# THE ELECTRON PULSE STRETCHER EROS

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## 1. Introduction

The Electron Ring of Saskatoon is designed as a pulse stretcher whose purpose is to bring the duty factor of the 250 MeV electron linear accelerator at Saskatoon from a value of $6.25 \times 10^{-4}$ to a value of 0.8 or more. The ring, into which the 1 $\mu$s long linac pulse is injected, is a racetrack shape of 73 m circumference. The electrons are then slowly extracted between linac pulses utilizing a resonance phenomenon. The reader is asked to consult Refs. 1 and 2 for a complete description of the design.

## 2. Optimization of the Design

In 1973 an optimization of the design, as regards to cost, was undertaken. It appeared immediately that the most expensive elements of the design were the quadrupoles and hexapoles, particularly those of the curved sections. Their aperture was over 10 inches. As suggested by K. Brown of SLAC, we examined the possibility of increasing the horizontal tuning, $\nu_x$, from a value of 3 1/3 to 5 1/3. The change might reduce the aperture required since the chromatic excursion is proportional to $1/\nu_x^2$. However, to achieve this, we had to change the structure and increase the number of units in the curved sections and also modify the structure of the straight sections. Figure 1 shows the present layout of the ring: A more detailed analysis of the considerations involved in the modification can be found in Ref. 3.

Figure 2 shows the graphs of the beam dynamic functions $\beta_x$, $\beta_z$ and the chromatic excursion function $g = dx_{co}/d_\delta$, where $x_{co}$ denotes the closed orbit, $\delta = p - p_0/p_0$, p is the momentum of the particle, and $p_0$ is the nominal momentum.

A further delicate adaptation of the straight and curved sections allowed a reduction in the aperture of all quadrupoles by a factor of at least two.

## 3. Monochromatic Extraction

The extraction process adopted is based on the 1/3 resonance which has been extensively described in the literature (see Ref. 1). Previous to this an achromatic extraction process was considered. A modification of the chromatic parameters of the ring enabled us to achieve a monochromatic extraction of the beam.

The area of the extraction triangle is plotted on the graph in Fig. 3. From this graph it can be seen that the particles along the curved segment from B to C are extracted. They cover an energy spread of 0.08%. If by some deceleration process (radiation, RF, betatron core) the stable particles of the beam can lose energy with time, they will be extracted at the same energy and within the same energy spread while the tuning of the machine remains constant.

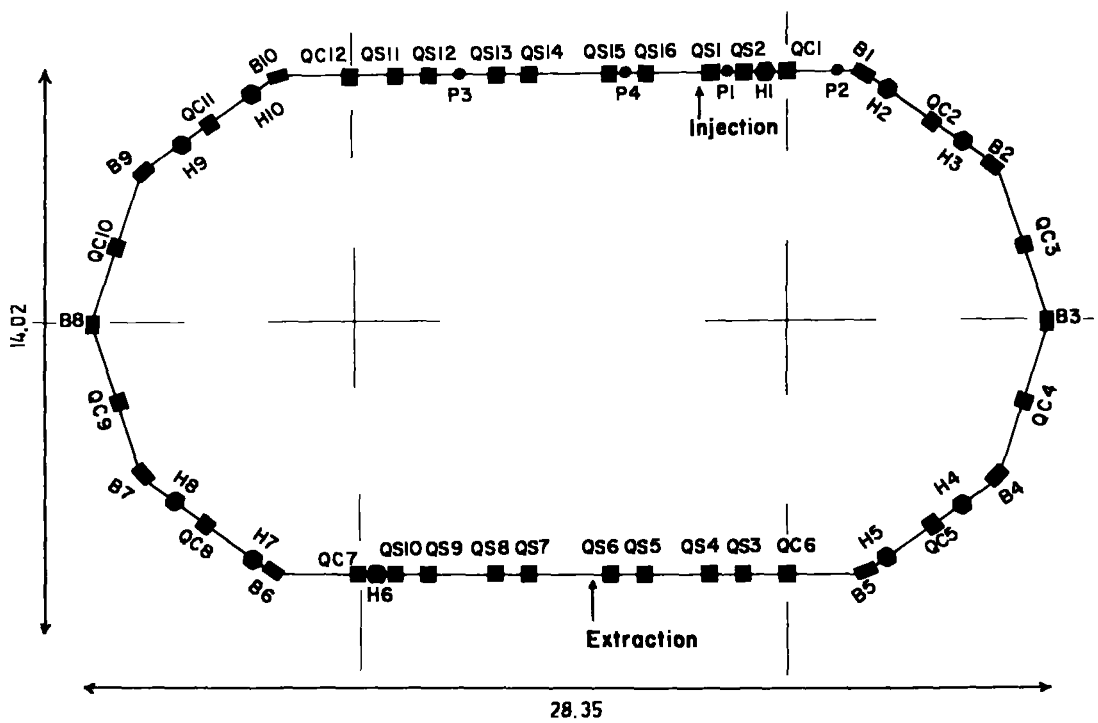


Fig. 1 EROS ring layout

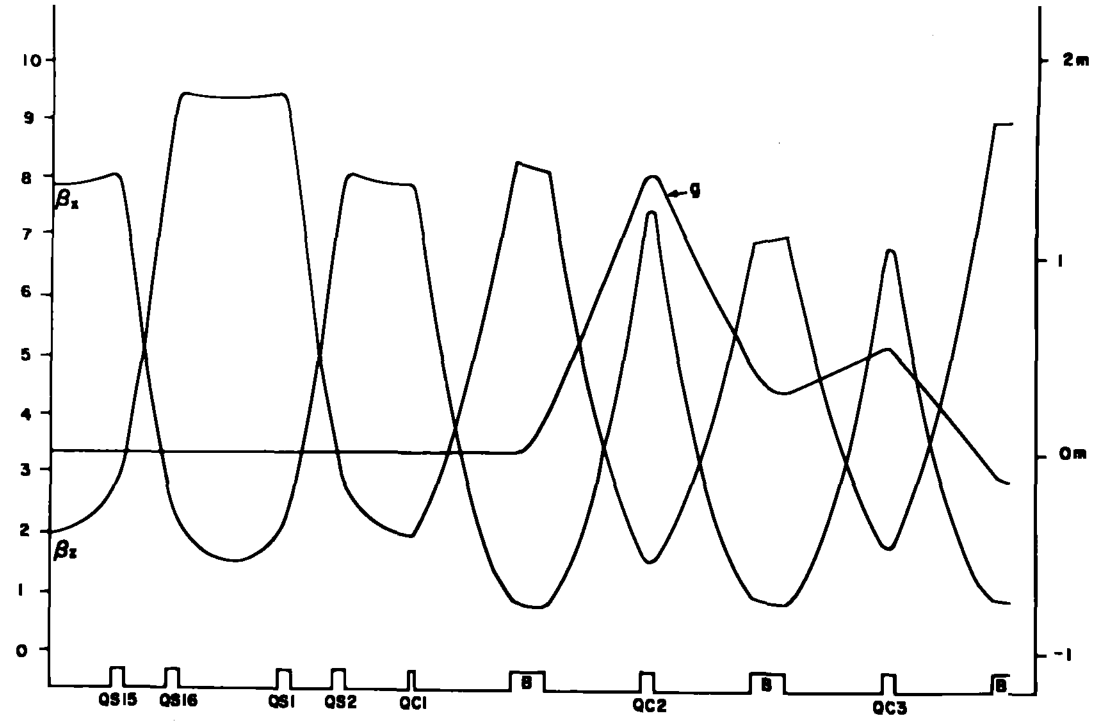


Fig. 2 $\beta_x$, $\beta_z$, g-function in half a curved section.

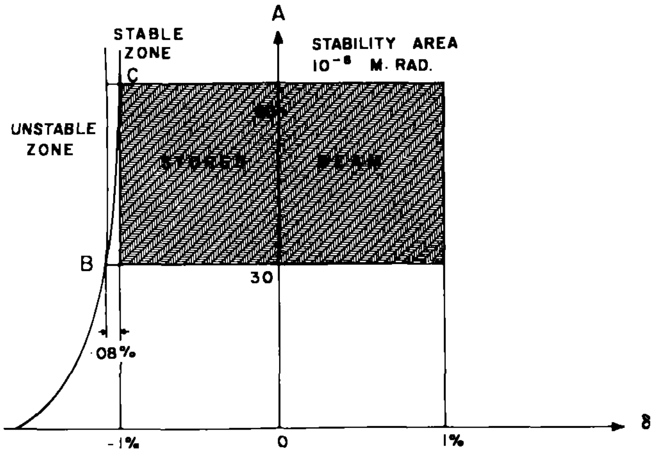


Fig. 3 Area of extraction triangle.

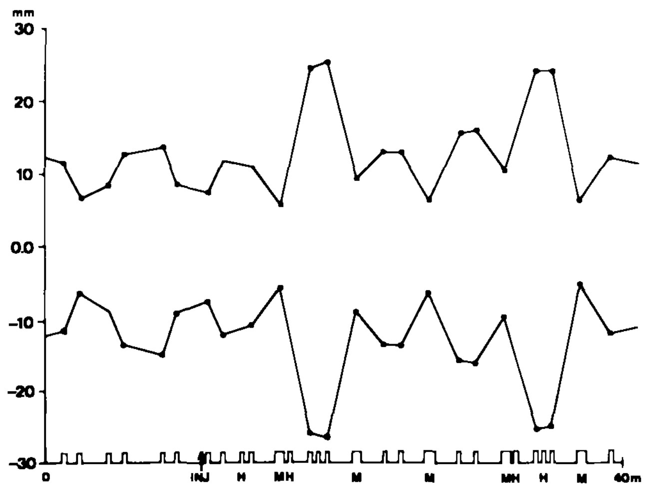


Fig. 4 Stored beam horizontal envelope.

Detailed calculation of particle tracing[4] shows this process works very well and leads to a beam size much in favor of the monochromatic extraction. The beam obtained by this extraction process is expected to have the following characteristics:

| | |
|---|---|
| Energy range | 150 to 250 MeV |
| Energy spectrum | 0.08% |
| Beam emittance - horizontal | 3 mm-mrad |
| - vertical | 25 mm-mrad |

The beam envelopes around the ring are as shown on Figs. 4, 5 and 6. In such an extraction the ring acts as a monochromator.

Extraction of the particles results from energy loss due to synchrotron radiation. The energy loss per turn is given by

$$\Delta E(\text{keV}) = 88.5\ \frac{E^4(\text{GeV})}{R(\text{m})}\ .$$

Assuming the energy spread is 1%, the energy to be lost for complete extraction is $\Delta E(\text{keV}) = 1 \times 10^4\ E(\text{GeV})$. The number of turns needed to lose this energy is then

$$N = \frac{1 \times 10^4\ R(\text{m})}{88.5\ E^3(\text{GeV})} = 113\ \frac{R(\text{m})}{E^3(\text{GeV})}\ .$$

Table 1 illustrates some values for our ring (remember R = 1 m). Since the ring is 73 m long, one turn takes 243.3 ns so that the total time (T) for full extraction can be computed and the allowable maximum repetition rate (Rm) for complete extraction is obtained easily (the accelerator natural repetition rate is 625 pps).

A pulsed betatron core could be used to increase the energy loss. The technical feasibility of this device is being studied.

We are also examining the use of a radio frequency cavity to achieve the required loss. One possible method is similar to that used on the ISR at CERN where they managed to accelerate particles by moving empty RF buckets through the beam.

Table 1
Radiation Losses and Repetition Rate in EROS

| E (GeV) | $\Delta E_{tot}$ (MeV) | N | T (ms) | Rm (pps) |
|---|---|---|---|---|
| 0.1 | 0.058 | $113 \times 10^3$ | 27.5 | 36.4 |
| 0.15 | 0.294 | $33 \times 10^3$ | 8.0 | 125 |
| 0.2 | 0.931 | $14 \times 10^3$ | 3.4 | 294 |
| 0.25 | 2.27 | $7.2 \times 10^3$ | 1.75 | 571 |
| 0.3 | 4.71 | $4.2 \times 10^3$ | 1.02 | 980 |

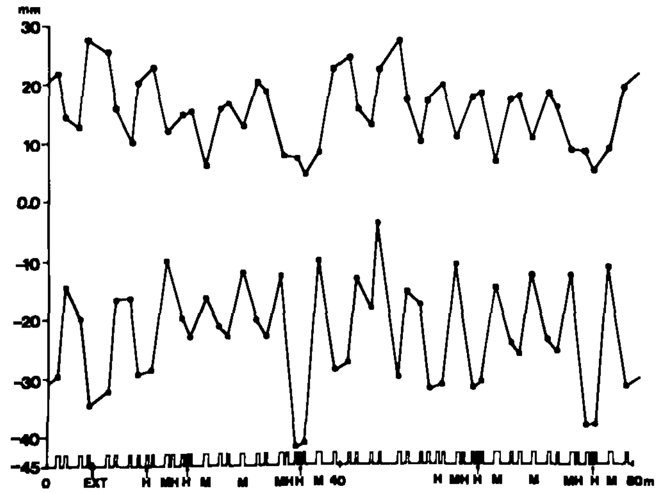


Fig. 5 Horizontal envelope during extraction.

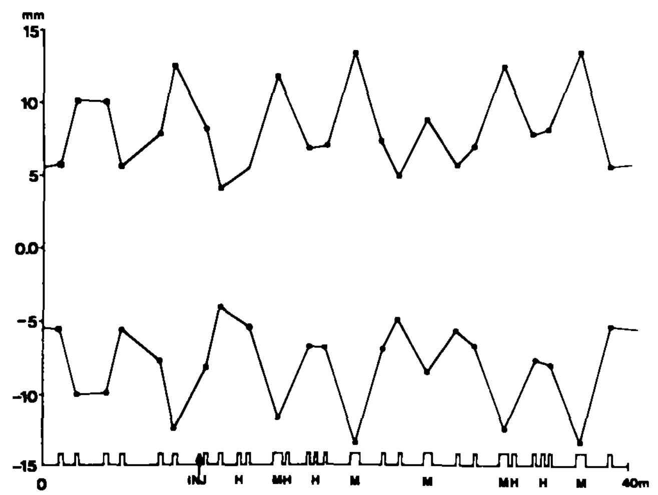


Fig. 6 Stored beam vertical envelope.

## 4. Main Magnetic Components of EROS

The perturbation of the ring design effected in 1973 by the presence of Karl Brown had a vast and beneficial impact on the magnetic components. The apertures of the quadrupoles and hexapoles were reduced from 10 inches in some parts of the ring to a uniform 4 inches all around. The bending magnets, although increasing in number from eight to ten were reduced considerably in size which allowed us to design them as rectangular units. The aim of the magnet design has been to achieve the required performance while keeping the construction as simple as possible.

### Bending Magnets

Table 2 shows the parameters that must be satisfied for the bending magnets. Using a gap height of 5 cm (leaving a little room for error in the placement of the vacuum box and anticipating larger vertical oscillations during tune-up), it was found that a pole width of 17.78 cm (7 in.) would be more than adequate, provided small rectangular shims were used at the sides of the pole to extend the width of the useable field. The computer program TRIM[5] was used extensively in the magnet design, and Fig. 7 shows a cross section of the proposed magnet, with the shaded area in the gap depicting the region of acceptable field levels (as ascertained by TRIM). The iron length of the magnet was evaluated using fringing fields given by TRIM and

Table 2
Bending Magnet Requirements

| | |
|---|---|
| Field required for 250 MeV | 8333 G |
| Deflection angle | 36° |
| Effective length | 61.808 cm |
| Poleface entrance angle | 18° |
| Poleface exit angle | 18° |
| Field index | 0 |
| Beam envelope in bending magnets: | |
| Max. vertical space occupied by beam | 2.80 cm |
| Max. horizontal space occupied by beam | 3.51 cm (including extraction) |
| Sagitta of 36° bend | 4.90 cm |
| Width of good field required | 8.41 cm |
| Definition of "good field" | ± 0.05% |
| Power supply stability | ± 0.005% (long term) |
| Field difference between any two magnets | < 0.1% |

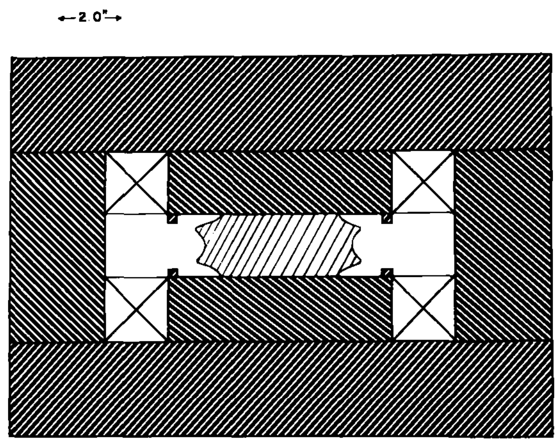


Fig. 7 Cross section through bending magnet.

Table 3
Quadrupole Requirements

| | |
|---|---|
| 1) Strength | $-1.828\ m^{-2}$ |
| Effective length | 0.25 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Max. field gradient | 15,233 G/m |
| Max. poletip inductance | 967.4 G |
| Number required | 8 |
| Designation | 5 QS 1.2 |
| 2) Strength | $1.922\ m^{-2}$ |
| Effective length | 0.25 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Max. field gradient | 16,017 G/m |
| Max. poletip inductance | 1016.9 G |
| Number required | 8 |
| Designation | 5 QS 1.2 |
| 3) Strength | $1.778\ m^{-2}$ |
| Effective length | 0.25 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Max. field gradient | 14,817 G/m |
| Max. poletip inductance | 941.0 G |
| Number required | 4 |
| Designation | 5 QC 1.2 |
| 4) Strength | $3.556\ m^{-2}$ |
| Effective length | 0.25 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Max. field gradient | 29,633 G/m |
| Max. poletip inductance | 1882.0 G |
| Number required | 8 |
| Designation | 5 QC 2.4 |
| Total integrated harmonic content at 4 in. aperture | 1% |
| Field difference between any two quadrupoles (tracking) | < 0.1% |
| Power supply stability | ± 0.005% (long term) |

Table 4
Sextupole Requirements

| | |
|---|---|
| 1) Strength | $-6.0\ m^{-3}$ |
| Effective length | 0.2 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Poletip inductance | 242 G |
| Number required | 2 |
| Designation | 5 S .4 |
| 2) Strength | $-7.65\ m^{-3}$ |
| Effective length | 0.2 m |
| Aperture | 12.7 cm (5 in.) diam. |
| Poletip inductance | 385.7 G |
| Number required | 4 |
| Designation | 5 S .4 |
| 3) Strength | $0.318\ m^{-3}$ |
| Effective length | 0.2 m |
| Aperture | 14.0 cm(5.5 in.)diam. |
| Effective poletip inductance (these are air-core magnets) | 15.6 G |
| Number required | 4 |
| Designation | 5.5 S .016 |
| Total integrated harmonic content permissible at 4 in. aperture | 10% |
| Magnetic field stability | 0.1% |

a simple ray tracing program, and it turned out to be 56.64 cm. The flux in the return yoke was 13.6 kG at a thickness of 7.5 cm; the reluctance of the iron was 3% of the total, and the magnet requires 35,000 At at maximum field.

## Quadrupoles

Table 3 shows the requirements for quadrupole magnets. Although an aperture of 10 cm would have been sufficient to handle the maximum extent of the beam in the ring, the aperture was increased to 12.7 cm for two reasons: (i) Since the ring is designed to handle electrons of 100 MeV or less, the poletip inductance of the quads at this energy would have been very low (300 gauss or less), and remanent field problems would probably be encountered which would jeopardize the fine tuning of the ring. (ii) The first harmonic produced in a quadrupole due to the non-infinite extent of the magnet and to the non-hyperbolic shape of the poles is the 12-pole ($n = 6$, which decreases with the fifth power of the radius as one moves inward), thus an increase in aperture to 12.7 cm would considerably decrease the harmonic content at the normalizing aperture of 10 cm. The pole pieces can thus be cut from 6 inch diameter circular steel rods, which simplifies the construction considerably. Further reduction of harmonic content can be achieved by careful assembly and machining, chamfering the pole-edges at the exit and entry planes of the magnet and using mirror-plates (field-clamps) with adjustable studs.[6] Prototype magnet tests will reveal if these steps are necessary.

To meet ring tuning requirements, the quadrupoles must be driven in four groups (three groups of eight magnets and one group of four). The poles of all the magnets of one group must therefore be driven in series by one power supply. Since we wanted to avoid high voltages, we decided to use small water-cooled coils of low impedance.

## Sextupoles

The requirements for sextupoles are outlined in Table 4. It can be seen that the poletip inductance of the iron magnets is quite low even after an increase in aperture; thus for low energy operation, remanent field problems could occur. Only experience will show the necessity of adding a degaussing cycle to the power supplies that drive them. Harmonic content should not be a problem, due to the increased aperture in both the iron-core and air-core magnets. The magnet coils are air-cooled and all of the magnets in each of the three groups indicated in Table 4 will be driven in series.

## References


[1] R. Servranckx, Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, Calif., p.1039 (1973).
[2] Saskatchewan Accelerator Laboratory, Internal Reports SAL-RING-16 to -25, -27 (unpublished).
[3] Saskatchewan Accelerator Laboratory, Internal Report SAL-RING-28 (unpublished).
[4] R. Servranckx, Particle Accelerators (in press).
[5] J. S. Colonias and J. H. Cole, Proceedings of the International Symposium on Magnet Technology, Stanford University, p.188 (1965).
[6] W. V. Hassenzahl, Proceedings of the International Conference on Magnet Technology, Brookhaven, p.469 (1972).