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A KAON FACILITY FOR TRIUMF

by

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ABSTRACT

A proposal is in preparation at TRIUMF for a 10-15 GeV, 100 μA proton accelerator as the basis of a kaon factory to yield beams of kaons, neutrinos and other secondary particles 100 to 1000 times more intense or with much better purity than those available at present. A whole range of new measurements would become possible in both particle and nuclear physics, e.g. symmetry violations in kaon decay, neutrino scattering, meson and baryon spectroscopy, hypernuclei, exotic atoms, K^+ studies of nuclear density, and resonance propagation in nuclei. A number of specimen experimental proposals is in preparation. Two options appear to be open for the 15 GeV accelerator. One would be a 30 Hz rapid-cycling proton synchrotron with separate accumulator and stretcher rings mounted in the same 80 m radius tunnel. The other would be a two-stage isochronous ring cyclotron using 5 T superconducting dc magnets. The first stage would be a 15 sector, 10 m radius machine going to 3.5 GeV, while the second stage of 42 sectors and 41 m radius would continue to full energy. The design of kaon beams of greater purity is also under way.

INTRODUCTION

The kaon remains one of the most fascinating creatures in the particle harem. Over the past thirty years its behaviour has led to a number of crucial discoveries in particle physics: strangeness, parity violation in the weak interaction, the violation of CP invariance and the existence of a fourth "charmed" quark, first suggested by the suppression of decays such as $K_L^0 \to \mu^+\mu^-$. Today the kaon continues to promise fundamental insights not only into particle physics but also into nuclear physics. Nevertheless the beams of kaons available at present are frustratingly weak ($\sim 10^5$ K^-/s) and heavily contaminated with pions (~ 10 π/K). Many desirable experiments are just not feasible. A similar

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*on leave from University of British Columbia situation holds for the neutrinos, antiprotons, hyperons and other secondary particles produced by GeV accelerators. The same was true for pion and muon physics before the advent of the pion factories. If anything the situation is worse for K and $\overline{p}$ beams which are of poorer quality than the π and μ beams were 10 or 15 years ago. Consequently there is a strong interest in building "kaon factories" - 5-30 GeV machines which would produce beams 100 to 1000 times more intense than those available at present or, at the sacrifice of some intensity, beams with much less contamination. (In view of the variety of particles available we should perhaps more correctly speak of a kaon/antiproton/ neutrino factory; nevertheless we shall stick with the shorter and pithier term on the excuse that it is hallowed by usage.) Proposals for kaon factories have come in the main from the existing pion factories, the reason for this being that these machines alone have adequate energy and current to act as injectors (the present GeV accelerators being limited in intensity essentially by their injectors).

Serious thinking about a kaon factory at TRIUMF began in 1977, and synchrotron[1] and cyclotron[2] design alternatives were published in 1978. A workshop to discuss the physics potentialities of a kaon factory was held in association with ICOHEPANS 8 in 1979.[3] A second Kaon Factory Physics Workshop was held at TRIUMF in 1981.[4] The funding of feasibility studies for a kaon factory began in 1981 with the aim of preparing a proposal for submission to the Canadian Government by 1983. Allowing a period of two years for negotiations with the funding agencies and further studies of any remaining technical questions, we might, if all goes well, expect funding and construction to begin in 1985 and be complete by 1990.

In order to co-ordinate the feasibility study a steering committee has been set up under the author's chairmanship together with working panels specializing in various areas with chairmen as listed below:

Science	E.W. Vogt
Initial experimental programme	D.A. Bryman
Experimental areas and facilities	E.W. Blackmore
Beam lines and spectrometers	G. Stinson
Accelerator	M.K. Craddock
Impact on existing programmes	D.G. Fleming

The next section provides a very brief introduction to some of the physics which a kaon factory would make possible. More complete information is available in the proceedings of the TRIUMF Workshops[3,4] and of similar meetings held at Brookhaven[5] and Los Alamos.[6,7] Subsequent sections deal with the design of kaon channels and high intensity accelerators.

PHYSICS POTENTIAL

Taking particle physics first we begin by considering kaon and hyperon decays. These heavy particles have a large number of allowed decay channels together with additional possibilities if symmetry violations occur. CP violation is of course a prime example since it has only ever been observed in K_L^0 decay. Here we need more accurate measurements of η_{+-} and η_{00}, studies of th muon polarization from $K_L^0 \to \pi^-\mu^+\nu$ and $K^+ \to \pi^0\mu^+\nu$, and a look at the weak decays of polarized Σ's. Lepton number nonconservation is another interesting possibility because of the light it might shed on interactions outside the standard model and on new particles in and beyond the supposed "desert". Thus a search for the strangeness-changing decay $K_L^0 \to \mu^\pm e^\mp$ would be very desirable; the present limit of 2×10^{-9} already tells us that horizontal gauge bosons must have masses >10 TeV.

Among the allowed decays of interest are those expected as higher-order electroweak interactions but suppressed by virtue of the GIM mechanism, such as $K_L^0 \to \gamma\gamma$, $K_L^0 \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, and those involving neutral currents such as $K^\pm \to \pi^\pm\mu^+\mu^-$ and $\Lambda \to ne^+e^-$. A very fundamental channel that has yet to be observed is that of kaon β-decay ($K^0 \to K^-e^+\nu$). In order to make a more accurate determination of the current-current interaction form factors and the "Cabibbo angles" of the Kobayashi-Moskawa parametrization, we need more detailed measurements of kaon and certain hyperon decays (e.g. $\Sigma^\pm \to \Lambda^0 e^\pm \nu$, $\Lambda^0 \to pe^-\nu$), including not only decay rates but also energy spectra, and angular and spin-momentum correlations.

A kaon factory would provide an intense source of both muon- and electron-neutrinos and antineutrinos in the intermediate-energy range. Neutrino-electron scattering with all four types of neutrinos would provide detailed tests of the Weinberg-Salam model. One could make accurate measurements of $\sin^2\theta_W$, observe charged-neutral current interference and make tests of electron universality. Neutrino oscillation experiments could also be attempted.

The spectroscopy of baryons and mesons requires considerably more precision particularly in the 1-2 GeV region. The development of theories such as "soft" QCD has led to some success in the prediction of resonance properties. Nevertheless there remain ambiguities and gaps which require more accurate measurements, and from a pragmatic point of view a more accurate knowledge of the K- and π-N interactions is needed as a basis for K- and π-nuclear studies. There is a particular need for polarization measurements on the KN interaction and for specific experiments to confirm the proposed weak coupling of the $[70,2]^+$ and $[70,0]^+$ multiplets to the elastic channel; indeed an experimental search for any evidence of the existence of a member of these multiplets would be valuable. The high intensity should permit production experiments like $\pi N \to \pi N^*$ and $\bar{K}N \to \pi Y^*$, which should allow the production of states not accessible from the elastic channel. The meson spectrum is less well known experimentally than that of the baryons but would be approachable again through production experiments such as $\pi N \to M^*_{ns}N$ and $KN \to M^*_s N$ to produce strange (s) and non-strange (ns) excited mesonic states. A full analysis of such experiments would provide an accurate meson spectrum within which it should be possible to separate the $q\bar{q}$ from any possible glueball states.

X-ray measurements on K-, $\bar{p}$- and Σ-atoms have in the past yielded accurate values for the masses and magnetic moments of these particles. With a kaon factory the accuracy of these measurements could be increased, and one may even reasonably hope to perform the same operation for the Ξ^- and Ω^-. Observations of the lowest X-rays from exotic hydrogen atoms would of course be a unique source of information on K-, $\bar{p}$-, Σ-, Ξ- and Ω^--p interactions at rest. Hyperon-nucleon interactions may also be approached through final-state interactions such as $K^{-3}He \to \Lambda pn$. Free hyperon-nucleon scattering probably requires more energy than is economically feasible for a kaon factory.

The availability of antiprotons will make possible a wide range of studies beginning with various aspects of the $\bar{p}p$ interaction. Exactly what will be important in 1990 will depend very much on what is learnt at LEAR beginning in

1983. To improve on the LEAR capabilities will presumably require building a $\bar{p}$ accumulator ring and a low-energy storage ring as at CERN.

Turning now to the study of nuclei, the nuclear scattering of K^+, K^- and $\bar{p}$ opens up interesting possibilities reflecting their different interactions with nucleons. The K^+ meson, whose interaction is weak and repulsive, especially for momenta below 800 MeV/c, has a mean free path of about 6 fm in nuclear matter and therefore promises to be a useful probe of neutron density. The K^-, on the other hand, being strongly interacting, with a rich resonance spectrum, offers possibilities for the study of resonance propagation in nuclei; in particular good low momentum beams (~400 MeV/c) would make possible a direct study of the propagation of the narrow $\Lambda(1520)$.

The study of hypernuclei would receive great impetus from the availability of better quality and more intense kaon beams. The systematics of hypernuclei and their excited states is just ripe for exploration, and it may be that the flux is sufficient to observe Ξ- and even Ω^--hypernuclei. Questions to be resolved include that of the hyperon-nucleon potential in nuclear matter, the strength of the spin-orbit force, the origin of the large isospin-violating component and why the Σ-hypernuclear states are so narrow. Recent experiments have very successfully exploited the (K^-,π) reaction but (K,γ) radiative kaon capture at rest could also be a useful tool for probing the distribution of the M1 strength. In fact the possibilities inherent in being able to infiltrate a nucleus with a baryonic probe unfettered by the Pauli principle are almost limitless. One can even go further and through the (K^-,K^+) reaction plant two units of strangeness and create double hypernuclei such as $\Lambda\Lambda$, ΞN and $^{6}_{\Lambda\Lambda}\mathrm{He}$. Finally in this context we may mention the perhaps far out but exciting possibility of creating a charmed nucleus via the (K,F) reaction.

To conclude this physics survey it is worth recording that even low-energy muon and pion experiments - the very stuff of pion factory physics - would be better served in terms of beam intensity at a kaon factory.

KAON BEAM LINES

Considering the various physics needs, our initial thinking has been to provide three charged kaon beam lines serving three different momentum ranges: 400-800 MeV/c, 1-2 GeV/c and 2-5 GeV/c. Each kaon channel would be fed by a separate proton line, the proton beam being switched between the three lines in synchronism with the time macrostructure of the accelerator (say 30 Hz). A new experimental hall of about 50 m × 100 m would be required to house this complex.

Of the three kaon channels only the low-energy one has yet received detailed attention. The pion contamination is worst for low momentum beams - often much worse than the designers had bargained for. Even after a theoretically clean separation it appears that >1% of the pions can remain within the kaon phase space. To determine which of a number of possible causes is responsible D.E. Lobb has carried out Monte Carlo ray-tracing studies. It appears that neither higher-order optical effects nor cloud pions from K^0 decay can account for the observed contamination. A third possibility - slit scattering off the magnet poles - is still under study but appears to be a more likely candidate.

Lobb[8] has also designed a channel to overcome the contamination problem (Fig. 1). This uses a double focus after the first bend in order to remove the pion halo before it reaches the separator. The line is symmetric about the midpoint of the separator and uses two sextupoles to eliminate certain aberrations. The length of the channel is 15.7 m, its momentum acceptance ±2% and its angular acceptance 12 msr (250 mrad horizontally × 60 mrad vertically).

ACCELERATOR DESIGN

The optimum accelerator energy will depend not only on the particle energies required for experiments but also on the beam intensities which can be produced. To clear up some uncertainty in the production cross sections for kaons and antiprotons, an experiment was mounted at the CERN PS last year involving scientists from TRIUMF, LAMPF, CERN and other labs.[9] Measurements were made for proton energies of 10, 18 and 24 GeV, 1 cm thick targets of carbon, copper and tungsten, and π^-, K^-, and $\bar{p}$ momenta of 0.4, 1.0 and 1.4 GeV/c. For all particles and targets the data are consistent with a linear increase in cross section with proton energy over this range (Fig. 2). For an intense flux of stopping K^- a proton energy of 10 GeV would be sufficient; but for 4-5 GeV kaons, antiprotons and neutrinos higher energies would be desirable. Bearing in mind the increasing costs associated with higher energies we have therefore aimed at a proton accelerator in the 10-15 GeV range. The accelerator specifications are summarized in Table I.

Experimental requirements on time structure span the whole spectrum from sharply pulsed to dc. For neutrino experiments very sharp pulses on a macro-

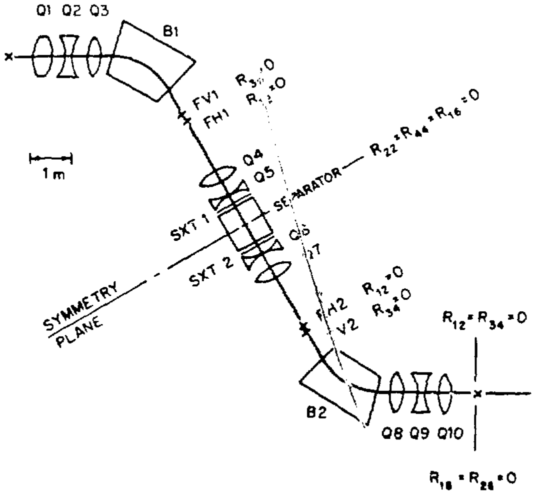

Fig. 1.
Lobb's KD channel for 550 MeV/c kaons.

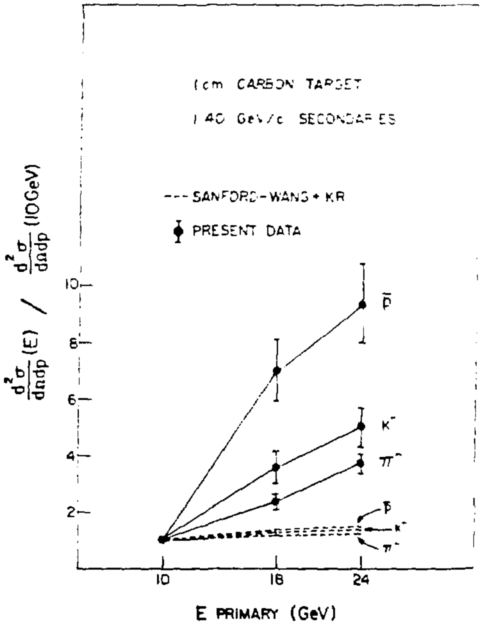

Fig. 2.
Energy dependence of the production cross-sections for 1.4 GeV/c $\bar{p}$, K^- and π^-, normalized at 10 GeV.

TABLE I

Kaon Factory Accelerator Specifications

Energy	10-15 GeV
Current	100 μA (6×10^{14}/s)
Spills	<10% at injection <1% at extraction
Time structure	
Macroscopic:	cw/pulsed ($1/10^4$)
Microscopic:	20-50 MHz
Injector	TRIUMF: 430 MeV 100 μA 23 MHz cw

scopic time scale are required, whereas for many-particle coincidence experiments dc beams are preferable. The microscopic time structure of the beam could be very valuable for particle identification, a pulse repetition period in the range of 20-50 ns being most suitable.

Of the accelerator options available, both synchrotrons and cyclotrons appear to be technically and economically viable; 15 GeV conceptual designs for each have been prepared and are being investigated in depth for their feasibility. Both Linacs and FFAG accelerators were considered to be too expensive, the former because of the long RF structure and the latter because of the magnet weight.

Figures 3 and 4 show how the synchrotron and cyclotrons might be laid out on the site to the north of the TRIUMF cyclotron. The synchrotron would require an 80 m radius tunnel built by cut and fill techniques. The cyclotron would consist of two stages, the first taking the beam to 3.5 GeV being of roughly the same diameter as the TRIUMF cyclotron and requiring a vault of roughly the same size. The second stage taking the beam to 15 GeV would be of 40 m radius and require a tunnel somewhat wider than that for the synchrotron.

SYNCHROTRON OPTION

Synchrotrons are characterized by pulsed operation at fixed radius in a small diameter vacuum chamber. In principle there is no limit to the energy they can attain and hence they have been the natural choice for proton accelerators greater than 1 GeV. Because of their low repetition rate (<1 Hz) and limits on the charge that can be contained at injection (< 0.5 μC at 200 MeV), currents accelerated by high-energy proton synchrotrons have been restricted to $\lesssim$1 μA. One way of overcoming this limit is to increase the magnet cycling rate as at the Fermilab 8 GeV booster where operation at 15 Hz has provided currents of 8 μA. Another way is to increase the injection energy because of the strong energy dependence of the space charge and instability limits. The maximum space charge per turn $\propto \beta^2\gamma^3 b(a+b)/R$ where β and γ are the relativistic velocity and energy factors, a and b are the semi-major and -minor radii of the beam, and R is the radius of the machine. Extracting from TRIUMF at 430 MeV to avoid electric stripping losses this limit would be raised to 16 μC per synchrotron turn. The instability limit would be of the same order of magnitude. Rather more conservatively, we would aim to inject 3.3 μC/turn and operate at a cycling

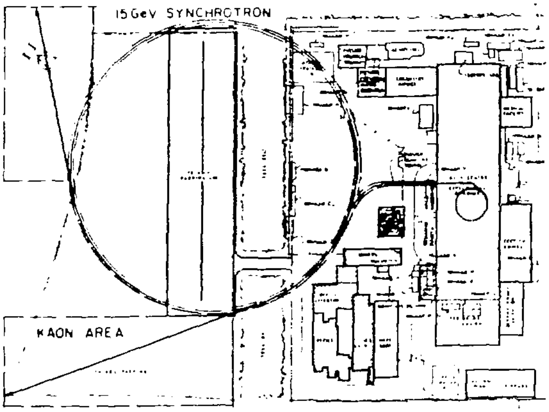

Fig. 3.
Possible site layout for 15 GeV synchrotron at TRIUMF.

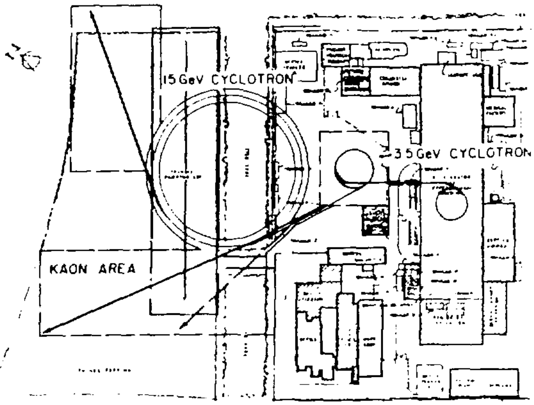

Fig. 4.
Possible site layout for 3.5 GeV and 15 GeV cyclotrons at TRIUMF.

rate of 30 Hz to achieve an average currentof 100 μA. Table II lists parameters for a synchrotron design due to L.C. Teng.[10]

In a rapid cycling synchrotron the magnet is part of a resonant circuit so that it is not possible to provide a flat top or bottom to the magnet cycle for injection or extraction if a duty factor of 100% is required. To collect the cw beam from TRIUMF while the synchrotron is accelerating, a separate accumulator ring is provided using small dc magnets. Similarly, to provide a non-pulsed extracted beam a 15 GeV stretcher ring would be built. This would also run dc and

TABLE II

Synchrotron Specifications[a]

Final energy	16 GeV
Radius	80 m
Repetition rate	30 Hz
RF frequency	46 → 62 MHz
Intensity	3.3 μC/pulse
RF cavities	
Number	50
Power	250 kW
Length	2.39 m
Lattice	
Type	DFOFD (combined function)
Cells	30
Magnetic field max	11.36 kG
Tune	7.41
Transition γ	7.42 (6.03 GeV)
Injection technique	H^- stripping

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[a] Ref. 10.

superconducting magnets would be used to reduce power costs. The three magnet rings could be mounted one above another in the synchrotron tunnel (Fig. 5).

The design of the three rings follows established procedures and should be straightforward. The design problems for the synchrotron option centre on transferring the beam from TRIUMF to the synchrotron because of the very different time structures. TRIUMF operates cw at 23.1 MHz while the synchrotron would be pulsed at 30 Hz, so that 770,000 beam pulses from TRIUMF have to be collected together in one turn of the accumulator for acceleration in the synchrotron. This mismatch is partially overcome by the 10.5 times larger radius of the synchrotron and its operation at twice the TRIUMF RF frequency. This enables 21 turns from TRIUMF to be stacked in overlapping boxcar fashion around the synchrotron (105 bunches since TRIUMF operates on the fifth harmonic). A further factor is gained by extracting the beam from TRIUMF in packets of at least 100 turns at a time. This leaves a factor of 73 to be made up by multi-turn injection into the accelerator. To avoid having to steer 73 turns into 73 different regions of transverse phase space, injection by H^- stripping has been proposed so that the turns may be overlaid without disturbing Liouville. Of course this requires extracting H^- ions from TRIUMF rather than protons as at present.

To compact 100 or more turns closely together in TRIUMF all that is needed is to decrease the energy gain per turn. This may be achieved either by lowering the dee voltage locally (by modifying the dees) or by slipping to a non-accelerating phase (by means of a magnetic field bump). Both methods have been investigated theoretically and appear to be capable of providing over 100 turns within an acceptable emittance (12π mm-mrad) and momentum acceptance (±0.5%). The RF method is favoured since it produces a longitudinal emittance shape better matched to the synchrotron bucket and may provide packets of as many as 180 turns.

The extraction of the H^- ions from TRIUMF has not yet been studied in detail but would take place in two stages. First, a pulsed vertical deflection separates the packet from later turns (the vertical restoring forces being weaker than the radial ones). Then electric and magnetic septa impart a radial kick out of the cyclotron. Because it is not possible to separate the last turns of a packet absolutely cleanly from those immediately following, a time gap must be arranged in the beam right at the ion source or some beam loss will have to be accepted at extraction. A time gap of 30% (duty factor 70%) should avoid any losses.

Injection into the accumulator by stripping the H^- ions in a foil is in itself straightforward but, because of the large number of turns (up to 15,000) made by the beam in the accumulator, measures must be taken to reduce the multiple scattering occurring on subsequent passages through the foil. This can be achieved with the help of four kicker magnets (Fig. 6). The stripping foil is mounted above the normal equilibrium orbit and the kicker magnets are switched on only when beam packets arrive from TRIUMF. Since this occurs for only 1% of the time, the multiple scattering is reduced to a safe level. The kickers would consist of one turn coils on a ferrite core and the performance required of them is fairly conventional - 340 G × 1 m, 1600 A, 90 kV, and a 220 ns flat-top with 50 ns risetime - except for the repetition rate (25 kHz for 180 turn packets from TRIUMF). The thyratrons and spark gaps normally used to trigger kickers have lifetimes of 10^9 pulses, which is fine for operation at 1 Hz but would be used up in 11 h in our application. An alternative which is under consideration and looks promising is to use hard tubes[11] which would have indefinite lifetimes. Another possibility for powering the kickers is to use

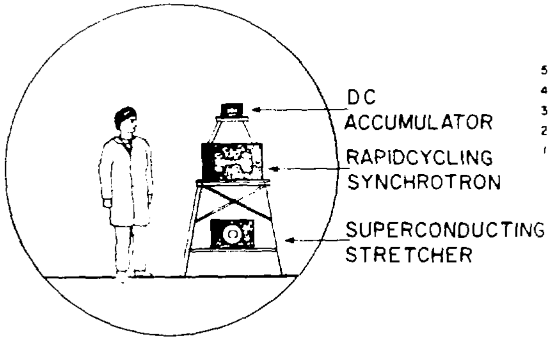

Fig. 5.
Synchrotron tunnel cross-section.

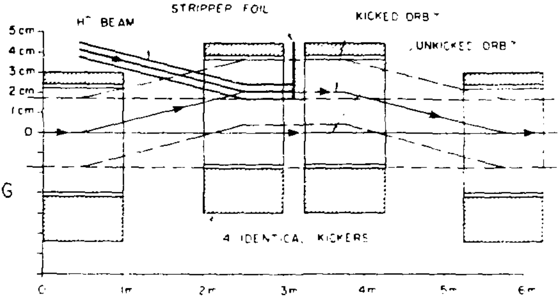

Fig. 6.
Four-kicker arrangement to alter equilibrium orbit during H^- injection.

magnetic switching circuits[12] which are expected to be capable of cw operation at several kHz.

CYCLOTRON OPTION

Isochronous ring cyclotrons running cw at some multiple of the TRIUMF RF frequency will have a time structure completely compatible with that of the TRIUMF beam. Because the turn separation is large at injection transfer of the beam from TRIUMF with 100% efficiency will be an essentially trivial operation. The current accelerable in such a machine is therefore limited only by what TRIUMF can provide, 100 μA or more. On the other hand, the energy attainable by a cyclotron is limited, by cost if not in principle. This is because the average orbit radius $R \sim \beta$, and as $\beta \to 1$ it becomes harder and harder to clearly separate the turns - an essential for clean extraction in a cw machine. In our initial design we have taken as a criterion that at maximum energy the turn separation shall be at least equal to the amplitude of the coherent betatron oscillations (the radial half-width of the beam). For clean extraction it is assumed that the turn separation can be doubled locally with the help of a betatron oscillation resonance. With this criterion a 15 GeV ring requires a radius of 41 m and 42 magnet sectors (Fig. 7) compared to 6 for TRIUMF. The magnets are powered by dc superconducting coils to provide a maximum field of 5 T. The relatively field free regions between the magnets are used for extraction, injection and the RF accelerating cavities (1 MV cavities based on the SIN model). Further details of the specifications are given in Table III.

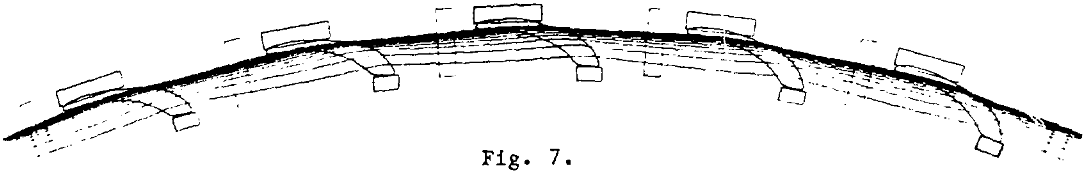

Fig. 7.
Five sectors from the 42 sector 15 GeV cyclotron, showing magnets, RF cavities and proton orbits.

TABLE III

Cyclotron Specifications

Stage	CANUCK I	CANUCK II
Injection energy	430 MeV	3.5 GeV
Extraction energy	3.5 GeV	15 GeV
Number of sectors	15	42
Radius (maximum)	10.1 m	41.4 m
Radius (minimum)	7.5 m	40.6 m
Number of cavities (1 MV)	9	54
RF frequency	46 MHz	115 MHz
Total RF power	5.9 MW	5.7 MW
ΔE/turn	8.5 MeV	51 MeV

The beam's time structure will be a cw stream of pulses at 43.4 ns intervals, the same as for TRIUMF. The bunch lengths will be smaller, however, because of the phase compression used in each of the two ring cyclotrons to restrict the phase spreads for the higher frequency cavities. This would result in the original ±10° (2.4 ns) bunches being reduced to 0.3 ns in width. A macro-pulsed beam could be achieved using 1/5 pulse selection together with 100-turn extraction from TRIUMF to give 0.3 ns pulses every 22 μs (duty factor $1/7 \times 10^4$). To maintain clean extraction the phase acceptance would have to be limited, reducing the beam intensity by a factor ~5. Alternatively, a 15 GeV accumulator ring could be constructed at a similar cost to that of the synchrotron stretcher.

To build the cyclotron in one stage would be prohibitively expensive since β ranges from 0.7 to 1.0, and the magnets would have to extend radially over 0.3×41 m ≈ 12 m. Instead, a small separate first-stage ring cyclotron takes the beam from 430 MeV to 3.5 GeV ($\beta = 0.98$) over a radial range of only 7.5 to 10.2 m; the radial range in the second stage then amounts to only 0.8 m.

Potential problem areas with these machines are:

1) Maintaining isochronism and vertical focusing to the highest energies
2) Crossing a number of betatron oscillation resonances
3) Separating the turns sufficiently for clean extraction
4) The superconducting coil design

To investigate the beam dynamic problems the proton orbits have been tracked through a magnetic field grid computed from the coil and steel configuration. As an example Fig. 8 shows the magnetic field contours and the proton orbits for the 3.5 GeV machine. These designs are isochronous to within ±5° while the axial and radial focusing is real over the whole energy range.

Since the betatron tune $\nu_r \simeq \gamma$ many integer and half-integer radial resonances are crossed in a high-energy cyclotron; these would be driven by imperfection harmonics of the magnetic field. In addition there are intrinsic resonances where $\nu_r = N/n$, N being the number of sectors and n any integer; these are driven by the intrinsic periodicity of the field and are most serious for low values of n. Vertical resonances where $\nu_z = n$ can also occur though it may be possible to design the magnet so that these are never crossed.

Studies of the intrinsic resonance $\nu_r = 30/3$ have been carried out in an old 30-sector 9 GeV design [a third order (n=3) resonance is the most serious that can occur]. Without any adjustment to the field the emittance was found to

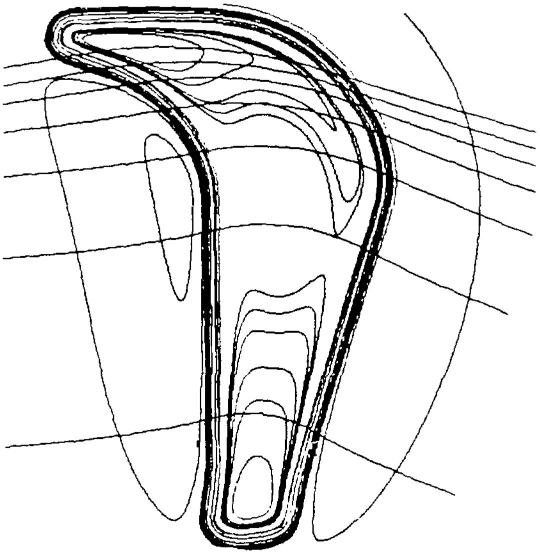

Fig. 8.
Magnetic field contours and proton orbits (at 0.5 GeV intervals) for one sector of the 15-sector 3.5 GeV cyclotron.

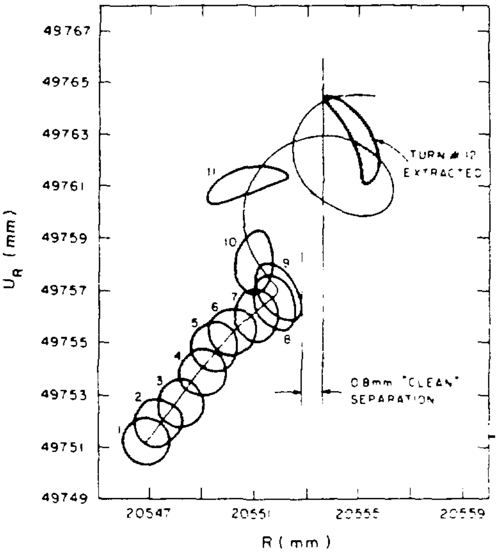

Fig. 9.
Clean separation of the final turn for extraction by excitation of the imperfection resonance $\nu_r = 12$.

be distorted enough to double the beam width but by controlling the second derivative of the field harmonic responsible, the distortion can be reduced to a 30% amplitude increase. Studies of imperfection resonances indicate that the tolerances required on the magnetic field are of the same order of magnitude as for TRIUMF.

Extraction studies have also been carried out in the 30-sector field in the neighbourhood of the $\nu_r = 12$ resonance. Figure 9 shows the radial beam emittance on successive turns near the resonance. At first there is considerable radial overlap but by exciting the 12th harmonic component at a suitable amplitude and phase, it was possible to provide a clear 0.8 mm separation between turns - sufficient for the leading edge of an extraction septum. Work is continuing to find the optimum conditions.

Much experience in the design of large dc superconducting coils is available from bubble chambers, compact superconducting cyclotrons, fusion devices, etc. The major potential problem in the present case is the non-circular shape of the coils, in particular the reverse curvature on one side. Experience with yin-yang and other exotically shaped coils, however, shows that such problems can be dealt with successfully by providing sufficient strengthening to resist the stresses. A preliminary design has been prepared utilizing a stainless steel support for the coil and stress calculations are under way. A study of the cooling options suggests that forced cooling by supercritical helium would be a better choice for this application than pool boiling.

A comparison of the beam properties to be expected from the synchrotron and cyclotrons is shown in Table IV.

TABLE IV

Comparison of Beam Properties

Property	Synchrotron	Cyclotron
Energy	16 GeV	15 GeV
Current	100 μA	100 μA
Pulse microstructure	2 ns every 16 ns	0.3 ns every 43 ns
Macrostructure - basic	1.7 μs every 33 ms $(1/2 \times 10^4)$	cw
Macrostructure - modified	cw (requires stretcher)	0.3 ns every 22 μs $(1/7 \times 10^4$ for 20 μA)
Variable energy	Probable	Possible
Polarization	Possible	Probable

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