A COMPACT AND HIGH-PROTON-YIELD MICROWAVE ION SOURCE FOR PROTON LINAC

T. Iga#, T. Seki, and S. Hara
Energy and Environmental Systems Laboratory, Hitachi Ltd., Hitachi, Ibaraki 319-1221, Japan

Abstract

A compact and high-proton-yield 2.45 GHz microwave ion source has been developed and tested on an AccSys Model PL-7 linac. The source that has an overall diameter of 115 mm uses permanent magnets and iron yokes. Microwave power was fed to a plasma chamber with a tapered ridged waveguide via a coaxial cable. A pulsed hydrogen beam of 45 mA was extracted from a 5 mm diameter aperture with a proton fraction of >90 % at 30 keV and a gas flow of 1 sccm. A 7-MeV proton current out of the linac equipped with the source reached up to 16 mA_{peak}, which exceeds its design value of 15 mA_{peak}. Excellent stability of no more than 1.5 % variation in both the ion source extraction current and the linac output current was also demonstrated in an 8-hour operation test.

INTRODUCTION

Ion linear accelerators (linacs) are currently in use for medical and industrial applications, as well as physics research. AccSys Technology, Inc. (AccSys) [1], an affiliate company of Hitachi, Ltd., has delivered such ion linacs worldwide. We have some linacs in operation for use as synchrotron injectors in proton beam therapy (PBT) systems and for the production of short-lived positron emitters. It has recently become common that non-specialist users of accelerators are required to operate and maintain those linacs. Under the circumstances, further improvement in manageability and maintainability on the current linacs will be beneficial to the customers.

In many cases, the ion source affects the characteristics above. Although the filamented ion source used in the current AccSys linacs is highly efficient [2], filament-related matters are inescapable. In contrast, microwave ion sources are inherently free from them. We have become aware that, from our experiences of designing and utilizing various types of microwave ion sources [3], their advantages are time stability and reproducibility of beams, simplicity or manageability in daily operation and routine maintenance, not to mention long lifetime.

In the meanwhile, it has been demonstrated at some laboratories that even small microwave ion sources can generate intense proton beams [4-6]. There seem to be few, however, that meet the requirements in size, gas consumption, proton current, etc. for the current AccSys linacs. Thus, we have also developed a new compact microwave ion source suitable for use on the linacs.

SOURCE DESIGN

To install a new microwave ion source on the current linacs with minimal modification, the source diameter must be 115 mm. Table 1 gives the major specifications to guarantee the same performance as the current source.

Since a prototype source we built first showed desirable performance [7], we redesigned it to fit in the existing source mount. In addition, we employed a coaxial cable section in a power feed line to utilize a compact microwave generator with a coax output in the future. The latest design of the compact microwave ion source is shown in Fig. 1. The pulsed microwave power launched from a 1.3-kW magnetron is introduced to the plasma chamber through a circulator, a power monitor, an E-H tuner, a DC waveguide break, a tapered ridged waveguide, and a quartz and Boron Nitride (BN) layered vacuum window. The coaxial cable was inserted between the E-H tuner and the DC waveguide break in this experiment.

The stainless-steel plasma chamber has a length of 53 mm and an inner diameter of 72 mm. A large portion of the inner surface of the plasma chamber is lined with a BN cup to enhance the proton fraction [8]. An array of rectangular permanent magnets surrounds the plasma chamber. A plasma electrode and a back yoke, both of which are made of iron, helps to produce the desired field distribution [7]. Hydrogen ion beams were extracted from a 5 mm diameter aperture of the plasma electrode and were accelerated to 30 keV by a triode system. The source body is isolated from the ground by an insulator.

Table 1: Major Target Specifications

Overall diameter of source body	115 mm
Hydrogen gas flow rate	<1.2 sccm
Extracted ion current (30 kV)	>30 mA_{peak}
H^+ ion fraction	>85 %

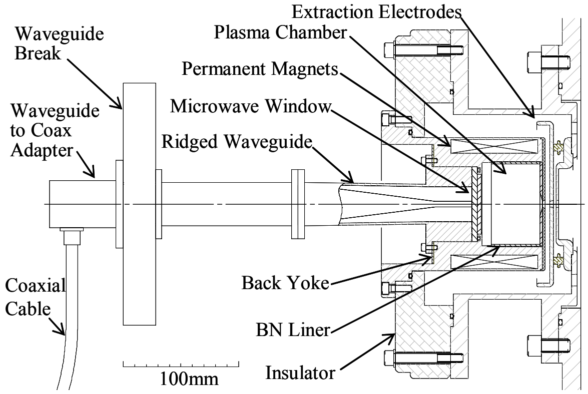

Figure 1: Compact microwave ion source equipped with a microwave power feed line employing a coaxial cable.

#takashi.iga.ty@hitachi.com

SOURCE PERFORMANCE

The source performance was characterized on a test stand. The magnetron was operated at a pulse repetition rate of 3-5 pulses per second (pps) and with a pulse width of 600 µs. A 0.1 pps operation and an on–demand pulsing for a few minutes' intervals were also demonstrated. The total beam current was evaluated by a power supply current using a current toroid. The ion species fraction was identified using a bending magnet. The acceleration gap in this experiment was 4.5 mm, and the accel/decel voltages were 30 kV and -2.2kV, respectively. The E-H tuner was adjusted once before a series of measurement.

Typical dependence of the current components in the beam and the proton fraction on the incident microwave power for a hydrogen mass flow rate of 1.0 sccm is given in Fig. 2. The requirement listed in Table 1 was satisfied even with the incident microwave power of 900 W. Since the proton current increased almost linearly with the power, the total current and the proton fraction reached at 45 mA and 91 %, respectively. The effect of the hydrogen gas flow rate on the beam current and the proton fraction with a constant microwave power of 1300 W is shown in Fig. 3. The optimum flow rate was 1.0-1.4 sccm because too much flow definitely enhances the production of molecular ions and a lesser flow can invoke unstable discharges.

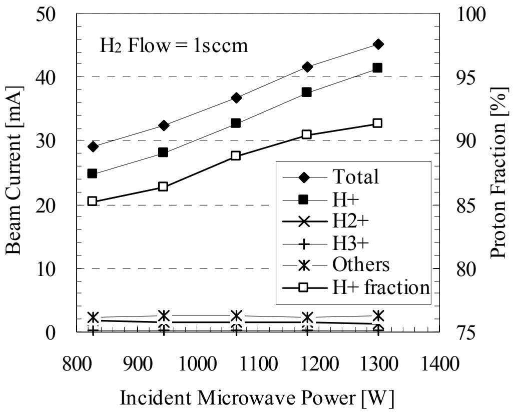

Figure 2: Beam current vs. incident microwave power.

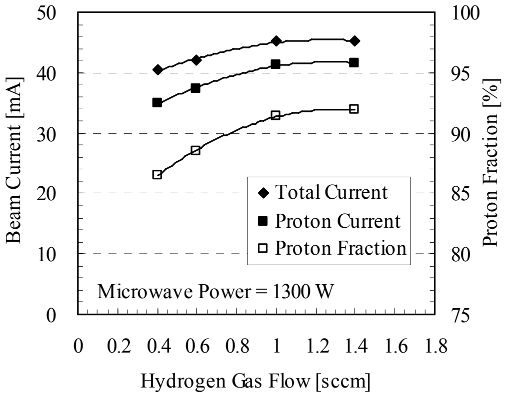

Figure 3: Beam current and proton fraction vs. gas flow.

In small ion sources, the dissociation of H_2^+ is the dominant process for the proton production, while the ionization of H atom is most effective in large sources [9]. It is considered that the BN cup, lining the sidewall of the chamber as well as the bottom, enhanced the later process even in this small source by recoiling the H atoms impinging on its surface into the plasma [8] and the high proton yield was achieved.

LINAC PERFORMANCE

The standard AccSys Model PL-7 linac consists of a 30-keV proton injector including a focusing lens, a Radio Frequency Quadrupole (RFQ) linac, a Drift Tube Linac (DTL) and two 425 MHz rf amplifiers. The output beam energy is 7MeV. The rf amplifiers were operated at 10 or 16 pps in this experiment. The pulse widths of rf power put into these cavities were 71µs and 122µs, respectively.

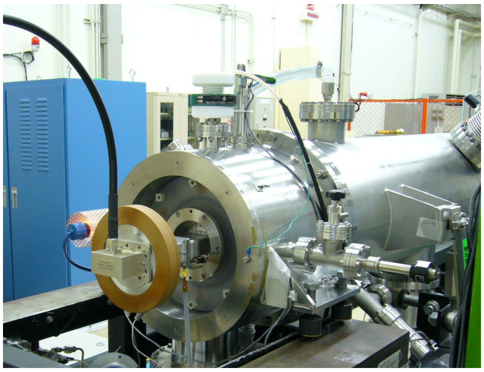

Figure 4: Photo of the compact microwave ion source installed on the AccSys Model PL-7 linac.

We have installed the developed source on the linac. Figure 4 shows a photograph of the source fitting in the mount on the injector chamber. The coaxial cable and the DC waveguide break are also seen. A conventional three-element Einzel lens was used to focus the extracted ion beam into the RFQ matching point. The acceleration gap of the triode system was chosen to 9.5 mm to achieve better matching of the focused beam to the RFQ input condition. The 7-MeV beam was launch at every two or one second in accordance with the source pulsing of 0.5 or 1 pps. The pulse width was limited to about 50 µs by that of the RFQ. An RFQ input current and a DTL output current were measured with current toroids embedded in the end wall of the RFQ and a Faraday cup at the exit of the DTL, respectively. A current drawn in to the high voltage electrode of the Einzel lens was also measured.

Figure 5 shows an example of measured waveforms. The extracted beam pulse was set to synchronize with the rf pulses at its end, because the proton fraction in the pulse reached as much as 97 % of its equilibrium at a range of 500-600 µs from ignition [7]. The abrupt reductions in the RFQ input current and the lens current are comparable in depth and are synchronized with the excitation of the RFQ cavity. It is apparent that secondary electrons from the RFQ cavity were drawn in to the HV electrode of the lens and they were suppressed with the RFQ rf power on [10]. We have tried to suppress this electron flow and accompanying momentary drop in the lens voltage during the pulse by adding two electron suppression electrodes to the three-element lens [11].

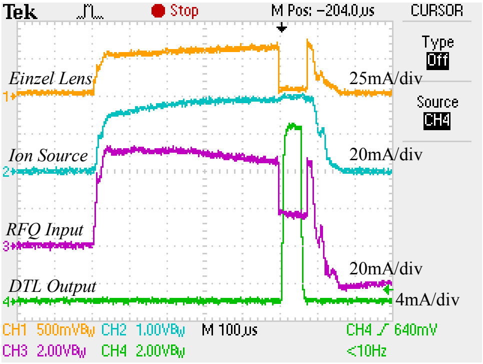

Figure 5: Oscillogram of the current waveforms.

Figure 6 shows the ion source extraction current I_{ext}, the DTL output current I_{out} and the transmission through linac I_{out}/I_{ext} as a function of the incident microwave power for a hydrogen mass flow rate of 1.2 sccm. The lens voltage was adjusted to maximize the DTL output current at each point. The microwave coupling to the source was slightly detuned here with the tuner. The maximum transmission was almost 50 % when the ion source extraction current was about 28 mA. At higher extraction currents, the DTL output current reached 16 mA while the transmission went down. Since the practical current limit in this linac is about 15 mA by design [12], this performance would be quite well at this moment.

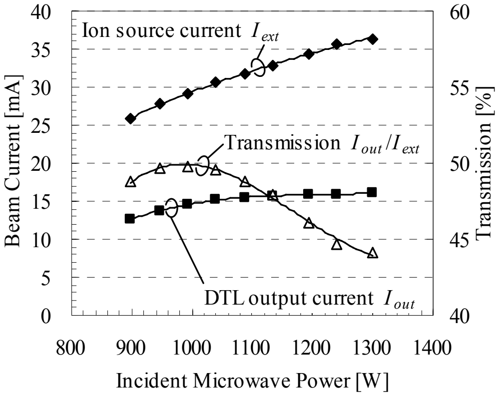

Figure 6: Beam current and transmission through linac vs. incident microwave power.

We have examined the time stability in both the ion source extraction current and the DTL output current by an 8-hour running test. The source was first operated at 16 pps for only 5 minutes while the rf amplifiers warmed up, then switched to 0.5 pps at the beginning of the test. The duty factor was 0.03 %. Figure 7 clearly shows that both of the currents were quite stable. In fact, the variations in the ion source current and the DTL output current were no more than 1.5 % and 1.1 %, respectively, without any adjustment in operation parameters during the test.

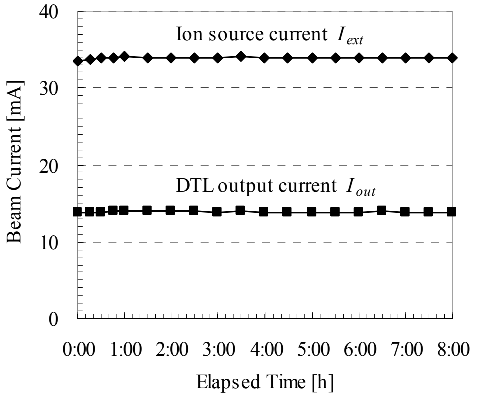

Figure 7: Stability of beam currents in 8-hour test.

We have already confirmed that no damage has been observed in the source and the lens after an accelerated (50 % duty factor) 110-hour test of another source [13] having similar configuration to the one just described. Converting the above result to the duty factor of 0.03 %, the 8-hour test is equivalent to an 183,333-hour run. Thus, a maintenance-free operation for entire life of the product could be expected, restricted to typical PBT applications where the beam is required for every two or three seconds.

ACKOWLEDGEMENTS

We would like to acknowledge valuable comments and suggestions received from Dr. R.W. Hamm of R&M Technical Enterprises, Inc. before starting this work. We also thank Dr. H. Seki of AccSys Technology, Inc. for his continued encouragement.

REFERENCES

[1] AccSys Technology, Inc. http://www.accsys.com/
[2] R. W. Hamm et al., Proc. 1981 Linear Acc. Conf., Los Alamos LA-9234-C, 309 (Oct. 1981).
[3] M. Tanaka et al., Rev. Sci. Instrum. **79**, 02B317 (2008).
[4] J.S.C. Wills et al., Rev. Sci. Instrum. **69**, 65 (1998).
[5] Z. Yao et al., Rev. Sci. Instrum. **79**, 073304 (2008).
[6] S.X. Peng et al., Rev. Sci. Instrum. **79**, 02A310 (2008).
[7] T. Seki et al., (to be submitted)
[8] T. Taylor and J.S.C. Wills, Nucl. Instrum. Methods Phys. Res. A **309**, 39 (1991).
[9] T. Morishita et al., Rev. Sci. Instrum. **75**, 1794 (2004).
[10] D. Swenson et al., PAC'07, Albuquerque, NM, June 2007, PAC07, TUPAS081.
[11] T. Iga et al., Proc. of ARTA2009, Tokyo, June 2009, p.57 (2009) (in Japanese).
[12] R. W. Hamm and G.D. Robinson, Jr., Proc. WTTC9, Turku, Finland, p.3 (May 2002).
[13] M. Tanaka et al., Nucl. Instrum. Methods Phys. Res. A **550**, 74 (2005).