RECENT DEVELOPMENTS AT THE NIRS-HIMAC INJECTOR

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Abstract

At NIRS-HIMAC, 473 patients have already been treated using carbon beams by August, 1998. Therapy is scheduled in the daytime, while basic research is carried out during the nights and on weekends. Various ion species from Proton to Xenon have been used for basic research. Much effort was made to develop a time-sharing-acceleration system to well utilize the capability of three ion sources (PIG, 10GHz-ECR, 18GHz-ECR). Such recent developments in the injector are described in this paper. Several applications of linac beams with an energy of 6MeV/n are also briefly presented.

1 INTRODUCTION

Since 1994, HIMAC has been routinely used for both clinical trials of cancer therapy and basic research. Details concerning the HIMAC facility and its design philosophy have already been reported at linac and accelerator conferences [1, 2].

Taking account of an increase in both the number of patients and requests for basic experiments, it is necessary to effectively increase the available beam time and the kinds of ion species. During this year 16 themes in medicine, 64 in biology, and 47 in physics are actually being carried out in basic research. To answer these various requirements, a time-sharing-acceleration (TSA) scheme has been developed in the injector [3]. By using this scheme, three kinds of ion species can be simultaneously delivered from the injector to two synchrotron rings and a medium-energy (6MeV/n) experimental cave.

In order to expand the usable ion species, improvements in the ion sources have also been made. In order to precisely and actually measure the ion-stopping position in a human body, the application of positron emitter nuclei with a PET camera is in progress. A secondary-beam course was installed, and a preliminary test has been made for the production of ^{11}C by bombarding a thick beryllium target with high-energy ^{12}C beams through the reaction process of projectile fragmentation. The production rate of ^{11}C was around 0.2% and its purity 97%. A considerable increase in the primary beam is necessary to obtain sufficient intensity in the secondary beams for medical application; particularly developments in the ion sources are expected. Related improvements in the RF system of the injector are also necessary to stably accelerate heavy ions with an *e/m* of around 1/7, which corresponds to the maximum design value.

The above-mentioned developments in the injector are mainly discussed from the viewpoint of reliability; also, the status of some experiments in basic research using 6MeV/n beams (from the injector) are briefly reported.

2 TIME-SHARING ACCELERATION

2.1 Magnet

As previously mentioned, the purpose of this TSA-scheme is to simultaneously supply different ion species from three ion sources to three courses: two synchrotron rings and the medium-energy experimental course. Figure 1 shows a schematic drawing of the HIMAC injector. All of the DC magnets in the existing injector were replaced by pulsed magnets by the end of March, 1998. For designing these pulsed magnets, a response time of 100ms is necessary for the normal TSA operation, in which the injector is operated with a repetition rate of 3Hz at maximum and a typical pulse width of 1ms. Practical improvements and modifications concerning the beam diagnostic devices are under progress for routine TSA operation.

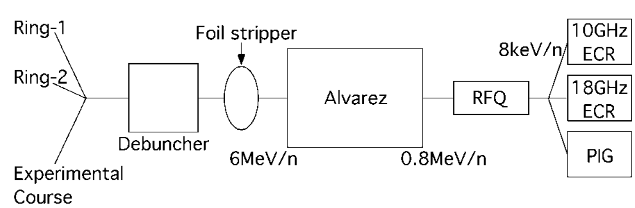

Fig.1 Schematic drawing of the HIMAC injector. Under TSA operation, one injector works as if it were three.

2.2 RF

An important point is to stably operate the RF system of RFQ and Alvarez cavities (100MHz) under different power levels, each of which corresponds to a different ion species (*e/m*). It is generally impossible to quickly control the tuning of cavities with mechanical tuners. In our case the highest power level is chosen; then, the tuning is optimized to this fixed condition. Although the cavities are not precisely tuned for the other two power levels, the RF operation is now satisfactorily stable for *e/m*-values between 1/2~1/6. Careful tests are now under way in terms of the stability for the case of very wide *e/m*-values, such as 1~1/7.

Another RF problem was occasional sparks in the final amplifier for Alvarez at a high power level. This phenomenon seems to mainly originate in the reflected power from the loop coupler of the Alvarez tank when sparking occurs, and to be enhanced at the amplifier output-cavity. It was thus difficult to stably accelerate heavy ions with an *e/m* of around 1/7. Concerning this problem, an idea has been tested, which is to slightly detune the amplifier output-circuit seen by the feedline, in order to make its impedance smaller at 100MHz and to suppress the amplitude of standing waves (SW). Along this line, a cold test was carried out by adjusting the position of a short panel in the output cavity while observing the SW-signal through the directional coupler, as shown in Fig.2. All of the results, including a high-power test, show that a frequency shift by 0.32MHz from 100.93 to 101.25MHz allows the amplitude of sparks to be reduced down to 30% with no reduction in the RF-power transmission. RF-down times due to sparks has thus become rare; it is possible to stably accelerate heavy ions, such as Xe^{20+}, though small sparks may still occur in the tank.

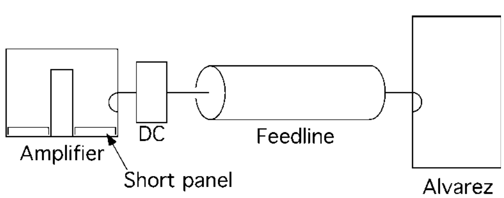

Fig.2 Schematic drawing between the final amplifier and Alvarez. A network analyzer is connected to a directional coupler (DC) to analyze the spectra of standing waves.

3 ION SOURCES

In the HIMAC injector, three ion sources have been operated in the pulse mode: PIG, 10GHz-ECR, 18GHz-ECR. All sources are normally operated at around 1Hz, according to the trigger pulses from synchrotrons; meanwhile the pulse width depends on the sources and elements. The detailed design of these sources has already been presented [4-6]. The present performance for typically-used ion species is listed in Table I. Each intensity is measured in front of the RFQ. In addition to Table I, several hundred eμA of N^{3+} and O^{3+} can also be easily supplied from three sources, though they are not usually used. Although the transmission efficiency between the source and RFQ is quite good for 10GHz-ECR (~70%), it has not yet been well optimized both for PIG and 18GHz-ECR, depending on the elements.

TABLE I. Typical peak intensities at the RFQ, in which the normalized acceptance is 0.6πmm·mrad. The transmission efficiency through the RFQ is about 93% for the below-listed intensity region.

PIG		10GHz-ECR		18GHz-ECR	
Elements	eμA	Elements	eμA	Elements	eμA
He^{1+}	550	H_2^+	360	Ar^{9+}	280
C^{2+}	650#1	C^{4+}	250	Fe^{9+}	35#2
Ne^{4+}	500	Ne^{4+}	350	Kr^{15+}	60
Si^{5+}	200#1	Ar^{8+}	200	Xe^{20+}	50#3
Ar^{7+}	300				

#1: by sputtering the graphite with (N_2+Ne) for C^{2+}, and the silicon single crystal with Kr for Si^{5+}.
#2: $Fe(C_5H_5)_2$ powder is used with O_2 for Fe^{9+}.
#3: abundance of ^{132}Xe is 27% and ^{84}Kr 57%.

3.1 PIG

In the typical production of Si^{5+} by PIG, the arc power is 6kW in peak (5A, 1200V), and the arc pulse width is 1.5ms; the duty factor is 0.15%. An extracted intensity of 400eμA has been routinely obtained by sputtering the silicon single crystal with Kr (~0.15cc/min). The stably-usable lifetime will be on the order of one week, depending on the arc power and elements; the recent results for Si^{5+} showed that it is 70hr with no adjustment. The electron bombardment power (~500W) to the upper cathode is stabilized in such a way that the error signal is fed back to the filament current, which is effective for stable operation in such a low-duty pulse mode. Figure 3(a) shows a pulsed beam-waveform of Ar^{8+}.

3.2 10GHz-ECR

Usually, carbon beams for radiotherapy are supplied from 10GHz-ECR with CH_4 (0.07cc/min); this source is basically maintenance free as long as gas materials are used. For the production of C^{4+}, the microwave power is about 500W with a pulse width of 8ms. An extracted intensity of around 350eμA has so far been routinely obtained owing to optimization for the position of the extraction electrode. A few hundred eμA of $^{13}C^{4+}$ and $^{36}Ar^{8+}$ are also produced for the nuclear physics experiments. Figure 3(b) shows a pulsed beam-waveform of C^{4+}.

3.3 18GHz-ECR

The production of heavy-metal ions has just started by using a newly-installed 18GHz-ECR with high extraction voltage (~60kV). For producing Fe^{9+}, $Fe(C_5H_5)_2$ powder has been preliminarily used with gas-mixing of O_2 (0.02cc/min). The lifetime is mainly subject to the amount of powder (0.15g at most), and the test results suggest that it is on the order of 70~80hr. Under the after-glow mode, a 45eμA of Fe^{9+} has been obtained from the source; the

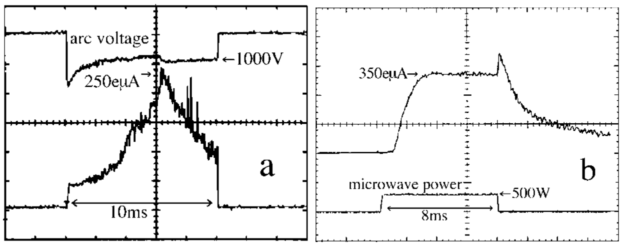

Fig.3 Pulsed beam-waveforms for PIG (a) and 10GHz-ECR (b). In such a low-duty pulsed PIG, the output of Ar^{8+} (highly-charged ions) is high during the early 6-7ms [4]. For the production of C^{4+} in the 10GHz-ECR, a smooth and rapid rising, and a clear afterglow-peak seem to be essential as an indication of stable operation.

microwave power is 1.2kW with a pulse width of 6ms. After its acceleration up to 6MeV/n, about 6eμA of Fe^{24+} or 10eμA of Fe^{23+} can be obtained by stripping through the thin carbon foil (100μg/cm^2). In the latter case, the usable intensity from the synchrotron is on the order of 1x10^{8}pps. The pulse width of the afterglow peak is about 1ms, which is sufficiently long compared to the injection time (~160μs) of a synchrotron ring. The sextupole magnet was optimized in order to expand an ECR zone (size of plasma), which resulted in an improvement of the yield by a factor 2-3 for gaseous ions; hence, 750eμA of Ar^{8+} and 400eμA of Ar^{9+} can be obtained from the source. Careful cleaning and sufficient aging of the gas-feeding quartz tube are essential to well maintain the source operation.

According to the requests from basic research groups, Mg^{5+}, Ca^{7+}, Ti^{7+} will be produced by PIG, and S^{5+}, Cl^{5+}, Ni^{9+} by 18GHz-ECR. B^{3+} and F^{4+} will also be tested by one of three sources.

4 BASIC RESEARCH

Several groups in atomic- and bio-physics have conducted experiments using 6MeV/n heavy-ion beams from the NIRS-HIMAC injector linac [7].

The projectile charge (z) dependence on the electron-emission rate from Al-foil (300μg/cm^2) has been measured using fully-stripped ions (He~Ar). The forward enhancement and its strong dependence on z were observed; the ratio between the forward and backward was 1.67 for z=18. This would be due to much forward δ-electrons pulled by the strong Coulomb field of the projectile in the outgoing projectile direction.

Through collisions with fully-stripped ions, the total ionization cross sections have been determined for both atoms and molecules with a good accuracy by using a parallel-plate electrode. Another group made a similar experiment using a secondary-ion mass spectrometer (magnet type).

Pulse-radiolysis experiments were carried out using He^{2+} in order to measure the time-dependent yields of water-decomposition products by the scavenger method. The product yields were found to be smaller than those determined by electron beams.

The energy loss of Ar^{18+} in a Z-pinch helium plasma has been observed using a TOF method. The standard Stark-broadening diagnostics gives an electron density ranging from 4 to 5x10^{17}/cm^3 for a helium plasma. The observed energy loss exceeds the value for cold helium gas, and agrees with the Bethe theory modified for the plasma.

The micro-structure of plasmid DNA (pBR322) irradiated with C^{6+} was analyzed using time-resolved fluorescence spectroscopy. The molecular behaviors of ethydium bromide (EB) intercalated between the base-pairs of DNA showed that the distance between the base pairs was expanded by 50% with the irradiation. The anticipated deformation in the double strand of the DNA has thus been proposed.

In order to strongly promote biophysical experiments, the dosimetory of C^{6+} beams has been conducted behind a thin Harvar (metal) foil with a thickness of 2.2μm and a diameter of 20mm. The results showed that the range of the beams was 14.2cm in air, and the long-time durability of this foil against the atmospheric pressure was satisfactory. A secondary-electron emission-type profile monitor (SEEM) has also been developed for irradiating biological materials, such as cells.

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