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COMMISSIONING OF CHINA ADS DEMO LINAC AND BASELINE DESIGN OF CiADS PROJECT*

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Abstract

China Accelerator Driven Subcritical System (C-ADS) program was launched in China in 2011, which aims to design and build an ADS demonstration facility with the capability of more than 10 MW thermal power in multiple phases lasting about 20 years. In the first phase, a demo linac has been constructed and commissioned successfully to demonstrate the key technologies of the high-power CW mode superconducting linac. Followed the China ADS roadmap, a superconducting driver linac with 500MeV and 5mA proton beam is designed for the second phase of China Initiative Accelerator Driven Subcritical System (CiADS) program. The commissioning results of the China ADS 25 MeV demo linac and the RAMI oriented beam physics design of CiADS linac are presented in this paper.

INTRUDUCTION

China Initiative Accelerator Driven Subcritical System (CiADS) program is a strategy project to solve the nuclear waste problem and the resource problem for nuclear power plants in China [1]. It consists three parts, a high-power superconducting proton linac, heavy metal spallation target and the sub-critical nuclear reactor. The high-power superconducting proton linac is comprised of warm temperature front-end accelerator, superconducting section and high energy transportation line, and it will accelerate 10mA proton beam to 1.5GeV [1]. The main design specifications of proton beam at the ultimate stage are shown in Table 1.

Table 1: Specifications of the Required Proton Beams

Particle	Proton	
Energy	1.5	GeV
Current	10	mA
Beam power	15	MW
RF frequency	(162.5)/325/650	MHz
Duty factor	100	%
Beam Loss	<1	W/m
Beam trips/year	<25000 <2500 <25	1s<t<10s 10s<t<5m t>5m

It is extremely challenging to design and build tens of MWs beam power proton linac, and there is no existing machine in the world. To study the key technology and main factor affecting high reliability and availability of high power accelerator, the accelerator R&D based on a demo linac named China ADS demo linac has been carried out. The China ADS linac has been constructed by the collaborations between Institute of Modern Physics(IMP) and Institute of High Energy Physics(IHEP). This demo linac is composed of an ion source, a low energy beam transport line(LEBT), a 162.5MHz radio frequency quadrupole accelerator(RFQ), a medium energy beam transport line(MEBT), a superconducting accelerating section which contains Half Wave Resonators (HWR) and Spoke resonators and a high energy beam transport line(HEBT). In this paper, the commissioning results of the demo linac and the baseline physics design of CiADS will be presented.

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COMMISSIONING OF CHINA ADS DEMO LINAC

China ADS demo linac is operated to accelerate CW proton to 25MeV with beam current of 10mA at 4.5K operation temperature. The total length is about 35m. The schematic view and the photo layout are shown in Fig.1.

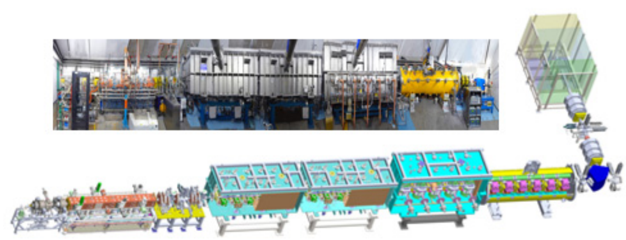

Figure 1: The schematic view and the photo layout of China ADS demo linac.

The installation of the demo linac at IMP has been started since August 2014. Up to now, the beam line includes a LEBT, a RFQ, a MEBT, three HWR Cryomodules, a Spoke Cryomodule, a HEBT and a beam dump which can sustain 100 kW beam power.

The 0.2mA CW proton beam with energy of 25MeV and the 12mA pulsed beam with energy of 26.2MeV were achieved in June 2017. The Fig.2 shows the 0.2mA CW beam current. The Time of Flight method is used for the energy measured, the measurement results and the simulation results are coincident as shown in Fig.3.

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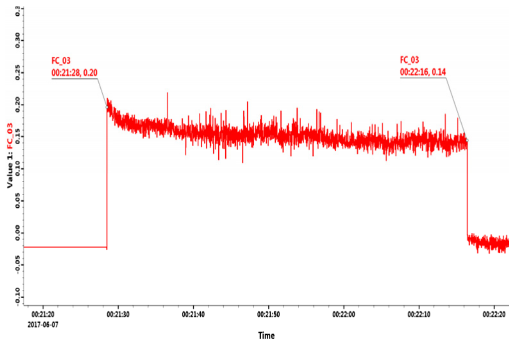

Figure 2: 0.2mA beam current of CW beam.

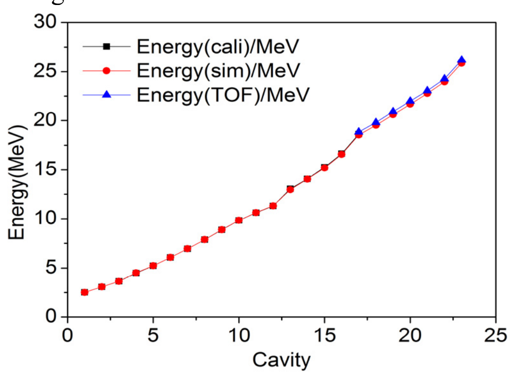

Figure 3: Comparison of measurement and simulated energy results.

For a high-power accelerator, the machine reliability is very important. The machine reliability studies with pulse beam and CW beam were carried out in the China ADS demo facility in December 2017. The fault is defined when the shutdown time duration is more than 10 seconds, and the RF power is CW mode for the pulse beam operation.

Operation Reliability with Pulse Beam

The pulse beam reliability operation study was carried out with two types of beam, 18 MeV proton beam at 1mA with 1Hz and 10us and 18 MeV proton beam at 10mA with 1Hz and 10us. According to the statistical results, for the two types of beam, the demo linac can run continuously for around two hours without fault. It indicates that the effect of beam power to the reliability of demo linac is not serious. From the statistical result as shown in Fig.4, the sources of fault are mainly from ECR ion source, RFQ, power supply, RF system and cryo-plant, and the reliability of the RF system is the lowest. Other systems those are not listed here have no fault.

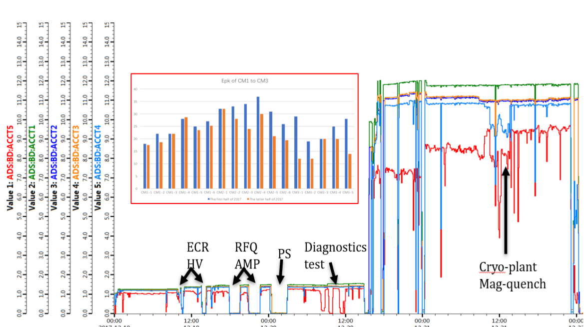

Figure 4: Pulse beam operation reliability test result.

For high power ADS accelerator, high availability is very important. Table 2 shows the availability of China ADS demo linac based on the pulse beam operation reliability test result. The availability is up to 88% [2]. The reasons of the fault maintenance time larger than 5minites, such as ECR ion source, Cryo-plant, power supply, are very clear, and they can be avoided in the next stage. However, the reasons of the trips from SRF maintenance time between 10 seconds and 5 minutes, are still under investigation.

Table 2: Availability of China ADS Demo Linac

Operation time (min)	Beam time (min)	Down time (min)	Availability
4050	3566	484	88%

Operation Reliability with CW Beam

Considering the deterioration effect of the high-power beam to superconducting accelerator device, the active protection mode of the machine protection system (MPS) is adopted. According to the beam simulation results, a series of protection conditions for each system of the accelerator are proposed. During the CW beam operation reliability test, The CW proton beam with 0.2 mA beam current can running 1.5 hours without beam trip as shown in Fig.5. The main reasons of beam trips are from RF system and control system. The beam trips from RF systems are mainly caused by phase error, and the beam trips from control system are mainly caused by beam position monitor.

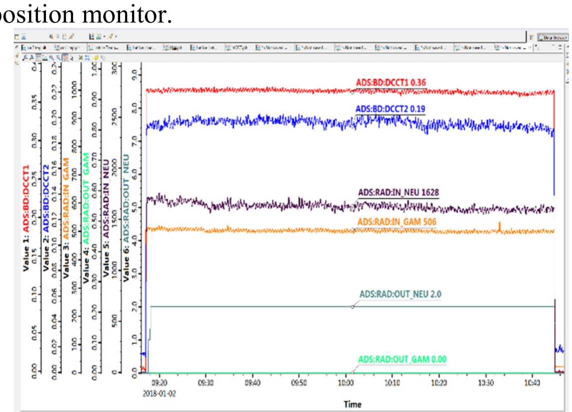

Figure 5: CW beam operation reliability test result.

Reliability analysis forms an important part of designing ADS accelerator. It helps to analyse` the performance, and gives insight to the weakness in design based on the predicted failures. Next step, a thorough reliability study at the China ADS demo linac will be continued to master the key physics and technology for high-power machine operation.

PRELIMINARY DESIGN OF CiADS LINAC

CiADS driver linac is defined to be 1.5GeV in energy,10mA in current and in CW operation mode in three phases. For the first phase, the beam energy is 500MeV, and the beam current is 5mA. The linac consists of a room temperature front end which is considered to do

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the beam quality control, a superconducting linac for highly efficient acceleration and an accelerator to target beam transport line (A2T) which is used to delivering beam to target. The schematic view of the CiADS linac is shown in Fig.6.

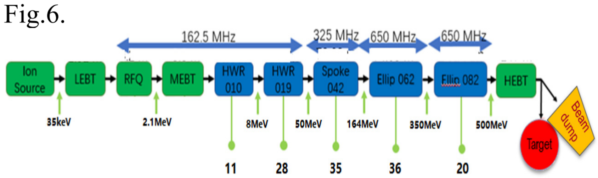

Figure 6: Schematic view of CiADS linac.

Room Temperature Front-end

The room temperature front-end consists of LEBT, RFQ and MEBT. The main function of the front-end accelerator is to guarantee beam quality by beam loss control. First, the design of the LEBT is mainly focus on the transverse beam quality control besides the matching between IS and RFQ. As shown in Fig.7, a 20deg bend magnet is selected to get rid of the H^{2+} and H^{3+} particles to avoid them losing in RFQ cavities. A chopper and diagnostics are included to characterise the beam structure and distribution. What is more, a collimation method is proposed to scrape the outside tail particles just at the end of the ion source to achieve a good transverse beam distribution [3]. The tail particles at the exit of LEBT are tracked back to the entrance of LEBT, and the evolution is shown in Fig.8. It will find that the tail particles exactly the outside ones at the entrance of LEBT. These tail particles can be removed in this way.

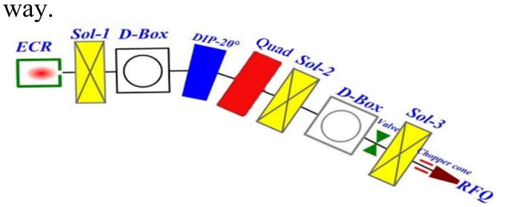

Fig.7 Schematic view of LEBT

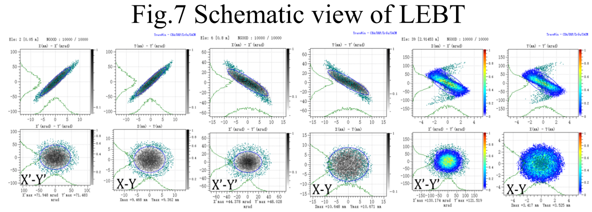

Figure 8: Evolution of the tail particles at the exit of the LEBT.

The 2.1 MeV Radio-frequency Quadrupole (RFQ) is a 4-vane type with a length of 4.57m. As the first RF element, the longitudinal beam distribution is determined by RFQ accelerator to a large extent. The longitudinal beam performance is very critical for beam loss control in the downstream superconducting section. The innovative adaptive-acceptance philosophy is adopted to decrease the 99.9% longitudinal emittance and the probability of beam loss in superconducting section at the cost of low accelerating efficiency. In order to decrease the effect of particle loss on cavity, smaller energy acceptance is kept in the first 150 cells as shown in Fig.9. The final ration of 99.9 % emittance to acceptance of superconducting section is less than 1/5[4].

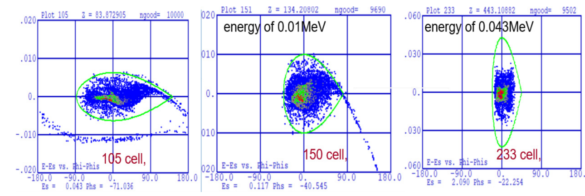

Figure 9: Longitudinal beam space evolution.

Between the RFQ and the superconducting linac, a MEBT, consisting of 7 quadrupoles and 2 RF buncher cavities, is designed to match the beam both in transverse and longitude. Double steering per quadrupole is considered to correct the beam trajectory, and finally there is a selection of beam instrumentation to sufficiently characterise the beam out of the RFQ.

Superconducting Section

The acceleration efficiency and beam loss control are two main issues in the superconducting section. It consists of five families of superconducting cavities which are defined using Particle swarm optimization algorithm (PSO) program based on the cost minimization. Table 3 shows the cavity parameters in CiADS linac.

Table 3 Cavity Parameters of SC Section in CiADS Linac

Cavity type	βg	Frequency MHz	Emax MV/m
Squeezed HWR	0.10	162.5	32
Taper HWR	0.19	162.5	32
3-cell Spoke	0.42	325	33
5-cell Elliptical	0.62	650	33
5-cell Elliptical	0.82	650	33

With the large energy range and the different acceleration structures, it is less effective to design the same focusing structure for the whole linac. Different periodic lattice in both the transverse and longitudinal planes are used for the best-fit to the different energy ranges as shown in Fig.10.

In the low energy part, As the defocusing effect of the RF field and space charge effect are evident, superconducting solenoids are used effectively to compact the lattice structure to increase the acceleration efficiency and acceptance. In addition, superconducting solenoids can be fit well into cryostats together with superconducting cavities, and this can help reduce the total length of the linac. For the high energy part, the quadrupole triplets are placed to increase the reliability and maintainability of this section. In addition, considering the effect of beam loss from beam halo on the superconducting cavities, the quadrupoles with beam pipe of 80mm are used to scraped the uncontrol halo particles, and the beam pipe of elliptical cavities are 100mm. Still full period lattice structure is a good choice to reduce the effect from mismatch. In

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addition, optimization at the location of structure transition and frequency jump is concerned seriously to immigrate the longitudinal beam loss.

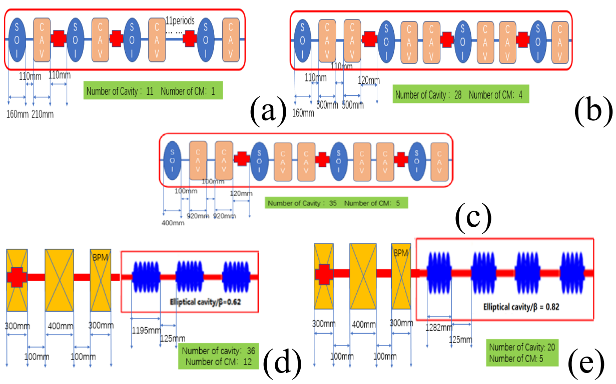

Figure 10: Focusing structure of each accelerating part (a)HWR010 (b)HWR019 (c)Spoke042 (d)Ellip062 with 6cells (e) Ellip082 with 5cells.

Based on the lattice structure mentioned above, design, optimization and multiparticle simulation have been done. The emittance evolution of three planes with different particles are shown in Figs. 11-12. There is no intense emittance oscillation in three planes. The 99.99% emittances growth are 14.3%, 19.9% and 24.4% in there planes respectively.

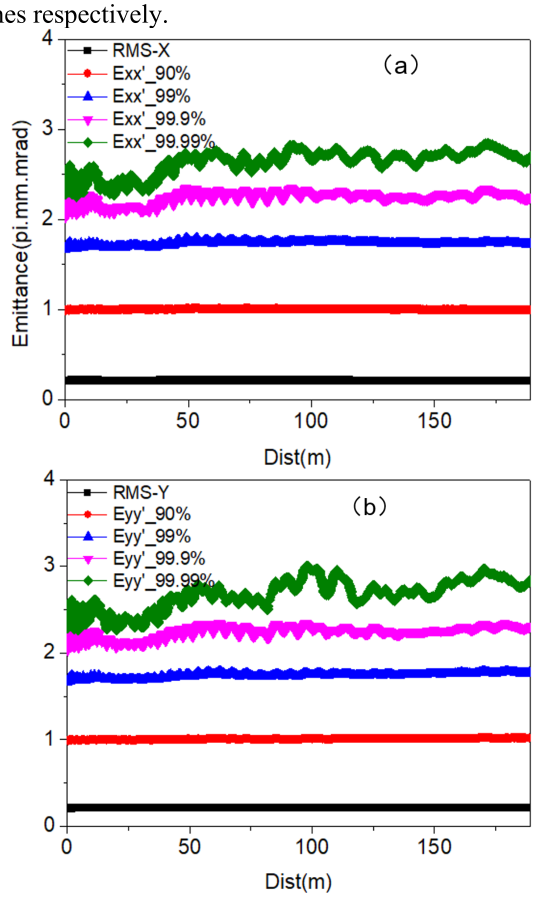

Figure 11: The emittance evolution with different particles along the SC section in the X (a) and Y(b) direction.

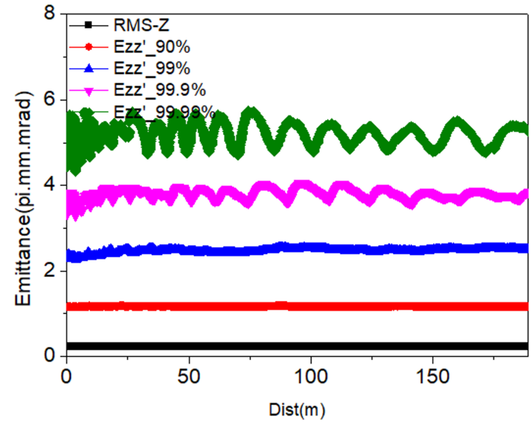

Figure 12: The emittance evolution with different particles along the SC section in the Zdirection.

Accelerator to Target Beam Line

A2T beam line is the coupling section between SC linac and target. Based on the requirements from Target, there are several specifications. The lossless transportation of 2.5 MW proton beam is the basic function. In the physics design, the beam out of superconducting section is matched to a 7 m period transport line which is used to achieve the envelope control by a series of quadrupoles. After the high energy transport line, the beam is horizontally deflected by two 10-degree dipole magnets, and after 25 m of linear transportation, the beam is deflected vertically downward by two 45-degree dipole magnets, and the deflection section is achromatic design. The Fig.13 gives schematic view of the accelerator to target beam transport line.

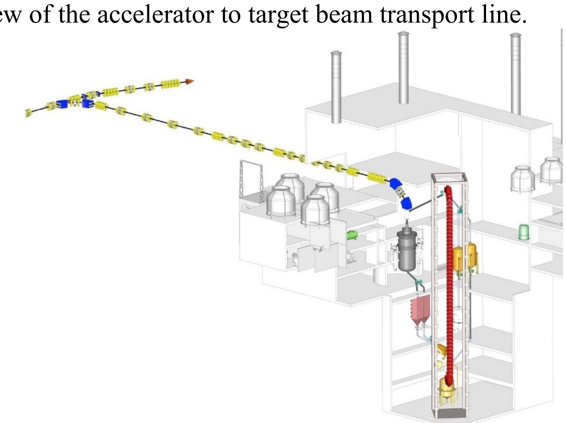

Figure 13: The schematic view of accelerator to target beam transport line.

Second, the homogenization of the beam on the 250 kW thermal power particle flow target is a crucial requirement for this A2T beam line, A radial-angular scanning method is considered to homogenize the power density, and the results of beam scanning for a Gaussian distribution is shown in Fig.14. The peak power density of the beam spot after scanning is 26 μA/cm2.

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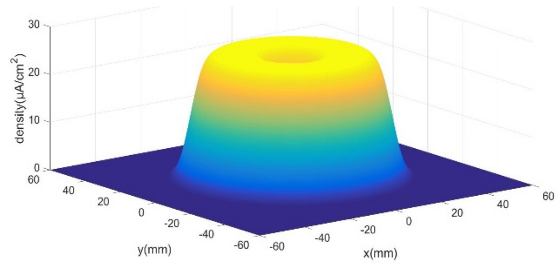

Figure 14: Beam spot density distribution after scanning.

In addition, the beam parameters measurement and reconstruction are critical to beam commissioning of the coupling experiment. So, some beam diagnostic instruments are placed in the periodic transport section to do the beam parameters measurement. Given the upgrade of the accelerator in the future, a 70 m extra space is also considered in this A2T beam transport line.

SUMMARY

The China ADS Front-end demo linac has been constructed, and the CW beam and reliability operation have been done. The 0.2mA CW proton beam with energy of 25MeV and the 12mA pulsed beam with energy of 26.2MeV were achieved. Preliminary reliability studies have been done. The availability is about 88%. Some improvements are considered to improve the reliability and availability.

The baseline physics design of CiADS linac with 500MeV and 5mA has been optimized based on the rules of the thumb in high-power proton linacs. The further engineering optimization and error analysis will be carried out in the next step.

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