HALF-INTEGER RESONANCE EXTRACTION FOR THE NAL ACCELERATOR

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Summary

The slow extraction from the main ring at NAL utilizes the half-integer resonance at $\nu_x = 41/2$. Extraction elements are three quadrupoles and one octupole. Two quadrupoles control the tune during the extraction while the third one is used to compensate for the tune fluctuation, thereby reducing the amount of the beam intensity modulation. The turn separation is produced by the average octupole field in the ring as well as by the special octupole which is located in phase with extraction quadrupoles. The size of turn separation is also controlled by a local bump in the closed orbit near the extraction septum. The beam has been extracted with the spill time up to 700 ms and with the efficiency of 85-90%. Together with a pinger, it is also possible to extract over 90% of the beam in less than 400 μs.

Half-Integer Resonance

For the slow extraction of the beam from the main ring, two different schemes, one with the non-resonant target scattering and the other with the third-integer resonance, were originally planned. In spite of the promising prediction of numerical calculations,[1,2] the performance of the scattering extraction at 200 GeV was rather disappointing. The extraction efficiency never exceeded ~20%. Admittedly, the scheme was not tested extensively and there may be ways of improving the performance.[1,3] The resonance extraction at $\nu_x = 61/3$ has been numerically studied in detail.[4] For this scheme to be successful, it is essential to control the ripple in the main quadrupole current (10^{-5} or less) and to compensate for the average octupole field in the ring. Since there is no stopband, the stable phase space area reappears when the tune crosses the resonant value and certain fractions of the beam remain in the ring unextracted. Correction octupoles, which are needed to avoid the beam getting trapped around outer stable points in phase space, are by no means trivial. For these reasons, it was decided to try the half-integer resonance extraction at $\nu_x = 41/2$ with the option of using the third-integer resonance kept open.

Qualitative features of the half-integer resonance can best be seen in the Hamiltonian formalism in which only average and resonating terms, that is, 41st harmonic component of quadrupole field plus 41st and 82nd harmonic components of octupole field, are retained.[5] Since the tune is normally 20.25 - 20.30 during the acceleration, the resonance will be approached from below. The convenient arrangement is then to have the resonant quadrupole and octupole fields in phase and of the same polarity. Measurements of the horizontal tune as a function of the orbit radius indicated the existence of a rather strong average octupole field ($B'''/B' = 3\sim4\ m^{-2}$) in the ring up to ~200 GeV excitation.[6] Beyond 200 GeV, the strength of the octupole field decreases and becomes negative above ~400 GeV. The role of the octupole field is to produce a stable central region in phase space and to provide a proper turn separation. The stable area will be gradually squeezed as the strength of the extraction quadrupole is increased. Portion of the beam which is spilled out of this area moves along an unstable flow line and eventually gets extracted. If the average octupole field in the ring is non-zero, there are two outer stable fixed points so that the beam always stays within a finite area. However, these points are so far away from the origin that, for all practical purposes, the entire phase space can be regarded as unstable when the strength of the extraction quadrupole field exceeds a certain value. The similar damping effect of the average octupole field on the third-integer resonance is much more serious.[4] Also, unlike the third-integer resonance, the central stable region does not reappear and the entire beam will be extracted. The momentum dependence of the tune arising from the chromatic aberration of main quadrupoles ($\Delta\nu_x \simeq -23\Delta p/p$) and from the sextupole field in dipoles ($\Delta\nu_x \simeq -17\Delta p/p$) will make particles with lower momentum extracted before those with higher momentum. In addition to the octupole field strength, the size of the turn separation depends strongly on the radial position of the extraction septum measured from the closed orbit. For an efficient extraction, a local bump in the closed orbit is essential and this should be adjustable independently for position and angle. One disadvantage of the half-integer resonance is the effect of the 41st harmonic component of the main quadrupole field (imperfection field). If this component is too large, the phase of quadrupole and octupole fields relative to the septum may become unsuitable for the extraction. The beam will then "come out" at places different from the septum location. The magnitude of the imperfection field can be found by measuring the width of the stopband around $\nu_x = 41/2$. Although there are still some uncertainties, the width seems to be narrower than 0.015 beyond ~200 GeV. If the extraction quadrupole were strong enough to produce a stopband width that is much

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larger than 0.015, the perturbation caused by the imperfection in the ring quadrupole field should not change the overall features of the extraction.

Numerical Studies

Extensive numerical calculations have been performed to investigate the characteristics of the half-integer resonance. In particular, the effect of ripples in the main quadrupole current on the modulation of the beam intensity has been studied in detail. The choice of the quadrupole and octupole locations, which is a compromise between the best possible place and the most convenient one from practical considerations, has been found to be satisfactory. Particles are initially distributed in an ellipse of the area 0.25π mm-mrad and are traced until they are either extracted or lost (radial oscillation amplitude larger than 5 cm) in the ring. The starting value of the tune due to main quadrupoles alone is 20.395 which is sufficiently away from 20.5 so that the linear betatron oscillation parameters of the ring are expected to be almost identical to those given by SYNCH calculation. When the tune fluctuation is more than ± 0.0001, which corresponds to a ripple of $\pm 0.25 \times 10^{-5}$ in the main quadrupole current, there is a distinct structure of the same frequency in the extracted beam. However, this structure is mostly eliminated by adding another quadrupole and making its strength oscillate out of phase with main quadrupoles. The average octupole field assumed for the calculation is $B'''/B' = 3.6\text{m}^{-2}$ which may be an overestimate for energies higher than 200 GeV. With this average field, the maximum turn separation of 1 cm for two turns is produced at the septum position of 2.5 cm. When the maximum allowed turn separation is 1 cm, which is the aperture of the septum, the average turn separation for all particles is approximately 6.5 mm. Thus the theoretically predicted extraction efficiency is 96-98% for the effective thickness of the septum between 5 and 10 mils.

Extraction Elements

The primary extraction elements are two iron-core quadrupoles, one air-core quadrupole and one iron-core octupole. Another octupole, which is identical to what is now in use, will be installed later. The maximum field strength of iron-core quadrupoles is $B'\ell = 120$ kG and the maximum of the octupole is $B'''\ell = 71{,}000\ \text{kG/m}^2$. The first iron-core quadrupole is driven by a specially modified power supply. This consists of two parallel DCR40-250A Sorenson power supplies. Modifications are made to provide ramping capabilities (0-500A with 5-Hz bandwidth) with inductive loading. The octupole is driven by a similarly modified supply with the same capabilities. The other iron-core quadrupole is a servo quadrupole and is driven by a 50V-50A transistor bank with 100-Hz bandwidth to give spill smoothing. The servo presently utilizes the circulating beam intensity in the ring to provide feedback information. Major components (0-360 Hz, 720 Hz, 1,440 Hz and 2,160 Hz) of the ripple in the main quadrupole current are detected and recombined to excite the air-core quadrupole with suitable phase shifting. The maximum amount of tune compensation is 0.004. The test of this quadrupole has not yet been completed. It is hoped that this quadrupole would be very useful in reducing the amount of intensity modulation. In the typical mode of operation, the main quadrupole excitation is increased to raise the tune from 20.27 at 300 ms before flattop to 20.4 at flattop. The first iron-core quadrupole is ramped from 100 ms before flattop to 40 ms into flattop. At 50 ms into flattop, rf is turned off and the servo quadrupole is activated. Three sets of local bumps provide the vertical and horizontal position control and the horizontal angle control of the closed orbit near the septum. Additional bump to control the vertical angle will be added in future.

Results of Performance Tests

The extraction system is still being tested for optimizing all parameters involved. However, no unforeseen difficulties have been encountered so far. There have been almost 1,000 hours of 200-300 GeV experimental runs with the slowly extracted beam. Three modes of extraction have been tried, each for different requirements of experiments. The first mode is the standard slow spill with the spill time up to 700 ms. Examples of this mode, shown in Figs. I - III, are all buffered ion chamber outputs. Modulation by the ripple in power supplies can be clearly seen in these pictures. In Fig. III, the structure with the revolution frequency (50 kHz) is caused by the ring only partially filled with the beam. Efficiency of the extraction depends critically on the alignment of the electrostatic septa and the Lambertson septum magnets. Positions of these units are remotely adjustable and they have been carefully aligned using efficiency and loss monitors. Fig. IV shows the efficiency and losses on the electrostatic septa and Lambertson magnets for different radial positions of the septa. The efficiency given in this graph is defined as

$$\varepsilon = \text{SEM/internal beam intensity}$$

where the extracted beam intensity is measured by integrating the output of a secondary emission monitor (SEM). The efficiency is increased by approximately 7% when the octupole is excited to its maximum value. However, there has been no systematic optimization of parameters for this case. The second mode of extraction, which may be called a coherent resonant extraction, is accomplished by bringing the beam close to the resonance and then kicking it by a pinger[7] into the unstable region in phase space. Fig. V shows the shortest spill presently attainable with the maximum rate of increase in the extraction quadrupole strength. When the pinger is used, 90% of the beam can be extracted in less than ~400 μs with no loss of efficiency. This is shown in Fig. VI where the beam is extracted once every two turns. The third mode of extraction is a combination of these two modes. Approximately 80% of the beam is extracted slowly and the remaining 20% is coherently extracted with a short spill time.

Major problems to be solved are: 1) optimization of the octupole strength for the best turn separation, 2) unpredictable change in the composition of various frequency components in the main quadrupole power supplies, and 3) tune fluctuations (~±0.001) due to the ripple in the dipole current which is not regulated as well as the quadrupole current. The tolerance requirements on the tune fluctuation will become less stringent if the range of the tune to be covered during the extraction is increased from the present value (~0.002 or less to cover the beam emittance and ~0.004 to cover the momentum spread). The momentum spread of the beam can be enlarged by simply switching the rf phase at the end of the acceleration such that the beam bunch sits on the unstable synchronous phase. A trial at 100 GeV increased the total spread from 0.13×10^{-3} to 0.9×10^{-3} after 2.5 ms. One disadvantage of this scheme is the possible motion of the extracted beam spot at places in the external transport line where the horizontal dispersion is large.

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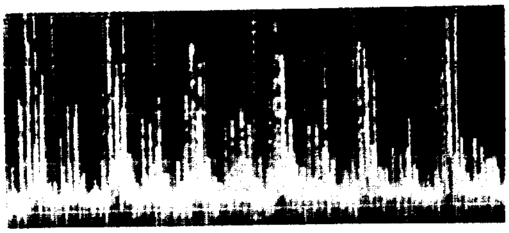


Fig. I.

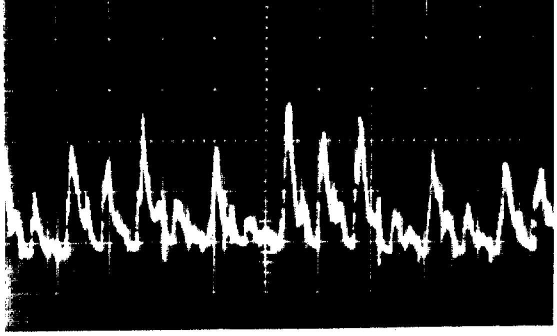


Fig. II.

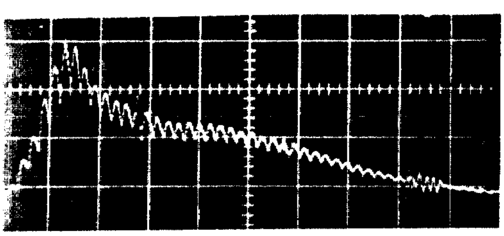


Fig. III.

Figs. I-III. Examples of slow spill. The time scale is 10 ms, 2 ms and 0.1 ms/div, respectively. In Fig. I, the frequency of the dominant component of modulation is 120 Hz. In Fig. III, the ring is partially filled with the beam and the structure with the revolution frequency (50 kHz) is clearly seen.

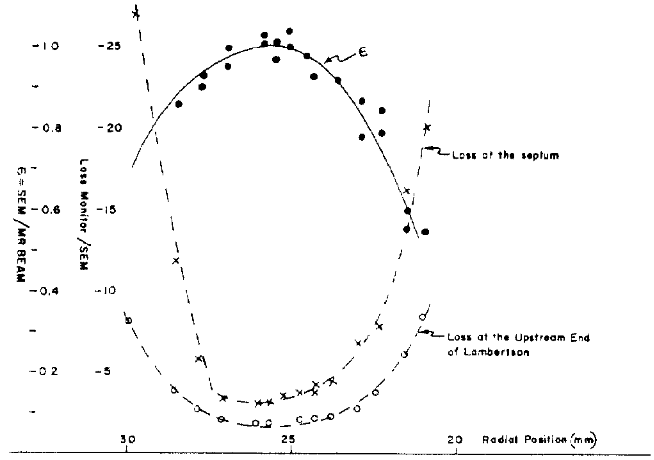
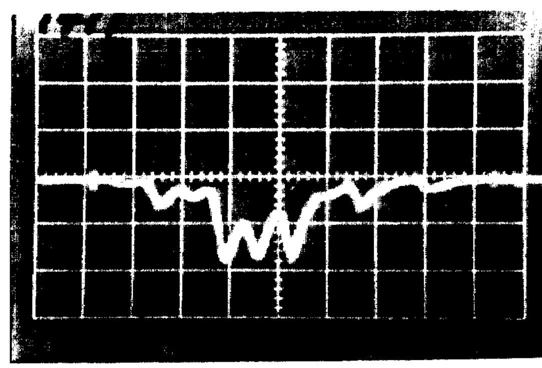


Fig. IV. Extraction efficiency and losses for different radial positions of the septum.



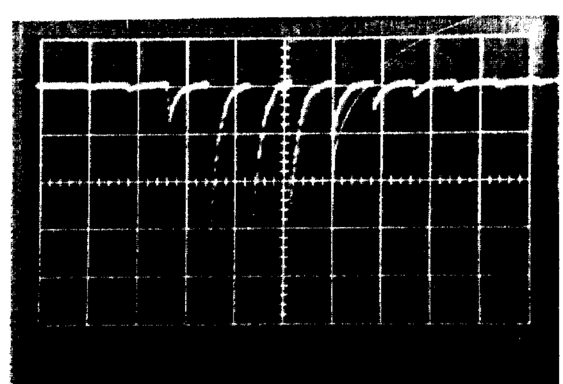


Fig. VI.

Fig. V-VI. Coherent resonance extraction. The time scale is 2 ms and 50 μs/div, respectively. Fig. V is the shortest spill attainable without the pinger. In Fig. VI, the pinger time is the same as the trigger time. The beam is extracted every two turns (42 μs).