A COMPACT HADRON DRIVER FOR CANCER THERAPIES WITH CONTINUOS ENERGY SWEEP SCANNING

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Abstract

The compact hadron driver for future cancer therapies based on the induction synchrotron concept, which has been proposed recently, is discussed. This is a fast cycling synchrotron that allows the energy sweep beam scanning. Assuming a 1.5 T bending magnet, the ring can deliver heavy ions of 200 MeV/au 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.

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 as shown in Fig. 1 by integrated with the ramping pattern of guiding magnet. Details of this scheme have been proposed in Reference [3]. Its essence will be described here.

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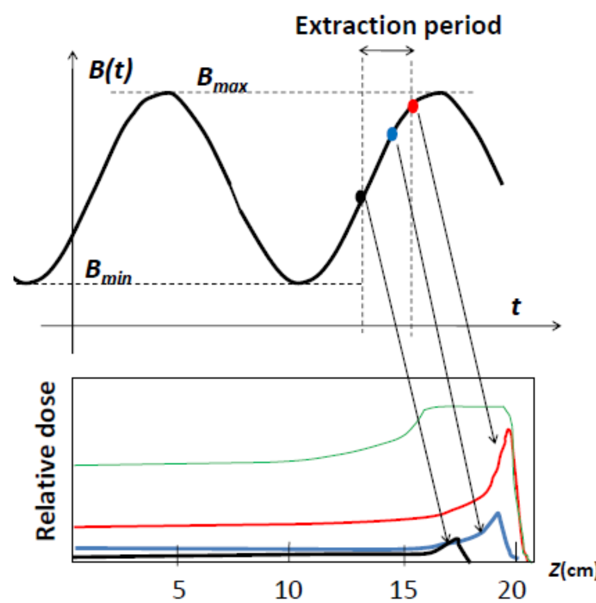

Figure 1: Energy sweep extraction in the same acceleration cycle and integrated dose along the path, where *B(t)* is the magnetic flux density of the guiding magnet.

In this paper, a practical method to realize the energy sweeping extraction from a fast cycling synchrotron is proposed.

Ring Lattice

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

i) Dispersion-free region for induction acceleration devices and injection device.
ii) Localized large flat dispersion region for the extraction device with the length of 3 m.
iii) Local betatron phase advance of $\pi/2$ for the fast extraction.

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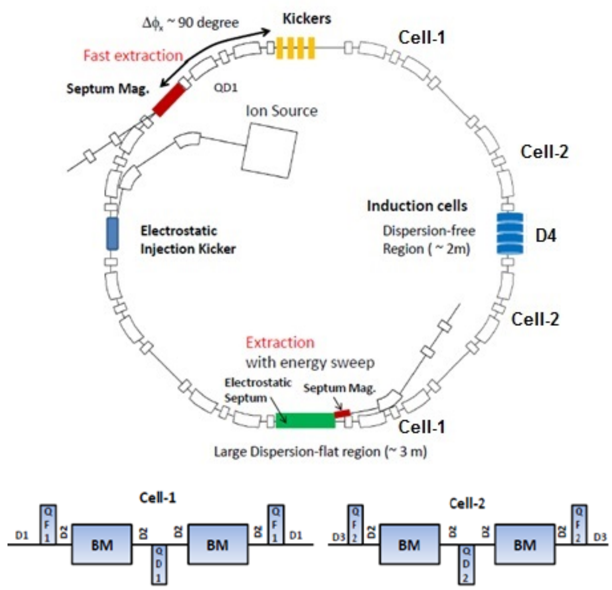

Figure 2: Outline of the driver ring and cell structure.

Table 1: Machine and Beam Parameters

Energy	656 MeV for proton 200 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
	$\rho = 2.8662$ m
	FODOF cell with edge focus of B
	Mirror symmetry
	$\nu_x / \nu_y = 1.3143/1.4635$
	2m long dispersion-free region 3m long flat large dispersion region
	α_p=0.273088 γ_T=1.92, E_T=864.7 MeV
Acceleration	Induction cells driven by SPS employing SiC-MOSFET $V_{acc} = \rho C_0 dB/dt$ (max 7 kV)
Vacuum	10^{-8} Pascal

SIMULATION FOR EXTRACTION

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. 3. Particles in a normal acceleration, where an entire bunch is accelerated to the end of acceleration cycle, behave as shown in Fig. 4. 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.

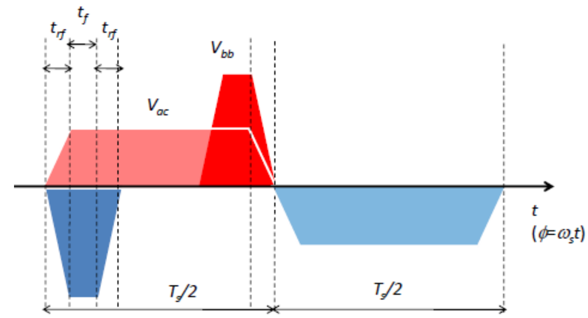

Figure 3: V_{ac} and V_{bb} profile in time before extraction, where T_s and ω_s are the revolution time period and angular revolution frequency of the synchronous particle t_{rf} is the rising and falling time period of both voltage.

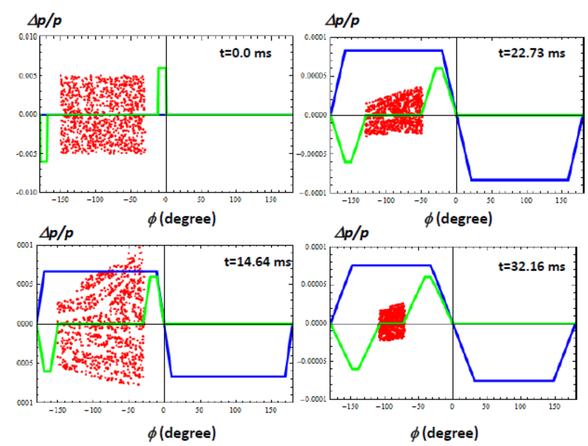

Figure 4: Phase plots of tracked macro-particles in the phase space with V_{ac} *(Blue)* and V_{bb} *(Green)*, where the voltage heights are shown in a relative unit.

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. 5. One finds that the small fraction of macro-particles continuously drifts down in the momentum space. At this stage, the spill is not controlled because any parameters are not optimized.

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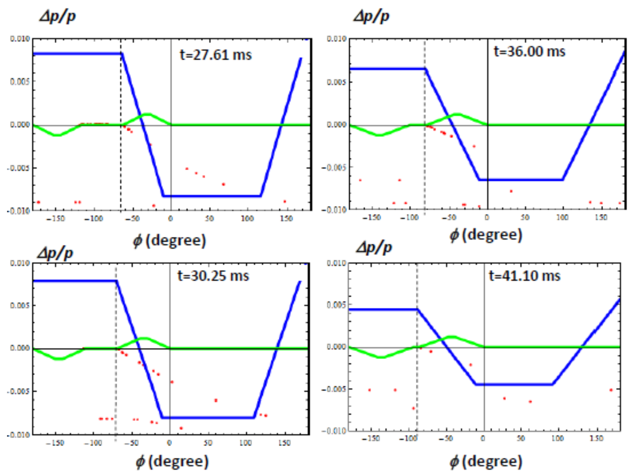

Figure 5: Phase plots of macro-particles leaving the barrier bucket region, where the bunch core is invisible, because its momentum spread is quite small. The position of broken lines, from which particles leak, must be noted.

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 ϕ_{ext} in Fig. 6, 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.

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

As shown in Fig. 7, The integrated spill profile as a function of time for three extraction cases with different timing of V_{ac} but constant ϕ_{ext} and 1,000 macro particles. It is clear that the spill profile depends on the extraction parameter δ. This parameter can be controlled so as 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.

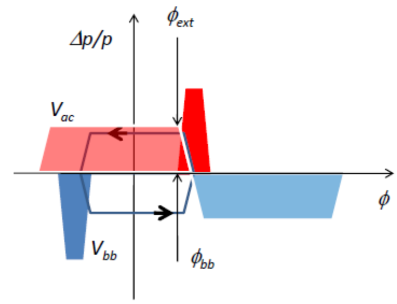

Figure 6: Phase space with the Vac profile adjusted for extraction.

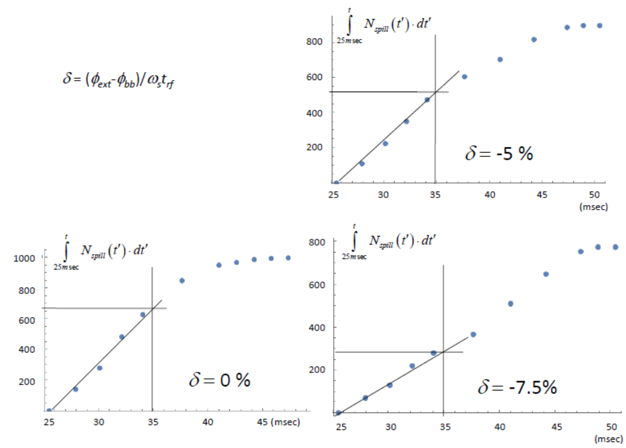

Figure 7: Integrated spill for different δ.

SUMMARY

The hadron machine with continuous energy scanning for cancer therapies has been designed and its performance has been confirmed by macro-particle simulations. There is no space to discuss a key device for energy sweep extraction, that is, electrostatic septum. We believe that this is realized utilizing the modern technology of variable voltage power supply employing a solid-state switch [3]. However, there are still several issues related with beam transverse emittance that must be studied hereafter.

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