ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-WEA2

COMPACT 2.45 GHz PMECR ION SOURCES AND LEBTS DEVELOPED FOR ACCELERATOR BASED RADIATION THERAPY FACILITIES AT PEKING UNIVERSITY

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Abstract

Recently, Accelerator Based Radiation Therapy (ABRT) facilities for cancer treatment, that includes ion therapy and BNCT, have been bloomed up rapidly and are being established as a future modality to start a new era of in-hospital facilities around the world. A high current, small emittance, easy maintenance, long lifetime, high stability and reliability ion source is crucially important for those ABRT facilities. Research on this kind of ion source has been launched at Peking University (PKU) ion source group for more than 30 years and some exciting progresses, such as hundred mA beam current of $H^+/N^+/O^+$ etc., less than 0.2 π·mm·mrad emittance, a continue 300 hours operation record of CW proton beam without spark have been achieved. In recent years, our involvement in the ABRT campaign has extended to include responsibilities for ion sources and LEBT section. In this paper, we will provide a summary of two compact PKU standard 2.45 GHz permanent magnet ECR sources (PM SMIS) that were developed for a proton therapy (PT) machine and an accelerator based BNCT facility (AB-BNCT). The individual structure of the sources as well as the LEBT along with the commissioning results will be presented then.

INTRODUCTION

Cancer is a general term for a large category of diseases that can affect any part of the body. It is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020, or nearly one sixth of deaths are due to cancer [1]. Many cancers can be cured if detected early and treated effectively. Radiation therapy (also called radiotherapy) is a cancer treatment that uses high doses of radiation to kill cancer cells and shrink tumors. There are two main types of radiation therapy, external beam and internal. External beam radiation therapy comes from a machine that aims radiation at the cancer. The machine does not touch but can move around the patient, sending radiation to a part of patient's body from many directions. External beam radiation therapy is a local treatment, it treats a specific diseased part of the body. Proton therapy (PT), heavier ions therapy (HI-RT) and boron neutron capture therapy (BNCT), are new highly targeted external beam radiation therapy for cancer treatment. Accelerator Based Radiation Therapy (ABRT) facilities are compact and useful tools to generate desired particles, such as energized protons, carbon ions or neutrons, to kill the cancer cells. Therefor ABRT has been bloomed up rapidly and is being established as a future modality to start a new era of in-hospital facilities around the world [2,3].

For any ABRT type PT or BNCT facilities, a proton beam with a current of several tens of mA in pulsed or continuous wave (CW) mode is required from the ion sources by the accelerator. The 2.45 GHz Electron Cyclotron Resonance (ECR) ion source is considered to be the optimal choice for ABRT facilities due to its advantages in high beam intensity, stable performance, low emittance, good reproducibility, high stability, simple structure, convenient maintenance, low cost, long lifespan and ability to operate in both CW and pulsed modes. Ion source group of Peking University (PKU) initiated an ABRT campaign by developing compact 2.45 GHz ECR ion sources and LEBT for these facilities.

The study on permanent magnet 2.45 GHz ECR ion sources (PMECR) started at 1980's at PKU [4]. Since then, several series of 2.45 GHz PMECR ion sources have been developed, including the PKU Standard permanent magnet Microwave Ion Source (SMIS) [5], Miniaturized Microwave ion source (MMIS) [6], Surface plasma electron source (SPS) [7], H_2^+/H_3^+ ion source [8], 2.45 GHz microwave driven H- source [9], O^{3+}, Ar^{3+} multicharged ion source [10] and C^{2+} ion source for PIMS [11]. The SMIS has achieved a proton beam of more than 130 mA at 50 keV with a Φ6 mm emittance aperture [5]. In June 2016, a long-term operation of 300 hours with a continuous wave proton beam of 50 mA@50 keV was conducted using the SMIS. Throughout this period, no sparks appeared and no plasma generator failure caused any interruptions to the beam. More than ten copies of SMISs have been developed for different facilities such as SFRFQ [12], PKYNIFTY [13], C-RFQ [14], DWA [15] and Proton therapy facility [16]. To better understand the discharge ignition and plasma sustain process within a miniaturized 2.45 GHz microwave driven ion source, a hybrid discharge heating (HDH) mode has been proposed at PKU [6]. Additionally, a global model based on electronic equilibrium equations has been proposed to explain H^+, H_2^+ and H_3^+ generation [17].

This paper primarily focuses on the compact permanent magnet 2.45 GHz ECR ion sources (PMECR) along with LEBT developed for a PT machine and a BNCT facility. The ion sources belong to SMIS type. In both cases, we have followed the same structure as PKUNIFTY by designing the ion source and the LEBT as a whole. In section II, we will present the commissioning results of the Proton Injector for PT Machine. Section III will depict details of the pulsed/CW proton PMECR and two-solenoid LEBT

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developed for a BNCT machine. A summary and discussion of next steps will be provided at the end of this paper.

PROTON INJECTOR FOR PT MACHINE

PKU involved the Proton Therapy Facility project was charged by Shanghai APACTRON Particle Equipment Company Limited and funded by the National Key Research and Development Program of China in 2018. Its 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) [16]. The output proton current at the exit of DTL should be higher than 12 mA. This LINAC accelerator requires an 18mA pulsed proton beam with an energy of 30 keV. The repeat frequency of the beam ranges from 0.5 to 10 Hz, with a pulsed length between 40 to 100 µs, and a pulsed raising edge less than 2 µs. Further details can be found in Table 1. Figure 1 depicts this LINACS from the ion source side, while Figure 2 provides a view from behind the beam direction.

Table 1: Beam Parameters at RFQ Entrance

Parameter	Value
Ion type	H^+
Energy	30±0.1 keV
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
Pulse length	40~100µs
Raising edge	≤2.0µs

Figure 1: A photograph of PT machine taken from ion source side.

The PT SMIS source test was conducted on PKU ion test bench at the end of 2019. Test results demonstrate that the source has the ability of delivering a proton beam with current from 10 mA to 90 mA when duty factor changes from 1% to 20% (0.5 Hz - 100 Hz) with the peak RF power. Its rms emittance less than 0.1 π·mm·mrad at 30 keV. The results displayed in Figure 3 is an example obtained with SAIREM GMP 30K SM microwave power supply during ion source qualification at PKU. As depicted in Figure 3, the beam current is 34 mA at 30 keV, the beam diameter located 250 mm downstream from the particle emitting plane is about 20 mm. H^+ faction is estimated to be around 91%, while its rms emittance is about 0.1 π·mm·mrad. All the data exceed the requirements of the machine.

Figure 2: A photograph of PT machine taken from end of LINAC.

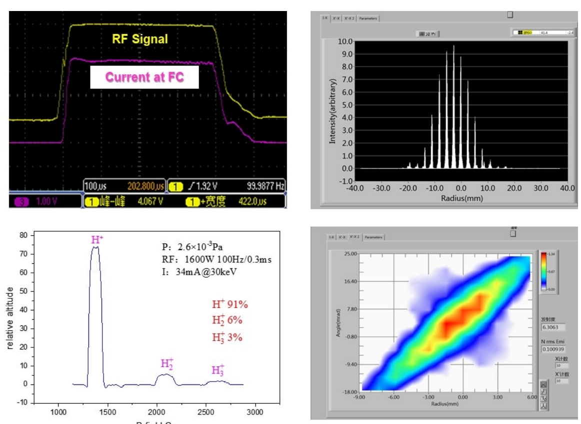

Figure 3: Result of PT SIMS proton source when RF is 1600W. (Beam current: up left, beam profile: up right, ion fraction: down left, RMS emittance: down right.)

The results of the proton injector commissioning were presented in Figure 4. This test was done using a new 2.45 GHz microwave generator produced by Xian SIGNUM High Voltage, which is a new Chinese company. The kicker power supply (No. JNHP19-01) was also provided by this company. As shown in Figure 4, the beam rise edge without/with chopper is 5 µs/2 µs. The current at ACCT equals to that reaches at FC2. This means that all proton ions that travel through ACCT can be injected into RFQ.

Figure 5 is a hard copy of LINAC commissioning result achieved at Match 2023. A proton beam with a current of 14.4 mA and energy of 7 MeV was achieved at the exit of DTL, which is much higher than the required 12 mA.

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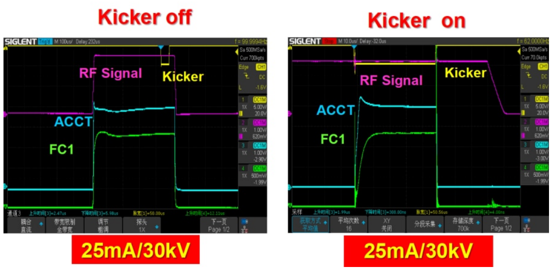

Figure 4: Beam current recorded with oscilloscope (OSC) at the end of LEBT w/o chopper.

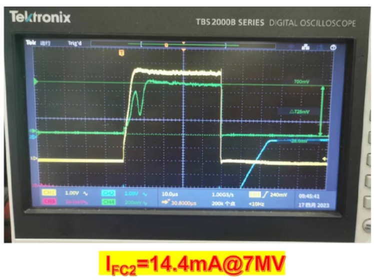

Figure 5: LINAC commissioning result. A 14.4 mA beam was obtained at 7 MV.

The PT injector has been delivering proton beams for this facility since the beginning of 2021. Up to now, no sparks have been recorded. Similar to other SMISs developed for SFRFQ, C-RFQ, PKUNIFTY, DWA, etc., no maintenance is required.

CW/PULSED PROTON INJECTOR FOR AB-BNCT FACILITY

The development of the accelerator base boron neutron capture therapy (AB-BNCT) facility, charged by the Joint Laboratory of Xi'an Jiaotong University and Huzhou Neutron Science Laboratory, is currently underway. The accelerator is a LINAC consisting of a 2.45 GHz ECR ion source, a two-solenoid LEBT, and a RFQ plus Cross-bar H-mode DTL (CH-DTL). A 20 mA proton beam should be delivered to the target for neutron production.

The required beam for this LINAC is a 30 mA@40 keV proton beam in both CW and pulsed mode. Its beam duty cycle should be adjustable from 0.5% to 100% at 200 Hz, with a normalized root mean square emittance of less than 0.2 π.mm.mrad. Parameters at the entrance of RFQ are listed in Table 2. In this framework, our group is responsible for designing and realizing both the CW and pulsed 30 mA@40 keV proton beams.

In order to provide a suitable beam for this facility, a proton injector that consisting of a standard PKU PMECR ion source (SMIS) and a two-solenoid LEBT was developed. Similar to the ones used for the PT facility, this source follows a Matryoshka doll style by embedding part of the ion source body into the extraction system and inserting the whole source into the first diagnostic box of LEBT. The dimensions of this source body are 100 mm ×Φ 100 mm, with a plasma chamber measuring 50 mm × Φ 40 mm. A well water-cooled three-electrode extraction system designed at 45 kV is also incorporated. The outside dimension of the SMIS is 160 mm × Φ 200 mm. Pictures displayed in Figure 6 show the source body, integrated source, and online source; while Figure 7 depicts the AB-BNCT proton injector (down). The total length of LEBT from plasma electrode to RFQ electrode is about 1130 mm.

Table 2: Parameters at the Entrance of RFQ for AB-BNCT Facility

Parameter	Value
Particle	H^+
Operation mode	CW (rare), pulse: 1~500Hz, 200Hz specific, length >200 μs
Energy	40 keV
Beam Current	> 30 mA
Normalized rms emittance at LEBT exit	< 0.20 π·mm·mrad
H^+ fraction	> 80%
Stability	24 h
Twiss parameter at RFQ entrance	α=1.484, β=5.622 cm/rad
Mismatching degree of TWISS parameter	<30%
Raise/Full edge	<1ms

Figure 6: Pictures of SMIS.

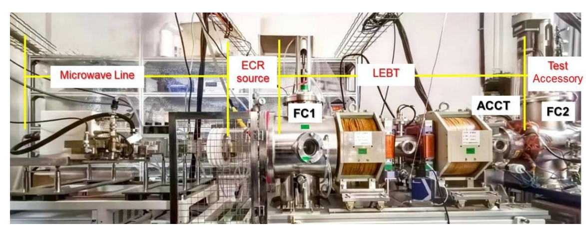

Figure 7: Picture of the proton injector for AB-BNCT.

The commissioning process for this AB-BNCT proton injector was carried out in two steps: ion source qualification and LEBT testing. Ion source qualification took place on a PKU ion test bench last year where characteristics such as beam intensity, distribution, emittance, and H^+ fraction were evaluated. With this SMIS, it was easily obtained that more than 60 mA hydron beam at 40 kV with H^+ fraction higher than 80% and rms emittance less than 0.11 pi.mm.mrad when changing duty factor from 10% to CW.

The RFQ acceptance tests of this proton injector was launched at the end of 2023. A four-quadrant diaphragm with a Φ4 mm aperture that used to simulate the entrance of RFQ electrodes, and a set of slit-grid emittance unit that follow a Φ4 mm aperture were used for this test [13].

This test was conducted in pulsed mode with a duty factor ranging from 5% to 90% due to the ACCT working range. The purpose of this test is to ensure that the current at FC 2 (I_{FC2}), which represents the future current into RFQ. At the same time, I_{FC2} should be closer to that obtained at ACCT (I_{ACCT}). Additionally, its emittance should be less than 0.2 π·mm·mrad. Furthermore, its twiss parameters and mismatching degree should meet the specified criteria.

The test results demonstrate that a beam with a current greater than 50 mA can be easily obtained at the FC 2 location. Simultaneously, the currents at FC 2 are equal to that at IACCT. Its rms emittance is from 0.09 π·mm·mrad to 0.112 π·mm·mrad, α is approximately 1.285, β is about 5.788 cm/rad, and the mismatching degree is 12.5%. Figure 8 provides two examples of the beam current at FC 1, ACCT and FC 2 when the duty factors were 70% and 90%.

The proton injector has been consistently delivering a proton beam to the RFQ since January 2024. There have been no recorded sparks during RFQ operation so far. A 33-mA proton beam was achieved at the exit of the RFQ at the beginning of July. Additional data is coming soon.

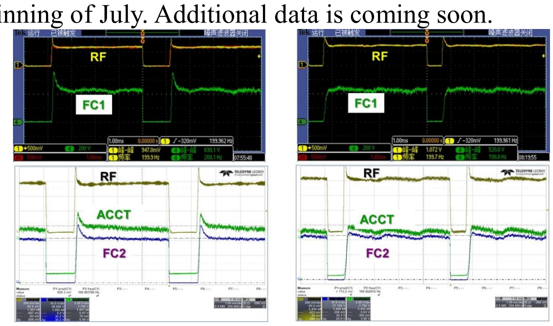

Figure 8: Beam current at FC 1, ACCT and FC 2 under different duty factor. (Left: duty factor is 70%. I_{FC1}: 45 mA, I_{ACCT}: 30 mA, I_{FC2}: 30 mA. Right: duty factor is 90%. I_{FC1}: 45 mA, I_{ACCT}: 30 mA, I_{FC2}: 30 mA.)

SUMMARY AND FUTURE PLAN

Two compact 2.45 GHz PMECR ion sources, along with their LEBT, have been developed for use in accelerator-based radiation therapy facilities at PKU. The ion sources are PKU compact standard 2.45GHz permanent magnet ECR ion sources, also known as SMIS.

The LINAC commissioning results for PT facilities demonstrate that the proton injector has met all requirements in every aspect. The LINAC has been in routine operation for over two years without any recorded sparks.

In the case of the AB-BNCT machine, results from RFQ acceptance tests confirm that the proton injector already meets the requirements for the LINAC.

Furthermore, a more compact SMIS is currently under design for use with a dynamitron type LINAC.

ACKNOWLEDGEMENTS

The authors express their gratitude to the colleagues from the Xi'an Jiaotong University-Huzhou Neutron Science Laboratory and Shanghai APACTRON Particle Equipment Company Limited for engaging in fruitful discussions. Furthermore, the authors thank State Key Laboratory of Nuclear Physics and Technology at Peking University for their valuable support.

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