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Radio frequency problems in connection with Proton-Synchrotron Linear Accelerators

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1. Introduction

The function of the linear accelerator is to accelerate protons to the energy of 50 MeV required by the synchrotron. This is achieved by subjecting the protons to a strong electric field, allowing them to drift through a field-free space, then repeating the electric field treatment and so on for a total of 110 times. The electric field alternates at a frequency of 202.56 MHz. Fig. 1 shows the mechanism of acceleration in its simplest form, Fig. 2 gives some idea of the accelerating structure and Fig. 3 shows the linear accelerator in relation to the synchrotron.

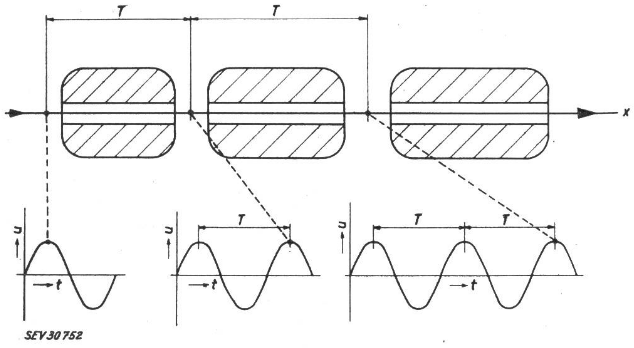

Fig. 1
Mechanism of acceleration of linear accelerator
t Time; *T* Period; *u* Voltage; *x* Particle injection

2. Accelerating Voltage

Protons enter the accelerating structure at an energy of 500 keV (that is the kinetic energy acquired by unit charge in being accelerated through a potential difference of 500 kV), and emerge from it with an energy of 50 MeV, i.e. 50×10^6 eV [1] [1]). They have therefore passed through a mean potential gradient of $50 - 0.5 = 49.5$ MV in 28.7 m, the length of the structure, or 1.73 MV/m mean gradient.

This high field at 202 MHz is obviously a task for a resonant cavity and therefore the accelerating structure consists of a cylindrical copper cavity surrounding the succession of accelerating gaps separated by the so-called "drift-tubes".

This high field is equally obviously a task for a high vacuum. This is provided by a steel outer envelope pumped by mercury diffusion pumps to a pressure of 5 to 10×10^{-6} mm Hg. For convenience the structure is divided into 3 sections or "tanks".

3. Peak Power Required

The three accelerating cavities operate in the E_{010} mode which gives a maximum electric field along the axis and a maximum magnetic field around the circumference which makes loop coupling of the input power practicable.

The equivalent shunt impedance of such a cavity considered as a parallel resonant circuit is not easy to calculate when it includes drift tubes and supports, and model measurements were used originally. The model measurements indicated shunt impedance leading to Q factors of the order of 8×10^4. The shunt impedances and voltages then yielded conservative peak powers of 1 MW for the first tank and 2 MW for the second and third.

4. Mean Power Required

The peak powers above are only required for 10 μs at a maximum repetition rate of 1 p.p.s. (pulse/second), but unfortunately cavities of such high Q take much longer than this to build up to maximum field and so one is obliged to apply power for at least 200 μs in order to assure a steady field. This leads to mean powers of 200, 400 and 400 W respectively.

5. Cavity build-up

Following the treatment of Slater [2], one can apply the conservation of energy to the problem of feeding power into the tank and one can then see that the power absorbed in the resistive losses in the cavity plus the rate of change of stored energy must be exactly equal to the power applied. Considering a square wave of input power one can then solve the differential equation and obtain an exponential rise of field in the

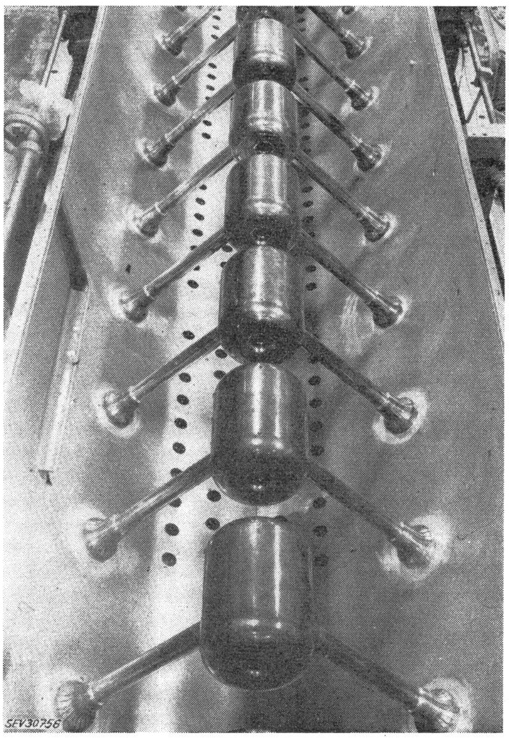

Fig. 2
Accelerating structure of linear accelerator

[1]) Refer to the Bibliography on p. 262.

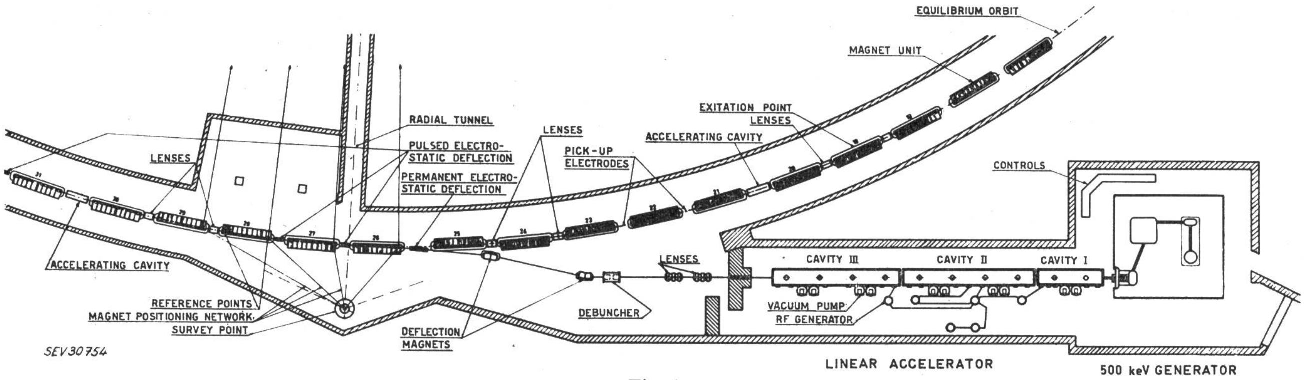

Fig. 3
Beam injection into the synchrotron

cavity of the form $1-e^{-(\omega/2Q_{L1})t}$. At the beginning of the pulse one sees that with no stored energy and no dissipative losses, no power goes in and therefore at some point on the feeder the input impedance of the cavity will be zero, i.e. a short circuit. As the field builds up, the rate of rise of stored energy will be initially very steep and will then fall off while the dissipative losses will increase fairly linearly, until finally the stored energy will reach a steady value practically speaking, no power will be therefore needed to change it and all of the input power will go into losses (represented by the shunt impedance). As far as the input impedance is concerned, this will increase exponentially from zero to a final value derived from the shunt impedance transformed down by the coupling loop. This should equal the characteristic impedance of the feed line for a match or maximum power transfer.

This simple picture (plus the reverse process of field decay) is modified in practice by two factors. The first one is that power is not applied as a square wave, and this will be considered later.

The second is that the 10 µs proton pulse requires work to accelerate it, and this must be supplied by the stored energy of the cavity. At the present beam current of 15 mA, the power required to accelerate this through 49.5 MV is 0.75 MW and this does not drop the field very seriously, but if, as one hopes, the beam will one day reach the order of 50 mA it will require 2.5 MW, and if this were to be supplied by the stored energy, the field would probably fall below the value for acceleration during the pulse. One solution would

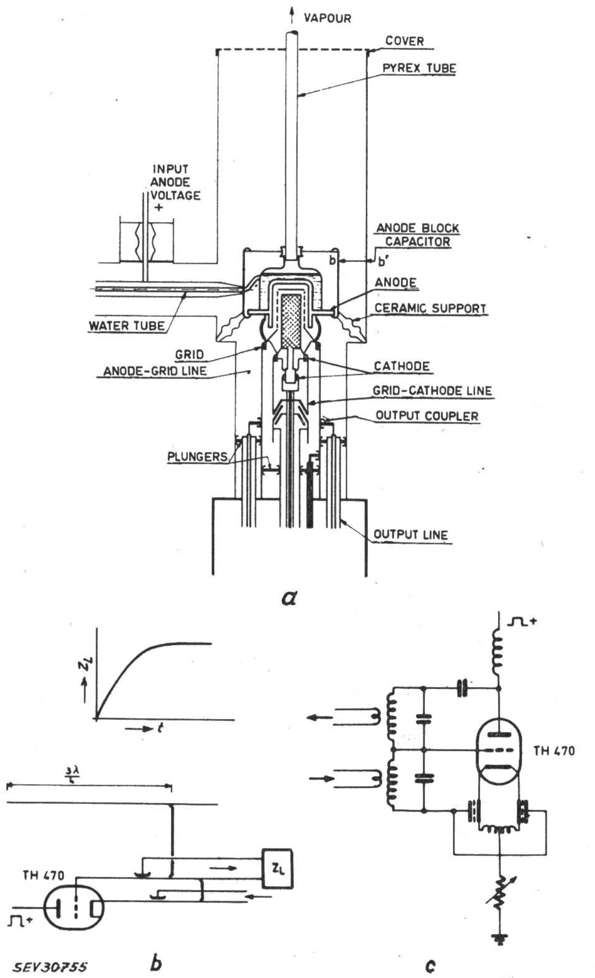

Fig. 4
Finel amplifier tube
a Cross-section; *b* parallel line equivalent; *c* lumped circuit equivalent

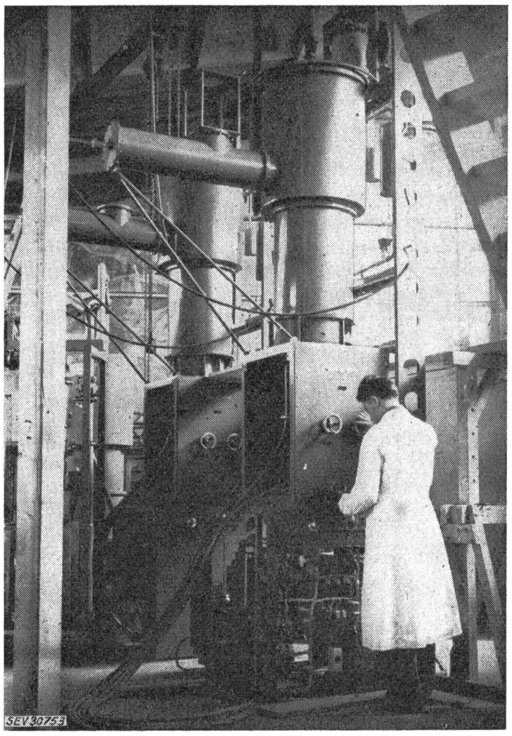

Fig. 5
Overall view of final amplifier

be to apply an additional 2.5 MW pulse to the structure at the instant of the proton beam. Whilst this would impose considerable power supply problems they should not be insurmountable, and one might further consider applying feedback in order to keep the field constant with varying beam currents.

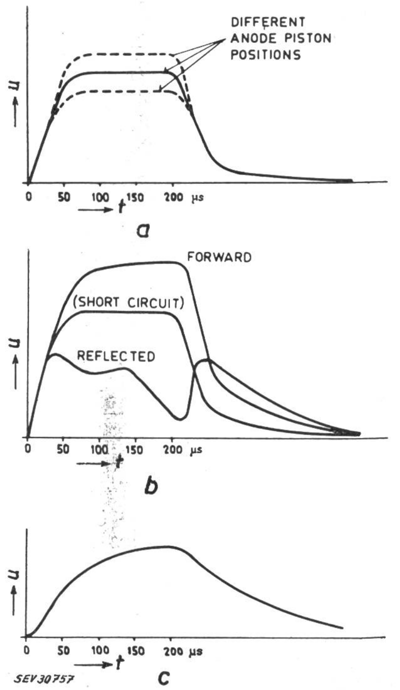

Fig. 6
Characteristics of the accelerating cavity
t Time; *u* Voltage
a Cavity voltage for different anode piston positions; *b* Line voltage variation for short circuit and accelerating cavity load; *c* Rise and fall of field in the accelerating cavity

Translating the whole problem into a mechanical analogy, imagine a flywheel driven by an electric motor which can supply constant mechanical power during a short pulse. Further, consider that a friction pad is held against the flywheel rim. Then the stored rotational energy of the flywheel will correspond to the stored electrical energy of the cavity, and the friction losses will correspond to the resistive losses. Dynamically, the diversion of input power from rate of increase of stored energy to dissipative power will be identical in the two cases. The analogy is completed by adding a second friction pad which is applied momentarily when the flywheel has reached a steady velocity to represent the beam pulse. The problem of maintaining this steady velocity during the pulse load can be recognised as a fairly familiar one in servo-techniques.

6. Final amplifier

The tube chosen to supply a peak power of 2.5 MW at a mean power of 500 W was the TH 470 manufactured by Thompson Houston of Paris, who also developed the 200 MHz cavity structure in collaboration with CERN.

Fig. 4a shows a cross-section of the complete assembly, and Fig. 4b and 4c the parallel line and lumped circuit equivalents. The tube is seen to function as a common grid amplifier with self-bias in a $^3/_4\ \lambda$ line. A complete description of the amplifier is given in reference [3] by *Zaccheroni.*

Fig. 5 shows an overall view of the amplifier.

7. Output circuit

Considering the parallel line equivalent circuit of Fig. 4b, one notes that the effective short circuit at the beginning of the pulse will couple into the anode cavity a reactance depending on the position of the short circuit. This can be arranged to limit the voltage on the line and in the anode cavity to a safe value, in effect by detuning the cavity. One is justified in fact in regarding the anode cavity as having two tuning pistons, one being coupled out of the cavity by a step-down transformer.

There are occasions when the accelerating cavity refuses to build up and under these conditions the input impedance remains zero during the whole pulse. One can then demonstrate that the anode cavity is off tune by moving the anode piston and seeing that the voltage on the output line varies very quickly with the anode piston position as in Fig. 6a.

Note that the voltage wave is by no means square and this is caused by high Q circuits further back in the drive chain.

Consider now the normal case when the accelerating cavity input impedance increases exponentially from zero to its final value. From Fig. 6a one sees that initially the line voltage measured with a reflectometer [4] increases very much as it does for a short circuit. After a certain time the output circuit begins to couple into the anode cavity a real and increasing load, but it also couples in less of the detuning reactance, and the net effect is that the cavity and line voltage rises above the value for a short circuit until at the end of the pulse the cavity is delivering its maximum power into a resistive load. The reflected wave increases with the forward wave until power be-

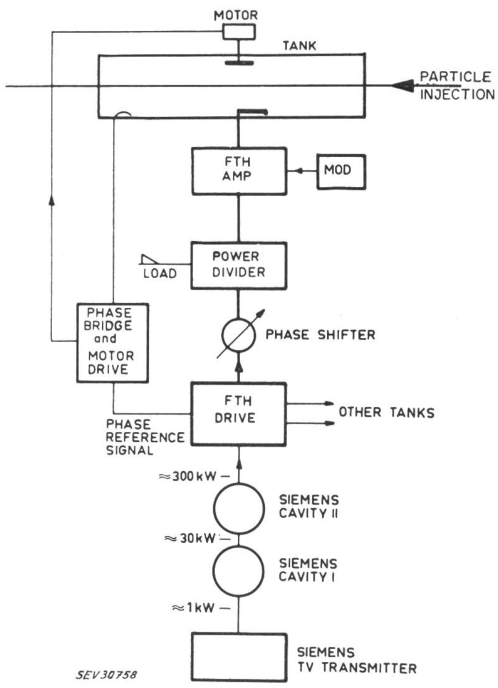

Fig. 7
RF power supply for one tank circuit

gins to enter the accelerating cavity and then falls down toward zero at the matched condition and up again as the cavity field decays. During the decay process one reaches a point at which the input power falls

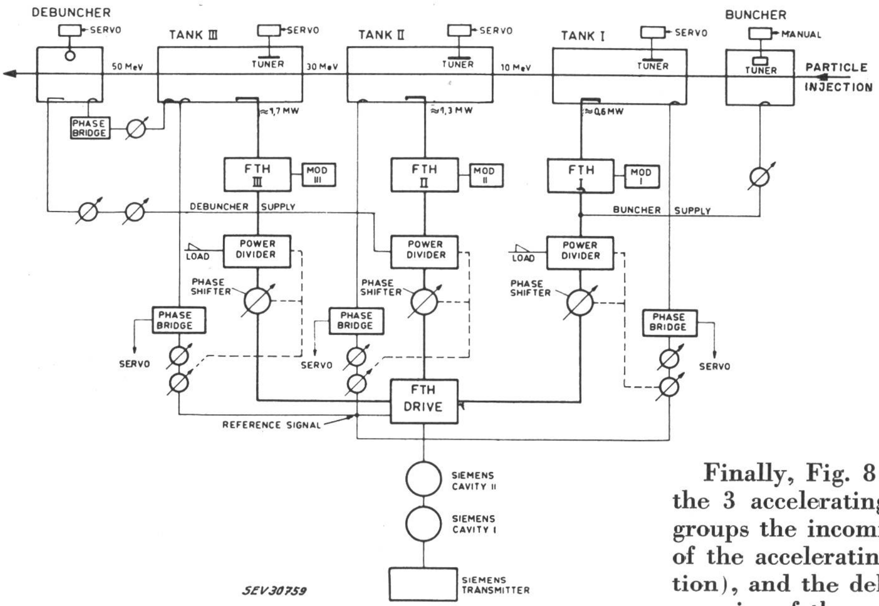

Fig. 8

Complete RF system for the 3 accelerating cavities, buncher and debuncher

more quickly than the cavity power and there can then be a net flow backwards into the amplifier as can be seen from the crossing of the forward and reflected waves.

Fig. 6c shows the rise and fall of field in the accelerating cavity. The departure from exponential at the beginning is explained by the departure from a square wave of input power.

8. Complete RF system

Fig. 7 shows the RF power supply system for one tank. In order to keep the RF field in phase in each gap of the three accelerating cavities it is necessary to impose a tolerance of $\pm 1°$ on the phase stability. This is achieved by comparing the phases in the cavities with a common reference phase and using the error signal to drive a tuner plate in the accelerating cavity so that having been tuned initially, the cavity remains in tune automatically. Water cooling of the cavities reduces the demands on the servo-tuning system. Each cavity can be moved in phase relative to its neighbour by means of a phase shifter in the drive line coupled to a second one in the reference line.

As can be seen, each final amplifier derives its power through a power divider [5] from the common Siemens chain plus drive amplifier. The Siemens chain has been described in detail by *U. Kracht* [6].

Finally, Fig. 8 shows the complete RF system for the 3 accelerating cavities plus the buncher (which groups the incoming protons in time around the part of the accelerating wave most favourable to acceleration), and the debuncher (which groups together the energies of the emerging particles).

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Technische Mitteilungen — Communications de nature technique

Commission Electrotechnique Internationale (CEI)

Sitzungen des ACET, des CE 48, des SC 39/48, des CE 50, der SC 50A und B und des CE 52 vom 13. bis 24. November 1962 in London

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Advisory Committee on Electronics and Telecommunication (ACET)

Das ACET ist ein beratendes Komitee des Comité d'Action (CA) in allen Fragen, welche die Nachrichtentechnik und Elektronik betreffen, und setzt sich aus den Präsidenten und den Sekretariaten der verschiedenen interessierten CE zusammen. Vorsitzender ist der Präsident der CEI, Prof. G. de Zoeten. Das Sekretariat wird vom Bureau Central betreut. Das ACET hatte am 18. November eine ganztägige Sitzung. Es wurden im wesentlichen folgende Probleme behandelt und Beschlüsse gefasst:

Das CE 49, Piezoelektrische Kristalle, bemängelte, dass die Publikation 68 der CEI, Klimatische und mechanische Prüfmethoden, zu wenig Rücksicht auf seine Bedürfnisse nehme und dass folglich daran gedacht wurde, eigene spezialisierte klimatische Prüfungen festzusetzen. Es wurde dem CE 49 aber sehr davon abgeraten und schliesslich beschlossen, das CE 49 solle dem CE 50 eine Liste der dringend benötigten Prüfverfahren zukommen lassen.

Das ACET diskutierte die Umschreibung des Tätigkeitsgebietes des neuen CE 52, Gedruckte Verdrahtungen, und legte den Text fest, der dem CA zur Beschlussfassung unterbreitet werden soll. Ebenso wurden Titel und Tätigkeitsbereich des CE 53, Rechenmaschinen und Informationsverarbeitung, zur Weiterleitung an das CA genehmigt; sie waren vorher mit dem TC 97 der ISO abgesprochen worden. In Bezug auf die graphischen Symbole für Rechenmaschinen wurde davon Kenntnis genommen, dass das CE 53 deren Ausarbeitung im Einverständnis mit dem CE 3, Graphische Symbole, dem TC 97 der ISO überlässt. CE 53 und CE 3 werden über die Arbeiten auf dem Laufenden gehalten.