DAΦNE TECHNICAL NOTE

INFN - LNF, Accelerator Division

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Note: **BM-2**

DAΦNE LINAC COMMISSIONING RESULTS

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The DAΦNE injector is composed by a ~ 60 m long Linac and by the Accumulator [1,2] a ~ 33 m long ring used for longitudinal and transverse phase space damping. The Linac, that produces and accelerates up to the collider operation energy both the positron and electron beams, has been designed and built by the USA firm TITAN BETA [3] under LNF specifications [4]. The installation and the system check-out have been done by TITAN BETA jointly with LNF personnel while the commissioning of both the electron and positron beams, has being entirely performed by LNF personnel only. The results of the Linac commissioning so far obtained are presented. The operation values of the beam parameters have been achieved and in some cases exceeded for both the electron and positron beams. The first paragraph of the note contains a general description of the system, paragraphs 2 and 3 present the beam results for electrons and positrons respectively and finally paragraph 4 includes remarks and concluding considerations.

1. System Description

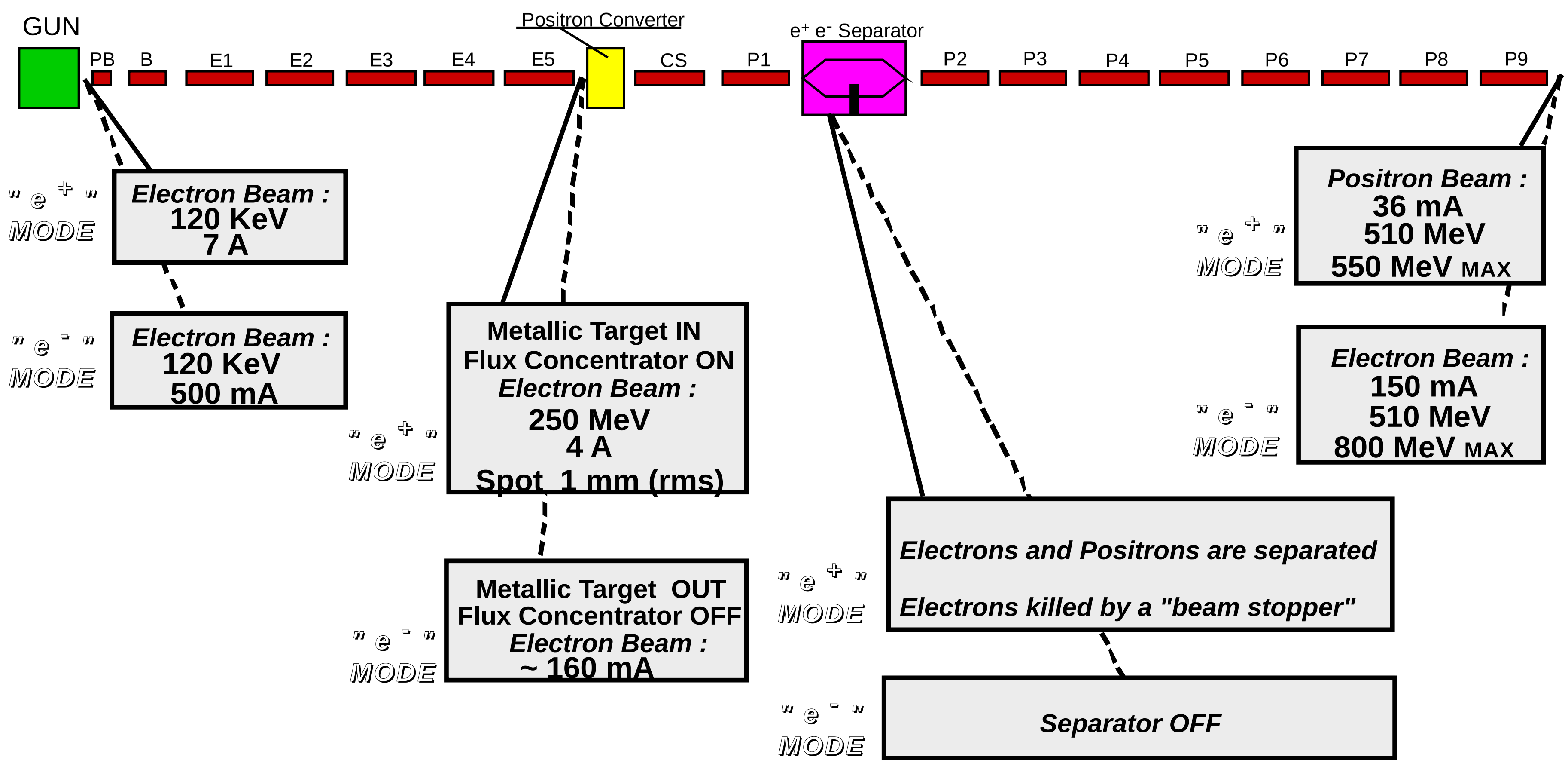
1.1. Linac Specifications

Table 1 summarizes the relevant beam parameters, for both the electron and positron beams, indicating for each of them the operation and design values. The achieved results will be presented in the paragraphs 2 and 3 of this note. The injection into the DAΦNE Accumulator takes place at the operation values. The design values were fixed according to different criteria: sparing the klystron with respect to the nominal capabilities to ensure high reliability and long lifetime, specially in the case of positron production; providing adequate e+/e- current and repetition rate to shorten the injection time; providing adequate energy spread and emittance in order to maintain good transmission along the transfer lines and good injection efficiency into the Accumulator. The operation with the positron and electron beams is not simultaneous and the switching time between the two modes is ~ 2 min. The target injection time, necessary to completely fill all the buckets of both the main rings, is 5 minutes, including the above mentioned switching time. The scheme of the two modes of operation, including the nominal values of the relevant quantities at some important points are showed in Fig. 1.

Table 1. DAΦNE LINAC Beam Parameters

PARAMETER	ELECTRON BEAM		POSITRON BEAM	
	Operation	Design	Operation	Design
Energy (MeV)	510	800	510	550
rms Energy Spread (%)	≤ 1.5	0.5	≤ 1.5	1.0
Macrobunch Current (mA)	≥ 150	≥ 150	≥ 10	36
Macrobunch Length, FWHM (ns)	10	10	10	10
Emittance @ 510 MeV (mm mrad)	≤ 10	1.0	≤ 10	10
Repetition Rate (pps)	50	50	50	50

FIGURE 1. DAΦNE LINAC OPERATION MODES



1.2. Linac Subsystems Description

The Linac system is composed by several different subsystems. A brief description of each of them will follow.

1.2.1. Injector

The injector subsystem includes a thermoionic electron gun, a prebuncher and a buncher.

The gun, a triode with Pierce geometry, is equipped with a 3 cm^2 dispenser cathode able to delivery up to 8 A peak current on a 10 ns FWHM pulse with a repetition rate of 50 Hz at 150 kV max. Typical operation values are 120 kV, 7 A in the positron mode and 120 kV, 0.5 A in the electron one.

The prebuncher (PB) is a RF cavity tuned at the fundamental frequency of 2856 MHz followed by a drift of 21.3 cm and by a 5 cells buncher (B) of the traveling wave 2/3π constant gradient type with a phase velocity of 0.75 c.

According to PARMELA simulations [5], the bunching system is able to confine the beam within 16 degrees of radio frequency.

1.2.2. RF Structures and Modulators

Figure 2 shows the Linac RF layout. The system, an S-band working at 2856 MHz, includes 4 klystrons Thomson TH2128C, with nominal output power of 45 MW, each one equipped with a SLED, the SLAC type pulse compressor device [6]. The typical shape of the RF pulses coming out from the klystron and the SLED is shown in Fig. 2. In our case, the nominal beam energy gain factor due to the SLED is 1.6.

With reference to Fig. 2, it is possible to see that 3 of the klystrons have exactly the same configuration consisting of an evacuated rectangular waveguide network with three 3 dB splitters arranged in order to divide the klystron power into 4 equal parts feeding each one an accelerating section. The fourth klystron has a 'special' configuration: half the power is sent to the capture section (CS), the first accelerating section downstream the positron converter (PC), while the second half is equally divided between two branches feeding the accelerating section P1 the first one, the prebuncher, the buncher and the accelerating section E1 the second one.

All the 15 accelerating sections (E1-E5, CS, P1-P9) are of the same type: the well known 3 m long, 2/3 π traveling wave constant gradient SLAC design structures [7].

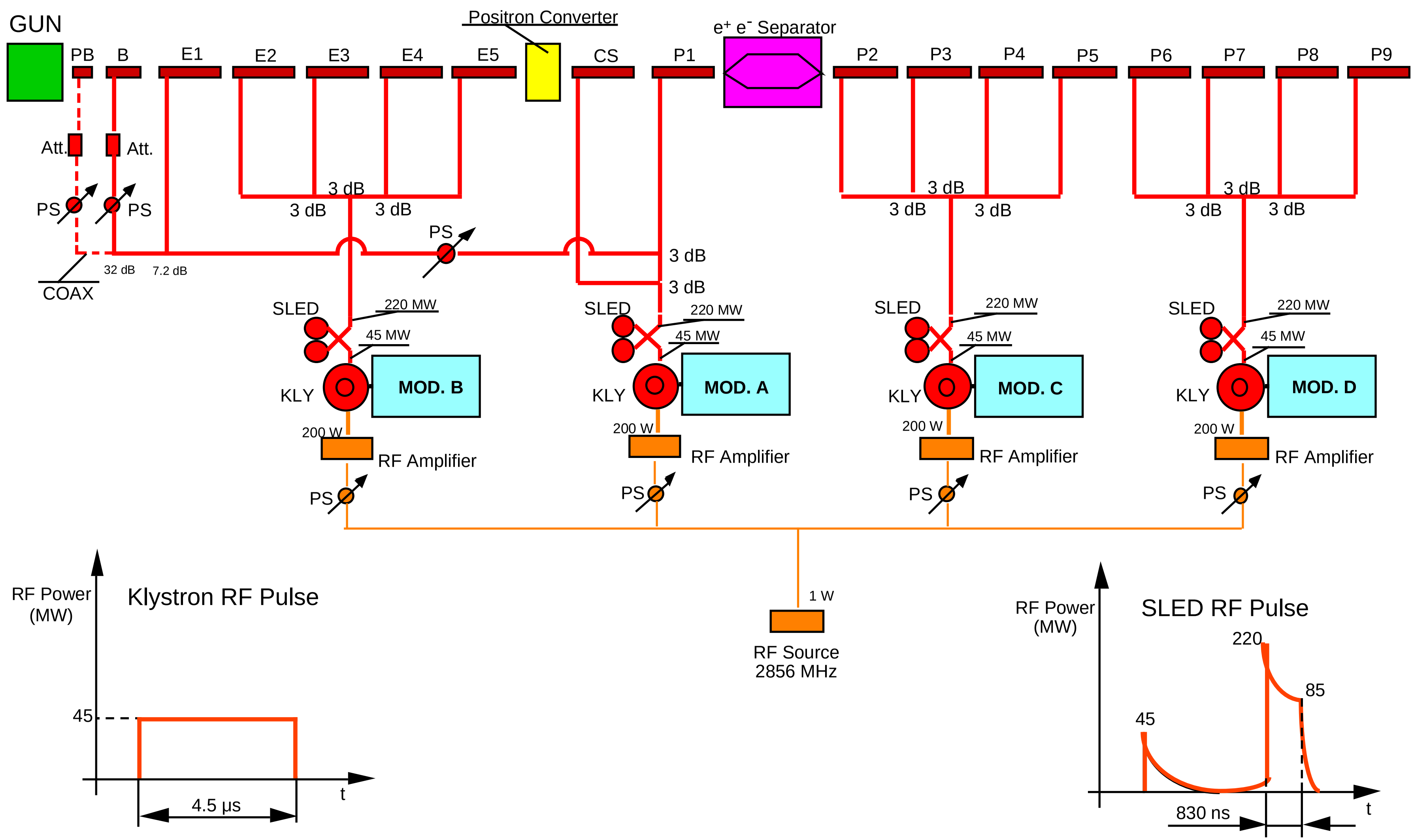
In our configuration, with 45 MW coming out the klystron, the nominal accelerating component of the electric field is 27.7 MV/m in the CS and 19.6 MV/m in the remaining accelerating sections.

The phase adjustments between the sections are performed by means of low power 360° phase shifters upstream the RF amplifiers of each klystron and by a high power 360° phase shifter that uncouples the CS from E1. The relative phasing between accelerating sections belonging to the same klystron network were regulated once and for all by properly adjusting the rectangular waveguides upstream the section inputs.

The above described configuration permits to change arbitrarily the phase of the CS with respect to E5. This is an important feature in the positron mode of operation, as it will be explained in the subsection 1.2.3 of this note.

The four modulators are able to produce a video pulse of 6 μs FWHM and 4.5 μs flat top with a peak power of 100 MW at 50 pps. A HV power supply with a resonant charging circuit charges a pulse forming network, composed by 8 LC cells, up to 50 kV. The switching thyratron is the EEV CX2168.

FIGURE 2. DAΦNE LINAC RF LAYOUT



1.2.3. Positron Converter

The positron converter subsystem is heavily based on the SLAC scheme. The conversion is obtained by interposing to the electron beam a metallic target and collecting the produced positrons by a capture system that transforms the transverse phase space by matching the acceptance of the downstream accelerating sections. The system allows the choice of 3 different targets, with thickness varying around 2 radiation lengths, built with an alloy of 75% of tungsten and 25% of rhenium. A remotely controlled actuator permits to extract the target from the beam path during the electron mode of operation.

The capture system is essentially composed by a tapered field DC solenoid, with a peak of 1.2 T, and by a pulsed coil, the SLAC design flux concentrator [8], which generates a solenoidal field that drops adiabatically from a peak of 3.7 T to zero in about 12 cm. Finally 7 m of DC 0.5 T uniform field solenoids, wrapping around the accelerating section CS and P1, complete the magnetic focusing of the capture system. The low energy positrons coming out from the target are not fully relativistic and because of this, a longitudinal phase lag appears reducing the capture and resulting in a large energy spread. The larger accelerating gradient present in the CS reduces this effect by accelerating the positron beam to relativistic energies in the shortest way. Another efficient knob to minimize this effect is the one offered by the CS RF phase. Operational experience and theoretical work by R.H. Miller and B. Aune at SLAC [9] have shown that, putting this RF phase in a way such to decelerate the incoming positrons, it is possible to sensitively improve the capture with respect to the case where the particles are initially accelerated. As already mentioned in subsection 1.2.2, the RF scheme of our LINAC allows to operate in both ways. The experimental results will be presented in paragraph 3.

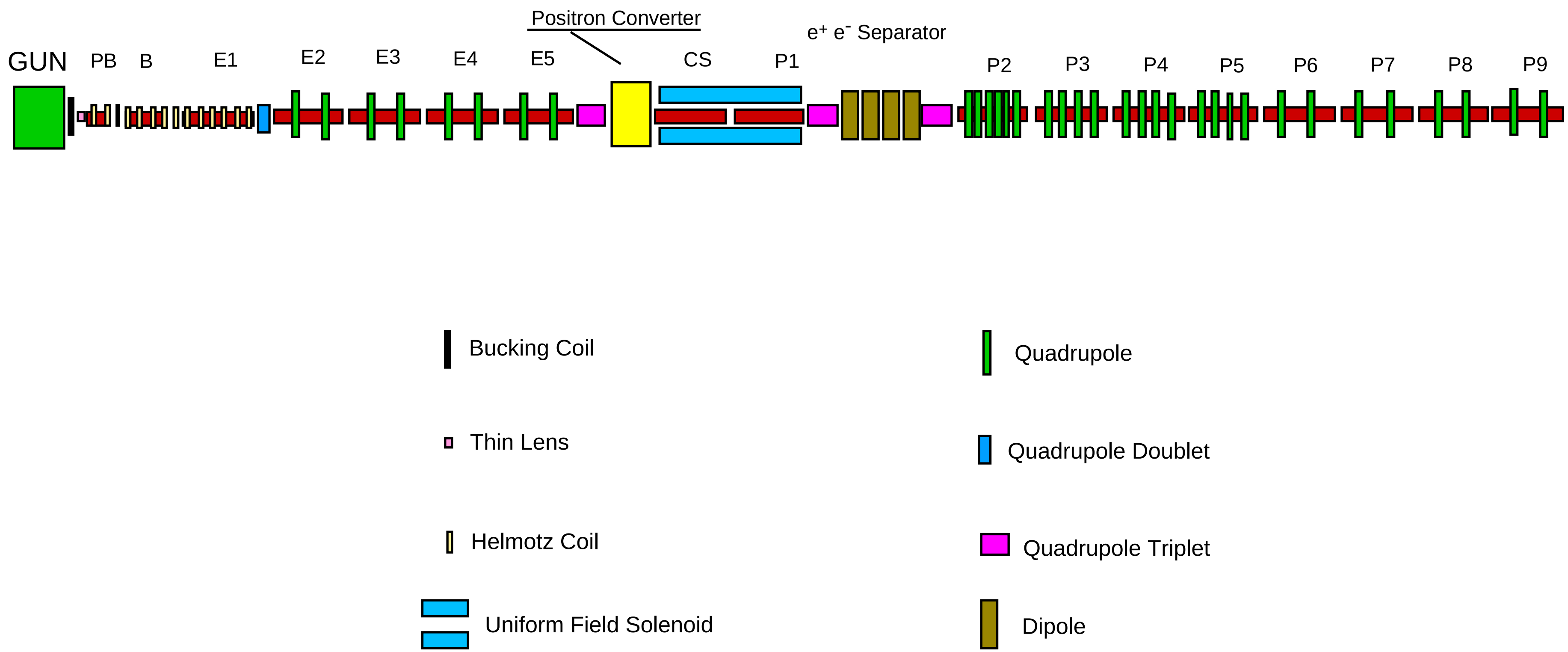
The nominal beam operation values at the positron converter are showed in Fig. 1. The nominal conversion efficiency is 0.9 %.

1.2.4. Magnetic Elements

The focusing system varies its conformation according to the requirements of the portion of the Linac interested. An easy way to describe this system is to follow a particle beam from the gun up to the Linac end. With reference to Fig. 3, the first coil that the beam finds is the bucking coil, used for reducing the presence of magnetic field in the gun cathode region, followed by a 'thin lens' whose solenoidal field brings the beam up to the prebuncher. The prebuncher, buncher and the accelerating section E1 are immersed into a 0.1 T solenoidal field produced by 14 Helmotz coils spaced 25 cm from each other. A quadrupole doublet between E1 and E2 allows matching between the solenoidal focusing system with the FODO that transports the beam up to the positron converter area. The FODO is composed by two quadrupoles per each of the 4 accelerating sections (E2-E4). The FODO step is about 1.5 m. A high gradient quadrupole triplet upstream the positron converter is used for focusing the beam into a 1 mm rms radius spot on the converter target. The focusing system on the positron converter area and on the accelerating sections CS and P1 has been already described in subsection 1.2.3. Downstream this part is placed the positron/electron separator which, in the positron mode, separates secondary positrons and electrons in 2 different paths and eliminates the electrons by means of a beam stopper. The separator is composed by 4 dipoles performing an achromatic bump, and by two quadrupole triplets for the matching at the input and at the output of the separator. In the remaining part of the Linac, from section P2 to P9, a FODO, composed by 26 quadrupoles and with step tapered according to the beam energy, completes the focusing scheme.

A network of vertical and horizontal correctors, a couple on each of the accelerating section approximately, permits the Linac orbit correction.

FIGURE 3. DAΦNE LINAC FOCUSING SYSTEM



1.2.5. Beam Diagnostics and Timing

Figure 4 shows the Linac beam diagnostics system which includes a total of 14 beam position monitors, 4 beam current monitors and 4 beam profile monitors. This configuration allows a relatively easy beam transport and monitoring along the Linac. Other important quantities like energy, energy spread and emittance are measured by dedicated devices placed on the transfer line downstream the Linac [10,11].

The position monitors are of the capacitive type with four electrodes, see Fig. 4. The voltages induced by the beam on these electrodes, properly combined, give the transverse position of the beam. In the actual configuration the 4 signals coming from the electrodes are directed into a single coaxial cable by means of delay lines that space the signals from each other by 15 ns and by a power summer that combines the signals into a 4 peaks comb. The advantage of such a scheme is that the number of cables is strongly reduced, saving money and gaining in simplicity. On the other hand some drawbacks exist: the delay lines introduce a different attenuation on the signals and the presence of spurious signals, due to reflections, can interfere with the contiguous signal altering the measurement result.

The current monitors are of the resistive wall type. The vacuum chamber continuity is interrupted by a ceramic gap and several resistors uniformly distributed around the gap create a resistive bridge, where the beam image current on the vacuum chamber can flow through. By monitoring the voltage drop on the resistors it is possible to derive the current value. Moreover the frequency response of the monitor is sufficient to reproduce the shape of the macrobunch (10 ns) with a good fidelity. Several examples of the current monitor signal are showed in paragraph 3.

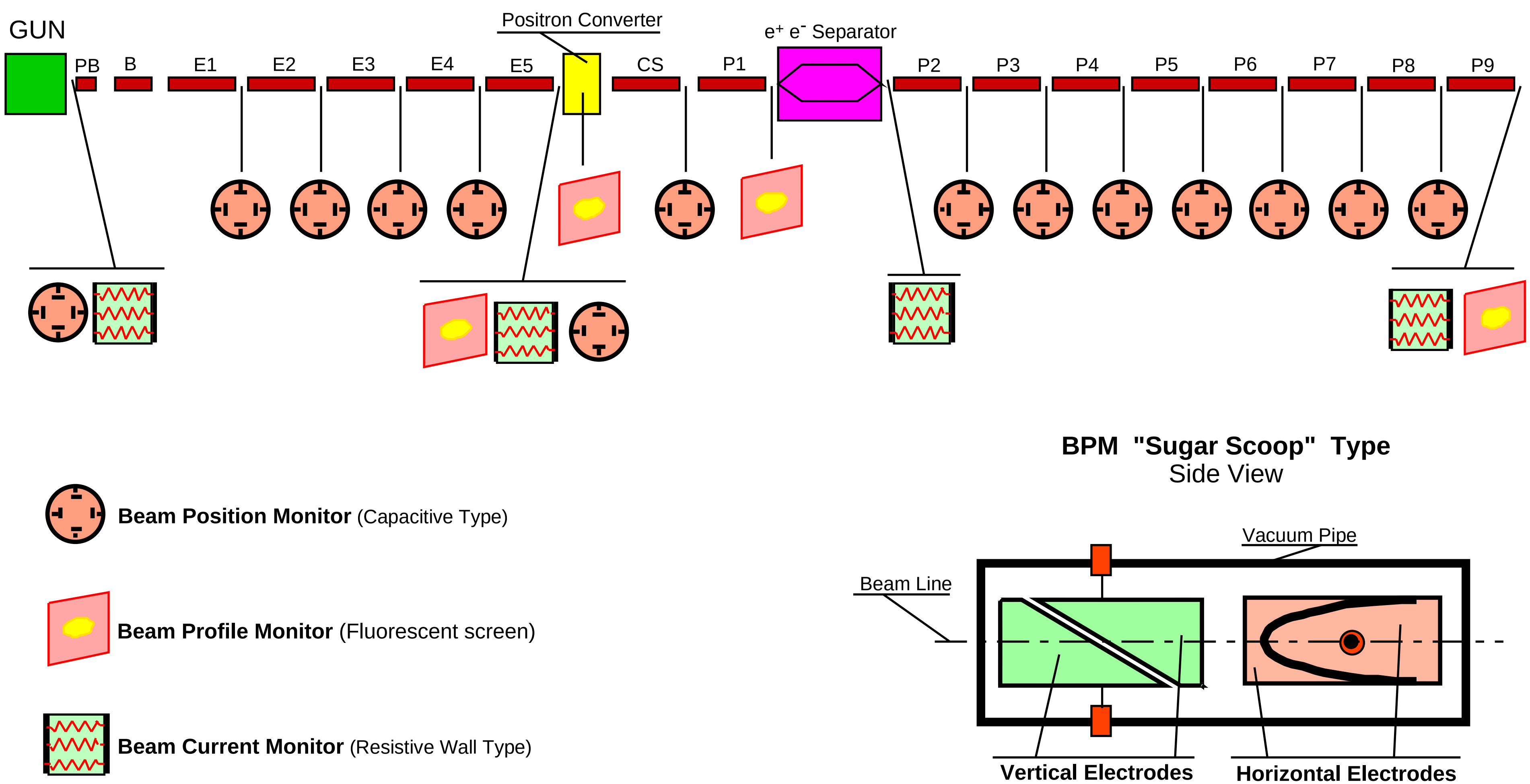
The beam profile monitors are fluorescent screens, obtained by oxidizing the surface of a thin aluminum plate. The oxide layer is doped with activating chrome compounds in order to enhance the fluorescent effect. It is worth to remark that one of these monitors is placed inside the positron converter housing at direct contact with the converter target. In this way it is possible to monitor the beam spot size on the target itself allowing the optimization of this parameter very important during the positron conversion.

Both the position and current monitor signals are connected to high speed amplifiers with remotely controlled gain. Anyway the monitors sensitivity without amplification allows the measurement with a reasonable signal to noise ratio, of the signals generated by bunches with macrobunch current down to 1 mA.

All these diagnostic devices are sensitive to the net charge of the particles passing through. For this reason the presence of the positron/electron separator, that stops the electrons in the positron mode of operation, permits the measurement of the parameters of the positron beam only from the separator down to the Linac end.

Concerning the timing, just few words to say that the system needs two different triggers, one for the modulator and RF subsystem and the other one for the electron gun. In the great majority of the cases, the trigger signals run on optical fibers in order to obtain insulation from ground noise.

Figure 4. DAΦNE Linac Beam Diagnostics



1.2.6. Vacuum

Figure 5 shows a schematic of the Linac vacuum system. The whole environment can be divided, by means of vacuum valves, into different parts: electron gun, klystrons and related accelerating sections, positron converter and so on. This configuration allows the replacement of parts in localized areas without breaking the vacuum in all the machine. A typical example of such a situation is the periodical replacement of a klystron tube. All the system is based on 45 l/s ion pumps, of the Varian noble gas diode type, distributed along the Linac between the accelerating sections. Critical parts like the electron gun and the positron converter area have a more powerful scheme with additional pumps with higher pumping speed, see Fig. 5. The pressure is measured by UHV vacuum gauges in the gun and in the positron converter areas and by monitoring the ion pump currents in the remaining parts of the machine. The design pressures are showed in Fig. 5, while the operation values inside the accelerating sections, practically stable since about 4 months after the beginning of the beam operation, are 5×10^{-9} Torr static (without beam) and 1×10^{-8} Torr dynamic (with beam).

1.2.7. Water Cooling

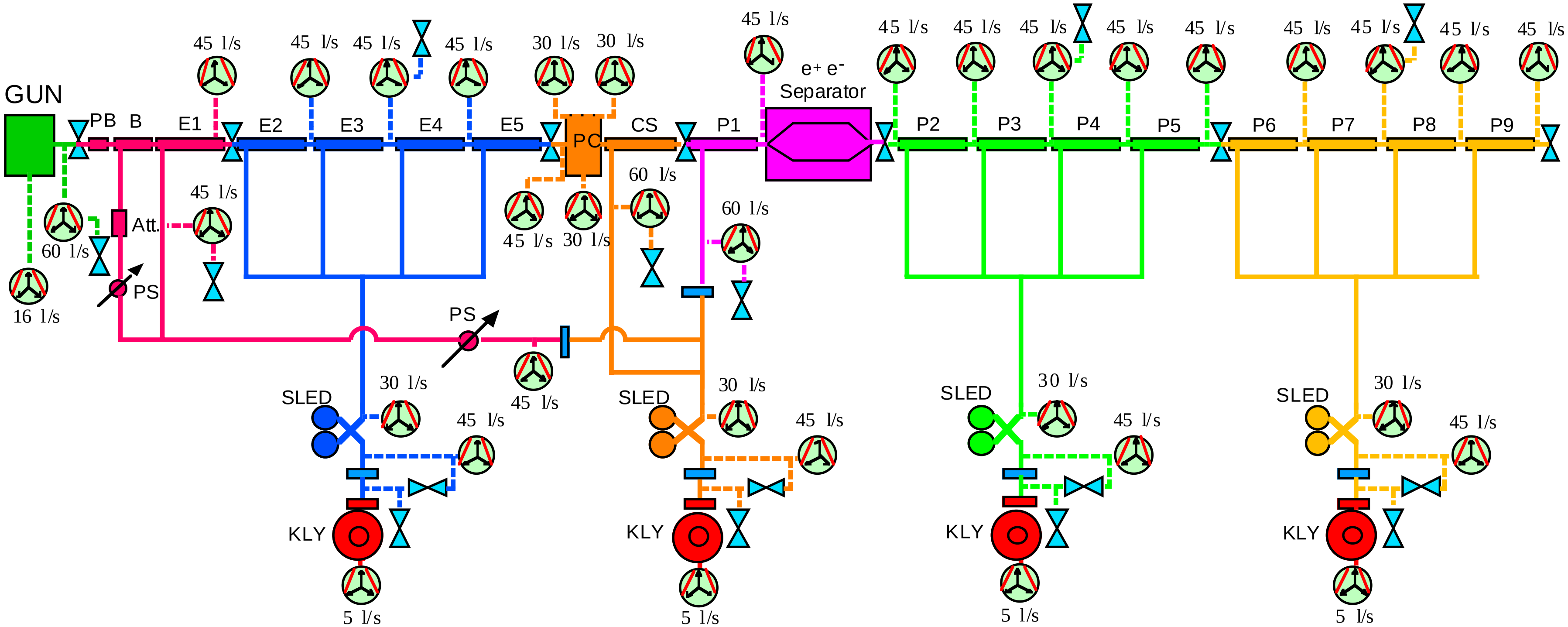
The Linac is equipped with three different cooling subsystems, the *accelerator waveguides*, the *accessory* and the *positron converter*. The more accurate one, the accelerator waveguides, uses a certain number of process controllers to keep at the operation temperature of 45 °C ± 0.1 °C all the narrow band RF structure, like SLED's, accelerating sections, prebuncher and buncher. The accessory system controls with an accuracy of ± 2 °C, the temperature of all the magnetic elements, of the klystrons and of a portion of the rectangular waveguides. Finally the last system, the positron converter one, is the smallest and controls the temperature of the elements in the positron converter area. The reason for this third system, which has an accuracy of ± 2 °C, is to separate that part of water which can be activated in the 'hot' environment of the positron converter.

1.2.8. Control System

The Linac has 2 independent control systems. The first one, the *main*, permits the setting of all the machine operation parameters and the monitoring of the low frequency signals as for example, magnet power supply readbacks, modulator HV power supply voltage and so on. The second one, the *diagnostic control system*, allows to measure and visualize 'high' frequency signals like those from the beam diagnostics and from the modulator and RF subsystems. Figure 6 shows a block diagram of both the system. The refresh rate of the systems is ~ 2 Hz.

The DAΦNE control room is far from the modulator hall where all the Linac hardware is placed. For this reason, both the consoles of the control system, the only parts situated in the control room, are connected to the hardware by the means of GPIB extenders.

Figure 5. DAΦNE Linac Vacuum System



RF Window

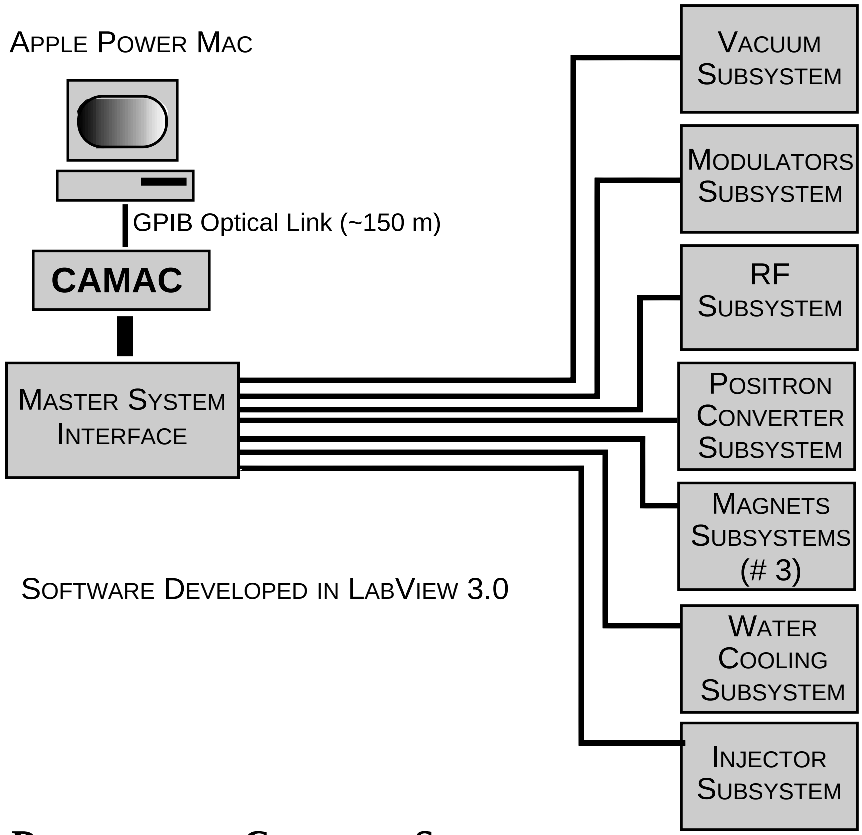
Ion Pump

Valve

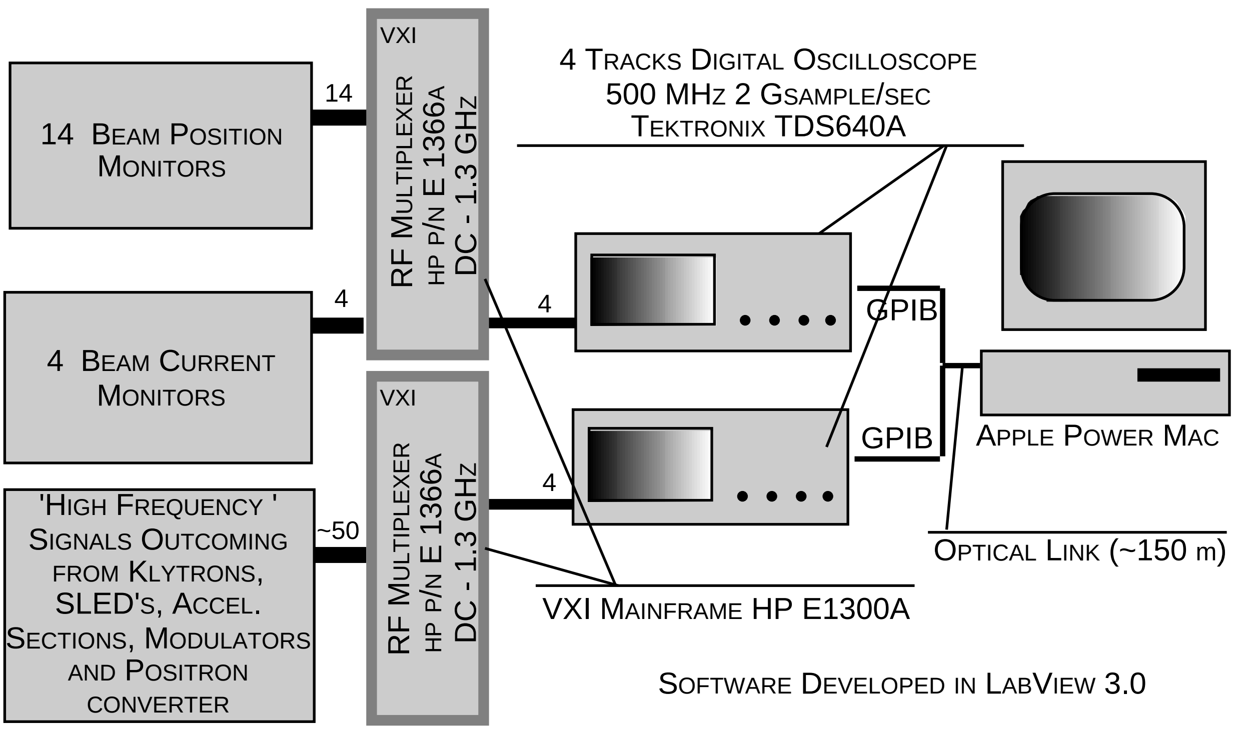
Design Pressures	
Accelerating Sections	5×10^{-8} Torr
Klystron Window Area	5×10^{-8} Torr
Rectangular Waveguides	1×10^{-7} Torr

FIGURE 6. DAΦNE LINAC CONTROL SYSTEMS

MAIN CONTROL SYSTEM



DIAGNOSTICS CONTROL SYSTEM



2. ELECTRON BEAM COMMISSIONING

The first operation with the electron beam in Frascati started on April 1996. Since then, 83 days of shifts with electrons, organized in one week units, have been done, 28 dedicated to the DAΦNE Accumulator injection and 55 to the Linac operation.

2.1. Linac Operation with Electron Beam

The specifications for injecting the electron beam into the Accumulator are very relaxed with respect to the Linac capabilities (compare in Table 1, the operation values with the design ones). For this reason a very reduced amount of time was spent in optimizing the Linac for the injection, more details are given in the next section. On the contrary a great part of the shifts has been dedicated to tune the various Linac subsystems up to the operating conditions. In particular the starting up and the debugging of subsystems such as the injector, the diagnostics and above all the RF, absorbed most of the time and of the manpower available. On the other hand this was a very profitable period, because the Linac staff achieved a complete hands-on knowledge of the system in all its parts.

Another time consuming task performed by using the electron beam, was the alignment of some of the uniform fields solenoids (UFS) placed downstream the positron converter (see Fig. 3). These magnets, composed by 6 long modules (1 m) and 2 shorter ones (0.5 m), presented a very poor quality manufacture. The main consequence of this, was a strong tilt and offset between the mechanical and the magnetic center lines in most of them. If the solenoid modules are not aligned according to the magnetic axis there exists a net bending effect on the beam that can sensitively reduce the capability of the system in capturing the positrons. A beam based alignment procedure was developed and applied obtaining a final scenario that permitted the achievement of the expected capture, as shown in paragraph 3.

It must be remarked that practically no shifts have been fully dedicated to bring the Linac up to its maximum performance in the electron mode. The reasons of this choice are essentially two: there is not a real need of pushing the Linac beyond the Accumulator injection values first and second we experienced some problems with the klystrons, that limited their output power to values lower than the nominal ones (this situation is better explained in paragraph 3). In any case the 'top' performance so far obtained concerning the energy is 700 MeV, while for the macrobunch output current no practical limit has been observed. In fact currents up to 1 A have been accelerated up to the Linac end.

Anyway, it must be remarked that, in order to maintain the rms energy spread within the acceptance of the transfer lines and Accumulator (± 1.5 %), the Linac output current value must be kept under ~ 300 mA.

No emittance measurement has been done so far.

2.2. DAΦNE Accumulator Electron Injection

The commissioning of the DAΦNE Accumulator with electrons started on May 1996 and it was completed on January 1997. Anyway, as already mentioned, only 28 days of that period were dedicated to the Accumulator injection.

The typical values of the Linac relevant quantities during this phase of the operation were, 50÷500 mA for the macrobunch current, 500÷520 MeV for the energy and ± 1÷3 % for the rms energy spread. As already mentioned in the previous section, the current value must be limited in order to match the ± 1.5 % energy spread acceptance of the transfer line and of the Accumulator. For values greater than ~ 300 mA, because of the beam loading in the accelerating sections, the energy spread rapidly increase and a relevant part of the beam is lost along the transfer line where the dispersion function is different from zero.

The cleanest way to control the Linac current is to vary the current coming out from the electron gun. In the DAΦNE Linac scheme this can be done by the parallel action of two knobs, the bias of the cathode grid and an RF attenuator situated downstream the 'fast pulser' board that generates the 10 ns gun pulse. The first regulation allows a fine tuning of the current value from 0 down to ~ -40 % of the maximum value, while the second one permits an attenuation variable in 3 steps valued around 0 %, -30 %, -60 %. Unfortunately during the last phase of the commissioning with electrons, the RF attenuator broke, and since no spare was available, we were forced to work with almost 5 A of the gun current. Such a situation explains the reason of the large values of energy spread indicated above.

3. POSITRON BEAM COMMISSIONING

The Linac positron commissioning started on July 1996 and it was completed on March 1997. Actually only 18 days of positron beam operation, divided into 5 shifts, have been done during this 9 months long period. The available time was shared between positron tests, Accumulator electron beam injection and for the great part, in the tuning of the hardware concerning the Linac, the Transfer Lines and the Accumulator.

The achievement of the operation performances in a so small number of days has been possible thanks to a careful organization and preparation of the tests and measurements to be done during the shifts with beam. Priorities and decisions concerning the tests to be performed were based on the analysis of the results of the previous shifts with beam.

3.1. Positron Tests

The critical parameters to be set for the positron production are the energy, the current, the position and the dimension of the electron beam impinging on the positron converter target (primary beam), the RF phase between the accelerating sections E5 and CS and the strength of the steering coils situated inside the uniform field solenoids around the sections CS and P1. An estimate of the beam energy at the positron converter, with ± 10% of accuracy, is obtained by energizing a steering coil placed at the end of the accelerating section E5 and measuring the beam deflection on the profile monitor placed before the quadrupole triplet upstream the positron converter, see Figs. 3 and 4. The current is measured by the current monitor upstream the positron converter. The position on the converter target is important because of the small aperture, 7 mm, of the downstream placed flux concentrator (see subsection 1.2.3). This implies that if the beam is not properly centered, a big part of positrons can be lost. The dimension must be kept small enough so that the produced positron beam transverse dimension matches with the capture system acceptance. Position and dimension can be monitored by the fluorescent flag placed on the target itself (see subsection 1.2.5). As already mentioned in subsection 1.2.3, two different RF phase settings of the CS accelerating section are possible, one that privileges the current against the energy of the positrons (CS in decelerating mode), the other one that privileges the energy against the current (CS in accelerating mode). Measurements related to this different modes are presented in subsection 3.1.4.

Finally, because of the non perfect alignment of the uniform field solenoids modules, an effective dipole kick is applied to the beam. In order to avoid the consequent beam deflection with losses of positrons on the accelerating section walls, this dipole component must be compensated. Six of the eight solenoid modules have inside a couple of horizontal and vertical steering coils, by which it is possible to perform this compensation.

When the primary electron beam impinges the positron converter target it generates the electromagnetic shower with consequent formation of electron and positron pairs. Both the particle types can be captured and transported along the sections CS and P1.

Moreover part of the electrons of the primary beam that passed through the target, can find the right RF phase and thus can be captured and accelerated. Since the electromagnetic monitors are sensitive to the net charge of the crossing beam, than the first place where it is possible to observe the positron beam only, is the current monitor downstream the positron separator, see Fig. 4. This monitor has a crucial importance during the tests with positrons, because by monitoring the current at this point it is possible to set all the above described knobs in order to optimize the positron capture.

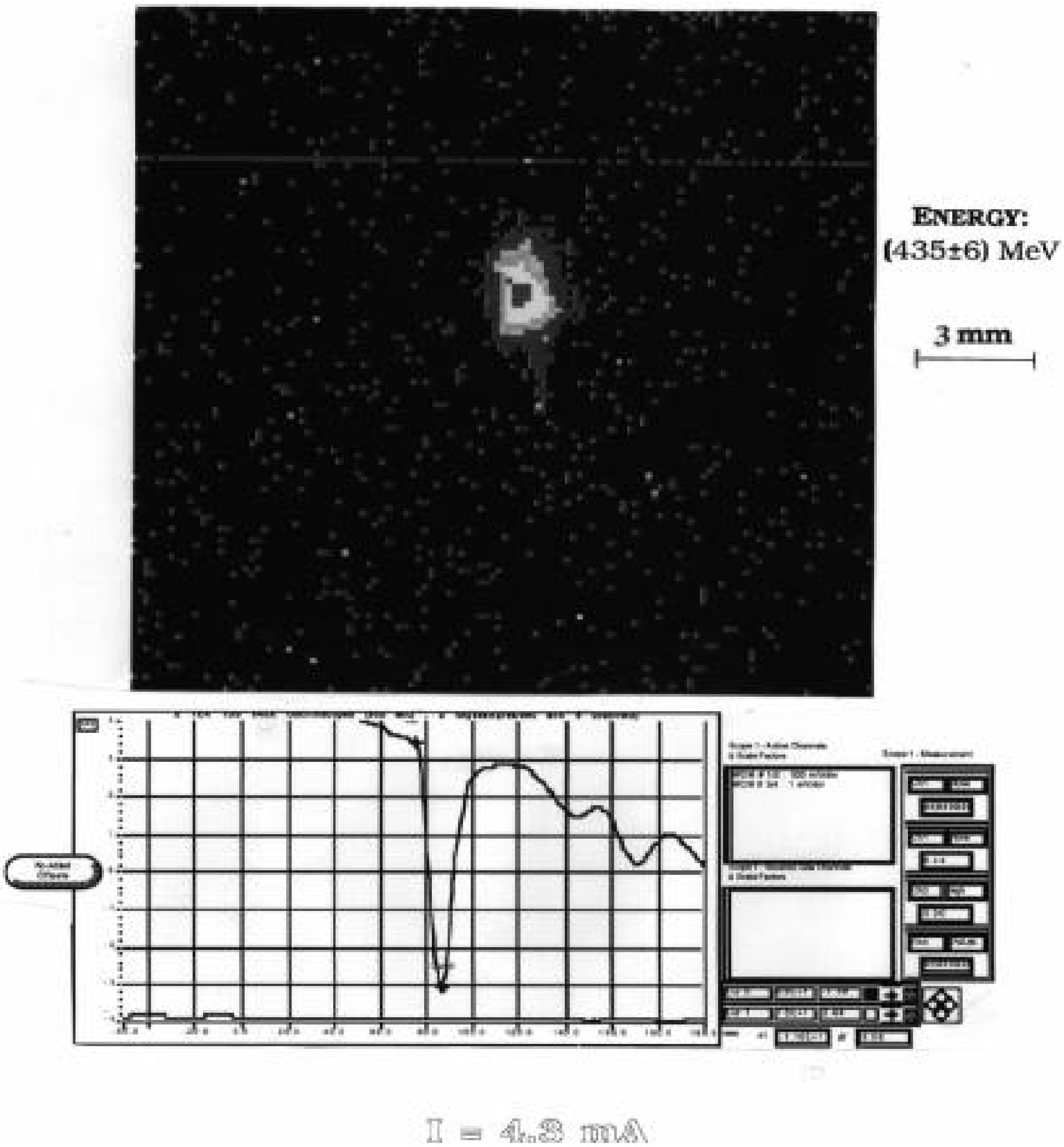
In the remaining part of this section the results of the positron commissioning are presented by following a chronological guideline. For each of the shifts are presented the experimental results, the analysis of the results themselves and the decision concerning the things to be done before and during the successive shift.

3.1.1. First Positron Beam on July 1996

The first test with positrons started on July 9. The electron beam relevant quantities at the positron converter target were: macrobunch current of 1,5 A, energy of ~ 80 MeV and rms spot size < 1 mm, against the nominal values of respectively 4 A, 250 MeV and 1 mm. The reason of these very low values of the current and of the energy are explained later. During the evening shift of July 11, the first positron beam on the current monitor at the end of the positron separator was observed: 600 μA! The day after, 2 mA of positrons were transported up to the Linac end. Unfortunately a serious failure in the electron gun, on July 13, forced us to interrupt the tests up to July 22. Finally on July 23, a positron beam with 4.3 mA, 435 MeV and 1.4 % rms energy spread was measured at the Linac output (see Fig. 7). The capture section was in the decelerating mode.

These values must be compared with the operation ones on Table 1.

The reason of the low value of the current at the positron converter was due to the a partial failure of the electronics of the electron gun that limited the current to 4.5 A instead of the nominal 8 A. The situation of the modulators and of the klystrons at that time strongly limited the energy of the beam either at the positron converter, 80 MeV instead of 250 MeV, or at the Linac output, 435 MeV instead of 550 MeV. In fact, with reference to Fig. 2 and Table 2, the severe failure on klystron B limited the energy at the positron converter, while the non completed conditioning of the modulators and klystrons C and D limited the energy of the positron beam at the Linac end.



I = 4.3 mA

Figure 7. Positron Tests on July 1996. Top: positron beam spot at the Linac output, viewed on a profile monitor (fluorescent screen type). Bottom: positron beam current at the Linac output measured by a current monitor (wall current monitor type). The horizontal scale is 20 ns/div.

Table 2. Klystrons Output Power (July 1996)

Klystron A	22 MW	C
Klystron B	5 MW	F
Klystron C	25 MW	M
Klystron D	34 MW	C, M
C≡RF CONDITIONING LIMITED; F≡FAILURE; M≡MODULATOR LIMITED		

An estimate of the energy of the positron beam at the Linac end, for a given output power of the klystrons, can be obtained by the expression:

$$E = SF\sqrt{(1-a)}\sum_{n=1}^{N}\sqrt{\frac{P_{k(n)}}{b_n}} \qquad (1)$$

where:

S ≡ Sled Gain Factor = 1.6
F ≡ Accel. Section Gain Factor [7]= 10.65 MeV/MW$^{1/2}$
a ≡ RF Network Loss Factor = 0.067
N ≡ Accelerating Section Total Number = 10
$Pk(n)$ ≡ k-th Klystron Output power
bn ≡ RF Power Division Factor
($b_1 = 2$, $b_j = 4$ $j = 2, 3, ..., N$)

With our numbers and with the CS accelerating section in the accelerating mode:

$$E_A = 32.92\left(0.60\sqrt{P_A} + \sqrt{P_C} + \sqrt{P_D}\right) \qquad (2)$$

If the CS is in the decelerating mode a reasonable estimate can be given by the expression:

$$E_D = 32.92\left(0.54\sqrt{P_A} + \sqrt{P_C} + \sqrt{P_D}\right) \qquad (3)$$

By using the values of Table 2 and expression (3) a value of 440 MeV, against the measured 435 MeV, is obtained. It must be remarked that the values of the constants in the above three formulae, were calculated by using the nominal quantities for the related quantities and not measured values.

Although the achieved results were still far from those necessary for the operation, the tests fulfilled some important tasks. First of all, complex and critical parts like the positron converter, the positron capture system, the flux concentrator pulser, the positron/electron separator and the RF phasing between sections belonging to the same klystron network, demonstrated their full capability of operation in the positron mode.

As a second point, a rough scaling of the obtained performances could be done in order to estimate the potential of the system. This can be obtained by linearly scaling the positron current at the Linac output with the energy and the current of the primary beam at the positron converter target (assuming the same beam spot size at the positron converter). This means, with the values of the July tests, an extra gain factor of 3.1 (250 MeV/80 MeV) for the energy and of 2.7 (4 A/1.5 A) for the current. The scaled value for the positron current at the Linac output is 35.8 mA against the design one of 36 mA. In reality the scaling with the energy is not linear, in fact a more accurate calculation (see Appendix) gives a scaled value for the current of 33 mA.

The relevant action items decided in preparation of the following positron test were: increasing the gun current up to the design value, replacing klystron B, tuning the 4 modulators to maximum performance and complete the RF conditioning.

To conclude this section, just some words for explaining the reason of the klystron B failure. This tube presented problems since its first operation: the maximum output power was limited to 35 MW instead of the nominal 45 MW. Because full output power was not necessary in the first period of operation it was decided to maintain the klystron on the beam line. The tube performed stably for a quite long period up to June 1996 when its output power started to drop rapidly. The tube was replaced and then sent to factory for repair. Only very recently we learnt from Thomson that the failure was due to the breaking of one of the three supports that hold the cathode in the right position. The repaired tube will be back in Frascati during the summer of this year.

3.1.2. Positron Tests on October 2-4, 1996

Klystron B was replaced on August 1996, while the electron gun trouble was successfully fixed on September. Unfortunately klystron C started, on September 96, to present serious arcing problems that limited the output power to 8 MW maximum. Even in this condition it was decided to perform three days of test with positrons, with the main goal of practicing with positron operation. The obtained results were 4.5 mA of positrons at the Linac end with an energy of 365 MeV. The current from the gun was 7.7 A while the one at the positron converter was 2.1 A. The energy of the electron beam at the positron converter was 135 MeV, the spot size < 1 mm rms and the CS was in the decelerating mode. The conditioning at full power of modulators and klystron was not completed at that time. Concerning klystron C, the arcing phenomena was so serious that we were planning to replace it with a spare one. Fortunately, on November 96, jointly with Thomson, a procedure for recovering a klystron in such a situation was found out, and the klystron C was completely recovered. This was a very important result, because it strongly increased the reliability condition of the tube. In fact, so far the procedure has been applied twice to two different klystrons successfully.

3.1.3. Positron Tests on December 19-20, 1996

During November and the first half of December 1996, great part of the attention and manpower were dedicated to the completion of the conditioning of both klystrons and modulators. The operation succeeded with the modulators but even if the klystrons were brought to saturation, their maximum output power, 37-42 MW, was sensitively lower than the nominal value of 45 MW. Anyway, by using expressions (2) and (3) it could be estimated that the positron energy at the end of the Linac should be > 510 MeV also with this level of power coming out from the klystrons.

The positron tests started on December 19 and in only 2 days 26.4 mA 395 MeV of positrons at the Linac output were obtained.

Table 3 summarizes the relevant results while Fig. 8 shows the signals from all the 4 current monitors placed along the Linac.

Concerning the positron current, the obtained results were very encouraging. In fact, comparing the numbers in Table 3 with the ones in Table 1, it can be seen that the achieved current value at the Linac end was sensitively beyond the operation value of 10 mA.

In addition, the low value of the energy at the positron converter, 150 MeV instead of 250 MeV, indicated that there was still a relevant margin for increasing the positron current. Also the transmission efficiency, between the Positron Separator and the Linac output, could be further improved.

On the contrary, the values of energy either at the positron converter or at the Linac end were sensitively lower than the expected ones, even taking into account the actual klystron output level. The reason of such a low value of the beam energy had to be sought in the RF subsystem components. For this reason it was decided to dedicate a 15 days campaign of RF measurements and tune-up of the RF system including SLED's retuning, RF monitors recalibration, check of the RF phase relation between accelerating sections belonging to the same klystron network and so on.

Table 3. e^+ Tests on December 96: Main Results

I_{GUN} = 7.3 A (nom. 7 A)		
I_{PC} = 3.8 A (nom. 4 A)	E_{PC} = 150 MeV (nom. 250 MeV)	σ_{PC} < 1 mm rms (nom. 1 mm rms)
I_{PS} = 46.3 mA		
I_{LE} = 26.4 mA (nom. 36 mA)	**E_{LE} = 395 MeV** (nom. 550 MeV)	**$\Delta E/E \approx$ 1.3 % rms** (nom. 1 % rms)

CONVERSION EFFICIENCY: 0.69 %
(nom. 0.9 %)

CAPTURE SECTION IN DECELERATING MODE

(PC: POSITRON CONVERTER; PS: POSITRON SEPARATOR; LE: LINAC END)

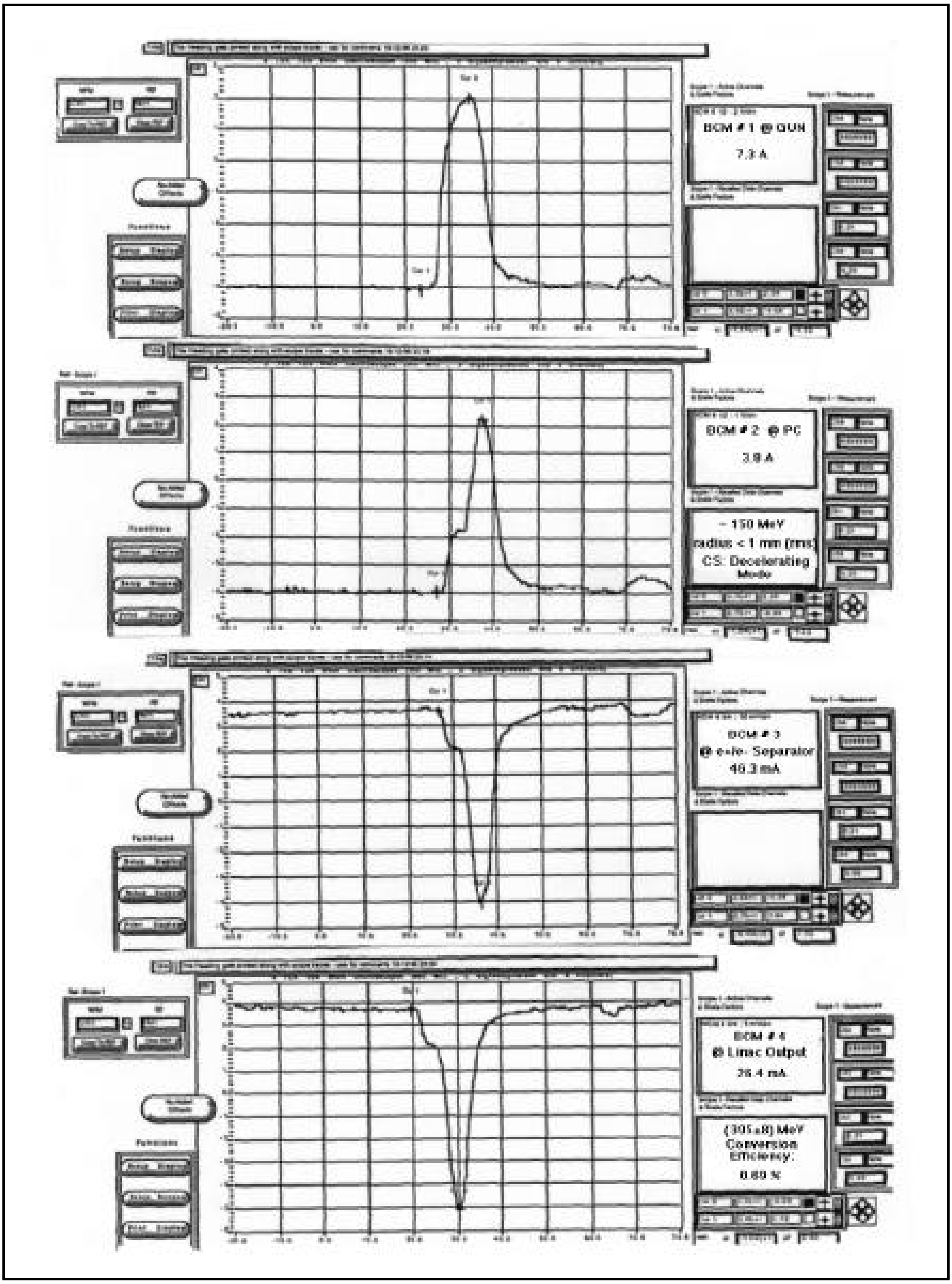


Figure 8. Positron Tests on December 1996. From top to bottom: beam current, measured by current monitors (wall current monitor type), at the Gun output (e^-), at the Positron Converter (e), at the Positron Separator (e^+) and at the Linac output (e^+). For all the four signals the horizontal scale is 10 ns/div. The peak current values can be read on Table 3.

3.1.4. Positron Tests on February 18-23, 1997

The RF tune-up campaign mentioned in the previous section, was carried out between the end of January and the beginning of February.

Every part of the RF system and of the modulators was checked out, in particular a lot of work was done around the SLED's, where a serious problem with the detuner was found and fixed in 2 of the 4 units.

The tests of February were completely dedicated to the achievement of the operation value of 510 MeV for the positron energy. Table 4 shows the achieved results and Fig. 9 the signals from 2 of the 4 current monitors.

Table 4. e^+ Tests on February 97: Main Results

I_{GUN} = 7.2 A (nom. 7 A)		
I_{PC} = 3.4 A (nom. 4 A)	E_{PC} = 170 MeV (nom. 250 MeV)	σ_{PC} < 1 mm rms (nom. 1 mm rms)
I_{PS} = 42.0 mA		
I_{LE} = 20.0 mA (nom. 36 mA)	**E_{LE} = 515 MeV** (nom. 550 MeV)	**$\Delta E/E$ < 1 % rms** (nom. 1 % rms)

CONVERSION EFFICIENCY: 0.59 %
(nom. 0.9 %)

CAPTURE SECTION IN ACCELERATING MODE

(PC: POSITRON CONVERTER; PS: POSITRON SEPARATOR; LE: LINAC END)

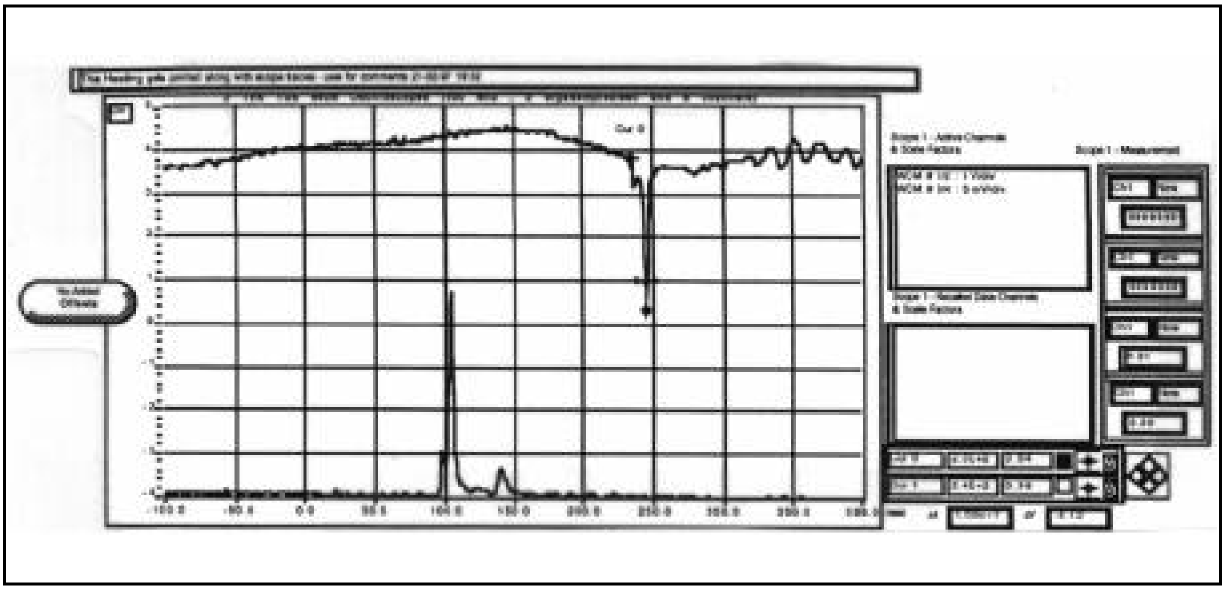


Figure 9. Positron Tests on February 1997. Signals from current monitors of the wall current monitor type. The horizontal scale is 50 ns/div. The peak values are given in Table 4. Top track: positron beam current at the Linac output. Bottom track: Electron beam current at the Positron Converter.

The most important result obtained during the February tests was the achievement of the value of operation for the energy of the positron beam at the Linac output. Such a situation allowed to accept the Linac on February 23, 1997, concluding the contract with the firm TITAN BETA.

The accomplishment of this important result was possible thanks to 2 major facts. First the tuning of the RF system (SLED's mainly) that allowed a relevant increase of the energy from 395 MeV up to 500 MeV. Second the switching of the CS accelerating section mode from decelerating to accelerating, which permitted a net gain in energy of 15 MeV. This situation can be observed in the graphs of Fig. 10, where the measured values of both the current and the energy of the positron beam at the Linac output vs. the RF phase of the CS accelerating section are showed . The only point showed, concerning the decelerating mode, corresponds to the CS phase position that maximized the positron energy at the Linac end. With reference to the same figure, it can be seen that the energy gain was 15 MeV, as already said, against a current decrease from 26 mA to 20 mA. It is interesting to note that the phase 'distance' between the accelerating and decelerating modes is not exactly 180 but 150÷160 RF degrees, in fair agreement with the R.H. Miller theory presented in reference [9]. Finally, it must be remarked that none of the other Linac regulations were changed during the measurement.

As an open question, to be answered before the following positron tests, it remained the one of better understanding the situation of the klystron output power.

As already mentioned in section 3.1.3, the measured values of this quantity were sensitively smaller than the nominal one. For this reason it was decided to perform a complete characterization of all the four tubes, including the recalibration of the monitors used for RF power measurements.

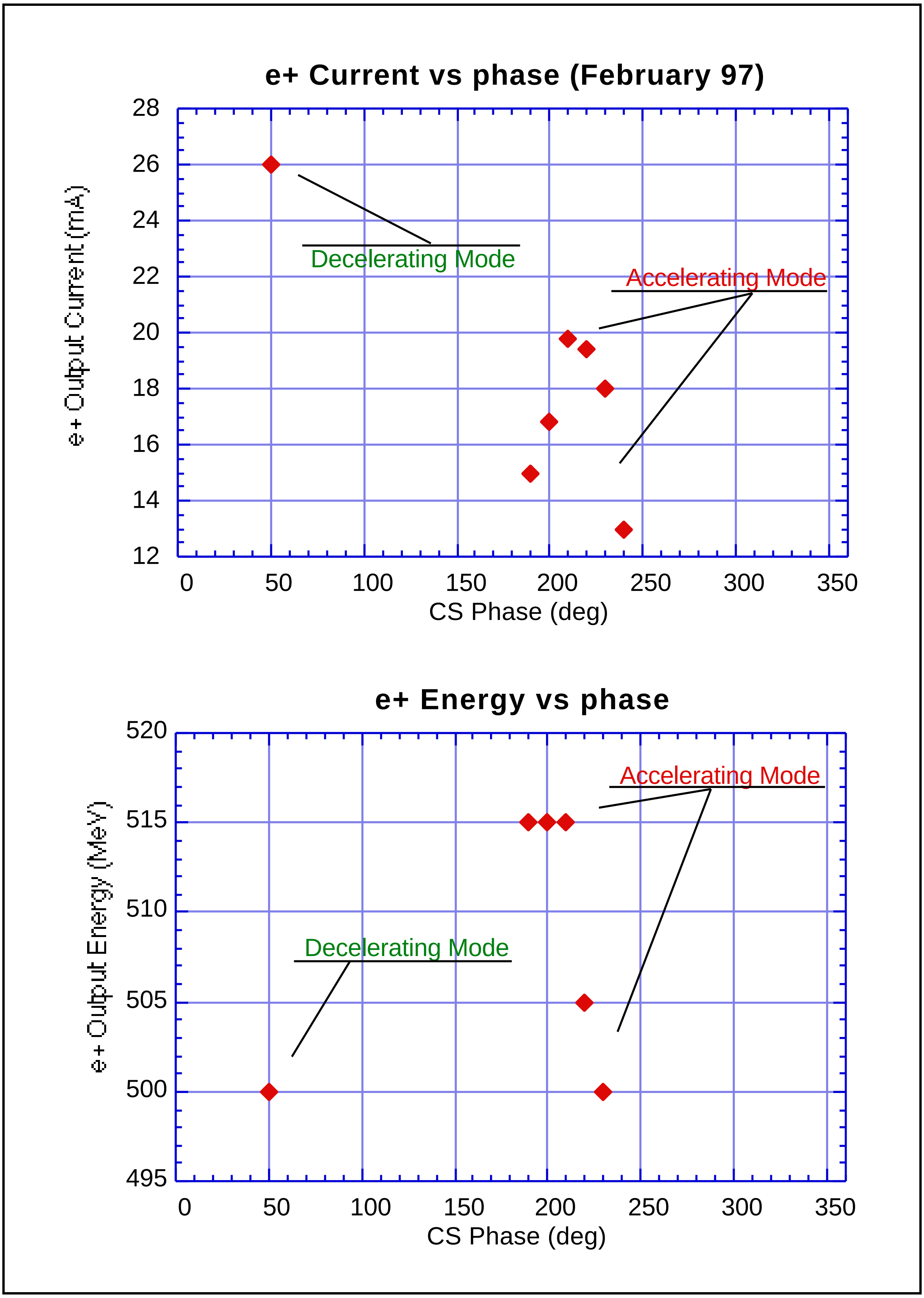


Figure 10. e+ Energy & Current at the Linac Output vs. CS Phase

3.1.5. Positron Tests on March 21, 1997

A one week shift, during the first half of March 97, was completely dedicated to klystron measurements. For each of the 4 tubes operating in the Linac, the saturation curve, the reflected RF power, the RF driver response, the perveance, the gun filament voltage and the current of the focusing coils were measured. In order to have a cross check, all the RF power measurements were performed twice by using a peak power meter in one case and RF detectors in the other one. Of course all of these RF detectors were completely calibrated on bench before the measurements. As a summary of this klystron characterization the maximum output power values measured from the tubes are showed in Table 5. The values are all below the nominal output power of 45 MW sensitively. Anyway by using the expression (2) it is possible to see that with such a values of power an energy of 528 MeV for the positron beam, should be obtained at the Linac end.

Table 5. Klystrons Output Power (March 1997)

Klystron A	41 MW
Klystron B	41.7 MW
Klystron C	36.8 MW
Klystron D	37.4 MW

A single day shift with positron beam was performed on March 21. Figure 11 shows the scope track of the current monitor signal at the end of the Linac, while Table 6 presents the results obtained.

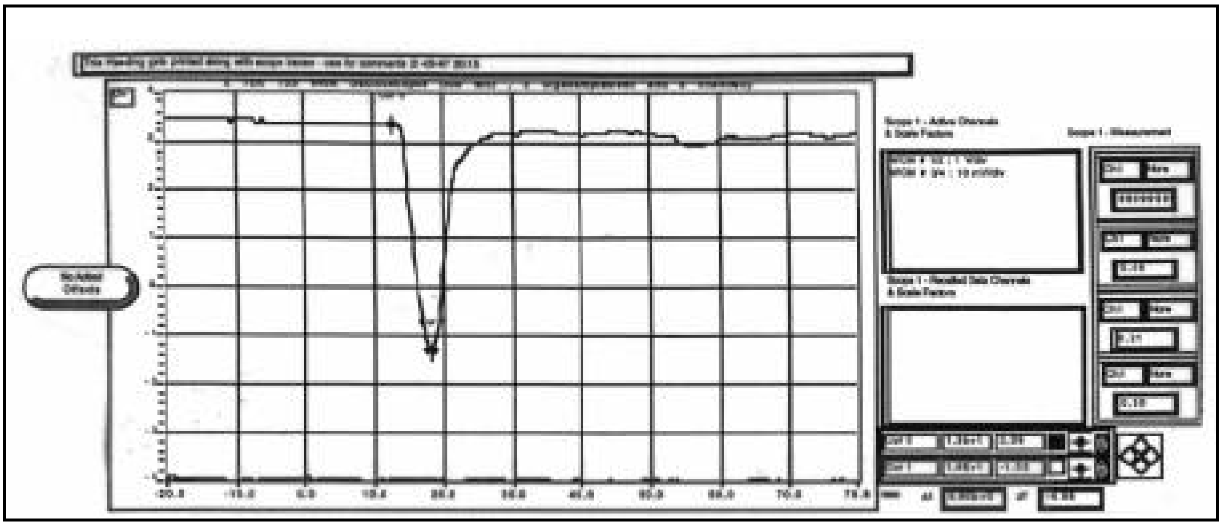


Figure 11. Positron Tests on March 1997. Positron beam current at the Linac output. The signal comes from a current monitor of the wall current monitor type. The horizontal scale is 10 ns/div. The peak value is 31.0 mA.

Table 6. e^+ Tests on March 97: Main Results

I_{GUN} = 4.6 A (nom. 7 A)		
I_{PC} = 2.4 A (nom. 4 A)	E_{PC} = 170 MeV (nom. 250 MeV)	σ_{PC} < 1 mm rms (nom. 1 mm rms)
I_{PS} = 44.0 mA		
I_{LE} = 31.0 mA (nom. 36 mA)	**E_{LE} = 535 MeV** (nom. 550 MeV)	**$\Delta E/E$ < 1 % rms** (nom. 1 % rms)

CONVERSION EFFICIENCY: 1.29 %
(nom. 0.9 %)

CAPTURE SECTION IN
ACCELERATING MODE

(PC: POSITRON CONVERTER; PS: POSITRON SEPARATOR; LE: LINAC END)

Some comments concerning the values on Table 6 are in order. First of all, the good result obtained with the energy: 535 MeV, in reasonable agreement with the expected 528 MeV. Second, the high current value at the Linac output, very close to the nominal one, and what is better the very high value of the positron conversion efficiency, more than 40% over the design value. This is a clear indication of the potentiality of the system in obtaining larger values of positron current. In fact, during this tests on March, the current at the positron converter was limited to only 2.4 A, because of a partial failure on the electron gun. Also the beam energy at the positron converter was limited to 170 MeV instead of 250 MeV, due to some problem at the SLED on klystron B probably. So by increasing these two quantities towards the nominal values (so far 3.8 A and 220 MeV have been already obtained), it will be possible to further increase the positron current at the Linac end.

4. CONCLUSIONS

The work done during the DAΦNE Linac commissioning permitted to achieve a clear view about the situation and the potentiality of this part of the DAΦNE injector. For all the relevant quantities the operation values necessary for the injection into the Accumulator have been achieved and overcome. Moreover the measured values are very close to the design ones, that were originally set in order to ensure a very conservative scenario for the operation.

The electron beam mode does not present critical aspects because of the Linac configuration, that allows performances largely over the injection requirements.

Concerning the operation with the positron beam, the value of current so far achieved is very close to the nominal one and, as explained in section 3.1.5, with still margin for further increase. The operation value for the energy during the Accumulator injection is 510 MeV, so the present value, 535 MeV, is large enough to permit the operation of the modulators and of the klystrons at 90% of their maximum capabilities. This situation should ensure a good reliability of the system during the operation, which is a very important goal. Moreover, there is still some margin for a minor increase of the energy by performing a fine tuning of the timing between the beam and the RF pulse and of the temperatures of each of the accelerating sections. An estimate indicated that an overall additional gain of the order of 10 MeV could be obtained. On the other hand, a relevant improvement of the energy performance could be achieved by taking the klystrons up to their nominal power of 45 MW. The klystron firm, Thomson, ensured its maximum collaboration in this direction and some tests on the tubes, like for example the measurement of the high order harmonics contribution, have been already scheduled for the near future. A klystron replacement option was also studied. In particular the Japanese firms Toshiba and Mitsubishi sell 50 MW tubes, that with minor adjustments can fit with our modulator system, from both the mechanical and the electrical point of view.

On April 1997, a 'hot run' of 8 hours of continuous operation was performed with the aim of checking the Linac stability and reliability. No relevant fault was observed.

Finally, in Table 7 are showed the 'milestones' of the DAΦNE Linac, from the contract signature up to the system acceptance.

Table 7. DAΦNE Linac Milestones

Contract Signature	January 16, 92
Conceptual Design Review	April 15, 92
Final Design Review	October 23, 92
Factory Tests	August 8, 94
Shipment to LNF	December 30, 94
Installation Completion	September 30, 95
Beam Commissioning Beginning	April, 96
Linac Acceptance	February 23, 97

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APPENDIX

Positron yield vs. conversion energy: an estimate formula

In the positron converter scheme where a primary electron beam impinges a metallic target, the number of pairs outcoming the target is a function of the target thickness and of the primary electron beam energy. Apart from a scale factor this relationship can be approximately expressed by [12]:

$$N(t,E_0) \quad E_0 b(E_0) \frac{\left[b(E_0)t\right]^{a(E_0)-1} e^{-b(E_0)t}}{\Gamma\left[a(E_0)\right]} \tag{A1}$$

where E_0 is the energy of the primary beam, t is the thickness of the target expressed in radiation lengths units and

$$a(E_0) = 1 - \frac{1}{2} b(E_0) + b(E_0) \ln {E_0}/{E_C} \tag{A2}$$

The function $b(E_0)$, that appears in A1 and A2, has a very small dependence from E_0 and it can be reasonably approximated by:

$$b(E_0) \approx 0.5 = b \tag{A3}$$

Finally the *critical energy* E_C present in equation A2 can be evaluated by:

$$E_C = \frac{610(\text{MeV})}{Z + 1.24} \tag{A4}$$

with Z the atomic number of the target material. The critical energy is that value where the primary electron energy losses due to ionization are equal to the ones due to bremsstrahlung.

Expression A1 presents a maximum N_{MAX} when t is equal to:

$$t_{MAX} = -\frac{1}{2} + \ln \frac{E_0}{E_C} \tag{A5}$$

$$N_{MAX} \quad E_0 b \frac{\left[a(E_0)-1\right]^{a(E_0)-1} e^{-\left[a(E_0)-1\right]}}{\Gamma\left[a(E_0)\right]} \tag{A6}$$

In the case of DAΦNE the tungsten (Z = 74) target thickness corresponds to t_{MAX} evaluated at E_0 = 250 MeV. If the energy of the primary beam is different from this value than an estimate of the relative variation of the yield can be obtained by:

$$R(E) = \frac{N\left[t_{MAX}(E_0 = 250\,MeV), E\right]}{N_{MAX}(E_0 = 250\,MeV)} = \frac{E(\text{MeV})}{250} \frac{\Gamma\left[a(250\text{MeV})\right]}{\Gamma\left[a(E)\right]} \left[a(250\text{MeV}) - 1\right]^{a(E)-a(250\text{MeV})} \tag{A7}$$

As example, it can be calculated $R(E)$ in the case of the positron tests described in the subsection 3.1.1 of this note where E was equal to 80 MeV:

$$a(250\text{MeV}) = 2.46 \qquad a(80\text{MeV}) = 1.89$$

$$\Gamma\left[a(250\text{MeV})\right] = 1.29 \qquad \Gamma\left[a(80\text{MeV})\right] = 0.958$$

$$R(80\text{MeV}) = 0.35$$

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