-6} in the SC sections in Injector-I with all errors and the correction schemes included. Particle trajectories in horizontal plane and phase plane in the MEBT1-1 and the SC sections of Injector-I is shown as Fig.5. Because of the RF errors some particles move out of the longitudinal acceptance in the SC section, and then they will not match to the transverse focusing and get lost.

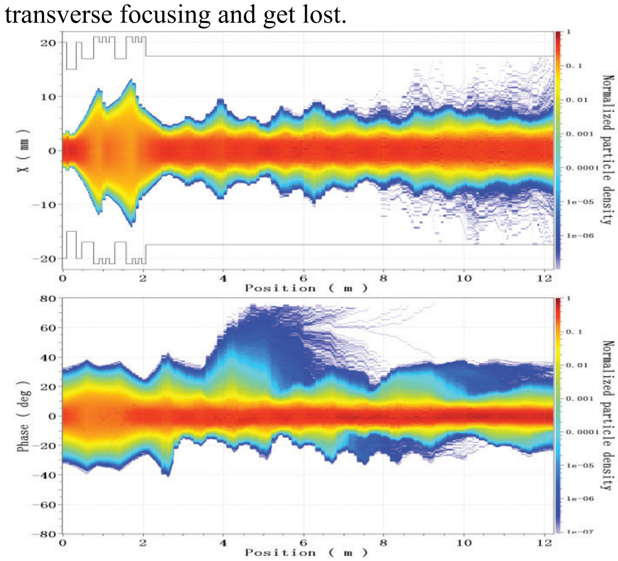

Figure 5: Particle trajectories in the horizontal plane and phase plane in the MEBT1-1 and the SC sections of Injector-I (The particles out of 75 degrees in phase plane are not shown).

To analyze the cause of beam loss, we study the different RF errors and different initial distributions. Table 2 shows the simulation results with 10^8 particles with different RF errors and all other errors using 3&5 standard deviation Gaussian distribution. From the results one can demand smaller RF errors to reduce the beam losses in the SC section. Figure 6 shows the beam loss with different initial distributions. We can see that the initial longitudinal distribution has a great influence here, which means the longitudinal acceptance of the SC section is relatively small. As a consequence, longitudinal emittance control and longitudinal distribution control as well as large longitudinal acceptance are the key to minimizing beam losses in low energy section.

Table 2: Simulation Results with Different RF Errors

RF errors sets with uniform distribution		Ex (%)	Ey (%)	Ez (%)	Beam loss
Amplitude (%)	Phase (°)				
0	0	9.3	8.1	50	7×10^{-8}
±0.5	±0.5	9.5	8.4	51	1.2×10^{-7}
±1	±1	9.7	8.5	57	1.5×10^{-7}
±1.5	±1.5	11.8	10.7	68	2.5×10^{-7}

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As the large total longitudinal emittance from the RFQ is difficult to reduce, it looks that enlarging the longitudinal acceptance of the SC section should be considered to minimize beam losses. So a shorter period Injector-I lattice have been designed, which have short length solenoids and larger longitudinal acceptance. Table 3 shows the comparison between long period lattice and short period lattice with same errors set mentioned in Table 1. Particle trajectories in horizontal plane and phase plane of short Injector-I are shown as Fig.7. From the above results one can see that the short period lattice has no beam loss with good error tolerance performance.

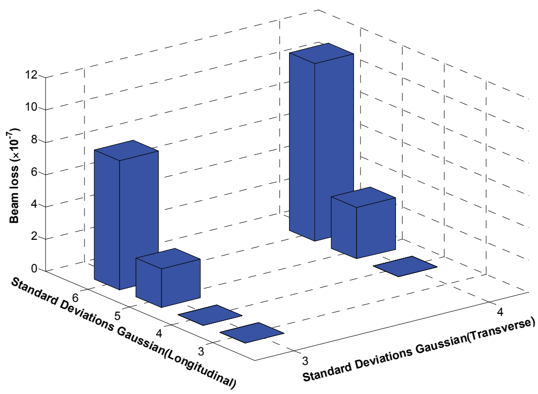
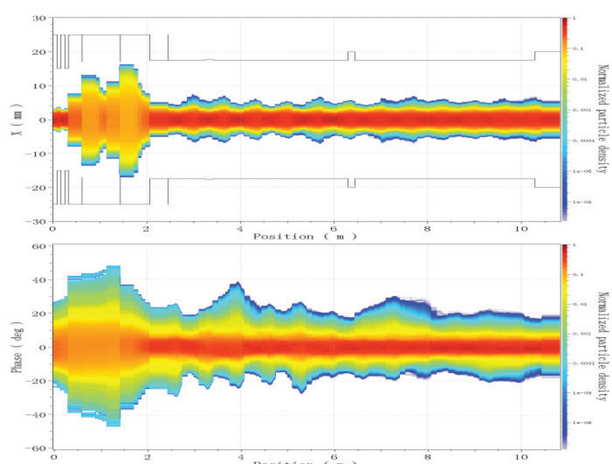


Figure 6: Beam loss with different initial distributions.



Fi ure 7: Particle trajectories in horizontal plane and phase plane of short Injector-I

Table 3: Comparison between Long Period and Short Period with Errors

Lattice	Ex (%)	Ey (%)	Ez (%)	Beam loss
Long period design	9.8	9.2	170	1.7×10^{-6}
Short period design	6.5	8.1	6.2	0

CONCLUSION

According to the detailed sensitivity analysis of alignment and RF errors, the error tolerance of both static and dynamic ones for Injector-I are presented in this paper. A correction scheme and monitor distributions are proposed. The rms residual orbit can be controlled within 0.4 mm and RMS emittance growth can be controlled within 10% with correction, but it still has 1.7×10^{-6} beam loss, which comes from the RF errors and small longitudinal acceptance. According to detailed analysis and simulations by tracking 10^5 particles through 1000 different linacs, as a consequence, longitudinal emittance control and longitudinal distribution control as well as large longitudinal acceptance are the key to minimize beam losses and emittance growth in low energy section. To minimize beam loss, a short period lattice has been designed and has no beam loss with good error tolerance performance.

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