THE KAON FACTORY AT TRIUMF

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ABSTRACT

The TRIUMF KAON Factory is designed to produce beams of kaons, antiprotons, other hadrons and neutrinos 100 times more intense, or cleaner, than are available now, for a broad range of particle and nuclear physics experiments. This will require a 100 μA beam of 30 GeV protons, to be produced by an interleaved sequence of two fast-cycling synchrotrons and three storage rings, with the existing TRIUMF H^- cyclotron as injector. An $11-million preconstruction study has enabled the overall design to be reviewed and prototypes of various components to be built and evaluated – fast-cycling dipole and quadrupole magnets, a dual-frequency magnet power supply, ceramic beam pipes with internal rf shields, an rf cavity (using perpendicular bias), an extraction kicker, an rf beam chopper, and production targets. Environmental, industrial and economic impact studies have also been completed and the cost estimates and schedule updated. The total cost of $708 million (Canadian) will be shared equally between Canada, British Columbia and international contributors; the first two-thirds of this sum have already been approved and negotiations for the remainder are under way.

1. INTRODUCTION

The TRIUMF Kaon-Antiproton-Otherhadron-Neutrino Factory is described in full in the original proposal[1)] and in the revised version[2–4)] issued in 1990. The basic aim is to accelerate a 100 μA beam of protons to 30 GeV, roughly 100 times the intensity available now. This would provide correspondingly more intense – or pure – beams of secondary particles (kaons, pions, muons, antinucleons, hyperons and neutrinos) for particle and nuclear physics studies on the "precision frontier", complementary to the "energy frontier". 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
- properties of hypernuclei
- K^+ and $\bar{p}$ scattering from nuclei.

The physics case for K factories is fully described in the proposals[1,4)] and in the proceedings of ten specialized workshops sponsored by TRIUMF in Germany, Italy, Japan and Canada during 1988-89. The strong international interest was confirmed by the attendance of 257 prospective users at a general workshop on "Science at the KAON Factory" held in Vancouver in July 1990 to initiate experimental collaborations.[5)]

From 1988 to 1990 the project was the subject of an $11-million pre-construction Engineering Design and Impact Study funded jointly by the governments of Canada and British Columbia. This comprehensive study was designed to provide all the information needed for the governments to take a funding decision. The topics covered include:

- review of the scientific justification
- accelerator and experimental facilities designs
- construction of prototype components
- design of buildings and tunnels
- review of cost estimates and schedule
- study of Canadian industrial capability
- environmental, legal and economic impact studies
- international consultations on funding.

This paper will review the results of these studies, and of the ongoing R&D, except for work on extracting H^- ions intact from the TRIUMF cyclotron, which is discussed in detail by Dutto[6)] and by Laxdal *et al.*[7)]

2. ACCELERATOR DESIGN

The TRIUMF H^- cyclotron, which routinely delivers 150 μA beams at 500 MeV, provides a ready-made and reliable injector. It would be followed by two fast-cycling synchrotrons, interleaved with 3 storage 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; circumference 216 m
C	Collector:	collects 5 Booster pulses and manipulates longitudinal emittance
D	Driver:	10 Hz synchrotron; accelerates to 30 GeV; circumference 1078 m
E	Extender:	30 GeV stretcher for slow extraction for coincidence experiments

This arrangement allows the B and D rings to run continuous acceleration cycles without flat bottoms or flat tops, as shown in the energy-time plot (Fig. 1). The use of a Booster permits a smaller normalized emittance and hence reduces the aperture and cost of the Driver magnets for a given space-charge tune shift. The use of a Booster also simplifies the rf design by separating the requirements for large frequency swing and high voltage (33% and 750 kV respectively for the Booster, and 3% and 2550 kV for the Driver). These high rf voltages are associated with the high cycling rates; the use of an asymmetric magnet cycle with a rise 3 times longer than the fall in the Driver reduces the voltage required by one-third, and the number of cavities in proportion. In the Booster the saving is less because more voltage is needed for bucket creation.

Figure 2 shows the proposed layout together with the tunnel cross sections. The Accumulator will be mounted above the Booster in the small tunnel and the Collector above the Driver in the main tunnel. The Extender will be installed towards the outer wall of the tunnel, separated by ~4 m horizontally from the Driver. Similar 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.

Separated-function magnet lattices are used with the dispersion modulated so as to lower its mean value and keep transition above top energy in all rings. This avoids transition-crossing problems such as emittance mismatch and change of rf phase under high beam loading. Racetrack lattices have been adopted for the C, D and E rings, and are being studied for the smaller rings;

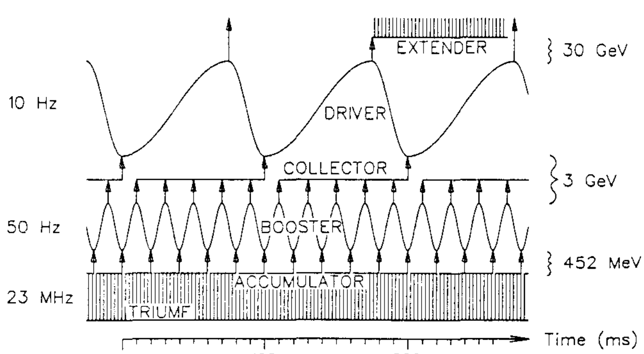

Fig. 1. Energy-time plot showing the progress of the beam through the five rings.

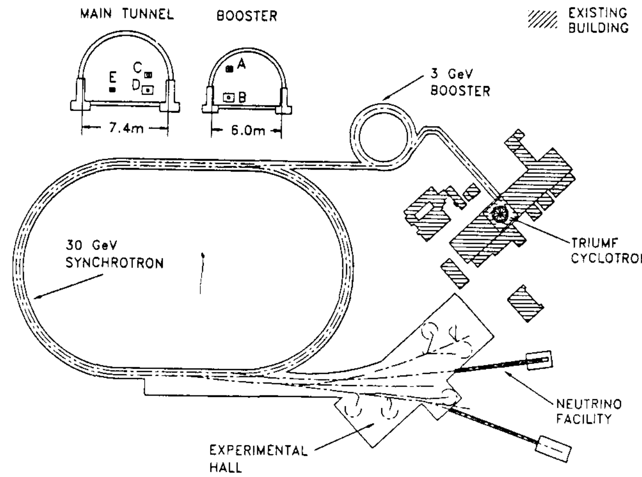

Fig. 2. Proposed layout of the accelerators and cross sections through the tunnels.

but the reference designs for the latter are almost circular, with superperiodicity 6 for the Booster and 3 for the Accumulator.

Injection into the Accumulator is achieved by stripping the H^- beam from the cyclotron, enabling many turns to be injected into the same area of phase space. The small emittance H^- beam is in fact "painted' over the much larger three-dimensional acceptance of the Accumulator 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.

3. BEAM DYNAMICS

In order to cut beam loss during slow extraction well below the usual 1%, racetrack lattices have been adopted for the C,D and E rings. These provide long straights with high β (100 m) at the septa and room for an additional pre-septum and for collimators downstream. Tracking simulations, which include power supply noise effects, suggest that the beam loss can be kept below 0.2%. The loss on the extraction elements amounts to 0.005%. The 180° arcs contain 24 cells, and are second-order achromats, normally tuned to $5 \times 2\pi$. The tune for the whole ring may be varied by ± 1 in each plane independently. A half-integer resonance may be used for extraction, to simplify the collimation process. Such a racetrack lattice is also convenient for the Driver synchrotron, allowing either for the insertion of Siberian snakes, or for tuning for low depolarization without snakes, using high-periodicity arcs and spin-transparent straight sections. Quadrupole matching sections for the Siberian snake have now been designed with very smooth excitation cycles.

Tracking studies show that the dynamic aperture of the lattice is as large as for the old circular design. Various measures have been taken to speed up the tracking. The first has been to vectorize and streamline the DIMAD code, resulting in six times faster operation. The second has been to use differential and Lie algebra techniques to produce higher order maps directly. A new tracking code DIMFAST, able to transfer maps with DIMAD, COSY∞ and DALIE, is now in use.[8]

The Booster reference lattice has 24 FODO cells with 6 OBOBBOBO missing-magnet superperiods. An alternative 3-cell superperiod (OBBBBO), derived from that proposed for the Moscow kaon factory booster[9] and providing larger dynamic aperture and dispersionless straight sections, is under study.[10] Such a lattice would require a larger circumference or, less favourably, a lower top energy for the Booster.[11] Wienands *et al.*[12] use a similar structure for the Low Energy Booster of the SSC. For both machines the new code package has enabled sextupole resonance correction schemes to be determined. Simulation studies of collimator arrangements for the Booster have shown that 80% collection efficiences can be achieved with copper and 90% with tungsten.

Longitudinal effects of importance include synchrobetatron resonances and coupled-bunch instabilities. Recent studies on these topics include the discovery of a rather tight tolerance (0.1%) on the vertical asymmetry in accelerating gap voltage[13] and the determination of stationary phase-space distributions in the presence of space charge.[14] A test stand has been set up for accurate measurement of the longitudinal impedance of components of the rings, using the TSD-calibration method.

To synchronize each of the five pulse trains from the Booster to about 1 ns, for transfer to the Collector, a feedback scheme has been devised, based on heterodyning the Booster's revolution frequency with an ideal frequency.[15] A scheme has also been devised for shortening the base length of the extracted proton bunches from 3 ns to 0.5 ns, for better timing in experiments.

4. MAGNETS AND POWER SUPPLIES

A prototype Booster dipole magnet has been built and its field measured.[16] The magnet is 3 m long with a pole gap of 10.7 cm and is designed to cycle at 50 Hz between 0.27 T and 1.12 T with a field uniformity $< \pm 2 \times 10^{-4}$ over ± 5 cm. The prototype is constructed from 26-gauge laminations of M17 (non-grain oriented) steel. The dc field surveys showed the field uniformity to be within specifications; ac surveys have also been made. A prototype quadrupole for the Booster has been built using indirectly cooled coils and its field measured. Initial reference designs have been made for the various other magnets needed, to establish dimensions, material requirements and costs.

The test stand used previously to investigate the dual-frequency excitation of a NINA synchrotron magnet has been reconfigured (Fig. 3) for testing the Booster dipole.[17] Four NINA magnets are wired in parallel to act as the dc bypass choke and there are new capacitor banks and power supplies. Both dipole and quadrupole have been tested at full power in ac tests with dc bias.

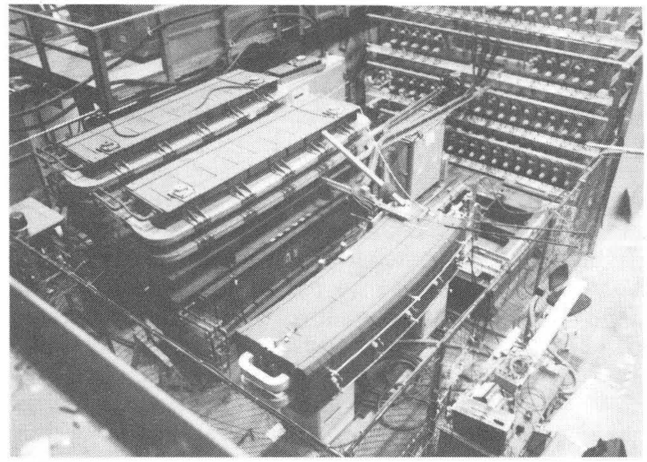

Fig. 3. Magnet test stand, showing the prototype Booster dipole (front), choke magnets (left) and capacitor bank (behind, right).

5. KICKERS AND CHOPPER

A prototype kicker of the transmission-line type has been built for Booster extraction – the most challenging case – based on CERN PS designs. A pulse generator and pulse forming network were obtained on loan from CERN and successfully modified to increase the cycling rate from 1 Hz to 50 Hz. Sufficiently flat 40 kV pulses were obtained, 600 ns long and with 5% –95% rise and fall times better than 30 ns.[18] Simulations show that pre- and post-pulse kicks can be suppressed using ferrite saturating inductors, bringing the entire 1% – 99% region within 30 ns.[19]

A prototype has also been built of the 1 MHz chopper[20] (Fig. 4) required in the transfer line from the cyclotron to create the 110 ns beam gap needed for kicker rise and fall. The stripline deflector plates must provide 38 kV-m with rise and fall <35 ns. Energy storage and power saving are provided by a 150-m (0.5-μs)-long coaxial delay-line cable 10 cm in diameter. Initial tests of this novel concept have been promising, 11 kV pulses being produced with rise and fall times of 22 ns, meeting the specification.

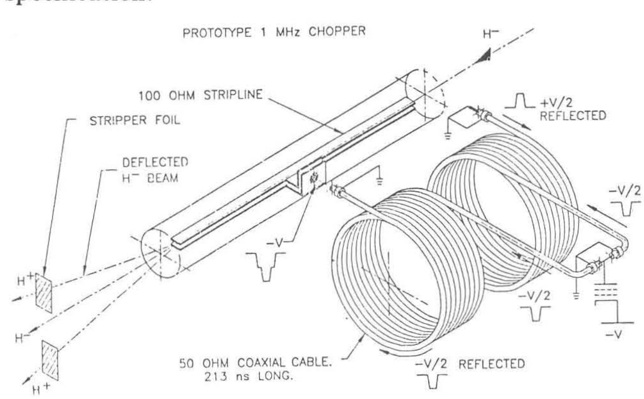

Fig. 4. Schematic diagram of rf beam chopper.

6. RADIO-FREQUENCY SYSTEMS

Recent work has concentrated exclusively on the full-scale prototype booster cavity built at LAMPF using perpendicularly-biased microwave ferrite.[21] Under dc bias at Los Alamos it produced relatively high voltages (over 100 kV), potentially reducing the number of cavities required and also the impedance presented to the beam and the likelihood of inducing coupled-bunch instabilities. The tuner has now been completely reconstructed at TRIUMF to permit ac operation, with stranded cable, a laminated yoke and improved cooling. The first high-power tests were successfully completed in 1991, demonstrating 50 Hz operation over the full 46–61 MHz range with the required maximum gap voltage of 65 kV (Fig. 5). This is believed to be the first full-scale demonstration of the superior capabilities of perpendicularly-biassed ferrite tuners.

Work is now proceeding on feedback control of the cavity. The fast feedback loop and a bias tuning loop around the amplifier chain have been successfully closed under dc biased conditions. Design of the rf control loops for ac biasing is underway, based on measurements of the frequency response of the tuner. The ac magnetic field of the tuner has also been measured.[22]

A new initiative is the testing on this cavity of a varactor, a magnetron-like capacitative tuning device, in collaboration with INR and RTI, Moscow.[9] This would avoid the magnetic field and eddy current problems associated with ferrite tuners.

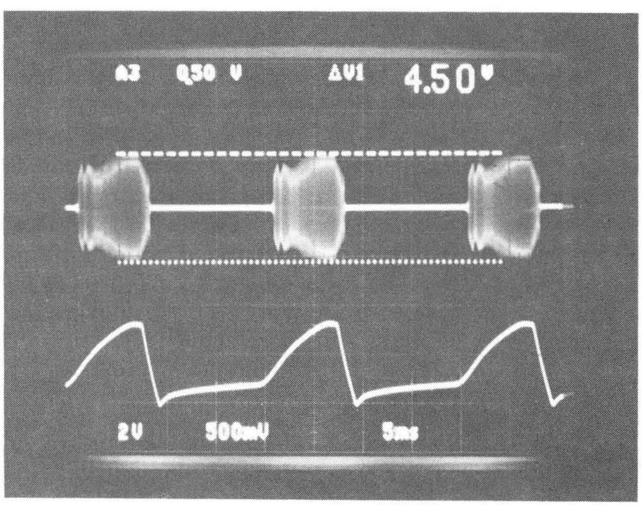

Fig. 5. High power operation of rf cavity using perpendicularly biassed ferrite. The top trace shows voltage at the accelerating gap (dashed lines indicate 65 kV), the lower trace the bias power supply current.

7. BEAM PIPE AND VACUUM

The high circulating beam current makes beam-induced multipactoring and ion desorption from the walls the most critical processes for the vacuum system. A hydrocarbon-free system is required with all metal elements pre-baked to 300°C, and pumps spaced no more than 5 m apart, an arrangement that will ensure a vacuum better than 10^{-8} Torr. An additional concern in the Extender ring, where the beam may be debunched, is the possibility of electron-proton oscillations; electrostatic collector plates will be needed to suppress these.

Ceramic chambers must be used within the fast-cycling magnets but must contain a conducting shield to provide a low impedance path for the image currents. Two shielding schemes are being considered and for each a 4-m-long prototype chamber is being constructed for the Booster dipoles.[23] That from RAL (UK), incorporating a separate wire cage, as used in the ISIS synchrotron, has been delivered (Fig. 6) and has successfully undergone vacuum tests; bakeout at 100 C appears to be essential for a quick pumpdown. RAL has subsequently doubled the length of the pipe segments to 50 cm and simplified the supports for the cage. That from SAIC (San Diego) has longitudinal silver stripes laid down directly in internal grooves in the pipe; three 1.3 m-long curved sections have now been completed and joined by glazing to form a single 3.9 m pipe. Recent vacuum tests achieved 2×10^{-9} Torr after 24 h bakeout at 100° C.

Short sections of pipe have also been produced with the stripes specially configured to form beam position and higher-order moment monitors. Tests with the 500 MeV cyclotron beam confirmed the expected position sensitivity, while lab tests have shown that quadrupole moments can be measured quite accurately.[24]

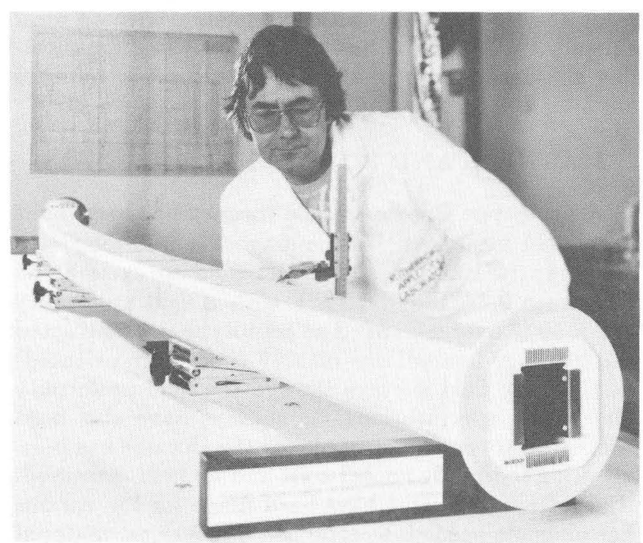

Fig. 6. Ceramic pipe and wire shield (RAL design).

8. COMPUTER CONTROL SYSTEM

The system architecture will be based on a general-purpose local area network, interconnecting the operator consoles (workstations), the microprocessor-based equipment controllers, the database management system, and the software development facilities. Object-oriented techniques have been used to specify a logical model of the entire control system organized in a hierarchical structure.

Two prototype development projects are under way to evaluate the design methodology. One project, to upgrade a PDP-11 based radio-isotope production control system on beam line 2C, has succeeded in replacing the PDP-11 hardware and software with less than 1 man-year of effort. New software now runs on VAX stations and employs a commercial graphical user-interface package. A second project is under way to control an auxiliary rf cavity in the cyclotron.[25)]

9. EXPERIMENTAL AREAS AND TARGETS

The slow extracted proton beam will be shared between two lines each with two production targets. Each target will feed at least two forward K and $\overline{p}$ channels, and in some cases backward μ channels. The six charged kaon channels will have maximum momenta of 0.55, 0.8, 1.5, 2.5, 6 and 21 GeV/c. With solid angle and momentum acceptances ranging from 8 msr × 6% for the lowest momentum channel to 0.1 msr × 1% for the highest, the maximum fluxes range from 0.6 to 3.7×10^8 K^+/s and from 0.7 to 11×10^7 $\overline{p}$/s. The 0.8 GeV design has been used for the new LESB3 channel at Brookhaven. Initial commissioning runs this summer have achieved fluxes of 3×10^6 $K^+/\mu C$ protons, with K^+/π^+ ratios up to 5:1, an order of magnitude improvement over LESB1.[26)]

A dedicated line and area is provided for polarized proton beams. The neutrino production target, fed by the fast extracted beam, is located in the main experimental hall for good crane access, but the neutrino experimental area is in a separate building. Target development has included both modification of an existing rotating graphite target (driven and cooled by water) from graphite to tungsten, and the construction of a prototype target rotated by a flexible cooling line. Successful tests have also been carried out on remote welding of aluminum flanges for high-radiation areas.

10. IMPACT STUDIES

The industrial capability study showed that nearly 200 Canadian firms are capable of being key contractors for high technology components worth $316 million. Over 85% of these components are accorded high priority in such areas as robotics, microelectronics and software.

The environmental impact study identified various concerns: ground water changes or contamination, noise, effects on trees and wildlife, cooling tower vapour, energy consumption, electromagnetic radiation from power lines, and public access to a nearby park. Following two public meetings, none of these was judged serious enough to require reconsideration of the project.

The economic impact study assessed the total industrial activity and employment that would be created during construction and operation. Even without counting the benefits from applications and spin-offs, it was concluded that nearly 80% of the project costs would eventually be recovered by the government in taxes and other revenues.

11. INTERNATIONAL PARTICIPATION

Funding for the project is being sought along the same lines as for HERA, where a number of countries have contributed accelerator components. To assess the prospects, a Canadian delegation visited several countries during 1989 under the auspices of the Department of External Affairs. In the US the NSAC Long Range Planning Committee recommended $75 million (US) for KAON construction and an additional $30 million for experimental equipment. The construction money has been included in DOE budget planning and was confirmed in the base budget recommended by the Schiffer subcommittee in April 1992. Germany, France and Italy have also promised support, proportional to the number of their potential users. Participation is also expected from Japan, where there is a large potential user community, a history of collaboration with TRIUMF, and strong support from the Nuclear and High Energy Physics Committees and from the Science Council of Japan. A number of other countries – Israel, PR China, South Korea, UK and Russia – will contribute manpower towards design and construction and equipment for experiments. Altogether the delegation estimated that the total foreign contribution to construction would be close to $200 million.

12. PRESENT STATUS OF THE PROJECT

The reports of the various studies, amounting to about 2800 pages altogether, were formally submitted to the governments of Canada and British Columbia in May 1990. The cost of the project is of course of major interest to government. With a six-year construction period, the total cost was estimated to be $708 million in 1989 Canadian dollars; the operating cost would $90 million per year. In September 1990 the province of British Columbia announced that it would increase its support from one-sixth to one-third of the total, or $236 million. In September 1991 the Government of Canada followed suit, offering a second $236 million. In October, however, an election and change of government in B.C. delayed progress while the new party settled into office. In May they renewed a pledge by the previous B.C. government to contribute to the operating costs. Canada responded by appointing the previous provincial minister and KAON champion, Stan Hagen, as leader of negotiations with other countries to confirm their pledges towards the remaining one-third of capital costs. These are scheduled to begin in August and be complete within a few months, enabling construction to begin in 1993.

13. ACKNOWLEDGEMENTS

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