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DESIGN OF TWO-TURN INJECTION INTO THE MAIN RING

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I. Introduction

The highest intensity of the 400 GeV beam that has been obtained so far is 2.49×10^{13} protons/pulse, half of the design value. It is therefore natural to consider a two-turn injection into the main ring as the quickest and the easiest way to achieve the design goal. There are of course other projects being actively pursued now for the same purpose; H^- injection into the booster, active beam dampers (horizontal and vertical) and the transition jump by pulsed quadrupoles[1] in the booster, improvement of the vacuum in the main ring, and the enlargement of transverse as well as momentum apertures of the main ring. Important as these are, it is difficult to predict in terms of the number of protons how much improvement one would achieve by them. Two-turn injections (or, more generally, multi-turn injections) have, in comparison, an appealing feature of simplicity in the concept and their (seemingly) predictable performance. Two different schemes of multi-turn inection into the main ring have already been proposed, one by Ruggiero[2] and the other by Teng.[3]

Ruggiero's scheme was based on the observation made by R. Stiening sometime ago that the momentum aperture of the main ring seems to be larger than what one would expect from its acceptance in the horizontal betatron space.[4] He proposed a multi-turn injection in the momentum space, that is, beam stacking by rf in the style of the ISR. In place of the present kicker (MK90), he uses a kicker with a shutter (mechanically movable screen). Since the kicker location is not particularly suitable for the purpose, the required momentum aperture is large, almost one percent. The modification needed in the 8-GeV transport line is hinted but not discussed in his report. Teng proposed a two-turn injection in the horizontal betatron space. The beam is injected horizontally, instead of the present vertical injection, and two kickers located 180° apart in phase are used to make a local bump in the closed orbit. Since two booster pulses stacked side by side are separated by at least 67 ms (one booster cycle) in their injection time, the shape of the first pulse in the horizontal phase space will be completely smeared out to the main ring acceptance shape before the second pulse is injected. The minimum acceptance required in the main ring is then four times the horizontal emittance of the injected beam. The modification in the 8-GeV transport line includes the replacement of two vertical dipoles (MV61 and MP70) by a Lambertson magnet which will be located at the end of the long straight section in the transfer hall. He later pointed out[5] that the double-kicker arrangement could also be used for a two-turn injection in the momentum space. This eliminates the need for a kicker with a shutter, a definite advantage. His report emphasized the importance of finding out the main ring acceptance.

The purpose of this note is to present several designs for two-turn injections. As such, it can simply be regarded as a natural extension of their works since the underlying principles are the same. At the same time, results from the recent measurements of the main ring aperture[6,12] will be taken into account, making designs presented here more realistic than the original version of Ruggiero and of Teng.

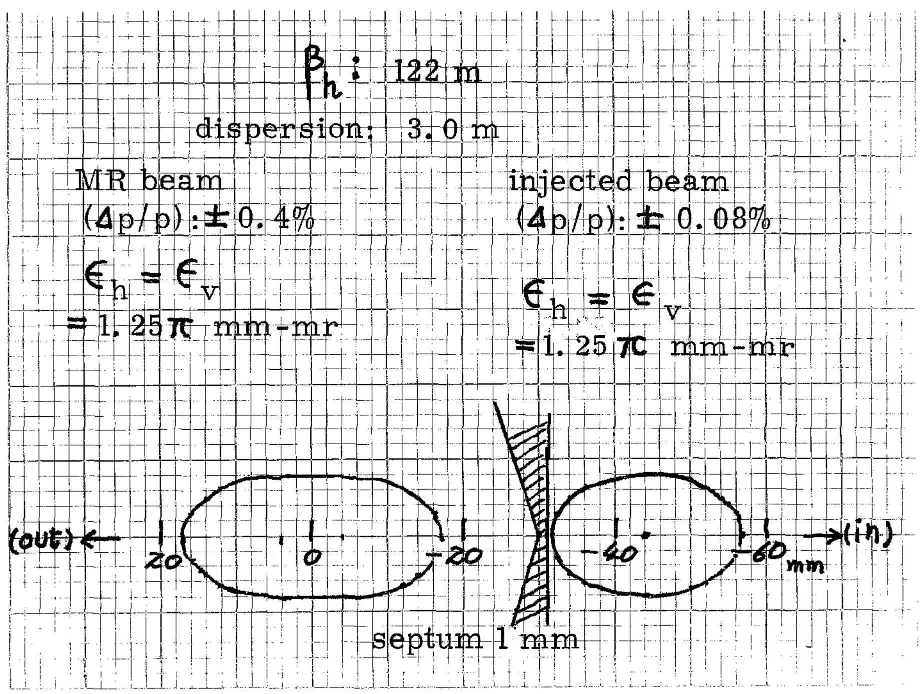
Since last June, the main ring group has been active in the project to understand the aperture limitation and to improve the acceptance. The outcome of this effort may very well influence the final design in a decisive manner. There is also an important question of possible impacts of the two-turn injection on the rf stacking in the doubler and on the doubler-main ring colliding beam experiments. In the main ring operation, effects on the extraction may become a dominant factor in deciding the type of the two-turn injection. Problems with the spill structure and an increase in the beam loss during the slow extraction could limit the usefulness of the two-turn injection strictly to internal target experiments. Although it is difficult to give complete answers to these questions at present, advantages and disadvantages of each scheme should be studied with these problems kept in mind.[7]

It is not the purpose of this report to promote a particular scheme over others. Rather, the report is intended to serve as a reference on technical aspects of the two-turn injection. Regardless of what scheme should be employed, it would be an outstanding success if the beam intensity could be increased by 50% or more of the present value without, at the same time, inducing an intolerable increase in the beam loss during the entire main ring cycle (injection, acceleration and extraction).

II. Modification of the 8-GeV Transport Line

This has been described in the report by Teng.[3] The present injection is in the vertical direction, the injected beam being on the proper horizontal orbit after the last horizontal bend MH50. The downstream end of the transport line is given in Table 1. Teng proposed to remove

MV61 and MP70 and to install a Lambertson magnet at the end of the long straight section. The injected beam is then on the proper vertical orbit after the Lambertson magnet. The center of the Lambertson in the radial direction was chosen to be at -42 mm (inside) from the main ring orbit. Five quadrupoles (MQ44, 45, 46, 50, 51) and one dipole (MH50) must be realigned to make the injection line almost parallel horizontally to the main ring orbit (see Fig. 3 of Ref. 3). Another possibility is to limit the necessary realignment to two last quadrupoles by introducing a horizontal dog-leg. A vernier dipole (4-4-30)[8] like HT1 of the present line placed at the MV61 (which will be taken out) is adequate for this with the capability of $B\ell = 3$ kG-m Ease of dispersion matching may prefer one scheme over the other but this has not been studied. The radial position of the Lambertson is essentially decided by the aperture requirement of the main ring. In this note, the center of the Lambertson is taken to be -44 mm and an example of aperture allocation is shown below.



One would probably like to have a longer (∿ 1 m) and weaker (∿ 2.5 kG) magnet than indicated in Ref. 2 in order to minimize the septum thickness. The modification applies not only to the two-turn injection into the horizontal betatron space but to the momentum space stacking as well. The original scheme by Ruggiero used a vertical kicker with a shutter at the present MK90 kicker location. When the kicker location is moved to A17 where the dispersion is more favorable, the vertical injection is almost impossible.

III. Two-Turn Injection in the Horizontal Betatron Space

The critical quantities for this scheme are the main ring acceptance in the horizontal space and the injected beam emittance. Results from the recent measurements[6] indicate a rather small acceptance. For 50% beam survival, the acceptance is (2.6 π ∿ 3.4 π) mm-mrad. The emittance of the 8-GeV beam is a function of the beam intensity. Above 2.5×10^{13} protons per 13 booster pulses, it seems difficult to make the emittance (90% of the beam) of the beam smaller than 1.2 π mm-mrad. This requies an acceptance of almost 5 π mm-mrad and one must depend on successful results from the current effort of the main ring group to enlarge the aperture.

In the original design by Teng, the horizontal bump is created by two kickers, one at F46 and the other at A12. The phase advance between two kickers is exactly 180° so that the bump is completely localized. Unfortunately, A12 with its small value of β_h is a "wrong" place for a horizontal kicker. A relatively large (-0.85 mrad) kick angle at A12 is the direct consequence of this. A more serious problem is the difficulty of relocating the extraction position-bump magnet from F46 to another place in order to make a space available for the kicker. In the designs given here, it is assumed that no extraction devices are to be moved.

For a local bump with less than 180° phase advance, one needs at least three kickers. These kickers will be located at F49, the present MK90 position (designated as "MK90"), and A13. Parameters for the horizontal betatron oscillation are

	F49	Lambertson	"MK90"	A13
phase	0°	45.4°	51.8°	126.5°
β_{h} (m)	67.4	122	64.5	91.7

At the Lambertson magnet, the center of the injected beam is at x = -44 mm and the injection angle is x' = -0.588 mrad. When the second series of thirteen booster pulses are being injected, the beam center of the first thirteen booster pulses (already in the main ring) is taken to be at x = -17 mm, leaving 13 mm distance to the septum. (See the figure on Pg. 4.) The required kick angles are

	F49	"MK90"	A13
first turn	-	0.273 mr	-0.447 mr
second turn	-0.263 mr	0.248 mr	-0.315 mr

These angles are all within the capability of the present MK90 kickers. Each unit of MK90 is 1.3 m long and the maximum kick angle for the 8-GeV beam is 0.45 mrad.[9] Timing of these kickers is the same as explained by Teng. The calculation of the kicker angles is given in Appendix A and the resulting orbits are shown in Fig. 1.

The principal advantage of this scheme is its inherent simplicity. No new trick is involved and the required field strength of kickers is not excessive. Unlike the booster multi-turn injection, there is no essential difference between the single-turn injection and the two-turn injection with the same kickers used for both cases. The major difficulty is of course the limited acceptance of the present main ring. It is hard to predict the transmission efficiency without more careful measurements of the transmission vs the beam emittance. The vertical emittance of the beam will certainly be increased due to horizontal-vertical couplings, both linear and nonlinear. According to beam studies, which were made at 100 GeV to 300 GeV in October last year,[10] approximately 10% of the horizontal emittance can be transferred to the vertical emittance even with a large ($\sim$ 0.06) tune splitting. For $\varepsilon_h = 5\ \pi$ mm-mrad, the increase of the vertical emittance by 0.5 π mm-mrad could be disastrous, especially for the extraction. During the coming shutdown in April, twelve quadrupoles will be rolled by 2.5 mrad each[11] in order to reduce the linear coupling. Controlling nonlinear couplings will be more difficult. One possible benefit arising from the larger horizontal emittance is a more uniform spill since, for particles with the same momentum, the tune spread due to the difference in the oscillation amplitude will become larger. This amplitude dependence acts as a buffer to the momentum dependence of the tune. According to Jack McCarthy, a study of this effect was not very successful because of the simultaneous increase in the extraction beam loss. This was done more than a year ago and a new investigation is being planned by Bruce Brown. Finally, the luminosity of the future main ring-doubler colliding beam cannot be increased with this scheme. The crossing is most likely vertical or head-on and the horizontal beam size is doubled as the main ring beam intensity is doubled.

IV. Two-Turn Stacking in the Momentum Space

Recent measurements by the main ring group[12] show the momentum acceptance of ±(0.22-0.33)% for 50% beam survival. There are reasons to believe that more careful adjustments of correction sextupoles will increase the acceptance, although it is difficult to predict how much. The original design by Ruggiero[2] with a kicker at "MK90" requires almost one percent momentum acceptance. This will be impossible without a substantial improvement of the correction system.

For stacking the beam in the momentum space, the distance between the centers of the injected and the stacked beams must be large enough to accommodate the beam size and the septum thickness,

$$\text{distance} \equiv 2\ \eta\ (\Delta p/p) = 2\sqrt{\beta_h}\sqrt{\varepsilon_h/\pi} + \text{(septum thickness)}$$

where $2\ (\Delta p/p)$ is the momentum separation of the two beams, ε_h is the horizontal emittance, η and β_h are respectively the horizontal dispersion and the Courant-Snyder parameter of the main ring lattice. For given values of ε_h and the septum thickness, one must minimize the momentum separation. A "Figure of Merit" is

$$\text{F. M.} = \eta/(1.5 + 1.1\sqrt{\beta_h})$$

for $\varepsilon_h = 1.2\ \pi$ mm-mrad and the septum thickness = 3 mm. It was pointed out by Tom Collins that F. M. reaches its maximum value at A17 as one moves downstream from the injection point. This maximum value is more than two times the value at "MK90" so that the required momentum separation is less than half of what is needed in the design by Ruggiero if the kicker is placed at A17. A17 is a medium straight and the kicker can easily coexist with the extraction position-bump magnet at this location. There are two different ways to inject the beam in the momentum space. One is to use a kicker with a shutter so that the stacked beam is shielded from the kicker field. The other is to use full aperture kickers which kick both the injected and the stacked beams.[5]

1. <u>kicker with a shutter</u>[13]

The momentum separation of the injected and the stacked beams is $2\ (\Delta p/p)$ and the center of the injected beam is at $x = -44$ mm as before. The injection angle x' and the kicker angle $\theta(A17)$ are then determined from the relations

$$x' = 0.0304 - 0.2818\ (\Delta p/p),$$
$$\theta(A17) = 0.6781 - 0.4574\ (\Delta p/p)$$

where x' and θ are in mrad and $(\Delta p/p)$ is in percent. The beam size at A17 for $\varepsilon_h = 1.2\ \pi$ mm-mrad and the momentum spread of $\pm 0.08\%$ is ($\beta_h = 95.8$ m, $\eta = 5.55$ m)

$$2\sqrt{(1.2\text{x}95.8) + (0.8\text{x}5.55)^2}\ \text{mm} = 23.2\ \text{mm}$$

As an example, take the shutter thickness of 3 mm. One needs the momentum separation

$$2\ (\Delta p/p)\ \text{in}\ \% = (2.32 + 0.3)/5.55 = 0.472\ \ (\equiv \pm.236\%)$$

so that

$$x' = -0.0361 \text{ mrad (injection angle)}$$
$$\theta(A17) = 0.570 \text{ mrad } (B\ell = 169 \text{ G-m at 8 GeV})$$

The corresponding orbits are shown in Fig. 2. One can always make a local orbit bump A11-A13-A15-A17 with existing steering dipoles to shift the injected beam closer to the center of the magnet aperture. An example of this with a 2-cm bump is also shown in Fig. 2. The stacked beam orbit (2) and the closed orbit (0) for the injected beam will also be shifted by the same amount but they are omitted from the figure in order to avoid a possible confusion.

2. <u>full-aperture kickers</u>

It is possible to avoid the complication of a kicker with a shutter if kickers are installed at three places to make a local orbit bump. In the design given here, they are at F49, A13 and A19. The horizontal injection is done by a septum magnet at A17 where the beam separation is again 2.62 cm corresponding to the momentum separation of 0.472%. The center of the injected beam at the septum magnet is somewhat arbitrary but the septum should not contribute to the aperture limitation of the main ring. The design here assumes -44 mm (the same as at the Lambertson) with the septum thickness of 3 mm, leaving a 29 mm space from the septum wall to the central axis. Proper kick angles are

(F49) =	0.211 mrad	(stacked beam only)
(A13) =	-0.216 mrad	(both beams)
(A17) =	0.780 mrad	(injected beam only)
(A19) =	-0.356 mrad	(both beams)

and the injection angle at the Lambertson is $x' = +0.222$ mrad. Orbits are shown in Fig. 3 where broken lines (1A) and (2A) assume a local closed-orbit bump (-3 cm at A13 and -1 cm at A15) by steering dipoles.[14] The bump is necessary to suppress the large outward excursion of the injected beam orbit between A13 and A15.

A two-turn injection in the horizontal betatron space is also possible with the same three kickers. Kick angles are

	F49	A13	A19
first turn	-	.105 mr	.542 mr
second turn	-.263 mr	.187 mr	.494 mr

However, the injection angles at the Lambertson are quite different in two schemes, -.588 mrad for the betatron space stacking and +.222 mrad for the momentum space stacking, so that realignment of 8-GeV transport elements is necessary in switching from one to the other. Orbits shown in Fig. 4 assume a local closed-orbit bump from A13 to A19 (bump size = -3 cm at A15 and at A17).

Detailed considerations for the beam stacking by rf will be given in the next section. The most appealing feature of the two-turn injection in the momentum space as designed here is the relatively modest requirement for the main ring momentum aperture. One recent measurement indicated the total momentum aperture for ∿ 90% beam survival to be 0.48% which should be adequate for the present design.[15] Horizontal and vertical beam emittances would presumably be no larger than those of the single-turn beam and the general beam quality should be better compared to the betatron space stacking. There are no obvious reasons to expect a more difficult control of the spill but this must be confirmed by intentionally increasing the momentum spread of the present main ring beam. Because of the momentum dispersion, the beam will be wider horizontally so that the extraction loss may not necessarily be smaller compared to the loss with the two-turn injection in the betatron space. If the dispersion at the crossing point of the main ring-doubler colliding beam is designed to be vanishingly small, one would gain in the luminosity with this injection scheme.

Operating a kicker with a shutter is probably one of the most difficult task in the momentum space stacking. Ideally speaking, one must open the shutter, accelerate the beam to the stacking orbit, and close the shutter in one booster cycle (1/15 sec). Any amount of time exceeding this will add to the injection front porch time and, because of the lifetime of the 8-GeV beam, reduce the overall efficiency. The use of full-aperture kickers, the second design here, eliminates this problem but three kickers and one septum magnet are needed instead of just one kicker. The manipulation of the rf system is by no means a simple matter at Fermilab where there is no experience. It should be emphasized here that many important aspects of the manipulation can be tried without actually injecting the second turn. The main ring group has already initiated rf studies for this purpose. Since the momentum stacking of many turns in the doubler is essential for the main ring-doubler colliding beam, the experience gained from the studies should be extremely valuable.

The most serious problem that might make this scheme impractical is probably the large momentum spread of the beam at transition. For a given longitudinal phase space area of the beam, the rf voltage and the acceleration rate at the transition, one can evaluate the expected momentum spread. This is given in Appendix B. With the phase space area larger than ∿ 0.5 eV-sec, it is difficult to keep the momentum spread to less than 1% which corresponds to ∿ 6 cm horizontal beam size. Since the increase in the phase space area is mostly caused by the rf stacking, the momentum spread depends critically on the details of the rf gymnastics. The stacking efficiency for a small number of turns is not a well-established quantity and it is essential to carry out extensive rf studies using the present main ring beam together with the second turn beam simulated by empty rf buckets. The study should also establish the capability of the present correction sextupole system to control the chromaticity for ∿ 1% momentum spread near the transition energy. Should these exercises reveal serious problems, one would have to resort to other remedies like a transition jump by pulsed quadrupoles.

V. Stacking of the Beam by RF

One of the most important quantities in the beam stacking by rf is the longitudinal phase space area occupied by the beam. It is customary to take the coordinates $(\Delta E/\omega_{rf},\phi)$ and express the area of each rf bunch in units of eV-s. Here ΔE is the energy measured from the synchronous value, ω_{rf} is the rf angular frequency and ϕ is the phase deviation from the synchronous phase. The design value in the White Book[16] is 3.2 eV-s for 84 rf bunches in the booster at extraction which gives 0.038 eV-s for each rf bunch. However, this assumes a rather low linac current (67.5 mA), four turns of which are injected in the horizontal betatron space at 200 MeV. The present mode of booster operation is a single-turn, high linac current (up to 300 mA) injection and the phase space area of the beam at extraction is expected to be more than the design value. On the other hand, the design value includes a dilution factor 2 and the beam loss, which can be as much as 50%, between the injection and the extraction may reduce the momentum spread. The only recorded measurement of the beam area at 8 GeV was made with the intensity of 1×10^{13} per 13 booster batches[17] and it indicated the area to be $S_{beam} = 0.014$ eV-s. The momentum spread and the phase spread of the beam matched to a stationary rf bucket are shown in Fig. 5 as a function of the beam phase space area. The rf voltage at extraction is assumed to be 300 kV but the dependence is rather weak,

$$(\Delta p/p) \propto V^{1/4}, \ \phi \propto V^{-1/4}$$

The area of the stationary bucket is much larger than the beam area,

$$S_{bucket} = 1.31\sqrt{V_{rf}(\text{in MV})} \ \text{eV-s}$$

The high rf voltage at extraction (300-350 kV) is necessary for the main ring-booster rf phase lock to be effective. For the intensity of more than 2×10^{13} per 13 booster batches, which is now available for a two-turn injection, one does not really know what value of S_{beam} should be reasonable. The longitudinal beam instabilities observed in the booster would certainly affect the final value.

The first group of 13 booster batches is injected into the orbit which corresponds to $\Delta p/p = -0.236\%$. In order to keep the momentum spread of the injected beam to $\pm 0.08\%$ or less, the booster rf voltage at extraction must be lower than

$$350 \text{ kV if } S_{beam} = 0.03 \text{ eV-s},$$
$$195 \text{ kV} \qquad = 0.04 \text{ eV-s},$$
$$120 \text{ kV} \qquad = 0.05 \text{ eV-s}. \quad \text{(See Fig. 5)}$$

One clearly needs a better phase lock system[18] than the present one if $S_{beam} \gtrsim 0.035$ eV-s. The injected beam is captured by main ring stationary buckets just as in the present single-turn injection mode but it must now be accelerated to the stacking orbit before the second group comes in. If a kicker with a shutter is in use, the shutter must be open for this. Since the magnetic field is kept constant, the acceleration is done by changing the stationary buckets to accelerating (moving) buckets with a non-zero synchronous phase. The stacking orbit is at $\Delta p/p = 0.236\%$ so that the total energy increase is 41.7 MeV and the rf frequency swing is 2.04 kHz. Once the beam is at the stacking orbit, the rf voltage is turned off, the shutter is closed and the second group is injected. The first group will be completely debunched in a few ms but its momentum spread will depend on how the rf is turned off, abruptly or adiabatically. The second group is accelerated and released at the same stacking orbit as the first group and, finally, the entire beam must be recaptured and decelerated to the center of the momentum aperture before the normal acceleration begins.

The first parameter to be fixed is the main ring rf voltage of the stationary bucket during the injection and the acceleration to the stacking orbit. The voltage must be large enough to contain the injected beam comfortably in the bucket. The area of the stationary bucket in the main ring is, at 8 GeV,

$$S_{bucket} = 0.60\sqrt{V_{rf}\text{(in MV)}} \text{ eV-s}$$

and the corresponding momentum height of the bucket is

$$\pm(\Delta p/p)_{bucket} = \pm 2.81 \times 10^{-3} \sqrt{V_{rf}(\text{in MV})}$$

Another requirement is that the main ring bucket should be matched to the booster bucket at extraction, if possible, in order to prevent a possible dilution of the beam phase space area. The matched condition and the dilution factor for unmatched conditions are shown in Fig. 6. For example, if the booster voltage is 300 kV, the matched voltage in the main ring is 1.43 MV; if the main ring voltage is 1 MV, the dilution factor is 1.2, i.e., the phase space area of the beam will eventually be increased by 20%.

There is a conflicting requirement that the bucket area should be as small as possible in order to minimize the disturbance on the already stacked beam when the second group is moved to the same location. The disturbance appears as a shift of the center momentum of the first group by

$$(\Delta p/p)_{shift} = -5.97 \times 10^{-3}\ S_{bucket}(\text{in eV-s}).$$

The relation is obtained equating the bucket area to the area occupied by a completely debunched beam ($\phi = 2\pi$) with $(\Delta p/p)_{shift}$ as its total momentum spread. The effect is independent of whether the bucket contains a beam or not. If the rf is turned off abruptly at the stacking orbit, the beam momentum spread is equal to the final momentum height of the bucket and this should not be too large as the eventual beam phase space area is proportional to this momentum spread. The area and the momentum height of moving buckets are shown in Fig. 7 as a function of the synchronous phase angle. The energy gain per turn is eV sin ϕ_s which gives the time required to accelerate the beam from the injection orbit to the stacking orbit. One probably keeps the voltage fixed and shrink the bucket by gradually increasing the synchronous phase angle. The process should be long enough ($\sim$ several ms) to have $\sim$ one phase oscillation but the optimum way to change the synchronous phase must be found from studies.

There is at present a practical limit to lowering the voltage produced by eighteen rf cavities in the main ring. Below $\sim$ 360 kV, cavities may trip to protect some circuits. With modifications, this could be lowered to $\sim$ 200 kV. It is of course necessary to lower the booster voltage as well by an improvement in the phase lock system in order to take the full advantage of the reduced main ring voltage.

There are several factors that must be taken into account in calculating the final phase space area of the beam. Unfortunately, the precise values of these factors are not known too well. The moving bucket should tightly fit the beam such that its area is the same as the beam area. In reality, this is not possible and one may have to include some margin. When the second group of booster batches is stacked on top of the first group, the beam in the first group not only shifts in its center momentum but a long tail toward lower momenta develops in the particle distribution. An overall dilution factor due to this could be as much as $\sim$ 2. A detailed study of this effect by computer simulation is being planned by one of us (A. G. R.). A microwave instability[17] which can increase the momentum spread of the beam during debunching is another uncertain factor but it is hoped that this could be controlled by a proper tuning of the cavities. Furthermore, the phase space density of the beam for this case is expected to be approximately half or less of the beam density in Ref. 17. In general, any instability caused by space charge effects should be much smaller compared to the present single-turn injection.

The following example is meant to be a summary of the discussion rather than a real design. It is based partially on educated speculations but more on (wishful) expectations.

Phase Space Area of the Beam - 0.05 eV-s

Booster rf Voltage at Extraction - 100 kV

Bucket Area and Height - 0.41 eV-s and $\pm 1.94 \times 10^{-3}$

Momentum Spread of the Beam - $\pm 0.76 \times 10^{-3}$

Main Ring rf Voltage - 300 kV

Bucket Area and Height (stationary) - 0.33 eV-s and $\pm 1.54 \times 10^{-3}$

Dilution Factor due to Mismatch - 1.26

Phase Space Area of the Beam - 0.05 x 1.26 = 0.063 eV-s

Moving Bucket: Final Synchronous Phase - 38°

Final Bucket Area - 0.077 eV-s

Final Bucket Height - $\pm 0.74 \times 10^{-3}$

Frequency Swing - 2.038 kHz

Stacking Time (sin ϕ_s linear in time) - $\sim$ 10 ms

Beam Momentum Spread on the Stacking Orbit - $\pm 0.74 \times 10^{-3}$

Shift of the Central Momentum (first group) - -0.46×10^{-3}

Dilution Factor due to the Tail in the Momentum Spread - 1.75

Total Momentum Spread of the Beam After Two Turns - $\pm 1.70 \times 10^{-3}$

Central Value of the Momentum Spread - $+1.40 \times 10^{-3}$

Phase Space Area of the Debunched Beam* - 0.57 eV-s

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*On the stacking orbit, the rf voltage is turned off abruptly.

Final Capture and Shift to the Center of the Momentum Aperture

rf Voltage - 1.33 MV

Final Synchronous Phase - 5°

Frequency Swing - 604 Hz

Deceleration Time - $\sim$ 5 ms

Momentum spreads of the beam at each stage of the stacking are schematically shown in Fig. 8.

Appendix A. Calculation of Kicker Angles for the Two-Turn Injection Into the Betatron Phase Space

Teng[3] discussed the optimum utilization of the phase space when two turns are injected. In the following, the beam shape of both turns is assumed to be identical and matched to the main ring acceptance (Fig. 4c of Ref. 3). The minimum acceptance that can accommodate two turns is then four times the beam emittance. It should be noted that the Courant-Snyder parameter α_h is not zero ($\alpha_h = -1.25$) at the Lambertson. For computing the optimum kick angles for the second turn, this is important.

The center of the first group of booster pulses at the Lambertson is at $x_2 = -17$ mm when the second group is being injected. This is achieved by the kicker at F49 with the kick angle of -0.263 mrad,

$$\theta_2(\text{F49}) = -0.263 \text{ mrad (second turn)}$$

The corresponding angle x'_2 at the Lambertson is -0.311 mrad. The center of the injected beam is $x_1 = -44$ mm. One must adjust the injection angle x'_1 such that the quantity $\eta = x' + (\alpha/\beta)x$ (and not the angle x') is the same for the two beams. From $\eta = x'_2 + (-1.25/122)x_2 = -0.137$ mrad $= x'_1 + (-1.25/122)x_1$, the injection angle x'_1 is found to be -0.588 mrad and the injection line alignment is specified. Next, kick angles at "MK90" and A13 should be such that the central particle with $x = (-44 - 17)$mm/2 $= -30.5$ mm and $\eta = x' + (\alpha/\beta)x = -0.137$ mrad is properly on the closed orbit after A13. The angle x' of this particle is then -0.449 mrad and two conditions, one for the position and the other for the angle matching of the closed orbit, give

$$\theta_2(\text{"MK90"}) = 0.248 \text{ mrad,}$$
$$\theta_2(\text{A13}) = -0.315 \text{ mrad. (second turn)}$$

For the first-turn injection, the injected beam (x_1 = -44 mm, x'_1 = -0.588 mrad) should be on the closed orbit after A13. This is done by taking

$$\theta_1(\text{"MK90"}) = 0.273 \text{ mrad,}$$
$$\theta_1(\text{A13}) = -0.447 \text{ mrad. (first turn)}$$

The kicker at F49 is off during the first-turn injection.

In practice, the minimum phase space dilution factor 4 is never realized, even with a perfect injection, when one takes into account the septum thickness and the momentum dispersion of the injected beam.

Appendix B. Momentum Spread of the Beam at Transition

In the absence of space charge effects, a matched bunch at transition has the phase spread $\pm\theta_o$ and the momentum spread $\pm(\Delta p/p)_o$ where[19]

$$\theta_o = K_1 (h/\gamma_t)^{2/3} (\Delta T)^{1/6} (m_o c^2 \ eV_t \ \cos\phi_s)^{-1/3} \sqrt{c/R} \sqrt{S_b}$$

$$(\Delta p/p)_o = K_2 (h/cp_t)(c/R)(S_b/\theta_o),$$

$$K_1 = 2^{1/3} \ 3^{1/6} \ \pi^{-5/6} \ \Gamma\ (2/3) = 0.78928,$$

$$K_2 = 2/(\pi \sqrt{3}) = 0.36755.$$

For the main ring in its standard mode of operation,

h = 1,113 (harmonic number)

γ_t = 18.749 (transition gamma)

ΔT = 1.745 MeV (energy gain per turn at transition)

$m_o c^2$ = 938.28 MeV

c = 2.9979×10^8 m/s

R = 1,000 m

S_b = longitudinal phase space area of the beam in eV-s

p_t = 17.567 GeV/c (momentum at transition)

V_t = peak rf voltage at transition

ϕ_s = synchronous phase angle at transition

With these parameters,

$$\theta_o(\text{rad}) = 73.71(eV_t \cos \phi_s)^{-1/3}\sqrt{S_b},$$

$$(\Delta p/p)_o = 6.981 \times 10^{-3}(S_b/\theta_o)$$

If the energy gain per turn $\Delta T \equiv eV_t \sin \phi_s$ is kept fixed and $eV_t \cos \phi_s$ is reduced ($\phi_s \to 90°$), the phase spread θ_o increases indefinitely and the momentum spread goes to zero. However, this is not valid since these expressions are derived under the assumption that the phase spread θ_o is small compared to unity,

$$\sin(\theta_o + \phi_s) - \sin \phi_s \simeq \theta_o \cos \phi_s$$

If one assumes $\theta_o \lesssim 0.5$ as a necessary condition,

$$(\Delta p/p)_o > 1.4(S_b)\%$$

For example, the momentum spread is more than ±0.7% for $S_b = 0.5$ eV-s. On the other hand, it is not clear if one should not be able to reduce the momentum spread by taking a larger value of θ_o. There is no analytical solution when terms of the order θ_o^2 or higher are taken into account. Numerical simulations seem to be the only way to find this out.

References and Footnotes

1. For a general review of the transition jump, see A. Sørenssen, Particle Accelerators, 6, p. 141 (1975).

2. A. G. Ruggiero, TM-498, June 11, 1974.

3. L. C. Teng, TM-644, February 16, 1976. For a more general discussion of the two-turn injection, see L. C. Teng, FN-104, October 10, 1967.

4. R. Stiening has not written any report on his findings. The phenomenon seems to exist not only in the main ring but in the CERN SPS as well. See SPS Commissioning Reports No. 14 (revised), 4 August 1976 and No. 28, 9 November 1976. Although one can "explain" the phenomenon in a hand-waving manner, there has never been any systematic treatment of this problem.

5. L. C. Teng, TM-644-A, March 8, 1976.

6. S. Pruss and F. Turkot, EXP-76 (10/25/76) and EXP-77 (10/25/76).

7. One may take a cavalier attitude here and just proceed ignoring all these problems. Arguments for or against this approach are clearly outside the scope of technical reports.

8. T. Toohig, TM-632, December 5, 1975.

9. J. McCarthy, private communications.

10. H. Pfeffer, S. Pruss, and F. Turkot, private communications.

11. D. A. Edwards and R. Stiening, EXP-27 (11/8/72).

12. S. Pruss and F. Turkot, EXP-78 (11/1/76) and EXP-79 (11/10/76).

13. This is based on the idea proposed by Stan Pruss.

14. In Figs. 1-4, orbit positions are accurately shown but angles are often deceptive. For example, in Fig. 3, the kick at A19 looks different for two beams in spite of the fact that the kicker is shared by both.

15. F. Turkot, private communications. The aperture can be increased to 0.56% if the electrostatic septa (ES40, 41) for extraction are turned off

during injection. The septum voltage usually starts at 40-60 kV and reaches the maximum value of ∿ 90 kV at the flattop. This procedure is necessary for avoiding possible damages to septum wires. The effect of the septum voltage on the tune of the injected beam has been investigated by B. Prichard, EXP-73 (3/27/75).

16. Design Report, National Accelelerator Laboratory (July, 1968), p. A-8.

17. E. J. N. Wilson, EXP-74 (6/6/75). The longitudinal coordinates used in this note (p. 5) are $(\Delta p/m_o c, \phi)$ instead of $(\Delta E/\dot{\omega}_{rf}, \phi)$. The conversion factor for the main ring at 8 GeV is 2.812 eV-s/radians and 0.005 radians correspond to 0.014 eV-s.

18. The main ring-booster phase lock starts at ∿ 1 ms before extraction. If the rf voltage is low, the synchrotron frequency is low and the information needed for the phase lock may not be obtained accurately. Quentin Kerns has been advocating a phase lock system which will start long before the extraction time.

19. These expressions are taken from E. D. Courant, FN-187, May 20, 1969. Some people use an expression for $(\Delta p/p)_o$ with $K_2 = 1/\pi$ instead of $2/(\pi\sqrt{3})$.

Table 1. 8-GeV Line: From MH-40/41 to MK90

Original Design Specification

The line comes down at 1.310 mr

1. MH40/41 (left bend) 104.84 mr

   Each unit 1.524 m long, distance between two units 0.2032 m.

2. drift 3.3678 m

3. MQ44 (horizontal focus) 1.31953 m

4. drift 0.2032 m

5. MQ45 (horizontal focus) 1.31953 m

6. drift 2.269 m

7. MQ46 (vertical focus) 1.31953 m

8. drift 26.541 m

9. MH50 (right bend) 24.338 mr. The line is on the MR-LS (1.524 m).

10. drift 1.7878 m

11. MQ50 (horizontal focus) 1.31953 m

12. drift 0.4032 m

13. MQ51 (vertical focus) 1.31953 m

14. drift 1.5451 m

15. MV60 (bend down) 31.496 mr, 1.524 m

16. drift 8.5513 m

17. MV61 (bend up) 22.352 mr, 1.524 m

18. drift 6.4142 m

19. MP70 (bend up), pulsed. 10.160 mr, 1.524 m

20. drift 33.1802 m; end of the long stright.

21. main ring QF (horizontal focus) 2.1336 m

Table 1 (Cont'd.)

22. drift 0.271018 m
23. QF' 1.31953 m. Station A11 is at 6" from this quadrupole.
24. drift 1.77292 m
25. QD' 1.31953 m
26. drift 0.346202 m
27. QD' 1.31953 m
28. drift 1.4611 m. MK90 (two kickers) here.
    Nominal kick angle 0.294 mr up.

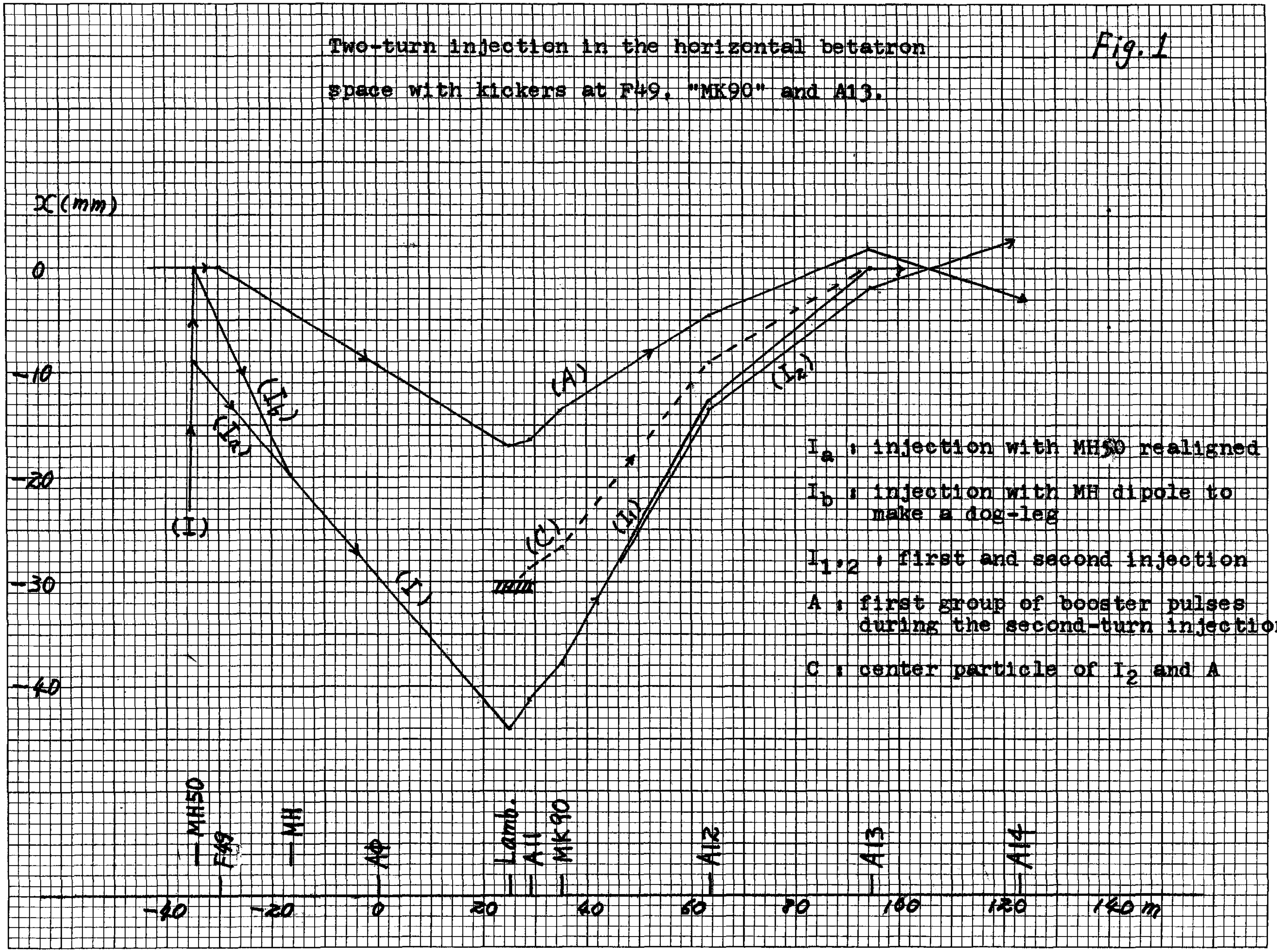


Fig. 1 Two-turn injection in the horizontal betatron space with kickers at F49, "MK90" and A13.

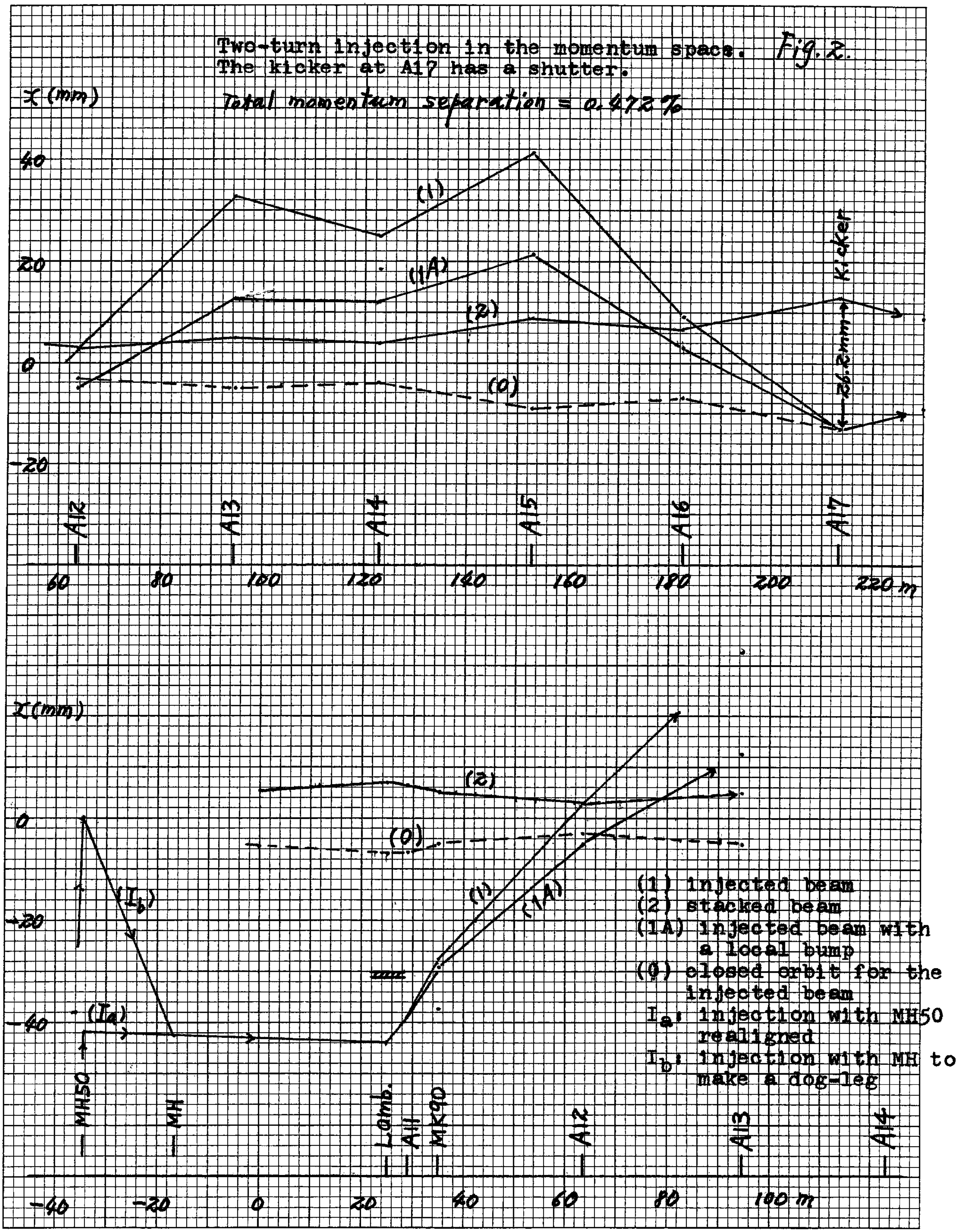

Two-turn injection in the momentum space.
The kicker at A17 has a shutter.
Fig. 2.
x (mm)
Total momentum separation = 0.472 %
(1)
(1A)
(2)
(0)
Kicker
26.2 mm
A12
A13
A14
A15
A16
A17
60
80
100
120
140
160
180
200
220 m
40
20
0
-20
x (mm)
(2)
(0)
(1)
(1A)
(Ib)
(Ia)
-40
MH50
MH
Lamb.
A11
MK90
A12
A13
A14
-40
-20
0
20
40
60
80
100 m
(1) injected beam
(2) stacked beam
(1A) injected beam with a local bump
(0) closed orbit for the injected beam
Ia: injection with MH50 realigned
Ib: injection with MH to make a dog-leg

Fig. 3 Two-turn injection in the momentum space
Injected beam kicked at A13, A17 and A19
Stacked beam kicked at F49, A13 and A19

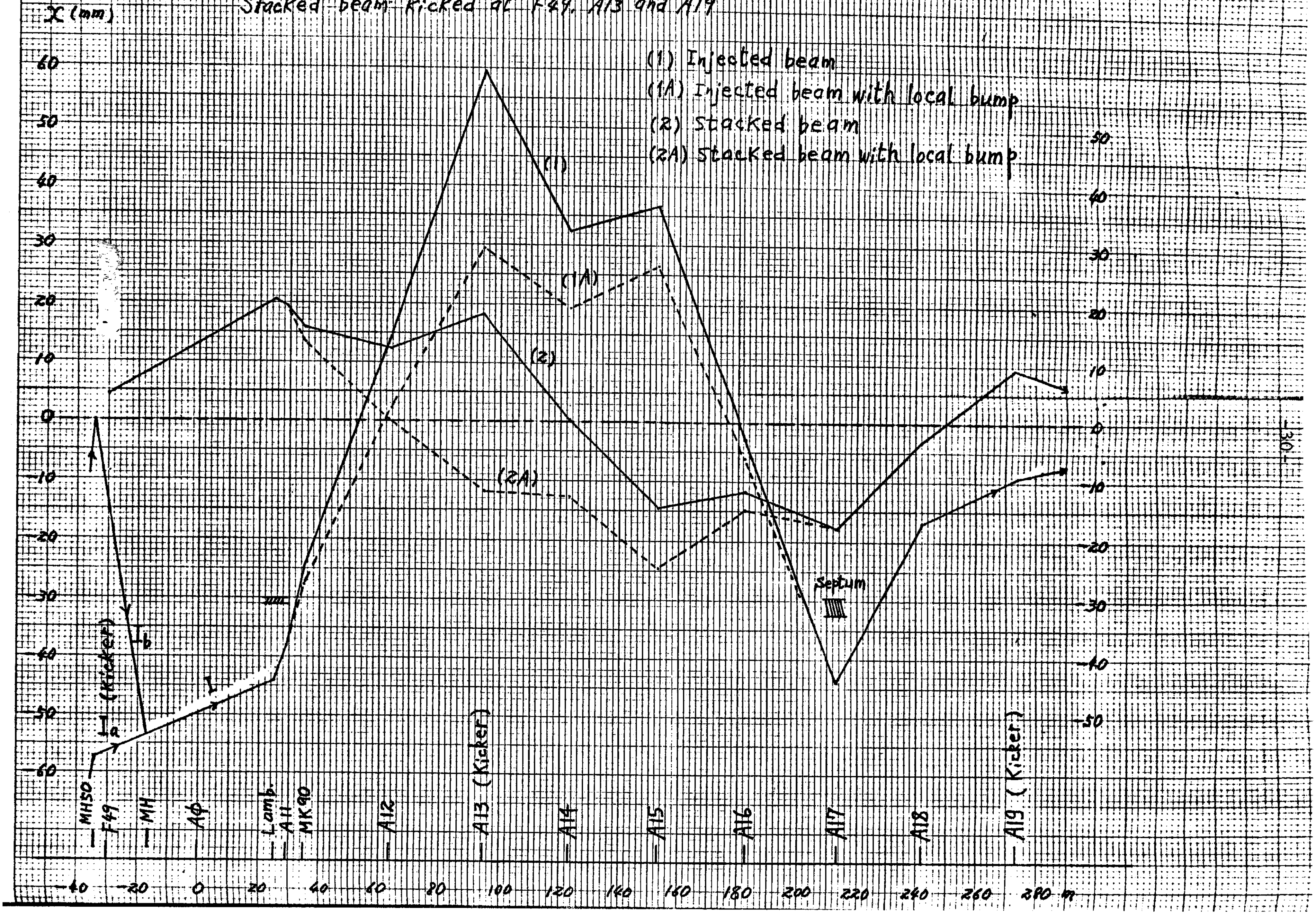
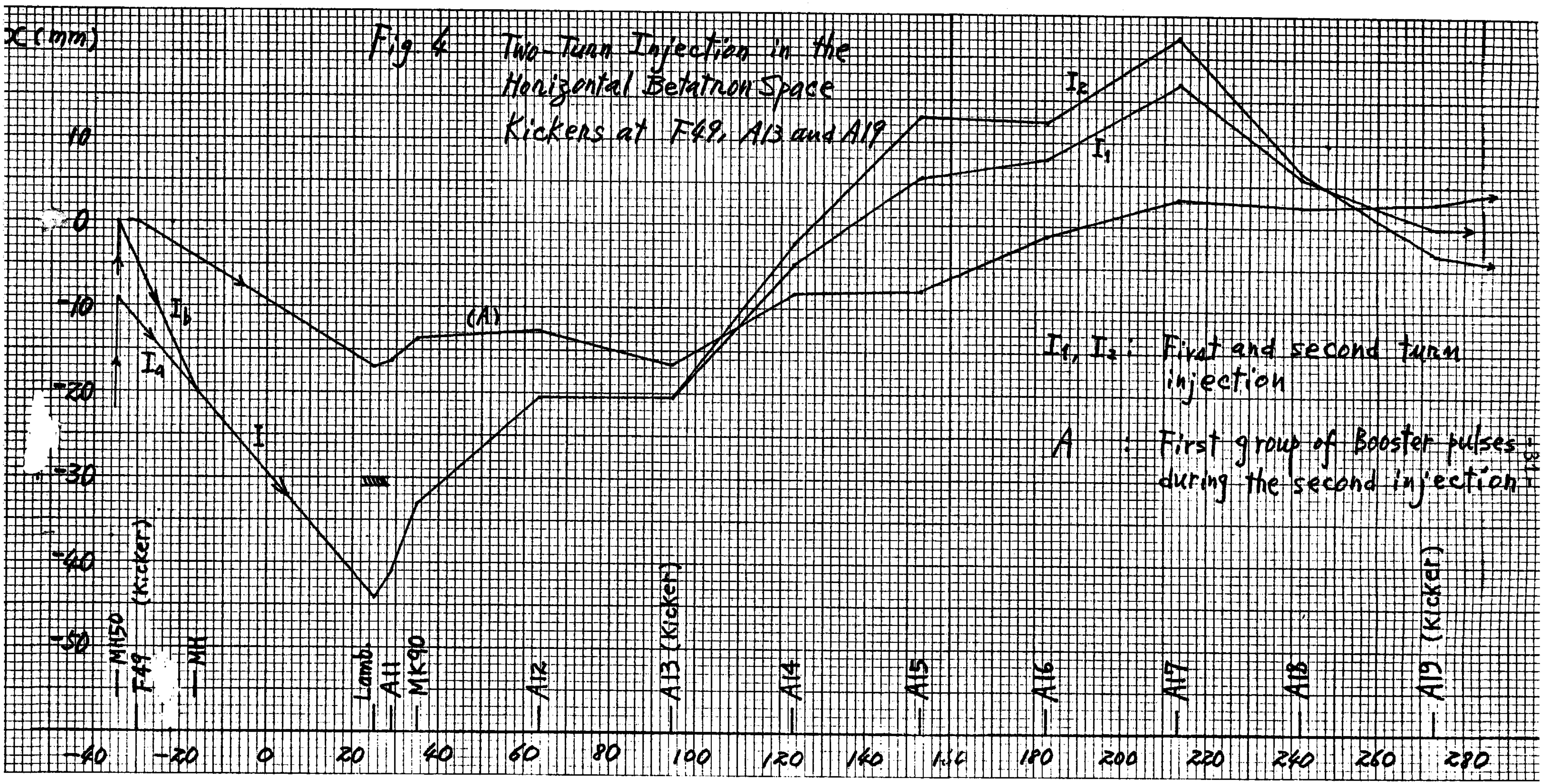


Fig. 4 Two-Turn Injection in the Horizontal Betatron Space Kickers at F49, A13 and A19



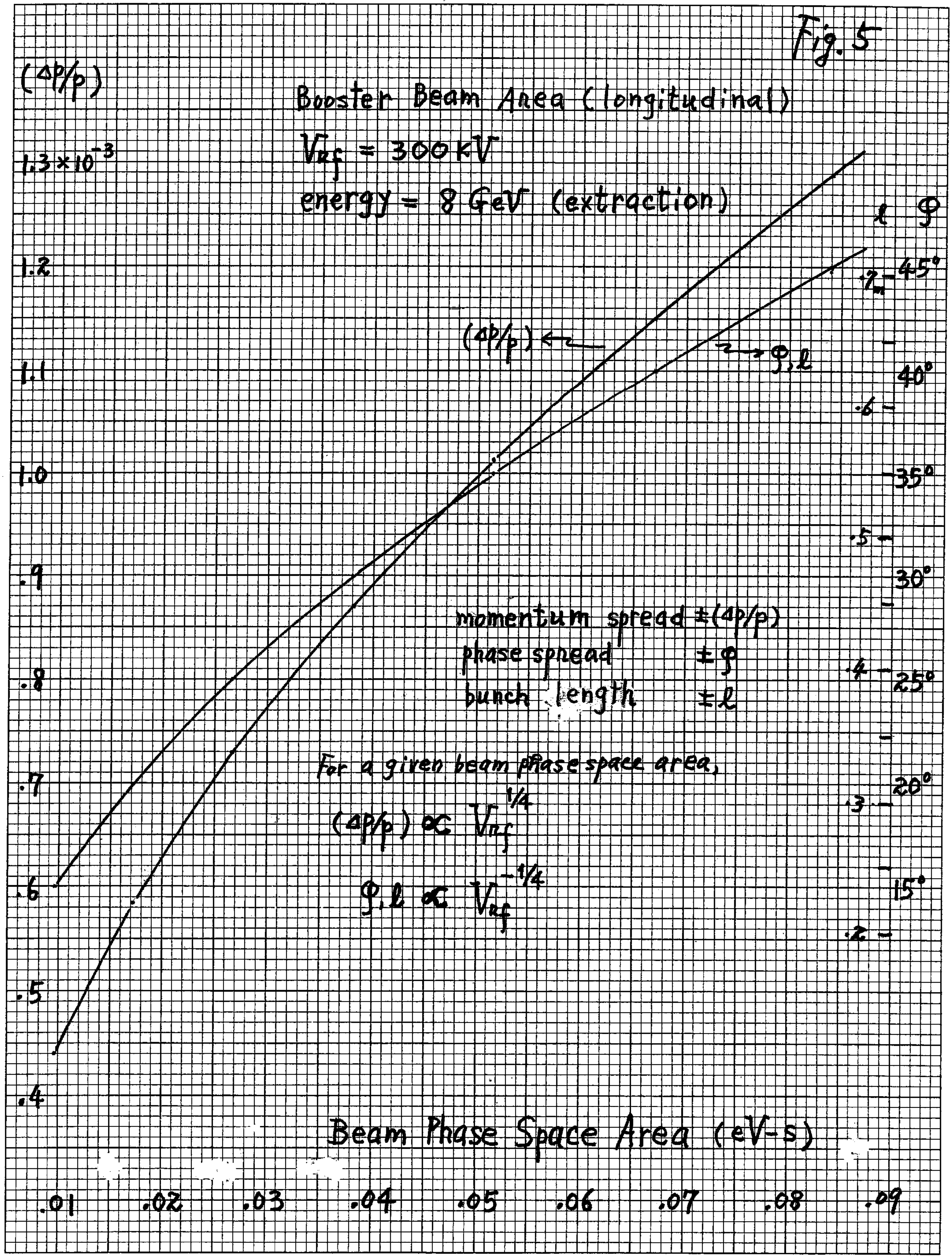


Fig. 5
Booster Beam Area (longitudinal)
Vrf = 300 kV
energy = 8 GeV (extraction)
(Δp/p)
1.3×10^-3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
l φ
.7 45°
40°
.6
35°
.5
30°
.4 25°
20°
.3
15°
.2
(Δp/p) ←
→ φ, l
momentum spread ±(Δp/p)
phase spread ±φ
bunch length ±l
For a given beam phase space area,
(Δp/p) ∝ Vrf^1/4
φ, l ∝ Vrf^-1/4
Beam Phase Space Area (eV-s)
.01
.02
.03
.04
.05
.06
.07
.08
.09

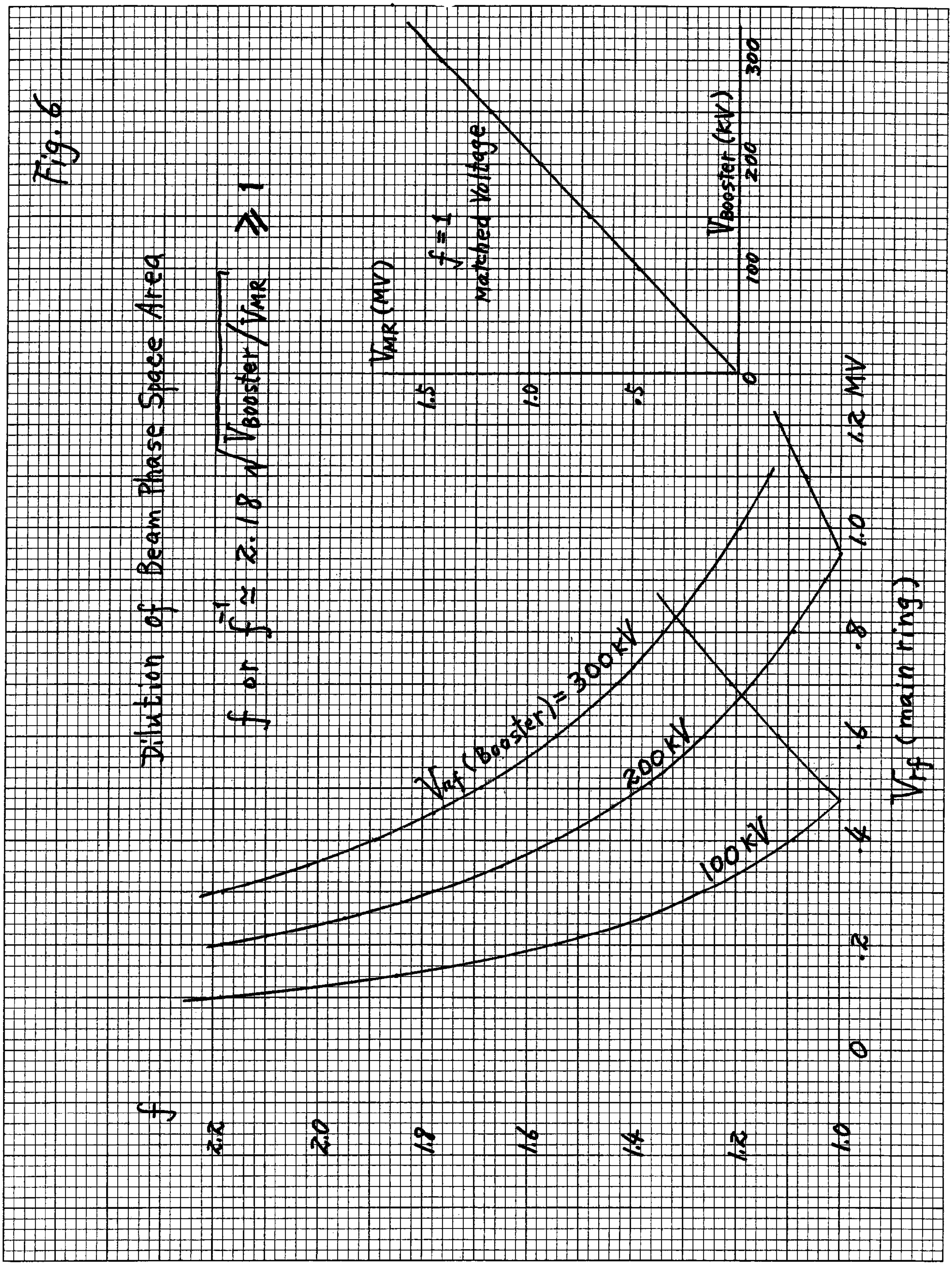


Fig. 6
Dilution of Beam Phase Space Area
f or f⁻¹ ≃ 2.18 √(V_Booster / V_MR) ≥ 1
f
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
.2
.4
.6
.8
1.0
1.2 MV
V_rf (main ring)
V_rf (Booster) = 300 KV
200 KV
100 KV
V_MR (MV)
1.5
1.0
.5
0
100
200
300
V_Booster (kV)
f = 1
matched Voltage

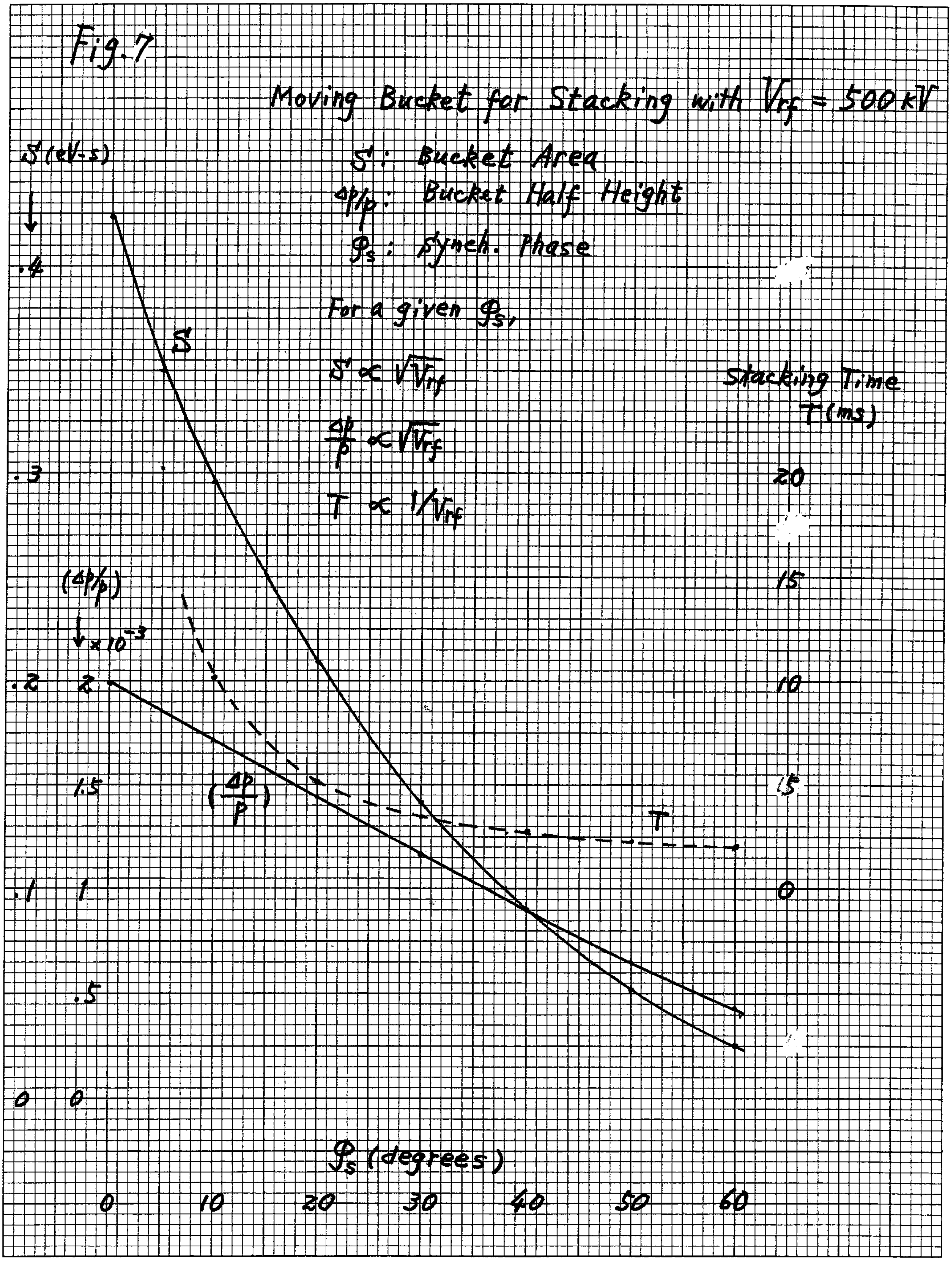


Fig. 7
Moving Bucket for Stacking with V_{rf} = 500 kV
S : Bucket Area
Δp/p : Bucket Half Height
φ_s : Synch. Phase
For a given φ_s,
$S \propto \sqrt{V_{rf}}$
$\frac{\Delta p}{p} \propto \sqrt{V_{rf}}$
$T \propto 1/\sqrt{V_{rf}}$
S (eV-s)
(Δp/p) × 10^{-3}
Stacking Time T (ms)
S
(Δp/p)
T
φ_s (degrees)
0
10
20
30
40
50
60
.4
.3
.2
.1
0
2
1.5
1
.5
0
20
15
10
5
0

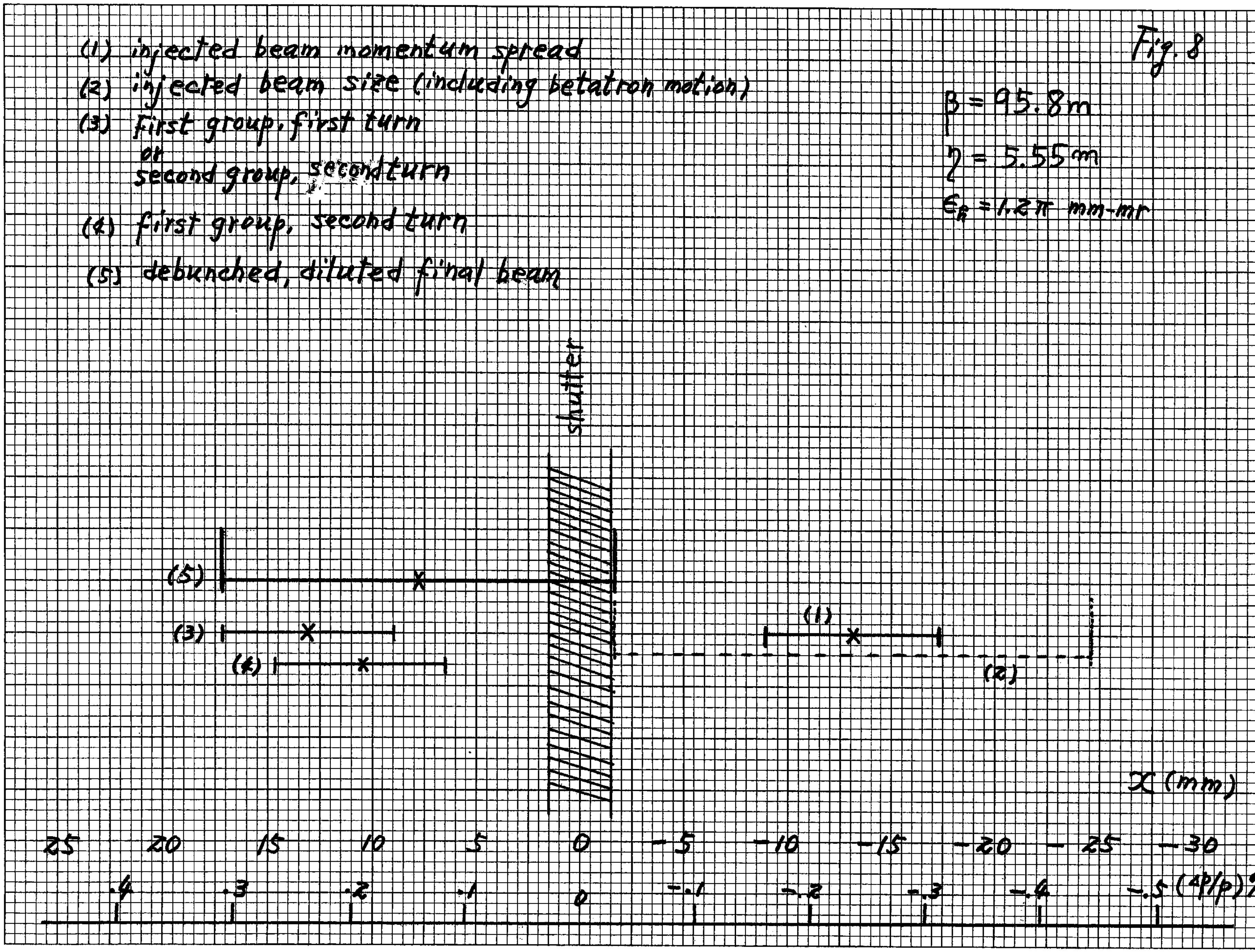


Fig. 8
(1) injected beam momentum spread
(2) injected beam size (including betatron motion)
(3) first group, first turn
or
second group, second turn
(4) first group, second turn
(5) debunched, diluted final beam
β = 95.8 m
η = 5.55 m
ε_h = 1.2π mm-mr
shutter
(1)
(2)
(3)
(4)
(5)
X (mm)
25 20 15 10 5 0 −5 −10 −15 −20 −25 −30
.4 .3 .2 .1 0 −.1 −.2 −.3 −.4 −.5
(Δp/p)%