SOME CHARACTERISTIC PROBLEMS OF THE NEW HIGH DUTY CYCLE SACLAY ELECTRON LINAC

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The electron linac being manufactured for the Saclay center of the French Atomic Energy commission will be a high duty cycle machine : 1 % at 550 MeV unloaded energy, 2 % at 350 MeV.

Figure 1 shows the V/I curves for different duty factors. An average beam power of 100 kW will be obtained with a peak current of 20 mA at 1 % duty and 14 mA at 2 % duty.

Positrons will be accelerated to about 500 MeV at 1 % and 350 MeV at 2 %. A beam transport system allows to use the beam at 200 MeV.

Energy definition must be better than 1 %, both in spectrum width and long term stability.

I- MAIN CHARACTERISTICS

- The pulse duration is 10 μs. However, 0.2 μs pulses will be available for testing purpose.

- repetition rate 1000 and 2000 pulses/sec.

This pulse rate may be changed to 12.5 c/s - 1600 c/s.

The machine uses 30 sections and 15 klystrons according to the following layout.

- section 1 is a 1.6 m buncher
- section 2 is a short section of 3 m, using the RF power left from 1 klystron feeding the buncher
- sections 3 to 6 are 6 m. long
- the positron converter is located after section 6, at the 80 MeV electron energy level
- following the positron converter, section 7 is high field section of 3 m length
- sections 8 to 30 are 6 m long each

The focussing uses the following :

- 400 gauss solenoïds up to section 6 (for electrons only)
- a 2800 gauss solenoïd for section 7 which follows immediately the positron converter
- 2200 gauss solenoïds for sections 8 to 18
- triplets of quadrupoles between sections 19 to 28.

The characteristics of all the components of the machine derive directly from the high duty cycle and energy definition required. In particular the narrow spectrum reflects on injections requirements, RF pulse quality, RF beam phase and so on temperature homogeneity and stability of the sections. The high average beam power reflects on the RF power source design and particularly careful beam control.

II- CHOICE OF OPTIMUM RF POWER AND LENGTH

The optimizations of RF power and length for lowest overall cost must be based on more elaborate arguments than the straightforward use of the relation

$$P_L = V^2 / R_s$$

In particular, account must be taken of the duty factor, which reflects on the cost of the RF units, and of the maximum accelerated current required (corresponding to RF power exhaust at the end of the sections). A more elaborate optimization is then possible, leading to a value of overall length but also to the choice of the unitary section and RF power sources, if practical considerations are taken in.

Fig. 2 shows the curves for RF power and accelerator total cost as a function of length for a given zero residual power at 60 mA.

It leads to :

- overall electrical length : 170 m
- number of sections : 30, of which 27 are 6 m long and 3 are shorter (high RF field)
- internal impedance : 81 MΩ
- RF power : 1.8 MW into each section
- klystrons : 15 klystrons of 4 MW peak power, 60 kW average power

III- SECTIONS

The main problems in such an accelerator come from the high average power which requires a great care in the control of the temperature of all elements, and also in the control of the beam.

Then the first approach is to develop section of the best possible quality, in MeV per megawatt. This condition leads to the choice of the $\frac{\lambda}{3}$ mode for the waveguide, and to irises as thin as possible. Cooling of the iris, arcing on the edge, mechanical strength, set the lower limit. The value of 3 mm has been kept as for the Orsay Linac, but the conical transition from iris to cylinder has been increased to $\pm$ 60º on a 12 mm radial extension.

As is known, the $L\omega = \frac{R_s}{Q}$ value depends on group velocity. It turns out that the product $L\omega . \frac{c}{v_g}$ is very close to a linear function of $\frac{c}{v_g}$

For 3 mm irises, including the $\left(\frac{\sin\theta}{\theta}\right)^2$ factor :

$$L\omega . \frac{c}{v_g} = 5.545 \left(\frac{c}{v_g} - 8\right)$$

as compared to :

$$L\omega . \frac{c}{v_g} = 5.820 \left(\frac{c}{v_g} - 9\right) \text{ for a } \frac{\pi}{2}$$

structure with 3 mm irises used for the Orsay Linac (These values are at 2998 Mc/s).

The quality factor Q depends a little on group velocity, thus varies along the structure but remains close to 13000 or over.

For many reasons, one has advantage to reduce the number of RF feed points and use sections as long as possible. 6,3 m seems close to a practical limit.

For a filling time of 0,85μs, then the group velocity has to vary from $\frac{c}{28}$ to $\frac{c}{89}$ approximately, to give a constant RF field law for 15 mA peak current loading, which is the typical operation.

However, the total attenuation has been kept low, so that the current corresponding to total RF exhaust is 70 mA for 1,8 MW input power, and to reduce the variation of energy due to beam loading variations, so that the stabilisation will be easier.

This gives the compromise value of 15 MeV per 1/2 MW per 6 section with a residual power of 0.5 MW at zero current.

If two of these sections are fed in parallel on one klystron, with 5 % power loss in the waveguides, the net outcome is 20,9 MeV per MW$^{\frac{1}{2}}$ per klystron.

In fact, this value does not represent the complete picture of the section. By reducing maximum possible peak current and increasing filling time, we could increase slightly the energy for the same power consumption. But this gives also smaller irises and then smaller positron beam, all things being equal. This fine arrangement of the structure can practically be changed during the construction process, and will depend also on the solution which will be taken about beam blow up correction.

Mechanical characteristics

Brazing : silver diffusion
Cooling 10 pipes Ø 12 mm
Cooling capacity 25 watts/ºC/centimeter
Nominal water flow 3 litres/sec per section

Figure 3 shows how the constant gradient law is approached by seven steps which allows the possibility, just by changing their length to modify the series impedance and filling time to match exactly the design operating condition.

Top view shows the shape of the individual cavities.

Cooling problem

For high average power, the cooling of the accelerator becomes a difficult problem, if one wants to insure a good uniformity of temperature along the accelerator. The number of RF penetrations is limited : one per section, or maximum 2 (one at each end) and the same water cools a certain length of accelerator. Then in order to remove heat, the temperature of the water is lower than that of the copper and is not a constant along the waveguide. The overall transfer coefficient from copper to water is of the order of 1.3 watt per degree C per square centimeter, this coefficient depends on water pressure, and Reynolds number and even if the entire outside area of the copper could be used for cooling ; there would be a temperature difference of 1 or 2 degrees between water and copper at each point. This difference is a function of the local rate of exchange then it is very important to control accurately the $\left(\frac{dP}{dz}\right)$ due to Joule effect.

On the RF input end, this factor depends only on the power given by the klystron. But on the opposite end, this factor can vary from a maximum value for no load to zero for current corresponding to RF exhaust.

Then, differences of temperature of the order of 1 or 2 degrees, (more than can be tolerated without correction) can exist.

In this accelerator, the cooling is made by 5 circuits in parallel, each one making one way and return along the cavities.

This design gives all the water pipes penetrations on the same plate which makes easier some mechanical problems, for example difference in expansion between copper waveguides and stainless steel vacuum envelope.

A little gain could be got by having one way pipes, but the general behaviour will not be changed.

A good increase in water to copper contact area is obtained by the grooves around the cavities in which the pipes are soldered.

The temperature of the copper depends on the water flow and the power density $W(z)$. To simplify the computation, one can assume that $W(z)$ is a linear function

$$W(z) = W_0\left(1 + \beta \frac{z}{L}\right)$$

β here is a parameter which represents the effect of beam loading. For $i = 0$, and the actual design, one has $\beta \approx 0,1$; $\beta = 0$ for $i = 15$ mA and $\beta = -0,1$ for $i \approx 30$mA approximately.

Let :

T_0 be the temperature of the input water

T_c (z) " " " " copper

L the length of the section

a the inverse of the cooling efficiency

($\frac{1}{a}$ in watts per cm of waveguide per degree C)

D the total water flow

$$b = \frac{1}{4.18\ Da}$$

Then one has :

$$T_c(z) - T_0 = \frac{a}{2} W_0 \left[1 + bL\left(1 + \frac{\beta}{2}\right)\right] - \frac{ab^2}{2} W_0 L^2 \left[\frac{\beta}{6}\frac{z^3}{L^3} + \frac{z^2}{L^2} - \left(\frac{\beta}{bL} + 1 + \frac{\beta}{2}\right)\frac{z}{L}\right]$$

For the chosen value of the water flow (3 litres per second) the temperature of the section varies then from 2,6º to 3,1º above temperature of input water, for i = 0, and 2,5 to 2,9 for i = 30 mA.

By choosing the pick up point for temperature control at 3,7 meters from input it turns out that phase shifts due to these temperature differences cancel, and that the optimum phase for the input RF is independent of current. Thus no adjustement of phase shifts is needed when the current is changed.

Beam blow up problem

For 10 μs pulse duration and 180 m long accelerator, with only one RF feed every 20 feet, beam drift according the known results from Stanford, could occur at roughly 10 mA peak current, for non accelerated beam. The effect of acceleration, and the very strong focussing power which is installed-solenoïds up to 100 meters, one triplet of quadrupoles every 20' up to the end - will give a substantial increase in critical current. However, some work is still on to investigate the propagation curves of the deflecting modes (fig. nº 4)

The condition of excitation of power in the deflection modes seems to be in the lower triangle between the propagation curve of the TM_{11}, $\psi = \pi$, and v = c lines.

The second beat frequency is a vanishing 2π mode which can also interact with a modulated beam. One condition to avoid these modes would be that the propagations curves for all cavities be above the 4500 Mc/s line.

In the actual section, only the second half is in this case. The beaver shape of the cavity made mainly for mechanical strength and better cooling, does not modify essentially the propagations curves of the TM_{11} mode, as was expected.

Since this mode is well coupled to the input waveguide for polarisation parallel to the guide and uncoupled (then the power is trapped) for polarisation 90º to it, a 90º rotation of the beam form section by solenoïd seems to be a good way to increase the critical current. Careful misalignment of the input end of each section is also envisaged.

IV- POSITRON GENERATOR

It is installed after section 6, at the level of 20 to 40 kW average power, at 80 MeV. After some thinking we decided to use a water cooled rotating tungsten target instead of a variation cooled wheel.

The movement of the target is elliptical (6 X 2,5 cm) swept about 5 times a second, instead of circular. This gives a longer path for the same total mechanical stress on the membrane on which the target is attached.

The tungsten is in 3 sheets and separed along the width to allow for difference in expension and change in shape.

Copper is cast around the tungsten and water pipe as close to the beam as possible.

A set of two lenses is used focus as much of the positron output into the following sections. A separate control for the entrance of the solenoïd to accurately control the matching of the positron beam to the solenoïd is provided. It can be considered as a "third lens" which controls the convergence of the beam.

Great care has been given to accessibility all parts, because no good information is available on radiation damage in such a high flux of photons and neutrons.

The high magnetic field region is obt obtained by an electro-magnet which can be separated in two parts for access to the beam pipe.

V- RF POWER SOURCES

The klystrons used are made by Thomson Varian, and have the following characteristics :

- Peak outpur power (nominal value)
  4 MW (1 % d.c)
  2 MW (2 % d.c)
- Average output power : 60 kW
- Perveance $\mu A/V^{3/2}$: 1,9 to 2,1
- Efficiency : ⩾ 35 % (1 % and 2 % d.c)
- Gain : ⩾ 46 db
- Peak beam voltage : 140 kV (max)
- Peak beam current : 91,5 A (max)
- Focussing current : 50 to 160 A
- Heater power : 500 W (max)

The klystron body is water cooled. The output window feeds into pressurized waveguide.

Among the different types of modulators which could envisaged delay line, hard tube with or without pulse transformer we had to consider the consequences of the high average power and the pulse quality.

The delay line type modulator, widely used now at low duty cycles is limited by the problem of the switching device and the difficulty of tuning the pulse shape.

In this particular case, two solutions were considered :

- use of 3 spark gap systems of the type we develpped for our Euratom machine
- use of two GHT6 thyratrons, of the MO valve company
- use of 3 or 2 delay lines and associated inductances and diodes

Flat top of 0.2 % are attainable with delay lines but are a very difficult problem. Also, such stability is obtained only for given operating conditions and is not maintained when varying output voltage.

This lead to the choice of hard tube modulators. A second choice was then to be made between direct triggering at 140 kV or use of a pulse transformer. The triggering of 140 kV seemed a year ago to offer considerably less life and reliability and we chose a solution using a 4.5 ratio pulse transformer and two F 6046 trigger tubes, at 40 kV.

The design characteristics of the modulators are the following :

- Peak power output : 12 MW
- Average power output : 135 kW
- Peak voltage : 140 kV
- Peak current : 91.5 A
- Load resistance : 1400 to 1900 Ω
- Pulse flat top : 0.1 % on a 10 μs pulse
  1 % for the first μs
- Long terme stability : 1 %
- Maximum backswing voltage : 55 kV
- Switch tubes : 2 CSF-F6046 at 40 kV
- Pulse transformer ratio : 4.6 at 1% duty
  3.4 at 20º duty
- Leak inductance : 90 μ Henry
- Distributed capacitance (secondary) 100 pF
- Dynamic impedance of the hard tube (primary) : 75 Ω
- capacitor bank : 3.75 μF
- Protection by crow bar for :
  maximum energy release : 800 Joules
  maximum energy current : 1000 A

VI- BEAM INJECTION

RF peak power is low in such accelerator, because of the high duty cycle. At 2 %, the maximum peak power available for a given section is 1 MW. Then the accelerating gradient is practically limited to a max between 3 to 4 MeV/meter. The bunching and preacceleration of the beam have to be made at low gradient, and a great care has to be taken to insure good beam quality.

In this view, a chopper at 3000 Mc/s is not absolutely necessary, but it helps to clean the beam and get all the charge concentrated in the bunches. This reduces beam losses along the accelerator. But then this chopper must not increase the beam radial phase space.

In order to save the beam concentration to a maximum, a focussing axial magnetic field is used as a component of the chopping system.

As shown by fig.5 our chopper consists of a rectangular cavity resonant in TM_{011} mode at a frequency of $\frac{\omega}{2\pi}$ to which is applied adc magnetic field B parallel to its long axis O_z. The electron beam from the gun enters the cavity along O_z.

If rf power is injected into the cavity, the electron beam is subjected to an alternating electric field parallel to O_x, and the X and Y components of motion are similar to those in a cyclotron. As no force is applied to electrons along O_z their speed $\frac{dz}{dt}$ remains constant. As the beam progresses through the cavity, the amplitude of its circular transverse motion increases to a radius R depending on geometrical length of the cavity and strength of the rf field.

A V-shaped slot is cut in the end wall of the cavity, the apex of the V being on O_z, so that electrons between phase angles and cross the end wall while the others are stopped. Thus bunches are formed of monokinetic electrons within a well determined phase interval.

A second cavity is arranged on the other side of the end wall driven by rf of opposite phase ; the motion of electrons through the second cavity is inverse to that in the first cavity and at the exit aperture the bunches are ejected with velocity parallel to O_z. Thus it is possible to chop an electron beam without introducing velocity modulation or increasing emittance.

The analyses has been made as a Doctor's theses by Mrs Richoux. As a practical figures, it leads in the present case to two coupled cavities of overall dimensions :

2 d = 155 mm
b = 65.8 mm
a = 20 mm

The cavity has a Q factor of 2000 and the necessary RFpeak power is 7 kW. This is the minimum to ensure that the electron orbit radius is large enough compared to the beam cross section diameter.

Under these conditions, beam interception by the median partition is about 75 %. As this chopper cannot operate properly at very short pulse durations, at 10 ns for instance, a circular hole is provided on the accelerator axis in the median partition for direct transmission of the beam.

It should be pointed out that this chopper is very advantageous for the bunch formation. Instead of introducing a density distribution in the beam, it acts as a diaphragm, cutting out a 90º phase length of uniform density in the electron beam.

This uniform bunch is then sent into a prebunching cavity of classical design which contracts it into a 20º bunch. This enters the buncher section, which is about 2 m long, and which uses most of the first klystron power.

The buncher has been designed for a constant relative phase for electrons at 30º from peak. Figures 6 and 7 give computed phase velocity and energy along the buncher, and bunch width as a function of time. These results come from a computing programm obtained by dividing the bunch into 9 smaller ones which are then considered as charged flat discs of constant radius. The space charge field from all discs is computed, and the total field on each one is devided.

The z movement of each disc is then calculated.

The design we arrived at is particularly insensitive to injection voltage and beam current variations as far as relative output phase is concerned.

VII- STABILITY

The high beam stability required has lead to a number of choices on the RF chain, temperature control, and other associated parts. The machine is designed for operation without any corrections controls by the operator.

All the control system is designed to be as stable as possible, and as trouble free as feasible, with a small number of adjustements and using minimum possible number of automatic loops. The idea is that the machine is naturally stable in itself. In order to achieve that goal, loops including the beam have been avoided. Only one is left final energy control.

Master oscillator

Choice has been made to use a reflex klystron stabilized by a high Q cavity as a CW master oscillator, because of the automatic frequency control by temperature. The first high power klystron is used for the buncher and section 2 and also for the feed line to the other amplifiers.

Temperature control

The principle is to use a "floating" temperature, the temperature of the main supply of water, as a fondamental temperature reference against which the temperatures of the sections are stabilized about $\pm$ 2º C.

This water cools also the cavity of the master oscillator the operating frequency is displaced of a fixed value of 100 Kc/s corresponding to the 2º C difference between sections and water.

Energy control

Final energy control is made by the signal received on twi beam detectors placed in the focal plane of the final bending magnet. The energy is changed by changing the phases of two last klystrons of the same amount opposite one to the other. This minimizes the possible reactions but on the spectrum quality.

Current control

It is made by action on the temperature of the emitting filament, then no change is made in the voltage of the gun, and so no action on the bunching of the beam.

Phase control

We try to design the buncher so that the output phase should be as insensitive as feasible to beam current.

The actual state of computation is not yet satisfactory.

It may be necessary to install an automatic phase control acting on the phase of the whole machine after the buncher so that adjustement of current may need no other adjustement.

RF distribution

One of the problems of a long machine is to maintain phase synchronization between the beam and the RF of each section One solution is to provide correcting devices which time the phase of each RF power source from an error signal taken on the section.

We have preferred to design the RF distribution in such a way that most of the causes for deviation be compensated by the very behaviour of the components. These causes are mainly temperature variations and frequency drift of the master oscillator. This makes the whole system essentially temperature insensitive. Frequency sensitivity is greatly reduced by a proper device of the distance between the general distribution coupler and the first section.

Althrough this should make the machine stable enough, we are providing a RF reference line which may be used to introduce phase correcting devices. This line is a coaxial line fed by C.w.power. It is designed to give, at every point along the accelerator, a phase reference identical to the phase of the beam modulation.

Energy and current regulation

In order to ensure the 1 % energy stability, its variations due to frequency or temperature drift must be corrected. This is done by acting on the phases of the last two klystrons. Current regulation is ensured by acting on the gun heater current Both actions have to be triggered by error signals. These signals come from measurements made at a 1 % wide slit located after an analyzing magnet which takes sam pling pulses.

If the current going through the 1 % slit and those falling on the two sides are measured separately, as A, B and C,and assuming that the spectrum is symetrical around the energy E_0, A - C will give an error signal on energy, independent of current stability to a second order approximation B will give a signal measuring current stability, independent of energy variations to a second order approximation.

APPENDIX I- RF DISTRIBUTION (Fig 8-9)

The first power klystron feeds the first section S_1 and supplies the drive power to the other power klystrons through a coaxial line. We want to minimize the effects on beam to RF phase of :

- The length of waveguide
- Temperature variations
- Frequency variations

If we assume that waveguides 1, 2. n, n' are all of different types and different temperatures, the phase differences between beam and wave at abcissa x_n and x_n + Lo are :

$$\varphi_n = 2\pi \frac{x'_n}{\lambda_0} + 2\pi \frac{L_n}{\lambda_0} + 2\pi \frac{\ell_n}{\lambda_{Gn}} - \left[2\pi \frac{\ell_1}{\lambda_{G1}} + 2\pi \frac{x_n}{\lambda_0} \right]$$

$$\varphi'_n = 2\pi \frac{x'_n}{\lambda_0} + 2\pi \frac{L_n}{\lambda_0} + 2\pi \frac{\ell'_n}{\lambda'_{Gn}}$$

For dispersive waveguide of length ℓ : $\Delta\varphi = \frac{2\pi\ell}{\lambda_G} \left(\frac{\lambda_G}{\lambda_0}\right)^2 \propto \Delta T$

For coaxial line : $\Delta\varphi = \frac{2\pi\ell}{\lambda_0} \propto \Delta T$

If T_0, T_1 and T_2 are the temperatures of the oscillator cavity, rectangular waveguides and coaxial lines :

$$\delta\varphi_n = \frac{2\pi L_n}{\lambda_0} \propto (\Delta T_2 - \Delta T_0) + 2\pi \frac{\ell_n}{\lambda_0} \propto (\Delta T_1 - \Delta T_0) \frac{\lambda_{Gn}}{\lambda_0} - 2\pi \frac{\ell_1}{\lambda_0} (\Delta T_1 - \Delta T_0) \frac{\lambda_{G1}}{\lambda_0} + 2\pi \frac{x'_n}{\lambda_0} \propto (\Delta T_2 - \Delta T_0) + 2\pi \frac{x_n}{\lambda_0} \propto \Delta T_0$$

$$\delta\varphi'_n = \frac{2\pi L_n}{\lambda_0} \cdot \propto (\Delta T_2 - \Delta T_0) + \frac{2\pi \ell'}{\lambda_0} \cdot \propto (\Delta T_1 - \Delta T_0) \frac{\lambda'_{Gm}}{\lambda_0} - \frac{2\pi \ell_1}{\lambda_0} \cdot \propto (\Delta T_1 - \Delta T_0) \frac{\lambda_{G1}}{\lambda_0} \pm \frac{2\pi L_0}{\lambda_0} \propto \Delta T_0 + 2\pi \frac{x'_n}{\lambda_0} \propto \Delta T_2 - 2\pi \frac{x'_n - x_n}{\lambda_0} \propto \Delta T_0$$

If we separate the terms in T_0, T_1 T_2, we have to minimize :

a) the effect of T_0

$$\frac{1}{\lambda_0} (\ell_n \lambda_n - \ell_1 \lambda_{G1}) + (x'_n + L_n - x_n) = \varepsilon_1 \qquad (2)$$

$$\frac{1}{\lambda_0} (\ell'_n \lambda'_n - \ell_1 \lambda_{G1}) \mp L_0 + (x'_n + L_n - x_n) = \varepsilon_2 \qquad (3)$$

b) the effect of T_1

$$\ell_n \lambda_{Gn} - 2\, \ell_1 \lambda_{G1} + \ell'_n \lambda'_{Gn} = 0 \qquad (1)$$

c) The term in T_2 can be reduced only by reducing ΔT_2 itself.

(1) Shows that an optium length l_1 can be chosen between the first klystron and section S_1 to reduce to a minimum the effects of ΔT_1.

(1) (2) (3) lead to two relations

$$\ell'_n + \frac{\lambda_{Gn}}{\lambda_0} - \ell_n \frac{\lambda_{Gn}}{\lambda_0} = L_0$$

which can be satisfied by chosing different dimensions for the waveguides of the two arms of the klystron
The other relation is

$$x'_n + L_n - x_n = \frac{L_0}{2} \qquad \text{For klystrons of odd number}$$

$$x'_n + L_n - x_n = -\frac{L_0}{2} \qquad \text{for klystrons of even number}$$

These set the optimum location of the couplers to the klystrons on the distribution line.

For ΔT_2, in order to avoid a 0.1ºC temperature regulation, expension joints can be inserted in the waveguide so that its overall length does not vary A 1ºC temperature stability is then acceptable.

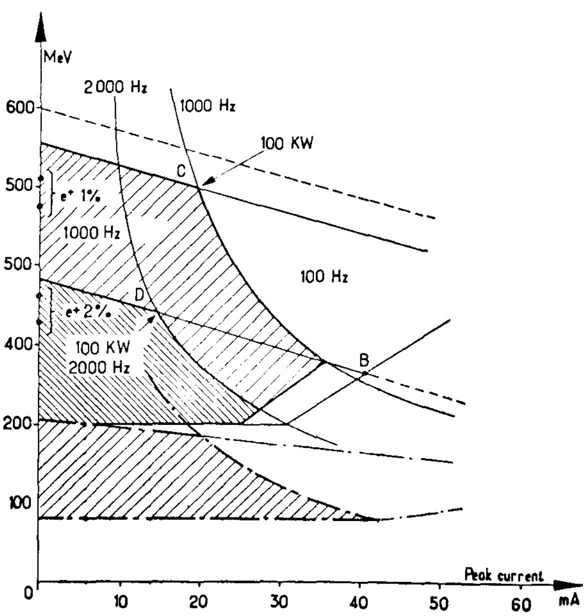


Fig. 1.

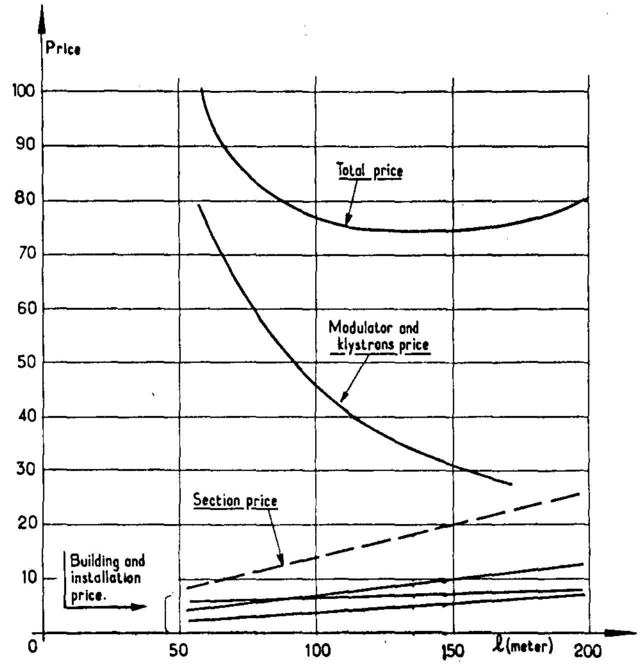
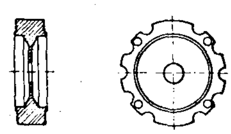


Fig. 2.



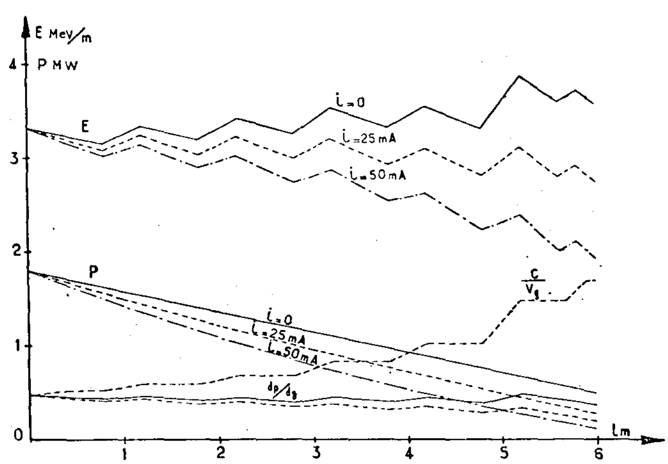


Fig. 3.

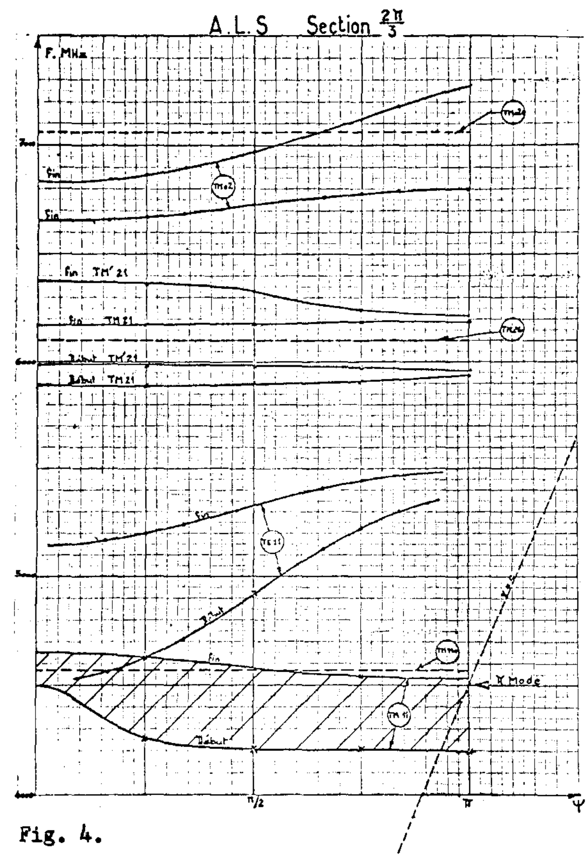


Fig. 4.

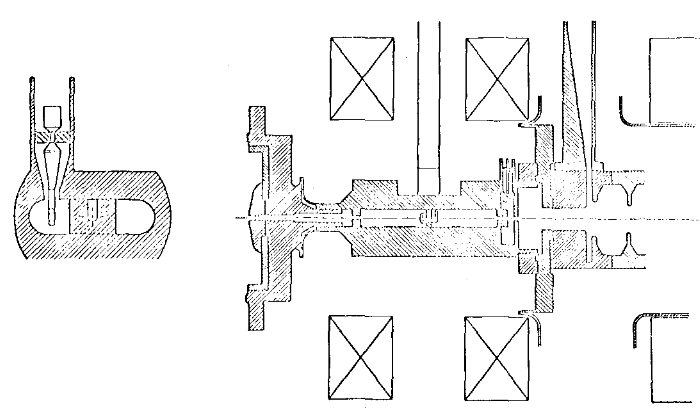
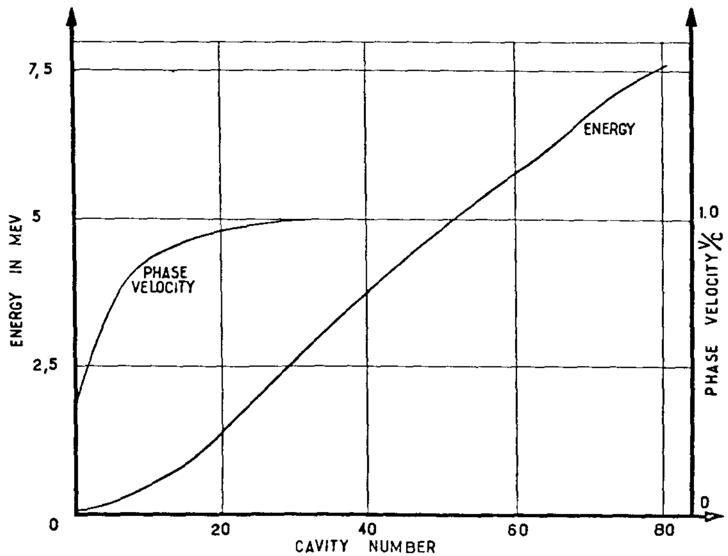
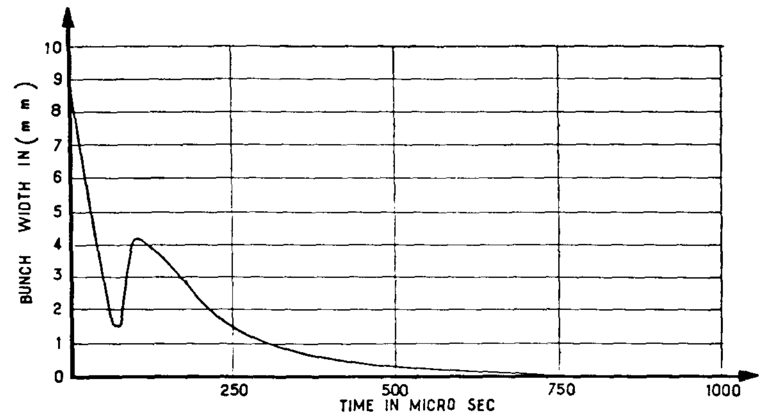


Fig. 5.



PHASE VELOCITY and ENERGY IN SUCCESSIVE CAVITY OF THE BUNCHER

Fig. 6.



BUNCH WIDTH AS A FUNCTION OF TIME IN THE BUNCHER

Fig. 7.

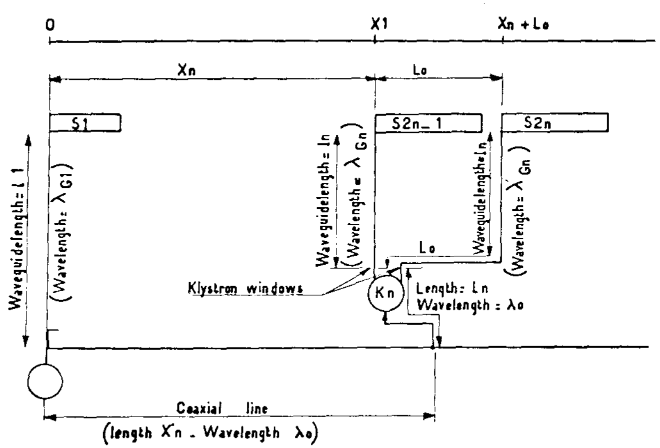


Fig. 8.

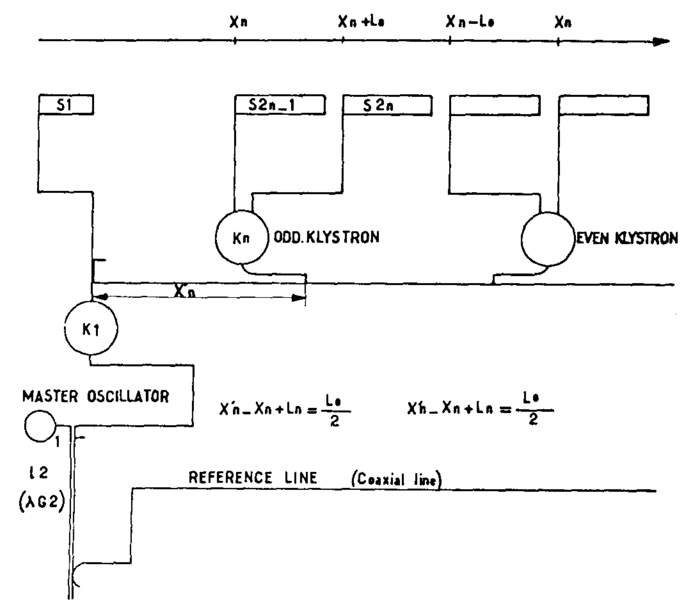


Fig. 9.