FIRST OPERATION OF THE HIGH DUTY CYCLE SACLAY ELECTRON LINAC (A.L.S.)

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Summary. Tests in CSF laboratories have given evidence for the excellent quality of the bunching in the first section. Tests on the site starting in january 1968 were performed during all the year. Operations with both electron and positron beams give many results, namely maximum electron energy 640 MeV with zero current and 540 MeV with 40 mA peak current and an energy distribution with FWHM 3 to 4/1000. The maximum peak current obtained was 60 mA and no beam break-up does appear.

Operations were performed at duty cycles of 1 % and 2 % with electron beam power of the order of 100 kW during many shifts of 30 hours ; energy stability was better than 1 % for 30 hours. Special devices helping to handle the beam inside and outside the linac at such a power level are described.

First measurements of e^+/e^- conversion efficiency give an intensity ratio of positron beam relatively to electron beam, above 400 MeV positron energy, of the order of 10^{-3} and improvements are expected.

I. The high duty cycle 600 MeV electron linac (A.L.S.) was built at Saclay for the "Département de Physique Nucléaire" of the french A.E.C. by the firm CSF (today Thomson-CSF). The accelerator was designed for aims and with solutions already explained at the Los Alamos Conference in 1966.

Acceptance tests were carried out at the end of 1968. The linac is now in operation and the first photonuclear experiment is just beginning.

Main calculated characteristics of the ALS are given in the following tables (warranted values are in brackets) :

Duty cycle (DC) : 10^{-2}	Electron beam
Maximum energy	: 640 [554] MeV
Maximum power	: 250 [100] kW
Maximum average current	: 800 [600] μA
Peak current	: 20 mA
obtained at an energy	: 585 [500] MeV
with energy definition :	
- FWHM	: 0.4 [1] %
- long term stability	: 0.4 [1] %
	Positron beam
Electron energy on conversion target	: 91 [75] MeV
with peak current	: 33 mA
Average positron current at the end of the linac	: 320 [160] nA
at energy	: 550 [475] MeV

Duty cycle (DC) : 2.10^{-2}	Electron beam
Maximum energy	: 453 [380] MeV
Maximum power	: 300 [100] kW
Maximum average current	: 1120 [840] μA
Peak current	: 15 mA
obtained at an energy	: 412 [340] MeV
with energy definition :	
- FWHM	: 0.35 [1] %
- long term stability	: 0.4 [1] %
	Positron beam
Electron energy on conversion target	: 67 [54] MeV
with peak current	: 17 mA
Average positron current at the end of the linac	: 300 [150] nA
at energy	: 386 [326] MeV

II. Main Features of the Accelerator

Sections

- . Length of the accelerator (approx.) : 200 m
- . Number of sections : 30
- . Length of each section (except short sections 1-2-7) : 6 m
- . RF mode (2999 MHz) (except the buncher : $\pi/2$) : $2\pi/3$
- . Q value > 14 000

Klystrons

- . Number of klystrons : 15
- . Type (Thomson-Varian) : TV 2013

. DC : 10^{-2}	RF peak power	: 4 MW	(2×2 MW)
	RF average power	: 60 kW	(2×30kW)
. DC : 2.10^{-2}	RF peak power	: 2 MW	(2×1 MW)
	RF average power	: 60 kW	(2×30kW)
	RF pulse length	: 11 μs	(at 99% level)

Modulators

- . Number of modulators : 8 (7 driving 2 klystrons each and 1 driving the first klystron)
- . Type of switching : Hard tubes
  Type (Thomson-CSF) : F 6046
- . Protection by crow-bar for maximum energy release : 800 Joules
  maximum energy current : 1000 A

Beam

- . Pulse duration : 10 μs
- . Repetition rate : 1000-2000Hz
  and continuously from : 6.25 Hz
- . Electron injection at : 40 kV
- . Positron converter between 6th and 7th section
- . Focusing by solenoids up to section 18 (2200 gauss) by quadrupole triplets after section 19.

III. Construction Schedule

1965 to 1967 :	. Design of different parts of the machine. . Construction of the main elements of the accelerator and of the buildings.
In march 1967 :	. Building was finished and the installation of materials started and continued during the year 1967. . At this time tests were being made on the first sections of the machine in the CSF laboratories at Corbeville.
In december 1967 :	The accelerator was completely installed (except for the e^+/e^- converter).
In january 1968 :	Tests were started first on the six first sections, then on the accelerator as a whole.
In march 1968 :	A beam of 60 mA - 10 μs was obtained at the end of the machine.
In may 1968 :	. 65 kW electron beam. . First positron beam measured at the end of the machine.
From july to october 1968 :	. First 100 kW electron beam (550 MeV - 180 μA). . Endurance tests at acceptance values.
November and december 1968 :	Acceptance tests both with electrons and positrons. This ended on the 18 of december.

IV. Results Obtained on the Buncher

Tests were conducted in the CSF laboratories with the buncher followed by a six meter section. At the maximum 120 mA peak current was injected with 1.7 MeV RF power.

Examination of the variation of the energy spectrum as a function of the relative phase between the 2 first sections gives with good accuracy that the phase extension of the bunch is roughly 5 degrees. An extra contraction of 1 degree can be expected after travelling through the second section.

Another result obtained with the buncher confirming the calculation is the independance of the output phase upon changing the accelerated current (fig. 1).

Both results are very useful in adjusting the whole accelerator.

They mean respectively indeed that :

First it is not necessary to adjust the phases of each section between RF signal and beam more precisely than by a few degrees because for instance ± 5 degrees with a narrow bunch of 4 or 5 degrees gives a maximum energy shift of ± 0.25 %. In fact it is very easy to adjust the phase of each section more accurately with a conventional solution.

Secondly the intensity on the gun can be changed without modifying the phase of the sections and the energy spectrum remains unaltered.

V. Adjustments and Stability

A very high definition in energy and narrow spectrum width and moreover a very stable operation practically without stopping during long runs are needed to use such high power beam.

These requirements were the main problem for the builder.

We have tried to design each part of the linac as intrinsically stable as possible and as trouble free as feasible with a small number of adjustments and using a minimum possible number of automatic loops for the whole of the control system.

Only two loops including the beam were provided : the first concerning final energy control on the last four sections and the second the accelerated beam current (loop including the beam current measured at the end of the accelerator with reaction on the gun). RF pilote cavity being cooled by the same water flow than the sections, an automatic tuning is provided to the whole linac operating at any temperature.

More details about this will be published in "Journal de Physique" and "L'Onde Electrique".

Results obtained were in good agreement with, or better than those expected. For instance, copper temperature stability in the cavities of sections is about 2/10° C in routine operation.

In addition automatic control against beam losses in the beam handling system was provided by coupling two ferrite peak current measuring devices monitored by the same test pulse so that any noticeable difference between the two measurements leads immediately to repetition rate turning down from 1000 or 2000 Hz to 6.25 Hz. (More details in CEA Note N-1032, p. 154).

Stability Features

After the various adjustments, some carried out in laboratory and the others at Saclay during the first period of operation, the routine stabilities obtained in the different parts of the machine were as follows :

RF	
. Modulator pulse flat top (including drop, jitter and oscillation) (fig. 2)	: 0.2 to 0.6 % on 11 μs
. Stability of the RF monitor (in 24 hours)	< 2 kHz
. Frequency shift due to water temperature shift (in 24 hours)	<10 kHz
. Cavities temperature (in 24 hours) variation	< 2/10° C
. Manual phase control	< 5 degrees
Beam	
. Mechanical alignment of section (with laser)	< 0.5 mm
. Magnetic alignment	⩽ 0.2 gauss
. Beam losses along the accelerator (at 100 kW)	⩽ 1 %
. Vacuum in the sections (at 100kW)	: 5.10^{-8} torr

VI. Results of Tests with Electron Beam. (Energy, Current, Spectrum, Divergence of Beam)

The following values are taken from the acceptance test results (figs. 3, 4, 5). Energy measurements were performed at a repetition rate of 6.25 Hz with an analysing magnet (Radius of curvature : 167.4 cm ; Deviation angle : 43°13') giving an energy resolution of 10^{-3}, associated with a variable width slit adjusted mostly at 0.27 % width and for high resolution measurements at 0.08 % and followed by a Faraday cup.

Duty cycle : 10^{-2}

Zero current energy	: 582 MeV
Energy at 30 mA peak current	: 500 MeV
Maximum peak current	: 60 mA
Energy at 60 mA	: 410 MeV
RF peak power at a section's input	: 1.8 MW
Total RF peak power	: 52 MW
Maximum energy at this DC (with 60 MW peak power)	: 630 MeV

Energy spectrum

FWHM	at 10 mA	: 0.34 %
	at 30 mA	: 0.72 %
	at 50 mA	: 0.8 %

As an example, an energy spectrum of 0.34 % FWHM means that :
. 78 % of the intensity is included in a 0.3 % bandwidth.
. 90 % of the intensity is included in a 0.6 % bandwidth.

Duty cycle : 2.10^{-2}

Zero current energy	: 422 MeV
Energy at 25 mA peak current	: 350 MeV
Maximum peak current	: 45 mA
Energy at 45 mA	: 300 MeV
RF peak power at a section's input	: 0.9 MW
Total RF peak power	: 28 MW
Maximum energy at this DC (with 30 MW peak power)	: 440 MeV

Energy spectrum

FWHM	at 5 mA	: 0.45 %
	at 24 mA	: 0.82 %
	at 40 mA	: 0.70 %

As an example, an energy spectrum of 0.45 % FWHM means that :
. 52 % of the intensity is included in a 0.3 % bandwidth.
. 82 % of the intensity is included in a 0.6 % bandwidth.

We have indeed detected on the Faraday cup put after a 0.08 % energy width slit associated with the analysing magnet a peak current of 6 mA at an energy of 500 MeV (that is in an energy width of 400 keV).

Intensity of Beam

The maximum intensity we have measured is 60 mA still with a good quality of energy spectrum and 10 μs pulse length.

That is exactly the expected value corresponding to the RF zero field at the end of each section.

Of course when sections were already in construction, reports were being made about the beam break-up phenomenon and it was clear that the first known results concerning large accelerators extrapolated for our machine would have given a maximum peak current lower than 10 mA at 10 μs pulse length at its maximal limit.

The structure of the sections was partially redesigned and the results of the tests showed that the chosen method was successful.

More details about this are given in another report at this conference.

We had succeeded also to accelerate a 40 mA peak current to an energy of 280 MeV in the first 18 sections and collecting the beam at 35 meters after the end of the accelerator after going through the last 12 sections without supplying them with any RF power.

Divergence of Beam

Measurements made just at the end of the 30th section gave beam diameter of 4 millimeters.

But in most of the tests the beam was running without the help of any extra magnetic lens through the first beam handling system and was examined at 15 meters from the end of the accelerator on a moveable screen operated by remote control. The size of the spot was measured with a TV unit, giving for typical beams an average diameter of 9 mm at 500 MeV and 11 mm at 300 MeV. The corresponding divergence of the beam at 500 MeV is approximately 0.17 mrad. Emittance of the beam is then about 7.10^{-5} rad×cm.

These values bear out those measured at the end of the first section, that is 3×10^{-3} rad×cm at 6.5 MeV.

Extrapolation for a 500 MeV energy gives : 4.5 10^{-5} rad×cm which is very near the measurements with the whole machine.

VII. Results of Tests with Electron Beam (Power and Stability)

These values were those to which the machine was adjusted during the endurance tests - 4 sequences of 24 hours each were imposed (2 × 24 H at each duty cycle) (fig. 6).

Duty cycle : 10^{-2} (sequence of the 4-5 Nov.68)	
Average power	: 98 kW
obtained with Energy	: 530 MeV
Intensity (peak)	: 18.6 mA
Energy spectrum FWHM during the 24 H run (%)	: 0.43 at 8p.m. 0.48 at 2a.m. 0.52 at 8a.m. 0.36 at 2p.m. 0.44 at 8p.m.
Drift of the peak energy (during the 24 H run)	: + 0.1 % - 0.5 %
Number of disjonctions	: 7
Time used by the disjonction or setting in order	: 5 minutes
Useful time versus total time during 24 H run at 98 kW	: 99.7 %

Duty cycle : 2.10^{-2} (sequence of the 12-13 Nov. 68)	
Average power	: 97 kW
obtained with Energy	: 335 MeV
Intensity (peak)	: 14.5 mA
Energy spectrum FWHM during the 24 H run (%)	: 0.34 at 2p.m. 0.40 at 8p.m. 0.50 at 2a.m. 0.45 at 8a.m. 0.80 at 3p.m.
Drift of the peak energy (during the 24 H run)	: - 0.36 % + 0
Number of disjonctions	: 9
Time used by the disjonction or setting in order	: 12 minutes
Useful time versus total time during 24 H run at 98 kW	: 99.2 %

Remarks

a) Vacuum during these runs was always better than 5.10^{-8} torr. Beam losses along the accelerator were very low.
b) During these tests it was not touch up to the initial adjustments.
c) Energy and spectrum measurements were made through a 0.27 % slit.
d) The beam at full power was collected at 35 meters of the end of the accelerator on a cylindrical target designed at Saclay (more details in CEA Note N-844 p. 173) made of aluminium and copper disks cooled with deionized water and included in three boxes surrounded by vacuum. Total effective target length was 30 radiation lengths.
e) After stopping completely the accelerator it tooks only about 15 minutes to adjust back the beam to a given known point of operation, starting from the time when the injection is on.

VIII. Results of Tests with Positron Beam

The positron generator installed after the 6th section is made of a water cooled rotating tungsten target (3 mm of thickness).

Tests with beam were the following :

a) Low Power Test

In order to know the efficiency between electrons and positrons beams two measurements were made at low duty cycle.

. First with a peak current of : 33 mA
  Efficiency was : 0.8 10^{-3}
. The second with a peak current of : 10 mA
  Efficiency was : 10^{-3}

In fact the positron current included in this values is the intensity at the end of the machine measured on a target installed at a distance of 35 meters after the 30th section.

Dimensions of beam spot on the screen at 15 meters from the end of the accelerator were :

Central diameter : 12 mm
Luminous edge of the spot : 28 × 20 mm
Energy spectrum has FWHM : 1.35 % at 466 MeV. (Measurement was made through a 1 % energy width slit).

b) High Power Test

Electron beam at high duty cycle on the conversion target was :

Energy of electrons : 84 MeV
Peak current : 30 mA
Duty cycle : 10^{-2} (1000 Hz - 10 μs)
Average power : 25 kW

Average positron current : 200 nA on the target, 35 m after the end of the accelerator.

Calculated value was 320 nA supposing an energy acceptance width of 5 MeV in the entrance of the first positron section (7th section).

In fact our different results are showing that the acceptance of the 7th section is better than expected. We hope that next tests will give results very near of the calculated value.

More details concerning positron beam are given in another report published at this conference.

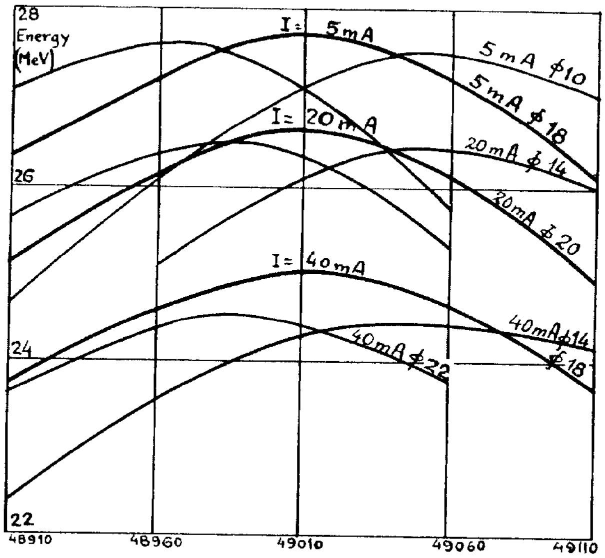

Fig. 1. Energy Phase Frequency Diagram with different beam intensity values.

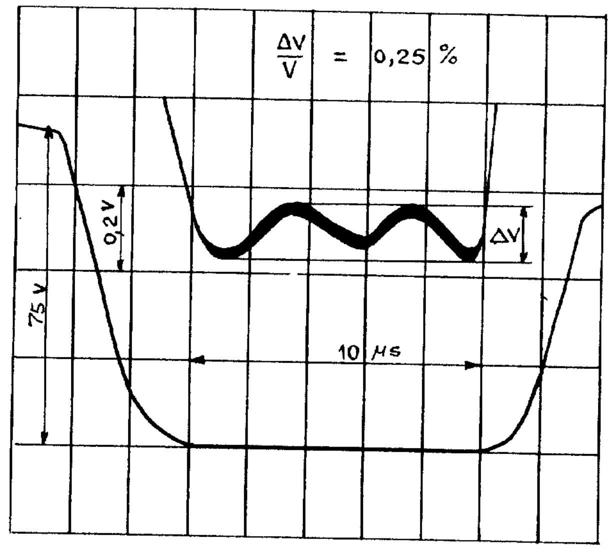

Fig. 2. Pulse Flat-Top of the Klystron Voltage at 120 Kv.

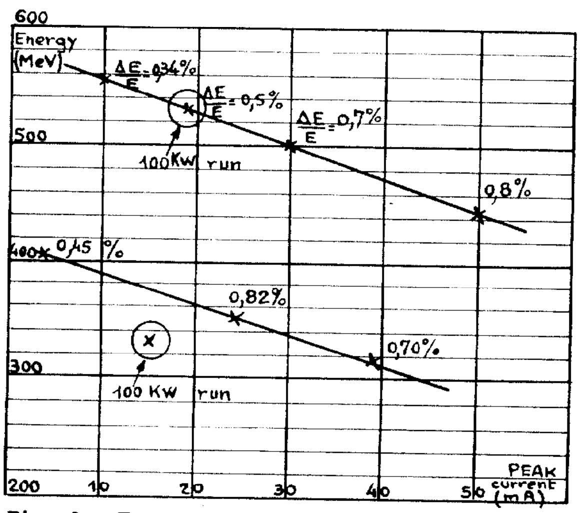

Fig. 3. Energy as a Function of Beam-Current.

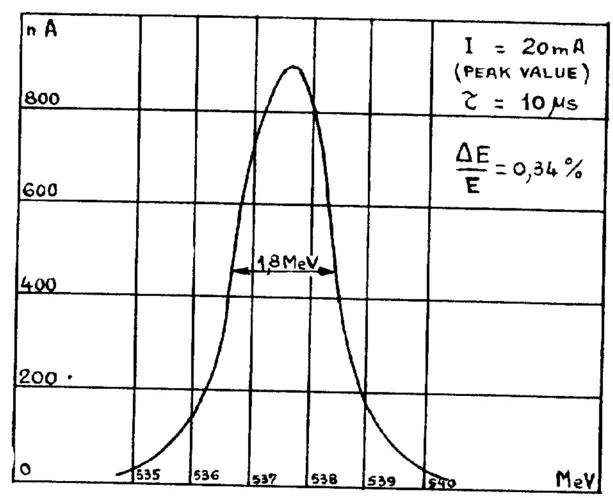

Fig. 4. Energy Spectrum of Electron Beam.

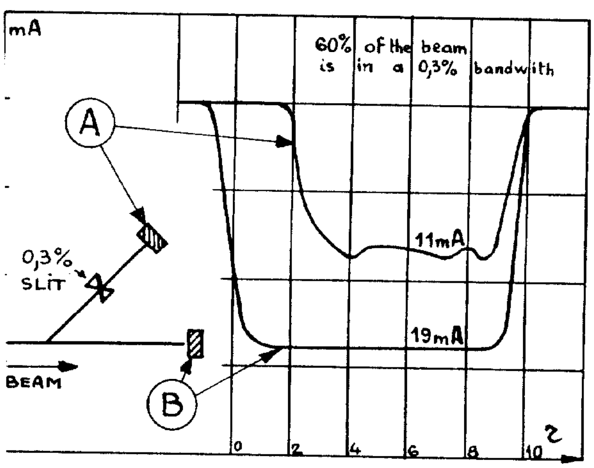

Fig. 5. Picture of Beam After a 0.3% Slit.

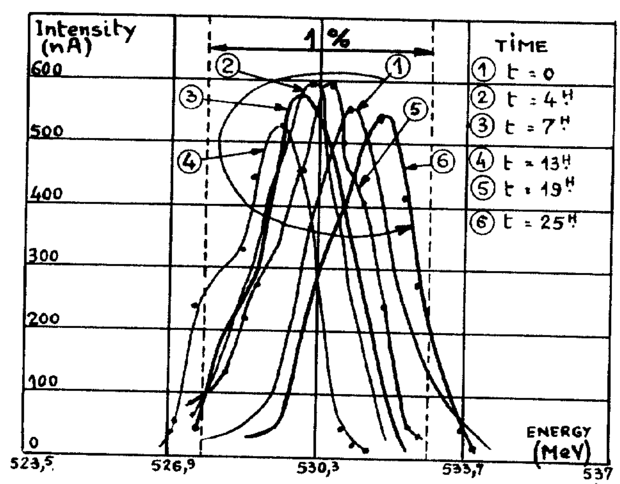

Fig. 6. Drift of the Peak Energy (During a 24^H run).