PROGRESS ON THE BEAM DYNAMCIS STUDIES FOR THE ADS INJECTOR I AND THE MAIN LINAC*

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Abstract

The ADS project in China is to build a proton Accelerator Driven sub-critical System around 2032. By using superconducting (SC) accelerating structures except the normal conducting (NC) RFQ, the driver accelerator runs in CW mode and accelerates the 10 mA proton beam from 35 keV at the ECR ion source exit to 1.5 GeV at the main linac exit to bombard the target to produce neutrons. To satisfy the restrict requirement on the stability, availability and reliability, two identical injectors will operate in parallel as hot spare for each other at the low energy part, while local compensation method will be used to accomplish beam dynamics rematch at the high energy part when certain device failure happens. Currently, there are two injector testing facility are being built at IHEP and IMP, respectively. The task of IHEP is to build a 10 MeV/325 MHz Injector I testing facility and accomplish the main linac design. Here, the progress on the beam dynamics studies for the ADS injector I and the main linac are presented.

INTRODUCTION

Figure 1 shows the layout of the ADS driver linac in China with parameters listed in Table 1 [1]. The ADS driver linac has very high beam power; the demanded stability, availability and reliability are also very high.

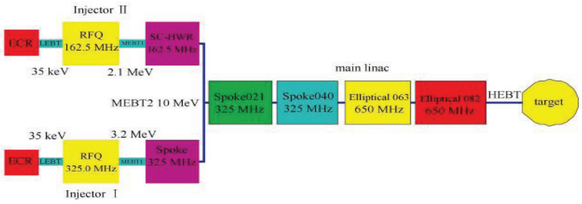

Figure 1: Layout of the ADS driver linac.

Table 1: Main Parameters Of The ADS Driver Linac

Parameters	**Values**
Operating mode	CW
Final kinetic energy	1.5 GeV
Beam current	10 mA
Beam power at target	15 MW
Beam loss	<1 W/m
Beam trips per year	<25000(1s<t<10s) <2500(10s<t<5m) <25(5m<t)

To validate the key technologies (the CW NC RFQ, the CW SC accelerating structures, etc.), two injector testing facilities based on 325 MHz and 162.5 MHz respectively are being built at IHEP and IMP. Finally, only one injector scheme will be chosen and two identical injectors will be built and operate as hot spare for each other at the low energy part. However, it is not realistic to build two linacs as hot spare at the high energy part; at this scenario, the solution to reach high stability, reliability and availability is to apply the local compensation method.

At present, the beam dynamics studies on the 325 MHz Injector I and the main linac are being carried out at IHEP. Since the final injector scheme is not decided yet, the main linac is designed and optimized to have the capability to accept the proton beams from both the 325 MHz Injector I and the 162.5 MHz Injector II. To transport the proton beams from the injectors to the main linac with acceptable beam quality deterioration, two funnelling beam lines are needed, several MEBT2 designs based on the 325 MHz Injector I have been found, but an idealized solution is still needed. On the other hand, due to the unavoidable existence of the parasitic modes in the ADS main linac, simulation has been conducted to quantify their effect on the beam quality.

ADS INJECTOR I TESTING FACILITY

Figure 2 shows the layout of the ADS Injector I testing facility. MEBT1 composed by 2 NC bunchers and 6 Quadruples is used to match and transport the beam from the RFQ to the downstream SC section. The SC section has two cryomodules (CMs), each of which consists of 7 single spoke cavities (β=0.12), 7 solenoids and 7 BPMs. In the SC section, a compact lattice by applying the short solenoid with a length of 170 mm and adopting a relatively large absolute synchronous phase for each cavity are applied to improve the beam quality.

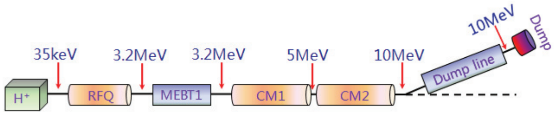

Figure 2: Layout of the ADS Injector I testing facility.

By using the Parmteq simulated beam distribution at the RFQ exit, the beam quality evolution from the MEBT1 entrance to the SC section exit of the Injector I has been studied, Fig. 3 shows the optimized results. To verify the stability of this design, a large amount of error analysis were carried out [2]. By applying the beam orbit correction and using the nominal misalignment and RF error settings, the RMS emittance growth rates in x/y/z are 5.6%/5.2% /9.4%, while they are 11.6%/12.2%/22.2% for the doubled misalignment and RF error settings, no beam losses were found. The effects of the input beam deviations at the MEBT1 entrance were also studied by applying the nominal misalignment and RF error settings;

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the allowed values of them with zero beam loss were found and are listed in Table 2.

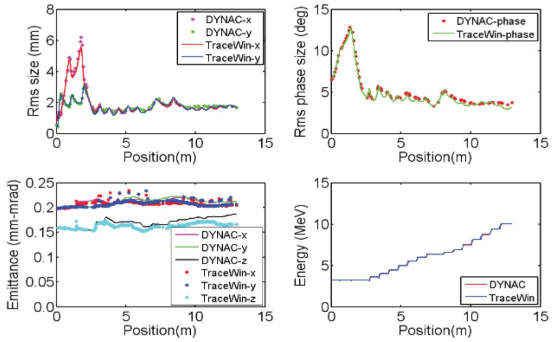

Figure 3: Optimized beam performance evolution from the MEBT1 entrance to the SC section exit.

Table 2: Allowed Values Of The Input Beam Deviations At The MEBT1 Entrance Of The Injector I With Zero Beam Loss

Deviation types	Rough ranges
x/y mismatch	<200%
z mismatch	<15%
x/y displacement	<13mm
x'/y' displacement*	<30mrad
Timing error	<2.5° / >–3°
Energy deviation	<+0.02MeV / >–0.04MeV
Current deviation*	<+10mA / >–10mA
Emittance deviation*	<100%

Even the deviations reach the listed maximum values, no beam loss was found. Thus, the actual allowed deviation values are larger than the listed ones. The maximum allowed value for the transverse displacement is limited by the corrector capability, which is not considered here.

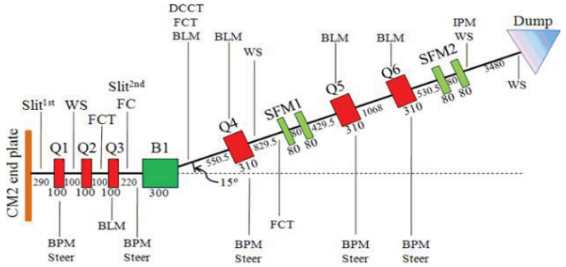

Figure 4: Final layout of the beam dump line.

In routine operation of the Injector I testing facility, a maximum beam power of 100 kW will be produced and transported to the beam dump. To solve the very high thermal load problem at the dump, the beam dump line is designed to expand and homogenize the transverse beam profile at the largest extent [3]. In the meantime, to accommodate with the beam commissioning plan of the Injector I testing facility, the beam dump line is designed to meet the requirement of the beam expansion and homogenization at three different energies (3.2 MeV, 5 MeV and 10 MeV). Figure 4 shows the final layout of the beam dump line at 3.2 MeV. When the beam energy is increased to 5 MeV (6.3 MeV in actual) and 10 MeV, the distance between the 2nd pair of step-like field magnets and the beam dump target needs to be increased by 300 mm with the locations of the other devices fixed. Figure. 5 shows the expanded and homogenized transverse beam profile at the beam dump entrance, the maximum power densities are all smaller than the maximum allowed power density 200 W/cm^2/sin (20°) =585 W/cm^2, which is determined by the dump target cooling system design.

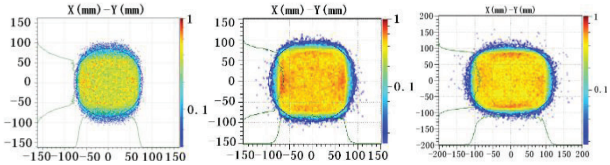

Figure 5: Expanded and homogenized transverse beam profile at the dump entrance (3.2 MeV/5 MeV/10 MeV).

Recently, the beam parameters at the LEBT exit have been measured. Table 3 shows the measured results, for comparison the simulated results are also listed.

Table 3: Beam Parameters At The LEBT Exit

Parameters	Design	Measurement
I_{beam}	10	11.5
α	2.41	2.18
β	0.0771m/rad	0.0774m/rad
$\varepsilon_{n,rms}$	<0.20mm.mrad	0.14mm.mrad

MEBT2 BASED ON THE ADS INJECTOR I

Figure 6 shows the 3 MEBT2 design schemes based on the ADS Injector I. All of them can successfully transport and match the 10 MeV/10 mA beam from the Injector I to the main linac with acceptable beam emittance growth and similar error tolerance. MEBT2 is the only place that can implement longitudinal beam collimation. It was found the transverse beam collimation in all the 3 designs can be realized very well. However, the longitudinal collimation is not so good. Therefore, an idealized MEBT2 design is still under investigation.

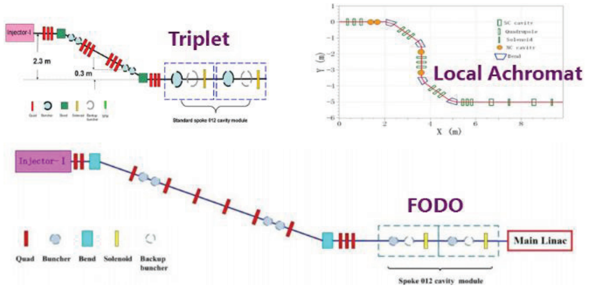

Figure 6: The 3 MEBT2 designs based on the 325 MHz ADS Injector I.

ADS MAIN LINAC

To cover the energy range from 10 MeV to 1.5 GeV, four types of SC cavities are needed or the ADS main linac. At present, the main linac design is optimized to have 36 Spoke021 cavities, 60 Spoke040 cavities, 42

Ellip063 cavities and 100 Ellip082 cavities. By adjusting the synchronous phase of each cavity and the magnetic field strength of each magnet in the corresponding lattice structure listed in Fig. 7, the current main linac design is capable to accept the beams from both the 325 MHz Injector I and the 162.5 MHz Injector II with the same layout. The matching between the two neighbouring sections is guaranteed by varying the parameters of the adjacent cavities and the transverse focusing devices. With warm transitions between the CMs, the replacement of the failed CMs can be easily carried out; the beam diagnostics and collimators can be arranged there.

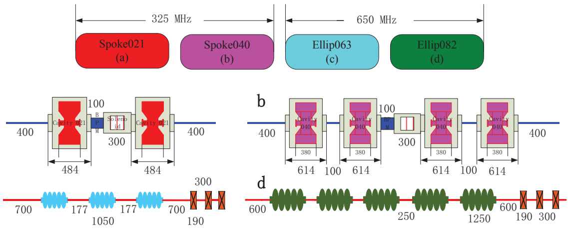

Figure 7: Lattice structure for the main linac sections.

Figures 8 and 9 show the beam emittance and envelope evolutions along the main linac for the current design. By using Gaussian distributed phase space distributions (3σ in transverse and 4σ in longitudinal) as inputs at the main linac entrance, the corresponding normalized RMS emittance growths in x/y/z are 1.4%/1.5%/7.2% and 5.6%/6.2%/1.0% for the Injector I and the Injector II, respectively. The preliminary error analysis has been done.

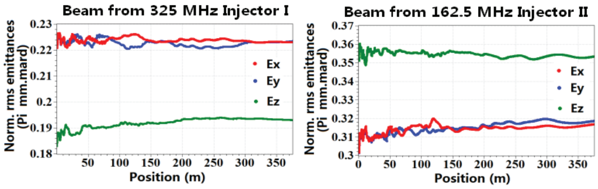

Figure 8: Beam emittance evolution along the main linac.

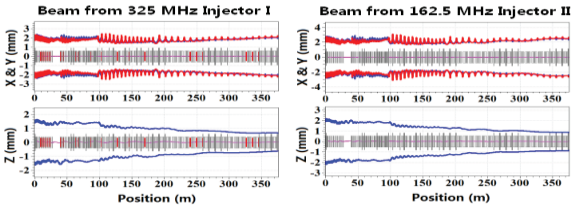

Figure 9: Beam envelope evolution along the main linac.

LOCAL COMPENSATION

For any accelerator, it is unavoidable for the failure of the key devices. To achieve the extremely high stability, availability and reliability required for the ADS driver accelerator, a design with a reasonable fault tolerance is pursued. Therefore, two identical injectors will be built for the ADS driver accelerator and operated as hot spare for each other at the low energy part. However, it is not cost effective to build two main linacs. To solve this problem, the only way is to adopt the local compensation method, which is more efficient at the high energy part.

In the ADS main linac, the devices which are possible to fail include the SC cavity, the SC solenoid and the NC quadruple. For the SC cavity failure, the RF settings of the neighbouring cavities and the field strengths of the focusing devices around the failed cavity can be adjusted to approximately recover the beam Twiss parameters and the beam energy back at the matching point. For the SC solenoid failure at the lower energy sections, a novel method by reversing the phase of one neighbouring cavity can be used to maintain both the transverse focusing and the longitudinal acceleration. At the higher energy sections, the NC triplet focusing is adopted, each quadruple is powered individually. Thus, in case of the quadruple failure, the triplet can be locally converted into a doublet very quickly.

The higher the proton beam energy, the more effective the local compensation method. However, the possibility of its application in the Injector I testing facility was also tried in case of the device failure. The results can be classified into 3 types. The 1st type is that the beam loss can be reduced but still stays at a high level; the 2nd one is that the beam loss can be reduced to an acceptable level and the facility can run constrainedly. While for the 3rd type, the beam quality can be almost recovered back, this opens the possibility to carry on the local compensation experiments before the main linac construction.

PARASITIC MODE EFFECT

When the proton beam traverses in the RF cavity, the excited parasitic modes (HOMs and SOMs) may drive the beam unstable; therefore it put a limitation on the normal operation of the accelerator. By using a numerical code SMD, the effects of the parasitic modes on the beam dynamics for the ADS driver linac has been investigated systematically in the Ellip063 and Ellip082 sections.

In longitudinal, the HOMs are of little concern as long as they are far away from the machine lines (MLs), those modes sitting on the ML are of little concern for the 10 mA beam. The frequency spread offers an additional detuning effect; it is beneficial to the longitudinal beam dynamics. The Q_{ext} of the SOMs provided by the RF power coupler is enough to suppress its effect.

In transverse, the multi-bunch emittance dilution caused by the input beam position and trajectory angle jitters is several times of that caused by the dipole HOMs. The strengthening of the cavity misalignment and the off-axis beam injection to the dipole mode effect is fairly low. Meanwhile, the dipole HOM sitting on the ML is not a concern.

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[3] Yang Zheng et al. “Transverse Profile Expansion and Homogenization at Target for the Injector Scheme-I Test Stand of China-ADS”, Accepted by CPC, 2014.