END-TO-END BEAM SIMULATIONS FOR C-ADS INJECTOR II*

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Abstract

The Injector II for the proposed Chinese Accelerator Driven System (C-ADS) is designed to accelerate proton beam to ~10 MeV with beam current up to ~ 10 mA. The accelerator system will include a proton ECR ion source, a Low Energy Beam Transport (LEBT), a room-temperature Radio Frequency Quadrupole (RFQ), a Medium Energy Beam Transport (MEBT), a Superconducting (SC) linac system and a High Energy Beam Transport (HEBT). Both RFQ and the SC linac will have a base frequency of 162.5 MHz. The accelerating cryomodules in the SC linac use SC half-wave cavities for acceleration, and SC solenoids with dipole correctors for transverse focusing and central orbit correction. End-to-end beam simulations starting with a realistic initial beam from the ECR ion source were performed using DYNAC code to evaluate the C-ADS Injector II accelerator system performance, perform code benchmarking with TRACK, and explore system design options for future optimization. The results of these beam dynamics studies will be presented in the paper.

INTRODUCTION

The C-ADS is a strategic project established by Chinese Academy of Sciences (CAS) to address the critical issue of nuclear waste processing for nuclear power plants, in order to meet the strong demands for nuclear power in China in the near future [1]. The accelerator driver of C-ADS will be a superconducting CW proton linac, capable to deliver ~ 15 MW beam power on the spallation target, with high reliabilities and minimum beam loss. Figure 1 shows conceptual schematic diagram of C-ADS project, which is expected to be completed in three phases by ~2032.

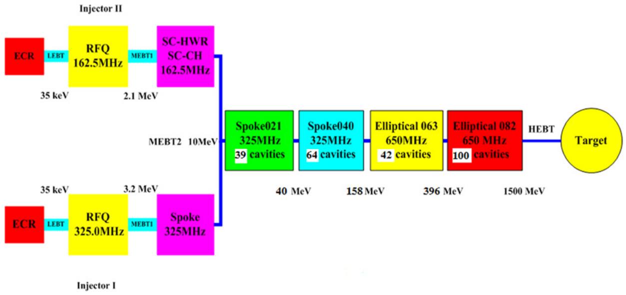

Figure 1: Conceptual schematic of C-ADS. The block diagram represents the items within the C-ADS technical scope.

The most important design requirement for the C-ADS driver linac is the high reliability, which requires establishing system redundancies in the accelerator system design. In the main linac section where the proton energy will be high enough (> 10 MeV), fast on-line local compensation method can be used for recovery of the device failure. At low energy, however, two identical injectors (one as the hot-spare) will be used to provide required redundancy for beam injection into the main linac. As shown in Figure 1, two injectors with different technical approaches are currently being developed at the Institute of High Energy Physics (IHEP) for Injector I and Institute of Modern Physics (IMP) for Injector II of CAS. One of the Injectors will be selected in the near future as the Injector for the C-ADS main linac based on their technical merit and achieved performance. The accelerator system design and the end-to-end beam simulations discussed in this paper are for the C-ADS Injector II Test Facility, currently under design and construction at IMP, as shown in Figure 2.

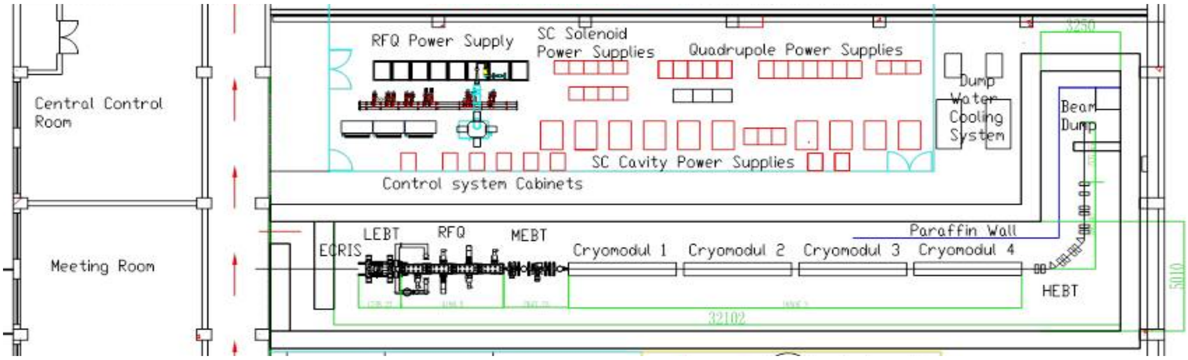

Figure 2: The layout of the C-ADS Injector II Test Facility at IMP, CAS.

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*Work supported by Michigan State University and Chinese Academy of Sciences

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THE ACCELERATOR SYSTEM OF C-ADS INJECTOR II TEST FACILITY

As Shown in Figure 2, the accelerator system of C-ADS Injector II consists of five segments [2]: Proton ECR Ion Source and LEBT to produce intense proton beam and provide required transverse beam matching at low energy, a RFQ for beam initial acceleration and focusing, a MEBT for beam transverse and longitudinal matching at medium energy, followed by a SC linac system to accelerate proton to the desired energy, and finally a HEBT to deliver accelerated proton beam to a beam diagnostics station and the beam dump in the IMP Test Facility.

ECRIS and LEBT: The proton ECR ion source have an extraction voltage of 35 kV, with an output proton beam current of ~10 mA and normalized RMS emittance of ~0.2 π mm-mrad. The proton beam is then transported and matched into RFQ by a short LEBT, consisting of two solenoid focusing magnets. The LEBT also has two beam diagnostics stations, and a beam chopper/dumper system for beam pulse and repetition frequency adjustment required by SC linac commissioning

RFQ: The 4-vane CW 162.5 MHz room temperature RFQ has total of 192 cells and accelerates proton beam from 35 keV to ~2.1 MeV with a transmission efficiency of ~99%. A nominal inter-vane voltage of 65 kV was adopted in the design, resulting in a moderate K_p of ~1.3 and a RFQ vane length of 4.2 m. The RFQ is currently under construction at IMP with collaborations with Lawrence Berkeley National Laboratory (LBNL).

MEBT: The MEBT will deliver the RFQ-accelerated proton beam to the SC linac. Seven quadrupole magnets and two room temperature QWR bunchers are used to achieve required beam transverse and longitudinal matching into the SC linac section with minimum emittance growth [3]. There are also sufficient beam diagnostics devices in the MEBT for adequate beam monitoring. Multiple beam collimators are located throughout the MEBT to minimize beam halo formation and uncontrollable beam loss downstream.

SC Linac: The superconducting linac will provide acceleration of the proton beam to the required final energy of ~ 10 MeV with beam intensity of ~10 mA [4]. It consists of total of four cryomodules with sixteen 162.5 MHz half-wave SRF cavities. Sixteen superconducting solenoid magnets inside cryomodules will provide required transverse focusing. Each solenoid will have horizontal/vertical dipole coils, together with a cold beam position monitor attached, to minimize beam central orbit distortions due to alignment errors of lattice elements. Figure 3 shows the layout of accelerating cryomodule of the SC linac. Additional beam diagnostic stations are also planned in the warm region between cryomodules for SRF cavity tuning and beam commissioning. The 162.5 MHz HWR cavity has been designed, prototyped, and tested in 2012 at IMP [1], and test results show the cavity performance exceeding the design field level.

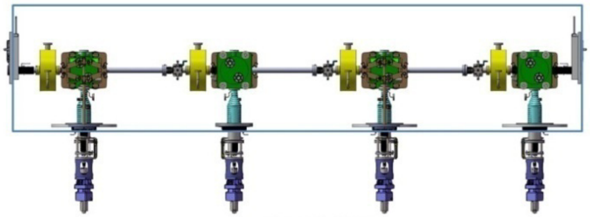


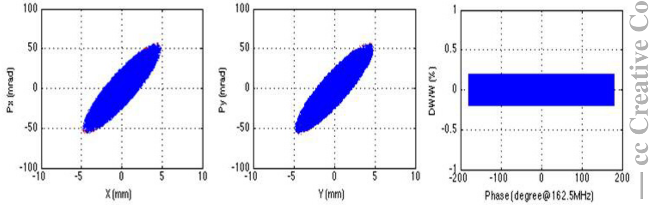
Figure 3: The layout of the accelerating cryomodule of Injector II SC linac.

HEBT: The HEBT will transport the accelerated proton beam to the beam dump and a final beam diagnostics station for Injector II performance evaluations. Several HEBT options are currently being evaluated for Injector II Test Facility. One of the options is shown in Figure 2. This option consists of a 90 degree achromatic bending, a single 162.5 MHz HWR cavity used as a buncher to control beam bunch length, and a four-quadrupole focusing system to achieve desired beam conditions either at the beam diagnostics station or beam dump.

END-TO-END BEAM SIMULATIONS

Extensive beam dynamics studies and end-to-end beam simulations for the C-ADS Injector II have been performed using TRACK at IMP previously [5]. Recently, the beam dynamics code DYNAC has been used in establishing on-line models of FRIB driver linac and the Re-accelerator (ReA3) at Michigan State University. Very good agreements were observed from code benchmarking between DYNAC, IMPACT and TRACK based on FRIB driver linac and ReA3 [6]. To evaluate the efficacy of using DYNAC as an on-line model for the C-ADS accelerator system, end-to-end beam simulations for the C-ADS Injector II were performed using DYNAC, and results compared to those obtained with TRACK.

The end-to-end beam simulations begin with DC proton beam from the ECR ion source at the entrance of LEBT with initial beam energy of 35 keV, a normalized transverse RMS emittance of ~0.18 π mm-mrad, and energy spread of ±0.2%. Figure 4 shows the initial proton beam phase space the entrance of LEBT based on ECR ion source extraction simulations.



Fisgure 4: Initial horizontal (left), vertical (middle), and longitudinal (right) phase spaces of proton beam at the entrance of LEBT used for the end-to-end simulations with both DYNAC and TRACK.

The C-ADS Injector II uses a short LEBT to achieve high beam transmission and minimize emittance growth. A space-charge compensation of ~90% is assumed in the beam simulations in LEBT for both DYNAC and TRACK. In the RFQ, DYNAC uses the relevant parameters from RFQ cell by cell data listed in the PARMTEQ output file for the RFQ, and in the SC linac, uses axial field distributions produced by the EM model of the accelerating cavities. The ideal magnetic element models for solenoid, dipole and quadrupole are used in the beam simulations with DYNAC.

The output phase spaces and particle distributions from the RFQ using DYNAC and TRACK are shown in Figure 5. In both cases, 50k macro-particles are simulated from the ECR ion source, through LEBT and RFQ. Between the two codes, difference in achieved proton beam energy is less than ~1%. The resultant beam RMS emittances are generally larger with DYNAC than that with TRACK, and achieved phase spaces are in reasonable agreement. The difference in the particles distributions are however, within the accuracy of measurements. Further beam dynamics studies are planned to investigate the possible causes for these difference.

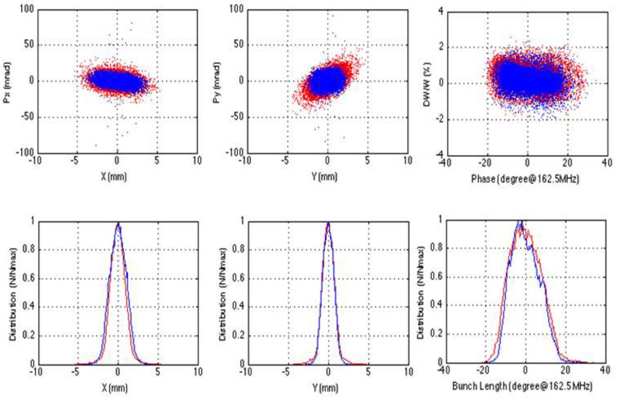


Figure 5: Output phase spaces (top) and particle distributions (bottom) in horizontal (left), vertical (middle) and longitudinal (right) planes of proton beam at the exit of RFQ with DYNAC (red) and TRACK (blue).

The simulated output phase spaces at the last beam diagnostics station of the HEBT using DYNAC and TRACK are shown in Figure 6, where a symmetric beam spot and minimum beam bunch length were obtained, and proton beam energy, intensity and emittances in order to evaluate the performance of the Injector II Test Facility. Again, between the two codes, difference in achieved proton beam energy is less than ~1%, and the obtained phase spaces are in reasonable agreement.

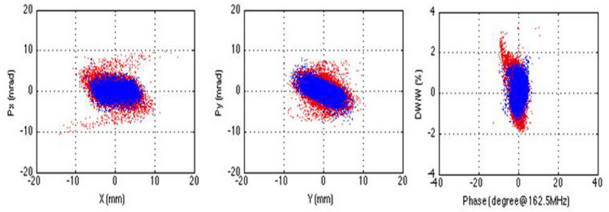


Figure 6: Output horizontal (left), vertical (middle), and longitudinal (right) phase spaces of proton beam at the last beam diagnostics station of HEBT with DYNAC (red) and TRACK (blue).

The resultant proton beam energy and RMS transverse envelopes (X/Y) along the Injector II using DYNAC and TRACK are shown in Figure 7, with good agreement obtained between the two codes.

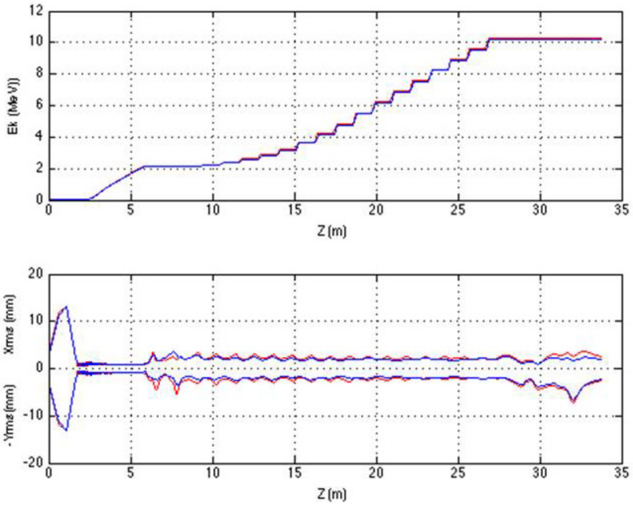


Figure 7: Simulated proton beam energy and transverse envelopes along the Injector II using DYNAC (red) and TRACK (blue).

SUMMARY AND CONCLUSIONS

The end-to-end beam simulations for C-ADS Injector II Test Facility currently under design and construction at IMP were performed using DYNAC code, and results compared with those obtained using TRACK code. Reasonable agreements between the two codes were observed. Due to its efficient computation, DYNAC has significant advantages in shorting execution time required for tracking large number of macro-particles in space-charge dominated, high power and low-loss proton linacs, such as C-ADS Injector II, and will be a good candidate for on-line modelling for early machine commissioning and regular operations in the future.

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