Laboratori Nazionali di Frascati

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THE KS – 3 MeV VAN DE GRAAFF INJECTOR OF THE FRASCATI ELECTRON SYNCHROTRON †

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The modifications apported to a standard 3 MeV Van de Graaff, used as injector for the 1100 MeV Frascati synchrotron, are reported.

They concern the voltage stabilizer, a compensation circuit that takes care of the fast variations of the voltage at the belt frequency, and the Pierce type electron source.

A few data concerning the synchrotron operation in the period Jan. 1–Aug. 31, 1960, are added.

Finally it is shortly described the project of a storage ring for 250 MeV electrons and positrons which is being built in Frascati.

1. Introduction

The Frascati synchrotron is an electron accelerator with a maximum energy of 1100 MeV, an average intensity of 5×10^9 electrons accelerated per pulse and a repetition rate of 20 pulses per second.

The electron beam coming from the injector at an energy of 2.6 MeV, goes through a system of magnetic lenses, then past an electrostatic inflector, which injects it tangentially into the synchroton magnetic field; there the electrons are accelerated up to the final energy by two radio frequency cavities.

At the maximum energy, 23 milliseconds after the injection, the electrons strike a tantalum target, 0.5 mm thick, equal to 0.13 radiation lengths; the experiments use the γ-ray beam thus produced which has a continuous spectrum of energy, up to the maximum electron energy, and a half-width of 3.5 mrad at 1000 MeV.

Fig. 1 shows a view of the synchrotron room; one can see the injector, the pipe connecting the injector to the inflector, along which are two magnetic lenses and four coils for the beam positioning, the electrostatic inflector and the radio frequency cavities.

The injector is a standard KS–3 MeV Van de Graaff of the High Voltage Engineering Corporation; a few modifications have been made, of course, and they are the subject of the following report.

I think that we must say, first of all, that these modifications have been limited as much as possible; our aim was to get, in a short time, a suitable injector for the synchrotron, whose prime requirement was reliability.

The modifications inside the tank have been confined to the cathode and its pulser; other modifications required a lot of time and experience that we do not have.

Unfortunately the time at our disposal to study the behaviour of the injector and the general problems of injection in the Synchrotron, has been very short indeed.

2. Injector Specifications

The specifications for the electron beam at the injector output fall into three classes:

2.1. Energy
2.2. Intensity
2.3. Optics

2.1. ENERGY

Because of the small acceptance in momentum of the inflector and the synchrotron, the electron energy must agree, within 0.1 %, with the inflector voltage and the synchrotron magnetic field. This means that a stability in energy of 0.1 % would be required, if the other two parameters were kept constant.

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† Report of the Synchroton Staff, Laboratori Nazionali di Frascati, delivered by Fernando Amman.

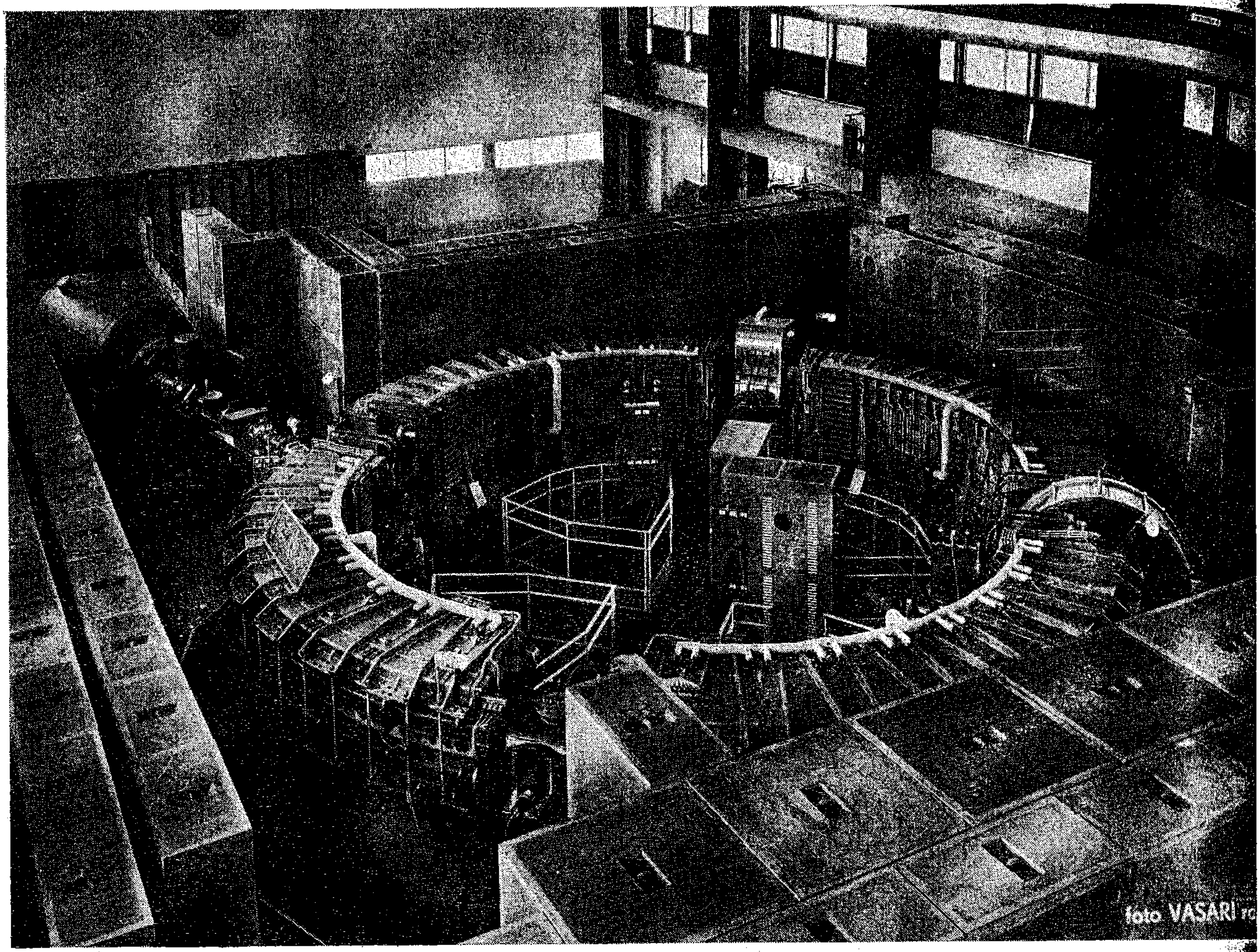

Fig. 1. The Frascati 1.1 GeV electron synchrotron. General view.

It is known that the voltage of a Van de Graaff has fast variations, with the belt frequency (their value depends on the belt). In the 3 MeV Van de Graaff it is usually between ± 0.5 % and ± 1 %.

The belt charge system at the base cannot of course take care of these variations at the belt frequency.

The corona stabilizer, used in positive machines, should be mounted on the high voltage terminal, and this produces a lot of problems.

Another easier system could be devised: to use the down belt charge, like a corona stabilizer, driven by a feedback signal transmitted to the high voltage terminal with a frequency-modulated light; but, as said before, we did not want to install anything inside the tank unless absolutely necessary.

Then, following more or less what had already been done at the Cornell University Synchrotron, we do not try to cancel the fast variations but vary the other two parameters, namely the inflector voltage and the magnetic field at the injection time, in agreement with the injector voltage.

This compensation takes care of the fast variations of the injector voltage, with a frequency band from about 0.1 c.p.s. up to very high frequencies.

Besides this the injector needs a low frequency stabilizer to hold the mean voltage constant within 0.1 %, with a high gain in the frequency range from zero to 0.1 or 0.2 cycles per second

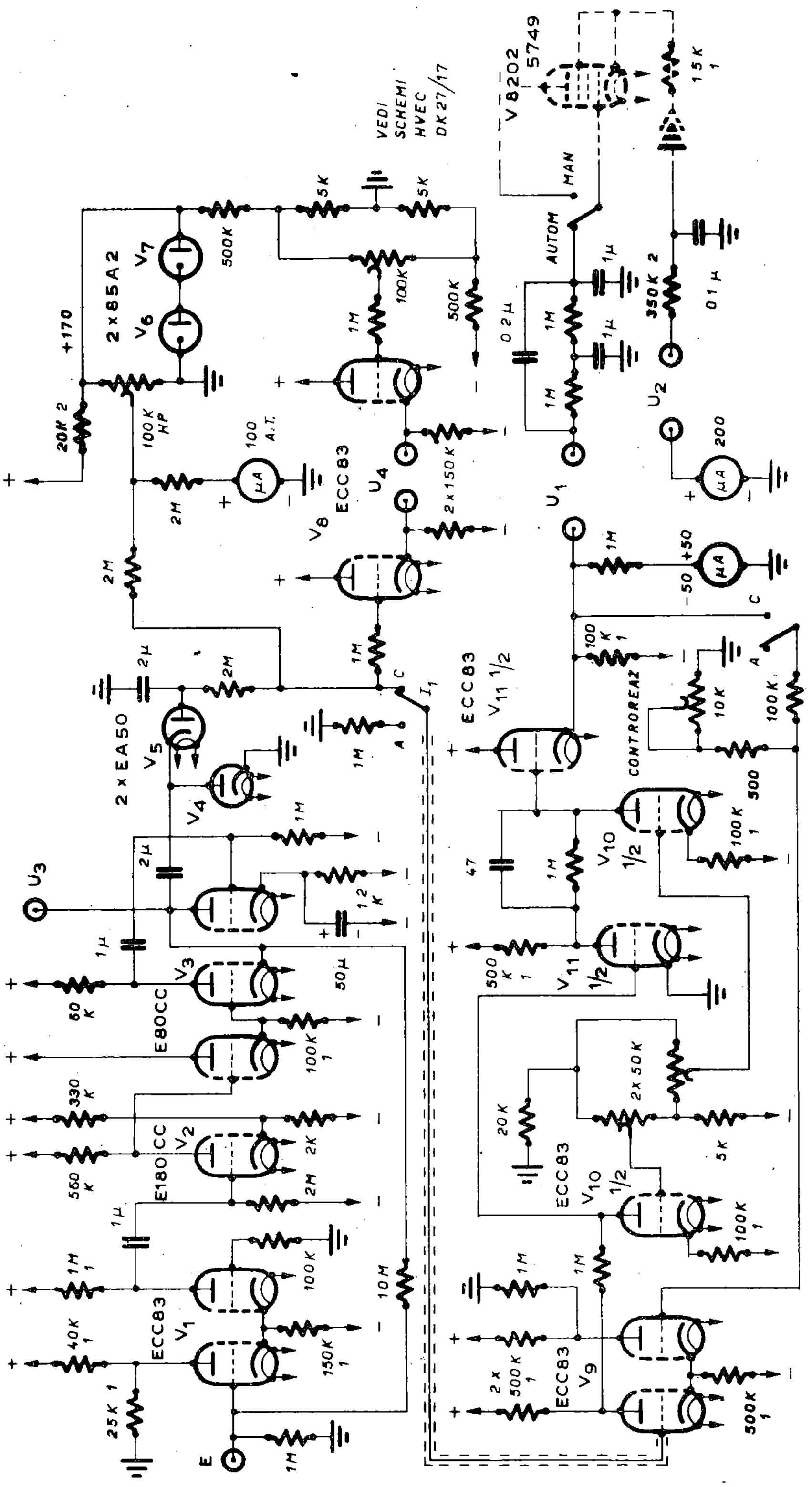

Fig. 2. Low frequency stabilizer.

2.2. INTENSITY

A 100 mA beam, in pulses of 2 μsec, is required. The original cathode has been changed and a Pierce type source is used.

2.3. OPTICS

The beam coming from the injector must have small divergence, of the order of 10^{-3} rad, and a diameter not greater than 2 cm, to avoid the use of many magnetic lenses.

This requires a careful design of the source.

3. The Low Frequency Stabilizer

A very simple equivalent circuit of the Van de Graaff voltage generator can be assumed to consist of a current generator (the belt charge system), a fixed time delay (the time for the charges on the belt to travel from the base to the terminal) and a time constant RC, R being the loading resistor and C the capacity between the terminal and ground. The time delay is of the order of 0.1 sec and the time constant 2.3 sec.

The open loop frequency response of the generator up to 2.5 c.p.s. (the point at which there is a 180° phase shift between input and output) has been measured; it is in good agreement with the above mentioned simple equivalent circuit.

The original stabilizer did not meet the requirement of a mean stability within 0.1 %.

We have built a new stabilizer, whose diagram is shown in fig. 2.

The signal from the generating voltmeter goes to an amplifier, whose gain is about 2000; its output is fed back to the input, with a change in phase of 180°, through a resistance of 10 MΩ. The amplifier is used to match the impedance and to cancel the effects of stray capacitances.

The output signal depends on the rotation frequency of the generating voltmeter; we use a frequency-stabilized supply, we had already for other equipment, whose stability is better than 0.1 %.

This AC signal, whose amplitude is 150 V peak to peak for a terminal voltage of 3 MeV, is rectified and compared with the reference voltage. The difference signal is amplified by a factor of 30, and after a network, goes to the grid of the pentode of the belt charge circuit. The pentode has a negative feedback due to the high resistance in its cathode. The other parts of the charge circuit are unaltered.

The network at the pentode grid is like the one mounted on the original stabilizer, except for the maximum attenuation frequency, which is lower; this allows a greater phase margin, and therefore smaller overshoots.

The open loop static gain of the system is 120–130. This is enough to hold constant the mean voltage of the Van de Graaff within 0.1 %, as required.

4. The 'Pick Up Compensation'

As has been mentioned before (section 2), the fast disturbances introduced by the belt cannot be corrected by the stabilizer; the "pick up compensation", which changes the voltage of the inflector and the magnetic field at the injection time, takes care of them.

The necessary information is obtained from a signal induced on a pick up electrode, mounted in a hole in the tank: this signal is proportional to the terminal voltage variation. The compensation circuit diagram is shown in fig. 3. There is a preamplifier, whose first stage is an electrometer tube, and two amplifiers, one for the inflector, and the other one for the injection timing.

The system is AC coupled: the time constants are greater than 20 sec, to allow a good linearity from high frequency down to 0.05 c.p.s. With this "pick up compensation" the result is the same as if the fast variations of the terminal voltage were decreased by a factor greater than 10, while holding constant the other parameters (inflector voltage and magnetic field at the injection time).

On this subject, it may be interesting to mention a phenomenon which occurred at the beginning of the synchrotron operation.

When the injected current was high, the accelerated intensity oscillated from zero to a maximum, with a period of the order of 5 seconds

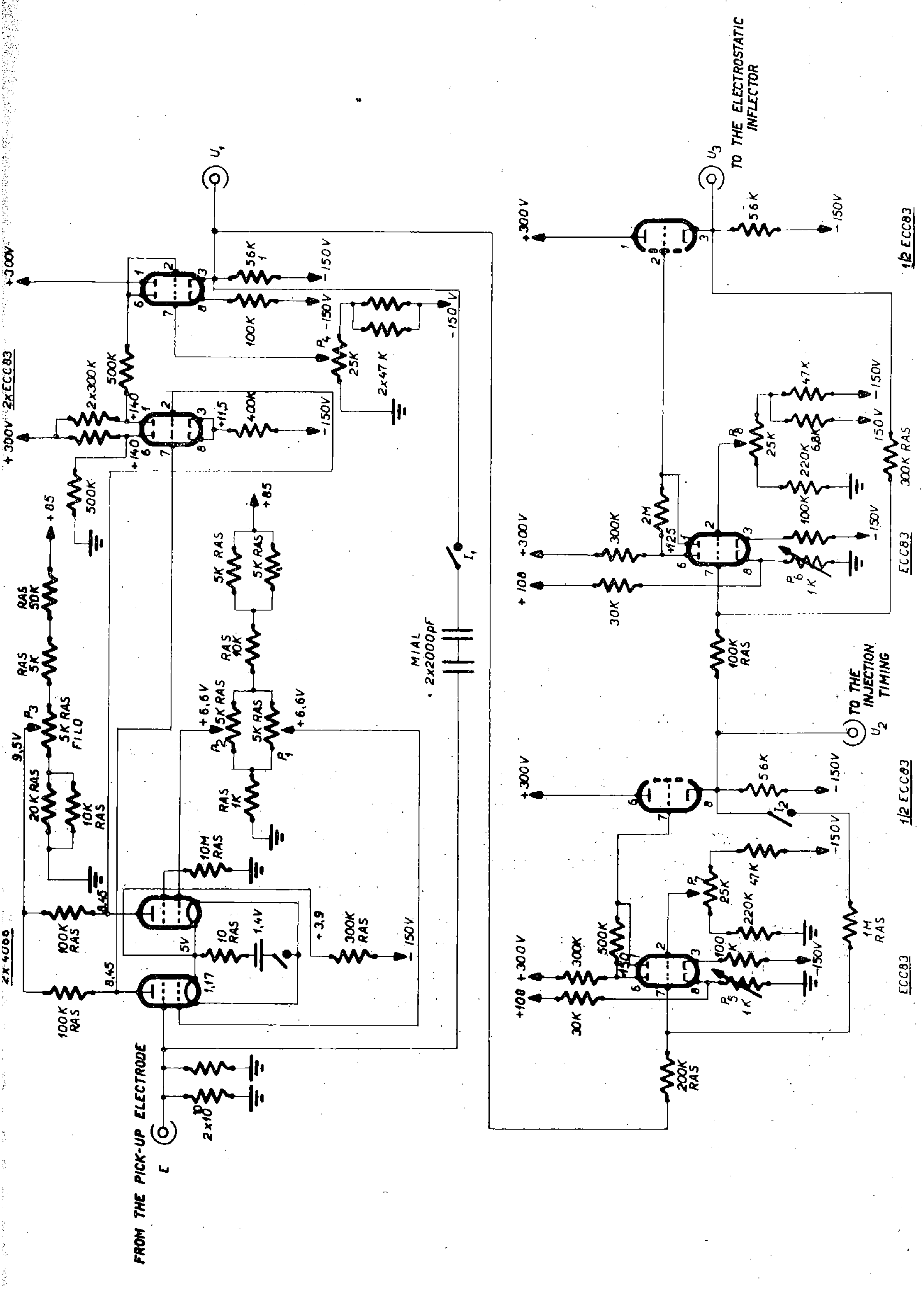

Fig. 3. Compensation circuit.

The pick up output had a similar behaviour, not justified by terminal voltage variations, because the signal from the generating voltmeter was regular.

This effect has been eliminated by shielding the Van de Graaff from the Synchrotron with concrete blocks, and the bushing of the pick up with lead.

We made the hypothesis that the effect was caused by a change in the characteristics of the dielectrics of the pick up (bushing and cable) in a strong radiation field, due to the high accelerated beam intensity. This change altered the behaviour of the compensation circuit, when the intensity was high, thus decreasing it to zero; at this point the compensation circuit recovered, the accelerated intensity increased up to a maximum, and the process repeated.

5. The Electron Source

The design of the source is based on the imposed condition that the electrons coming from the filament must keep parallel trajectories while they are accelerated.

With this condition we found a differential equation for the potential along the tube, which depends on the beam current density; this equation must be integrated numerically. However useful information can be drawn directly: the limiting value of the electric field in the tube when the kinetic energy approaches infinity always with the above mentioned condition of parallel trajectories, is given by:

$$E_\infty = \sqrt{\frac{\pi W_0}{\varepsilon_0 qc}J} = 2.43 \times 10^4 \sqrt{J}$$

where: E_∞ is the limiting value of the electric field, in V/m,

J is the beam current density, in A/m^2;

W_0 is the electron rest mass in energy units;

ε_0 is the vacuum permittivity;

c is the speed of light.

The value of the electric field given by this relation differs by 13 % at 1 MeV, and 7 % at 2 MeV from the exact value. From this we get that at a maximum energy of 2.6 MeV, corresponding to a mean electric field in the tube of 15.3 kV/cm, the upper limit of the current density for a parallel beam is 4 × 10^3 A/m^2.

We roughly evaluated the space charge effect on the electron beam, in the interval 100 keV 2.6 MeV, supposing it parallel at 100 keV, for current densities higher than the limit given above; at 10^4 A/m^2 we get a divergence of the order of 10^{-3} rad.

As this divergence is small enough, the source has been built so that the potential along the tube axis has the calculated values up to about 80 kV; from here on the field is practically uniform.

Using an electrolytic tank, we determined the voltages of the grid and the first three electrodes that gave the electric field we wanted on the tube axis.

The grid voltage is given by a pulser, which we will talk about later on; the electrodes voltage i determined by the resistors between the planes.

The results obtained with this source are sufficiently good; the beam divergence is of the order of 2–3 × 10^{-3} rad at 50 mA.

A point we think must be improved, is the voltage distribution to the first electrodes; the resistors change in value with time and the optics get worse.

The source is composed of a Pierce-shaped tantalum electrode, equipotential with the filament; in its center, in a hole 6 mm in diameter is the tantalum filament, which is shielded at the back to decrease the power radiated; at 8 mm from the filament there is the grid, with a hol 5 mm in diameter, supported by three ceram spacers: the grid is made with very pure and polished aluminum. Fig. 4 is a view of the source mounted in the accelerating tube. Th filament is made with tantalum wire, 0.5 mm i diameter, drawn to a cross-section of abou 1 × 0.2 mm^2, arranged in a zig-zag shape withi a circle 5 mm in diameter.

The zig zag has been preferred to the spiral because with the spiral arrangement the electro beam had a hole in the center, due to the magnetic field of the heating current.

With these filaments we obtained 100 mA a the output of the Van de Graaff, with a power about 40 W. Usually we work with 40 mA, and the heating power is 30–35 W.

The mean lifetime of the filaments is 300 hours; we prefer to change them every two weeks, which means 250 hours of active life, rather than to wait for their failure.

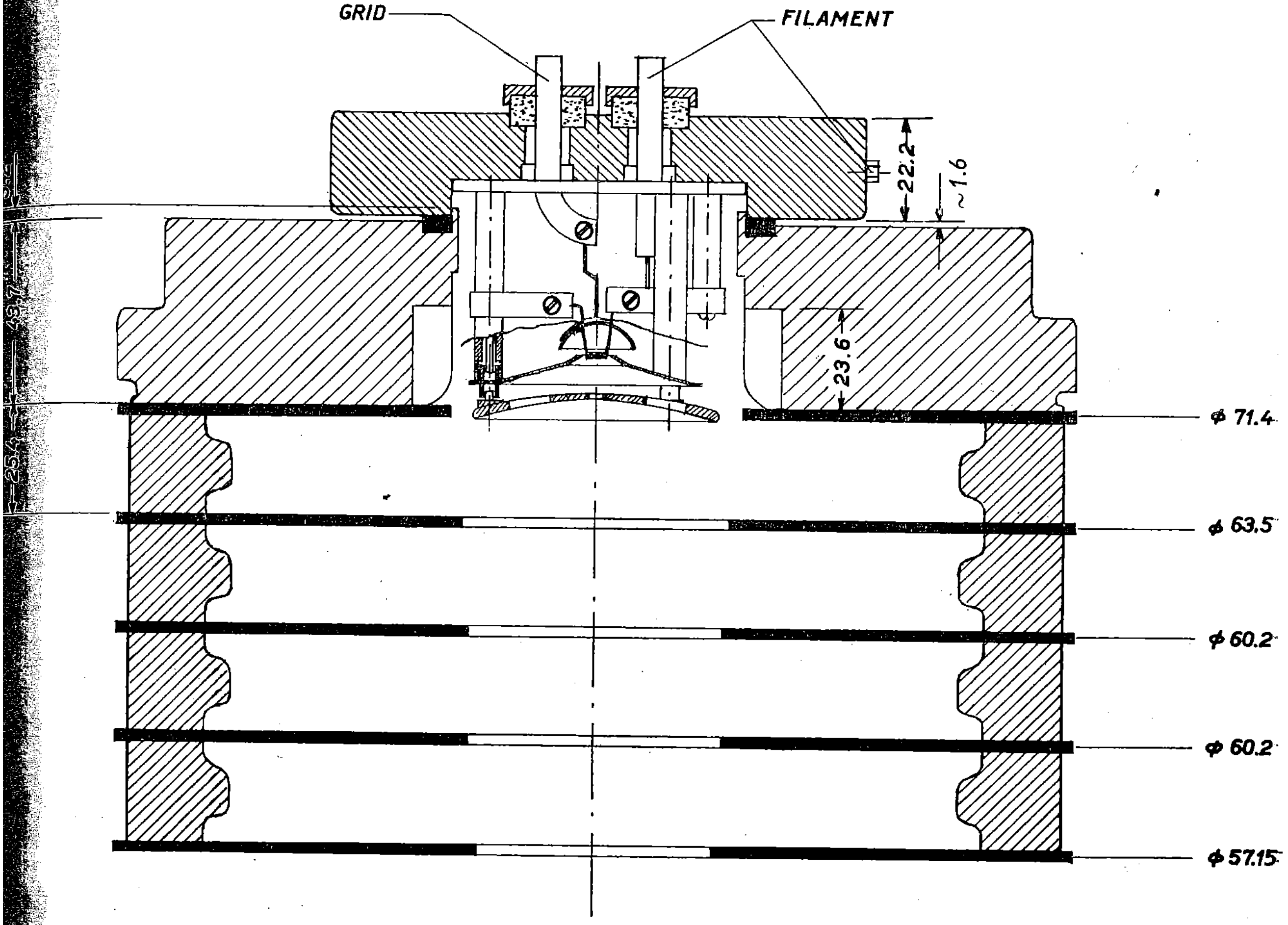

Fig. 4. Electron source.

The pulsed beam is obtained by swinging the grid, which is normally at —500 V with respect to the filament, up to +5000 V for 2 μsec. In fig. 5 is the circuit diagram of the pulser.

A light pulse from a neon (type GE-NE2) mounted inside the tank is transmitted with a light pipe to the terminal and detected by a 931-A photomultiplier, which drives the pulser; this includes an amplifier and a thyratron, at the plate of which there is a wave-shaping line which determines the pulse length.

The pulse, brought up to 6000 V by means of a pulse transformer, then goes to the grid.

The pulse height is variable from outside by changing the plate voltage of the thyratron. The grid pulse has a jitter smaller than 10^{-7} sec (of the order of 10^{-8} sec); this is obtained by keeping the neon lamp normally on and driving it, during the pulse, with a current 200 times larger than the rated current.

6. Injector and Synchrotron Operation

We think it useful to give here an idea of the operating conditions and performance of both the injector and synchrotron.

The schedule for approximately the last year has been as follows: 132 hours per week of operation, of which 126 are assigned to experiments, in shifts of 21 hours per day; on Mondays, 13 hours for the normal maintenance (this in-

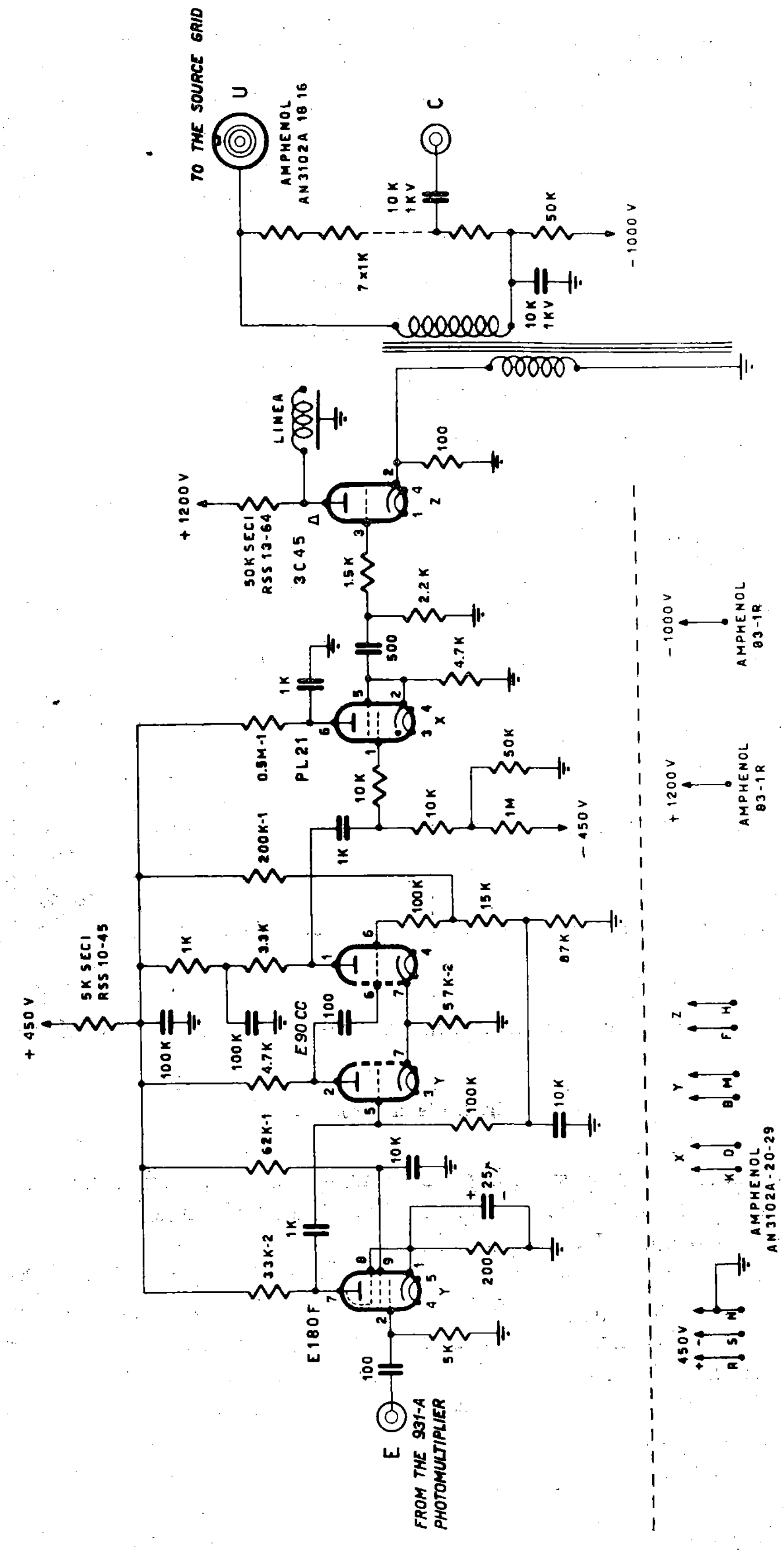

Fig. 5. Electron source pulser.

cludes, once every two weeks, changing the injector cathode).

The running time in the period January 1–August 31, 1960, has been 4020 hours, 98 of them have been spent for the injector conditioning (something less than half an hour per day); the time lost for failures, in the same period, has been 434 hours, 170 of them for injector failures.

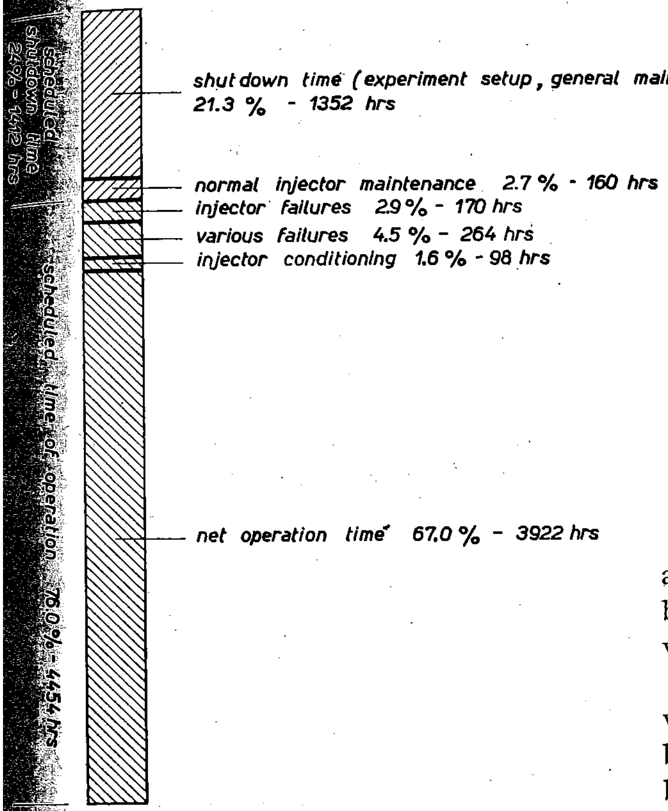

Fig. 6. Injector and synchrotron operation (period Jan. 1–Aug. 31, 1960).

For the injector, normal maintenance has amounted to 160 hours; the tank has been opened 20 times.

All these figures are displayed together in fig. 6; the net efficiency of the synchrotron has been 67.0 %; the efficiency with respect to the scheduled time of operation 88.2 %.

Before we examine the kind of failures we had to the injector, we must recall that our Van de Graaff runs at 2.6 MeV, with a very low average current (1–3 μA); therefore, as is actually the case, we should not expect many electrical faults.

The failures we have had up to now are mainly mechanical, and the weak point has been the bearings of the upper pulley.

With the rated load and speed, the average lifetime of the bearings used should be of the order of 8000 hours; in 7000 hours we had an average lifetime of 1750 hours; the discrepancy between the two figures is probably due to the vibrations which decrease the life of the bearings.

Besides the upper pulley failures (the first of which caused a short circuit to the motor, the breaking of a shield and, in consequence, of the belt), after 5500 hours the accelerating tube has been changed, because the first insulator towards the terminal had some tracks on the glass inside.

As far as the synchrotron as a whole is concerned, the maximum γ-ray beam obtained up to now is 8×10^{11} equivalent quanta per minute, which corresponds to about 6×10^9 electrons accelerated per pulse, with an injected beam of 40 mA; up to this limit the accelerated intensity increases roughly linearly with the injected intensity. With higher injected current, the accelerated intensity does not increase; this is caused, at least in part, by a coupling between the two radio frequency cavities, due to the beam itself, which excites synchrotron oscillations and therefore sets a limit to the intensity.

However this is not, probably, the only cause; all accelerators show this "saturation" phenomenon.

A complete study of the problem would certainly require a long machine time; for the time being, we prefer to carry it on at odd moments because the intensity already obtained justifies the full effort being devoted to experiments.

7. A Storage Ring for Electrons and Positrons

It may be interesting, to spend a few words on a project on which part of the synchrotron staff is now working.

Following a proposal of Prof. Touschek, of the University of Rome, last March has been decided the construction of a small storage ring for 250 MeV electrons and positrons; it should be ready for operation at the beginning of the next year, 1961.

The magnet weights 8 tons; the equilibrium orbit radius is 58 cm; it is a weak focusing magnet with $n = 0.6$ and four quasi-straight sections; the stainless steel donut, in which are stored on the same orbit both the electrons and the positrons, has a cross section of 45 mm × 90 mm; the radiofrequency cavity, which takes care of the radiation losses (600 eV per turn at 250 MeV), is at 155 Mc/sec with 10 kV peak to peak.

The injection of electrons and positrons into the storage ring will be obtained with a double conversion, bremsstrahlung on an internal target in the synchrotron, and pair production on two converters in the storage ring.

First are injected, for instance, the electrons produced on one of the converters, for a certain number of synchrotron pulses; then the whole storage ring is moved, while the γ-ray beam stays at the same place, another converter is inserted in the storage ring and the positrons produced on this second converter are injected. Of the total number of electrons and positrons produced by the γ-ray beam in the two converters, a small part, within a certain energy range, around 250 MeV, and within a certain angle, will be accepted in the storage ring.

The factors affecting the beam lifetime are essentially the vacuum and the radio frequency voltage; in our case, with an RF voltage of 10 kV, the most limiting factor is the vacuum which gives a lifetime of 2 hours at 10^{-8} mm of Hg, and a factor of 100 longer at 10^{-10} mm of Hg.

With a vacuum of 10^{-8} mm of Hg (but we should get a better vacuum), we should, in principle, store up to 10^5 particles.

With these intensities it will be practically impossible to do high energy physics research, except, may be, with nuclear emulsions.

But what certainly can be done, is the study of the behaviour of the storage ring; using the irradiated light (about 10^7 photons per electron per second in the visible range at 250 MeV) we will be able to study a circulating beam of 100 electrons. The intensity necessary to study the interactions between e^+ and e^- (annihilation, π and μ mesons pair production, π^0 production) should be of the order of 10^8 particles, to get a reasonable counting rate for counter experiments (between 1 count/sec and 0.01 counts/sec).

We do not exclude, of course, if we will be able to find some way to improve the injection efficiency, to get the above mentioned intensity that will allow some high energy physics research with this storage ring; but we consider that its purpose will be achieved if it will allow a better understanding and a check of the theory of the particle storage process.

DISCUSSION

Speaker adressed: F. Amman (*Frascati*)

Question by: Kai Siegbahn (*Uppsala*)

Question: Did I understand you correctly that an increase in the injector current above 100 mA would not increase the output current of your synchrotron. What is then the reason for this?

Answer: The relationship between the injected current and the output current in our synchrotron has a non-linearity, which sets in for injected currents of the order of 30–40 mA; the increase of the injected current beyond this value does not increase the output current.

All the electron accelerators present this phenomenon, which, for the time being, has not yet been explained. We are trying to understand it, but we did not reach any conclusion up to now. We know that the time of the acceleration cycle in which the non linearity sets in is between the injection and about 5 μsec after it, and probably is connected with the radiofrequency capture.