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SOME NOTES ON THE NEW LINAC STRUCTURE ALIGNMENT

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INTRODUCTION

These notes assemble some details on possible techniques of alignment for the new Linac accelerating structure and as discussed in a meeting *) on October 9th, 1975, the resulting workload for ISR survey group. One of the aims here is to reply to questions raised in a Memorandum from W. Coosemans and E. Menant of Survey Group (ISR) to E. Boltezar concerning "Alignement du Nouveau Linac" (ISR/SU/WV/EM/sg). Most of the information under the following heading, "Alignment Activities" is based on discussions with E. Boltezar with complementary details coming from G. Plass and P.H. Standley. As far as possible these notes take account of the discussions of 9th October but it must be understood that at this stage variations from any prescribed procedure may occur depending on manufacturing quality, assembly facilities in the PS South Hall and eventual timetable for installation in the Linac tunnel. The required tolerances are also given in a separate section.

In Appendix I, "Alignment Philosophy for the New Linac Structure", there is a qualitative justification for what, after all, represents a major departure from other linac alignment procedures. A brief summary is given in Appendix 2 of the standard analysis from which one derives the transverse position tolerances for drift-tubes. Appendix 3 summarises the aspects of the structure alignment to be undertaken by ISR Survey Group.

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*) Present at meeting were E. Boltezar, W. Coosemans (ISR), H. Haseroth, E. Menant (ISR), G. Plass, T.R. Sherwood, P.H. Standley and D. Warner.

ALIGNMENT ACTIVITIES

One consequence of the philosophy for the structure alignment (Appendix 1) is that one should use mechanical measuring methods in preference to optical ones especially at short distances. These mechanical techniques are standard procedures in machine tool precision work and there are several valid alternative methods all giving the required precision. In practice one expects to use the experience gained on the two sections of Tank I to perfect the techniques.

a) Preparations in the Linac Tunnel

Some of the following work has already started in collaboration with Survey Group (ISR). Initially one must set out two (painted?) lines of moderate (± 2mm) precision on the concrete floor; one corresponds to the beam axis (projected vertically downwards) and a line parallel to the former but at 300 mm towards the South Hall corresponds to the structure reference axis. On these lines will be marked longitudinal positions of supports for LEBT components, tanks and HEBT components (beam axis) and positions of optical target support monuments (reference axis). Base plates have to be set into the concrete floor at the positions marked on Fig. 1.

The necessity, type and positions of monuments have given rise to considerable discussion. One needs at least two reference monuments in the linac tunnel during structure installation to ensure that the linac axis is set-up with known geometry relative to the PS booster and the PS itself *). However, to work with precision on a path of 35m (or more) requires considerable care and good control of ambient conditions so for practical reasons one will also require "secondary" monuments with ∿10m separation to obtain acceptable (relative) precision. Note also that one works successively on Tanks I, III and II over a period of at least six months. Permanent (concrete) monuments are preferred by the surveyors but only one is feasible near the linac structure due to the amount of other apparatus to be installed. So except for this permanent monument close to the output of Tank III, one foresees removable monuments for supporting optical targets at 1860 mm above floor level (600 mm above the beam axis) at four other positions along the machine.

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*) The new linac axis should be horizontal and at the same level as the existing injection line to the Booster. This is nominally 1260 mm above the floor of the new linac tunnel.

It is proposed to make rigid steel structures with sufficient cantilever in the (calibrated) target support region to avoid the accelerator components (including structure sections). These removable monuments can be calibrated on a measuring machine so that the main error arising is in replacement on the base plate. They may also be required after the completion of linac installation for measurements leading to the analysis of possible structure displacement and its correction (if necessary). Note that such an independent sighting line is unnecessary for checking that the tanks have remained relatively aligned (the basic proton dynamics requirement).

Referring to Fig. 1, consecutive pairs of monuments define the local reference lines for individual tanks with the precise longitudinal positions chosen to give least interference with adjacent components. Monuments Nos. 2 and 5 define the reference axis while No. 1 may eventually be unnecessary. As the HEBT reference axis is 550 mm vertically above the beam axis one will probably also need an adapting jig to transfer targets between the structure reference axis and the HEBT axis at the "permanent" monument (No. 5).

Throughout these notes it has been assumed that spherical optical targets and seatings compatible with our Taylor-Hobson micro alignment telescope would be used; within this limitation Survey Group are free to choose any convenient methods for calibration of monuments and further alignment activities.

b) Dimensional checks of accelerating structure including drift tubes

In addition to standard acceptance tests for structure components the dimensions critical for alignment will be carefully measured. On the accelerator tank sections, the end flanges and the top surface will be checked for flatness and parallelism or perpendicularity to the cavity axis defined by the centres at the end flanges.

The drift tube support girder will have an essentially rectangular section but it is not clear yet whether it will have reference surfaces ready machined on top and sides or alternatively only seatings for reference surfaces which are to be calibrated later.

For the radial alignment of drift tubes, dimensions of particular interest are the concentricity of the quadrupole axis with the precise outer diameter of drift tube, and the quadrupole orientation about its axis relative to the axis of the (stainless steel) support stem. The important dimensions determining the gap and cell geometry are overall drift tube length and squareness of end faces to the tube axis. A more difficult dimensional check is that the stainless steel support tube should be a straight cylinder with axis intersecting perpendicularly with the drift tube axis.

For the smaller items the facilities and personnel of linac group and PS workshops should suffice but for tank sections and girders we may need the support of central workshop mechanical checking.

c) Preliminary assembly of structure

In principle the measurements made in b) should allow the prediction of how tanks and girders will fit together and, in particular, whether the assembled tank axis defined by the centres at the end flanges is tolerably close to the axis of individual tank sections. The squareness of the end flanges relative to the tank section axis determines the deviation of the assembled tank from a continuous cylinder. But this source of alignment error could be corrected by setting the girder top reference surfaces during the preliminary assembly so that for all sections of the tank they are coplanar and horizontal. The drift tubes for a complete tank would eventually be set at constant vertical displacement from the top reference surfaces.

Setting-up the girder top reference surfaces can be done using dimensions of tank sections assembled individually with their girders but there is no doubt that assembly of adjacent parts of sections before setting the reference surfaces will be a sounder procedure. Both sections of Tank I should be joined together in the South Hall linac assembly area (adjacent to the new linac building). This experience will determine the approach for Tanks II and III where one might otherwise leave the reference surface setting-up until final assembly in the linac tunnel. The reference surfaces on the sides of the girder are either ready machined or set parallel to the girder centre line (at the same distance on all girders). When the girder reference surfaces have been established the corresponding (local) beam axis is also defined and two target supports per girder can be set mechanically on to the reference axis 600mm above and 300 mm horizontally displaced from the beam axis.

It is also useful at this stage to mount the drift tubes on the girders, making the vacuum seals between the copper stems and girder bottom surface and at the same time adjusting the drift tube to lie along or parallel to the beam axis. A quick alignment check will verify the useful range of adjustment and give the upper limit of required shim size for setting the vertical positions.

d) Tank and girder alignment in the linac tunnel

After assembly of complete and correctly loaded tank in the linac tunnel, a useful check of top reference surfaces and deflection (due to the increased separation tank supports) can be made using spirit levels. (Maximum deflection has been calculated as less than 50μ in the worst tank). The first stage of the optical alignment is to adjust the tank supports so that the two targets on the end flanges lie on the reference axis. At this stage the girder bushes that receive the tank pins can be adjusted (horizontally) by shims so that the girder targets also lie on the reference line. There should be no error in vertical position if top surface references and target offset have been made correctly. For all tanks one can use monuments closest to each end of the tank to define the local reference axis.

e) Alignment of drift tubes

The girder reference surfaces, once set relative to the beam axis, can be used for mechanical alignment of drift tubes if one supports the girder horizontally with the drift tubes accessible. The drift tube has two adjusting screw mechanisms acting on the support stem to rotate the stem in a spherical seating so that with an arm of ~ 400 mm the drift tube moves (over a small range) essentially along the linac axis and perpendicular to it, respectively. Vertical adjustments of the drift tubes can also be made by screws but fixed shims will be substituted when the adjustments are completed.

Using the measured drift tube lengths, one can set up specified linac unit cell lengths by adjusting the drift tube to drift-tube separation (with several sound methods of measurement possible). Accumulative errors in drift tube position should be avoidable, as the girder end faces can be used as reference for longitudinal positions of extreme drift tubes on girder.

For the radial alignment one sets the drift-tube cylindrical surface at fixed distances from the girder reference planes in horizontal and vertical directions. One feasible method would be with a measurement jig using (at least) two clock gauges to locate on the outside surfaces of the drift tube. This apparatus can be continually checked against a fixed master gauge. A cross check on the alignment could be made relative to a standard straight edge supported close to the drift tubes. The techniques suggested can be readily applied by mechanics experienced in the use of precision machine tools so personnel for this activity can be found in linac group or PS division.

f) Alignment checks on the complete linac

After replacement of the aligned sets of drift tubes in the tank, the end covers (sometimes forming part of the intertank region) will be fitted and their alignment checked mechanically. A repeat of sequence (d) may be advisable, at least for Tank I. When the linac is completely installed it will still be possible to replace and use alignment monuments Nos 3 and 4 but one would not normally want any of the monuments in place during operation. As indicated in Appendix I the important alignment errors to avoid are relative displacements of adjacent components, in this case adjacent girders, so that the use of the tank end targets to define a secondary line for a given tank would be sufficient to verify that the alignment is satisfactory. If, after some time, the linac alignment became sufficiently bad to affect the measured output beam, then one would need the independent monuments to analyse fully the causes of misalignment and to readjust the tanks and girders.

g) General

Note that items b), c) and d) are repeated for all tanks which will be installed in the order I, III and II respectively. After initial experience has been obtained the techniques developed for checking the alignment of the complete linac should be applicable during a maintenance period without the help of Survey Group.

TRANSVERSE POSITION TOLERANCES FOR STRUCTURE COMPONENTS

Choosing to separate "short distance" and "long distance" tolerances makes the specification rather more complicated than the traditional one of a single radial tolerance relative to an ideal straight line. However, the aim here is to make the quoted tolerances more consistent both with those reasonably obtainable and with the proton dynamics requirements. The notion of a smooth curve is difficult to express as a tolerance so one considers that the curve consists of a chain of shorter straight lines. Note that tolerances quoted apply to vertical (y) and horizontal (x) positions independently and that the axis of a quadrupole is assumed defined by the outer cylindrical surface of its drift tube.

A. Drift tube transverse positions (mechanical measurements)

i)	± 0.05 mm	w.r.t. straight line 1m long	on same girder (i–iii)
ii)	± 0.07 mm	w.r.t. straight line 2m long	
iii)	± 0.10 mm	w.r.t. straight line length of girder	
iv)	± 0.10 mm	relative alignment adjacent d.t.'s on different girders	
v)	± 0.15 mm	relative alignment full d.t.'s in different tanks	
vi)	± 0.10 mm	relative alignment end drift tube and adjacent ½ drift tube	

B. Girder and tank transverse positions (survey measurements)

vii)	± 0.05 mm	relative alignment of adjacent optical targets with $<$ 1m axial separation
viii)	± 0.15 mm	alignment of girder targets relative to straight line between corresponding tank end targets
ix)	± 0.25 mm	alignment of tank end targets relative to straight line defined by Tank I (input) and Tank III (output)

When the straight line in i) and ii) includes the end drift tube on a girder, one end of the line is defined by this drift-tube. Similarly in iii), the line is completely defined by the two end drift tubes. Tolerances iv) and v) are cross-checked by the simpler measurement vii) but in turn this implies a precise setting-up of the end drift tube relative to the optical target (±0.05 mm).

It must be added that the figures quoted above assume corresponding tolerances in manufacture of drift-tubes, quadrupoles, girders and tank sections and stability of the assembled structure.

Distribution

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APPENDIX I

ALIGNMENT PHILOSOPHY FOR THE NEW LINAC STRUCTURE

A motivation for this Appendix is that the proposed alignment procedure (radial position of drift tubes) is significantly different to that on any other full scale linac. In particular, mechanical measurement methods will be used wherever possible (e.g. for drift tube positions relative to their girder) and optical methods will be used over longer distances ($>$3 m) where it is necessary to establish a common line for all structure sections and to relate it to the geometry of the PS complex. This approach has been adopted because we believe that linac alignments achieved so far are generally unsatisfactory as regards :

a) the physical specifications ;

b) the methods used ;

c) the resulting alignment precision especially after operating for a year or more.

Regarding a), physical tolerances are traditionally quoted as root mean square radial deviations from the ideal straight beam axis whereas what matters in a strong focussed linac is r.m.s. radial deviation relative to a smooth curve itself having small amplitude and long period variations relative to the ideal line. Computations have indicated that for a focusing structure like our linac, the smooth curve can have a peak deviation from the ideal line of up to $\sim$1 mm if the period is 2 x radial oscillation wavelength.

As an indication typical operating conditions proposed for the new linac would give $\sim$3, $\sim 2\frac{1}{2}$ and $\sim$2 radial oscillations in Tanks I, II and III respectively.

Hence one should in practice direct attention firstly to ensuring best precision for relative alignment of adjacent drift tubes, then to relative alignment of drift tubes on the same girder and finally to the complete linac assembly.

For b), alignment methods usually used *) follow from the idea that one needs to ensure that the drift tubes are precisely on an

*) At Berkeley, however, they have reported a method involving a current carrying wire stretched along the linac axis to define the line of the quadrupole magnetic centres. This seems a good example of a relative drift-tube to drift-tube method.

ideal straight line, hence a "long distance" method (telescope or laser) involving light paths often greater than 10 m is chosen. This procedure seems illogical if the important measure is the relative alignment of adjacent drift tubes which are separated by less than 500 mm (centre to centre). A purely optical method brings problems with precise optical targets and their seatings in drift tube apertures, and turbulence and operator fatigue (telescopes). In order to apply mechanical measuring devices (straight edge, spirit level, micrometer, clock gauge, etc.) one requires accessibility and shorter working distances, both of which are present when using removeable drift tube support girders (less than 3.5 m long). The drift tube outer cylindrical surfaces are used to define the axis of the quadrupole which is the important parameter in the radial alignment.

An acceptable alignment precision is, in part, a consequence of the specification a) and method b) but more important in the long term is the stability of the whole structure when subject, for example, to vacuum forces, temperature changes and building settlement. However, according to a) one can tolerate the long wavelength effects (movement or flexion of a complete tank) if there are negligible random effects also introduced. The development of the girder support has stimulated a detailed investigation into the expected deformation and flexion of assembled cavities related to the position of the two supports. In addition proper elastic constraints for the drift tube support stems are essential to reduce random effects. Ample provision of reference surfaces on tank sections and girders will allow us to check cavity distortion under operating conditions.

A consequence of the above is that one cannot really justify accurate optical sighting along the beam axis and in fact it would be difficult to implement. Hence, the standard reference axis defined initially by the calibrated "monuments" will be external to the accelerator structure, (600 mm above and 300 mm to one side of the beam axis), and will be useable with the machine completely assembled, for checking tank and girder alignment.

APPENDIX II

EFFECT OF ERRORS IN DRIFT TUBE TRANSVERSE POSITION

The most difficult alignment tolerance to respect in practice is in radial position of quadrupoles *) relative to the beam axis and it is also the relevant one for the global alignment under discussion in these notes. The treatment used here follows Gluckstern (p. 802 of Linear Accelerators, Ed., Lapostolle and Septier) and in particular we use his result (Eq. 13) which can be expressed as

$$\delta Y = A \Delta y$$

where δY is the r.m.s. value of the set of possible (coherent) beam displacements at the linac output resulting from a global r.m.s. displacement error Δy (in quadrupole position) where one assumes the individual displacement errors are uncorrelated and each has r.m.s. value Δy. Factor A depends on the operating conditions of the linac (.e.g., quadrupole gradient, ϕ_s), number of drift tubes, etc., and is derived from a rather lengthy analysis of the transverse transfer matrices along the linac. For operating conditions corresponding to $\mu = 39^o$ (μ = phase advance of betatron function per FD focusing period) two limiting cases are $I = 0$ and $I = 150$ mA whence $A \simeq 37$ and 44 respectively. At the end of the linac we can set an absolute maximum value of beam displacement as 4 mm and take this as $2 \times \delta Y$ i.e., $\Delta y < 0.05$ mm. We interpret this as a mechanical engineering tolerance of ±0.10 mm.

These are "short distance" tolerances into which are folded errors in quadrupole magnetic centre relative to the magnet yoke outer diameter, errors in magnet centring in the drift tube body, errors in the drift tube diameter as well as the errors in setting the drift tubes relative to the reference line. Note that Gluckstern also considers the notion of "short distance" tolerance : "The effect of magnet misalignments can be greatly reduced by assembling doublets or triplets with high pre-

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*) When discussing alignment it is the "quadrupole displacement which is important but we often assume that the drift tube outer cylinder is concentric with quadrupole axis so talk of "drift tube displacements".

cision and then aligning these assemblies in the linac". The same arguments apply to both transverse directions (horizontal = x, vertical = y) separately, and an overall "radial" tolerance is not considered a useful notion as maximum beam displacements in x and y cannot occur simultaneously.

APPENDIX III

SUMMARY OF SURVEY GROUP (ISR) WORK ON LINAC STRUCTURE ALIGNMENT

These notes have not dealt with the alignment of the preinjector, LEBT and HEBT though in fact the first two items mentioned are urgent and have the most influence on the timetable proposed below. (For details concerning preinjector and LEBT respectively H. Haseroth and M. Weiss should be consulted.)

As far as the linac structure is concerned, Survey Group will be concerned principally with a) setting up the structure reference axis and b) alignment of the large components, viz. complete tanks and their girders, to this axis. Any methods compatible with the Taylor-Hobson target seatings and telescope (already available in Linac Group) may be chosen to meet the transverse position tolerances specified (telescope, laser or stretched nylon cord seem the most likely alternatives at present). In the following we list the alignment activities (as in the notes) indicating Survey Group participation and some tentative finishing dates (depending on component delivery).

a) Preparations in the Linac Tunnel

Full participation of survey group is required, the final goals being to mark positions of all the major components in the Linac tunnel (12 Dec. 1975) and establish the reference axis with its five monuments (13 Feb 1976). The design of the monuments is to be compatible with adjacent components especially near to the reference axis. Any necessary concrete work should start as soon as possible. As an indication, the pre-injector and LEBT alignment will be necessary as installation proceeds (Jan. 1976 to May 1976).

b) Dimensional checks of accelerating structure including drift tubes

Mechanical methods only proposed.

c) Preliminary assembly of structure

Mechanical methods probably sufficient at this stage though preliminary trials of longer distance methods (Survey Group) may be possible when two sections of Tank I are assembled in the South Hall (April 1976).

d) Tank and girder alignment in the Linac tunnel

This includes nearly all of the actual structure alignment work for which Survey Group is responsible. (Tank I, July 1976; Tank III, November 1976 ; Tank II, February 1977).

e) Alignment of drift tubes

Mechanical methods.

f) g) Alignment checks on complete Linac

To be done by Survey Group at installation time (March 1977). Periodic checks of overall Linac alignment should be possible later, e.g., during a maintenance period, without the active support of Survey Group.

Further information and drawings can be obtained from D. Warner and E. Boltezar.

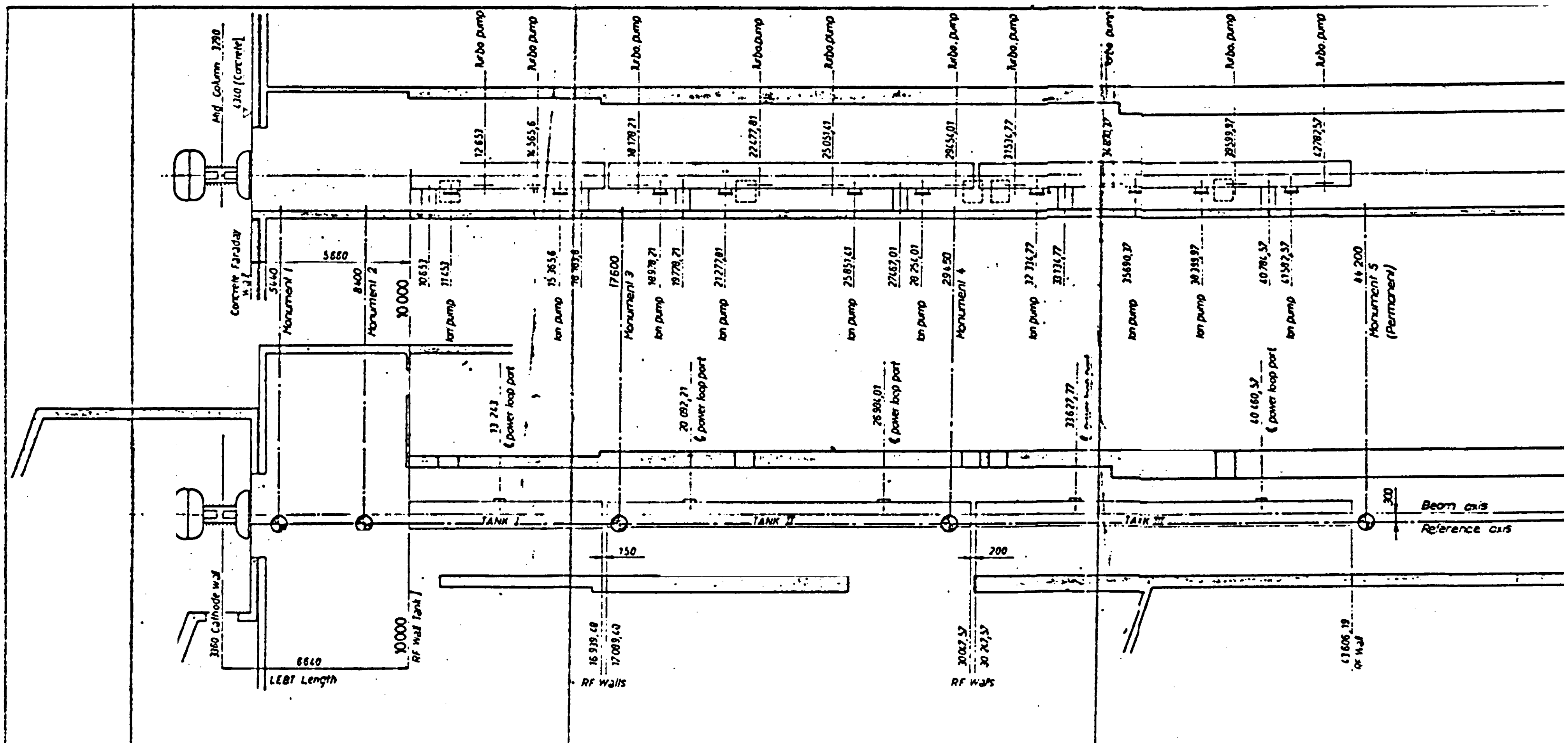

FIG. 1: New Linac longitudinal coordinates