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DEVELOPMENT FOR BEAM INJECTOR USING LASER-DRIVEN ION ACCELERATION

H. Sakaki†, S. Kojima, T. -H. Dinh, M. Hata, T. Miyatake, M. Nishikino, T. Shirai, K. Kondo
QST, Kyoto, Japan
K. Ohtomo, H. Tsutsui, Sumitomo Heavy Industry, Tokyo, Japan
H. Kuroki, N. Inoue, Hitachi Zosen, Osaka, Japan
H. Matsumoto, Kyushu Univ., Fukuoka, Japan
S. Oishi, A. Okano, K. Ishii, Nara-Women's Univ., Nara, Japan

Abstract

A quarter of a century has passed since the discovery of the mechanism of laser-driven ion acceleration [1, 2]. This mechanism makes a compact ion accelerator than the present accelerators, and many applications, especially an ion therapy, are proposed on the ion user's studies. To develop ion applications, it is necessary to increase the beam delivery efficiency using in the beam line adapted to the characteristics of the energetic ions transported. However, 25 years after the discovery of laser-driven ion acceleration with ultrashort pulsed high-current ions, there are currently no benchmark codes to simulate its transport system for application. We are beginning to construct a prototype of laser-driven ion injector for benchmarking and to investigate the beam parameters in a simulation. In this report, we describe our ongoing project "Quantum Scalpel" for heavy ion therapy using laser-driven ion acceleration and the commissioning of a prototype for this application.

QUANTUM SCALPEL PROJECT

HIMAC in Japan, a facility dedicated to heavy particle therapy, has been in operation since 1996. HIMAC had a huge site area of 120 x 65 m to accelerate various heavy-ions other than carbon beams, which are usually used for heavy particle therapy.

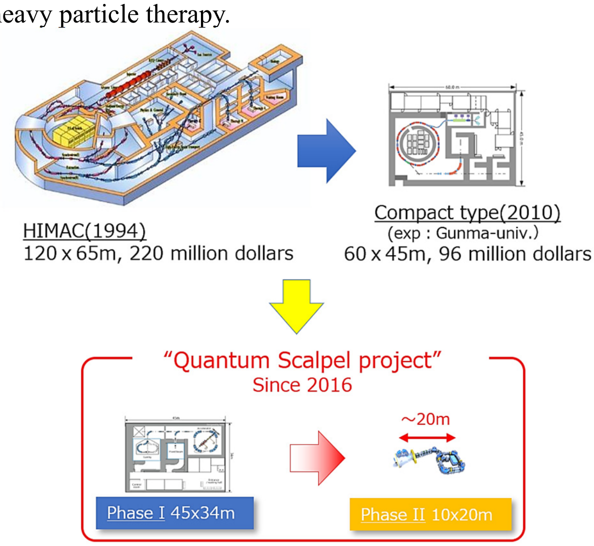

Figure 1: Accelerator for advanced heavy-ion therapy in Japan.

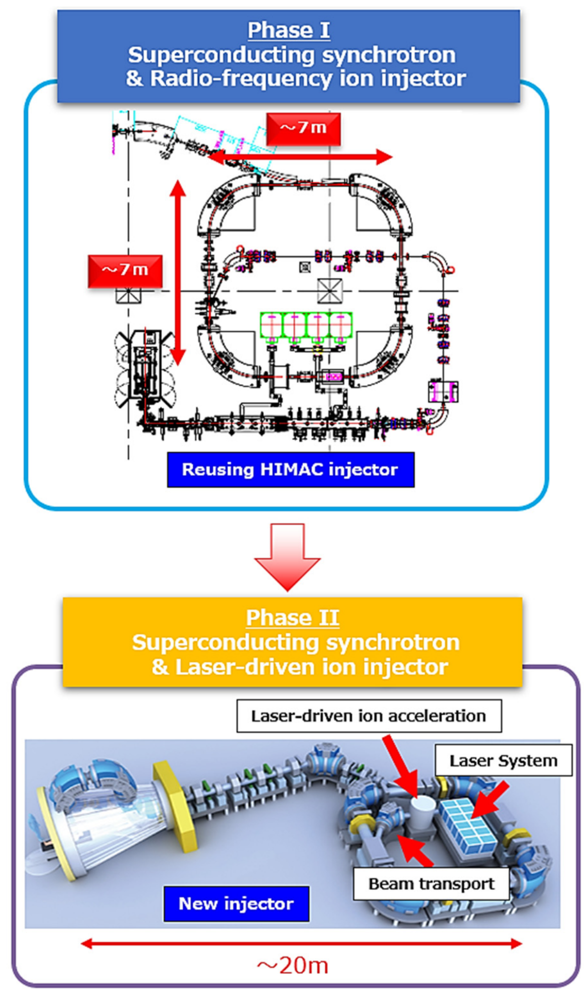

Figure 2: General view of Quantum scalpel project.

A dedicated 60 x 45 m carbon therapy facility was developed around 2010. However, it was also too large to be installed in an urban area in Japan, so a downsizing project, Quantum Scalpel [3], with novel ion acceleration technologies was started in 2016. The project was named "Quantum Scalpel" to describe the quantum-effect ion beam those cuts through the affected area like a surgical scalpel. The project is divided into two phases. In Phase I, an accelerator unit will be built in a newly developed 7 x 7m superconducting synchrotron using the current high-frequency ion injector: reusing HIMAC injector.

† email address: sakaki.hironao@qst.go.jp

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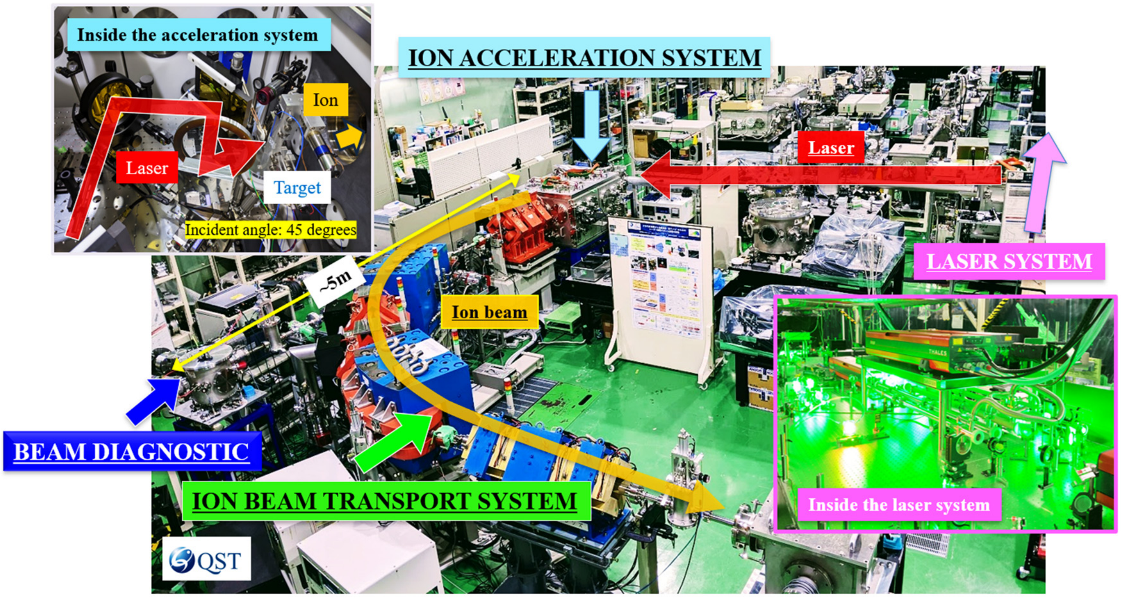

Figure 3: Photograph of the prototype ion acceleration injector consisting of laser system, ion acceleration system, and ion beam transport system (straight beam line).

In Phase II, the facility will be built in a superconducting synchrotron with injectors using laser-driven ion acceleration, aiming at a size of about 20 m including the superconducting gantry (Figs. 1 and 2).

PROTOTYPE OF LASER-DRIVEN ION INJECTOR

The project requires a 4 MeV/n carbon beam from the laser-driven injector towards the synchrotron. However, the laser system installed in the test bench can currently deliver only ~1 J on-target, so we planned to obtain benchmark data on carbon below 1 MeV/n (the magnetic rigidity of the system: Bρ=0.407 Tm). When the beam transport system with this value of Bρ, it will obtain enough data for benchmarking beam transport. We reused the system used in the SPring-8 injector LINAC, which was shut down after upgrade to the new injector SACLA, to obtain benchmark data as soon as possible. This system in the SPring-8 injector LINAC is a 250 MeV electron beamline used for beam diagnostics in the electron-positron conversion section and consists of a 35 T/m Quadrupole-triplet (Q-triplet), two 1.3 T bending magnets and a 12 T/m Quadrupole-doublet. Although the diameter of the beam pipe is small for ion transport with an inner diameter of 35 mm, Bρ of the 250 MeV electron is 0.833 Tm, this value is prioritized for a benchmarking system. The prototype laser-driven ion injector is constructed by combining a laser system, an ion acceleration system that includes a taped laser irradiation target, and an ion beam transport system reused from the SPring-8 injector LINAC, in Fig. 3.

BEAM COMMISSIONING

To generate high energy ions, the incident laser, Ti:sapphire laser beam (wavelength: 800 nm), is p-polarized at an angle of 45 degrees to the target normal. The laser, approximately 50 mm diameter, is focused by an f/2.7 off-axis parabolic mirror (OAP). The laser is focused by the OAP to a diameter of approximately 6 µm (FWHM). The laser has an energy of about 700 mJ (on target) and an ultrashort pulse with a duration of 40 fs (FWHM). Thus, the final focused intensity of the laser on the target surface is about 6×10^{19} W/cm^2, and the time domain profile of the laser has a high contrast of $<10^{-9}$. The target base material is 7.5 µm thick polyimide, since the benchmarking started with the diagnosis of the proton beam characteristics.

Beam Diagnostic

The accelerated ions are measured with an energy diagnostics using a Thomson Parabola Spectrometer (TPS) [4] and an Emittance diagnostics using Q-scans at the Q-triplet. A schematic diagram of the straight beam line diagnostic system is shown in Fig. 4. Laser-driven accelerated ions are transported to the beam diagnostic system while being focused by the Q-triplet found 40 cm away from the target. The beam diagnostic system is equipped with a TPS or a Scintillator screen (for the Q-scans), and the Thomson parabola shape of the proton beam and the transverse shape on the screen are recorded by a camera.

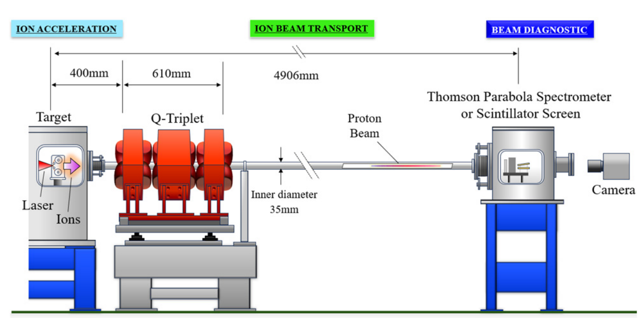

Figure 4: Straight beam line diagnostic system.

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Proton Beam Energy

The beam energy without and with the Q-triplet magnetic field gradients are diagnosed by the TPS. Figure 5 (A) shows the TPS measurements for the case where the Q-triplet is 0.0 T/m, and (B) shows the case where a magnetic field gradient of QT-1=2.71, QT-2=-3.52, and QT-3=3.41 T/m is applied to the Q-triplet. Note that in the figure the light purple line of the design proton trajectory overlaps the black line of the actual trajectory data. In the 0.0 T/m case, there are parabola lines for protons with a cutoff energy of 2 MeV and carbon of multiple charges. In the case with the magnetic field gradients, its measures mainly protons at 1.36 ± 0.06 MeV (dE = ~4.4%).

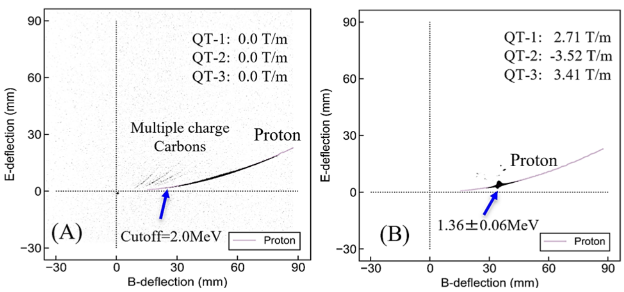

Figure 5: TPS results of without and with the Q-triplet magnetic field gradients

Quadrupole Scan

An emittance measurement is performed by Quadrupole-scan (Q-scan) with varying the magnetic field gradient of the third magnetic field of the Q-triplet. The experimental data of the screen measured by varying the magnetic field of QT-3 are shown in Fig. 6. In the case of the smallest beam size case, the beam centre size is focused to ~1 mm φ.

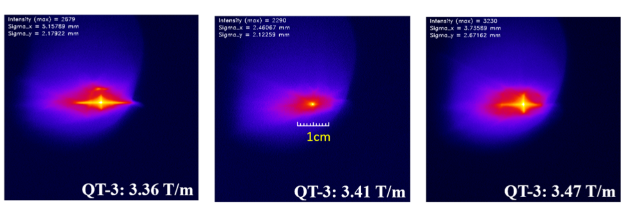

Figure 6: Focused beam profile by the Q-scan.

Emittance is obtained from the profile of the Q-scan, which shows the beam size in x (Fig. 7-A) and y (Fig. 7-B) with varying K values. Due to the imperfect performance of the laser beam in the current laser system, the beam profile fluctuates with each shot. This effect is transferred to the ions, and the ion beam profile is not stable. The normalize-rms-emittance obtained from these data is 0.168 π mm-mrad for x and 0.064 π mm-mrad for y. The x-direction is worse than the y-direction, but this may be due to the laser spot shape being a long ellipse in the x-direction since the angle of incidence to the target is 45 degrees. Laser-driven ion acceleration produces ions from a point source with a small spot size, so this value is better than that of a generalized ion source, non-laser-driven type. However, compared to other laser-driven ion acceleration data using similar laser system, the value is about three times worse [5]. The reasons for this may be that we use a thicker target with larger incident angle, no energy filter on the scintillator screen (the beam size is affected by dE), and that the cutoff energy of the protons is less than half due to imperfect laser stability. These issues will be the subject of improvements in future.

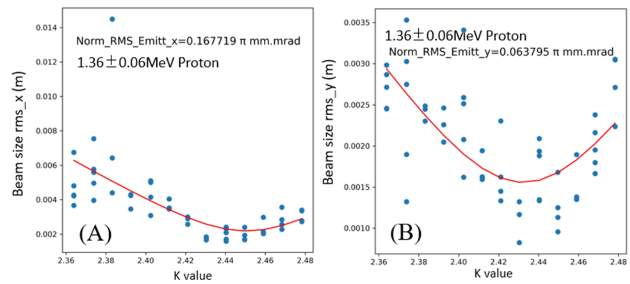

Figure 7: Beam size vs K values data by the Q-scan.

CONCLUSION

For the early realization of the applications, it is necessary to complete the benchmarking of simulations to set up a code for the design of a laser-driven ion acceleration injector. To this goal we have completed the prototype injector and started commissioning. We are particularly interested in understanding the characteristics of carbon ion beams from laser-driven ion acceleration as soon as possible. And we will create a benchmark Particle In Cell (PIC) code [6] that provides a seamless connection between laser-driven ion acceleration (micro range) and the synchrotron (macro range) by 2027, and use this code to design a demonstration laser-driven ion injector ready by about 2030.

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