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LATTICES FOR THE DOUBLER

We describe the properties of lattices in terms of the derived functions α, β, and ψ (or $\mu = 2\pi\nu$), where these terms arise in our description of betatron oscillations as a ray equation -

$$y = a\left(\frac{\beta}{\beta_o}\right)^{\frac{1}{2}}\cos\psi \text{ -}$$

or as a rewriting of the transfer matrix -

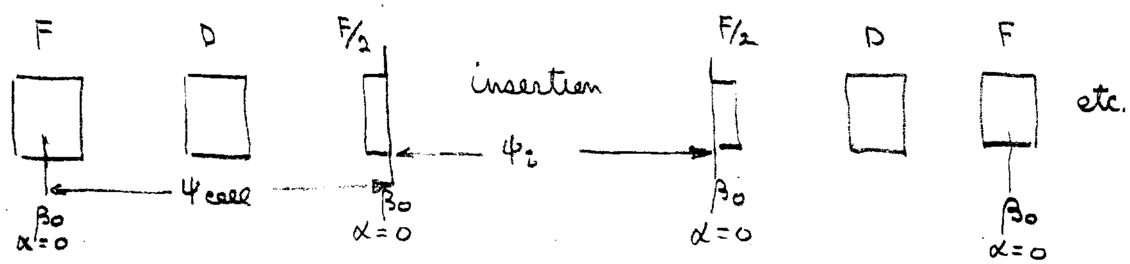
$$M_{12} = \begin{pmatrix} \left(\frac{\beta_2}{\beta_1}\right)^{\frac{1}{2}} (\cos\psi + \alpha_1\sin\psi) & (\beta_1\beta_2)^{\frac{1}{2}}\sin\psi \\ & \left(\frac{\beta_1}{\beta_2}\right)^{\frac{1}{2}}(\cos\psi - \alpha_2\sin\psi) \end{pmatrix} .$$

These expressions become useful only after we have insisted that the functions repeat after 1 turn (ψ increases by μ per turn). Actually we want a lot more repetition than that! The repeat matrix is

$$M = \begin{pmatrix} \cos\psi + \alpha\sin\psi & \beta\sin\psi \\ & \cos\psi - \alpha\sin\psi \end{pmatrix} \qquad (\psi = \mu \text{ for 1 turn})$$

Our first step is to evaluate M for 1 turn, starting from a particular point, by multiplying the usual matrices for each quad and space. We can then evaluate μ and α and β for this point. The rest of the lattice functions are found from the general form. One might find $|\cos\mu|>1$, a stop-band, but readjusting quad strengths will allow solution.

For the simple FODO lattice, the repeat is every cell. In this case the maximum β, and hence maximum beam envelope, is in the F quad. Its value depends primarily on the cell length. We now want to insert special sections into this lattice.



If the transfer matrix for the insertion can be written in repeat form with $\alpha = 0$, $\beta = \beta_o$, ψ = any ψ_i, then the simple FODO function is undisturbed. This is a beta-matched insertion. Let us suppose that we find instead that we have the general form starting with $\beta_1=\beta_0$ $\alpha_1=0$ but obtaining $\beta_2=\beta_0+\Delta\beta$, $\alpha_2=\Delta\alpha$. We must close one turn as before and using the new β and α evaluate new functions in the FODO region. We will find:

a) $\mu \neq \psi_i + \varepsilon\psi_{cell}$ and we have a stop-band of total tune width $\frac{1}{2\pi}\left(\frac{(\Delta\beta/\beta_o)^2 + (\Delta\alpha)^2}{1 + \Delta\beta/\beta_o}\right)^{\frac{1}{2}}$.

b) The new betas at previous β_o points now oscillate with 2ψ and an amplitude $A = \frac{1}{2\sin\mu}\left(\frac{(\Delta\beta)^2 + (\beta_o\Delta\alpha)^2}{1 + \Delta\beta/\beta_o}\right)^{\frac{1}{2}}$ about a mean value $(\beta_o^2 + A^2)^{\frac{1}{2}}$.

This means that mismatching necessarily causes loss of effective aperture in the regular part of the lattice and this loss is particularly severe as we approach 1/2 integer tune. All lattices designed for the doubler are beta-matched.

A second aspect of matching refers to the closed orbit for off-momentum particles

$$x = \eta\ \Delta p/p.$$

Again there is a very simple repetitive pattern in FODO cells with the same bending magnets in each cell. The maximum (η_o) occurs with β_o in the F quad. If the insertion transports η from η_o to η_o and $\eta'=0$ then we have an eta-matched insertion. If it transports it to $\eta_o+\Delta\eta$ and $\Delta\eta'$ then the recomputed eta - which must close by definition - will oscillate with ψ and an amplitude, at the η_o points, $\frac{1}{\sin\mu/2}\,(\Delta\eta^2+(\beta_o\Delta\eta')^2)^{\frac{1}{2}}$ about η_o.

The doubler insertions are not eta-matched because the main ring is not eta-matched and we are stuck with its magnet pattern. In each sector (1/6 ring) η oscillates from 2 to 6 M, with three peaks!

Design Restraints

The doubler is to be placed in the main-ring tunnel, which is not circular. The out-of-round is caused by the relatively small regions without bending magnets and to about 1% of the radius, but this is 30 feet or three times the tunnel width! It should be no surprise that most useful modifications from the main-ring lattice place the doubler outside the tunnel, or blocking the passage, for extended regions. I am resigned to reproducing the main-ring form bend-center by bend-center and therefore accept the location of the doubler under the main-ring magnet stands.

There are a few modifications which are desirable or necessary where one can achieve orbit closure without much difficulty.

One necessary adjustment is in the long straight sections. The downstream group of 4 dipoles cannot match the main-ring bending center because of length differences. One must move the upstream threesome by 4/3 the amount in the opposite direction. The orbit is displaced laterally by a small amount but it closes. This is a painful necessity because it squeezes the quad doublet space, as we shall see.

A desirable change is to steal one half magnet from each side of the straight section where the wire septum is located and to put this bending in normal magnets in the straight section center. The purpose is to create a shield to prevent neutral radiation from the wire septum from entering the superconducting magnets and quenching them. Some readjustment of the remaining magnets is necessary.

In a similar vein I suggest using a short filler space which will appear in the medium straight to create a pair of beam-stops between larger diameter half-magnets. The purpose is to catch radiation from beam-limiting collimators in the medium straights.

The most important and extensive modification arises from the following very practical problem. The use of longer doubler magnets has avoided placing magnet connections inside main-ring stands except at the center of the magnet group. This one connection (out of 5) has caused more than 90% of installation difficulties! I am seriously proposing that we shorten the magnets by an average of 1 foot. If one length is used there will be 5 bad locations, if two lengths then at least 2. It is clearly necessary to rotate the doubler with respect to the main-ring but one must do so without creating an impossible survey problem.

The doubler is located from the main-ring quads by very awkward measurements. A simple rotation would make every cell different! (That out-of-round again.) This is a hazardous situation particularly in the future during rush magnet repairs or replacement.

There is a simple (but not obvious) solution. Rotate the regular parts of the machine upstream by (say) 1 foot in a manner that all cells have the same relation to the main-ring. We then do not close at any medium or long straight section but this can be corrected by rotating the medium straight pair by 24" (instead of 12), and the upstream threesome by 52.24", and there is space for this extra motion! This readjustment completely removes stand interference, something which cannot be done in the longer magnet lattice.

Magnet Lengths

A magnet is physically defined by its slot length, the space occupied by the magnet and its share of the connecting gear. A main-ring magnet has a 251" slot. The long doubler magnet has 264" and I propose that half be short doubler magnets at 240" slot. We do need to know $\int Bdl$ but we usually talk about central field so an effective length is useful. The main ring dipoles are 239" effective and the design doubler has been 252", both 1 foot less than the slot. I have just discovered that the doubler magnets warm are built to give 254.5" effective and somewhat less cold. A design standard must be set because doubler quads are in series.

The following designs are based on 45 kG in 252 or 228" bending magnets in series with 19.666 kG/inch quads. Obviously the designs must change slightly.

Note that the longer magnets actually need 42.0 kG for 1000 GeV, and the mixed set need 44.1; both under the design value of 45 kG.

Designs

The diagrams illustrate the essential features of three lattice designs: the main-ring, a doubler design using longer magnets (I), and a design using two lengths which average 1" longer than the main-ring. The latter design, which I recommend strongly, could be implemented with a single length magnet with minor changes.

The diagrams are not to scale. They are outrageously distorted to make readily apparent the differences and relations between the lattices. (They are very difficult to draw.) Quadrupoles are fat boxes and bending magnets are skinny ones. All dimensions are in inches, and effective lengths are shown.

The Standard Cells are shown in figure 1 which is largely self-explanatory. Note that the actual mini-straight available is reduced by magnet ends, connection boxes, etc. Note also the relative position of the beginning, center, and end of the quads. The medium straight section diagrams show how a filler space develops and how it can be used to advantage in radiation traps.

The Normal Long-Straights are shown in figure 2. The design logic starts by adjusting relative ends and center to be the same and for the quad in the standard cell, thus preserving anti-symmetry which makes the vertical the same as the horizontal read backwards. I terminate the doublet 24" short of the main-ring doublet to allow for a warm-up box without letting the doubler intrude into the main ring clear space. The other end of the doublet is determined by the bending center adjustment for closure. Lattice I squeezes the doublet space but Lattice II has an extra move of the upstream threesome because of the rotation which opens up the doublet. Note the special length magnet in the threesome. The doublet strengths are chosen to give a beta-match, until one is close this is a trial-and-error procedure. The end quad determines the precise value of α, β (not separately) at the center and is adjusted to give the best match to the main ring for direct injection. The match cannot be perfect: in I we increase emittance by 8%, in II by 6%.

The procedure is highly iterative, requiring retuning of the standard cells to obtain the correct tune. Lattice II would have

ν = 19.418 in anticipation of high-beta sections which lower the tune slightly.

Hi-Beta Straights

I have for some time been suggesting that a higher beta at the upstream end of F and A sectors would improve extraction. I did not realize:

a) that it is easily obtainable. See figure 3. One simply inverts F and D in the doublet. This became clear after I stole half-magnets to provide a diversion of the radiation from the wire septum, and tried to use the extra space one could get in the doublet of lattice I. Lattice II has enough space. Of course I want to use enlarged quadrupoles and perhaps bending magnets locally. They have now been designed.

b) the effect on extraction is almost a miracle. Whereas previously we had doubts that it could ever work, we now feel that it will be a considerable improvement over the main ring. The extracting beam need never extend beyond .8 inches in the rest of the machine, which is within the design good field region.

We must pay a little bit. I do not mean the special magnets - that is a trivial price to avoid enlarging all magnets - but to some small lattice problems. First we have introduced a slight asymmetry but one would need enormous systematic errors before they could use this asymmetry to compete with random errors. Second, we have added an η wobble. It is not large, 12-18", but it makes each sector somewhat different. For me this is an awful arithmetic nuisance, but I brought it on myself. The insertions are very well behaved on retuning and momentum change. Chromatic aberrations are only about 10 inches at the 9000 inch β.

Lo-Beta Straights

I do not include a design because I am not satisfied. At present practical designs have an enormous η wobble. I do not believe that well-behaved long storage is possible in this case. We will keep trying, particularly in lattice II which has not been investigated. Solutions are of course possible, it all depends on how much extra circuitry and cryogenics one is willing to tolerate.

Hi-Eta Stacking Section

This is a modification to the regular part of the lattice which can be turned on and off at injection. The purpose is to permit rf stacking in the present restricted magnet aperture.

I have been unwilling to accept the a priori elimination of beam stacking because of small magnet apertures or inadequate correction space. My simple aim is to be able to deliver as many protons per day from the doubler as from the main ring. The benefit to experimenters, and hence to the whole lab, is enormous. The difficulty arises not from the size of the stack but from the necessity of two well separated beams just before stacking.

New beam is placed on an off-momentum orbit. To inject it one must use a shielded kicker and then remove the shield. The medium straight is an excellent place for this kicker, however to allow adequate space for the shield we were forced to consider momentum displacements that were too far into the bad field region. Stacking therefore was dropped from design considerations.

In figures 4 and 5 I illustrate a complex but practical modification which changes this decision. The numbers along the bottom are strengths of added quads in units of the standard quad at injection energy. (Present tuning quads are this strong, but one would not use them unless their quality is improved by at least an order of magnitude.)

The quads can be adiabatically turned on and off with beam in the machine. This insertion is completely matched; α, β, η and tune in both planes. The effect is best illustrated in figure 5 which shows the added space for the shield without putting the new beam thru bad field elsewhere. Of course one must take special care near the injection point. The picture also shows how the new beam is injected. The path is similar to normal injection except that the orbit bump is different.

The new beam is still far out from the point of view of random errors. With a well corrected stack there will still be differences at the new beam which must be corrected. For example:

random	normal quad	error cause	horizontal orbit	difference
	skew quad		vertical orbit	
	normal sext		tune,	stop-bands
	skew sext		coupling	
	octupole		chromaticity	
			1/3 resonances	

- etc., and the numerical values of these errors are such that some correction is required. The magnets in previous rf stacking have been very, very much better but this does not mean we can't do it -- provided one adopts a lattice with some extra space for more than the obvious corrections. Lattice II provides this space.

figure 9.

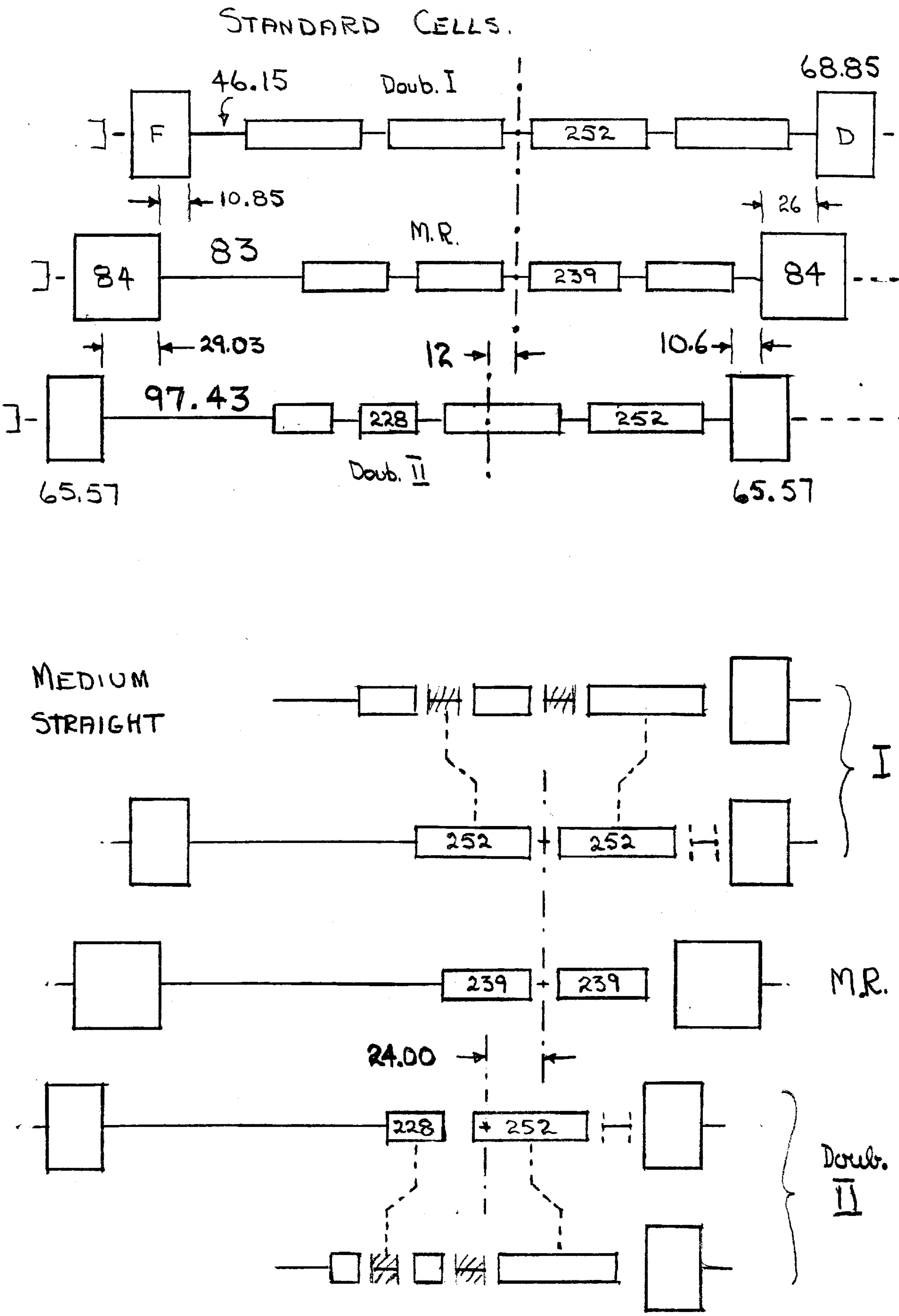

STANDARD CELLS.
46.15
Doub. I
68.85
F
252
D
10.85
26
M.R.
83
84
239
84
29.03
12
10.6
97.43
228
252
Doub. II
65.57
65.57
MEDIUM
STRAIGHT
I
252
252
239
239
M.R.
24.00
228
252
Doub.
II

figure 2.

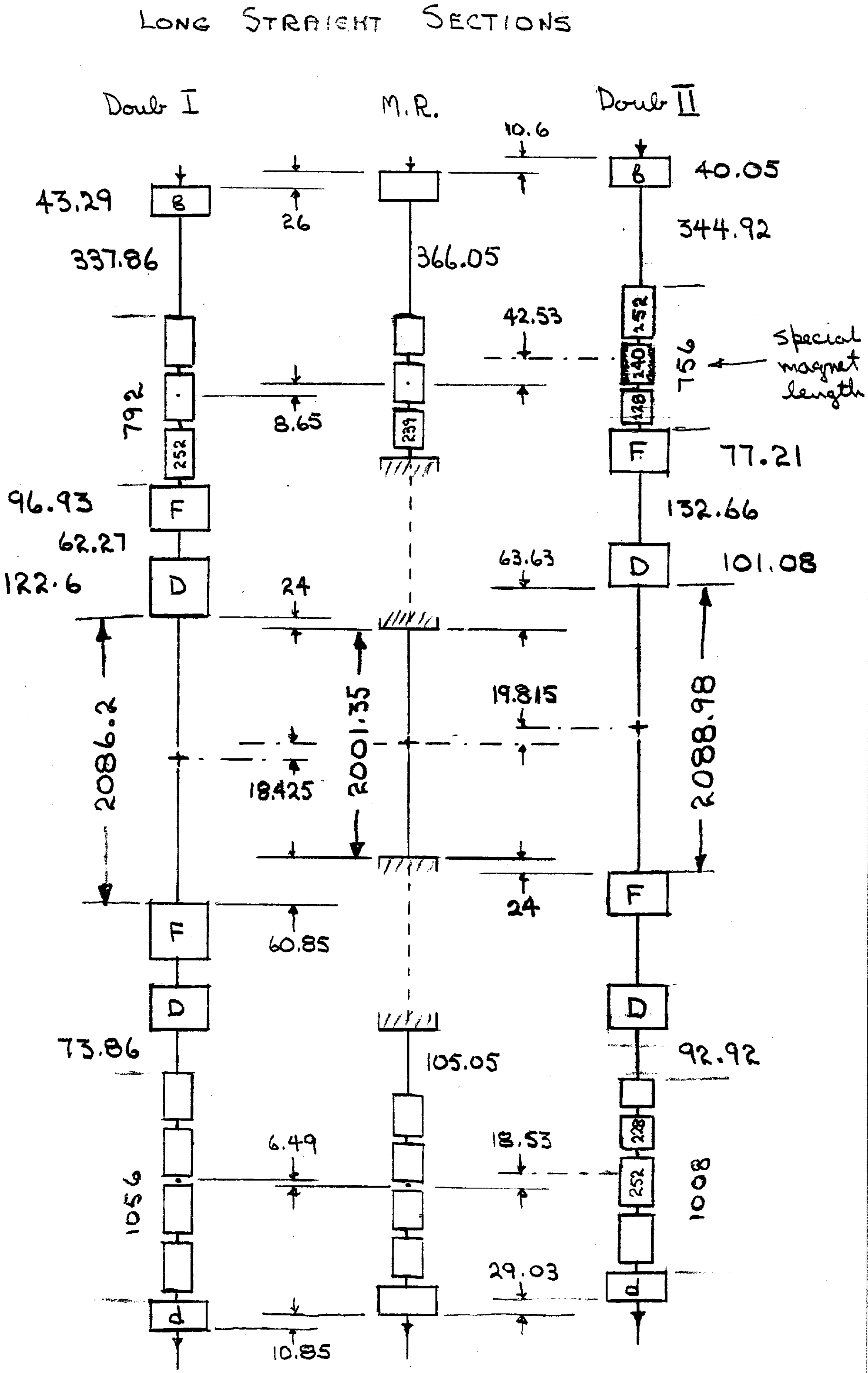

LONG STRAIGHT SECTIONS
Doub I
M.R.
Doub II
10.6
40.05
43.29
B
26
344.92
337.86
366.05
42.53
252
240
756
special magnet length
128
792
8.65
239
252
F
77.21
96.93
F
132.66
62.27
63.63
D
101.08
122.6
D
24
2086.2
2001.35
19.815
2088.98
18.425
24
F
F
60.85
D
D
73.86
105.05
92.92
228
6.49
18.53
252
1008
1056
29.03
d
d
10.85

figure 3

Long Straight Sections for Extraction

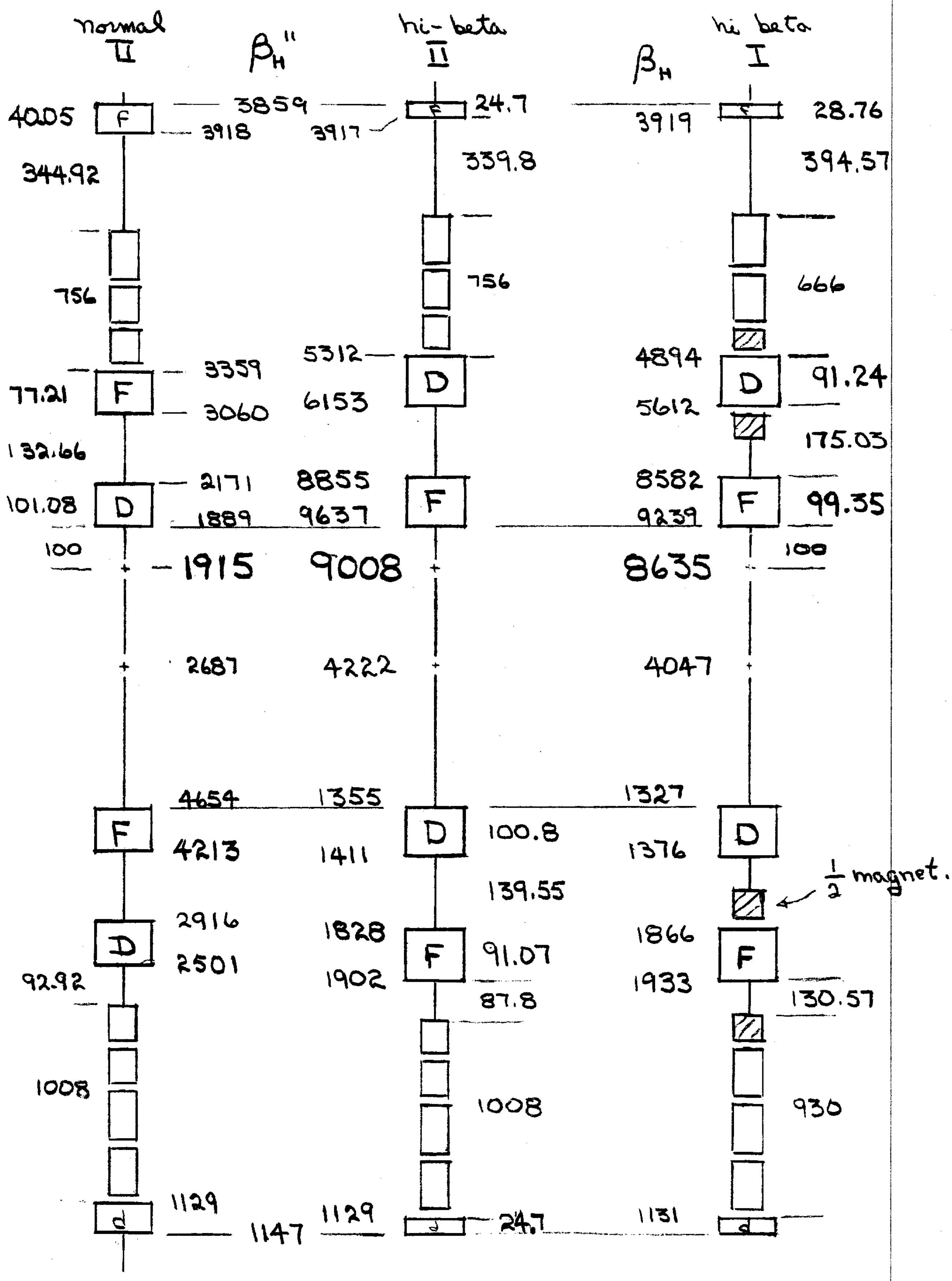


figure 4.

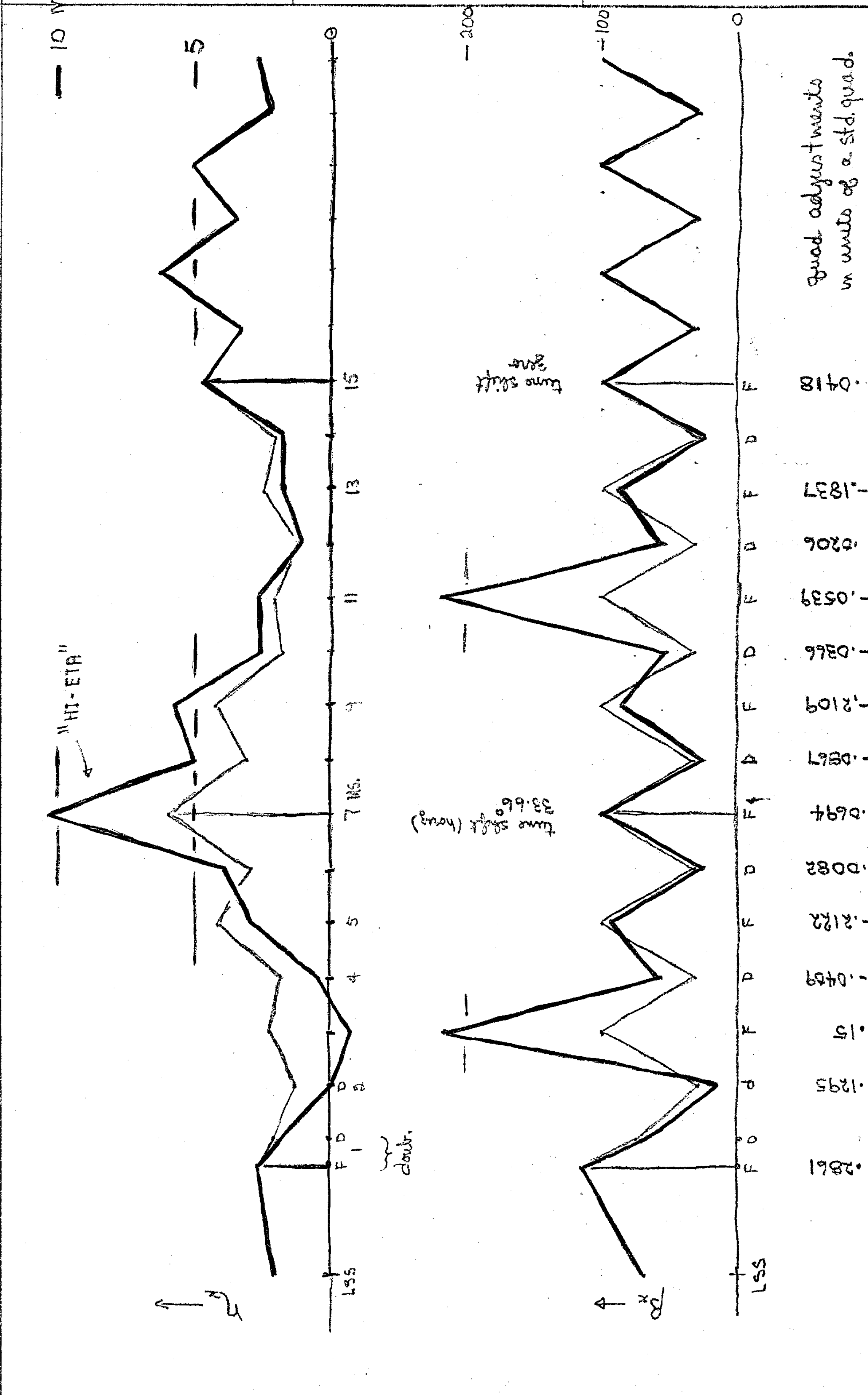
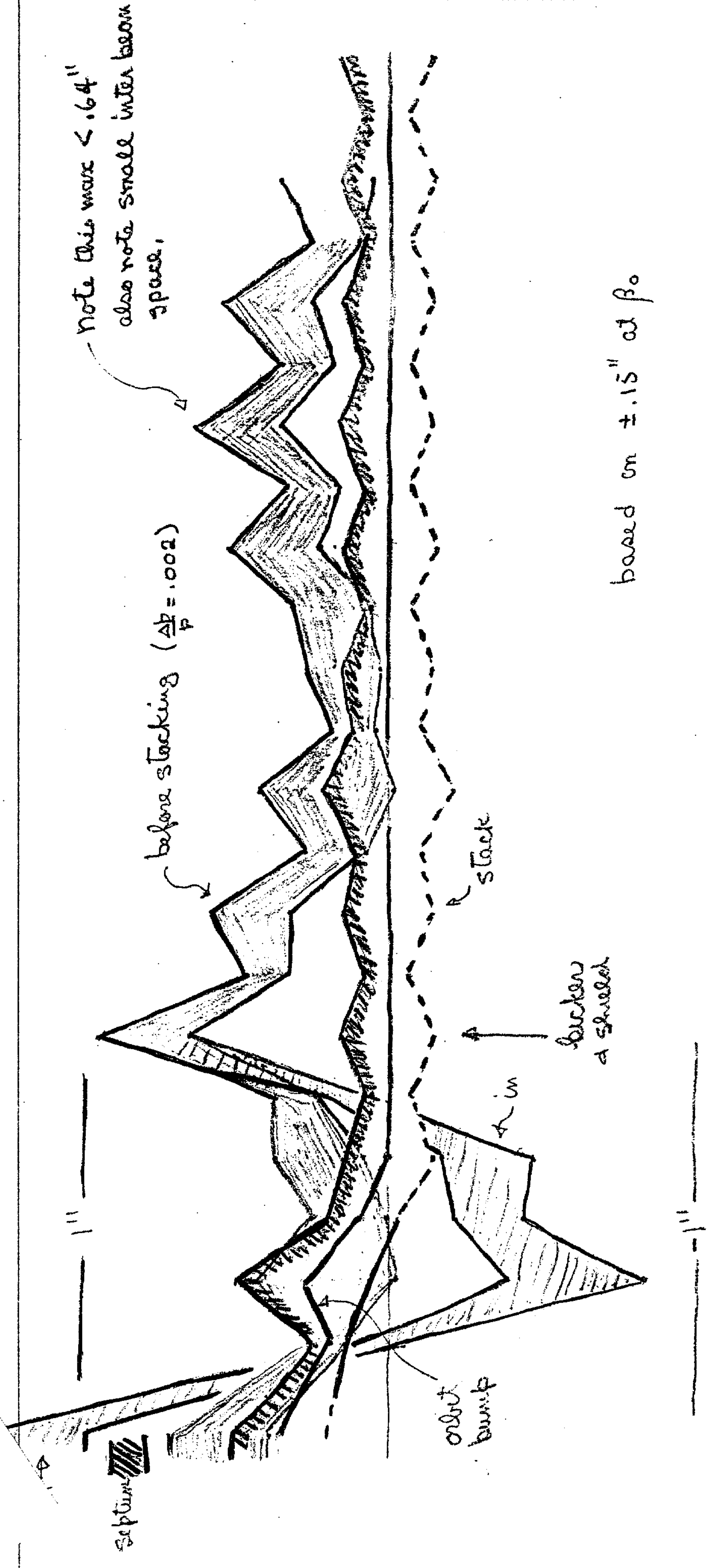

10 M
5
200 M
100
0
quad adjustments
in units of a std. quad.
"HI-ETA"
time shift
zero
time shift (hours)
33.66°
7 NS.
doubt.
LSS
.2861
.1295
.15
-.0409
-.2122
.0082
.0694
-.0867
-.2109
-.0366
-.0539
.0206
-.1837
.0418

figure 5.


note this max < .64"
also note small inter beam space.
before stacking (Δp/p = .002)
stack
kicker & shield
in
orbit bump
septum
1"
1"
based on ±.15" at β₀