PRODUCTION OF HIGH-CURRENT PROTON BEAMS WITH A MICROWAVE ION SOURCE FOR ACCELERATORS

M. Tanaka*, S. Hara, T. Hae, T.Iga, K. Saitou, K. Amemiya, K. Hiramoto, S. Kakiuchi**
Hitachi, Ltd., Power and Industrial Systems R&D Laboratory, Hitachi, 319-1221, Japan
**Hitachi, Ltd., Nuclear Systems Division, Hitachi, 317-8511, Japan

Abstract

A microwave hydrogen ion source was developed to improve reliability, and to increase operation time of proton accelerator application systems. The ion source needs no filament in the discharge chamber, which leads to reliability improvement and less maintenance time. The developed source produced a maximum hydrogen ion beam current of 70 mA (high current density of 360 mA/cm^2, beam energy of 30 keV) with a 5 mm diameter extraction aperture and 1.2 kW microwave power. The proton ratio was increased with an increase in rf power and reached around 90 % at 1 kW. Measured 90 % beam normalized emittance was 0.4 π mm mrad. Rise times of rf power and beam current to 90 % of final values were about 30 and 35 μs respectively at a pulse operation mode with 400 μs pulse width and 100 Hz repetition rate. The dynamic range of beam currents was enlarged (3-63 mA) in the pulse mode with a modified rf waveform to assist ignition of microwave discharge. These performance parameters will be desirable for pulse operation accelerator applications like proton therapy systems. Long time operation stability (150 h) was confirmed at a beam current of 51 mA; change in the current was 2%.

1. INTRODUCTION

Recently, proton accelerator systems have been developed for many applications such as proton beam cancer therapy, neutron sources by atomic reaction at proton beam target, RI production systems, and etc. We have developed a high-current hydrogen microwave ion source to increase beam output and reliability for the accelerator application systems.

We Hitachi have long studied on microwave ion sources for industrial applications. Around 27 years ago, Sakudo started development of the microwave ion sources [1] and accomplished a commercial source to produce heavy ion beams for ion implantation in semiconductor fabrication processes. Amemiya developed a cylindrical microwave ion source for MeV acceleration of mA class high-charge-state heavy ions with RFQ in a high-energy implanter [2]. Tokiguchi and Seki have worked on oxygen microwave ion sources to fabricate SOI wafers [3].

We have also worked on development of high-current low-emittance bucket type ion sources for nuclear fusion devices and accelerators [4, 5].

We developed a new hydrogen microwave ion sources based on the above technologies to improve performance of the proton accelerator application systems.

Although T. Teilors[6], J. Sherman[7], R.Gobin[8] had already developed hydrogen microwave ion sources, pulse generation of ion beams were not investigated precisely. We especially worked on production of hydrogen ion beams with short pulse width (several hundred μs) and high beam current of several tens mA for pulse operation accelerator systems like medical accelerators applied to cancer therapy. In this paper, outline of the developed microwave ion source and experimental results on pulse hydrogen ion beam generation are described.

2. EXPERIMENTAL

Outline of the microwave ion source is shown in Fig. 1. Microwaves (2.45 GHz) generated by a magnetron were introduced into a cylindrical discharge chamber through a wave guide and rectangular-circular mode converter. The chamber was made of stainless steel and had inner diameter of 90 mm. A high density hydrogen plasma was produced in the discharge chamber, to which around 1 Sccm hydrogen gas was supplied. Magnetic field of around 0.08-0.09 Tesla, parallel to the ion beam axis, was applied to the discharge chamber using two coils to couple the microwave with the plasma. For extracting ion beams from the chamber, a three grid extraction system was employed as shown in Fig.1: plasma grid (PG), deceleration grid (DG) and grounded grid (GG). Deceleration voltage (-2kV) was applied to DG in order to suppress back stream electrons from beam plasma generated downstream of the grids. PG has an extraction

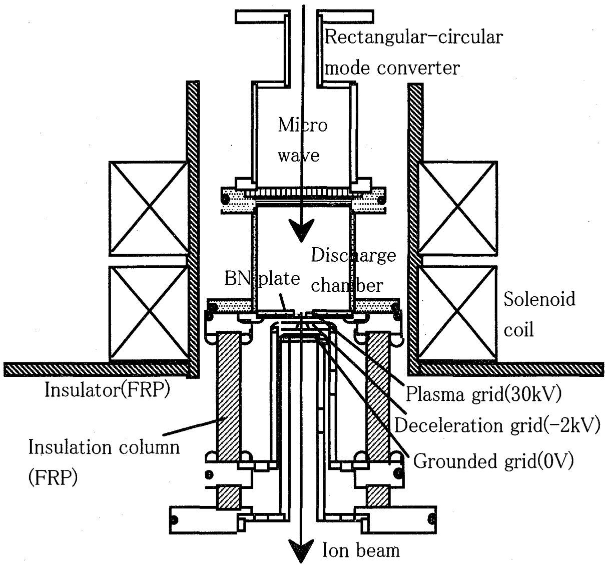

Figure 1: Outline of the microwave ion source.

---

*masanobu-a_tanaka@pis.Hitachi.co.jp

aperture of 5 mm diameter. Ion beams are accelerated typically by 30kV between PG and GG. Structure of extraction apertures of the grids and gaps between grids are optimised to reduce beam divergence and emittance using beam trajectory simulation [9, 10].

Total extracted ion beam current was measured with a Faraday cup (diameter: 34 mm) set 400 mm down stream from GG. Emittance measurement was conducted with the first slit set 190 mm downstream from GG and a Faraday cup equipped with the second slit set 400 mm downstream. Mass spectra of the extracted ion beams were measured by a magnetic mass separator and a Faraday cup.

3. EXPERIMENTAL RESULTS

3.1 Dependence of beam current on microwave power

Dependence of pulsed beam current on forward microwave rf power is measured as shown in Fig. 2. Pulse width was 400 μs and repetition rate was 100 Hz. Beam current increased approximately proportional to rf power in the range of 600-1200W and reached to 62 mA at 1200 W. Lowest limit power and beam current to maintain pulsed discharge stably was about 380 W and 14 mA. The highest beam current was increased to maximum value of 70 mA (360 mA/cm^2) by optimizing magnetic field by the solenoid coils. Beam current of more than 100 mA can be obtained by increase in extraction aperture diameter to more than 6 mm. Proton content in the beam was more than 90 % at the rf power higher than 1 kW.

3.2 Characteristics of beam rise in pulse mode

It is desirable to reduce rise time of the pulsed beam current for injecting beam into pulse operation accelerators with as little beam loss as possible. Typical output beam pulse width of linacs for proton therapy synchrotrons is 50 μs and injection beam pulse width for the linacs is several hundreds μs.

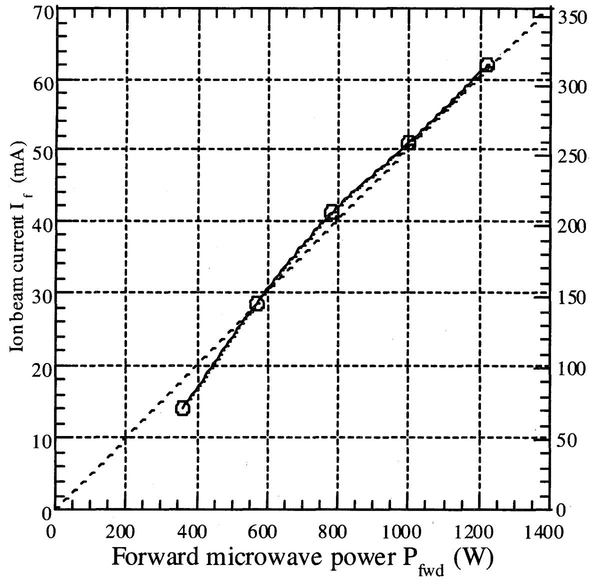

Figure 2: Dependence of beam current on rf power

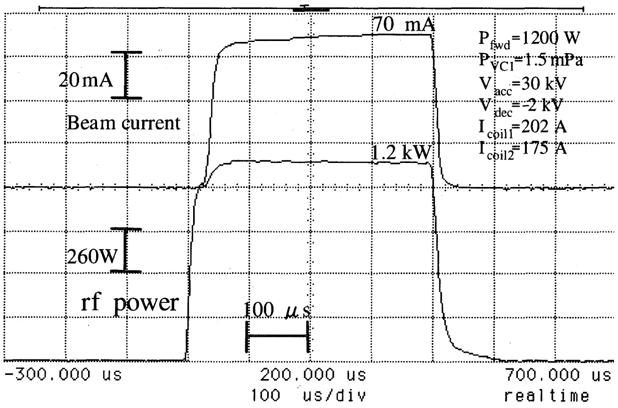

Figure 3: Pulse waveform of beam current

Pulse waveform of beam current obtained for the maximum current beam at a pulse operation mode with 400 μs pulse width and 100 Hz repetition rate is shown in Fig.3 with rf power waveform. Rise times of the rf power and the beam current to 90 % of final values were 30 and 35 μs respectively. Total rise time was about 60 μs. We also investigated time dependence of ion beam contents by the magnetic mass separator. It is shown in Fig.4. Most of ion contents were H_2^+ just after the start of beam rise and ratio of H^+ increases rapidly to around 70 % in 100 μs. The time to reach 90% H^+ ratio was around 200 μs.

Discharge process is considered to be as follows according to these results. Ignition of the discharge is generated by ionization of hydrogen molecules and energetic electrons in the discharge plasma cause dissociation of molecules. This promotes production of H^+. Time constant of this process is around 200 μs, which is considered to decide rise time of the H^+ ratio. Beam pulse after the 200 μs rise time can be appropriately used for the pulsed beam acceleration of the linacs.

3.3 Emittance and current density distribution

Emmitance of the pulsed beam was measured as shown in Fig. 5. 90% normalized emittance was 0.4 π mm mrad

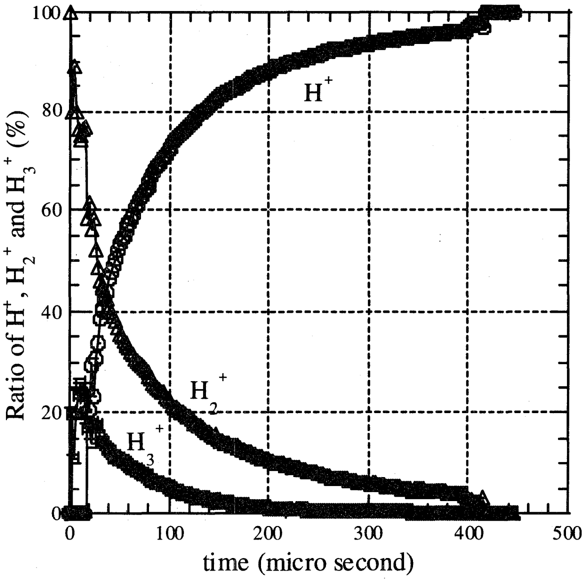

Figure 4: Time dependence of ion contents

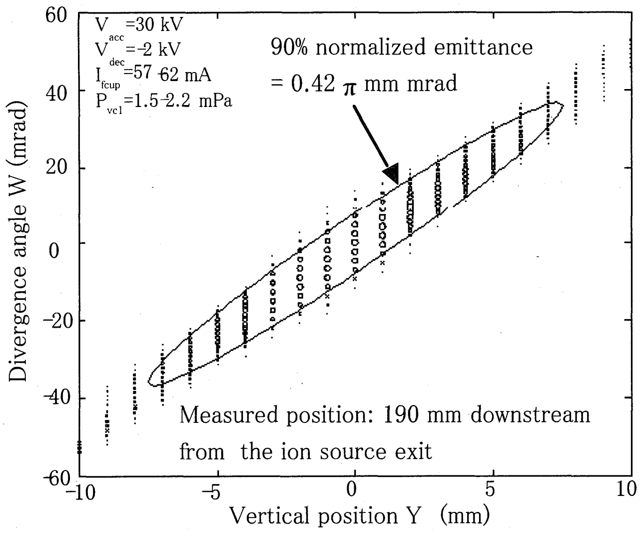

Figure 5: Measured emittance diagram

for the beam current of around 60 mA. This emittance can be acceptable for most of general linacs. Vertical beam current density distribution was calculated according to the measurement. The distribution can be fitted to a Gausian distribution with a small beam tail of less than 5%. 90% diameter of the beam was evaluated to be about 11 mm by integration of the current density distribution.

3.4 Extension of beam current dynamic range by modified rf pulse waveform

It is difficult to maintain stable pulsed discharge if microwave rf power is decreased to lower than the limit value for decreasing beam current as described in Sec. 3.1. We modified the rf waveform to assist ignition for stable discharge at the lower rf power as shown in Fig.6. At the start of the discharge, microwave rf power was set 960 W, which is high enough for ignition. Rf power was decreased to 320 W to decrease beam current after around 100 μs from the discharge start. As a result, discharge can be maintained stably with the low rf power, which is lower than the lowest limit power described in Sec.3.1. Beam current can be changed by this method over the wide dynamic range from 3.3 mA to 60 mA without any changes in ion source operation parameters except for microwave power. These performance will be desirable for expanding beam current dynamic range of pulse operation accelerator applications like proton therapy systems.

3.5 Evaluation of long time operation stability

A 150 h running test of the ion source was conducted to evaluate long time operation stability. Ion beams of 51 mA (260 mA/cm^2) were produced with 1kW rf power, 400μs pulse width and 100Hz rate in the test. Beam current can be maintained to be 51 mA with a change of ± 2% without feed back control. No damage of ion source parts was found after the test. Only a maintenance part is a magnetron outside vacuum chamber.

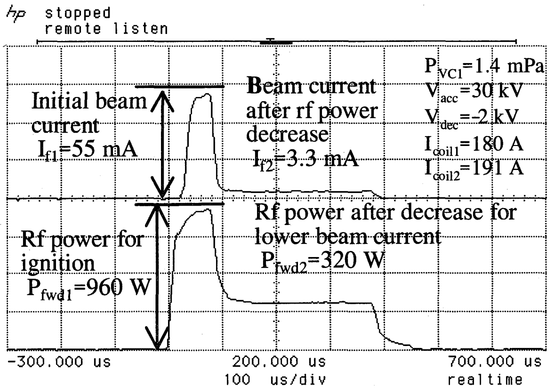

Figure 6: Modified rf waveform for stable production of lower current beam

4. CONCLUSION

A microwave ion source was developed for proton accelerator applications systems. It is confirmed that the ion source has enough ability to supply high-current proton beams stably to the systems at both DC and pulse mode operation. Maximum beam current obtained was 70 mA (360 mA/cm^2) with proton ratio beyond 90%, 400μs pulse width and 100Hz repetition rate. Normalized 90% emittance was 0.4 π mm mrad (rms emittance:0.1 π mm mrad) at beam current of 60 mA. Rise time of the pulsed beam current and proton ratio were 60 μs and 200 μs, respectively, which can be acceptable for pulse operation accelerator systems like proton therapy systems. 150 h operation stability was also confirmed with no damage of any parts and long time maintenance free operation can be expected according to this result and magnetron life time.

We have proceeded to the next research step in which we are developing a lens system for focusing ion beams for injection to RFQ.

REFERENCES

[1] N. Sakudo, et al., Rev. Sci. Instr., 48 (1977) 762.
[2] K. Amemiya, et al.,Nucl. Instrum. Methods Phys. Res., B37/38(1989) 87.
[3] K. Tokiguchi, et al.,Rev. Sci. Instrum., 71 (2000) 952
[4] M. Tanaka,IEEE Trans. Plasma Sci. 25(1997)1412.
[5] M. Tanaka, et al.,Proc. of 2000 meeting of the Atomic Energy Society of Japan, Aomori, Japan, 2000, p.171(in Japanese)
[6] T. Teilor and Jhon S.C. Wills, Nucl. Instrum. Methods Phys. Res., A309(1991)37.
[7] J. Sherman, et al. Rev. Sci. Instrum., 69(1998)1003.
[8] R. Gobin, et al., Rev. Sci. Instrum., 69(1998)1009.
[9] M. Tanaka, et al., Nucl. Instrum. Methods Phys. Res., A449(2000) 22.
[10] Y. Ose, et al.,Proc. of the 10th Symp. on Ion Sources and Ion-Assisted Tech., Tokyo, 1986, p.207.