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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 experiments in particle and nuclear physics. 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 accelerator components to be built and evaluated. Environmental, industrial and economic impact studies have also been completed. Payment of one-third of the total cost of $708 million (Canadian) has been approved by the Government of British Columbia; a further third is expected from international sources, on the basis of inter-governmental consultations. A decision on the final third is expected from the Government of Canada before the end of 1990.

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 this year. The basic aim is to accelerate a 100 μA beam of protons to 30 GeV, roughly 100 times the intensity available at present. This would provide correspondingly more intense – or pure – beams of secondary particles (kaons, pions, muons, antinucleons, hyperons and neutrinos), as first proposed by Basargin *et al.*[5], 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.

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 notable example was the setting of a lower limit of 380 GeV on the mass of any right handed W-boson by a muon decay measurement at TRIUMF in 1982. Others include improved confirmation of muon-electron universality and the first observations of the muonium Lamb shift and of the breakdown of charge symmetry in neutron-proton scattering.

For kaon decay the branching ratios attainable for various channels will be improved by two orders of magnitude, pushing up the mass limits on scalar Higgs bosons and exotic particles such as leptoquarks. A comprehensive justification of the physics case for K factories may be found in the proposals[1,3] and in the proceedings of the ten specialized workshops sponsored by TRIUMF in Germany, Italy, Japan and Canada during 1988-89. Some reviews are also given in the proceedings[6] of the INES-89 Seminar on Intermediate Energy Physics, held in Moscow a year ago. 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.

Over the last two 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
- review of the accelerator and experimental facilities designs
- construction of prototype accelerator and target 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.

The initial stages of this study were reported[7] at INES-89; after a brief review of the basic design, this paper will emphasize the progress made during 1990.

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

The energy-time plot in Fig. 1 shows how 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

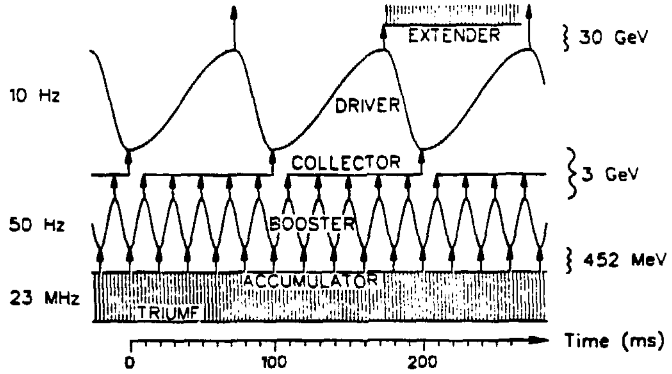


Fig. 1. Energy-time plot showing progress of the beam through the five rings.

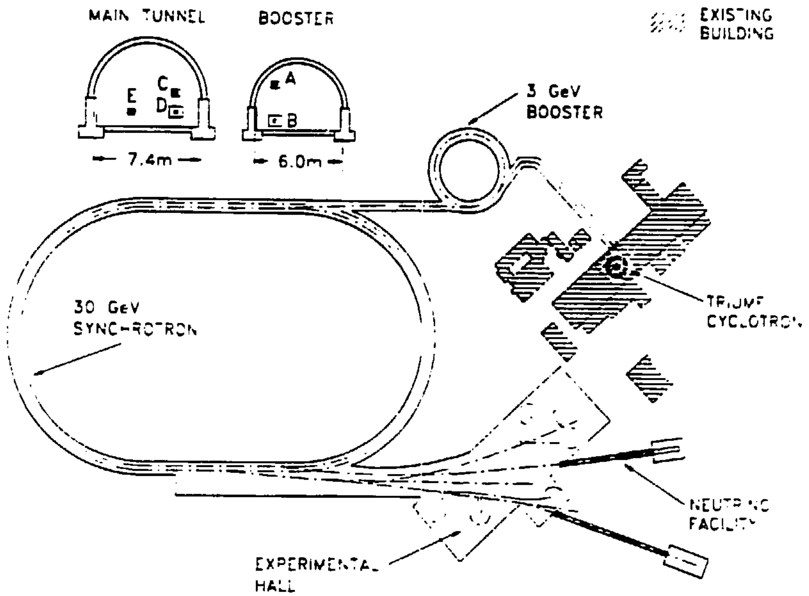


Fig. 2. Proposed layout of the accelerators and cross sections through the tunnels.

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 or 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 (Fig. 1) 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.

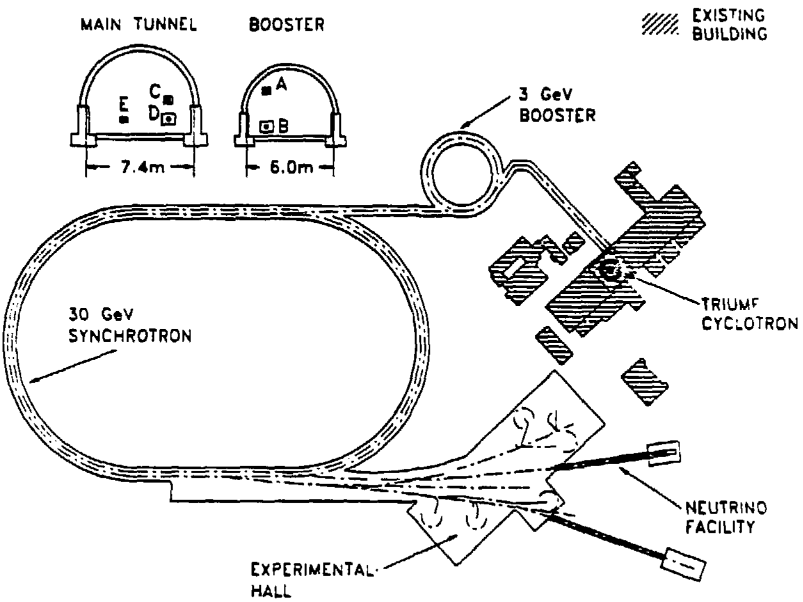
Figure 2 shows the proposed layout of the accelerator rings and experimental areas, together with cross sections through the tunnels. The Accumulator will be mounted above the Booster in the small tunnel and the Collector above the Driver on the inside of the main tunnel. The Extender would be installed towards the outer wall of the tunnel, separated by $\sim$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 drive its mean value towards zero, enabling transition to be kept 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 beam from the injector 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.

Beam dynamics

In order to cut beam loss at slow extraction well below the usual 1%, racetrack lattices have now been adopted for the C,D and E rings (Servranckx *et al.*[8]). 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



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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 make tracking computations faster. 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 (Servranckx[10]).

Longitudinal collective effects, which have been studied both analytically and by simulation, include coupled-bunch instabilities induced by empty rf buckets, dilution of the longitudinal emittance by means of high harmonic cavities, and the behaviour of space-charge dominated beams which are hollow in longitudinal phase space. In the latter case an apparent inconsistency between theory and simulation[11] has now been resolved. Koscielniak[12] and Baartman show that the non-linear parts of the steady-state wakefields, which are usually neglected, may produce large changes in instability thresholds; for instance higher-order radial dipole modes may have lower thresholds than the rigid mode. Commonly-used beam stability codes do not take account of this effect.

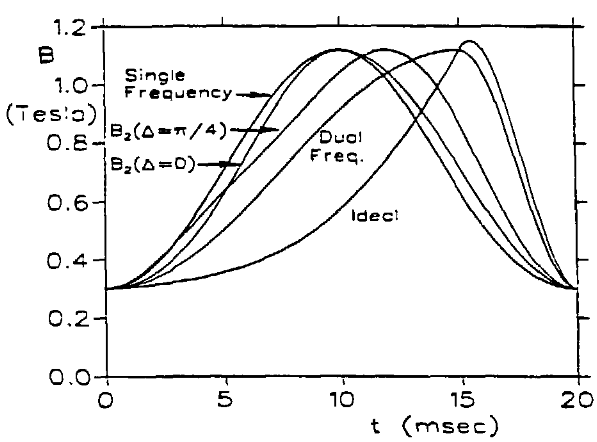

Fig. 3. Various magnetic field waveforms considered for the Booster (including some with second harmonic components at phase Δ).

Various magnet waveforms have been investigated[13] with the aim of simplifying the radio-frequency system. An "ideal" waveform (Fig 3) is derived giving constant bucket area for constant rf voltage. This not only simplifies the rf system but minimizes the rf voltage. The magnetic field rises very slowly at first but faster and faster as top energy is approached. Although digitally controlled power supplies are more expensive than resonant ones, there might be an overall cost saving in the smaller Booster ring where the rf voltage would be reduced from 750 kV to 500 kV. Further advantages of this scheme are that it avoids initial increases in both $\Delta\nu_x$ and ν_s, that programmable supplies give extra flexibility. and that separate supplies for dipoles and quadrupoles should allow accurate tracking to be achieved between them.

Magnet Development

A prototype Booster dipole magnet has been built (Fig 4) and the field distribution is now being measured. 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. The first tests are now underway with ac excitation. A prototype quadrupole for the Booster is also under construction. Initial reference designs have been made for the various other magnets needed, to establish dimensions, material requirements and costs.

Magnet Power Supplies

The test stand used previously to investigate the dual-frequency excitation of a NINA synchrotron magnet has now been reconfigured for testing the Booster dipole. Four NINA magnets are now wired in parallel to act as the dc bypass choke and there are new capacitor banks and power supplies. Ac excitation tests are being carried out at 50 Hz and the peak-to-peak current swing has reached 1500 A, with a target of 4000 A.

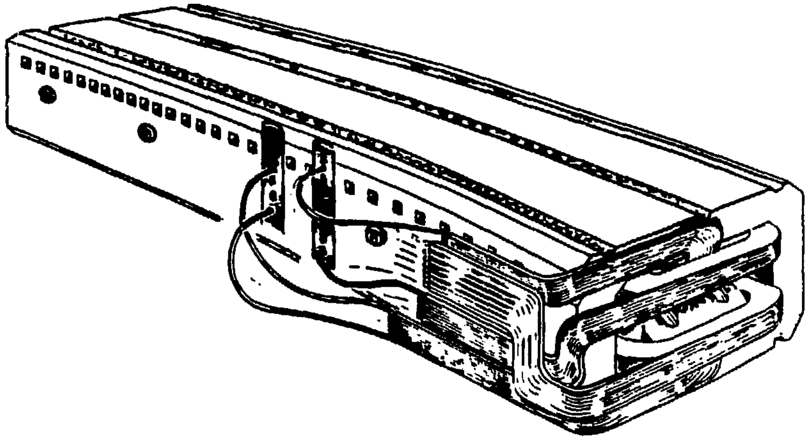

Fig. 4. Prototype Booster dipole magnet.

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[14] (Fig 5) of the 1 MHz chopper 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, with 8 kV pulses being produced with a rise time of 23 ns.

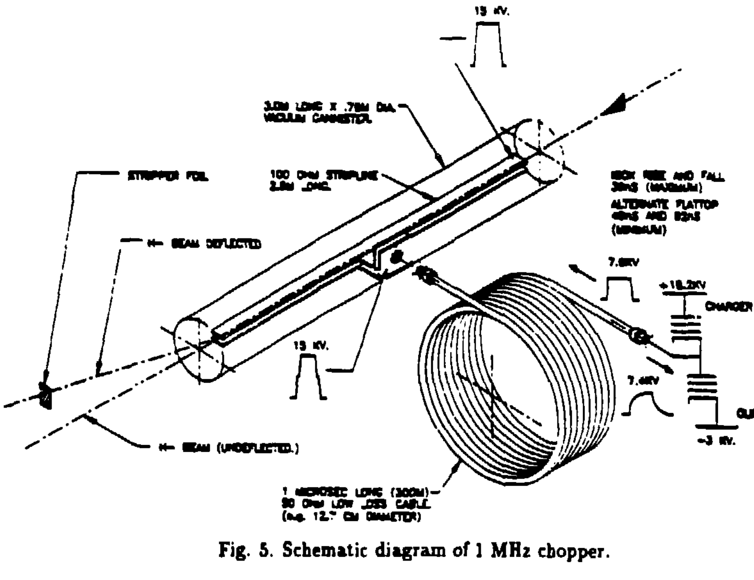

Fig. 5. Schematic diagram of 1 MHz chopper.

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 hence 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[15]. Tests with signal-level rf have confirmed that the 46-61 MHz frequency range is achievable with 50 Hz biasing, just as for dc operation (Fig 6). Tests at higher rf power levels are just beginning.

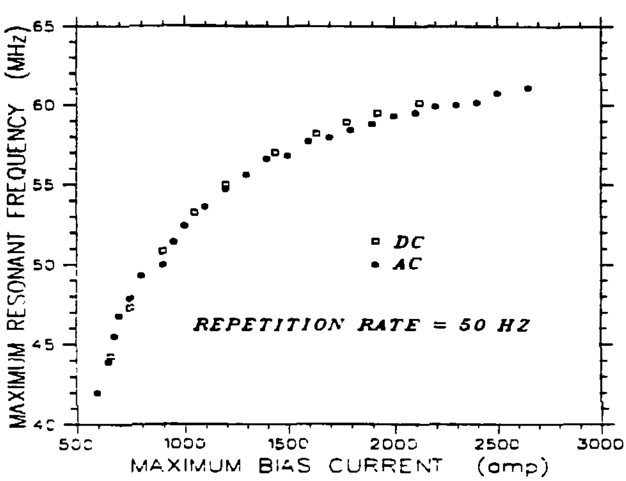

Fig. 6. Booster cavity frequency versus tuner bias current for dc and 50 Hz ac biasing.

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. That from RAL (UK), incorporating a separate wire cage, as used in the ISIS synchrotron, has been delivered and is now undergoing vacuum tests. That from SAIC (San Diego), with longitudinal silver stripes painted on the inside walls, should be complete by the end of the year. SAIC is also constructing a short section of pipe with the stripes specially configured to form a beam position monitor.

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. Next month a commercial control package incorporating a distributed real-time database will undergo operational tests on the cyclotron beam line 2C system, which is used to deliver 70-100 MeV beams for isotope production. A test platform has also been assembled based on a SUN 3/60 workstation and two VME crates to study the use of CASE tools, C-code generators and message-passing operating systems to help in the creation of control software.

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 $\nu_r=3/2$ 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 20 μA. Design of the 4-segment magnetic channel which will steer the H^- beam out of the cyclotron is now under way and one segment has been completed and installed in the cyclotron. The first tests with beam have confirmed that it can circulate within 15 mm of the septum coil – the operational distance – without disturbance. Detailed design of the front end of the external beam line is also under way.

Experimental Areas and Targets

The layout of the experimental area is shown in Fig 7. 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 × 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 $\bar{p}$/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.

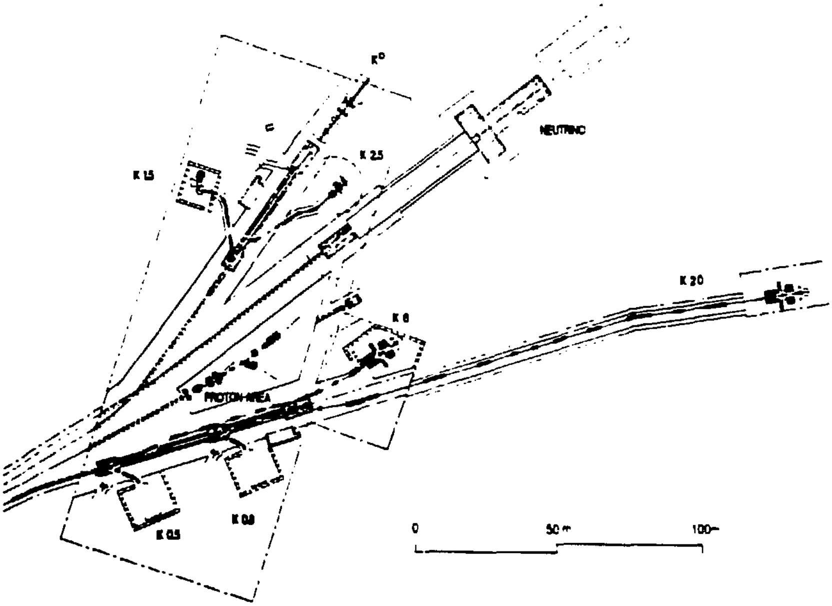

Fig. 7. Layout of the experimental areas and primary and secondary beam lines.

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 taking into account any 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.

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 the DOE budget request for FY 1992-6. 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.

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 is 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 Canadian provinces could bring in another third. The remaining third would be provided by the Government of Canada. The question will be going to the cabinet within the next few weeks and we look forward to a favourable decision before the end of 1990.

Acknowledgements

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