ERROR ANALYSIS AND BEAM LOSS CONTROL IN THE C-ADS MAIN LINAC *

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Abstract

The China ADS (C-ADS) driver linac is defined to deliver a CW proton beam of 1.5 GeV in energy and 10 mA in current. To meet the extremely high reliability and availability, it is very important and imperative to perform detailed error analysis to simulate the real machine, where the errors always exist. Through error analysis the proper closed-orbit correction scheme and the maximum tolerable hardware and alignment errors can be found. This paper presents the method to optimize the apertures of elements in the C-ADS main linac to minimize beam losses. According to the detailed sensitivity analysis of different errors, the static and dynamic errors for the main linac are proposed. The correction scheme is described, and with the correction scheme the residual orbit can be controlled very well. The influence of the correctors and BPM failures on the correction scheme is also studied. The simulation results with errors are reported in this paper.

INTRODUCTION

The China ADS (C-ADS) driver linac is defined to deliver a CW proton beam of 1.5 GeV in energy and 10 mA in current [1]. The C-ADS linac includes two major sections: the injector section and the main linac section. The main linac boost the energy from 10 MeV up to 1.5 GeV and the lattice structures for each section of the main linac are shown in Fig. 1. Beam loss rate of 1 W/m is widely used in high-power proton accelerator, mainly for hands-on maintenance. It turns out that the beam loss rate should be controlled within 7×10^{-8} /m at the higher energy part. To meet the extremely high reliability and availability, it is very important and imperative to perform detailed error analysis to simulate the real machine. The simulation results of main linac with errors are reported in this paper.

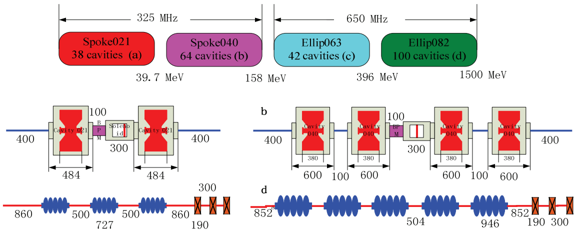

Figure 1: Schematic view of the lattice structures for the main linac sections.

APERTURE CHOICE

For the transverse acceptance, it is limited by the nonlinearity of the RF defocusing at low energy and by the physical aperture of the beam pipes at higher energy. A smaller acceptance in the warm transitions helps to avoid beam losses in the cryomodules (CM). Here the acceptance in the transition sections shown in Fig. 2 is taken as at last half of the one in the cryomodules, where acceptance is $admittance_x=\pi R^2/\beta_x$. The beam apertures of the superconducting cavities which are important design parameters have been designed and other apertures have been chosen accordingly considering the acceptance and uniformity. Apertures of all elements are shown as Table 1.

Table 1: Element Apertures in the Main Linac Section

Main linac	**Element**	**Apertures (mm)**
Spoke021 section	SC cavity and drift	40
	Solenoid	50
Spoke040 section	SC cavity and drift	50
	Solenoid	50
Ellip063 section	SC cavity and drift in CM	100
	Quadrupole and drift in transition section	70
Ellip082 section	SC cavity and drift in CM	100
	Quadrupole and drift in transition section	70

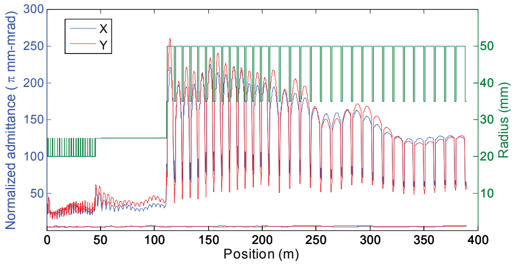

Figure 2: Apertures and calculated admittances along the main linac.

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SIMULATIONS CONSIDERING DIFFERENT SOURCES OF ERROR

All the devices having electromagnetic field influence over the beam should have installation errors. We can classify the possible sources of error into three groups: misalignment errors; field errors; BPM uncertainty. The errors mentioned above can be classified in two different types according to their different variation properties with time: static errors and dynamic errors. RF field errors caused by the random jitter of power supply are sources of dynamic errors and by setting when first tuning belong to static errors. The residual orbit cause by static errors can be corrected by correctors and BPMs with proper correction scheme discussed in next section. In current simulation, we do not distinguish between static and dynamic errors of RF fields.

Considering the simulation results and engineering design, the errors used for error studies are shown in Table 2 [2-4]. The errors are generated randomly with uniform distribution. In this section simulations, 500 sets of errors are generated and applied to the corresponding elements and 10^5 particles are tracked for each set.

Table 2: Amplitudes of Errors Used for Error Studies

Error No.	**Error description**		**Tolerance**	
			Static	**Dynamic**
1	Magnetic displacement	Quadrupole	±0.1 mm	±2 μm
		Solenoid	±1 mm	±10 μm
2	Magnetic element rotation (mrad)		±2	±0.02
3	Magnetic element field		±0.5%	±0.05%
4	Cavity displacement		±1 mm	±10 μm
5	Cavity rotation (mrad)		±2	±0.02
6	RF amplitude fluctuation		±1%	±0.5%
7	RF phase fluctuation		±1°	±0.5°
8	BPM uncertainty		±0.1 mm	

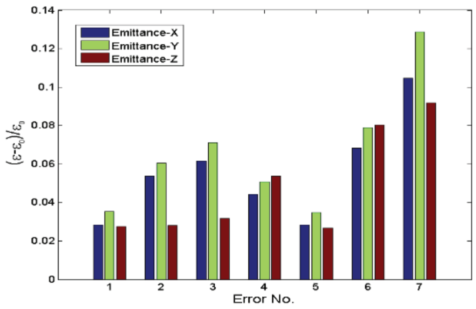

Figure 3: Comparison of the sensitivity to different sources of errors of Table 2.

Emittance growth is an important question. In this paper the emittance refers to RMS emittance. Figure 3 shows the effect of different kinds of errors on the transverse and longitudinal emittance growth at the exit with correction scheme. The emittance growth $\Delta\varepsilon/\varepsilon_0=(\varepsilon-\varepsilon_0)/\varepsilon_0$ relative to the case with no errors (ε_0) is plotted as function of error tolerances listed in Table 2. The ε is the rms emittance at the exit of the linac with errors using the following expression: $\varepsilon=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\varepsilon_i^2}$. We can find that both transverse emittances and longitudinal emittance are affected greatly by RF errors.

CORRECTION SCHEME

The multi-particle simulations show the residual orbit is too large without correction, and it has beam loss with errors, so the correction scheme is necessary. According to the lattice design, the transverse phase advance per period is about 20~70 degree, a pair of corrector and BPMs in one period is responsible for one-to-one correction scheme. The BPMs' uncertainty including the BPM misalignment and electronic accuracy influence the correction result shown as Fig. 4. From the simulation results, we can see that BPMs' uncertainty affect maximum RMS residual orbit slightly in solenoid focusing section and greatly in quadrupole focusing section. The misalignment of BPMs can be aligned up to a few tens micro meters by BBA method [5] and the reading noise of BPMs is about 30 μm, so the BPM uncertainty adopts 0.1 mm in the simulation.

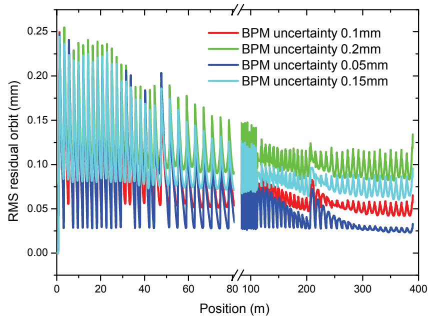

Figure 4: Rms residual orbit with different BPM uncertainty.

We choose one-to-one correction scheme to maintain the RMS residual beam orbit below 0.25 mm while keeping the maximum deviation below 0.6 mm with static errors as shown in Fig. 5. Dynamic errors can lend to rms residual orbit about 0.1 mm maximum which cannot be corrected also shown as Fig. 5. According to above simulation the correction scheme works well but needs a lot of BPMs which means a great cost. Considering to BPMs' failure and reduction of BPM number, we study the effect of lost BPM or reduce BPM in different period shown as Fig. 6. From the residual orbit result and about 8% additional emittance growth BPMs' failure should be avoided especially in solenoid focusing section for larger misalignment errors.

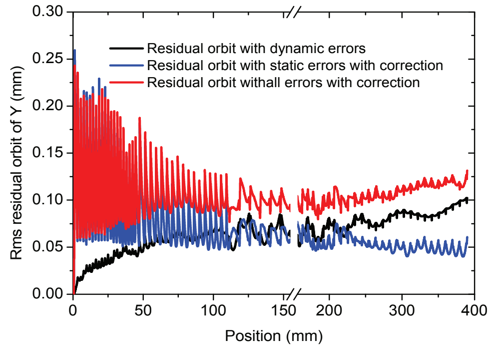

Figure 5: Rms residual orbit with different errors with correction.

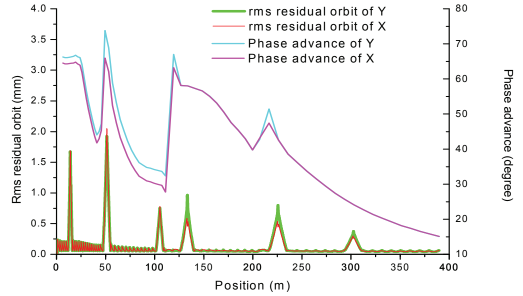

Figure 6: Rms residual orbit with BPM failure and phase advance along linac.

MULTIPARTICLE SIMULATION RESULTS WITH ERRORS

According to previous error study to reduce beam loss, we redesign the main linac to keep the synchronous phase larger than 10 times the RMS phase width throughout the main linac. Multiparticle simulation with errors have been performed with 4&5 standard deviation Gaussian distribution. The errors are generated randomly with uniform distribution as Table 1. In this section simulations, 1000 sets of errors are generated and 10^5 particles are tracked for each set. The simulation results are shown as Table 3 and Fig. 7. Although there are no beam loss, we can see that some particle have big phase spread and have indication of longitudinal halo from the density distribution of longitudinal plant.

Table 3: Emittance Growth with Errors in Different Plant

Emittance growth (%)		Without errors	With errors
Horizontal	Mean	4.4	20
	Max		78
Vertical	Mean	4.0	21
	Max		70
Longitudinal	Mean	3.4	13
	Max		55

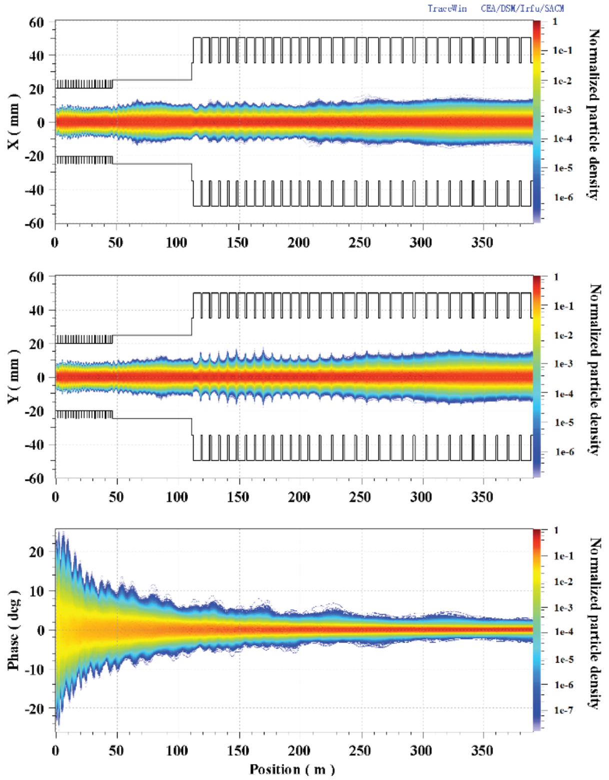

Figure 7: Particle trajectories in horizontal plane and phase plane of main linac.

CONCLUSION

According to the detailed sensitivity analysis of different errors, the static and dynamic errors for the main linac are proposed. This paper presents the method to optimize the apertures of elements in the C-ADS main linac to minimize beam losses. The correction scheme is described, and with the correction scheme the rms residual orbit can be controlled within 0.25 mm. From simulation results the dynamic errors can also lead to large residual orbit. The influence of BPM failures is studied. The simulation results with errors are reported in this paper.

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