Status Report on Bypass Studies for the SSC

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November 1988

Introduction

The intent of this note is to summarize the current status of bypass studies for the SSC and provide a guide to existing documentation on this subject. The subject of a bypass for the SSC was first discussed in some detail at the 1986 Snowmass Summer Study by Johnson,[1] by a working group on experimental facilities[2] and by Lederman.[3] Following the Snowmass Summer Study, members of the Central Design Group participated in the study of numerous bypass options during the last half of 1986 and during 1987. Lederman and Teng[4] and Teng[5] have also studied various aspects of the bypass issue, in particular the "one-campus" concept.

Some of the key technical documents related to bypass studies, including internal CDG memos, are included as appendices to this report. These appendices are

A. Sanford memo of October 9, 1986
B. Gilchriese memo of June 26, 1987
C. Updated bypass summary table of July 3, 1987
D. G. Drouet and T. E. Toohig, "Configuration of SSC Lattices to the ISP Template," SSC-N-404
E. Drouet memo of November 9, 1987
F. L. C. Teng, "Studies of One-Campus and Two-Level Configurations for the SSC," updated version of SSC-N-506

In addition, one bypass variant is described in this report, since existing notes are of too poor quality to be included as an appendix.

Cost and Other Assumptions

Important issues in assessing the bypass options are the incremental costs associated with extra tunneling for a bypass and for additional magnets to be placed in the bypass tunnel. In order to estimate an <u>incremental</u> cost, an assumption about nature of the SSC without a bypass or any provision for a bypass must be made. In this report and most of the appendices, the baseline SSC design is the referred to as the 90° lattice design.[6] This design does not include provisions for a bypass of any type. For historical reasons incremental costs are referred to this baseline design.

To complicate matters for the uninitiated reader, the land requirements (template) given in the Invitation for Site Proposals (ISP) were such as to provide an increased circumference to allow for the possibility of a latter addition of a bypass. Hence the baseline design, the 90° lattice, falls inside the ISP template. Thus, by our definition, an incremental cost is associated with the lattice design allowing for a latter addition of one type of bypass that would fit within the ISP template.

Simplified cost assumptions have been made to obtain the cost of the bypass tunnel and the additional magnets for the bypass. These costs were obtained from Appendix A as described in Appendix B. The simple assumptions are

- tunnel costs are $4M per kilometer
- magnet costs are $0.12M x (number of horizontal dipoles + number of quadrupoles)
- cost of AE/CM and EDIA are 15 percent of the tunnel + magnet costs
- contingency is taken as 25 percent of the tunnel + magnets + AE/CM/EDIA cost

Clearly these assumptions are somewhat crude but are sufficient to estimate the incremental costs associated with the bypass options.

Motivations for considering bypass options include increased operational flexibility and the possibility of concentrating infrastructure facilities on one side of the SSC ring. Assigning a cost to operational considerations is very difficult in the absence of an SSC experimental program and a collider operations scenario. We make no attempt to do so in this report, nor has this been done in a quantitative manner in any of the appendices or elsewhere. Assigning costs to support facilities also requires some model for the SSC experimental program and also depends on the nature of the SSC site. Thus you will not find in this report or elsewhere a reliable quantitative estimate balancing the increased cost of a bypass against potential reductions in costs for support facilities.

Bypass Options

The basic layout of the SSC with clustered IR regions is given in Fig. 2 of Appendix D. Many different bypass designs have been studied for the SSC lattice. The first was a bypass of the entire Far Cluster containing the two present and two future experimental areas. Since that time, alternative bypass scenarios have been considered for bypassing one, two, or three straight sections. The mechanics of all of these bypasses are essentially the same—they require the addition to the regular lattice of "transition regions," partially empty cells at each end of the bypass section which allow the beams to be directed into either the main or the bypass leg, thus somewhat increasing the overall circumference of the machine. Within the bypass leg, every attempt has been made to duplicate the lattice structure found in the main leg—that is, the bypass leg consists of "insertion modules" composed of a horizontal dispersion suppressor, an experimental straight section, and another dispersion suppressor. There are several constraints which the bypass designs must satisfy

- both branches of the bypasses must have the same total horizontal bending;
- there must be sufficient separation between the branches to allow independent operation;
- the design must fit within the ISP footprint;
- the linear optics of both branches must match the machine at the end of the bypasses;
- the beam-path length for both bypass legs must be carefully adjusted in order to assure collisions at all of the appropriate locations in both modes of operation; and
- the transition regions must be duplicated on both sides of the machine in order to assure geometric closure.

In addition to the above requirements, it is highly desirable that the free space for the experimental insertions in the bypass leg be the same as that in the main leg so that the same IR design could be used in either leg. That is to say, if a bypass design has "empty" regions inside the dispersion suppressors equal to or greater than the length of 11 normal half cells, as is the case in the standard SSC lattice design, then any of the previously-studied insertions desired could be used in the bypass without modification.

The Far Cluster bypass satisfies all of the above. It fits within the ISP footprint as the footprint was designed around it. Three options were considered for the bypass optics: (1) a simple beam bypass with no experimental areas, (2) a bypass with four possible experimental areas each the length of the standard design, and (3) a bypass with two experimental areas each twice the length of the standard design for very long experiments.

Two other "simple" bypass designs were studied, both of which fit into the ISP footprint: a bypass of two IRs and a bypass of a single IR. The double bypass has free regions of 11 and 15 half cells in the two legs and so causes no difficulties for the IRs. The single bypass has free spaces of 11 and 19 half cells, and thus would not require a new IR design. However, the path-length difference is very small in the single bypass and cannot be made to produce collisions at all of the IRs without an approximate 10 percent reduction in overall luminosity.

Another type of bypass considered was the triple bypass, which could be used to have all of the experimental and utility straight sections on one side of the machine in a single campus. In order to maintain the same total number of straight-sections, the cluster was increased from having two utilities and two IRs to having two utilities and two branches, each having three IRs. Here there were the additional options of having both utilities at one end of the bypasses or having one utility at each end of the cluster. In either case, in order to fit into the footprint, the straight-section free space had to be reduced from 11 half cells to a mixture of 9, 10, and 11 half-cell lengths. These bypasses do require a redesign of both the utility and experimental straight sections. The 9 half-cell straights are rather small, and their linear optics are not as good as they could be, although they are adequate.

In the one-campus, triple-bypass case, the three IRs in each leg could be any mixture of high- or medium-luminosity areas, with some cost to the expected machine performance. The SSC was designed with the medium-beta and low-beta IRs "paired" in order to produce a cancellation of the chromatic effects from the very large beta values in the triplet quadrupoles. For this reason, it is most desirable to have the two low-beta IRs run with the same value of b^* and with a betatron phase advance difference of N + 90°. This cannot be done for all three of the triple bypass IRs. Studies have been made on the effects of not pairing the IRs which show some detrimental effects, although these effects are not too serious.[7,8] These designs and their layout with respect to the ISP template are summarized in Appendix D. Some of the details of numbers of magnets and so on are given in Appendix B and updated in the table of Appendix C. The principal conclusion from these studies is that it appears feasible to devise lattices for single, double, triple and quadruple bypasses such that the collider ring will fit within(or very nearly within) the ISP template, although in some cases some additional work would be required to understand the exact placement of the high-energy injector to fit within the template.

Studies have also been made of the "one-campus" concept and are given in Appendices D, E and F and also below. In the best studied variant, three interaction regions are located on one side(the injector side) of the ring, leaving a single crossing point on the far side of the ring—see the drawing below. Some aspects of this option are described in Appendices D and E.

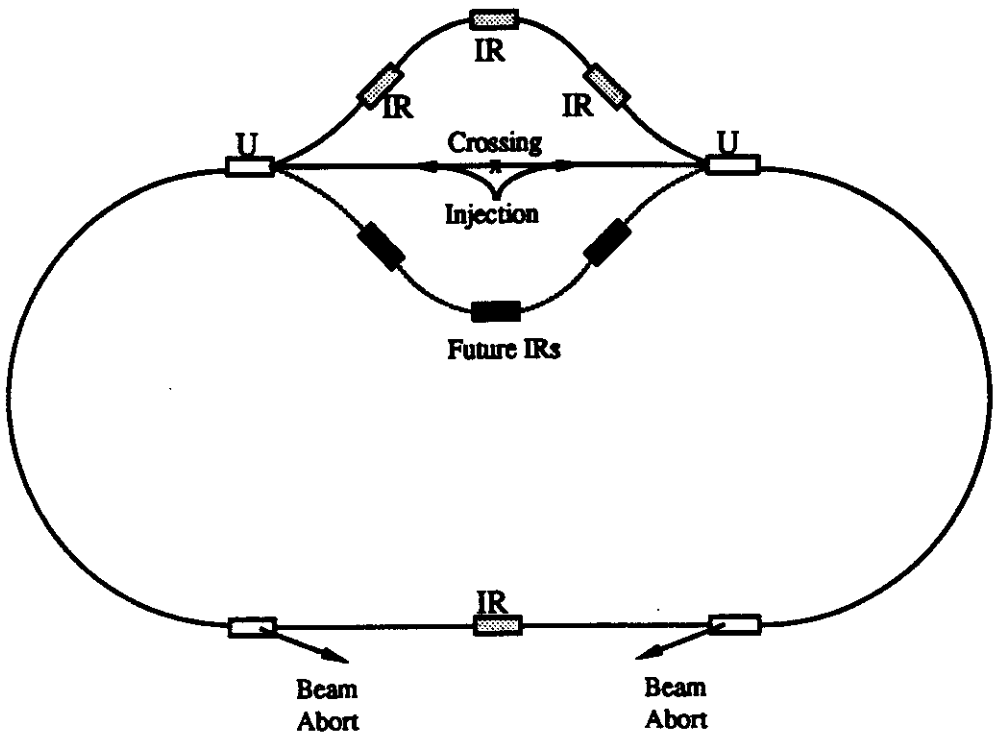


Fig. 1. A possible "one-campus" model for the SSC.

There are a number of possible options in this model for placement and operation of the injector—see Appendix D and Fig. 2 (as an example).

Summary of Costs

Estimates of the incremental costs (as explained in section 2) for the various bypass options are summarized in the Table below, mostly taken from Appendix E.

	1	2	3	4	5	6	7
Cost of additional tunnel	8	28	32	40	36	62	52
Cost of additional magnets	8	51	61	82	30	65	108
AE/CM and EDIA	2	12	14	18	10	19	24
Contingency	5	23	27	35	19	36	46
Total cost (M$)	23	114	134	175	95	182	230

Column 1: 90° lattice plus transition regions to fit within ISP template
Column 2: Bypass one IR (single bypass)
Column 3: Bypass two IRs (double bypass)
Column 4: Bypass three IRs (triple bypass)
Column 5: One-lab configuration (Fig. 1) with one triple bypass
Column 6: One-lab configuration (see Fig. in Appendix E) with two triple bypasses
Column 7: Bypass four IRs (quadruple bypass)

The sharp-eyed reader will wonder why column 5 is not one-half of column 6. All but column 5 are taken directly from Appendix E. My estimates differ slightly from those of Drouet, hence the few million dollar difference.

Footnotes and References

1 D. E. Johnson, *A Possible Beam Bypass for the SSC Clustered IR Region*, Proc. of the 1986 Snowmass Summer Study on the Physics of the Superconducting Super Collider, pgs. 515-517.

2 E. D. Courant et al., ibid., pgs. 503-514.

3 L. Lederman, ibid., pg. 518.

4 L. Lederman and L. Teng, Fermilab TM-1452 (April 1987).

5 L. C. Teng, Fermilab TM-1520 (SSC-N-506). The updated version of this report, including some corrections not included in SSC-N-506, is included as Appendix F.

6 A. A. Garren and D. E. Johnson, *The 90° (September 1987) SSC Lattice*, SSC-146.

7 A. A. Garren and D. E. Johnson, *Status of the SSC Lattice Design*, SSC-151.

8 A. A. Garren and D. E. Johnson, *Chromatic Properties of the 90° (September 1987) SSC Lattice*, SSC-N-375

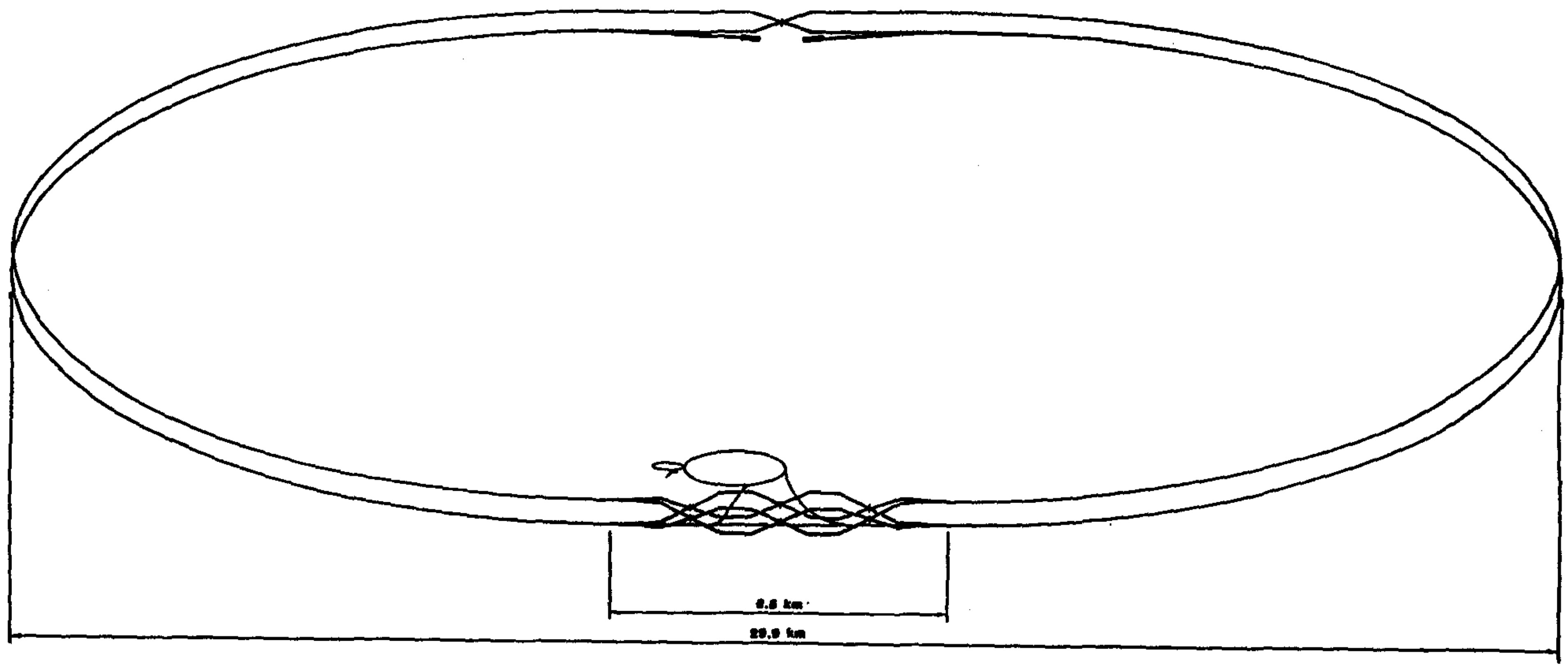


Figure 2

Appendix A

D R A F T 2960S

To: M. Tigner
From: J. Sanford
Date: October 9, 1986
Subject: Snowmass Results

Since Snowmass, we have looked at a number of bypass configurations. In addition, an evaluation was made of the adjustments suggested for the experimental halls. This memorandum attempts to pull together the topics covered in the memos that we have prepared. Since they have been distributed, I'll only enumerate them here:

August 25 - Experimental Halls by JRS

August 25 - East Cluster Bypass by JRS

September 22 - Test Beam Facility by TET

September 30 - West Cluster Bypass by JRS

Perhaps it is best to address the material by looking at an "oversimplified" summary of the costs associated with the different options. The costs for the impacted technical systems have been scaled on the basis of the number of dipoles plus quadrupoles compared to the number in the CDR. The principal elements are as follows:

Item 1 - If the SSC were fitted with a bypass around the East Cluster:

Conv Sys:	add 14.2 km of tunnel with utilities	Cost:	47,800 K$
Tech Sys:	add 628 dipoles and 204 quads		+ 96,800 K$
			144,600 K$

Item 2 -	If the SSC were modified by locating all the experimental facilities on the West side with a bypass:		
Conv Sys:	add 18.9 km of tunnel w/ utilities	Cost:	76,500 K$
Tech Sys:	add 628 dipoles and 216 quads		97,300 K$
			173,800 K$
Item 3 -	If the four developed collision halls were enlarged to accommodate the experiments discussed at Snowmass:		
Conv Sys:	add 160,000 cubic meters	Cost:	65,200 K$
Item 4 -	If the 1 TeV test beam was rotated around to make use of extraction facilities and enclosures on the West side:		
Conv Sys:	sub one extr. enclosure, etc	Cost:	-1,400 K$
Tech Sys:	sub one extr. system		-1,000 K$
			-2,400 K$
Item 5 -	If a 20 TeV beam were provided from the West side of the collider:		
Conv Sys:	add target station & expt'l hall	Cost:	+ 4,600 K$
Tech Sys:	add extr. & transport system		+12,000 K$
			+16,600 K$

Note that the costs developed so far do not include any beam optics elements for providing more than the four interaction regions. There would be additional technical and conventional costs for any developed experimental areas on the bypasses.

One must also be reminded that there are additional costs to be considered above the base for ae/cm, edia, and contingency. To get an example of possible overall costs, consider the rounded off costs for a bypass on the East and the enlarged halls, each with their multipliers.

Item 1 - East Cluster Bypass	Cost:	145 M$	
AE/CM on Conv & EDIA on Tech		+ 20	
	Subtotal	165	+ 4 more IRs
Contingency		+ 30	
	Total	195 M$	

Item 3 - Enlarged Experimental Halls	Cost:	65 M$
AE/CM on Conv & EDIA on Tech		+ 10
	Subtotal	75
Contingency		+ 20
	Total	95 M$

In this example an overall estimate has been made for these two enhancements. This would have to be added to the total of 3,010 M$ in the CDR, yielding a potential increase of 9.6%. A word of caution - the experimental hall cost estimate increment results from a major extrapolation, and I must await the estimate increase being done by RTK.

Perhaps an allowance for a bypass might be considered by providing for "stubs" where the bypass might be build in the future. In this case, the initial expense would be for the larger circumference collider ring. In the case of a provision for a future East bypass, the ring circumference would increase by 2.33 km and 64 more quadrupoles. In this case, the cost including costs for ae/cm, edia, and contingency comes to 20 M$.

I believe that a further analysis would show that there are potential savings in operating funds (for the same overall research program) by virtue of the increased efficiency that would be derived from the ability to switch between "beamlines" as the readiness of experiments indicated. Of course, we would no doubt attempt a more ambitious research program, thereby not realizing the potential savings, but that's not all bad......

cc: G. Gilchriese
D. Johnson
M. Riddle - RTK
T. Toohig
S. Wojcicki

June 26, 1987

To: A. Chao, G. Drouet, A. Garren, D. Groom, D. Johnson, J. Sanford, M. Tigner T. Toohig and S. Wojcicki

From: Gil

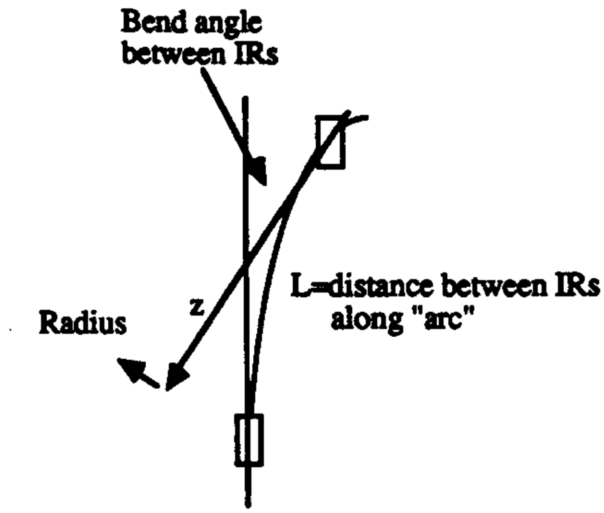
Subject: Bypass summary -2nd UPDATE

I have attempted to summarize the numbers associated with the various bypass options that have been discussed - see below. Drawings also exist but require viewing in full size.

	CDR	90°	ISP	Single Bypass	Double Bypass A	Double Bypass B	Triple Bypass A	Triple Bypass B
Circumference(m)	82944	83631	85698	86373	86373	86373	86373	86373
Length of bypass(m)	n/a	n/a	10869	4227	5370	6055	7198	7198
No. of transitions	0	0	4	4	6	4	4	4
No. of initial IRs	4	4	4	4	4	4	4	4
No. of potential IRs	6	6	10	8	12	10	14	14
No. of dipoles in main ring	7680	7664	7696	7680	7688	7680	7680	7680
No. of dipoles in bypass	n/a	n/a	516	200	228	252	304	304
Total number of dipoles	7680	7664	8212	7880	7916	7932	7984	7984
No. of quads in main ring	1776	1564	1596	1628	1632	1648	1648	1648
No. of quads in bypass	n/a	n/a	232	108	156	176	192	192
Total number of quads	1776	1564	1828	1736	1732	1824	1840	1840
No. vert. dipoles in main ring	232	176	176	160	160	160	160	160
No. of vert. dipoles in bypass	n/a	n/a	88	40	80	80	80	80
Total number of vert. dipoles	232	176	264	200	240	240	240	240
Distance between IRs(m)-outer	2400	2285	2291	2285,2(2742)	2285	2285	1828	1828
-inner					2285	2285,2514	1942	1942
Bend between IRs(mr)-outer	106	82	82	82,2(108)	82	82	72	72
-inner	n/a	n/a	69		41	82,89	52	52
Min. trans. sep at IPs (m)	n/a	n/a	33	36	27	27	24	24
Muon separation (m)	127	94	79	134	47	94	49	49
IRs-No.xL/LCH main ring			6x11	4x11+2x10	6x11	2x11+4x15	6x11+2x9	6x11+2x9
bypass	n/a	n/a	4x11	1x13	2x11	2x11	2x10+1x9	2x10+1x9
Relative luminosity in bypass	n/a	n/a	1	0.98	0.947	0.95	1	1

CDR - lattice as in CDR(no bypass) - does not fit within ISP footprint.
90° - 90° lattice(no bypass) - does not fit within ISP footprint.
ISP - 90° lattice with transitions for bypass. Bypass 4 IRs of far cluster.
Single Bypass - bypass one IR on each side possible
Double bypass - bypass two IRs.
Triple bypass A - bypass 3 IRs. Injection into utilities at either end of cluster.
Triple bypass B - bypass 3 IRs. Both utilities at one end of cluster.
LCH=half-cell length=114.25 m

I have also estimated the muon flux from the neighboring IR using Van Ginneken's calculations(likely to be an overestimate). The relevant geometry is shown below



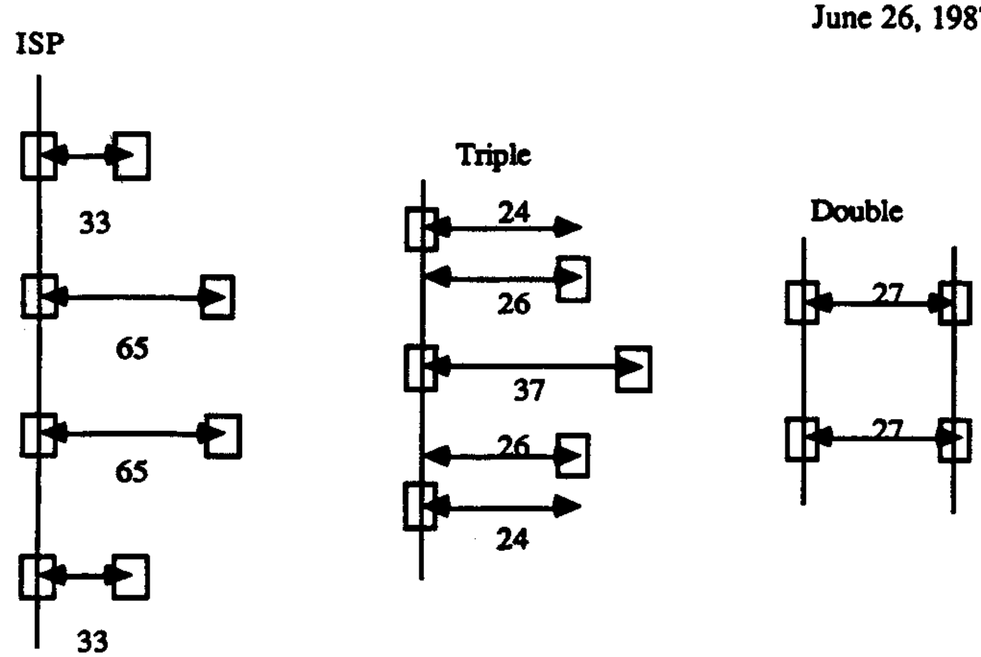
The muon flux isodose contours per interaction are shown in Fig. 1. I take z = 2 km and plot the dose per year vs. radius, where the radius is defined above. The results are shown in Figs. 2 and 3 for dose in rem/year and for muons/m^2-sec assuming an interaction rate of 2.16 x 10^{16} per year or 10^9 per second. To calculate the flux I have assumed 1 rem = 3.5x 10^{11} muons/m^2. Ignoring the effects of magnets, the muon dose is very well collimated along the tangent from the IR within about 10m radius or less.

This muon dose is a potential problem to experiments in the outer legs in the bypass schemes. The transverse distance between the tangent from one IR to the ring at the next IR is given by 0.5*distance between IRs*bend angle. I call this distance the muon separation. The values are given above in the table. I have used the inner bend angles to calculate the distance. In the case of the triple bypasses, I used a separation of 1900 m.

What does this imply? In the case without additional experiments in the bypass lines or no bypass at all, the muon "beam" will be well separated from the experiments. However, unless additional effective shielding can be implemented(by dispersing the muons) assembly halls if they exist must go on the inside of the ring in all cases that fit within the ISP footprint; the muon beam would go right through the assembly hall if it were on the outside of the ring.

What happens if there is a bypass? The transverse separation between the IPs in the three bypass schemes are illustrated below. The values are the beam-to-beam separations.

June 26, 1987



Where the muon "beam" goes relative to the IPs in the bypass is shown in Fig. 4. What are the conclusions from examining this figure?

1) For the ISP bypass there will likely be a restriction on access to the two inner collision halls in the bypass if the halls are sufficiently wide and if the interaction rate in the neighboring IRs is high. In any case one cannot safely ignore the muon flux for the two inner IP halls. Probably can be ignored for the two outer IPs.
2) For the triple bypass, the middle IP in the bypass will see the muon "beam". Situation for outer IPs is marginal given uncertainies - cannot ignore muons for these IRs either but might be OK.
3) For the double bypass, again situation is marginal and depends on the width of the hall and details of the calculation. Probably OK.

These conclusions are based on muon fluxes which ignore magnetic deflection and on Van Ginneken's calculations which are thought to be pessimistic by perhaps as much as a factor of 10. To investigate the viability of the bypass schemes further, the calculations of muon fluxes from the IRs must be improved.

Other possibilities are to have the bypass and main ring at different elevations and/or to twiddle some more to change the separation for the double or triple bypasses.

Another concern is the location of the utilities/IRs in the case of the triple bypass options. In the ISP lattice with bypass, the distance from the lower utility to the ISP site boundary(as measured along a tangent to the ring) is about 7.2 km. In Triple Bypass A this distance is about 6.2km. In Triple Bypass B this distance is also about 6.2 km. This would imply that the muon flux from the 20 TeV abort dumps would be greater at the site boundary or alternatively one would need to move the boundary.

In the Triple Bypass B case, part of the injector complex lies outside the ISP boundaries ie. would need to slide the boundary by about the radius of the HEB.

June 26, 1987

I have also tried to crudely summarize the costs of the bypass options based on costs from a note by Jim Sanford of October 9, 1986. The costs per magnet assume some mix of dipoles to quads(about 3:1) which is not too accurate for all the cases - need costs per dipole and costs per quad to make better estimate. Also costs includes(?) vertical dipoles. In Jim's note two different costs per km of tunnel are given. I have taken the larger. AE/CM + EDIA is taken as 15% of the tunnel+magnet costs and contingency is taken as 25% of the tunnel+magnet+AE/CM+EDIA costs.

	ISP	Single Bypass	Double Bypass A	Double Bypass B	Triple Bypass
Cost of bypass tunnel(M$)	$43	$17	$21	$24	$29
Cost of bypass magnets(M$)	$90	$35	$46	$51	$60
AE/CM and EDIA(M$)	$20	$8	$9	$11	$13
Contingency(M$)	$38	$15	$17	$22	$25
TOTAL(M$)	$192	$75	$94	$108	$127

Cost per km of tunnel(M$) = 4.00
Cost per magnet(M$) = 0.12

July 3, 1987

Bypass Summary Table

	CDR	90^0	ISP	Single Bypass	Double Bypass A	Double Bypass B	Triple Bypass A	Triple Bypass B
Circumference(m)	82944	83631	85698	86373	86373	86373	86373	86373
Length of bypass(m)	n/a	n/a	10869	4230	5370	6055	7198	7198
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Total number of quads	1776	1564	1828	1736	1732	1824	1840	1840
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Distance between IRs(m)-outer	2400	2285	2291	2285,2(2742)	2285	2285	1828	1828
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Bend between IRs(mr)-outer	106	82	82	82,2(108)	82	82	72	72
-inner	n/a	n/a	69		41	82,89	52	52
Min. trans. sep at IPs (m)	n/a	n/a	33	36	27	27	24	24
Muon separation (m)	127	94	79	134	47	94	49	49
IRs-No.xL/LCH main ring			6x11	4x11+2x19	6x11	2x11+4x15	6x11+2x9	6x11+2x9
bypass	n/a	n/a	4x11	1x11	2x11	2x11	2x10+1x9	2x10+1x9
Relative luminosity in bypass	n/a	n/a	1	0.94	0.947	0.95	1	1

CDR - lattice as in CDR(no bypass) - does not fit within ISP footprint.
90^0 - 90^0 lattice(no bypass) - does not fit within ISP footprint.
ISP - 90^0 lattice with transitions for bypass. Bypass 4 IRs of far cluster.
Single Bypass - bypass one IR on each side possible
Double bypass - bypass two IRs.
Triple bypass A - bypass 3 IRs. Injection into utilities at either end of cluster.
Triple bypass B - bypass 3 IRs. Both utilities at one end of cluster.
LCH=half-cell length=114.25 m

SSC-N-404

Configuration of SSC Lattices to the ISP Template

G. Drouet, T. E. Toohig
SSC Central Design Group
November 1987

Prior to the 1986 SSC Snowmass Summer Study, D. Johnson devised an ingenious switching scheme to parallel the cluster region of the SSC lattice with a second branch[1]. This bypass scheme was originally conceived as a way to commission the accelerator without interfering with installation of the experiments. Later it would allow the construction of the future collision halls without turning off the entire experimental program. When presented at the summer study, it was perceived by experimenters as a way to provide a wider variety of interaction regions than were available in the CDR. In particular, it could provide at least one region for experiments with very low values of transverse momentum[2]. The possibility of providing the full complement of IR halls specified for the project while deferring development of the far campus until after initial understanding of the physics was pointed out by Lederman[3,4].

The Invitation for Site Proposals[5] (ISP) issued by DOE included a template to define the land requirements for siting the SSC. The template provided an allowance in the circumference for an additional three cells at each end of the clusters to allow for possible later addition of a bypass. The template from the ISP is shown in Figure 1.

In conjunction with studies on the desirability of using a 90° per cell lattice in place of the 60°/cell design of the CDR, a number of options were studied by D. Johnson and A. Garren. These are related to the ISP template in Figures 2-6. The minimum 90°/cell lattice, Figure 2, falls inside the template, since no switch allowance is made in the circumference. Figures 3-6 display a range of solutions that will fit the template more or less well, all with switch provisions. A task force under M.G.D. Gilchriese studied the relative costs of the various options[6]. These were tabulated in Table I (after Gilchriese) in anticipation of the SSC 1987 summer study. The bypass option costs are for fully implemented bypasses with four IR crossings in each case.

When the construction and operational features of the monopolar bypass options, Figures 3-6, are studied, two concerns emerge. One is the close spacing of the branches, especially when the size of the IR halls and the finite width of the tunnels are taken into account. The second is the question of muons from the inner branch causing personnel radiation problems in the IR halls of the outer branch hall when the inner branch is operating. This muon problem can be alleviated by a suitable longitudinal offset of the halls in the inner and outer branches to adjust the radial offset of the muon cones from the inner branch at the locations of the IR halls. Figure 7 illustrates both the space constriction and the proximity of the muon cone for the monopolar bypass solutions. The intrinsic difference in length for the two branches of the monopolar solution also leads to a difference in the RF tune for the two branches.

In a refinement of the bypass solution, Johnson and Drouet have developed a bipolar arrangement that eliminates the problems of muon interference and of space limitations for the IR halls. This has been described by Drouet[7] and is illustrated in Figure 8. In Figure 9, an optimized fit to the ISP template is achieved by reducing the magnetic field in the arc dipoles. Figures 10 and 11 are details and illustrate the injection lines for a bipolar and monopolar injector respectively. In this model, the injection line tunnels are contructed as a FODO channel along the straight line connecting the two arcs. With the addition of a segment to complete the tunnel between the two injection points, the injection lines provide an alternate trajectory for tuning the machine independently of the experimental setups. The Far Cluster, initially, would consist only of such a FODO channel, which might be of conventional quadrupoles. The primary beam aborts would be on this far side, symmetric with the injection short straight sections as illustrated in reference 7.

Details of clearances for IR halls and machine tunnels are shown in Figures 13 and 14. In this bipolar switch arrangement, the muon cone near an IR hall is from another IR hall in the same branch so that it would not be present when there is access to the hall.

A comparison of the relative costs of such a bypass design with estimates of earlier designs is given in Table I, after Drouet.

[1] D.E. Johnson, "A Possible Beam Bypass for the SSC Clustered IR Region," Proc. of the 1986 Summer Study on the Physics of the Superconducting Super Collider, 515-517

[2] E.D. Courant, et al. "Summary Report of the IR Working Group," ibid., 503-514

[3] L.M. Lederman "A One Lab SSC Configuration," ibid, 518

[4] L.M. Lederman, L.C. Teng "A 1-Campus SSC," Fermilab TM-1452 (April 1987)

[5] "Invitation for Site Proposals for the Superconducting Super Collider (SSC)", DOE/ER-0315 (April 1987)

[6] M.G.D. Gilchriese, "Bypass Summary - UPDATE," memo (20 June 1987)

[7] G. Drouet, "Bypass Update," memo (9 November 1987)

	ISP	SINGLE BYPASS	DOUBLE BYPASS	TRIPLE BYPASS
Cost of bypass tunnel (M$)	$ 43	$ 17	$ 21	$ 29
Cost of bypass magnets (M$)	$ 90	$ 35	$ 39	$ 60
AE/CM and EDIA (M$)	$ 20	$ 8	$ 9	$ 13
Contingency (M$)	$ 38	$ 15	$ 17	$ 25
TOTAL (M$)	$192	$ 75	$ 87	$127

Cost per km of tunnel (M$) = 4.00
Cost per magnet (M$) = 0.12

Table I: Cost of bypass only. The costs of the bypass options are crudely summarized based on costs from a note by *Jim Sanford of October 9, 1986*. The costs per magnet assume some mix of dipoles to quads (about 3:1) which is not too accurate for all the cases - need costs per dipole and costs per quad to make better estimate. Also costs include vertical dipoles. In Jim's note, two different costs per km of tunnel are given. I have taken the larger. AE/CM + EDIA is taken as 15% of the tunnel+magnet costs and contingency is taken as 25% of the tunnel+magnet+AE/CM+EDIA costs.

	1	2	3	4	5	6
Cost of additional tunnel	8	28	32	40	62	52
Cost of additional magnets	8	51	61	82	65	108
AE/CM and EDIA	2	12	14	18	19	24
Contingency	5	23	27	35	36	46
	23	114	134	175	182	230
Number of straights for IR's	6	7(+1)	8(+2)	11(+3)	6(+6)	10
Number of inline IR's	6	6	6	8	0	6

Column 1: 90° lattice plus transition regions to fit within the ISP footprint
Column 2: Single bypass (2 x 1IR + 1IR + 4IR's)
Column 3: Double bypass (2 x 2IR's + 4IR's)
Column 4: Triple bypass (2 x 3IR's + 5IR's)
Column 5: 3-way switch (2 x 3IR's + 2 FODO bypasses)
Column 6: Quadruple bypass (2IR's + 2 x 4IR's)

Table II: Differential costs with basic 90° cell lattice (bypass implemented)

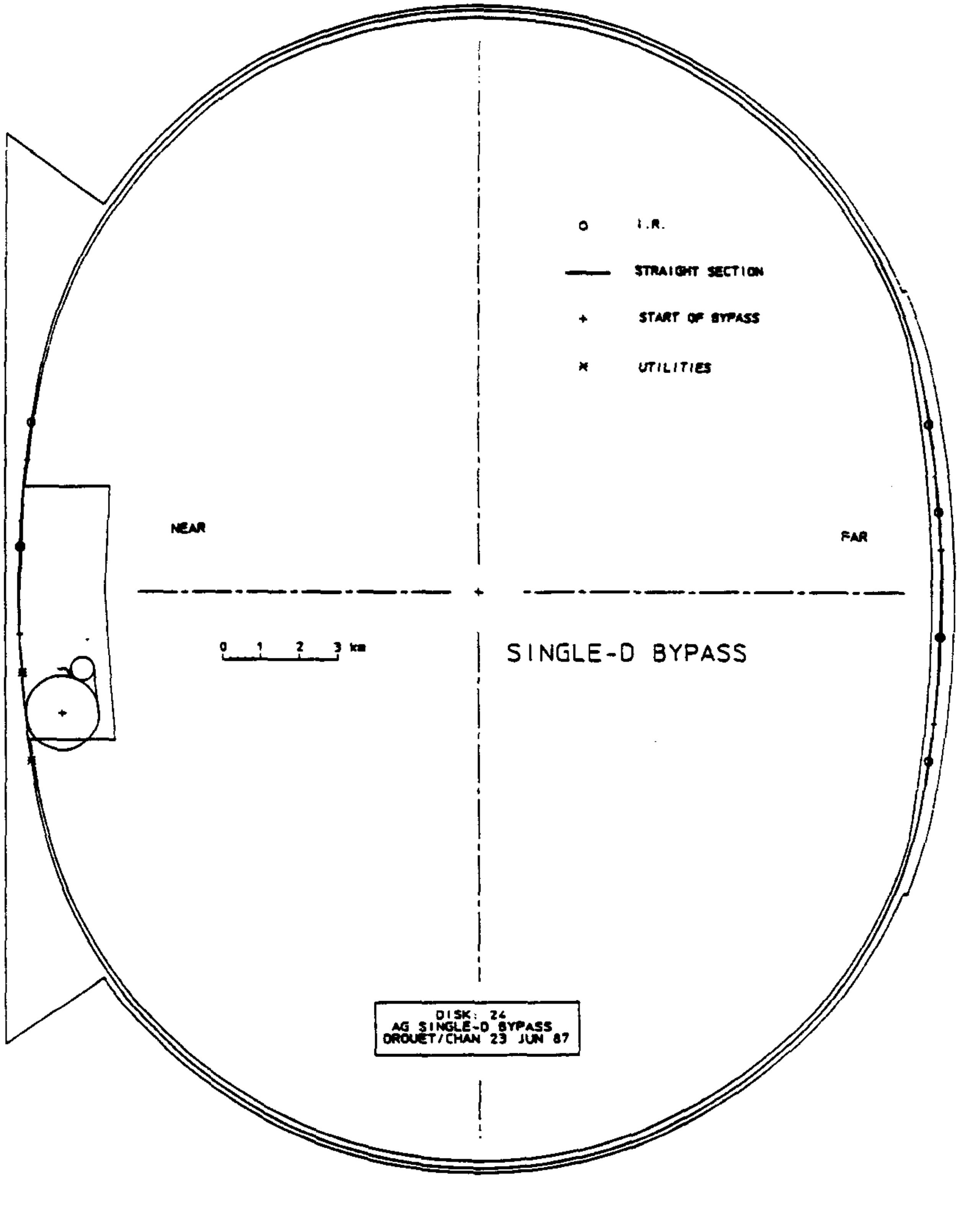
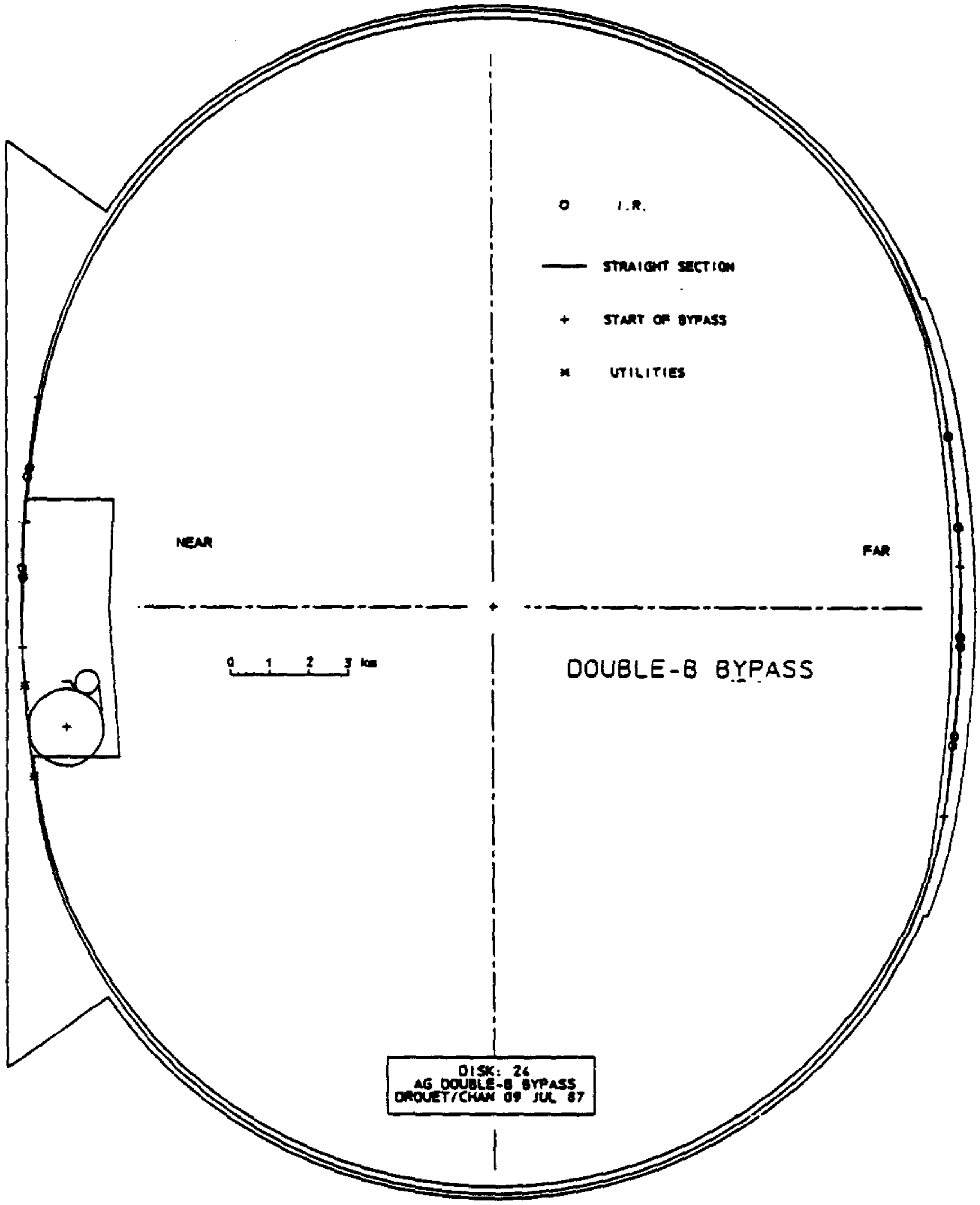
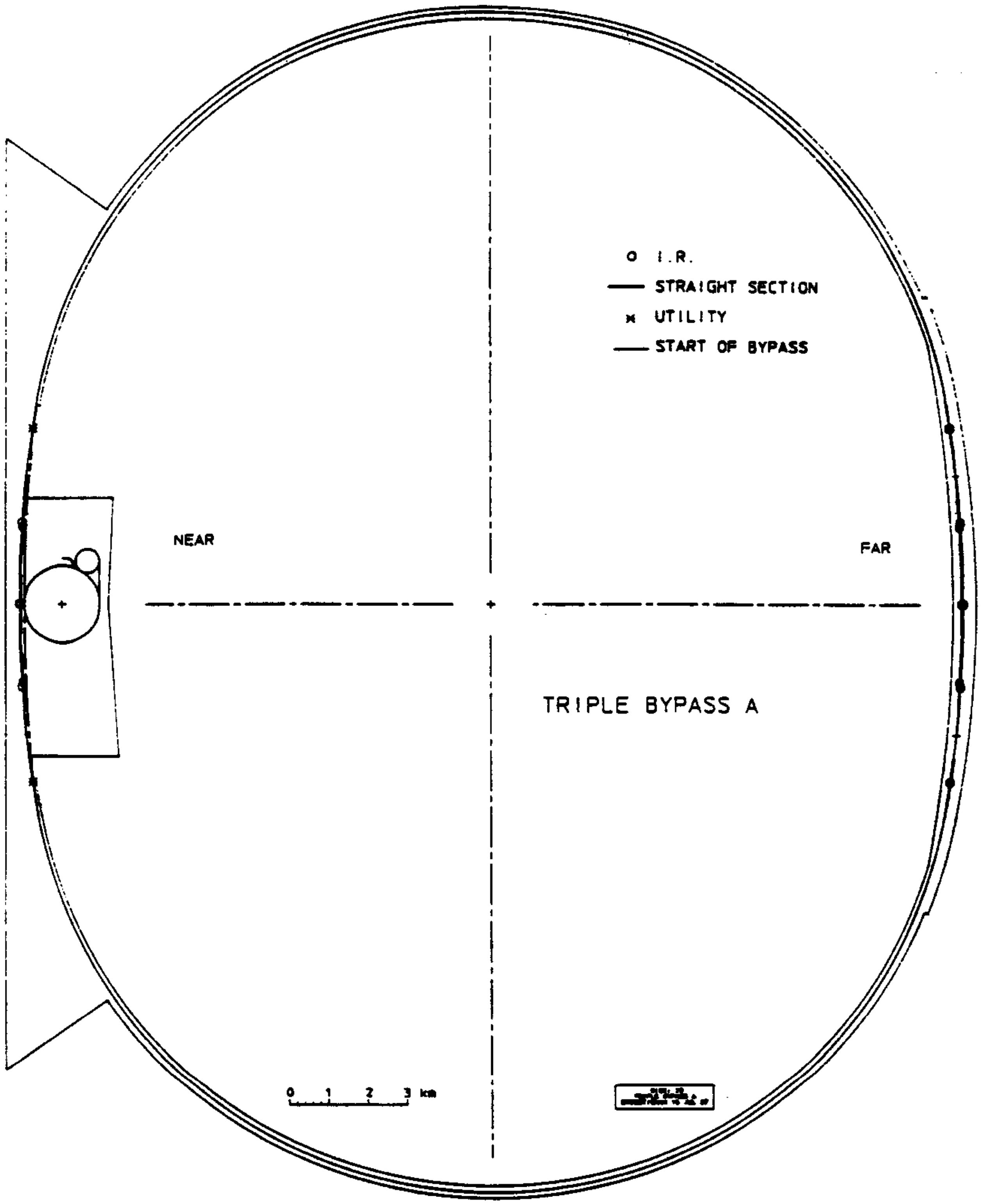

I.R.
STRAIGHT SECTION
START OF BYPASS
UTILITIES
NEAR
FAR
0 1 2 3 km
SINGLE-D BYPASS
DISK: 24
AG SINGLE-D BYPASS
DROUET/CHAN 23 JUN 87

Figure 3.



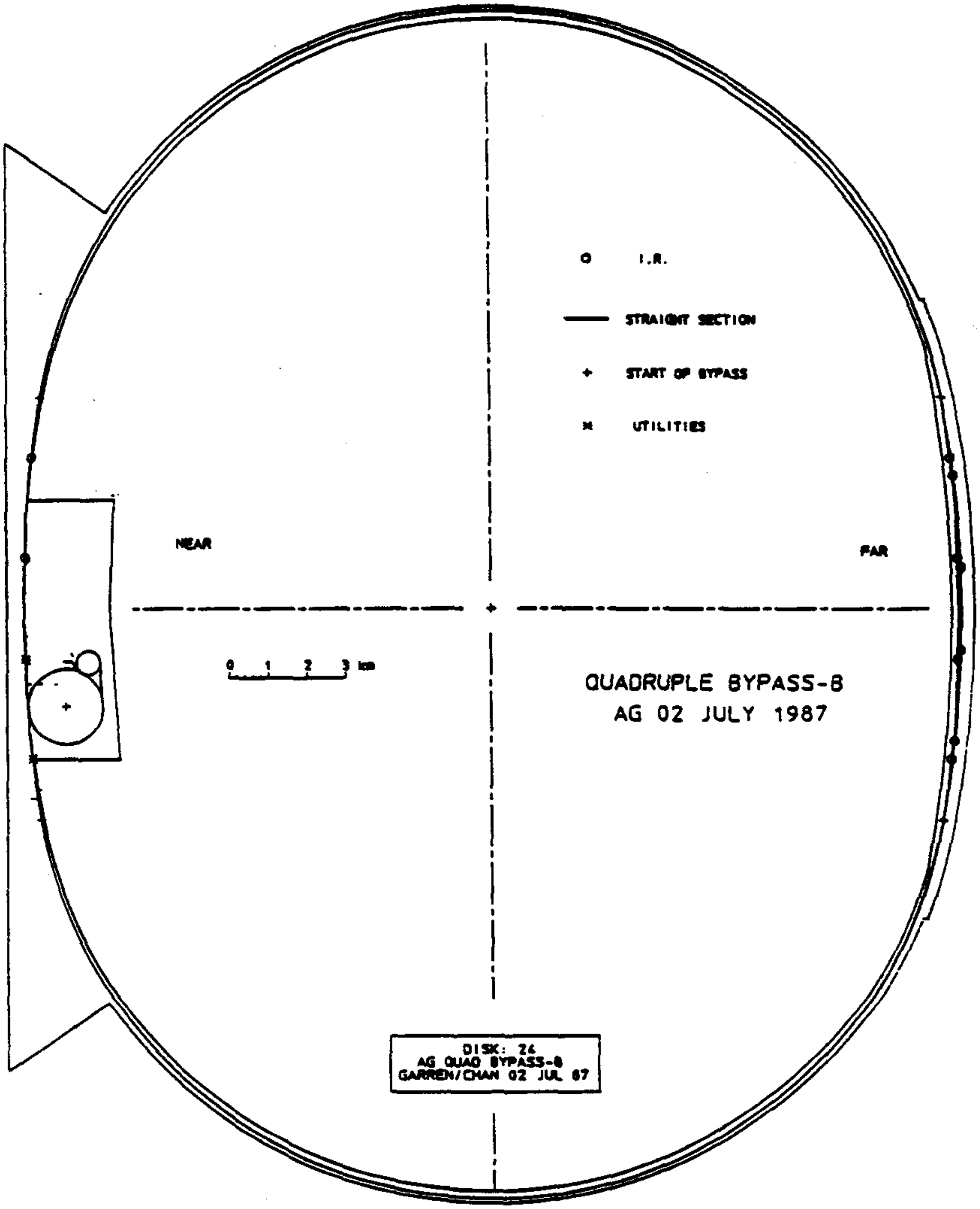
I.R.
STRAIGHT SECTION
START OF BYPASS
UTILITIES
NEAR
FAR
0 1 2 3 km
DOUBLE-B BYPASS
DISK: 24
AG DOUBLE-B BYPASS
DROUET/CHAN 09 JUL 87

Figure 4.



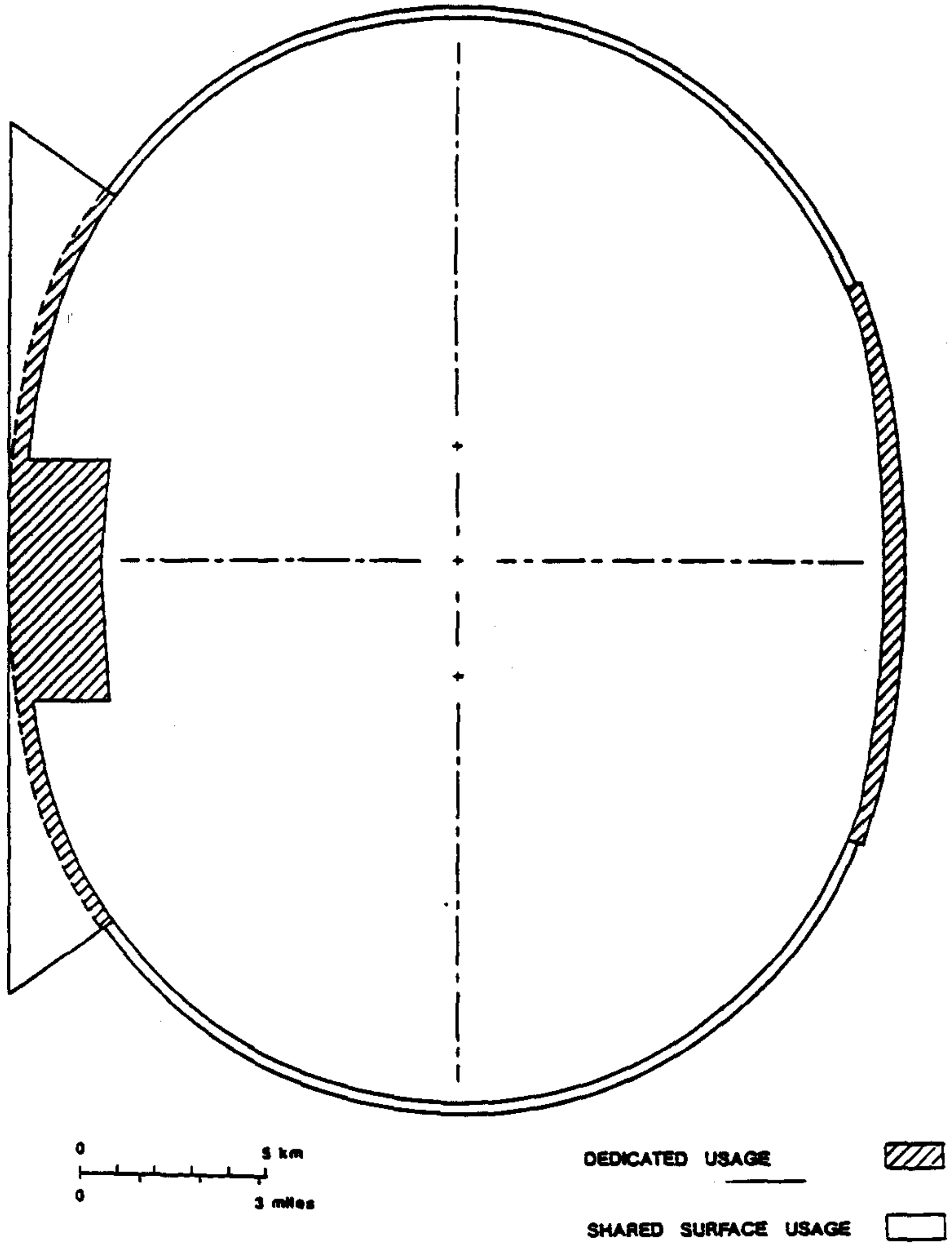
I.R.
STRAIGHT SECTION
UTILITY
START OF BYPASS
NEAR
FAR
TRIPLE BYPASS A
0 1 2 3 km

Figure 5,



I.R.
STRAIGHT SECTION
START OF BYPASS
UTILITIES
NEAR
FAR
0 1 2 3 km
QUADRUPLE BYPASS-8
AG 02 JULY 1987
DISK: 24
AG QUAD BYPASS-8
GARREN/CHAN 02 JUL 87

Figure 6.



LAND AREAS FROM I.S.P.

Figure. 1.

SSC CENTRAL DESIGN GROUP	
83A237	LAND AREAS FROM I.S.P.
SHEET OF	DWN BY RH REV DATE
SCALE	APPR BY TT DATE 4-29-87

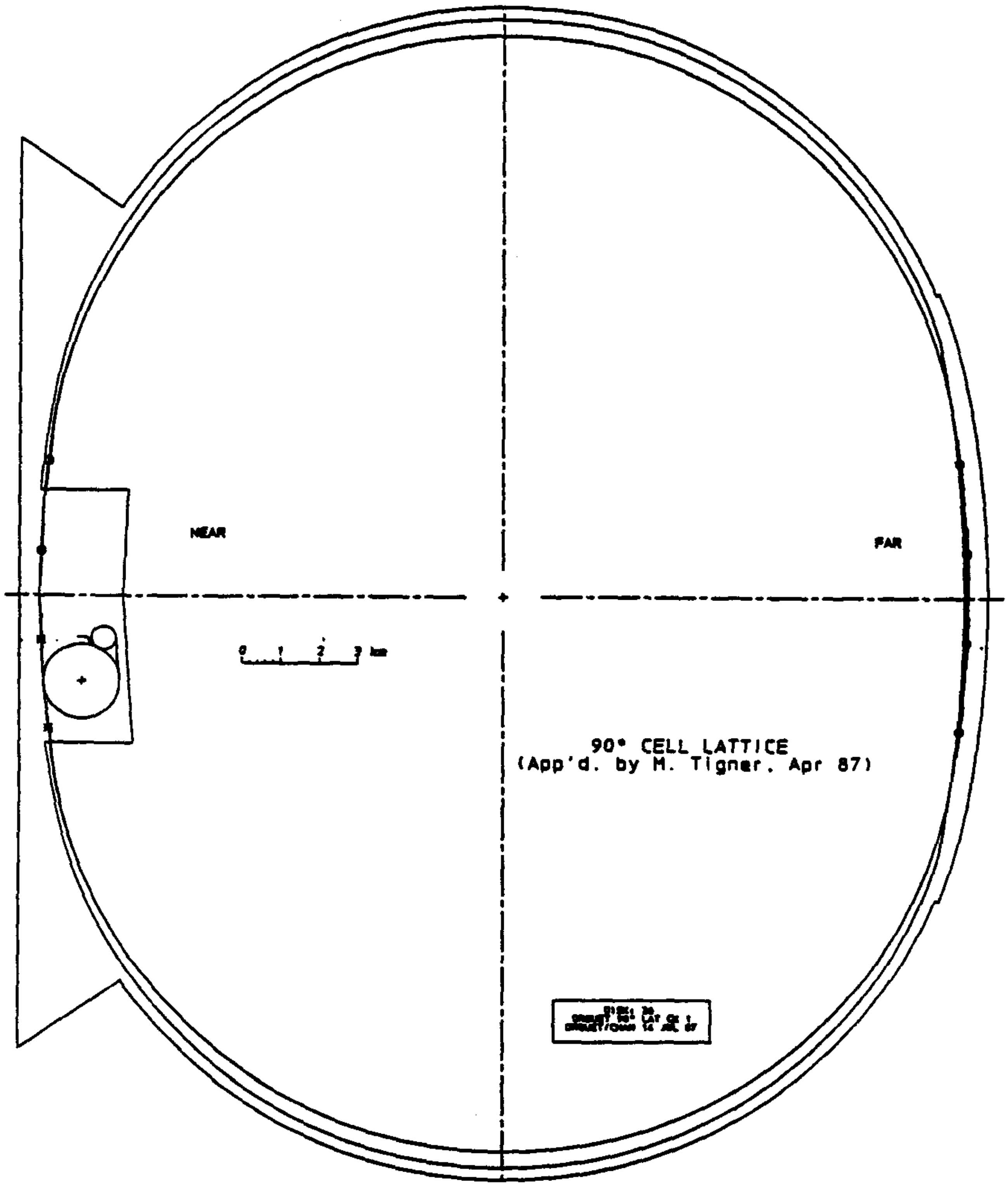
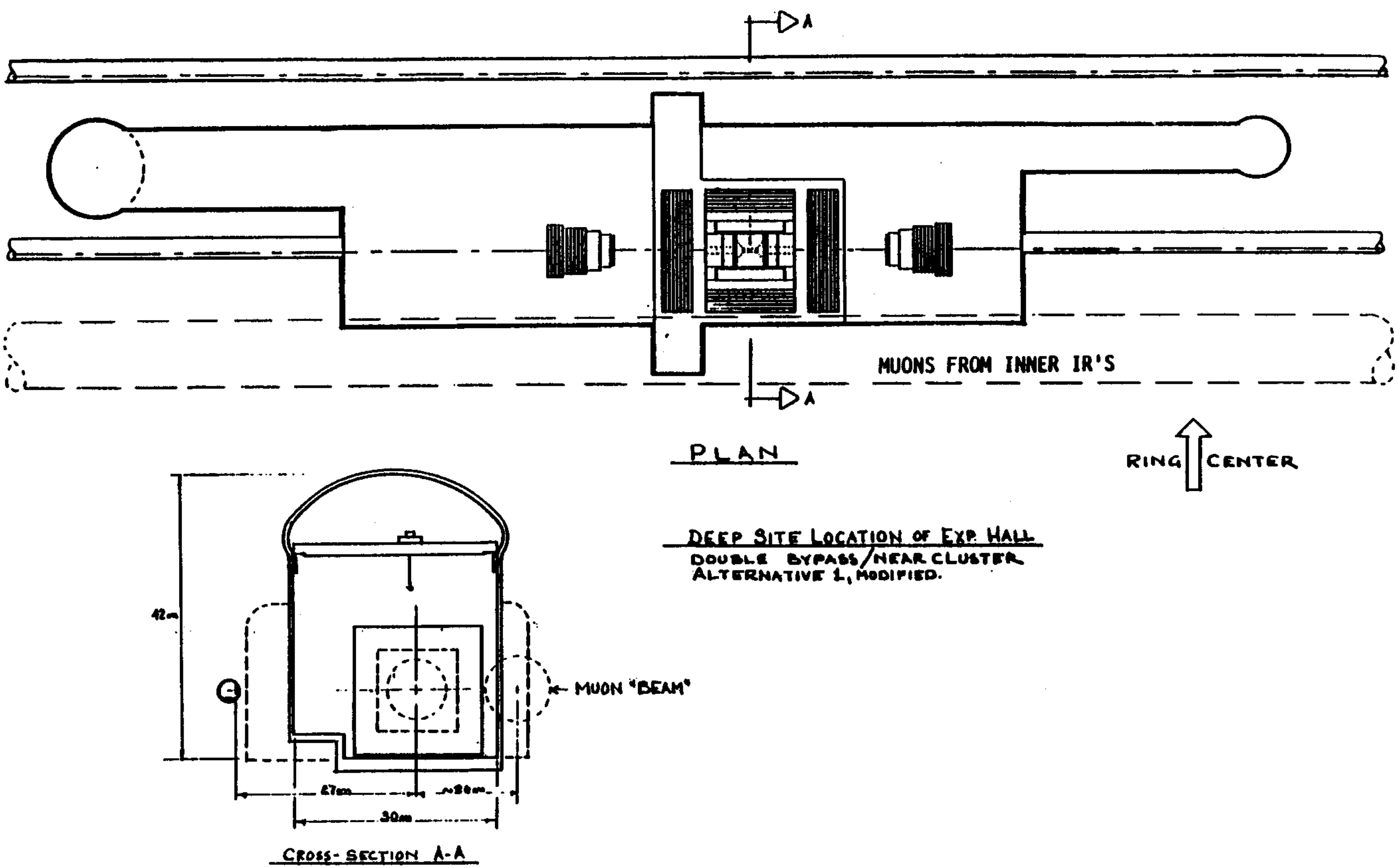


Figure 2.

Figure 7.


A
A
MUONS FROM INNER IR'S
PLAN
RING CENTER
DEEP SITE LOCATION OF EXP. HALL
DOUBLE BYPASS/NEAR CLUSTER
ALTERNATIVE 1, MODIFIED.
42m
MUON "BEAM"
27m
~20m
30m
CROSS-SECTION A-A

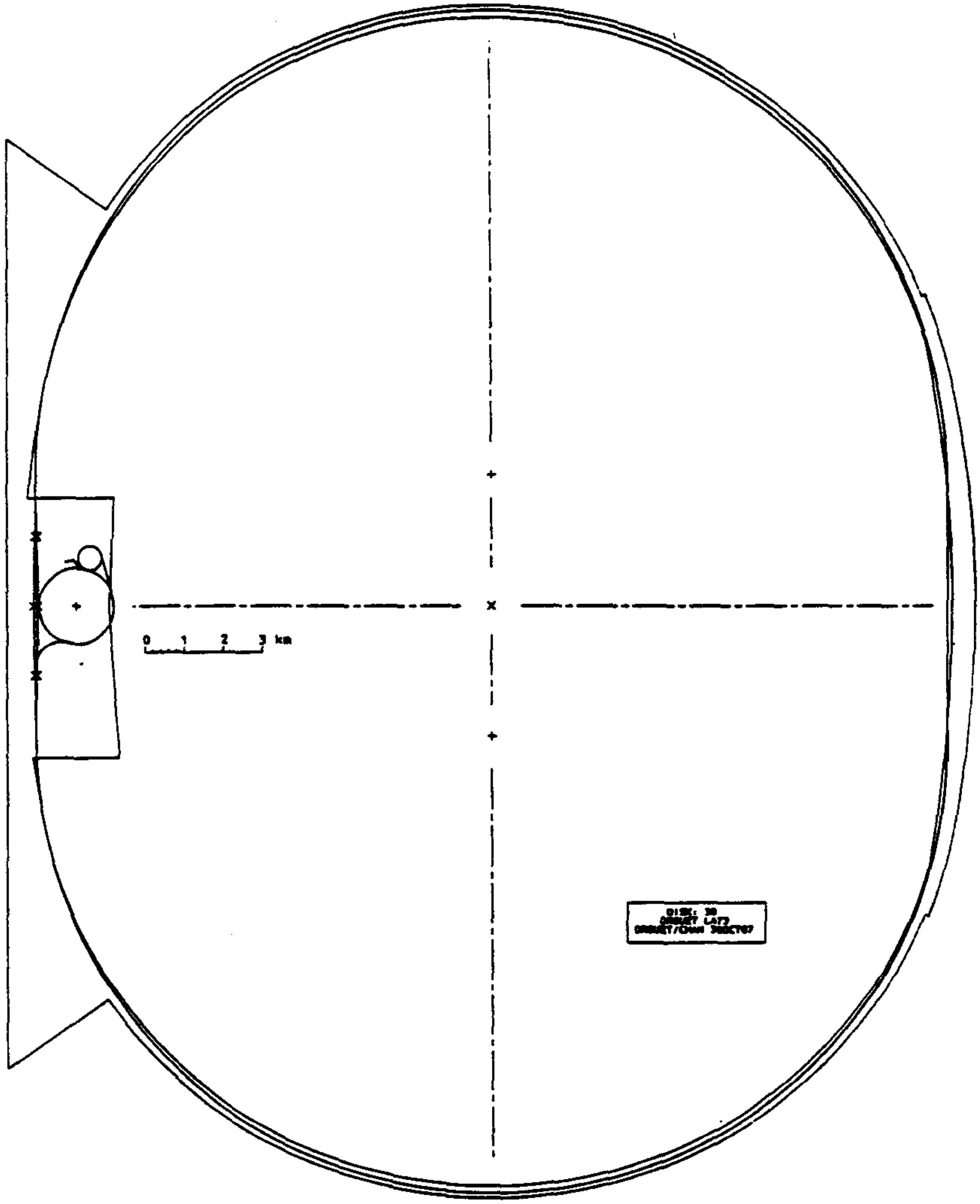


Figure 8.

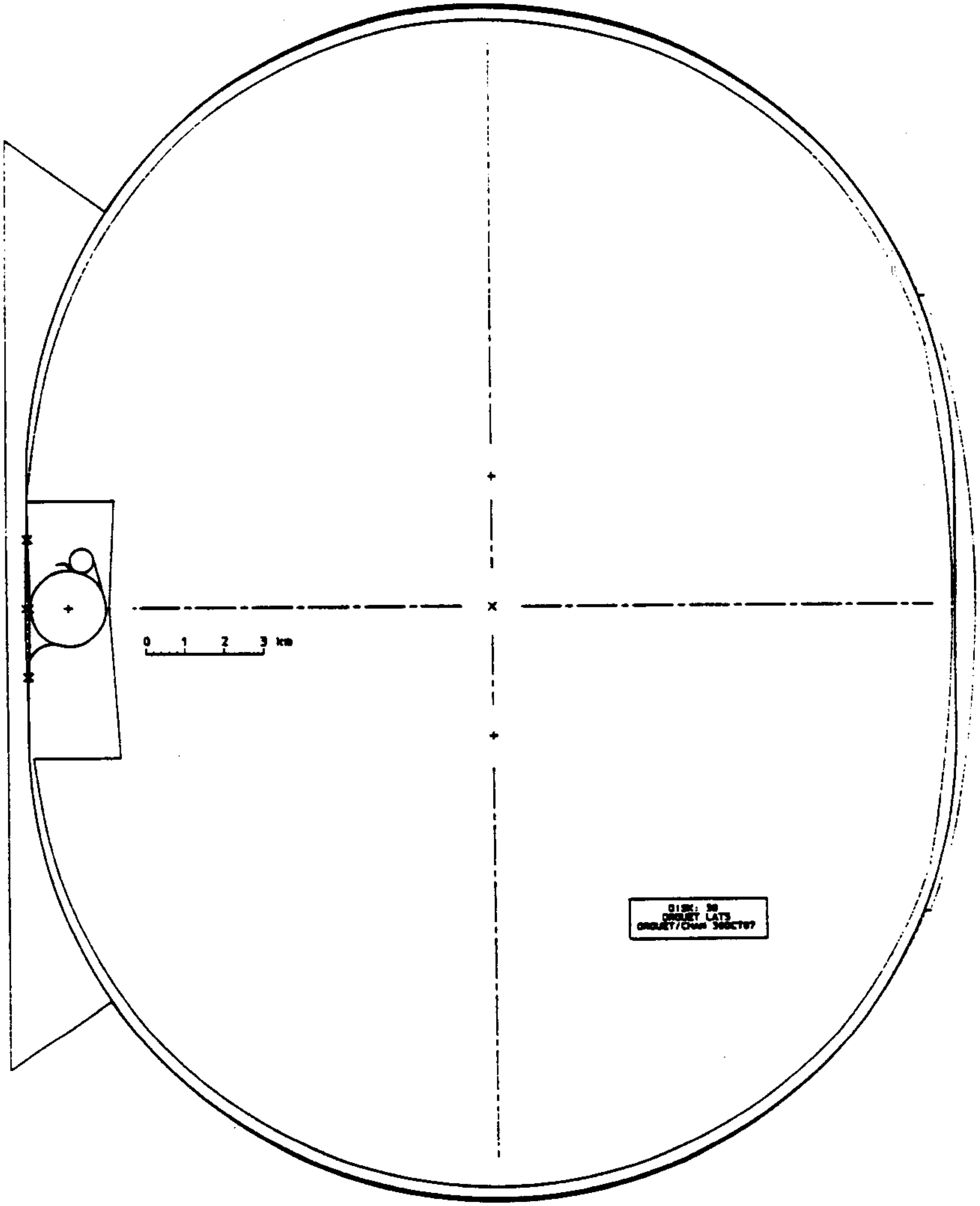


Figure 9.

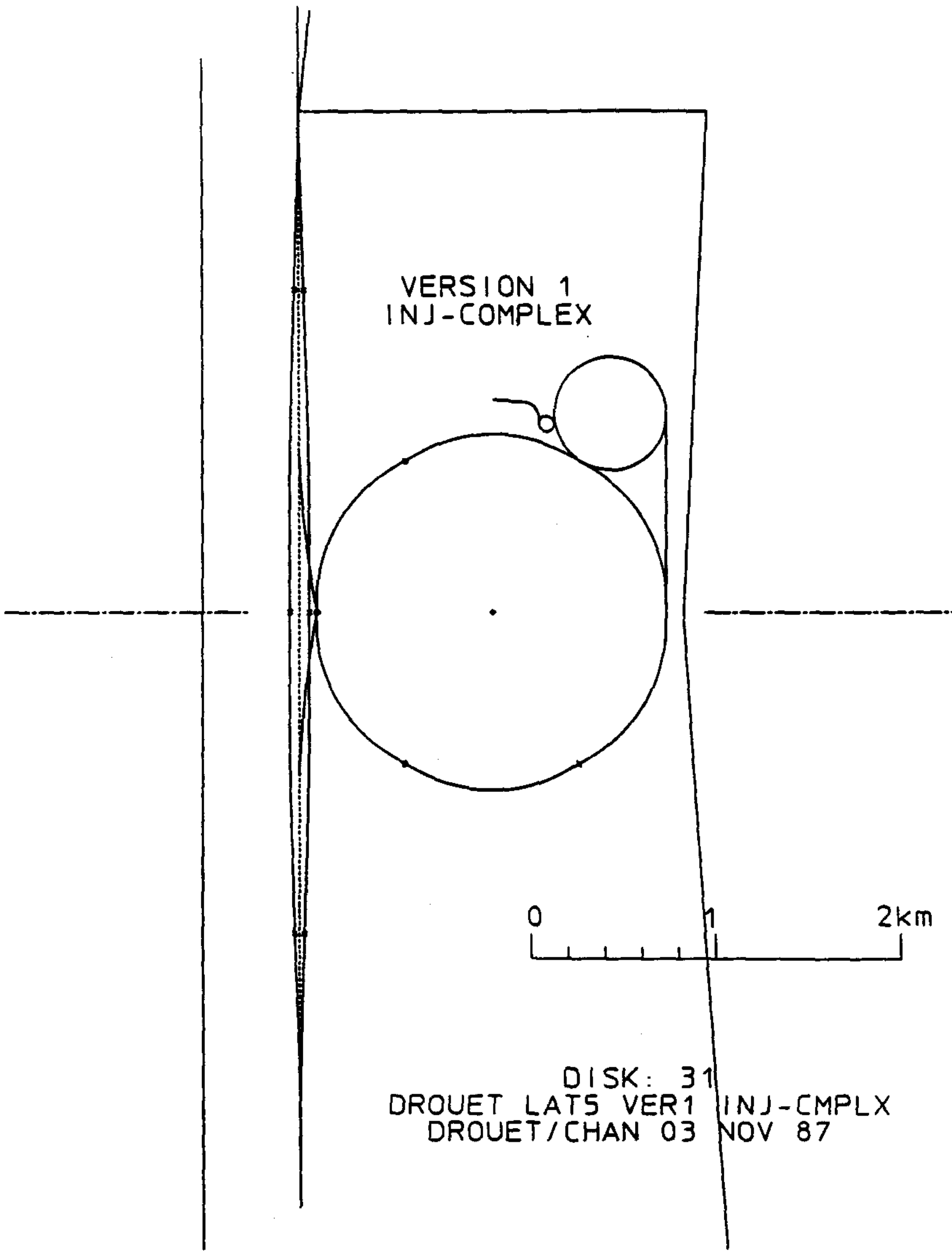

VERSION 1
INJ-COMPLEX
0
1
2km
DISK: 31
DROUET LATS VER1 INJ-CMPLX
DROUET/CHAN 03 NOV 87

Figure 10.

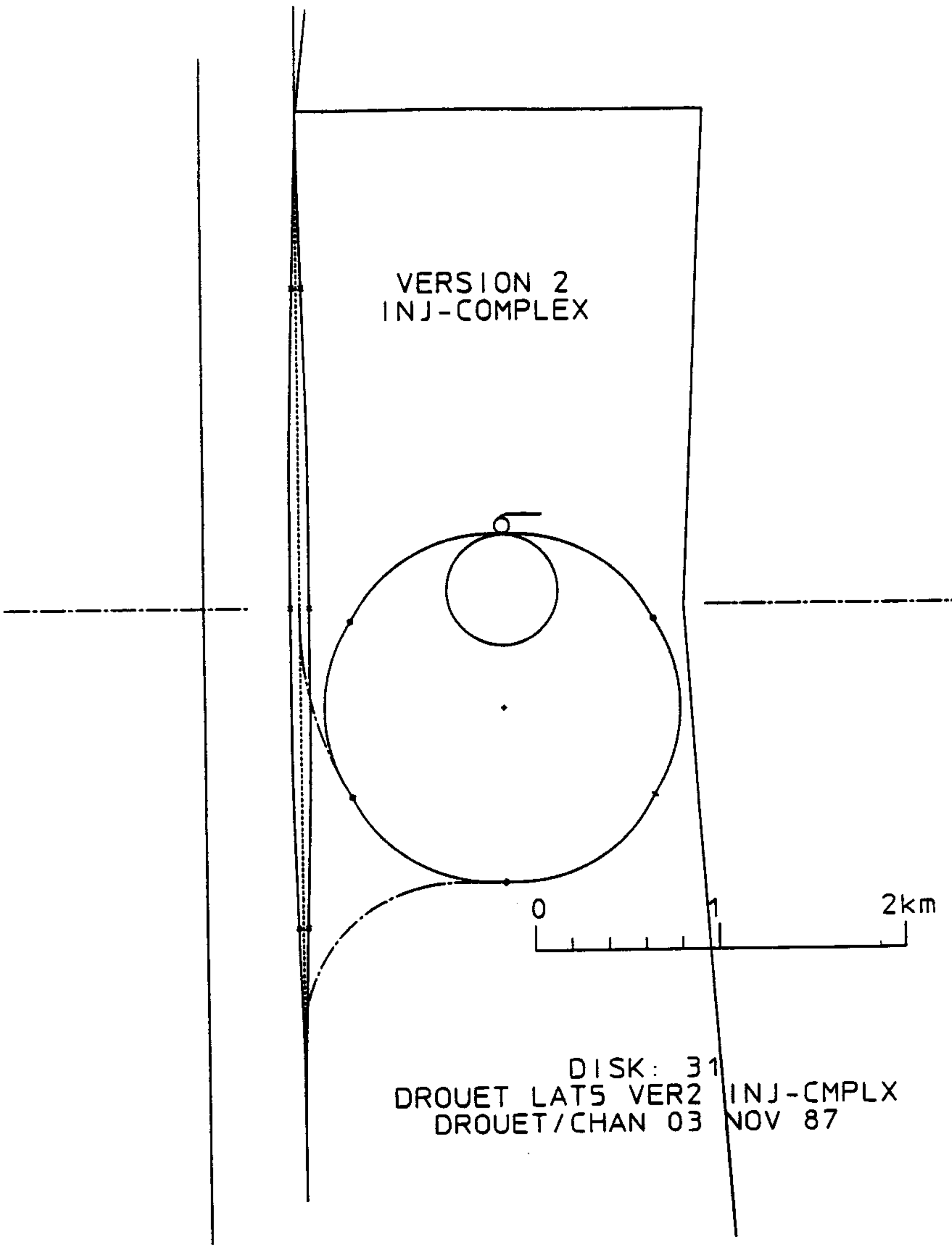
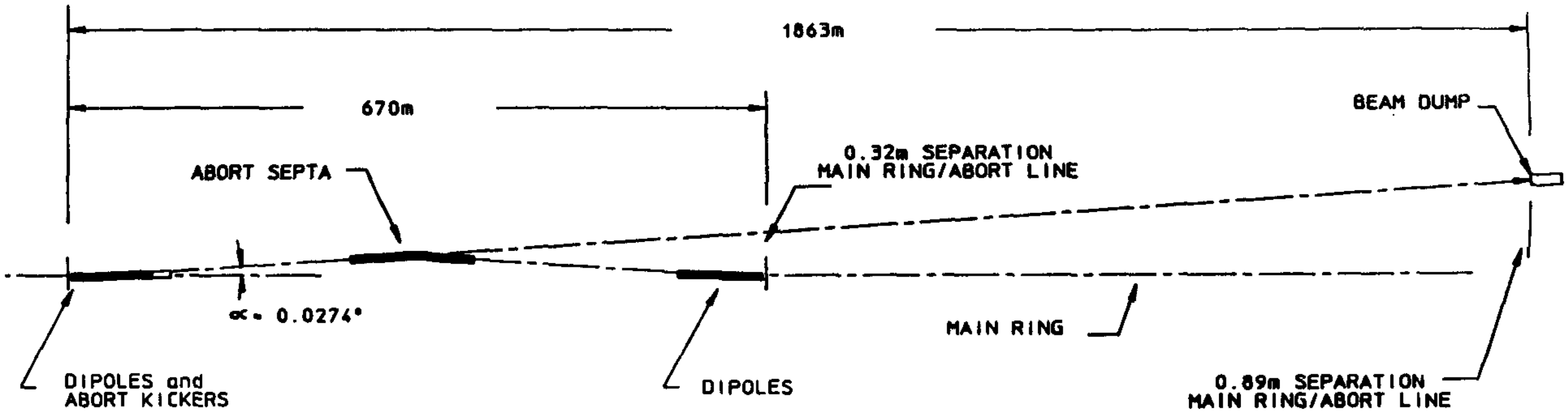

VERSION 2
INJ-COMPLEX
0
1
2km
DISK: 31
DROUET LATS VER2 INJ-CMPLX
DROUET/CHAN 03 NOV 87

Figure 11.



LAT3-13 NOV 87 GEOMETRY OF ABORT SEPTA - EXTERNAL BEAM LINE

DISK: 31
DROUET LAT3 ABORT SEPTA1
DROUET/CHAN 13 NOV 87

Figure 12.

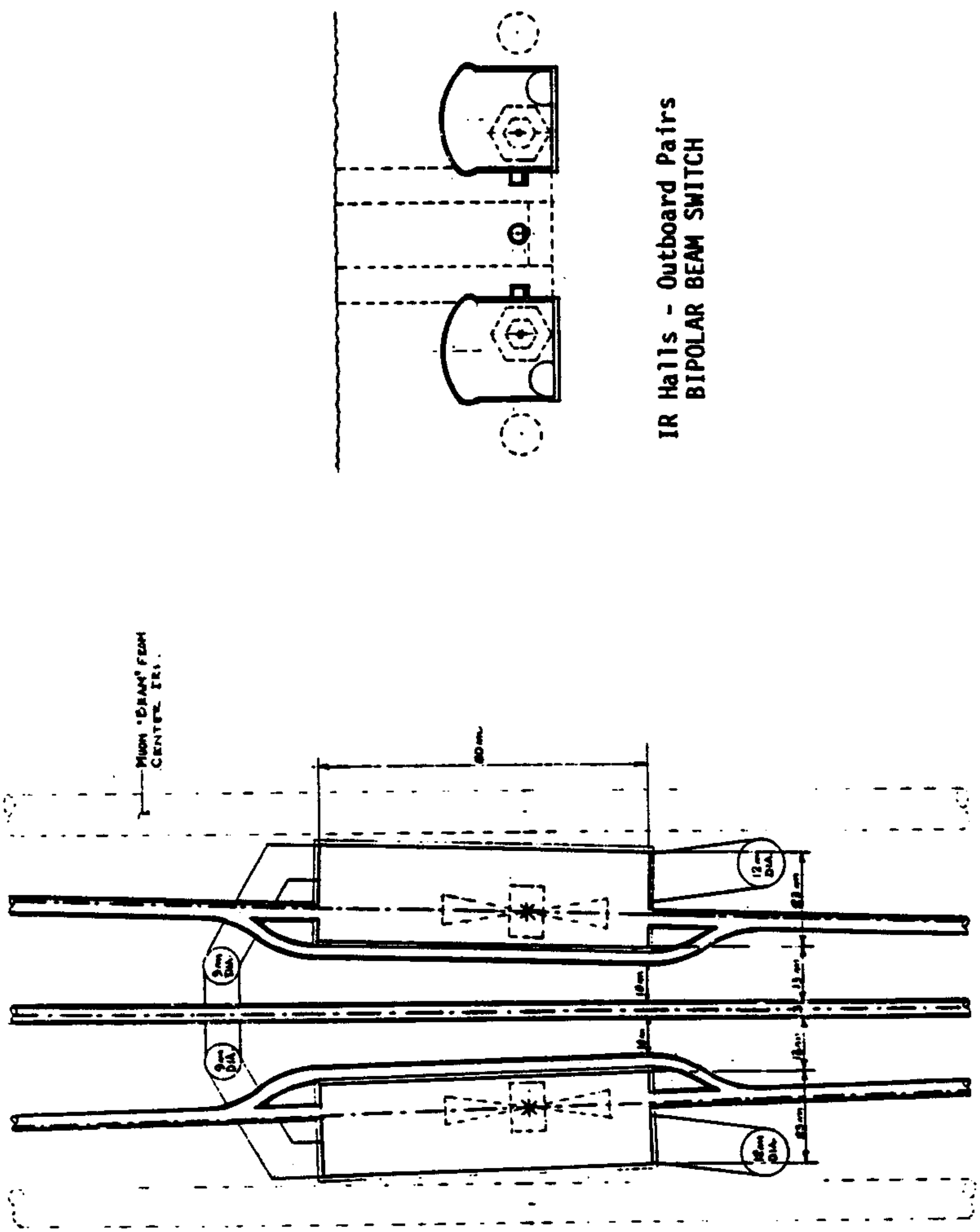


Figure 13.

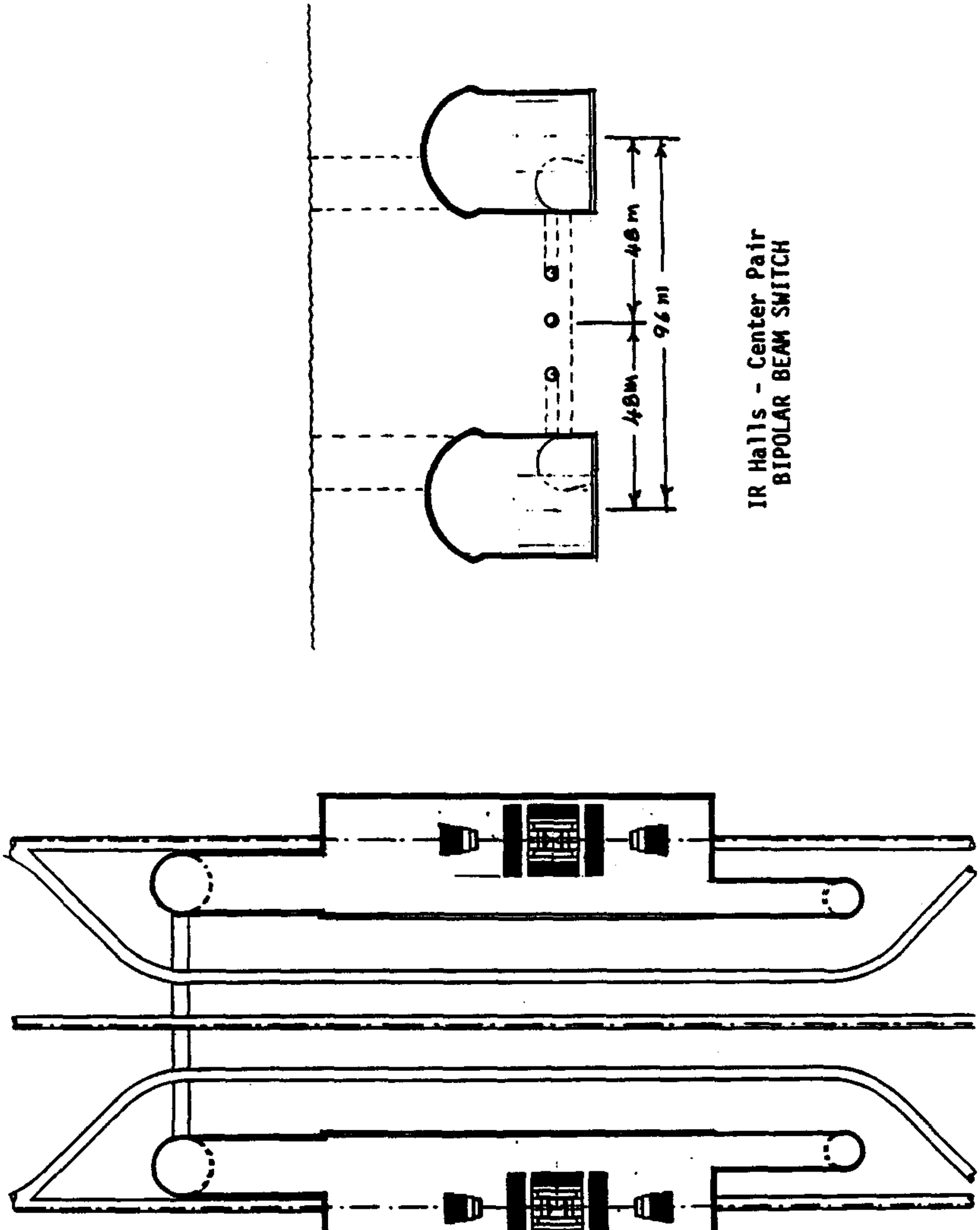


Figure 14.

November 9, 1987

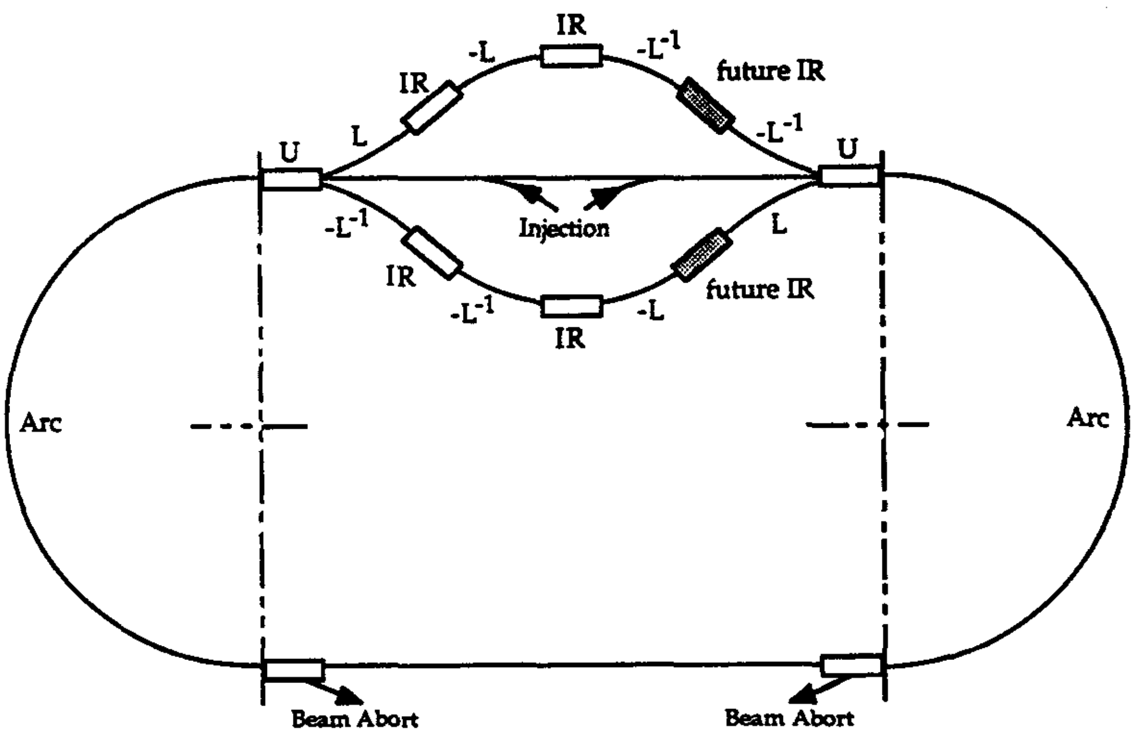
MEMORANDUM

To: A. Chao, A. Garren, G. Gilchriese, D. Groom, D. Johnson, C. Quigg, J. Sanford, M. Tigner, T. Toohig, S. Wojcicki

From: G. Drouet

Subject: Bypass Update

I would like to update Gil's memo dated June 20, 1987 by adding figures related to a (bipolar) triple IRs bypass, as shown below.



D. Johnson's data: U = straight for injection = 355 m

IR = 1150 m

L = 9 half-cells of 65 m = 585 m

GROSS PARAMETERS OF THE LATTICE:

- 2 arcs of 160 cells → 7680 dipoles
- R_{arcs} = 11637.4 m
- Circumference = 86120 m
- Length of the bypass: 2 × 6500 m
- Nbr of initial IRs = 4
- Nbr of potential IRs = 6 (+ 6 in the far cluster)
- Nbr of dipoles in main ring = 7680
- Nbr of dipoles in by-pass = 2 × 144
- Total nbr of dipoles: 7968
- Nbr of quads in main ring: 1436
- Nbr of quad in by-pass: 2 × 184
- Total nbr of quads: 1804
- Nbr of vertical dipoles in main ring: 0
- Nbr of vertical dipoles in by-pass*: 2 × 88
- Total nbr of vertical dipoles: 176
- Distance between IRs: 1735 m
- Bend between IRs: 30 mr
- Transverse separation at IP (external): 49 m
- Transverse separation at IP (internal): 98 m

Initially, the far cluster consists of a long straight section of 6500 m and accommodates the aborts; eventually it can be equipped with another six experimental areas without impacting the operation of the machine.

This configuration almost fits within the ISP land area and would fit if the arc radius were slightly increased by about 150 m (1.3%) (i.e., decreasing the bend angle of the dipoles or field by the same figure).

With the same unit prices used by Gil (cost per km of tunnel = 4 M$; cost per magnet = 0.12 M$), the following table of differential costs can be established (M$). The baseline is the adopted 90° cell lattice (which does not conform to the ISP template).

---

* Assumes: Two low-β and two medium-β insertions.

	1	2	3	4	5	6
Cost of additional tunnel	8	28	32	40	62	52
Cost of additional magnets	8	51	61	82	65	108
AE/CM and EDIA	2	12	14	18	19	24
Contingency	5	23	27	35	36	46
	23	114	134	175	182	230

Column 1: 90° lattice plus transition regions to fit within the ISP footprint

Column 2: Bypass one IR (single bypass)

Column 3: Bypass two IRs (double bypass)

Column 4: Bypass three IRs (triple bypass)

Column 5: (Double) Triple bypass; one-lab configuration

Column 6: Bypass four IRs (quadruple bypass ISP)

Solution 5 allows commissioning and accelerator studies independant of the experiments. Compared to the other solutions, solution 5 doesn't need a cryogenic plant in the far cluster and initially avoids the development of this area (utilities, roads buildings . . .). The advantages of a single laboratory during the first phase have been detailed in depth in the following :

- L. M. Lederman and L. C. Teng, "A One-Campus SSC," (April 1987)
- M. Marx, "Cost Benefits of an Experimental Bypass at the SSC," (Draft, May 5, 1987)

I recommend that thorough attention should be paid to this option, and that more detailed studies should be made of the lattice and the effects of muon beams near the experimental areas.

Appendix F

STUDIES OF ONE-CAMPUS AND TWO-LEVEL CONFIGURATIONS FOR THE SSC

L. C. Teng
Fermi National Accelerator Laboratory*, Batavia, Ill. 60510

ABSTRACT

The geometries and the magnet lattices for an SSC where the desired eventual six interaction regions are provided on two bypass branches in the same campus is studied. The single campus approach has many obvious advantages. In addition, it would be natural to build the campus and the remainder of the ring which is simply a big beam transport, on different levels each optimized for its own functional requirements. Such a two level configuration is also investigated. Injection into such rings is discussed and their incremental costs are estimated.

In this report we investigate in some detail the geometry and the cost of two modifications in the configuration of the SSC.

1. One-campus configuration — the possibility and the advantages of this configuration were first pointed out by L. Lederman[1] and later further elaborated by L. Lederman and L. Teng.[2] Assuming, as in the Conceptual Design, that the fully developed and exploited SSC has 6 interaction regions (IR's) equipped with detectors and that for about half of the time a detector needs to be serviced and/or modified, one should then have a two-branch bypass with 3 IR's on each branch. And to minimize the campus length one should inject into 2 utility straight sections located on the trunk line just beyond the ends of the bypass, denoted as Case C in Ref. 2. The odd number of vertical crossings in each branch brings opposite rings to the top-side for identical injection geometry from above (or below) and yields good overall symmetry between the two rings. This implies, of course, that there must be another crossing (presumably without collision) in the long long straight section diametrically opposite from the Campus.

2. Two-level configuration — With the one-campus configuration the circumference of the collider is clearly divided into two sectors with totally different functions. The Campus sector serves all the active functions such as injection, acceleration, beam abort, beam collision and the performance of physics experiments with massive detectors. The remaining sector and by far the greater part of the circumference is just a big beam transport and serves only the inert function of channeling the beam leaving the Campus back to the Campus. Because of the difference in function the optimal physical arrangements for the active "Campus" and the inert "Transport" sectors may be quite different. Specifically, the optimal elevation for these two sectors are different: the active Campus should be easily accessible and hence closer to the grade level, and the inert Transport should be deeper underground to minimize interference with the use and habitation of the ground above.

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

For the basic SSC we assume the following parameters[1] (each ring):

Phase advance per normal cell	90°
Half cell length, l	114.25 m
No. of dipoles per half cell	6
Bend angle per dipole, θ	1.64 mrad
Length of Interaction Region (IR) or Utility Region (UR)	$11l$
Length of Curved Region (CR) between IR's	$9l$
Bend angle per CR	50θ (82 mrad)
Length of Arc Region (AR)	$295l$
Bend angle per AR	1766θ (2896 mrad)
Total number of dipoles	3832
Circumference	$732l$ (83631 m)

We also need an all purpose matching region (MR). Such an MR is shown in Fig. 1. The section is composed of four 90° cells with 6 half-cells filled with bending dipoles. This section matches zero dispersion ($D = D' = 0$) to zero dispersion and has unity transfer matrices in both planes independent of the length l_M and the bend angle θ_M which can be adjusted to match the geometry. We shall identify a specific matching region by MR(l_M , θ_M).

ONE-CAMPUS CONFIGURATION (ONE-LEVEL)

Symmetric Bypass

The principal function of the CR in the basic SSC lattice is to eliminate interference from muons produced in neighboring IR's. But as we shall see later (Appendix A) the CR as specified is longer than necessary. For the symmetric bypass shown in Fig. 2 we choose to use MR ($6l$, 24θ)'s to connect IR's. The IR length is held fixed so that the beam combining geometry and the low-β and the medium-β quadrupole arrangements are unchanged. The same is true with the UR. The parameters of the MR are chosen so that the end Interaction Points (IP's) are separated by a convenient distance. With these choices the parameters of the symmetric bypass are (each ring):

Minimum length of Campus to include all IP's

$34l = 3.9$ km

Separation of the end IP's $= s = 76.4$ m

Increment of total tunnel length over the basic SSC

$\Delta L = 123l = 14.1$ km

Increment of total bend angle over the basic SSC

$\Delta\theta = 192\theta = 315$ mrad

RMS μ-beam radius at neighboring IP $= r_\mu = 4.6$ m

(Beam/IP separation $= 38$ m $> 8r_\mu$)

Unipolar Bypass

In this case a larger bend angle between the end UR's and IR's helps to create the separation between the branches. Therefore we will keep the basic CR's with bend angle $\theta_C = 50\theta$ at these locations as shown in Fig. 3. The separation between the branches is then created by inserting the two staggered straight sections of lengths l_I (inner branch) and l_O (outer branch). The most straightforward way to match across l_I and l_O is to use the straight matching sections MR $(l_I,0)$ and MR $(l_O,0)$. We shall assume the same separation $s = 76.4$ m for easy comparison with the symmetric case. This value is also close to the minimum required to accommodate the large detector halls on both IP's. The parameters so obtained are:

Outer branch straight length

$$l_O = \frac{\cos\theta_C}{\sin\theta_C} s = 930.0 \text{ m} = 8.14l$$

Inner branch straight length

$$l_I = \frac{\cos 2\theta_C}{\sin\theta_C} s = 920.6 \text{ m} = 8.06l$$

Minimum length of Campus to include all IP's

$34l = 3.9$ km

Separation of the IP's $= s = 76.4$ m

Increment of total tunnel length over the basic SSC

$\Delta L = 139.6l = 16.0$ km

Increment of total bend angle over the basic SSC

$\Delta\theta = 148\theta = 243$ mrad

RMS μ-beam radius at:

Nearest neighboring IP $= r_{\mu 1} = 4.6$ m

(Beam/IP separation $= 38$ m $> 8r_{\mu 1}$)

Second neighboring IP $= r_{\mu 2} = 7.2$m

(Beam/IP separation $= 76$ m $> 10r_{\mu 2}$)

TWO-LEVEL CONFIGURATION

We assume that the active "Campus" of the ring, the section that includes the 6 IR's, is horizontal and at an elevation d_V above that of the inert "Transport" which is also horizontal. We need a vertical dogleg at each end of the Campus to produce the elevation difference.

Symmetric Bypass

Referring to Fig. 4 we see that the end section ABCD is made into a symmetric dogleg in a plane tilted at an angle α from the horizontal. Such a dogleg will produce a vertical displacement. The matching region CE should be on a plane tilted at angle $\pi - \alpha$ from horizontal. This reverses the vertical component of the field and leaves the horizontal component unchanged. Thus the horizontal projections of CD and CE will bend in opposite directions and the vertical projection of ABCE will be identical to that of ABCD.

We will keep the axes of the quadrupoles untilted (no rotation about the beam axis) so that any coupling of beam optics in the two transverse planes is introduced only by the skewed bending of the dipoles. It should be easy to compensate for this weak coupling by the trim skew quadrupoles which are already included in the lattice.

The Tilted Regions AB, CD and CE are denoted by TR and are formed by the very versatile all purpose matching regions with lattice given in Fig. 1. The length and bend angle will be denoted by l_T and θ_T. The projected horizontal (θ_H) and vertical (θ_V) bend angles are given by (see Appendix B).

$$\tan\theta_H = \tan\theta_T \cos\alpha$$

$$\tan\theta_V = \tan\theta_T \sin\alpha$$

The total horizontal and vertical excursion d_H and d_V from A to D of the dogleg are given by

$$d_H = \left(2l_T \frac{1-\cos\theta_T}{\theta_T} + l_U \sin\theta_T\right)\cos\alpha$$

$$d_V = \left(2l_T \frac{1-\cos\theta_T}{\theta_T} + l_U \sin\theta_T\right)\sin\alpha$$

For all our cases θ_T, θ_H and θ_V are small enough so that these formulas can be approximated as

$$\theta_H = \theta_T\cos\alpha \qquad d_H = (l_T + l_U)\theta_T\cos\alpha$$

$$\theta_V = \theta_T\sin\alpha \qquad d_V = (l_T + l_U)\theta_T\sin\alpha$$

If the same SSC dipoles are used for the MR, only 36 dipoles can be accommodated in a length $8l$. Hence we have the additional condition

$$l_T = \frac{8}{36}\frac{\theta_T}{\theta} l$$

For a numerical example we use the following values.

1. $\theta_H = 24\theta$. We assume that the projected horizontal bend angle remains the same as in the one-level configuration.
2. $U = 11l$. The length of the end utility straights is unchanged so that the matching and the injection configurations are the same as in the one-level case.

3. $d_V = l$. For some of the proposed sites the bedrock is ≈ 400 ft below grade. If one assumes that the Transport section is in the rock (best for tunneling) and the Campus section is near the grade level $d_V = l = 114.25$ m is about right.

From the above equations we have

$$d_V = (l_T + l_U)\theta_T \sin\alpha = \left(11 + \frac{8}{36}\frac{\theta_H}{\theta_T}\right) l\theta_T \sqrt{1 - \left(\frac{\theta_T}{\theta}\right)^2}$$

or

$$\frac{d_V}{l} = \left(11 + \frac{8}{36}\frac{\theta_T}{\theta}\right)\sqrt{\theta_T^2 - \theta_H^2}$$
$$= \theta\left(11 + \frac{8}{36}\frac{\theta_T}{\theta}\right)\sqrt{\left(\frac{\theta_T}{\theta}\right)^2 - 24^2}$$

With $d_V/l = 1$ this gives the following parameters for the TR:

Bend angle $= \theta_T = 39.17\theta = 64.22$ mrad

Tilt angle $= \alpha = 0.9113 = 52.2°$ (and $127.8°$)

Projected horizontal bend angle $= \theta_H = 24\theta = 39.35$ mrad

Projected vertical bend angle $= \theta_V = 30.95\theta = 50.75$ mrad

Length $= l_T = 8.70l = 994$ m

and the following parameters for the ring:

Vertical excursion of dogleg = level difference between Campus and Transport $= l = 114.25$ m $= 375$ ft

Increment of total tunnel length over the one-level configuration $= \delta L = 35l = 4.0$ km

Increment of total bend angle over the one-level configuration $= \delta\theta = 91\theta = 149$ mrad

Unipolar Bypass

Referring to Fig. 5 we see that the outer branch end section ABCDE is topologically the same as the mirrored dogleg of the symmetric bypass denoted as ABCE in Fig. 4, except in this case the central straight length l_U is replaced by $l_U + l_O$ and we want the projected horizontal bend angle θ_H of the tilted regions AB and DE to be 50θ, the same as that of the one-level configuration. We also keep l_O and l_I unchanged so as to get the same separation between the two branches.

The inner branch end section ABCFG is a little more complicated. The tilted region CF should be a helix with fixed pitch angle θ_V and projected horizontal bend angle $\theta_H = \theta_C = 50\theta$. The bend angle θ_S along the helix is given by (see Appendix B)

$$\sin\theta_S = \sin\theta_H \cos\theta_V$$

But for values considered here it is a good approximation to simply set

$$\theta_S = \theta_H = 50\theta$$

To bend the orbit back to horizontal we need a vertical MR (l_I , θ_V). It is easy to see that this will bring the 3 inner branch IR's in a horizontal plane roughly on the same elevation as the 3 outer branch IR's. The TR parameters are:

Bend angle $= \theta_T = 53.71\theta = 88.07$ mrad

Tilt angle $= \pi - \alpha = 2.7676 = 158.6°$

Projected horizontal bend angle $= \theta_H = 50\theta = 81.98$ mrad

Projected vertical bend angle $= \theta_V = 19.62\theta = 32.18$ mrad

Length $= l_T = 11.93l = 1363$ m

and the parameters of the two-level ring are

Vertical excursion of dogleg = level difference between Campus and Transport $= l = 114.25$ m $= 375$ ft

Increment of total tunnel length over the one-level configuration $= \delta L = 21.4l = 2.44$ km

Increment of total bend angle over the one-level configuration $= \delta\theta = 7.42\theta = 12.2$ mrad

COSTS, REMARKS AND CONCLUSIONS

Several remarks are in order.

1. We have not worked out the transport across the long straight section diametrically opposite the Campus.
   The design should, however, be straightforward.

2. We have not adjusted the circumferences to give integer rf harmonic numbers. But with the very large circumferences this adjustment should be trivially small.

3. In the end UR of the top ring the injection and the switching between branches can both be accommodated in the central ±330 m long free drift space. One possibility is shown in Fig. 6. The ring orbit is switched between the branches by a switching magnet W_D located near the right end of the drift space which deflects the orbit by ±1/2 mrad. The magnet W_D is an integral part of the ring and has to ramp up with all the ring magnets.

   The injection beam at 1 TeV enters from the left at a downward angle of, say, 3 mrad + 60 μrad and is switched to follow the active branch, say branch 1, by the upstream injection switching magnet W_U and the tilted ramped septum S_1. W_U deflects the beam by ±1/2 mrad in the beam plane and S_1, deflects the beam horizontally 1 mrad and vertically 3 mrad (total deflection $\sqrt{10}$ mrad tilted at angle $\tan^{-1}$ (1/3) from vertical). After S_1 the beam approaches the branch 1 orbit vertically downward at a 60 μrad angle and crosses the orbit just beyond W_D.

There it is deflected vertically 60 μrad onto the ring orbit by a vertical fast kicker K_V. The strengths of these magnet elements are given in Fig. 6 and are all quite modest. The dispersions generated by these small deflections although small, should be included in the detailed matching design.

The end UR of the lower ring has an identical orbit switching system but no injection system.

4. For injection into the two end UR's the most convenient location for the $\approx$ 1 km radius High Energy Booster (HEB) is in the middle of the Campus straddling the two branch lines as shown in Fig. 7. The major advantage of this arrangement is that bipolar operation of the HEB is not needed. Beams extracted from diametrically opposite straight sections of HEB are channeled by long but relatively straight transport lines to the end UR's. These transport lines and the tunnels housing them could be quite simple and inexpensive.

   If the HEB is capable of bipolar operation one can extract oppositely circulating beams from the same straight section and inject them into neighboring utility straights of the SSC rings as in Case A of Ref. 2. This arrangement, in addition to requiring the hard bipolar operation of a superconducting HEB, would need a longer Campus.

5. With the injection geometry shown in Fig. 7, for all 4 configurations — symmetric and unipolar bypasses, one- and two-levels — the minimum size of the Campus to enclose the injector and all 6 IR's is about 5 km long by 2.5 km wide. To this one must add the abort/external beams area, the arc areas, the service and access areas, and the necessary easements.

6. To make some rough estimates of the cost differentials we shall use the 1987 unit-costs given by the Central Design Group, namely

   Tunnel cost (CT): \$4M/km

   Magnet cost (CM): \$0.15/dipole + 20% for quadrupoles

   EDIA = 15% (CT + CM)

   Contingency = 25% (CT + CM + EDIA)

The incremental costs for the one-campus and the two-level configurations are given in the table below (two rings).

	One-Campus			Two-Level		
	ΔL	=	14 km	δL	=	4 km
	ΔM	=	2 × 192	δM	=	2 × 91
Symmetric bypass	CT	=	\$56 M	CT	=	\$16 M
	CM	=	\$69 M	CM	=	\$33 M
	EDIA	=	\$19 M	EDIA	=	\$ 7 M
	Cont.	=	\$36 M	Cont.	=	\$14 M
			\$180 M			\$70 M
	ΔL	=	16 km	δL	=	2 km
	ΔM	=	2 × 148	δM	=	2 × 54
Unipolar bypass	CT	=	\$64 M	CT	=	\$ 8 M
	CM	=	\$53 M	CM	=	\$19 M
	EDIA	=	\$18 M	EDIA	=	\$4 M
	Cont.	=	\$34 M	Cont.	=	\$8 M
			\$169 M			\$39 M

This table shows that the incremental cost of the Unipolar Bypass configuration is slightly less. On the other hand, the Symmetric Bypass configuration is simpler and neater and has many construction, alignment and operation advantages which are well worth the slightly higher cost.

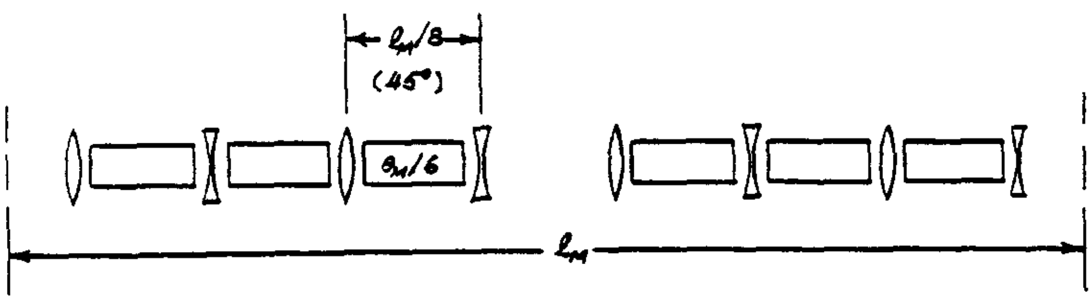


Fig. 1. An all purpose matching region denoted as MR(l_M, θ_M) which matches zero dispersion to zero dispersion and has unity transfer matrices in both transverse planes and adjustable length l_M and bend angle θ_M.

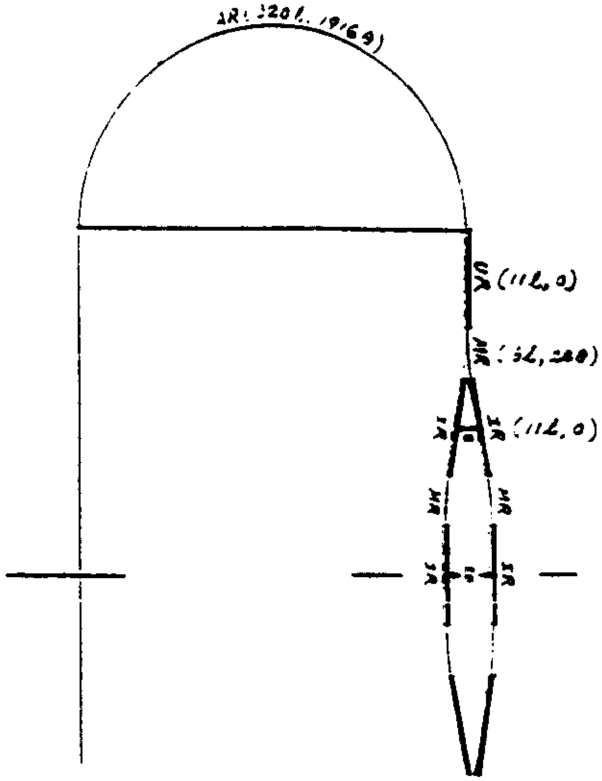


Fig. 2. One-campus one-level configuration with symmetric bypass (not to scale).

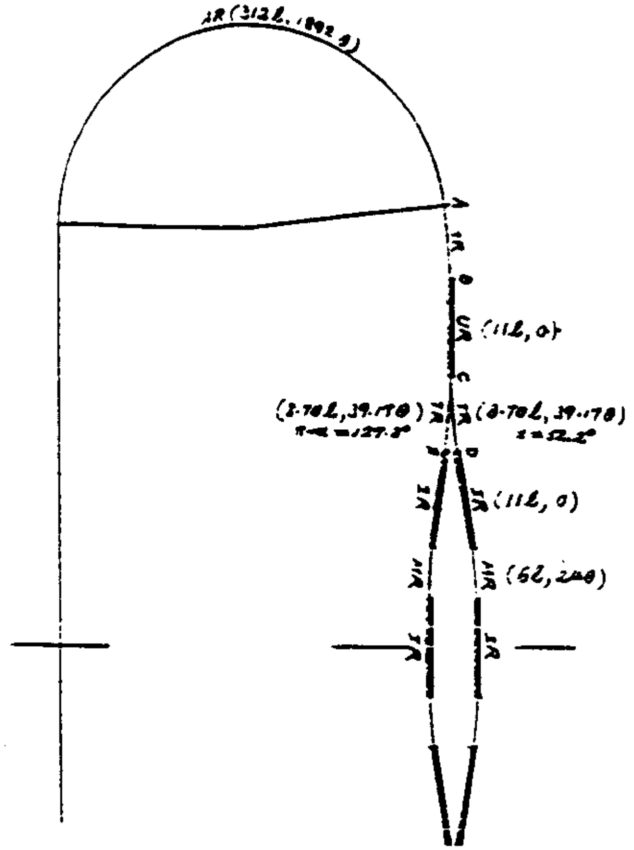


Fig. 4. Two-level configuration with symmetric bypass (not to scale).

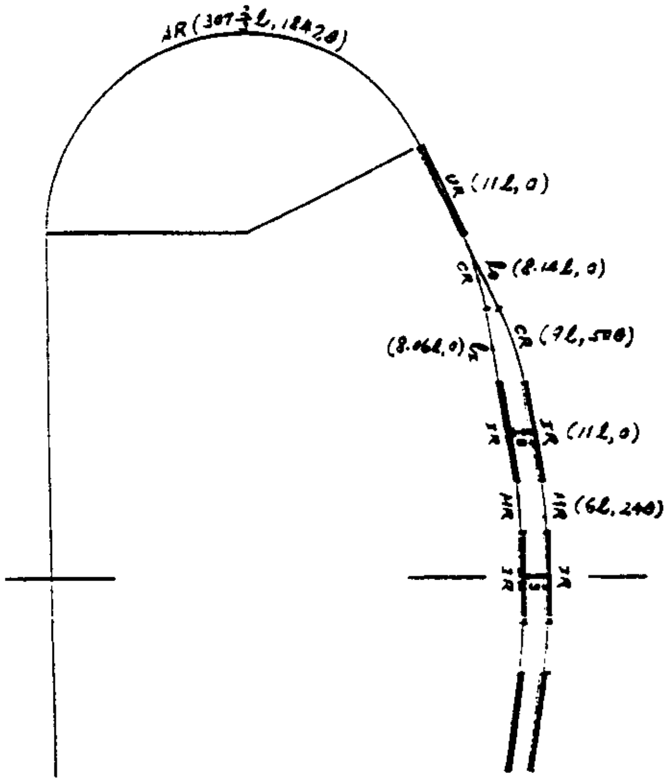


Fig. 3. One-campus one-level configuration with unipolar bypass (not to scale).

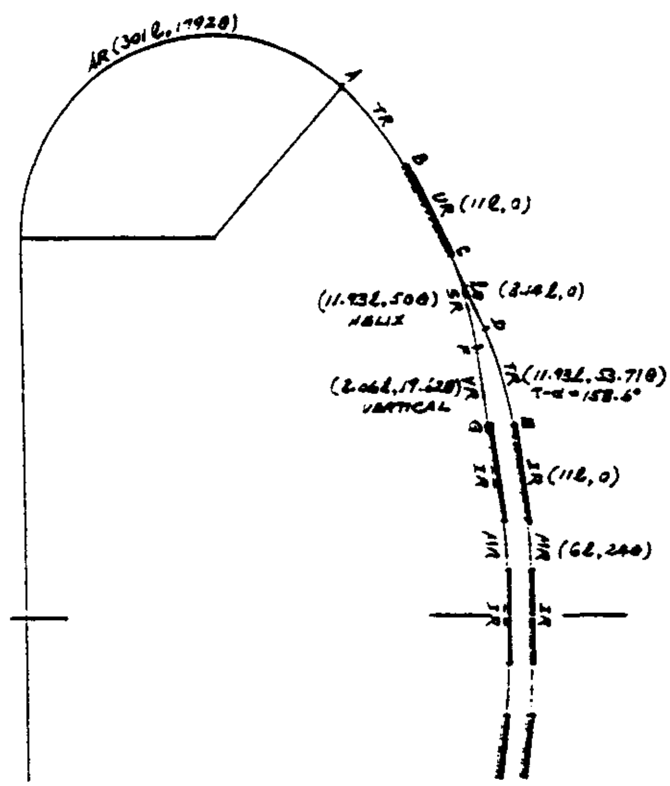


Fig. 5. Two-level configuration with unipolar bypass (not to scale).

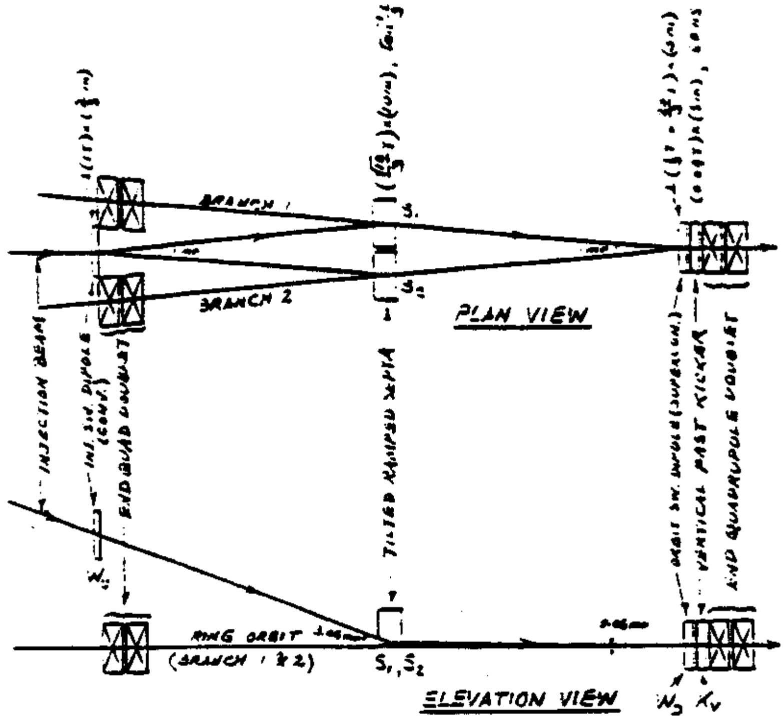


Fig. 6. Injection and branch-switching systems in the central drift space of an end utility region (not to scale).

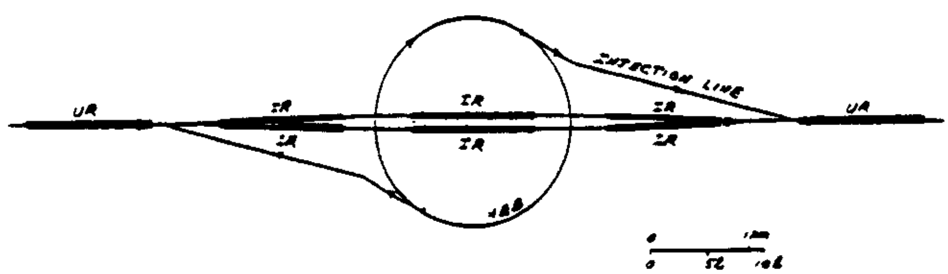


Fig. 7. Optimal positioning of a unipolar high energy booster injector and the injection transport lines.

APPENDIX A

RMS Cone Angle and Radius of the Muon Beam from an IP

The high energy muons from an IP are produced essentially at 0° (or 180°). When they go through a thickness l_μ of earth shielding all muons with parallel momentum

$$p_\parallel < \left(0.4\frac{\text{TeV}}{c}/\text{km}\right) l_\mu$$

are ranged out. Here we have taken

$$\frac{dE}{dx} \sim 2\ \text{MeV/g/cm}^2, \quad \text{and}$$
$$\text{Density of earth} \sim 2\ \text{g/cm}^3$$

The muons that penetrated the earth shielding will have gained an rms perpendicular momentum through multiple Coulomb scattering of the amount

$$p_\perp = (1.5\text{GeV/c})\sqrt{l_\mu(\text{km})}$$

Where we have taken the radiation length of earth to be $\sim 25\ \text{g/cm}^2$. Thus, the rms cone angle of the muon beam is

$$\theta_\mu \equiv \frac{p_\perp}{p_\parallel} = \frac{4\ \text{mrad}}{\sqrt{l_\mu(\text{km})}}$$

and the rms radius of the μ-beam after going through l_μ length of earth is

$$\sigma_\mu = \theta_\mu l_\mu = (4\text{m})\ \sqrt{l_\mu(\text{km})}$$

All IP's should be located several σ_μ away from one another's muon beams.

APPENDIX B

Geometry of Tilted Dogleg Orbit and Helix Orbit

1. One half of the dogleg is shown in Fig. B1. The orbit is the curve ABC, A being the start and C being the midpoint of the dogleg. The angles involved are

   Tilt angle $= \alpha = \angle AOD$

   Bend angle $= \theta_T = \angle AOB = \angle BPQ$

   Projected horizontal bend angle $= \theta_H = \angle EPQ$

   Projected vertical bend angle $= \theta_V = \angle GPQ$

   The relationship between the angles are

$$\tan\theta_H = \frac{EQ}{PQ} = \frac{BQ}{PQ}\cos\alpha = \tan\theta_T\cos\alpha$$

$$\tan\theta_V = \frac{GQ}{PQ} = \frac{BQ}{PQ}\sin\alpha = \tan\theta_T\sin\alpha$$

   The lateral excursions are

$$\begin{aligned} d_H &= 2\ DU = 2\ AW\cos\alpha \\ &= 2\left(AB\frac{1-\cos\theta_T}{\theta_T} + BC\sin\theta_T\right)\cos\alpha \\ &= 2\left(l_T\frac{1-\cos\theta_T}{\theta_T} + \frac{l_U}{2}\sin\theta_T\right)\cos\alpha \end{aligned}$$

$$\begin{aligned} d_V &= 2\ FV = 2AW\sin\alpha \\ &= 2\left(l_T\frac{1-\cos\theta_T}{\theta_T} + \frac{l_U}{2}\sin\theta_T\right)\sin\alpha \end{aligned}$$

2. A section of a helix orbit is shown in Fig. B2 as AE. Plane ABCD is tangent to the orbit cylinder and AC is tangent to the orbit at A. Similarly EFGH is the tangent plane and EG is tangent to the orbit at E. We have also made AC=EG. Plane ABCD is parallel-translated to EIKH. The angles are

   Orbit bend angle from A to E $= \theta_S = \angle KEG$

   Horizontal projection of bend angle $= \theta_H = \angle IEF$

   Vertical pitch angle of helix $= \theta_V = \angle KEI = \angle GEF$

   The relation between these angles is

$$\frac{\sin\theta_S}{\sin\theta_H} = \frac{GK/EK}{FI/EI} = \frac{EI}{EK} = \cos\theta_V$$

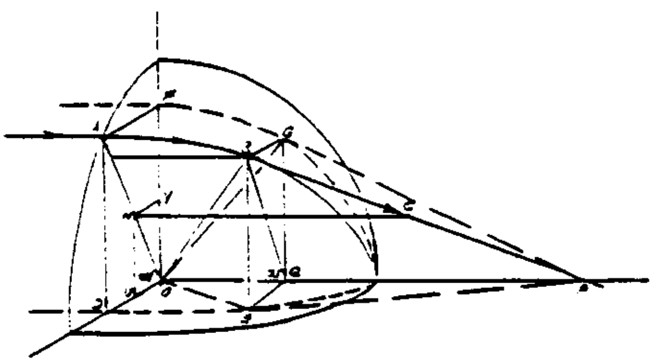


Fig. B1. Geometry of a tilted dogleg orbit.

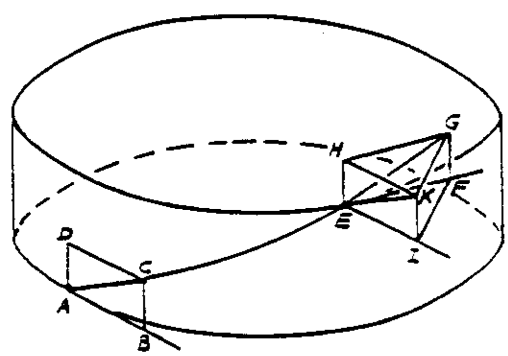


Fig. B2. Geometry of a helix orbit.

REFERENCES

1. L. M. Lederman "A One Lab SSC Configuration" *Proceedings of the 1986 Summer Study on the Physics of the SSC*, p. 518

2. L. M. Lederman and L. C. Teng "A One-Campus SSC" Fermilab report TM–1452 (April 1987)

3. A. A. Garren and D. E. Johnson "The 90° (September 1987) SSC Lattice" SSC–146.