IH-DTL AS A COMPACT INJECTOR FOR A HEAVY-ION MEDICAL SYNCHROTRON

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Abstract

Compact linacs, consisted of a Radio-Frequency-Quadrupole (RFQ) linac and an Interdigital H-mode Drift-Tube-Linac (IH-DTL) having the same operating frequency of 200 MHz, were designed for an injector of heavy-ion medical synchrotrons. For beam focusing of IH-DTL, the method of Alternating-Phase-Focusing (APF) was applied. The total length of the RFQ linac and the IH-DTL is as short as 6 m. With the two linacs, carbon ions of $^{12}C^{4+}$, produced by an ECR Ion-Source (ECRIS), are accelerated to 4.0 MeV/u with the beam intensity of 380 eμA. The compact linacs were constructed and installed in NIRS. We have succeeded to accelerate carbon ions with the APF linac for the first time.

INTRODUCTION

With development of accelerator physics and technology, number of compact linear accelerators as well as cyclotrons has been constructed around the world, and is utilized for medical and industrial applications. At the National Institute of Radiological Sciences (NIRS), cancer therapy using energetic carbon ions, as provided by the Heavy Ion Medical Accelerator in Chiba (HIMAC), has been carried out since June 1994 [1], and more than 4,000 patients have been treated until now. With the successful clinical results, projects of constructing these accelerator complexes, dedicated to the cancer therapy, are initiated over the world. To construct such the complex, construction costs as well as a size of the complex itself are issue, because existing complexes are costly and large in size. Therefore, the development of cost-effective and compact accelerators for a hospital-based complex is needed for the increased use of the heavy-ion therapy.

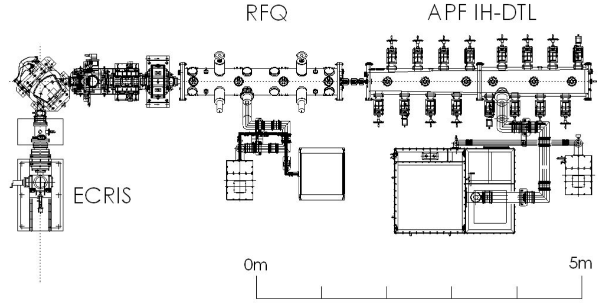

Figure 1: A schematic drawing of the compact injector.

In the development of the hospital-based accelerator complex, the design of an injector plays a key role, because the existing heavy-ion linacs such as Alvarez linacs are quite large. The size of the injector would affect the total size of the complex as well as total costs of construction. Therefore, we developed the compact injector for the heavy-ion medical synchrotrons.

The compact injector consists of the ECRIS and two linacs, which are the RFQ linac and the IH-DTL having the same operating frequency of 200 MHz. A schematic drawing and major parameters of the compact injector are shown in Figure 1 and Table 1, respectively. In this paper, design as well as performance of the compact injector is described.

Table 1: Major Parameters of the Compact Linacs

Parameters	RFQ	IH-DTL	Units
Injection energy	0.01	0.61	MeV/u
Extraction energy	0.61	4.0	MeV/u
Operating frequency	200	200	MHz
q/m	1/3	1/3	-
Cavity length	2.5	3.4	m
Cavity outer diameter	0.42	0.44	m

DESIGN OF LINACS

Beam Dynamics

Beam optics of the RFQ linac was designed by using the PARMTEQ code. By optimizing cell parameters for acceleration of $^{12}C^{4+}$, and using the rather high operating-frequency of 200 MHz, we could design the compact cavity; length and outer diameter of the cavity are 2.5 m and 0.42 m, respectively. The RFQ linac can accelerate carbon ions of $^{12}C^{4+}$ having 10 keV/u, as produced with the ECRIS, up to 608 keV/u. The normalized emittance of the extracted beam from the RFQ linac was calculated to be 0.68 π•mm•mrad.

Carbon ions, as extracted from the RFQ linac, are then accelerated with the IH-DTL up to 4.0 MeV/u. For beam focusing of the IH-DTL, the method of APF was applied [2]. This method utilizes the focusing and defocusing strengths as provided by the rf acceleration field by choosing the positive and negative synchronous phases alternately at each gap. By analogy with the principle of strong focusing, both longitudinal and transverse stability of beam motion could be obtained just with the rf acceleration field. By using this method, no additional

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focusing elements has to be installed in the cavity, making the cavity structure significantly simple as well as cost-effective. This also indicates that drift tubes can be designed smaller and shorter, and therefore allowed us to employ higher operating-frequency and lower injection-energy than ever before with conventional DTLs. Although the APF linacs have such the attractive features, it has never been practically used since it was first proposed in 50s, because the design of the synchronous phases is quite difficult, and focusing strengths of the rf field are generally weak.

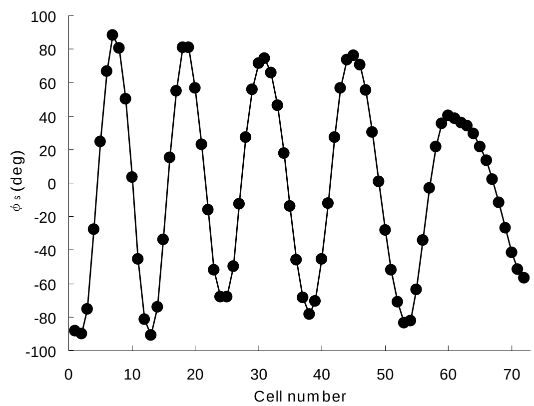

Figure 2: Synchronous phase as a function of the cell number.

Since the stability of beam motion for the APF linac relies only on the rf acceleration field, the entire characteristic of the beam dynamics depends strongly on a choice of the synchronous phase at each gap. Therefore, a major effort was devoted to optimize the phase array. By using a sinusoidal-like function to describe the phase array, as given in Figure 2, and performing beam dynamics simulations iteratively, we succeeded to optimize the phase array [3]. The calculated transmission was reached to as high as 99.6%. Parameters, calculated for the APF IH-DTL, are summarized in Table 2.

Cavity

The RFQ linac has a conventional four-vane structure. Since the technology of this structure is well-established, no special R&D work had to be done, and the design of the cavity was made with the well-known Superfish code.

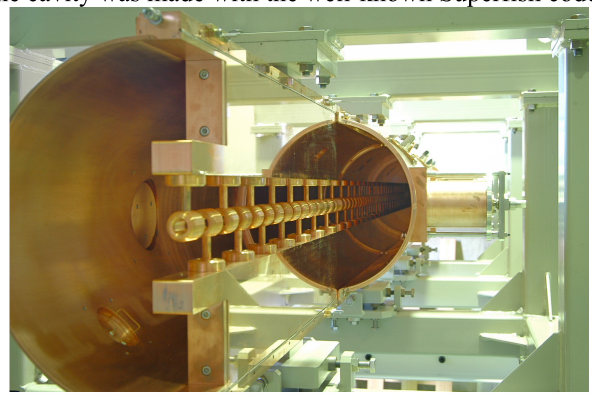

Figure 3: A picture of the model cavity (view from the downstream).

Table 2: Parameter Calculated for the APF IH-DTL

Parameters	Valu	Units
Number of unit cell	72	-
Trans. 90% emittance of injected beam (normalized)	0.68	π•mm•mrad
Trans. 90% emittance of extracted beam (normalized)	0.80	π•mm•mrad
Long. 90% emittance of injected beam	1.3	π•keV/*u* •ns
Long. 90% emittance of extracted beam	1.6	π•keV/*u* •ns
Momentum spread	±0.1	%
Transmission	99.6	%

For the APF IH-DTL, the IH structure was employed. The IH structure, which was first proposed in the 1950s, was known to provide high shunt impedance, and thus the rf power consumption would be significantly lower than that of Alvarez linacs at the energy range up to 10 MeV/*u* [4]. However, development of this structure was delayed against that of the Alvarez linacs, because the electric-field distribution could not be calculated precisely with existing two-dimensional electromagnetic-field solvers.

With the advent of three-dimensional field solvers, it became possible to calculate the electromagnetic field in the IH cavity. Although these solvers have recently been applied to design the cavities of linacs, the accuracy of the

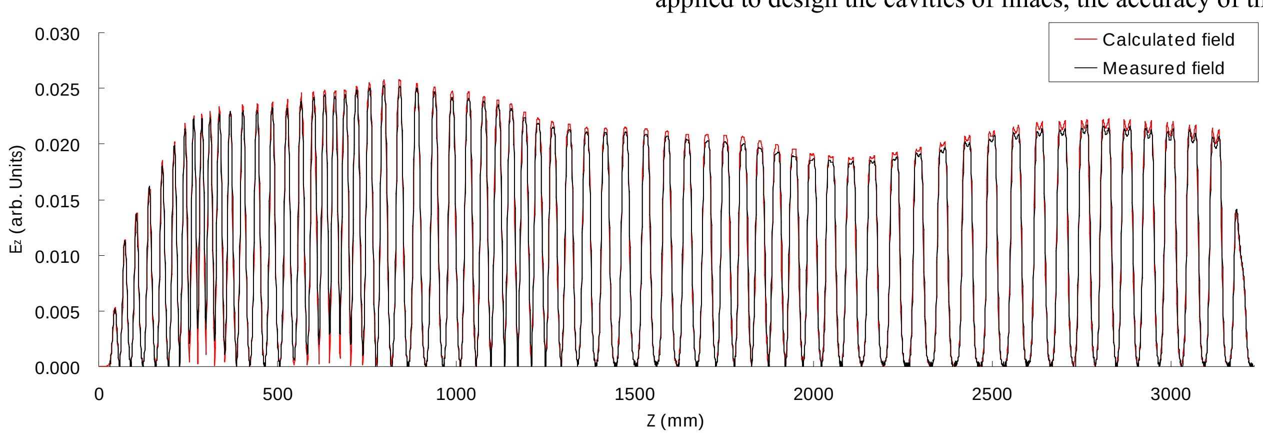

Figure 4: Electric field along the beam axis as functions of the beam coordinate, *Z*, for the model cavity. The black and red curves show the measured and calculated electric field with MWS, respectively.

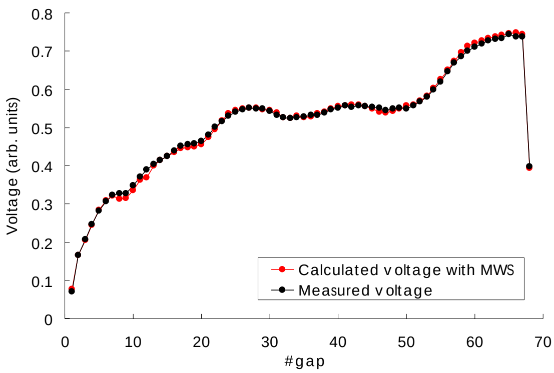

Figure 5: Gap voltages along the beam axis as functions of the gap number for the model cavity. The black and red dots show the measured and calculated gap-voltages, respectively.

solvers was not confirmed. Therefore, we constructed a full-scale model cavity of the APF IH-DTL, and compared its electric-field distribution with calculations.

A picture of the model cavity is presented in Figure 3. The length of the cavity is approximately 3.2 m, and the 67 drift tubes are installed on the upper and lower ridges. The cavity has four sections with different diameters to obtain a uniform electric field over the entire cavity. Fine adjustment of the electric field can be made with 15 inductive tuners, installed on the side wall, and end-ridge-cuts. All the cavity components were made with deoxidized copper.

The electromagnetic field of the model cavity was calculated with the three-dimensional solver, Micro Wave Studio (MWS) [5]. The calculated field is shown by the red curve in Figure 4. We see that the calculated distribution was rather uniform, although the field intensity around the first few gaps is lower than those for the rest of them.

The electric-field distribution along the center of the beam axis was measured using the perturbation method, and fine adjustments of the electric-field distribution with the tuners were made so as to reproduce the calculated field distribution. The measured field after the fine adjustments is shown by the black curve in Figure 4. We found that the measured field distribution agreed well with the calculated field with MWS.

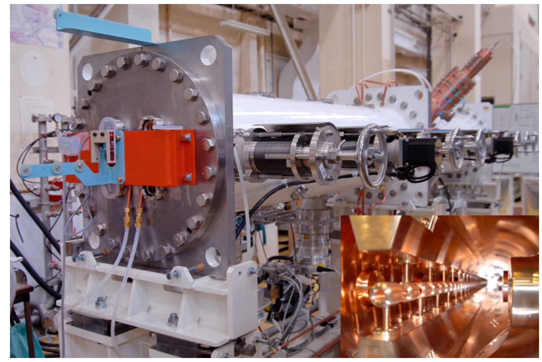

Figure 6: A picture of the APF IH-DTL during turning of the electric-field distribution in the cavity.

Having integrated the measured and calculated electric-field distributions, we could obtain the gap-voltage distributions as shown by the black and red dots in Figure 5, respectively. The overall voltages agreed with those calculated within an accuracy of ±2%. With these results of the comparisons, we concluded that the three-dimensional field solver would provide the sufficient accuracy in the calculated electric field.

The essential design of the model cavity was adopted to that for the cavity of the APF IH-DTL, although shapes of the drift tubes, ridges and structure of the tank were refined so as to accept the rf power for the acceleration of $^{12}C^{4+}$. To further obtain a uniform electric-field over the cavity, the inner diameter was designed to vary smoothly from 282.5 mm to 364.0 mm. Fine adjustments of the electric field were made with the 16 inductive tuners and the end-ridge-cuts as used in the model cavity.

A picture of the APF IH-DTL is shown in Figure 6. The electric-field distribution was measured with the perturbation method, and finely adjusted with the tuners so as to reproduce the designed electric-field distribution, which was calculated with MWS and used in the beam dynamics simulations as described previously. The measured and designed electric-field distributions are shown by the black and red curves in Figure 7, respectively. We see that the electric-field distributions are quite uniform as compared with that for the model cavity, because of the smooth change in the inner diameter. The measured and designed gap-voltage distributions, as calculated by integrating the electric-field, are shown by

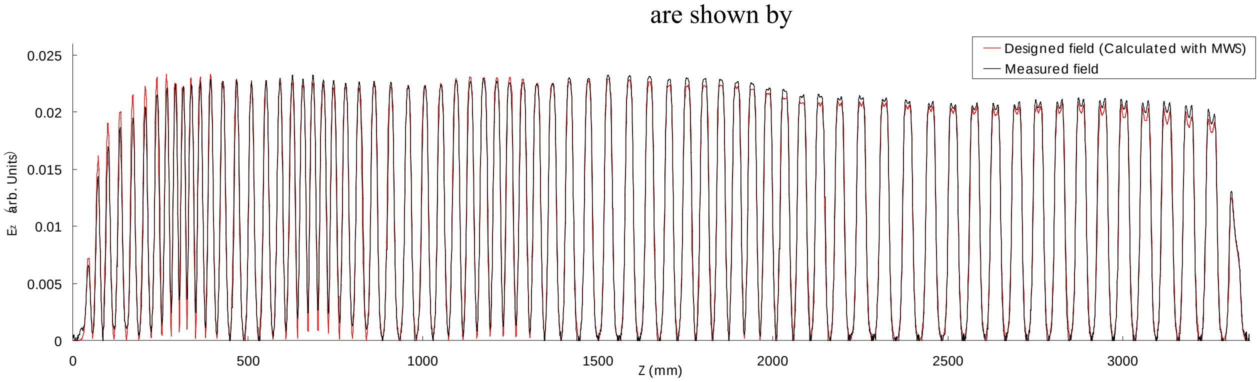

Figure 7: Electric field along the beam axis as functions of the beam coordinate, Z for the APF IH-DTL. The black and red curves show the measured and designed electric field, respectively. The designed field was calculated with MWS.

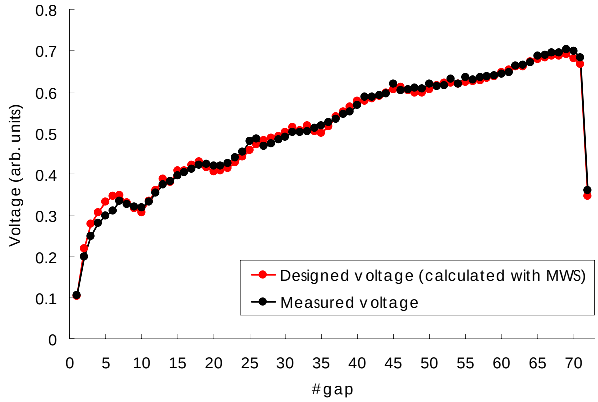

Figure 8: Gap voltages along the beam axis as functions of the gap number for the APF IH-DTL. The black and red dots show the measured and designed voltage, respectively.

the black and red dots in Figure 8, respectively. Although the measured and designed voltages around the first few gaps differ by 10%, most of the gap voltages were tuned to the designed voltages within a tolerable accuracy.

The quality factor of the cavity after the tuning of the electric-field distribution was measured to be Q_m=12,000, corresponding to 80% of the calculated value with MWS, Q_c=15,000 Considering the measured quality factor, the required rf power was estimated to be approximately 360 kW. The effective shunt-impedance was calculated to be 110 MΩ/m, which is remarkably higher than those of conventional linacs.

BEAM ACCELERATION TESTS

ECRIS and RFQ Linac

Prior to complete the entire compact-injector system, a beam acceleration test with the ECRIS and RFQ linac was made. The ECRIS and the RFQ linac were installed with the low-energy beam-transport (LEBT) line. To determine characteristics of the accelerated beam from the RFQ linac, a beam analyzing line, consisting of beam-transport and diagnostic devices, was placed downstream of the RFQ linac. In the test, the beam currents were initially measured with Faraday cups, FCN1 and FCN2, which located upstream and downstream of the RFQ linac, respectively. The measured currents of $^{12}C^{4+}$ with each cups were I_{FCN1}=412 eμA and I_{FCN2}=334 eμA. The corresponding transmission through the RFQ linac was

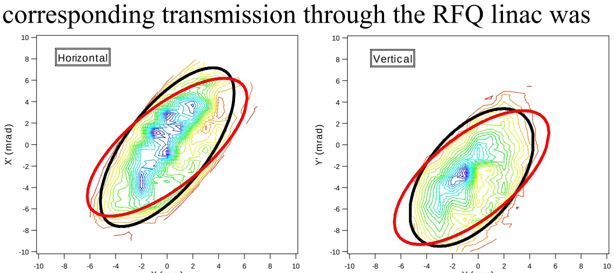

Figure 9: Contour plots show the horizontal and vertical phase-space distribution of a carbon beam from the RFQ linac (see text).

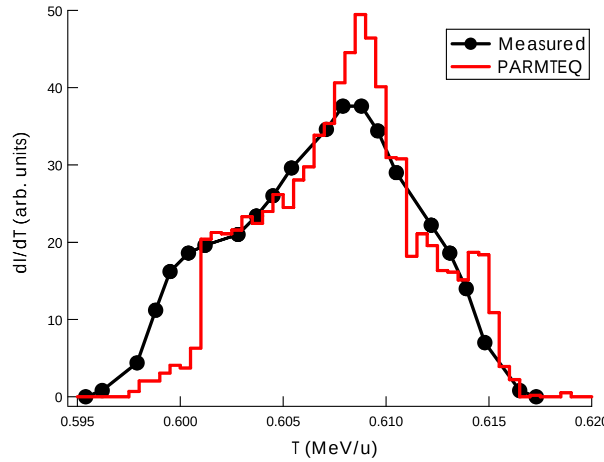

Figure 10: Kinetic energy distributions of a carbon beam from the RFQ linac. The filled dots and histogram show the results of the measurement and a PARMTEQ calculation, respectively.

estimated to be $\tau_{RFQ}= I_{FCN2}/ I_{FCN1}$=81%. Transverse phase-space distributions of the accelerated beam were measured using emittance monitors, installed in the beam analyzing line. The results are shown by the contour plots in Figure 9. The normalized values of horizontal and vertical 90% emittances were determined by fitting the distributions with an ellipse to be 1.02 and 0.954 π•mm•mrad, respectively, which are larger by 30% than those calculated with the PARMTEQ code. For a direct comparison, the calculated distributions showing the 90% emittance are also plotted by the red curves in Figure 9.

The accelerated beam was analyzed, and a kinetic-energy distribution was determined as shown in Figure 10. The result of the PARMTEQ calculation is also plotted by the histogram in the figure. The average energy was calculated with the measured distribution being $\langle E \rangle$=608.1 MeV/u, which is in good agreement with the designed value.

Entire Compact-Injector System

Finally, the APF IH-DTL was installed downstream of the RFQ linac to perform the beam acceleration test of the entire compact-injector system. The beam analyzing line was realigned downstream of the APF IH-DTL. The beam current of $^{12}C^{4+}$ having 4.0 MeV/u as accelerated with the APF IH-DTL was measured to be 380 eμA. With the known transmission of the RFQ linac, τ_{RFQ}~81%, and

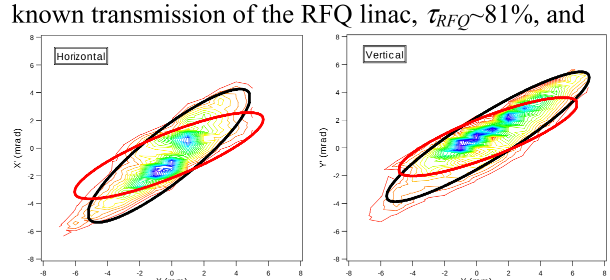

Figure 11: Contour plots show the horizontal and vertical phase-space distribution of a carbon beam from the APF IH-DTL (see text).

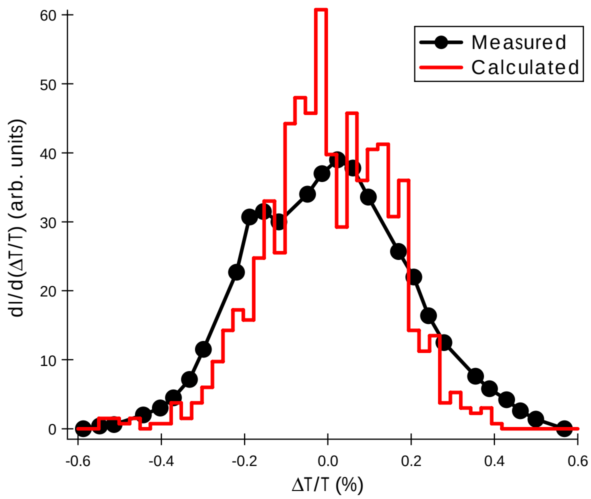

Figure 12: *ΔT/T* distributions of a carbon beam from the APF-IH-DTL. The filled dots and histogram show the result of the measurement and a tracking simulation, respectively.

measured current of the ECRIS during the test, I_{FCN1}=490 eμA, the transmission through the APF IH-DTL was estimated to be $\tau_{IH}=380/(I_{FCN1}\times\tau_{RFQ})$~96%, which is comparable with the calculated value of 99.6%.

The phase-space distributions were measured as shown by the contour plots in Figure 11. For a comparison, the calculated distributions showing the 90% emittance are also plotted by the red curves in Figure 11. The normalized values of the horizontal and vertical 90% emittances were estimated to be 1.09 and 1.11 π•mm•mrad, respectively, which are larger than the calculated values; this might be attributed to the small emittance of the injected beam, as used in the calculation.

A kinetic energy distribution was measured, and the average energy was determined to be $\langle E\rangle$=4.000 MeV/*u*, which was slightly lower than the calculated energy of 4.029 MeV/*u*. However, as seen in the measured and calculated *ΔT/T* distributions, plotted in Figure 12, the measured energy spread of $\Delta T/T=\pm0.4\%$ is comparable to that calculated with the simulation.

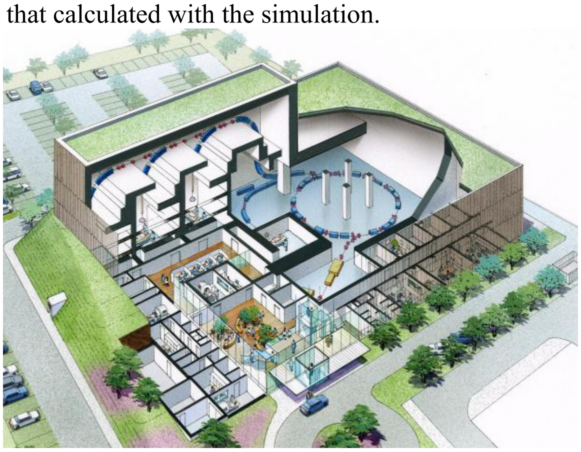

Figure 13: A schematic drawing of the compact therapy complex for the Gunma University.

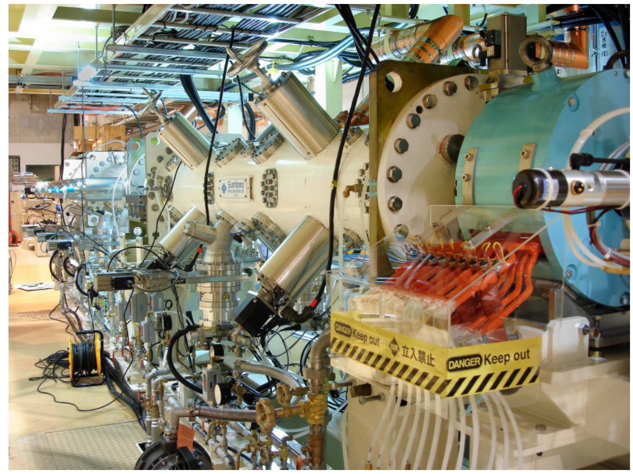

Figure 14: A picture of the compact injector system, as installed in the injector room of the HIMAC.

PRESENT AND FUTURE PLAN

With these successful results of the beam acceleration tests, the design of the compact accelerator complex for the heavy-ion therapy had been completed, and the construction of the first compact complex started at the Gunma University. As shown in Figure 13, the compact complex consists of the injector, synchrotron ring and three treatment rooms. The design of the injector is identical to that, described here. Installation of the injector was completed, and we expect to have a first beam on the treatment rooms in next autumn.

Our compact injector was reinstalled in the injector room of the existing HIMAC complex, and will be used as a second injector. To provide carbon beams for the HIMAC synchrotrons, we are currently constructing a beam transport-line downstream of the APF IH-DTL.

SUMMARY

The compact injector, consisting of ECRIS and two linacs, which are the RFQ and the APF IH-DTL, was designed and constructed. The acceleration tests were performed, and we have succeeded to accelerate carbon ions with the APF linac for the first time. The results of the tests demonstrated its excellent performance.

The total length of the two linacs was reduced to approximately 6 m, which is considerably shorter than that of the existing heavy-ion linacs. With this successful result, the construction of the first compact therapy complex had started at the Gunma University.

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