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Evolution in the LEBT Design (3rd Version): Choice of Quadrupole Triplets

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1. Recapitulation

The first version of LEBT has been presented in the "Project study for a new 50 MeV Linear Accelerator for the CPS", CERN/MPS/LINP 73-1, editor D.J. Warner; the essential parts of it are reproduced in this note on Figs. 1, 2.

The decision to include another empty drift space in LEBT has lead to the second version, contained in G. Plass, "Summary of Discussions in 1973 of the Linac Design Committee", MPS/LIN/Min 74-1 (see Fig. 3).

A further evolution of LEBT has been reported in I. White, "Linac Design Committee", MPS/LIN/Min 74-2 : following up the general policy concerning the choice of quadrupoles (see T.R. Sherwood, "Pulsed Quadrupole magnets for the New Linac", MPS/LINP/Note 73-11), the BNL quadrupoles of 4" aperture and a length of 4" and 7.5" respectively, have been chosen for the four identical triplets of LEBT; the layout of LEBT has been modified accordingly, but a complete drawing has not been issued.

All the above modifications have been made by keeping the input, output, as well as the intermediate matching conditions at the boundaries of LEBT sections the same as in the original version.

2. Reasons for a New LEBT Version

A preliminary analysis of space problems in LEBT revealed that the 4" BNL quadrupoles, forming the first triplet, could not be housed in the cathode of the HT column, as foreseen, due to lack of radial space. A special triplet is needed for this purpose, which should at best reconcile HT and beam optical requirements.

The necessity to reconsider the situation at the input to LEBT has been taken as a reason to reconsider the optics of the whole part of LEBT dealing with unbunched beam. In this note, the "measuring", "limiting" and "transition" sections of LEBT are dealt with and are brought into a rather final form.

3. Input Beam Characteristics and Matching Conditions

The beam intensity, density distribution, emittance size and shape form the characteristics of the beam one would like to know at the input to LEBT. As these values are not available, one has to speculate about them by combining our present knowledge of the 500 keV beam with information, at 750 keV, coming from other laboratories.

The transfer of the "nominal" beam in LEBT (3rd version) is calculated with input values as follows:

Beam intensity : 200 mA
Density distribution : uniform
Marginal emittance : $65\ \pi \cdot 10^{-6}$ m rad at 750 keV
Beam radius : $\hat{r}$ = 10 mm ($\hat{r}$ = 15 mm previously)
Maximum divergence : $\hat{r}'$ = 25 m rad ($\hat{r}'$ = 20 m rad previously)

Safety factors which are put on the design are:

a) for beam intensity: LEBT must be capable of handling intensities up to I = 300 mA

b) for density distributions: the radii (and divergences) of the beam calculated with uniform distributions are multiplied by a factor <u>1.25</u> for the determination of aperture requirements.

c) for linearity in quadrupoles: only ∿ 80% of the aperture is to be occupied by the beam in the worst case. (This means that the quadrupole aperture must be $2 \cdot r_{max} \cdot 1.25 \cdot 1.25$, which is about <u>3 times</u> the maximum radius of the <u>uniform</u> density beam.)

The <u>matching conditions</u> in the part of LEBT dealing with continuous beam are in principle easy to fulfil except for the beam limiting section. This section does not contain any quadrupole and in order to limit the beam proportionally in angle and diameter, two four-jaw apertures are placed at a determined distance and the beam emittance at the first aperture has to meet the condition:

$$\frac{\alpha_1}{\beta_1} = \frac{t_{11}}{t_{12}} \quad (1),$$

where α_1, β_1 are the CLS* parameters characterising the emittance and t_{11}, t_{12} are the elements of the first row of the transfer matrix acting from aperture one to aperture two.

For a given distance L between apertures, one can satisfy the above condition by many pairs of values α_1 and β_1. However,only those values α_1, β_1 are interesting, which bring about reasonable α_2 and β_2 at the second aperture. The best one can do is to fix a convenient distance L and then choose α_1 and β_1 so as to have:

$$\begin{aligned} \alpha_2 &= -\alpha_1 \\ \beta_2 &= \beta_1 \end{aligned} \quad (2)$$

The outcomes of calculations of the limiting section are represented in Fig. 4 in the form $L = f(\alpha_1)$, with β_1 as parameter; values of α_2 and β_2 are also indicated, as well as curves along which the condition (2)

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* Courant, Livingston, Snyder

is fulfilled. With the aid of Fig. 4, a convenient L is chosen: L = 680 mm; the corresponding values of α_1 and β_1, for I = 200 mA and 300 mA respectively are $\alpha_1 \cong 3.1$, $\beta_1 = 1.2$ and $\alpha_1 \cong 4.5$, $\beta_1 = 1.55$ respectively.

4. The 3rd LEBT Version

Having fixed the matching conditions at the limiting section, the measuring section can be dealt with. The beam is the largest in this section, so it is determinant for the choice of quadrupoles. It is intended to have all the triplets, starting from the second one, the same.

Fig. 5 shows an optimised case where BNL 3" aperture quadrupoles are used for the second triplet. The distance between quadrupoles in triplets is minimum (∿2 cm between iron cores); nevertheless, aperture requirements are not met at the second triplet (aperture is smaller than three times the beam radius).

The aperture requirements are, on the contrary, met by the 4" BNL quadrupoles, see Figs. 6a and 6b; these figures represent the 3rd LEBT version, containing the measuring, limiting and transition sections. The specifications are given in Fig. 7.

The first triplet of LEBT is made of special quadrupoles, permitting rather high gradients and having small outer dimensions. It is supposed that outer diameters of ∿ 15 cm are compatible with the design of a new cathode for the 750 kV DC accelerating column.

To diminish the mutual influence of quadrupoles in a triplet, the spacing between BNL quadrupoles (core to core) has been fixed to 9 cm, i.e. roughly equal to the aperture diameter. At BNL and NAL this spacing is only 2 cm; measurements on triplets are planned in order to assess the role of the spacing on the triplet performance. A smaller spacing reduces somewhat the beam size, as can be seen by comparing Figs. 8a, 8b, where triplets have 2 cm spacings, with Figs. 6a, 6b.

5. Tolerances and Inherent Errors in a System

The determination of quadrupole tolerances in a transport system can be done in several ways. A direct and reliable, but rather lengthy method consists in simulating quadrupole errors and then calculating if the beam quality after the transport stays in preset limits. If there are inherent errors in the system, the tolerances may, in some cases, be deduced from them, making the above lengthy calculations superfluous.

As inherent errors in the LEBT one considers beam intensity and density fluctuations. Non-uniform density distributions of the ellipsoidal type can in principle be perfectly well matched with linear external focusing forces and remain stationary. Non-linearities in lenses should therefore be compared not to non-linearities in space charge forces, but rather to fluctuations in these latter values.

The focusing of LEBT (before the buncher), determined for a given beam intensity, is valid for any of the ellipsoidal density distributions having the same rms values [1]. Fluctuations in intensity [2] and rms values of the new preaccelerator beam are estimated to be, together, less than ± 5%. One can calculate an average focusing action of the LEBT and compare it to an average space charge action; as the lenses occupy only ∿¼ of the LEBT, the ratio between these actions is given with:

$$f = \frac{\frac{1}{4}\, v\, r\, G}{I/(2\pi\varepsilon_o v r)} = \frac{1}{2}\, \pi\varepsilon_o\, r^2\beta^2c^2\, \frac{G}{I} \qquad (3)$$

The symbols in (3) have their usual meaning and f is a factor which fixes the permissible error in quadrupole fields; taking the above estimate for inherent errors (5%), the integrated quadrupole field has to satisfy the following formula over all of the useful aperture :

$$\left| \frac{\int_{-\infty}^{\infty} B(r,\phi)\,ds - r \int_{-\infty}^{\infty} G(o,\phi)\,ds}{r \int_{-\infty}^{\infty} G(o,\phi)\,ds} \right| < \frac{0.05}{f} \qquad (4)$$

Putting values in (3) - $\bar{r}$ = 20 mm, $\bar{G}$ = 4 T/m, I = 200 mA - one obtains f $\simeq$ 16 and for allowed integrated field errors according to (4):

$$\leq 0.3\%, \text{ at } r = 20 \text{ mm} \qquad (5)$$

Conclusion: if the 4" BNL quadrupoles satisfy the condition (5), i.e. if their integrated field errors are $\lesssim$ 0.3% until $\sim$ 50% of the aperture radius, they can be accepted without a further analysis concerning quadrupole tolerances.

6. Future Evolution of LEBT

In the 3rd LEBT version (Fig. 6), the most important section, dealing with bunching and matching to the Linac input, is missing. It will be determined in connection with the choice of definitive operating conditions for tank I.

The 3rd LEBT version contains only focusing elements; the specification of other elements will follow:

magnetic elements :	steering coils
RF elements :	bunchers [3]
measuring elements :	beam transformers
	emittance devices
	beam profile measuring devices
	pick-up station (for longitudinal density measuring)
limiting elements :	4-jaw apertures
	sieves

The diameter of the vacuum chamber in LEBT is not constant; it is $\sim$ 7 cm at the first triplet and $\sim$ 10 cm at the others. The size of the vacuum chamber between the triplets and in the bunching section is not yet fixed, but will probably be $\sim$ 8 cm and 4 cm respectively.

References:

1. F. Sacherer, "Rms Envelope Equations with Space Charge", CERN/SI/Int. DL/70-12.
2. J. Knott and M. Weiss, "Analysis of stability of Linac Parameters and Beam", MPS/LIN/Note 72-4
3. D.J. Warner, "RF Power Requirements for the 405 MHz Buncher", MPS/LIN/Note 74-2.

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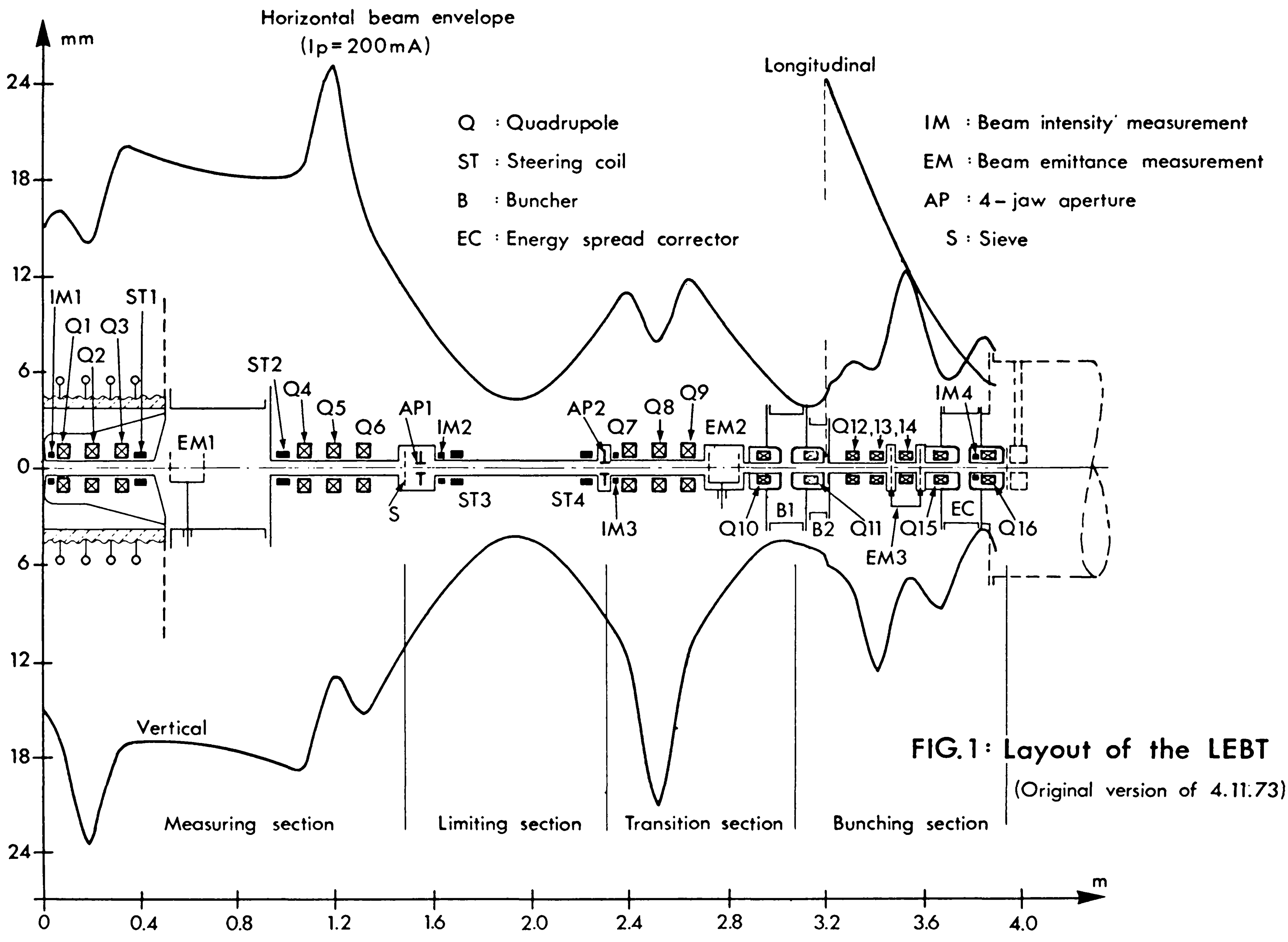


FIG. 1: Layout of the LEBT

(Original version of 4.11.73)

<u>Input Conditions</u> (preaccelerator beam characteristics)

I_p = 200 mA

E = $65 \cdot 10^{-6}$ π m rad

beam radius : ∿ 15 mm; β = 3.46

beam divergence : ∿ 20 m rad; α = - 4.36

<u>Output Conditions</u> (Linac matching requirements)

$\phi_s = -30^{\circ}$
$\Delta = \pm 25$ keV } longitudinal phase plane

$\alpha_H = 3.70$
$\beta_H = 0.379$ } horizontal phase plane

$\alpha_V = -3.46$
$\beta_V = 0.365$ } vertical phase plane

(horizontal and vertical phase planes: CLS parameters)

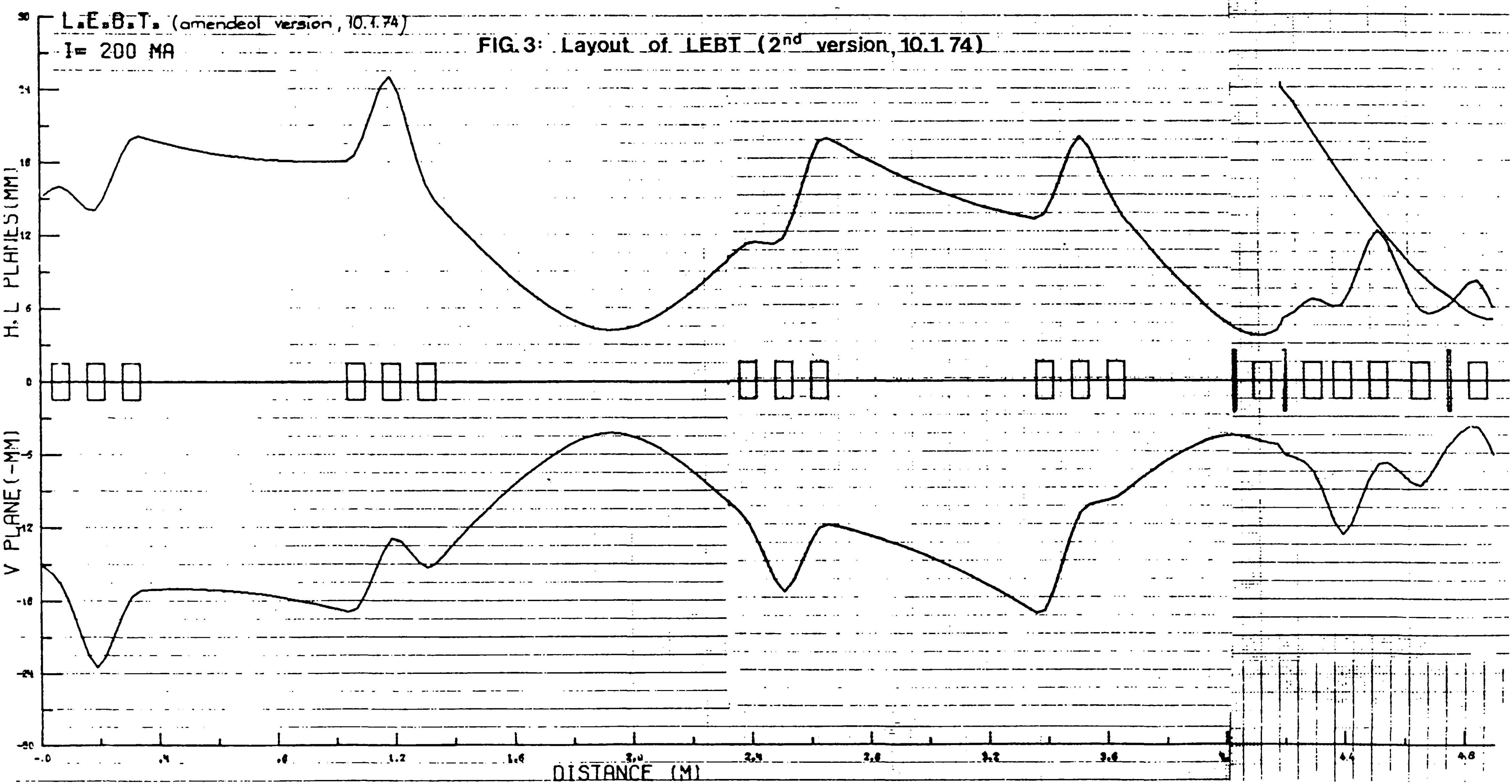
<u>Specification of the LEBT</u> : length 3.90 m

Quadrupole Specific.	Quad. identif.	Length (mm)	Aperture (mm)	Gradient (T/m)
Measuring Section (1.49m)	Q1	60	60	- 5.89
	Q2	60	60	11.79
	Q3	60	60	- 6.96
	Q4	60	60	7.33
	Q5	60	60	- 13.35
	Q6	60	60	7.77
Beam limiting section (0.83m)	--			
Transition Section (0.71m)	Q7	60	60	- 11.61
	Q8	60	60	19.15
	Q9	60	60	- 12
	Q10	60	30	- 2.4
Bunching Section (0.87m)	Q11	60	30	3.82
	Q12	60	30	- 13.09
	Q13	60	30	22.49
	Q14	60	30	- 22.10
	Q15	60	30	18.30
	Q16	60	30	- 26.14

Buncher voltages (kV) : B1 : 42.1; B2 : 21; EC : 24.98
Bunching efficiency : ∿ 70%

<u>FIG. 2 :</u> PARAMETERS OF THE L.E.B.T. (as computed)

FIG. 3: Layout of LEBT (2nd version, 10.1.74)



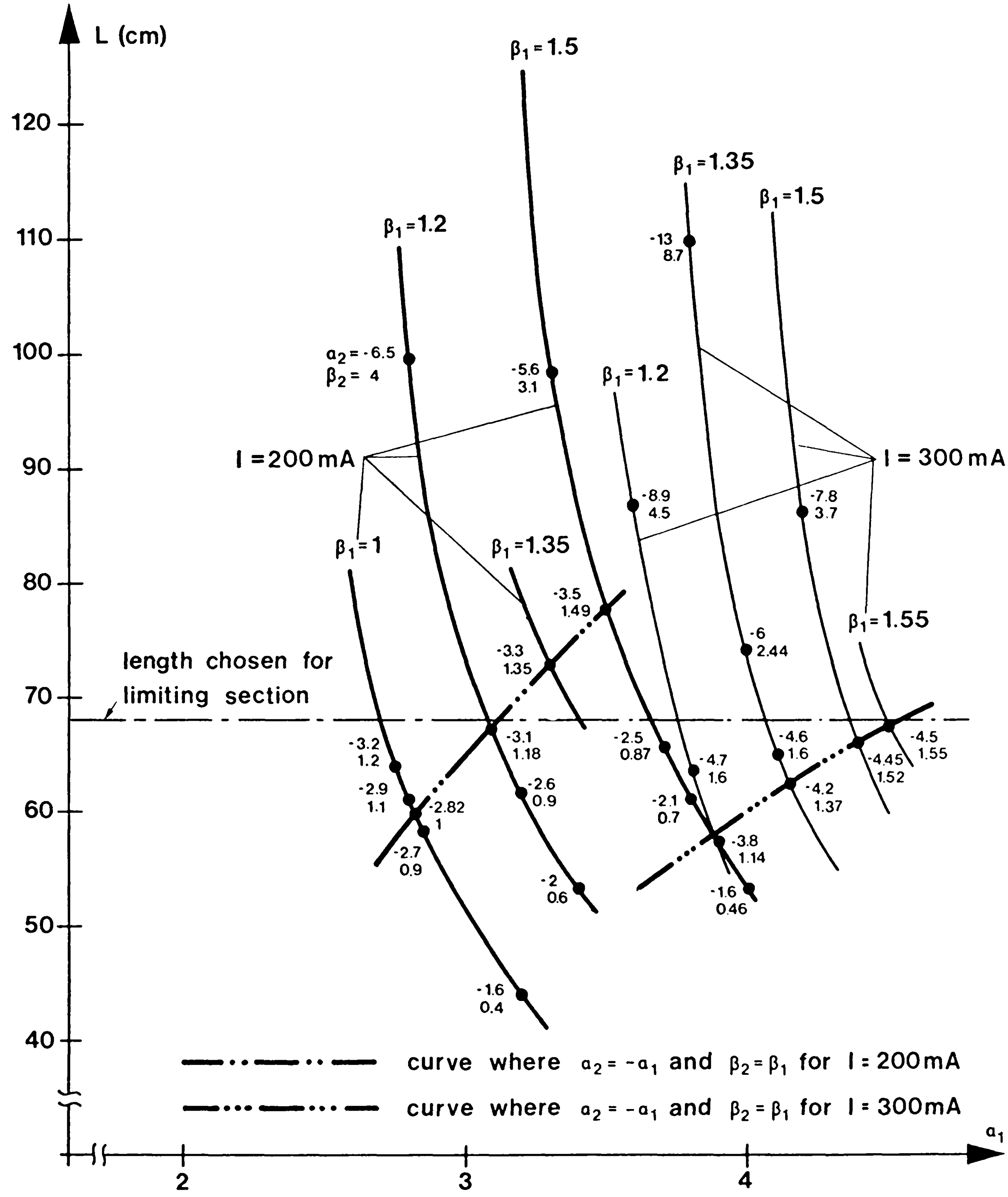


FIG. 4: Length of limiting section as function of input beam characteristics (α_1, β_1, I); output values (α_2, β_2) are indicated.

FIG. 5: Measuring section - BNL 3" aperture quadrupoles in the 2nd triplet

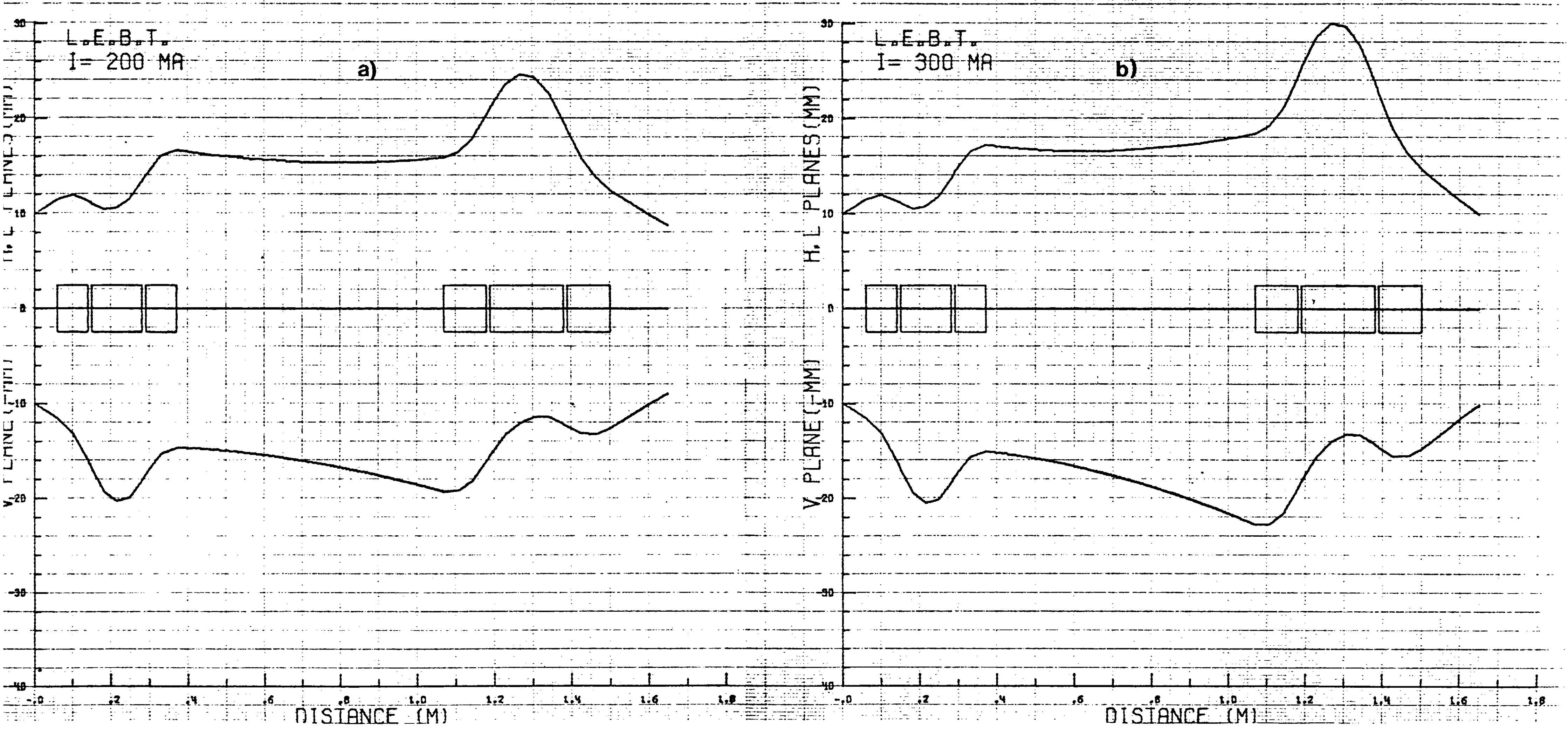
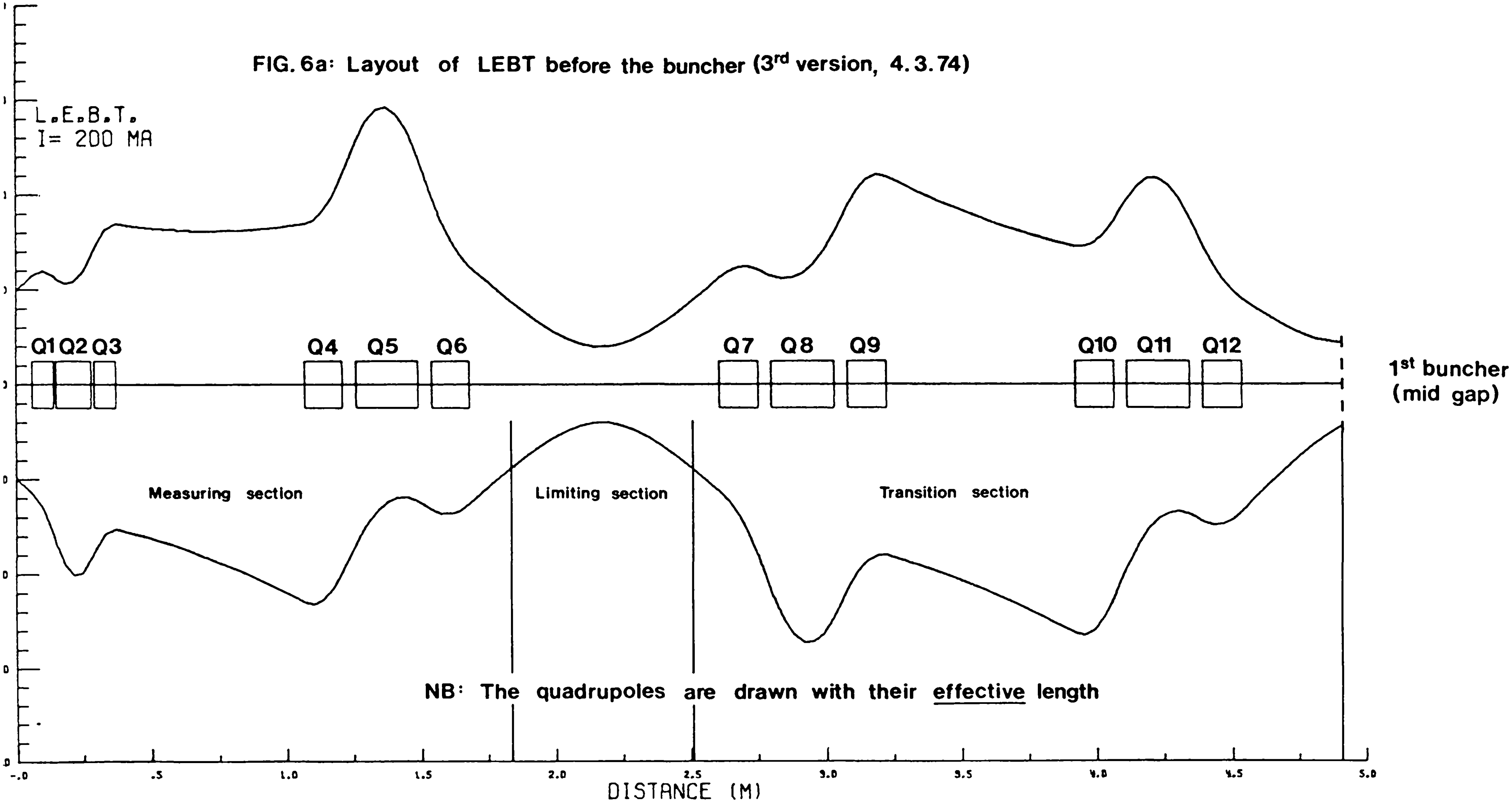


FIG. 6a: Layout of LEBT before the buncher (3rd version, 4.3.74)



NB: The quadrupoles are drawn with their effective length

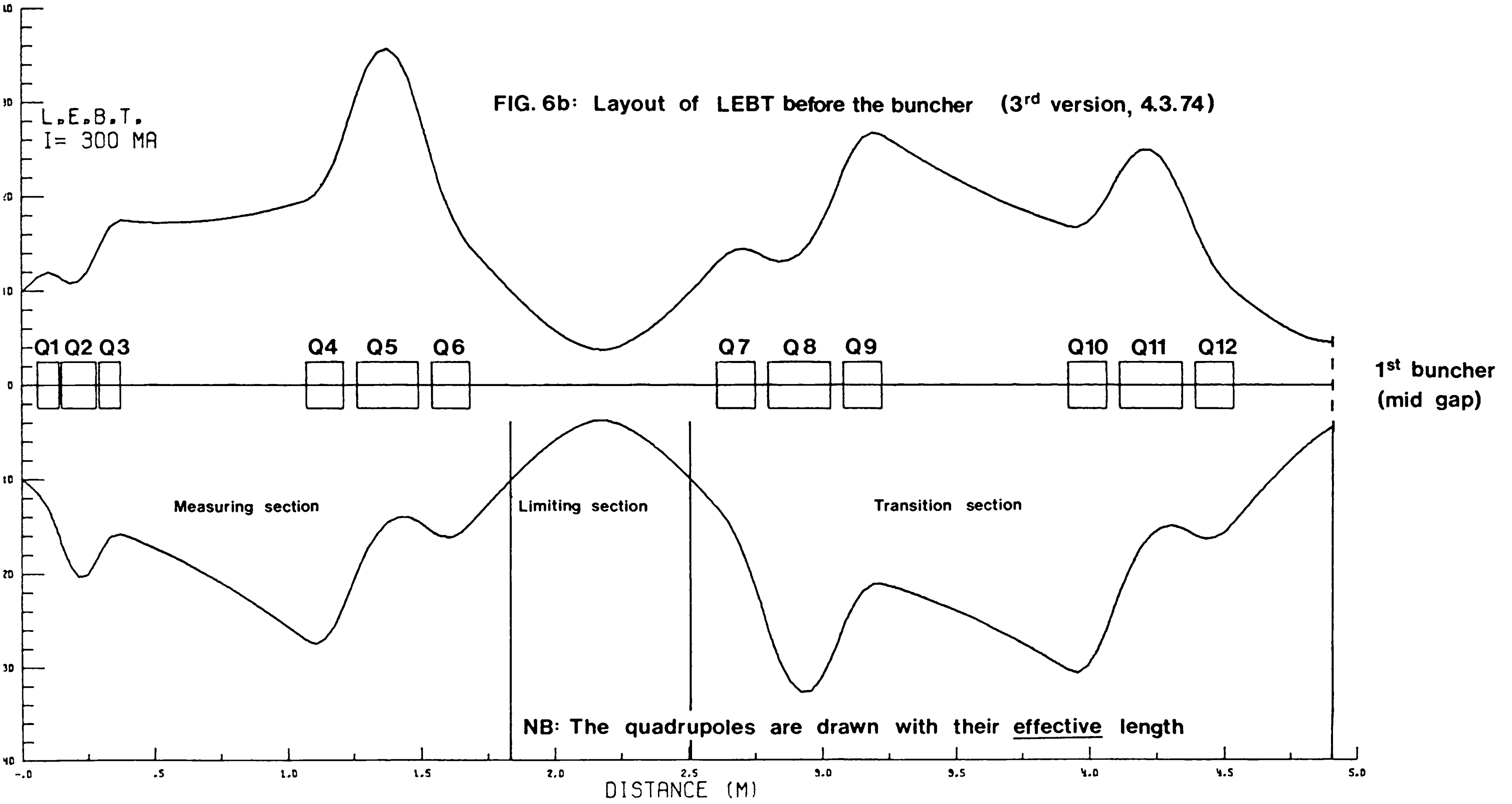


FIG. 6b: Layout of LEBT before the buncher (3rd version, 4.3.74)

Input Conditions (preaccelerator beam characteristics)

I_p = 200 mA (nominal) and 300 mA (maximum)

E = 65.10^{-6} π m rad

beam radius : 10 mm ; β = 1.54

maximum divergence : 25 m rad ; α = - 3.71

Output Conditions (at mid gap of 1st buncher)

beam radius : 4.4 mm

$\alpha_H = 0.03$; $\alpha_V = 1$; $\beta_H = \beta_V = 0.3$

Specification of LEBT before buncher (only focusing elements)

Total length : 4.91 m

Quadrupoles : arranged in symmetric triplets with spacing of 2 cm in the first one and 9 cm in others.

	Quad. identif.	Length (mm)	Aperture (mm)	Gradient (T/m)	
				I = 200 mA	I = 300 mA
Measuring section (1.83 m)	Q1, Q3 Q2 Q4, Q6 Q5	60 120 100 190	70 70 100 100	- 7.2 7.9 3 - 3	- 7.2 7.8 3.2 - 3.2
Beam limiting section (0.68 m)					
Transition section (2.4 m)	Q7, Q9 Q8 Q10, Q12 Q11	100 190 100 190	100 100 100 100	- 3 2.9 2.9 - 2.9	- 3 3 3 - 3

NB. Quadrupoles from Q4 onwards are as BNL 4" ones.

FIG. 7: Focusing parameters of LEBT before buncher (3rd version, 4.3.74)

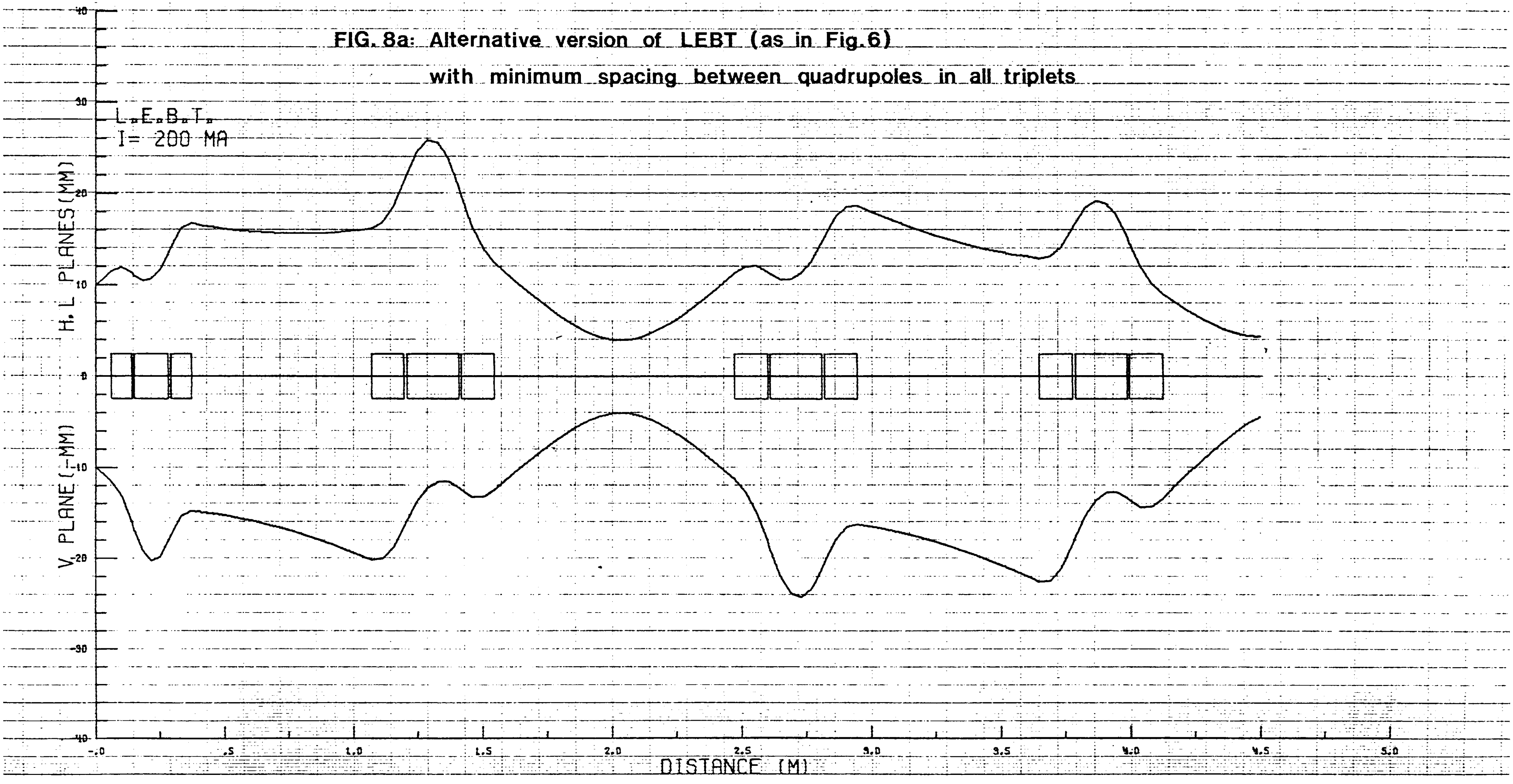


FIG. 8a: Alternative version of LEBT (as in Fig.6) with minimum spacing between quadrupoles in all triplets

FIG. 8b: Alternative version of LEBT (as in Fig. 6) with minimum spacing between quadrupoles in all triplets