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PHYSICS AND TECHNIQUE OF ACCELERATORS

Slow Resonant Extraction from Ion Synchrotron for Technological Applications

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Abstract—Slow resonant extraction from the synchrotron makes it possible to provide relatively stable beams for a long time. The principle of slow extraction is intentionally exciting the third-order resonance by controlling detuning and sextupole strength with the gradual release of particles from inside to outside a stable separatrix. The Budker Institute of Nuclear Physics (BINP) develops the ion synchrotron for a wide range of technological applications. This paper describes slow resonant extraction from an ion synchrotron with betatron oscillation excitation by a transverse RF field.

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GENERAL DESCRIPTION OF THE SYNCHROTRON

The synchrotron is designed to accumulate and accelerate a wide range of ions, from protons to bismuth Bi^{41+} ions. The main parameters of the accelerator are presented in Table 1. The outline view of the synchrotron is shown in Fig. 1.

The synchrotron has a mirror-symmetric structure, the symmetry axis of which passes through the centers of rectilinear gaps, with a zero dispersion function. One of the gaps is designed to install intake—exhaust systems in it. In the opposite gap, there is an electron cooling facility and six quadrupole lenses that provide equal and sufficiently large (about 10 m) β functions in the cooling section.

One feature of the synchrotron is the presence of two modes of beam output. Single-turn fast extraction is carried out at maximum energy and the released beam is output to the bypass channel. Slow resonant extraction is carried out in a wide range of energies. Both extraction modes use the same Lambertson-type magnetic septum.

Table 1. Main parameters of the synchrotron

Parameters	Value
Perimeter, m	94.1
Injection energy protons/Bi^{41+}, MeV/n	7.5/4
Maximum energy protons/Bi^{41+}, MeV/n	700/36
Magnetic hardness, T m	4.47
Maximum field, T	1.6
Betatron frequencies, Q_x/Q_z	3.24/3.19
$\beta_{x\max}/\beta_{y\max}$, m	15.3/25.8
$\eta_{\max}$, m	5.3
Natural chromatism, ξ_x/ξ_z	−3.6/−6.3
Critical energy, γ	2.86
Orbit compaction factor	0.123
Frequency protons/Bi^{41+}, MHz	0.4–2.61/0.294–0.862
Intensity, protons/Bi^{41+}	$10^{11}/10^9$
Beam emittance during injection, π cm mrad	6

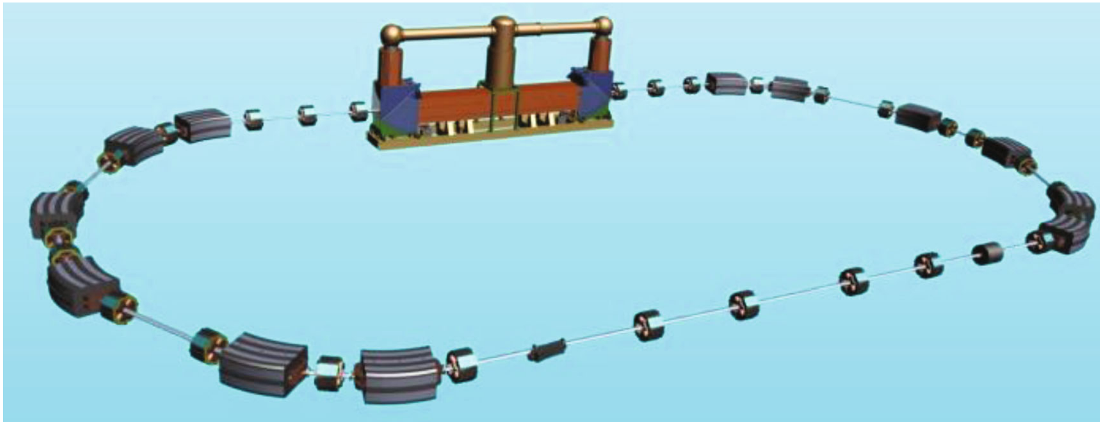

Fig. 1 Sketch of the ion synchrotron.

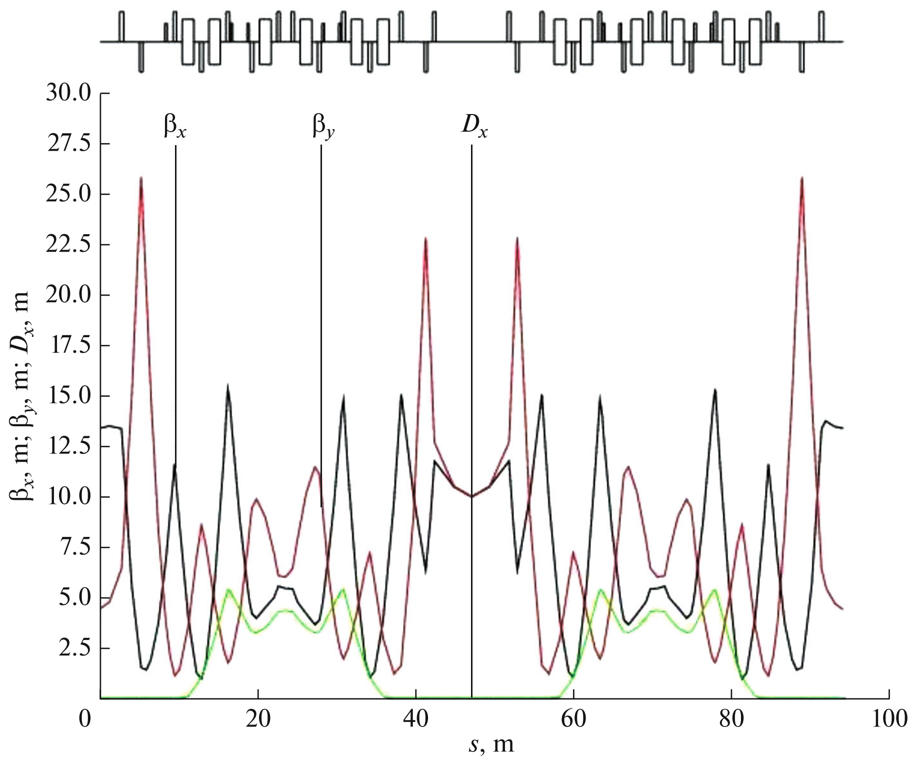

Fig. 2 Optical functions of the synchrotron.

SLOW RESONANT EXTRACTION

For slow extraction from the synchrotron, one-dimensional resonance of the third order is used. The horizontal betatron frequency is set near the resonant frequency with some small detuning. A sextupole lens is used to create a resonant perturbation harmonic. In this case, a separatrix appears with a characteristic triangular shape (Fig. 3).

The area of the separatrix, inside which the particles perform stable oscillations, in the normalized phase space is equal to

$$\varepsilon_{\text{stab}} = \frac{48\sqrt{3}\pi^2}{S^2}(\delta Q)^2, \quad (1)$$

where δQ is frequency detuning from the resonant value. Value S, in the thin lens approximation, is expressed as follows:

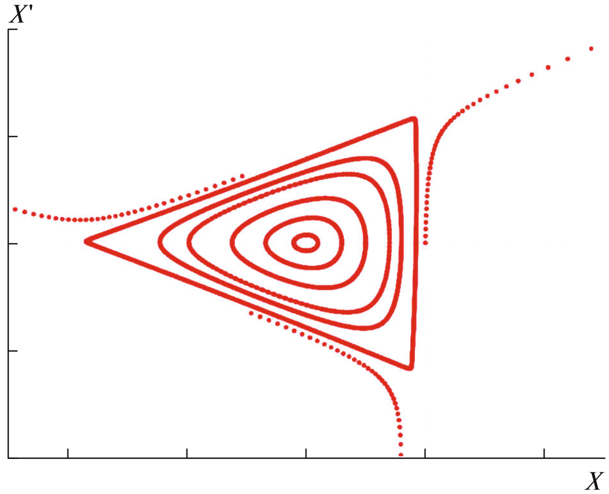

Fig. 3. Phase trajectories of beam particles for different oscillation amplitudes.

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

where β_x is the horizontal beta function at the location of the sextupole; l_s is the effective length of the lens. With an increase in the oscillation amplitude, the beam particles leave the region of stable motion and, after a finite number of revolutions, fall into the gap of the electrostatic septum. In the septum, the particles receive an additional blow in the radial direction and, at the same turn, are removed from the ring using a magnetic septum.

The slow extraction mechanism is conveniently depicted in terms of amplitude and relative momentum, known as the Steinbach diagram. The region of stable oscillations in such parameters is, in the first approximation, bounded from above by two straight lines. To leave the beam particles from the stability region, either a betatron core is used, which slowly changes the beam energy (Fig. 4), or transverse RF buildup to increase the amplitude of betatron oscillations [1]. To control the uniformity of the extraction, amplitude modulation of the buildup voltage is carried out. As a rule, in a circuit with an RF drive, it is possible to obtain a greater uniformity of output than when using a betatron core due to a higher feedback frequency. The sufficiently high requirements for extraction uniformity, ~5% throughout the entire extraction, predetermined the extraction mechanism using RF buildup.

SYNCHROTRON EXHAUST SCHEME

The resonant harmonic of the perturbation is created by a pair of identical sextupole lenses, which are located at the edges of the inlet–outlet gap in places with a zero dispersion function. Due to the incursion of the horizontal betatron phase ~4π/3 between the sextupoles, the resonant harmonic doubles. The zero dispersion function at the locations of the sextupoles provides independent control of chromatism and the magnitude of the resonant harmonic.

Immediately before extraction, the equilibrium orbit in the electrostatic and magnetic septums (see Fig. 5) is locally distorted with the help of special bump magnets. Two magnets spaced apart in the phase of betatron oscillations by ~π are used to bump the orbit in the magnetic septum; the rest are used to bump the electrostatic septum. After that, the frequency of horizontal betatron oscillations is brought to the resonant value $Q_x = 10/3$, with detuning $\delta = -0.01$, and the HF buildup of horizontal oscillations is turned on. The beam particles extracted from the separatrix fall into the gap of the electrostatic sep-

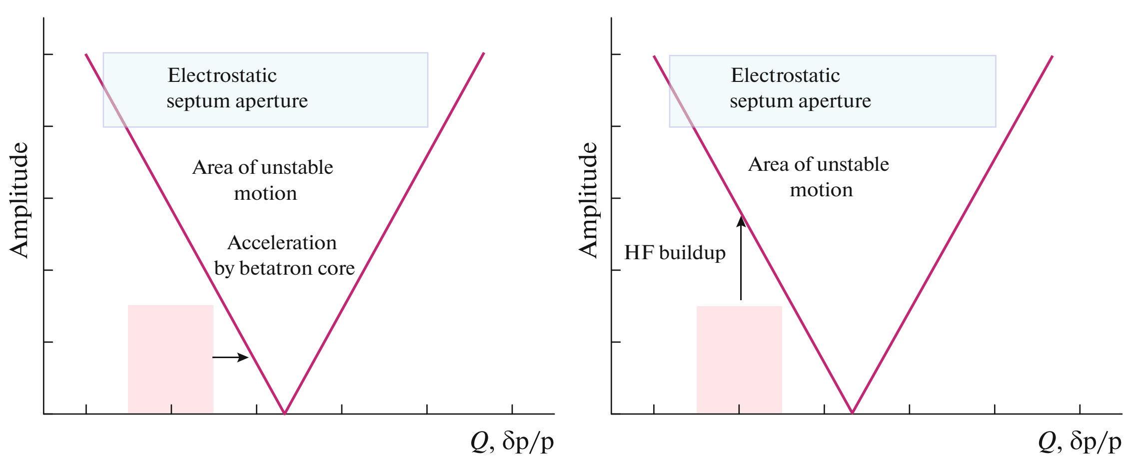

Fig. 4. Slow extraction mechanism based on acceleration by a betatron core (left) and based on an increase in the amplitude of betatron oscillations by HF buildup (right).

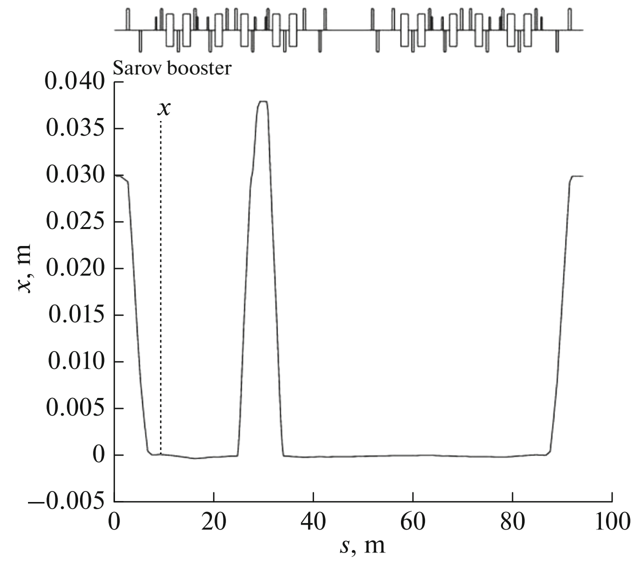

Fig. 5. Equilibrium orbit distortions in electrostatic and magnetic septums.

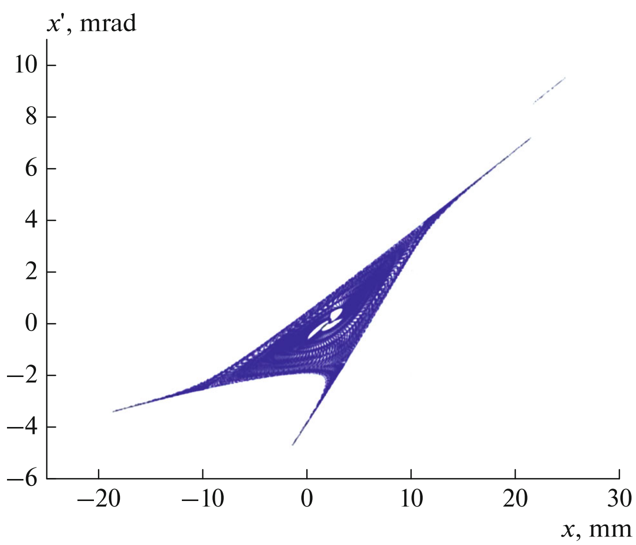

Fig. 6. Phase portrait of the beam after passing through the electrostatic septum.

tum, where they receive a horizontal impact of ~1.3 mrad and, at the same revolution, are thrown behind the knife of a Lambertson-type magnetic septum. The parameters of the electrostatic septum are shown in Table 2.

The phase portrait of the beam after passing through the electrostatic septum is shown in Fig. 6. It can be seen that, in order to minimize beam losses at the knife, it is highly desirable to rotate the septum relative to the longitudinal axis by an angle of ~8 mrad. To do this, adjustment nodes are provided on the inner surface of the septum body, which allow one to turn the knife relative to the vacuum chamber.

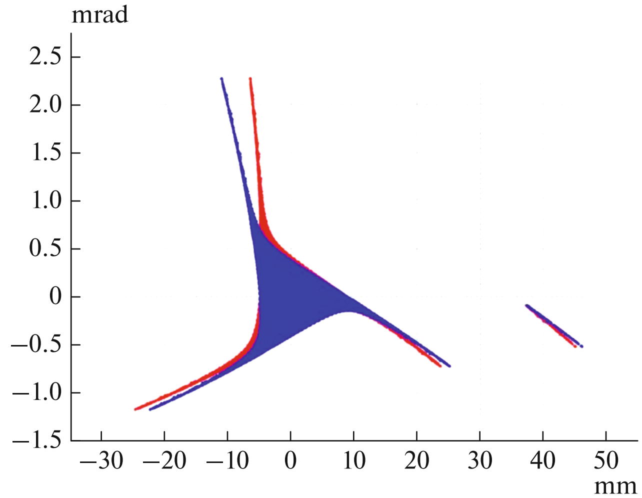

Fig. 7. Phase portrait of the beam at the entrance to the magnetic septum (blue) and at the exit from it (red).

The horizontal distance between the circulating and emitted beams in the magnetic septum is ~10 mm at an impact of 1.3 mrad. This gap is sufficient to accommodate a ferromagnetic knife 5 mm in thickness and the walls of the vacuum chambers.

ELEMENTS OF THE SLOW EXTRACTION SYSTEM

An electrostatic septum is installed inside a heating vacuum volume ~300 mm in diameter (see Fig. 8). On the body of the septum there is a mechanism for tensioning a molybdenum foil, 100 μm in thickness, which serves as a septum knife. The titanium cathode is fixed on two support insulators. The body of the septum has the ability to rotate horizontally by an angle of ±10 mrad to minimize slow extraction losses.

To compensate for natural chromatism, eight sextupole lenses are used, installed in the arches of the

Table 2. Electrostatic septum parameters

Parameters	Meaning
Impact angle, mrad	1.3
Distance from knife to equilibrium orbit, mm	21
Horizontal clearance, mm	7
Knife length, mm	300
Knife thickness, mm	0.1
Maximum voltage, kV	–50
Full length of the septum, mm	500
Losses, %	~5

Fig. 8. Electrostatic septum model.

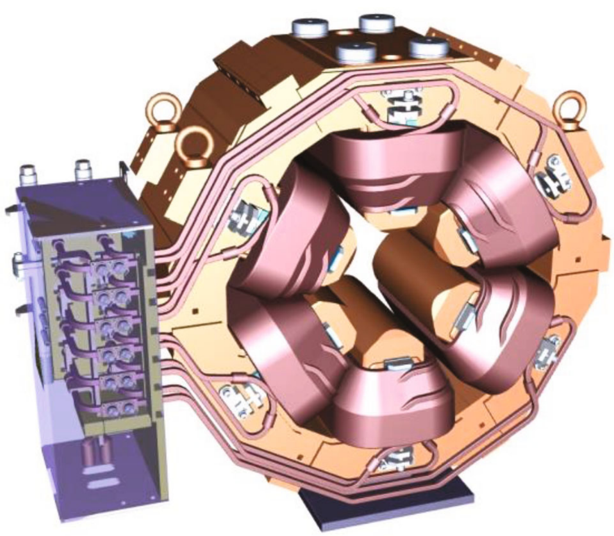

Fig. 9. Sextupole lens model.

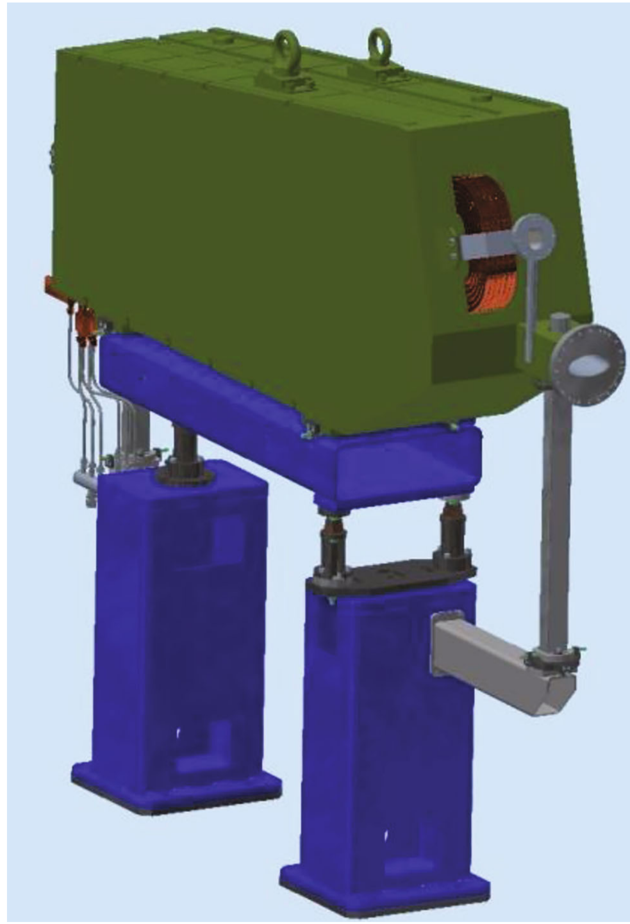

Fig. 10. Lambertson magnetic septum model.

ring. Also, to create a resonant harmonic, two sextupoles are used in a rectilinear gap. The design of the chromatic and resonant sextupoles is identical, despite the significant difference in the magnitudes of the gradients. The parameters of the sextupole magnet are shown in Table 3.

The extraction is carried out in a vertical plane using a Lambertson-type magnetic septum (see Fig. 10). The circulating beam is brought to the sep-

Table 3. Parameters of the sextupole lens

Parameters	Value
Number of magnets	8
Max gradient $\partial^2 B_y/\partial x^2$, T/m^2	177.8
Inscribed circle diameter, mm	150
Magnetic length, mm	292.2
Good field area, mm	Ellipse 70 × 30
Maximum current *I*, A	300

Table 4. Magnetic septum parameters

Parameters	Value
Number of magnets	1
Max magnetic hardness, T m	4.47
Maximum field, T	0.7
Current integral, kA turns	23.04
Angle of rotation	16°
Extraction trajectory radius, mm	6400
Pole length, mm	1711
Magnetic length, mm	1787

Table 5. Parameters of bump magnets

Parameters	ES Bump Magnets	MC Bump Magnets
Number of magnets	5	2
Correction angle, mrad	25	7.5
Maximum magnetic field, T	0.29	0.056
Magnetic length, mm	282	615
Rated current I_{nom}, A	300	300

tum magnet knife using two specialized bump magnets (see Table 5) and is thrown behind a ferromagnetic knife 5 mm in thickness. Rectangular magnetic screens are made at the ends to prevent the field from falling into the orbit of the circulating beam.

CONCLUSIONS

One feature of the ion synchrotron developed at the BINP, Siberian Branch, Russian Academy of Sciences, is the presence of two extraction modes: slow at resonance and fast single-turn. This paper presents the results of calculations of slow extraction from a synchrotron with high efficiency. The optical structure of the synchrotron is optimized to minimize beam losses for both slow and fast extractions. The same outlet magnetic septum is used in both cases. Also, this paper presents the calculations and preliminary design of all elements of the extraction: electrostatic and magnetic septums, sextupole lenses, and bump magnets.

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