DEVELOPMENT OF THE C-ADS SRF ACCELERATOR AT IHEP*

Fang Yan†, Huiping Geng, Cai Meng, Yaliang Zhao, Huafu Ouyang, Shilun Pei, Rong Liu, Feisi He, Tongming Huang, Rui Ge, Yanfeng Sui, Qiang Ye, Xiaoping Jing, Fengli Long, Jungang Li, Quanling Peng, Dizhou Guo, Zusheng Zhou, Haiyin Lin, Xinpeng Ma, Qunyao Wang, Guangwei Wang, Hua Shi, Gang Wu, Shengchang Wang, Ningchuang Zhou, Qiang Ma, Zhenghui Mi, Peng Sha, Xinying Zhang, Yaoyao Du, Jun He, Huizhou Ma, Lingda Yu, Ying Zhao, Xiaoyan Zhao, Fang Liu, Yanhua Lu, Lin Bian, liangrui Sun, Rui Ye, Xiaohua Peng, Dayong He, Ouzheng Xiao, Yao Gao, Zhenghua Hou, Yuan Chen, Xiangchen Yang, Hongyan Zhu, Bo Li, Lan Dong, Heng Li, Xitong Sun, Linglang Dong, Ping Su, Jianping Dai, Jianli Wang, Shaopeng Li, Jianshe Cao, Yunlong Chi, Weimin Pan
Key Laboratory of Particle Acceleration Physics and Technology
Institute of High Energy Physics (IHEP), Chinese Academy of Science, Beijing 100049, China

Abstract

The 10 MeV accelerator-driven subcritical system (ADS) Injector I test stand at Institute of High Energy Physics (IHEP) is a testing facility dedicated to demonstrate one of the two injector design schemes [Injector Scheme-I, which works at 325 MHz], for the ADS project in China. The ion source was installed since April of 2014, periods of commissioning are regularly scheduled between installation phases of the rest of the injector. Early this year, continuous wave (CW) proton beam has been successfully obtained with energy of 10 MeV and average beam current around 2 mA. The single spoke cavities with smallest developed beta ($\beta_g = 0.12$) were applied on Injector-I and successfully commissioned. Single spoke cavities with higher beta ($\beta_g = 0.21$) were also adopted for the last cryomodule of 25 MeV proton linac, and 150~200 µA CW proton beam were shooting through recently. This contribution reports the details of the development of the C-ADS SRF accelerator at IHEP and the challenges of the CW machine commissioning.

INSTRUCTION

ADS project in China was launched in year of 2011 intending to develop the concept and design of a 1.5 GeV high intensity SC linac with the aim of building a demonstration facility for accelerator-driven subcritical system (ADS) in multiple phases. The driver linac will be operating in continuous wave (CW) mode and delivering 15 MW beam power eventually. The linac includes two major sections: the injector section and the main linac section. The injectors accelerate the proton beams up to 10 MeV and the main linac boost the energy from 10 MeV up to 1.5 GeV.

In the first five year stage: 2011 to 2016, the injector on basis of two different frequencies have been developed in IHEP and IMP independently to demonstrate two different design schemes of the injector [1,2]. Scheme I (so-called Injector I) is on basis of 325 MHz Room-Temperature (RT) RFQ and single spoke type cavity with same frequency and scheme II (so-called Injector II) is on basis of 162.5 MHz RT RFQ and HWR cavity with the same frequency.

The specifications of the injector-I are listed in Table 1. Although the injector is designed to be operated on CW mode with average beam current of 10 mA, considering of the CW operation difficulty for high intensity proton linac and experience lacking with newly developed spoke cavities, the CW operation is not the acceptance goal for the first five year. However we still pursue to achieve CW proton beam with energy of 10 MeV and average beam current as high as possible.

Table 1: ADS Injector-I Test Facility Specifications

ADS Injector-I test facility specifications	
Particle	Proton
RF frequency (MHz)	325
Output Energy (MeV)	10
Average Current (mA)	10
Beam power (kW)	100
Duty factor (%)	100
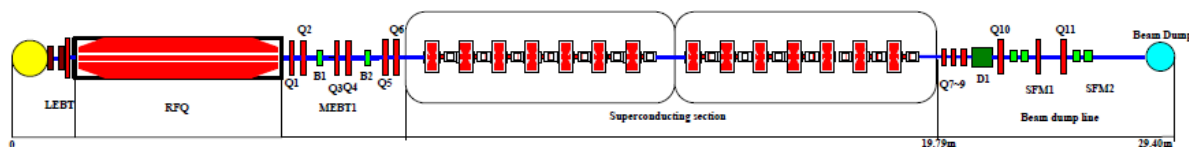
Figure 1: The schematic layout of the 10 MeV test stand in IHEP.

Projects/Facilities

New proposals/concepts

INJECTOR-I TESTING FACILTIY

The general layout of the ADS injector-I linac is shown in Fig. 1. The Injector-I is composed of an Electron Cyclotron Resonance (ECR) ion source, a Low Energy Beam Transport (LEBT) line, a 4-vane type copper structure Radio Frequency Quadrupole (RFQ) with frequency of 325 MHz, a Medium Energy Beam Transport (MEBT) line, a superconducting section adopting fourteen 325 MHz single spoke cavities with β_g of 0.12 for acceleration, fourteen SC solenoids for transverse focusing, fourteen Beam Positon Monitors (BPM), an energy divergence system and a beam dump line.

The Design Philosophy and Frequency Choice

CW operation is a critical objective for high intensity proton linac of ADS applications. The main obstacles preventing CW operation of a RT structure is the heat deposit as high power needed to be feeding in. It becomes a common understanding that the superconducting proton linac is the best choice as an ADS driver accelerator [3,4], and the lower of the input energy for SC section, the easier for the realization of the CW operation. With recently approved superconducting RF technology, especially the success of the medium-beta elliptical cavities at SNS [5,6] and the test results of low beta spoke cavities [7,8] and HWR cavities [9,10], it is thought that a proton linac with superconducting accelerating structures except the RFQs is possible. Another advantage of using superconducting cavities is that one can use independently phased resonators to make local compensation [11] when some cavities fail during operation. This is very important to achieve the very strict reliability for ADS accelerators. Even more, the RF power sources based on modular solid-state amplifiers for short superconducting cavities (such as single-spoke cavities) also help to increase the reliability of the linac. Besides, another key point in designing a linac is that beam loss has to be kept to be as low as possible along the linac, and the SC cavity is benefit than RT structure because of much bigger aperture.

The Injector frequency choice is basically determined by the RT RFQ. One reason for choosing 325 MHz RFQ is the acceleration effectiveness and smaller cavity size. The drawback originates from big size for the accuracy control difficulty of the fabrication and welding along with the big deformation after welding. Another reason is that if 325MHz is selected, there will be no frequency jump for the transition between the injector to main linac. As the transition part could easily be a source for halo development as matched beam is hard to be achieved with strong space charge effect at low energy part where the periodical lattice is discontinued, and the situation would be worse if there is a frequency jump. Because average beam current specification is the same for both Injector, 325 MHz choice is benefited for attenuated space charge effect comparing with half frequency if the longitudinal beam size out of injector kept to be the same for both frequency choices. On the other hand, if keeping the space charge effect to be the same, the longitudinal beam size out of the injector has to

be increased for the 162.5 MHz choice. Bigger longitudinal beam size means more cavities numbers, and thus more cost. Other design considerations are presented in details in reference [1, 12].

Physics Design and Fabrications

Reference 1 also introduced the detail design of each section for Injector-I testing facility. I will only state the SC part here for easy reference. The 325 MHz superconducting β_g=0.12 single spoke cavity (Spoke012) is selected for the acceleration from 3.2 MeV up to 10 MeV. This is the first spoke type cavity with lowest geometry beta in the world. The designed accelerating gradient of E_{acc}=6.08 MV/m was adopted according to horizontal test of the first spoke012 prototype cavity in Sep. 16, 2013 (Max. achieved gradient: E_{acc}=6.5 MV/m). Although the testing results later show much better performance with higher gradient of: E_{acc}=7-10 MV/m, the conservative design is still kept to ensure the success of the project goal for 10 MeV output beam energy because there aren't any spoke cavity in the world testified by the beam so far and we are the first one. However the conservative design with E_{acc}=6.08 MV/m instead of 7 MV/m leads to the cost of two more cavities (from twelve to fourteen) comparing with the initial design.

Previously, the SC linac of Injector I was designed to be one single cryomodule with all Spoke012 cavities inside. It was divided into two cryomodules (total fourteen cavities) finally because of the common sense of the difficulties during the installation, collimation and maintenance. However for two cryomodule design, the distance between cold to warm transition has to be kept to be as short as possible for avoiding matching difficulty caused by break-off. Originally a warm BPM between the cryomodules was planned to help the beam tuning in case the cold BPMs do not perform as expected. But it was abandoned soon after the evaluation of the space needed for the warm BPM (at least 100 mm). Finally a 570 mm distance is kept in between.

The ADS Injector I period length of the SC section lattice is 0.674 m as shown in Fig. 2. One focusing period of Spoke012 section consists of one Spoke012 cavity, one SC solenoid and one cold BPM. The cavity string of the Testing Crymodule (TCM) with two cells assembled together are shown in Fig. 3. Figure 4 shows the first cryomodule (CM1) of Injector-I after installation of the cavity string with seven SC cells.
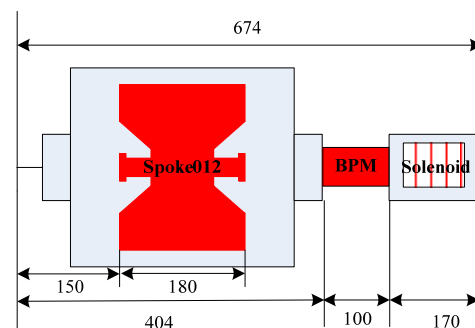

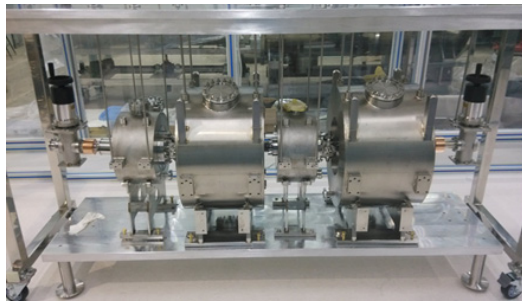Figure 2: The lattice structure of the Spoke012 section.

Figure 3: The cavity string of the TCM with two period of the lattice.

Figure 4: The first cryomodule of Injector-I.

Pulsed Beam Commissioning

The injector is periodically arranged for commissioning according to the fabrication stages and the acceptance targets. The ECR, RFQ test stand, TCM test stand, 5 MeV test stand and Injector-I test stand are successively conditioned with pulsed beam initially and the testing results meet the phased goals at each stages.

The Injector-I with all the assembling finished installation in the tunnel at May of last year as shown in Fig. 5. The conditioning began from May 5th with 20 μs pulsed beam and repetition frequency of 2 Hz. The output energy at the exit of CM2 reached 10.67 MeV with beam peak current of 10.6 mA at July 19th of year 2016. The cavity operating gradients are shown in Table 2. The relative low operating gradient of the first cavity originates from the contamination by an accidental vacuum leak of the upstream section. The beam transmission through the cryomodule is 100%. The beam energy divergence at the exit of the cryomodules has also been measured by the Energy Divergence Analysis system, The RMS value of the energy divergence is 3.2‰ for 10.67 MeV and 10.6 mA peak current proton beam, which is consistent with the simulation.

Table 2: The Operating Gradient of the Fourteen SC Cavities @ 10.67MeV

Cav. #	1	2	3	4	5	6	7
E_p(MV/m)	17.1	24.4	29.1	26.4	30.6	33.7	26.3
Cav. #	8	9	10	11	12	13	14
E_p(MV/m)	26.0	26.0	28.6	27.8	31.0	30.7	19.2

Figure 5: The two cryomodules of Injector-I installed in the tunnel.

CW Beam Commissioning

We accumulated valuable experiences and collected lots of data during the commissioning of injector-I with pulsed mode. However, the CW commissioning is much difficult than pulsed operation. The CW operation of the whole testing facility could not be realized, as the RFQ could not conditioned up to the specified power in CW mode in the first two years conditioning until a new RFQ was fabricated and replaced the old one. However, the CW operation of the RFQ do not mean the CW operation of the SC cavities, neither the CW operation of the beam. The CW commissioning was interrupted by frequently trips of the elements along the linac. Thanks for the machine protection system, which was conditioned for a long time during the pulsed mode operation, the whole linac system is not destroyed during the CW commissioning except once (The beam pipe was burned out at the small aperture position of the Step Field Magnet: SFM). Although the efficiency is relatively low, big damages are avoided to the maximum extent.

Lots of efforts have been made to keep the stability of the machine when shooting CW beam through, the beam loss is controlled by all means along the whole linac, especially in the SC section. Besides, we started with smaller beam current with less than 1mA either than the specified value of 10mA, and gradually rising up. Finally, the stable operation time went from dozen seconds up to several minutes and finally more than twenty minutes with output energy of 10 MeV and average beam current of ~2 mA. The maximum stable operation time reached until now is 23 min with output energy of 10 MeV and average current of 1.6 mA CW proton beam as shown in Fig. 6. The figure include the information of output energy at the exit of RFQ/cryomodule and the beam current. The RFQ could deliver higher current CW beam up to 10 mA, but the SC section could not handle high intensity beam while beam loading effect is not compensated and frequency control loop is absent.
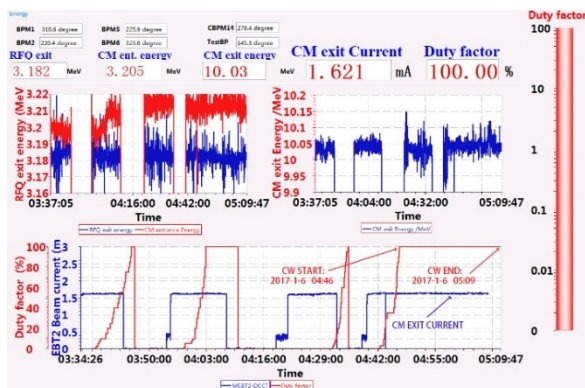
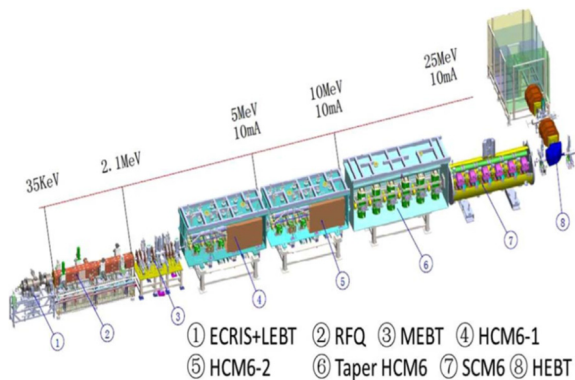Figure 6: CW commissioning results of Injector-I.

25MeV PROTON LINAC

Figure 7: Schematic layout of the 25 MeV test stand in IMP [13].

To verify and demonstrate the frequency jump possibility at low energy section, a 25 MeV test stand as shown on Fig. 7 is proposed on basis of Injector-II of IMP. Two more cryomodules (CM3 & CM4) are added right after the last cryomodule of Injector-II. CM3 is designed on basis of 162.5 MHz HWR taper structure cavity with beta geometry of 0.15. CM4 is designed on basis of 325 MHz single spoke type cavity with beta geometry of 0.21. The frequency jump happens between CM3 to CM4 with transition energy of around 18MeV. IHEP is responsible for the design, fabrication, assembling and commissioning of CM4. Figure 8 shows the schematic layout of CM4.
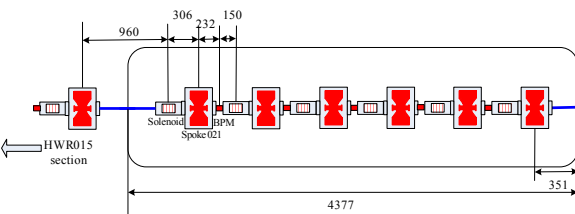

Figure 8: Schematic layout of the CM4 for 25 MeV test stand.

Figure 9: The cavity string of CM4

Figure 10: The CM4 cryomodule of 25MeV linac with all the assemblings.

The installation of CM4 was finished last September, the assembling of the whole linac was launched at the beginning of this year. Figure 9 shows the cavity string of CM4 before installed inside the cryomodule. Figure 10 shows the CM4 cryomodule with all the assembling. Figure 11 shows the beam envelope evolution along the SC section simulated by TraceWin [14] code (the information of the first three cryomodules are provided by IMP). The commissioning results confirmed the design with output energy of 26.1 MeV and peak current of 12.6 mA (as shown in Fig. 12) through the SC linac. The energy was measured by two downstream BPM using Time of Flight (TOF) method. The BPM signals are shown in Fig. 13. 25 MeV CW proton beam with average beam current of 150~200 μA have been obtained after the pulse mode conditioning.
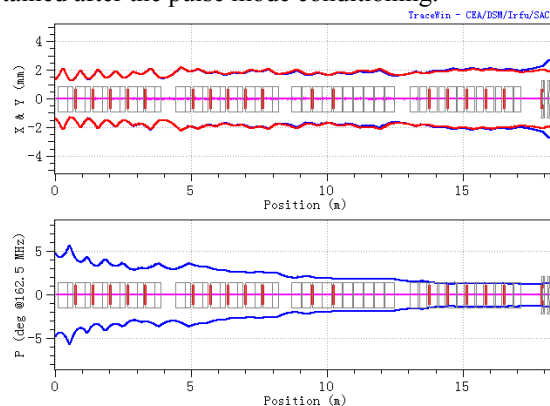

Figure 11: The envelope evolution of the superconducting section of 25MeV test stand.
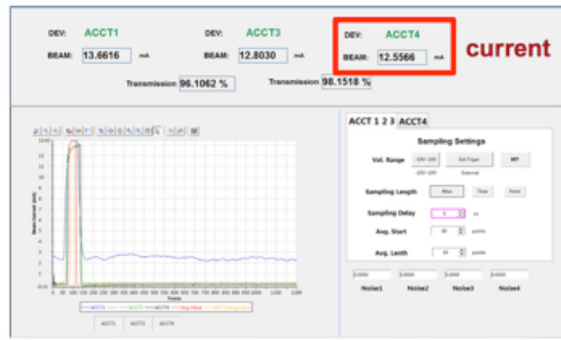
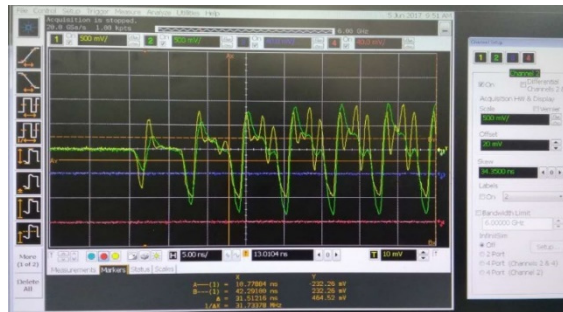Figure 12: the transmission through the SC section of 25MeV linac.

Figure 13: the downstream BPM signals at the exit of the 25 MeV test stand.

CONCLUSION

The China ADS injector-I testing facility has been commissioned successfully using pulsed and CW beam. The maximum energy achieved at the exit of the Injector is 10.67 MeV with peak beam current of 10.6 mA. CW proton beam with energy of 10 MeV and average beam current of around 2 mA has been obtained at the exit of the linac recently. The CW beam with average beam current of 1.62 mA lasted for 23 minutes stably without trip of any devices. Preliminary experiment results that have been obtained are encouraging but further work is still needed to be done for better understanding of the phenomena that occur in high duty cycle operation of the linac. CW commissioning of the Injector is still ongoing. Beam loading effect of the SC section will be compensated and frequency control loop of the SC cavity will be added to ensure CW operation with higher average beam current and longer operation time.

More experiments as well as some improvements are foreseen.

ACKNOWLEDGEMENT

The authors want to thank all the C-ADS colleagues both at IHEP and IMP for the great effort made during the construction and successful commissioning during each stage of the Injector-I testing facility and the joint conditioning of 25 MeV CW linac.

REFERENCES

[1] F. Yan, S. L. Pei, *et al.,* "Physics design of a 10 MeV injector test stand for an accelerator-driven subcritical system", *Phys. Rev. ST Accel. Beams* 18, 054201 (2015).

[2] J. Y. Tang, Z. H. Li, *et al.,* IHEP-CADS-Report/2012-01 E.

[3] R. L. Sheffield, "Utilization of Accelerators for Transmutation and energy production", in *Proc. HB2010*, "Sept. 27-Oct 01, Morschach, Switzerland, paper MO1A01, pp. 1−5.

[4] J.-L. Biarrotte, "Beam dynamics studies for the fault tolerance assessment of the PDS-XADS Linac design", in *Proc. EPAC04*, Lucerne, Switzerland, July 2004, paper TUPLT057, pp. 1282−1284.

[5] G. Ciovati *et al.*, in *Proc. PAC01*, Chicago, Illinois, June 2001, paper ROAA005, pp. 484−486.

[6] W. Hartung *et al.,* "Status report on multi-cell superconducting cavity development for medium-velocity beams", in *Proc. PAC03*, Portland, OR, May 2003, paper TPAB070 pp. 1362−1364.

[7] K.W. Shepard, "Status of low and intermediate velocity superconducting accelerating structures", in *Proc. PAC03*, Portland, OR, May 2003, paper ROPA003 (Ref. [12]), pp. 581−585.

[8] J. R. Delayen, "Intermediate-velocity superconducting accelerating structures", in Proc. LINAC 2004, Luebeck, Germany August 2004, paper TH301, pp. 589−593.

[9] A. Facco et al., "Constructionand testing of the Beta=0.31, 352 MHz superconducting half-wave resonator for the SPES project ", in *Proc. EPAC04*, Lucerne, Switzerland, July 2004, (Ref. [10]), paper TUPKFO22, pp. 1012−1014.

[10] A. Facco *et al.,* "Low- and intermediate-beta, 352 MHz superconducting half-wave resonators for high power hadron acceleration", in *Proc. EPAC06,* Edinburgh, Scotland, June 2006, paper MOPCH165, pp. 448−450.

[11] J.-L. Biarrotte, "Beam dynamics studies for the fault tolerance assessment of the PDS-XADS Linac design", in *Proc. EPAC04*, Lucerne, Switzerland, July 2004, paper TUPLT057, pp. 1282−1284.

[12] Z. H. Li, P. Cheng, *et al.,* Physics design of an accelerator for an accelerator-driven subcritical system, Phys. Rev. ST Accel. Beams 16, 080101 (2013).

[13] S. H. Liu, *et al.,* "Physics design of the CIADS 25 MeV demo facility", *NIM-A*, 843 (2013) 11-17.

[14] http://irfu.cea.fr/Sacm/logiciels/index3.php