IMPROVEMENT PROGRAMME

LINAC

Linac Group, edited by C.S. Taylor

INTRODUCTION

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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 this 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, 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 the existing 50 MeV beam quality,

and   4. beam quality measurements.

This report 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 that this is pre-dominantly a space charge problem in the low energy region from the pre-injector onwards, and so in 1967 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. The combined effect of these benefits will be analysed 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 (Chabert, Martini, Promé, Veyrou, 1969), populating the 6-dimensional phase volume realistically with particles (Eadie and Martini, 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 there 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) and is being developed to be used in connection with the beam dynamics programme. For the pure drift part of this problem with non-uniform radial distribution, a compu-ter programme has been developed by the University of Rennes, working in colla-boration with CERN (Tanguy, 1969), (Warner, 1969).

It is anticipated that the 3 MeV Alvarez accelerator will be extremely useful for the comparison of computed dynamics with measurement (Boltezar et al, 1968) and it will also to a large extent replace the 50 MeV machine as a develop-ment 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 (Huguenin et al, 1969). 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 for the common research in Lyon, will be an extrapolation of existing CERN techniques(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 gap pres-sure (Lefèbvre, 1968). 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 (implying the design and construction of a new tank from this energy to 10 MeV).

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.

These aims should be accomplished bearing in mind the need to achieve the highest standards of reliability*.

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 (F. Chiari, 1969). This has involved the modification of the monostable square wave generator and final amplifier, and the

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

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.

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

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,

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 (R. Dubois, 1969) because of its simplicity and compactness, 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.

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	= $\pm$ 10^{-3} ($\pm$ 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 30 - 90 A by the resonant discharge of a capacitor, which results in a semi-sinusoid 500 μs long, permitting a reasonably constant current ($\pm$ 2 ^{o}/oo) during the passage of a 20 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 Brookhaven) a different design of quadrupole supply might be needed, and there would not be much sense in carrying out an expensive rebuild 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 > 100 μs 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, 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 seemed 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 techniques will be applied to controls and indications, and the accelerating field level will be stabilized by fast local feedback loops with the reference points computer controlled. 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).

The biggest items of construction will be the new modulators and 2 kW transmitter 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 centers 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 (Goebel, 1968) provide another reason for the re-allocation of the Linac Controls (Tallgren, 1969).

Possible Sites for a New Linac Control Position

Without any major civil engineering untertakings, 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, or an extension of the Computer Room.

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 problems of operating the Linac from a remote control centre.

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. It is therefore proposed that during this period we build up the Linac computer terminal as a remote control centre both for the Linac and as far as practicable for the Injection Line, moving eventually to a final location preferably near 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 (recent information is that 3×10^{12} has been achieved). 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 varia-
    tion during the 20 μs which will be the limit in beam pulse length
    until some time in 1970.

2. By the introduction of sieves and slits, into the 50 MeV beam, the
    intensity will be reduced to a value at which space charge effects
    in the PS 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 Ionisation Beam
Scanner 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 cover the common acceptance of the 3 turns (Nielsen, 1967)
in order to minimise the problem of charge dependent instabilities. It will be
of interest to discover whether this aggravates dilution problems due to non-
linear space charge coupling. The importance of these non-linear effects has
been recently demonstrated for beams at lower energy by trajectory computations
for 6000 line charges 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
Of 1.5 m, 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 the emittance contours which contain respec-
tively 40 mA and 80 mA. 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

An obvious and simple figure of merit for the 50 MeV beam is the
current averaged over the pulse. Successive pulses can be stored and processed
to yield a mean value and standard deviation as a measure of reproducibility,
as well as giving the percentage of lost pulses, etc.

A more stringent criterion for quality would be given by the beam
current passing through a fixed emittance limitation on the way to the Booster,
as the result could be much sensitive to coherent radial jitter as well as to
emittance and density changes.

Finally, if it were possible to arrange a momentum selection after the
emittance limitation, to pass only those particles lying within the nominal
Booster energy acceptance, the measured current pulse would also be sensitive
to changes in mean energy and energy spread. The injected beam would then contain

only particles of known energy, energy spread and transverse emittance, and
the measured current pulse would tell the operator how many "good" particles he
was injecting, making the statistical analysis and the interpretation of Booster
behaviour more meaningful.

If it were feasible, a 360° on-line spectrometer giving sufficient
dispersion after 180° to permit the limitation of the beam energy spread would be
a possible solution, but the scheme proposed at NAL for analysing a short burst 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 could be considered for the Booster injection line
as an addition to the original proposition for analysing pulses intermediate
between Booster pulses, but this would require a serious engineering study.

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, 1968) and the originally proposed 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 protons lying simultaneously within a given horizon-
tal 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 (Booster Report, 1967)
for the Booster injection line should provide a very close approximation.

GENERAL TIME-TABLE, LINAC 1969 - 1973

	1969	1970	1971	1972	1973

Pre-injector and Tank I

Pre-injector study period

Energy Decision

Design and construction pre-injector and tank I

Installation and Test, South Hall

Installation Linac

General Linac

Long pulse and higher repetition rate

LCP changes

Booster Injection Line   Stage I

Stage II

Booster Tests

Booster Operation

I.S.R.

Provisional Shut-Downs

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