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RESONANCE SLOW EXTRACTION FROM ION SYNCHROTRON FOR TECHNOLOGICAL APPLICATION

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Abstract

Third-order resonance slow extraction from synchrotron is the most common use extraction method for external target experiments nuclear physics, proton and heavy ion therapy, since it can provide relatively stable beams in long time. The principle of third-order resonant slow extraction is intentionally exciting the third-order resonance by controlling detuning and sextupole strength to gradually release particles from inside to outside stable separatrix. BINP develop the ion synchrotron for wide range of technological application. The present paper describes slow extraction method with exiting betatron oscillations by the transverse RF-field. Such extraction technique provides stable current extraction for entire extraction time. The paper present simulation of slow extraction driving RF-knockout.

INTRODUCTION

The synchrotron will produce beams of protons accelerated up to 4 GeV and wide range of ion species including $^{209}Bi^{41+}$ up to 36 MeV/n respectively (see Table 1).

Table 1: Synchrotron Specifications

Characteristics	Value
Circumference, m	168.37
Beam injection energy proton/$^{209}Bi^{41+}$, MeV/n	700 / 36
Maximum energy proton/$^{209}Bi^{41+}$, MeV/n	4000 / 400
Magnetic rigidity, T·m	16.2
Max dipole field, T	1.6
Critical γ	6.39
Tune, Q_x/Q_z	6.65 / 4.61
Natural chromaticity, ξ_x/ξ_z	-10.2 / -10.1
Acceptance hor/ver, π cm·mrad	7.5 / 1.9
Beam intensity, protons/$^{209}Bi^{41+}$	10^{12} / 10^{8}
Momentum compaction factor	0.024
Proton beam emittance under injection, π cm·mrad	0.52
Frequency revolution proton/$^{209}Bi^{41+}$, MHz	1.46 ÷ 1.75 / 0.48 ÷ 1.27

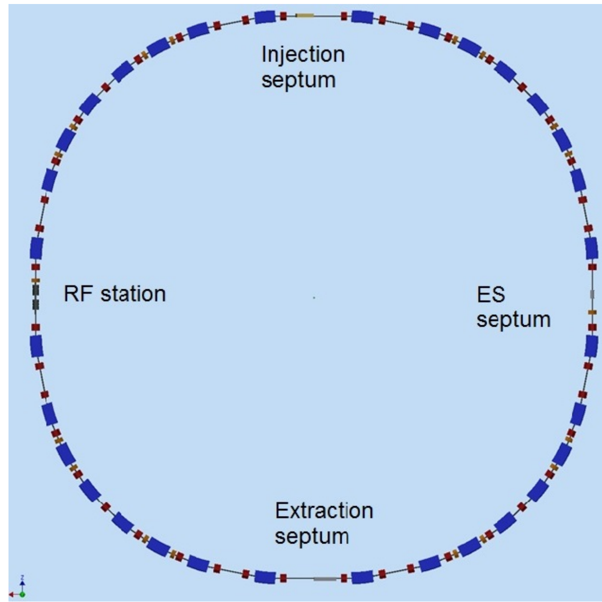

Figure 1: General layout of synchrotron.

The general layout of synchrotron is presented in Fig.1. The synchrotron optics is characterized by four super periods and four closed dispersion bumps (see Fig. 2). The injection and extraction septum magnets, RF-cavity and electrostatic septum located in free dispersion drifts. One resonance sextupole used for extraction is located close to RF-cavity. For slow extraction convenience the synchrotron operates below critical energy in the entire range of energy.

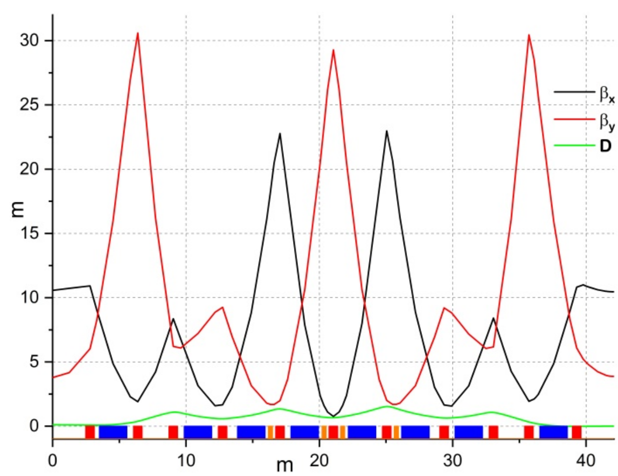

Figure 2: Lattice function of synchrotron quarter.

SLOW EXTRACTION

The slow extraction from synchrotron based on the third order horizontal resonance. The sextupole magnet excites resonance harmonics. When the excitation achieves a cer-

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tain level, the circular trajectories in phase space are distorted into triangular trajectories. After exceeds of certain level the triangular trajectories become open. The area of the single particle stable triangle is the acceptance and its value:

$$\epsilon_{stable} = \frac{48\sqrt{3}\pi^2}{S^2}(\delta Q)^2, \tag{1}$$

where δQ is particle detuning. The normalized sextupole strength in thin lens approximation:

$$S = \frac{1}{2}\beta_x^{3/2}\frac{l_s}{B\rho}\left(\frac{d^2B_z}{dx^2}\right) \tag{2}$$

The useful representation of the beam is provided by the amplitude-momentum space, called the Steinbach diagram (see Fig. 3).

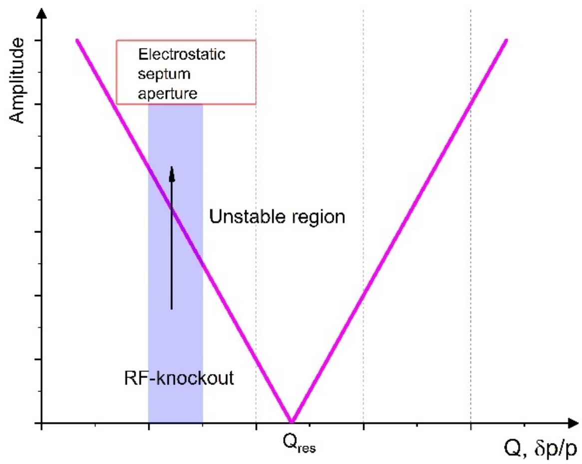

Figure 3: Steinbach diagram show RF-knockout driving mechanism.

In RF-knockout extraction [1] the beam is excited in the horizontal phase space by a radio frequency or by stochastic noise with right range of the frequency. The amplitude of betatron oscillation increase and, without changing the tune of the particles, they go from the stable region. The beam will gradually leave the triangle stable region without changing energy. The momentum spread of the extracted beam is equal to the momentum spread of the circulating beam, unlike the case of extraction by the betatron core.

LAYOUT OF THE EXTRACTION SCHEME

To initiate slow extraction the horizontal closed orbit locally distorted in the electrostatic and magnetic septums azimuths. The local orbit bump creates by eight dipole correctors - four regular correctors and four special bump magnets (see Fig. 4), which ensures the electrostatic septum limits the synchrotron horizontal aperture during the extraction process. After that horizontal betatron tune shifts to resonance value Q_x=20/3 with small detuning and switch on the resonance sextupole. Finally, RF-knockout extraction method applying without varying ring optics. In electrostatic septum the extracted particles gets horizontal kick inside ring. The performance of electrostatic septum with 0.1 mm titanium foil indicates in Table 2. The spill in x-s plane between electrostatic and magnet septums is shown in Fig. 5.

Table 2: Electrostatic Septum Specifications

Kick angle, mrad	1.0
Distance from foil to closed orbit, mm	42
Gap, mm	9
Effective length, mm	500
Max voltage, kV	-90
Overall length, mm	720
Spiral step, mm	8
Beam loss, %	~2
Total mass, kg	~150

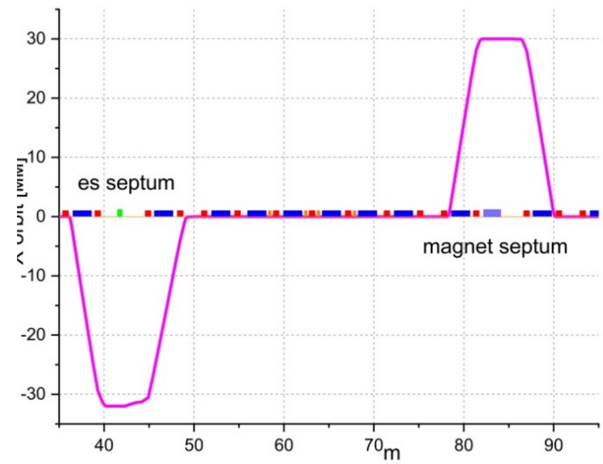

Figure 4: Closed orbit bumps in electrostatic and magnet septum azimuths.

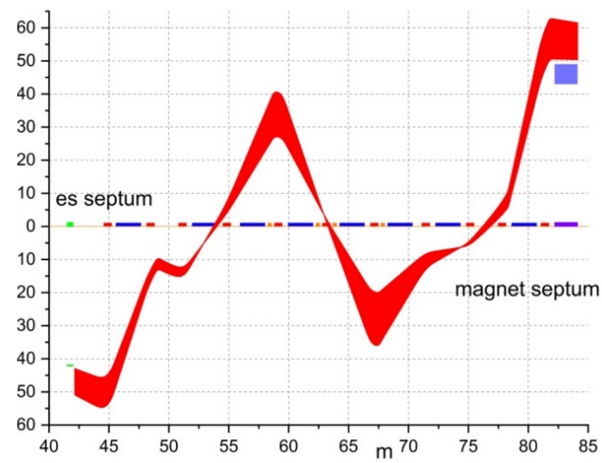

Figure 5: Spill position between electrostatic and magnet septums.

The phase space portrait in the entrance and exit of Lambertson type magnetic septum is shown on Fig. 6. The gap between circulating and extraction beams is about 8 mm that sufficient for magnetic septum with thickness 5 mm.

TIME STRUCTURE OF SPILL

For research of extracted beam spill structure the particle tracking code was developed. The 6D tracking of the particles through the lattice of synchrotron is performed calculating the corresponding first order transfer matrices.

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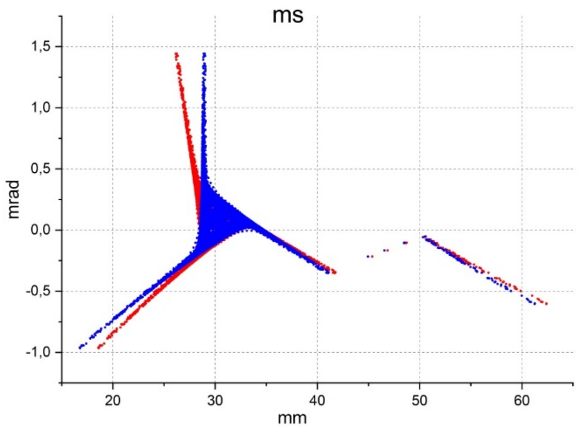

Figure 6: Phase space portrait beam at slow extraction in entrance (red) and exit (blue) of magnetic septum.

The tracking through the sextupoles and kicker is performed with thin lens approximation. The RF signal waveform can be defined by the user. Initially the normal distribution in the horizontal and vertical phase space is generated. The horizontal particle coordinate at the electrostatic septum is verified. If the particle position exceed septum knife the particle marked as extracted and turn number and coordinates are stored in the output file.

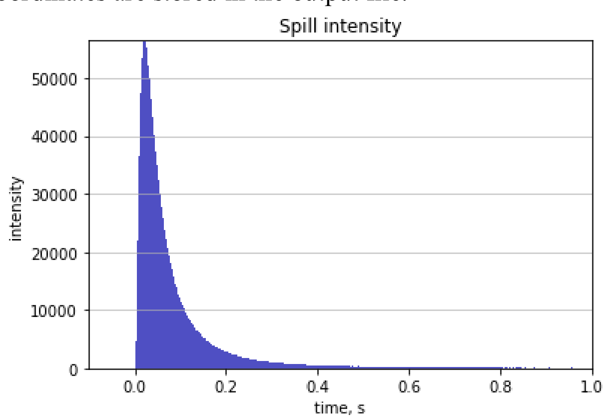

Figure 7: Spill structure for constant amplitude of RF-knockout.

The spill structures for constant amplitude of RF which provide kick angle 0.2 μrad is shown in Fig. 7. Such intensity fluctuation not acceptable for beam irradiation application. For this purpose, it was considered optimizing the AM function of RF-knockout. The radial distribution function in normalized phase space can be expressed by using the Reyleigh distribution function as [2]:

$$p(r) = \frac{2r}{\sigma^2} e^{\left[-\frac{r^2}{\sigma^2}\right]}, \tag{3}$$

where σ is the standard deviation. The σ increases through in RF-knockout slow extraction. Thus, the number of the extracted particles can be expressed as:

$$\frac{dN_{ext}}{dn} = N_0 \frac{d\sigma^2(n)}{dn} \frac{r_0^2}{\sigma^4(n)} exp\left[-\frac{r_0^2}{\sigma^2(n)}\right], \tag{4}$$

where r_0 is a separatrix size. In order to provide a flat spill Eq. 3 should be kept constant during extraction.

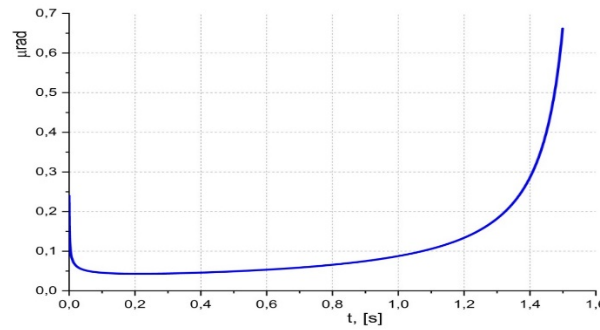

Figure 8: AM function in kick angles values of RF-knockout vs extraction time.

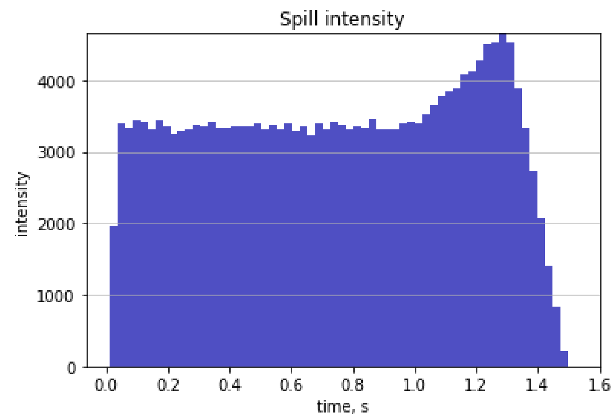

Figure 9: Spill structure for new AM function.

For extraction time 1.5 s the derived AM function for flat spill is presented in Fig. 8. The tracking simulation with determined AM modulation was carry out. The spill structure for this case is shown in Fig. 9. Clear that spill is flat up to 1 sec extraction within 5 % fluctuation. For kick angle ~0.7 μrad the electric field strength is 3.3 kV/m for 1m length deflection plate. This value is moderate and rf power amplifier for such RF knockout is available.

CONCLUSION

After analysis and evaluation, the feasibility of the RF-knockout extraction in the synchrotron for technological application has been developed. A flat spill is possible with an amplitude modulation of the signal. The simulation showed that for the first part of extraction the beam intensity is constant within a fluctuation less than 5 %. In order to get constant extraction also for the last part, the feedback system could be useful.

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