# Time Controlled Monochromatic Extraction from EROS

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## Abstract

With no ring RF present the duration of the resonant extraction of electrons from the pulse stretcher ring, EROS, depends on the rate of energy loss due to synchrotron radiation. At energies above 150 MeV, the extraction process proceeds too quickly and the duty factor suffers. The extraction time can be extended by trapping the beam with the ring RF and later spilling it at a controlled uniform rate. This is done by repeatedly shifting the phase of the RF. At an energy of 300 MeV, for example, this technique has been used to increase the duty factor of the extracted beam from 15% to near 100% while maintaining the monochromatic quality ($\Delta\delta = 0.02\%$) of the beam. At low energies, the speed of the extraction can be increased by using a pulsed quadrupole. In this case only the instantaneous extracted energy spread remains monochromatic.

## Introduction

EROS (Electron Ring of Saskatchewan) is a pulse stretcher ring (PSR) designed to "stretch" the pulsed beam from the Saskatchewan electron linac into a continuous beam. In the process the duty factor is increased from 0.03% to near 100%. The operating principle is to store each pulse from the linac in the ring and to extract the current uniformly over the time between pulses. Monochromatic resonant extraction[1] is used. The injected beam parameters and the PSR characteristics are given in Table 1.

For monochromatic extraction the horizontal chromaticity, $\chi_x$, is non-zero and the ring is tuned slightly off a one-third resonance. For EROS, $\nu_x \approx .3$ and $\chi_x \approx -10$, so that as particles lose energy they approach the resonance.

With no RF cavity active in the ring the extraction process is straight forward. As electrons lose energy through synchrotron radiation they approach the resonance and are extracted. A particular particle energy, E, relative to the reference energy $E_0$ is given by $\delta = (E - E_0)/E_0$. In relative coordinates the energy spread of the beam is give by $\Delta\delta$. The tune is adjusted so that particles with the lowest energy are at a tune where the betatron motion becomes unstable and resonant extraction begins.

Table 1. Injected beam and PSR specifications

| Injected beam | | |
|---|---|---|
| Energy (E) | 50 - 300 | MeV |
| Energy spread ($\Delta E/E$) | ± 0.1 | % |
| Microstructure | 2856 | MHz |
| Phase spread | 120 | degrees |
| Repetition rate | 0 - **360** | pulses/second |
| Pulse length | 0.2 - 1.0 | μs |
| Peak current ($I_{max}$) | 200 | mA |
| Transverse emittances ($\varepsilon_{x,y}$) | 0.3 | mm-mrad |
| Duty factor (DF) | 0.036 | % (max.) |
| **PSR** | | |
| Horizontal tune ($\nu_x$) | (4).3 | (nominal) |
| Vertical tune ($\nu_y$) | (4).8 | " |
| Horizontal chromaticity ($\chi_x$) | | |
| natural | − 4.1 | |
| adjusted | − 15 - + 5 | |
| Vertical chromaticity ($\chi_y$) | | |
| natural | − 6.0 | |
| adjusted | 0 | |
| Momentum compaction ($\alpha_p$) | 0.048 | ($\Delta L/(L\ \Delta\delta)$) |
| Length (L) | 107.909 | meters |
| RF frequency (F) | 2856 | MHz |

The beam is extracted with a small energy spread, $\Delta\delta_{ext} \leq 0.03\%$, so the extraction time is essentially proportional to the injected energy spread, $\Delta\delta_{inj}$. The rate of energy loss is proportional to $E^4$ and the rate of change of $\delta$ is $\Delta\delta_{rad}$ /turn = $8.852 \times 10^{-14}\ E^3$ , where E is in MeV. (The radius of curvature of the EROS dipoles is 1.0 m.) This gives an extraction time of

$$\text{extraction time} \approx \frac{\Delta\delta_{inj}}{\Delta\delta_{rad}/\text{turn}} = 1.13 \times 10^{13}\ \frac{\Delta\delta_{inj}}{E^3}\ \text{turns.}$$

EROS nominally operates with injected energy spread of $\delta\Delta_{inj} = 0.002$ and an injection repetition rate of 360 pulses per second. Allowing some time to inject the next pulse we wish to extract over 7600 turns. Under the above conditions a beam energy of about 150 MeV is best suited to extract over all the time between beam pulses. Simulations of the time profile for "natural" extraction are shown in Figure 1.

At energies above 150 MeV the rate of energy loss is too fast and the duty factor is decreased. At low energies the rate of energy loss is too slow and the beam is not completely extracted between pulses and the extraction efficiency suffers. Several techniques have been investigated to control the rate of extraction to extract the beam uniformly and completely at all energies.

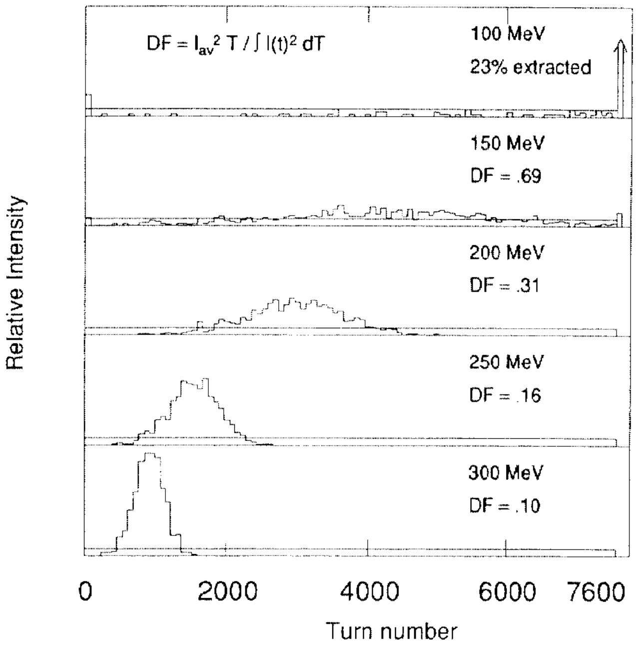

Figure 1. Simulations of "natural" extraction.

## Control Techniques

### Energy spread and repetition rate

Some adjustment to the extraction time is achieved by adjusting the energy spread of the injected beam or changing the injection repetition rate. This has limited application.

At high energies the extraction time can be increased by increasing the energy spread of the injected beam. The energy acceptance of the EROS ring is only about 0.4%, however, and at most high duty factors can be extended to about 170 MeV. At higher energies the ring RF must be used to slow the rate of energy loss in the ring.

At low energies the injected energy spread can be reduced or the linac can be operated at a lower repetition rate to allow efficient extraction of all the injected beam. In either case the amount of extracted current is reduced. For high current operation the ring RF or a pulsed quadrupole has to be used.

### Ring RF

Several techniques using the ring RF can be used to control the rate of extraction. At all energies the beam can be trapped in an RF bucket and then the bucket can be used to create a desired rate of energy loss by adiabatically modulating the frequency of the ring RF. At high energies the ring RF can be used to trap the beam and particles can be spilled from the bucket at a controlled rate, either through modulating the amplitude of the bucket or through abrupt phase shifting of the bucket. After leaving the bucket particles extract through the normal mechanism of synchrotron radiation loss.

Frequency modulation: The RF voltage necessary to trap the injected beam in RF buckets is 0.15E kVolts where E is the beam energy in MeV. Once particles are trapped by the RF, the RF frequency can be slowly varied to change the energy of the particles and cause them to extract. At the start of extraction the PSR horizontal tune is adjusted so that the minimum energy of the RF bucket is just outside the region of unstable energies. The energy spread of the particles in the RF bucket is approximately that of the injected beam as shown in Figure 2.

To extract over 7600 turns, one half the RF bucket must be moved into the region of unstable energies. The required rate of energy change per turn is

$$\frac{\Delta\delta_{RF}}{\text{turn}} = -\frac{1}{2}\,\frac{\Delta\delta_{inj}}{7600} = -1.3 \times 10^{-7}/\text{turn},$$

where $\delta_{RF}$ is the reference energy of the bucket.

The required frequency change, $\Delta F$, is determined by the ring momentum compaction, $\alpha_p$, and is given by

$$\frac{\Delta F}{F} = -\alpha_p \Delta\delta_{RF}.$$

This amounts to a frequency shift of 0.018 kHz per turn and a total shift of frequency of 0.137 MHz over 7600 turns. The small amount of shift required ensures the process is adiabatic and the particles remain trapped in the RF bucket.

Changing the frequency of the ring RF is equivalent to changing the phase, $\phi$, of the ring RF since $\Delta\phi = -2\pi L \Delta F/(F\lambda)$, where $\lambda$ is the RF wavelength and L the ring circumference. At turn number T the total phase shift is given by

$$\Delta\phi(T) = 2\pi\,\alpha_p\,\frac{\Delta\delta_{RF}}{\text{turn}}\,\frac{L}{\lambda}\,\frac{T(T+1)}{2} \approx -2.0 \times 10^{-5}\,T^2 \text{ radians}.$$

As the bucket moves partially into the unstable region and particles undergo synchrotron oscillations there is a good chance that some particles will become unstable at low energies and then become stable again as the energy increases. Since some growth in betatron amplitude results when the particle is unstable, the overall effect is to increase the emittance of the stored beam. This can lead to an extracted horizontal emittance up to ten times larger than when no RF is used and the energy spread of the extracted beam is also increased.

Amplitude modulation: To avoid the coupling between synchrotron and betatron motions it is best to have the bucket remain outside the region of betatron instability. Particles can be made to extract by decreasing the amplitude of the RF bucket so that some particles are lost from the bucket and extract by losing energy through synchrotron radiation. By tailoring the RF voltage amplitude over the extraction time good duty factors can be achieved[2].

Abrupt phase shifting: An alternative to reducing the RF amplitude is to abruptly shift the phase of the RF bucket every few hundred turns so that at each shift some particles are lost from the bucket and are extracted. The abrupt phase shift is applied every few hundred turns to allow the particles remaining in the bucket to redistribute themselves inside the bucket over a few synchrotron revolutions. By controlling the size of the phase shift as time goes on good duty factors can be achieved[3].

For example, every 200 turns the abrupt phase shift could be

$\Delta\phi = \pm 12\ (1 + .0004\ T)$ degrees

where T is the turn number. The sign of the phase shift is varied to allow the total phase to be between 0 and 360 degrees. The term with T allows a higher percentage of the remaining particles to spill as the particle population is depleted.

Abrupt phase shifting and amplitude modulation both have the advantage of preserving the small extracted horizontal emittance and energy spread inherent in the monochromatic extraction process.

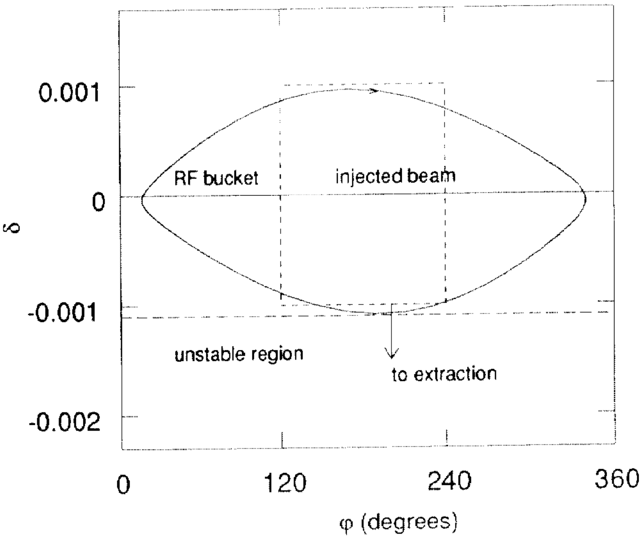

Figure 2. RF bucket and injected beam.

### Pulsed quadrupole

At low energies the rate of extraction can be increased by using an air-core quadrupole to ramp the horizontal tune towards the resonant tune during the desired extraction time. The tune shift required is $\Delta\nu_x \approx 0.03$ and the required quadrupole strength is

$$\Delta k_q = \frac{4\pi\Delta\nu_x}{\beta_x l} m^{-2},$$

where $\beta_x$ is the machine betatron function at the quadrupole position and $l$ is the effective length of the quadrupole. Changing the ring tune in this way causes the beam to extract over a wider range of energies and the extracted energy spread is about that of the injected beam.

Simulations were done to see if a pulsed quadrupole could be used to slow the extraction process at high energies. A tune shift away from the extraction resonance resulted in an overall delay in the extraction process but little improvement to the duty factor.

### Simulations

The above extraction processes have been simulated using particle tracking to investigate the relative merits of the various techniques. In each case the same injected beam was used. The PSR chromaticities and strength of the extraction sextupoles were also the same. The results are given in Table 2. While the extraction characteristics given are best results from the simulations and represent design goals, they also serve to indicate the relative merits of the different techniques.

Table 2. Characteristics of extracted beam - simulations

| Energy (MeV) | Mode | DF [efficiency] | $\varepsilon_x$ (mm-mrad) | $\Delta\delta_{ext}$ (full) |
|---|---|---|---|---|
| 100 | Natural | 0.81[23%] | 0.20 | 0.01% |
| 150 | Natural | 0.69 | 0.20 | 0.01% |
| 200 | Natural | 0.31 | 0.28 | 0.015% |
| 300 | Natural | 0.10 | 0.85 | 0.03% |
| 100 | Freq mod | 0.77[100%] | 4.0 | 0.2% |
| 300 | Freq mod | 0.75 | 3.5 | 0.2% |
| 300 | Ampl mod | 0.80 | 0.89 | 0.03% |
| 300 | Abrupt shift | 0.75 | 0.93 | 0.03% |
| 100 | Pulsed quad | 0.61[100%] | 0.3 | 0.15% |

## Experience

To date, EROS has operated at energies from 118 MeV to 293 MeV. At high energies the technique of abrupt phase shifting has been used because of ease of control and the superior extracted beam quality indicated in the simulations. At low energies the pulsed quadrupole technique was tested satisfactorily.

Attempts to move the RF bucket into the unstable region by using continuous phase shifting were unsuccessful. The difficulty is the slow response time (about 3 turns) in resetting the fast phase shifters through 360 degrees as the total phase shift accumulates. During the reset time excess numbers of particles are lost from the bucket.

### Abrupt phase shifting

The result of extracting using abrupt phase shifting is shown in Figure 3 for a beam energy of 293 MeV. The injection repetition rate was 180 pulses per second so the total extraction time was 5.56 ms. The spill during the first millisecond with the RF on represents particles not initially trapped by the RF bucket. Also shown is the RF phase as a function of time. At about 4.7 ms a continuous phase shift of 16 degrees per turn was introduced to move the bucket away from the remaining particles so they would be extracted.

Measurements of the extracted emittances and energy spread indicate that the phase shifting process does not appreciably degrade the quality of the extracted beam.

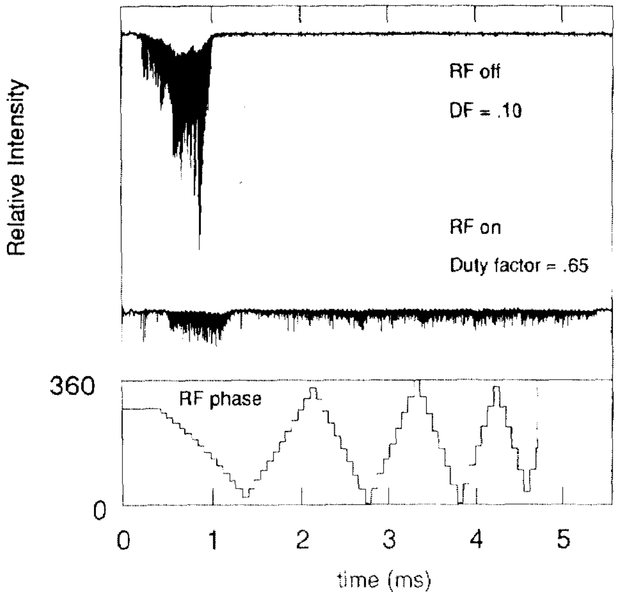

Figure 3. Extracted beam from EROS using abrupt phase shifting at 293 MeV.

### Pulsed quadrupole

The pulsed quadrupole technique was tried at an energy of 118 MeV. The result is shown in Figure 4. The natural extraction time is suitable for a repetition rate of 180. With the pulsed quadrupole the extraction time is cut in half. By tailoring the form of the tune shift higher duty factors should be possible. As expected the energy spread of the extracted beam was increased with the pulsed quadrupole in use.

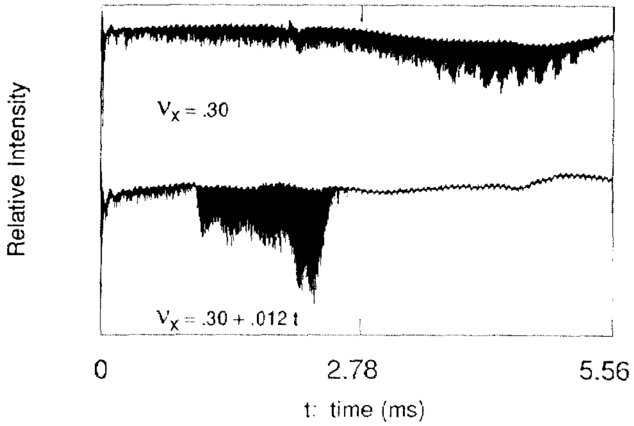

Figure 4. Extracted beam from EROS using pulsed quadrupole at 118 MeV.

## References

[1] R. Servranckx, Saskatchewan Accelerator Laboratory, Internal Report SAL-Ring-27 (1972).

see also reference [2]

[2] L. O. Dallin, IEEE Trans. on Nucl. Sci. NS-32 (1985) 3039.

[3] L. O. Dallin, IEEE Part. Accel. Conf. (Chicago, 1989) 22.