1. Ultracold Neutron Source System

The UCN source technology proposed is a superthermal source based on downscattering of cold neutrons (CN) in superfluid He-II [?]. Fig. 1 displays a schematic of the proposed UCN source.

Neutrons are liberated by proton-induced spallation from a tungsten target. The neutrons are moderated in room temperature heavy water and then 20 K heavy water ice down to cold neutron energies. The moderator system is surrounded with a graphite reflector to reflect as many neutrons as possible back into the source assembly. The cold neutrons are down-scattered by phonons in superfluid ^{4}He (He-II) to ultracold neutron (UCN) energies. Heat is removed via heat conduction in the He-II to the ^{3}He cryostat and the ^{4}He-^{3}He heat exchanger. UCN are transmitted horizontally through a series of valves to experiments.

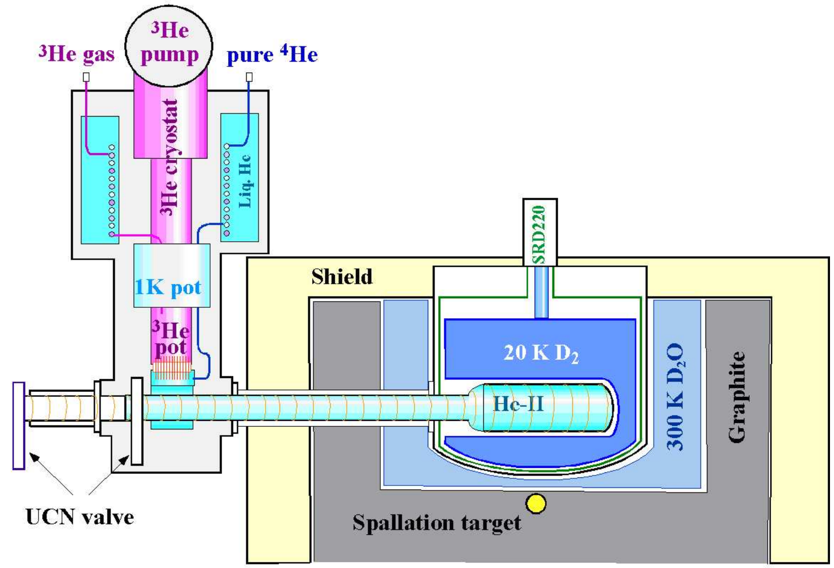

Figure 1: Schematic diagram of the UCN source system for CSUNS. The proton beam would impinge into the page upon the spallation target.

The Ultracold Neutron Source System refers to the cryogenic components of the UCN source itself. These include the following items which are displayed schematically in Fig. 1:

- the ^{3}He cryostat
- a ^{3}He gas circulator
- pumps
- the He-II bottle (UCN production volume)
- a ^{4}He isotopic purification system
- UCN guides to the experimental port

The combined cost of these items is $2.1M. The cost has been estimated based on the previous experience of Y. Masuda in procuring the parts for the prototype UCN source in Osaka.

2. Neutron Moderators and System

The Neutron Moderators and System include the following items (referring again to Fig. 1):

- a GM cryostat for the 20 K D_2O ice

- the room-temperature D_2O vessel and system
- the D_2O moderator material
- the graphite reflector

The cost of the D_2O moderator material is based on the cost per unit volume of the liquid, which is ???. For the room-temperature moderator volume, it is important to have a sufficient length of D_2O seen by the neutrons for them to come into thermal equilibrium with the material. This minimum length is ??? cm. Similar considerations hold for the cold moderator, which will be 20 K D_2O ice, giving a length scale of ??? cm. These lengths sets the dimensions of the warm and cold D_2O volumes, which are ??? cm^3 and ??? cm^3, respectively. This results in a cost of $??? overall for D_2O.

The Gifford-McMahon (GM) cryostat is used to cool and house the cold volume of D_2O ice to 20 K. The cost is $??? and is based on the costs incurred in the construction of the same device for the prototype UCN source. The graphite reflector is is $??? and is based on materials costs.

There are also costs for the water-tight vessel, which would be custom fabricated from aluminum.

This gives the total cost of $1M, which is dominated by the cost of the D_2O moderator material itself.

7. Neutron EDM equipment

The neutron EDM equipment includes test equipment for the highest priority physics experiment that would eventually be conducted at the UCN source.

We require $1.9M to complete experiments and tests related to the future neutron EDM project.

Included in this cost are ...

3. Proton Beamline

The UCN source would be located in the Meson Hall at TRIUMF. A schematic diagram displaying the floorplan is presented in Fig. 2.

One attractive feature of this location has been the cost savings that can be achieved by reusing a great deal of existing infrastructure. For example, there is already a considerable amount of shielding in the area, shielding experiments from the proton beamline BL1A which will be used to drive the experiment. Additionally, should radioactive components need to handled, there is easy access to remote handling hot cells. These would be used for servicing, for example, components of the spallation target. There is also an existing 50 T crane in Meson Hall, which would be used, for example, for stacking shielding blocks. The central location of the Meson Hall site-wide would also allow easy access to the future helium liquifier for TRIUMF.

The UCN facility would be installed in Meson Hall after the completion of PiENu, which is expected to complete running in January of 2012. A considerable amount of preparatory work must be done before that time, so that installation of the UCN source can take place on schedule.

In 2012, the M13 and M11 pion beamlines would be decommissioned to make space for the UCN source, and a new proton beamline would be constructed to deliver proton beam from BL1A onto the spallation target for the UCN source.

One of the primary reasons for the choice of the Meson Hall location was the ability to periodically switch the beam onto the UCN target in a one minute on, three minutes off fashion, similar to the operation of the prototype source in Japan. The beam-off periods are required to achieve low background rates for experiments product counting experiments. Low backgrounds are often required for the types of sensitive physics experiments that would be conducted at TRIUMF. Often these experiments require counting mode detection of UCN, neutron decay products (electrons or protons), or the gamma lines resulting from UCN or CN captures in materials. A distinct advantage of this pulsed operation of the spallation source is that the experiments have lower background when compared to experiments conducted at reactor UCN sources. Generally, those types of sources are plagued by large backgrounds simply because the neutron source cannot be rapidly switched off. This would be true of both the ILL, and Munich reactor sources. In contrast, experiments at TRIUMF would be conducted when protons would not be striking the spallation target, with considerable reductions in backgrounds from both fast neutrons and gamma rays.

The mechanism proposed to achieve beam pulsing is as follows. The proton beam in Meson Hall would be operated as usual, running down the beamline BL1A line across the south side of Meson Hall, most of the beam being dumped into a high-power beam dump at the far southeast corner of the hall (the so-called TNF dump). Periodically, a portion of the beam would be "kicked" from beamline 1A to UCN through the use of kicker magnets that will be described momentarily. The rest of the time the beam to other users in meson hall would be completely undisturbed from normal operation.

Fig. 2 shows the proposed layout in the meson hall and was created by a TRIUMF designer [**?**]. Beam would be delivered to the UCN source by a kicker and septum system. A beamline would be constructed to divert 40 μA of the 500 MeV proton beam onto the spallation target of the UCN source.

The beamline shown in Fig. 2 is based on design work and an optics study presented in Ref. [**?**]. A schematic diagram showing the layout of steering and focusing magnets proposed in that design note is presented in Fig. 3(a). The results of an optic simulation are presented in Fig. 3(b). The results indicate that the beam spot size on the spallation target can be controlled reliably using the focusing elements as designed. The design note thereby specifies the parameters of the magnets required for the beamline.

Located upstream and downstream of the 1BVB2 dipole are new fast kicker magnets, indicated by K1 and K2. Together, they deflect the proton beam by 10 mr, offsetting the beam by 65 mm at the start of a magnetic septum. The septum then bends the beam by a further 115 mr, displacing the beam from the BL1A axis by 220 mm at the dipole 1UB1 (BN1). This dipole deflects the beam by a further 15 degrees. The final dipole magnet, 1UB2 (BN2), deflects the beam by 45 degrees. Following those magnets, smaller steering magnets are required to position the beam accurately on a tungsten spallation target at the centre of the UCN source. An initial optics study for this configuration is also reported in Ref. [**?**].

An important consideration for the UCN source is to minimize conflicts in proton beam sharing with other TRIUMF users. In the Meson Hall, we will impact mainly μSR users using muon-spin relaxation (μSR) for condensed matter and materials science studies. These user are accomodated by the M9, M15, and M20 muon production targets and beamlines. The primary impact of the UCN source is an overall sharing arrangement with μSR users, so that the two sets of users would receive beam simultaneously. On average, 7% of the beam would be delivered to the UCN spallation target, the remaining 93% being delivered as usual to the μSR users. Meson production targets and beamlines located downstream of the UCN source would therefore remain unaltered and would continue to operate as usual.

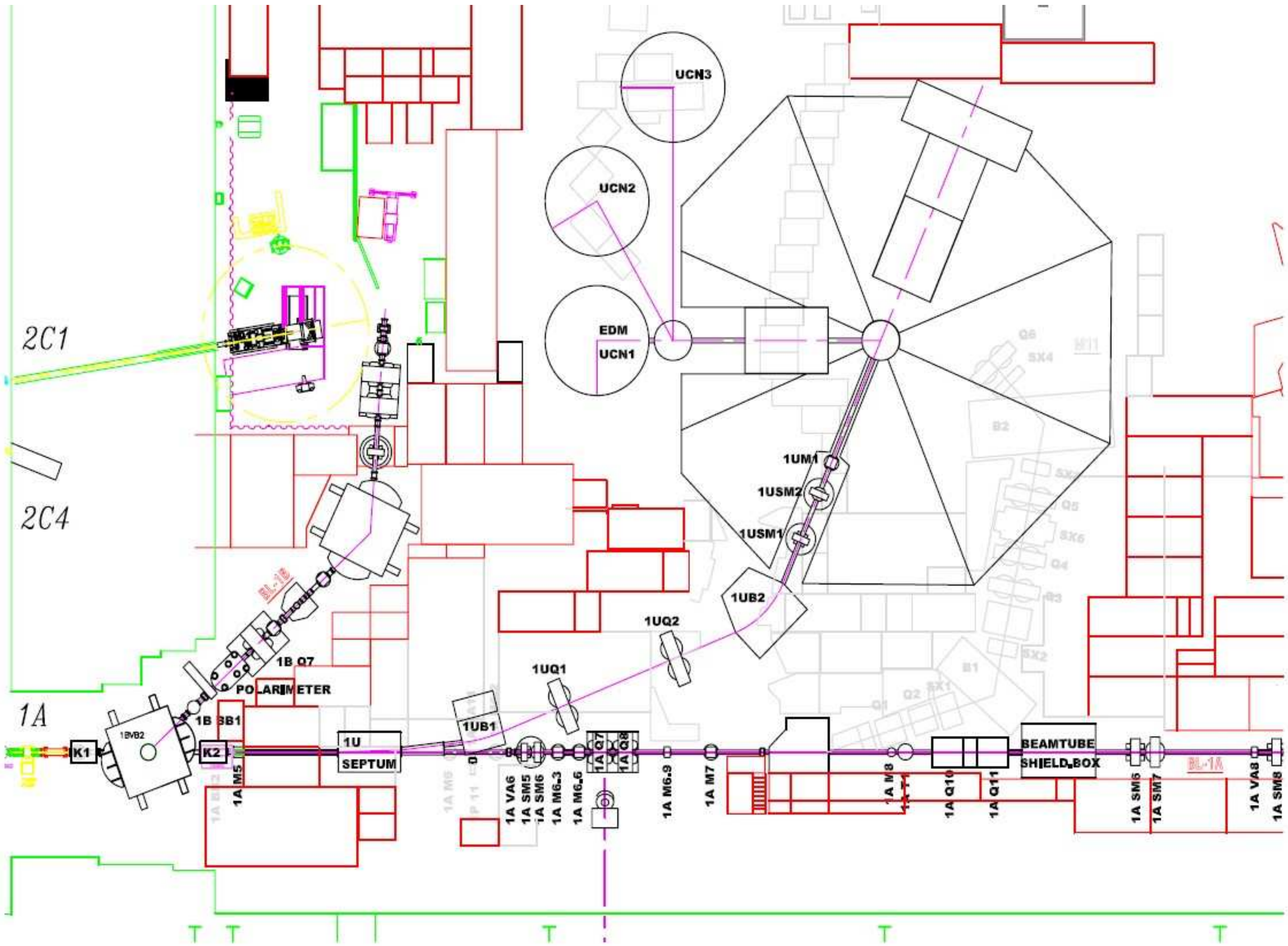

Figure 2: Location of the UCN facility in the Meson Hall (TRIUMF).

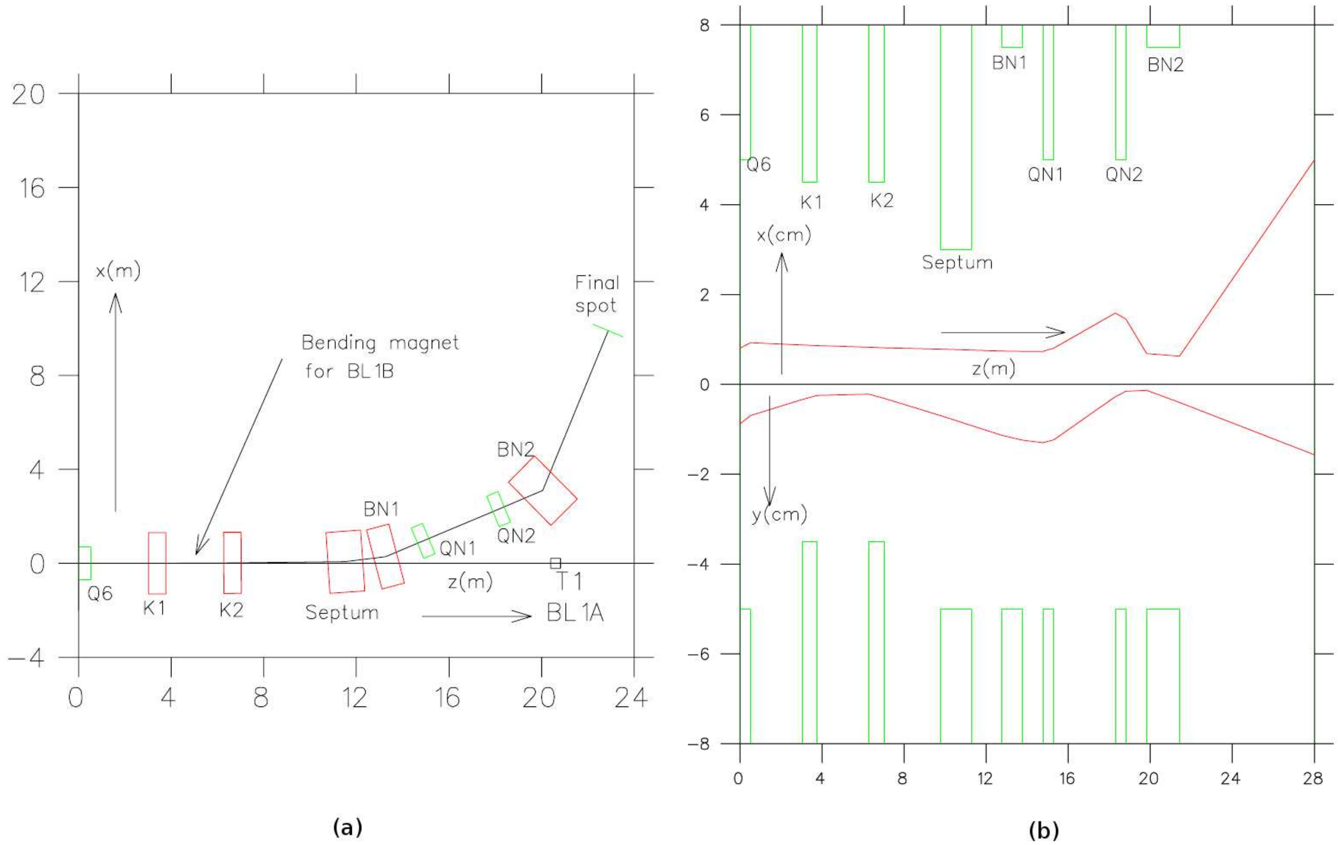

Figure 3: Beamline optics design from Ref. **??**. (a) Layout displaying kicker (K1, K2), septum, dipole (BN1, BN2), and quadrupole (QN1, QN2) magnets. (b) Optics simulation results displaying beam envelopes.

The details of this beam sharing arrangement are dictated by the beam conditions as they exist at TRIUMF. The macro-structure of the proton beam is described pictorially in Fig. 4. The normal time structure of the proton beam is shown on the top panel of Fig. 4. A 1 kHz pulser in the injection line interrupts the beam once per millisecond for a short time of 10 μs to 40 μs. The exact time of the beam-off gap can be adjusted, and this is normally done in relation to beam tuning for ISAC.

Fast kicker magnets with a risetime of 5 μs would turn on during the brief beam-off interval and would remain on for 1 ms, directing beam to the UCN source. The kicker magnets would then turn off in the next beam-off interval. By adjusting the duty cycle, one can vary the split between UCN and downstream users. The lower two panels of Fig. 4 illustrate a 2:1 split, for example simultaneous 80 μA delivery to downstream users and 40 μA to UCN. This scheme makes no change to the beamline 1A optics and does not affect the instantaneous beam current to other users. The UCN source would typically take beam at 40 μA for 1 minute, then receive no beam for a further 4 minutes, during which time the ultracold neutron experiments would take data.

TRIUMF engineers have begun to design kicker magnets with rise and fall times on the order of a few μs and a flat-top of 1 ms or more [?]. The 1 in 3 duty cycle requires a large average current in the kickers and fast power supplies.

The material and human resource requirements for the proton beamline are displayed in Table 2. Below, we discuss the material costs. Manpower contributions will be discussed as a separate line item.

The kicker magnets (K1 and K2), the septum, and the two dipole magnets (1UB1 and 1UB2) will be purchased new. The quadrupoles 1UQ1 and 1UQ2 will be reused from a decommissioned beamline. Existing power supplies from the M11 (to be decommissioned) are suitable for the quadrupoles and for the dipole 1UB1. The larger dipole magnet 1UB2 is a higher power magnet and requires a new power supply.

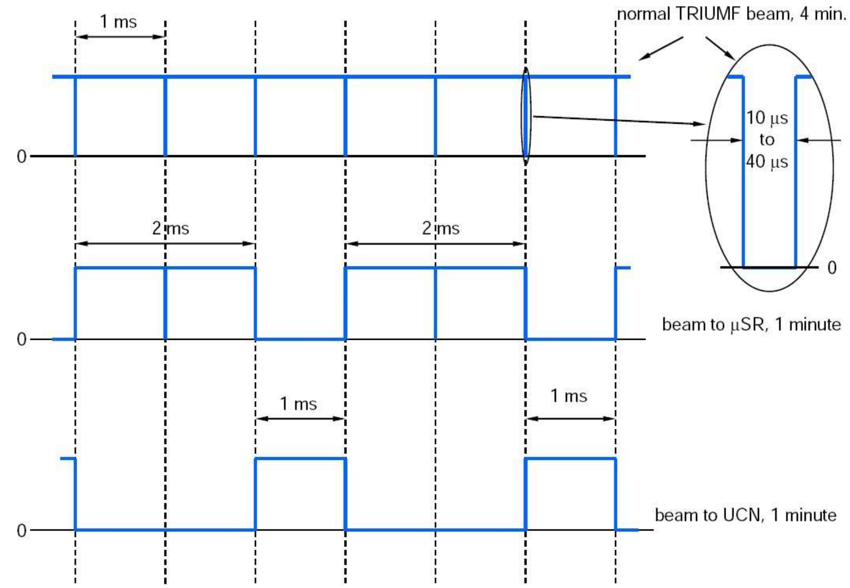

Figure 4: Proposed method of sharing the proton beam between the UCN source and other meson hall users. Every 4 minutes, the UCN source takes a minute of beam in the form of a 1 ms burst every 3 ms. The instantaneous beam current is not affected and the total loss of integrated beam to downstream users is about 7%. The exact details of the time division will depend on what specifications are achievable for the fast kicker magnets.

The main cost of K1 and K2 is in their special fast pulsed power supplies. The power supplied must also be located as close to the magnets themselves as possible so that inductance can be minimized. The magnets themselves will be simply be one turn of large conductor, and will be custom fabricated at TRIUMF. Based on the cost for similar projects and on the advice of experts at TRIUMF [?], the kicker magnets will cost \$250 k. The power supplies will cost \$400 k.

The septum magnet is more specialized and is consequently more expensive. A magnet that is not susceptible to radiation damage is required in this case. Based on the costs of comparable radiation-hard septum magnets at TRIUMF (e.g. the septum downstream of T1) we have estimate a cost of \$520 k for the septum.

Based on the cost of previous dipole magnets purchased by TRIUMF (the TRIUMF 2AB1/2 dipoles), the dipole magnets for the UCN proton beamline will cost \$125k each.

In cases where existing magnets and power supplies will be used, we have made allowances for moving and re-connecting. The estimates also include a number of smaller magnets, beamline instrumentation and safety systems (see Table **??**).

Overall, this results in the estimate of \$2,330,000 for the beamline components. Manpower estimates will be discussed and are included as a separate line item.

4. Spallation Target and Remote Handling

The spallation target itself will be made of one stopping length of tungsten or lead. The target also requires a mounting system, a cooling system, and the apparatus must designed in such a way that safe extraction can be conducted for servicing.

Fortunately, TRIUMF has successfully designed and constructed several spallation targets in the past. We have determined that a previously designed spallation target system can be used for the UCN spallation. This has therefore resulted in significantly reduced design and construction time, since the system will be a copy of something previously constructed at TRIUMF. The entire system will be custom fabricated at TRIUMF. The cost of the target system is also well-known for the same reason: that a similar one was just recently constructed.

The cost breakdown for the spallation target and associated systems is shown in Table 3. The materials cost is \$130k. Manpower will be discussed as a separate line item.

5. Shielding

Radiation safety procedures at TRIUMF will be strictly adhered to in this project. Radiation shielding will be used to ensure human safety. The shielding must be used to encase the spallation target and, to a lesser extent, the UCN source.

Calculations of the shielding requirements for the project have been conducted by the TRIUMF radiation safety group. Fig. 5 shows the results of these calculations [**?**] which give thickness of shielding in steel followed by concrete that should be used to ensure that dose rates to humans can be reduced to an acceptable level outside the shield package. In these calculations, the design proton beam specifications of a current of 40 μA and beam energy of 500 MeV were used. The beam was assumed to stop in a tungsten target 1.5 m from the floor. The effect of the neutron moderators around the tungsten target was not estimated. The calculation simply assumed that the target is surrounded by 0.5 m of empty "keep-out" space in all directions before the radiation shielding was allowed to begin, whereas normally this keep-out zone would be inhabited by the UCN source system, moderators, spallation target system, and where possible additional shielding. This calculation can therefore be regarded as a conservative treatment. The thicknesses displayed in Fig. 5 reduce the dose rate immediately outside the shielding to less than 3 μSv/hr. This is comfortably below the 10 μSv/hr guideline for low occupancy areas such as walkways.

Using these guidelines from TRIUMF, the total volume of shielding required can be calculated, assuming a particular geometry for the shield package, and that the steel and concrete will be available in block form for easy stacking using the Meson Hall crane. This results in a requirement of 150 m^3 steel and 450 m^3 concrete.

To estimate the costs to acquire this shielding, we have relied on previous experience at TRIUMF. In 2002, TRIUMF purchased steel blocks fabricated locally (in Vancouver) at a cost of \$10,000/m^3. These were fabricated to precise tolerances and a standard 2'x3'x5' block size and instrumented with I-bolts for easy installation with a crane. Correcting this cost for current steel prices results in a price increase \$14,000/m^3 for newly made steel blocks. In cases where the precision and custom shape of new steel is not required, Energy Solutions (Oak Ridge, TN) offers slightly radioactive recycled steel at one dollar per 10-ton block. From a practical standpoint, the cost for such steel would be completely determined by transportation charges. Transportation costs to a rail yard in Vancouver are \$2000/m^3. For the shielding estimates we have assumed 50 m^3 of new steel (in the central regions where precise tolerances are required) and 100 m^3 of recycled steel. This results in a cost of \$900k for the steel shielding.

For the concrete shielding, we have based the cost on TRIUMF experience from the onsite fabrication of 29 concrete shielding blocks in 2001. Correcting for inflation, removable concrete shielding would cost \$2000/m^3 [?], resulting in a cost of \$900k for the concrete volume. Additionally, we require \$20k for the staging and installation of this significant mass of shielding materials. These costs are summarized in the lower half of Table 3.

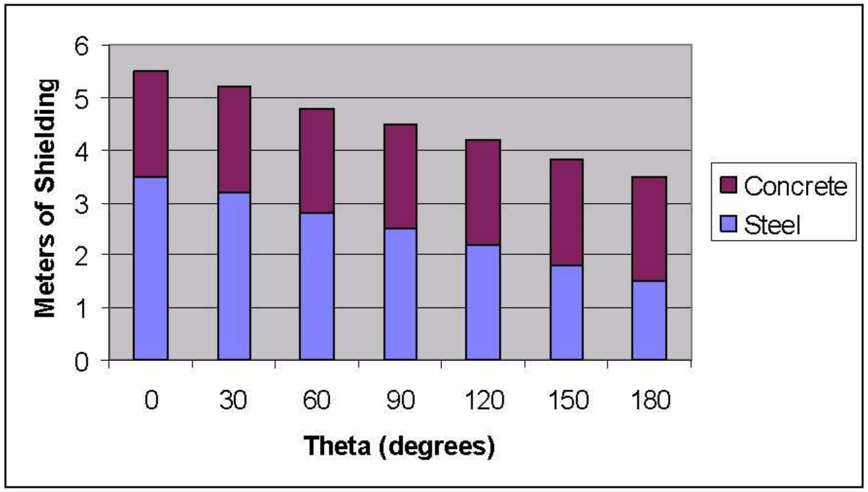

Figure 5: Shielding required for a 40 μA, 500 MeV proton beam incident on a thick tungsten target. The design dose rate is 3 μSv/hr immediately outside the shielding.

6. Installation of Japanese Sections in Canada

Electrical power, water for cooling, and compressed air systems will be needed to operate the Japanese equipment (the UCN source system and the CN moderators and system) in Canada. The materials costs associated with installation of these services will be \$40k and are displayed in Table 4. Manpower for installation will be discussed in the manpower line item.

8. Engineering, Design, and Technical Manpower

A detailed breakdown of human resources requirements is shown in Tables 2 to 4, which have been referred to in the previous sections. All the time estimates have been determined in discussions with TRIUMF engineers [?, ?]. Generally, they are benchmarked against the copious experience of these individuals in completing projects similar to this one.

In table 1, we have collected together from these tables a summary by major category. The numbers displayed in the table have also been converted to person-years. A total of 33.5 person-years will be required to successfully complete the engineering, design, fabrication, and installation of the infrastructure.

TRIUMF director Nigel Lockyer has generously agreed to contribute manpower totalling 16.7 person-years to the project. In converting this manpower total to a dollar figure for an "in-kind" contribution, the conversion factor of \$100k to one person-year has been used, and has been agreed upon with TRIUMF. This results in an in-kind contribution from TRIUMF of \$1,670,000.

The remainder of manpower will be contracted following the policies and procedures of TRIUMF, and will be billed to the University of Winnipeg at the same rate of \$100k/person-year. This results in a cost of \$1,680,000 in cash for engineering, design, and technical manpower.

In the initial stages of the infrastructure acquisition, the manpower will be focused on engineering and design work. In the later stages, it will be

Item	Phys	Engr	Desn	Mach	Cntrl	Tech	Total
Proton beamline	1.5	6.0	3.9	2.2	1.1	8.0	22.7
Spallation target	0.3	0.3	0.5	0.5		0.5	2.1
Shielding	0.9	0.7				0.5	2.1
Installing Japanese sections	1.6	1.6	1.0	0.5	0.5	1.4	6.6
Total	4.3	8.6	5.4	3.2	1.6	10.4	33.5

Table 1: Canadian human resource requirements for the UCN facility in person-years. The columns indicate person-years divided into the categories of Physicists, Engineers, Designers, Machine Shop, Controls, and Technicians. Technician figures include mechanical, electrical, and vacuum technicians.

focused on fabrication, installation, and other technical work. The spending profile will consequently be flat over the four years of the infrastructure project.

Physics Design of Moderators and Source

For the optimal and successful operation of the UCN source for maximal density, it is crucially important to maximize the flux of cold neutrons into the ultracold production volume (the superfliud ^{4}He). In our source this requires optimizing the detailed geometry of the surrounding graphite and D_2O, which moderate the neutrons. The problem is very similar to the optimization of neutron production in a nuclear reactor. Acsion Industries, a private company located in Pinawa, MB, has copious experience in this field. We have therefore approached Acsion to assist us in this task, and they have already created a preliminary model of the UCN source.

The University of Winnipeg has signed a memorandum of understanding (MOU) with Acsion, contracting for services in completing this design, and in the completion of an MCNPX computer model of the UCN source. The work will be conducted over the entire four-year course of the infrastructure acquisition because iteration of the design will be required in communication with our Japanese collaborators. The MOU also mentions other services that Acsion will provide, including operational health physics support, government relations, and a significant commitment to training of highly qualified personnel in the used of the MCNPX computer model.

Acsion staff will provide 1000 hours of labor per year towards these activities over four years. The total cost of the work is $900k, of which half ($450k) is contributed in-kind by Acsion. The in-kind contribution consists of 1/3 of the manpower cost (normally charged at a rate of $150/hr), access and training on the modelling software valued at $100k, and a license for intellectual property valued at $150k.

The remainder of the costs ($450k) will be paid to Acsion by the University of Winnipeg in monthly installments over 48 months, and will be supported 50-50 by CFI funds and the Manitoba Research & Innovation Fund supported by the Government of Manitoba.

V.Verma/M.Keyzer

Resources for Five Year Plan (2010-2015)

UCN(Beam Line - Version 2) **Funded by TRIUMF** Date: May 1, 2008 **Rev#3**

	Sub-projects/Work Packages	**Mat'l & Supplies (K$)**	**Human Resource Requirements (Person Months)**											
			Phys	**Engr**	**Design**	**M/Shop**	**Cntrls**	**Technicians**					**Outside**	**Total**
								Mech	**Vac**	**RF**	**Elect**	**Comp**		
1	Beamline:													
2	Kicker magnets (2)	250	6	18	18	6		12			5			65
3	Septum(1) + protection monitor	520	1	9	6	4		4						24
4	Dipoles (2); 15 degree (new) and 45 degree (re-use)	250	1	3	6	2		4						16
5	2 quadrupoles (move from M20)	20		2		1		3						6
6	Steering magnets (4)	5		1		1		2						4
7	Power Supplies (install and connect) -->	30		2	1	1		3			3		3	13
8	P/S for 2 kickers(400k), 1 septum(100k)													0
9	P/S for 2 dipoles (may use M11 and 1B - 10k)													0
10	P/S for 2 quadrupoles (may use M11 suppllies) 5k													0
11	P/S for 5 steering magnets 20k													0
12	Total for all power supplies (to buy)	535		6										6
13	8 inch beam pipe and shine blockers	20		2	3	3		3						11
14	Beamline hardware													0
15	vacuum system	50	1	1	2	1			4					9
16	Move beam moitors	20	0	2		1		3						6
17	Diagnostics - electronics inluded in above													0
18	controls	250	3	6	1	1	12	1			4			28
19	Safety - ACCS	30	1	2	1	1	1	2			1		1	10
20	Safety - RMS	50	1	2	1	1		4			2			11
21	Services - (electrical)	200	1	2	3	1		1			1		10	19
22	Services - (water and air)	80	1	2	2			1					4	10
23	Vacuum boxes (kickers, septum, diploles)													0
24	Assembly, installation, and commisioning	20	2	12	3	4		24	6		3			54
25														0
	Total	**2330**	**18**	**72**	**47**	**28**	**13**	**67**	**10**	**0**	**19**	**0**	**18**	**292**
Note:	**2010**	732												78
Outside=Consultants	**2011**	916												92
Vendors	**2012**	458												92
Contractors	**2013**	224												30
	2014													

Explanation:
version 2 has a re-designed beamline that takes a dipole from beamline 1B. The beam is also more separated at the first (1UB1) bender so it can be simpler. There is only one kicker
On version 2 we have also removed some double counting, for example on vacuum boxes and beamline hardware.
Steering magnets and beam moitors will be moved from 1B

Table 2: Resource estimates for the new proton beamline.

V.Verma/M.Keyzer

Resources for Five Year Plan (2010-2015)

Project: UCN(Spall. Targ. & shielding -v2) **Funded by TRIUMF** Date: May 1, 2008 **Rev# 3**

	Sub-projects/Work Packages	Mat'l & Supplies (K$)	Human Resource Requirements (Person Months)											
			Phys	Engr	Design	M/Shop	Cntrls	Technicians					Outside	Total
								Mech	Vac	RF	Elect	Comp		
1	SPALLATION TARGET													
2	Target (including containment jacket, window and support)	30	2	2	3	3	0.5	3			0.5			14
3	Water cooling (included in "Target")													0
4	Small secondary target													0
5	Target suspension system(now incuded in next line)													0
6	Remote handling, tranfer flask, target suspension	100	2	2	3	3		3						13
7	Targeting monitor and interlock													0
8	Safety intelocks													0
9	Vacuum system													0
10	**SPALATION TARGET TOALS**	**130**	**4**	**4**	**6**	**6**	**0.5**	**6**	**0**	**0**	**0.5**	**0**	**0**	**27**
11														0
12	SHIELDING													0
13	Removable concrete shielding (450 m3 @ 2k/m3)	900		4	3									7
14	Steel shielding (150 m3)			4	3									7
15	(100 m3 recycled steel @ 2k/m3 = 200k)	200												0
16	(50 m3 new steel at 14k/m3 = 700k)	700												0
17	Preparation and Installation	20		3	2	1		6					2	14
18	**SHIELDING TOTALS**	**1820**	**0**	**11**	**8**	**1**	**0**	**6**	**0**	**0**	**0**	**0**	**2**	28
19														0
20														0
21														0
22														0
23														0
24														0
25														0
	Total	**1950**	**4**	**15**	**14**	**7**	**0.5**	**12**	**0**	**0**	**0.5**	**0**	**2**	**55**
Note:	**2010**	1800												49
Outside=Consultants	**2011**	400												71
Vendors	**2012**	245												45
Contractors	**2013**													
	2014													

Explanation:
Version 2 is based on a new design, placing the spallation target beside, rather than under, the moderator. We have used an existing TRIUMF design for a vertical extraction remote handling sytem.
The trasfer flask is now the existing TRIUMF meson hall flask.
The monitor, inerlocks and vacuum system are part of the beamline
The water cooling is part of the target
The small secondary target has been deleted.
We have assumed using more recycled steel and less new steel

Table 3: Resource estimates for the spallation target and shielding.

V.Verma/M.Keyzer

Resources for Five Year Plan (2010-2015)

UCN(UCN Install Japanese sections -v2) **Funded by TRIUMF** Date: May 1, 2008 **Rev#2**

Sub-projects/Work Packages	**Mat'l & Supplies (K$)**	**Human Resource Requirements (Person Months)**											
		Phys	**Engr**	**Design**	**M/Shop**	**Cntrls**	**Technicians**					**Outside**	**Total**
							Mech	**Vac**	**RF**	**Elect**	**Comp**		
UCN SOURCE - JAPAN		8	5	3	3		8					1	
MODERATORS - JAPAN		10	10	5	3		7					1	36
INSTALL JAPANESE EQUIPMENT - TOTAL		**18**	**15**	**8**	**6**	**0**	**15**	**0**	**0**	**0**	**0**	**2**	**64**
SERVICES													
Electrical	30	1	2	2		1				2		4	12
Water and Air	10		2	2		1						4	9
SERVICES TOTAL	**40**	**1**	**4**	**4**	**0**	**2**	**0**	**0**	**0**	**2**	**0**	**8**	**21**
Total	**40**	**19**	**19**	**12**	**6**	**2**	**15**	**0**	**0**	**2**	**0**	**10**	**85**
2010													11
2011													22
Vendors **2012**													42
Contractors **2013**													10
2014													

Explanation:
The design and construcion of the room temperature and 20K moderators have now been taken on by Japan, so this sheet shows only the TRIUMF resources to install the Japanese sections.

Table 4: Estimate of TRIUMF resources needed to install the Japanese sections.