ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB208

ENERGY SWEEPING BEAM EXTRACTION BY THE SEPTUM MAGNET ASSISTED WITH CHARGE EXCHANGE FOR A HADRON THERAPY

T. S. Dixit†, A. Shaikh
Society for Applied Microwave Electronics Engineering & Research (SAMEER), Mumbai, India
T. Kawakubo, T. Adachi, K. Takayama
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

An energy sweeping compact rapid cycling hadron therapy based on a fast cycling induction synchrotron has been proposed by KEK and SAMEER as the next generation of hadron therapy machine. For energy sweep extraction, a C5+ beam is injected, captured and trapped in the barrier bucket. A fraction of the beam is continuously released from the barrier bucket by controlling the timing of barrier pulse generation. Released C5+ ions merge into the coasting beam and moves inwards with ramping of the guiding main magnets. Ions in the coasting beam eventually hit the carbon foil placed inside the beam chamber wall. As a result, C5+ is converted to C6+ and beam orbit is largely changed as it traverses through the downstream bending magnet. This notably facilitates C6+ beam extraction, resulting in a relatively small kick angle of the septum magnet. When the septum is excited in the same way as that of the main magnets, the extracted C6+ beam always places on the center of the irradiation beam line. LISE++ simulations demonstrated the charge exchange efficiency of almost 100% for expected beam energy. The feasibility of the switching power supply for the septum magnet has been studied.

INTRODUCTION

Energy sweeping compact rapid cycling hadron therapy (ESCORT) [1] based on a fast cycling induction synchrotron [2] has been proposed for the next generation of hadron therapy, and KEK and SAMEER are currently collaborating on the engineering design work. ESCORT has two notable features: a hadron beam bunch is extracted in 1 turn at an arbitrary timing and with a desired energy, and a continuous beam is extracted for a desired duration with an expected energy variation in time. It is crucial that the extraction timing and energy in the 1 turn extraction and the extraction time duration and energy range in the energy sweep extraction can be changed cycle by cycle, although the driver accelerator is always operated in the same repetition pattern of 10 Hz. Generally, a combination of a kicker magnet and septum magnet is used for the 1 turn extraction of a C6+ beam. Beam extraction at an arbitrary timing should be possible if the excitation currents for the kicker and septum magnet and their firing are controlled. The original circuit architecture of their power supplies has been developed and the details are discussed in this paper.

Energy sweeping extraction using charge conversion from C5+ to C6+ has been proposed. For this purpose, a carbon stripping foil is introduced. The orbit of the converted C6+ beam is dramatically changed as it passes through the downstream bending magnet. Consequently, the orbit separation for extraction is sufficient for the septum magnet to work. The feasibility of energy sweep extraction associated with charge conversion is examined here.

It is important that energy sweeping extraction is performed in any time region or a different energy range within the same acceleration cycle. The extracted C6+ beam can sweep a tumor from its front edge to its other edge at 10 Hz without causing undesired activation around the irradiation device. We stress that this quick irradiation is much faster than natural movement of an organ associated with respiration over 4 or 5 s.

OFF-MOMENTUM BUMP ORBIT FOR ONE-TURN EXTRACTION

The lattice and lattice functions of the ESCORT driver accelerator are shown in Figs. 1 and 2. The sufficiently long straight sections accommodate the injection/extraction and acceleration devices. A large acceleration voltage per turn is easily solved by increasing the number of induction cells with an output voltage of 2-3 kV/cell. Some regions of the 2.5-m-long straight section and the 4-m-long straight section are occupied by the kicker magnet and septum magnet system, respectively. The off-momentum acceleration of the barrier-trapped C6+ bunch is turned on slightly earlier than desired extraction timing t_{ext}, shown in Fig. 3 and continues until the bunch center achieves $\Delta p/p = 0.20$ % at $t = t_{ext}$ as shown in Fig. 4.

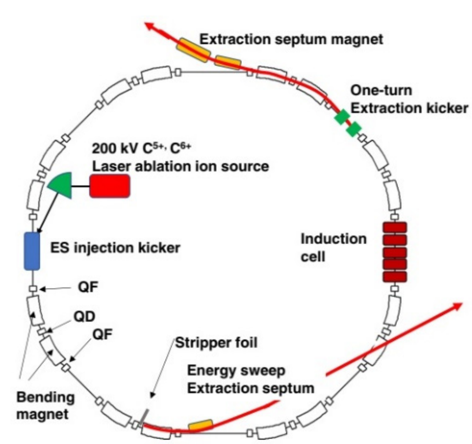

Figure: 1 Lattice of the ESCORT ring.

† tanuja@sameer.gov.in

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB208

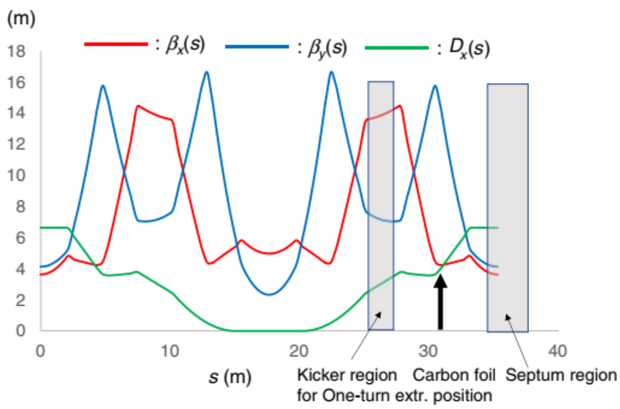

Figure: 2 Lattice functions and extraction device regions for kicker, carbon foil, and septum magnet.

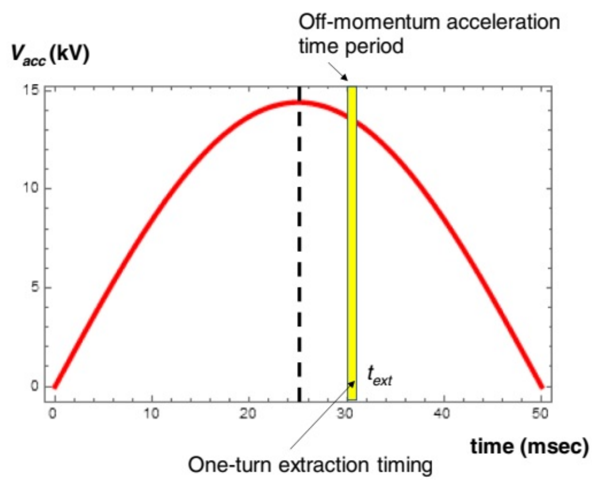

Figure 3: Required acceleration voltage profile and off-momentum acceleration time period.

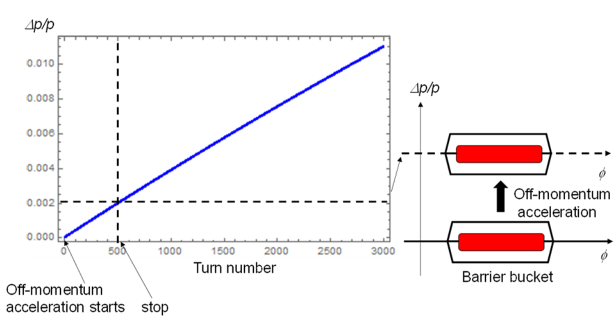

Figure 4: Evolution of momentum deviation associated with off-momentum.

Eventually, a bump orbit of D(s).Δp/p ~ 0.7–1.4 cm is created in the short and long straight section for extraction. This size of orbit bump can assist the 1 turn extraction kickers greatly.

The extraction orbit and parameters of the extraction devices have been optimized. A typical extraction orbit is shown in Fig. 5.

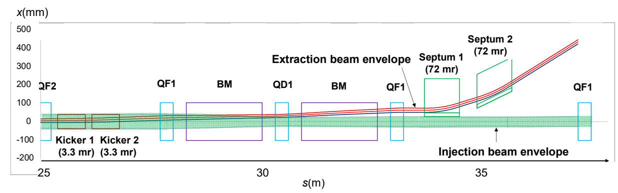

Figure 5: Beam envelopes in the 1 turn extraction region.

EXTRACTION ORBIT FOR ENERGY SWEEPING EXTRACTION

A schematic of the extraction region is shown in Fig. 6. The extraction system simply consists of the stripping foil located between quadrupole magnet (QD1) and bending magnet (BM) and the septum magnets in the 4-m-long straight section. The beam is coasting over the energy sweeping time period. The extraction orbit of the converted C6+ ion is uniquely determined by the effect of decreasing bending radius through the bending magnet downstream.

The most striking effect of charge stripping in extraction is the large orbit separation just at the exit of the bending magnet (Fig. 6). This substantially relaxes the septum magnet parameters, such as field strength or physical length.

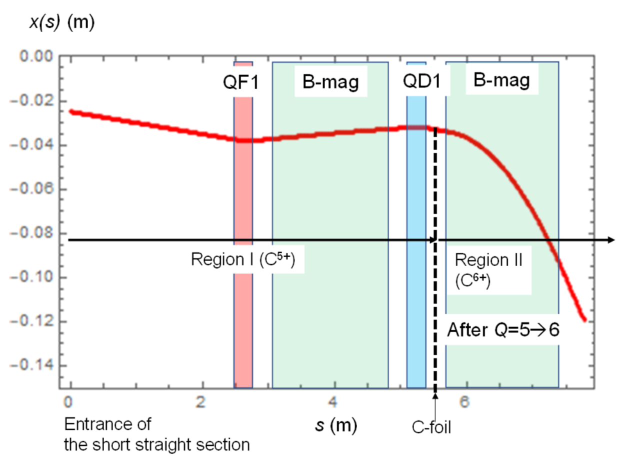

Figure 6: Extraction orbits of a carbon ion with the momentum deviation of $(\Delta p/p_0)_I = -1\%$ in Region I.

In Fig. 6, a typical orbit through Regions I and II is shown in red. At first glance, we expect a large orbit deviation from the circulating orbit that is x = 0 m beyond the exit of the bending magnet, which seems to require a wide-aperture ceramic chamber and a specific shape of quadrupole focusing magnet (QF1) that can accommodate the extracted beam in the outer region of the magnetic poles. The C5+/C6+ beam distributions with a finite emittance from the 2.5-m-long straight section to the 4-m-long straight section are shown in Fig. 7. The septum magnets occupy the long straight section, which is ramped in a ramping pattern in time similar to the main bending magnet.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB208

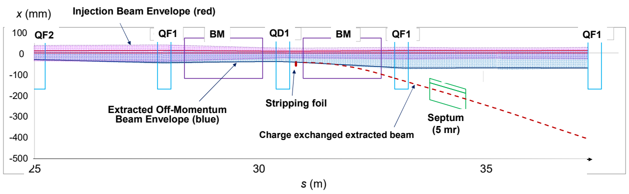

Figure 7: Beam envelope and beam centroid in energy sweep extraction.

Carbon Stripper

Carbon stripper foil has long been used for H-injection into synchrotrons and charge exchange extraction from proton cyclotrons. Currently, carbon foil is commonly used to generate C6+ from C4+ after the low-energy injector linac (6–8 MeV/au) and before the driver synchrotron in carbon therapy. Charge conversion efficiency of almost 100% has been reported. Carbon stripper foil should be feasible for charge exchange at the extraction energy in ESCORT. To confirm the feasibility of the foil, computer simulation using ETACHA4 in LISE++ code was carried out [3].

Next, ETACHA in LISE++ was used to calculate the charge conversion ratio from C5+ to C6+ as a function of carbon foil thickness for different energies (Fig. 8). Above a foil thickness of 1000 μg/cm^2, the conversion efficiency was saturated at close to 100% for the energy range of interest. The energy sweeping extraction is expected to work with stripper carbon foil of 1000 μg/cm^2 thick being set at the expected position. The total magnitude of the power deposited on the foil is small, suggesting that forced cooling is unnecessary.

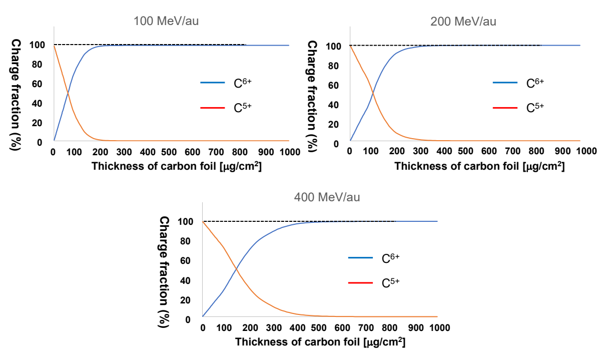

Figure 8: Charge conversion efficiency for C^{5+} of 100 MeV/au, 200 MeV/au, and 400 MeV/au.

Kicker and Septum Magnet Power Supply

Kicker magnets themselves are nothing new and any explanation for this will be unnecessary. However, the power supply for the present kicker is specific. An equivalent circuit of the kicker power supply to meet the demand is shown in Fig. 9. Initially, the switch (SW-1) is turned on and the high-voltage power supply (HV) begins to charge the pulse forming network (PFN) consisting of two parallel 25 Ω co-axial cables 20 m long. When the voltage of the PFN reaches the value corresponding to the desired extraction energy, SW-1 is turned off. Then, switch SW-2 is turned on at the extraction timing determined from irradiation planning. The circuit current flows to the kicker magnet through the two parallel 25 Ω co-axial cables and reflects at the short-end. The reverse current with the opposite voltage goes though the kicker magnet, transmission cable, SW-2, PFN, diode (D), and generates losses at the 12.5 Ω matching resistor (R). In the next acceleration period, the PFN is charged again at and stop when the PFN voltage reaches the required value. This charging PFN voltage can be changed pulse-to-pulse so as to match the varying extraction energy. Therefore, changing the turn-off timing of SW-1 to match the extraction energy is mostly crucial for this circuit.

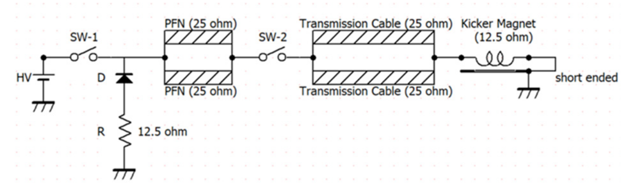

Figure 9: Equivalent circuit of the kicker magnet power supply.

Septum magnet is needed not only for energy-varying one turn extraction but also for energy sweep extraction. The magnets themselves are same for both extraction, but their power supplies are different. The septum magnet for energy varying 1 turn extraction must be excited with the high current, resulting in a large kick angle. As the extraction energy is changed pulse to pulse, the peak current through the septum coil should be changed so as to match the extraction energy [4]. The equivalent circuit of the power supply for the septum magnet for energy-varying 1 turn extraction is shown in the Fig. 10.

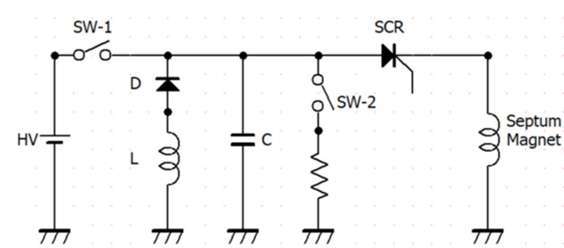

Figure 10: Circuit architecture of the septum magnet.

SUMMARY

Two methods of beam extraction from the fast cycling induction synchrotron were proposed with the maximum use of the localized large flat dispersion function in the extraction region and barrier bucket induction acceleration in the ESCORT driver ring. The feasibility of the energy sweeping extraction using stripper carbon foil, which is a simple low-cost device, was examined. Typical circuit examples for the kicker and septum to allow this have been described.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB208

REFERENCES

[1] L. K. Wah *et al.*, "Compact hadron driver for cancer therapies using continuous energy sweep scanning", *Phys. Rev. ST-AB*, vol. 19, p. 042802, 2016. doi:10.1103/PhysRevAccelBeams.19.042802

[2] K. Takayama *et al.*, "Induction acceleration of heavy ions in the KEK digital accelerator: Demonstration of a fast-cycling induction synchrotron", *Phys. Rev. ST-AB*, vol. 17, p. 010101, 2014. doi:10.1103/PhysRevSTAB.17.010101

[3] O. B. Tarasov and D. Banzin, "LISE++: Radioactive beam production with in-flight separators", *Nucl. Inst. Meth. B,* vol. 266, pp. 4657-4664, 2008. doi:10.1016/j.nimb.2016.03.021

[4] T. Kawakubo *et al.*, "Energy-varying beam extraction from a fast cycling hadron therapy driver assisted by large momentum deviation and charge exchange", *Phys. Rev. ST-AB*, vol. 24, p. 011601, 2021. doi:10.1103/PhysRevAccelBeams.24.011601