TOWARDS A SLOW EXTRACTION SYSTEM FOR THE TRIUMF KAON FACTORY EXTENDER RING WITH 0.1% LOSSES

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Abstract

In order to reduce extraction losses a modified third-integral slow extraction system is proposed using a 0.5 m long and 10 μm thin electrostatic pre-septum. Various factors limiting the extraction efficiency like power-supply noise and synchrotron oscillations are investigated analytically as well as by simulation, and the losses are estimated to be as low as 0.2%. The extracted beam emittance is about 0.2π mm-mrad. For chromatic extraction a reduction in momentum width of the extracted beam by a factor of 2.5, resulting in an extracted momentum bite of less than 30 MeV/c FWHM, can be achieved without emittance blowup. The duty factor typically is between 55% and 65%. Between 1.8% and 3.7% of the particles did not get extracted by the resonant system. First investigation of half-integer extraction indicates possible difficulties in achieving small extracted emittances.

Introduction

Slow-extraction systems currently in operation allow in general for 1% or 2% of the circulating beam to be lost due to the thickness of the electrostatic septum. For the high-current proton accelerators proposed for the hadron facilities or kaon factories, losses this high will lead to unacceptable levels of radiation in the machine, causing problems with maintenance and the expected lifetime of the components of the accelerator. For 100 μA average extracted beam no more than about 0.1% losses, properly collimated, are tolerable especially if hands-on maintenance on most parts of the machine is to be possible. To achieve this in a slow extraction system is difficult due to limitations in septum thickness and gap size.

At TRIUMF we investigated a third integral resonant extraction system with a short (0.5 m long) electrostatic pre-septum in addition to the 'standard' slow extraction setup. Since thermal deformation of the septum increases proportional to its length squared, this septum can indeed be made very thin. In addition, the shortness of the septum reduces the effect of beam divergence. Using 10 μm wires, about 15 μm effective thickness can be achieved if the body of the septum is made of INVAR. Estimates also show that the wires can withstand the power density of the beam, especially if carbon fibres are used. If the septum gap is chosen to be 20 mm the deflection of the beam is about 0.05 mrad at a high voltage of 100 kV, avoiding the use of oil feed-throughs. The stepsize is then limited to 15 mm or less in order to have some clearance to the beam.

In order to calculate the basic parameters for the extraction system, sextupole strength and range of tune variation needed for extraction, we need to specify the radial position of the septum and the lattice functions.

For the Extender ring we chose the following parameters:

$$\begin{aligned} \beta &= 100\text{ m} \\ \alpha &= 0 \\ \epsilon &= 4.6\,\pi\text{ mm}-\text{mrad} \\ \text{stepsize} &\geq 10\text{ mm} \\ \text{sextupole angle } \theta_s &= 360^\circ\,. \end{aligned}$$

Using the formulae of Symon,[1] we can calculate the normalized sextupole strength A to be $1.13\text{ m}^{-1/2}$. The distance in tune from resonance at which extraction begins is $\Delta\nu = 0.011$. These parameters describe the basic setup of the extraction system.

Extraction Losses

Given a septum of 10 μm thickness and 0.5 m length and given a stepsize of 10 mm, the extraction losses are limited by the divergence of the extracted beam since it increases the apparent width of the septum. If we want this increase in width to be less than 10 μm the divergence in the extracted beam has to be less than 20 μrad, and the maximum extracted emittance allowed is 0.2π mm-mrad. The total losses would be 0.2%. In the following we will investigate the factors influencing the extracted emittance.

The absolute minimum emittance of the extracted beam is given by Liouville's theorem, since we 'slice-up' phase space over the extraction cycle. In the TRIUMF-KAON Extender ring, the circulating emittance is 4.6π mm-mrad and we extract over about 30000 turns, therefore

$$\delta\epsilon = \frac{\epsilon_{\rm circ}}{n_{\rm turns}} = 1.5\times10^{-4}\,\pi\text{ mm}-\text{mrad}\,. \tag{1}$$

Even if the separatrices are made to lie on top of each other during the course of extraction—this is achieved by programmed orbit bumps—this ideal value is of little significance for the actual performance of the system. The emittance will be increased by variations in machine tune and variations in the lattice functions arising from noise on the power supply for the quadrupoles as well as chromaticity of the tune and the lattice functions. Because they are unpredictable in nature (noise) or different for each particle (chromaticity) no correction for these variations can be applied.

Variations in tune will lead to an increase in the rate of tune change per turn, S_ν, thereby effectively reducing the number of turns in Eq. (6). Associated with this is an increase in emittance,

$$\delta\epsilon = 2\,\frac{S_\nu}{\Delta\nu}\,\epsilon\,. \tag{2}$$

We take as a typical number a maximum slope S_ν of 10^{-4} per turn and get for our scenario a value of 0.1π mm-mrad. This emittance blow-up is therefore already orders of magnitude larger than the minimum value from Eq. (6). Also, Eq. (7) sets a lower limit on the value of $\Delta\nu$, requiring a minimum strength of the sextupole below which the system will get too sensitive to inevitable tune variations.

The second contribution to the emittance arises from variations of the lattice functions. Given the particle's position in normalized phase space, we can calculate the variation of its position in (x, x') space due to a variation in α and β. We are only interested in variations in x' since in all practical cases the extracting separatrix will be very nearly horizontal, giving rise to a spatially extended beam with small divergence such that variations in x do not significantly affect the emittance. From the transformations we derive

$$\frac{dx'}{d\beta} = -\frac{1}{2}\,\frac{x'}{\beta}\,, \quad\text{and}\quad \frac{dx'}{d\alpha} = -\frac{x'}{\beta}\,. \tag{3}$$

Assuming 10^{-4} relative noise on the quadrupole field we will get a relative variation in β of 10^{-3} since the tune of the ring is about ten and thus, for a beam size of 10 mm, $dx'/x' = 5\times10^{-3}$. If $x' = 1$ mrad, we get $dx' = 10$ μrad and, for a beam size of 10 mm, $\delta\epsilon = 0.1\,\pi$ mm$-$mrad.

A setup with low average x' is favoured which suggests using a position with low α for the pre-septum, thus reducing dx' as well as $d\alpha$. Variations in α then become negligible since $d\alpha/\alpha$ is approximately constant for a given lattice and given variations in quadrupole strength.

It appears therefore that the goal of $0.2\,\pi$ mm-rad for the emittance can be met, provided the noise on the quadrupole current does not exceed 10^{-4} level. This requirement should be easily met, and in fact, a standard TRIUMF power supply investigated for this showed noise of about $1-2\times10^{-4}$ in current. Tune variation due to quadratic chromaticity was found to be negligible for our case. Variation in β due to chromaticity is of the same order of magnitude as given above but can be reduced by correcting the chromaticity of the lattice functions at position of the pre-septum.

The above effects are present in achromatic extraction schemes where the machine chromaticity is corrected and the full momentum bite of the circulating beam is extracted at any given time. It is of advantage, however, to be able to maintain the machine chromaticity and extract the beam shifting the tune towards the resonance by either deceleration or acceleration. In this way only particles with their individual tune close to the resonance will be extracted, and because the tune is proportional to the momentum only a small momentum bite will be extracted at any given time. We can calculate the momentum spread of the extracted beam,

$$\frac{\delta p}{p} = \sqrt{4\pi\,\sqrt{3}\epsilon_{\rm circ}}\,\frac{A}{\xi}\ , \tag{4}$$

where ξ is the chromaticity, $d\nu/d(\delta p/p)$. To avoid correlation between the position of the particles in phase space and their momentum, the lattice functions α, β, η, and η' have to be chosen such that the following equation is fulfilled:

$$\xi = 6A\left(\frac{\eta}{\sqrt{\beta}}\left(\sin\theta_s + \alpha\cos\theta_s\right) + \eta'\sqrt{\beta}\cos\theta_s\right)\ . \tag{5}$$

This condition is equivalent to the one given by Hardt.[2]

There is, however, emittance blow-up due to synchrotron oscillations that modulate the speed of tune change especially for particles at large synchrotron amplitudes,

$$\delta\epsilon = \frac{2\sqrt{\pi\,\epsilon_{\rm circ}}}{4\sqrt{3}}\,\frac{\delta p}{p}\,\frac{\nu_s\,\xi}{A}\ . \tag{6}$$

Equations (4) and (6) show that, if $\delta\epsilon$ is to stay at or below a certain value, the extracted momentum spread is determined by the product

$$\frac{\delta p}{p}\,\epsilon_{\rm circ}\,\nu_s\ ,$$

but independent of the choice of the chromaticity ξ and the sextupole strength A. It thus appears that the only machine parameter influencing the extracted momentum bite is the synchrotron tune ν_s.

For the TRIUMF-KAON Extender ring, $\nu_s = 0.0013$ and $\delta p/p = \pm0.16\%$. If ξ is 10, we get

$$\frac{\delta p}{p} = \pm0.05\%\ , \qquad \text{and} \quad \delta\epsilon = 0.3\,\pi\ \text{mm}-\text{rad}\ .$$

For chromatic extraction, emittance may therefore be somewhat enlarged and we may have to trade momentum resolution in favour of a reduced beam emittance.

Lattice

From the above it is clear that a very flexible extraction section is necessary in order to be able to achieve the values for the lattice functions required by the different extraction scenarios, chromatic and achromatic. We therefore designed a new racetrack lattice for the TRIUMF-KAON Extender ring that can accommodate the needs in a very flexible way.[3] The arcs have regular FODO structure and are tuned for a total phase advance of $5\times2\pi$ per arc. All arc cells are completely filled with bending magnets. The straight sections consist of a two-cell transformer and a section where the β function can be varied over a wide range while maintaining the tune of the machine. Dispersion can be created by tuning the arcs away from the integer value. Figure 1 shows an example of a straight section together with

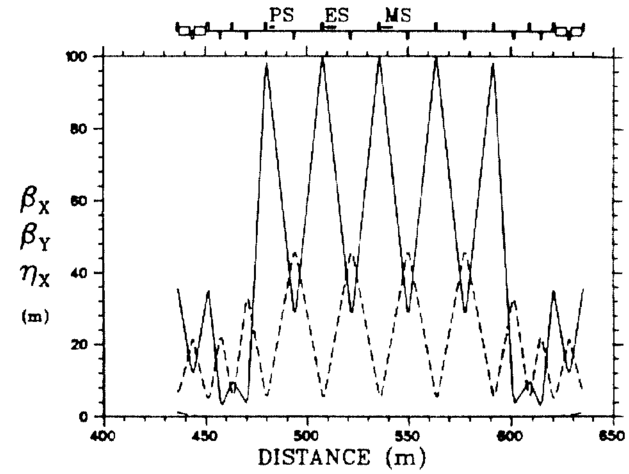

Fig. 1. Straight section and last arc cells of the newly developed racetrack lattice. PS denotes the position of the pre-septum, ES the position of the main electrostatic septum, and MS the position of the magnetic septum.

the last arc cells. The positions of the extraction septa are indicated.

Simulations

In order to study the dynamical aspects of the extraction system, we used our extraction code SLEX to perform Monte-Carlo simulations. The simulations were carried out by numerically integrating the equations of motion in a rotating normalized coordinate system as given by Symon[1] using a fourth-order Runge-Kutta differential-equation solver optimized for speed. All effects outlined above were taken into account and could be varied in order to study their influence. Longitudinal tracking was done using difference formulae given by Hereward.[4] Only horizontal transverse phase space and longitudinal phase space was included in the simulation and no space charge was included.

2000 particles uniformly distributed in 4-dimenisonal phase space were tracked through the system for 2400 turns. In order to study the effect of quadrupole-power-supply noise and ripple, random noise with a peak value of about $\pm1\times10^{-3}$ and 60 Hz ripple of the same magnitude was superimposed on the tune, representing 10^{-4} relative variation in quadrupole current since the machine tune is on the order of 10. A limit of 10^{-2} per turn was set in the slew rate of the tune in order to simulate the reluctance of the magnets to follow fast variations of the voltage. The resulting effective maximum slew rate of the tune was 10^{-4}.

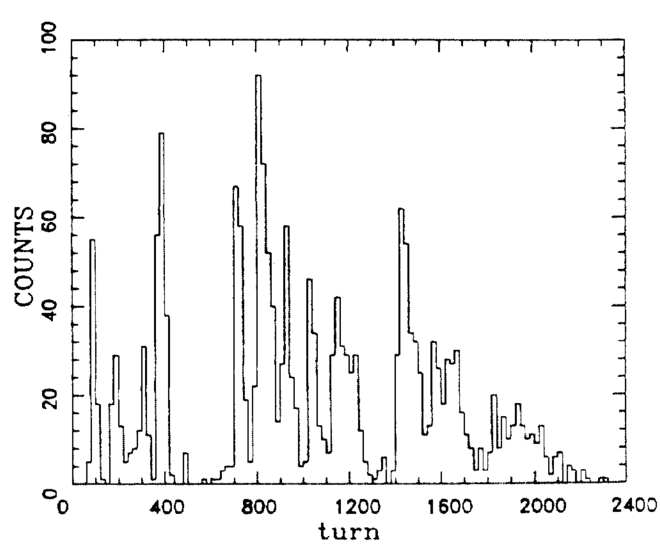

Fig. 2. Intensity distribution of extracted beam for achromatic extraction.

Figure 2 shows the intensity distribution during the extraction cycle, giving a duty factor of $(55 \pm 4)\%$. The fraction of particles remaining in the machine at the end of the cycle was $(1.8 \pm 0.3)\%$. These particles will be taken care of by the fast extraction system provided for in the ring. No septum hits were observed in this particular run, indicating that the losses are indeed at the 10^{-3} level. The extracted emittance is 0.19π mm-rad. This value is in good agreement with the analytical estimates.

More interesting is the simulation of chromatic extraction. Chromaticity was set to −10.7 for the simulation, and the η function at the pre-septum was about 5 m. Figure 3 again shows the intensity distribution, giving a duty factor of $(64 \pm 4)\%$. Power supply noise has less pronounced an effect in this case than for achromatic extraction. The explanation is that for chromatic extraction the tune range is much larger than for achromatic extraction since the full chromatic tune spread of the circulating beam has to be shifted through the resonance. In accordance, sensitivity for tune variations is reduced. The emittance of the extracted beam is 0.18π mm-rad, more or less the same as in the previous case. Four particles hit the septum, again consistent with 0.2% losses. The fraction of particles remaining in the machine is $(3.7 \pm 0.4)\%$. This figure rises further when we try to reduce the momentum bite by either decreasing the tune range $\delta\nu$ or increasing the chromaticity.

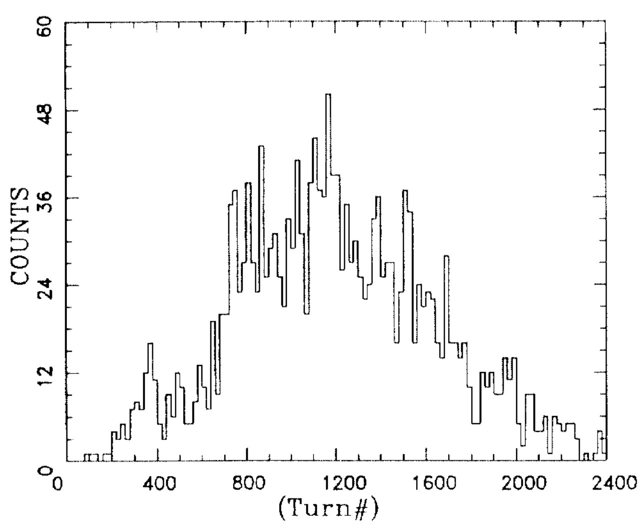

Fig. 3. Intensity distribution of extracted beam for chromatic extraction.

Figure 4 shows the momentum distribution of the extracted beam. From the Gaussian fit to the distribution we extract a width of 0.078% or 24 MeV/c FWHM, in reasonable agreement with the predicted value of 0.1%. Since the circulating beam has a momentum bite of 0.21% FWHM, resolution has increased by about a factor of 2.5. The reduction is present not only in momentum width but also in bunch length, by roughly the same factor. This can be important for particle separation especially in low-energy kaon channels.

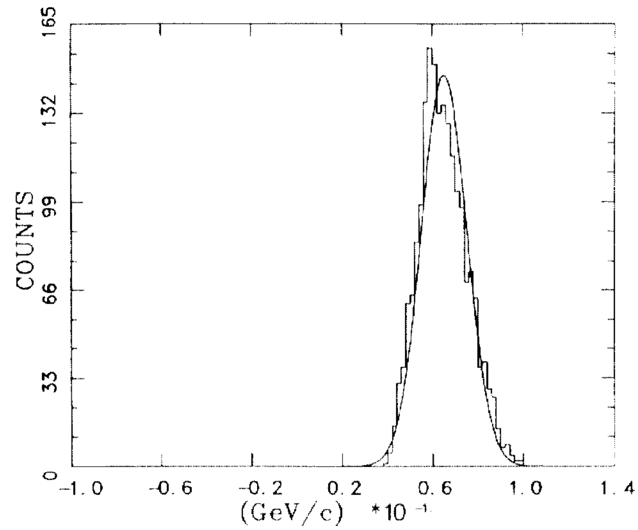

Fig. 4. Momentum distribution of extracted beam for chromatic extraction. The superimposed Gaussian curve is the result of a fit to the distribution.

1/2 Integral Extraction System

We recently started investigating half-integer slow extraction in order to be able to compare the performance with that of the third integral system. Half-integral extraction differs from third-integral extraction in that the resonance used has non zero stop-band width, which can be controlled by the strength of an extra quadrupole. This in principle enables us to empty the ring completely by the resonant mechanism. Also, since the stable phase space area has an approximately elliptical shape enclosed by the separatrices with two outgoing branches, it can be made very narrow in the extraction plane and thus good collimation of the losses is easier than for the third integer extraction.

On the other hand a larger aperture for the ring will be required. Also the separatrices have parabolic shape. Since they can change position as well as shape during the extraction cycle the extracted emittance should in principle be somewhat larger than for third-integral extraction. For the same reason it is more difficult to keep the step size constant over the cycle, possibly requiring a larger septum gap. Proper choice of the lattice parameters appears to be more important in this case to achieve a low-emittance extracted beam.

We are extending our code to include simulation of half-integer extraction. The equations of motion as given by Suzuki and Kamada[5] are used. Preliminary investigation indicates that with an achromatic half-integer system $0.2\ \pi$ mm-mrad extracted emittance and therefore 0.2% losses may be difficult to achieve. The duty factor was between 65 and 70%, and there is indication that the duty factor is less sensitive to quadrupole noise than for the third-integer system.

References

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