The TRIUMF KAON Factory

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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 (already approved) and international contributors. The federal decision is expected shortly.

I. 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 last year. 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 [1,3] 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].

Over the last two and a half years the project has been 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.

II. 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:	main 10 Hz synchrotron; accelerates beam to 30 GeV; circumference 1078 m
E	Extender:	30 GeV stretcher ring 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. 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

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number of cavities in proportion. In the Booster the saving is less because more voltage is needed for bucket creation.

Figure 1 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 now been adopted for the C,D and E rings, but the smaller rings 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.

III. BEAM DYNAMICS

In order to cut beam loss at slow extraction well below the usual 1%, racetrack lattices have been adopted for the C,D and E rings (Servranckx *et al.* [6]). 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.

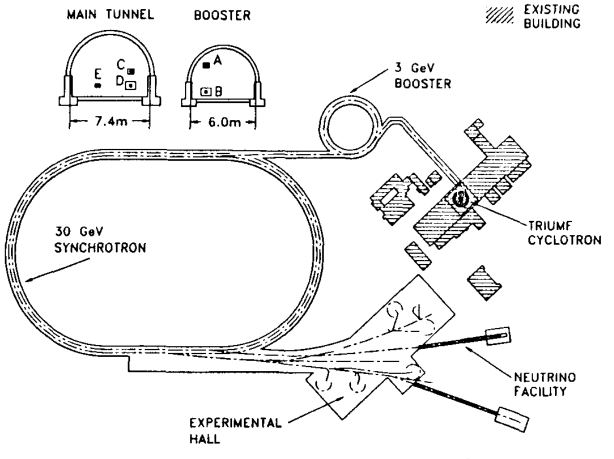

Fig. 1. Proposed layout of the accelerators and cross sections through the tunnels.

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 approach has been to vectorize and streamline the DIMAD code, resulting in six times faster operation. The second, more radical, approach is to use differential algebra techniques to produce higher order maps directly [7].

The Booster lattice has 24 FODO cells with 6 OBOBBOBO missing-magnet superperiods. An alternative dipole arrangement (OBBBBO), based on that proposed for the Moscow kaon factory booster [8], is under study and promises to provide a larger dynamic aperture and dispersionless straight sections [9]. Simulation studies of collimator arrangements for the Booster have shown [10] that 80% collection efficiences can be achieved with copper and 90% with tungsten.

Longitudinal collective effects which have been studied recently include the influence of the density distribution on coupled-bunch beam stability [11], determination of stationary distributions in the presence of space charge [12], the effects of non-linear steady-state wakefields (normally neglected in bunched-beam theory) [13], and the seeding of coupled-bunch modes by uneven bucket populations [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 [15].

IV. MAGNETS AND POWER SUPPLIES

A prototype Booster dipole magnet has been built and the field distribution is now being 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. An initial magnetic field survey has been made under dc excitation and shows the field uniformity to be within specifications. A prototype quadrupole for the Booster has also been built using indirectly cooled coils. 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 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 at 50 Hz.

V. 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 rise and fall times better than 30 ns. With the kicker connected the field rise time was over 80 ns rather than the 57 ns desired, and some modifications are under way to improve the impedance matching.

A prototype has also been built of the 1 MHz chopper [18–21] (Fig. 2) 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, 16 kV pulses being produced with rise and fall times close to specification.

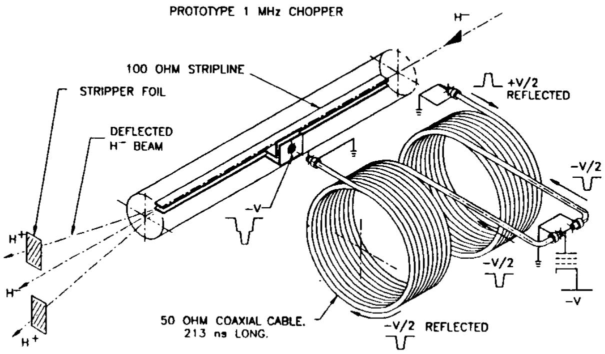

Fig. 2. Schematic diagram of rf beam chopper.

VI. Radio-frequency Systems

Recent work has concentrated exclusively on the full-scale prototype booster cavity built at LAMPF using perpendicularly-biased microwave ferrite. 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 have recently been successfully completed [22,23], demonstrating 50 Hz operation over the full 46–61 MHz range with the required maximum gap voltage of 65 kV (Fig. 3). This is believed to be the first full-scale demonstration of the superior capabilities of perpendicularly-biassed ferrite tuners.

Recent rf control studies include estimates of the tuner accuracy and bandwidth required with and without fast feedback [24], and evaluation of schemes for controlling rf transients in the heavily beam-loaded Collector as each of the 5 pulse trains is injected [25].

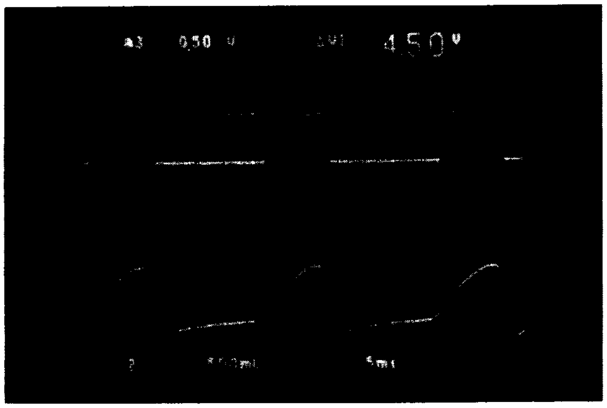

Fig. 3. High power operation of rf cavity using perpendicularly biassed ferrite. The top trace shows voltage at the accelerating gap (dashed lines indicate 65 kV), the lower trace the bias power supply voltage.

VII. 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 [26]. That from RAL (UK), incorporating a separate wire cage, as used in the ISIS synchrotron, has been delivered and successfully undergone vacuum tests (Fig. 4). 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. A short section of pipe has also been produced with the stripes specially configured to form a beam positon monitor. Tests with the 500 MeV cyclotron beam confirmed the expected sensitivity and showed a linear response to position [27].

VIII. Computer Control System

The system architecture will be based on a general-purpose local area network, interconnecting the operator

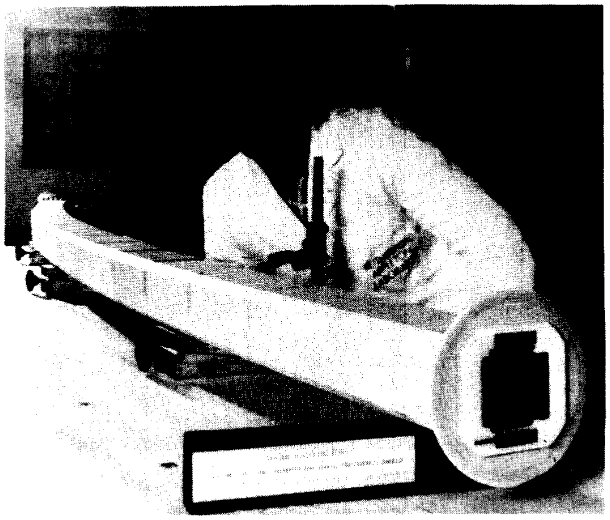

Fig. 4. Ceramic pipe and wire shield (RAL design).

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 [28].

IX. H^- EXTRACTION FROM THE CYCLOTRON

To extract H^- ions (instead of stripping them to protons as in normal operation) a conventional extraction system is being developed. With 18 kV on an rf deflector, which excites the ν_r=3/2 resonance, and 50 kV on the electrostatic deflector, 87% of the beam (100 μA macropulses at 5% duty factor) has been transmitted through the latter. The other 13% is stripped by a narrow foil shadowing the septum and protecting it from heating and irradiation; the resulting protons may be dumped or steered into an experimental beam line. In recent tests the average beam current was successfully raised to 30 μA. Design of the 4-segment magnetic channel which will steer the H^- beam out of the cyclotron is under way and one segment has been completed and installed in the cyclotron. Beam tests show full transmission through the channel (Fig. 5) without any disturbance to the circulating beam [29]. Detailed design of the front end of the external beam line is also under way.

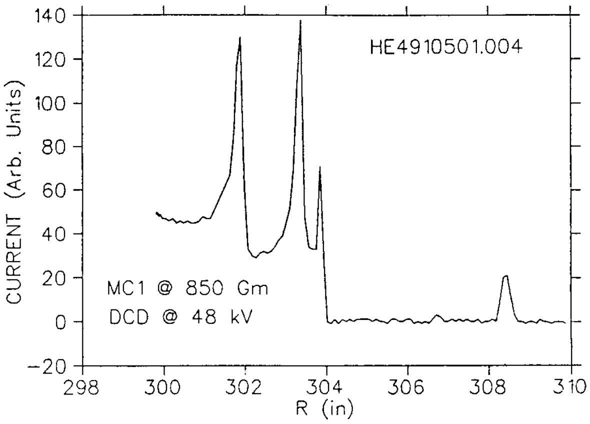

Fig. 5. Radial beam density scan in the cyclotron, showing separated beam downstream of the magnetic channel.

X. 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 $\bar{p}$ 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 x 6% for the lowest momentum channel to 0.1 msr x 1% for the highest, the maximum fluxes range from 0.6 to 3.7 x 10^8 K^+/s and from 0.7 to 11 x 10^7 $\bar{p}$/s. 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.

XI. 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 a number of 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, it was decided that none of these was 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.

XII. 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. 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 strong scientific support. A number of other countries – Israel, PR China, South Korea, UK and USSR – 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.

XIII. 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 on 24 May 1990. During the summer they were reviewed by the Interdepartmental Committee on Big Science and the National Advisory Board on Science and Technology, for advice to the ministers and cabinet.

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. The province of British Columbia has recently announced that it would increase its support from one-sixth to one-third of the total, or $236 million. As indicated above, contributions from other countries and other Çanadian provinces could bring in another third. The remaining third would be provided by the Government of Canada. The question is now in front of the cabinet and we look forward to a favourable decision within the next few weeks.

XIV. ACKNOWLEDGEMENTS

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