

# THE STATUS OF CiADS SUPERCONDUCTING LINAC \*

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## Abstract

CiADS (China initiative Accelerator Driven System) approved by Chinese government at 2016 aims to build the first ADS experimental facility to demonstrate the nuclear waste transmutation. The CiADS driving linac can accelerate 5 mA proton beam to 500 MeV at the beam power up to 2.5 MW with the state-of-the-art accelerator technologies. The challenging programs include beam loss control-oriented physics design, high performance CW operated superconducting cavities, SRF cryomodules, and highly efficient RF amplifier system. As the driving linac of the ADS system, the RAMI characters will serve as the design philosophy to guide the physics design and the choice of technical routes. The physics design and key technologies of the high-power machine are described in the paper.

## INTRODUCTION

Driven by the national demand for the safe disposal of nuclear waste and the potential for breeding nuclear fuel to generate advanced energy, Chinese ADS (C-ADS) was proposed years ago as one of the solutions for a cleaner nuclear fission power source [1]. The roadmap of the Chinese ADS program with four phases is shown in the Fig. 1. The R&D program of key technologies including SC linac [2], target and blanket was implemented successfully in the past year.

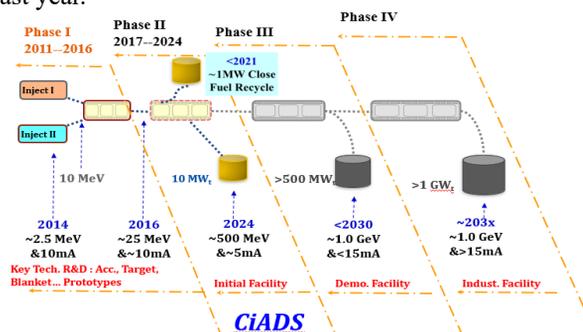


Figure 1: The roadmap of Chinese ADS program.

CiADS (China initiative Accelerator Driven System) as the second step was launched at 2018. The CiADS driven linac is designed to accelerate 5 mA proton beam to 500 MeV in CW mode. As shown in Fig. 2, the linac mainly consists a normal conducting Front-end section, a section, a Radiofrequency Quadrupole (RFQ) linac, and a Medium Energy Beam Transport (MEBT). The SC section accelerates proton from 2.1 MeV and 500 MeV and includes three families of SC cavities with different frequencies and structures: HWR010&019, SPOKE042, Ellipse062&082. The HEBT is designed to deliver 2.5 MW

proton beam to either a bending A2T section or a straight beam dump, which is capable of handling one tenth of total beam power. The space is reserved in HEBT to house another 10 cryomodules to readily increase the energy to 1 GeV.



Figure 2: The layout of the CiADS driven linac.

The preliminary TDR parameters of CiADS linac are specified in Table 1.

Table 1: TDR Parameters of CiADS Linac

Parameter	Description
Beam energy	500 MeV(upgrade to 1GeV)
Beam current	5 mA(upgrade to 10mA)
Operation mode	CW and pulse
Beam stability	±1%@100ms for energy ±2%@100ms for intensity ±1mm@100ms for centroid
Beam reliability	>80%@3 months

## DESIGN PHILOSOPHY OF THE LINAC

Unlike the traditional accelerator based experimental facility, CiADS driving linac has very strict requirement for operation availability from the downstream target and reactor system. The specification of beam trip on the reactor is defined in the time scale of second, which is the most challenging issue for the linac. The overall design is followed by RAMI-oriented principle.

### Reliability

The reliability of hardware is the foundation of the whole accelerator system. To increase the reliability of hardware, standardization and redundancy are the basic consideration. For the key elements, such as superconducting cavities and magnets, are designed to be operated at 80% of the target value, which also benefits the fault-compensation scheme. The standardization is applied to the design of RF amplifier and magnet power supply systems. The solid-state amplifier and modular power supply integrated with standard unit will be used in the CiADS linac.

### Availability

The availability of the driven linac is a high-level systematic problem. Except for the spares and design redundancies of the hardware, a fast beam recovery in one second with compensation scheme is an effective way to improve the beam availability. In this scheme, the artificial intelligence technology under development has the potential to realize the beam recovery. Also, a Machine Protec-

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tion System (MPS) should be implemented with the balance between beam availability and machine safety. In the beam dynamics design, the aperture in the room temperature section is smaller than that in the superconducting to immigrate beam loss in cold section.

### Maintainability

Maintainability is quite challenging for the high-power superconducting proton linac. Firstly, the average uncontrolled beam loss must be limited to below 1 W/m level to facilitate hands-on maintenance. Secondly, the hardware is placed in the warm section as possible as we can and the mechanical design with the characteristics of easy dismounting and assembling. Thirdly, the online performance recovery technologies of superconducting cavities are developed to short the maintenance intervals.

### Inspectability

The inspectability is critical for the high-reliability high power SC linac. The on-line beam diagnostics devices are placed sufficiently not only for the beam tuning but also for the beam recovery. The other critical system, such as high-voltage RF system, are inspectable at some critical locations, which is beneficial to detection of the hardware problems.

## BASELINE PHYSICS DESIGN

Beam loss control is the most challenging issue and the ultimate optimization goal. Beam halo caused by the nonlinear effect, such as space charge effect and nonlinear RF field, is the main source of beam loss. Based on the target, the overall layout is divided in to three sections according to the function shown in the Fig. 2.

### Room Temperature Front-end

The room temperature front-end consists of a LEBT, an RFQ and a MEBT. Its main function to guarantee beam quality by beam halo immigration both in the transversal and longitudinal phase space.

A bending LEBT is designed to improve the transverse beam quality by scraping the outer particles and impure ions  $H_2^+$  and  $H_3^+$ . A chopper and diagnostics are included to characterise the beam structure and distribution. A collimation scheme is proposed to scrape the outside particles just at the end of the ion source to achieve a good transverse beam distribution.

The 4-vane type Radio-frequency Quadrupole (RFQ) accelerator is designed to accelerate proton beam from 35 keV to 2.1 MeV within 5 meters. The high transmission and longitudinal beam performance are the critical optimization objectives for the reliable operation and beam loss control in the downstream superconducting section. The input energy and general bunch section are emphatically optimized to achieve an admirable result. The 99.9% longitudinal emittance is  $3.5 \pi \text{ mm} \cdot \text{mrad}$  with the acceleration efficiency high to 99.3%.

A MEBT with the function of beam reconstruction, halo scrape and matching. The lattice of MEBT designed under

the consideration of the phase smooth with adjacent section. The beam instrumentation is placed with beam reconstruction experiment. The halo immigration is implemented with scraper separated with certain phase advance.

### Superconducting Acceleration section

A SC acceleration section including includes three families of SC cavities is designed to accelerate a 10 mA proton beam to 500 MeV. The beam loss is controlled to be lower than 1 W/m strictly. The 90-degree phase advance limit at zero current and beam matching among different sections are followed to compress the formation of beam halo. The smoothness of phase advance is comprised with the acceleration efficiency. In view of the uniformity and feasibility in the engineering implementation, 6-m length of cryostat for all five section is determined. The main RF characteristics of the SC linac accelerating cavities are summarized in Table 2.

Table 2: Main RF Parameters of the CiADS SC Linac

Cav. Type	Freq (MHz)	R0 (mm)	Epk (MV/m)	Eout (MeV)
HWR010	162.5	40	26	7
HWR019	162.5	40	28	47
Spoke042	325	50	28	170
Ellip062	650	100	28	350
Ellip082	650	100	28	500

### HEBT & Beam Dump

The HEBT with FODO lattice will deliver the proton beam to a 300-kW test beam dump. A 60-m long space is reserved for the upgrade plan in the next stage. What is more, the key technologies used in the A2T coupling section, such as beam homogenization, beam diagnostics, beam window, will be demonstrated with beam at HEBT.

## KEY TECHNOLOGIES

The basic key technologies have demonstrated in the first phase of Chinese ADS program, such as superconducting cavities, solenoids, solid-state amplifier. While for the large-scale CiADS linac, there are still some R&D topics including operation-stability of superconducting cavities, high-efficiency amplifier system and cryomodule.

### Superconducting cavities

Cavity tuning and the related parameters are the most difficult design tasks and interacts with the most design boundaries. The RF amplifiers of CiADS are supposed to leave a bandwidth of 100 Hz for SRF cavities, which implies the unwanted cavities frequency shift, including Lorentz Force Detuning (LFD), microphonics, pondermotive effect, etc., shall be smaller than 10 Hz. How to design cavities and tuners with high tuning precision and low detuning coefficient was quite tricky for the mechanical design.

There are five types of cavities in CiADS linac, the double spoke cavities with optimal beta 0.42 is the most difficult task for the monarchical structure. Here we can take the mechanical design of Spoke042 cavity as an example.

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In order to control the LFD, stiffening rings were added inside the nose and spoke area, and the thickness of helium vessel was enlarged to 4 mm. These measures successfully reduced the LFD and dF/dP coefficient. But the cavity became too heavy and too stiff to tune.

To make Spoke042 a tunable cavity, further optimization was needed. After a series of calculation, we found the corner wall area and beam port wall area contribute very little to the stiffness of the whole cavity, and we managed to reduce the thickness of those area to 2 mm as shown in the Figs. 3 and 4. With all these improvements, Spoke042 cavity's stiffness and tuning parameters fell into the acceptable window drawn by LLRF and mechanical design.

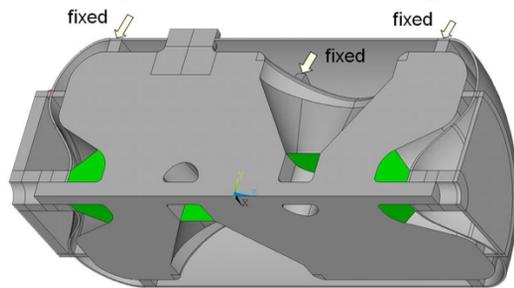


Figure 3: Spoke042 cavity structure. Green parts are extra stiffening at nose and spoke.

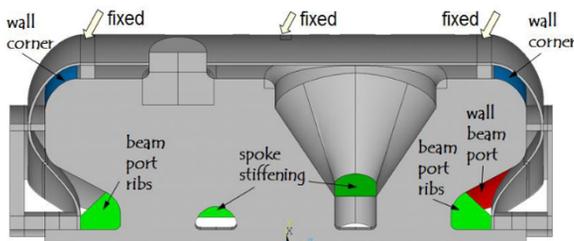


Figure 4: Blue and red parts are thinned areas.

### Solid-state Amplifiers

SSPA (Solid State Power Amplifier) is chosen as the technical route of RF power source in order to be able to flexibly schedule and upgrade in future plans. The beam power upgrade under the fixed coupling of the input coupler was chosen for engineering implementation consideration. The selection of SSPA output level becomes a challenge work to reduce the waste of RF power caused by the basic unit selection. In order to minimize the reflected power during the upgrade process, the matching beam current determined at 5.5 mA. The calculation of the RF power includes reflection power by mismatch, RF power for LLRF control and transmission loss. Based on the calculation result of the RF power requirements in different upgrade processes with one of physical design, the minimum unit of combination power level is selected, and the utilization of different combination scheme as shown Fig. 5. The "665" combination is the final optimal choice. The total rated RF power at different construction phase is shown in Fig. 6.

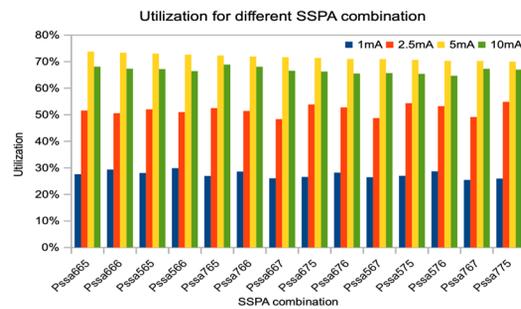


Figure 5: SSPA utilization with different basic unit.

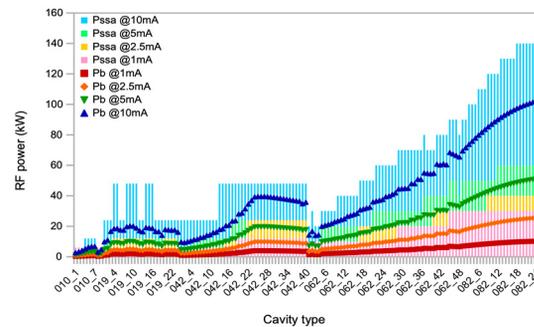


Figure 6: SSPA upgrade plan.

### Cryomodules

Two types of cryomodules with cylindrical and rectangular shape are designed for these cavities. According to the previous operation experience, mechanical alignment at 2 K is one of the most challenging issues. Two approaches are used in CiADS cryomodule design process to minimize the misalignment. One is to move the main support structure to room temperature region in order to avoid bigger shrinkage at low temperature. The other one is to optimize the mechanical structure at low temperature, such as bottom to top support, Kelvin upholder. The design of specific mechanical structures for superconducting cavity support system is shown in Fig. 7.

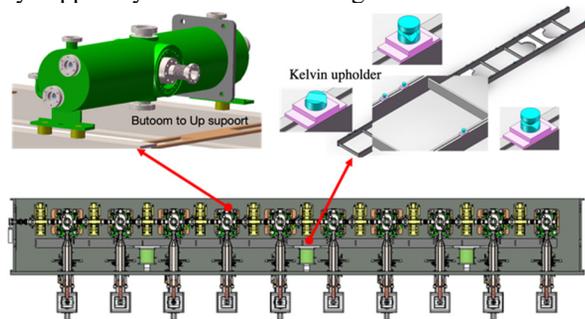


Figure 7: Specific mechanical structures for superconducting cavity support system.

### SUMMARY

The CiADS project is launched from the beginning of 2019. The driven linac as the most powerful accelerator is optimized to minimize the beam loss with novel design idea. The key technologies related to cavities, amplifiers and cryomodules are summarized. More work will be carried out to solve the technical problems in next step.

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