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KAON FACTORIES

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Abstract. Proposals for high intensity proton synchrotrons (typically providing 100 μA $(6 \times 10^{14}$ p/s) at 30 GeV have been made in Canada, Europe, Japan, the U.S.A. and the U.S.S.R. 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, avoidance of transition crossing, separate collector and stretcher rings, three-dimensional beam painting at injection, bucket-to-bucket beam transfer, perpendicular biassing of microwave ferrite in the rf tuners, the use of Siberian Snakes to preserve polarization, and the addition of a pre-septum to make slow extraction >99.8% efficient. Other characteristic features include rapid cycling rates, booster stages, H^- injection, low impedance enclosures, powerful feedback systems for control of beam instabilities and beam loading, and local collimation systems for handling beam loss. This paper reviews the general features of kaon factory accelerator design and the status of the various proposals.

INTRODUCTION

Strong initiatives are being pursued in a number of countries for the construction of *"kaon factory" synchrotrons capable of producing proton beams 100 times more intense* 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 of kaons and hyperons
- CP violation
- meson and baryon spectroscopy
- meson and baryon interactions
- neutrino scattering and oscillations
- quark structure of nuclei
- hypernuclear properties.
- K^+ and $\bar{p}$ scattering from nuclei.

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". One example is the setting of a lower limit of 380 GeV on the mass of any right-handed W-boson by a muon decay measurement[1] at TRIUMF in 1982. A comprehensive justification of the physics case for kaon factories may be found

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in the four proposals[2–5] so far published and in the proceedings of recent "Intersections" conferences[6]. The possibilities for future K-decay and CP-violation measurements were discussed in depth at Snowmass '88 (Ref. 7) and at the Rare Decay Symposium[8].

This paper will first introduce the general design features of kaon factory accelerators and then give brief descriptions and status reports for individual projects.

KAON FACTORY ACCELERATORS

The proposed kaon factories aim at energies in the 30-100 GeV range with proton currents of 25-100 μA. Proposals have come from the three existing pion factories at LAMPF, PSI and TRIUMF (these laboratories being unique in already possessing operating machines with adequate energy and current to act as injectors) and from that nearing completion near Moscow, and also from a European consortium and from an INS-KEK collaboration in Japan. The energy and intensity parameters for the proposed machines are listed in Table I along with those for some existing proton synchrotrons. More details can be found in the proposals themselves[2–4] and in the proceedings of the recent Santa Fe "Workshop on Hadron Facility Technology"[9] and Los Alamos Accelerator Design Workshops.[10–11]

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 $\bar{I}$. N is critical because it determines the incoherent space charge tune shift (and spread) $\Delta\nu$, given by[12]

$$\Delta\nu = -\frac{r_p}{\pi}\frac{N}{\epsilon^*}\frac{FGH}{B_f}\frac{1}{\beta\gamma^2}\,. \tag{1}$$

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 $\bar{I}$ 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[13] for microwave stability:

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

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

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)
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)	(0.38)	(6)	(4)
- with Stretcher		(8)	(0.77)	(6)	(4)
Fast Cycling[b]					
Argonne IPNS	0.5	14	30	0.3	4.0
Rutherford ISIS	0.75	130(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)
Kaon Factories[a]					
LAMPF AHF	60(100)	25	12	1.3	0.5
TRIUMF	30	100	10	6	2.8
European HF	30	100	12.5	5	2.5
Japanese HP (Ph. II)	30	100			
Moscow KF	45	125	6.25	12.4	3.2
Boosters[b]					
LAMPF AHF	2.2[c]/6/10	25	12	1.3	0.5
TRIUMF	3	100	50	1.2	2.7
European HF	9	100	25	2.5	2.5
JHP (Phase II)	2	200	50	2.5	6.7
Moscow KF	7.5	250	50	3.1	3.2

[a]slow extraction [b]fast extraction [c]linac

The existing higher energy machines achieve average beam currents of $\approx 1\ \mu$A. 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 $\approx 2\times 10^{13}$. The circulating current $\bar{I} \approx 1A$. The booster synchrotron at present under construction at Brookhaven[14] will raise the injection energy into the AGS to 1.5 GeV and allow N to be raised a factor 4. For this and other reasons explained below all the kaon factory proposals include boosters.

The highest intensities have been achieved in machines using faster cycling rates (10-50 Hz). The record current (for a synchrotron) is 130 μA at the Rutherford ISIS spallation neutron source[15], 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 kaon factory synchrotrons are all designed to operate at $\sim$10 Hz, a little slower than the Fermilab booster, but 25 times faster than existing 30 GeV machines.

COMMON FEATURES OF THE PROPOSALS

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

Rapid Cycling

This restricts the charge Ne required per pulse (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 ($\sim$ 1 MV), implying multiple cavities and a relatively high synchrotron tune ($\nu_s \geq$ 0.05). The latter initially caused concern about excitation of low order synchro-betatron resonances ($\ell\nu_x + m\nu_y + k\nu_s = n$) crossing the working area in tune space. Recent work by Wienands and Baartman, reported by Suzuki[16], has however shown that only first order resonances have strong effects, and these need not be crossed.

Booster Synchrotrons

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 100μA to be achieved with only moderately fast cycling rates $\sim$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 (12-60 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 $\bar{I} \lesssim 3$ A, a level which is not expected to present serious problems.

Collector and Stretcher Rings

These dc storage rings, respectively preceding and following the main synchrotron, remove the need for flat bottoms or flat tops in its magnet cycle (Figure 1), and thereby enable its cycling rate and average beam current to be increased. Either ring typically gives a factor 2, both a factor 3. A separate stretcher also simplifies the design by separating the requirements for slow extraction (high β, 10^{-5} magnet stability, bunch manipulation for complete debunching, tolerance of relatively high beam spill) from those for acceleration (uniform quadrupoles and regular β, fast cycling magnets, numerous rf cavities).

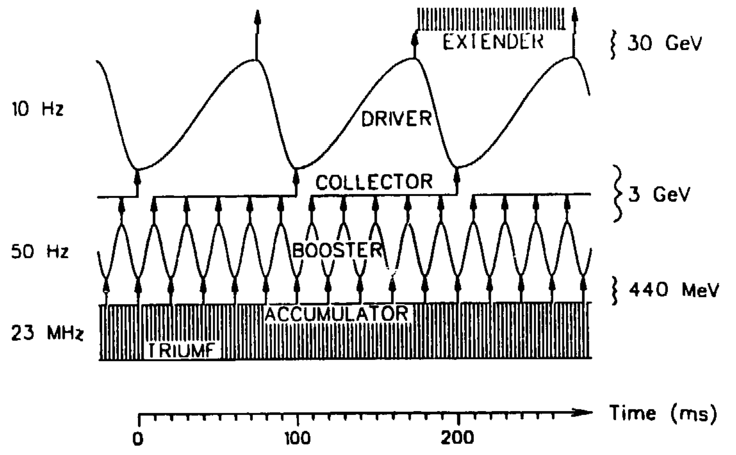

FIGURE 1 Energy-time sequence for the TRIUMF KAON Factory, showing how the Collector and Extender (stretcher) rings allow continuous cycling of the Driver synchroton.

Dual-frequency Magnet Cycle

Most designs propose the use of a slow rise, typically 3 times longer than the fall, for the main synchrotron; this reduces the very large rf voltage needed, and hence the number of cavities, by 1/3. (For boosters the voltage saving is much less, because of the need to maintain adequate bucket area.) Power supplies providing such a cycle were first developed at Argonne by Praeg[17], with the encouragement of Los Alamos, and full-scale test stands are currently in operation at KEK and TRIUMF.

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, in order to achieve a high charge per pulse.

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" 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. Development work at Rutherford, KEK and LAMPF has led to foils with 2, 3 and even 4 free sides!

Bucket-to-bucket Transfer

Bunches are transferred from bucket to bucket between accelerators and storage 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.

Avoidance of Transition Crossing

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 $\gamma_t \simeq \sqrt{R/\langle\eta_x\rangle} \simeq \nu_x$, 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 lattices with missing dipoles or modulated quadrupoles may be used to alter $\langle\eta_x\rangle$ and drive γ_t out of range.

Siberian Snakes

The periodicity 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. "Siberian Snakes" would be used instead.

Control of Beam Instabilities

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 octapoles, 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 seen by the beam. To obtain low impedance in the ceramic vacuum chambers needed in fast-cycling magnets, Rutherford[15] use internal wire cages. SAIC (San Diego), sponsored initially by LAMPF and now by TRIUMF, are developing ceramic tubes with metallic stripes on the inner surface[19].

The need for high energy gain per turn, but low impedance, led LAMPF to investigate high-Q cavities using perpendicularly biassed yttrium-garnet ferrite, rather than the conventional parallel-biassed NiZn. Gap voltages of 140 kV were obtained under dc conditions, and ac tests should begin soon at TRIUMF. The HERA proton cavities also use this type of ferrite[20].

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[21], 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. The beam current and any spills will be carefully monitored, and where some loss is expected, near injection and extraction elements, collimators and absorbers will be provided and equipment designed for remote handling. To allow for beam blow-up the magnet apertures are designed to accommodate some growth in the beam emittance. Computer simulations[22] suggest that addition of a pre-septum to a conventional slow extraction system could reduce the beam loss from typically 1% to < 0.02%. (This might take the form of a very thin (50 μm) foil or of a massless magnetic septum.)

INDIVIDUAL FEATURES AND STATUS

Three of the proposals – LAMPF, EHF and JHP – are at present dormant as far as their high-energy stages are concerned. Their proponents are now concentrating on proposals for injectors in the 1–1.6 GeV range. The other two proposals (Moscow KF and TRIUMF) remain very active, with well-funded pre-construction studies under way.

Los Alamos Advanced Hadron Facility[2]

The LAMPF group has favoured higher energies (60 GeV) and lower currents (25 μA) than the other proposals, citing the availability of high momentum secondary beams for glueball searches and Drell-Yan studies of the nucleus. Because of the limited space on the mesa they are now looking at a location 100 m lower in the canyon and considering a 100 GeV x 50 μA synchrotron with a separate stretcher. With CEBAF and RHIC ahead in the funding pipeline for nuclear physics projects in the U.S. the earliest date for a start to construction would be 1996. Present efforts are therefore being concentrated on a linac extension from 0.8 to 1.6 GeV and a compressor/storage ring for neutrino and spallation neutron physics.

European Hadron Facility

The 1987 EHF proposal[4] for a 100 μA proton beam was based on a 1.2 GeV linac, 9 GeV booster synchrotron, 9 GeV holding ring (collector) and 30 GeV synchrotron and stretcher rings. The relatively high energy booster (half the circumference of the main ring) enables the holding ring to be placed in the booster tunnel (halving its length), reduces the closed orbit distortions due to Siberian Snakes in the main ring, and increases the scope for experimental use of the booster beam, making staged construction a possibility.

A big step forward was achieved in late 1988 when LNL Legnaro, near Padova, agreed to sponsor the project. The Legnaro EHF would have similarities to the Brookhaven scheme, using a "pre-booster" synchroton (1.2 GeV protons, 1 GeV/n ions) to accelerate both protons from a new 650 MeV linac and heavy ions from the existing tandem and the ALPI superconducting linac now under construction. A "pre-holding ring" would also be installed in the pre-booster tunnel (half the circumference of the booster), to avoid flat bottoming the booster and to provide cooling for radioactive heavy ions produced by an ISOL target. A proposal for these two small rings is to be completed by the end of 1989.

Japanese Hadron Project[23]

The JHP is a joint INS/KEK project to be located at KEK. It is being pursued in stages, and up to now efforts have been concentrated on the first stage, which will consist of a 1 GeV proton linac, a compressor/stretcher ring, and a 6.5 MeV/n heavy ion linac. Experimental areas will be provided for the multidisciplinary use of nucleons, pions, muons, neutrinos, spallation neutrons and both stable and radioactive heavy ions. The 200 μA proton linac will also serve as a higher energy injector for the KEK PS, increasing its space charge limit by a factor 2.1. A proposal for the first stage was submitted in 1988 and is moving through the approval process. No details of the kaon factory stage have yet been published.

Moscow Kaon Factory[5]

This is a project of the Institute for Nuclear Research of the Academy of Sciences of the USSR and will be located at their Troitsk laboratory outside Moscow where their 600 MeV 500 μA proton linac meson factory, now nearing completion, will act as injector. The booster will accelerate 250 μA beams to 7.5 GeV, the main ring 250 μA fast extracted, or 125 μA slow extracted, at 45 GeV. A single storage ring in the main tunnel can act as either collector or stretcher. The project was approved in 1987 as part of the government plan for High Energy Physics in the USSR. A R5 million budget is available for prototyping in the coming year. Construction is scheduled to start in 1993.

TRIUMF KAON Factory

The TRIUMF Kaon-Antiproton-Otherhadron-Neutrino Factory aims to provide 100 μA beams either slow or fast extracted at 30 GeV. An alphabetical sequence of five rings is proposed (Figure 1): Accumulator, 3 GeV Booster, Collector, 30 GeV Driver synchrotron and Extender (stretcher). The first is needed to accumulate the cw beam at 450 MeV from the existing H^- cyclotron, which currently delivers 150 μA beams with 88% reliability. Local power costs would permit 9 months' beam delivery per year, as at present. The proposed site layout is shown in Figure 2. The main tunnel provides room for the later installation of a 100 GeV 25 μA ring using superconducting magnets.

The project is now two-thirds of the way through an 18-month-long $11-million preconstruction engineering design and impact study. This involves prototyping accelerator components, civil engineering design, and studies of environmental effects, economic benefits and international participation. The prototyping work includes dipole and quadrupole magnets, dual-frequency magnet power supplies, kicker magnets and pulse-forming networks, rf cavities, ceramic vacuum chambers with rf shields, computer controls and production targets. Experimental studies on the cyclotron have also confirmed that H^- ions can be extracted with 90% efficiency past an electrostatic septum without irradiating it, the remaining 10% being pre-stripped and extracted as protons. Other papers at this conference describe work on lattices[24], injection[25], beam stability[26], beam pipe impedances[27],

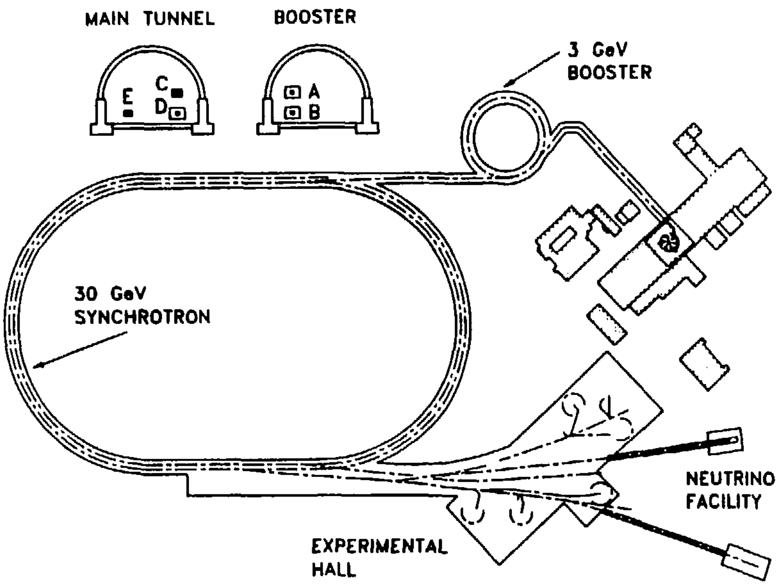

FIGURE 2 Proposed site layout for the TRIUMF KAON Factory.

beam loading[28] and the vacuum system[29].

It is hoped to fund the project in a similar way to HERA. The Province of British Columbia has already agreed to provide the buildings and tunnels (~$100 million). In the U.S. the new NSAC Long Range Plan recommends $75 million (U.S.) support for KAON spread over the five-year construction period as "exceptionally cost-effective". In West Germany the planning committee for Medium Energy and Nuclear Physics has recommended support. Participation is also expected from Japan and Italy, proportionate to the number of their potential users. A number of other countries will contribute manpower towards design and construction and equipment for experiments. Altogether there seems to be the potential for one-third of the total cost of $571 million (1987 Canadian dollars) to be provided by foreign partners. The Pre-construction Study report will be submitted to the Canadian government early in 1990 and its funding decision is expected by mid-year.

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