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INSERTIONS FOR COLLIDING-BEAM STORAGE RINGS

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Two high-energy colliding-beam storage rings were studied. Both rings can store beams of 1000 GeV at a bending field of 35 - 45 kG obtained with superconducting magnets. Each will have eight interaction straight sections with lengths of ∿1000 m each for the larger rings and ∿250 m each for the smaller rings. For both rings the curved sections consist of separated-function FODO cells with a phase advance of 90° per cell. This choice of phase advance is advantageous for locating beam deflecting elements. Dipoles are placed in the drift spaces O to form the curved section. The simplest structure for the straight section is a continuation of the normal cells but without the bending dipoles. Thus, the length of a straight section, same as that of a curved section, should be an integral multiple of half-cell length.

The beams in the two rings collide in the straight sections for particle-physics experiments. In the collision region the beam characteristics are modified to meet the requirements of individual experiments. To obtain specific beam characteristics a number of contiguous half-cells are removed and replaced by special-function insertions. The lengths of all insertions should, therefore, also be integral multiples of half-cell length. The following special function insertions are useful.

1. Crossing insertion - the curved sections of the two rings are stacked one above the other with a separation of the order 1 m between beams. In this insertion the two beams are brought vertically together.

2. Low-β insertion - in which the beams are made narrow in the collision region, thereby giving high luminosity ($\sqrt{\beta} \propto$ beam transverse width).

3. High-β insertion - wider beams are more parallel, hence desirable for some experiments.

4. Low-dispersion (or zero-dispersion) insertion - in which the position (η) and angle (η') dispersions are made small (or zero) in the collision region.

5. High-dispersion insertion - High dispersion can provide a better definition for energy of an interaction.

6. Tune-adjusting insertion - The phase advance across the insertion can be adjusted over a wide range of values to set the tune ν of the ring at good operating values.

For the present purpose it is adequate to give examples of a few more essential types of insertions. All parameters are computed using the thin-lens and thin-bend approximation which is fairly good for these insertions. The optics and dispersion matchings are obtained using the program MAGIC (Magnet Insertion Code)[1] in which all elements are assumed to be "thin" and matching equations together with constraint conditions are solved by the Variable Metric Minimization Method.[2]

We assume a normal cell length of 60 m and that each one of eight curved sections contains 16½ cells, hence has a length of

990 m. The bending angle per cell is, therefore, 47.6 mrad. With a phase advance of 90° per cell and using thin-lens-and-bend approximation one gets for normal cell orbit parameters

$$\beta_F = (1 + \frac{1}{\sqrt{2}}) \times 60 \text{ m} = 102 \text{ m}$$

$$\alpha_F = \mp (\sqrt{2} + 1) = \mp 2.41$$

$$\beta_D = (1 - \frac{1}{\sqrt{2}}) \times 60 \text{ m} = 17.6 \text{ m}$$

$$\alpha_D = \pm (\sqrt{2} - 1) = \pm 0.414$$

$$\eta_F = \frac{1}{4} (2 + \frac{1}{\sqrt{2}}) \times (47.6 \text{ mrad}) \times (60 \text{ m}) = 1.93 \text{ m}$$

$$\eta_F' = \pm \frac{1}{2\sqrt{2}} (2 + \frac{1}{\sqrt{2}}) \times (47.6 \text{ mrad}) = \pm 0.0456$$

$$\eta_D = \frac{1}{4} (2 - \frac{1}{\sqrt{2}}) \times (47.6 \text{ mrad}) \times (60 \text{ m}) = 0.923 \text{ m}$$

$$\eta_D' = \mp \frac{1}{2\sqrt{2}} (2 - \frac{1}{\sqrt{2}}) \times (47.6 \text{ mrad}) = \mp 0.0218$$

It is important that the dipoles and quadrupoles should be physically resonable with superconducting magnets. In the thin-lens and thin-bend approximation, the dipole strength (bend-angle) is

$$\theta \equiv \frac{\text{(field)} \times \text{(length)}}{\text{(B}\rho\text{ of particle)}}$$

and the quadrupole strength is

$$k \equiv \frac{\text{(field gradient)} \times \text{(length)}}{\text{(B}\rho\text{ of particle)}} .$$

In a normal half-cell, one gets

$$\theta = 23.8 \text{ mrad}$$

$$k = 2\sqrt{2}/60 \text{ m} = 0.0471/\text{m} .$$

A. Crossing insertion

An insertion which brings the two beams vertically together without altering the optics of the beams is shown in Figure 1 together with the β-functions. This insertion with a total length of $\Sigma\ell$ = 90 m will replace 1½ normal cells. The optical functions α and β at either end match those of a normal cell. As shown in Figure 1 the beams collide immediately to the right of the fourth bend. One can, of course, trim the bend-angles to keep the beam slightly separated at that point and use additional small vertical dipoles to form collision regions with desired geometry at desired locations farther to the right.

The vertical bends in the insertion introduce a small amount of vertical dispersion. It is possible to construct a crossing insertion in which the vertical bends are achromatic. Such an insertion will have to be longer and more complicated.

In or near the collision region it is unavoidable that some quadrupoles will be used in common by both beams. These quadrupoles will produce opposite focusing actions (F versus D) on the two beams going in opposite directions. Hence, it is expected that all pairs of corresponding quadrupoles between the two rings will have the same field-gradient polarities, hence opposite focusing actions on the two beams, as exhibited in Figure 1.

An insertion which replaces an even number of half-cells will have to match from F to F and from D to D. The focusing actions of such a symmetric insertion have reflection symmetry about the midpoint. An insertion which replaces an odd number of half-cells will match from F to D and from D to F. For such an antisymmetric insertion the focusing actions of the horizontal and the vertical planes are midpoint reflections of each other, hence the phase advances in the two planes are identical. Antisymmetric insertions are, therefore, preferred.

B. Low-β insertion

An example of a 2½ - cell (150 m) antisymmetric low-β insertion is shown in Figure 2 together with the β-functions. The low-β values in both the horizontal and the vertical planes at the midpoint where the beams collide are 1 m. The total free drift length on either side of the midpoint when the lengths of physical quadrupoles are taken into account is about 18 m. This length is limited by the very high maximum β values elsewhere in the insertion when the midpoint β, or β^*, has the extreme low value of 1 m. With higher β^* this central free drift space can be made longer. Presumably several similar insertions with various low β^* values and central free drift lengths can be made available to satisfy specific experimental needs.

C. Zero-dispersion insertion

For such an insertion, one has to satisfy not only the zero-dispersion conditions of $\eta = 0$ and $\eta' = 0$, but also the geometric conditions that the beam should end up along the same straight line. An example is given in Figure 3 where starting from an F-quad zero-dispersion is accomplished in two cells (120 m) with four bends. In order to keep dipole strengths physically reasonable the insertion starting from a D-quad must be 3½ cells (210 m) long, as shown in Figure 4.

D. Tune-adjusting insertion

It is desirable to be able to adjust the tune of the ring over a range of $\delta\nu = 0.5$. With one such insertion in the ring the range of the phase advance adjustment should then be $\delta\psi = 2\pi\delta\nu = 180^{\circ}$. Figure 5 shows a 1½ cell (90 m) antisymmetric insertion (equal horizontal and vertical phase advances) with four quadrupoles. The proper quadrupole strengths are plotted against the desired phase-advance ψ in Figure 5. The corresponding β-functions for certain ψ's are also plotted. The phase advance in this case ranges from 105° to 285°. With computer control of the quadrupole strengths it should be possible to vary ψ by one single knob. If for some reason it is desirable to have a larger adjustable tune range one can use two or more of these insertions. In the case when the end quads are not allowed to change, six quadrupoles are needed for the insertion as shown in Figure 6. The phase advance ψ is now adjustable from 120° to 300°.

In all the example insertions given above the thin-lens and bend parameters are chosen to be physically obtainable with superconducting magnets. The exact thick lens and bend parameters can be computed using the program TRANSPORT with the approximate parameters as initial trial values.

Now we can construct an example for the structure of a complete straight section. We assume a straight section 16 cells or 960 m in length. Since the dispersion function η has a periodicity of four cells (for a lattice with a 90° phase advance per cell), the choice of a 16-cell straight section automatically matches η-function at both ends. Furthermore, by making curved sections an odd number of half-cells in length and straight sections an even number of half-cells as in our case, the focusing sequence in the two rings is therefore identical. The example is shown in Figure 7. In this example there are two low-β, zero-dispersion collision regions available for two experiments. (A small amount of vertical dispersion is introduced by the vertical bends in the crossing insertions.) A tune-adjusting insertion can be installed in the straight section for the beam with F - F sequence. The tune-adjusting insertion for the second beam can be installed in some other straight section where the polarity of the focusing sequence is reversed.

Described here is a design concept and procedure for straight sections with maximum flexibility for experiments. The thin-lens and bend parameters serve to illustrate the practicability of this concept and procedure. For realistic engineering designs further detailed studies must be made. Also omitted here, are considerations of two injection insertions (one in each ring) for beam injection into the rings and two dump insertions (one in each ring) for fast extraction and dump of the beams.

REFERENCES

1. M. Lee, W.W. Lee and L.C. Teng, "Magnet Insertion Code", NAL Report TM-447 (Oct. 1973)

2. W.C. Davidon, "Variable Metric Method for Minimization", ANL-5990 (Rev. 2) (Feb, 1966). Also program "Variable Metric Minimization", ANL-Z013S (1967)

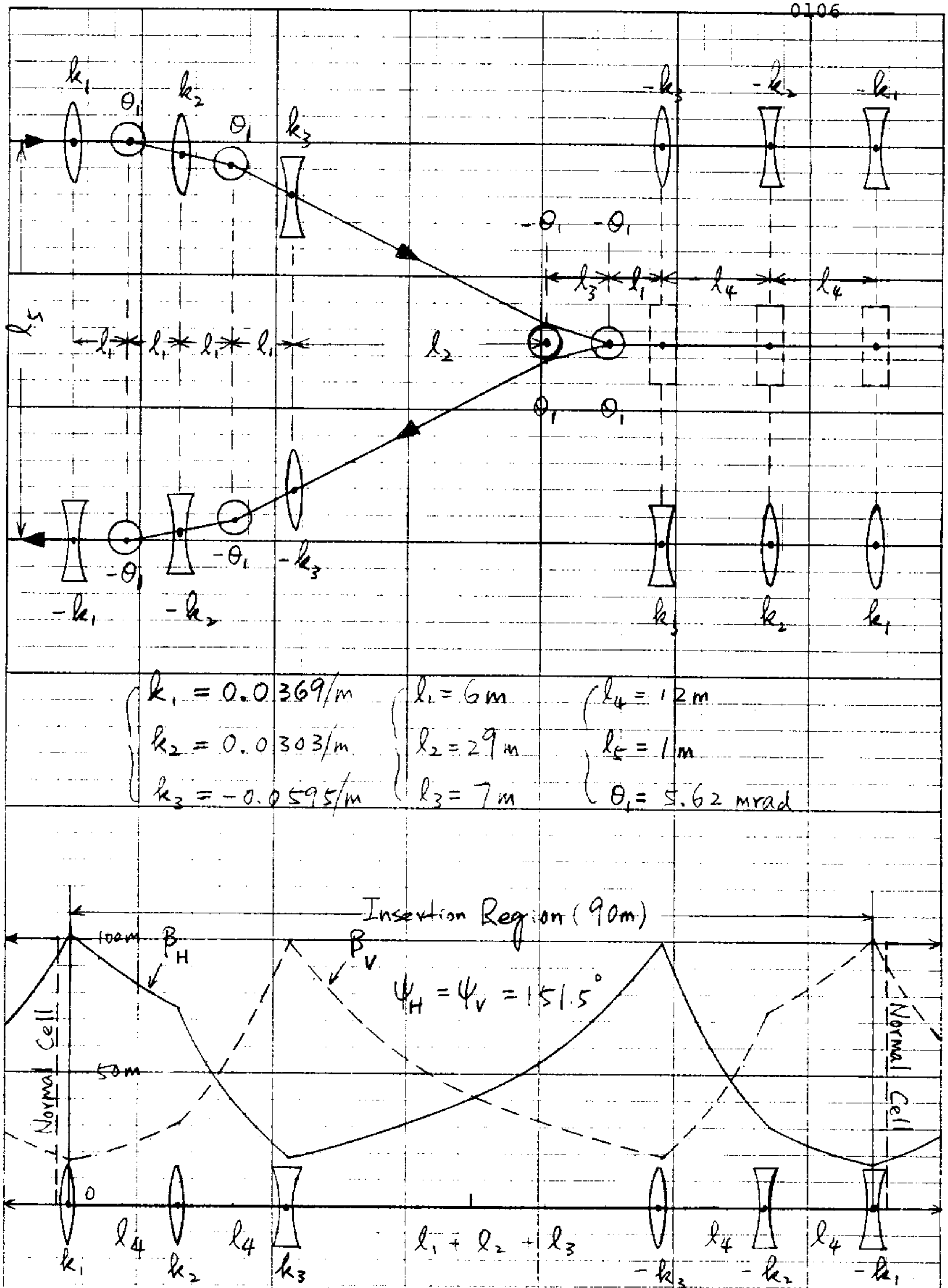


Fig. 1 Crossing Insertion

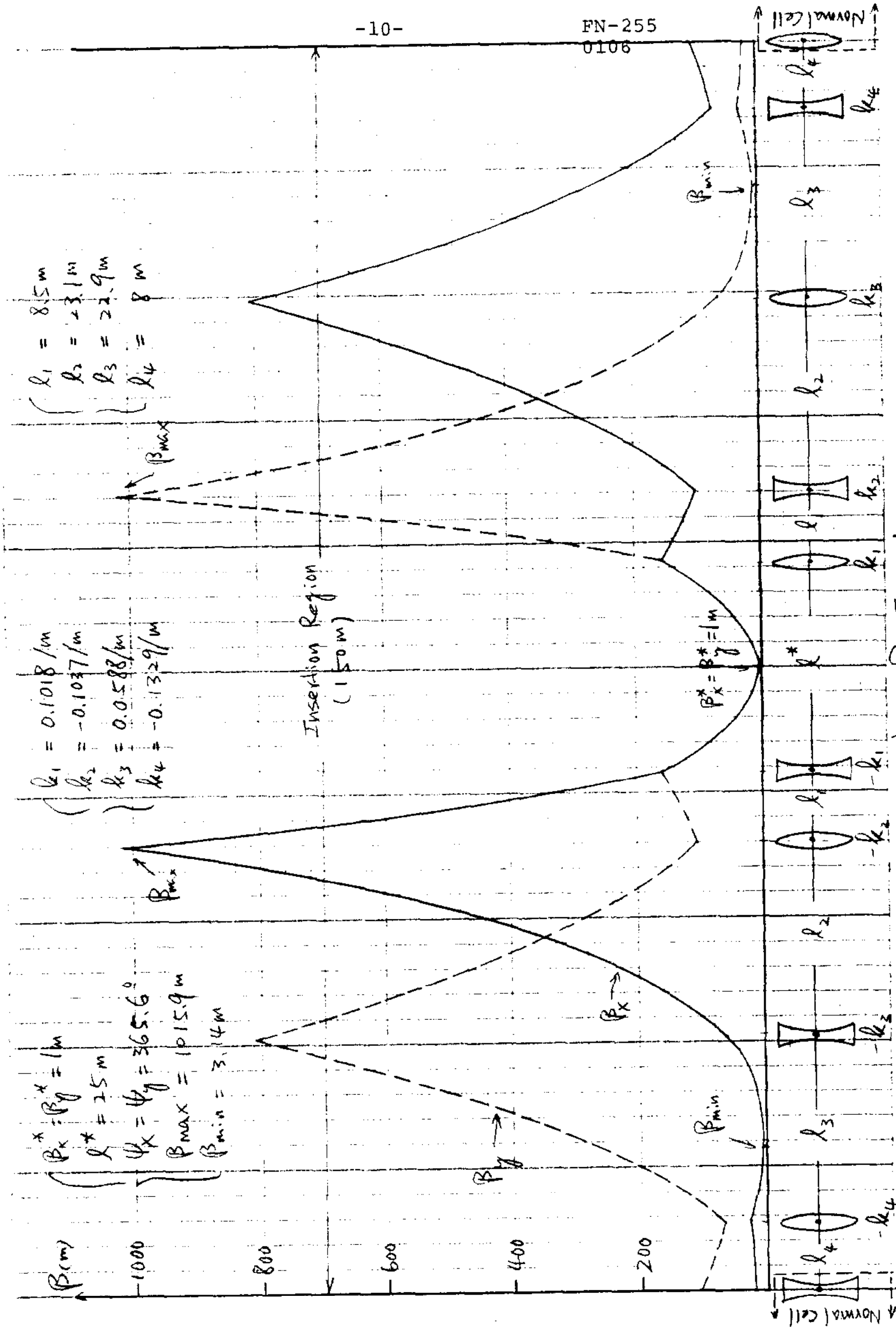
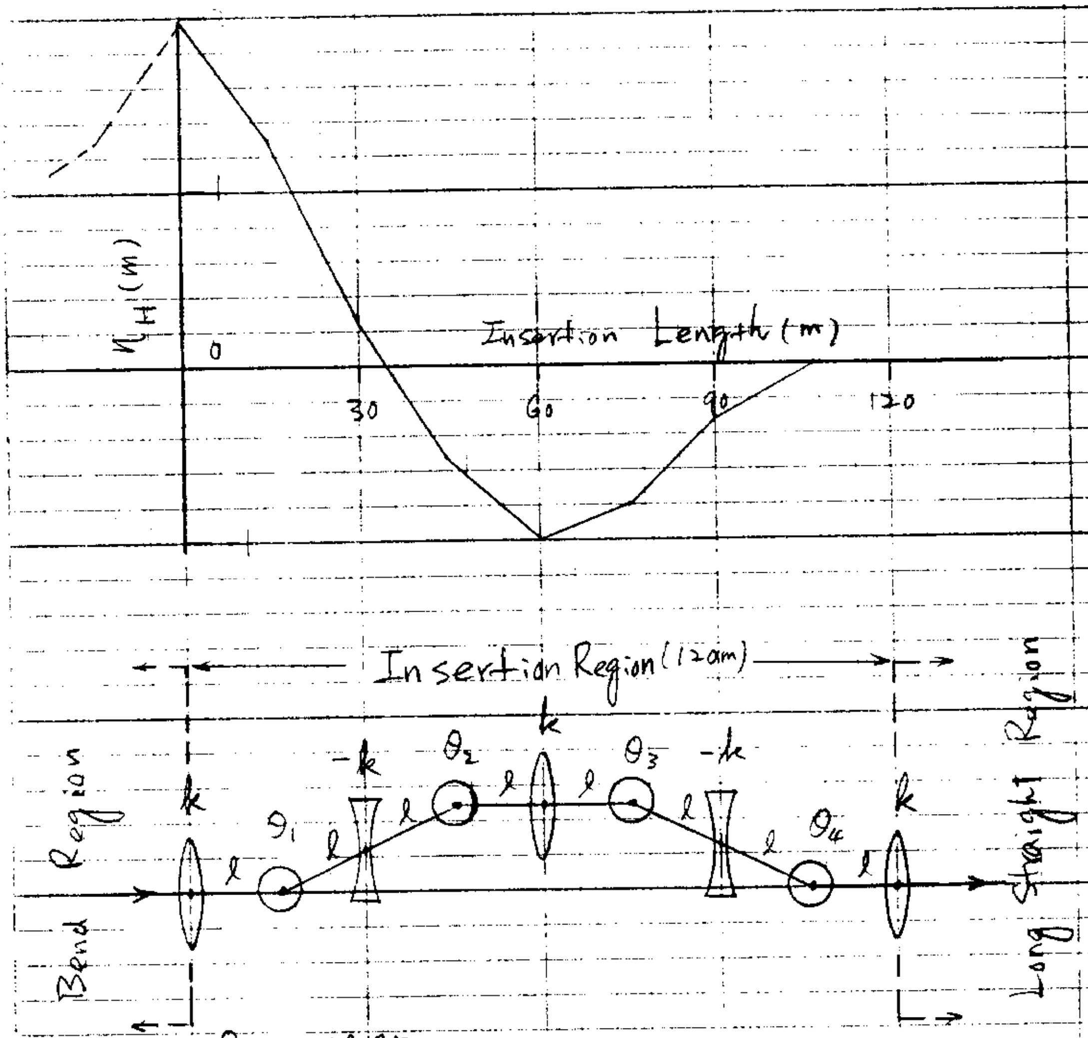


Fig. 2 Low-β Insertion



$\theta_1 = -18.85$ mrad

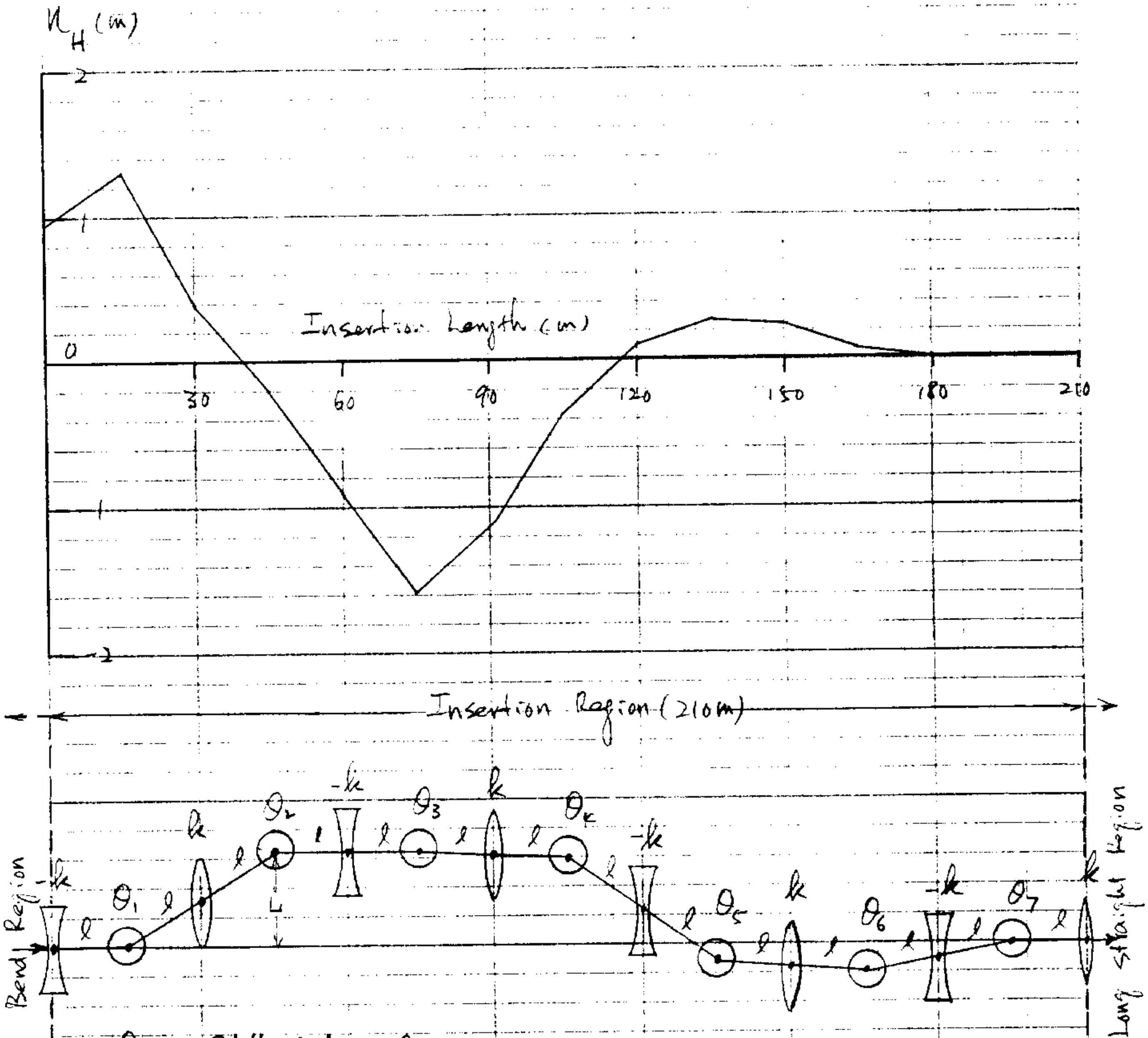
$\theta_2 = 18.55$ mrad

$\theta_3 = 19.45$ mrad

$\theta_4 = -19.15$ mrad

$k = 0.047$ $\quad l = 15$ m $\quad L = 0.515$ m

Fig. 3 Zero-Dispersion Insertion



$\theta_1 = -21.4$ mrad
$\theta_2 = 21.4$ mrad
$\theta_3 = 2.0$ mrad
$\theta_4 = 21.4$ mrad

$\theta_5 = -21.4$ mrad
$\theta_6 = -79$ mrad
$\theta_7 = 59$ mrad

$k = 0.047$ $\quad l = 15$ m $\quad L = 0.642$ m

Fig. 4 Zero-Dispersion Insertion

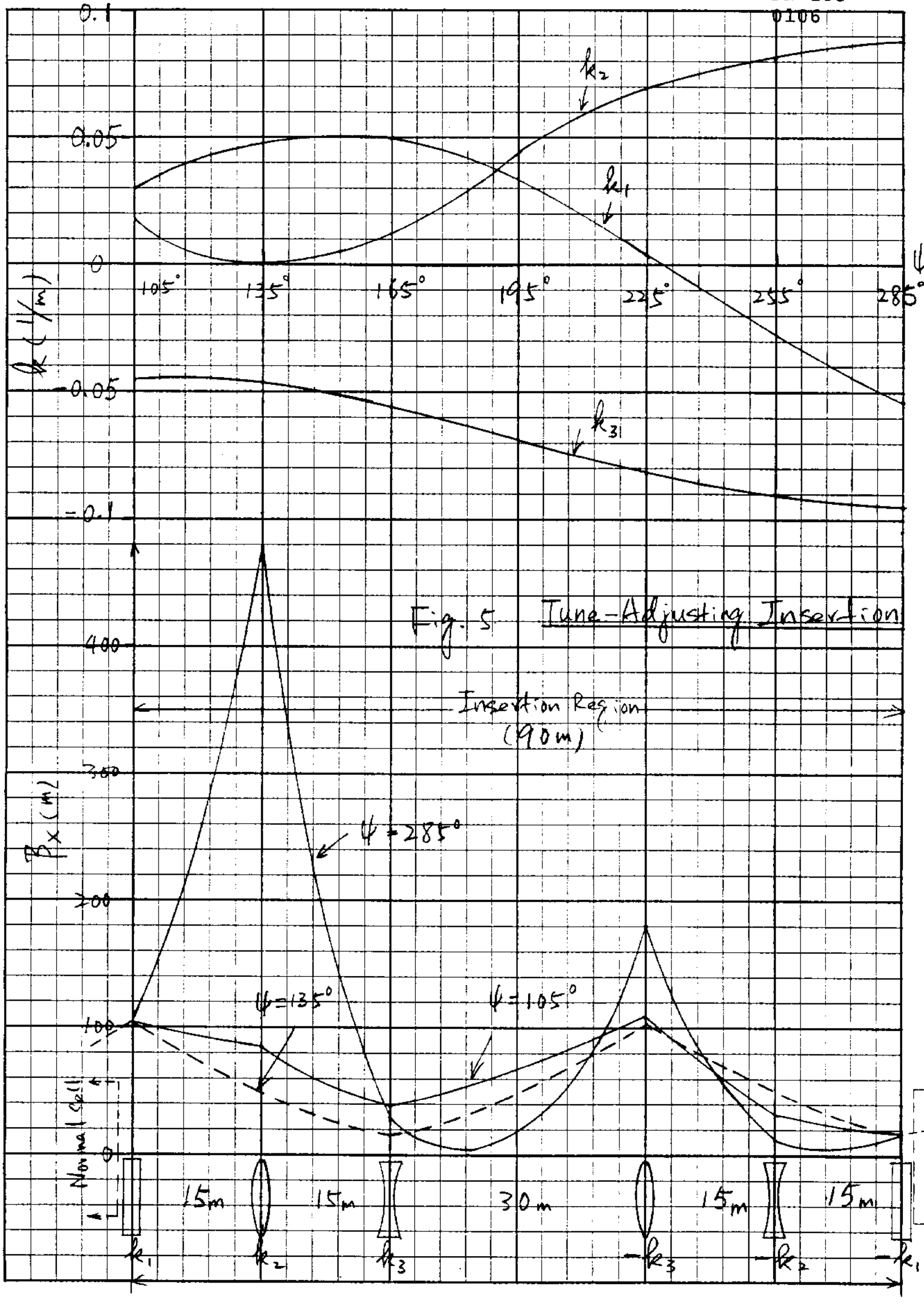


Fig. 5 Tune-Adjusting Insertion

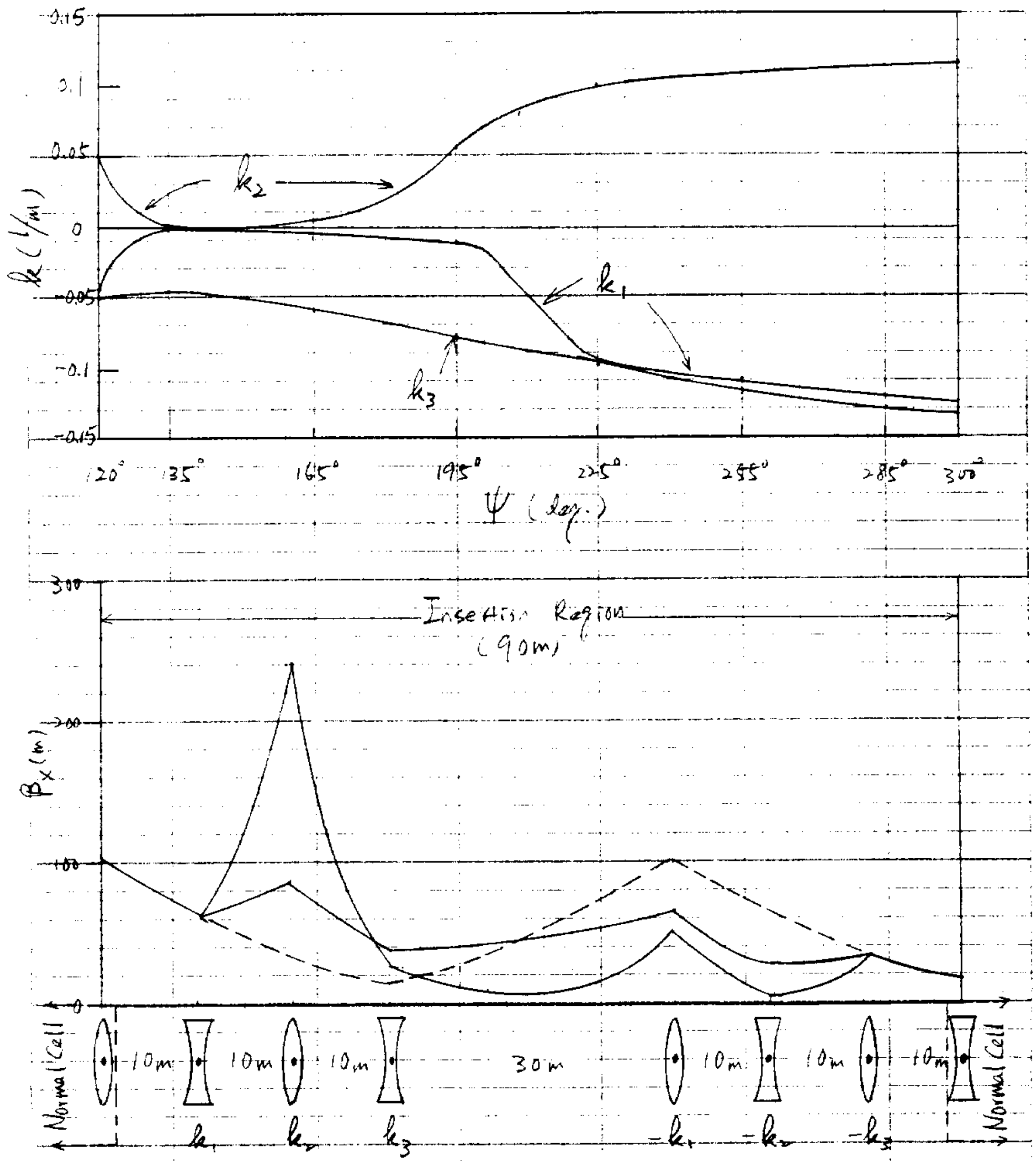


Fig. 6 Tune-Adjusting Insertion

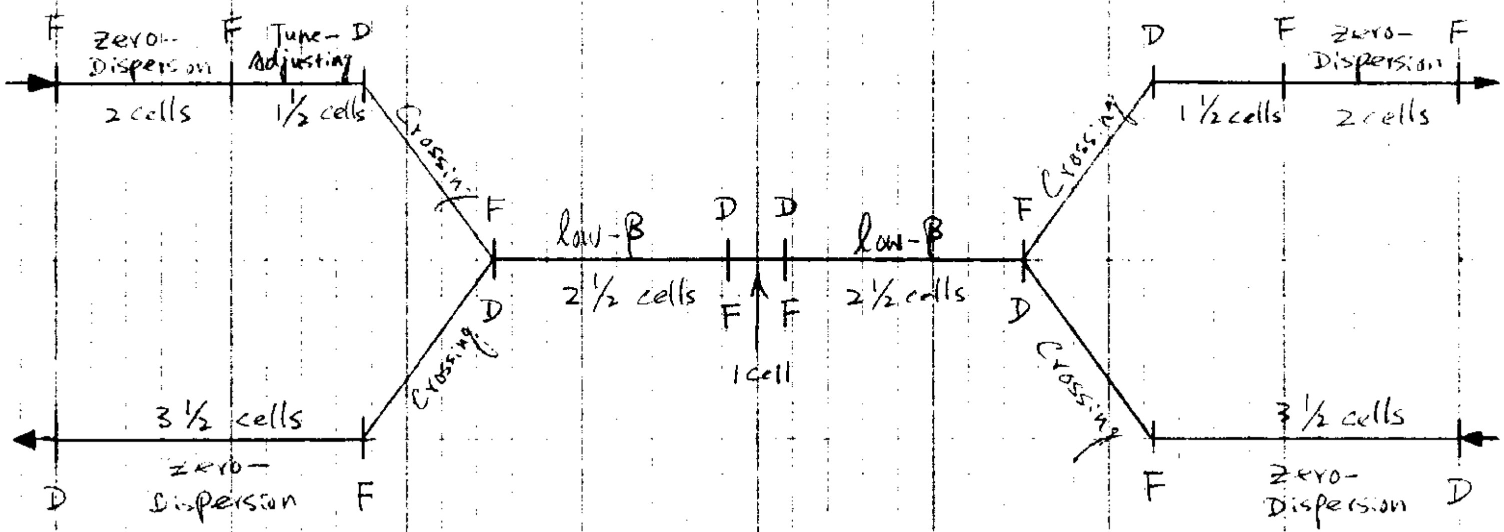


Fig 7 Insertions for a 16-cell long straight section