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# Cost Optimisation Studies of High Power Accelerators

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**Abstract.** Cost optimisation studies are carried out for an accelerator based neutron source consisting of a series of linear accelerators. The characteristics of the lowest cost design for a given beam current and energy machine such as power and length are found to depend on the lifetime envisaged for it. For a fixed neutron yield it is preferable to have a low current, high energy machine. The benefits of superconducting technology are also investigated. A Separated Orbit Cyclotron (SOC) has the potential to reduce capital and operating costs and initial estimates for the transverse and longitudinal current limits of such machines are made.

## INTRODUCTION

The high power accelerators proposed for transmutation of material such as radioactive waste and plutonium are expensive both in terms of the capital and running costs. Acceptability of this accelerator technology rests not only on the benefits, the feasibility and the technical risks, but also on the delivery of the most cost effective solution. Thus it is important that the cost drivers are understood.

A required neutron yield can be met by an infinite number of combinations of beam current and energy as the yield is proportional to the product of beam current and the number of neutrons per incident proton which is a function of beam energy. This is illustrated in Figure 1 which shows curves of constant neutron yield, $5 \times 10^{18}$n/s in this case, for a proton accelerator with a lead target, a $^{238}$U target, and an enriched uranium target where the neutron yield is assured to be ten times that of the $^{238}$U yield. The curves are formed from neutron yield data obtained from the literature [1,2].

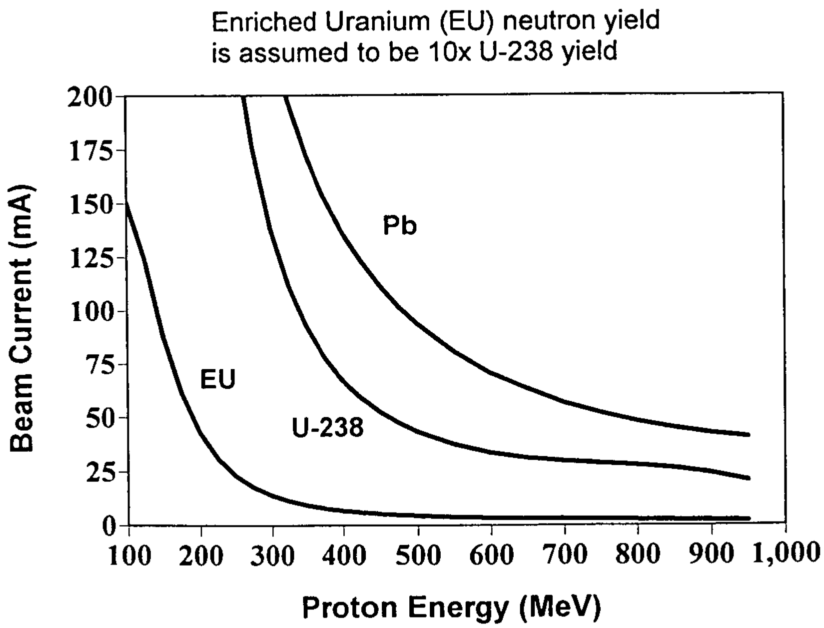


Fig. 1. Curves of constant neutron yield ($5 \times 10^{18}$ n/s)

The question then arises as to which combination of current and energy, whilst keeping the neutron yield constant, leads to the lowest cost accelerator. Furthermore each combination can be subject to a cost optimisation procedure in terms of overall power and length of the machine. This paper describes such cost optimisation studies for a linear accelerator with final energy greater than 100MeV. A simple cost model is used to calculate the capital and running costs of the accelerator. Following that the potential for cost reduction through the use of superconducting accelerators is illustrated.

The capital and running costs can be reduced through the use of a cyclotron. However the high currents need for transmutation applications have not been demonstrated in a cyclotron. The Separated Orbit Cyclotron (SOC) has the potential for high current beams and preliminary calculations are presented of the transverse current limit for such a machine.

## BASELINE ACCELERATOR CHOICE

The cost optimisation studies were carried out for a baseline accelerator similar to that proposed by Los Alamos [3]. It is assumed to comprise of an injector up to 100keV, a Radio Frequency Quadruple (RFQ) up to 7MeV, a Drift Tube Linac (DTL) up to 20MeV, a Bridge Coupled Drift Tube Linac up to 100MeV and a Coupled Cavity Linac (CCL) up to the final energy. The ions species is protons, the accelerators are at room temperature and are driven by 350MHz klystrons to the end of the DTL after which 700MHz klystrons are then used for the BCDTL and the CCL. Figure 2 shows a schematic of the accelerator.

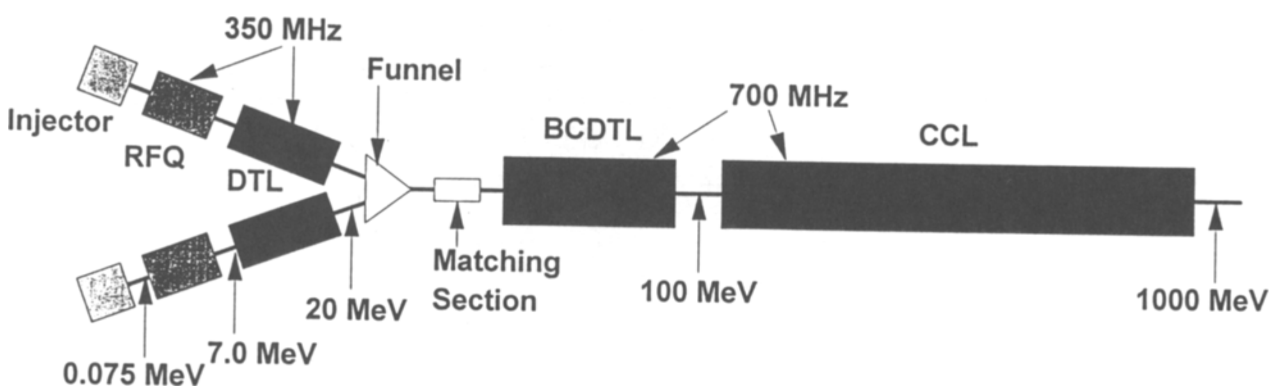


Fig. 2. Baseline accelerator choice

### Bore Size Issues and Shunt Impedance Modelling

For such high power accelerators activation of the machine is a key issue and the bore size is usually many times the rms beam size. For the Los Alamos design this factor increases from 13 to 26 as the beam energy increases. From a model by Wangler [4] the beam size decreases with decreasing beam current. Thus we allow the bore to change with beam current whilst keeping a ratio between the bore to beam radius equal to that used by Los Alamos. Reducing the bore leads to increased power efficiency through an increase in the shunt impedance. Figure 3 shows the relationship between beam radius and beam current derived from this model at 100MeV. This was assumed to be the case at all energies although at higher energies the beam size reduces giving further scope for shunt impedance improvement.

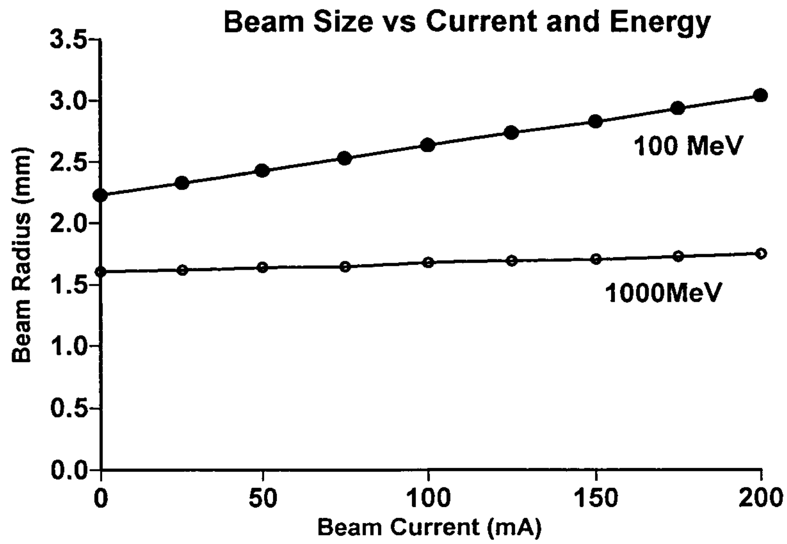


Fig. 3. Relationship between beam radius and beam current

In the modelling the design of the accelerator up to the 100MeV injection point of the CCL was assumed to be fixed. The generic Los Alamos CCL cavity design was optimised for highest power efficiency by varying the shape of the cavity to maximise the effective shunt impedance using the SUPERFISH code. This effective shunt impedance is defined as $0.85ZT^2$ where Z is the calculated shunt impedance, T is the transit time factor and the 0.85 factor allows for losses in coupling slits, coupling cavities and bridge cavities. In conjunction with the changing bore size at different currents, the shunt impedance for any current and energy can be obtained and this is shown in Figure 4. These shunt impedances can now be used in the cost modelling.

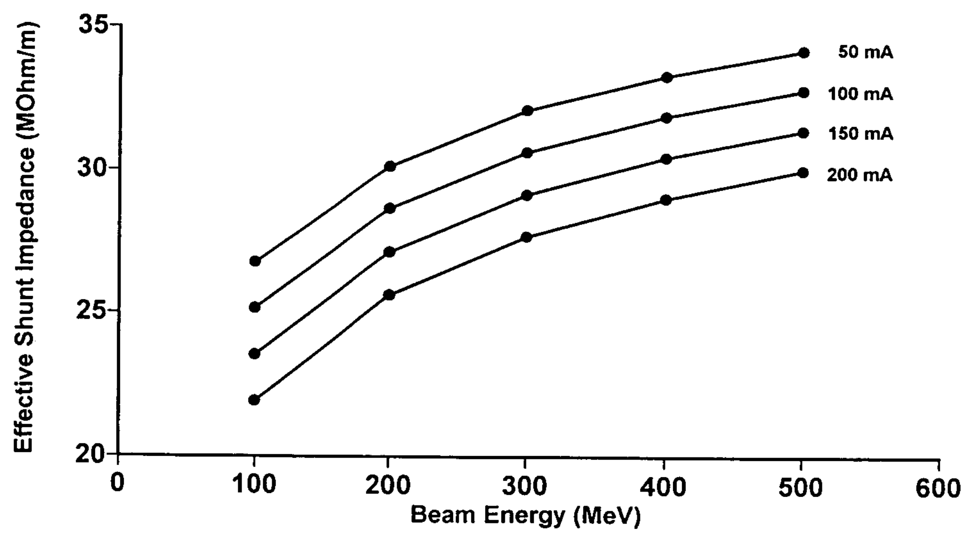


Fig. 4. Variation of CCL shunt impedance with beam energy and current.

## COST MODEL

The aim of the cost modelling is to obtain the total costs (capital and running) of the accelerator for a matrix of currents and energies. Curves such as that shown in Figure 1 can be imposed on the matrix and the costs for a constant neutron yield obtained by interpolation.

The inputs to the cost model are given in Table 1 below.

**Table 1. Inputs to the Cost Model**

| Parameter | Comment or Value |
|---|---|
| Shunt Impedance | Obtained from SUPERFISH |
| Cost of CCL Structure | £170k/meter |
| Capital Cost of RF System | £1/Watt for 1MW klystrons |
| Cost of Accelerator to CCL | Scaled from £50M for a 250mA machine |
| RF Tube Lifetime | 50,000 hrs |
| RF Tube Replacement Cost | £350k |
| AC to RF Conversion Efficiency | 58% |
| AC Power Costs | 4.25p/kWhr for UK |
| Staff | 100 at AEA rates |
| Availability | 0.75 |
| AC Requirement for Balance of Plant | 25MW |
| Synchronous Phase | 30° |
| Power Losses in RFQ, DTL, Funnel, BCDTL | 11MW |

A factor is added to the total capital cost for the cost of the linac tunnel and buildings.

The cost model is implemented in a spreadsheet. For a particular choice of beam current, beam energy and energy gradient in the CCL the total power requirements are calculated along with their cost over a chosen lifetime of the machine. Also calculated is the total capital cost of the machine. These are combined to give the total costs over the lifetime. The costs of the target systems, decommissioning and the cost of money are not included in the calculation at this stage of our studies.

This process is repeated for different accelerator energy gradients for each combination of current and energy to find the minimum cost for that combination. That such an optimum exists is demonstrated by writing the cost of a linear accelerator, C, as

$$C = C_F + C_L L + C_P P \tag{1}$$

where $C_F$ are fixed costs, $C_L$ is cost of the structure per unit length, L is the length of the accelerator, $C_P$ is the cost of power and P is the power required to operate the cavity. Since the power and length of the machines are related by

$$P = (E_0T)^2 L/ZT^2 \tag{2}$$

where $E_0T$ is the average electric field and also

$$\Delta W = E_0 T \; L \cos \phi \tag{3}$$

where $\Delta W$ is the energy gain over the length of the accelerator and $\phi$ is the synchronous phase. Hence we obtain

$$P = \frac{\Delta W^2}{(ZT^2) \, L \cos^2 \phi} \tag{4}$$

ie. the cavity power is inversely proportional to the length of the machine. Thus from equation (1) it can been seen that there is an optimum length and so an optimum energy gradient.

The cost model, using simple equations such as these above, is used to calculate the accelerator power, length, capital and operating costs for 50, 100, 150 and 200mA beams at energies of 100, 200, 300, 400 and 500MeV finding the optimum energy gradient for each combination.

## COST OPTIMISATION FOR A ROOM TEMPERATURE MACHINE

An example of the cost optimisation for a 50mA, 400MeV accelerator is shown below in Table 2.

**Table 2. Cost Optimisation of A 50mA, 400MeV Accelerator**

| | Energy Gradient (MV/m) | Total Linac Length (m) | Total AC Power (MW) | Linac Capital Cost (£M) | 10-Year Cost (£M) | 40-Year Cost (£M) |
|---|---|---|---|---|---|---|
| Capital Optimum | 2.38 | 344 | 121 | 181 | 644 | 2034 |
| 10-Year Optimum | 1.25 | 529 | 101 | 202 | 603 | 1807 |
| 40-Year Optimum | 0.70 | 833 | 91 | 265 | 636 | 1749 |

The table shows three cases: firstly where the capital costs are optimised, secondly where the capital plus ten years running costs are optimised and thirdly where capital plus forty years costs are optimised. As the lifetime of the accelerator increases the energy gradient ($E_0T$) and the length increase whilst the power decreases. This is a direct consequence of the increasing dominance of the power costs for the accelerator over its lifetime. It is worth pointing out that the lowest cost machines also appear to be those of lowest technical risk ie. low Kilpatrick factor.

Turning now to the case of a constant neutron yield, Figure 5 shows the total ten and forty years costs as a function of beam current for two neutron yields (the second being three times the first). In this case the energy gradient is fixed at 1MeV/m. For both neutron yields there appears to be optimum beam current corresponding to minimum cost.

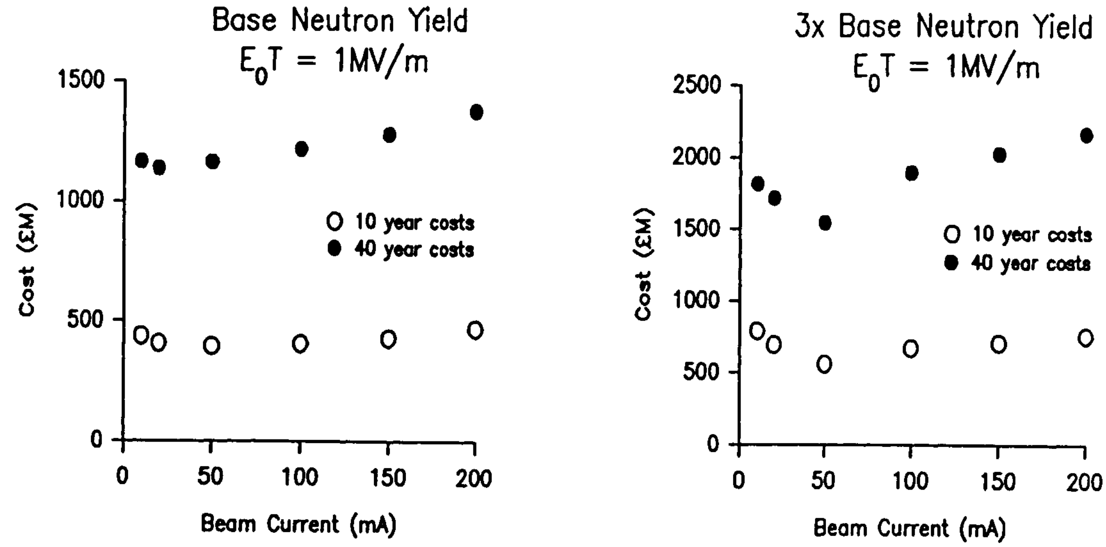


Fig. 5. Accelerator costs for a constant neutron yield and energy gradient

The results of optimisation including free choice of the energy gradient are shown in Figure 6. The beam energy, accelerator length, accelerator power and a relative unit cost over forty years, ie. £/neutron, are plotted against beam current. Here there is no minimum. The cost increases monotonically with the beam current. It is preferable to work at the lowest current and highest energy. This is due to the behaviour of the neutron yield with energy - the number of neutrons per sec per incident Watt of beam power is higher at higher energies than it is at lower energy.

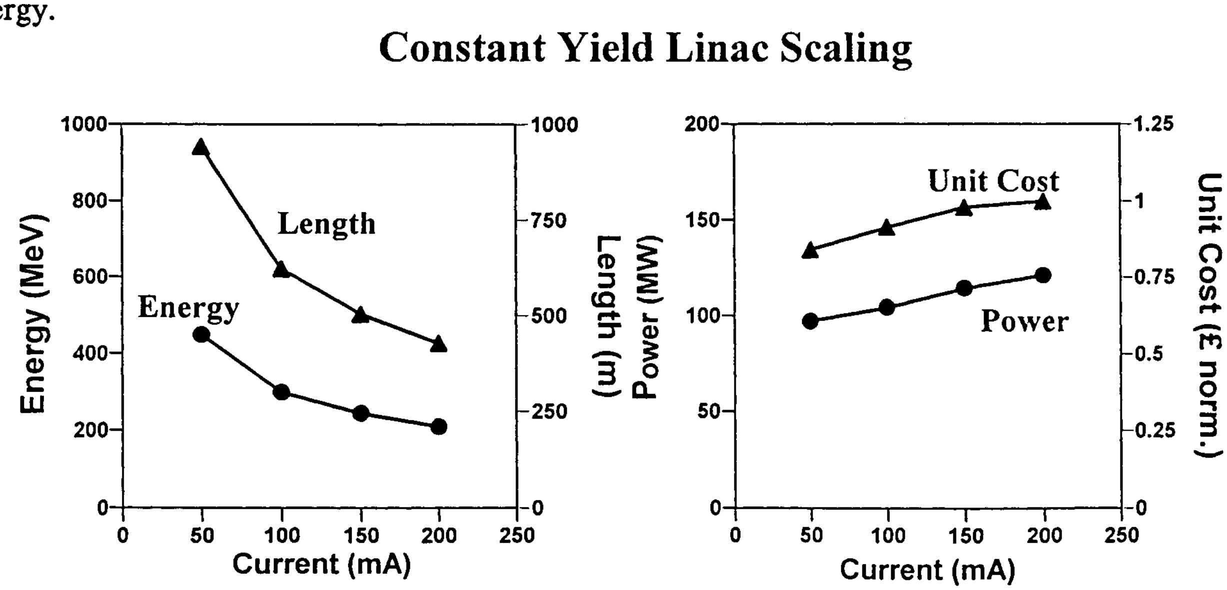


Fig. 6. Accelerator power, energy, length and relative unit cost (~£/neutron) for a constant neutron yield

## Options for Cost Reduction

The costs over the lifetime are dominated by the annual power consumption and so means of reducing the electricity costs have been sought. Two methods have been identified.

The first option is to install a gas turbine generator on the site to provide the power required for its facility. The electricity costs over the lifetime are removed but this is balanced to some degree by the capital and running costs of the generator. Furthermore the generator can be available for up to 90% of the time whereas the accelerator may have an availability of 75%. The surplus electricity generated can be sold back to the utilities for additional income. For a 100MW power requirement this can lead to savings of ~ 45%. Furthermore, increasing the generation capacity beyond the power requirements can lead to increased income through electricity sales thus further reducing the costs.

A second option is to reduce the duty factor of the accelerator. Although the overall power requirements will increase for a fixed neutron yield the power consumed will reduce due to the decreased duty factor. This reduction in power must be compensated by an increase in accelerator energy and length. For the 100MW generator operating at 50% accelerator availability the forty year cost savings are ~ 55%.

## Use of Superconducting Linear Accelerators

The power consumption in the accelerator which dominates the cost of the machine arises from the beam power and the power dissipated in the cavity walls. Although the beam power cannot be reduced the cavity power can be reduced to negligible levels through the use of superconducting accelerators.

The principle disadvantage of such accelerators is the present status of their development. A variety of superconducting linacs have accelerated electrons or heavy ions at low currents (less than a few mA) but their use at high currents such as that required for transmutation of material is untested. The work at Argonne National Laboratory [4] on a 355MHz cavity has concluded that gradients of ~7MeV/m are realisable at a power consumption of 20W with an extra 25% of length required for superconducting solenoids to focus the beam.

In superconducting accelerators loss of beam will not only lead to activation of the machine but may lead to quenching of the superconducting state. Furthermore availability may be affected due to the cool down/warm up times associated with maintenance and inspection of the accelerator.

In order to assess the implications for accelerator costs of superconductivity the following methodology is adopted

a) the superconducting accelerator begins after the RFQ
b) the accelerating gradient is 7MeV/m
c) cavity power loses are those as given by studies at ANL (~ 2.9W/MeV)
d) commercial helium liquefiers are used
e) cost of manufacturing the niobium coated copper linac structure is twice that of a room temperature structure.

The liquid helium plants for cooling the machine can be commercial units such as those used at the JET project at Culham. The specifications are given in Table 3 below.

**Table 3. Helium Liquefier Specification**

| | |
|---|---|
| Cooling Capacity (W) | |
| Accelerator | 270 |
| Pipework | 130 |
| Total | 400 |
| Capital Cost (£M) | |
| Liquid He Plant | 1.1 |
| Liquid $N_2$ Plant | 0.25 |
| Electricity Usage | 250kW |
| Maintenance Costs | £40k/yr |

This data was used in the cost model for the case where there is a gas turbine generator with capacity in excess of that required by the facility. Table 4 shows the benefits to be gained in using superconducting technology for a 50mA, 320MeV accelerator.

**Table 4. Parameter Ratios For Superconducting/Room Temperature Accelerator**

| | |
|---|---|
| Length | 15% |
| AC Power | 44% |
| Capital Costs | 47% |
| Running Costs/Year | 81% |
| 40 Year Cost | 59% |

There are no proposals or designs for high current superconducting linear accelerators at present due to the lack of development of the technology. However, the potential benefits for future machines are clear subject to the solution of the problems associated with the use of superconducting technology in these high power accelerators.

## THE SEPARATED ORBIT CYCLOTRON

So far it has been demonstrated that the costs of linear accelerators are high; the costs being driven by power usage over there lifetime such linacs are also large. A cyclotron is compact and makes efficient use of the cavities and so would seem to offer potential for overall cost reduction. The problem is that to date the comments available from cyclotrons have been limited at most to ~ 1-1.5mA [5]. However the Separated Orbit Cyclotron (SOC) appears capable of transporting much higher currents.

Figure 7 shows a schematic of an SOC. The machine consists of a number of sector magnets with rf cavities between them. There are radial gradients in the magnetic sectors (a FODO lattice is shown although it could be more complex) to provide strong focusing. It is this strong focusing that permits the transport of high current beams. Thus the SOC resembles a rolled up linac but since the same cavities are used many times as the beam follows its spiral path it is highly power efficient. The turn separation in an SOC can be made to be a constant, whereas in a conventional cyclotron the turn separation decreases with increasing radius. This feature not only aids injection and extraction, but allows a large bore size to beam size ratio to be maintained thus reducing activation. In order to maintain a constant orbit separation, the energy gain per turn must increase with increasing energy and radius. The velocity of the particles increases to keep them in phase with the accelerating voltage.

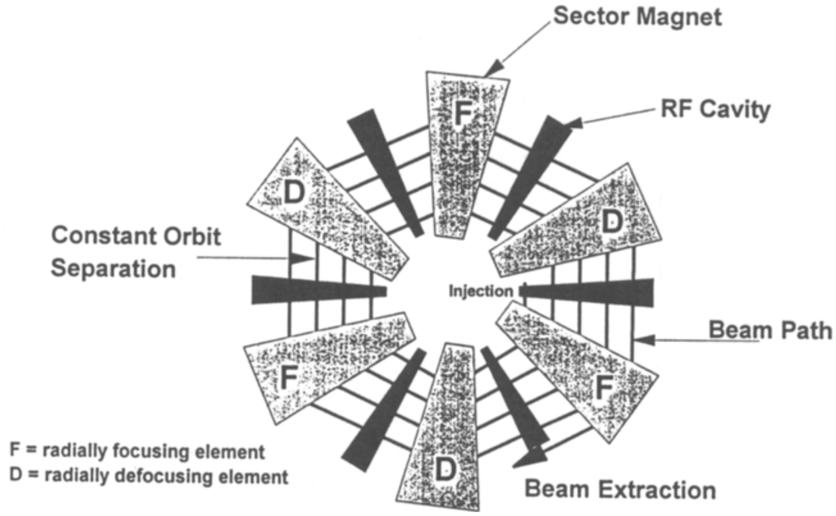


Fig. 7. The Separated Orbit Cyclotron

A 65mA, 1GeV three stage SOC was proposed in the mid-sixties at AECL in Canada [6] although no detailed evidence was presented to verify that the machine could transport such a current. A lower energy lower current (5µA, 43MeV) machine with superconducting magnets and cavities is being built in Munich [7]. Thus, as well as determining the potential cost reductions associated with an SOC, it is important to understand just what the current limits are for such a machine.

Due to the similarity between the SOC and the linac, the model by Wangler [4] for the current limits in a linac can be applied. This has been done for the case of the FODO lattice shown in Figure 7. The dependence of the transverse current limit, $I_t$, on the machine parameters is given by

$$I_t \propto \beta\, a^2 B^2 \Lambda^2 H^2 \tag{5}$$

where $\beta$ is the relativistic factor, a is the beam radius, B is the magnetic field on the equilibrium orbit and $\Lambda$ is the filling factor which is the fraction of the orbit occupied by the focusing elements and H is the number of focusing periods.

Usually in a linac the longitudinal current limit is far greater than the transverse limit but for the cyclotron consideration must be given to it. This is because the average accelerating field tends to be much greater in the linac. The longitudinal current, $I_\ell$, has the following dependence on the machine parameters

$$I_\ell \propto \beta\, \Delta r\, a\, B^2 \Lambda^2 H^2 \tag{6}$$

where $\Delta r$ is the orbit separation.

In Figure 8 the transverse current limit is plotted as a function of the number of focusing sectors for an injection energy of 20MeV, a B-field of 1.64T, a beam radius of 2.0mm, a filling factor of 0.55 and an orbit separation of 6cm.

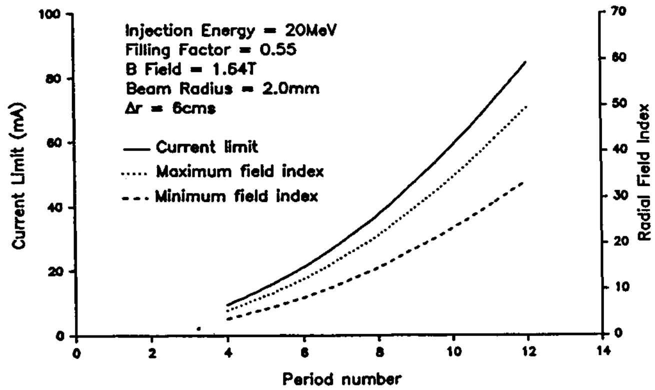


Fig. 8. The tranverse current limit in an SOC and the maximum and minimum radial field indices

From the diagram it can be seen that a current of ~ 80mA can be obtained. In practice the current used might be a fraction of that calculated in this way. Further optimisation of the parameters can lead to higher currents. Obviously, detailed beam dynamics calculations will be needed to verify the current limit. Also from Wangler's model the upper and lower limits to the radial field indices in the focusing channels can be calculated. This is based on the limits of the zero current phase advance, $\sigma_o$, where in order to limit emittance growth there is the requirement that $\sigma_o < \pi/2$ [4]. For the case above the longitudinal current limit is ~ 1A.

## ACKNOWLEDGMENTS


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## REFERENCES


[1] Nakamura, T., et al, *Atomic Data and Nuclear Data Tables* 32, 471-501 (1985)

[2] Carpenter, J.M., *Nuc. Instr. Methods* 145, 91-114 (1977)

[3] Lawrence, G.A., *Nuc. Instr. Methods* B56/57, 1000-1004 (1991)

[4] Wangler, T.P., Space Charge Limits in Linear Accelerators, *Los Alamos Report* LA-8388 (1980)

[5] Schryber, U., Upgrading the PSI Accelerator Facility for High Intensity Operation, in *Proceedings of the Third European Particle Accelerator Conference*, 1992, pp. 173-177.

[6] Bartholomew, G.A., and Tunicliffe, P.R. The AECL Study for an Intense Neutron Generator, *AECL Report* 2600 (1966)

[7] Trinks, U., Assman, W., and Hinderer, G., *Nuc. Instr. Methods* A244, 273-282 (1986)