PROPOSAL FOR A SOUTH AFRICAN NATIONAL ACCELERATOR FACILITY FOR PHYSICS AND MEDICINE

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Abstract

The methods used to select the best accelerator for a national facility for research in the physical sciences, neutron and proton therapy and isotope production are discussed. The analysis showed that a 200 MeV (proton) separated-sector cyclotron will best meet the needs. Some detailed aspects of the design of this accelerator have been studied. The proposed machine will be able to accelerate light and heavy ions and will be capable of delivery external beam currents larger than 100 μA up to proton energies of 80 MeV with very high extraction efficiencies. The main parameters of the cyclotron and of possible injectors are given.

1. Introduction

There are at present six nuclear accelerators in South Africa, the largest being a 110 cm classical cyclotron, a 6 MV EN tandem Van de Graaff and a 5,5 MV CN Van de Graaff accelerator.

Several years ago it became apparent that these accelerators would not meet the future demands of nuclear physics, nuclear medicine (for accelerator produced isotopes) or of radiotherapy (mainly neutron therapy). Investigation of the requirements of these different fields by a group of nuclear physicists under the auspices of the South African Institute of Physics in 1971 revealed that reasonably large accelerators will be required to cater for the needs of the mentioned fields. Limitation of manpower and funds in a smaller country as well as the advantages associated with interdisciplinary research led to the investigation of the possibility of pooling the resources of the physical and medical fields to obtain a joint facility which could meet the requirements of the respective fields better than more limited separate facilities. At that stage a separated-sector cyclotron was proposed as a national accelerator facility for joint use by physics and medicine. This proposal received support from most of the nuclear physicists in the country as well as from various medical groups. The main advantage of the separated-sector cyclotron is that it in principle offers the dual capabilities of delivering high quality beams of energetic light and heavy ions for nuclear research as well as high intensity external beams of lower energies for isotope production and neutron therapy.

On the recommendation of the Scientific Advisory Council a feasibility study for a national accelerator facility was started at the beginning of 1974 after receiving a grant of R200 000 from the Cape Provincial Administration. The purpose of this study was to ascertain present and future requirements for accelerators in South Africa and to select the most appropriate accelerator for the country.

2. The Methods and Outcome of the Feasibility Study

The feasibility study was controlled by a Board representing the different interested groups and organisations in the country. The technical work was directed by a project committee consisting of the leaders of medical, physical and accelerator task groups. The task groups included specialists from many research groups in South Africa and also made use of consultants from other countries.

As the method used by the study will be published elsewhere in more detail it will only be summarised very briefly here. The first step was to identify the diverse fields which are already using or are expected to make use of accelerators in future. Special efforts were made to estimate the future trends of these fields by extrapolating from present developments and by studying the plans of groups elsewhere. The requirements of each field were finally expressed in terms of the beams of accelerated particles required (table 1).

Table 1. Beam requirements of the Different Fields.

Field and Weighting Factor	Beam Requirements
	Light ions
Nuclear Physics (14)	Protons : $20<E_p<200$ MeV
General Physics (4)	D to He : ~50 MeV/nuc.
Nuclear Chemistry (4)	Beam intensities < 10 μA
	Heavy ions
	He to Ar : 15-50 MeV/nuc.
	Intensity - 1pμA to 10 pnA
	High beam quality
Neutron therapy (10)	D and H ions of 16 to 100 MeV Beam intensities 100 to 10 μA
Proton therapy (2)	E_p < 200 MeV
Proton Radiography (2)	Intensity ~ 1 μA
Radiobiology (2)	Similar to properties given above
Isotope production (14)	E_p < 80 MeV and E_d < 80 MeV at a few fixed energies Beam intensities > 100 μA

The relative importance of each field for South Africa was taken into account by means of the weighting factors shown in table 1. This table shows that the medical and physical fields were considered of equal importance and that the most important fields are nuclear physics and chemistry, neutron therapy and nuclear medicine (isotope production).

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Nine different accelerators were included in the study for the selection of the most suitable accelerator. The beam properties of the various accelerators considered were determined by estimation where not otherwise possible. The usefulness of each accelerator for each field was judged using a tabulation method described by Dunford1). Members of the project committee allocated a number between 0 and 10 to denote the usefulness of each accelerator for each field considered. The higher the number the better the accelerator caters for the needs of the given field. Thereafter a figure of merit was obtained for each accelerator in each field by multiplying the allocated figure by the weighting factor for the respective field. The sum of all the figures of merit of the individual accelerators over all the fields considered gives the overall figure of merit for the accelerator as a national accelerator facility as shown in table 2.

The real annual costs of the respective accelerators were compared, using the concept of total annual cost. This was arrived at by requiring that the total capital cost (accelerator, auxiliary equipment and building) be redeemed together with 10% interest on the capital over the estimated useful competitive lifetime of the accelerator. The total annual cost for each accelerator was obtained by adding this figure to the annual running cost and subtracting the estimated annual income from isotope production if applicable. The total annual cost for each accelerator, together with an index of benefit per unit cost (figure of merit/annual cost) is shown in table 2.

Table 2. Comparison of Different Accelerators

Accelerator	Figure of Merit	Benefit/Unit cost	Capital Cost for Facility R x 10^6	Useful Lifetime (years)	Total Annual Cost R x 10^6
13 MV T	50	29	4,7	5	1,72
20 MV T	105	73	7,65	15	1,44
30 MV T	178	79	11,5	20	2,25
60 MeV SPC	201	148	6,61	12	1,36
80 MeV SPC	253	181	7,47	15	1,4
80 MeV PLA	240	247	8,07	15	0,97
100 MeV SSC	363	271	9,03	15	1,34
150 MeV SSC	422	291	10,03	18	1,45
200 MeV SSC	512	322	11,14	20	1,59

T = Tandem Van de Graaff
SPC = Solid-Pole Cyclotron
PLA = Proton Linear Accelerator
SSC = Separated-Sector Cyclotron

The result of the analysis is that both the figure of merit and the benefit per unit cost indicate that a 200 MeV separated-sector cyclotron will be the most suitable national accelerator for South Africa.

It is envisaged that the weekly allocation of accelerator time in terms of 8 hour shifts will be as follows : Nuclear physics and chemistry - 11 shifts, isotope production - 3 shifts, neutron therapy - 4 shifts and accelerator maintenance and development - 3 shifts, with an annual period of 4 weeks for major alterations to the accelerator.

A weighting method, similar to the one used for the selection of the most suitable accelerator was used for the siting of the accelerator. The availability of radiotherapists and cancer patients in different regions of the country carry the most weight in this case followed by the presence of sufficient airfreight connections to other major medical centres for the effective distribution of short-lived isotopes. This resulted in a recommendation that the cyclotron be sited in the vicinity of Cape Town in the proximity of the present two, and a planned third, large training hospital.

3. The Properties of the Proposed Separated-Sector Cyclotron

The main parameters of the machine are summarised in table 3. The choice of machine parameters was dictated by the requirements of users in the different fields (see table 1), and by the need for ease of construction and operation and the high degree of dependability necessary for routine use of the machine for neutron therapy and isotope production.

The general layout of the separated-sector cyclotron with four 34^0 sector magnets and 2 deltas in opposite valleys is shown in figure 1.

The rather low maximum magnetic field of 1,265 T for 200 MeV protons was chosen for the following reasons2) :

(i) To increase the orbit radius and therefore the maximum orbit separation at deflection

(ii) To give more space in the centre of the cyclotron for the injection elements and also more space for the deflection system

(iii) To ease the shaping of the magnetic field for variable energy operation by excluding the effects of magnetic saturation in the pole tips of the magnets

(iv) To make it possible to increase the energy constant ($k = E.A/q^2$) of the cyclotron for heavy ions by increasing the magnetic flux density

(v) To limit the orbit frequency of 200 MeV protons to 6,5 MHz so that commercially available short wave power amplifiers can be considered for 4th harmonic acceleration at 26 MHz if so desired.

Calculations and model measurements on deltas and half-wave resonators showed4) that voltages of up to 250 kV on the deltas will be possible at an energy loss of about 90 kW for each delta and resonator. The high energy gain per turn (1 MV x q, where q is the change of the ion), combined with the choice of the magnet size leads to orbit separations of 9,9 mm and 23,7 mm respectively for 200 MeV and 80 MeV protons. Single turn extraction of high quality pulses of 1 ns duration will therefore be possible up to the maximum proton energy of 200 MeV for physics experiments, with the cyclotron operating in a fixed orbit mode. The large orbit separation at lower energies and high voltages on the deltas makes it possible to extract beams of high intensity with very high efficiency using either single or multiturn extraction. The limited number of turns in the machine will also serve to reduce the effects of beam resonances, and errors in the magnetic fields, thus improving the overall transmission of the machine. This, in combination with the high deflection efficiency, will minimise residual radioactivity in the cyclotron thereby easing maintenance appreciably.

Table 3. Parameters of the Separated-Sector Cyclotron

Magnets	
4 Sector magnets of 34^0 angle	
Magnet gap	60 mm
Maximum magnetic flux density	1,265 T
Bρ at extraction	2,1496 T.m
Energy constant (ExA/q^2) for heavy ions	200
Weight of 4 magnets (iron)	1200 t
Power for main coils	500 kW
Pole face windings	~ 20 pairs/gap
Rf-system	
2,49^0 deltas	
λ/2 resonator for each delta with frequency range of	8,67 - 26 MHz
Harmonic numbers	4, 12 and 20
Maximum Rf-amplitude	250 kV
Rf-power (2 resonators without beam)	180 kW
Master Oscillator Power Amplifier system	
Tuning by short circuit plates and variable capacitance to delta	
Vacuum system	
Pressure	3 x 10^{-7} torr
Pumps - cryo and Ti-sublimators	
Beam geometry	
Injection radius (Centre of valley)	0,832 m
Extraction radius (Centre of valley)	3,629 m
Orbit separation at extraction	
(i) 200 MeV protons, 1 MeV/turn	9,9 mm
(ii) 80 MeV protons, 1 MeV/turn	23,7 mm
Energy multiplications	25

Space is also available in the two valleys between the magnets not taken up by the main deltas for the future installation of flat-topping resonators for the dee voltages. This will increase the duty cycle of the cyclotron and make single turn extraction of high intensity beams with pulses of longer phase length possible.

A frequency range of 3 : 1 in the Rf-system makes it possible to accelerate all ions at the peak delta voltages. This eliminates changes in the phase length of the pulses during acceleration, as described by Müller and Mahrt$^{3)}$.

The question of suitable injector accelerators for the separated-sector cyclotron is a crucial one, especially in respect of obtaining beams of sufficiently high quality and intensity for both light and heavy ions, and of sufficiently high charge states for heavy ions. The approach followed is to design the main cyclotron to be compatible with various possible injectors but to start the project by using a small solid-pole cyclotron as a simple and dependable injector for light and heavy ions without any charge stripping between the two machines. The main parameters of the injector cyclotron are presented in table 4. For physics experiments with light ions the injector and main cyclotron will be operated in constant-orbit mode. For heavy ions the injector cyclotron will be operated only partially in constant-orbit mode while for the medical work, where higher beam intensities are required, it will be operated at maximum dee voltages at a few selected energies. The maximum proton beam energy of the injector cyclotron was chosen to be 8 MeV. This is a reasonable compromise, so that the main cyclotron, with a fixed injection geometry, will be compatable with diverse injectors for heavy ions such as a 6 MV CN van de Graaff accelerator (which

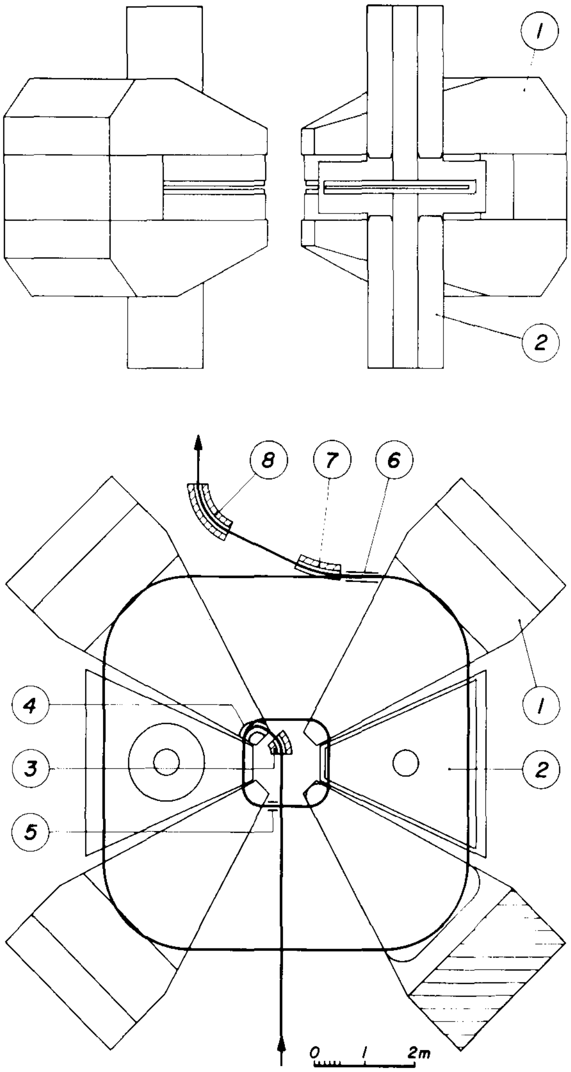

Figure 1. Side and top view of separated-sector cyclotron
1. Magnet; 2. Rf-resonator and delta; 3. Bending magnet for injection; 4. Magnetic septum for injection; 5. Electrostatic septum for injection; 6. Electrostatic septum for extraction; 7. Magnetic septum; 8. Bending magnet.

is already available) as well as larger solid-pole cyclotrons.

Table 4. Parameters of k = 8 MeV Solid-Pole Injector Cyclotron

Magnet	
Average magnetic flux density	1,04 T
Extraction radius	0,4 m
Rf-system	
2,90° dees	
Frequency range	8,67 - 26 MHz
Harmonic numbers	2, 6, 10
Particle energies	
Protons (maximum)	8 MeV
Other ions (maximum)	8 x q^2/A

Table 5. Heavy Iron Capabilities of k = 200 Separated-Sector Cyclotron for Different Injectors for an Energy Multiplication of 25 in the Main Cyclotron

Ion	SPC $q_2/q_1 = 1$ K_i = 8 MeV	6 MV V.d. Graaff	SPC $q_2/q_1 = 2,5$ K_i = 50 MeV
	(MeV/n)	(MeV/n)	(MeV/n)
^{14}N	16(4^+)	21,4(5^+)	50(7^+)
^{20}Ne	12,5(5^+)	15(6^+)	50(10^+)
^{40}A	6,13(7^+)	7,5($^+$)	28(15^+)
^{84}Kr	1,4(7^+)	3,4(11^+)	6,4(15^+)

SPC = solid-pole cyclotron
K_i = energy constant of injector

Table 5 shows the beam energies for different heavy ions for a k = 200 MeV separated-sector cyclotron in combination with the following injectors :

(i) A K_i = 8 MeV solid-pole cyclotron used as injector for light ions, injecting heavy ions without charge stripping ($q_2/q_1 = 1$) into the main cyclotron

(ii) A 6 MV CN Van de Graaff, accelerating doubly charged ions which are stripped to higher charge states in a thin foil before being injected into the main cyclotron

(iii) A K_i : 50 MeV solid-pole cyclotron with charge exchange in a foil with the final and initial charge states of the ion in the ration of 2,5 : 1 ($q_2/q_1 = 2,5$)

The charge state of the ion accelerated in the separated sector cyclotron is inserted in brackets after the ion energy in MeV/nucleon.

The injector giving the highest energy beams is the K_i = 50 solid pole cyclotron, followed by the 6 MV Van de Graaff accelerator and the small solid-pole cyclotron. It is envisaged that at first only the latter injector will be used. A decision about additional injectors will be made at a later date.

A feasible injection system consists of a bending magnet at the centre of the cyclotron followed by a magnetic channel in a pole tip and an electrostatic channel. Deflection can be achieved by an electrostatic channel followed by a septum magnet and a bending magnet.

The relationship between the betatron frequencies, γ_r and γ_z, is shown for protons of different maximum energy in fig. 2. The results of a numerical calculation for 200 MeV protons compares well with the results of an analytical approach. The analytical results are therefore presented for the other energies.

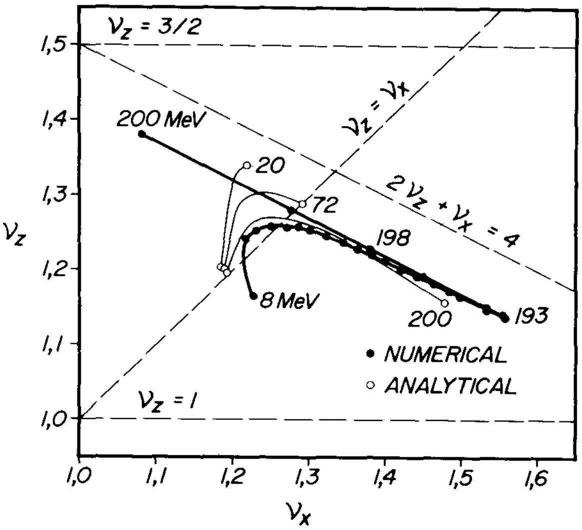

Figure 2. γ_z versus γ_x diagram for the cyclotron

The authors wish to acknowledge the contributions by the other members of the Project Committee in the selection of the most suitable accelerator and also the contribution of the members of the Accelerator Task Group to this project.

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DISCUSSION

Y. JONGEN: You seem to show that for the same energy a separated sector cyclotron is cheaper than a single-pole cyclotron. Can you comment on this?

W.L. RAUTENBACH: Yes, the reason is as follows: the comparative cost on the one hand depends on the useful lifetime. We estimated that a conventional solid-pole cyclotron would have a useful lifetime of say about 15 years. The separate sector cyclotron will have a useful lifetime of about 20 years. On the other hand, the income from isotope production from a solid-pole cyclotron is estimated to be roughly one quarter million rand per year and the income from a separate-sector cyclotron to about 3/4 of a million rand per year. This is due to the fact that the intensity of the external beam of a separated sector cyclotron will be higher than that of a solid-pole cyclotron and that it will not be as badly activated.

M.A. CHAUDHRI: What factors did you take into consideration while fixing the criterion of maximum energy and maximum beam intensity regarding the medical applications like therapy and isotope production?

W.L. RAUTENBACH: The newest information as far as we know about neutron therapy is that the oxygen enhancement ratio for neutrons goes down with increasing energy of the neutron spectrum. Measurement at Maryland University have shown that the oxygen enhancement ratio is down to about one for neutron spectrum with an average energy of about 50 MeV. Such a spectrum can be obtained by using protons or deuterons of 100 MeV on beryllium. For proton therapy you need about 180-200 MeV to be able to reach the deepest parts of the body. For proton radiography, 200 MeV will already be very useful although one may like to go to slightly higher energies. For isotope production, you can look at the yield curves. If you go to higher energy, you produce all the isotopes of the specific element by spallation reactions. Using 80 MeV or lower energy protons one can still produce specific isotopes with sufficient yield and purity for nuclear medicine.

A. PASCOLINI: In your decision method to choose the accelerator, how did you fix the weighting coefficients for the various fields?

W.L. RAUTENBACH: It was fairly easy to do this. We started by allocating equal weighting factors to the physical sciences and medicine because both groups have comparable needs in South Africa. Then we had to decide the relative importance of neutron therapy by, for instance, looking at the number of patients (∿ 1'500/year) which may eventually benefit from its further development. We estimate that the isotopes produced would in five years time be used in diagnostic procedures on ∿ 50'000 patients. By discussing these questions in a group which consists of physicists, medical and accelerator people who have worked together for about a year, you start to get to know the language of the different disciplines and it is then possible to sort everything out.

E.G. MICHAELIS: In your general form chart, the ordinate is determined by the political considerations which you have just explained; the abscissa should be much more objective. Yet you showed that linacs, usually regarded as very expensive machines, had only half the annual cost of a tandem. How do you explain this?

W.L. RAUTENBACH: The linac considered is a 80 MeV machine accelerating protons, nothing else. We estimated the capital cost of this machine by looking at the cost of injectors to synchrotrons. The main reason why the annual cost of the linac is low is because it is really a good isotope producing machine. You can get a fairly good income from that machine and the physicists are also not so interested in it, which means you are able to use it for isotope production.

R. WIDERÖE: How do you estimate the possibility for realizing the project?

W.L. RAUTENBACH: I think the possibility for the moment is rather high, because we got all the heads of the radiotherapy departments in South Africa (six of them) agreeing that they want the accelerator for neutron therapy. They are also satisfied with the siting. The nuclear medicine people are also very interested in isotope production. There was a referendum among the nuclear physicists in 1971 when 75% of them voted for one national accelerator facility. I think there is about a 80 or 90% probability of getting the funds within six months or so.

M.A. CHAUDHRI: Keeping in view the medical needs -- you are specifying that a 50 MeV average neutron beam could be advantageous -- one can achieve the same effect with much smaller and cheaper machines. For example, we have shown that 50 MeV protons would be able to provide a neutron beam with an average energy from 40-50 MeV using a ^{7}Li target. Moreover, as far as the isotope production is concerned, one achieves enough yields to satisfy the needs not only of South Africa but even of a country many times its size with a 50-60 MeV machine producing a proton beam of a few 100 µA, which would be more than sufficient. This argument applies to most isotope producing reactions including (p,4n) reactions. Our detailed calculations show that many millicuries of various isotopes are produced in most cases with a machine of such size.

W.L. RAUTENBACH: One must consider that the cyclotron will only be used ∿ 6 hours per week for isotope production and that higher energies are required to produce important isotopes like ^{123}I. We would also be willing to sell isotopes to other countries. As far as the energy range is concerned, one can obtain more energetic neutron spectra by using thin targets, but so far we have not yet seen any hard and fast results using thick targets. If you are willing to use thin targets with all the complications of getting rid of the beam going through, you may be able to use beams of lower energy but higher intensity. Our feeling is that one cannot only make out a very strong case for 200 MeV protons from the nuclear physics point of view, but you also have a very strong case for proton therapy and neutron therapy in the same place because the results of therapy can depend on the people who are doing it, not only on the machine. We originally were only considering protons of 100 MeV, but as the study progressed we found that a 200 MeV would probably be the better solution in the long run, say over 20 years or so.

D. LAMOTTE: For neutron therapy will you envisage a vertical beam in such a way to be able to realize the treatment of the patients in horizontal position?

W.L. RAUTENBACH: Yes, we are still working on that. The doctors finally want to have an isocentric system or nearly isocentric. This can be done, but so far we decided to start with perhaps not the most convenient set-up, i.e. a horizontal beam and one or more vertical beams. More elaborate systems will later be installed when more experience is available.

W.A. VAN KAMPEN: You mention for your open-sector cyclotron an injection energy of 8 MeV and said also that at the centre it was a little bit cramped. Would it not be less expensive to have a somewhat higher injection energy giving more room for injection in your open-sector cyclotron?

W.L. RAUTENBACH: Yes and no. If you are willing to live only with light ions, then you can go to higher energies, that is no problem; but if you want to accelerate heavy ions you have the problem of energy multiplication in a machine with fixed injection and extraction radii. From 8 MeV to 200 MeV gives you a multiplying factor of 25 and that fits in fairly well with a 6 MV Van-de-Graaff injector; it is also compatible with a solid-pole cyclotron.

M.A. CHAUDHRI: Can you give an idea about the cost of the whole project and its distribution amongst the machine itself and other auxiliaries like isotope producing facilities, neutron therapy set-ups, etc?

W.L. RAUTENBACH: The over-all cost of the building and shielding is about 5 million rand and that of the machine and auxiliary equipment 8 million rand including salaries. For neutron therapy the position is as follows: at the moment we have a fairly simple system and have budgeted something like 400'000 rand, which would be about 0.56 million dollars, for the beam equipment. But we only delivered the beam after the main magnet into the collimator. What is coming after that is ordinary medical treatment -- we are not going to pay for that -- that is another project. The cost does not include the shielding, just the beamline.