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Beam Transfer - Normal and Reverse Directions

The beam transfer system from the main ring to the doubler has been worked out previously by L. Teng (Fermilab Tev Program, April 1977). T. Collins and H. Edwards have studied the same problem also showing that there are no essential difficulties in achieving a clean beam transfer, at least in the normal direction. The system presented in this note is an extension of these works. There are several uncertainties which make it impossible to design the system in a definitive manner at present. The doubler lattice used here is the one by T. Collins (TM-797, June 7, 1978; D. Johnson, UPC No. 21) without any special insertions like high-beta or low-beta. Recently, a new lattice with shorter dipoles has been proposed by T. Collins. This will undoubtedly change the design of many machine functions including the beam transfer. The allocation of long straight sections for various machine functions is still being discussed and the final arrangement will certainly modify the design. For the $p\bar{p}$ colliding mode of operation, the number of transfered bunches will be substantially less than the normal one of $\sim$1,000 and the intensity of each bunch may be an order of magnitude higher than the normal value. It is quite possible that their influence on the injection timing and the beam characteristics may require certain changes in the design.

I. Beam Characteristics

A. Injection Energy

The doubler beam line is 25.50" ($\sim$65 cm) below the main ring beam line and the beam must be brought down in less than 50 m distance (the length of a long straight). The upper limit of the momentum is then decided by the integrated bend field of septum magnets and the kicker strength. The lower limit, on the other hand, is dictated by the field quality of doubler magnets. Measurements clearly indicate a rather poor field quality at the excitation current of 200A (47 GeV/c). Beyond 1,000A (236 GeV/c), the field quality is essentially independent of the current. It is assumed here that the transfer momentum is 150 GeV/c which corresponds to 635A. More careful designs of septum magnets and kickers may show a possibility of using a higher momentum value.

Below 1,000A, the magnetic field is modified by hysteretic magnetization which is produced by the induced current in superconducting filaments. The resulting field distortion in dipole magnets is mostly sextupole field and its magnitude depends strongly on the field ramp. For the measurement of multipole components, the excitation current is usually raised up to 4,000A and then reduced to zero. In the actual operation of the doubler, the lowest current of the ramp should be chosen such that the field at beam transfer is the same as the measured one. This is now being investigated by the magnet measurement group.

B. <u>Longitudinal Emittance</u>

The latest measurement by H. Miller (EXP-87, March 21, 1978) at 125 GeV/c gives 0.37 eV-s (90% of the beam, bunch spreader off) when the beam intensity is 1.9×10^{13}. There are reasons to believe that this value could be reduced by improvements in the main ring injection phase lock and in the transition crossings in the booster as well as in the main ring. The value used here is 0.25 eV-s. The phase and the momentum spreads of the beam in the main ring are shown in Fig. 1 for various stationary rf voltage values. At $\sim$1 MV/turn, the beam injected into the doubler is expected to have a momentum spread of less than $\pm0.25\times10^{-3}$. The contribution to the beam size due to the dispersion is then less than ±1 mm near long straight sections. When the beam is transfered to accelerating rf buckets of the doubler (50 GeV/s, synchronous angle = 133°), there will be a mismatch and the momentum spread of the circulating beam increases to $\pm0.33\times10^{-3}$ or more depending on the main ring rf voltage at the time of transfer. (See Fig. 2.) Any error in the phase lock system will contribute to a further increase in the momentum spread and in the emittance. It is desirable to limit the error to within $\pm5^{\circ}$.

If the beam is transfered into stationary rf buckets with constant magnetic field, there will be no mismatch and the momentum spread of the beam may be reduced by reducing the rf voltage. There may be a limit to the minimum value of momentum spread one can achieve; too small values might induce microwave instabilities.

C. Transverse Emittance

For a single-turn injection of H^+ to the booster, the emittance measured in the 8-GeV transport line is $(1.0 \sim 1.2)\pi$ mm-mr. If there are no dilutions caused by mismatching or nonlinear fields, the emittance at 150 GeV/c will be 0.7π mm-mr. As a more realistic value, 0.15π mm-mr is used for the design. There are as yet no reliable data for the case of multi-turn H^- injection into the booster. General "feeling", not supported by any hard evidence, is that the emittance is the same or slightly larger.

II. Apertures

The doubler beam line is radially away from the main ring line by 10 mm, this for the possibility of 200 GeV x 1,000 GeV pp colliding experiments. As a consequence, the main ring beam must have a momentum offset of +0.35% during the beam transfer which is near the limit of the main ring momentum aperture. The septum magnets should not be too close to the beam axis, although how much space is comfortable for the main ring injection is a point for which one can argue in many different ways. In the present design, the kicker in the main ring for the normal transfer is placed at station #48 immediately upstream of the septum magnet in order to prevent a large beam excursion at that point. It is even more difficult to decide on the safe limit of the beam excursion in the doubler. H. Edwards suggests ±20 mm for the circulating beam and ±28 mm for the single-passage beam between the septum magnet and the final kicker. These values are based on the field quality of doubler dipoles. For quadrupoles, the available data are not yet usable for this purpose but the design given here assumes ±30 mm. It is very important to establish the clear aperture of the beam in the future design.

III. Simple Description of the System

One important restriction in the design of the transfer system is the limited choice of the kicker location in the doubler. Kickers must be placed only at "warm" places which are stations #17 and #48. In the main ring, all stations are available in principle except where there are already major devices (for example, extraction quadrupoles and bump dipoles). Except at #48 and #17 where one and two dipoles are missing, respectively, the available space for a kicker or a bump magnet is not much more than one meter. Long straights A (present injection and extraction) and F (main ring rf stations) are obviously not available for the beam transfer. Since there will be at least one colliding area and one beam abort area, there are only two remaining long straights to install the transfer system. Normal and reverse transfers could be at the same long straight or at two different places, the choice being dictated by other considerations which are too numerous to even list here. One feature which is a special advantage is that there is no need to reshape the beam in the transverse phase space with quadrupoles. The doubler lattice is identical to the main ring lattice as far as the focusing characteristics are concerned.

Vertically, the system is a simple dogleg with two Lambertson magnets which are most likely pulsed. In order to ease the problem in the radial direction, the one near station #49 is $\sim$10 m away (the center position) from the upstream quadrupole while the other one is close to the downstream quadrupole. The center-to-center distance of two Lambertsons is approximately 37 m.

Radial positions of the beam center are shown in Fig. 3 for the normal direction transfer and in Fig. 4 for the reverse direction. For the normal direction, the closed orbit is a combination of the natural closed orbit of $\Delta p/p = +0.35\%$ and a local bump between #46 and #17. The bump is not completely local but the maximum perturbation outside is less than 3 mm. The beam is kicked outward by the kicker at #48 and this produces a separation of 15 mm at the septum magnet. The beam size there is $\pm$3mm(H)x $\pm$4mm(V). There is a three-magnet bump (#48, #11, #13) in the doubler giving again a separation of 15 mm between the injected beam and the circulating beam. The beam size at the second Lambertson is ±4mmx ±3mm. The final kicker is at #17 so that there are some radial excursions of the beam between the Lambertson and the kicker. It might be necessary to introduce another small local orbit bump (#13, #15, #17) if the excursion of 20 mm at #15 is too large.

For the reverse direction, the main ring kicker is at #13 and the doubler kicker at #48. The latter is rather strong, $B\ell = 2.68$ kG-m. All Lambertsons are rotated by some amount to make radial kicks as well as the main vertical bends. Admittedly, this is not a very attractive feature. Specifications for various elements are given in Appendix.

IV. Layout of the System

So far, two schemes have been proposed, one by L. Teng (UPC No. 18) and the other by T. Collins. These are shown in Figs. 5 and 6, respectively. In both cases, the normal and the reverse transfers are at two different locations. This arrangement is convenient for placing two or more steering dipoles between Lambertsons. In Layout II, four doubler rf cavities can be placed in LS-C together with these steering magnets. The beam dump must be removed from the present location, LS-D, to LS-E for Layout II. If this is done, all elements needed in the main ring for beam transfer can be installed without removing any major items which now exist. For Layout I, all needed spaces are clear at present. Bump magnets in the main ring can be similar to the vernier dipole 4-4-30 with the length shortened to ∿20" instead of the present 41.5" (coil-to-coil). In Layout II, the presently available kicker at C48 can be used for the normal transfer. With the vertical gap of 1.5", aborted beams as specified by F. Turkot (UPC No. 20) can easily clear the kickers in the doubler.

V. Miscellaneous Comments

1) Steering in both radial and vertical directions must be

provided. In the radial direction, local bumps in the main ring and in the doubler can be used with a proper ratio to obtain a position-only or an angle-only change. It is easy to introduce a vertical local bump in the doubler, #47 - #11 - #14 for the normal transfer and #47 - #49 - #12 for the reverse transfer. The latter produces an almost pure position change, -0.0014 mr for 1 mm change. The corresponding figure for the other bump is -0.015 mr for 1 mm. One probably needs vertical steering magnets between two Lambertsons to make an orthogonal set together with these orbit bumps. From the available vertical space, one sees that there is enough space to install four steering dipoles of the type vernier 4-4-30. Each of them can produce a 0.8 mr kick at 150 GeV/c.

2) According to J. McCarthy who is designing kickers for the beam transfer, the flatness of the kick field during 20 microsec is $\sim$2% with ripples of 1 to 2 MHz. In addition, because of the rise time (400 ns) of the kicker in the main ring, bunches at the beginning of the pulse may get as much as 10% less kick compared to other bunches. In order to avoid this, it is necessary to have a gap of at least 600 ns. The initially planned operation with twelve (instead of thirteen) booster batches will be very comfortable with a gap of more than 1 microsec. The same problem exists in the doubler where the fall time of the kicker (400 ns) will again affect the leading edge of the pulse when it comes back to the kicker. The magnitude of this is again approximately 10%. The injection error from the ripple alone will cause the coherent oscillation of the following amplitude:

normal injection	±0.9 mm at the maximum beta positions
reverse injection	±1.3 mm at the maximum beta position

This must be damped by fast dampers like the one we have in the main ring. How fast this should be damped before the beam gets smeared in the phase space depends very much on the tune spread within each bunch. With the chromaticity correcting sextupoles, we should be able to limit this to 0.002 or less. One thousand oscillations will probably smear the coherent oscillation and the damage will be done by then. One must damp the oscillation within ∿ 50 revolutions or less. The 10% effects coming from the rise and fall time will be difficult to control by fast dampers. For the normal operation of the doubler as a fixed-target accelerator, one may avoid the effects by sacrificing twenty or so bunches. For $p\bar{p}$ mode of operation, depending on the detailed structure of the bunch arrangement, one may have to try something more elaborate and more expensive.

3) Since the entire system is confined to a relatively short distance, any perturbation in the phase advance should not affect the overall performance. For example, if a low-beta insertion is introduced for the colliding and if, for some reason, it is necessary to inject with the insertion in existence from the beginning, the phase advance in a sector may change 30 to 40 degrees. It is then easy to readjust local orbit bumps to compensate for this.

4) T. Collins suggested that, for $p\bar{p}$ mode, the reverse $\bar{p}$ transfer should be done before the normal p transfer. The position of the kicker at #17 for the normal transfer favors this order.

VI. Momentum Stacking

The usefulness of the doubler for fixed-target experiments will be enhanced significantly if the intensity can be increased to 10^{14} level. With the single-turn beam transfer, the intensity is of course never more than the main ring intensity and, realistically speaking, it will be less than $\sim 4\times10^{13}$ for a long time to come. Besides, the beam quality (longitudinal and transverse phase space area) certainly deteriorates as the intensity is increased. This may make a clean beam transfer very difficult. It would be much better if one could transfer ten turns of 1×10^{13} each and the momentum stacking seems to be the only method for this. The momentum stacking in the doubler has been discussed most recently by A. G. Ruggiero (TM-727, April 1977). The kicker position #17 is fortunate in that the momentum dispersion function is large (5.8 m) at this place. Since one must avoid a beam loss of even a very small amount, it is essential that the dispersion at the kicker position is as large as possible.

T. Collins suggested a high-dispersion insertion (UPC No. 23) which raised the dispersion at #17 to almost 10 m. It requires certain excitations of trim quadrupoles from stations #11 to #26. The largest excitation is at #11 where $B'\ell$ is 55 kG. This is slightly more than the design value of 52 kG for trim quadrupoles. Since almost all trim quadrupoles will be excited to some level for tune adjustment, it is not immediately obvious that there will be enough strength left for the high-dispersion insertion at all locations. The simultaneous correction of the injected and the stacked beam is another problem one must seriously consider. Nevertheless, it seems possible to think about the momentum stacking and a trial design is shown in Fig. 7. The space available for the kicker with field shielding is nominally 17 mm but there will be long tail in the stacked beam and this value is not excessive. If one assumes a bucket area of 4 eV-s, the acceleration may be rather slow. For example, with 1.55 MV/turn, the synchronous phase angle is only 7^{o} and it takes $\sim$90 seconds to accelerate the beam from 150 GeV/c to 1,000 GeV/c.

Appendix: Magnets and Kickers for Beam Transfer

beam momentum = 150 GeV/c, momentum offset = +0.35%

phase space area of the beam: longitudinal 0.25 eV-s
transverse 0.15π mm-mr

A. normal direction (See Fig. 3)

1. main ring
   a) bump magnets
      #46 1.4 m from quadrupole (β_H= 90.5 m)
      #17 10 m from quadrupole (β_H=65.6 m)
      $B\ell$=±1.02 kG-m
   b) kicker
      #48 3 m from quadrupole (β_H=99.7 m), $B\ell$=1.85 kG-m
   c) Lambertson
      center position at 10 m from quadrupole (β_H=55.5 m)
      septum angle = 40^o
      $B\ell$= 8 m x 10.8 kG, rotated by 1.93^o

2. doubler (radially out from main ring by 10 mm)
   a) bump magnets: (#48, #11, #13), $B\ell$=+0.7 & -0.36 kG-m
   b) kicker #17 4 m from quadrupole (β_H=83.8 m)
      $B\ell$=1.23 kG-m
   c) Lambertson
      end of long straight (β_H=106 m at the center)
      $B\ell$= 8 m x 10.8 kG, rotated by 0.39^o

B. reverse direction (See Fig. 4)

1. main ring
   a) bump magnets: #46 & #17, $B\ell$=±0.72 kG-m
   b) kicker: #13 (β_H=90.2 m), $B\ell$=0.744 kG-m
   c) Lambertson
      end of long straight (β_H=114 m at the center)
      $B\ell$= 8 m x 10.8 kG, rotated by 1.10^o

2. doubler

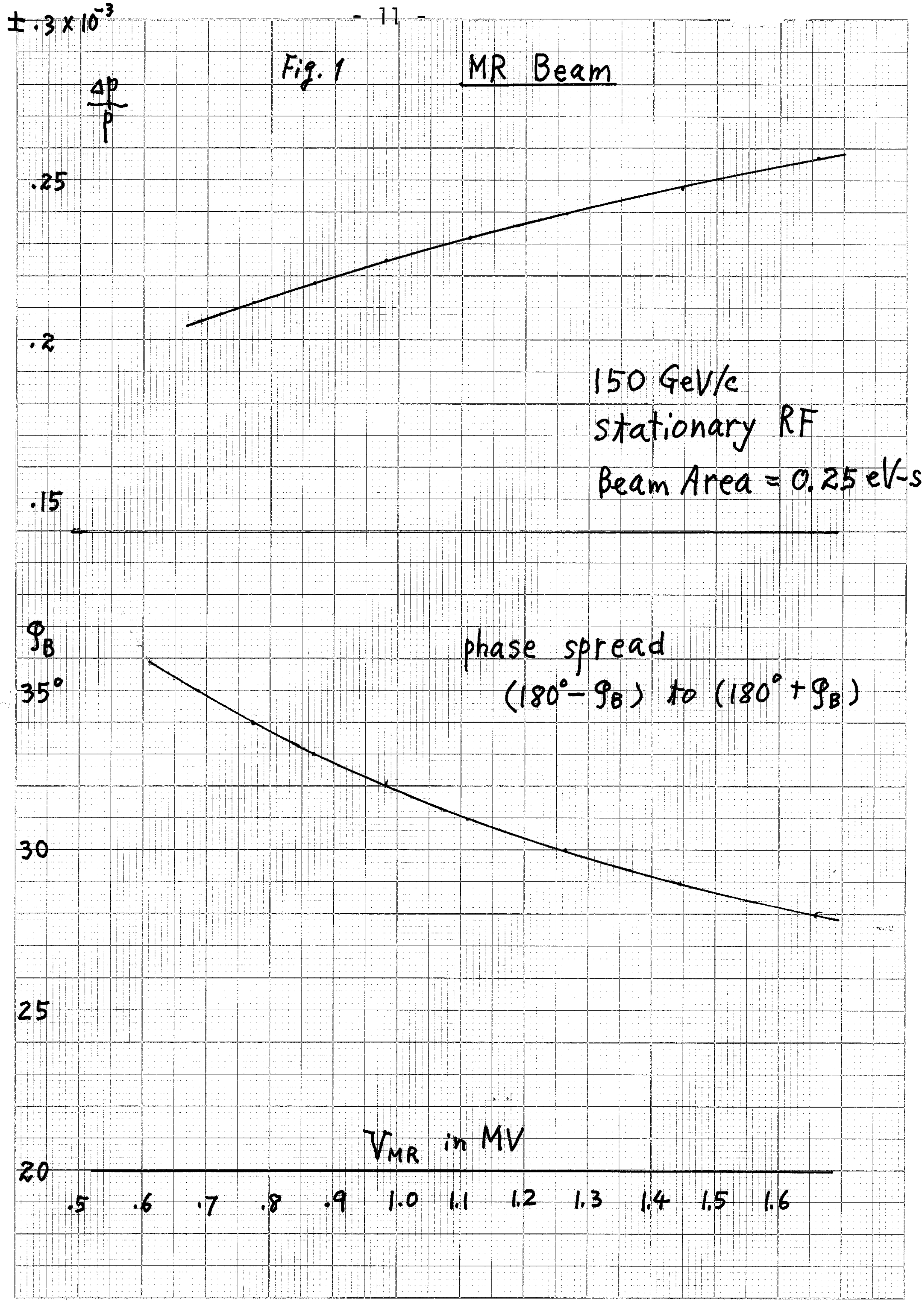
a) bump magnets: (#46, #48, #11), $B\ell$=+0.89 & -0.60 kG-m

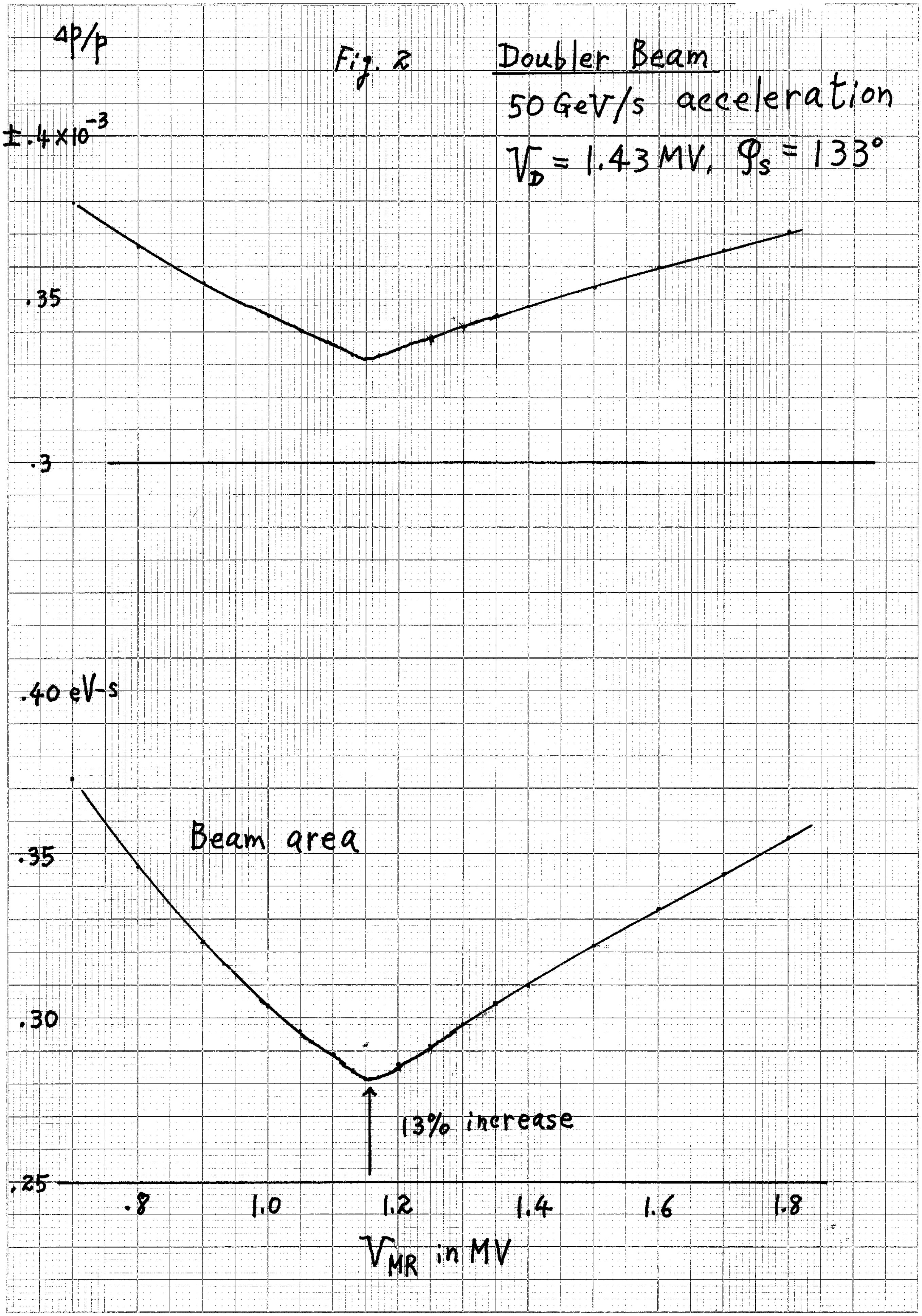
b) kicker: #48 (β_H=95.0 m), $B\ell$=2.68 kG-m

c) Lambertson

center position at 9.8 m from quadrupole

$B\ell$= 8 m x 10.8 kG, rotated by 2.17^o


±.3×10^-3
Fig. 1
MR Beam
Δp/p
.25
.2
.15
150 GeV/c
stationary RF
Beam Area = 0.25 eV-s
φB
35°
30
25
20
phase spread
(180° − φB) to (180° + φB)
VMR in MV
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6


Δp/p
Fig. 2
Doubler Beam
50 GeV/s acceleration
V_D = 1.43 MV, φ_s = 133°
±.4×10⁻³
.35
.3
.40 eV-s
Beam area
.35
.30
.25
13% increase
.8
1.0
1.2
1.4
1.6
1.8
V_{MR} in MV

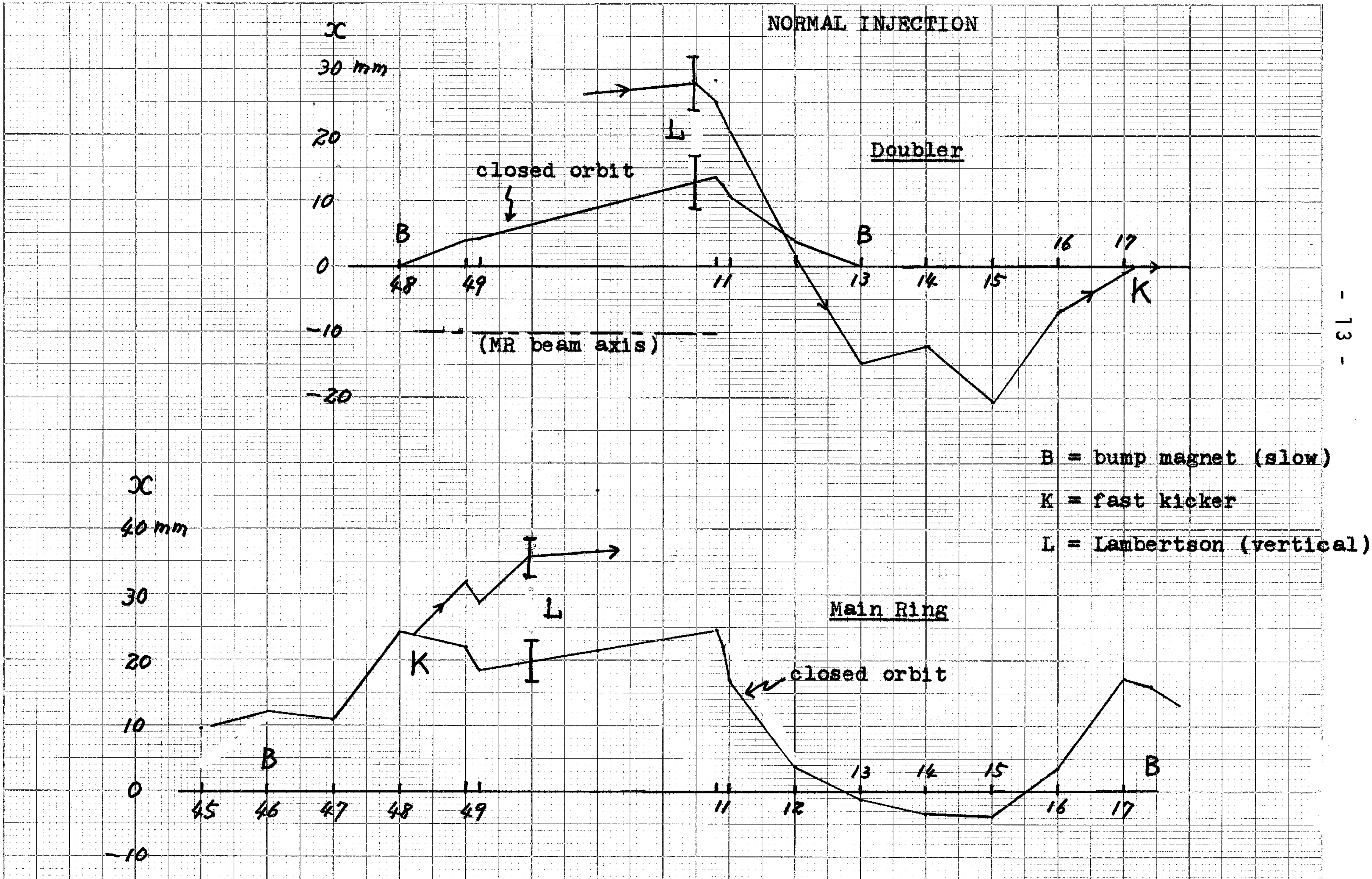

NORMAL INJECTION
Doubler
x
30 mm
20
10
0
-10
-20
closed orbit
L
B
48
49
11
13
14
15
16
17
K
(MR beam axis)
B = bump magnet (slow)
K = fast kicker
L = Lambertson (vertical)
Main Ring
x
40 mm
30
20
10
0
-10
45
46
47
48
49
11
12
13
14
15
16
17
closed orbit

Fig. 3

REVERSE INJECTION

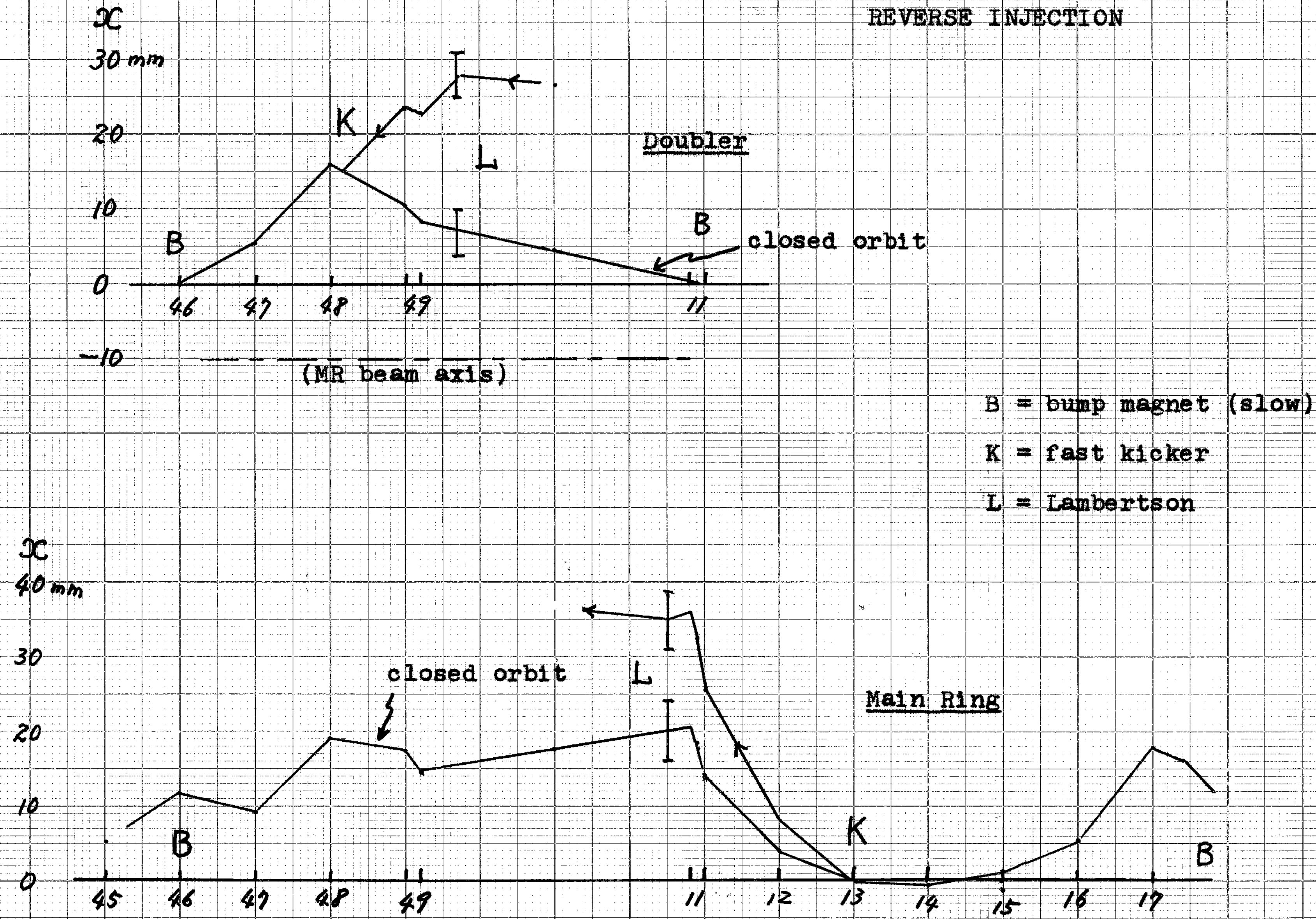
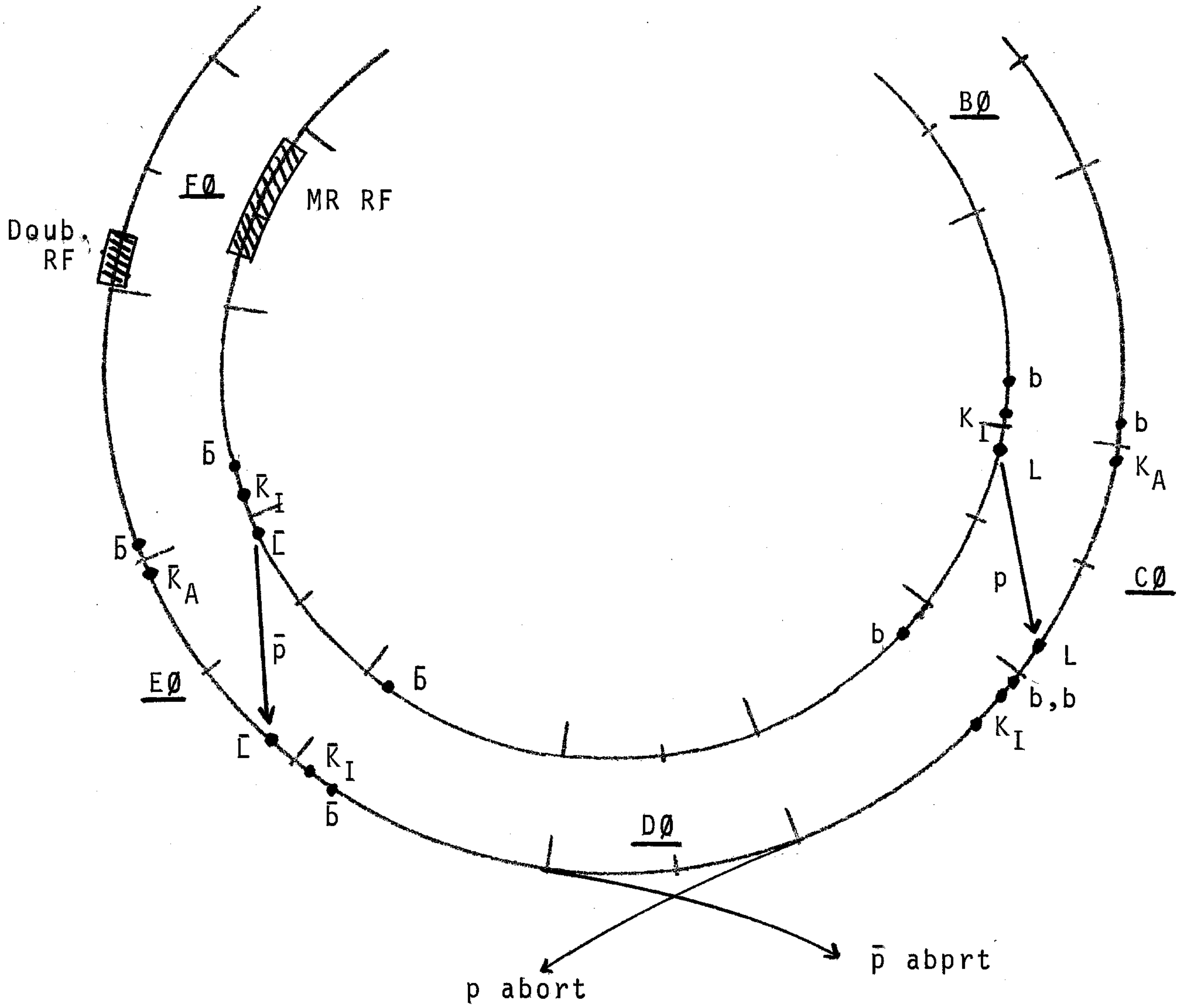


Fig. 4

Fig. 5

Layout I (L. Teng, UPC #18)

inner circle: main ring
outer circle: doubler

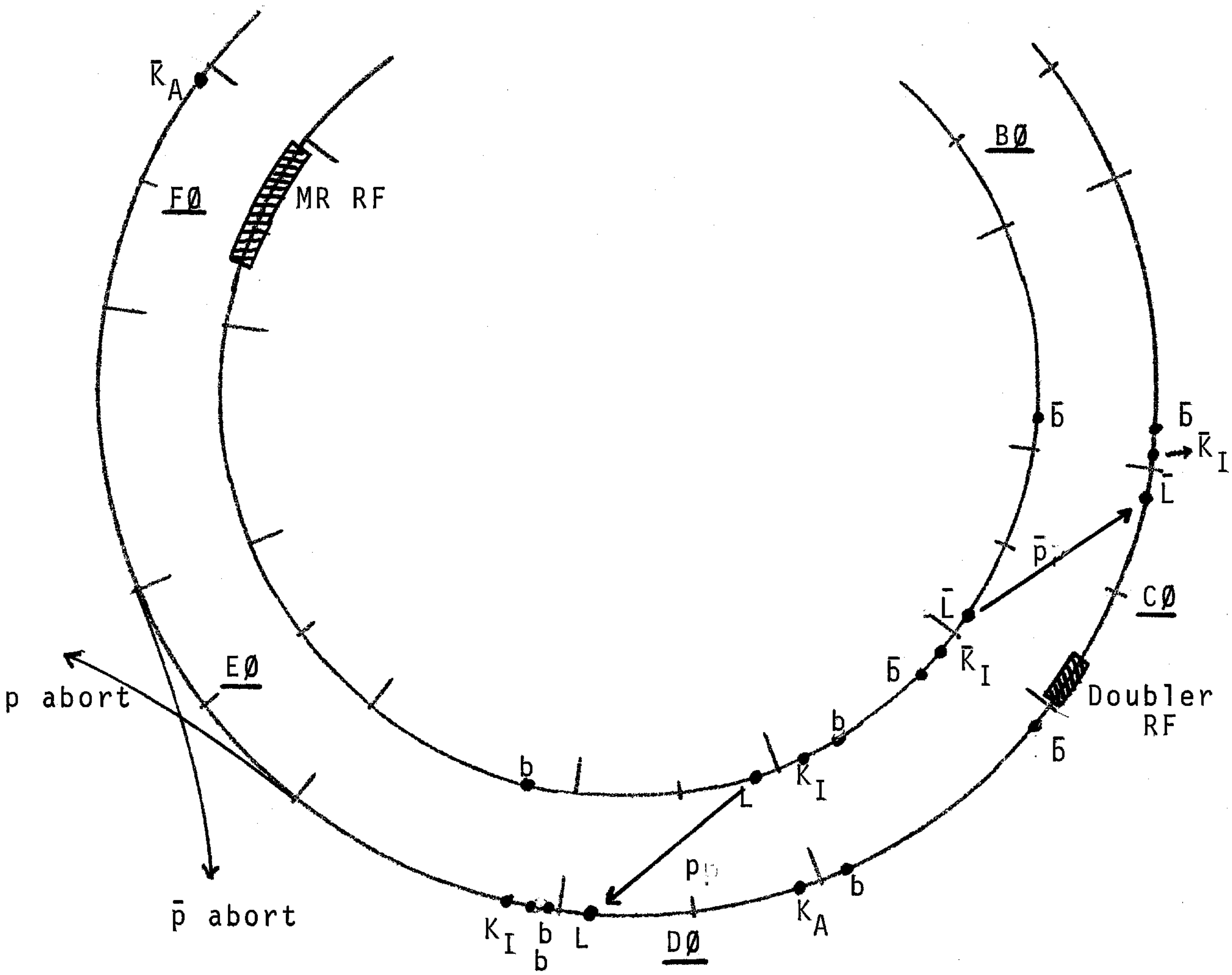


	main ring	doubler
L & L̄ (Lambertsons)	LS-C, LS-E	LS-C, LS-E
K_I & $\bar{K}_I$ (kickers)	B48, E13	C17, D48
b & Б (bump magnets)	(B46-C17) (D46-E17)	(B48-C11,13) (D46-E11)
K_A & $\bar{K}_A$ (kickers for abort)		LS-C & LS-E

Fig. 6

Layout II (T. Collins)

inner circle: main ring
outer circle: doubler



	main ring	doubler
L & $\bar{L}$ (Lambertsons)	LS-D, LS-C	LS-D, LS-C
K_I & $\bar{K}_I$ (kickers)	C48, C13	D17, B48
b & $\bar{b}$ (bump magnets)	(C46-D17) (B46-C17)	(C48-D11, 13) (B46-C11)
K_A & $\bar{K}_A$ (kickers for abort)		LS-D, LS-F

Fig. 7 Momentum Stacking

Station #17 with a high-eta insertion

β_H=94.7m η_H=9.73m

longitudinal area = 0.25 eV.s.
transverse area = 0.15π mm-mr

150 GeV injection, $(\Delta p/p)=\pm 0.23\times 10^{-3}$

8 turns stacked

stacked beam

momentum spread = 1.2×10^{-3} (full)

longitudinal area = 3.4 eV.s.

moving bucket for stacking

35 kV, ϕ_s = 31° (final)

energy shift -456 MeV
freq. swing 456 Hz
duration ~1 sec/turn
$(\Delta p/p)_{bucket}$ $=\pm 1.24\times 10^{-4}$ (final)