OPERATING RESULTS OF THE ELECTRON RING OF SASKATCHEWAN (EROS)

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Abstract

The pulse stretcher ring, EROS, is designed to convert the pulsed electron beam of the linear accelerator of the Saskatchewan Accelerator Laboratory to a CW beam, increasing the duty factor from 0.036% to near 100%. The ring has been operating since December 1986, when a low intensity beam was stored for a few seconds. By the following spring beam storage times up to 20 minutes were achieved and some machine parameters were measured. The measurement of the betatron tunes, ν_x and ν_y, and the machine beta functions, β_x and β_y, showed that the ring lattice was operating as designed. Resonant extraction was first confirmed in the fall of 1987, with an extraction efficiency of 95%. The extracted emittances were about 1.0 (π) mm-mrad in both planes and the energy spread less than the injected energy spread of 0.1%. The nuclear experimental program began in the summer of 1988 with up to 4 μA of CW beam routinely extracted from 150 to 200 MeV. In February 1989 the ring RF was used to increase the duty factor from 12% to 52% at 250 MeV. Future commissioning plans include the introduction of multiturn injection to increase the current and the adjustment of the chromaticities, χ_x and χ_y, to reduce the extracted emittances and energy spread.

Introduction

The Pulse Stretcher Ring (PSR), EROS, is designed to "stretch" the pulsed beam from the Saskatchewan electron linac into a continuous beam, increasing the duty factor from 0.03% to near 100%. The energy spread from the linac is first reduced from 1.0% to 0.1% by an Energy Compression System (ECS). The characteristics of the linac and the extracted beam are given in Table 1. More details of the PSR are given in the references[1,2].

The operating principle is to store each pulse from the linac in the PSR and uniformly extract the beam over the time between pulses. The mode of extraction is the one-third resonance monochromatic extraction[3]. In this mode the horizontal chromaticity, χ_x, is non-zero and the ring is tuned slightly off the one-third resonance so that as electrons lose energy through synchrotron radiation they approach the one-third resonance and are extracted. The resonance is excited by sextupoles in achromatic sections of the ring. PSR machine parameters are given in Table 2.

Table 1. Linac and PSR specifications

Linac		
Energy range	50 - 300	MeV
Frequency	2856	MHz
Repetition rate	0 - 360	pulses/second
Peak current	200	mA
Pulse length	0.2 - 1.0	μs
Energy spread	± 1.0	%
with ECS	± 0.1	%
Phase spread		
with ECS	120	degrees
Transverse emittances	0.3	mm-mrad
Duty Factor (max.)	0.036	%
PSR - extracted beam		
Energy range	50 - 300	MeV
Maximum CW current	70	μA
Energy spread	± 0.01	%
Vertical emittance	0.3	mm-mrad
Horizontal emittance	0.3 - 0.6	mm-mrad
Duty Factor	→ 100	%

Table 2. PSR machine parameters

Horizontal tune	(4).3	(nominal)
Vertical tune	(4).8	"
Horizontal chromaticity		
natural	− 4.1	
adjusted	− 15 - + 5	
Vertical chromaticity		
natural	− 6.0	
adjusted	0	
Momentum Compaction	0.048	($\Delta L/(L\,\Delta\delta)$)
Length (L)	107.909	meters
RF frequency	2856	MHz

The synchrotron energy loss goes like the fourth power of the beam energy. At an energy of about 180 MeV the energy loss is such that the injected energy spread of 0.1% will extract over the time between pulses when the maximum repetition rate of 360 Hz is used. At lower energies the extraction time is too long. In this case the injected energy spread or the repetition rate must be reduced, both involving the loss of total current. At higher energies the extraction proceeds too fast and the duty factor suffers. This can be improved to some extent by increasing the injected energy spread but to achieve high duty factors at the highest energies it is necessary to slow the energy loss by using the RF cavity[4] in the PSR.

Several RF mechanisms have been investigated using tracking simulations and the PSR. These include modulating the RF amplitude[5] and fast phase shifting of the RF bucket. The ring RF is also needed to store the beam to make tune measurements and possibly for the inclusion of an internal target in the ring.

To improve the emittances of the extracted beam the chromaticity of the ring must be adjusted. These adjustments will be made with eighteen sextupole magnets in the bend (dispersion) regions of the ring. Finally, the maximum current will be increased by operating with multi-turn injection.

Measurements

Many measurements have been made to date of both the PSR machine parameters and the extracted beam characteristics. The close agreement between these measurements and tracking simulations indicates the ring lattice is performing as designed.

PSR Parameters

The parameters measured include the tunes, the quadrupole contributions to the chromaticities and the lattice betatron functions.

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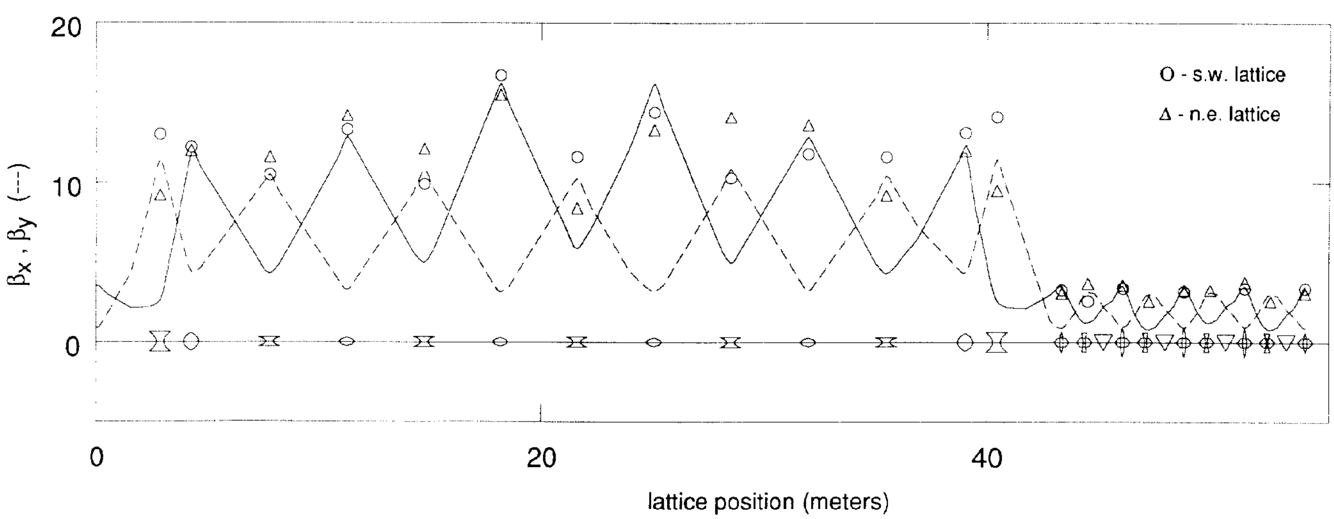

Figure 1. Theoretical betatron functions and measured maxima.

Tune: The ring tunes, ν_x and ν_y, are measured by using a harmonic kicker at a single location in the PSR. The harmonic kicker delivers a sinusoidally varying kick with a maximum amplitude of a few microradians in either plane. The kicker frequency, F_k, can be varied from 0 to 2.778 MHz, the revolution frequency of the ring, F_{rev}. The harmonic kick is applied to a stored, damped beam. The frequency of the kick is varied slowly until the kicker frequency is matched to the tune of the PSR. At this time a destructive resonance is established and the beam is seen to blow up when observed at a synchrotron light port in the ring. The kicker amplitude must be as small as possible to produce an effect but excite the resonance over a very narrow band. The fractional part of the tune is given by

$$\nu = \frac{F_k}{F_{rev}} .$$

The harmonic kicker also causes the beam to blow up at frequency

$$F_k = (1 - \nu) F_{rev} .$$

This serves as a check that the correct resonance is being measured. The measured tunes agreed with theoretical values within 1% and are accurate to about 0.1%. The desired tune settings are made with minor adjustments to the PSR quadrupoles.

Chromaticity: The chromaticity is defined by

$$\chi = \frac{\Delta \nu}{\Delta \delta}$$

where δ here refers to a particular relative energy with respect to a reference energy. By measuring the tunes at two different values of δ for the same ring configuration the chromaticity can be deduced. The energy shift, $\Delta\delta$, can be produced by running the ring RF at a slightly different frequency or by introducing a continuous phase shift per turn, ΔL. The energy shift is given by

$$\Delta\delta = \frac{\Delta L}{\alpha L} = -\frac{\Delta F}{\alpha F}$$

where α is the momentum compaction of the ring.

The chromaticity sextupoles were operated with successful extraction over a theoretical range of chromaticities from -15 to -5. Due to technical difficulties the adjusted chromaticities could not be measured at this time.

An approximate measurement of the natural chromaticity of the ring can be made by changing all the ring dipoles by the same amount. In this case the orbit through the bend regions (and the chromaticity sextupoles) will remain the same and the chromaticity measured will be the contribution of all the quadrupoles only. In this case the energy shift is given by

$$\Delta\delta = \frac{\Delta B}{B}$$

where B is the field of the dipoles.

The quadrupole contribution to the chromaticities was measured to be $\chi_{quad,x} = -5.1$ and $\chi_{quad,y} = -3.6$ which compares favourably with the theoretical values of -5.1 and -4.2. With no chromatic sextupoles turned on, the PSR is believed to be operating at chromaticities near those given in Table 2.

Betatron Functions: The betatron functions at the positions of the quadrupoles in the PSR lattice were measured by varying the strength of the individual quadrupoles and observing the change in the ring tune which resulted. The betatron function is given by

$$\beta = \frac{\sin \sqrt{\Delta k} L}{\sqrt{\Delta k} \sin 2\pi\Delta\nu}$$

where k is the quadrupole strength in m^{-2} and L is the quadrupole length in meters. The measured maxima of both β_x and β_y are shown in Figure 1 in comparison with theoretical curves.

Storage Time: For tune measurements it is convenient to store the beam for some minutes. The synchrotron light may be observed at all dipoles in the PSR while two dipoles are equipped with phototubes for signal analysis. Synchrotron light has been observed for up to 20 minutes from a single 2 mA, 300 ns pulse. The decay time constant was 2 minutes.

For use with internal targets, currents up to 500 mA will be required to be stored for some milliseconds. Figure 2 shows the stored beam intensity at a repetition rate of 6 Hz for a 40 mA beam, near the highest current injected to date. Also shown is a closeup of the first several turns where it appears some beam intensity is lost. This is either an artifact of the phototube electronics or an undesirable beam halo. (The low intensity just before the first turn of injection is due to beam loss while the fast kicker is turned on for injection.)

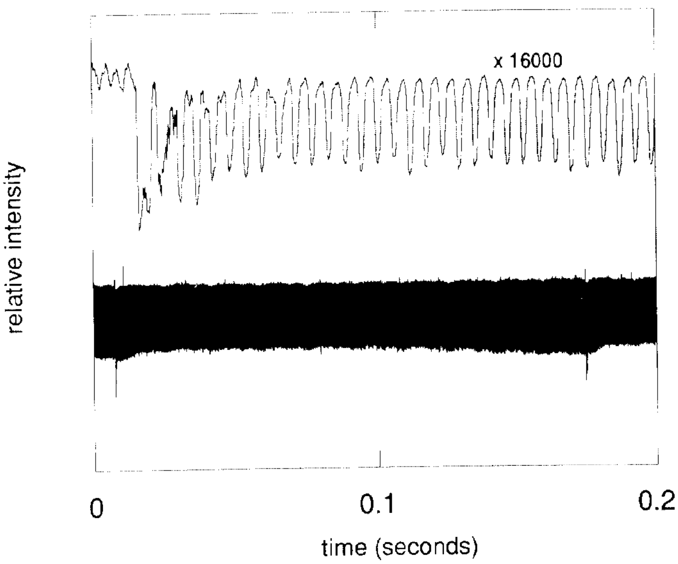

Figure 2. Stored 250 MeV, 40 mA beam at 6 Hz.

Extraction Characteristics

Measurements on the extracted beam have mainly concentrated on determining the extraction efficiency and the duty factor. Crude estimates have been made of the extracted emittances and energy spread.

Extraction Efficiency: The injected current is estimated from a current toroid in the injection line or measured directly in beam dumps at straight through ports on either of the first dipoles in either bend. The extracted beam is measured in a beam dump at the end of the extraction line. With careful adjustment of the orbit at the location of the extraction septum it is possible to extract nearly all the beam injected into the PSR. Extraction efficiencies exceeding 95% have been achieved with injected (average) currents up to 4 μA.

Duty Factor: The duty factor of the extracted beam is measured by placing a scintillator directly in the extraction line, monitoring the scintillations with a phototube and displaying the information on a digital scope. The digitized information can be dumped from the scope and integrated to determine the duty factor. The duty factor is given by

$$\text{Duty Factor} = \frac{I_{av}^2 \int dt}{\int I(t)^2 dt} .$$

To scan the entire extraction time (2.778 ms at a repetition rate of 360) the resolution of the digital information is 400 ns. The ring revolution time is 360 ns so the scope is slowly scanning the microstructure of the beam. Integrating the digital information, then, gives an approximate value of the duty factor including the microstructure of extracted current.

Emittance and Energy Spread: Tracking simulations have shown that the emittance and energy spread of the extracted beam are directly proportional. A scan of the beam extracted from EROS through a pin hole just before the beam dump indicated the energy spread to be <0.1%, less than the injected energy spread. The emittances in both transverse planes was crudely measured to be about 1 mm-mrad, in agreement with the measured energy spread. More accurate measurements will be possible with the completion of the extended extraction line and the associated spectrometers.

Operating Experience

Increased experience with injecting, storing and extracting a beam from EROS has led to very satisfactory performance of the PSR from 150 to 250 MeV with extracted currents ranging from some nanoAmps to 4 μA. Highlighting the commissioning to date, was the recent extraction of the beam using the ring RF to increase the duty factor.

Injection

Injection to date has been done using one fast kicker[6] to displace the vertical closed orbit over a single turn. In the horizontal plane the beam is either injected on axis for storing or an angular displacement is introduced to produce the hollow phase space necessary for efficient extraction. The injected beam is matched to the closed orbit of the ring in both planes by steering coils in the injection line which can produce a desired shift and angular displacement at the injection point. As well, orbit correctors in the ring may be used to create a local shift in the position and orientation of the closed orbit.

The fast kicker is turned off in less than 10 ns immediately after the tail of the injected pulse. The kicker timing is adjusted by observing the beam downstream from the kicker and adjusting the timing until an unkicked beam just begins to appear. For clean injection a pulse length no greater than 320 ns is used.

Orbit Control and Storage

To achieve good storage times much work was done to establish a good working orbit. Once established it has been possible to scale the entire ring from 150 to 250 MeV with only minor adjustments necessary to recover a good setup. Adjusting the orbit is facilitated by separate control of the ring dipoles so they can be used to make orbit corrections. Also useful are local orbit bumps at positions in the ring where the acceptance is reduced and careful steering is required. Beam spill monitors strategically located around the ring must indicate negligible spills for both successful storage and safe operation. Although global orbit correction has been planned for use at higher currents this has not been done to date.

To match the ring energy (as defined by the dipoles) to the injected energy, all the dipoles are adjusted together until the storage is optimized. This procedure has confirmed the ring is aligned near the correct length as optimizing the storage time results in a damped orbit that has minimal steering in the bend region focusing elements.

Extraction

To date monochromatic extraction has proceeded using the natural chromaticities of the ring, in particular $\chi_x = -4.5$. The horizontal tune is adjusted just below the one-third resonance and the resonance is excited by two sextupoles in the achromatic regions of the ring. The tune is finely adjusted until the resonant extraction is observed on a scintillator located near the extraction septum. Again, closed orbit bumps are used to adjust the position and angle of the orbit at the extraction septum in both transverse planes. Once the beam is seen downstream in the extraction line the injection coordinates may be readjusted to optimize the extraction efficiency.

Synchrotron Extraction: With the ring RF off, particles in the ring will lose energy through synchrotron radiation and coupled with the chromaticity will approach the one-third resonance and be extracted. Figure 3 shows synchrotron extraction for energies of 200 and 250 MeV, normalized to the same total current. The fourth power of energy loss with energy is clearly evident between

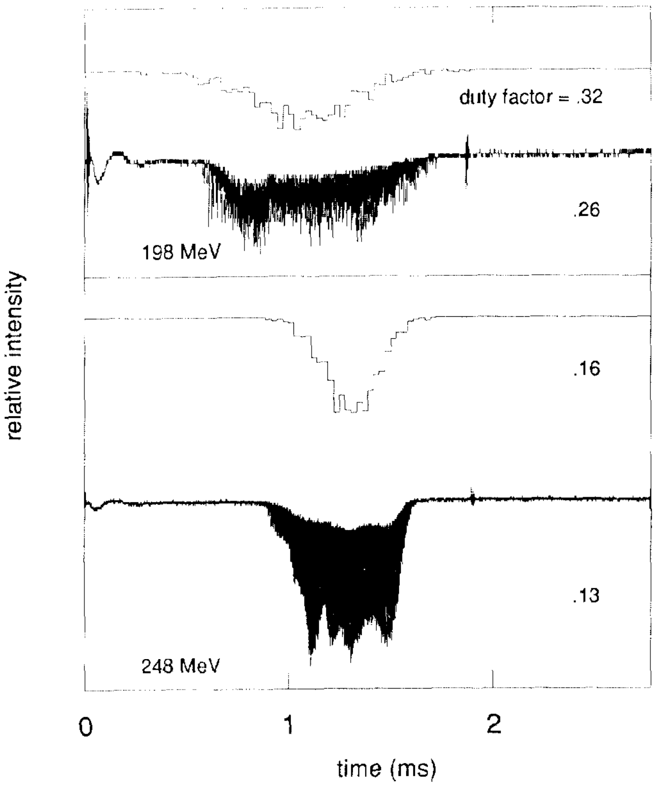

Figure 3. Theoretical and observed extraction at 200 and 250 MeV.

the two energies where the duty factor goes from 26% at 200 MeV to 13% at 250 MeV. Tracking simulations show the distribution of the extracted beam is consistent with an injected beam with a Gaussian energy distribution of $\sigma = 2.5$ at $\delta = 0.1\%$. For comparison the histograms of the tracking simulations are shown.

Not shown is the result at 150 MeV where the extracted distribution was broader than the extraction time at 360 Hz. In this case the tails of the energy distribution were clipped with energy slits in the injection line and duty factors exceeding 60% produced. Reducing the repetition rate, along with reducing the energy spread, will be used to extract the beam at lower energies.

RF Extraction: To increase the duty factor at high energies the RF cavity in the ring must be used to slow the rate of energy loss.

Early tracking simulations had shown that this could be accomplished by trapping the beam in the RF bucket and slowly spilling the beam from the bucket by reducing the bucket amplitude. This was to be done by vector addition of the output of two matched klystrons. For this purpose we had two fast phase shifters each with a range of 180 degrees. The RF bucket amplitude, δ_{RF}, goes like the fourth root of the RF power. Failure to match the power of the two klystrons to better than 2% meant that the bucket amplitude could not be reduced to less than 40% of maximum. Since amplitudes approaching zero are necessary this technique was not tried with the PSR.

Subsequent simulations showed that it is possible to delay the beam by phase shifting the RF bucket and spilling the beam every few hundred turns. Examples of phase shifting simulations for a 250 MeV beam are shown in Figure 4. In the first example, the RF bucket is shifted every 200 turns by

$$\text{phase shift} = -12\ (1 + .00036\ T)\ \text{degrees} \qquad (1)$$

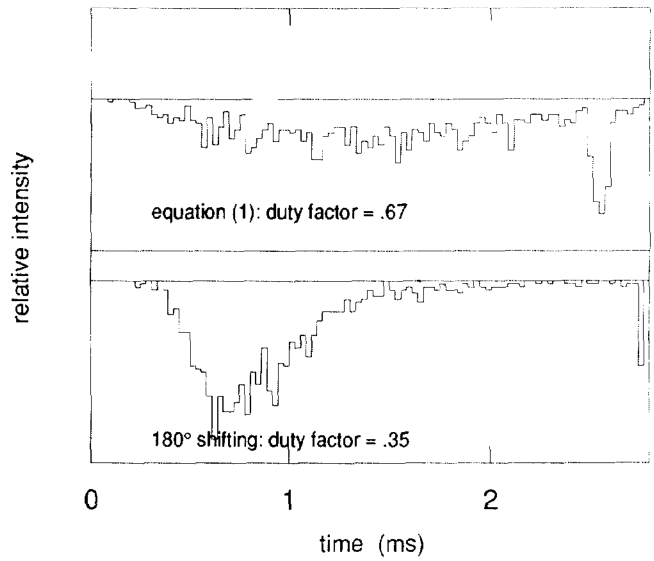

Figure 4. Simulated RF extraction using phase shifting as given by equation (1) and using 180 degree/continuous shifting.

where T is the turn number. The turn dependent coefficient increases the spill area as the beam population is depleted. At 6000 turns a continuous phase shift of 36 degrees per turn is applied which effectively moves the RF bucket above any remaining beam which is then extracted.

The ring RF power input was reconfigured to put both phase shifters in series with a single klystron so that 360 degrees of phase shift was available at a fixed amplitude of 600 watts, corresponding to $\delta_{RF} = 0.15\%$ at 250 MeV. The response of each phase shifter over the full range is about 200 ns or less than 1 turn. Each phase shifter is run from 0 to 180 degrees and set at one-half the desired shift value.

During the last beam time, phase shifting was attempted but failed to produce the desired result. As well, attempting to measure the chromaticity by introducing a continuous phase shift per turn, resulted in failure to store the beam. A continuous phase shift of 50 degrees per turn resulted, however, in an increase of duty factor from 13% to 36%! Using variations on equation (1)

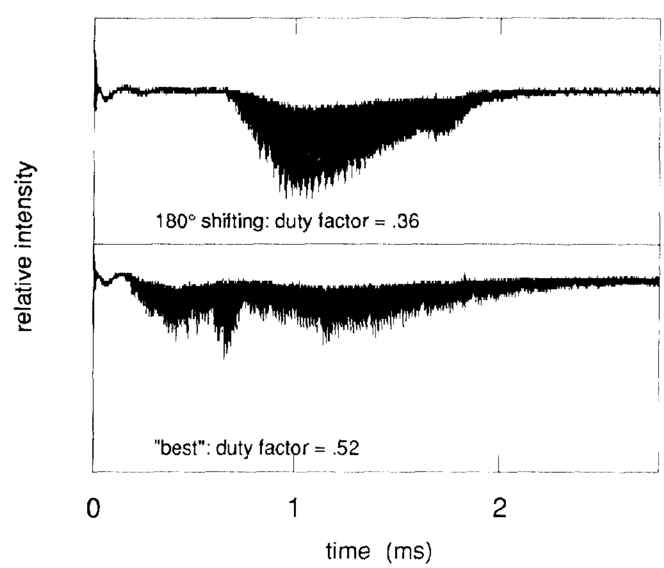

Figure 5. Observed RF extraction at 250 MeV.

coupled with continuous phase shifting eventually resulted in a "best" duty factor of 52%. The RF extraction results are shown in Figure 5.

After the last run an investigation of the phase shifters revealed that one phase shifter was not operating at all. What was thought to be a continuous phase shift of 50 degrees was actually a continuous phase shift of 25 degrees but only over a range of 180 degrees. This introduced a phase shift of 180 degrees every 7.2 turns. It was reassuring that a tracking simulation of this 180 degree/continuous phase shifting closely reproduced what had been observed. This is the second simulation example of Figure 4. (The shifting done to produce the "best" duty factor is now understood to have had a 180 degree shift component as well.)

With a pulse length of about 300 ns and using some hundreds of turns to run up the injection fast kicker, a maximum duty factor of about 80% is the best that can be expected. With phase shifting fully operational this should be possible.

Conclusions and Future Plans

More accurate measurements of the extracted energy spread and emittances will be possible with the improved analyzing power of the extended extraction line now being completed. Electron scattering into high resolution spectrometers will also assist in these measurements. As emittance measurements become more accurate more effort will be put into tailoring the injected beam for emittance matching.

Improvements to the extracted energy spread and emittances should also result from operating the ring at chromaticities of $\chi_x = -15$ and $\chi_y = 0$. The horizontal value is a feature of monochromatic extraction while the vertical value is best for beam matching. Chromaticity measurements should be possible with a fully operational phase shifting system but chromaticity effects will be investigated regardless.

Table 3. PSR extraction achievements

Energy range	150 - 250	MeV
Maximum CW current	8	μA
Minimum CW current	~1	nA
Extracted energy spread	<0.1	%
Vertical emittance	~1	mm-mrad
Horizontal emittance	~1	mm-mrad
Duty Factor	>50	%
(Maximum stored current	40	mA)

An upper limit of 200 mA injected current is possible with single turn injection. Higher currents and some improvement to the duty factor will be achieved injecting over two or three turns. The second fast kicker necessary for multiturn injection has been installed in the ring and awaits some electrical installation. Discrepancies in the vertical betatron functions and the vertical chromaticity indicate that some ring realignment may be necessary before going to very high currents.

The achievements of the EROS pulse stretcher ring are summarized in Table 3. Progress to date is very satisfactory but much work remains to be done to achieve the design goals outlined in Table 1. Since July 1988, several thousands of hours of CW beam have delivered to perform intermediate energy nuclear physics experiments. Hopefully PSR developments will keep up with the increased demands for higher (and lower!) CW currents and smaller emittances.

References

[1] R. Servranckx and J. L. Laclare, "Concept and general design of an electron pulse stretcher," IEEE Trans. Nucl. Sci. NS-18 (1971) pp. 204-206.

[2] J. C. Bergstrom, H. S. Caplan, R. V. Servranckx and B. E. Norum, "SORE - A pulse stretcher for the Saskatchewan 300-MeV linac," IEEE Trans. Nucl. Sci. NS-30 (1983) pp. 3226-3228.

[3] J. L. Laclare and R. Servranckx, "Injection in a ring with non linear elements and energy selective resonant extraction from a ring," IEEE Trans. Nucl. Sci. NS-18 (1971) pp. 207-209.

[4] J. Haimson and B. Mecklenburg, "A CW nonsynchronous traveling wave structure for a 300 MeV pulse stretcher ring," IEEE Particle Accelerator Conference (1987) pp. 1919-1921.

[5] L. O. Dallin, "High duty factor, monochromatic extraction from EROS," IEEE Trans. Nucl. Sci. NS-32 (1985) pp. 3039-3041.

[6] C. B. Figley, "A high speed electrostatic kicker for the pulse stretcher ring at the Saskatchewan Accelerator Laboratory", Nucl. Inst. Meth. Phys. Res. A273 (1988) pp. 59-62.

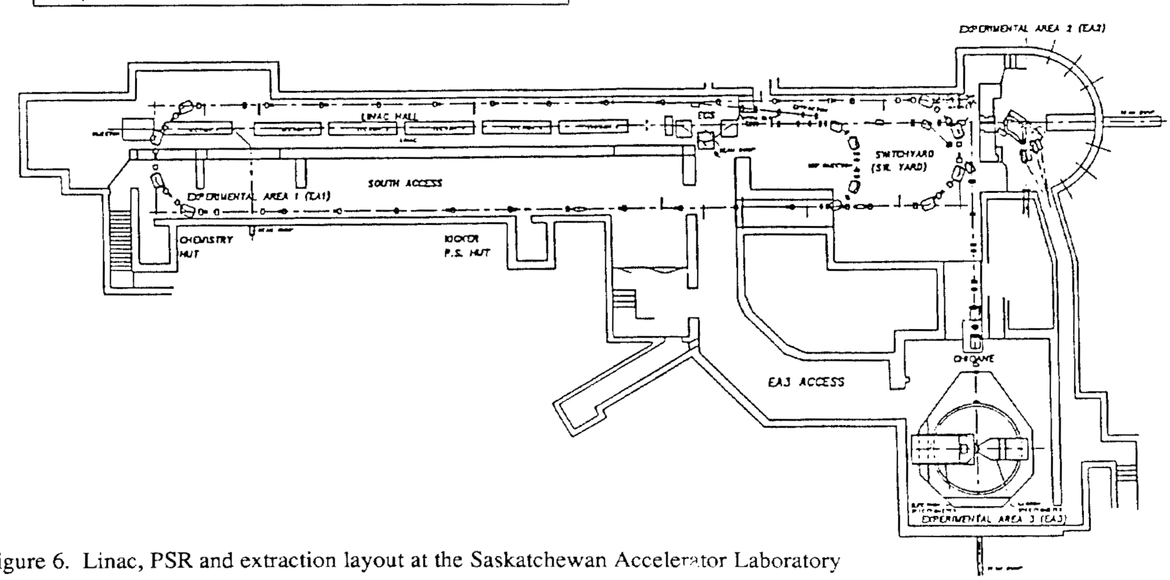

Figure 6. Linac, PSR and extraction layout at the Saskatchewan Accelerator Laboratory