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PULSED NEUTRON SOURCES AT KAON

I.M. Thorson, P.A. Egelstaff* and M.K. Craddock
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3

ABSTRACT

The proposed KAON Factory facility at TRIUMF consists of a number of synchrotrons and storage rings which offer proton beams of energies between 0.45 and 30 GeV with varying pulse amplitudes, widths and repetition rates. Various possibilities for feeding these beams to a pulsed neutron facility and their potential for future development are examined. The incremental cost of such a pulsed neutron facility is estimated approximately.

I. INTRODUCTION

During the past ten years countries involved in major neutron scattering programs (e.g. U.S.A., U.K. and Japan) have developed pulsed neutron sources based on high intensity proton accelerators. These sources offer the neutron scattering communities in these countries, the opportunity to build programs of research in new areas of science, and to both extend and complement their existing programs on reactor sources. After several years of development the new pulsed sources are operating on a reliable, continuous basis and many neutron spectrometers are in operation at each one. Other countries are becoming interested in this field also. For example the U.S.S.R. is considering several possible pulsed neutron sources based on the Moscow Meson Factory. Canada has played an important role in the development of neutron scattering but, because of its limited resources, has limited its efforts to focused programs at its two reactor sources (NRU and MNR). The advent of the KAON Factory proposal at Vancouver offers Canada the opportunity to bring about a diversification of its neutron scattering program at a reasonable cost ($\leq$\$50 M), by building a modern pulsed neutron facility. This diversification would occur in three significant categories, geographical location, kinds of neutron scattering instruments and areas of science investigated. The object of this paper is to discuss the possible kinds of pulsed neutron sources which may be built in conjunction with the KAON Factory, and to recommend a choice which is economically and technically viable, and which is competitive in some respects with other pulsed sources and with Canada's reactor source program.

The basic KAON facility proposal has not changed substantially since the previous report to ICANS[1]. The recent Project Definition Study (PDS) funded by the Canadian federal and British Columbia provincial governments has established more detailed specifications and cost estimates for the various components of the facility. At the request of the Canadian Institute for Neutron Scattering an examination was recently undertaken at TRIUMF[2] of the incremental accelerator and target/moderator components required to achieve a compet-

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*Present address University of Guelph, Guelph, Ontario

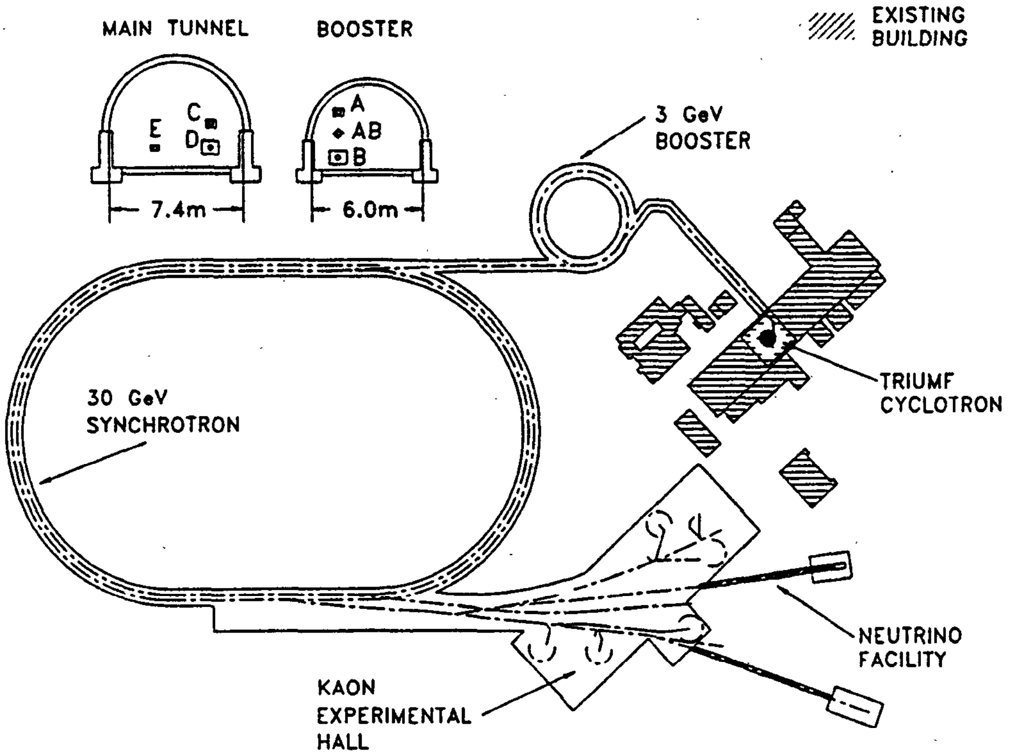

Fig. 1. The KAON facility layout following the 1989/90 project definition study.

itive pulsed neutron facility. The possibilities and requirements for simultaneous intensity optimization for both peak and integral flux beams from a single target/moderator were also addressed in reference 2 and elaborated in a later submission[3] to this meeting.

The facility layout resulting from the PDS is shown in Fig. 1. This layout takes into account the constraints of the site and others related to design contingencies and future expansion possibilities. Figure 1 shows the race-track configuration for the main rings which allows more space in the straight sections for beam conditioning and transfer elements. This layout has more possibilities for "add-ons" such as a pulsed neutron facility (PNF).

No experimental area from the intermediate energy (3 GeV) stage is currently included in the KAON plan although a 3 GeV beam could be available a year ahead of any 30 GeV staged operation. The construction schedule for the KAON project is very compressed. Only about 20 months is allowed from approval-in-principle to the beginning of the construction of the Booster tunnel and building; thus, any decisions about contingency provisions for adding a neutron facility, or any other 3 GeV facilities, without impacting other construction and installation work will need to be made early in that period.

In Section 2 we describe the components currently included in the revised KAON proposal following the PDS and enumerate the possible accelerator options and limited neutron facility possibilities within the presently planned KAON facilities and housing. Section 3 outlines the experimental hall, transfer line and target/moderator/shield assembly requirements for a dedicated add-on pulsed neutron facility. Section 4 defines the medium term developmental options that would be required to up-grade the facilities from Section 3 to a competitive world-class facility. Finally in Section 5 we discuss conclusions and some recommendations.

II. PRESENT KAON FACILITIES

A Accelerators and Beam Storage Rings

The KAON facility complex consists of two synchrotron accelerators and three proton beam storage rings as well as the present TRIUMF cyclotron used as a beam injector. The synchrotrons, being pulsed accelerators, require accumulation of the cw beam from the cyclotron in a storage ring, called the A ring or Accumulator, for approximately 20 ms; this ring has a circumference of 215 m and a circulation period for the 450 MeV protons of 0.85 μs. At the end of the accumulation cycle the beam is transferred, in one turn, to the Booster synchrotron, or B ring, of the same circumference, where it is accelerated in the next cycle to 3 GeV intermediate energy; the increased proton velocity shortens the circulation time for the protons to 0.65 μs. At the end of this cycle the beam from the Booster is transferred, again in one turn, to the Collector storage (C) ring that is 5 times as long as the A and B rings. The A and B rings operate continuously with a 50 Hz repetition rate accepting beam essentially continuously from the cyclotron at a design current of 100 μA. Five successive pulses from the B ring fill the C ring; every 100 ms the content of the C ring is transferred to the D ring, the Driver synchrotron, that accelerates it on the next 10 Hz cycle to the final 30 GeV energy. At the end of that cycle the beam is transferred in one turn (3.5 μs) to either a pulsed beam line such as the neutrino experimental facility or to the Extender storage (E) ring. The circulating beam in the E ring is continuously "spilled" over the next 10 Hz cycle into the slow extraction beam lines for bombardment of the meson production targets for experiments requiring continuous beams.

The pulsed neutron possibilities at KAON are summarized in Table 1 in order of increasing additional requirements beyond the basic KAON facility. Lacking any experimental facilities for the 3 GeV beams the only "parasitic" possibility is associated with the 30 GeV neutrino facility. The plans for the facility are still in the conceptual design stage. The single-pulse intensity would be higher than that from any presently available pulsed neutron facility but at 30 GeV is far beyond the optimum energy. The energy could be reduced to the 3 GeV coming from the C-ring without substantial loss of intensity and only marginal ($\sim$3%) lengthening of the pulse length if this solved any background problems commensurate with the priority of the experiments. It would probably require a separate, but fairly modest, extraction system from the D ring to accommodate the larger beam emittance on injection to, compared to extraction from the D-ring after the acceleration cycle. The big disadvantage would, however, be the competition for beam time that reversion from parasitic to priority status of the neutron facility operations would entail.

Table 1
Pulsed Neutron Possibilities at KAON

Proton Charge per Pulse μC	Pulse Length μs	Repetition Rate Hz	Proton Energy GeV	KAON Rings Required	Target Station Location	Additional Accelerator and Transfer Line Components Required	TRI-DN-K137 Option
10	3.6	$\leq$10	3–30	A,B,C,D	KEH*	***	1,3
2	0.65–0.85	$\leq$50	0.5–3	A,B	NEH**	Beam Line BC to NEH	2,4
2	0.85	$\leq$50	0.45	A	NEH	Beam Line AB to NEH	5
10	0.4	$\leq$10	0.45–1	A	NEH	New Booster/ Compressor Ring	6
>10	$\leq$0.4	$\leq$10	$\sim$1	–	NEH	+ New KAON Injector	7

* KEH – KAON Experimental Hall, associated with neutrino facility
** NEH – Neutron Experimental Hall, additional to KAON
*** Nothing for 30 GeV; may need larger extraction line from D-ring for 3 GeV.

The options defined in the first line of Table 1 are the only ones that would not require a separate experimental hall with the advantage in cost savings and disadvantage in competition for space in the presently envisaged KAON experimental hall that would accrue. The combined neutrino/neutron facility, however, could be moved to a dedicated experimental hall if the interest warranted the increased scope for the project. The options listed in the last four lines of Table 1 all involve beams from the KAON project at 3 GeV or less. Thus, lacking any experimental facilities associated with such beams, any neutron facilities would require an additional experimental hall as discussed below. The options in line 2 involve extraction of full beam pulses from the complete or truncated acceleration cycles in the Booster synchrotron. Extraction of beam at energies below 3 GeV would probably require larger but only modestly more expensive extraction system components, again because of the larger beam emittance at lower energies. The 2 μC single pulse is limited by the charge holding capacity of the A ring and the B ring at injection so that reduction in the 50 Hz repetition rate, which can probably be done on a pulse-to-pulse program control, would reduce time-integral intensity to both the neutron production and kaon production by complementary amounts.

The third line in Table 1 shows the most interesting possibility that would have very modest incremental accelerator requirements for a useful pulsed neutron facility. The option depends on the fact that charge holding capacity of the A-ring is limited by phase space consideration and does not depend, to first order at least, on the filling rate of the fixed-field ring. The injected current required from the cyclotron and the irreducible, absolute losses will of course be proportional to the total current to both the KAON facility and a PNF. The incremental cost associated with increasing the TRIUMF cyclotron current to 250 μA, dissipating the additional beam in beam dumps and increasing the repetition rate of the A-ring extraction system by a factor 2 is expected to be in the $5M range. In principle the repetition rate of the A ring could be increased further to say 150 or 200 Hz but the necessary intensity available from the cyclotron becomes more problematic and the frame-overlap problems greater, unless the extracted beam from the A ring is fed to further accumulation stages.

Based on a linear interpolation of the neutron yield above an effective energy threshold of 100 MeV, which fits the available data within their probable errors, the neutron yield from 450 MeV protons from the A ring on high mass targets would be one-half that at the near optimum 800 MeV of the existing ISIS and LANSCE facilities. The 0.85 μs pulse length does not degrade the thermal neutron pulse length or peak intensity significantly. The root-mean-square deviation on the thermalization time from the mean of a 0.85 μs wide square wave is 0.25 μs which broadens the 1.0 μs standard deviation for 2 MeV neutrons slowing to 1 eV in hydrogenous moderators by only 3%; at 10 eV the relative increase is about 30%. Of course, neutron conservation indicates peak intensities inversely proportional to pulse width.

The last two lines on Table 1 show options with much greater cost and potential for satisfying future pulsed neutron facility requirements. Line 4 shows the possibility of increasing the pulse charge by accumulation of say five 2 μC pulses from the A ring in a new booster-compressor ring of the same circumference, in which they would the be accelerated to 1 GeV and compressed to 0.4 μs. The design and development of such a facility appears to be feasible but would not be trivial and is estimated very roughly (and conservatively) to cost the order of $50M. Line 5 of Table 1 shows the possibility that the KAON project might at some time in the future develop an alternative injector; this would then open up other possibilities based probably on high-current linear accelerators and storage rings that might have spare capacity at modest incremental costs for feeding a pulsed neutron facility. The total cost for such an advanced facility would likely be in $100 M range, however.

B Pulsed Neutron Facilities in KAON Experimental Hall

As indicated above, the plans for the neutrino facility at KAON are still in the conceptual design stage. It consists of an optimal thickness meson production target followed in the forward direction by a long (~100 m) flight path for their decay into muons and μ-neutrinos. Because the meson (pions, kaons, etc.) mean-free-paths are longer (by 30 to 100%) than for the incident protons approximately 70% of them suffer collisions in the primary beam targets. Previous neutrino experimental facilities have used multiple quadrupole or toroidal magnetic horn focusing systems placed immediately downbeam of the production targets to augment the "kinematic focusing" of the neutrino precursor mesons. Thus the basic target requirements for neutron and neutrino facilities are compatible but the competition for space in the immediate vicinity of the targets for moderators, target cooling and neutrino-precursor focusing devices is likely to vary from problematic to severe depending on design choices. These design requirements are overshadowed by the currently unresolved problems associated with radiation damage of the targets by pulsed, concentrated proton beams; they may well require uncontained liquid metal targets, unless the spot sizes required for neutrino-precursor production can be relaxed substantially.

The neutrino production target (but not the meson decay flight path, beam stop or neutrino detector) is currently planned to be in the KAON experimental hall, but not included in the initial installation. Thus the associated neutron facilities would compete for space outside the shielding but inside the hall with other KAON facilities.

III. INCREMENTAL REQUIREMENTS FOR A PNF AT KAON

A Transfer Beam Lines and Tunnels

The additional beam extraction components required for the options cited in Table 1 were mentioned briefly in their descriptions above. None of them requires additional components not already required for the KAON facility that are technically problematic or particularly expensive. They will be discussed further here only to the extent that they affect the possible site layout options and are constrained by accelerator/storage ring design considerations.

To minimize the cost of transfer beam lines to a pulsed neutron facility they should start at an intermediate point in the present A-B and B-C transfer lines between the rings, at the exit of a suitable dipole bending magnet. Because these transfer points in the present design are ~180 degrees apart the minimum cost transfer from both A and B rings cannot be obtained simultaneously, forcing an early selection for which option in Table 1 to optimize the layout. Although the injection and extraction points from the rings might be moved they have many soft and hard constraints. The second overall layout constraint for a pulsed neutron facility at KAON would be to leave enough space between the extraction point on the present facility and the experimental hall to install further stages of accumulation and/or acceleration of approximately the same size as the A/B-ring tunnels and tangential to the beam transfer line to the PNF hall. The layout shown in Fig. 2 satisfies these requirements for a beam from the A ring with only a modest perturbation of the reference site layout. A layout for a beam extracted at minimum cost from the B ring would require much more extensive modifications to the reference site layout but is not precluded at this stage.

Although the totals are smaller - roughly in proportion to primary beam energy above an effective 100 MeV threshold – the specific radioactivity induced in components would be the same order as those in the KAON production target areas. This provides an incentive for a layout that allows handling all such components by a common system. The layout shown in Fig. 2 does not, unfortunately, achieve that objective.

B Pulsed Neutron Facility and Hall

The only additional major components required for a pulsed neutron facility at KAON besides the beam transfer lines would be the target/moderator/shield assembly and the experimental hall to house them. Based on the PDS results the tunnels for single beam transfer lines will cost about \$8K per metre and experimental halls approximately \$2 K per square metre, the latter with basic services included. Thus a 75-m tunnel for a transfer beam line from the A/B ring and a 2,500 m^2 experimental hall would cost about \$0.6M and \$5M, respectively.

Table 2
Approximate costs of KAON PNF

	$M
Beam Transfer Line and Tunnel	1.6
Experimental Hall	5.0
Accelerator Modifications	5.0
Target/Moderators/Shielding	20.0
Total	31.6

The 100-m transfer beam line itself, as shown in Fig. 2, would cost about $1M, again based on PDS results. The largest component would be the target/moderator/shield assembly for a PNF. The capital cost of the ISIS target was £3.5M in 1979 UK£. Approximately one third of this total was for shielding which was recovered from within the laboratory and might therefore have had a considerably higher cost for new material, say double, making the effective true cost nearly £5M. At C$2=£1 the 1979 cost of reproducing the ISIS target would be approximately $10M; inflation since 1979 has probably doubled that price to $20M. The cost of an initial installation might be reduced considerably by using a simple molten lead target instead of the depleted uranium target at ISIS and fewer and less elaborate neutron beam gates and collimators, but at the price of a factor 2.3 loss of intensity beyond the factors of 2 for each of the reduced beam current and energy. The peak thermal neutron flux in a water moderator immediately following the 0.85 μs long, 2 μC pulse of 450 MeV protons on a lead target would be 6 x 10^{14} $\mathrm{cm^{-2}s^{-1}}$, with a time integral over the 50 Hz repetition rate lower than that by a factor 100 in an "infinite" H_20 system[3]. The costs for an initial system are summarized in Table 2.

IV. FUTURE DEVELOPMENT POSSIBILITIES OF KAON

The least costly development for the improved performance of a PNF at KAON would be increasing the repetition frequency of the Accumulator ring beyond the factor 2 multiple of 50 Hz discussed above to, say, 150 or 200 Hz, and using the extra cycles to increase the repetition rate and hence the integral current to the PNF. This development would be much more interesting if it could be combined with a subsequent accumulation stage to increase the pulse size and reduce the PNF repetition rate. The limitation on how far this extrapolation of the A-ring frequency can be taken is expected to be set by gross beam spill limitations, in any of the cyclotron or the A or B rings. Because the beam from the cyclotron is extracted at 450 MeV the dominant spill mechanism, $\mathbf{v} \times \mathbf{B}$ electromagnetic stripping, is essentially eliminated leaving residual gas stripping of the H^- ions and space-charge induced emittance growth as the limitations. The present cyclotron limitation is estimated to be at approximately the 500 μA level although this must still be demonstrated within the additional constraint of restricting the longitudinal (phase) width of the micro pulses extracted from the cyclotron to the phase width capable of loss-free acceleration by the Booster synchrotron rf system operating at, basically, twice the frequency of the cyclotron system. Operation of the cyclotron at 500 μA and the A ring at 200 Hz would allow diversion of 300 μA to a PNF with a 75% duty factor, for the 1 in 4 pulses required to feed the Booster synchrotron. The only components in the A ring that would be under increased stress would be the extraction kicker magnets that would be required to operate at the increased frequency and the injection stripping foils that must operate at the higher current. The effects associated with the large number of turns collected in the A ring would, on the other hand, be relieved.

The addition of a further stage of accumulation and acceleration to an enhanced repetition rate A ring would put a KAON-based facility at the forefront of pulsed neutron facilities.

The option in line 4 of Table 1, cited above in II *A*, envisages a combined accumulator/accelerator/compressor in a single B′ ring of the same length as the A and B rings of the primary KAON facility. It would accumulate multiple – say five – 2μC pulses from the A ring; during the period when the A-ring was accumulating beam to feed to the B ring the B′ ring would accelerate its accumulated charge to 1 GeV and, possibly, compress the longitudinal 40 micro pulse beam structure using an auxillary rf system to shorten the extracted pulse length. Because the B′ ring would have the same lengths as the present A and B rings they should, if possible, share the same tunnel, avoiding the need for the second ring tunnel shown in Fig. 2.

Total beam intensities beyond the present design current of 200 μA of ISIS will require further neutron production target development to avoid the problems encountered with the present depleted uranium metal targets. Although they impose a factor of more than 2 loss in source strength, molten lead or lead-bismuth are expected to be more reliable and forgiving of transient conditions and radiation damage problems.

V. CONCLUSIONS

From the realization that there may be considerable spare capacity for accumulating 450 MeV protons in the A ring of the KAON accelerator complex the development of a pulsed neutron facility at TRIUMF must be taken as a serious possibility. A major advantage of using this starting point is the avoidance of competition with the rest of the KAON facility for beam time or intensity. It does, however, depend on adequate, increased intensity from the TRIUMF cyclotron in more restricted rf phase width than has been required for meson production. The determination of these capabilities and limitations of the TRIUMF cyclotron, required for confirmation of the KAON design in any case, should have a high

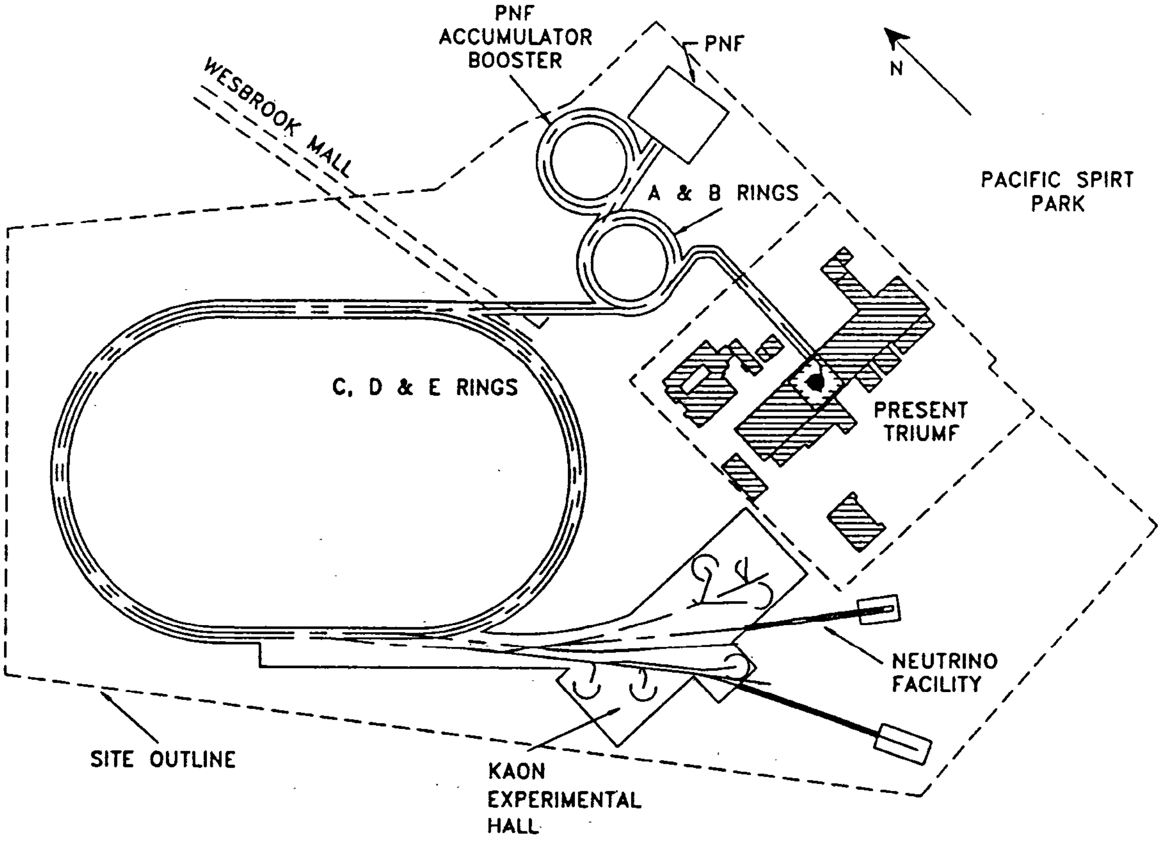

Fig. 2. The KAON layout including a possible pulsed neutron facility.

priority. If this determination is positive it would open the possibilities for the step-wise development of a competitive, world-class pulsed neutron facility that could attract national and international support and enhance Canadian neutron beam science.

The use of the full 100 μA, 3 GeV beam from the Booster synchrotron would have the advantage of increased intensity and 25% shorter pulse length compared to a facility based on direct delivery of the 0.45 GeV beam from the Accumulator. The total source strength for a 100 μA, 3 GeV proton beam on a lead target would be a factor $\sim$2 greater than that from the 200 μA, 0.8 GeV beam on the depleted uranium target at ISIS. The flux in hydrogenous moderators from such a source might, however, be discounted somewhat by the extended spatial distribution of the source depending on the target-moderator design. The disadvantage in the long term with such a facility would be the unavoidable competition for beam time and/or intensity with kaon production in the basic facility. Although the long term development of this option appears to be more limited than the preferred option discussed above, it should be preserved if possible for the initial operation of the 3 GeV facility, especially if the extraction alignments and site layout can be rearranged to allow them to feed a common target assembly from both options at reasonable beam transfer line and housing costs.

The use of the full 30 GeV, 10 μC, 10 Hz beams (although they would require separate target/moderator facilities, at least in the absence of an unencumbered neutrino facility) could have the highest single-pulse, thermal neutron intensity of any recyclable facility in the world, at least until the Moscow KAON Factory becomes operational[4].

Although the space available for a neutron experimental hall as shown in Fig. 2 appears to be adequate for an initial facility, the possible future requirements for long flight-paths and additional or specialized target halls would need to be reviewed before construction started to avoid, as far as possible, future changes of venue, with the additional cost that would incur. At a minimum, beam transfer line tunnel stubs should be installed downstream of the A-B and B-C transfer lines from the Booster tunnel to allow subsequent completion of such lines with minimum disruption to the KAON facility.

Accelerator-based pulsed neutron facilities are competitive and complementary to fission reactors and are capable of satisfying many beam users requirements, and of developing new areas of science. A PNF facility at TRIUMF that is capable of upgrading, though not initially world-leading, is a very attractive $40M initial investment in a field that has many technological spin-off possibilities.

REFERENCES

[1] I. M. Thorson, Proceedings of ICANS VII, Oxford, July 8–12, 1985, RAL Report-85-110 Vol. 1 p86, (1985).

[2] I.M. Thorson and M.K. Craddock, *Pulsed Neutron Facilities and the KAON Factory*, TRI-DN-K137 (September 1990).

[3] I. M. Thorson, *Simultaneous Pulsed/Integral Neutron Facility Optimization*, this Conference, Target Station Workshop Session.

[4] N.V. Kolmichkov, V.D. Laptev, V.A. Matveev, L.N. Latisheva, S.V. Serezhnikov, S.F. Sidorkin, N.M. Sobolevsky and Yu. Ya. Stavissky, *Superintensive Pulse Slow Neutron Source SIN Based on K-Meson Factory*, These proceedings.

Q(R.Pynn): Could you explain again the additional costs that would be involved for your various options? In particular what would 100μA, 450MeV, 10Hz & 0.4μsec pulse length cost you in addition to the currently projected cost of KAON?

A(I.M.Thorson): As will be clearer in the written text of my talk the incremental cost for a pulsed neutron facility addition to KAON would come in two parts. The first is for the target/moderator/shield assembly, experimental hall, beam transfer lines and tunnels; the approximate cost of C$30M would give us a 450MeV, 100μA, 50Hz, 0.8μs facility. A subsequent acceleration stage (to ~1GeV) and accumulation stage (to 10μC at 10Hz) is estimated at C$50M; the achievement of 0.4μs pulse length would not be a first or second priority but might be necessary for beam extraction reasons.