MPS/Int. LIN 69-6/Draft
20.2.1969

IMPROVEMENT PROGRAMME

LINAC

Linac Group, edited by C.S. Taylor

INTRODUCTION

Recent developments in operational instrumentation at 50 MeV have made it clear that under routine operating conditions the beam intensity lying within 30 π mm mR transverse acceptance and within the energy limits ± 150 keV is of the order of 65-70 mA. Typical figures are 90 mA total, with 90% lying within the transverse acceptance, of which 80 to 84% is within ± 150 keV for the duration of injection. Under peak conditions much higher figures have been obtained, but at present these highly tuned conditions are of debatable interest as they require a large amount of work for a small improvement in PS performance.

Briefly, the object of the Improvement Programme for the Linac is to improve the beam quality so that the 100 mA within 30 π mm mR and ± 150 keV required by the Booster is achievable under normal operating conditions, with some margin of reserve, and to maintain this quality constant over a long beam pulse of 100 μs (10 μs at present) and at a repetition period of 0.6 seconds (nominally 0.9 seconds minimum at present).

This higher average beam quality problem is being approached from two distinct directions.

The first approach, working with the machine more or less as it is at the moment, is to try to bring the average performance nearer to the peak by :

1) better control of the significant parameters by means of elaborated instrumentation and data acquisition, with eventually the application of automatic control on a limited scale, and

2) better control of the physical state of the machine, including surfaces and vacuum, alignment tolerances, etc., particularly in the low energy region up to 500 keV.

The second approach, which will involve major surgery, is to make better use of the high phase space density available from the duoplasmatron ion source, mainly by raising the pre-injector energy above 1 MeV and thereby reducing the space charge dilution which occurs at present in the 500 keV energy region.

The design of a new pre-injector of energy greater than 1 MeV is the subject of a collaboration between the University of Lyon, Saclay and CERN, while the design of a new Tank I to accelerate from pre-injector energy to 10 MeV will be based on the 3 MeV studies at present being prepared in the South Hall Extension.

It is proposed to install the new pre-injector and Tank I or new "front-end" in 1973, i.e. after the completion of the Booster, which means that for the start-up of the Booster one expects to have a Linac beam of the required quality at the measurement point on the injection line, but with no margin of reserve until the modification in the following year. For the sake of completeness it should be mentioned that the study and realisation of the injection line is being carried out for the SI Division by a section of the Linac Group. Some aspects of this line, in particular the beam measurement equipment, will be included in the discussion which follows. This discussion will be divided into 4 sections :

1. the instantaneous beam quality,
2. the engineering problem of maintaining this quality constant over the duration of the beam pulse,
3. the maximum use of existing 50 MeV beam quality (including a discussion of single and multi-turn injection),

and 4. beam quality measurements.

This chapter will be concluded with a time-table for this work.

1. INSTANTANEOUS BEAM QUALITY

In a previous report (Taylor et al, 1968) it was pointed out that the 4-fold improvement in pre-injector phase space density which resulted from the installation of the duoplasmatron/short column combination in 1966 produced only a 2-fold improvement in 50 MeV density. There are several indications tha this is pre-dominantly a space charge problem in the low energy region from the pre-injector onwards, and so in 1968 a preliminary study was carried out (Huguenin et al, 1968) in order to assess the technological problem of raising the pre-injector energy and in order to evaluate separately some of the benefits in beam quality to be gained by higher injection energy. Work is now in progress to express the combined effect of these benefits by the computation of the three 2-dimensional densities at 50 MeV as a function of injection energy, using a space charge dynamics programme which is being developed in collaboration with Saclay (Martini and Eadie 1968). Another advantage of higher injection energy, unrelated to particle motion, is the effect on tank breakdown. If we were to inject at 1.5 MeV, this would eliminate the first 10 gaps of the present Alvarez structure,in which gaps most of the R.F. sparking takes place - in fact these is little sign of sparking beyond the 6th gap in the present Tank I of the Linac. All the evidence at the moment points to inter-electrode distance as being the dominating factor in proton linac breakdown (Davies, 1969).

Besides the studies of the proton dynamic in the presence of space charge in the Linac itself, there is the problem of the transport, matching and bunching of the pre-injector beam. A six-dimensional programme exists already for the case of bunched uniform radial distributions (Vermeulen, 1967). For the pure drift part of this problem with non-uniform radial distribution, a computer programme has been developed by the University of Rennes, working in collaboration with CERN (Tanguy, 1969).

It is anticipated that the 3 MeV Alvarez accelerator will be extremely useful for the comparison of computed dynamics with measurement (Warner et al, 1968) and it will also to a large extent replace the 50 MeV machine as a development and test-bed for instrumentation and proton Linac techniques. On the basis of this work the new Tank I will be designed and constructed, and it is planned to test the tank in the South Hall during 1972 in preparation for its installation on the Linac in 1973.

In parallel with these studies of beam behaviour, a study programme has been embarked upon for the design of the new pre-injector. The first part of this, the development of an accelerating tube capable of holding off high voltages greater than 1 MeV is being carried out in collaboration with the Institute of Physics of the University of Lyon, who are constructing a testing hall for this work and making available a 1.2 MeV generator. The accelerating tube will be an extrapolation of existing CERN technique (Huguenin et al, 1966). This work will also be of direct interest to Lyon as such a tube is required for the heavy ion accelerator at present under study there. The collaboration with the Saturne Injector Group at Saclay concerns the beam dynamics and the design of the high voltage generator. Discussions have started concerning the construction for CERN of a H.T. generator > 1 MeV for the project. This again would be an extrapolation of existing techniques, which in this case have been applied successfully to a 750 keV generator under gas pressure (Viennet et al,). There is also some interest in their method of proton extraction, which holds out the possibility of more uniform density across the beam and reduced dilution caused by non-linear space charge coupling.

By December, 1969, it is hoped to have sufficient experimental and theoretical data available for a firm proposal to be made to build a new pre-injector to a certain energy, and to continue from this energy to 10 MeV in an R.F. structure.

2. ENGINEERING OF THE LONG BEAM PULSE

The problems with a lengthened beam pulse are in general :

1) to redesign the various power supplies which provide accelerating and focusing fields so that these fields remain constant for the 100 μs of beam pulse and are unaffected by the passage of the proton pulse,

2) to provide for the increased dissipation of heat in the power supplies and in the accelerator itself,

3) to take steps to cope with the higher radiation levels to be expected with 20 times the present mean beam current,

4) to make all new equipment as reliable as possible

We shall now consider separately the specific problems of the main systems of the Linac.

1. PRE-INJECTOR

a) Ion Source

Arc Pulser : A new pulser capable of producing a 90 Amp. 100 μs pulse has already been developed. This has involved the modification of the monostable square wave generator and final amplifier, and the re-design of the output pulse transformer. At the cost of an additional 30 W of power it has been found possible to bias off the transformer core flux so that 1.8 times the former B_{max} is usable.

---

* Reliability is inextricably linked with the problem mentioned in the Introduction of bringing the average performance nearer to the peak, but will be included here for convenience.

Figs. 1 and 2 show the resulting arc current and voltage pulses.

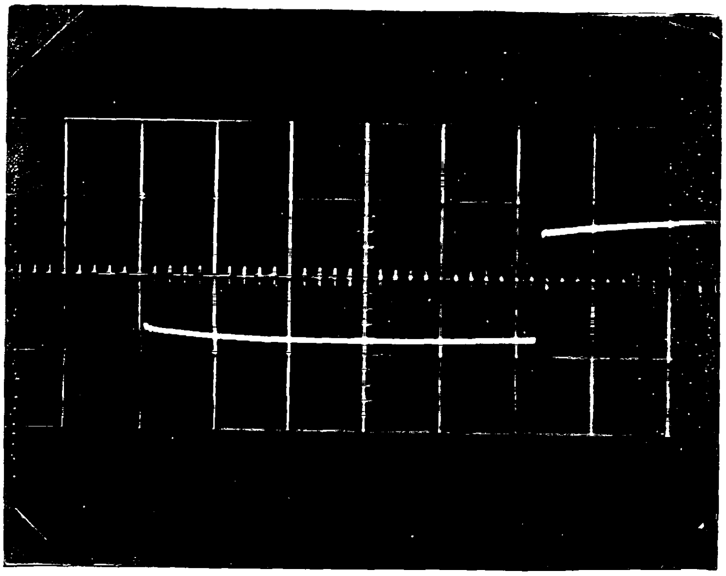

Fig. 1. Arc Current
50 A/cm, 20μs/cm

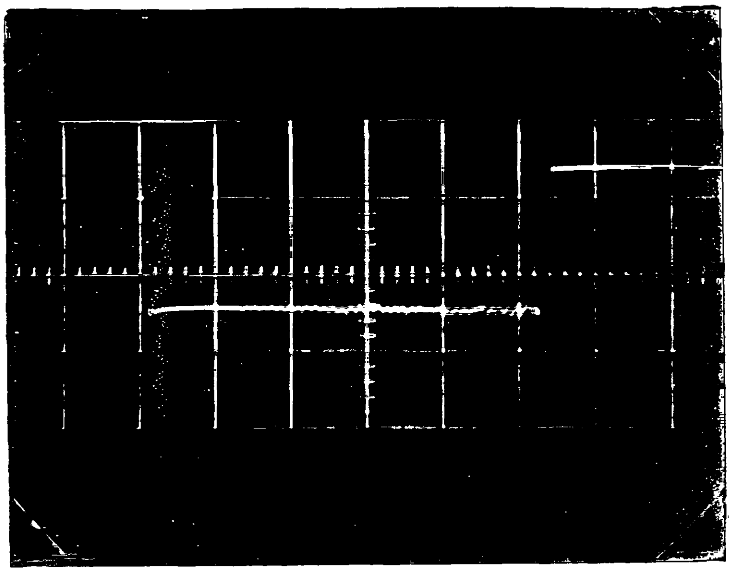

Fig. 2. Arc Voltage
100 V/cm, 20μs/cm

Extraction Supply : In a similar manner the extraction pulse transformer has been modified to produce a 100 μs pulse (Fig. 3), the main difficulty being the induced voltages in the bias windings which had to blocked by means of a filter.

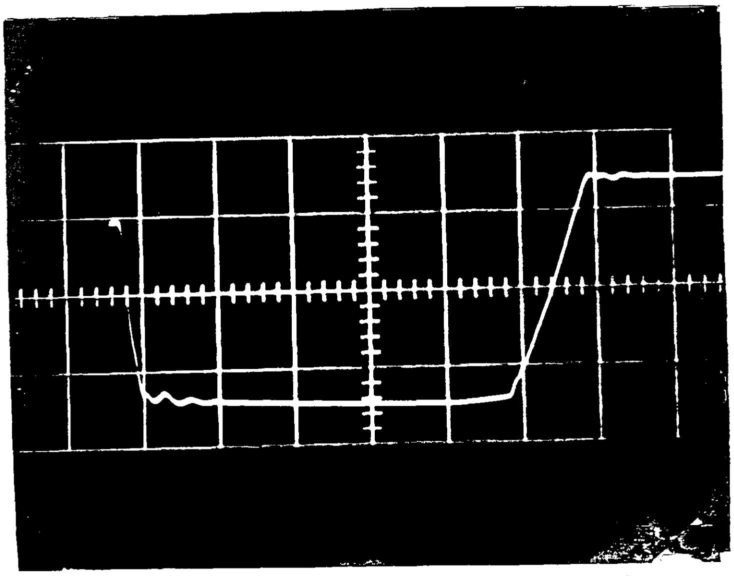

Fig. 3. Extraction Voltage Pulse
25 kV/cm, 20μs/cm

Extraction Grid : In the interests of reliability, the previous tungsten wire grid has been replaced by a grid in tantalum, formed by spark erosion of a 0.125 mm sheet. This process gives a transparency of 80% and a mechanically more robust grid which has functioned without fault for 4 months.

b) High Tension Beam Loading Compensation

Since mid-1966, the fall in the terminal voltage of the pre-injector due to the passage of the beam has been compensated by a primitive but fairly efficient circuit employing a triggered spark gap and an auxiliary 100 kV generator. For the longer pulse there is a wide choice of possible compensating circuits :

1) a programmed over-voltage regulated by a hard tube in the spark-gap circuit as at Brookhaven at present,

2) a cathode follower regulator driven by a grounded-cathode stage as produced for Los Alamos by Haefely,

3) two series regulator tubes with a H.F. modulation on one of them as proposed by Haefely for the Brookhaven Conversion.

4) a cathode follower driven by an isolating pulse transformer.

We have chosen the last solution because of its simplicity, the main problem being the design of the transformer for an adequate bandwidth and voltage hold-off. The circuit has been tested on open and closed loop in the lab. but has yet to be tested on an accelerating tube with beam.

Fig. 4 shows the circuit of the regulating system, and Fig. 5 the physical arrangement. The specification for the system is as follows :

Beam current (including secondary electrons) = 1 A max
Beam pulse length = 100 μs
Repetition rate = 2 pps
Residual H.T. variation = ± 10^{-3} (± 500 V at the present energy)

2. FOCUSING

The magnetic focusing elements which will be affected by the increase in beam pulse length are the pulsed triplets which match the pre-injector beam to the Linac and the pulsed quadrupoles in the drift-tubes of Tank I. [The other focusing elements included in the Linac responsibilities are the D.C. quadrupoles of Tanks II and III and the D.C. matching triplets between the Linac and the PS. It is proposed to replace the motor-generator set which supplies the D.C. tank quadrupoles by a solid-state supply for reasons of reliability and maintenance].

At present the pulsed quadrupoles are wound with a large number of turns having an inductance of the order of millihenries and a resistance of the order of ohms, and they are excited to currents of 50 - 70 A by the resonant discharge of a capacitor, which results in a semi-sinusoid 500 μs long, permitting a reasonably constant current during the passage of the 10 μs beam at the maximum of the sinusoid. These quadrupoles should remain in service until 1973 when the new Tank I will be installed. If it were clear that we would use the same type of quadrupole in the new tank it would be worthwhile to rebuild the supplies now for the longer pulse length and then to use the same supplies for the new tank. If on the other hand, cogent reasons appear for using a small number of turns and higher currents in the new tank quadrupoles (as is being done at Los Alamos and Brookhaven) a different design of quadrupole supply might be needed, and there would not be much sense in carrying out an expensive re-build of the present equipment to last only until 1973. A relatively simple modification has been described recently (Warner, 1968) which, by the addition of a harmonic resonant circuit, extends the plateau to > 100μs for only a small increase in quadrupole dissipation (10 - 20%), and this could be the most flexible way of dealing with the long pulse until 1973. The increased repetition rate, requiring a higher charging current, could be provided by increasing the number of parallel regulating tubes 3C33 from two to four, as has in fact been already done for the matching triplets.

In the coming months these problems will be studied in detail so that one can decide either on such a minimum cost solution, or on a complete rebuild which must be compatible with the new tank quadrupoles.

From the point of view of the mechanical engineering of the accelerating structure, the most desirable solution is that which produces no significant increase in dissipation in the drift-tube quadrupole, and therefore does not require the connection of the water-cooling circuits, which were provided originally but never connected since the need for water cooling secured marginal.

3. R.F.

For some years the Linac has been operated with two final R.F. amplifiers per accelerating cavity, one supplying a long pulse (200 μs) for filling the cavity to the required accelerating level, and the other (20 μs) replacing the energy extracted by the beam.

In principle, by installing 5 MW triodes (TH 516) in the beam loading compensation amplifiers one should be able now to compensate beams up to 200 mA for a duration of 20 μs. However, the input circuits of the final amplifiers are still in the original form, i.e. designed for the power levels of few hundreds of kW required by the 2.5 MW tube triode (TH 470),and are inadequate for the power levels required by the TH 516. Therefore the programme of improvements planned for the R.F. system during the next few years includes not only the extension of pulse lengths (200 μs and 20 μs respectively for the main and compensating amplifier to be increased to 300 μs and 100 μs) but also a redesign of the input and drive circuits. At the same time digital technique will be applied to controls and indications, and the accelerating fields will be stabilized by local feedback loops with the reference points computer controlled (Block, 1969). Automatic phase control using digital techniques has already been developed for the 3 MeV accelerator (Block et al, 1969).

The proposed modifications have been described in detail in an internal memorandum (Block, 1968) from which we show the general schematic of the proposed system (Fig. 6).

The biggest items of construction will be the new modulators, which it is planned to have manufactured by industry to a detailed specification.

4. RADIATION, CONTROLS AND DATA HANDLING

Discussion of future control problems for the Linac - 50 MeV Injector Line - Booster liaison have led to the conclusion that the Injection line and Linac controls need to be closely associated, as do the Injection line and Booster (and of course the Booster and PS). It seems necessary therefore to find a solution which can group all the control centres in or near the present MCR and control computer region. At the same time the increased radiation levels to be expected in the present Linac Control Position provide another reason for the re-allocation of the Linac Controls. The points will be examined in more detail in the following paragraphs.

a) Radiation

After the completion of the PS improvement programme, the anticipated radiation level at the present Linac control position will surpass the tolerance limits for prolonged exposure of personnel. Radiation in this area is generated by the Linac itself, the PS and in future also by the beam transfer lines to ISR and the West experimental area. K. Goebel has made an assessment of the future situation and concludes : "The radiation level produced by the Linac itself, (for 20 times higher average current), mainly the fast neutron doses are about as large as the ones expected from the ISR beam stopper for 10^{13} p/sec; the values might approach 100 mrem/h at the access doors. Radiation from X-rays of the ion source and muons from the targets are about an order of magnitude smaller. The wall of the Faraday cage or the ion source, etc., can be shielded in order to reduce the X-radiation below 1 mrem/h. To reduce the fast neutron radiation, a wall of about 80-100 cm concrete must be built covering the tunner cross section. This must be located at the entrance of the first Linac tank. Another possibility would be to displace the Linac Control and to close the present Linac area entirely during operation".

From our side we can conclude that the X-ray shielding does not present any particular difficulties, however, a shielding wall of 80-100 cm of concrete in the congested area between the pre-injector and tank I looks rather objectional, and would present serious difficulties for transport of major items into or out from the Linac area. The preferred solution is therefore to move the control position. This does not exclude an X-ray screening, in order to permit that one can start up at least the pre-injector locally.

K. Goebel, Radiation problems in the Linac area with respect to the PS Improvement Program, 6 June 1968.

b) Possible Sites for a New Linac Control Position

Without any major civil engineering undertakings, it seems we have two possible sites to consider : a) Outside the shielding wall in the corner of the South Hall close to the Linac, b) Somewhere close to MCR, eventually in the present Counter Room.

Solution a : Advantages of this solution are the nearness to the present control area. The thickness of the present wall is not adequate, and a labyrinth shield must be arranged for the door opening to the Linac. Eventual radiation risk from future experiments in the South Hall must also be considered.

Solution b : The possibility of finding a suitable space at MCR is of course an open question, but could perhaps be solved in the context of finding space for the controls of the Booster. An obvious advantage would come from the close contact with the operation of the Booster and the PS. Another advantage is the closeness to the process computer, which in future will play an increasing role for the operation.

The disadvantage of this site is the distance to the Linac for inter ventions which cannot be handled remotely. A passage across the South Hall on the level of MCR could in this case save valuable time. On the positive side, we get the decrease of distance between LCP and the Linac laboratories.

The final decision depends ultimately on many factors and considerations outside the Linac Group. However, the important conclusion for our part is that we should prepare ourselves and find workable solutions to the problem of operating the Linac from a remote control centre.

c) Development Work for a Remote Control Position

We are in the advantageous situation that the work already started, in developing hardware for connecting Linac parameters to the computer, will provide us with solutions to several of the new problems we have to consider in connection with a remote control position. This does not mean that the running of the Linac would depend on the running of the computer, but rather that the Linac operator on an interrupt basis can ask the help of the computer for data acquisition and eventually optimization routines. However, the access and control by the computer can be considered to pose problems similar to operation from a remote position.

The present Linac computer terminal offers the possibility to simulate the running of the Linac from a distance. We can therefore gradually build up the capabilities of the remote control centre. Once satisfactory solutions have been found, the actual transfer of the Linac control position to any chosen site can more or less be considered as a cabling and installation problem. At the moment it is estimated that we have a respite time of about two years before the move becomes mandatory.

Parameter Acquisition : Without the help of the computer, we can, as at present, make use of the pulse burst coming from our A/D converters for presentation on Nixie displays. However, when the number of converted parameters gets high, we must provide some type of matrix selector, where we can choose at will from the remote position say four parameters out of all available for simultaneous display. Such a matrix can be constructed using high level integrated circuit logics.

Control of Parameters : The STAR control system has already a manual access foreseen, which we can exploit for manual control at the future control position. This requires a suitable parameter selector panel at the control position. After a parameter has been selected, a pulse train is sent to act on a stepping motor at Linac. This motor can turn a helipot or perform any other mechanical work, as moving ball tuners or phase shifters. By standardising on this type of control even for parameters which at present are not considered for connection onto the computer, any future extension of computer control can swiftly be arranged.

One of the operational uses of the computer control which is expected to be of increasing importance is in the setting up of pre-set condition, for example

1) the setting of the 500 keV and Tank I parameters to give maximum 500 keV beam intensity at the end of Tank I as a routine check on the pre-injector performance and alignment,

2) the switching of the relevant Linac parameters to give optimum 20 μs beam quality for multi-turn measurements.

Analog Signals : A quick survey showed that there are about 100 analog signals which are of interest for the running and setting up of the Linac. It looks rather prohibitive to bring all these signals to a remote control position, particularly since one never can look at all these signals at the same time. Again a switching matrix seems to be the solution, where one can pick out at will, say two signals to be sent to the remote control position over matched cables for display on a double beam scope of high brightness (at least 10 kV acc. voltage). Suitable matrices are made by the industry, the only objection might be the price, around $ 10 000 for a matrix of 100 inputs and four independent outputs.

Our analog presentation of the beam currents must also be re-studied, since the present system cannot cope with beam pulses of 100 microsec. The present pre-amplifiers in this system were built with early transistor technology as base, and are highly non-linear. These could to-day with advantage be replaced by integrated operational amplifiers.

Measurement Equipment : The future arrangement of the Linac with its beam transfer line to the Booster is foreseen to make use of a big number of movable slits for beam measurements. A new control system for these slits is under development in the Linac Group. It makes use of multiplexing for control of movements by stepping motors and reading of shaft encoders for position indication. Again, the selection of a particular slit is made with the help of a push-button selector panel. Automatic selection over the computer is also foreseen.

d) Conclusion

It is proposed that in the next two years we build up the Linac computer terminal as a remote control centre both for the Linac and as far as practicalbe for the Injection Line, moving eventually to a final location preferably near the MCR and Booster control centre.

3. USE OF PRESENT BEAM

Multi-turn injection has been in regular operational use for several years in the A.G.S., and has also been used operationally in the PS. With beams of 20 to 30 mA the A.G.S. has been able to accept several turns and accelerate intensities in excess of 2×10^{12} ppp. Increases in the Linac intensity to

40 to 50 mA recently have apparently had small effect on the A.G.S. intensity, although the ease of reaching 2 × 10^{12} has increased. At CERN it was found possible to achieve the "standard" intensity of 10^{12} ppp at the end of 1965, with injected currents up to 50 mA for an injection period a little less than 3 turns, but with > 100 mA available in a single turn the next year attention became once more concentrated on the single-turn behaviour.

Since the engineering of several-turn injection is included in the Booster project, it would seem desirable to investigate the matter more fully on the PS, both with the object of increasing the understanding of the multi-turn process with intense beams and with the possibility of achieving higher PS intensity.

It is proposed to approach the problem in the following manner :

1. The Linac will be adjusted to give maximum beam quality without variation during the 20 μs which will be the limit in beam pulse length until some time in 1970.

2. By the introduction of sieves into the 50 MeV beam, the intensity will be reduced to a value at which space charge effects will be expected to be unimportant, i.e. of the order of 10 mA; and the injection parameters will then be adjusted for the optimum acceptance of 3 turns.

3. The emittance and current will then be increased progressively and the effect on the injection process and on the circulating beam studied. Use will be made where possible of the IBS in order to follow the evolution of the beam profile with increased charge.

An attempt will be made to limit the emittance of the injected beam to a value which will just cover the common acceptance of the 3 turns, in order to minimise the problem of charge dependent instabilities. It will be of interest to discuss whether this aggravates dilution problems due to non-linear space charge coupling. The importance of these effects has been recently demonstrated for beams at lower energy by trajectory computations for 6000 particles acted upon by non-linear space charge forces (Tanguy, 1969). Considering only the effect of the self-fields on the beam in a drift-space, it is shown that for a 100 mA beam at 750 keV there is an increase in area of the order of 30% - 40% for both the 40 mA and 80 mA constant contours. In addition there is a considerable distortion of the ellipse which in a focusing system with Q shift would produce further effective area increases. This work is being extended to include focusing in order to find whether an asymptotic state is reached, and after how long.

4. BEAM MEASUREMENTS

If one is looking for a figure of merit which will summarize the quality of the 50 MeV beam in one number the obvious first approximation is the total intensity in mA. The values from successive pulses can be sorted and processed to yield a mean value and standard deviation as a measure of reproducibility, as well as the simpler statistics of percentage of lost pulses, etc.

A more stringent criterion would be given by the quantity of beam passing through a fixed emittance limitation on the way to the Booster, as the result would then be sensitive to coherent radial jitter as well as to emittance changes.

Finally if it were possible to arrange a momentum selection after the emittance limitation passing only those particles which lie within the nominal Booster energy acceptance the measured pulse would be sensitive also to changes in mean energy and energy spread. The injected beam would then contain only particles of known energy, energy spread and transverse motion, and the measured pulse would tell the operator how many "good" particles he was injection, making the interpretation of Booster behaviour somewhat simpler.

A 360^{o} on-line spectrometer giving sufficient dispersion after 180^{o} to permit the limitation of the beam energy spread is probably feasible, but the scheme proposed at N.A.L. for analysing a few microseconds of the injected pulse (NAL, 1968) seems to be almost as informative, that is one could obtain a computer read-out of the percentage of beam within a given energy spread as is done at present on the PS, but for a small time sample of the actual injected pulse. Such a scheme is being considered for the Booster injection line as an addition to the original proposition of analysing pulses intermediate between Booster pulses.

During stable operation, i.e. when there is small pulse to pulse variation, the complete analysis of the intermediate pulses by the single-pulse emittance device (Têtu,) and the spectrometer will produce figures for emittance orientations, phase-space densities, energy spread and time variations of these parameters which will be representative of the pulses actually injected into the Booster, whereas during periods of machine difficulties or for regression analysis of machine variations, information concerning the actual injected pulse may be very useful.

To sum up this discussion, one would like to have available for each injected pulse the number of milliamperes lying simultaneously within a given horizontal and vertical emittance and a given energy spread, this figure providing a unique criterion for evaluating and comparing Linac performance, reproducibility and reliability.

While it does not appear practicable at present to measure this figure directly on the injected beam, the proposed instrumentation for the Booster injection line should provide a very close approximation.