RESULTS ON SOME EUROPEAN LINEAR ACCELERATORS

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A - EURATOM LINEAR ELECTRON ACCELERATOR

This accelerator was built for Euratom for the purpose of neutron measurements.

It is installed at GEEL (Belgium), a town situated 50 miles North of Brussels near the Belgian-Dutch border.

It is a linear electron accelerator of the disk loaded waveguide type working at 2998 Mc/s.

I - GENERAL DESCRIPTION

The accelerator is made of 2 sections as follows :

- section 1 which includes the buncher and accelerates the electrons to about 20 MeV
- section 2 accelerates the electrons to 40 MeV at 200 mA peak current.

Section 1 and section 2 are each 4 m. long.

The RF power is supplied by two CSF klystrons F 2041 (KA 437). These tubes use an oxyde coated cathode, five cavities and a water cooled collector. These are provided with two parallel rectangular waveguide outputs each equipped with an RF ceramic window.

The nominal performances of the accelerator are obtained when using the klystrons under the following conditions :

- peak output power : 12 MW
- pulse duration : from 0,6 µs to 2,6 µs
- pulse repetition frequency : up to 1000 Hz

This klystron can operate at 25MW peak power and 18 kW average power.

One modulator is used to feed the 2 klystrons.

The characteristics of this modulator are the following :

- nominal peak power : 85 MW
- maximum repetition frequency : 1000 to 1300 Hz
- pulse length : 0,6-1,6-2,6 µs
- ripple amplitude at 2,6 µs : 2 %

The modulator uses the classical principle of a lumped constant delay line. A common DC supply feeds 2 delay lines associated each to one klystron.

Discharge of delay lines is controlled by a sparkgap system.

Electron gun

The electron gun is designed to produce high peak currents. It is of the triode type, and has a coaxial structure, in which delay lines and triggering system are included.

The control grid and the cathode are part of a highly damped resonant cavity at 600 MHz.

Between the gun output and the accelerator input a premodulation cavity is provided, to improve phase bunching.

Typical characteristics are :

- d.c anode voltage : 40 kV
- grid cut off voltage : - 800 V
- grid voltage for SA : + 1500 V

This gun has been designed so as to operate with any pulse length from 0,006 µs to 6 µs.

For pulses shorter than 0,050 µs, a coaxial delay line is used and the switch is a thyratron inserted in the coaxial structure of the discharging circuit.

II - GENERAL PERFORMANCES

The energy-current performances are the following :

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	Zero current energy at 12 MW	Peak Current	Energy spectrum width	Average power at the target	Neutron flow
	MeV	Amp.	MeV	W	N/sec.
10 ns 1000 Hz	57,5	3	57,5 to 48,5	1600	5,7 10^{12}
100 ns 880 Hz	57,5	1	57,5 to 29	3800	1,36 10^{13}
1 µs 380 Hz	57,5	0,2	39,5 to 43,5	3200	1,15 10^{13}
2 µs 250 Hz	57,5	0,2	39,5 to 43,5	4200	1,5 10^{13}

These values are the acceptance tests performances ; it is assumed that each klystron feeds the sections at 12 MW-9 kW.

The accelerator is designed in such a way as to allow the increase of these performances as follows :

1- By increasing the RF power : the 2 klystrons can deliver 25 MW peak power and 18 kW average power.

2- By increasing the number of sections (4 instead of 2). Most parts of the general layout are designed in view of this possibility.

The computed performances become the following :

	Zero current energy at 25 MW	Peak Current	Energy spectrum width	Average power at the target	Neutron flow
	MeV	Amp.	MeV	W	N/sec.
10 ns 1000 Hz	90	5	90 to 75	4100	1,5 10^{13}
100 ns 880 Hz	90	1 1,8	90 to 61 90 to 38	6600 10000	2,3 10^{13} 3,5 10^{13}
1 µs 380 Hz	90	0,6	42	10000	3,5 10^{13}
2 µs 250 Hz	90	0,6	42	12600	4,6 10^{13}

III - DESIGN PARAMETERS

1 - The iris loaded circular waveguide is used on the $\frac{\pi}{2}$ mode. The first section with its buncher is descriped in chapter V. The second section design parameters are the following:

		P = 12 MW	P = 25 MW
Energy at zero current	MeV	36,25	52,5
Energy at 400 mA (at the crest of the wave)	MeV	20,65	36,9
Maximal electrical field at 400 mA	MV/m	8,25	12,8
Residual power at zero current	MW	4,8	10,80
Current for zero field	A	0,4	0,61
RF power losed/cavity	W	max 32	max 80

Internal impedance : 39 MΩ
Shunt impedance Q.Lω : 45 MΩ/m average value
Power attenuation : 4 dB

Filling time : 0,49 µs
Constant field current : 0,1 A
$\left(\frac{c}{v_g}\right)_0$ = 24,2

The waveguide is **calculated for** constant field at 100 mA.

The c/v_g along the structure varies following the law :

$$\left(\frac{c}{v_g}\right)_z = \frac{(c/v_g)_0}{1 - \frac{z}{5,3}}$$

The load in which the residual power is dissipated consists of low Q cavities. This load is 50 cm long and is watercooled by the same circuit as the first part of the sections.

Electrical field and RF power variation at zero current and 0,4 Amp. current are shown on Figure 1.

IV - SHORT PULSES

With very short pulses, the energy stored in each cavity is immediatly absorbed by the beam. The RF power cannot be regenerated during this time. Here are calculated both energies stored and absorbed for the case of 100 nanosecondes with 1 Amp. beam current.

It is well known that the stored energy depends on the RF frequency of the accelerator :

$$W_{ST} = \frac{E^2}{\omega \times R_s/Q} = \frac{E^2}{2\pi c} \times \frac{\lambda^2}{\lambda R_s/Q}$$

Because $\lambda R_s/Q$ is a constant, the stored energy is proportional to the square of λ .

It results that, in the case of short pulses, the choice of L Band would be appropriate but the other performances at long pulses make necessary the choice of S Band.

	Beginning of the section	Middle part of the section	Terminal part of the section
Electrical field at zero current	8,25 MV/m	9,3 MV/m	10 MV/m
Average value during the pulse	6,5 MV/m	7,3 MV/m	7,75 MV/m
$L\omega = R_{shunt}/Q$	3500 Ω/m	4000 Ω/m	4500 Ω/m
stored RF energy $W_{ST} = E^2/\omega . L\omega$	0,97 J/m	1,08 J/m	1,10 J/m
Energy delivered to the beam (assumed 1A and 100 ns)	0,65 J/m	0,73 J/m	0,78 J/m
Ratio between energy delivered and energy stored	67 %	68 %	71 %
Energy bandwidth $\Delta E = \frac{\omega . L\omega . I}{2}$	3,5 MV/m	4 MV/m	4,5 MV/m
$\Delta E / E$	53 %	54 %	57 %

RF peak power = 12 MW

V - BUNCHING AND PREBUNCHING

Prebunching is made with a cavity excited at 3 to 5 kW from a coupler on the first section input waveguide. This produces a concentration of 75 % of the beam intensity within a 90º phase angle.

At the entrance of the accelerator, a new bunching effect occurs, due to the configuration of the RF coupler from rectangular waveguide to the iris loaded section.

This bunching is such that all electrons entering between 90 to 210º go out of the second cavity between 50 to 10º, which corresponds to a bunch compression factor of 3.

The resulting phase extension after the very first accelerating cavities is about 15º, a dimension close to the minimum tolerable in view of the space charge fields in the bunch.

The buncher section will be computed using an analog computer for the required intensity of the beam. The computation involves three steps :

- Dynamics of the center of the bunch, to obtain a rough estimate of the field and phase law.

- Phase oscillation neglecting space charge, giving an estimate of the bunch dimensions.

- Correction of phase oscillation by space charge effects, assuming constant beam diameter, which means that radial forces are cancelled by magnetic focusing.

The magnetic field law for the buncher is given on Fig. 2.

At the end of the buncher the energy of the electrons is 3 MeV with nominal current. The phase velocity of the wave will not be exactly speed of light so that the beam slips 18º up to the end of the section.

The phase slip being approximately independant of the entering phase, for this range of energy and small phase changes the dimension of the bunch is not changed.

Figure 3 shows the assumed variation of the relative phase along the first part of the first section.

Figure 4 shows the energy and the phase of the bunch center in relation to the length of the section.

VI - RESULTS

The results obtained during the acceptance tests (August 1965) are shown in Figures 5 - 6 - 7 - 8 - 9 - 10.
Very short pulse measurements have been made with the kind participation of the Euratom Linac group.

1 -The following results were obtained during the preliminary tests :

- 10 nanoseconds beam current = 3,6 Amp.
- 2 microseconds : beam current= 0,535 A. (at 20 MW RF power)
- Pulse length shorter than 10 nanoseconds could be obtained up to 6 (It should be noted that the rise time is of 3,5 nanoseconds on fig. 11).

2 -At short pulse duration the spectrum width becomes tighter than calculated when pulse length is no longer negligible compared to the filling time, due to the regeneration in RF power of the cavities during the pulse time.

For instance, results obtained three durations 100 - 200 - 500 ns, with a product beam current x pulse duration = constant = 100 nanoseconds are the following.

Energy spectrum extremities

z = 100 ns	I = 1 A	20 and 65 MeV
z = 200 ns	I = 0,5 A	30 and 62 MeV
z = 500 ns	I = 0,2 A	36 and 63 MeV

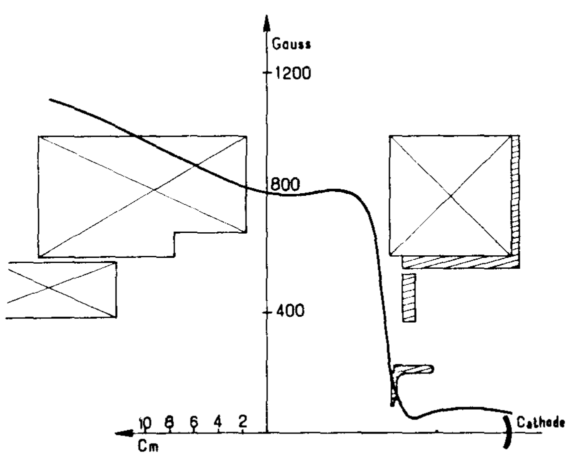


Fig. 1. Electrical field and power along the second section.

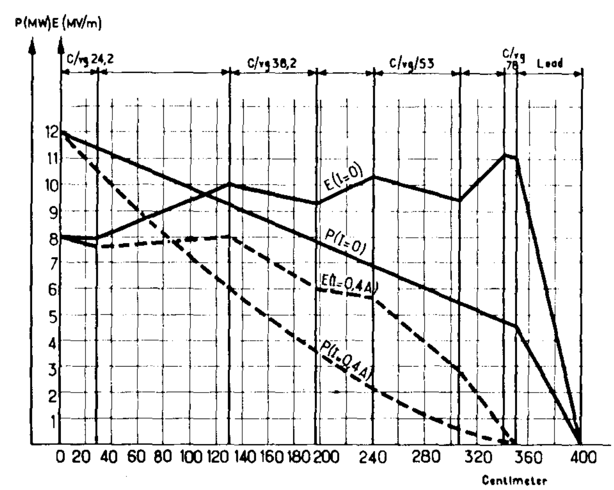


Fig. 2. Magnetic field law at the beginning of the accelerator.

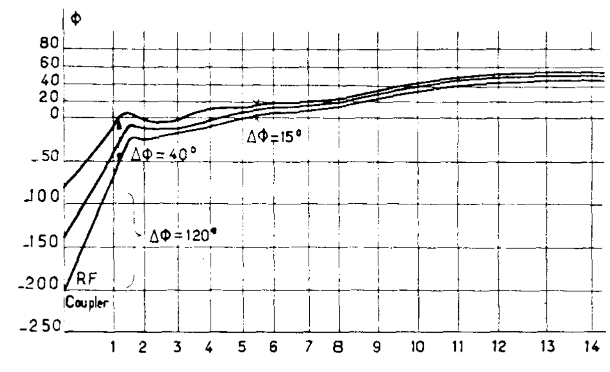


Fig. 3. Phase drift of the bunch along the first cavities.

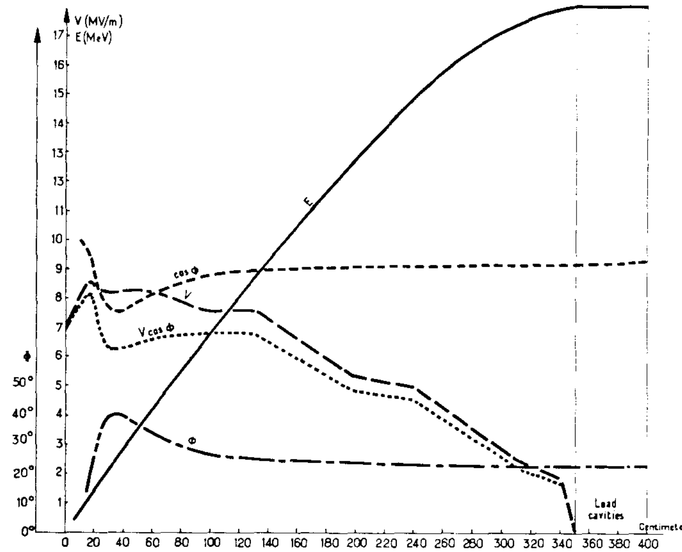


Fig. 4. First section--phase, electrical field, and energy curves (peak current = 0.4 A).

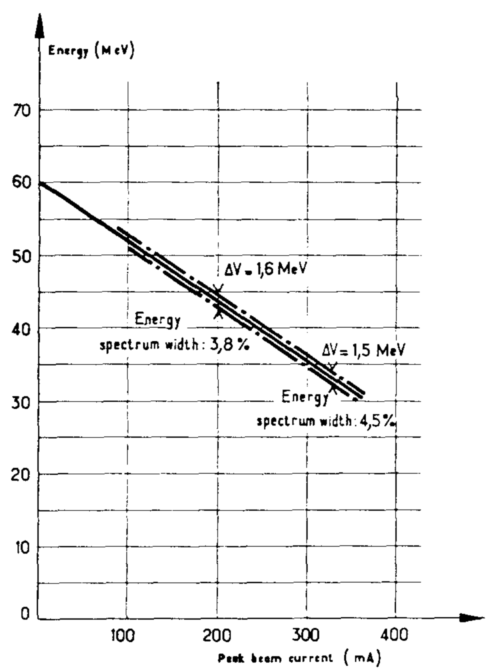


Fig. 5. Energy current performances. Beam pulse length = 1 μs.

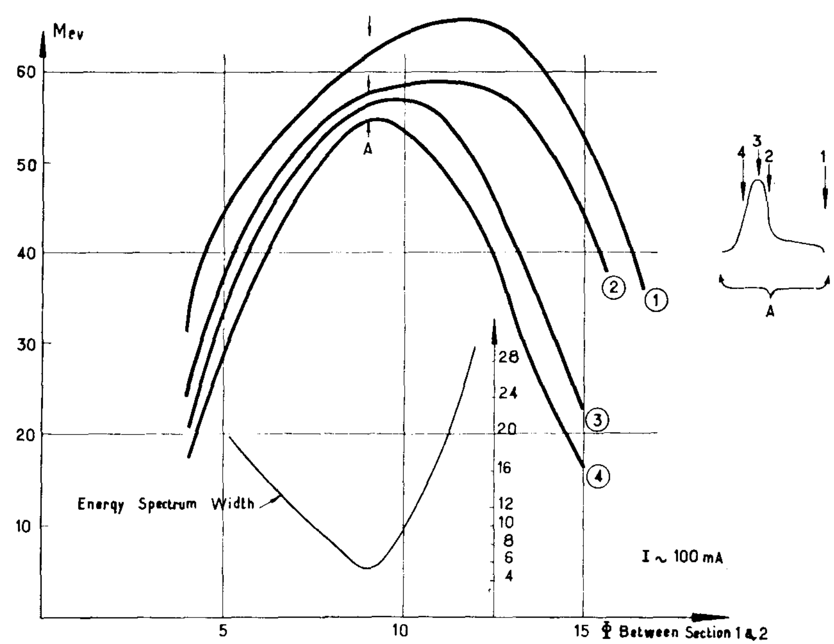


Fig. 6. Energy-phase curves.

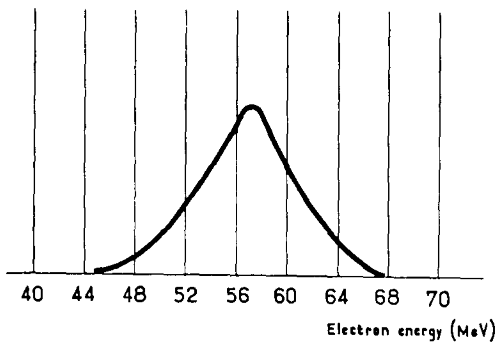


Fig. 7. Pulse length = 10 ns.
Beam current = 3 A.

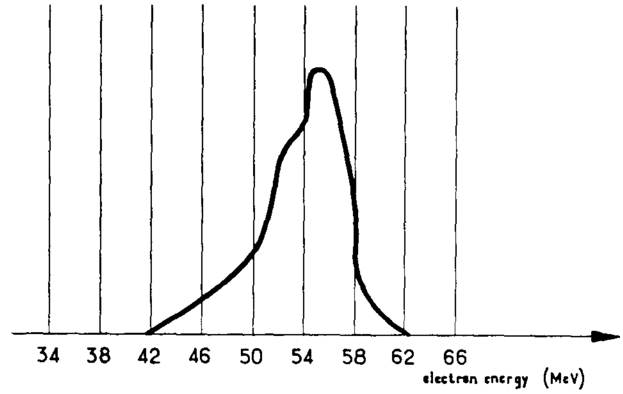


Fig. 8. Pulse length = 20 ns.
Beam current = 1.8 A.

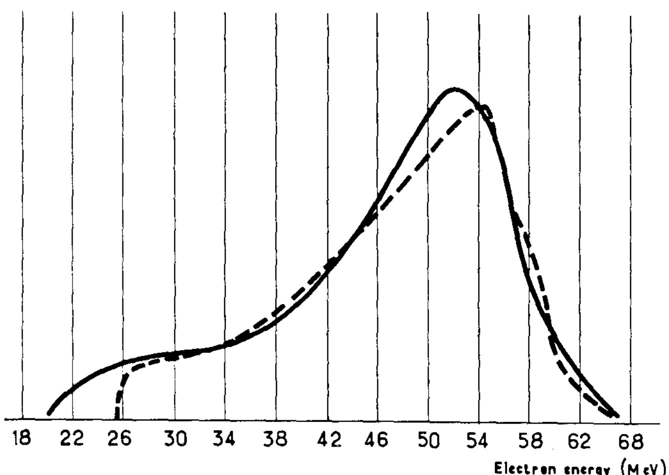


Fig. 9. Pulse length = 100 ns.
Beam current = 1 and 1.2 A.

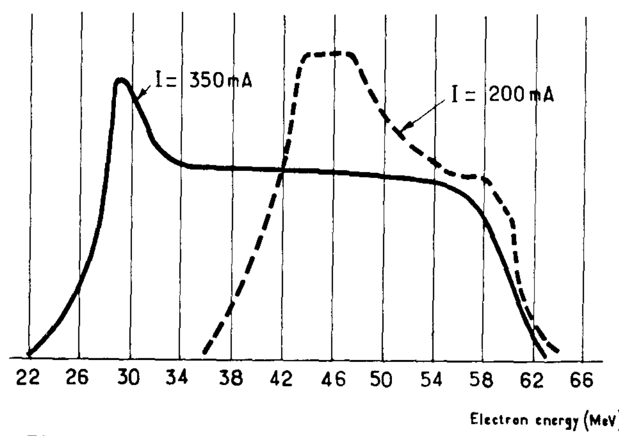


Fig. 10. Pulse length = 500 ns.
Beam current = 200 and 350 mA.

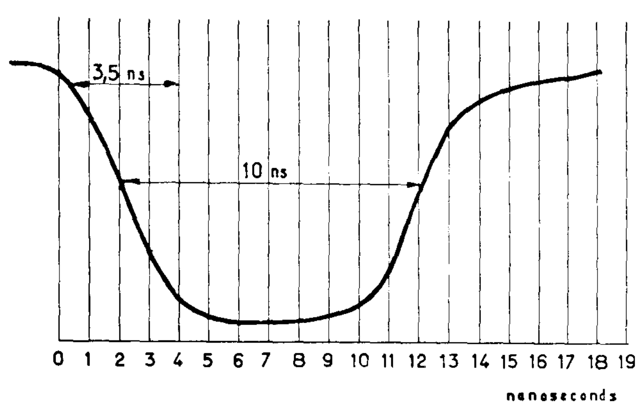


Fig. 11. Pulse length = 10 ns.
Beam current = 3 A.
Pulse repetition frequency = 1000 Hz.
(Measured on oscilloscope 185B,
Hewlett-Packard--1000 MHz).

B - THE 300 MeV LINEAR ACCELERATOR OF MAINZ (GERMANY)

This accelerator is installed at Mainz University (Institut für Kernphysik) in Germany.

It is now in operation.

I- GENERAL DESCRIPTION

The accelerator consists of :

- 8 sections each 4.20 m long
- 8 klystrons (CSF - F 2042) operating at 20 MW - 10 kW
- 4 power modulators
- Injector and driver modulators
- Triode gun
- The total length between gun and target is 60 m
- The beam focussing system consists of solenoïds up to the 4th section and then of two triplets
- The secondary vacuun of each section is maintained by use of a 200 l/s ionic pump

II- MAIN FEATURES

A- Electron beam energy :

at zero current : 320 MeV
at nominal current : 200 MeV

B- Electron beam average power : 14 kW

C- Accelerated beam current

300 mA for a pulse length : 2.6 µs
600 mA for a pulse length : 0.2 µs

D- Energy spectrum width

for 2 µs pulse length : 2.7 % at 320 mA peak beam current

E- Beam pulse length : 0.2 to 5 µs

F- Pulse repetition frequency

It is continiously variable up to 500 Hz

III- CHARACTERISTICS OF THE SECTION

They are of the same type as those of the Euratom Accelerator.

Because of the energy requirement the sections are here in little longer (2o cm)

The first section includes the buncher.

The RF power is provided for 20 MW The acceptance tests were obtained with an average power of 15 MW.

The characteristics of the section are the following (Fig 1) :

Energy at zero current	49.4 MeV
RF peak (power)	20 MW
Energy at 400 mA (bunch at the crest of the wave)	27 MeV
Maximal electrical field at 400 mA	10,5 MV/m
Residual power at zero current	7 MW
Current for zero field	0.5 A
Internal impedance	44 M Ω
Shunt impedance	48 M Ω/m (average value)
Power attenuation	4,5 db
Filling time	0.52 µs
Constant field current	0.1 A

$(c/v_g)_z = 0$

$$(c/v_g)_z = \frac{(c/v_g)_0}{1 - \frac{z}{5.3}}$$

IV- PERFORMANCES

a) At 2.6 µsand a repetition frequency of 100 Hz, the average beam power is 14 kW.

b) At small currents the energy bandwidth is tighter ; for instance at 2.6 µs and 45 mA accelerated, the energy bandwidth is 2 %

c) The pulse risetime of the accelerated beam is shorter than 100 nanosecondes for a beam intensity smaller than 200 mA.

d) At 0.2 µs the repetition frequency is 500 Hz.

Pulse Duration	Zero current Energy	Beam peak current	Nominal Energy	Energy Bandwidth
	MeV	mA	MeV	
2.6 µs	320	270	202	4 %
2 µs	320	320	200	2.7 %
0.5 µs	320	370	165 to 320	
0.2 µs	320	600	145 to 320	

The acceptance tests of the accelerator took place in december 1965.

They are illustred by figures 2 . 3 . 4 . 5 . 6 . 7

Beam diameter and divergence (1)

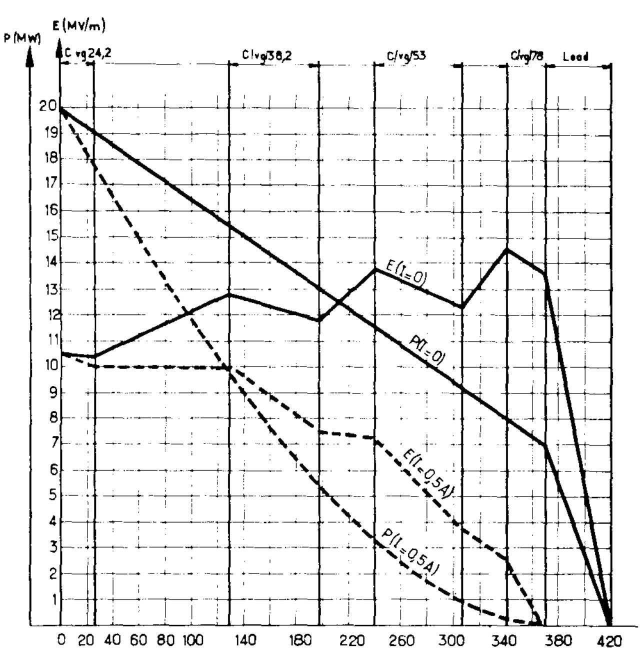
Measurements at the end of section give :

Beam diameter at the end of the accelerator = 7 mm

Beam diameter after a driftspace of 20 meters (without focussing) = 15 mm

Divergence of the beam = ± 0.2 m Radian

(1) These measurements have been made with the collaboration of the Kernphysik Linear Beschleuniger group.



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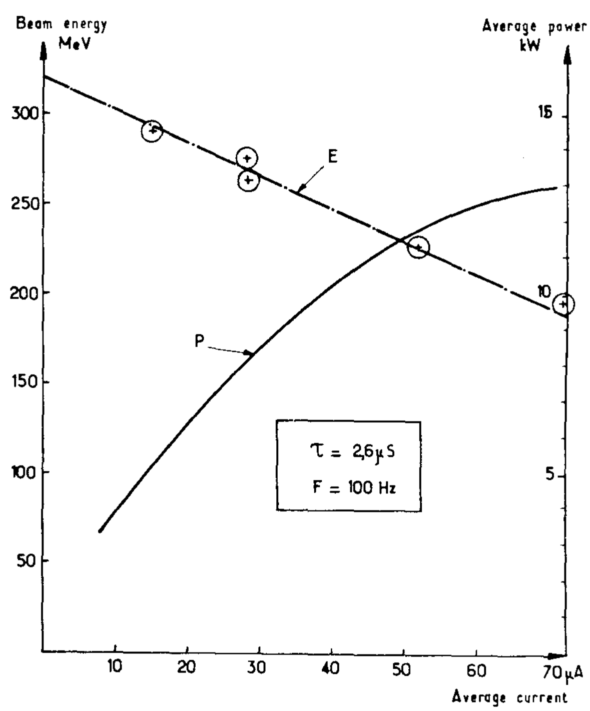
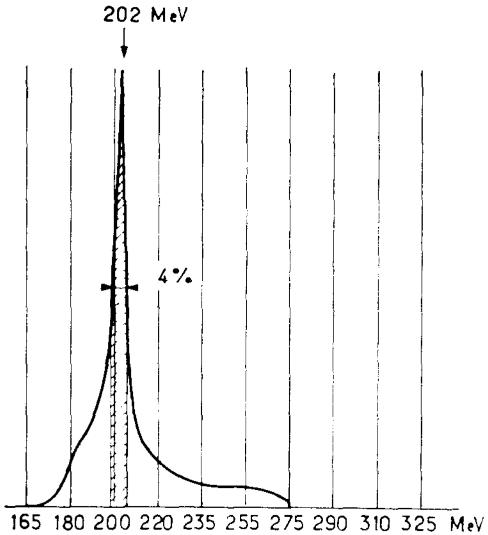


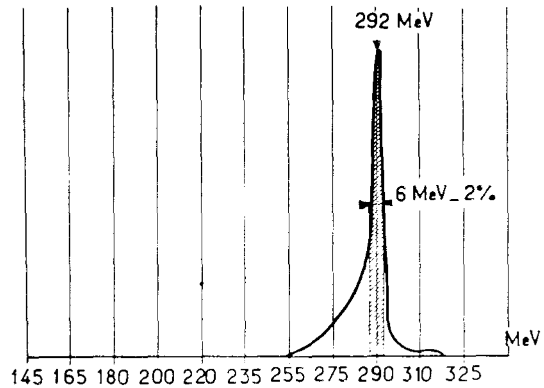
Fig. 2. Energy current diagram.



60 % of the current in 6 % energy band width

I = 275 mA τ = 2,6 μs

Fig. 3. Energy spectrum width.



50 % of the current in 2 % energy band width

I = 45 mA τ = 2,6 μs

Fig. 4. Energy spectrum width.

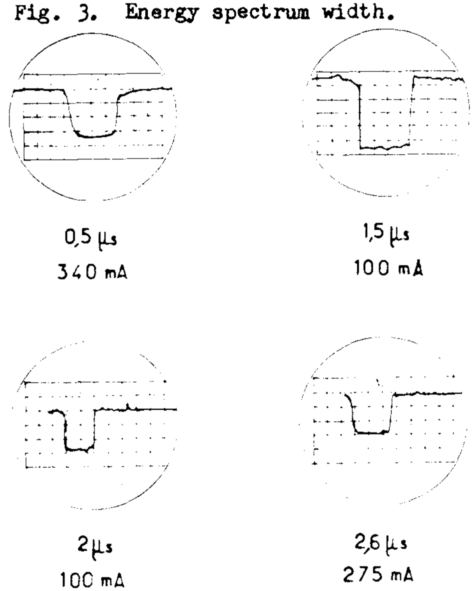
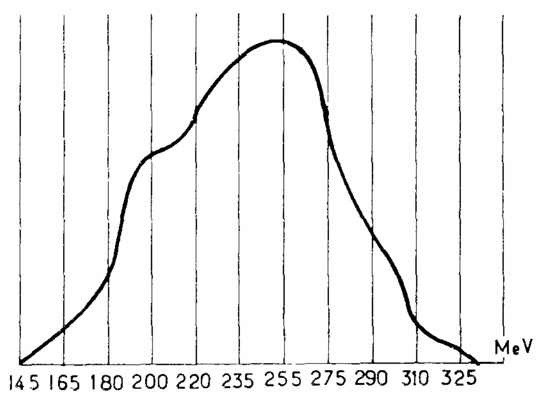


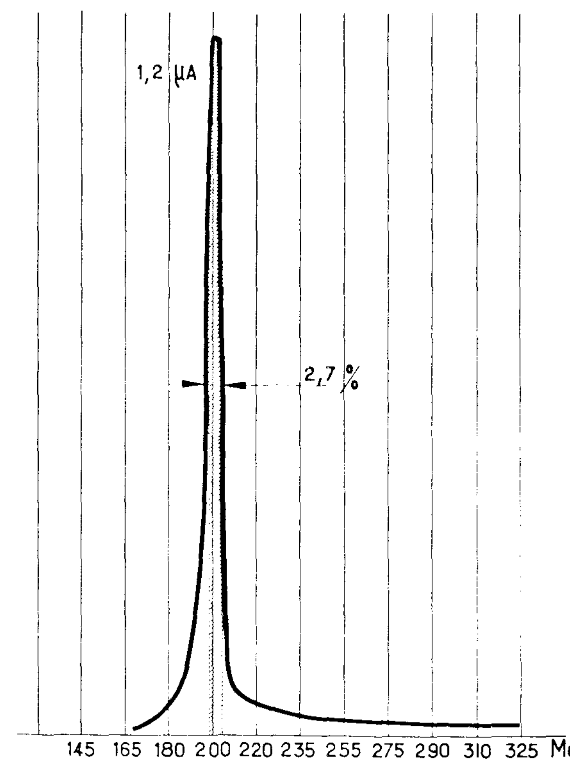
Fig. 6. Beam current on the target.



Peak current = 0,6 A

Pulse duration = 0,2 μs

Fig. 7. Energy spectrum width.



65 % of the current 8 % energy band width
I = 320 mA τ = 2 μs

Fig. 5. Energy spectrum width.