FUTURE PROGRAMME OF THE 50 MeV LINAC

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The 50 MeV linear accelerator has been in operation as the P.S. injector for 12 years. During this period the pre-injector and 500 keV drift space has been rebuilt (1966) and recently several other major components have been replaced to meet the requirements of the 100 μs beam pulse, and for maintainability reasons. These comprise the R.F. modulators and low level drive chain, the pulsed and D.C. quadrupole supplies for the tanks, and the 50 MeV transfer line to the P.S., which is being transformed for clean vacuum and a double debunching system. In addition the control and measurement circuits are almost all of recent vintage, partly because of the 100 μs pulse conversion and the PSB transfer line, and partly because of the evolution towards digital control.

The purpose of this note is to propose a programme to meet the future requirements. The general approach will be to discuss a feasible operating philosophy for the future, then to examine the present situation in the 50 MeV Linac, and finally to consider what must be done to bring it up to the required standard.

OPERATING PHILOSOPHY

The future requirements of the 50 MeV beam can be summarised briefly* as reproducibility and reliability. Generally speaking, both short-term or pulse-to-pulse reproducibility, and reliability, can be obtained by attention to engineering detail**, but long-term reproducibility, from one setting-up to another for example, is entangled with many other questions, such as how we expect the complex of accelerators to be operated, as well as with reliability problems, as we shall see later.

On the basis of past experience with the Linac and P.S., a reasonable method of operating the Linac in the future would be as follows :

1) the machine is first optimized for maximum 5-dimensional density at 50 MeV, i.e. maximum intensity through an energy spread limitation and a horizontal and vertical emittance limitation (or for minimum Linac energy spread or minimum debunched energy spread, etc.).
2) any separable sub-system such as the R.F. system is then tuned up itself to give the required tank levels and phases with minimum power or voltage levels throughout the system, and to produce the lowest sensitivity to small fluctuations [1].
3) the values of all parameters are then stored in a computer look-up table for future recall of the maximum density beam.
4) if different Linac settings are seen to be required as a result of inclusion of Linac controls in the optimization of the downstream machine, then the Linac sub-systems are re-optimized to the new values and a second look-up table is stored, and etc.

From that point onwards, setting-up for different requirements becomes a matter of calling the appropriate table, ideally with fast-acting controls to permit pulse-to-pulse changes.

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* a more detailed definition and discussion will be found in the Appendix.

** catastrophic failures lasting for weeks or months must be avoided at all costs, so that great care has to be exercised over the provision of spare accelerating tubes and generators etc., over the manipulation of heavy weights near the accelerating structure, and over fire hazards etc.

This degree of reproducibility implies that every variable which significantly affects the production, focusing or acceleration of the protons can be controlled, i.e. measured and set to its correct value.

We shall now consider the present state of the Linac in the light of this reproducibility criterion, and consider also some reliability questions.

PRESENT LINAC SITUATION

REPRODUCIBILITY

Firstly, while there are now well over 100 parameters connected as computer acquisition addresses, there are as yet only a dozen or so control addresses available of the many hundreds required*, so that a lot of hardware remains to be constructed, installed and commissioned. Fortunately, there are already design solutions to most of the problems[2)]. A satellite computer is being proposed to facilitate the data handling.

Secondly, several components in the R.F. system (mainly flexible cables) are working close to the breakdown limit [3)], so that considered as a sub-system its variables could not always be set to the optimized values even if complete acquisition and control were available. It is proposed to remove these un-controlled constraints by replacing the flexible cables by rigid co-axial line recuperated from the Rutherford Lab. P.L.A. Later, the R.F. system may be re-arranged to permit fast level and phase changes in the tanks.

Thirdly, there are processes in the low energy region, such as electron neutralization [4)] and anomalous beam loading of the buncher, which cannot at the moment be controlled.

Fourthly, in the accelerating structure, as in the R.F. system, there are varying breakdown limits [5)] (in Tank I and in the buncher) which on occasion prevent standard values from being reached at each setting-up.

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* the control and acquisition addresses are at present manipulated via an interactive display, the next stage probably being an interpreter program mode for faster and simpler exploitation of the computer.

RELIABILITY AND MAINTAINABILITY

As one can conclude from the Introduction, only the accelerating structure and its vacuum system remain of the original Linac hardware after 12 years of operation.

The vacuum system could probably still be kept going for a long period [6] but it will require a large amount of maintenance and repair, so that the annual costs for keeping it running, including electricity and water (around 120 kFr. total per annum) would pay for a replacement ion pumping system in 5 years or so.

Of the three tanks of the accelerating structure, Tank I gives the greatest cause for concern because of the possible consequences of quadrupole failure [7]. The 42 quadrupoles themselves have survived some 150 million pulses without a single failure but the insulation resistance is decreasing,and to replace one in the event of failure the drift-tube has to be removed, repaired, re-installed and re-aligned, which could be a lengthy process. More serious is the strong probability of a long period of R.F. formation after the repair, with perhaps several weeks of below-normal tank level, non-standard 50 MeV properties, and erratic behaviour. In simpler terms, it would hardly be acceptable to the waiting accelerator complex to be told that 'we are sorry but Tank I is breaking down and there is nothing we can do about it'.

POSSIBLE SOLUTIONS

The simplest solution to the problem of uncontrolled variables and constraints would be to rebuild Tank I and the 500 keV drift space more or less in their present form, incorporating the results of the neutralization studies and removing the breakdown constraints and the varying beam loading in the buncher, using careful constructional techniques and a clean vacuum, as has been done in the 3 MeV machine. The 3 MeV quadrupole design is practically identical with the present 50 MeV design, except that more efficient water cooling has been arranged. This permits n = 1 focusing and has contributed to the peak analysed beam intensity of 240 mA recently achieved at 3 MeV.

With such a rebuild one could expect a controlled machine with a better intensity working margin, and the drift tubes would be designed for improved maintainability in the event of quadrupole failure. Rapid changes of tilt for deuteron acceleration could also be included in the design. On the basis of 3 MeV and debuncher cavity costs, a copper-clad 10 MeV tank should cost no more than 150 kFr. for the tank itself, 160 kFr. for the drift-tubes, and 50 to 150 kFr. for the quadrupoles, depending on how much one wanted to modify the previous design. An additional 300 kFr. would cover the pumps [8] tuners, loops and supports, bringing the total capital cost to 660 to 760 kFr.

At this point one should ask whether the advances in accelerator technology and concepts cannot offer a solution better adapted to the requirements than the Alvarez structure, in spite of its distinguished past record. For example, the high surface electric fields (around 25 MV/m) held in the new debuncher cavities cause one to ask whether 10 MeV could not be more flexibly reached by groups of standard cavities (as in the UNILAC project [9]). The complexity of control of phases and levels, in order to produce different beam properties or for different particles, is not a particularly difficult problem with computers available, and a complete Linac constructed in this way could be considered as a device for varying the transfer beam properties, including energy, at will. An interesting alternative to the debuncher-type cavity at the low energies is the helix structure which was resurrected in CERN a few years ago and is currently being intensely studied for the German projects.

The linear space charge optimization programs and the non-linear multi-particle programs being developed will make it possible to evaluate some of the advantages and disadvantages of this approach, and the effect of a proton beam on the maximum supportable cavity and helix fields could be investigated experimentally in the South Hall. Concerning costs, the copper-clad debuncher cavities cost about 15 kFr. each from the CERN workshops, but it is estimated that with the additional power amplifiers required by this proposal the total cost would not be very far from that of an Alvarez tank.

It should be possible to present the best solution for a 10 MeV rebuild as a definite proposal after a year's design study. Construction and thorough beam testing in the South Hall might take two years so that the 10 MeV assembly would be ready for installation from the end of 1974. Close examination of the second and third tanks could show that faults are likely to develop there in brazed joints, O-ring unions, or quadrupoles. It would probably be operationally convenient in that case to use ex-P.L.A. drift-tubes as temporary replacements, and to replace the tanks one by one after the Tank I installation.

The possibility of building a second entirely new Linac should be mentioned for completeness[17].This is not very interesting on reliability grounds,as the early operating life of a complicated assembly is usually unimpressive, but if good reasons emerged for a new machine of radically different characteristics, this would be a different matter.

CONCLUSIONS

Consideration of the future requirements and present limitations of the 50 MeV Linac have led to a proposal to rebuild the 500 keV drift space and Tank I. A design study will be necessary in order to establish firm cost estimates, but it seems likely that the rebuild from 500 keV to 10 MeV will cost in capital less than a million Swiss Francs and would be completed by late 1974.

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APPENDIX

FUTURE REQUIREMENTS OF THE 50 MeV BEAM

It is convenient to consider the Linac beam properties under a number of defined headings.

1) BEAM QUALITY

Defined as an instantaneous value of intensity or phase space density.

The present specification for injection into the P.S.B. calls for 100 mA within ± 150 keV after complete debunching, and within 30 π mm mR. This can be met by the present Linac, and higher performance is not considered to be of great interest to the downstream machines at the moment, but rather would allow the Linac a working margin in the event of minor troubles.

2) BEAM PULSE UNIFORMITY

Defined as constancy of the quality during the pulse.

This depends mainly on the ion source pulse shape and on the efficiency with which the various beam-loading compensation systems function. The pre-injector high voltage system uses a hard-tube feedback loop, whereas the tank R.F. levels are corrected by programmed compensation. Initial tests up to 30 μs already show that the 50 MeV emittance and energy spread can be made reasonably constant over this pulse length. A fast feedback (and possibly feedforward[10]) system, which senses the tank field and controls the final amplifier grid bias, should come into operation during the next year and is expected to simplify the operational problems.

3) REPRODUCIBILITY

Defined as constancy of the quality from pulse-to-pulse (short term) or from run to run (long term).

Short-term

Data logging and treatment of Linac parameters started some years ago[11] and a histogram published in the Dubna 1963 Conference Proceedings showed that the intensity fluctuations were at that stage quite small, the standard deviation being 0.34% of the mean. In recent years the beam reproducibility has suffered on occasions from the major hardware changes which have been made in the R.F. system notably during maintenance shut-downs, allowing less time for routine work and tuning up [12) 13)], and the increased power levels [3)] throughout the system have also taken their toll (by quiet sparking on contacts).

At the present moment coefficients of variation of around 2% are normal at the P.S. input. The main effect of abnormally wide variations in Linac beam quality from pulse-to-pulse is that optimisation of the P.S. becomes very difficult or practically impossible. Figures of around 2% appear to be satisfactory.

Long-term

This has been discussed in the text, but it should be added that trustworthy instrumentation is essential as a check on the settings for a given beam. One other important implication of long-term quality reproducibility is that mechanical boundaries should be of sufficient rigidity to be considered as controlled variables or constraints.

4) RELIABILITY

Evaluated by :

1. the fault percentage or the ratio of fault down-time to scheduled time ("forced down time" in the literature [14) 15)]),

and 2. the mean time between failures.

Periods of bad pulse-to-pulse reproducibility could reasonably be included in the fault down-time. Since 1962 the fault percentage has been around 3%, with a peak of 3,5% in 1965. By concentrating on routine maintenance and by providing adequate spares it should not be difficult to reduce this figure, provided that one is not overtaken by inadequate maintenance and diagnostics of the rapidly increasing digital electronics.

The mean time between failures has not so far been given much consideration as an operating criterion. For the two machine runs around Easter, which were rather bad from the Linac fault point of view, mtbf's of around 20 hours were recorded (with standard deviations of the times between failures also around 20 hours, implying an approximately exponential law of failure). There is some liberty in design towards either infrequent failures by over-dimensioning, or more frequent failures made palatable by quick diagnosis and replacements. From the P.S. experimenters' point of view it seems that the effect of interruptions varies with the state of the experiment, i.e. frequent failures may even be beneficial during setting up, but disturbing during data collection. At the moment it is difficult to draw conclusions as to which is the more appropriate design approach in general. It seems that in either case, the experimenters appreciate most a fairly precise forecast of when the beam will be restored, so that tape and film changes etc. can be planned [16], and this could be regarded as another reliability criterion.

5) MAINTAINABILITY

Evaluated by the time and effort required to keep an apparatus in working condition, including time required for repairs.

This is especially relevant to the present vacuum system, consisting as it does of mechanical backing pumps, refrigerator compressors and motors, diffusion pumpsheaters, freon and trichlorethylene circuits, water circuits, level and pressure indications and interlocks, control buttons, relays and contactors, and manual and automatic valves. A great deal of detailed modifications and medium-scale rebuilding has gone into the system over the years, and it is now very reliable, i.e. is responsible for a very small fault percentage. Nevertheless it requires constant effort to keep it in this state.

6) FLEXIBILITY

Defined as the ease with which the machine can respond to changing needs [18].

In control terms it implies that constraints are a comfortable distance away from normal working points, as for long-term reproducibility, so that various optima can be explored safely. Converted to hardware terms it implies that properties like tank tilt and focusing can be varied over a wide range.