ERROR AND TOLERANCE STUDIES FOR INJECTOR II OF C-ADS

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Abstract

The proposed Accelerator Driven System (ADS) driver linac is being designed in Institute of Modern Physics (IMP). The driver linac is designed to work at rf frequency 162.5MHz and accelerate proton to final beam energy of 10MeV/u. Because of the high final beam power (100 kW) specified for the linac operation, beam loss must be limited to avoid radiation damage. Misalignment and rf error analysis for cavities and focusing elements after RFQ were performed, and correction schemes developed using the computing code TRACK. The simulation results are presented, and the misalignment and rf error specifications are given for the ADS Linac.

INTRODUCTION

Recent in these years the China Accelerator Driven System (C-ADS) is proposed and used for future fusion reactors. It is planned to build and test a demonstrator accelerator at full beam current 10mA at 10 MeV/u. In the initial stage, the two demonstrating front-ends operating in CW mode are being designed in IMP and IHEP independently. The front-end in IMP consistes of a ECR ion source (35KeV/u), a low energy beam transport (LEBT), a 162.5MHz 4-vane RFQ for bunching and pre-accelerating to 2.1MeV/u, a medium energy transport (MEBT), and the sc linac section (see Fig. 1). The MEBT, consisting of 7 quadrupoles and 2 bunchers, converts the beam output from RFQ to a symmetric beam in x and y directions in order to matching the sc linac. There are two cryomodules in the sc linac section based on independently phased superconducting (SC) 162.5MHz half-wave resonator cavities (HWR) and SC solenoids.

The error study simulations for the above front-end after RFQ are presently being performed in IMP. We present the results of the simulations performed with the ANL code TRACKV39. The code enables precise calculating of particle tracking, taking into account realistic 3D fields of the accelerating and focusing elements and also effects of space charge. We utilize the linux version of TRACKV39 to simultaneously run the simulations on 100 cpus of the cluster [1].

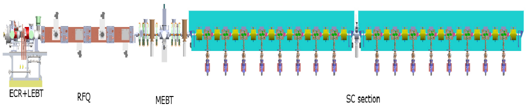

Figure 1: Layout of the C-ADS driver linac.

ERROR STUDY STRATEGY

Before dealing the different types of error, it is important to remark that two families of errors have to be coped for [2]:

- static errors: the effect of these errors is detected and corrected. The strategy of the correction scheme is established to correct these errors (see below). For an error of amplitude A, the value has a uniform probability to be between −A and +A.
- dynamic errors: these errors are not corrected. They are induced by the vibrations of the RF field or mechanical vibrations from the environment. For an error of rms amplitude σ, a Gaussian distribution truncated at ±3σ is used for them.

The goal of the error study is two-fold: define the alignment and RF error tolerances of the linac, to be built in 2013, and examine the robustness of the linac design as a whole. The RFQ design has already been decided upon and the RFQ is now being built. The beam distribution used at the input of the MEBT accounts for the RFQ output, which has an energy of 2.1 MeV/u and its normalized RMS emittance is estimated to be $\varepsilon_x = \varepsilon_y =$ 0.32 mm.mrad and ε_z = 0.31 mm.mrad. The average current over the RF pulse is 10 mA and this is the intensity used in the error study simulations as it is the meaningful value for space charge effects.

This analysis is done in two stages [3]. First, the sensitivity of the linac to one single error is determined in order to evaluate the individual contribution and fix an acceptable limit on each type of error. Then, all errors are combined simultaneously to verify the set of tolerances determined previously and estimate the overall degradation of the beam properties.

We have applied 5 possible alignment errors and 4 RF errors to any active element. The alignment errors are sketched in Fig. 2. They include transverse position errors which represent the distance between the centre of the element and the ideal centre of the beam line in the two transverse planes; and angle errors which represent the 3 angles between the ideal beam line reference and the reference system of the element. For magnets these values are referred to the magnetic centre i.e. they represent the 3 angles between the ideal beam line reference and the system in which the magnet is a perfect quadrupole.

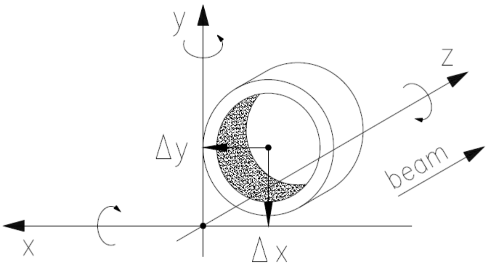

Figure 2: Sketch showing the alignment errors applied to the quadrupoles [4].

We have applied static/dynamic gradient errors to the focusing elements: they represent the percentage deviation from the nominal field. For cavities static/dynamic phase errors are also applied, in degrees.

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The relevant output beam parameters are studied. A statistical analysis is performed on the relevant beam parameters observing the average, the maximum value and the standard deviation. We are mainly interested in the following beam parameters: beam loss, beam envelope, beam centroid and the relative emittance increase Δε, which in each run is expressed with respect to the nominal case, i.e. the case where beam is transported through the ideal linac without errors [3]:

$$\Delta\varepsilon = \frac{\delta\varepsilon_{err} - \delta\varepsilon_{nom}}{\delta\varepsilon_{nom}}$$

where $\delta\varepsilon_{err}$ and $\delta\varepsilon_{nom}$ are the emittance growth of the beam through the linac with and without errors. For single errors every error simulation consists of 200 runs, with 1.0×10^5 macro-particles each. This number is increased to 10^6 particles per bunch for the global simulations.

A correction scheme has been implemented. The beam center trajectory is controlled by using steerers which kick the beam in both planes. The correction scheme relies on steering coils (H and V), attached to every quadrupole and solenoid, associated with the downstream beam position monitors (H and V) located at the selected position in MEBT and in every solenoid passage.

RESULTS FOR THE ERROR STUDY

Individual errors have beam performed on the elements: quadrupoles, solenoids, HWR cavities and bunchers. For each of the nine types of errors defined above, we perform simulations while varying the maximum allowed amplitude of the error. This aims to determine the amplitude of each error minimizing beam degradation (no beam loss). As an example, Fig. 3 and Fig. 4 display the average emittance increase with respect to the nominal case and maximum rms beam centroid, if a random roll angle (H and V) of varying maximum amplitude is applied to all the solenoids of the SC section. In this case, the generated emittance growth and maximum rms beam centroid approximately rises linearly with the roll angle.

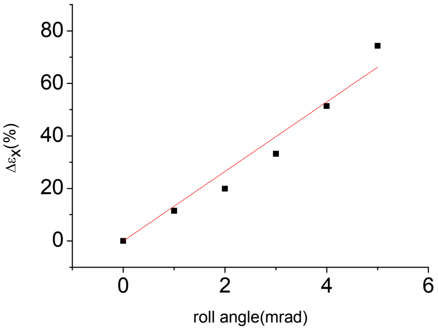

Figure 3: Emittance growth when both transversal rotations are applied to all SC solenoids as a function of the maximum rotation amplitude. Superposed is a linear fit.

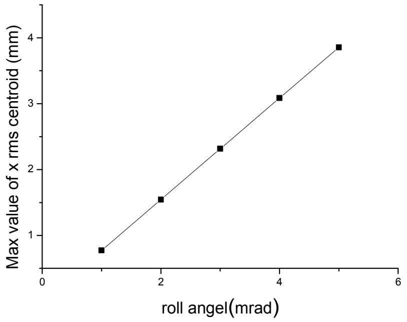

Figure 4: maximum rms beam centroids when both tansversal rotations are applied to all SC solenoids as a function of the maximum rotation amplitude.

Table1 presents tolerances for all errors and particle loss is not detected within the quoted amplitudes. After determining independently what seems to be an acceptable upper bound for each type of error, we verify their validity and estimate the total degradation of the beam properties using a global error simulation. This lengthy simulation with 106 macro-particles per bunch combines all types of errors simultaneously and particle loss is found. Finally, correction simulations are run on the results obtained when applying the nine errors within the tolerances on the linac. The sensitive parameters appear to be the solenoid transverse alignment and rotation, also the quadrupole transverse alignment. The RF amplitude and phase should be appropriately chosen to prevent big longitudinal emittance increase. Relatively little effect is due to any other errors. Under these conditions which account for a realistic linac structure, the average transverse emittance growth with respect to the nominal case is found to be on the order of 86% and 267% respectively. They reduce to 34% and 82% after correction (see Fig. 5).

Table 1: Tolerances of All Errors

Margin	**Error type, Amplitude**	**Solen-oids**	**Quad-rupoles**	**HWR Cavities**	**Bunch-ers**
Translation	δ_x (mm)	1.0	0.3	1.5	1.0
	δ_y (mm)	1.0	0.3	1.5	1.0
Rotation	R_x (mrad)	3.0	5.0	5.0	5.0
	R_y (mrad)	3.0	5.0	5.0	5.0
	R_z (mrad)	0.0	5.0	5.0	5.0
Static field	$(\Delta A/A)_s$(%)	0.01	0.01	0.5	0.5
Dynamic field	$(\Delta A/A)_d$(%)	0.05	0.05	0.5	0.5
Static phase	ϕ_s(deg)	×	×	0.5	0.5
	ϕ_d(deg)	×	×	0.5	0.5

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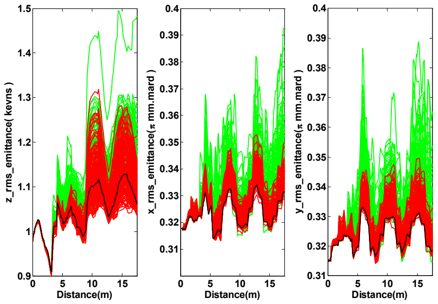

Figure 5: the beam rms emittances based on 200 runs, green, red and black colors correspond to the three cases only with errors, both with errors and corrections, without errors (nominal case) respectively.

We can see from Fig. 6 that the beam centroids are well brought to the beam axis by correction, with rms value controlled below about 1mm.

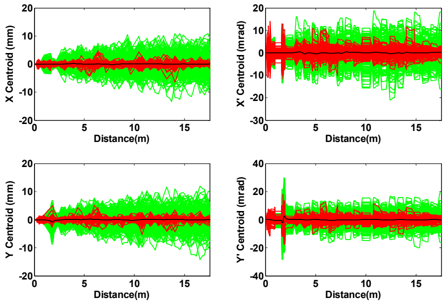

Figure 6: Beam centroids comparison between the above three cases.

Figure 7 represents the particle loss before and after correction. The particle loss is almost controlled below 10 except very few runs inducing large particle loss, and reduces to below 10 with correction. As a conclusion, the linac correction can have a great effect on modifying the degradation of the beam properties induced by the linac errors.

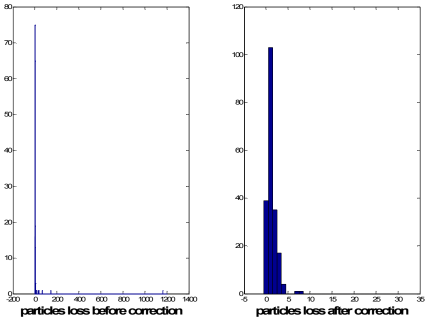

Figure 7: Particle loss before (left figure) and after correction (right figure). A few runs with large particle loss have been observed in the left figure and it can be modified by correction shown on the right.

CONCLUSIONS

We have described the error study simulations on the C-ADS driver linac (2.1MeV/u to 10MeV/u) with 9 alignment and RF errors applied on each of the four linac elements: quadrupole, solenoid, SC HWR cavity and buncher. Fist we considered an initial stage where the impact on the beam properties of element misalignment error and RF error was determined. This led to the determination of the alignment and RF tolerances for the linac. The most sensitive parameters were found to be the transverse alignment of the solenoids and quadrupoles, as well as the solenoids orientation around the transversal axes. Global simulations were then run with all errors combined simultaneously to verify tolerances and determine the overall beam degradation. Under the chosen tolerances, the general results is good except a run with particle loss up to about 1200 has been observed. We may need to reduce some tolerances in order to prevent large particle loss for a minority of simulation runs, although correction can have a good effect on modifying beam degradation.

ACKNOWLEDGEMENTS

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