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. In the first five-year phase, a 25 MeV demo linac has been successfully built to demonstrate the key technologies of the driven linac. Beam commissioning activities have been carried out to study the high-power beam physics. Followed by the previous phase, China Initiative Accelerator Driven Subcritical System (CiADS) is approved contain a superconducting proton linac with 500 MeV and 5 mA. In this paper, the commissioning results of the demo linac and the beam dynamics design of CiADS linac based on commissioning experiences are presented.

1. Introduction

China Accelerator Driven Subcritical System (C-ADS) is a strategy program to solve the nuclear waste problem and the resource problem for nuclear power plants \cite{1}. It consists three parts, a high-power superconducting proton linac, a heavy metal spallation target and the sub-critical nuclear reactor. Based on the requirement of this program, the linac will accelerate 15 mA proton beam to 1.0 GeV as the ultimate goal \cite{1}. The main design specifications of proton beam at the ultimate stage are shown in Table 1.

| Particle          | Proton | Unit  |
|-------------------|--------|-------|
| Energy            | 1.0    | GeV   |
| Beam current      | 15     | mA    |
| RF frequency      | 162.5/325/650 | MHz  |
| Duty factor       | 100    | %     |
| Beam loss         | 1      | W/m   |
| Beam trips/year   | <2500  | 1s≤t<10s |
|                   | <2500  | 10s≤t<5m |
|                   | <25    | t>5m  |

It is extremely challenging to design and build tens of MWs beam power proton linac because there is no experience in the world. So, the ultimate goal of C-ADS will be implemented in four steps as shown...
in Figure 1. In the first stage, in order to study the key technology and main factor affecting high reliability and availability of high power accelerator, the accelerator research and development (R&D) program based on a demo linac named China ADS demo linac has been carried out. In the second stage, Chinese initiative Accelerator Driven system (CiADS) is approved, and a superconducting proton linac with 5 mA 500 MeV will be constructed to verify the coupled technology. In this paper, we mainly focus on the commissioning results of C-ADS demo linac and the baseline beam dynamics design of CiADS superconducting proton linac.

Figure 1. C-ADS development roadmap

2. Commissioning of China ADS demo linac

China ADS demo linac is designed to accelerate CW proton beam to 25 MeV with beam current of 10 mA at 4.5 K operation temperature. The total length is about 35 m. The schematic view and the photo layout are shown in Figure 2.

Figure 2. The schematic view and the photo layout of China ADS demo linac.

The China ADS demo linac was constructed by the collaborations between Institute of Modern Physics (IMP) and Institute of High Energy Physics (IHEP), and the installation of this demo linac at IMP has been started since August 2014. This demo linac is composed of an ion source, a low energy beam transport line (LEBT), a 162.5 MHz radio frequency quadrupole accelerator (RFQ), a medium energy beam transport line (MEBT), a superconducting accelerating section, a high energy beam transport line (HEBT) and a beam dump which can sustain 100 kW beam power.

Since 2014, the beam commissioning has been carried out continuously. The 0.2 mA CW proton beam with energy of 25 MeV and 12 mA pulsed beam with energy of 26.2 MeV were achieved in June 2017. The Figure 3 shows the beam commissioning results of the 0.2 mA CW beam current for around 2
minutes. The Time of Flight method is used for measuring the beam energy. The measurement results and simulation results are agreed well with each other, which is shown in Figure 4. This demo linac is a research device, and the beam loss, machine stability, machine protection and other issues related to high power beam will be studied using this machine step by step. As the beam power arise, some deficiencies in physical design and in engineering construction emerge. In the next commissioning, the beam current will be increased step by step, and the beam transmission characteristics with different beam power will be further studied.

![Image](image1.png)

**Figure 3.** 0.2 mA beam current of CW beam.

![Image](image2.png)

**Figure 4.** Comparison of measurement and simulated energy results.

The machine reliability is very important for the operation of ADS accelerator which is directly related to the machine safety and availability. So, in the commissioning of China ADS demo facility in December 2017, a preliminary machine reliability study with pulse beam and CW beam were carried out. The faults number of the shutdown time duration more than 10 seconds are counted, and also, the various sources that caused machine fault are analysed.

### 2.1 Operation reliability with pulse beam

The 18 MeV pulse proton beam reliability operation study was carried out with two types of beam of 1 mA at 1 Hz 10 us and 10 mA at 1 Hz 10 us. According to the statistical results, the demo linac runs
continuously for around two hours without fault with the two types of beam. The study results indicate that the effect of low beam power on the reliability of demo linac is not serious. From the statistical results shown in Figure 5, 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 worst. Other systems not listed here have no fault in this reliability test. The statistical results are shown in Table 2.

![Figure 5. Pulse beam operation reliability test result.](image)

Table 3 shows the availability of China ADS demo linac based on the pulse beam operation. The availability is up to 88 % [2]. The reasons of the fault maintenance time larger than 5 minutes, such as ECR ion source, RFQ, power supply, Cryo-plant, are clear. The reasons of the fault from ECR-IS and RFQ are arc protection which will be improved by condition. Noise disturbance is the main cause of power supply fault, and the electromagnetic shielding needs to be considered in the next work. The improvement of the control logic is the main work to reduce avoid the fault from cryo-plant.

| Planed operation time/minutes | Actual running time/minutes | Failure frequency |
|-------------------------------|----------------------------|------------------|
| ECR 4050                      | 3997                       | 6                |
| RFQ 4050                      | 3973                       | 2                |
| RF system 4050                | 3972                       | 21               |
| Power supply system 4050      | 3950                       | 1                |
| Cryo-plant system 4050        | 3867                       | 1                |

Table 3. Availability of China ADS Demo Linac

| Operation time (min) | Beamtime (min) | Down time (min) | Availability |
|----------------------|----------------|-----------------|--------------|
| 4050                 | 3566           | 484             | 88 %         |

2.2 Operation Reliability with CW Beam
Considering the deterioration effect of the high-power beam on superconducting accelerator device, active protection mode is adopted for the machine protection system (MPS), and a series of strict protection conditions for each system are proposed. The CW proton beam with 0.2 mA beam current lasts for 1.5 hours without beam trip as shown in Figure 6. The reasons of beam trips are mainly from RF system which is closely related to the liquid helium instability caused by the 4K cryo-plant, the interference from environmental vibration sources, and cavity sparkling. This problem will be considered carefully in the CiADS program.

![Figure 6. CW beam operation reliability test result.](image)

Reliability analysis is beneficial to give insight to the weakness of physics design based on the predicted failures. Next step, an in-depth reliability study will be continued to gain insight into the key physical mechanisms and technical issues that affect the operation reliability of high-power accelerator.

Up to now, China ADS demo linac goes into the machine research phase. As the second stage of the C-ADS project, CiADS has been carried out based on the engineering requirements and the operation experience of China ADS demo linac. The preliminary beam dynamics design of CiADS linac is presented as following.

### 3. Preliminary Design of CiADS Linac

CiADS driver linac will deliver a 500 MeV, 5 mA proton beam in CW operation mode, and it is composed of two major sections. One is the normal conducting section and the other is the superconducting (SC) section. The normal conducting section contains an electron cyclotron resonance (ECR) ion source with frequency of 2.45 GHz, a low energy beam transport (LEBT) line, a four-vane type copper structure radio frequency quadrupole (RFQ) with frequency of 162.5 MHz and a medium energy beam transport (MEBT) line. The normal conducting section will accelerate proton beam to 2.1 MeV. The SC section as the main accelerating section will accelerate the proton beam from 2.1 MeV up to 500 MeV. Then, the beam is transported to the beam dump and target going through the high energy beam transport (HEBT) line. The schematic view of the CiADS linac is shown in Figure 7.

![Figure 7. Schematic view of CiADS linac.](image)
3.1 Room Temperature Front-end

The room temperature front-end consists of LEBT, RFQ and MEBT. Based on the operation commissioning experiences of China demo linac in beam loss, the main function of the front-end accelerator is to get good beam quality.

The LEBT physics design is mainly focus on the transverse beam quality control as well as the matching between IS and RFQ. As shown in Figure 8, a 20-degree bend magnet is selected to get rid of the H\textsuperscript{2+} and H\textsuperscript{3+} particles to avoid them losing inside RFQ cavities. A chopper and diagnostics are included to control the beam structure and detect the beam distribution. What is more, a collimation method is proposed to scrape the outside tail particles just at the end of the ion source for 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 of the phase space is shown in Figure 9. The tail particles are exactly the outside ones at the entrance of LEBT.

![Figure 8. Schematic view of LEBT.](image)

The Radio-frequency Quadrupole (RFQ) accelerator is 4-vane type structure with 4.57 m in length, and the output energy is 2.1 MeV. The longitudinal beam performance out of the RFQ is very critical for beam loss control in the downstream superconducting section. The innovative adaptive-acceptance philosophy, focusing on small acceptance to get a small output emittance by losing some tail particles in RFQ, is adopted to decrease the 99.9 % longitudinal emittance and also reduce the probability of beam loss in superconducting section. In order to decrease the effect of particle loss on cavity, smaller energy acceptance is kept in the first 150 cells with low beam energy as shown in Figure 10. The final ratio of 99.9 % emittance to acceptance of superconducting section is less than 1/5 [4].

![Figure 9. Evolution of the tail particles at the exit of the LEBT.](image)

![Figure 10. Longitudinal beam phase space evolution.](image)
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 longitudinal. Double steers per quadrupole are considered to correct the beam trajectory. Based on the beam commissioning experience of the previous demo linac, the beam parameters reconstruction is very important for the prediction of the beam transmission performance. Beam emittance measurement is the common method to get beam parameters. Direct measurement and indirect measurement are two general methods. Based on the experimental experience of emittance measurement in the previous demo linac, the phase space of direct emittance measurement has the disadvantages of signal discontinuity and low signal-to-noise ratio, in addition, the slit is easily damaged. So, we prefer to use the indirect emittance reconstruction method by the beam profile measurement. For the structure design of the MEBT in CiADS linac, all the focusing elements and beam diagnostics are placed fully considered the requirements of matching and beam parameter reconstruction.

3.2 Superconducting section

The superconducting section is the main accelerating part in the CiADS linac, the it will accelerate 5 mA proton beam up to 500 MeV. To cover the whole energy from 2.1 MeV to 500 MeV, five types of superconducting cavities are chosen. Table 4 shows the cavity parameters of CiADS linac. The peak electric field is determined considering the operation stability caused by cavity sparking of the previous demo linac commissioning experiences.

Given the demands of beam quality, some guidelines are required to be considered in the design process. The most important design philosophy is the following:

1. Transverse period phase advances for zero current beams should be below 90° to avoid the structure resonance [1].
2. Wave numbers of oscillations need change adiabatically along the linac, especially at the lattice transitions with different types of focusing structure and inter-cryostat spaces [5].
3. Avoid strong space charge resonances through the judgment of Hofmann's Chart [6–9].
4. Minimize the emittance growth and beam halo formation caused by mismatching in the lattice transition section.
5. Enough redundancy to avoid the beam loss along the linac.

Based on the beam characteristics of different energy part, Different lattice structure in both the transverse and longitudinal planes are selected as shown in Figure 11.

| Cavity type         | β opt | Frequency (MHz) | E_{max} (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             |

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 reduces 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 quad-
rupoles with beam pipe of 80 mm are used to scraped the uncontrol halo particles, and the beam pipe of
elliptical cavities is 100 mm. Still full period lattice structure is a good choice to reduce the effect from
mismatch. In addition, a beam position monitor at the transition of two cryomodules is placed. Based
on the commissioning experience of China ADS demo linac, the beam position detection at the transition
is necessary to prevent the damage of the pipe caused by the beam with large deflection angle.

![Figure 1](image1.png)

**Figure 1.** 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, the further optimization and multiparticle simulation
were carried out. The emittance evolution of three planes with different particles are shown in Figure
12 and Figure 13. There is no intense emittance oscillation in three planes. The 99.99 % emittances
growth are 14.3 %, 19.9 % and 24.4 % in three planes respectively. It indicates that the beam matching
along the linac are good.

![Figure 2](image2.png)

**Figure 12.** Emittance evolution along the SC section in the X (a) and Y(b) direction.
Figure 13. Emittance evolution along the SC section in the Z direction.

3.3 Accelerator to target beam line

Accelerator to target beam line (A2T) is the coupling section between SC linac and target, and it needs to have following functions. The lossless transportation of 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 get small beam size by a series of quadrupoles. After the high energy beam transport line, the beam is horizontally deflected by two 10-degree dipole magnets, and after 25 m linear transportation, the beam is deflected vertically downward by two 45-degree dipole magnets, and the deflection section is achromatic design. The Figure 14 gives schematic view of the accelerator to target beam transport line.

Figure 14. The schematic view of accelerator to target beam transport line.

The beam homogenization 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 Figure 15. The peak power density of the beam spot after scanning is 26 μA/cm².

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. Given the upgrade of the accelerator in the future, a 70 m extra space is also considered in this A2T beam transport line.
4. Summary

The China ADS Front-end demo linac has been constructed, and the CW beam operation and reliability study have already begun to be done. The 0.2 mA 25 MeV CW proton beam and the 12 mA 26.2 MeV pulse beam were achieved. The results of preliminary reliability studies indicate that the availability of China ADS demo linac is about 88%. Next, some further studies in physics and technology of high-power accelerator will be done.

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

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6. References

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