HIGH DUTY FACTOR, MONOCHROMATIC EXTRACTION FROM EROS*

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Abstract

Simulations of the monochromatic extraction process in the pulse stretcher ring (PSR) of the Saskatchewan Accelerator Laboratory have been done using several different RF techniques. The effects of the extraction sextupoles on circulating particles cancel over several turns unless the PSR tune approaches a 1/3 integer resonance condition. This is accomplished by having a large chromaticity (-15) and allowing the energy of the particles to decrease either through synchrotron radiation losses or by changing the RF frequency of the PSR cavity. In the synchrotron loss mode the particles can be delayed by trapping them in the RF bucket and spilling them at a later time by abruptly lowering the RF voltage. Results indicate that it should be possible to extract a beam with a duty factor greater than 70%, an energy spread of $\pm 10^{-4}$ and horizontal emittance less than 0.8 mm-mrad for all operating energies.

Introduction

Simulations of the extraction process for our PSR have been done to optimize the quality of the CW electron beam produced. The criteria for high quality in the extracted beam were low energy spread ($\Delta p/p = \delta \rightarrow \pm 10^{-4}$), small transverse emittance in the horizontal plane ($\varepsilon_x \rightarrow 0.3$ mm-mrad) and to a lesser extent a high duty factor (DF>40%). As well, consideration had to be given to physical constraints such as the reduction of the flux of electrons on the extraction septum and the requirements of injection.

The simulations concentrated on the 1/3 integer mode of operation. Some simulations done with the 1/2 integer mode indicated a poorer quality extracted beam. Also, the 1/2 integer mode limits the pulse length at injection. Consequently the 1/3 integer mode will be our primary mode of operation.

The PSR has been described under its earlier name SORE[1] and for the main part the ring has remained unchanged. One exception is the inclusion of 18 quadrupole-sextupole magnets in the bend regions allowing for good control over the chromaticities without having to resort to troublesome pole face windings on the dipoles. The ring parameters are given in Table 1 along with the characteristics of the beam at injection.

Table 1. PSR parameters

INJECTED BEAM		
Energy	50 - 350	MeV
Frequency	2856	MHz
Rep rate	60 - 720	pulses/second
Pulse length	0.2 - 0.7	μsecond
$\varepsilon_x, \varepsilon_y$	0.3	mm-mrad
δ	$\pm 10^{-3}$	
Phase spread (φ)	$\pm 60°$	
PSR		
ν_x	(4).3033	(nominal)
ν_y	(4).800	
χ_x	-15.	
χ_y	0.	
Momentum compaction (α_p)	0.04828	
Length	107.9085	meters
RF	2856	MHz

* Electron Ring of Saskatoon

The beam will be injected onto the closed orbit vertically and off the closed orbit horizontally as shown in figure 1. The two turn injection (pulse length=0.7 μsec), the energy spread of the beam and the high chromaticity of the ring cause the beam to quickly fill a hollow ellipse with inner and outer areas of 10.1π and 13.9π mm-mrad. These areas help determine the energy spread of the extracted beam.

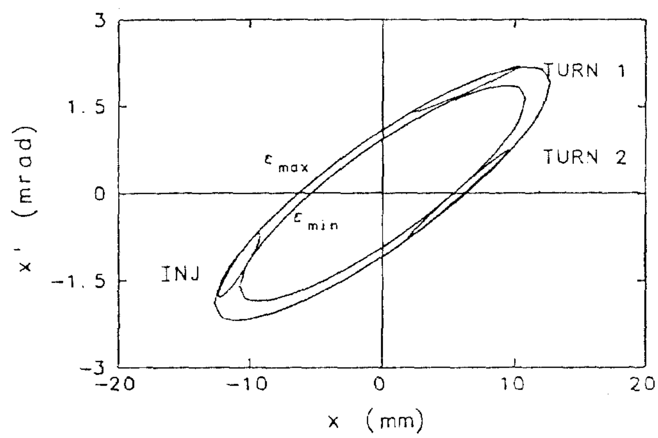

Figure 1. Two Turn Injection and Beam "Areas"

One Third Integer Resonance

The 1/3 integer resonance is excited by two sextupole magnets of opposite polarity diametrically located in the two straight (achromatic) regions of the PSR. With no RF structure acting in the ring, the beam will slowly lose energy through the mechanism of synchrotron radiation (as well as parasitic losses). With a change of energy of $d\delta$ the tune (ν_x) of the ring changes according to $d\nu_x = \chi_x\, d\delta$. Small sextupole fields are all that is necessary to induce unstable motion on the beam as it approaches resonance. Figure 2 shows this effect at the extraction position for a given electron as it loses energy from $\delta = -0.001$. With no sextupoles acting the electron would lie on the ellipse shown. The effect of the sextupoles is to distort this ellipse until it approaches the shape of a triangle as the energy decreases. At a given time the instantaneous emittance of the electron can be defined as $\varepsilon_{inst} = \gamma x^2 + 2\alpha x x' + \beta x'^2$ where α, β and γ are the machine parameters at the extraction position. This is not a true emittance but serves as a measure of how much the electron is perturbed from an elliptical path. At some energy the motion becomes unstable and the electron jumps from branch to branch outside the triangle and is intercepted along one branch by the extraction septum. The interior of the triangle represents an area (A_s) where stable motion still exists. The value of this stable area is plotted against beam energy (δ) in figure 3. The slope of the curve is proportional to χ_x and inversely proportional to the sextupole strength (S). For monochromatic extraction it is desirable to make this slope as steep as possible. Hence we have $\chi_x = -15$ and low sextupole strengths.

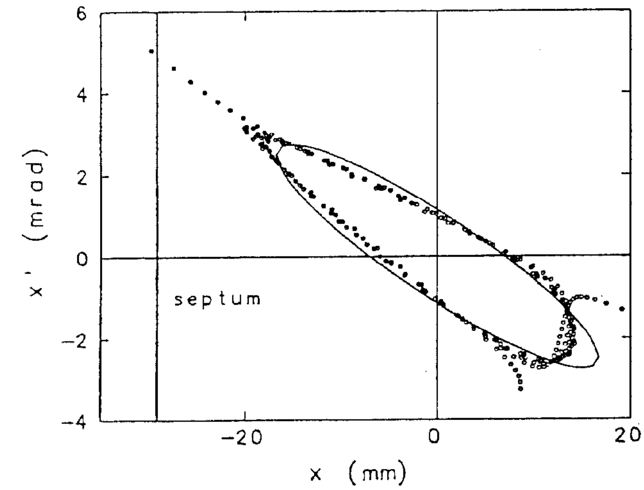

Figure 2. 1/3 Order Resonance

Monochromatic Extraction: Also shown in figure 3 is a projection of the injected beam as defined by its energy spread ($\delta=\pm10^{-3}$) and the inner and outer areas of the phase space ellipses of figure 1 together with a plot of $A_{inst}(=\pi\varepsilon_{inst})$ for two representative electrons. As can be seen from the oscillations in A_{inst} the effect of the sextupoles cancel over many turns until the unstable region is encountered and the extraction process begins. If the extraction process is sufficiently fast the electrons will be extracted with an energy spread indicated by the projection onto the energy axis. For this reason the strength of the extraction sextupoles cannot be made too small.

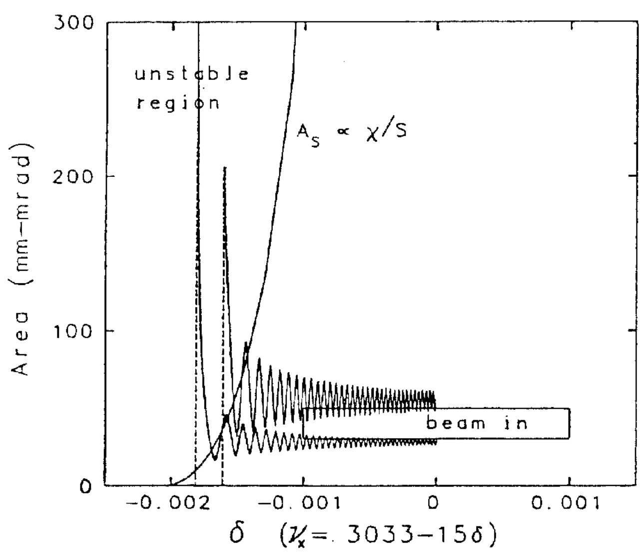

Figure 3. Monochromatic Extraction

Simulations

Simulations of the extraction were done with the tracking code DIMAT[2]. To accurately track particles over thousands of turns it is necessary to use the matrices of all elements to second order. Attempts to concatenate the matrices in any way introduced erroneous results. The simulations consisted of tracking several hundreds of electrons through up to 7600 turns assuming a rep rate of 360 pulses/second. The electrons represented a uniform distribution of particles for $\delta=\pm10^{-3}$, ε_x=0.3 mm-mrad and ε_y=0.3 mm-mrad. The extraction septum was set at -29 mm and electrons moving beyond this position defined the extracted beam.

Synchrotron Extraction

Figure 4 shows the results for simulations at 150, 200 and 300 MeV where the beam was under the influence of synchrotron radiation losses only. (The synchrotron loss in the ring is $d\delta=0.0002951E^4$ per turn where E is the energy in GeV.) In each case the energy spread is excellent ($\delta_{out}<\pm10^{-4}$) and the horizontal emittance very reasonable (see Table 2). The emittances are defined by an ellipse which will enclose 90% of the extracted beam. The increase in emittance and energy spread at higher energies can be explained by the fact that at higher energies the relative synchrotron energy loss per turn is greater and the beam penetrates further into the unstable region before extraction. This results in smaller extraction triangles with larger pitches along the extraction branch.

Clearly at this stage, however, the criteria of low energy spread and small emittance have been met. It remains only to improve the duty factor at higher energies where the beam loses energy too quickly. To this end different combinations of injected energy spread and linac rep rates can be utilized to match the extraction time to the time between pulses. An alternative approach is to control the beam with an RF system in the ring.

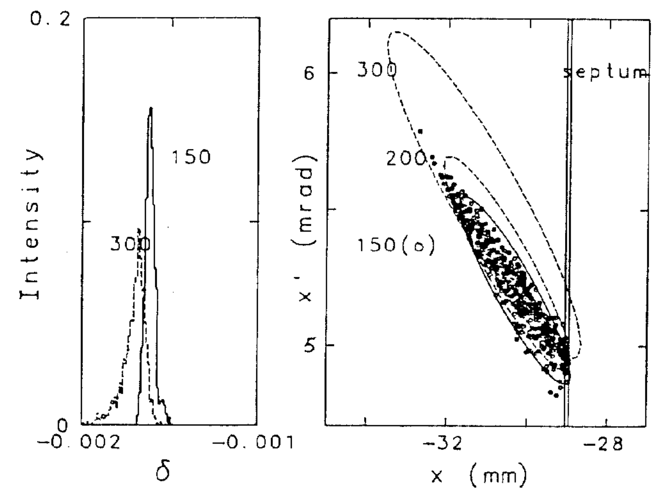

Figure 4. Synchrotron Extraction a) δ_{out} and b) ε_{out}

RF Extraction

Frequency Modulation: RF in the ring is necessary to store the beam for diagnostic purposes. Since the RF will be present several RF techniques were investigated to see if the duty factor could be increased at higher energies. All the techniques involve trapping the beam in an RF bucket and using the bucket to control the rate at which electrons approach the unstable region. The first attempt to control the beam involved frequency modulation. In this instance the beam was completely trapped in an RF bucket and the bucket was lowered in energy by adiabatically increasing the frequency (F) of the cavity ($dp/p=-\alpha_p^{-1}dF/F$) at such a rate that the top of the bucket reached the extraction region just as the extraction time neared its end. Although the duty factor was improved in this way there were disastrous effects on the energy spread and emittance. As electrons rotate around the RF bucket they continuously enter and leave the unstable region and the monochromatic process is destroyed. From this it becomes apparent that if an RF bucket is to be used it must be kept away from the unstable energy region.

Several other possible RF techniques were used to allow a controlled spill of electrons from a bucket located in the stable region. Pulsing the RF or phase slipping the RF with respect to the beam were tried with minimal success.

Voltage Modulation: The most promising technique involves the voltage modulation of the RF bucket.[3] Originally all electrons were trapped in the bucket just outside the unstable region and then the voltage of the bucket was decreased according to

$$V=V_0(1-5.23\times10^{-4}T+1.06\times10^{-7}T^2)$$

where V_0 is the initial voltage and T is the turn number. (V was set to zero after T=6000 for 300 MeV and after 4000 for 200 MeV.) As the voltage drops electrons become untrapped and approach the unstable region under the influence of the synchrotron radiation loses only. Although the duty factor was increased, a larger energy spread and emittance was observed than for the synchrotron only extraction. To remedy this the bucket was moved further from the unstable region and the beam injected as shown in figure 5. In this case only part of the beam is injected into the bucket while a fraction of the electrons are free to be immediately extracted. These are followed by the electrons spilled from the bucket at a later time. Not only is the duty factor improved without sacrificing energy spread or emittance but the voltage requirement for the RF is reduced as well.

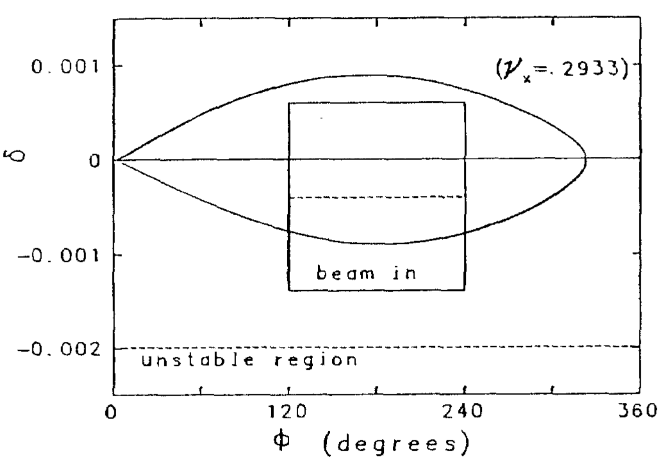

Figure 5. RF Bucket at 300 MeV

A plot of the duty factor for 300 MeV is shown in figure 6. Again $\delta_{out}<\pm10^{-4}$, $\varepsilon_x=0.7$ mm-mrad while the duty factor is now greater than 40%. (Note, however, that over turns 1000 to 6600 the duty factor is greater than 75%.) Improvement in the duty factor may result from optimizing the voltage modulation but this will remain for the experimental program once the PSR is commissioned.

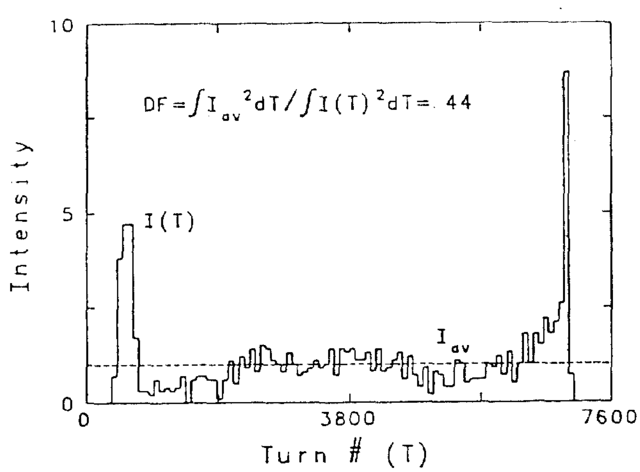

Figure 6. Duty Factor at 300 MeV

Results

The results of the simulations are summarized in part in table 2. Included with the extracted energy spread, emittance and duty factor are the percentage of septum hits and a description of the emittance parameters and beam position (x_0 and x'_0) relative to the closed orbit. The septum hits were calculated according to how many electrons would have hit a septum that was 100μ thick and curved to present the smallest shadow in phase space. A lower flux on the septum is desirable and thinner septum designs are now under investigation. Fewer hits would result from moving the septum further out but the emittance would increase. Alternatively, the sextupole strengths could be increased but the energy spread would suffer.

The extracted beam parameters (α,β) are consistent over all energies and the beam centroid is located near $x_0=-31$ mm and $x'_0=5.5$ mrad.

Table 2. Summary of Extraction Simulation Results

Energy(MeV)	150	200	200	300	300
*	Syn	Syn	VM	Syn	VM
ν_x	0.3033	0.3033	0.2933	0.3033	0.2933
ε_x(mm-mrad)	0.21	0.26	00.33	0.60	0.70
x_0(mm)	-30.2	-30.5	-30.6	-31.1	-31.1
x'_0(mrad)	5.20	5.28	5.35	5.55	5.58
α_x	2.24	2.24	2.24	2.24	2.24
β_x	10.0	10.0	10.0	10.0	10.0
E_{out}(MeV)	149.76	199.67	199.54	299.49	299.29
δ_{out}(FWHM)	0.8×10^{-4}	0.8×10^{-4}	0.8×10^{-4}	1.4×10^{-4}	1.4×10^{-4}
DF	0.76	0.35	0.58	0.11	0.44
septum hits	4.9%	3.9%	3.8%	4.4%	2.2%

* Syn: Synchrotron extraction
VM: RF extraction with voltage modulation

Conclusion

A high duty factor, monochromatic beam with low emittance will be available from EROS. If RF is used to increase the duty factor, voltage modulation of a bucket situated away from the unstable region is desirable to preserve good energy spread and emittance.

Simulations will continue in an effort to reduce the flux of electrons on the extraction septum. As well the effects of parasitic losses in the ring will be investigated for high currents where these losses equal the synchrotron radiation losses for a 300 MeV beam. Under these circumstances emittances will be greater and RF will be required to produce a high duty factor at all operating energies.

References

[1] J. C. Bergstrom et al., IEEE Trans. Nucl. Sci. NS-30 (1983) 3226.

[2] R. V. Servranckx and K. L. Brown, "Users Guide to the Program DIMAT", SLAC Report 270 UC-28 (A), March 1984.

[3] T. P. Dielschneider, Sask. Accel. Lab. Report EROS-TM-PSR-RF-03, February 1985.