Nuclear Instruments and Methods in Physics Research A 843 (2017) 11–17

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Physics design of the CIADS 25 MeV demo facility☆

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ARTICLE INFO

Keywords:
CIADS
Beam dynamics
Beam matching
Frequency jump
Error analysis

ABSTRACT

A superconducting linac has been proposed and under constructed to demonstrate the key technology and the feasibility for CIADS(China Initiative Accelerator Driven System)linac. This linac will accelerate the 10 mA proton beam to 25 MeV. There are some challenges in the physics design for the high power superconducting accelerator. In this paper, we focus on the matching between different cryomodules (CMs) and the frequency jump. This paper presents the physics design study together with the design principles and the simulation results with machine errors.

1. Introduction

China Initiative Accelerator Driven System(CIADS) is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China. It aims to design and build an Accelerator Driven Subcritical System (ADS)demonstration facility in multiple phases lasting about 20 years. The driven linac will deliver a 1.5 GeV, 10 mA proton beam in CW operation mode. The general layout is shown in Fig. 1. The driver linac is composed of two major sections. One is the normal conducting section and the other is the superconducting (SC) section. The normal conducting section is composed of 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 1.5 GeV. Then, the beam is transported to the beam dump going through the high energy beam transport (HEBT) line. For a high intensity proton superconducting linac running in CW mode, there are no operational experiences in the world so far. In order to overcome the challenges in technology and in physics, an experimental device with an energy of 25 MeV is proposed and constructed. Fig. 2 shows the schematic layout of the 25 MeV demonstration facility. In this paper, the beam dynamics design and simulation for LEBT, RFQ, MEBT, and SC section will be presented in detail.

2. Design philosophy and consideration

Hands on maintenance and machine protection set strict limits, 1 W/m and 0.1 W/m respectively, on beam losses and have been a concern in high power linacs [1]. Therefore it is crucial to design a linac, which does not excite beam halo and keeps the emittance growth at a minimum level to avoid beam loss. Given the demands of stability and reliability, some guidelines are required to be considered in the design process. Although a lot of the design philosophy for the linac has been addressed in previous literature, we still consider some of them so important to be stated here, and the most important factors in designing our machine are the following:

(1) Transverse period phase advances for zero current beams should be below 90° to avoid the structure resonance [2].
(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 [3].
(3) Avoid strong space charge resonances through the judgment of Hofmann's Chart [4–7].
(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.

3. Physics design of different section

The 25 MeV demo facility consists of ECR ion source with 2.45 GHz

☆ Supported by the National Natural Science Foundation of China (Grant No. 91426303 and NO. 11525523)
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http://dx.doi.org/10.1016/j.nima.2016.10.055
Received 7 June 2016; Received in revised form 27 October 2016; Accepted 28 October 2016
Available online 01 November 2016
0168-9002/

Fig. 1. The general layout of the CADS linac.

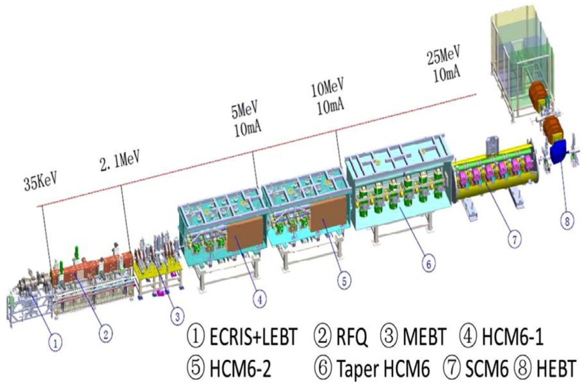

Fig. 2. Schematic layout of the 25 MeV demo facility.

frequency, LEBT, RFQ, MEBT, SC section and beam dump, as shown in Fig. 2. The 35 keV proton beam from the ion source is bunched and accelerated to 2.1 MeV by a 162.5 MHz RFQ. The LEBT is used to match the beam between the ion source at the RFQ, and also to provide chopped beam for commissioning. The SC section accelerates proton beam from 2.1 to 25 MeV employing HWR cavities (162.5 MHz) and Spoke cavities (325 MHz). The beam dump line follows right after the SC segment.

3.1. Ion source and LEBT

For the 25 MeV demo facility, an ECR ion source with 35 keV is chosen. A LEBT downstream the ECR ion source is used for matching between the ion source and the RFQ. The LEBT consists of two solenoid lenses, vacuum pumps, and beam diagnosis aperture. The length of the LEBT is 1670 mm. A cone has been installed at right before the RFQ entrance to substantially reduce the unwanted particles, such as $^2H^+$ and $^3H^+$, from getting into the RFQ [8,9]. The schematic figure of the LEBT and the chopper is shown in Fig. 3. This accelerator will be a CW machine, but the pulsed beam is an essential choice for the beam tuning stage. The front end needs to have the ability to provide adjustable beam. The particle trajectories along the LEBT and the phase space distribution with matched Twiss parameters at the RFQ entrance by the TRACK [10] code are illustrated in Fig. 4.

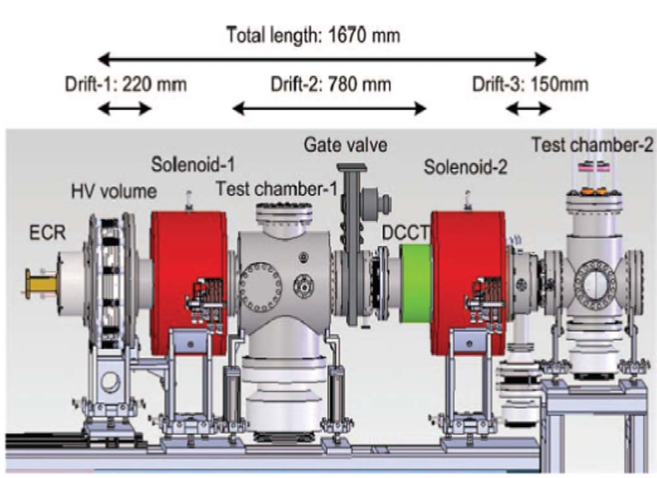

Fig. 3. The layout of the LEBT.

3.2. RFQ

The CW RFQ plays a critical role in the CIADS driven linac. So, for this demonstration facility, a four vane RFQ has been designed in collaboration with the Lawrence Berkeley National Laboratory and fabricated at the workshop of the Institute of Modern Physics, Chinese Academy of Sciences [11]. This RFQ works at the frequency of 162.5 MHz and accelerates the proton beam of 15 mA from 35 keV to 2.1 MeV. The choice of the 162.5 MHz frequency is beneficial for the small surface power density because of its big size. Another advantage is the large aperture for lower frequency, that means larger acceptance. The main parameters of the RFQ are listed in Table 1. The total accelerator length of the RFQ is 4.208 m. It is composed of four coupled physical segments and each segment includes four technical modules connected together with flanges. Full model of the RFQ is shown in Fig. 5, and it has 16 pairs of pi-mode rods and 80 tuners [12]. The beam transport simulation along the RFQ was carried out using the PARMTEQM [13] code with a 4D-Waterbag input distribution, and 100,000 macroparticles were assumed for the initial distribution. Fig. 6 shows the output phase space distribution of the RFQ. The simulated RFQ output distribution has been used for the design of the SC linac.

3.3. MEBT

The MEBT is used to match the beam between the RFQ and the SC sections with low emittance growth. There are seven quadrupoles and two bunching cavities to match the beam with the desired Twiss parameters in both transverse and longitudinal directions as shown in Fig. 7. As seen from Fig. 8, there are two beam waists formed in the middle and at the end of MEBT by three upstream quadrupoles and four downstream quadrupoles of the first bunching cavity [14]. MEBT is designed to contain diagnostic devices to measure the beam parameters after the RFQ cavity. There are four BPMs residing inside the quadrupoles and one BPM exists at the end of the MEBT. Two Alternating Coupled Current Transformers (ACCT) in the front and at the end of MEBT are placed to measure the beam current. Two sets of emittance scanning devices composed by slit wire scanner installed in the D-box (diagnostics box) to get the vertical and horizontal emittance in the middle of MEBT, One double direction wire scanner is installed between the sixth quadrupole and the seventh quadrupole. One Faraday cup (FC) is also placed inside the D-box.

3.4. Superconducting section

One of the most difficult problems is to efficiently accelerate the beam from the low energy at the RFQ exit to higher energy while maintaining beam quality at the same time [2]. For the 25 MeV superconducting linac, low-beta HWR cavities with $\beta = 0.10$ and $\beta = 0.15$ in 162.5 MHz and spoke cavities with $\beta = 0.21$ in 325 MHz were chosen to accelerate the beam from the 2.1 MeV at the RFQ to 25 MeV. The fabrications of the HWR cavities with $\beta = 0.10$ and $\beta = 0.15$ have been completed and the horizontal tests have successfully performed. In the rest part of this paper, we focus on the beam matching at the transitions and the frequency jump.

3.4.1. Beam matching at the transitions

Beam matching at the transitions is very important for minimizing emittance growth and beam halo formation. Next, the longitudinal matching is discussed. In the absence of space charge, the rms envelope evolution meets the following equation:

$$R'' - \frac{\epsilon}{R^3} = 0 \tag{1}$$

We assume ϵ remains constant, so beam size is proportional to $\sqrt{\beta}$. The longitudinal β function in a drift obeys the relation: