ESCORT: Energy sweep compact rapid cycling hadron therapy

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Abstract. The Energy Sweep Compact Rapid Cycling Hadron driver for future cancer therapies based on the induction synchrotron concept is described. This fast cycling synchrotron that allows the energy sweep beam scanning. Assuming a 1.5 T bending magnet, the ring can deliver heavy ions of 430 MeV/u at 10 Hz. A beam fraction is dropped from the barrier bucket at the desired timing and the increasing negative momentum deviation of this beam fraction becomes enough large for the fraction to fall in the electrostatic septum extraction gap, which is placed at the large D(s) region. The programmed energy sweeping extraction makes spot scanning beam irradiation on a cancer area in depth possible.

1. Introduction
3D spot scanning of hadron beams to cancer tissues of human organs is of most concern in this society [1]. We will focus on spot scanning by the energy sweeping extraction from a fast cycling induction synchrotron [2]. A hadron bunch captured in the barrier bucket is continuously accelerated by the induction flat voltage and a fraction of the beam bunch is spilled out from the stable barrier bucket by non-adiabatically changing timing of the acceleration voltage controlling trigger signal in the desired time period. Equilibrium orbits of spilled out particles move inward depending on the dispersion function D(s) and those particles enter into the electrostatic septum gap region to be further deflected inward, and then propagate through the extraction region downstream consisting of extraction device such as a Lamberson magnet to put on the extraction beam line. Start of the extraction and a number of spilled out particles are simply determined by controlling of the gate signal. Thus, we can obtain a driver beam for the cancer therapy with the function of 3D spot scanning, the energy of which changes continuously in the same acceleration cycle. Details of this scheme has been proposed as compact driver in Reference [3]. Its essence will be described here.
2. Beam Parameters

The ring has the two-fold symmetry as shown in Fig. 2. Its super lattice has a mirror symmetry, which consists of two sorts of F-B-D-B-F cell in Fig. 3. The lattice profile is similar to that of the CERN design PIMMS [4] Two long dispersion-free straight sections are occupied by the injection system and induction acceleration cells for acceleration and confinement. One long straight section with a large flat dispersion function is occupied by the extraction system for energy sweeping scanning. The other is partially occupied by the kicker magnets for the fast extraction, which is used in a combination with the septum magnet placed downstream with a betatron phase advance of 90 degrees.

Properties of the lattice design and machine parameters [3] as shown in Fig. 2 and Table 1 must comprise of:

- Dispersion-free region for induction acceleration devices and injection device.
- Localized large flat dispersion region for the extraction device with the length of 4 m.
- Local betatron phase advance of $\pi/2$ for the fast extraction.

![Figure 1. Energy sweep extraction in the same acceleration cycle and integrated dose along the path, where $B(t)$ is the magnetic flux density of the guiding magnet.](image-url)
**Figure 2.** Outline of the driver ring and cell structure.

**Figure 3.** Super-symmetry lattice functions.
Table 1. Machine and beam parameters.

| Machine | Beam parameters |
|---------|-----------------|
| Energy  | 430 MeV/nucleon for $A/Q = 2$ ion |
| $C_0$   | 52.8 m          |
| Ion species | Gaseous/Metal ions |
| Ion source | Laser ablation IS, ECRIS |
| Injector | 200 kV (electrostatic) |
| Ring    | fast cycling (10 Hz) |
|        | $B_{max} = 1.5$ Tesla |
|        | $\rho = 4.42928$ m |
|        | FODOF cell with edge focus of B |
|        | Mirror symmetry |
|        | $v_x/v_y = 1.88024/1.69714$ |
|        | 2m long dispersion-free region |
|        | 4m long flat large dispersion region |
|        | $\alpha_p = 0.0396646$ |
|        | $\gamma_T = 5.0211$ |
| Acceleration | Induction cells driven by SPS |
|        | employing SiC-MOSFET |
|        | $V_{acc} = \rho C_0 dB/dt$ (max 7 kV) |
| Vacuum  | 10-8 Pascal     |

3. Simulation for extraction

3.1. Energy sweeping extraction

In this driver ring, a hadron bunch is trapped in the barrier bucket and accelerated with the induction voltage pulse as shown in Fig. 4. Particles in a normal acceleration, where an entire bunch is accelerated to the end of acceleration cycle, behave as shown in Fig. 5. In the energy sweep extraction mode, the flat edge of $V_{acc}$ pulse is moved to the rising edge of positive $V_{bb}$ pulse just in 1 turn at the extraction timing. Insufficient magnitude of the acceleration voltage allows an artificial and continuous leak of a fraction of macro-particles beyond the assumed extraction timing.

Figure 4. $V_{ac}$ and $V_{bb}$ profile in time before extraction, where $T_s$ and $\omega_0$ are the revolution time period and angular revolution frequency of the synchronous particle $t_{rf}$ is the rising and falling time period of both voltage.
Figure 5. Phase plots of tracked macro-particles in the phase space with $V_{ac}$ (Blue) and $V_{bb}$ (Green), where the voltage heights are shown in a relative unit.

3.2. Spill drop from the barrier bucket

For this simulation, the gate signals for the $V_{ac}$ voltage pulses are changed beyond the starting time of extraction so that the flat edge of $V_{ac}$ becomes to be equal to the rising bottom of positive $V_{bb}$. Particles entering into the positive barrier region, where the $V_{ac}$ voltage profile has a negative slope are affected by an insufficient acceleration voltage. As the result, a lager negative momentum deviation is generated. These particles leave the barrier bucket region or trapped region to move downward further. Eventually, they arrive the boundary region of $\Delta p/p = -10^{-2}$, beyond which a particle entering into the electrostatic septum region is kicked inward in the horizontal direction by the electrostatic fields. Typical examples of the phase plot with the spill drop from the barrier bucket are shown in Fig. 6. One finds that the small fraction of macro-particles continuously drifts down in the momentum space. At this stage, the spill is uncontrolled because any parameters are not optimized.

Figure 6. Phase plots of macro-particles leaving the barrier bucket region, where the bunch core is invisible, because its momentum spread is quite small. The position of broken lines, from which particles leak must be noted.

4. Spill Control

The spill size can be controlled, where the turning-off time of $V_{ac}$ is changed in a programmed manner. If some of particles being trapped in the barrier bucket are not given a required energy matching to the guiding magnet pattern, they will leave the trapping region or the barrier bucket and drifting downward in the longitudinal phase space. This is a key feature of spill control. Acceleration is uniquely determined by $V_{ac}$. Its downhill profile in time is steep and its starting phase of falling-down
in $V_{ac}$, which is indicated by $\phi_{ext}$ in Fig. 7, is maneuvered by gate-control for the switching power supply. This timing is always adjusted in the programmed manner or by means of feed-back from the spill monitoring system. The procedure for spill control is shown below.

- $\phi_{ext}$ is instantaneously moved to near the left edge of
- the right barrier voltage pulse ($\phi_{bb}$) at the starting time of spill extraction.
- Then, $\phi_{ext}$ is changed to satisfy the expected spill profile in the programmed manner or watching
an actually extracted spill profile.

As shown in Fig. 8, the integrated spill profile as a function of time for three extraction cases with different timing of $V_{ac}$ but constant $\phi_{ext}$ and 1,000 macro particles. It is clear that the spill profile depends on the extraction parameter $\delta$. This parameter can be controlled to meet a requirement on the spill profile. Such a typical example is given in Reference 3, where the constant spill is maintained up to the end of acceleration. Actually the programmed spill profile is realized by a program loaded on the field programmed gate array (FPGA). Real time feedback control may be also possible by watching an actual spill in the acceleration cycle.

**Figure 7.** Phase space with the $V_{ac}$ profile adjusted for extraction

**Figure 8.** Integrated spill for different $\delta$

### 5. Crucial devices for energy sweep extraction

From the beam dynamics point of view, it is the most important issue how the extracted beam with different energy in the acceleration cycle is guided to the beam handling region in the transverse direction for the 2D spot scanning along the extraction beam line. If all guiding devices including the extraction devices are ramped in the same way as the main guiding magnets in the ring, the ideal orbit should be common at any extraction timing and the extracted beams can enjoy the same lattice function of the extraction beam line through the entire acceleration cycle. Extraction devices desired for the present purpose of the electrostatic septum and Lambertson magnet, which seem to be also practical from the engineering point of view, are considered here.
5.1 Electrostatic septum

The maximum voltage generated by a DC power supply such as the Cockloft-Walton is usually added across the ES gap [3]. It seems to be difficult to introduce the additional pulse voltage generator in the ES high voltage circuit, because the additional voltage pulse has to have the well controlled time transient profile varying in a wide range of more than 50 kV as to correspond to the extraction from a middle stage in the acceleration cycle.

For this purpose, a novel charging method to employ a combination of high power solid-state switches and discharging switch has been studied [3]. Its equivalent circuit as shown Fig. 9. Its performance in a nominal operation is described as below.

- The DC power supply $V_1$ always charges the electrostatic septum through the charging resistor $R_1$ to a voltage of order of -50 kV before extraction.
- Switch 1 transfers charge the load from the other DC power supply $V_2$ so that the required voltage profile $V(t)$ proportional to $\beta \gamma^2$ is satisfied beyond the extraction starting time. Time constant of the voltage build-up is determined by the circuit constants such as the resistance of the charging resistor $R_2$, floating inductance $L$, parameters of the coaxial cable connecting between the $V_2$ and the load, and the capacitance of the electrostatic septum. Switch 1 is discretely and repeatedly tuned on and off in a well programmed way.
- After completing the extraction, the discharging switch $S_2$ is turned out until the voltage of the load reaches lower than $V_1$.
- Just after the acceleration cycle, the above process is repeated.

In order to confirm the feasibility of this programmed charging process, the SPICE simulation has been carried out, especially focusing on the charging process from $V_1$ to $V_2$. The SI-Thyristor is assumed as a solid-state switching element for $S_1$, which has a rising/falling time of 200 nsec. Finite but relatively fast switching characteristics give no notable effects on the charging performance of current concern. Simulation results are shown in Fig. 11, where $R_1$, $L$, and $C$ are assumed to be 9.58 MΩ, 1µH, and 1200 pF, respectively. It is noted that the capacitance of 1200 pF is very close to that of the existing KEK 12 GeV PS electrostatic septum with the similar size as the present demand. $S_1$ is turned on and off 8 times during the assumed extraction time period, as shown in Fig. 10. It is emphasized that the discrepancy from the ideal voltage profile is less than 1%. Further improvement seems to be possible by introducing more frequent switching performance.

![Figure 9. Equivalent circuit of the electrostatic septum and its high voltage supplies](image-url)
The switching performance is simulated by using a simulation code, SPICE.

![Figure 10. Time table of Switch On/Off](image)

![Figure 11. Ideal and simulated voltage patterns with the discrepancy between both](image)

5.2 Lambertson magnet

A usual septum magnet is excited by the transient current, which is generated in the circuit architecture consisting of a condenser bank, resistor, diode, and thyatron as a switch, and transformer (magnet itself). The field profile is uniquely determined by the circuit parameters and switching time of the thyatron [5]. The peak field is used for extraction. Its time constant of change in the magnetic fields is different from 10 Hz or does not meet the current demand. It is unknown whether or not additional circuit components or parameters can be chosen to meet the demand on the ideal extraction field profile.
Here a Lamberston magnet as seen in Fig. 12 is considered as an extraction magnet device instead of the septum magnet. It is emphasized that the Lambertson magnet is excited in a similar way as that of the main magnets of the ring. This is a crucial point why this magnet is used in the present proposal. The Lamberston magnet extracts the beams in the vertical direction in a limited space. However, the angle and position of the beam line at the edge of the magnet are still interfere to the adjacent quadrupole magnet (QF1) and bending magnet as seen as in Figs. 13 and 14. In such a case, the beam aperture for extraction must be put in the magnet return yoke. Perturbations of this modification on the circulating beam are limited and their compensations are possible.

Figure 12. Cross-section of Lamberton magnet.

Figure 13. Extraction beam orbit and downstream.
6. Conclusion
The hadron machine so-called ESCORT with continuous energy scanning for cancer therapies has been designed and its performance has been confirmed by the macro-particle simulations. We believe that this is realized utilizing the modern technology of variable voltage power supply employing a solid-state switch. However, there are still several issues related with beam transverse emittance that must be studied.

7. References
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