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Shielding Calculations and Design for the ATF H-line System

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1. Introduction

The ATF group plans to install a new pulse compression system in the straight beam transport line immediately following the accelerator sections that are housed below the mezzanine in building 820. This involves removal of the existing transport line and shielding and replacing it with new focusing and bending elements which form a chicane designed to provide beam compression. The new focusing elements (quadrupoles) are designed so that their position with respect to the beam line axis can be adjusted in order to minimize beam steering caused by misalignments. This requires ready access to the adjustment mechanism and impacts the shielding design. The addition of dipole bending magnets in the line also leads to potential beam loss points which are not present in the existing beam line and not covered in the original Safety Assessment Document for the Accelerator Test Facility. This report covers the results of shielding calculations, presented in Appendix I for reference, and the shielding design for the new system.

2. Operating Parameters

The normal and maximum possible operating parameters for the facility are those given in section 3.6.1 of the ATF SAD and are summarized in the following table:-

	Normal	Maximum
Output Beam Energy	75 MeV	120 MeV
Pulse Repetition Frequency	1.5 Hz	6 Hz
Radio-frequency Pulse Length	3.5 μS	3.5μS
Beam Pulse length (nominal)	10 pS	10 pS
Beam charge in one pulse	0.5 nC	* 1 nC
No. of beam pulses / macropulse	1 to 10	100

* The maximum charge of 1nC may not be practical for 100 bunch operation since it will, in general, cause beam loading in the electron gun that would change the beam energy and could cause the beam to be lost in the gun region and not be accelerated through the accelerating sections. In fact, for a charge of 1nC per beam bunch there could be a change in gun voltage of more than 6.5% during the duration of the 100 beam bunches and it is unlikely that this mode of operation at this level of charge would be useful for any of the planned experiments. At the present time the best operation, in multi-bunch mode has been with about 10 bunches with 0.5 nC or less per bunch.

For the purposes of this document we have calculated the maximum beam loss that can occur at the full energy of 120MeV, at the maximum pulse repetition of 6 Hz, with 100 beam pulses, and with the maximum practical charge that can be effectively accelerated through the two accelerating sections. However, the ATF present and future experimental program does not require or involve operation in 100 bunch mode at a repetition rate of 6 Hz so the impact of limiting the multi-pulse operation to 1.5Hz and the multi-bunch operation to 10 bunches with 1 nC per bunch will be presented. For the SAD the maximum total number of electrons at full energy was calculated to be 3.6×10^{12}/ sec. We shall assume this same number for our calculations. The measured "dark current" electrons that are produced by field emission from the cathode of the electron gun give rise to a total charge of 100pC at 5MeV at a repetition rate of 1.5 Hz. Only 10% of this charge is accelerated through the linac sections so that, even at the maximum repetition rate of 6Hz, only 2.4×10^{8} electrons/sec are produced. This is negligible compared to the charge produced by photo-electrons in 100 bunch operation and is only~0.7% of the charge for operation at 1nC charge and 6Hz in single bunch mode.

3. Current Operational Experience and Future Operating Plans

The ATF has been operating for more than 12 years at the normal operating parameters given in the table presented in Section 2 of this document. The radiation levels outside the shielded area have been monitored with the use of TLD's and the data obtained is presented in Figure 1. It can be seen that for the High Bay Area that is occupied by persons who are not part of the ATF staff (Locations75,76 and 77 in the figure) the levels are very low thus verifying the integrity of the existing shielding for all operations to date. There are a few regions occupied by ATF staff where, in the early years, the levels have approached or exceeded 100mRem for the year. However, the shielding has been upgraded so that , in recent years, the annual total has not reached 100mRem. The existing hardware installed at the ATF is not capable of operating at 120MeV energy with 1 nC in each of 100 micro-bunches, at a pulse repetition rate of 6Hz. Neither does the present or future experimental program require operation at this level. There could be a future upgrade of the radio-frequency power system at a level that would provide 120 MeV beam energy at a repetition rate of 1.5 Hz, but this would not provide for 100 micro-bunch operation. Any future planned operation would not go beyond 120MeV energy with 10 micro-bunches and a pulse repetition rate of 1.5Hz. Furthermore the experimental program is not likely to require operation in multi-bunch mode fore more than 10% of the beam operating time.

An upgrade to 100 micro-bunches would require extensive work on both the radio-frequency and laser systems and is not in the ATF long term plans. Should this work become a priority it would be necessary to provide active radiation monitoring for beam losses and read back and monitoring of quadrupole and dipole magnet current or field, with an appropriate alarm system to alert the machine operator in the case of a failure. This operating mode would be the subject of a future full safety review. Thus data presented in this report for the maximum operating mode is to be used for reference only.

4. Beam Loss Modes at 120 MeV

Beam losses in the new H-Line can occur in the following locations:-

- At any point inside or at the exit of any of the dipole bending magnets due to either a miss-setting of the magnet current or a fault in the magnet.
- At points in the transport line where the beam size is at a maximum due to dispersion or a miss-setting of a quadrupole.
- At beam profile monitors when they are inserted into the beam during beam line set up.

In the first case all of the beam could be lost at essentially a point location, while in the other two cases the beam loss would be distributed over some distance and not all of the beam would strike metal surfaces and be stopped there. In the calculations we will study these losses in detail and recommend shielding to prevent them from producing radiation levels outside the shield that could result in an annual dose to an individual of 100mRem.

Under normal operating conditions, with a correct set of quadrupole and dipole set points, essentially no beam losses should occur, since the beam pipe apertures are considerably larger than the beam size. Furthermore, most of the operation of the ATF is carried out with a single electron bunch in each radio-frequency pulse and at a repetition rate of 1.5 Hz. The multi-pulse operation is only scheduled for 10% or less of the available operating time so this will impact the calculations (There are no experiments scheduled at this time that require multi-pulse operation). For normal operation of the facility in multi-bunch mode we will assume for the purpose of these calculations that there may be a loss of 1% of this beam at specific locations along the beam line and calculate the radiation level outside of the accelerator tunnel due to this loss.(This 1% figure is a conservative number since the beam normally occupies only about 30% of the beam aperture when at its maximum size under normal operation)

5. Radiation Safety Hazards

When the electron beam strikes the beam pipe or other parts of the accelerator bremsstrahlung photons are produced. Unless the angle of incidence is less than ~ 2 degrees 120MeV electrons are too energetic to be stopped by the beam pipe so that, unless lead shielding or other metal such as the steel of dipole bending magnets or quadrupoles is along their beam path, they will continue in air until they strike the concrete shield wall of the accelerator tunnel where they would be stopped. Normally lead of sufficient thickness to stop the electrons is placed close to the point where they strike the beam pipe so that photons are produced in the lead shield. The photons also give rise to neutrons that are shielded by the concrete shield walls of the accelerator tunnel.

6. Radiation Shielding

The shielding is provided to attenuate radiation produced by electron losses. Generally it is designed to stop electrons in lead, although in some cases the electrons may be stopped in the steel or copper coils of focusing quadrupoles, or bending magnet dipoles. There will also be some reduction in energy of the electron beam as it passes through the stainless steel wall of the vacuum pipe and in some cases through connection flanges.

Generally, the bremsstrahlung are also attenuated in lead and the resulting neutrons are shielded by concrete or other equivalent shielding material. For the purposes of our calculation we assume that operation at the maximum levels will occur for only 10 % of the available operating time or 240 hours per year. Most of the beam losses that contribute to the radiation levels will occur due to either miss-setting of focusing or bending elements during set up or machine studies or by the insertion of profile monitors into the beam for observing the beam size while making magnet adjustments. We will conservatively assume that this tune up time may occur for 20 hours per month or 240 hours per year. However, only 10% of this time, or 24 hours, would be at the maximum operational level. Most of the time set up would be conducted in single bunch mode at low repetition rate (1.5Hz). Accidental losses due to failure of machine components will be covered in a separate section of this document.

In the ATF SAD Section 4.5.2.2.2 it was assumed that the 100 micro-bunch mode would be carried out for 50% of the available time, or 1200 hours per year. However, in practice this multi-bunch mode is much less frequent, and as stated earlier, even when used, typically 10 rather than 100 micro-bunches are utilized and at a charge of 1 nC or less per beam bunch. The existing hardware at the ATF is not capable of producing 100 micro-bunches, each with a charge of 1nC, and there are no present, or future plans to upgrade the facility to this level of operation. Any upgrade of this nature would require extensive study and would call for continuous, on line, monitoring of magnet currents and radiation levels in order to detect equipment failures and interrupt beam operation before radiation dose outside the shielded area becomes a hazard.

7. Review of Existing Shielding

The original shielding for the Accelerator Test Facility was designed to accommodate operation of the accelerator with "dark current" electrons produced in the electron gun and accelerated through the accelerating sections. Because these electrons are produced during almost the entire radio-frequency pulse, there is a wide energy spread in the beam and this would result in large beam sizes near focussing elements in the transport line, giving rise to electrons striking the beam pipe and producing photons. Therefore, 2 to 4 inch thick walls were provided on top and alongside all of the focussing elements. The existing shielding for the ATF accelerator sections and transport line in Building 820 is shown in Figures 5 and 6 of the ATF SAD which are included here for review. Two to four inch thick lead walls were provided above, and alongside respectively, of groups of quadrupole focusing magnets where it was anticipated beam losses could occur during tune up of the accelerator. The lead is there to provide shielding for the Bremsstrahlung photons produced when electrons strike the walls of the beam pipe through which they are passing. The electrons are energetic enough to pass through the wall of the beam pipe, if they strike it at an angle of > 2 degrees, and enter the lead shield where more photons are produced. These photons produce giant resonance neutrons that are then in turn shielded by the 3.5 feet thick concrete or equivalent tunnel roof and wall. A two inch thick lead wall is adequate for most shielding purposes and no account was taken for the shielding provided by the steel poles and /or copper coils of the quadrupole magnets. In this sense the shielding was over designed. However, it was deemed easier to build walls using standard 4x2x8 inch lead bricks than to design, fabricate and support specially shaped lead collimators for shielding purposes. The four inch side wall thickness was required to provide mechanical stability.

8. New Shielding Design

After many years of operating the ATF, we have a much clearer knowledge of how and where beam losses may occur and how much beam may be lost. Current generation linear accelerators utilize a laser excited photo-cathode so that very short (<10pS) micro-bunches are produced. This results in low energy spread, low emittance electron beams which are typically only a few mm in radius at their maximum beam size and therefore only occupy a region of the order of 1/3 of the beam pipe. Thus, under normal operating conditions, no electrons strike the beam pipe. Furthermore, most of the "dark current" electrons produced at the gun are lost in the low energy transport section before the accelerating sections and only 2×10^{8} electrons/sec would be accelerated to 120MeV at the 6Hz repetition frequency. This is negligible compared to the 3.6×10^{12} electrons/sec produced by operating the accelerator at its maximum operating condition.

Therefore, for the new shielding design we shall investigate each potential beam loss point in more detail and take into account all potential shielding materials. This will allow us to design the necessary lead shielding size and location to properly protect personnel occupying regions outside and immediately adjacent to the shield wall of the tunnel.

8.1 Shielding for normal operation in multi-bunch mode

As stated earlier we do not anticipate any significant beam loss in the transport line under normal operation since electrons that would not have been within the acceptance of the accelerating sections are stopped in the low energy beam transport region before they reach the accelerator. However in order to estimate the levels of radiation that could be produced outside the accelerator tunnel we have assumed a 1% beam loss at some specific locations along the beam line. (This is a conservative assumption since the beam typically only occupies about one third of the available space within the beam pipe) The detailed calculations are given in Appendix I and the results for photon radiation are summarized in Table I below.

It can be seen that operation at the maximum level as presented in the ATF SAD would result in unacceptable radiation levels outside of the shielded area. This is true for both the original shield design, as presented in the SAD and for the new shielding design. However, operation at the levels currently utilized during normal ATF operation, even at an increased energy of 120 MeV, is acceptable.

TABLE I, MAXIMUM PHOTON DOSE RATES OUTSIDE THE SHIELDED AREA UNDER NORMAL OPERATING CONDITIONS

LOCATION OF BEAM LOSS	1.5 Hz,1 bunch operation at 1nC		1.5 Hz, 10 bunch operation at 1nC/bunch		6 Hz, 100 bunch operation at 1nC/bunch	
	With no Shielding	With Lead Shielding	With no Shielding	With Lead Shielding	With no Shielding	With Lead Shielding
Quadrupole region at 90 degrees	90μR/Hr.	<1μR/Hr.	0.9mR/Hr.	9μR/Hr.	36mR/Hr.	360μR/Hr.
First Dipole Magnet Region	9μR/Hr.	<0.1μR/Hr.	90μR/Hr.	<1μR/Hr.	3.6mR/Hr.	36μR/Hr.
Profile Monitor at 90 degrees	5.5mR/Hr.	100μR/Hr.	55mR/Hr.	1mR/Hr.	2.2R/Hr.	40mR/Hr.
At Dipole after hitting profile monitor	11.7mR/Hr.	67μR/Hr.	117mR/Hr.	670μr/Hr.	4.7R/Hr.	23mR/Hr.
At Faraday cup / Beam stop, 0 deg.	10.8mR/Hr.	22μR/Hr.	108mR/Hr.	215μR/Hr.	4.32R/Hr.	8.6mR/Hr.
At Faraday cup / Beam stop, 90 deg.	45mR/Hr.	90μR/Hr.	450mR/Hr.	900μR/Hr.	18R/Hr.	36mR/Hr.

9. <u>Accidental Beam Losses</u>

Accidental beam loss can occur if a beam line element such as a quadrupole or dipole loses its source of power or the power source is incorrectly set. The worse case situation would be total loss of power for an individual quadrupole or dipole. We will investigate the radiation produced in this situation assuming the required shielding is in place for normal operational situations. It is anticipated that an accidental loss situation will be detected quickly since the beam will no longer be useful for the experiment under way and the beam loss will be observed by the Control Room operator who monitors the beam at all times. If the operator leaves the Control Room, the laser shutter is inserted to stop the beam at the source. We will estimate the radiation losses caused by equipment malfunction for each of the operating modes given in Table I.

9.1 Failure of a Quadrupole Power Supply

Failure of any individual quadrupole power supply will cause the beam to grow large in either the horizontal or vertical dimension, depending upon the quadrupole polarity. In general, some fraction of the beam will strike the beam pipe at a point downstream of the failed element and exit through the steel beam pipe. The program TRANSPORT was used to simulate transport through the first quadrupole triplet immediately following the accelerating sections and up to the first dipole of the chicane. The results of the second order calculation are shown in Figure 2.

It can be seen that if the failure occurs in the first quadrupole of the quadrupole triplet the beam will grow larger in one and smaller in the other dimension and will probably not strike the beam pipe. It will be mismatched to the subsequent transport elements and not provide useful beam at the experiment. Failure of the center element of a quadrupole triplet will certainly cause some beam to strike the beam pipe. Failure of the third element of a triplet will also cause the beam to grow smaller in one dimension and larger in the other resulting in some beam striking the beam pipe and causing mismatch. Calculations of dose rates for this and other loss situations are presented in Appendix I. The maximum dose rates outside the shielded area are given in Table II.

9.2 Failure of a dipole power supply

Failure of any of the dipole power supplies would result in the electron beam striking the beam pipe somewhere within one of the dipoles of the chicane. With 4 inches of lead shielding in place alongside the dipoles and 6 inches above the gap of the first dipole the maximum radiation dose rates outside the shielded area are given in Table II.

TABLE II, MAXIMUM PHOTON RADIATION DOSES OUTSIDE THE SHIELD WALL UNDER FAULT CONDITIONS WITH LEAD SHIELDING IN PLACE

FAULT CONDITION	1.5 Hz, 1 bunch operation at 1nC	1.5 Hz, 10 bunch operation at 1nC/bunch	6 Hz, 100 bunch operation at 1nC/bunch
Center quadrupole power supply at zero	250μR/Hr.	2.5 mR/Hr.	100mR/Hr.
Dipole power supply failure	172μR/Hr.	1.72mR/Hr.	69mR/Hr.

10. <u>Recommended Shielding</u>

Based on the calculations presented above and in the Appendix the following lead shielding is recommended.

10.1 Shielding around beam profile monitors

Four inch thick lead walls are required along the side and top of each beam profile monitor. In order to achieve this it is recommended that a mirror be used in conjunction with the CCD camera so that it can be mounted on a horizontal plane along the beam line and towards the accelerating cavities. The lead should extend from an inch before the center of the beam position monitor to 3 or 4 inches beyond it. The lead should also extend 4 inches below the center of the monitor. This should allow the use of standard 2x4x8 inch lead bricks for the shielding and allow upstream access to the beam position monitor.

10.2 Shielding in the straight after each quadrupole triplet

As stated in Appendix I, cylindrical or rectangular lead shields 8 inches in length and extending 12 inches from the beam line center should be placed at the nearest convenient location after each quadrupole triplet. It may be desirable to combine this shield with the shield for the profile monitors and also to extend the beam profile shield up to the exit of the third quadrupole of the triplet in order to accommodate any possible beam loss there.

10.3 Shielding around the dipole magnets in the chicane

Shielding around the first dipole of the chicane is largely required to shield the photons produced when off energy electrons are stopped in the steel of the magnet yoke whenever a beam profile monitor is inserted upstream of the dipole. (accidental failure or miss-setting of the dipole magnet is also considered). 6 inches of lead is required immediately above the gap region of this dipole and this should extend 4 inches on each side of the beam line center. Photons emitted at angles that would cause them to miss this lead shield would be attenuated by increased lengths of steel, copper and concrete and would not give rise to high radiation levels outside the shield wall. 4 inches of lead shielding is required on both sides of the dipole, opposite the beam pipe vacuum chamber. Again, this should extend 4 inches on each side of the beam line center.

Beam loss in the other 3 dipoles of the chicane will only occur if dipoles are miss set or a power supply fails. Because these losses occur further from the tunnel roof only 4 inches rather than 6 inches of lead is required above the gap region in these magnets. The same 4 inches is required along each side of these dipoles, opposite the beam chamber.

10.4 Shielding around the beam stop/monitor after the third dipole

Although this device is only used for beam set up it does intercept the full beam and requires 6 inches of lead shielding around it in order to reduce the dose outside the tunnel to manageable levels.

10.5 Physical shielding design

The lead shielding that will be provided in order to conform with the above recommendations is shown in Figure 3. The chicane is not shown in this figure since there are no plans to install it at this time and it, together with the associated beam stop, will be the subject of a future review.

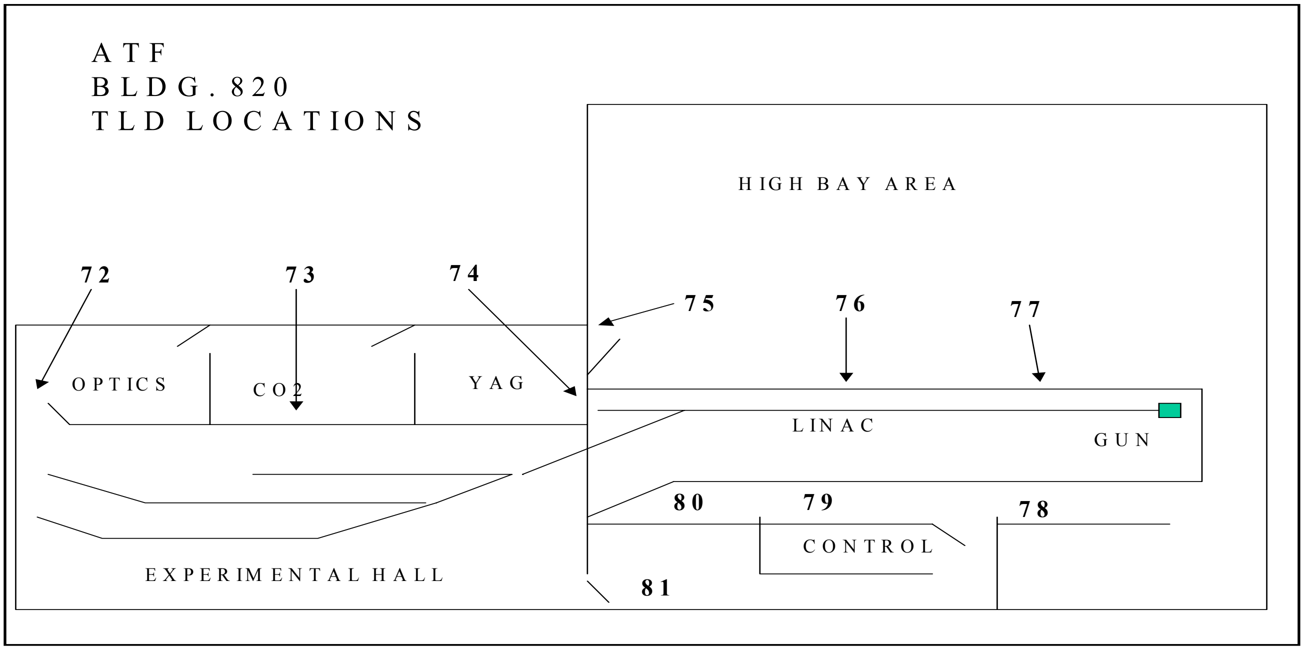
11. Summary

Beam loss and shielding calculations based on the normal and maximum operating levels of the Accelerator Test Facility have been presented treating both normal operational losses and accidental losses. Most of the time that the machine is operational there are minimal or no beam losses in the H-line region. The shielding is required mainly for setting up or study times and for accidental losses. The maximum potential operational level is not in the immediate plans and may never be required. However, safe operation of a facility of this sort is a major concern so the shielding has been designed with this in mind.

	TLD 72 Neutron	TLD 72 Gamma	TLD 73 Neutron	TLD 73 Gamma	TLD 74 Neutron	TLD 74 Gamma	TLD 75 Neutron	TLD 75 Gamma	TLD 76 Neutron	TLD 76 Gamma
1995	13	40	3	4	26	212	7	0	11	3
1996	14	122	4	1	8	148	6	0	8	2
1997	5	18	3	0	7	89	3	2	4	7
1998	5	110	1	0	7	3	3	0	3	0
1999	94	43	9	34	7	1	1	9	3	4
2000	11	54	3	0	11	6	4	0	3	0
2001	26	68	3	0	3	9	0	0	2	0
2002	3	8	0	0	0	2	0	0	0	0

	TLD 77 Neutron	TLD 77 Gamma	TLD 78 Neutron	TLD 78 Gamma	TLD 79 Neutron	TLD 79 Gamma	TLD 80 Neutron	TLD 80 Gamma	TLD 81 Neutron	TLD 81 Gamma
1995	6	0	12	7	12	5	160	37	5	2
1996	1	1	5	5	9	0	145	38	5	0
1997	1	7	3	11	6	0	206	35	3	0
1998	2	1	2	0	3	0	29	4	2	0
1999	3	7	3	7	19	4	17	14	10	8
2000	3	14	4	2	4	3	60	7	3	0
2001	2	0	4	0	3	0	84	2	4	0
2002	0	0	0	0	0	0	23	0	1	0

Figure 1. ATF TLD Totals for the Years 1995 Through 2002 (Annual Totals are in mRem)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H I G H B A Y A R E A
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Y A G
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8 1

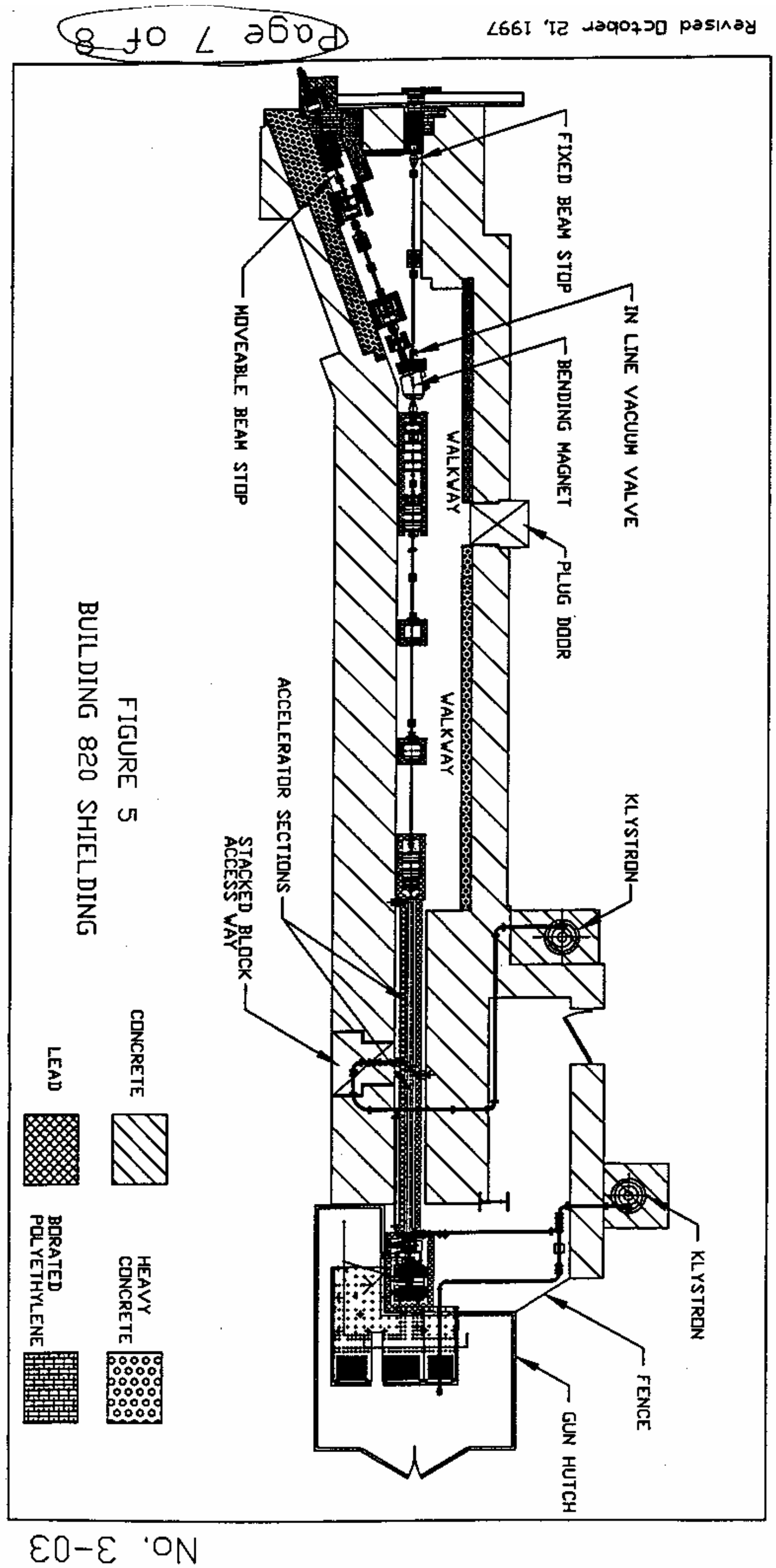

FIGURE 5
BUILDING 820 SHIELDING

No. 2-00

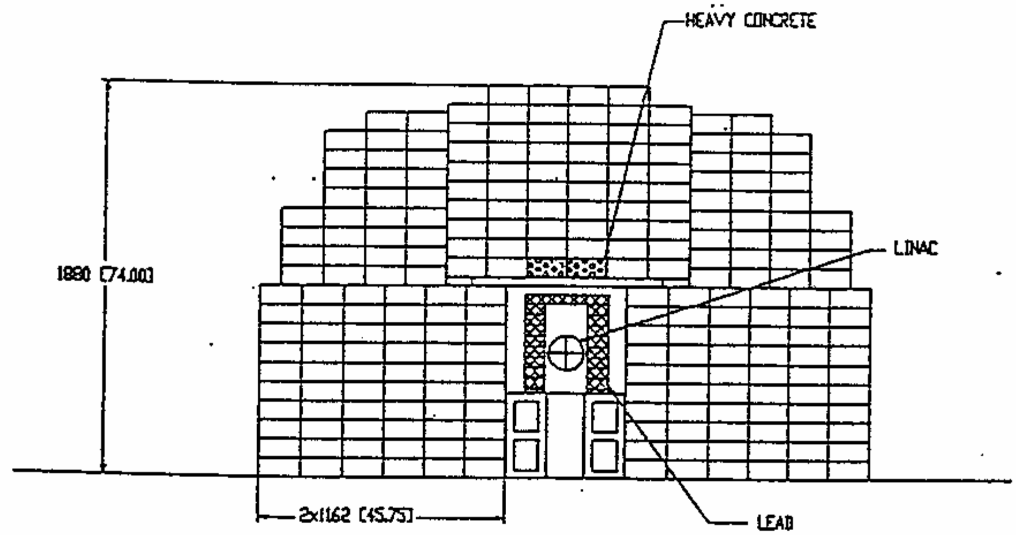

FIGURE 6A
SECTION AT LINAC

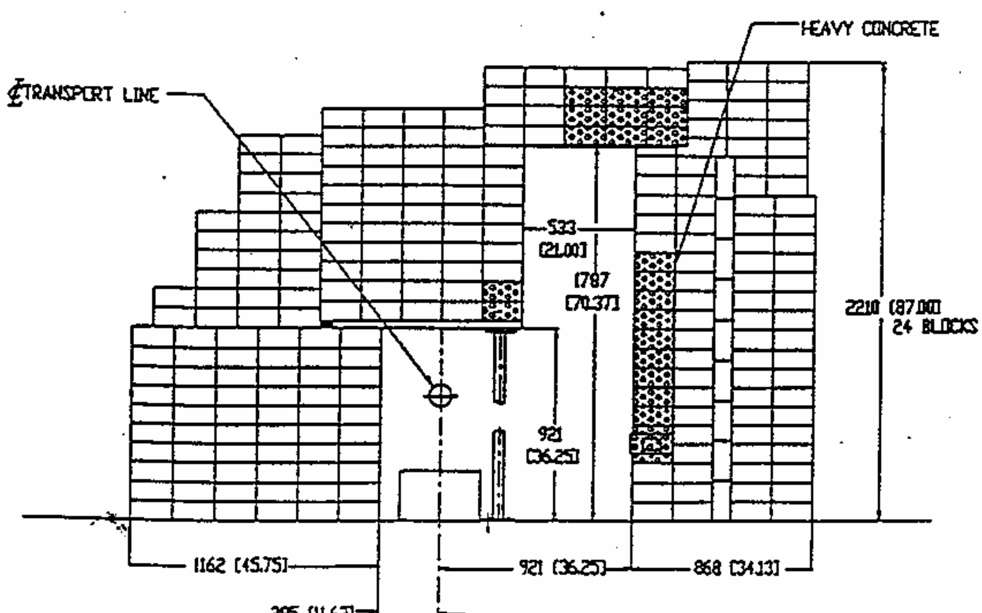

FIGURE 6B
SECTION AT TRANSPORT LINE

Transport through a Quadrupole triplet when individual quadrupoles are set to zero
TRANSPORT run to give a double waist at the input to the first dipole of the chicane
Q1=3.542kG, Q@= -1.382kG, Q3=2.248kG

	Quads.set at above		Q1 set to zero		Q2 set to zero		Q3 set to zero		
Dist. in m.	x in mm.	y in mm.	x in mm.	y in mm.	x in mm.	y in mm.	x in mm.	y in mm.	
0	2	2	2	2	2	2	2	2	
0.35	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	
0.49	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	Q1 Start
0.64	1.23	3.03	2.06	2.06	1.23	3.03	1.23	3.03	
0.765	0.17	4.79	2.09	2.09	0.17	4.79	0.17	4.79	Q2 Start
1.065	3.93	5.18	3.8	0.89	3.12	9.02	3.93	5.18	
1.19	6.23	3.7	5.35	0.23	4.4	10.78	6.23	3.7	Q3 Start
1.34	7.08	2.85	5.62	1.35	4.62	16.25	8.99	1.94	
1.47	6.09	2.84	4.44	2.64	3.65	24.33	11.38	0.42	
2.27	0.21	2.8	2.79	10.61	2.31	74.11	26.12	9.05	
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7	Series 8	

Figure 2 - Transport through quadrupole triplet

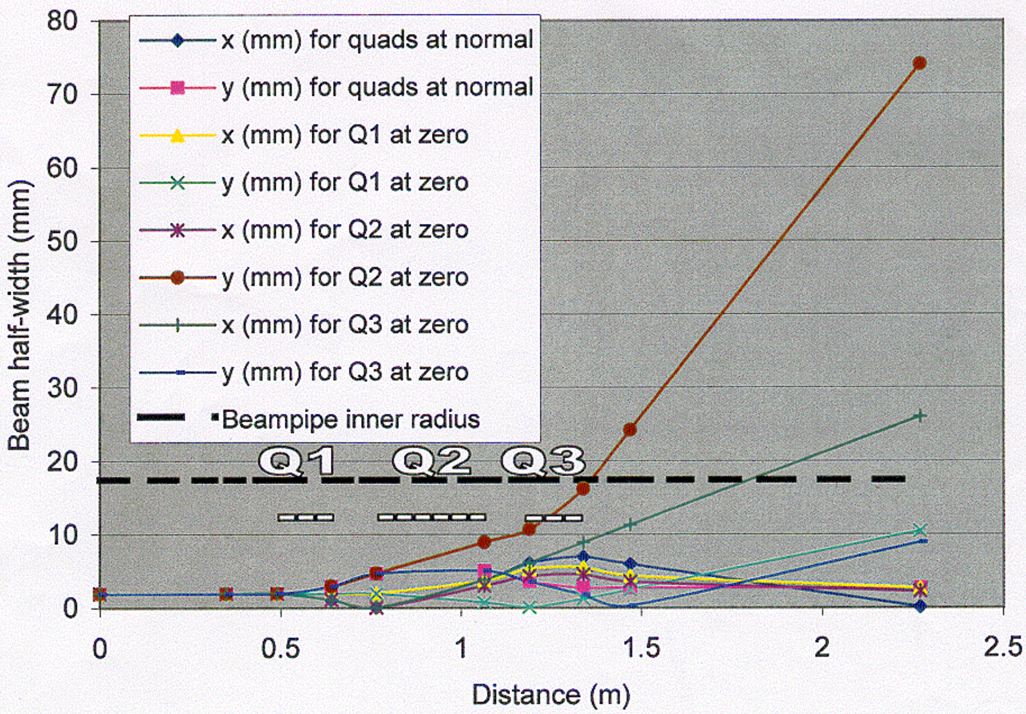

Figure 3. New shielding configuration