DESIGN STUDY OF A DPIS INJECTOR FOR A HEAVY ION FFAG *

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Abstract

A new heavy ion injector linac is proposed for providing heavy ion beams to a fixed field alternating gradient (FFAG) accelerator in Kyushu University. A combination of the new intense laser source based injector and the FFAG will be able to accelerate high current ion beams with 100 Hz of a repetition rate. The planned average current reaches 7 µA with carbon 6+ beam.

A NEW INTENSE PULSED ACCELERATOR

To obtain large beam power within a limited space, cyclotrons have been chosen since they provide CW beams even with relatively small peak beam current. In this report, we propose a new approach to utilize comparatively large beam power using a laser ion source and a FFAG synchrotron accelerator.

Generally a synchrotron can have larger peak current than cyclotron has, however most of the time is occupied for ramping up and down the bending magnets in the operation and the beam pulse width is very limited. To increase the total beam power, it is effective to have high repetition rate. The maximum repetition rate is about 1 to 25 Hz for normal conducting synchrotrons [1]. Recently FFAG accelerators are being focused as high repetition synchrotrons and some FFAGs have already been built by KEK and Kyoto University groups both lead by Y. Mori [2]. It has been proved to operate it at 100 Hz in KEK and possibly it will run at 1 KHz. Also FFAG has large transverse acceptance and is expected to deliver large current.

A laser ion source (LIS) has an advantage to induce a powerful pulsed beam and can operate at high repetition rate which is restricted by a driver laser system. A typical flash lamp pumped solid laser can reach 100 Hz and a LED pumped laser easily achieves above 1 kHz operation with good stability. Hence both a laser source and a FFAG are operational at same high frequency range. Since a LIS can provide large current, beam losses in a transport line which connects from the ion source to a first stage accelerator, typically RFQ, was always tough issue. To overcome this difficulty caused by space charge effect, direct plasma injection scheme (DPIS) has been studied. Using the DPIS, several tens of mA heavy ion beams have been accelerated effortlessly in an RFQ [3]. A rapid cycle LIS with DPIS and a high current heavy ion RFQ suit a FFAG well to boost the beam power.

In Kyushu University, a new facility called "Center for accelerator and beam applied science" is established [4]. A new building was already constructed to accommodate a FFAG accelerator which was originally designed and constructed in KEK as a prototype 150 MeV FFAG. The installation of the FFAG to the new building is in progress. A small proton cyclotron will be used as an injector in the first stage and in the next stage we plan to install a new injector system to provide heavy ions for various application including medical, engineering studies and educational activities. A photo of the FFAG and its design parameters are shown in Fig. 1 and Table 1.

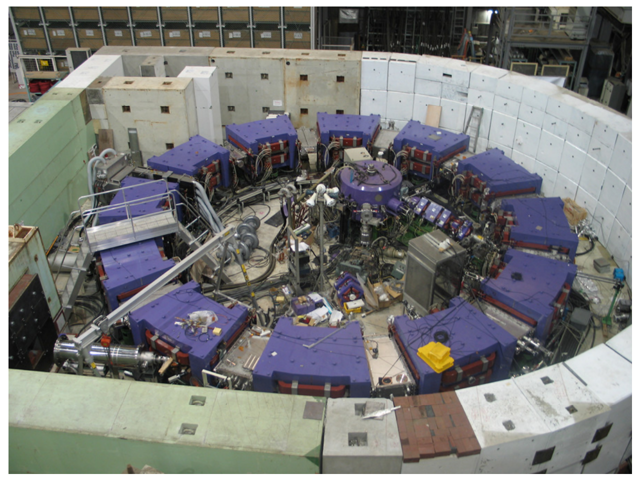

Figure 1: 150 MeV FFAG in KEK.

Table 1: Design Parameters of 150 MeV FFAG

Energy	10 – 125 MeV (proton) 2.5 – 31 MeV/u (C^{6+})
Type of magnet	Triplet radial (DFD)
Number of cell	12
Average radius	4.47 – 5.20 m
Magnetic field	Focus: 1.63 T Defocus: 0.78 T
Revolution Frequency	1.5 – 4.2 MHz (proton) 0.78 – 2.3 MHz (C^{6+})
Repetition rate	100 Hz (2 RF cavities)

The proposed heavy ion injector will accelerate fully stripped ion beams up to 2.5 MeV/u with the highest available current which will be induced by a conventional table top laser system with the DPIS.

LASER ION SOURCE

Beam Pulse Width

The harmonic number of the FFAG ring is one and revolution period at the injection energy is 1.28 µs. With single turn injection scenario, the required beam pulse

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width is about 1.2 - 1.3 μs with adiabatic beam capturing which can build up the distributed beam over the 360 degree of the injection RF cycle. Using the DPIS, we can provide sufficient number of particles with the short period. In this case, we can assume the acceleration RF phase of the FFAG at the beam injection. If the Separatrix occupies 150 degree of phase acceptance, the required beam pulse width is 0.53 μs. The LIS was designed to produce slightly longer than 0.53 μs of the pulse duration.

Laser System

We assumed a flush lamp driven Nd-YAG laser as a driver since it is commercially available and has good stability (typically a few %). To provide fully stripped ions from light to medium species efficiently, more than 1 J per shot of the laser energy is recommended. To obtain 100 Hz operation, it may need to have multiple oscillators. Table 2 shows the planned laser parameters for the injector.

Table 2: Laser Parameters for FFAG LIS

Media	Nd - YAG
Wave length	1064 nm
Oscillator	2 stages (multiple)
Pulse width	5 - 7 ns (Q switched)
Energy	1.5 J
Repetition rate	100 Hz

Induced Ions from the DPIS Geometry

A LIS consists of a laser, a target material and extraction electrodes. Particularly in the DPIS, RFQ vanes are used as negative electrodes of the extraction system. The positive electrode, plasma target and the space between them are all biased to high voltage which corresponds to the injection energy of the RFQ. Firstly a plasma induced by a laser shot on the target. The plasma is started to expand and is ionized during laser irradiation, typically in several ns. After ionization, the plasma keeps expanding like a cloud and the gravity center of the cloud moves perpendicular to the target surface. All these processes appear in the enclosed space by a high voltage cage. At the beam extraction point, the ion beam begins when the head of the plasma cloud reaches and ends when the tail passes. The moving velocity of the plasma and its distribution are determined by a laser power density on the target. However we have the minimum laser power density since fully stripped ions, like C^{6+} is required. The laser power density should be more than 10^{12} W/cm^2. To optimize the beam pulse width, the drift length is adjusted around 0.5 m. The expected peak current of the C^{6+} beam reaches about 300 mA assuming the positive extraction hole of 8 mm in diameter.

Expected Beam Characteristics

Assuming the irradiation condition, we measured charge states distributions from a carbon graphite target in BNL. Thales – SAGA 230/10 laser system was used and the laser energy was set to 1.5 J. A convex mirror were placed 100 mm from the target surface. The incident angle to the target was 15 degree off from the perpendicular line. Figure 2 shows the expected charge distribution and the currents converted from the measured data. The pulse length of C^{6+} beam was 0.63 μs (above 10% of the peak value). The experimental setup was same as described in ref. [5].

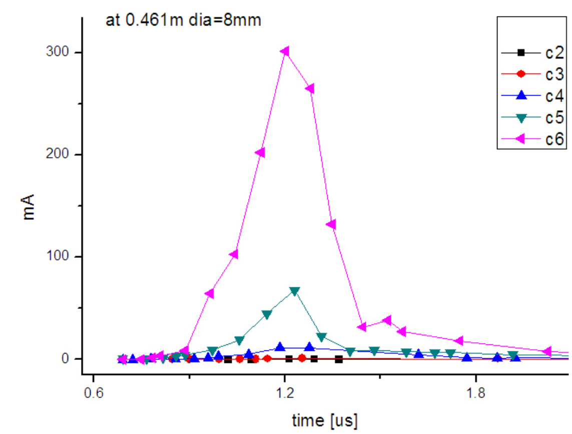

Figure 2: Re-constructed currents based on the measurements.

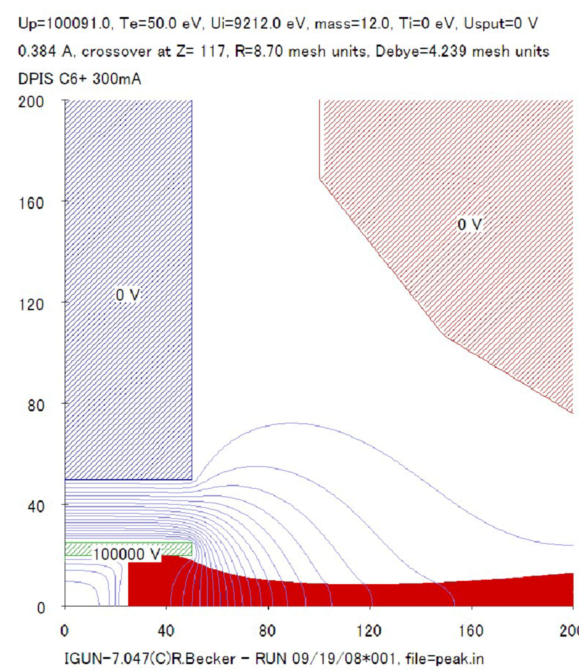

Figure 3: Beam extraction simulation by IGUN.

The beam extraction condition of C^{6+} beam with small fractions of other charge states was simulated by using IGUN [6]. The applied bias voltage is 100 kV to obtain a matched condition of the extraction. Table 3 shows the Twiss parameters of the predicted beams at the peak current. The study of other species production is in progress.

Table 3: The Simulated Extracted Beams

	Current (mA)	ε rms (mm mrad)	α	β (mm/rad)	γ (rad/mm)
C^{4+}	11.9	35.7	1.16	63.7	0.0369
C^{5+}	62.1	35.5	1.16	63.7	0.0368
C^{6+}	300	35.5	1.16	63.7	0.0368

RFQ

The RFQ was designed to be fit into the inside of the FFAG ring. By adopting the DPIS, the ion source part can be made very compact. The plasma drift length is about 0.5 m and the entire source part needs around 0.7 m in length. The injection energy was given by the plasma extraction condition as 100 kV (50 keV/u). The kilpatrik limit factor (14.7 MV/m at 200 MHz) was set to 2.3 supposing a vane tip curvature equals to the average bore radius. Since the required beam pulse length is short and the probability of RF break down will be small even adopting a high bravery factor. Also by controlling the multpole components in the field, a smaller vane tip curvature can be applied and the electric field strength can be reduced. The operation RF frequency was chosen as 200 MHz due to an availability of an existing RF amplifier. The design parameters of the RFQ are summarized in Table 4.

Table 4: DPIS RFQ for FFAG

Energy	0.05 – 2.5 MeV/u
Cell number	215
Vane length	4.28 m
Frequency	200 MHz
Inter-vane voltage	140 kV
Average bore radius	5.0 mm
$m_{max.}$	2.25
$a_{min.}$	2.9 mm

The power consumption was estimated as 580 kW by scaling from an existing 4-rod DPIS RFQ. The beam pulse is much shorter than the RF build up time, so that the duty factor of the RFQ is determined by a Q value of the cavity. Assuming 5000 of the Q value, the duty factor is about 2.5 %. Since the beam pulse is only 0.5 µs, the effect of the beam loading will be negligible. The tracking simulations in the RFQ were done by using PARMTEQ [7] and Pteq-HI [8]. In the Pteq-HI calculation, three charge state ions, C^{4+}, C^{5+} and C^{6+}, were tracked simultaneously. The peak currents shown in Table 3 as the input beam condition resulted 205 mA of the accelerated C^{6+} current. The beam spread in the longitudinal phase space is shown in Fig. 4.

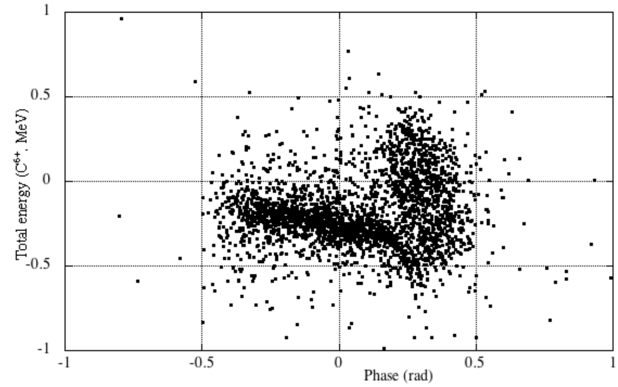

Figure 4: Simulated C^{6+} output beam in longitudinal phase space.

The simulation based on the above discussion predicted that the RFQ provides average current of 8 µA to the FFAG.

CONCLUSION

A new injector using DPIS was designed to accelerate C^{6+} beam with a 200 MHz RFQ. The laser ion source will provide 300 mA C^{6+} beam and the RFQ will provide 186 mA at peak. If we assume 10 % and 5 % beam losses at the beam injection and extraction of the FFAG The average output current will be 7 µA. The total beam power will be 400 W. Let us note that we adopted 100 Hz as the repetition rate of the entire accelerator system in the discussion, however it can be increased up to 1 KHz by modifying the RF system of the FFAG and the laser system.

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