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Estimation of Study IIb costs based on Study II *

Robert B. Palmer, BNL, Upton, NY, USA;
M. Zisman, LBNL, Berkeley, CA, USA

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Abstract

Starting from a Study II Work Breakdown, element costs per unit length, integral RF Voltage, or net acceleration are derived. These costs are then applied to the Study IIb parameters after scaling for magnetic fields, radii, stored energy, rf gradient etc. Savings relative to Study II are given. Relative savings by subsystem are also given.

1 Introduction

The following analysis is intended only as a status report on the collaboration's ongoing efforts to reduce that cost. It is not intended to yield an accurate cost estimate.

At this time major efforts have been directed at three major components: Phase Rotation, Cooling, and the higher energy part of the Muon Acceleration. This work is still ongoing, and work on some has not yet started. Nevertheless, a comparison with Study II suggests substantial progress.

2 Study II Component Costs

Component costs, taken from the study II[1] Cost Work Breakdown (Cost_WBS-6.xls), are given, with some rearrangement, in tables 1a and 1b. On the right side of the tables, system lengths and, for RF, acceleration are given, together with the subsystem costs divided by length or, for RF, either acceleration voltage (*), or actual acceleration (†).

Conventional construction costs, for convenience in scaling, have been listed under the individual subsystems. When study II lumped such costs for several subsystems, they have been divided in proportion to the subsystems lengths.

Table 2 gives a summary of total Study II subsystem costs. Sums are given a) for all subsystems, b) without the proton driver, and c) without either proton driver or target and capture systems. Site utilities are taken to be proportional to this "subtotal 1" at (7.83%)[2] and when added give "subtotal 2". 10% is now added, as was done in Study 1, to cover other items, including control systems, to give the final totals as they appear in table A2 of Study II. Note that these totals do not include engineering and other overheads, and they are in the year dollars (2001) as in Study II.

Table 0a: Study II Costs (part 1)

*Work supported by US Department of Energy contract DE–AC02–98CH10886

	M$	Length	k$/m	GeV	M$/GeV
Proton Driver	**167.69**				
Conventional	21.88				
Technical	145.81				
Target & Capture	**91.54**	17			
Conventional	30.22				
Technical	61.35				
Drift	**5.78**	18			
conventional	18/298x19.54= 1.18 [1]		65.6		
Sol Magnets	2.78		154		
PS	0.04				
Vac	.25				
Shield	.28				
Cryo	.25				
Diagnostics	1.0				
Phase Rotation	**306.74**	260		.344*	
Conventional	260/298x19.54=17.05[1]		65.6		
Induction	252.08				732*
Magnets	29.67		114		
Vac	4.39		17		
Cryo	0.55		2.1		
Diagnostics	3.0		11.5		
Mini-Cooling, Flip & Transport	**11.27**	20			
Conventional	20/298x19.54=1.31[1]		65.6		
Magnets + PS	3.5+3.36=6.86		343		
Absorber + cryo	3.07		1.53		
Buncher & Matching	**75.58**	60			
Conventional	60/168x19.54=6.99[1]		116		
Magnets + PS	50.91		848		
Vacuum	2.66		44		
Cryo	.28		4.7		
200 MHz warm RF (6.9 MV/m)	2.5			.044*	57*
200 MHz PS	2.98			.044*	68*
400 MHz warm RF (7.5 MV/m)	0.75			.007*	107*
400 MHz PS	3.53			.007*	504*
Diagnostics	5.0		83		

Table 1b: Study II Costs (part 2)

	M$	Length	k$/m	GeV	M$/GeV
Cooling	**310.21**	108		.888*	
Conventional	108/168x19.54=12.55[1]		116		
2.75 cell Magnets+ps	36.06		771		
1.65 cell Magnets+PS	96.41		1580		
Vacuum	4.34		40		
Cryo	3.36		31		
Warm 200 MHz RF (16.1 MV/m)	17.75			.888*	20*
200 MHz PS	105.62			.888*	119*
Absorbers	6.12				
Diagnostics	28		259		
Match	**56.71**[2]	18.15		.055†	
Conventional	18/1804x19=0.19 [2]		10.5		
Magnets+PS+Cryo	34.68		1910		
Warm RF + PS	19.11				347†
Vac	0.73		40		
Diagnostics	2		108		
Pre-Acc	**136.83**[2]	430		2.25*	
Conventional	430/1804x19=4.53 [2]		10.5		
Solenoid Magnets	14.74		34.3		
SCRF Cav	41.36				18.38*
RF PS	52.01				23.11*
Cryo	13.44				5.97*
Vac	6.75		15.7		
Diagnostics	4		9.3		
RLA	**350.94**[2]	3261		17.5/4=4.37†	
Conventional	1356/1804x19=14.53[2]	1356	10.5		
Arc Magnets + Power	60.82	2541	23.9		
Arc Vac	10.54	2541	4.1		
Straight Magnets	9.22	720	12.8		
Straight Vac	4.17	720	5.8		
SCRF cavities (17 MV/m)	63.36			4.40†	14.4†
RF PS	89.16			4.40†	20.26†
Cryo	28.86			4.4†	6.55†
Special + transport Magnets	66.28				
Diagnostics	4.0	3261	1.2		
Storage Ring	**82.47**				
Conventional	28.12				
Tech	54.35				
Control Room	**15**				
Nu Detector	**10**				

Note 1 : Conventional costs have been divided between subsystems in proportional to the system lengths

Note 2 : It is assumed that the conventional costs for the matching and pre-accelerator are included in the RLA costs

Table 2: Study II Cost Summary

	All	no Driver	no Driver or Target
	2001 M$	2001 M$	2001 M$
Subtotal 1 (from Table 1)	**1620.5**	**1452.8**	**1361.3**
Site Utilities (7.83% of sub-total 1)	126.94	113.8	106.6
Subtotal 2	**1747.5**	**1566.6**	**1467.9**
10% for other items including controls	174.7	156.7	146.8
Total (no EDIA, or escalation etc.)	**1922.2**	**1723.3**	**1614.7**

3 Estimated Study IIb subsystem costs

3.1 Introduction

The Neutrino Factory design that forms part[3] of the APS Multi divisional Neutrino Study[4], represents a concept for a Neutrino Factory with substantial improvement over that defined in the Feasibility Study II??. The performance defined by muons per initial proton is maintained, but in the new design, both signs are captured, cooled, accelerated and injected into the storage ring, and generate interlaced beams of both neutrinos and antineutrinos essentially simultaneously. The performance is thus effectively doubled. The design is also significantly smaller and cheaper, as will be discussed in this note.

Most of the estimates of Study IIb subsystem costs will be obtained by scaling from those given above for Study II. It will thus be convenient to keep them in the same year dollars as Study II (2001).

The proton driver costs given in Study II are for the upgrade of the BNL AGS, and are thus BNL site dependent. They will not be included in the following discussion.

3.2 Target and Capture

Table 3: Study IIb Target and Capture Costs

	M$	Length	Scaling
Target & Capture	**89.7**	11.5	
Conventional	30.22 - 0.36=29.86		length
Technical	61.35 - 1.56=59.79		length x $B^{.577}$

The Study IIb Target and Capture cost estimate is given in table 3.The system is assumed to be essentially the same as that in Study II, but the transport in which the field is tapered down is shorter by 5.5 m because it tapers from 20 T to 1.75 T (as used in Study IIb) instead of from 20 T to 1.25 T (as used in the front end of Study II). The cost is thus slightly less. Conventional costs are reduced by 5.5 times the Study II conventional cost per m of the Study II drift: 5.5 x 0.0656 = .36 M$. Component savings are estimated by subtracting the cost of 5.5 m of a the solenoid transport taken from the drift in Study II, scaled by the field to the 0.577th power as given in the second solenoid cost formula from Mike Green[5]: 5.5 x 0.256 x $(1.5/1.25)^{\cdot}577$ = 1.56 M$.

3.3 Drift

Table 4: Study IIb Early Drift Costs

	M$	Length	k$/m	Scaling
First 18 m Drift	**6.43**	18		
conventional	1.18		65.6	length
Sol Magnets	3.37		154x1.21=187	length x $B^{.577}$
PS	0.04x1.21=0.05			length x $B^{.577}$
Cryo	.25x1.21=0.3			length x $B^{.577}$
Vac	.25			length
Shield	.28			length
Diagnostics	1.0			same
Next 82 m Drift	**19.27**	82		
conventional	5.38		65.6	length
Magnets + PS	11.35		114x1.21=138	length x $B^{.577}$
Cryo	.21		2.1x1.21=2.5	length x $B^{.577}$
Vac	1.39		17	length
Diagnostics	0.94		11.5	length

The Study IIb drift cost estimates are given in table 4. The first 18 m of drift, in either study, is more expensive than later beam transports because of required radiation shielding in the early part. We therefor treat the first 18 m of drift separately from the subsequent transport. Study IIb costs for the first 18 m are taken from Study II with a correction for the higher specified solenoid fields (1.75 T vs 1.25 T) by the factor $(1.75/1.25)^{.577} = 1.21$; using the second solenoid cost formula from Mike Green[5].

The subsequent drift requires less shielding and is thus be cheaper. In Study II, there is no further simple drift from which to scale this cost. Instead, we take the costs of the magnets, power supplies and cryogenics included in the Study II phase rotation induction linacs, corrected for the higher (1.75 vs. 1.25 T) fields by the factor $(1.75/1.25)^{.577} = 1.21$ obtained from the second solenoid formula from Mike Green[5].

This estimate is conservative because the transport magnets in the Induction Linacs of Study II had to meet more difficult requirements and had more complicated cryostats in order that they be introduced inside the induction cores.

3.4 Buncher and Phase Rotation

Table 5: Study IIb Buncher and Phase Rotation Costs

	M$	Length	k$/m	GeV	k$/GeV	Scaling
Buncher	**44.84**	49.25		.12		
Conventional	5.71		116			length
Magnets +PS	20.16		115x3.59=409			length x $(BR^2)^{.577}$
Cryo	0.37		2.1x3.59=7.54			length x $(BR^2)^{.577}$
Vacuum	2.17		44			length
200 MHz RF 9 MV/m	4.29			.12	20x(16.1/9)=36	$V/\mathcal{E}$
200 MHz PS	8.05			.12	120x(9/16.1)=67	$V\mathcal{E}$
Diagnostics	4.09		83			length
Phase Rotation	**84.52**	56.25		0.469		
Conventional	3.69		65.6			length
Magnets + PS	23.00		115x3.59=409			length x $(BR^2)^{.577}$
Cryo	0.42		2.1x3.59=7.54			length x $(BR^2)^{.577}$
Vac	0.96		17			length
200 MHz RF 12.5 MV/m	12.1			.469	20x(16.1/12.5)=25.8	$V/\mathcal{E}$
200 MHz PS	43.70			.469	120x(12.5/16.1)=93.2	$V\mathcal{E}$
Diagnostics	0.65		11.5			length

The Study IIb Buncher and Phase Rotator component cost estimate is given in table 5.

The buncher and phase rotator in Study IIb is quite different from the induction system in Study II. In Study II, a drift initially generates a correlation between energy and time. Subsequently, a relatively slow voltage pulse from induction linacs, decelerates the higher energy early particles, and accelerate the lower energy later particles, to produce a nominally monoenergetic long spill. An adiabatic 200 MHz RF buncher is used to bunch the beam to allow subsequent cooling and acceleration. In the Study IIb scheme there is again an initial drift, but this is followed by a high frequency adiabatic buncher. Because the energy time correlation is changing along the beam path, so the RF frequencies have to be adjusted with their positions. Phase rotation is then achieved, using high frequency RF acting on the bunched beam, with the phase adjusted to decelerate the higher energy early bunches, and accelerate the lower energy later bunches, to produce a nominally monoenergetic long bunch train. The system is cheaper because it avoids the expensive induction linacs, is almost as efficient per sign, and works simultaneously on both bunches.

Conventional, vacuum and diagnostics costs are scaled from Study II Buncher assuming cost proportional to length.

The focusing in Study IIb consists of an essentially continuous solenoid at 1.75 T, as in the drift, but with a radius (65 cm), sufficient for it to remain outside of the RF cavities. For the cost of this solenoid we again scale from the Study II induction linac transport magnet costs (114 k$/m), corrected, using Green's second solenoid formula[5], by the factor $\propto (B\ R^2\ L)^{.577}$: $[(1.75/1.25)x(.65/.3)^2]^{.577} = 3.59$. This estimate is conservative, because it is again scaled from the more difficult transport solenoids inside the induction linacs of Study II.

The cavities and needed RF power supplies are scaled with integrated acceleration voltage (0.12 GeV) from the Study II cooling RF costs (20 M$/GeV for cavities and 120 M$/GeV for power supplies). These costs are scaled for the different average accelerating gradients (9 MV/m in the buncher, 12.5 MV/m in the phase rotator, compared with 16.1 MV/m in Study II cooling). Cavity cost/GeV inverse with gradient, power supply cost/GeV proportional to gradient.

3.5 Cooling

Table 6: Study IIb Cooling Costs

	M$	Length	k$/m	GeV	k$/GeV	Scaling
Cooling	**185.09**	80		.816		
Conventional	9.28		116			length
Magnets	38.9		$771x(189/382)^{.662}$=486			$\propto$ *length x* $\times\ U^{.662}$
Cryo	0.72		7.54 x 486/409 = 8.96			$\propto$ *length x* $\times\ U^{.662}$
Vacuum	3.2		40			length
200 MHz RF 15.25 MV/m	17.22				20x(16.1/15.25)=21.1	$V/\mathcal{E}$
200 MHz RF PS	92.8				120x(15.25/16.1)=114	$V\mathcal{E}$
Absorbers	2.27		0.5x6120/108=28			length/2
Diagnostics	20.7		259			length

The Study IIb Cooling component cost estimate is given in table 3.5. Conventional, vacuum and diagnostics costs are scaled from Study II Cooling assuming costs proportional to length.

The focusing lattice in Study IIb is very quite different from that in Study II. In Study IIb a simple alternating solenoid array (FOFO) is used instead of the more complicated Study II tapered SFOFO lattices. To scale between such different lattices, we use the first solenoid formula from Mike Green[5] that depends on total stored magnet energy (cost $\propto U^{.662}$). The stored energy per unit length in the Study IIb, compared with that in the first Study II lattice is in the ratio 189/382=0.49. the cost per m of the Study II first lattice was 771 k$/m, so the new cast per m is taken to be 771 x $(189/382)^{.662}$=486 k$/m.

As a confirmation of the scaling used, we note that Study II final higher field and shorter (1.65 m) lattice was estimated at 2.04 times that of the early lattice. This ratio is in reasonable agreement with that estimated by Green's first formula of a factor $(1039/382)^{.662})$=1.94.

This is a conservative estimate because the new lattice has, besides a smaller stored energy, is also simpler: it uses only a single type of solenoid, and, when powered, there are no inter-coil forces. In contrast, the Study II lattice employed two types of magnets and had very large inter-coil forces between the "focus" coil pair.

The cost of cryogenic systems to cool the magnets in the new cooling system cannot be taken from the Study II case because those costs cooling of absorbers. Instead we scale cryogenic costs from the bunch and phase rotation sections (7.54 k$/m) scaled by the relative magnet costs (409 $/m in buncher vs. 486 $/m in the new cooling) giving 7.54 x 486/409 = 8.96 k$/m.

The RF in Study IIb cooling is nearly the same as that in Study II. Costs are scaled with integrated acceleration gradient (0.816 GeV) from the Study II cooling RF costs (20 M$/GeV for cavities and 120 M$/GeV for power supplies). These costs are further scaled for the average accelerating gradients (15.25 MV/m vs. 16.1 MV/m in Study II): cavity cost/GeV inverse with gradient, power supply cost/GeV proportional to gradient.

The cost per unit length for the LiH Absorbers is taken as half that for the hydrogen absorbers of Study II (0.5x6120/108=28 k$/m). This is a guess, hopefully conservative, since we do not yet have any engineering study of such absorbers.

3.6 Matching to Linac

Table 7: Study IIb Matching Costs

	M$	Length	k$/m	Scaling
Match to Pre-Acc	**23.1**	15		
Conventional	0.16		10.5	linear
Magnets+PS+cryo (1)	4/106x(38.9+0.7)=1.49			cells
Magnets+PS+cryo (2)	3/45x9.2=2.1			cells
Warm RF and PS	14x(0.16 + 0.87)=14.4			cavities
SC RF	3/92 x (23.9+30+7.8)=2.01			cavities
Vac	0.80		40	length
Diagnostics	2.14			length

The Study IIb Matching component cost estimate is given in table 7. Conventional, vacuum and diagnostics costs are scaled from Study II Matching assuming cost proportional to length.

In the Study II case, the beta vs momentum in the SFOFO cooling lattice had a highly non-linear character, with low betas at the upper and lower momentum limits and a maximum beta in the center. Matching this to the almost linear beta vs. momentum in the Pre-Accelerator was difficult and required a relatively complicated matching lattice. The Study IIb match is simpler and less expensive because a) the beta functions both before and after the match have similar linear momentum dependence and b) the match is only between 0.8 to 2.7 m betas, compared with 0.2 to 2.7 m betas in Study II.

The new matching section consists of two parts:

1. The first consists of 4 cells that are magnetically very similar to the 106 cells in the Study IIb cooling channel.The magnet costs are thus taken to be 4/106 times the sum of magnets and cryogenics: 4/106 x (38.9+0.72)=1.49. This is conservative since the coils in the matching four cells have progressively lower currents and could thus be somewhat cheaper. The warm RF cavities in these first 4 cells are essentially identical to those in the cooling, but there are progressively more per cell in each of the four

cells. The RF and RF power costs are taken to be proportional to the number of these warm cavities (14) times their costs per cavity in the cooling (17.22/106 = 0.16 M$ for cavities, and 92.80/106 = 0.87 M$ for power supplies)

2. The second part consists of 3 cells that are essentially identical to those at the start of the following Pre-Acceleration superconducting linac. Costs of the magnets for the 3 cells is taken as 3 times the linac magnet cost divided by their number (52) in the pre-accelerator. Similarly the SC RF costs are scaled by the same factor of 3/52.

The total is 23.1 M$ which is 70% of that given in the APS Report[3], that had been estimated without an actual design, and was based on a more conservative scaling.

3.7 Pre-Acceleration

Table 8: Study IIb Pre-Acceleration Costs

	M$	Length	k$/m	Scaling
Pre-Acc	**98.52**	302		
Conventional	3.17		10.5	length
Solenoid Magnets & PS	52/53x14.74=14.47			cells
SCRF cavities (17 MV/m)	92/134x41.36=28.4			cavities
RF power	92/134x52=35.7			cavities
Cryo	92/134x13.44=9.23			cavities
Vac	4.74		15.7	length
Diagnostics	2.81		9.3	length

Pre-Acceleration component cost estimate is given in table 8. Conventional, vacuum and diagnostics costs are scaled from Study II Pre-Acceleration assuming cost proportional to length.

The estimates given in the APS report were made prior to a real design, either for the pre-acceleration linac, or for the following RLA. Since that report, a more realistic design[6] has been generated, and is used here. Note that this pre-accelerator has a larger transverse acceptance (30 π mm) than that in Study II (15 π mm). It also has a lower energy.

The Pre-Acceleration magnet costs are scaled with the number of cells (52) in Study IIb, compared with those (53) in Study II, giving 52/53x14.74=14.47. The small decrease in number of cells, despite the lower energy is a reflection of the requirement for a larger transverse acceptance.

The Pre-Acceleration RF cavities, RF power supplies, and Cryogenics cost are scaled from Study II by the number of cavities: 92 vs. 134, giving costs of 92/134x41.36=28.4, 92/134x52=35.7, and 92/134x13.44=9.23 respectively, and with length for magnets, vacuum and conventional.

The total is 86.86 M$ which is 24% higher than the APS number due primarily to higher SCRF costs; the increase arising from a lower average accelerating gradient and lower average RF phase in the linac. The earlier estimate assumed the use of shorter focus solenoids, a resulting higher average RF gradient, higher RF phases and thus a shorter linac. These modifications are listed below under possible future savings.

3.8 RLA

Table 9: Study 1.5 to 5 GeV RLA Costs

	M$	Length	k$/m	Scaling
RLA	**99.6**			
Conventional	(189+2x195)/1804x19= 6.10	579	10.5	length
Arc Magnets + Power	84/160x60.82= 31.9			cells
Arc Vac	3x195/2541x10.54= 2.43	585	4.1	length
Straight Magnets	21/48x9.22=4.03			cells
Straight Vac	189/720x4.17= 1.09	189	5.9	length
SCRF cavities (17 MV/m)	(21x4/48x8)x63.36= 13.86			cavities
RF PS	(21x4/48x8)x89.16= 19.50			power
Cryo	(21x4/48x8)x28.86=6.31			power
Injection	2x1.22=2.44			signs
Switchyards	.54 + .37 = .91			.844 $U^{.459}$
Transport	180/1260 x 5/3 x 37.28 = 8.88			angle x momentum
Diagnostics	(90+21)/(160+48)x4=2.12			cells

The Study IIb RLA component cost estimate is given in table 9.

A dog bone design, rather than the race-track used in Study II, is favored for its easier switchyard designs. Study IIb RLA accelerates from 1.5 to 5 GeV RLA,compared with a 5 to 20 GeV in Study II. The estimate in the APS report was based on a simple scaling. That given here is based on a more detailed design[6].

The new design uses a single 189 m linac with 21 cells, each with 4 RF cavities. The number of passes is 3.5, compared with 4 for Study II. There are two arcs in the same tunnel at one end and a single arc at the other. The arcs all have the same shapes, circumferences of 195 m, and have 28 cells each.

Conventional costs are scaled with total tunnel lengths (189+2x195)x10.5 k$. Vacuum costs are scaled with total linac and arc lengths (189+3x195). Since the RF gradients assumed are the same, RF cavity, power and cryogenic costs are all scaled with the relative numbers of cavities (21x4)/(48x8) multipied by the Study II cavity, power, and cryogenic costs of 63.36, 89.16, and 28.86 M$ respectively.

Focusing in both Study II and Study IIb is provided by quadrupole triplets. In the linacs, the triplets have the same linear dimensions and phase advances per cell as in Study II, but the cells and betas are smaller by the factor 9/15, and the initial momenta are smaller by a factor 1.5/5. As a result, the gradients are less by a factor=1.5/5 x 15/9 = 0.5, the apertures are larger by $\sqrt{9/15x5/1.5} = \sqrt{2}$, their pole fields are less by $1/\sqrt{2}$, and their stored energy $\propto B^2R^2$ are the same. Taking the cost to be related to the stored energy gives the same unit costs, and we can scale the total costs by the relative numbers of linac cells (21/48).

In the arcs, the cells in Study IIb are 9 m compared with 11.5 m in Study II, and the average arc momenta is 3 GeV/c compared with 12.5 GeV/c. Assuming the same phase advances, the average gradients are less by the factor 0.31, the apertures greater by the factor $\sqrt{9/11.25x4.2} = 1.83$, the pole fields less by 0.57 and the stored energies greater by 1.08. The cost would then scale as this factor times the relative number of cells 84/160.

The total arc bending angle in Study IIb is 3 x 420 =1260 degrees compared with 7 x 180=1260 degrees, which is coincidentally, the same. The average bending momentum is 3 vs 12.5 GeV/c, so the total required B dl is less by 0.24, the B dl per magnet is 0.24 x 153/84 = 0.44, and, for the same magnet lengths, the stored energies scale as $0.42^2 \times 1.83^2 = 0.65$. Unfortunately, we do not know the relative costs of the Study II quadrupoles and dipoles. If we assume that they were the same, then the cell costs for Study IIb would be (3 x 1.08 + 0.65)/4 =0.97 times the Study II costs. If the quads cost half of the dipoles, the factor is

0.91. A conservative assumption is to assume the cell costs are the same and again scale the arc costs by the number of arc cells: 90/160

The switchyard consists simply of two 1.4 T dipole magnets (see fig. 1) whose cost is estimated from the first all magnet formula from Mike Green[5]: Cost=0.844 $U(MJ)^{.459}$ M\$. This formula was derived for superconducting magnets, but it is assumed that conventional magnets would have similar or lower costs. The two estimated switchyard magnet costs are .54 and .37 M\$.

In estimating the cost of the injection chicane and transport magnets, we can follow the above conclusion that costs are approximately proportional to the numbers of magnets, independent of the momenta of the transported beams. The cost of the Study II input chicane is doubled to include injection of both signs (1.22 x 2 = 2.44). Transport lines consist of two 90 degree arcs connecting the RLA to the first FFAG. Their cost is taken from the return arcs, scaled by bend angles and momentum divided by average arc momenta (180/1260 x 5/3 x (34.75+2.53) = 8.88).

Diagnostic costs are scaled by the total number of cells (90+21)/(160+48)=.53 times 4 gives 2.12 M\$.

The total of 99.6 M\$ is 21% higher than that in the APS study. The increase is almost entirely from higher estimated arc costs resulting from their greater size. The possibility of decreasing their size, as scaling suggests is possible, is listed below as a possible further saving.

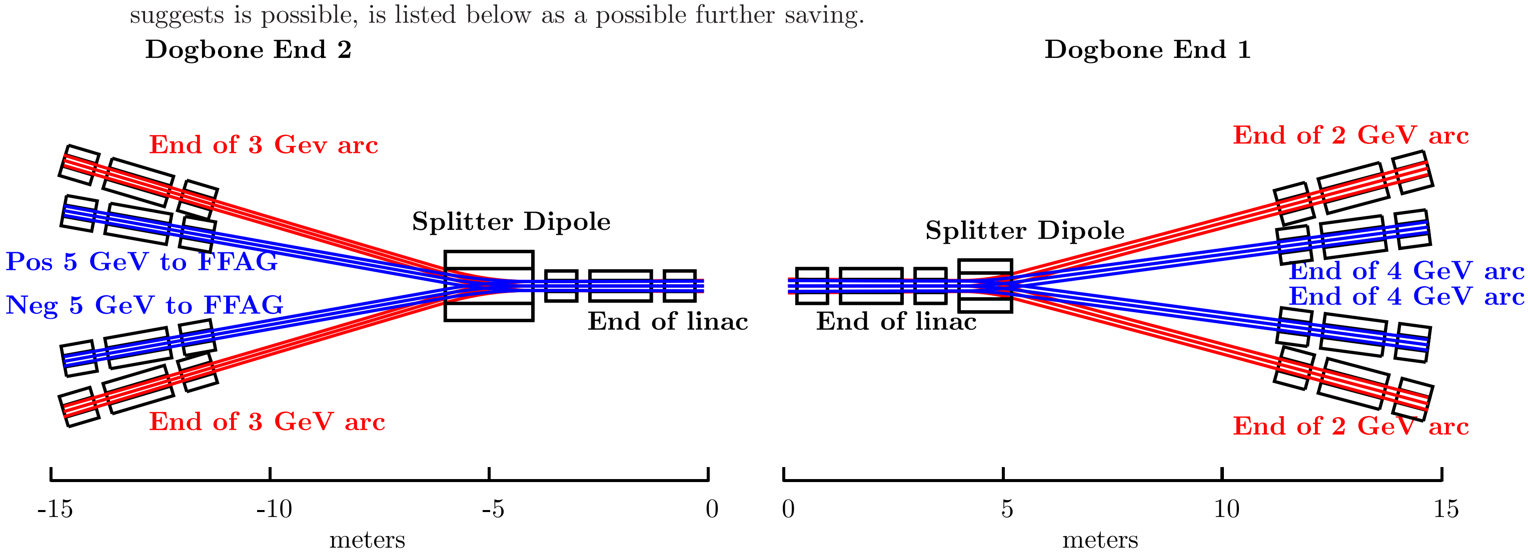

Fig. 1 Proposed RLA Switchyards at either end of the linac.

3.9 FFAG's

Table 10: Study IIb FFAG Costs

	M$	Length	k$/m	Scaling
FFAG 5-10	**91.1**			
Tech + Conventional	83.1			costing algorithm
Injection/extraction	2			stored energy
Beam Transport Magnets + Vac	6	200	28.0	length
FFAG 10-20	**109.1**			
Tech + Conventional	93.1			costing algorithm
Injection/extraction	2			stored energy
Beam Transport Magnets + Vac	14.0	500	28.0	length
Both FFAG's	**200.2**			193

The Study IIb FFAG component cost estimate is given in table 10. The costs for all technical and conventional costs are taken from a cost algorithm[7]. This algorithm when applied to the Study II RLA gives a higher cost than given in that study. The algorithm thus appears to be conservative when compared with Study II. The lattices used for this cost estimate were for triplet lattices optimized including consideration of decay loss assuming a "muon cost" of 5 M$ per 1% of decay.

Injection/Extraction kickers are assumed to be driven by typical induction linac power sources, and will contain similar amounts of magnetic materials. The costs are taken from a length of the Study II Induction linac that has the same pulsed energy.

Transfer line lengths are taken from Palmer's report on Injection/Extraction at TRIUMF and include lines for both signs. The cost per m of these transport lines is taken from the RLA arcs(magnets, PS, and vacuum: 23.9+4.1=28.0 k$/m).

3.10 Storage Ring, Neutrino Profile Monitor & Control Room

Table 11: Study IIb Storage Ring Costs

	M$	Length	k$/m	Scaling
Storage Ring	**82.47**	358		
Conventional	28.12	358	78.5	same
Tech	54.35	358	152	same
Control Room	**15**			
Nu Detector	**10**			

The Study IIb Storage Ring component cost estimate is given in table 11.

Storage ring costs are taken, without modification, from Study II. In that case, sited at BNL, there was a constraint that no part of the downward tilted ring should fall below the nearby water table. This constraint forced the construction of the ring in an artificial hill and also required unusually high, and not cost optimized, bending fields to keep the ring small. The cost at another location, without this constraint, would probably be less.

4 Summary of Study IIb Costs, and Comparison with Study II

4.1 Savings by subsystem

Table 12: Study IIb Costs

System		M$		M$	%
Target, capture, 18 m drift		**97.3**		**96.1**	**99**
	Target	91.5	Target	89.7	
	18 m Drift	5.8	18 m Drift	6.4	
Bunch and Phase Rotate		**393.6**		**148.6**	**38**
	Rotator	306.7	82 m Drift	19.3	
	Mini-Cool	11.3	Buncher	44.8	
	Buncher	75.6	Rotator	84.5	
cool		**310.2**		**185.1**	**60**
Acceleration		**544.2**		**421.4**	**77**
	Match	56.7	Match	23.1	
	Pre-Acc	136.8	Pre-Acc	98.5	
	RLA	350.9	RLA	99.6	
			FFAG 1	91.1	
			FFAG 2	109.1	
Ring		**82.5**		**82.5**	**100**
Total		**1427**		**934**	**65**

Percentage cost reductions for each subsystem are summarized in table 12

4.2 Additional Costs in Study IIb, calculated as in Study II

Table 13: Study II Cost Summary

	no Driver 2001 M$	no Driver or Target 2001 M$
Subtotal 1 (from above)	**958.8**	**869.1**
Site Utilities (7.83% of sub-total 1)	75.1	68.1
Subtotal 2	**1033.9**	**937.1**
10% for other items including controls	103.4	93.7
Total (no EDIA, or escalation etc.)	**1137.2**	**1030.8**
Study II Totals (no EDIA, or escalation etc.)	**1723.3**	**1614.7**
Reductions	**66 %**	**64 %**

The summary of estimated Study IIb Costs is shown in table **??**. Some part of the target station cost is likely to have been covered by the needed shielding, remote handling, and high radiation area utilities built for the super-beam. Thus the additional cost for the neutrino factory may be expected to fall somewhere between the totals with the target (1133 M$) and that without it (1047 m$).

References

[1] Editors S. Ozaki., R.B. Palmer., M.S. Zisman, J.C. Gallardo, "FEASIBILITY STUDY-II OF A MUON-BASED NEUTRINO SOURCE", June 14, 2001; http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

[2] In the actual Study II, these were taken proportional to technical items only, but the numerical result is the same and the calculation is simpler

[3] "Neutrino Factory and Beta Beam Experiments and Development"; BNL-72369-2004, FNAL-TM-2259, LBNL-55478 http://www.aps.org/neutrino/loader.cfm?url=/commonspot/security /getfile.cfm&PageID=58766

[4] "The Neutrino Matrix DNP, DPF, DAP, DPB JOINT STUDY ON THE FUTURE OF NEUTRINO PHYSICS" http://www.aps.org/neutrino/index.cfm

[5] M. A. Green, R. Byrns, S.J.St. Lorant; *Estimating the cost of superconducting magnets and refrigerators needed to keep them cold*; LBNL-30824 & Advances in Cryo Eng. 37, Feb 1992

[6] Alex Bogacz, http://www.fnal.gov/projects/muon_collider/FridayMeetings /December%203%2C%202004 /Low%20Energy%20Stages%20-%20Dogbone%20Muon%20RLA%20–%20Bogacz.pdf

[7] Robert B. Palmer and J. Scott Berg, "A Model for Determining Dipole, Quadrupole, and Combined Function Magnet Costs," in *Proceedings of EPAC 2004, Lucerne, Switzerland*, EPAC, European Physical Society Accelerator Group, 2004, p. 1807.

[8] Scott Berg, private communication.