KAON FACTORIES IN 1987

M.K. Craddock
Physics Department, University of British Columbia, and TRIUMF,
4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3

Summary

Proposals for high intensity proton synchrotrons (typically providing 100 μA (6×10^{14} p/s) at 30 GeV) are being made in the U.S.A., Canada, Europe and Japan. These beams would be roughly 100 times more intense than those available now and would yield equivalent increases in the fluxes of secondary particles (kaons, pions, muons, antiprotons, hyperons and neutrinos) - or cleaner beams for a smaller increase in flux. The ability to investigate rare processes on the "precision frontier" opens new avenues to fundamental questions in both particle and nuclear physics, complementary to traditional approaches via the "energy frontier". The demand for higher currents has led to novel features in many of the accelerator designs: asymmetric magnet cycles, separate collector and stretcher rings, beam painting at injection, bucket- to-bucket beam transfer, avoidance of crossing transition, perpendicular biasing of ferrite, and the use of Siberian Snakes. Other characteristic features include booster stages, rapid cycling rates, H^- injection, low impedance enclosures, powerful feedback systems for control of beam instabilities and beam loading, and local collimation and fast abort systems for handling beam loss.

Introduction

Strong initiatives are being pursued in a number of countries for the construction of "kaon factory" synchrotrons capable of producing 100 times more intense proton beams than those available now from machines such as the Brookhaven AGS and CERN PS. Such machines would yield equivalent increases in the fluxes of secondary particles (kaons, pions, muons, antiprotons, hyperons and neutrinos) - or cleaner beams for a smaller increase in flux - opening new avenues to various fundamental questions in both particle and nuclear physics. Major areas of investigation would be rare decay modes, CP violation, meson and hadron spectroscopy, antinucleon interactions, neutrino scattering and oscillations, quark structure of nuclei, and hypernuclear properties. Experience with the pion factories has already shown how high beam intensities make it possible to explore the "precision frontier" with results complementary to those achievable at the "energy frontier". A comprehensive justification of the physics case may be found in the two proposals[1,2] so far published and in the proceedings of the recent international conferences at Mainz[3] and Lake Louise[4].

This paper describes proposals for upgrading the AGS and for building kaon factories in Canada, Europe, Japan and the U.S.A., emphasizing the novel aspects of accelerator design required to achieve the desired performance (typically 100 μA at 30 GeV). More details can be found in the proposals themselves and in the proceedings[5] of the recent Santa Fe "Workshop on Hadron Facility Technology". Earlier design work is referred to in review papers by Thiessen[6] and Craddock[7].

High Intensity Proton Synchrotrons

In considering the maximum intensity which can be accelerated in a synchrotron, two parameters are of particular importance, the number of particles per pulse N and the circulating current I. N is critical because it determines the incoherent space charge tune shift (and spread) $\Delta\nu$, given by[8]

$$\Delta\nu = -\frac{r_p}{\pi}\frac{N}{\varepsilon^*}\frac{FGH}{B_f}\frac{1}{\beta\gamma^2}\ . \qquad (1)$$

Here $r_p = 1.5347 \times 10^{-18}$ m, the classical radius of the proton, ε^* is the normalized beam emittance, B_f is the bunching factor, F, G and H are form factors describing the effects of image forces, transverse density distribution and aspect ratio respectively, and β and γ are the usual Lorentz speed and energy factors. In order to avoid coming too close to lower-order resonances $\Delta\nu$ should be kept below 0.2. The $\beta\gamma^2$ factor makes this condition most critical near injection.

The circulating current I is important through its involvement in longitudinal space charge effects and beam stability. It determines the effect of space charge on bucket height, and appears in the Keil-Schnell-Boussard criterion[9] for microwave stability:

$$\left|\frac{Z_\parallel}{n}\right| < \frac{V_p}{\bar{I}}\left(\frac{\Delta p}{p}\right)^2 B_f|\eta|\beta^2\gamma. \qquad (2)$$

Here $Z_\parallel$ represents the effective impedance of the beam pipe, n is the mode number, $V_p = m_pc^2/e = 938$ MV, $\Delta p/p$ is the fractional momentum spread in the beam, and the parameter $\eta \equiv \gamma_t^{-2} - \gamma^{-2}$. The energy dependence of this expression is somewhat complicated because every factor is energy-dependent except V_p and $\bar{I}$.

The energy and intensity parameters, including N and $\bar{I}$, are listed in Table I for existing and proposed high energy proton synchrotrons. The existing higher energy machines achieve average beam currents of ~1 μA. These currents are limited both by slow-cycling rate (<1 Hz) and by low injection energies (<200 MeV) into their first synchrotron stages, restricting N to ~2×10^{13}. The circulating current $\bar{I} \approx 1$A.

Table I. High-intensity proton synchrotrons.

	Energy (GeV)	Average current (μA)	Rep. rate (Hz)	Protons/ pulse N ($\times 10^{13}$)	Circulating current $\bar{I}$ (A)
Fast Cycling[b]					
Argonne IPNS	0.5	14	30	0.3	4.0
Rutherford ISIS	0.75	45(200)	50	(2.5)	(6.1)
Fermilab Booster	8	7	15	0.3	0.3
AGS Booster	(1.5)	(20-40)	(7.5)	(1.8-3.5)	(4-8)
Slow Cycling[a]					
KEK PS	12	0.32	0.6	0.4	0.6
CERN PS	26	1.2	0.38	2	1.5
Brookhaven AGS	28.5	0.9	0.38	1.6	0.9
- with Booster		(4-8)		(7-14)	(4-8)
Proposed Boosters[b]					
TRIUMF	3	100	50	1.2	2.7
European HF	9	100	25	2.5	2.5
LAMPF AHF	15	25	12	1.3	0.5
JHF Booster	2	200	50	2.5	6.7
Kaon Factories[a]					
TRIUMF	30	100	10	6	2.8
European HF	30	100	12.5	5	2.5
LAMPF AHF	60	25	12	1.3	0.5
Japanese HF	30				

[a] Slow extraction [b] Fast extraction

Higher intensities have been achieved in machines using faster cycling rates (10-50 Hz). The record current (for a synchrotron) is 45 μA at the Rutherford ISIS spallation neutron source[10], and this will be raised to 200 μA when commissioning is completed. The number of protons per pulse N will be 2.5×10^{13}, only a little more than in the slow-cycling machines, but the circulating current $\bar{I}$ will rise to 6 A.

The proposed kaon factories aim at energies in the 30-60 GeV range with proton currents of 25-100 μA. Proposals have come from all three existing pion factories at LAMPF, SIN and TRIUMF (these laboratories being unique in already possessing operating machines with adequate energy and current to act as injectors),

CH2387-9/87/0000-0819 $1.00 © IEEE
PAC 1987

and also from a European consortium and from Japan. All the proposals involve intermediate booster synchrotrons as well, with energies in the 3-15 GeV range. Raising the injection energy into the main ring has a triple purpose. In the first place it raises the tune-shift limit on the charge per pulse for a reasonable normalized emittance ε^* to $N \sim 6 \times 10^{13}$ ppp. This enables the desired current of 100 μA to be achieved with only moderately fast cycling rates ~10 Hz. Secondly, for a given ε^*, it significantly reduces the magnet aperture required for the main ring, and hence its cost. Thirdly it simplifies the design of the rf acceleration system. In a fast-cycling machine the much more rapid acceleration requires a much higher rf voltage than has been conventional at slower cycling rates — about 2 MV for a 10 Hz 30 GeV machine. At the same time a large frequency swing (20-30%) is required when starting from pion factory energies of 500-800 MeV. The use of a booster enables these demands to be handled separately. Almost the entire frequency swing can be provided in the booster at relatively low rf voltage, while the main ring provides the 2 MV with only a few percent frequency swing. The booster is usually smaller and therefore must cycle faster (15-60 Hz) in order to fill the circumference of the main ring. The charge per pulse would be $N \sim 10^{13}$, comparable to existing machines injected in the same energy range. The circulating current in both booster and main ring would be $\bar{I} < 3$ A, a level which is not expected to present serious problems.

Many of the design features required for these high energy high intensity machines are common to all the proposals; to avoid repetition I will describe these common features before those that distinguish the various proposals. First, however, it will be appropriate to discuss the project already under construction at Brookhaven to enhance the AGS performance by the addition of a booster synchrotron.

Brookhaven AGS Booster

This is in fact a multi-purpose project aimed at the acceleration of heavy ions as well as polarized and unpolarized protons[11-13]. Funding began in October 1985 and the project is expected to be complete by the end of 1989. The Booster ring is one-quarter the circumference of the AGS and is located in the angle between the linac tunnel and the AGS ring. The modes of operation for various particles are illustrated in Fig. 1, where the time scale covers the 2.8 s of a

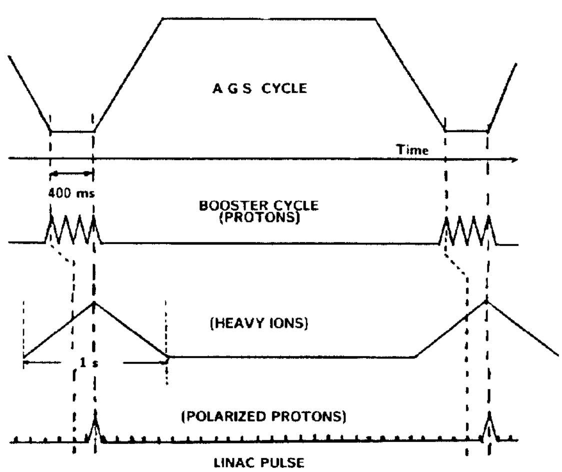

Fig. 1. Injection programs with the AGS Booster.

single slow extracted pulse. For unpolarized protons four booster pulses would be injected at a 7.5 Hz repetition rate within a 400 ms flat bottom, enabling the present 1.6×10^{13} ppp to be increased to 7×10^{13} ppp. Initially protons would be accelerated to 1.5 GeV although the bending capability provided for heavy ions would eventually allow protons to be accelerated to 2.5 GeV. For heavy ions a slower acceleration time is required in the Booster, and only one pulse would be injected into the main ring. For polarized protons there is the option of stacking 20 or so pulses in the booster ring before injecting them into the AGS. Further improvements beyond this program include the possibility of adding a 30 GeV stretcher ring and of making modifications to the AGS (rf, etc.) to accommodate $>5 \times 10^{13}$ ppp and increase the beam intensity to as much as 2×10^{14} p/s (32 μA).

Common Features of the New Proposals

The rather similar performance specifications for the various kaon factories have led to a number of common design features — many of them novel and aimed at completely avoiding processes producing beam loss.

Rapid Cycling. This restricts the charge required per pulse Ne (and hence the tune spread $\Delta\nu$) and the circulating current I (and hence beam loading and instability problems) as described above. Frequencies much above 1 Hz imply the use of resonant rather than ramped magnet power supplies. The rapid acceleration also requires a relatively high rf voltage gain per turn (~1 MV), implying multiple cavities and a relatively high synchrotron tune ($\nu_s > 0.01$). The latter in turn implies that low order (low $k + \ell + m$) synchro-betatron resonances of the form $\ell\nu_x + m\nu_y + k\nu_s$ impinge on the working area in tune space. To avoid exciting these the rf cavities must either be placed in a dispersionless region, or else with a symmetry which does not produce dangerous nth harmonic fields[14].

Booster Synchrotrons. As described above, these increase the charge Ne acceptable in the main ring, reduce the magnet apertures required there and hence its cost, and at the same time simplify the rf design by separating the requirements for large frequency swing and high voltage.

Asymmetric Magnet Cycle. All designs propose the use of a slow rise, typically 3 times longer than the fall; this reduces the rf voltage needed, and hence the number of cavities, by 1/3. Full-scale power supplies providing such a cycle have been developed at Argonne by Praeg[15], with the encouragement of Los Alamos.

H^- injection. Injection into the first ring by stripping an H^- beam enables Liouville's theorem to be bypassed and many turns to be injected into the same area of phase space.

Painting Phase Space. In fact it is not necessary or desirable to inject every turn into exactly the same area; the small emittance beam from the injector must be painted[16] over the much larger three-dimensional acceptance of the first ring to limit the space charge tune shift. Painting also enables the optimum density profile to be obtained and the number of passages through the stripping foil to be limited.

Bucket-to-bucket Transfer. Bunches are transferred from bucket to bucket leaving the injector and between rings. This avoids the losses inherent in capturing coasting beams. The buckets are made large enough that no more than 60% of their area is occupied.

Empty Buckets. A group of adjacent buckets, ~100 ns long, is left empty to allow time for the extraction and injection kickers to turn on and stabilize.

Transition Crossing Avoided. The magnet lattices are designed to place transition outside the acceleration range, avoiding the emittance mismatch and beam losses associated with crossing it in fast-cycling machines, and the difficulties anticipated in making a phase jump under high beam loading. In conventional a.g. proton synchrotrons with regular dipole lattices, the momentum dispersion $\eta_x \equiv \Delta x/(\Delta p/p) \approx R/\nu_x^2$ (constant) and hence the transition energy $\gamma_t \approx \sqrt{R/\langle\eta_x\rangle}$

$\approx \nu_x$, typically in mid-acceleration range. The use of a highish energy booster (say >6 GeV) makes it possible to avoid crossing transition simply by choosing a high tune for the booster and a low one for the main ring. With a lower energy booster, superperiodic missing dipole lattices may be used to alter $\langle\eta_x\rangle$ and drive γ_t out of range.

Siberian Snakes. The superperiodicity of the magnet lattices also drives depolarizing resonances. Pulsed quadrupoles can be used to jump the lower energy resonances in the boosters, as at the AGS. At higher energies, however, it becomes impractical to build quadrupoles fast enough and strong enough. Instead it is proposed to use "Siberian Snakes".

Control of Beam Instabilities[17]. In spite of the large circulating currents, the rapid cycling times give instabilities little time to grow to dangerous levels. Coupled-bunch modes, driven by parasitic resonances in the rf cavities and by the resistive wall effect, are damped using the standard techniques (Landau damping by octopoles, bunch-to-bunch population spread and active damping by electronic feedback). The longitudinal microwave instability, which tends to have a rapid growth rate, is avoided by making the longitudinal emittance sufficiently large and by minimizing the high frequency impedance in the vacuum chamber as seen by the beam. To allow for beam blow-up the magnet apertures are designed to accommodate at least 50% growth in the beam emittance.

Control of Beam Loading. The high beam powers involved (several MW) imply high loading if the rf system is not to be excessively expensive. To provide stability under these conditions powerful rf control systems have been devised, based on experience at CERN, including fast feedback around the power amplifiers and phase, amplitude, tuning, radial and synchronization feedback loops. One-turn-delay feedforward is used to control transient loading effects.

Control of Beam Loss. Successful operation of a high-intensity accelerator depends crucially on minimizing beam losses and the activity they produce. Where some loss is expected, near injection and extraction elements, collimators and absorbers will be provided and equipment designed for remote handling. Efforts are being made to reduce the spills on slow extraction systems to ~0.1%. The beam current and any spills will be carefully monitored, and in case of the beam becoming unstable at any time through component failure or power excursions, fast-abort systems will dump the entire beam safely within one turn.

Los Alamos Advanced Hadron Facility

The LAMPF II proposals[1] for a 45 GeV, 32 μA facility have aimed at higher energies but lower currents than the other schemes. It was argued that higher energy protons would be more suitable for Drell-Yan studies of quark confinement in the nucleus, besides providing higher momentum secondary beams. In fact it was aimed to achieve 60 GeV by running the main ring bending magnets at 2.0 T. These proposals have now been superseded by studies of a generic "advanced hadron facility" — a combined kaon factory and pulsed cold-neutron source[19]. Figure 2 shows the proposed layout, with the existing 800 MeV linac injecting every other H^- pulse into a new 1200 MeV linac, perhaps using superconducting cavities, to give a 500 μA, 60 Hz H^- beam at 2 GeV. For pulsed neutron and neutrino production each of the H^- pulses would be stripped into one ring of a 5-ring 2 GeV compressor (à la CERN PS Booster) operating at 12 Hz. The compressor occupies the 330.8 m circumference tunnel previously designated for the LAMPF II 6 GeV booster. The extracted beam pulses would be directed at a combined 1 MW spallation neutron and stopped-pion neutrino target. The target would be boosted and optimized for cold and ultracold neutrons to give 36 times the annual yield of the PSR.

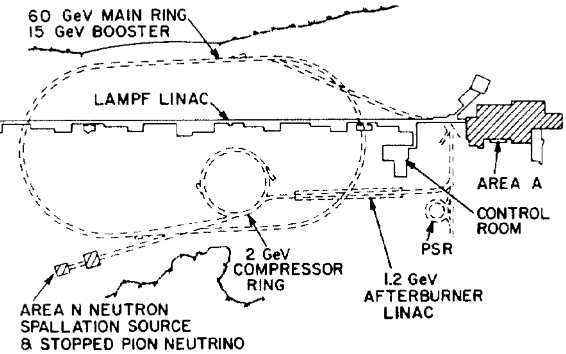

Fig. 2. Proposed site layout for an advanced hadron facility.

The 25 μA H^- beam for the kaon factory will bypass the compressor and be stripped directly into a 15 GeV booster installed with the 60 GeV LAMPF II main ring in a 1333.2 m long racetrack tunnel. With this arrangement neither a main-ring flat bottom nor a collector ring is required; moreover, the magnetic energy can be transferred back and forth between the booster and main ring using just a single magnet power supply, eliminating all chokes and one condenser bank.

Both synchrotrons use separated function magnets. The race-track lattice common to the main ring and booster consists of several functionally different sections — two 144° bending arcs, four 18° missing magnet dispersion suppressors, four short matching sections, and two 90 m long straight sections to accommodate rf cavities, beam transfer elements, and Siberian snakes. The 28 m long high-β section will reduce the beam spill on the slow extraction septum. The working point (ν_x = 7.45, ν_y = 6.45) was chosen close to a half-integer resonance for slow extraction. The high average dispersion in the bending arcs ($\eta_x \approx 6$ m) keeps the transition energy below the acceleration range (γ_t = 6.4, 5.06 GeV). Alternative options including a separate stretcher ring and a half-size booster are under consideration.

The Los Alamos group is pioneering a number of potentially important technical developments. First among these is the use of an asymmetric magnet cycle[15] with slow rise and fast fall to reduce the rf voltage requirements. In laboratory tests full control of the flat-top and flat-bottom current and slope was demonstrated[20].

Secondly, in an effort to reduce the cost of tunable high-power rf systems, the Los Alamos group is developing rf cavities in which the ferrite is biased with magnetic field perpendicular rather than parallel to that of the rf. With Trans-Tech G810 ferrite this results in cavities with much higher Q values. A full-scale cavity has been built giving R/Q = 35 Ω and a tuning range of 20%. Initial tests at fixed frequency and without cooling have achieved 140 kV on a single gap for 15 minutes at 60% duty factor[21].

The third development concerns the design of suitable vacuum chambers for the fast-cycling magnets. There must be a conducting surface on the inside of the chamber to prevent the build-up of electrostatic charge and also to provide a low-impedance path for the high-frequency image currents involved in maintaining beam stability. On the other hand eddy currents must be suppressed to minimize heating and magnetic field distortion. The only present example of such a system is at the Rutherford ISIS synchrotron, where a ceramic vacuum chamber is used, fitted with an internal cage of longitudinal wires to provide an rf shield. SAIC consultants are building test sections of a ceramic vacuum chamber with the conducting surfaces provided by metallizing the internal surface with silver stripes[22]. Measurements of the beam coupling impedance are under way [23]. The system offers a smaller magnet aperture but will require careful design of the end connections.

The initial LAMPF II proposal appeared in December 1984. The second edition in May 1986 eliminated one experimental area without cutting down the number of secondary channels by using the MAXIM scheme of C. Tschalär to produce beams to the left and right of each target. The total cost, including ED&I but not contingency, was estimated to be M$292. By comparison an AHF would cost M$305.

TRIUMF KAON Factory

The TRIUMF Kaon-Antiproton-Other hadron-Neutrino proposal is based on a 30 GeV main "Driver" synchrotron 1072 m in circumference accelerating 10 μC pulses at a 10 Hz repetition rate to provide an average beam current of 100 μA. For the reasons explained above a Booster synchrotron is used to accelerate protons from the TRIUMF cyclotron at 450 MeV to 3 GeV: this machine is 1/5 the radius of the main ring (Fig. 3) but cycles

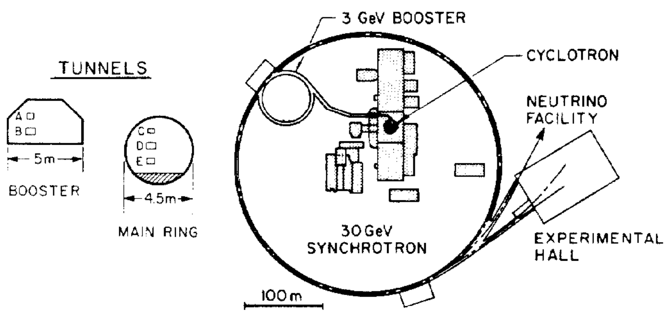

Fig. 3. Proposed layout of the TRIUMF KAON Factory accelerators, and cross sections through their tunnels.

five times faster at 50 Hz. The Booster energy is chosen to minimize the total cost of the project. This depends mainly on magnet costs, and in particular on the magnet apertures. The minimum cost condition occurs when the emittances set by the space charge tune shift formula (1) are the same for both machines[24].

Each of the three accelerators is followed by a dc storage ring to provide time-matching and finally a slow extracted beam for coincidence experiments. These are relatively inexpensive, accounting for only 25% of the total cost. Thus the TRIUMF cyclotron would be followed by a chain of five rings, as follows:

A	Accumulator:	accumulates cw 450 MeV beam from the cyclotron over 20 ms periods
B	Booster:	50 Hz synchrotron; accelerates beam to 3 GeV
C	Collector:	collects 5 Booster pulses and manipulates longitudinal emittance
D	Driver:	main 10 Hz synchrotron; accelerates beam to 30 GeV
E	Extender:	30 GeV stretcher ring for slow extraction

As can be seen from the energy-time plot (Fig. 4) this arrangement allows the cyclotron output to be accepted without a break, and the B and D rings to run continuous acceleration cycles without wasting time on flat bottoms or flat tops; as a result the full 100 μA from the cyclotron can be accelerated to 30 GeV for either fast or slow extraction. Figure 4 also shows the asymmetric magnet cycles used in both synchrotrons.

Figure 3 shows the location of the Accumulator above the Booster in the small tunnel, and of the Collector and Extender rings above and below the Driver in the main tunnel. Identical lattices and tunes are used for the rings in each tunnel. This is a natural choice providing structural simplicity, similar magnet apertures and straightforward matching for beam transfer.

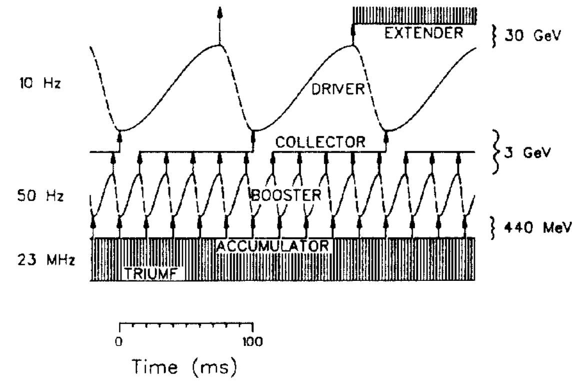

Fig. 4. Energy-time plot showing the progress of the beam through the five TRIUMF KAON Factory rings.

Separated function magnet lattices are used with a regular FODO quadrupole arrangement, but with missing dipoles arranged to give superperiodicity 6 in the A and B rings and 12 in the C, D and E rings. This automatically provides space for rf, beam transfer and spin rotation equipment. It also modulates the dispersion function η_x and drives its mean value $\langle\eta_x\rangle$ towards zero, enabling transition to be driven above top energy in both machines. Not only does this avoid crossing transition, but it is no longer advantageous to correct the natural chromaticity, so that sextupole magnets are needed only for error correction, and geometric aberrations in the beam are essentially reduce to zero. A high γ_t is achieved, without perturbing the other lattice functions too strongly, by bringing the horizontal tune value ν_x towards, but not too close to, the integer superperiodic resonance. Values of $\nu_x \approx 5.2$ for the S = 6 Booster and $\nu_x \approx 11.2$ for the S = 12 Driver prove to be quite convenient. Associated choices of $\nu_y = 7.23$ and 13.22, respectively, keep the working points away from structural resonances and allow room for the anticipated space charge tune spreads, $\Delta\nu_y = 0.18$ and 0.11.

In the absence of zero-dispersion straights, nearby synchro-betatron resonances are suppressed by placing the rf cavities symmetrically with the magnet superperiodicity. For the Booster those resonances near $\nu_x = 5$ and $\nu_y = 7$ are eliminated, except for fifth harmonic variations in the cavity voltages and seventh harmonic errors in vertical dispersion.

Depolarizing resonances are of comparable strength to those in the AGS; the superperiodicity is stronger but passage is more rapid. Using the same pulsed quadrupole techniques as in the AGS, Wienands[25] has shown that 75% transmission of polarization is achievable. Alternatively a three-twist helical snake made from 6 discrete dipole magnets could be fitted into two straight sections to prevent any depolarization and restrict the orbit excursions to 9 cm at 3 GeV.

At injection into the A and B rings the rf accelerating system will operate at 46.1 MHz, twice the radio frequency of the TRIUMF cyclotron. So that every other rf bucket is not missed the radius of these rings is made a half-integer multiple (4.5) of that of the last orbit in the cyclotron. The Booster cavities are based on the double gap cavities used in the Fermilab Booster. They will develop a voltage of 26 kV at each gap for a frequency swing of 46-61 MHz[26]. Twelve cavities will develop the required voltage of 580 kV. The cavities for the other rings are based on the single gap cavities designed for the Fermilab main ring. For the main synchrotron, 18 cavities, each developing 140 kV, give a total of 2520 kV with a frequency swing from 61.1-62.9 MHz. To keep the rf power within a factor two of the 3 MW beam power and to provide stability under high beam loading conditions, a powerful rf control system has been designed[18], based on experience at CERN, as described above.

The Accumulator ring is designed to provide the matching between the small emittance cw beam $[(2\pi \text{ mm}\cdot\text{mrad})^2 \times 0.0014 \text{ eV-s})]$ from the TRIUMF cyclotron and the large emittance pulsed beam $[31 \times 93 (\pi \text{ mm}\cdot\text{mrad})^2 \times 0.048 \text{ eV-s})]$ required by the Booster. The Accumulator will stack a continuous stream of pulses from the cyclotron over a complete 20 ms Booster cycle (20,000) turns using H^- stripping together with phase space painting. The stripping foil lifetime is estimated to be > 1 day. The painting is achieved by a combination of magnetic field ramping, vertical steering, and energy modulation using additional rf cavities in the injection line.

At present, of course, the H^- ions are stripped in the process of extracting them from the cyclotron. To extract them whole a new extraction system will be required, and elements of this have been under test for the last year[27]. The first element is an rf deflector operating at half the fundamental frequency: it deflects alternate bunches in opposite directions. Because the cyclotron operates on an odd harmonic (h=5) and the $\nu_R = 3/2$ resonance is nearby, this produces a coherent radial betatron oscillation. Although successive turns are not completely separated a radial modulation in beam density is produced. An electrostatic deflector is then placed so that the septum is at a density minimum. In fact the septum is protected by a narrow stripping foil upstream so that no particles hit it; instead they are safely deflected out of the machine. The particles entering the electrostatic deflector eventually pass into magnetic channels[28] and then into the Accumulator injection line. The magnetic channels have only just become available but tests with the first two elements have demonstrated 85% extraction efficiency.

The proposal was submitted to TRIUMF's funding agencies in September 1985. The total cost, including salaries and E,D&I, but not contingency, was estimated to be M$427 (1985 Canadian dollars). Two review committees were set up, one of specialists, the other multidisciplinary. These gave both physics and machine design a high rating but concluded that it should not be funded at the expense of existing science activities — new money would be required. Two economic studies have also been performed, indicating that there would be strong direct economic benefits and a good potential for industrial spin-offs. The provincial government of British Columbia has made the KAON Factory its first choice of federally funded projects, and has agreed to provide the $88 million needed for buildings and tunnels. Negotiations are now under way for the pre-construction R&D budget.

European Hadron Facility

The first European scheme for a kaon factory came from SIN. This was for a 20 GeV 80 μA synchrotron fed from the 590 MEV SIN cyclotron and the proposed ASTOR isochronous storage ring (Joho[29]). Rapidly growing support led to the formation of an international study group. The conceptual design has been discussed at a number of workshops over the last eighteen months, and a reference design[30] was agreed on in March 1986. The latest details are given by Bradamante[31].

The layout of the proposed EHF is shown in Fig. 5. To accelerate 100 μA to 30 GeV the main ring cycles at 12.5 Hz; it is fed by a 9 GeV booster and a 1.2 GeV linac, both cycling at 25 Hz. Collector (here called "holding") and stretcher rings are included in the design to follow the booster and main ring, respectively. The choice of a relatively high 9 GeV for the Booster energy raises the cost of the entire project by about 10% over the minimum at ~4 GeV but offers a number of advantages. Not only does it provide greater opportunities for interesting physics at an intermediate construction stage but it brings the booster

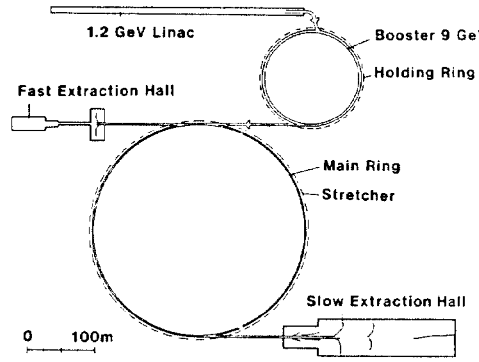

Fig. 5. Schematic layout for the European Hadron Facility.

circumference to half that of the main ring, allowing the collector to be placed in the booster tunnel, halving its length and equalizing the number of rings in each tunnel. The desire to accelerate polarized protons plays an important role in this design, and with 9 GeV injection the Siberian snakes in the main ring will cause less closed orbit distortion.

Although the design is officially "siteless" the circumference of the main ring has been chosen equal to that of the CERN ISR for reference purposes. The advantages of tunnel-stuffing are clearly as obvious if Europe as they have been in the USA. Besides the tunnel, CERN's site offers other advantages — the existence of interim injectors, the availability of the West Hall after the experimental program has moved to LEP, and the infrastructure (even if only as a model for an independent EHF laboratory). The most obvious advantage to CERN would be the provision of a back-up PS. But these are mere speculations and at the moment it seems more likely that the EHF would be located elsewhere, say in Italy or at SIN.

All the rings use separated-function magnets and superperiodic lattices with transition energy outside of the acceleration range. The booster and holding ring use an interesting doublet lattice with S = 6 and nine cells in each superperiod. Dipole magnets are omitted from three cells, two of which can then be made dispersionless and therefore suitable for the location of rf cavities. The quadrupole doublets give low β-functions and high tunes ($\nu_x = 13.23$, $\nu_y = 10.22$); the transition energy $\gamma_t = 12.55$. The main ring consists of four 90° arcs connected by dispersionless straight sections. Each arc contains 11 regular FODO cells including missing dipole dispersion suppressors at each end. Each straight consists of 2 quadrupole doublet cells. Two straights are used for Siberian snakes, two for injection and extraction, and all four for rf cavities. The stretcher lattice is not yet settled; a racetrack stretcher in a separate tunnel is under consideration.

The 1200 MeV linear injector consists of a series of linacs of different types. Following the H^- ion source and dc acceleration to 30 keV, two RFQs operating at 50 MHz and 400 MHz take the beam to 200 keV and 2 MeV, respectively. A 400 MHz drift tube linac then accelerates the ions to 150 MeV and finally a 1200 MHz side-coupled linac to 1200 MeV. Two out of 24 SCL buckets are filled, and these are then painted over the central 50% of the 50 MHz Booster bucket to provide the desired density distribution.

Work is continuing with the aim of producing a formal proposal this spring. Some temporary office space has been made available at CERN and the study group has made this their headquarters. The total cost is estimated to be MDM867, not including controls, contingency and inflation.

Japanese Hadron Facility

In recent years there has been considerable interest in kaon factories in Japan. Thus Kyoto University[32] has proposed a 25 GeV 50 μA fast-cycling synchrotron, a stretcher ring, and antiproton accumulation and storage rings. At KEK and the University of Tokyo[33] there has been a longstanding interest in increasing the intensity of the KEK 12 GeV PS by using a higher energy booster (1-3 GeV). There has also been the independent GEMINI project[34], a spallation neutron source and pulsed muon facility, based on an 800 MeV 500 μA proton synchrotron.

These schemes have now been assimilated into an even more ambitious project, the Japanese Hadron Facility[35], which would provide not only a kaon factory and pulsed neutron and muon sources, but also 1-2 GeV pions and 1-3 GeV/u heavy ions, including radioactive species. The proposed injection complex is shown in Fig. 6. A 1 GeV 200 μA linac will supply proton beams

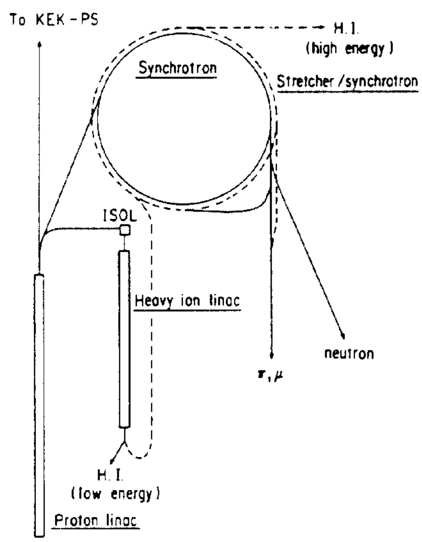

Fig. 6. Injector complex for the Japanese Hadron Facility.

either to the KEK-PS (currently limited by the tune-shift at 500 MeV), to an ISOL heavy ion source, or to a 2 GeV 200 μA fast-cycling synchrotron. This 50 Hz, 27 m radius machine again serves multiple purposes. The fast-extracted protons can be used directly for pulsed muon, neutrino or neutron production, or they can be transferred to (i) the KEK-PS for even higher energy injection, (ii) a 30 GeV kaon factory synchrotron (whose design details are not yet available) or (iii) a stretcher ring in the same tunnel, whose slow extracted beam would provide 1-2 GeV proton and pion beams for counter experiments. The stretcher can also act as a slow-cycling 0.5 Hz synchrotron to accelerate protons to 3.2 GeV or heavy ions to 1.3 GeV/u (q/A = 1/2). Heavy ions would be injected at 8 MeV/u from a separate heavy ion linac. A proposal for the 1 GeV proton linac is understood to have been submitted recently.

Conclusions

At high energies a variety of important questions in both particle and nuclear physics could be attacked using the more intense and/or clean beams of kaons, antiprotons, neutrinos and other particles that 100 μA proton beams from 30-60 GeV kaon factories could supply. In response to these rich possibilities a booster is under construction at the Brookhaven AGS and proposals for kaon factories have been completed at LAMPF and TRIUMF and are in preparation in Europe and Japan. Some of the projects termed "hadron facilities" also involve pulsed muon and spallation neutron sources, and heavy ion facilities. It seems likely that at least one of these projects will be funded within the next few years.

Acknowledgements

The author is delighted to acknowledge the information and material that have been generously supplied by F. Bradamante, H. Foelsche, E.B. Forsyth, H. Sasaki, L. Teng, H.A. Thiessen, and T. Yamazaki. He is also grateful to Jana Thomson for her accurate preparation of the paper.

References

[1] A proposal to extend the intensity frontier of nuclear and particle physics to 45 GeV (LAMPF II), LA-UR-84-3982 (1984).
The physics and a plan for a 45 GeV facility that extends the high-intensity capability in nuclear and particle physics, LA-10720-MS (1986).
[2] KAON Factory Proposal, TRIUMF (1985).
[3] Proc. Intl. Conf. on a European Hadron Facility, Mainz, ed. Th. Walcher (North Holland, 1987).
[4] Proc. 2nd Conf. on Intersections between Particle and Nuclear Physics, Lake Louise, May 1985, ed. D.F. Geesaman, AIP Conf. Proc. 150, (1986).
[5] Proc. Intl. Workshop on Hadron Facility Technology, Santa Fe, February 1987, AIP Conf. Proc. (in press).
[6] H.A. Thiessen, IEEE Trans. Nucl. Sci., NS-32, 1601 (1985).
[7] M.K. Craddock, IEEE Trans. Nucl. Sci., NS-30, 1993, (1983); and in ref. 4.
[8] K.H. Reich, K. Schindl, and H. Schönauer, 12th Int. Conf. On High Energy Accelerators, ed. F.T. Cole, R. Donaldson, Fermilab, p. 438 (1983).
[9] E. Keil, W. Schnell, CERN-ISR-TH-RF/69-48 (1969); D. Boussard, CERN-Lab:II/RF/Int. 75-2 (1975).
[10] G.H. Rees, these proceedings.
[11] Y.Y. Lee, IEEE Trans. Nucl. Sci., NS-32, 1607 (1985).
[12] H. Foelsche, in reference 5.
[13] E.B. Forsyth and Y.Y. Lee, these proceedings.
[14] T. Suzuki, Part. Accel. 18, 115 (1985).
[15] W. Praeg, IEEE Trans. Nucl. Sci., NS-30, 2873 (1983).
[16] V.C. Kempson, C.W. Planner and V.T. Pugh, IEEE Trans. Nucl. Sci., NS-28, 3085 (1981).
[17] R. Baartman, these proceedings and in Ref. 5.
[18] F. Pedersen, IEEE Trans. Nucl. Sci, NS-32, 2138 (1985); TRI-DN-85-15, (1985).
[19] H. A. Thiessen, these proceedings.
[20] E.J. Schneider, ibid.
[21] C.C. Friedrichs, R. Carlini et al., ibid.
[22] B. Butler and M. Featherby, ibid.
[23] L. Walling, D. Neuffer et al., ibid.
[24] U. Wienands and M. Craddock, TRI-DN-86-7 (1986).
[25] U. Wienands, these proceedings.
[26] R.L. Poirier and T. Enegren, ibid.
[27] G.H. Mackenzie, R.E. Laxdal et al., ibid.
[28] J.B. Pearson, E. DeVita, et al., ibid.
[29] W. Joho, Proc. 10th Int. Conf. on Cyclotrons and their Applications, East Lansing, ed. F. Marti, IEEE, New York, p. 611 (1984).
[30] Feasibility study for a European Hadron Facility, EHF-86-33 (1986); and F. Bradamante, in Ref. 3.
[31] F. Bradamante in reference 5.
[32] K. Imai, A. Masaike et al., Proc. 5th Symposium on Accelerator Science and Technology, KEK, p. 396 (1984).
[33] T. Yamazaki, Proc. KEK Workshop on Future Plans for High Energy Physics, March 1985, preprint UTMSL-116.
[34] H. Sasaki, and GEMINI Study Group, Proc. Int. Collaboration on Advanced Neutron Sources VII, Chalk River, 1983, AECL-8488, p. 50 (1984).
[35] M. Kihara, in reference 5.