MISMATCH STUDY OF C-ADS MAIN LINAC *

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Abstract

The C-ADS accelerator in China is a CW (Continuous-Wave) proton linac with 1.5 GeV in beam energy, 10 mA in beam current, and 15 MW in beam power. To meet the extremely low beam loss rate and high reliability, it is very important to study the beam halo caused by beam mismatch. To avoid the envelope instability, the phase advances per period are all smaller than 90 degree in the main linac design. In this paper, the results of the emittance growth and the envelope oscillations caused by mismatch in the main linac section are presented. To meet the emittance growth requirement, the transverse and longitudinal mismatch factors should be smaller than 0.4 and 0.3, respectively.

INTRIDUCTION

The ADS driver linac in China (C-ADS) is demanded to deliver a CW proton beam with 1.5 GeV in energy and 10 mA in current [1]. It is composed by two major accelerating parts: the injector and the main linac. The main linac is designed to boost the beam energy from 10 MeV up to 1.5 GeV with four accelerating sections, which the lattice structures of are shown in Fig. 1. The solenoid focusing is applied in the two spoke cavity accelerating sections and the triplet focusing is used in the two elliptical cavity accelerating sections.

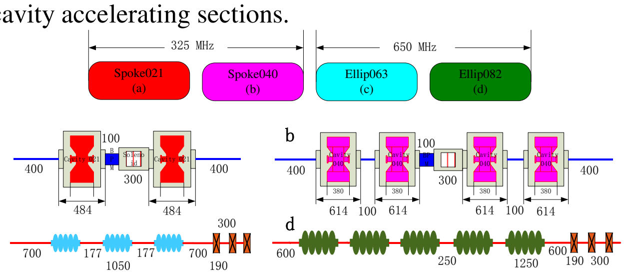

Figure 1: Schematic view of the lattice structures for the main linac sections.

Beam loss rate of 1 W/m is widely used in the high-power proton accelerator, which is mainly determined by the hands-on maintenance requirement. To meet the extremely high reliability and availability, it is very important and imperative to study beam loss mechanism. Beam halo caused by mismatch is one major source of beam loss. The impact of misalignment errors and field errors is also very important [2]. With the presence of nonlinear components, the filamentation effect will lead to a real emittance dilution. The emittance increase due to the mismatch is very important in the ADS accelerator where the beam loss is concerned, and the betatron modulation has the similar impact. Some mismatched modes can exhibit an instability when the phase advance without space charge per focusing period is greater than 90° and the tune depression is low [3]. More than a filamentation, a mismatched beam can be unstable if the channel working point is not properly set. In this paper, the simulation results of the ADS main linac with beam mismatch are presented.

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MISMATCH

If the ellipse in phase space of injected beam is not matched to the downstream focusing system, there will be additional oscillations of the rms beam envelopes, which produce a larger sized beam at some locations and a smaller sized beam at other locations. In this scenario, it is convenient to define a mismatch factor, which is a measure of the increase in the maximum beam size resulted from a mismatch. Suppose that the matched beam phase space ellipse is defined by

$$\gamma_m x^2 + 2\alpha_m x x' + \beta_m x'^2 = \varepsilon$$

and a mismatched beam phase space ellipse with same area is defined by

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon .$$

Then the mismatch factor can be expressed as

$$M = \sqrt{\frac{\Delta + \sqrt{\Delta^2 - 4}}{2}} - 1 \qquad (1)$$

where $\Delta = \beta_m \gamma + \gamma_m \beta - 2\alpha_m \alpha$.

The rms emittance growth due to beam mismatch whatever the beam distribution can be given by [4]

$$\xi = \frac{\varepsilon_{rms,mismatched}}{\varepsilon_{rms,matched}} = \frac{1}{2}\left(\frac{\beta_m}{\beta} + \frac{\beta}{\beta_m} + \frac{\beta_m}{\beta}\left(\alpha - \frac{\beta}{\beta_m}\alpha_m\right)^2\right) \qquad (2)$$

and the total emittance growth is given by

$$\eta = \xi + \sqrt{\xi^2 - 1} = (1 + M)^2 . \qquad (3)$$

In addition, filamentation of the particle distribution in phase space can cause emittance growth. Progress has been made in understanding halo production due to parametric resonances between single particle and the oscillating mismatched beam core. The mismatch of DC beams is described by 2 well known eigenmodes [3]. For bunched beams, there are 3 eigenmodes [5], a pure transverse quadrupole mode

$$\sigma_{env,Q} = 2\sigma_t \qquad (4)$$

and a high mode and a low mode which couple the transverse and longitudinal directions

$$\sigma^2_{env,H} = A + B,\ \ \sigma^2_{env,L} = A - B \qquad (5)$$

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with

$$A = \sigma_{t0}^2 + \sigma_t^2 + \sigma_{l0}^2/2 + 3\sigma_l^2/2$$
$$B = \sqrt{\left(\sigma_{t0}^2 + \sigma_t^2 - \sigma_{l0}^2/2 - 3\sigma_l^2/2\right)^2 + 2\left(\sigma_{t0}^2 - \sigma_t^2\right)\left(\sigma_{l0}^2 - \sigma_l^2\right)},$$

where σ_t, σ_{t0}, σ_l and σ_{l0} are full and zero current transverse and longitudinal tunes. With smooth approximation, one can get the corresponding eigensolutions for quadrupole mode

$$\Delta a_x/a = -\Delta a_y/a = A_m \cos\left(\sigma_{env,Q}\, s/L + \phi\right),\ \Delta b/b = 0 \quad (6)$$

and for high and low mode

$$\Delta a_x/a = \Delta a_y/a = g_{H/L}\Delta b/b = A_m \cos\left(\sigma_{env,H/L}\, s/L + \phi\right) \quad (7)$$

with

$$g_{H/L} = \frac{\sigma_{t0}^2 - \sigma_t^2}{\sigma_{env,H/L}^2 - 2\left(\sigma_{t0}^2 + \sigma_t^2\right)} \quad (8)$$

g_H is always positive and g_L is always negative. This approximation is not valid for extensively elongated bunches.

MULTIPARTICLE SIMULATION RESULTS

According to the definition of mismatch, usually there are two adopted cases in twiss parameters for one mismatch factor

$$\beta = (1+M)^2 \beta_m,\ \alpha = (1+M)^2 \alpha_m,\ \Delta a/a = M \quad (9)$$

and

$$\beta = \beta_m/(1+M)^2,\ \alpha = \alpha_m/(1+M)^2,\ \Delta a/a = -M/(1+M). \quad (10)$$

In the multiparticle simulation, one track 5×10^6 particles with 5σ&6σ Gaussian distribution. The transverse and longitudinal rms emittance growths are controlled to be smaller than 25% and 20% without beam loss respectively, which is the same level emittance growth caused by errors.

Firstly, we study the filamentation effect with space charge lead to emittance growth. Because of the symmetry in transverse of solenoid focusing structure we just simulated emittance growth caused by mismatch in x plane. Due to the x/y coupling caused by solenoid in transverse direction and space charge effect, the emittance growth in three planes shown in Fig 2. For this case, the mismatch factor should be smaller than 0.5 to meet the designed requirement. For the longitudinal mismatch, the simulation results are shown in Fig 3. The simulation results agree well with the theoretical ones given by Eq. 2. The longitudinal mismatch factor should be smaller than 0.3, as shown in Table 1.

Table 1: Emittance Growth Caused by Mismatch in One Plane

Mismatch factor			Ex	Ey	Ez
x	y	z	%	%	%
0	0	0	2.7	3.2	4.2
0.5	0	0	24.5	26.6	8.0
0	0	0.3	6.6	7.4	18.2

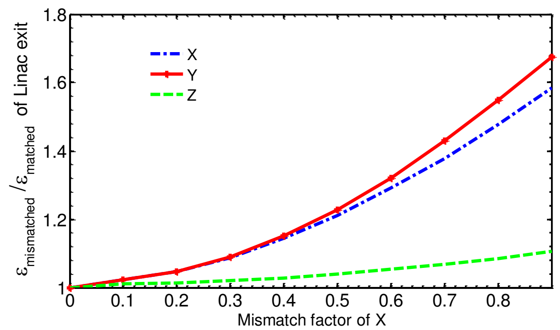

Figure 2 : Emittance growth caused by mismatch in x plane.

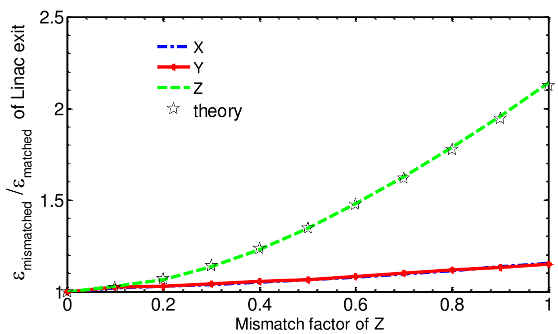

Figure 3: Emittance growth caused by mismatch in z plane.

The frequency of the three eigenmodes for the ADS main linac are shown as following

$$34^\circ \le \sigma_{env,Q} \le 140^\circ, 38^\circ \le \sigma_{env,H} \le 155^\circ, 27^\circ \le \sigma_{env,L} \le 107^\circ.$$

Because the frequency of high mode is smaller than 180°, there are no envelope instability. Figure 4 shows the parametric resonance between single particle and envelope oscillating. There are 1/2 parametric resonance for quadrupole mode and low mode and 1/3 parametric resonance for high mode in the ADS main linac. The low order resonances are the most dangerous ones and the high mode or low mode can excite a parametric resonance either in the transverse or longitudinal direction, so slow mode should be considered carefully.

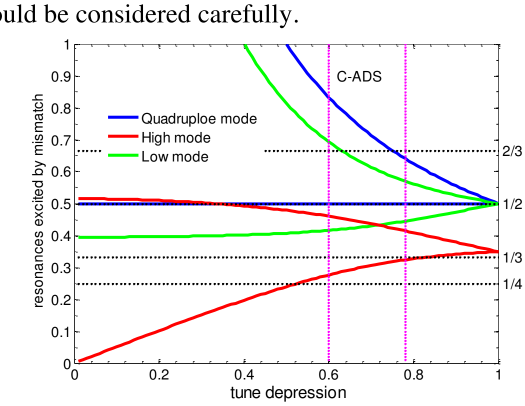

Figure 4: Parametric resonance excited by mismatch.

Because the envelope modes defined by beam size, there are different beam mismatch in three planes to excite these modes. For the quadrupole mode, one should keep

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quadrupole mode mismatch factor is smaller than 0.3, which means transverse mismatch factor is smaller than 0.4 to meet the requirement, and the emittance growth is shown in Fig 5. Because of the coupling effect of solenoid envelope oscillation become stable fast for quadrupole mode, which are shown in Fig 6. The g_H of high mode is 0.28 for C-ADS main linac, which means bigger longitudinal mismatch. The emittance growth is shown in Fig 7, one should keep longitudinal mismatch factor within 0.3. However, the g_L of low mode is -1.42, which means bigger transverse mismatch and the emittance growth is shown in Fig 8. Low mode mismatch factor should be smaller than 0.2 that means transverse mismatch factor smaller than 0.4. According to the simulation results shown in Table 3, transverse mismatch factor should be smaller than 0.4 and longitudinal mismatch smaller than 0.3.

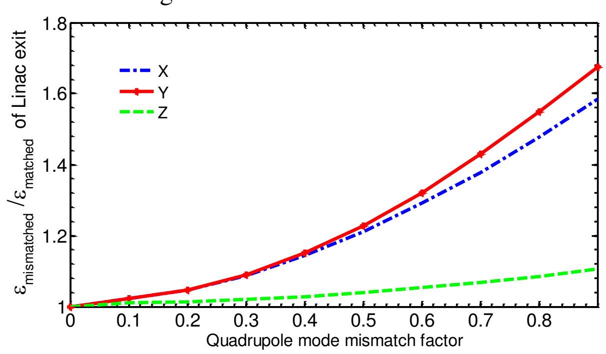

Figure 5: Emittance growth with quadrupole mode mismatch factor.

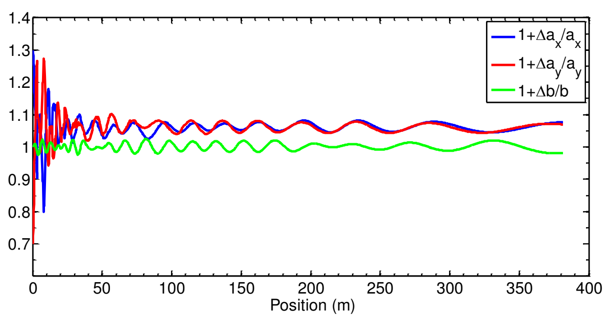

Figure 6: Envelope oscillation with 0.3 mismatch quadrupole mode.

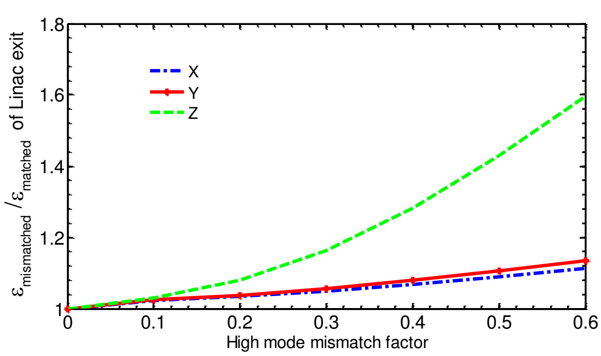

Figure 7: Emittance growth with high mode mismatch factor.

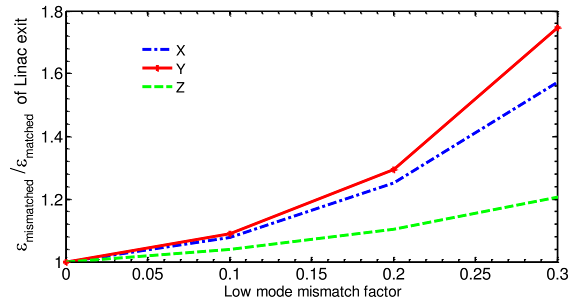

Figure 8: Emittance growth with low mode mismatch factor.

Table 2: Emittance Growth Caused by Mismatch

Mode		Mismatch factor			Ex	Ey	Ez
		x	y	z	%	%	%
		0	0	0	2.7	3.2	4.2
Quad.	0.3	0.3	0.43	0	23.9	23.3	6.9
High	0.3	0.08	0.08	0.3	7.7	9.0	21.2
Low	0.2	0.4	0.4	0.2	28.5	30.0	15.1

A mismatch with equal amplitudes in transverse and longitudinal directions can lead to an excitation of the high and low mode simultaneously and the emittance growth is bigger. Figure 9 shows the envelope oscillation with 0.4 mismatch in transverse and 0.3 mismatch in longitudinal. One can see that envelope oscillation becomes larger, which is because of mismatch.

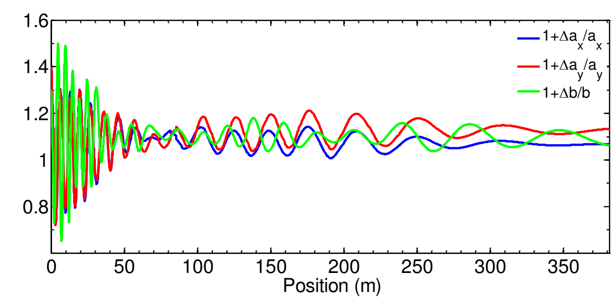

Figure 9: Envelope oscillation with 0.4 mismatch in transverse and 0.3 mismatch in longitudinal.

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