Design and construction of the MEBT1 for CADS injector scheme II *

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Abstract: A Medium Energy Beam Transport line 1 (MEBT1) has been designed for Injector Scheme II of the China ADS project. To match the beam from RFQ to Superconducting (SC) Half Wave Resonator (HWR) sections with emittance preservation, the MEBT1 has been designed to be mechanically compact. Working at 162.5 MHz, the MEBT1 transports a 10 mA, 2.1 MeV proton beam using seven quadrupoles and two bunching cavities within 2.7 meters. Three collimators are placed between every two adjacent quadrupoles to collimate the beam halo. Design and construction of the MEBT1 are presented in this paper.

Key words: MEBT, CADS, match, collimation, QWR

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1 Introduction

The China Accelerator Driven System (CADS) project started in 2011, aiming to solve the nuclear waste problem and energy shortage problem. As a pilot project, the goal of the R&D phase is to build a 25 MeV proton linac by 2016 and to solve some critical technical problems of proton linacs working in continuous wave (CW) mode. Two different Injector Schemes are proposed: IMP (Institute of Modern Physics, Chinese Academy of Sciences) is responsible for building Injector Scheme II and IHEP (Institute of High Energy Physics, Chinese Academy of Sciences) is responsible for Injector Scheme I [1–4].

The main parameters of Injector Scheme II are presented in Table 1. The frequency of Injector Scheme II has been chosen to be 162.5 MHz to minimize the difficulties in the CW RFQ techniques. Injector Scheme II includes an Electron Cyclotron Resonance Ion Source (ECRIS), a Low Energy Beam Transport line (LEBT), a room temperature Radio Frequency Quadrupole accelerator (RFQ), a Medium Energy Beam Transport line 1 (MEBT1), superconducting (SC) half-wave resonator (HWR) sections and a diagnostics plate (D-plate) designed for commissioning. The output energy of the RFQ is 2.1 MeV which is lower than the neutron proton copper reaction threshold in order to decrease the risk of neutron activation of the material, so that hands-on maintenance can be done quickly after the machine shuts down.

The function of MEBT1 is to match the beam from RFQ to SC sections with low emittance growth. To transport high intensity beam through the SC sections with small beam losses, halo particle collimation is also considered at MEBT1.

Table 1. Main parameters of injector scheme II [4].

parameters	value
ion species	proton
frequency	162.5 MHz
ion source energy	35 keV
beam current	10 mA
RFQ output energy	2.1 MeV
injector scheme II output energy	10 MeV

2 Design and simulation

2.1 Physical design

MEBT1, from its design stage, considers the special requirements of the SC section with high intensity CW beam The RFQ output beam is asymmetric in both horizontal and vertical planes. To avoid the transverse envelope blowing up and to get better matching for MEBT1, the α_x and α_y from the RFQ is required to be less than 1 which has been achieved by adjustment of the last cell

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length of the RFQ [5, 6]. However, the beam commissioning result of the Spallation Neutron Source (SNS) RFQ has shown some discrepancy between the measured TWISS parameters and the design value [7]. The matching ability of MEBT1 reserves some margin to cover this discrepancy.

The SC sections of Injector II are periods of one solenoid and one cavity, where phase advance in the transverse and longitudinal planes is designed to avoid the resonances from space charge [2]. The SC solenoid focusing channel leads to a round (symmetric) entrance beam to reduce emittance growth due to coupling of horizontal and vertical phase space. The round beam is defined as $\alpha_x=\alpha_y$, $\beta_x=\beta_y$ and $\varepsilon_x=\varepsilon_y$.

Once the beam current and phase advance of the SC sections are fixed in the design, the best matching TWISS parameters in front of the SC sections will be obtained, and are slightly different from with a round beam. This difference comes from the quadric electric and magnetic (EM) field distribution of the SC HWR cavities.

Because the RFQ output beam is not round, while the SC section input beam is round, a quadrupole is the only method to match transversely under this condition. As for the longitudinal phase space, two TWISS parameters, α_z and β_z, are matched by the bunching cavities. Table 2 shows the TWISS parameters before and after MEBT1.

Table 2. TWISS parameters before and after MEBT1.

	RFQ exit	SC entrance
α_x	0.230	−0.088
β_x/(m/rad)	0.229	0.509
α_y	−0.314	−0.102
β_y/(m/rad)	0.112	0.522
α_z	−0.456	1.471
β_z/(m/rad)	1.653	0.948

The MEBT1 lattice is designed and simulated by TraceWin code, employing hard edge model quadrupoles and bunching cavity EM fields from CST MWS (Micro Wave Studios). The first physical element of the SC sections is a solenoid, thus the last element of MEBT1 is a bunching cavity. As seen from Fig. 1, there are two beam waists formed in the middle and at the end of MEBT1 by 3 quadrupoles upstream and 4 quadrupoles downstream of the first bunching cavity. There are two bunching cavities at −90° to match the beam longitudinally to the desired α_z and β_z, as shown by Fig. 2. The bunching cavity positions are optimized with small envelopes both transversely (⩽6 mm) to deduce transverse RF defocusing strength and longitudinally (⩽40°) to minimize longitudinal emittance growth due to nonlinear RF focusing strength.

The mismatch factor defined by TraceWin is minimized during MEBT1 design [8]. The nominal physical parameters of seven quadrupoles and two bunching cavities are listed in Table 3. Positive quadrupole strength indicates horizontal focusing. The two bunchers are named Buncher1 and Buncher2.

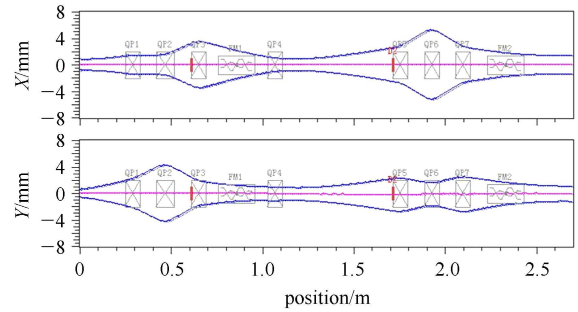

Fig. 1. (color online) Transverse RMS envelope along MEBT1.

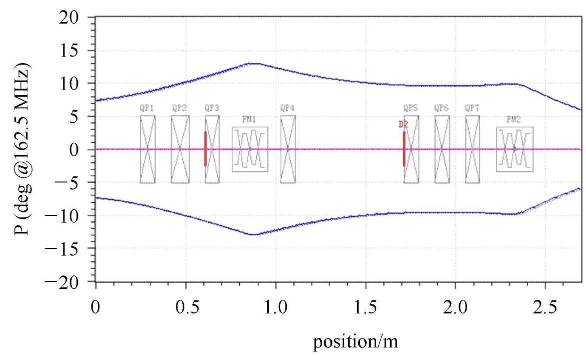

Fig. 2. (color online) Longitudinal RMS envelope along MEBT1.

Table 3. Nominal parameters of quadrupoles and bunching cavities.

element	strength	aperture/mm	length/m
$Q1$	8.241 T/m	54	0.08
$Q2$	−15.135 T/m	54	0.10
$Q3$	15.592 T/m	54	0.08
$Q4$	−5.778 T/m	54	0.08
$Q5$	−10.836 T/m	54	0.08
$Q6$	17.453 T/m	54	0.08
$Q7$	−11.637 T/m	54	0.08
Buncher1	107.4 kV	40	0.28
Buncher2	134.7 kV	40	0.28

2.2 PIC simulation

The particle in cell (PIC) simulation of MEBT1 is performed by 100000 particles at 10mA employing 6-dimensional (6D) beam distribution by Track simulation of the RFQ, as seen in Fig. 3. The output beam distribution of MEBT1 by TraceWin can be seen in Fig. 4.

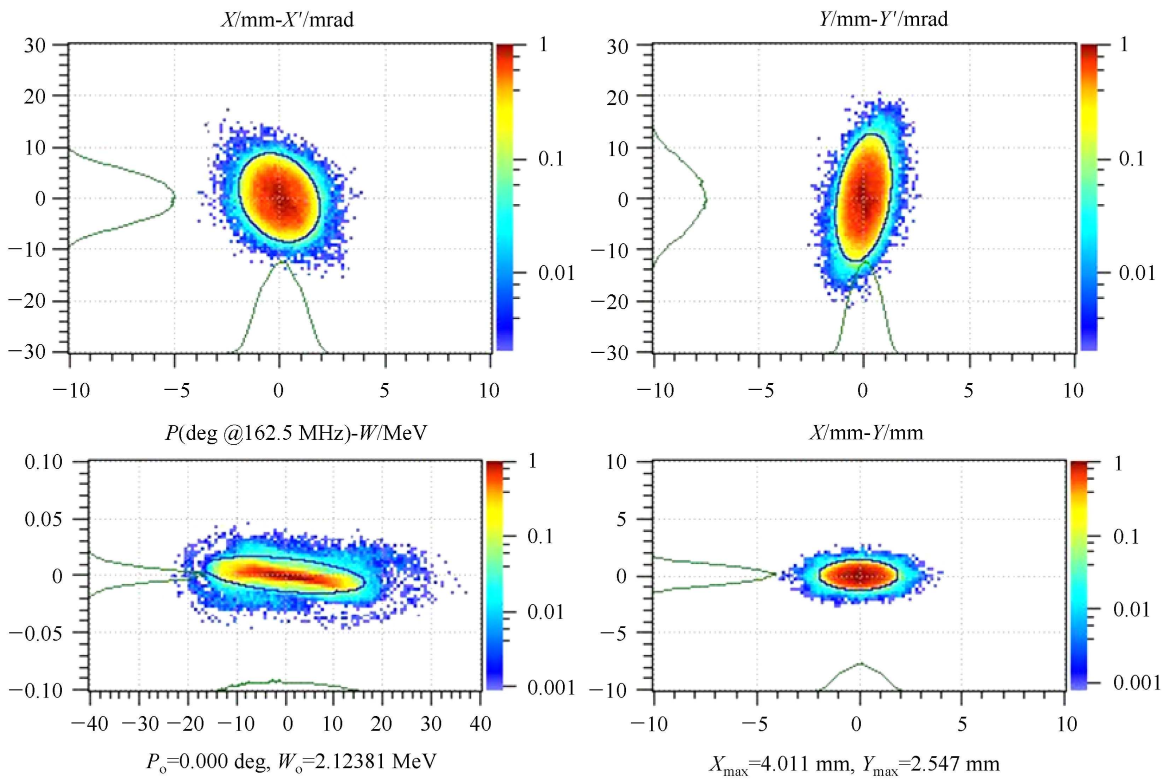

Fig. 3. (color online) RFQ output distribution by Track code.

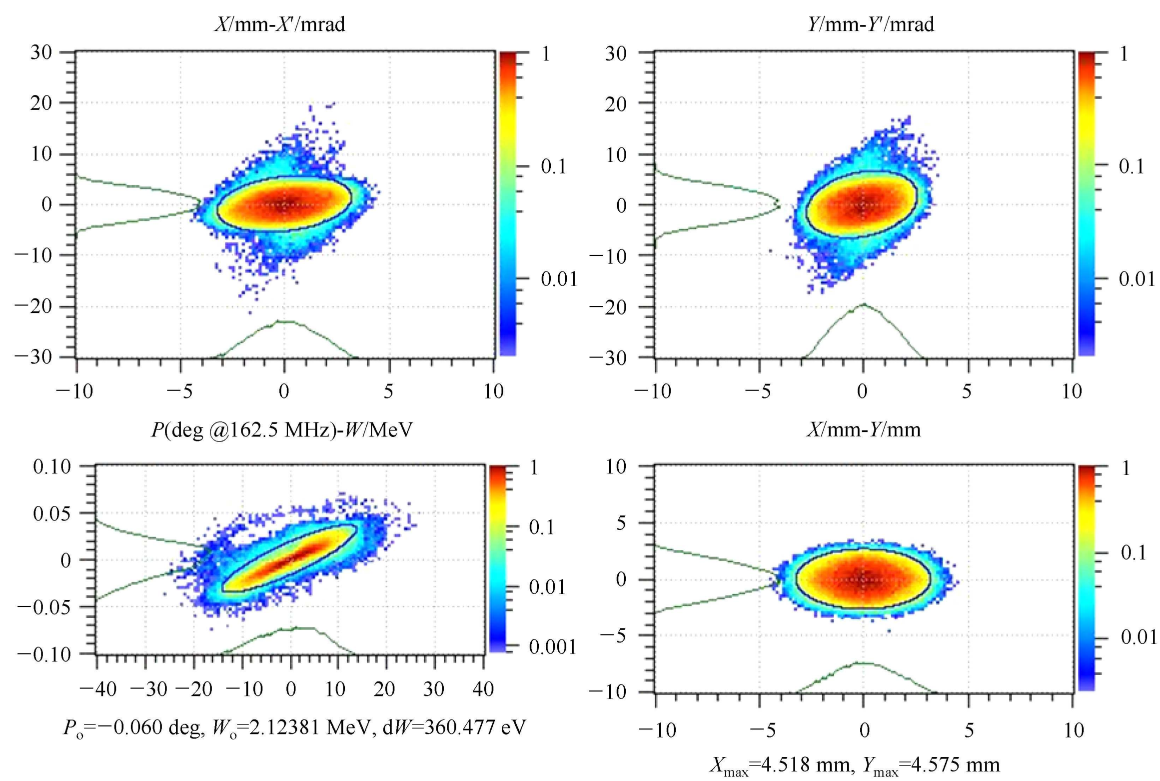

Fig. 4. (color online) MEBT1 output distribution by TraceWin code.

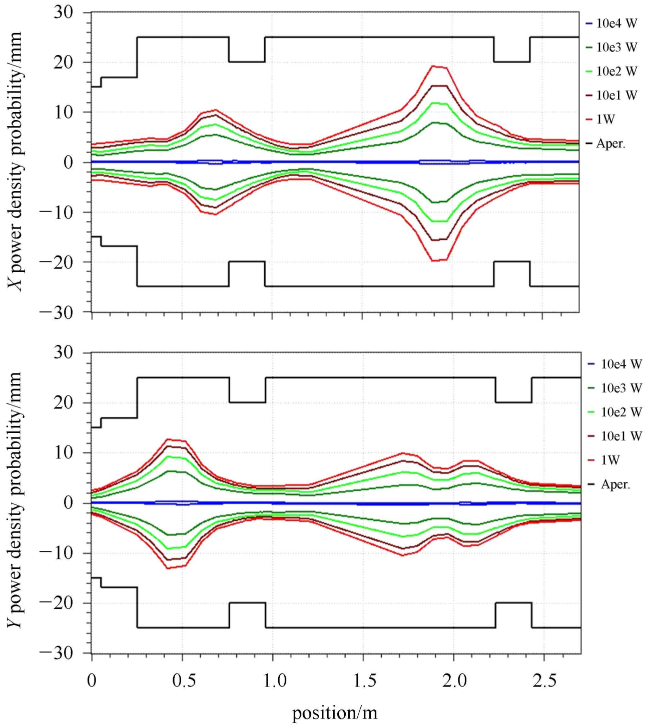

Fig. 5. (color online) Beam density level along MEBT1, up (horizontal), down (vertical).

Table 4. RMS emittance before and after MEBT1.

	RFQ exit	SC entrance
ε_x/πmm·mrad	0.219	0.234
ε_y/πmm·mrad	0.214	0.230
ε_z/πmm·mrad	0.266	0.272

The beam density level along MEBT1 is shown in Fig. 5 where the maximum envelope is 11 mm, which is well below the 25 mm- half vacuum aperture of the quadrupoles.

The emittance growth through MEBT1 is below 10%. Table 4 shows the normalized rms emittance before and after MEBT1 by TraceWin. The error analysis of MEBT1 and SC section has given out the MEBT1 alignment requirement and steers strength [9].

3 Hardware

3.1 Collimation

There are a significant number of halo particles from RFQ in the transverse phase space, as shown by Fig. 3 and Fig. 4. Meanwhile some un-accelerated particles around 35 keV could transport through the RFQ and then have a larger envelope than the accelerated particles (2.1 MeV) at the first two quadrupoles of MEBT1. These particles may be lost at the high energy part of the linac and could be harmful to the SC cavities. The SNS (Spallation Neutron Source) beam commissioning results have shown the effectiveness of collimation at the MEBT [10]. To minimize losses at high energy SC sections, beam collimation is considered during the MEBT1 design. Collimation is also one important reason that the output energy of RFQ is chosen to be 2.1 MeV, which means a lower radiation level at MEBT1 when halo particles are lost on the collimators.

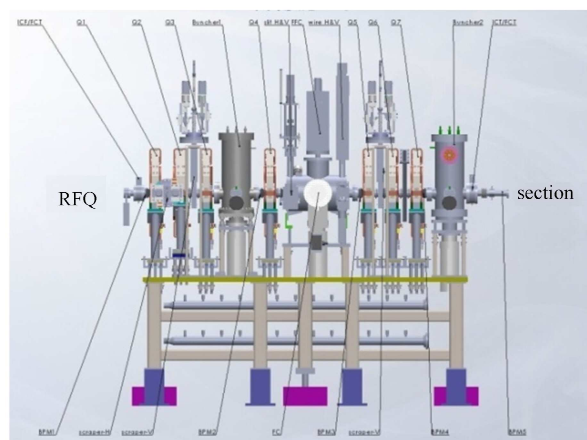

Fig. 6. (color online) Layout of MEBT1.

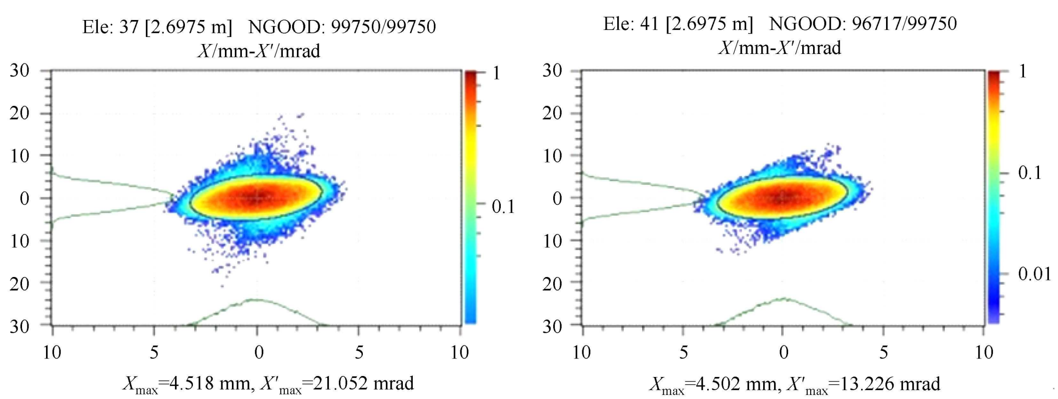

Fig. 7. (color online) Simulated un-collimated (left) and collimated (right) vertical phase space at the end of MEBT1.

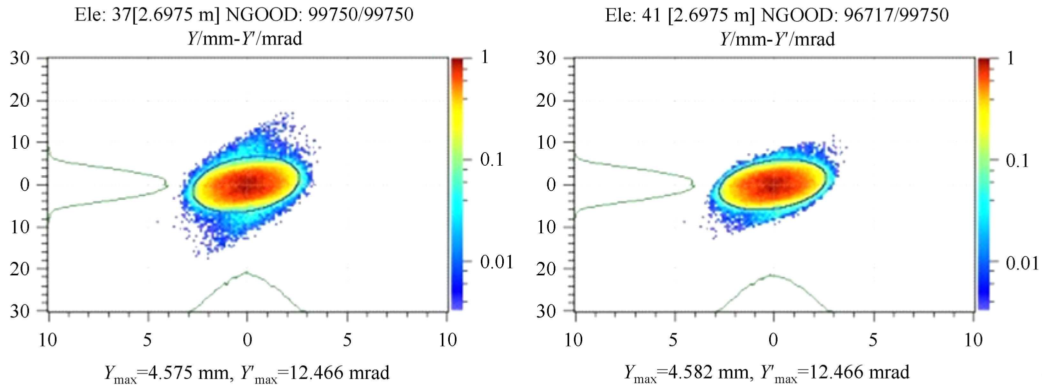

Fig. 8. (color online) Simulated un-collimated (left) and collimated (right) horizontal phase space at the end of MEBT1.

At the initial stage of MEBT1, one horizontal collimator is placed between Q1 and Q2, one vertical collimator is placed between Q2 and Q3, and another vertical collimator is placed between Q5 and Q6, as shown in Fig. 6. The simulation of the vertical collimation shows the halo particles are significantly reduced, as seen by Fig. 7. If one more horizontal collimator is placed between Q6 and Q7 to replace the existing wire scanner, horizontal halo particles can be reduced too, as shown by Fig. 8. From the simulation, 3.1% of all particles are collimated, and can be seen as halo particles. The collimators are designed to be adjustable to ease beam tuning, as shown in Fig. 9. The collimator jaws are copper-based with a water cooling channel inside, and titanium-plated to withstand high intensity CW beam power. Based on the initial beam experiment results of the collimation, implementation of more collimators at MEBT1 will be considered in future.

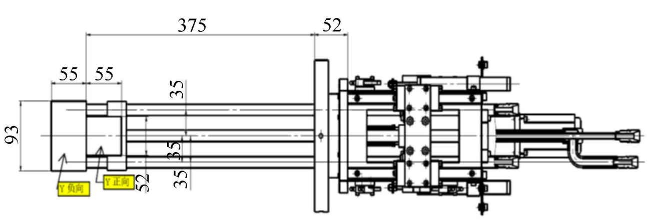

Fig. 9. Vertical collimator at MEBT1.

3.2 Magnets

The quadrupole magnets are designed with a maximum strength of 24 T/m, which is 1.4 larger than the nominal physical parameters. Four button-type beam position monitors (BPMs) with bellows are put inside Q1, Q4, Q5 and Q7. The shapes of the quadrupole and BPM are designed to fit together. The pole length of the quadrupole with BPM inside is 52 mm, while the BPM length is 150 mm. The clear gap between quadrupole and BPM is 1 mm with quadrupole aperture 54 mm and BPM size 53 mm. Four special legs are welded on the

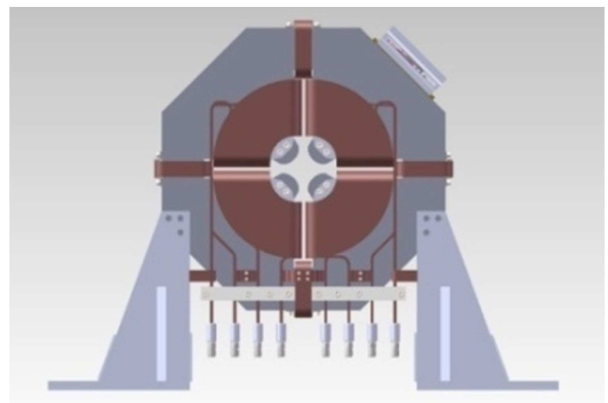

Fig. 10. (color online) Quadrupole model.

Fig. 11. MEBT BPM.

BPM to stand on the flat surface of the quadrupole pole in order to support and align the quadrupole and BPM together. The quadrupole model is shown in Fig. 10. The BPM is shown in Fig. 11.

3.3 Bunching Cavities

The effective voltages of the bunching cavities are 107.4 kV and 134.7 kV, which are too high for a pill-box-type cavity while working at CW mode. Thus a two gap quarter wave resonator (QWR) NC cavity is adopted for the bunching cavities due to its higher shunt impedance, lower gap voltage and easier cooling. The outer circle of the QWR inner drift tube is shifted down 1.5 mm to minimize the dipole effect to the beam. The outer conductor of the QWR is made of stainless steel with 200 μm copper plating. The inner conductor and two drift tubes at the outer conductor are made of oxygen-free copper. Two such bunching cavities have been fabricated and passed high-power conditioning. The effective voltage of the two QWRs has achieved 160 kV with RF power of 10 kW. Fig. 12 shows one of the QWRs under high RF power conditioning.

3.4 Beam diagnostics

No diagnostics except BPMs can be put inside the SC cryo-modules. Thus the only place to arrange online diagnostics is MEBT1 at the injector. MEBT1 is designed to contain as many diagnostic devices as possible. There are five BPMs with four inside the quadrupoles and one at the end of MEBT1. There are also two Integrated/Fast Current Transformers (ICT/FCTs) in front and at the end of MEBT1, one horizontal and one vertical slit together with one horizontal and one vertical wire scanner in the D-box (diagnostics box) in the middle of MEBT1, and one double direction wire scanner between Q6 and Q7. One Faraday cup (FC) and fast Faraday cup (FFC) are also put inside the D-box. Based on these diagnostics, beam transverse and longitudinal emittance can be obtained during beam commissioning.

Fig. 12. (color online) NC QWR under power conditioning.

4 Conclusions

The MEBT1 of CADS Injector II has been designed and constructed at IMP. PIC simulation shows that MEBT1 meets the requirements of matching between RFQ and SC sections, and emittance preservation. Simulations show that the use of three collimators can reduce beam halo. A compact mechanical design has been achieved and MEBT1 has been assembled online. Two QWR type bunching cavities have been built and achieved 134.7 kV effective design voltages in CW mode. The initial beam commissioning result of MEBT1 has shown that a 10 mA beam can pass through MEBT1 with 100% transmission efficiency.

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