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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 preseptum. Various factors limiting the extraction efficiency are investigated, and the losses are estimated to be as low as 0.2%. The extracted beam emittance is found to be about 0.2π mm-mrad for achromatic extraction. For chromatic extraction a reduction in momentum width of the extracted beam by a factor of 2.5 will result in an extracted momentum bite of less than 30 MeV/c FWHM. This figure is limited by emittance blow-up due to synchrotron oscillations, which in turn increases extraction losses. Following the analytical estimate of the performance of the extraction system, simulation results are shown.

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.

Reducing extraction losses by an order of magnitude by scaling existing systems, however, is not possible. Either the thickness of the septum is reduced by a factor of ten to about 10 μm; this is not feasible since the thickness of the septum is already dominated by thermal deformation due to the length of the septum (ca. 5 m). Or the stepsize is increased by a factor of ten, to about 100 mm; this necessitates a septum gap of about 150 mm and voltages above 1 MV to achieve a reasonable deflection of the beam, which again is not a practical alternative.

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At TRIUMF we found a solution to this dilemma by using 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. We choose a moderate β function of 100 m in order to get enough separation at the pre-septum. The pre-septum is placed 36 mm away from the center of the circulating beam. We then calculate the normalized sextupole strength, A, according to Symon[1]

$$A = \frac{dQ_s}{18\pi(Q_s^2 - Q_0^2)}, \qquad (1)$$

where

$$dQ_s = \frac{S_s}{\sqrt{\beta}\cos\theta_s}, \qquad (2)$$

is the stepsize in the normalized rotating coordinate system of Symon,

$$Q_s = \frac{x_s - \frac{Q_0}{\sqrt{3}}\sqrt{\beta}\sin\theta_s}{\sqrt{\beta}\cos\theta_s}, \qquad (3)$$

is the septum position in normalized phase space, and

$$Q_0 = \sqrt{\frac{\pi\,\epsilon_{\text{circ}}}{\sqrt{3}}}, \qquad (4)$$

is the position of the unstable fixed point closest to the septum. ϵ_{circ} is the emittance of the circulating beam. S_s is the stepsize and x_s is the distance of the pre-septum from the centre of the beam. θ_s is the phase angle of the sextupole before the septum.

For the Extender ring we chose the following parameters:

$$\begin{aligned}\beta &= 100\ \mathrm{m}\\ \alpha &= 0\\ \epsilon &= 4.6\,\pi\ \mathrm{mm{-}mrad}\\ S_s &= 10\ \mathrm{mm}\\ \theta_s &= 360^\circ\,.\end{aligned}$$

The normalized sextupole strength A is then 1.13 $\mathrm{m}^{-1/2}$. The distance in tune from resonance at which extraction begins is given by

$$\langle\nu\rangle = 2\,\sqrt{3}\cdot A\cdot Q = 0.011\ . \tag{5}$$

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 0.2 π 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 4.6 π mm-mrad and we extract over about 30000 turns, therefore

$$\delta\epsilon = \frac{\epsilon_{\mathrm{circ}}}{n_{\mathrm{turns}}} = 1.5\times10^{-4}\,\pi\ \mathrm{mm{-}mrad}\ . \tag{6}$$

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,

$$\delta\epsilon = 2\,\frac{S_\nu}{\langle\nu\rangle}\,\epsilon\ . \tag{7}$$

We take as a typical number a maximum slope S_ν of 10^{-4} per turn and get for our scenario a value of $0.1\,\pi$ 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 $\langle\nu\rangle$, 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

$$\frac{dx'}{d\beta} = -\frac{1}{2}\frac{x'}{\beta}\,, \tag{8}$$

and

$$\frac{dx'}{d\alpha} = -\frac{x'}{\beta}\,. \tag{9}$$

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 $dx'/x' = 5\times10^{-3}$. If $x' = 1$ mrad, we get $dx' = 10$ μrad and, for a beam size of 10 mm,

$$\delta\epsilon = 0.1\,\pi\,\mathrm{mm{-}mrad}\,.$$

It is to be noted here that this value is independent of the value of the β function since the relative change in β is independent of the absolute value of β, and the size of the extracted beam does not depend directly on the β function. A setup with low average x' is favoured, however, suggesting a position with low α for the pre-septum, which reduces 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 desirable, however, to be able to maintain the machine chromaticity and extract the beam shifting the tune towards the resonance by either deceleration or acceleration. 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,

$$\frac{\delta p}{p} = \sqrt{4\pi \sqrt{3}\epsilon_{\text{circ}}}\,\frac{A}{C}\,, \tag{10}$$

where C 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:

$$C = 6A\left(\frac{\eta}{\sqrt{\beta}}\,(\sin\theta_s + \alpha\cos\theta_s) + \eta'\sqrt{\beta}\cos\theta_s\right)\;. \tag{11}$$

This condition is equivalent to the one given by Hardt.[3]

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

$$\delta\epsilon = \frac{2\sqrt{\pi\,\epsilon_{\text{circ}}}}{4\sqrt{3}}\,\frac{\delta p}{p}\,\frac{\nu_s C}{A}\;. \tag{12}$$

Equations (10) and (12) show that, if $\delta\epsilon$ is to stay at or below a certain value, the extracted momentum spread is determined by the product

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

but independent of the choice of the chromaticity C 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 $\delta p/p = \pm 0.16\%$. If C is 10, we get

$$\frac{\delta p}{p} = \pm 0.05\%$$

and

$$\delta\epsilon = 0.3\,\pi\ \text{mm}-\text{rad}\;.$$

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

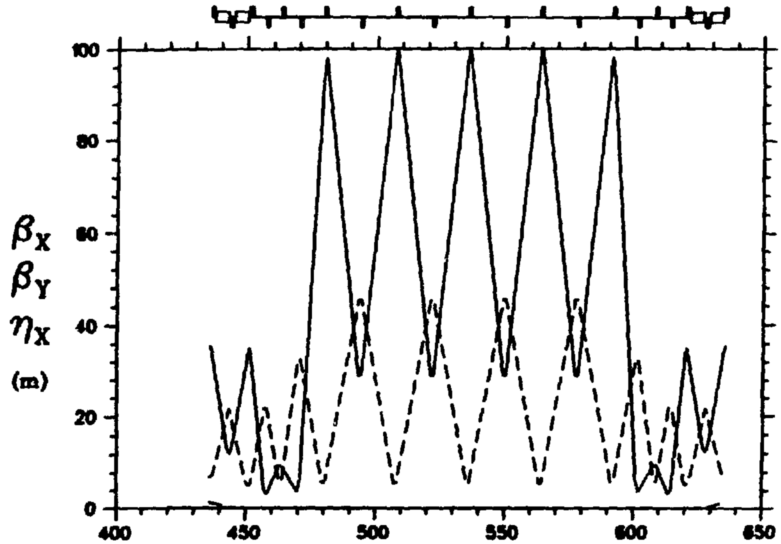

Fig. 1. Straight section and last arc cells of the newly developed racetrack lattice. PS denotes the position of the pre-septum, ES the position of the main electrostatic septum, and MS the position of the magnetic septum.

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 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.

The extraction system simulated had the same parameters as given in the above treatment. Starting with uniform distribution in four-dimensional phase space, 2000 particles were tracked through the system for 2400 turns. Achromatic and chromatic extraction was studied in this way. In order to study the effect of quadrupole-power-supply noise and ripple, random noise with a peak value of about $\pm 1 \times 10^{-3}$ 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}.

Figure 2 shows the intensity distribution during the extraction cycle, giving a duty factor of $(55 \pm 4)\%$. The ragged structure of the distribution is due to the modulation of the tune with the noise. In order to be able to empty the

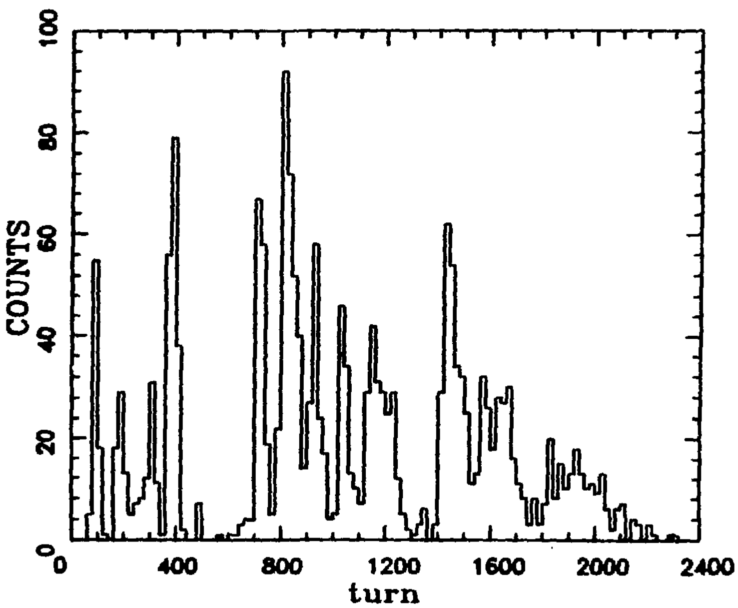

Fig. 2. Intensity distribution of extracted beam for achromatic extraction.

ring as completely as possible, resonance crossing took place at turn 2000 with the tune moving away from the resonance for the next 400 turns. 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. Figure 3 shows the horizontal phase space occupied by the extracted beam. The smallest circumscribing ellipse (SCE) has an emittance of $0.19\,\pi$ mm-rad. This value is in good agreement with the analytical estimates.

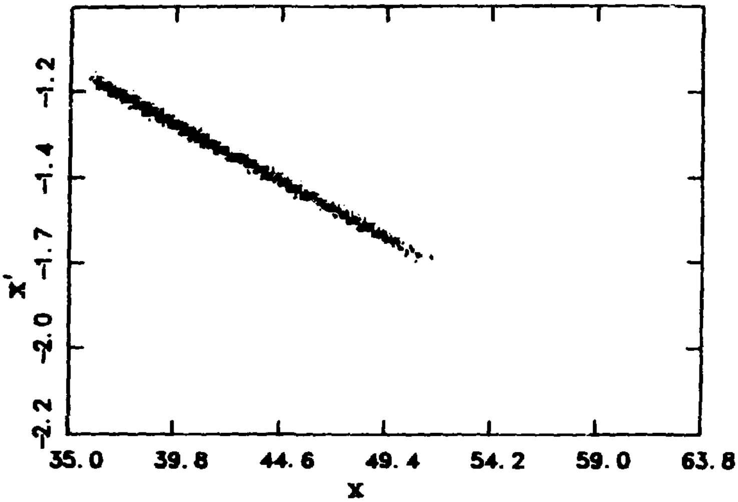

Fig. 3. Area in horizontal phase space occupied by extracted beam for achromatic extraction. The scales are in units of mm and mrad, respectively.

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 4 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 $0.17\,\pi$ mm-rad SCE, more or less the same as in the previous case. One particle hit the septum, again consistent with less than 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 (ν) or increasing the chromaticity.

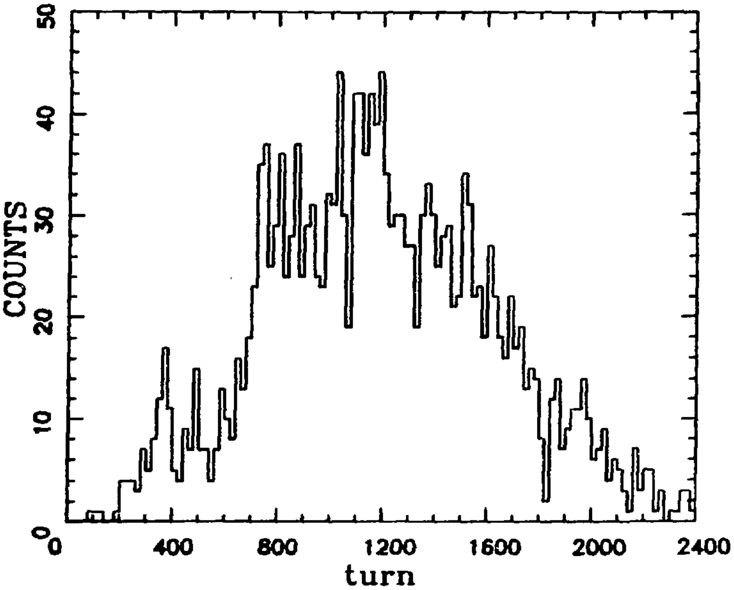

Fig. 4. Intensity distribution of extracted beam for chromatic extraction.

Figure 5 shows the momentum distribution of the extracted beam. From the Gaussian fit to the distribution we extract a width of 0.088% or 27 MeV/c FWHM, in good 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. An interesting effect is apparent in the longitudinal phase-space plot, Fig. 6, namely a reduction 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. Finally, in Fig. 7 the variation of the extracted momentum over the extraction cycle is shown. The momentum shift that is apparent could be reduced by a more elaborate extraction program varying both the tune and the momentum in a suitable manner. Any gain in momentum width would be small, however, since the distribution broadens towards the middle of the extraction cycle.

SUMMARY

In this paper we outline a way to reduce the inevitable losses in a slow-extraction system to the 0.1% level using a short and very thin electrostatic pre-septum. Using approximate analytical formulae we derive limits on the extracted beam emittance and on the parameters of the extraction system in order to maintain low losses even under tune and lattice-function variations

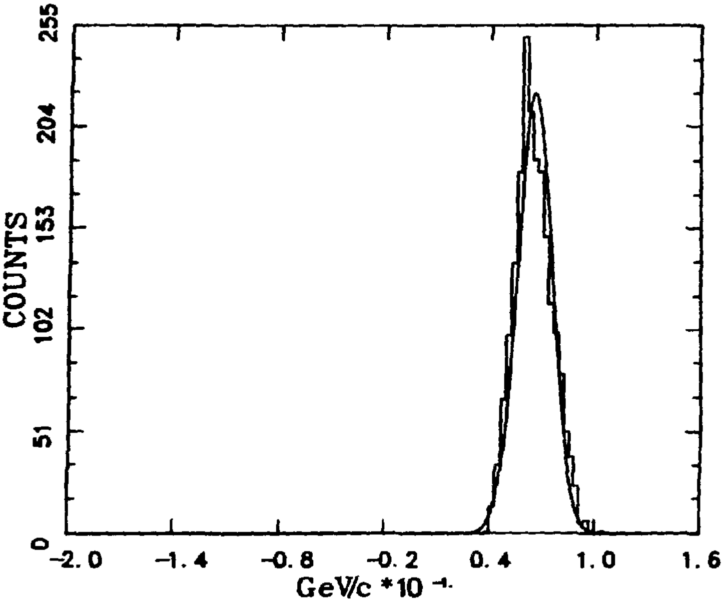

Fig. 5. Momentum distribution of extracted beam for chromatic extraction. The superimposed Gaussian curve is the result of a fit to the distribution.

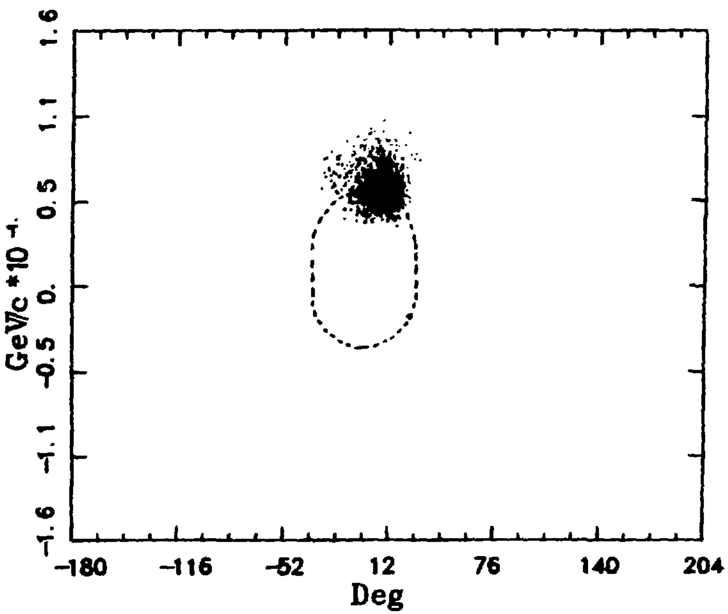

Fig. 6. Longitudinal phase space occupied by the chromatically extracted beam. The dashed ellipse represents the area occupied by the circulating beam.

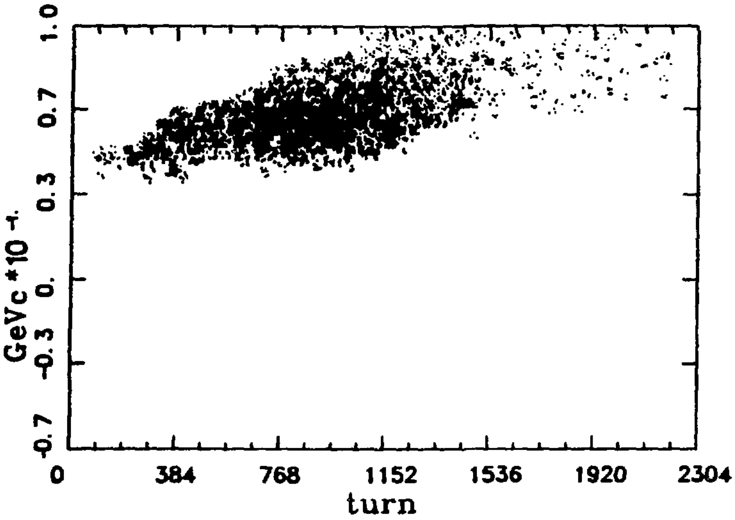

Fig. 7. Variation of the momentum of the extracted beam with time for chromatic extraction.

that are inevitable in a real machine. Performance of the system was tested by a Monte-Carlo simulation. We find that extraction losses of about 0.2% are achievable while the extracted beam emittance is less than 0.2π mm-rad. With chromatic extraction the momentum width of the extracted beam can be reduced by a factor of 2.5 without compromising emittance or extraction losses. The duty factor is between 55% and 65%. The number of particles remaining in the machine due to the vanishing stop-band width at small emittances is 1.8% for achromatic extraction and 3.7% for chromatic extraction.

The results of our simulation studies are consistent with the analytical predictions.

REFERENCES

1. K.R. Symon, Reports FN-130, FN-134, FN-140, FN-144, Fermi National Laboratory, Batavia, IL (1968).
2. W. Hardt, PS/DL/LEAR Note 81-6, CERN (1981).
3. R.V. Servranckx, Report TRI-DN-88-3, TRIUMF (1988).
4. H.G. Hereward, PS Division Report 66-6, CERN (1966).