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A LOW EMITTANCE COMPACT PROTON INJECTOR FOR A PROTON THERAPY FACILITY*

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Abstract

To meet the requirements of a Proton Therapy Facility funded by National Key Research and Development Program of China, a new compact ion source-LEBT integrated proton injector was developed at Peking University (PKU). It consists of a typical PKU permanent magnet compact 2.45 GHz ECR ion source (PMECRIS) and an electrostatic LEBT (low energy beam transport) with an electrostatic lens, a beam chopper, a set of beam steers, an ACCT, a bellow, an e-trap and a valve. A 1200 L/s molecular pump is adopted to maintain the vacuum for this integrated injector. The total length from RF matching plane to RFQ front flange is about 450 mm. Chopper is used to shorten the pulse length from ms to µs with sharp edges. Test results of this PMECR source prove that it has the ability of delivering a proton beam with current from 10 mA to 90 mA with duty factor of 3% (100 Hz/0.3 ms) and its rms emittance less than 0.1 π mm·mrad at 30 keV. The acceptance tests of this integrated injector have been performed with a 30 keV hydrogen beam. A required proton current of 18 mA with ripple wave less than ± 0.1 mA successfully passed through a Ø20 mm aperture diaphragm at RFQ entrance flange. Its rms emittance is about 0.06 π mm·mrad.

INTRODUCTION

Particle radiotherapy (RT) is currently the most advanced form of radiotherapy that protons (P-RT) or heavier ions (HI-RT) used for cancer treatment can provide a more favorable dose distribution compared to X-rays. Despite a somewhat higher cost compared to megavoltage X-rays, PT holds great potential for significant advances in cancer care and research. Protons (z = 1) have always low linear energy transfer (LET) and their advantage is limited to the sparing of the normal tissue due to the Bragg peak. However, it has been recently observed that the increased LET of slow protons at the end of their range can lead to unexpected toxicities, such as brain necrosis [1]. Carbon ions (z = 6) are a good compromise because they have low LET in the entrance channel and high LET in the tumor region [2]. For this reason, carbon ion therapy is currently ongoing around the World [3]. However, carbon ion therapy is more expensive than proton therapy, because large synchrotrons are needed to accelerate heavy ions compared to compact cyclotrons used in proton therapy [4]. Therefore more interests are focused on proton therapy [5].

The first proton radiotherapy (P-RT) application was carried out at the Lawrence Berkeley National Laboratory (LBNL) in 1954 [6]. Since then, many institutes carried out clinical trials with proton beams around the World [7]. To meet the P-RT facilities requirement, various ion sources that were originally designed for non-medical use are implored for this purpose. Ion sources used for P-TR facilities are listed in Table 1.

Table 1: Proton Ion Sources Used for P-TR Facilities

Inst.	Source type	Current /mA	Pulse length /µs	Fre-quency /Hz
IBA/Sumitomo	Hot filament PIG	0.01	CW	CW
Varian	Cold cathode PIG	—	CW	CW
Loma Linda University	Duo-plasmatron	70	50	0.5
Hitachi	Microwave ion source	30	600	0.2-0.33
Mitsubishi	2.45 GHz ECRIS	25	—	—

In 2018, a synchrotron-based Proton Therapy Facility was funded by National Key Research and Development Program of China. The LINAC mainly consists of a proton injector that includes an ion source with a Low Energy Beam Transport line (LEBT), a 3 MeV Radio-Frequency Quadrupole (RFQ) and a 7 MeV Drift Tube LINAC (DTL). Topics such as beam stability and reliability as well as the facility size and construction cost are careful evaluated for development of the whole new accelerators including ion sources and LEBT.

This paper mainly focuses on the proton injector that should deliver an 18 mA@30 keV pulsed proton into RFQ cavity. Parameters required by RFQ for this proton injector are listed in Table 2.

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Table 2: Beam Parameters at RFQ Entrance

Content	Parameters	Method
Ion type	H^+	H_2
Energy	30 ± 0.1 keV	PKU PMECRIS + E LEBT
Ion source current	20~30 mA	
LEBT current	>18 mA	
Beam stability (LEBT)	±1 mA	
Emittance (RMS, Norm)	⩽0.2 π mm·mrad	
Repeat frequency	0.5~10 Hz	Pulsed plasma + Kicker
Pulse length	40~100 μs	
Raise edge	⩽2.0 μs	

PROTON INJECTOR SETUP

A proton injector consists of a proton ion source and a LEBT. As mentioned in literature [8], for a higher current accelerator it is better to design an ion source and LEBT as a whole. Before starting the design, the most important thing is to choose a suitable ion source and a feasible beam focusing method LEBT. Here a PKU type permanent magnet compact 2.45GHz ECR ion source with an electrostatic LEBT combination proton injector was proposed for this proton LINAC. The mechanical view of this proton injector is shown in Fig. 1.

Ion Source

As a competitive single charged ion producer, 2.45 GHz ECR ion source has advantages of high ion current intensity, low emittance, good reproducibility, high stability, simple structure, convenient maintenance, low cost, long life and ability to operate in both CW and pulsed mode. It has been chosen by IPHI, IFMIF, SPIRAL2, ESS, PKU-NIFTY and other high current proton facilities around the world. Study on 2.45 GHz ECR ion source at PKU can tract back to 1980's. Since then, we have developed nearly ten sources for different facilities, such as SFRFQ [9], PKYNIFTY [10], C-RFQ [11], DWA [12], etc. The source used for P-RT is similar to the one used for PKUNIFTY. The operation microwave frequency is 2.45 GHz, RF matching is fulfilled through dielectric microwave window, and beam is extracted through a triple- electrodes extraction system. A piece of thin BN disk toward the plasma is used to protect the microwave window from the bombarding of electrons. A Ø5mm hole is used for beam extraction. The out dimension of the source is about Ø200×150mm. A WR284 rectangular waveguide plus a homemade high voltage break wave guide (HV break) has been adopted to isolate most wave guide sections from high voltage. With the help of the HV break, the high voltage region of the ion source is limited within a Ø200 mm × 230 mm area. Similar to the design of PKU-NIFTY, this source body is also inserted in to the extraction column, and the extraction system is embedded inside the vacuum vessel. Both the source body and the extraction system cannot be viewed from the front of the injector (Fig. 1).

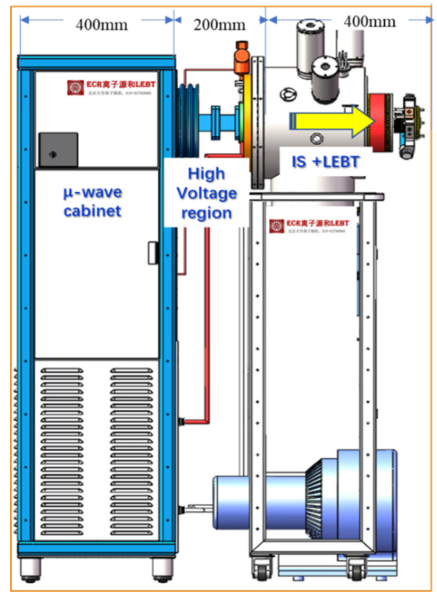

Figure 1: The mechanical view of the proton injector.

The LEBT

An electrostatic lenses LEBT (E-LEBT) is chosen for this design because the beam intensity is lower for this project and E-LEBT has the specificity characteristic of simple structure, limited length and low cost. In 2013, an E-LEBT was successful developed to transport a 50 mA proton beam at 40 keV to DWA (Dielectric Wall Accelerator) for China Academy of Engineering Physics (CAEP) at PKU [12]. This one is somewhat similar to that one. A kicker just follows the extraction system. Beam kicked off by kicker will be absorbed by a water-cooled shielding box. A set of X-Y steers and a lens are located inside this shielding box. Items including part of ion source, kicker, steers and lens are installed inside a stainless steel vacuum vessel. Under this vessel, a TYFB-1200 molecular pump (Beijing Taiyueheng Company) is installed to achieve vacuum for the whole injector. Outside the vessel are an ACCT (Bergoz Co.), a valve with bellow and an e-trip at the entrance of RFQ. The total length from RF matching plane to RFQ front flange is about 450 mm, including 300mm LEBT and 150 mm ion source.

Ancillaries

Besides the items mentioned above, some words should be addressed on the ancillaries for this injector. High voltage power supplies are Glassman products. The 2.45 GHz microwave generator (No. JNMW19-01) and the kicker power supply (No. JNHP19-01) are manufactured by a new Chinese company, Xian SIGNUM High Voltage. The control subsystem of this injector is based on Siemens Simatic TIA Portal V15.

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COMMISSIONING RESULTS

System Commissioning was done in two stages, source test and injector test. The source test that was finished in middle of 2019. The commissioning of the whole injector was completed at the end of 2019. Because of the COVID-19, the onsite test was delayed to the end of 2020.

Ion Source Test

The intention of source test is to obtain the beam current, its emittance and the ion factor. It was done on PKU ion source test bench that has the ability to measure beam current, beam distribution, emittance [13] and ion fraction. Test results of this PMECR source prove that it has the ability of delivering a proton beam with current from 10 mA to 90 mA with duty factor of 3% (100 Hz/0.3 ms) when the peak RF power changes and its rms emittance less than 0.1 π·mm·mrad at 30 keV. Results plotted in Fig. 2 is an example when the peak rf power was set at 1600W. As shown in Fig. 2, the beam current is 34 mA at 30 keV, its mrs emittance is about 0.101 π·mm·mrad and the H^+ faction is about 91%.

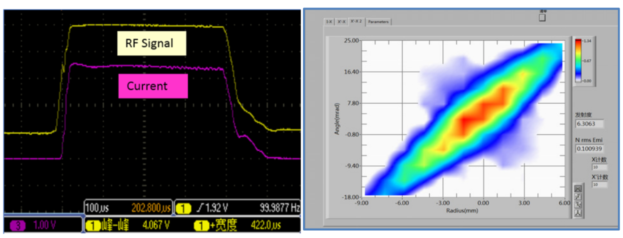

Figure 2: Result of this proton source when RF is 1600W. Beam current (up), Emittance (down).

Injector Commissioning

The acceptance tests of this integrated injector have been performed with the help of a set of slit-grid emittance unit that integrated a Faraday cup inside. This emittance unit is installed at the end of LEBT, where RFQ will locate during the LINAC commissioning. The goal of this commissioning is to achieve a proton beam that can pass through a Ø20 mm aperture diaphragm at RFQ entrance flange with current higher than 18 mA, transmission efficiency >95%, pulse rise edge <2 µs and beam rms emittance <0.2 π mm·mrad.

A shorter pulse beam with 40µs~100µs length is achieved through two steps. First, through pulsing the RF power, a long pulse beam with pulse length from 0.3 ms to 1 ms is produced by the ion source. Its repeat frequency is set at the required one by RFQ that changes from 0.5 Hz to 20 Hz. Second, shorter pulse beam with pulse length of 40-100 µs is obtained by shorten the long pulse (0.3 ms to 1 ms) through a kicker. Beam current and beam transportation efficiency are monitored with the online ACCT and Faraday cup. Meanwhile, beam emittance and its distribution are measured with this slit-grad emittance measurement unit. To gain enough data for emittance measurement construction, the repeat frequency RF power changes to 100 Hz.

A 10 mA to 30 mA proton beam with repeat frequency of 0.5 Hz to 100 Hz, pulse length from 40 µs to 100 µs, beam rise edge less than 2µs with rms emittance smaller than 0.1 π·mm·mrad can be easily obtained when the peak RF power changes from 1000 W to 2500 W and gas flow is set from 0.7 sccm to 2.3 sccm. Beam transmission efficiency from ACCT to FC is about 95%. Its rms emittance changes from 0.07 π·mm·mrad to 0.1 π·mm·mrad when the current increases from 18 mA to 30 mA. No steer is needed for beam calibration.

Pictures in Fig. 3 are beam current records with kicker off (up) and kicker on (down) at ACCT and FC. The beam intensity at ACCT and Faraday are 19 mA and 18 mA respectively. The raise edge of the beam is 2µs. Its rms emittance is 0.07 π·mm·mrad (205 mm after the RFQ entrance).

This injector already delivers 30 keV proton beam more than 400 hours since middle of 2019. No spark has been observed during its operation. The onsite test of the injector was done on 11 Dec. 2020 at PKU. The installation at user's place was finished at the beginning of year 2021. It is routinely deliver proton beam to RFQ since March 2021.

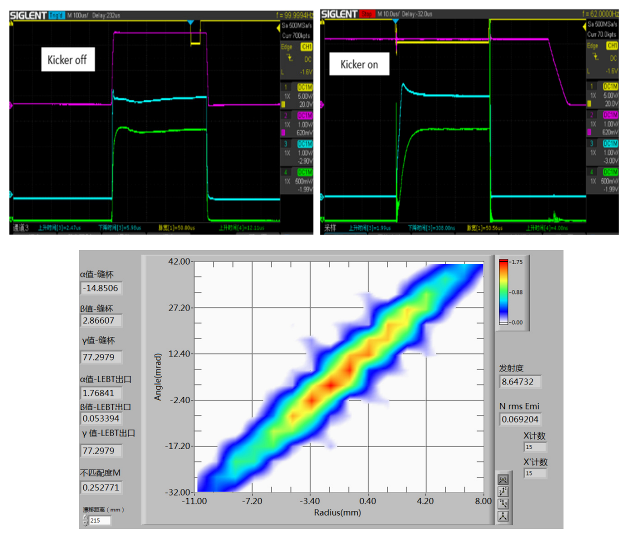

Figure 3: Beam current records with kicker off (up) and kicker on (middle) at ACCT and FC, and its emittance (down). Red: Microwave signal; Yellow: Signal of kicker; Blue: Current at ACCT; Green: Current at Faraday.

SUMMARY AND PROSPECT

A proton injector was developed at PKU for P-RT facility. It was based on a combination of a PKU type compact permanent magnet 2.45 GHz ECR ion source and an E-LEBT. Beam produced by this injector match the requirement of RFQ facility. RFQ commissioning is on the way.

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