KAON FACTORIES

M.K. Craddock
Physics Dept., University of British Columbia, and TRIUMF, Vancouver, B.C., Canada V6T 2A3

Summary

Kaon factories would provide beams 100-1000 times more intense than those available from present accelerators in the 10-30 GeV range. More intense or cleaner secondary beams of kaons, antiprotons and neutrinos would be of particular interest for high precision experiments and studies of rare processes in both particle and nuclear physics, e.g. symmetry violations in K-decay, neutrino scattering, meson and baryon spectroscopy, hypernuclei, exotic atoms, K^+ studies of nuclear density and resonance propagation in nuclei.

The various accelerators proposed include both fast-cycling synchrotrons providing 100 μA proton beams at 15 to 32 GeV and superconducting isochronous ring cyclotrons giving 100-400 μA at up to 15 GeV. This paper describes these designs and the various technical problems associated with them.

Introduction

Two frontiers may be recognized in the uncovering of new phenomena in subatomic physics - those of high energy and high intensity. The race to higher energies has always left ground behind it only partially explored - a factor which the pion factories have successfully exploited over the last few years with their 200-800 MeV high intensity accelerators. These have made possible the observation of very rare processes and high precision comparisons with theory. The same opportunity now arises for accelerators of 10 to 30 GeV - "kaon factories" - capable of generating beams 100-1000 times more intense than those available at present. Indeed there is additional justification in that grand unified theories are predicting particles with rest energies far above the practical aspirations of any laboratory - and therefore observable only indirectly through higher order effects (like those responsible for rare decay modes) in experiments involving the largest possible number of particles.

The kaon itself remains one of the most fascinating of the elementary particles. 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 $K_L^0 \rightarrow \mu^+\mu^-$. 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 (~10^5 K^-/s) and heavily contaminated with pions (~10 π/K). Many desirable experiments are just not feasible. A similar 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 $\bar{p}$ beams, which are of poorer quality than the π and μ beams were 15 years ago. Consequently there is a strong interest in building kaon factories to produce beams much more intense than those available at present or, at the sacrifice of some intensity, much less contaminated. (In view of the variety of particles available we should perhaps more correctly speak of a kaon/antiproton/neutrino factory, but the shorter term is hallowed by usage.)

High intensity accelerators at high energy were being considered at MURA[1] in the late fifties. The term "kaon factory" possibly first appeared in print in a paper by Basargin, Komar et al.[2] in 1973. The case for kaon factories has been made at a number of recent workshops: Brookhaven[3] (1976), TRIUMF[4,5] (1979, 1981), LAMPF[6-8] (1981, 1982) and Santa Cruz (1983). 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). The strong continuing interest in kaon physics is evidenced by the series of international conferences held at Zvenigorod (1977), Jablonna (1979), Rome (1980), and Heidelberg[9] (1982).

Experimental topics of particular interest at a kaon factory include -

- Rare kaon and hyperon decays;
- CP violation;
- Neutrino scattering and oscillations;
- Hyperon production, scattering and reactions;
- Meson and baryon spectroscopy;
- Hadron-nucleon interactions (πN, KN, NN, YN);
- Antinucleon interactions;
- K^+-nucleus scattering;
- Hypernuclear physics;
- (K^-,K^+) double strangeness exchange reactions;
- Resonance propagation in nuclei;
- Exotic atoms;
- Muon physics (muon fluxes will be an order of magnitude higher than at the pion factories).

Accelerator Energy and Beam Characteristics

The question of accelerator energy is a complicated one, depending on the one hand on what secondary particle species, momenta and intensities are deemed desirable, and on the other hand, in view of the relative costliness of handling high intensity beams, on what funds are potentially available.

What momentum beams are required for the major secondary particles $(K,\bar{p},\nu)$? For kaons nuclear studies require primarily slow or stopping beams. Hadronic interactions and spectroscopy need beams of a few GeV/c, while some rare decay studies would be best served at ~5 GeV/c. The antiproton situation is complicated by the LEAR project at CERN, the impact of whose cooled and pure beams cannot yet be fully assessed. In the short term the kaon factories will probably tend to restrict their interest to $\bar{p}$ beams >1.3 GeV/c, the maximum attainable by LEAR; in the long term they would presumably build their own $\bar{p}$ cooling and storage systems. For neutrinos there is no clear energy threshold or limit, but production and reaction rates increase linearly with primary beam energy, favouring the highest energy possible.

To clear up some uncertainty in the production cross sections for kaons and antiprotons, an experiment was mounted at the CERN PS in 1981 involving scientists from TRIUMF, LAMPF, CERN, Rome and Saclay.[10] 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. 1(a)]. It is of interest that this increase is much more rapid than that predicted by the Sanford-Wang formula[11] with kinematic reflexion applied (although the shape of the momentum spectrum for a given primary energy does agree

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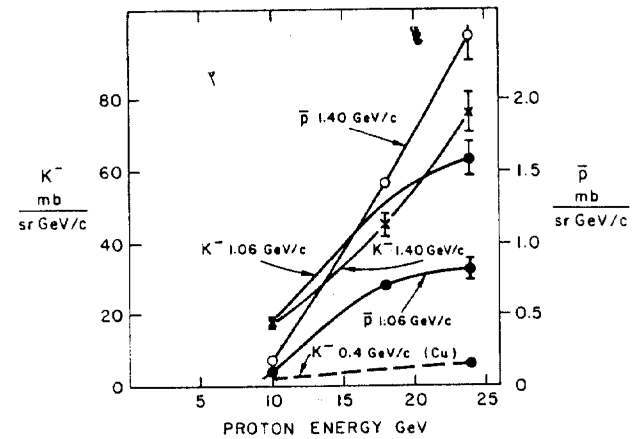

Fig. 1(a) Production cross sections on a 1 cm tungsten target as a function of proton energy.

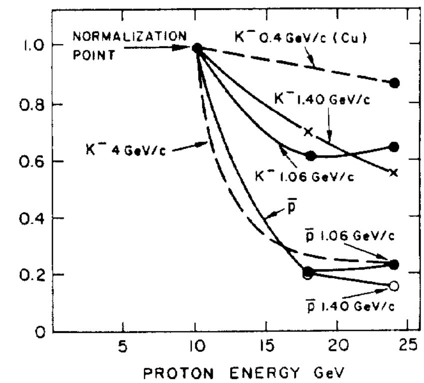

Fig. 1(b) Relative cost per particle assuming facility costs scale with proton energy.

with the formula). If the assumption is made that facility costs scale with proton energy the curves in Fig. 1(b) show how the relative cost/particle varies with incident energy.[12] For both K's and $\bar{p}$'s this drops sharply from 10 to 18 GeV but then remains almost unchanged to 24 GeV. This would put the most cost-effective energy for production of <2 GeV/c K and $\bar{p}$ between 15 and 20 GeV. The Sanford-Wang momentum spectrum for 16 GeV protons on a beryllium target[13] indicates that for 5 GeV/c the K^+ flux has only fallen off 10% from the peak, the K^- flux 50%, so this proton energy would also be quite suitable for higher momentum kaons. Higher energies would of course increase the intensities and momentum ranges of secondary beams, at increased cost.

The primary beam currents under consideration for kaon factories are ~100 μA (6×10^{14}/s). This would give about two orders of magnitude improvement over existing beams in this energy range. Such currents would seem to be technically feasible and would be sufficient to make possible the significant new experiments on which the projects are predicated - either by straightforward increases in rate, or by improving beam purity through more selective separation.[14]

Experimental requirements on time structure span the whole spectrum from sharply pulsed to dc. For neutrino experiments very sharp pulses on a macroscopic time scale are required (~10^{-5}), 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.

Variable energy and polarized primary beams would appear to be of specialized interest. Interest in the former is centred on the 1-5 GeV region. As to the latter, polarized proton beams from 1-30 GeV are expected to be available at Saclay and BNL, and since these are primary beams further increases in intensity are unlikely to be crucial. (At high energies polarization transfer is expected to be inefficient, so that the production of polarized neutrons or antiprotons is not at stake.)

Accelerator Design

As mentioned above the MURA group had proposed a high intensity FFAG accelerator in 1962-3. Sarkisyan[15] has compared various accelerator types as kaon factories, with particular attention to cyclotrons. Teng[16] has reviewed the potential of existing proton synchrotrons as kaon factories. Their intensity limits are set at injection by space charge and phase space considerations. The former limit is set primarily by the transverse incoherent tune shift[17]

$$\Delta\nu = -\frac{N r_p}{\pi\nu}\left\{\left[\frac{1}{b(a+b)} + \frac{\varepsilon_1}{h^2}\right]\frac{1}{B\beta^2\gamma^3} + \left[\frac{\varepsilon_1}{h^2} + \frac{\varepsilon_2}{g^2}\right]\frac{1}{\gamma}\right\}$$

where N is the number of protons in the ring, $2\pi R$ the circumference, $r_p = 1.54 \times 10^{-16}$ cm, B the bunching factor, β and γ the relativistic velocity and energy factors (at injection), a and b the semi-major and -minor radii of the beam cross section, h and g the half heights of the vacuum chamber and magnet gap and ε_1 and ε_2 are geometrical factors. To achieve high currents (I=Nf) we clearly need high repetition rate f, large apertures and high energy injection. At low energy (<<1 GeV) the self-force term dominates and N ~ $\beta^2\gamma^3$, but at higher energies the image force terms take over and N ~ γ.

The Liouvillean limitations requiring each injected proton pulse to be directed to a different region of phase space can be avoided by injecting by H^- stripping. By this means the fast-cycling 8 GeV booster at Fermilab has achieved a record intensity of 8 μA. The use of the booster as a kaon factory has been discussed by Stiening[18] and by Brown and Hojvat.[19] The present fast extracted beam would not be suitable for many experimental requirements, so either a slow resonant extraction system or a dc stretcher ring would have to be installed. Operation could be compatibly interspersed with fixed target use of the main ring, but not with $\bar{p}p$ collider operation.

Because of their critical need for a high intensity (100 μA) injector at several hundred MeV, recent interest in kaon factories has been centred at the pion factories. TRIUMF, LAMPF and now SIN are considering fast-cycling synchrotrons as kaon factory post-accelerators. TRIUMF is also invèstigating a pair of superconducting isochronous cyclotrons for reaching 15 GeV. These various schemes listed in Table I will be discussed in the following sections, in order of decreasing conventionality.

Table I
Kaon factories

	LAMPF II	SIN	TRIUMF (CANUCK)	
Energy	32 GeV	15-20 GeV	16 GeV	15 GeV
Current	100 μA	50 μA	100 μA	100-400 μA
Injector	linac 800 MeV	cw cyclotron 590 MeV	cw cyclotron 500 MeV	
Booster	↓	ASTOR 2 GeV	↓	CW cyc'n 3.5 GeV
Accelerator	60 Hz PS	50 Hz PS	30 Hz PS	CW Cyc'n

LAMPF II Synchrotron

The LAMPF 800 MeV pulsed linac is well suited as an injector to a pulsed high energy machine. The reference design[20] is based on a 32 GeV synchrotron cycling at 60 Hz with 10^{13} protons/pulse to give a 100 μA primary beam. A comparison with the Fermilab booster (8 GeV at 15 Hz) shows that this is quite an ambitious project, and it might therefore be staged to give say 16 GeV for initial operation. A number of designs have been studied.[21-24] Further parameters from the present reference design are given in Table II.

Table II
LAMPF II Reference Design

Maximum energy	32 GeV
Repetition rate	60 Hz
Circumference	1011 m
Superperiodicity	4
Bending cells	48
Non-bend cells	20
Lattice type	FODO
Quadrupole field	8.1 kG
Dipole field	16.0 kG
Radio frequency	40 → 48 MHz
RF cavities	60 × 450 kV

Four long straight sections are included, one for extraction, one for collimation to avoid machine activation, and two for the rf system; high beta cells will be designed for the straights. The phase shift in the bending cells is exactly $\pi/2$, to ensure that the straights are completely dispersionless. The 60 Hz repetition rate keeps the required charge/pulse down to levels where space charge effects are of no significance, and are compatible with sending alternate linac pulses to LAMPF II and the PSR.

The most challenging technical problems concern the rf system and magnets. One possibility is to use a system of cavities and tuners similar to those on the Fermilab main ring. An alternative being investigated for reduced cost and higher efficiency is to have the bias field on the ferric tuners perpendicular to the rf magnetic field as in microwave applications. A small test cavity has been built and with it a constant Q of 1500 has been obtained over an 8% tuning range.

The reference site layout is shown in Fig. 2 with the synchrotron located in a tunnel beneath the LAMPF linac. A fast extracted beam is taken westwards for neutrino and pulsed muon experiments. A stretcher in the same tunnel provides a slow extracted beam to be sent eastwards to six or more independent lines. A

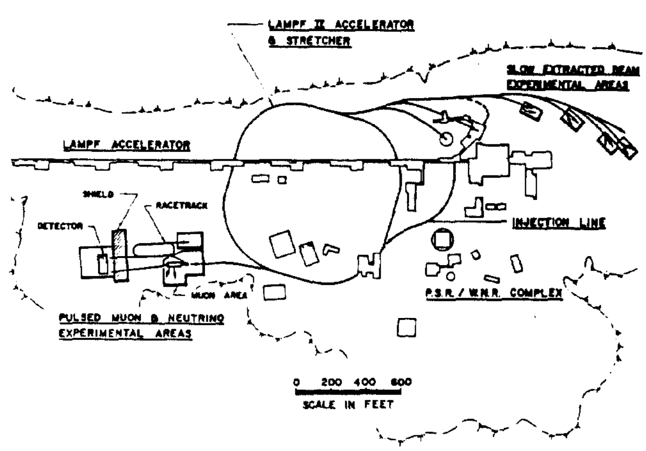

Fig. 2. Proposed LAMPF II layout.

possibility under study is to build the stretcher ring and switchyard entirely from samarium-cobalt permanent magnets. Mechanically tunable quadrupoles are already available.

TRIUMF Synchrotron

A TRIUMF kaon factory was first proposed by J.R. Richardson[25] in 1977 in the form of a 10 GeV rapid-cycling synchrotron followed by a slow-cycling 40 GeV antiproton factory. The current reference design is based on a 16 GeV fast-cycling machine accelerating 100 μA. Extracting from TRIUMF at 430 MeV to avoid electric stripping losses, the space charge limit would be raised to 16 μC per synchrotron turn. Rather more conservatively, we would aim to inject 3.3 μC/turn and operate at a cycling rate of 30 Hz to achieve the specified current. Table III lists parameters from a reference lattice due to L.C. Teng.[26]

Table III
Synchrotron Specifications

Final energy	16 GeV
Radius	76 m
Repetition rate	30 Hz
RF frequency	46 → 62 MHz
Intensity	3.3 μC/pulse
RF cavities	50 × 250 kW
Lattice type	FODO(Sep.Fn.)
Cells	32
Tune	7.82
Amplitude function	$4.5 \text{ m} < \beta < 25 \text{ m}$
Injection technique	H^- stripping

Because the magnet is part of a resonant circuit it is not possible to provide a flat top or bottom to its cycle for injection or extraction with a high duty factor. 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 16 GeV stretcher ring would be built. This would also run dc and superferric magnets would be used to reduce power costs. The three magnet rings could be mounted one above another in the synchrotron tunnel (Fig. 3).

The design of the three rings follows established procedures and should be straightforward. The design problems for the synchrotron option centre on matching[27] 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 times larger radius of the synchrotron and its operation at twice the TRIUMF rf frequency. This enables 20 turns from TRIUMF to be

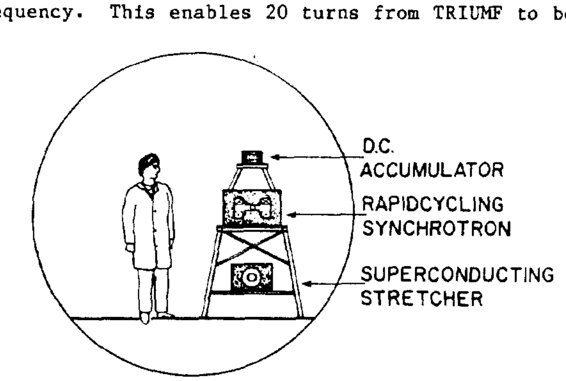

Fig. 3. Synchrotron tunnel cross section.

stacked in overlapping boxcar fashion around the synchrotron (100 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 77 to be made up by multi-turn injection into the accelerator. To avoid having to steer 77 turns into 77 different regions of transverse phase space, injection by H^- stripping is proposed. Of course this requires extracting H^- ions from TRIUMF rather than protons as at present. (Alternative options which look interesting[27] are (a) to transfer H^0 atoms, using foil stripping for both extraction and injection, and (b) to perform enhanced turn compaction (12,000 turns) in a separate 440 MeV isochronous storage ring TRISTOR.)

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 installing $\lambda/4$ coaxial line decelerators[12]) 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 ($\pm 0.5\%$). 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 deflexion 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 15,400) 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 aid of separate but intersecting stacking and storage orbits in the accumulator.[26] 154 packets are first stacked in a single boxcar and its interleaved twin. A single kicker magnet is then used to switch this boxcar into the storage orbit, which does not intercept the stripper foil, while stacking proceeds in the next boxcar. Leaving 1 out of 5 TRIUMF bunches empty the kicker rise time would be 30 ns, with a repetition rate of 300 Hz - within the state of the art.

SIN-ASTOR Synchrotron

The SIN scheme[28] is based on a 15-20 GeV, 101 m radius, proton synchrotron cycling at 50 Hz. With the 590 MeV isochronous cyclotron running at 50 MHz cw there are the same time-matching problems as at TRIUMF. The proposed solution, however, is rather different, involving use of the proposed 2 GeV ASTOR machine as an intermediate stage, as well as an accumulator in the same tunnel as the synchrotron. ASTOR is a 16 sector, 14.4 m radius, cyclotron which can be run in two modes by altering the phasing of the accelerator cavities. As a regular cyclotron it produces 50 MHz cw beam pulses; as a storage device 250 turn packets are compacted by phase expansion[29] and extracted at 700 Hz. 14 packets therefore have to be accommodated in each accumulator pulse. The greater radius provides 7 boxcars around the accumulator and two packets are placed in each boxcar in different regions of betatron phase space. Since ASTOR works on the 16th harmonic an 80 µs long pulse is required from the 590 MeV machine to fill 250 turns. The 700 Hz repetition rate thus implies supplying ASTOR at 5.6% duty factor, the remaining 94% being available for 590 MeV experiments. Taking account that 3 out of the 16 bunches in ASTOR would be left empty to allow a clear 60 ns rise time for the extraction kicker, a 1 mA current at 590 MeV would provide 46 µA for acceleration to high energy.

TRIUMF: CANUCK High Energy Cyclotrons

An alternative for TRIUMF is to avoid any time mismatch by building high energy isochronous ring cyclotrons[30-31] running cw at some multiple of the TRIUMF rf frequency and having a time structure completely compatible with that of the TRIUMF beam (CANUCK = Canadian University Cyclotrons for Kaons). 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 incoherent 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 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 IV.

Table IV
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

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 $\simeq 12$ m. Instead, a small separate first-stage ring cyclotron takes the beam from 430 MeV to 3.5 GeV (β = 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. The site layout is shown in Fig. 4.

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 $\pm 10°$ (2.4 ns) bunches being reduced to 0.3 ns in width. A macro-pulsed beam could be achieved using 1/5 pulse

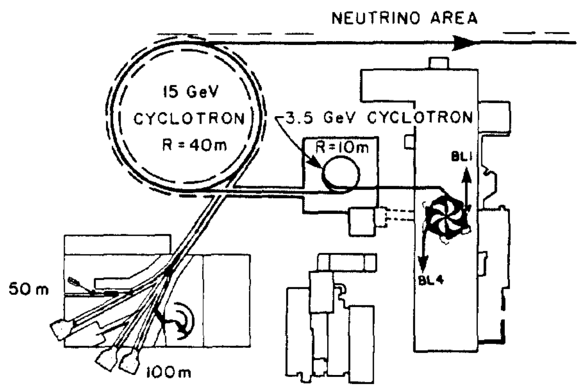

Fig. 4. Layout for TRIUMF CANUCK cyclotrons.

selection together with 100-turn extraction from TRIUMF to give 0.3 ns pulses every 22 μs (duty factor 1/7 × 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.

Potential problem areas with these machines are:
1) Maintaining isochronism and vertical focusing
2) Crossing the betatron oscillation resonances
3) Separating 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.[32] 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. Vertical resonances where $\nu_r = n$ can also occur though it may be possible to design the magnet so that these are never crossed.

Studies[33] of the intrinsic resonance $\nu_r = 30/3$ have been carried out in an old 30-sector 9 GeV design (this third order n=3 resonance is the most serious occurring). Without any adjustment to the field the emittance was found to 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[33] have also been carried out in the 30-sector field in the neighbourhood of the $\nu_r = 12$ resonance. Below the resonance there is considerable radial overlap but by exciting the 12th harmonic component at a suitable amplitude and phase, it is 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.

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