CHALLENGES AND PERFORMANCE OF THE C-ADS INJECTOR SYSTEM*

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Abstract

Along with the rapid development of nuclear power plants in China, treatment of the nuclear waste has become a crucial issue. Supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (CAS), the Chinese Accelerator-Driven System (C-ADS) project is now on-going. The accelerator of C-ADS is a superconducting (SC) Continues Wave (CW) proton linear accelerator (linac) with 1.5GeV energy and 10mA beam current. In the injector part many challenges to developing technologies including Radio Frequency Quadrupole (RFQ) and low β SC cavities and related hardware's. This paper presents the progress of development of C-ADS injectors and related hardware.

ROADMAP OF C-ADS

In January 2011, a special program of nuclear energy promoted by the CAS - Advanced Fission Energy Program - was launched. This program is a strategic plan with its long-term planning until 2032 (see Figure 1). The R&D of the first phase has been funded by the "Strategic Priority Research Program" of CAS.

(i) Phase I (R&D Facility)

- Accelerator goal: 10 mA × 250 MeV
- Reactor goal: 10 MWth
- Schedule goal: Before the end of the decade
- Short term goals: 5 MeV by 2015; 25 MeV by 2016

(ii) Phase II (Experimental Facility)

- Accelerator goal: 10 mA × 1 GeV
- Reactor goal: 100 MWth
- Schedule goal: Approximately 2032

(iii) Phase III (Demonstration Facility)

- Accelerator goal: 10 mA × 1.5 GeV
- Reactor goal: 1000 MWth

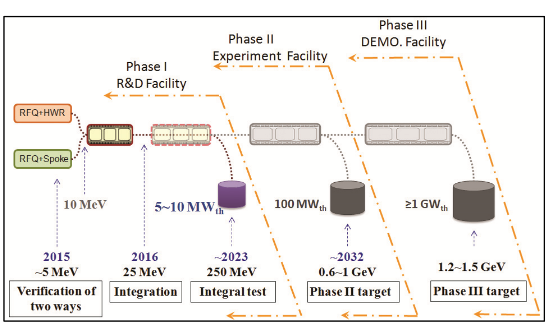

Figure 1: Road map of C-ADS project.

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DESIGN OF C-ADS LINAC

Proton Beam Requirements for C-ADS

C-ADS are anticipated as a demonstration facility for transmutation of nuclear waste on an industrial scale, and would require a beam power of at least 10 MW. Besides the high beam power, the reliability of the machine should be very high. The design specification of the proton beam for C-ADS is shown in Table 1.

Table 1: Specifications of the Required Proton Beams of C-ADS

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

Design Philosophy of the C-ADS Linac

The C-ADS linac is an extremely challenging accelerator, and there is no existing model in the world yet. The concept may share features in common with several other high power accelerators being developed in the U.S. and Europe, such as Project-X, MYRRHA, IFMIF and EURISOL.

With the approved SC Radio Frequency (RF) technology, especially the positive test results of low β Spoke resonators and Half Wave Resonators (HWR) at FNAL and ANL, and the success of the medium β Elliptical cavities at SNS, it is believed that an all superconducting proton linac except the RFQ is possible and favored due to the difficulty to deal with huge heat deposit in a CW room-temperature acceleration structure. Another advantage of using superconducting cavities is that one can use independently phased resonators to make local compensation when some cavities fail during operation. This is very important to achieve the very strict demands for the reliability of the ADS driving accelerator. So, C-ADS linac uses SC acceleration structures except the RFQs, and works in CW mode.

The RF frequencies for the main linac have been selected as 325 MHz for the Spoke cavity section and 650 MHz for the Elliptical cavity section. However, two different designs employing different RF frequencies are

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pursued for the two injectors in the technical developing phase. One is 325 MHz for Injector-I at Institute of High Energy Physics (IHEP) and the other is 162.5 MHz for Injector-II at Institute of Modern Physics (IMP).

The most crucial requirement for developing and operating an ADS accelerator is the very high reliability, reflected by the different numbers of beam trips for different durations, as shown in Table 1. To achieve the goal, special design methods in the driver linac have to be adopted. The hardware will be designed and operated with conservative performance margins, and will incorporate fault-tolerant capabilities in the physics design. However, no matter how we improve the hardware's reliability performance, it should be expected to meet some failures of important devices with a much lower frequency. The accelerator design has to deal with these situations. Both global and local compensation methods have been proposed to tackle cavity failures in superconducting linacs, with the latter being considered suitable for meeting the very high reliability in ADS linacs. In C-ADS linac, the local compensation-rematch method has been further developed to deal with the failures of two kinds of major components: SCRF cavities and transverse focusing elements including SC solenoids and room-temperature quadrupoles.

For the very low energy part, it is difficult to apply the local compensation method, thus two parallel injectors will be employed. When one is in the online operation mode, the other is operated as a hot-spare and can be switched to the online mode quickly.

Another key issue in designing the linac is that beam losses should be kept as low as possible along the linac, with a usual acceptance of 1 W/m for all high-power proton accelerators. This is especially difficult for the C-ADS, since it has a beam power about 10 times higher than the most powerful existing linac such as the SNS linac. And, this means a beam loss rate of 7×10-8/m at the higher energy part for C-ADS linac, requiring very delicate error and beam loss studies.

Layout of C-ADS Accelerator

The accelerator layout is shown in Figure 2. It consists of four distinct regions:

- Injector (0-10 MeV): Two alternatives are being developed: one based on an ion source, 325 MHz Radio Frequency Quadrupole (RFQ), and 325 MHz low β single Spoke resonator named Spoke012; and the other on an ion source, 162.5 MHz RFQ, and 162.5 MHz low β HWR named HWR010.
- Low β acceleration (10-147 MeV): Two types of single Spoke resonators operating at 325MHz will be utilized - one at β=0.21 (Spoke021), the other at β=0.40 (Spoke040). A total of 96 cavities are required.
- High β accelerator (147-1500 MeV): Two types of Elliptical cavities operating at 650 MHz will be utilized - one at β=0.63 (Ellip063), the other at β=0.82 (Ellip082). A total of 142 cavities are required.
- MEBT2 and HEBT. The second Medium Energy Beam Transport line (MEBT2) transports and matches the beam from either of the two injectors to the main linac, while the High Energy Beam Transport (HEBT) delivers high energy beam to the neutron target.

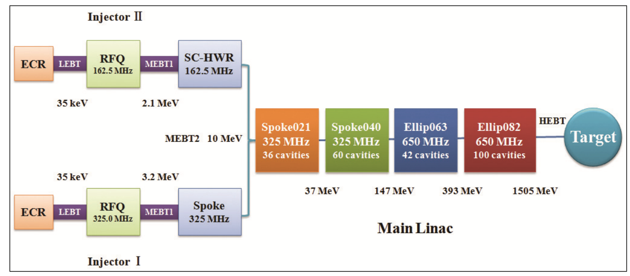

Figure 2: Layout of C-ADS linear accelerator.

R&D OF KEY ACCELERATOR TECHNOLOGIES

RFQ Accelerators

A RFQ accelerator is used to simultaneously bunch, focus and accelerate the very low energy (20-95 keV) beam from the proton source to energy in the range 2-7 MeV. For an ADS accelerator system, the RFQ is typically normal conducting and work in CW (100% duty cycle) mode, and it is one of the most challenging technical aspects of any ADS accelerator system. Although several RFQ accelerators capable of providing CW proton currents in the range 30 to 100 mA have been developed and demonstrated performance levels that meet the requirements for industrial-scale ADS systems, C-ADS paid much attention to the RFQ accelerator from the very beginning.

Two prototype RFQ accelerators have been designed, fabricated and commissioned (see Figure 3). One is a 325 MHz RFQ (named RFQ-I), responsible by IHEP and the other is 162.5 MHz RFQ (named RFQ-II) by IMP. The main parameters of these two RFQs are shown in Table 2.

Table 2: Main Parameters of Prototype RFQs for C-ADS

Parameters	RFQ-I	RFQ-II
RF frequency (MHz)	325.0	162.5
RF power (kW)	300	110
Beam current (mA)	10	10
Injection energy (keV)	35	35
Output energy (MeV)	3.2	2.1
Inter-vane voltage (kV)	55	65
Maximum modulation	2	2.3
Beam transition	98.7%	99.5%
εn.rms.t (πmmmrad)	0.2/0.2	0.3/0.3
εn.rms.l(πMeV-deg)	0.06	0.05
Accelerator length(cm)	467.0	420.8

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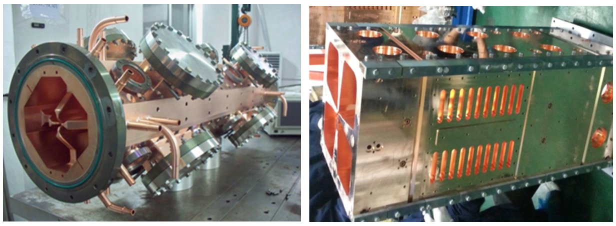

Figure 3: The RFQ-I and RFQ-II (1/4 part).

Superconducting RF Cavities

The SC RF technologies in the context of C-ADS linacs are of the following advantages and therefore selected for C-ADS project:

- High accelerating gradients (~20 MV/m) and therefore lower capital and operating costs,
- Low RF structure power dissipation which leads to efficient transfer of RF power to the beam,
- Large aperture to reduce interception of halo particles,
- Extremely low vacuum to minimize beam-gas interactions thereby reducing beam loss,
- Potential for high reliability with a linac architecture in which one SC cavity is powered by a single RF source and SC cavities are maintained as online spares.

Seven types of SC cavities have been designed and prototyped almost in parallel. They include HWR, Spoke and Elliptical cavities, and may meet the requirement to accelerate the proton beam from low energy (2-3 MeV) to the target 1.5 GeV. Their main parameters and typical vertical test (VT) results are summarized in Table 3.

Totally seventeen Spoke012 cavities, eight Spoke021 cavities, two Spoke040 cavities, two Elliptical082 and 12 HWR010 cavities were developed (see Figure 4 and Figure 5) and vertically tested and exceeded the operation specification, which is noted as the "target" in Figure 6 and Figure 7.

Figure 4: Spoke012, Spoke021, Spoke040 cavities.

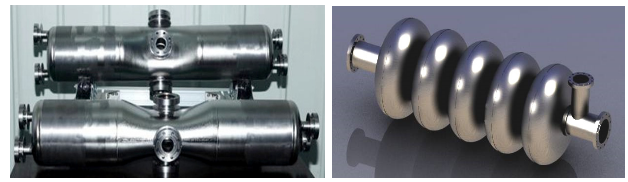

Figure 5: HWR010, Elliptical082 cavities.

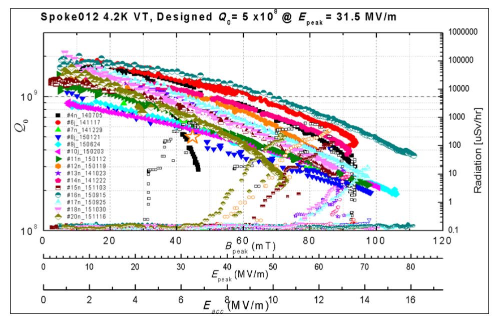

Figure 6: Vertical test results of Spoke012 cavities.

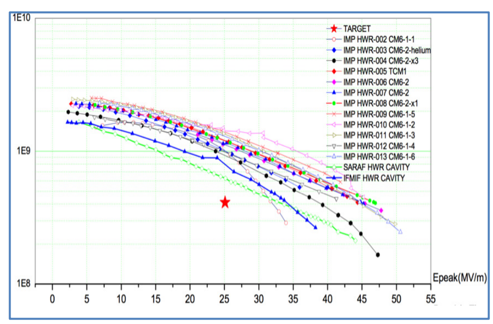

Figure 7: Vertical test results of HWR010 cavities.

Table 3: Design Specifications and Vertical Test Results of SC Cavities for C-ADS

	Spoke012	**HWR010**	**HWR015**	**Spoke021**	**Spoke040**	**Ellip063**	**Ellip082**	**Unit**
Frequency	325	162.5	162.5	325	325	650	650	MHz
β_0^*	0.14	0.10	0.15	0.24	0.46	0.63	0.82	-
Aperture	35	40	40	50	50	100	100	mm
L_{eff}	0.129	0.185	0.277	0.221	0.424	0.757	0.985	mm
E_{acc} Max	6.5	4.5	6.5	7.5	6.8	13.5	16.0	MV
E_{peak}	32.5	25	32	24/31	25/32	29/38	28/36	MV/m
B_{peak}	46	50	40	50/65	50/65	50/65	50/65	mT
Temp	4	4	4	2	2	2	2	K
P_{loss}	<10	<10	<15.5	<16.8	<6.5	<21	<39	W
E_{acc} Max @VT,4K	13	8.5	12.5	11	11.5	N/A	9	MV/m
Q_0 Max @VT, 4K	1.8	3	3	2	2	N/A	1.7	$\times 10^9$

*β_0 is the optimum β for single Spoke cavities, while it is the geometrical β for Elliptical cavities

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In parallel with the SC cavities development, the corresponding RF Solid State Amplifier (RF SSA), Low Level RF (LLRF) system, high power input couplers, tuners and Cryomodules (CM) for the two injectors have also been developed.

INTEGRATION AND COMMISSIONING OF INJECTORS

In order to develop the relevant techniques and the beam tuning method, the short term and principal goal of phase I for C-ADS is to construct two 10 MeV injectors with different schemes.

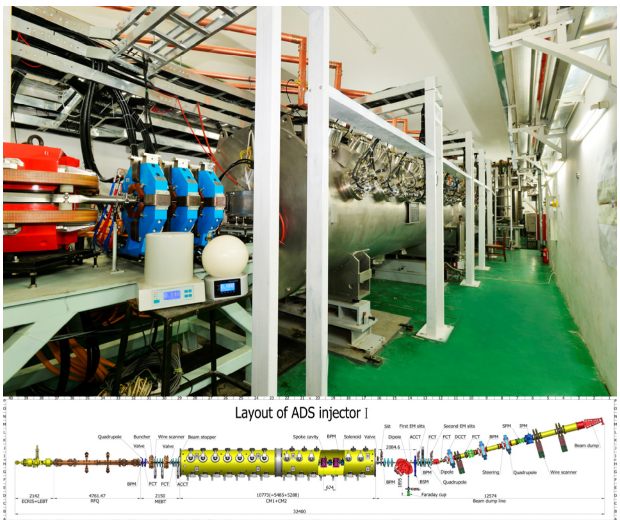

Figure 8: C-ADS Injector-I at IHEP

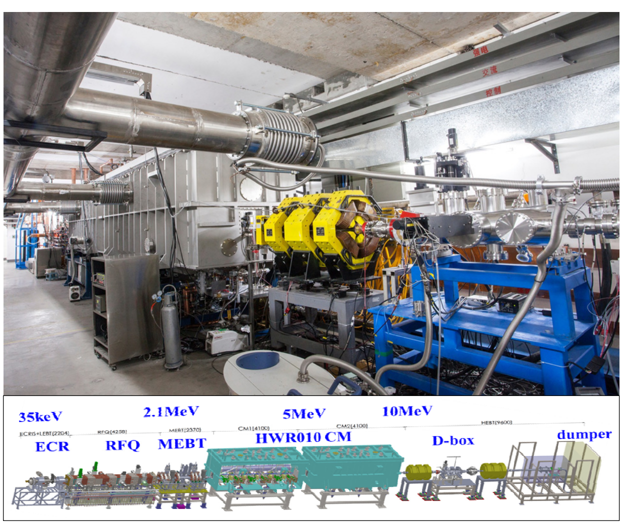

Figure 9: C-ADS Injector-II at IMP.

The Injector-I and Injector-II are integrated and commissioned by several stages during 2013-2016.

Finally, in May 2016, the Injector-I at IHEP (see Figure 12) and Injector-2 at IMP (see Figure 13) was integrated, consisting of the ECR ion source, LEBT, RFQ, SC Cavities, MEBT and beam stop. Injector-I consists of total 14 Spoke012 cavities in the CM1 and CM2, employ SSA and microTCA LLRF system and operating at 2K temperature (see Figure 8). Injector-II consists of total 12 HWR010 cavities in the CM1 and CM2, employ SSA and customized LLRF system and operating at 4 K temperature (see Figure 9).

Commissioning of Injector-I

On September 25th, 2014, the ECR Source + LEBT + RFQ have been commissioned with max. 90% duty factor beam, the beam power is 32.4 kW. Yet, the CW beam has not been achieved since RFQ-I encountered some troubles in RF conditioning at high power for CW operation. The highest CW RF power reached is only 200 kW.

On October 28th, 2015, the CM1 output reached 6 MeV with pulsed beam at 2 K temperature.

On June 15th, 2016, the CM2 output reached 10.1 MeV/10 mA with 20 μs pulsed beam at 2 K temperature. The transition rate of SC cavities is 100%. The measurement of beam energy and current and transition rate are shown in Figure 10 and Figure 11 and Figure 12.

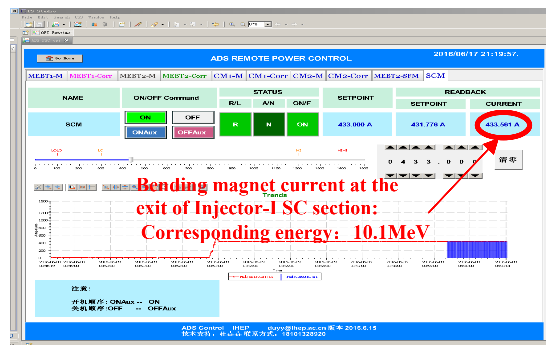

Figure 10: Beam energy measurement of Injector-I.

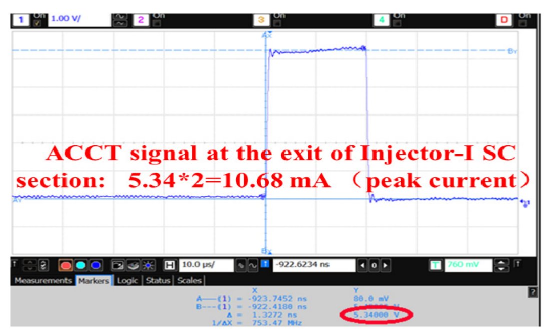

Figure 11: Beam current measurement of Injector-I.

Figure 12: The transition rate of SC cavities.

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At present continues beam commissioning and machine studies on going in order to get stable beam and understanding behavior of SC linac and proton beam. The final goal of beam commissioning is to get CW proton beam with 10 MeV/10 mA.

Commissioning of Injector-II

On June 6th, 2014, the ECR Source + LEBT + RFQ have been commissioned first beam with 2.16 MeV.

On June 30th, 2014, operated 4.5 hrs with 10 mA CW beam.

On June 6th, 2015, a low duty pulsed beam with current of 10.1 mA and energy of 5.2 MeV was achieved.

On January 2nd, 2016, operated 450 min with 4 MeV/1.7 mA CW beam, see history record in Figure 13.

At present Injector-II is under commissioning and expect to get 10 MeV proton beam soon.

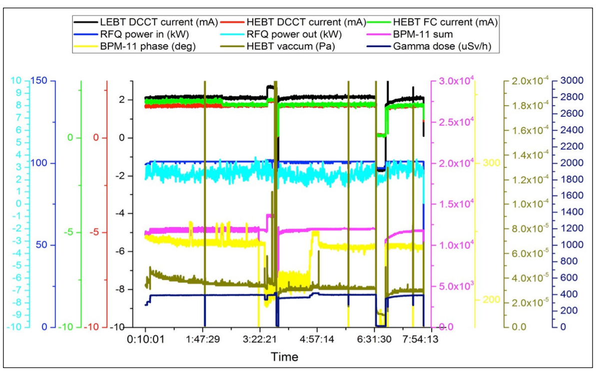

Figure 13: History record of 4MeV/1.7mA/CW/450min of injector-II.

CONCLUSION

There are active programs in many countries to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation. Among them, MYRRHA and C-ADS are the representative projects, already partly funded and expected to become operational in the near future.

For the tens of MW beam power required for industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.

Over the past five years of Phase I, C-ADS has made significant progress in the R&D of the SC linac. One of the exciting achievements concerning the SC linac is that a CW RFQ and several types of lowβSC cavities have been developed successfully.

In the end of year 2015, China Initiative ADS (CIADS) project is officially approved by Chinese government. The CIADS is a 6 year (2017-2022) project; the site is located in the Huizhou city region in Guangdong province south part of China.

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