Status of the HIMAC Injector

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Abstract

At NIRS-HIMAC, by the end of July 2000, 837 patients have already been treated using carbon beams. One of the recent developments is a smaller number of fractionation. Actual fractionation is 4 times per week for Liver, and is 9 times per 3 weeks for Lung. The required beam intensity has thus increased up to 300 eμA of C^{2+} at the source and 2×10^9 pps of C^{6+} at the isocenter. Furthermore, since the installation of the secondary beam (^{11}C and ^{19}Ne) course for therapy is almost completed [1], the high intensity for primary beams is now a prior subject in the HIMAC system. Various ion species and stable operation are also being requested for basic studies. This report describes the recent improvements and developments in the HIMAC injector.

1 INTRODUCTION

HIMAC has been used for both clinical trials of cancer therapy as well as basic research. Recently, the number of fractionation has been reduced; particularly, this number for Liver is only 4 and each dose is larger than 10 Gy. The required intensity for the accelerator has thus increased. At present, an intensity of 2×10^9 pps for carbon beams is routinely necessary at the isocenter; a 10 GHz ECR ion source is normally used for therapy and the two other sources are used for backup in the daytime. Ion sources produce around 300 eμA of C^{2+}; hence, Alvarez and RFQ linacs are operated with a charge-to-mass ratio (*e/m*) of 1/6 before charge stripping. Various ion species from H to Xe (including metallic ions) are used for Physics and Biology experiments during the nights and on weekends; Penning (PIG) and 18 GHz ECR ion sources are usually used. Construction of the secondary beam line is already completed and preparation for therapy with ^{11}C is under progress, which will allow us to precisely check the irradiation position with a PET camera. An electron cooler system was installed in the lower synchrotron ring and preliminary tests have just started [2]

In the injector system, much ef fort was made to improve the ion source capability and reliability under high-power RF (100 MHz) operation in two linacs and a debuncher. Using various combinations of pulse-to-pulse ON/OFF in three Alvarez tanks, the HIMAC injector can deliver beams with four energies (6.0, 4.3, 2.6 and 0.8 MeV/n).

2 LINACS

2.1 RFQ

According to a recent increase of ion species having an *e/m* value of ~1/7, the maximum RF power of the RFQ usually requires almost the design value, at which the maximum surface field is 20.5 MV/m (1.8 kilpatric value). A careful aging process and a good vacuum are thus necessary to attain such operation. The choice of C^{2+} (*e/m*=1/6) at the source for therapy in the daytime would be effective regarding both high intensity and daily aging. In order to test the longitudinal RF chopping into the synchrotron [3], the dependence of the transmission efficiency on the input energy was measured by using a He^{1+} beam with a peak intensity of 500 eμA. The result is shown in Fig.1, and agrees well with the PARMTEQ simulation.

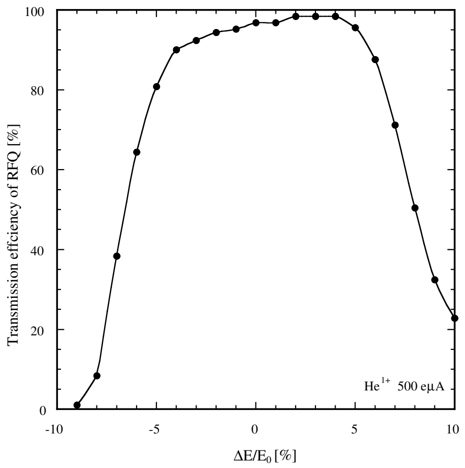

Fig.1 Dependence of transmission efficiency of RFQ on the input energy (7.2~8.8 keV/n). Only an acceleration voltage for the source terminal was changed. The center energy (0%) in the X-axis corresponds to 8 keV/n (E_0).

2.2 Alvarez (DTL)

The Alvarez linac consists of three tanks, each of which has its own RF-amplifier system, which can be independently operated. In the present time-sharing-acceleration [4], the RF level for each tank is usually controlled by pulse-to-pulse; three levels correspond to three different *e/m* values of ion species from three ion sources. If this level is set to zero (RF is OFF), a non-acceleration mode can be produced and the energy can be decreased to those of two tanks, one tank, and no tank (output energy of RFQ), which are 4.3, 2.6, 0.8 MeV/n, respectively. In order to realize such operation, we calculated the excitation parameters for Q-magnets in the drift tubes, and acceleration tests were successfully performed. Such low-energy beams are mainly used for experiments in Physics and Biology at a very high-LET (Linear Energy Transfer, dE/dX) region. An additional beam test was carried out to determine the difference in the efficiency of both charge stripping ($C^{2+} \rightarrow C^{6+}$) and injection into the ring between 4.3 and 6.0 MeV/n carbon (C) beams; the results showed it was small and that there is no problem in the routine operation for therapy under the 4.3 MeV/n injection. For the case of 2.6 MeV/n C beam, the emittance growth and reduction in stripping efficiency are not negligible; however, it will be usable if the intensity of the ring is limited to below 1×10^9 pps.

Since the Alvarez tank is sometimes operated at around a maximum power of 1.4 MW (*e/m*~1/7), the probability of trouble may be somewhat increased; it is thus necessary to prepare spare tubes (Siemens RS2074SK) under good condition. For this, a test bench (Fig.2) was installed; at present, test at around 100 kW (peak) and some improvements of the output circuit are possible.

Fig.2 Photograph of a new test bench for testing a 1.4 MW RF tube (Siemens RS2074SK).

3 ION SOURCES

3.1 PIGIS

PIGIS is particularly expected to produce non-gaseous ions, such as C^{2+}, B^{3+}, Si^{5+} and other metallic ions [5]. Recently, we found that an ion-pumping effect due to the pulsed arc current is effective to realize low-gas pressure for producing high charge-state ions [6]. One problem is the considerable mixture of oxygen; the reasons for this have not yet been clarified. At present, the difficulty in the operation is fortunately not severe; however, this oxygen seems to have reduced the lifetime of the filament down to the order of one week, though it is practically acceptable.

3.2 10 GHz ECRIS

This source is usually used for producing C^{2+} for therapy, and sometimes H_2^+ and Ar^{8+} for experiments [7]. Regarding the intensity and charge state for the production of carbon ions, the CO_2 gas is superior to CH_4 for producing C^{2+}; on the contrary, CH_4 is superior for C^{4+}. The lifetime is primarily determined by carbon deposition on the wall of the plasma chamber; the insulation and electron supply from the wall would gradually become worse. Due to some improvements concerning these problems, the present lifetime is very long: a half year under typical operation.

3.3 18 GHz ECRIS

18 GHz ECRIS has been mainly used to produce ions heavier than Ar, such as Fe^{9+}, Kr^{13+}, Xe^{20+} [8]. Much effort has been made to reduce the effects of space charge at the extraction region: 1) the radial magnetic field was optimized; 2) the diameter of the ECR zone was enlarged for reducing the density of flux lines. The ion-density distribution could thus become more uniform, and the intensity was increased by a factor of 4.

3.4 Compact ECRIS

A compact ECRIS using permanent magnets has been developed for future heavy-ion cancer facilities [9]. The expected intensity is a few hundred eμA for C~Ne ions with *e/m*≥1/3. Since the test results of 2.45 GHz were far below this requirement, this source has been designed to operate under around 10 GHz. A preliminary beam tests were made under various mirror-field strength (6.5~8 kG) using the existing 10 GHz ECRIS. The results suggest that an improvement in the intensity by a factor of 2~3 is necessary.

4 OTHER DEVELOPMENTS

4.1 Emittance monitor for ion sources

HIMAC ion sources can produce the intensity of the order of emA, depending on the ion species and charge state. In this case, the transmission efficiency (η) between the source and RFQ has not been good and is around 50%. Although space-charge effect may play an important role, details have not yet been clarified. In order to study this and to optimize this efficiency, two emittance monitors will be installed just downstream PIG and 18 GHz ECR ion sources. Information from both this and the existing emittance monitor upstream the RFQ is expected to be useful for an improvement in η.

4.2 Automatic measurement of charge distribution after stripping

In order to understand the charge distribution after the stripper (100 $\mu g/cm^2$, carbon foil), an automatic device was developed. The current for the bending (analyzer) magnet is swept and the field strength (NMR) value is fed to a computer, while the excitation for Q magnets is also changed according to each *e/m*. The beam current is detected by a Faraday cup. In this case the transmission efficiency of the beams with various charge states (between the foil stripper and Faraday cup) is almost constant and close to 100%. Figure 3 shows an example for Fe ions, which agrees well with that of the theoretical calculations.

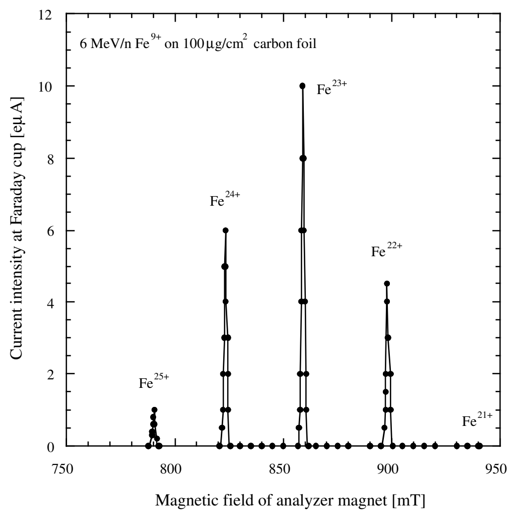

Fig.3 Charge distribution of Fe ions after stripping at 100 $\mu g/cm^2$ carbon foil with impact of 6 MeV/n Fe^{9+} ions. The fraction of Fe^{23+} is largest, and is usually used for the injection into the ring.

4.3 Beam profile monitor

Using secondary electrons (SE) from thin foils [10], a beam profile monitor has been developed [11]. The SE-type monitor is usually used for biophysical experiments, as a nearly non-destructive type in the energy region of 6 MeV/n. A clear profile can be measured for each pulse, under which the peak intensity is on the order of eμA. In order to vary the dose to the biophysical materials, the pulse width is usually changed by an electrostatic chopper (placed upstream the RFQ) between 1 and 350 μs at a repetition cycle of ~1 Hz. This monitor is also applicable to observe the micro-bunch structure of the linac beams with a risetime of 100 ps [12].

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