

Frascati, Feb. 1, 1992

Note: **LC-3****LINAC TO ACCUMULATOR AREA TRANSFERLINE (LAAT)
& DAΦNE-LINAC SPECTROMETER (DLS)**

The LINAC front-end transferline (LAAT)^[1] and the spectrometer (DLS) used to monitor the LINAC beam energy is presented.

1. LAAT - Linac to Accumulator Area Transferline

The LAAT layout is shown in Fig. 1. It is a straight transferline, twenty eight meter long. It consists of eight quadrupoles and it is capable to transport beams with the following features:

Max energy:	800 MeV
Max energy spread:	$\pm 1.5\%$
Max emittance:	10 mm mrad

The initial values of the beam parameters has been derived from the simulations done by Titan Beta (the DAΦNE-LINAC manufacturer). The LINAC-Accumulator transferline needs different initial optical functions according to its mode of operation (electrons or positrons). LAAT satisfies these different matching by varying the strength of its last four quadrupoles (Q5 ÷ Q8).

Fig. 2 and Fig. 3 show the optical functions and the beam envelopes, for both modes of operation, as calculated by the LEDA code [2], while in Table 1 the transportline components and their maximum magnetic values are listed.

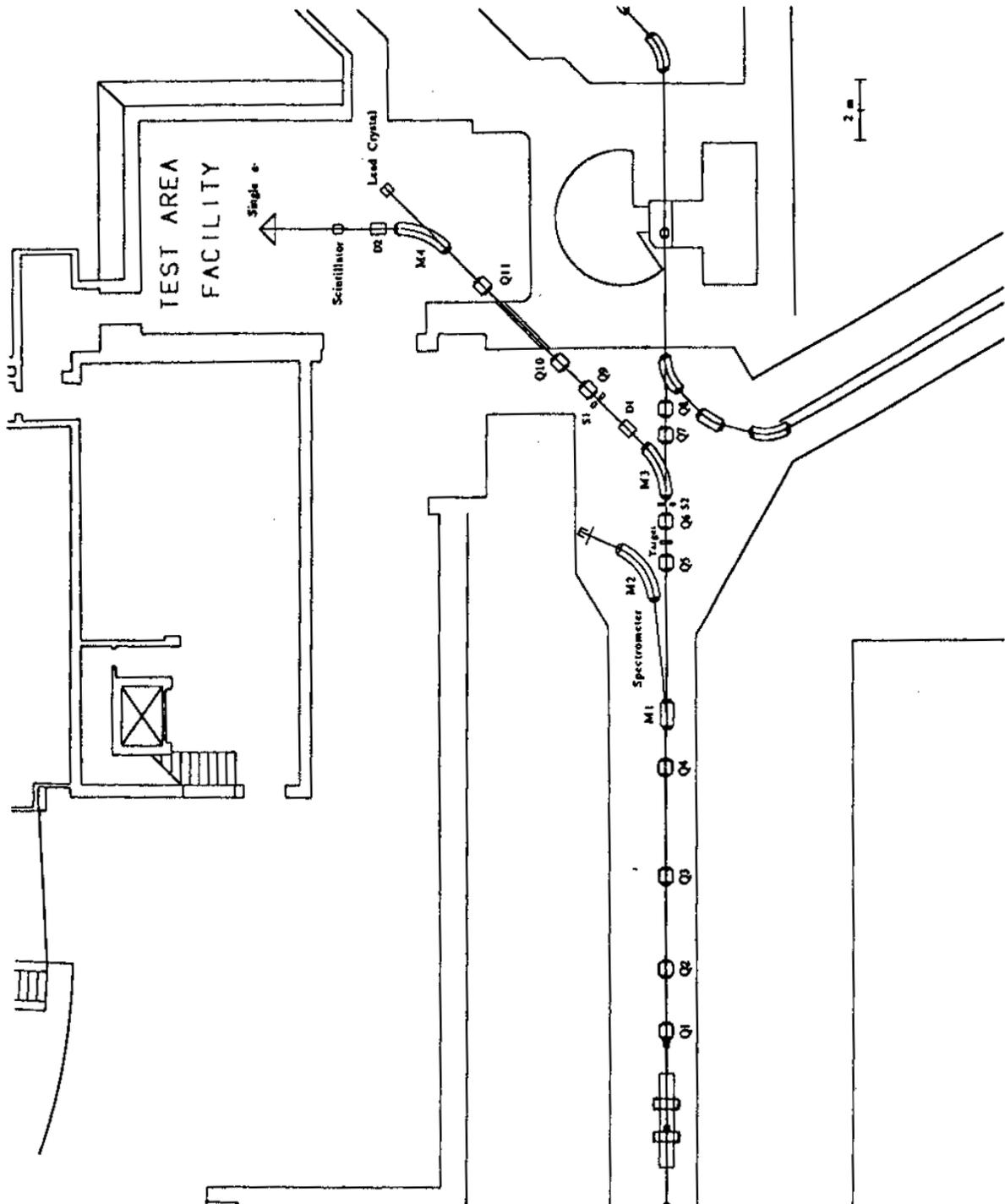


Figure 1: LAAT layout

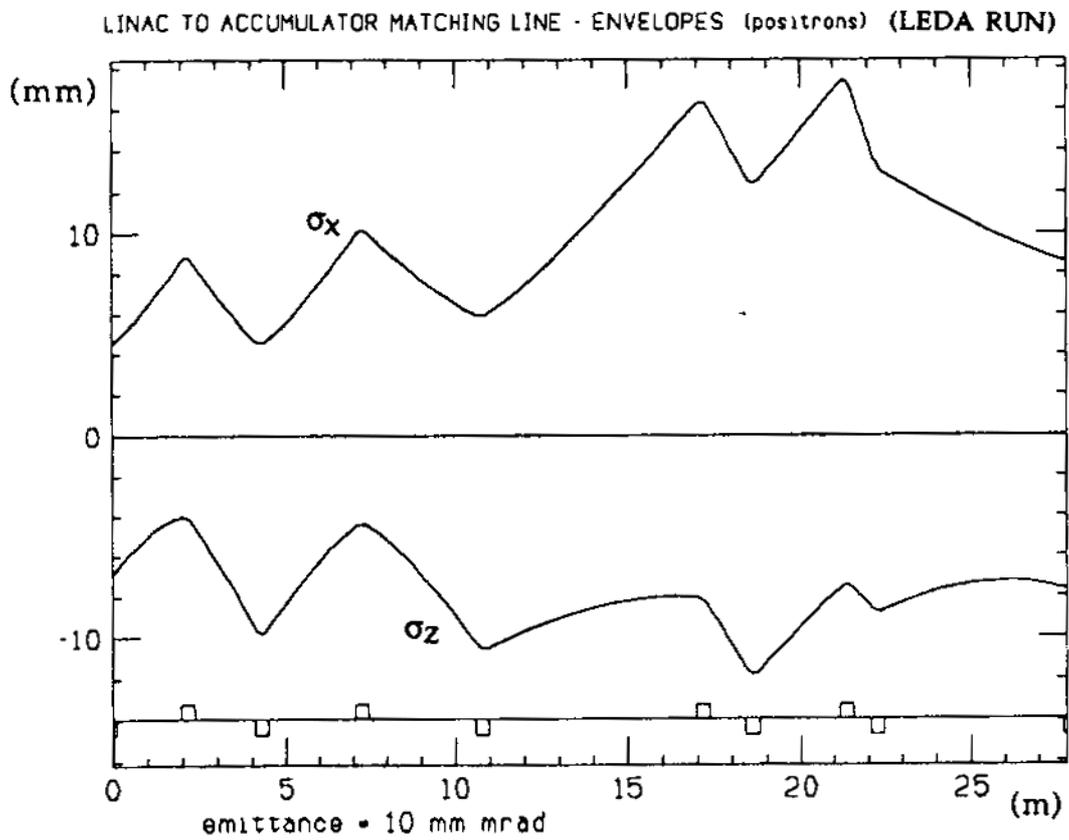
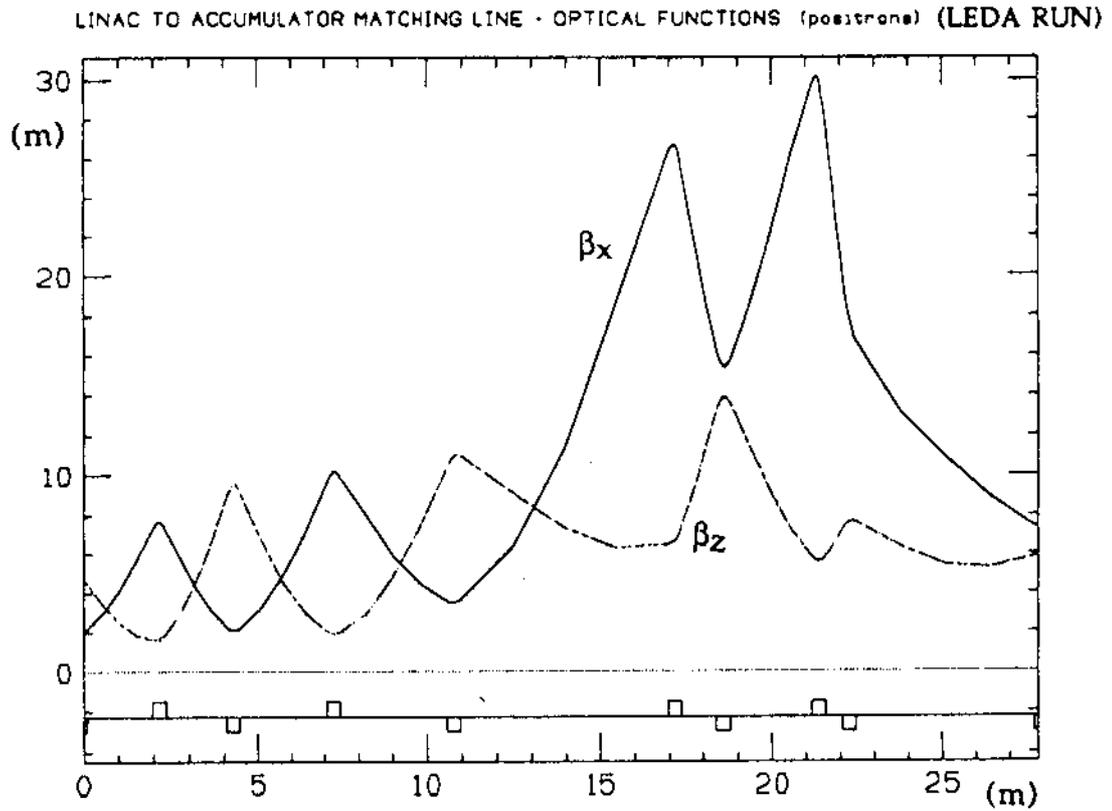


Figure 2 : LAAT optical functions and envelopes (positrons).

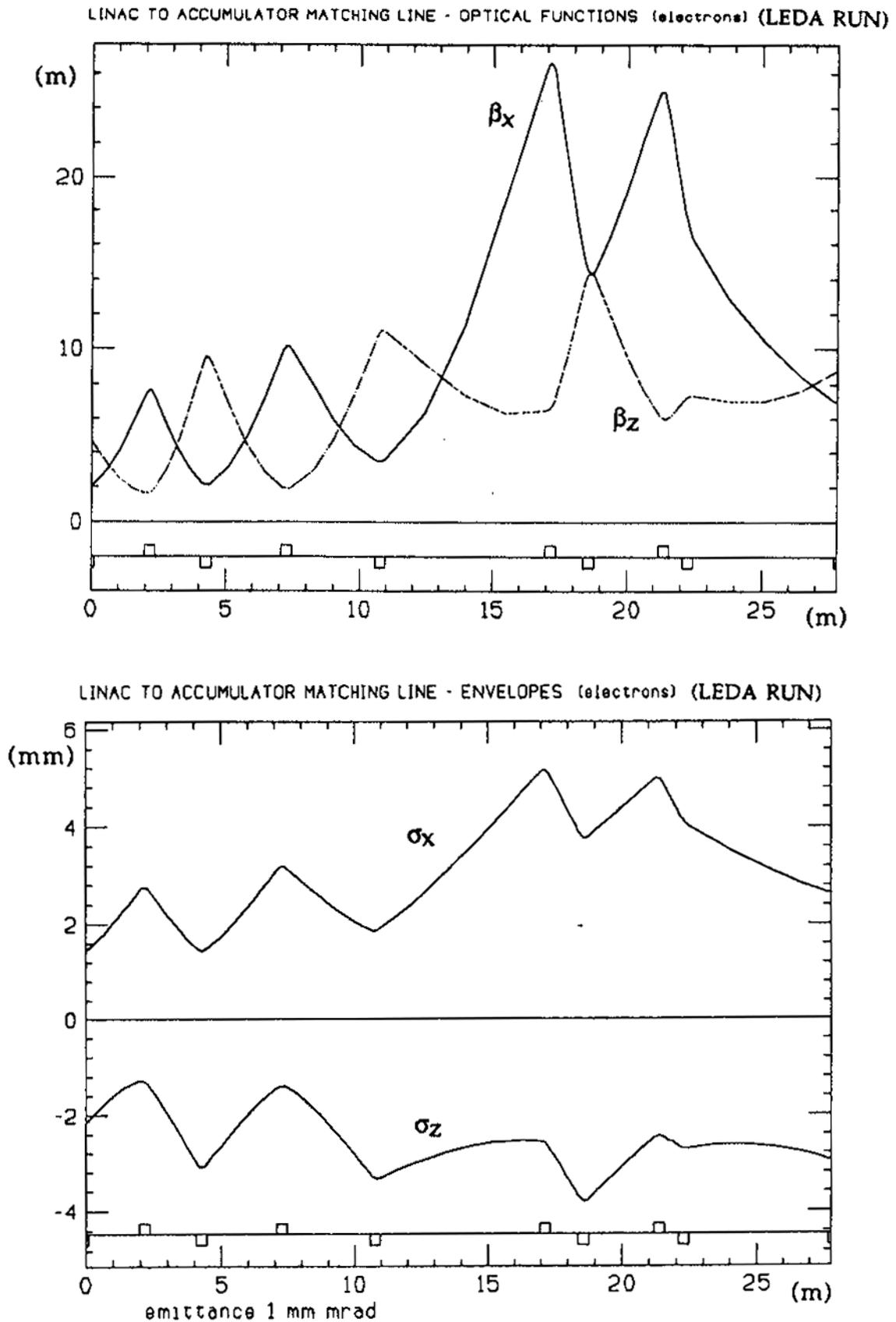


Figure 3 : LAAT optical functions and envelopes (electrons).

Table 1 - Transport line components and their maximum magnetics values.

	Mag. length (m)	G (T/m)	Stay Clear Aperture Ø (m)
drift	1.85		
Q ₁	0.40	3.74	0.07
drift	1.70		
Q ₂	0.40	3.79	0.07
drift	2.60		
Q ₃	0.40	2.59	0.07
drift	3.10		
Q ₄	0.40	1.96	0.07
drift	6.00		
Q ₅	0.40	2.21	0.07
drift	1.00		
Q ₆	0.40	2.69	0.07
drift	2.40		
Q ₇	0.40	2.13	0.07
drift	0.50		
Q ₈	0.40	1.50	0.07
drift	5.25		

2. DLS - DAΦNE-LINAC Spectrometer

The DLS layout is shown in Fig. 4. It consists of a small angle pulsed magnet followed by a DC large angle sector magnet (spectrometer magnet) having an hodoscope in its focal plane.

The pulsed magnet allows an "on line" mode of operation: one out of 50 bunches will be bent into the spectrometer magnet.

The two magnets configuration has been chosen in order to simplify the DLS construction. In particular the small angle (small field) pulsed magnet allows to have a not expensive pulsed power supply, and moreover a DC spectrometer magnet can have good features without hard constructive difficulties and too large costs.

2.1 DLS Features

The resolving power of an energy spectrometer is given by [3] :

$$R_D = \frac{D_x \Delta E / E}{2 \sigma_x} \quad (1)$$

where D_x and σ_x are the horizontal dispersion and beam envelope at the hodoscope plane and $\Delta E/E$ is the energy spread of the beam.

The energy resolution is given by:

$$\frac{\delta E}{E} = \frac{1}{R_D} \frac{\Delta E}{E} \quad (2)$$

As we have said before, the hodoscope is in the focal plane of the spectrometer magnet. This means, for a sector magnet, a distance $\rho \cotg(\phi)$ from the end of the magnet itself (ϕ is the bending angle).

For our configuration we have after some algebra:

$$2 \sigma_x = \frac{2\rho_2}{\sin \phi_2 \cos \phi_1} \sqrt{\frac{\varepsilon (1 + \alpha_0^2)}{\beta_0}} \quad (3)$$

and

$$R_D = \frac{1}{2} \sqrt{\frac{\beta_0}{\varepsilon (1 + \alpha_0^2)}} (\sin \phi_1 + \sin \phi_2 \cos \phi_1) \frac{\Delta E}{E} \quad (4)$$

where β_0 and α_0 are the beam optical functions at the beginning of the pulsed magnet, ε is the beam emittance, ϕ_1 is the bending angle of the pulsed magnet and ϕ_2 and ρ_2 are the bending angle and the radius of the spectrometer magnet.

In DLS configuration:

$\phi_1 = .1138$ rad	see table 4
$\phi_2 = \pi/3$ rad	"
$\rho_2 = 1.723$ m	"
$\alpha_0 = -1$	LEDA simulation (Fig.5)
$\beta_0 = 5$ m	"

the energy spread assumed for the positron beam is:

$$\Delta E/E = 3 \% (\pm 1.5 \%)$$

with

$$\varepsilon = 5 \div 10 \text{ mm mrad}$$

while for the electron beam

$$\Delta E/E = 1 \% (\pm 0.5 \%)$$

$$\epsilon = 1 \text{ mm mrad}$$

The main spectrometers characteristics are listed in Table 2.

Table 2 - Spectrometer features

positron beam			
ϵ (mm mrad)	R_D (%)	$\delta E/E$ (mm)	$2 \sigma_x$
5	10.4	± 0.15	5.7
10	7.4	± 0.21	8.0
electron beam			
1	7.7	± 0.07	2.5

The positron beam will have $\pm 1.5\%$ energy spread. The spectrometer is optimized to measure $\pm 2\%$, but it will be able to accept beams up to $\pm 3\%$ energy spread (this feature will be very useful during the Linac commissioning. The field uniformity (which mainly affects the magnet cost), will be dimensioned for $\pm 2\%$ energy spread beams (see § 2.2), while the stay clear zone (vacuum chamber dimensions) will be dimensioned to accept up to $\pm 3\%$ energy spread.

Table 3 - Magnets Stay Clear Aperture

	Gap (cm)	Pole width (cm) (stay clear zone respect to the central orbit)
Pulsed magnet	3.5	± 2.5
Spectrometer magnet	3.0	± 4.0

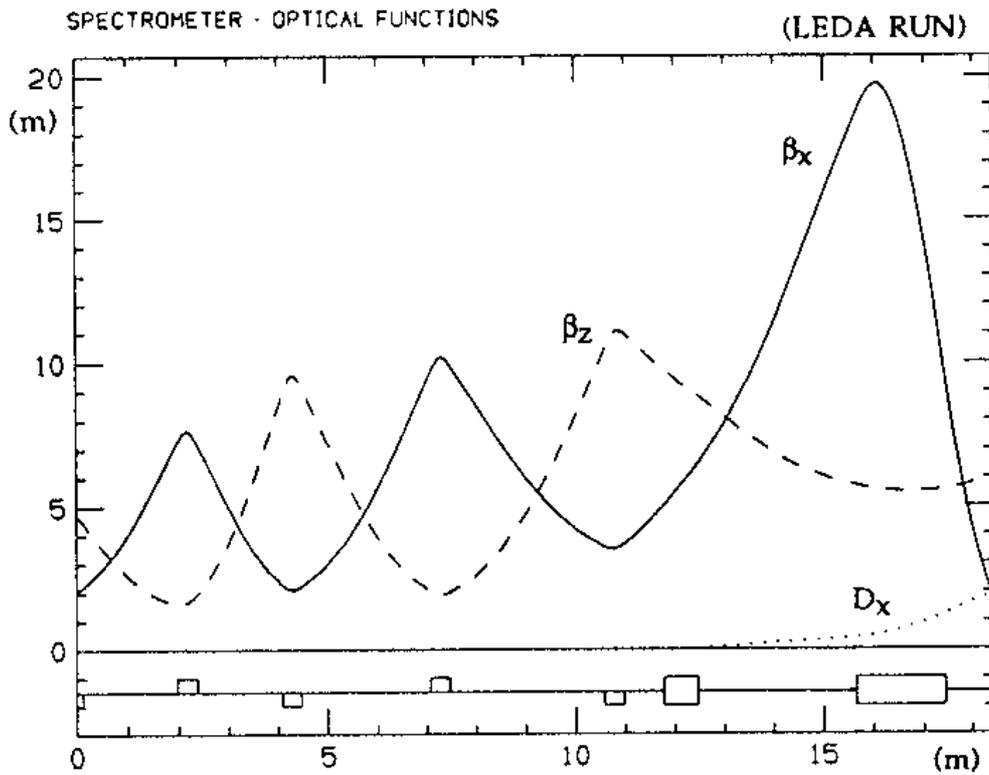


Figure 5 : DLS Optical functions.

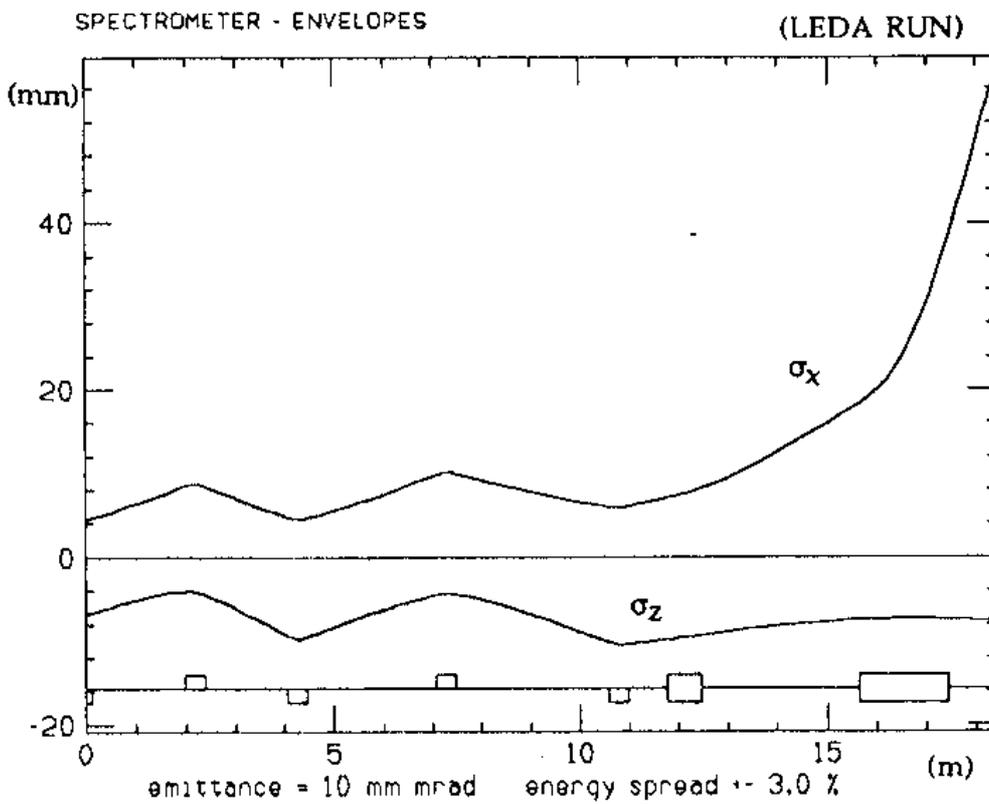


Figure 6 : DLS Maximum beam envelope.

2.2 Multipolar terms and second order aberrations in the spectrometer magnet

The field inside the magnet can be written as

$$B = B_0 \rho \sum_{n=0}^{\infty} \frac{k_n}{n!} x^n \quad (5)$$

$$k_0 = \frac{1}{\rho}$$

In a **H type magnet**, for symmetry reasons, it is $k_1 = 0$. Therefore the most important term will be the one with $n = 2$ (sextupolar term). With a good approximation we have:

$$B = B_0 + \frac{k_2}{2} x^2 \quad (6)$$

The k_2 term, which depends on constructive tolerances, has to be chosen in order to have no significant effect on the beam dynamic.

To this aim we have used a tracking code (MULTITRANS [4]) in which the sextupole effect is treated as a series of thin lenses along the magnet.

Fig. 7 shows the tracking results at the hodoscope plane with and without sextupolar terms. The straight lines in the figures represent the best fit.

No significant effects are observed if we construct the magnets with the following field uniformity.

Pulsed magnet:

$$\frac{\Delta B}{B} = -0.2 \% \quad @ \quad x = \pm 2.5 \text{ cm} \quad (7)$$

Spectrometer magnet:

$$\frac{\Delta B}{B} = -0.2 \% \quad @ \quad x = \pm 4.0 \text{ cm} \quad (8)$$

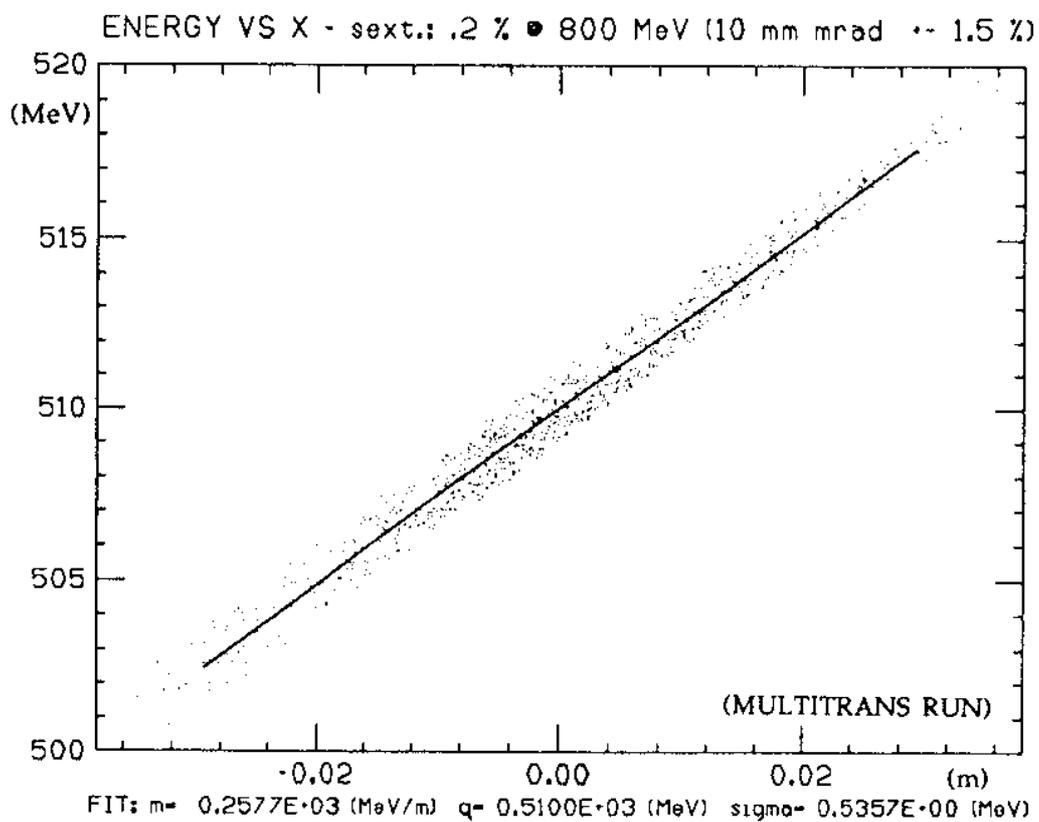
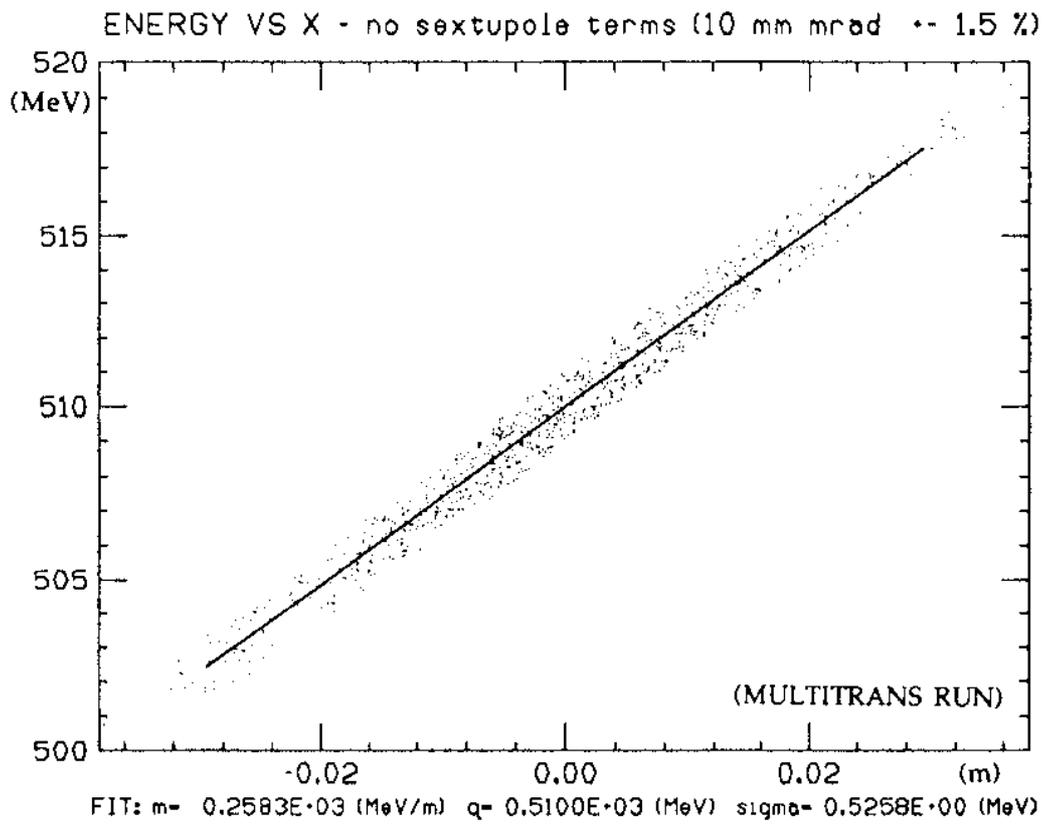


Figure 7 : Beam @ the hodoscope plane.

Another effect to analyze is the second order aberration. To the first order development, the horizontal position is given by:

$$x = C x_0 + S x_0' + D \frac{\Delta p}{p}$$

but for a more accurate analysis we have to take into account the second order terms (those proportional to x_0^2 , $x_0'^2$, $x_0 x_0'$, $x_0 \Delta p/p$, etc.). For a bending magnet the most important one is the $x_0'^2$ term. It can be shown [5] that this term vanishes if

$$\rho \left(\frac{k_1}{R_1} + \frac{k_2}{R_2} \right) = C_1 + C_2 \tag{9}$$

where

$$\frac{1}{k_{1,2}} = \cos^3 \gamma_{1,2} \left[1 + \left(\frac{\rho}{S_{1,2}} + \text{tg } \gamma_{1,2} \right)^2 \right]^{3/2} \tag{10}$$

and

$$C_{1,2} = \frac{\rho^2 \left(\frac{\rho}{S_{1,2}} + 3 \text{tg } \gamma_{1,2} \right)}{S_{1,2}^2 \left[1 + \left(\frac{\rho}{S_{1,2}} + \text{tg } \gamma_{1,2} \right)^2 \right]^{3/2}} \tag{11}$$

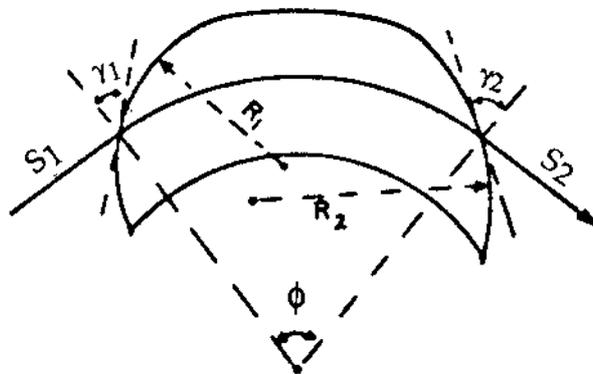


Figure 8: Second order aberration for a bending magnet.

In order to have a shape as close as possible to a standard sector magnet, we can set $\gamma_1 = \gamma_2 = 0$ (see Fig. 8). The (10) and (11) become:

$$k_{1,2} = \frac{S_{1,2}^3}{\left(S_{1,2}^2 + \rho^2\right)^{3/2}} \quad (12)$$

$$C_{1,2} = \frac{\rho^3}{\left(S_{1,2}^2 + \rho^2\right)^{3/2}} \quad (13)$$

In DLS configuration the object is at infinite distance from the magnet and the image is at its focus F ($S_1 = \infty$, $S_2 = F$), thus:

$$k_1 = 1 \quad k_2 = \frac{F^3}{\left(F^2 + \rho^2\right)^{3/2}}$$

$$C_1 = 0 \quad C_2 = \frac{\rho^3}{\left(F^2 + \rho^2\right)^{3/2}}$$

by (7)

$$\rho \left[\frac{1}{R_1} + \frac{F^3}{R_2 \left(F^2 + \rho^2\right)^{3/2}} \right] = \frac{\rho^3}{\left(F^2 + \rho^2\right)^{3/2}}$$

Let us put $R_1 = R_2 = R$ in order to have a symmetric magnet. Since $F = \rho \cotg \phi$, we obtain with some algebra:

$$R = \rho \left[\left(1 + \cotg^2 \phi \right)^{3/2} + \cotg^3 \phi \right] \tag{14}$$

By assuming:

$$\rho = 1.723 \text{ m} \qquad \phi = \pi/3$$

we get:

$$R = 2.984 \text{ m}$$

In conclusion, in order to eliminate the aberration, the magnet faces have to be circular shaped (see Fig. 8) with $\gamma_1 = \gamma_2 = 0$ and $R_1 = R_2 = R = 2.984 \text{ m}$ (physically, this correction corresponds to introduce a sextupolar field term). This means that with a half pole width of 4 cm we will have a sagitta h (between the straight shape of the standard magnet and the circular shape of the one without aberration) of 0.27 mm.

This small value indicates that the effect of the aberration is surely negligible, therefore we can build a standard sector magnet.

Table 4 shows the bending magnets parameters.

Table 4 - Bending magnets parameters

	Type	Radius (m)	(rad)	Magnetic Length (m)	Stay clear zone		Field Uniformity* B/B (%) @ ± x (cm)
					Gap (cm)	Width* (cm)	
Pulsed magnet	H or C par. faces laminated	6.0	.1138	0.63	3.5	± 2.5	-0.2 @ ± 2. (with .44 T @ 800 MeV)
Spectr. magnet	H sector solid	1.723	/3	1.804	3.0	± 4.0	-0.2 @ ± 4.0 (with 1.55 T @ 800 MeV)

* with respect to the central trajectory.

REMARK. To avoid magnetic flux dispersion on the beam line due to the spectrometer magnet, it should be necessary to put a shield between the magnet and the beam path.

2.3 DLS hodoscope

To achieve the resolving power indicated in table 2, a proper hodoscope has to be built.

If we choose to optimize the resolution for positron beam ($\epsilon = 10$ mm mrad, $\frac{\Delta E}{E} = \pm 1.5\%$), the resolution for the electron beam will be worst.

In order to avoid this problem we suggest a "two resolution hodoscope" (see Fig. 9).

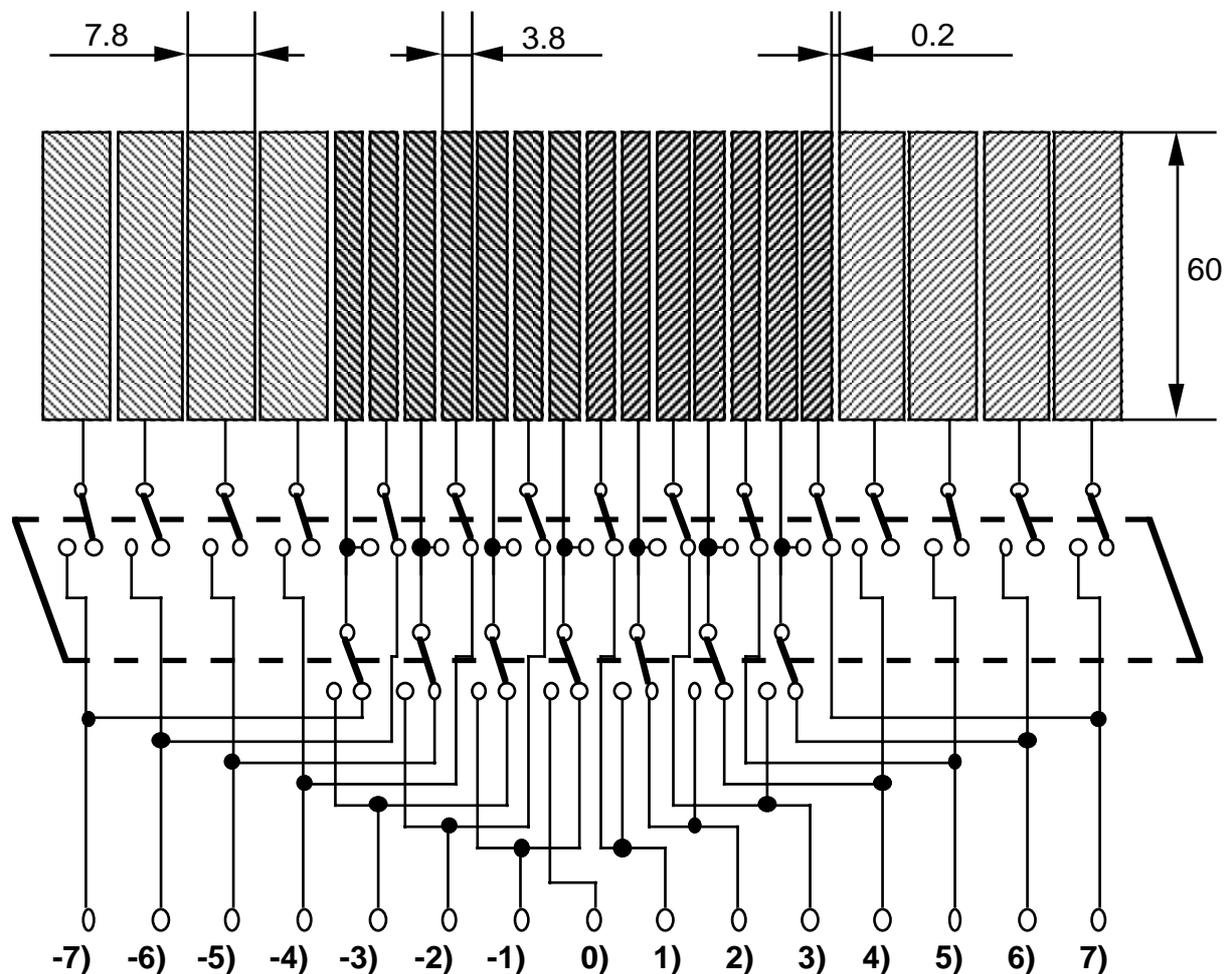


Figure 9 : Two resolution hodoscope.

By switching in the high resolution mode we obtain this configuration

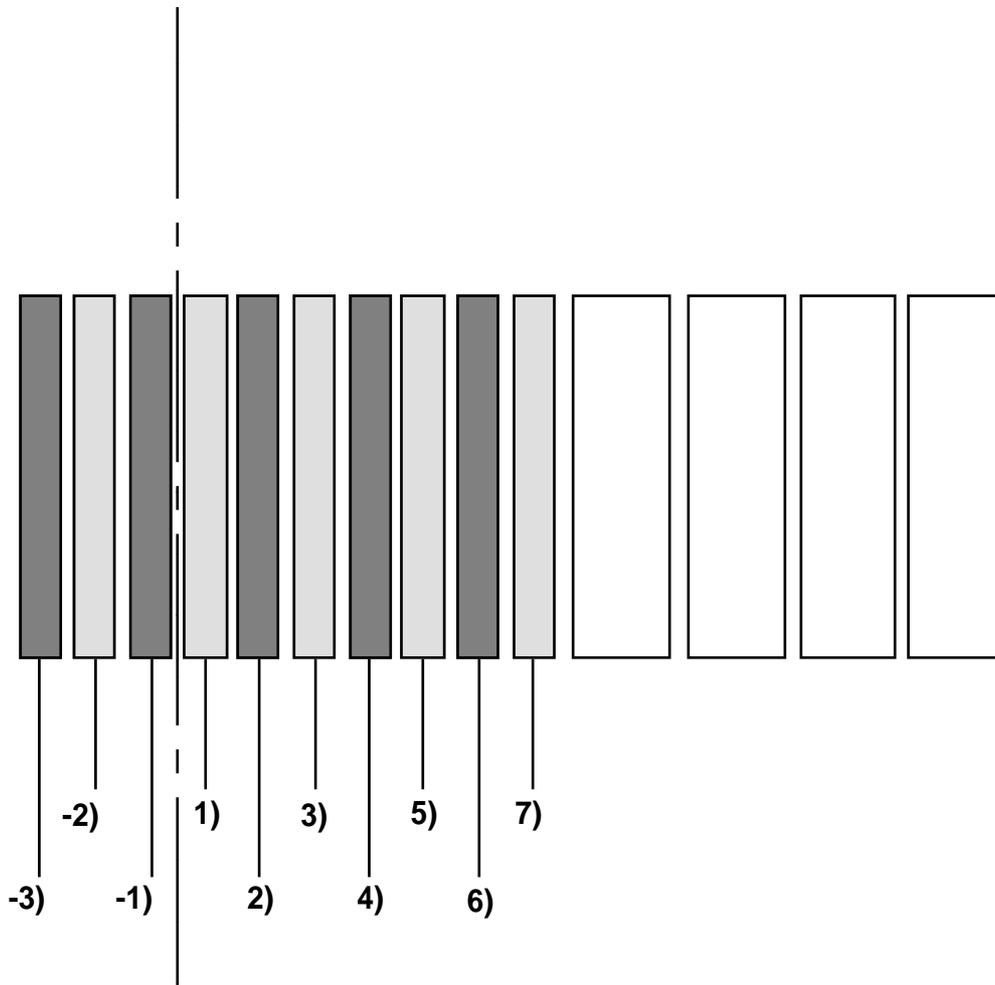


Figure 10 : hodoscope high resolution mode.

Table 5 - hodoscope high resolution mode

Channel*	Position (mm)	Energy (% of central energy)
1)	0 ÷ 4	0.1 ± 0.1
2)	4 ÷ 8	0.3 ± 0.1
3)	8 ÷ 12	0.5 ± 0.1
4)	12 ÷ 16	0.7 ± 0.1
5)	16 ÷ 20	0.9 ± 0.1
6)	20 ÷ 24	1.1 ± 0.1
7)	24 ÷ 28	1.3 ± 0.1

* The 'negative' channels have changed sign values.

or in the low resolution mode

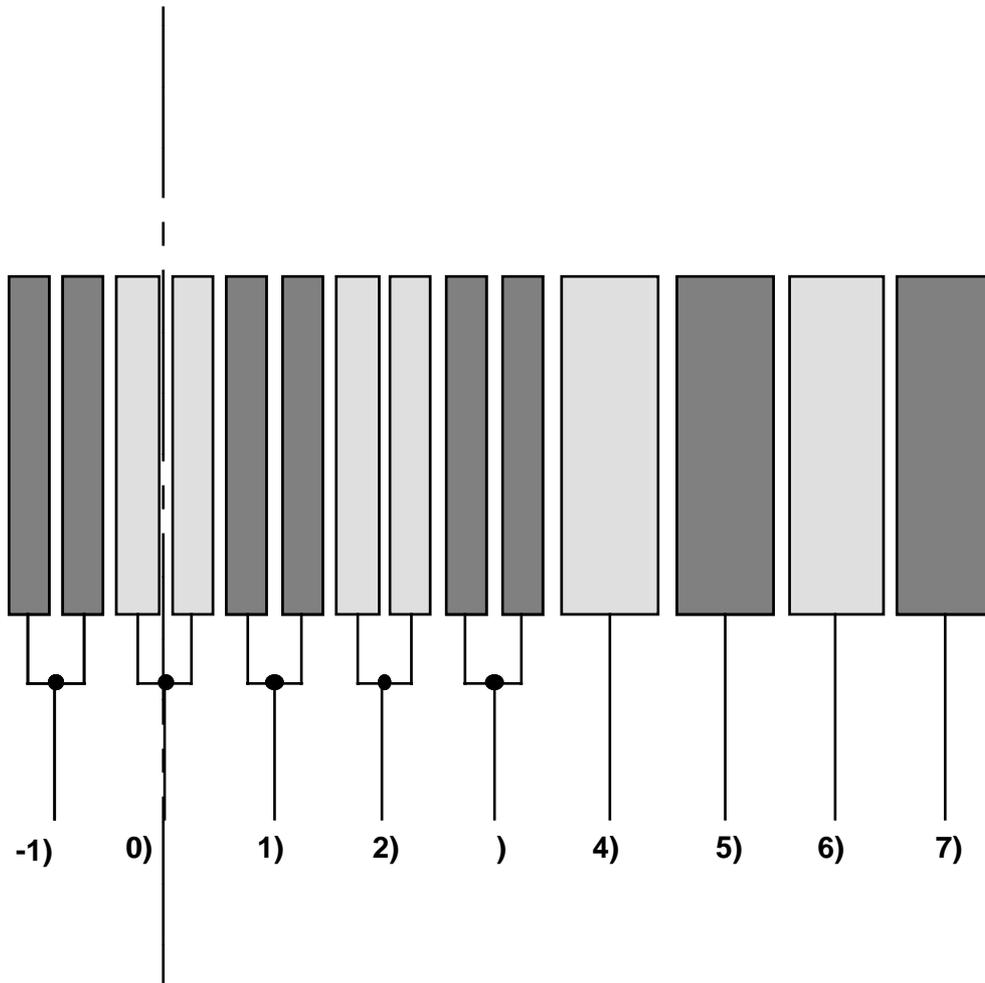


Figure 11 : hodoscope low resolution mode.

Table 6 - hodoscope low resolution mode

Channel	Position (mm)	Energy (% of central energy)
0)	- 4 ÷ 4	0.0 ± 0.2
1)	4 ÷ 12	0.4 ± 0.2
2)	12 ÷ 20	0.8 ± 0.2
3)	20 ÷ 28	1.2 ± 0.2
4)	28 ÷ 36	1.6 ± 0.2
5)	36 ÷ 44	2.0 ± 0.2
6)	44 ÷ 52	2.4 ± 0.2
7)	52 ÷ 60	2.8 ± 0.2

* The 'negative' channels have changed sign values.

As it is well known an hodoscope use the electron secondary emission of the metallic stripes, which is, to a good approximation proportional to the primary current (beam bunches).

If we want to measure currents down to 1 mA, by assuming the ratio between the secondary and primary currents equal to 5 %, we will get a secondary current of $\sim 50 \mu\text{A}$.

The ± 1 % energy spread will be within five hodoscope stripes, therefore by assuming (for a rough estimate) an uniform current distribution, we will have in every stripe a minimum current value of

$$i_{\min} = 10 \mu\text{A}$$

If this current flows through a 50Ω resistance it will generate a voltage:

$$V_{\min} = 0.5 \text{ mV}$$

This value can be increased if we sum the voltage caused by many beam bunches. Of course in this case we will obtain the mean value over these bunches.

Every hodoscope channel must have electronics able to treat this minimum value and also the maximum one which will be about 200 times larger:

$$V_{\text{MAX}} = 100 \text{ mV}$$

The possibility of constructing a more sophisticate hodoscope is under study. We are analyzing the possibility of using scintillating optic fibers and photomultipliers, instead of metallic targets. This solution should ensure an improvement in terms of velocity, temporal precision and insensitivity to magnetic fields.

2.4 Pulsed power supply

The pulsed magnet will have a resonant circuit type power supply. Figure 12 shows a schematics of the circuit.

It uses a switching power supply to charge the capacitor. A semiconductor controlled rectifier will allow the capacitor to discharge on the magnet coil. The diode D allows the energy recovery. The commutation from the electron to positron mode can be easily obtained by dephasing of π the SCR trigger.

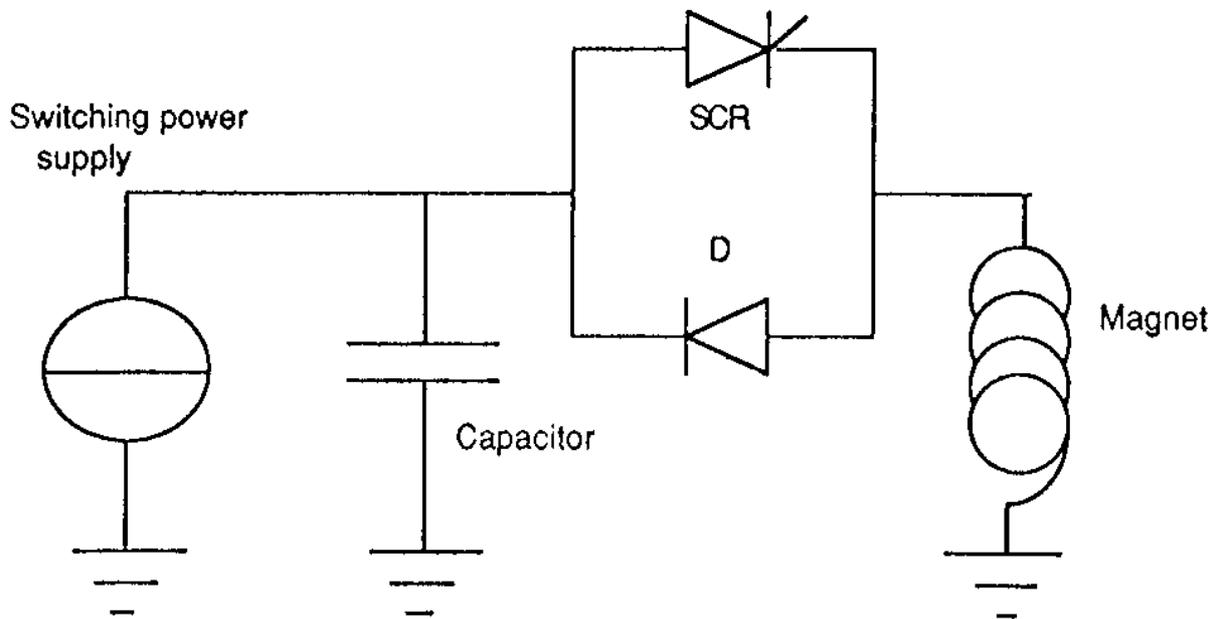


Figure 12 : Pulsed magnet power supply.

Let us calculate the circuit parameters. The magnetic volume of the magnet is given by:

$$V_m = (L + g) g w$$

where L is the magnetic length, g the gap height and w the pole width. The sum in parenthesis take into account the fringe fields.

By using the values of Table 4 and by assuming, for an estimate, w = 9 cm, we get:

$$V_m = 2.1 \times 10^{-3} \text{ m}^3$$

The energy stored in the circuit is given by

$$E = \frac{B^2 V_m}{2 \mu_0} = \approx 161 \text{ joules} \tag{15}$$

for B = 0.44 T @ 800 MeV.

This energy will be stored in the magnet coil, so this must have an inductance

$$L = \frac{2E}{I^2} \quad (16)$$

but

$$NI = \frac{B g}{\mu_0}$$

If we assume $N = 12$, we get:

$$I \approx 1020 \text{ A} \quad (17)$$

by substituting (17) and (15) into (16), we get:

$$L \approx 309 \mu\text{H} \quad (18)$$

In order to match the 50 Hz Linac operation, we assume the resonant period of the circuit $T = 10 \text{ ms}$ and the repetition rate equal to 1 Hz, therefore the capacitor will have a value

$$C = \frac{1}{L \omega^2} = \left(\frac{T}{2\pi}\right)^2 \frac{1}{L} \cong 8.2 \text{ mF} \quad (19)$$

To reduce power losses the magnet will be laminated. The total losses are given by the sum of the losses in the iron, eddy currents in the vacuum chamber and Joule effect.

We have for each Kg of iron a loss of [6]

$$\frac{P_{iron}}{Kg} = C_h B^{1.6} \left(\frac{v}{50}\right) + C_p \left[\delta B \left(\frac{v}{50}\right)\right]^2$$

where

- C_h = hysteresis coefficient = 2.3
- C_p = eddy currents coefficient = 4.8
- v = resonance frequency
- δ = thickness of the sheets in mm

if $\delta = 0.3 \text{ mm}$

$$\frac{P_{iron}}{Kg} \cong 1.57 \text{ W/Kg} \quad (20)$$

Let us assume for a rough estimate, the magnet as a parallelepiped with a volume

$$V = (0.35 \times 0.45 \times 0.63) \times 0.7 \approx 0.07 \text{ m}^3$$

where the 0.7 factor take into account the gap and the coil room. The specific weight of iron is about 7.86 ton/m³ thus the weight of the magnet is

$$W \approx 550 \text{ Kg}$$

and by (20)

$$P_{iron} \approx 0.860 \text{ KW} \quad (21)$$

The eddy current losses in the vacuum chamber can be calculated through the formula

$$\frac{P_{ec}}{Kg} = \frac{\omega^2 B^2 w^2}{24 \rho \gamma}$$

where ρ is the resistivity of the chamber material and γ its specific weight.

Thus for a stainless steel chamber ($\rho=1 \mu\Omega/\text{m}$, $\gamma = 7.86 \text{ ton}/\text{m}^3$)

$$\frac{P_{ec}}{Kg} \cong 3.3 \text{ KW}/\text{Kg} \quad (22)$$

If we assume the chamber as a stainless steel pipe with 4 cm height, 5 cm width, 0.7 m length and 2 mm thickness, we obtain a volume of about $2.5 \times 10^{-4} \text{ m}^3$ and consequently a weight of about 2 Kg.

By using (22) we get

$$P_{ec} \approx 6.6 \text{ KW} \quad (23)$$

To calculate the Joule effect losses we must evaluate the resistance of the magnet coil:

$$R = \frac{N \rho l}{S}$$

but

$$l \approx 2(w + L) \approx 1.6 \text{ m}$$

for copper $\rho = 0.018 \mu\Omega \text{ m}$, and using a conductor with square section of 8.3 mm side and with an inner hole of 5.2 mm diameter ($S \approx 48 \text{ mm}^2$)

$$R \approx 7.3 \text{ m}\Omega$$

By using this value and the (17) we obtain for the Joule effect losses

$$P_{je} = R \left(\frac{I}{\sqrt{2}} \right)^2 \approx 3.8 \text{ KW} \quad (24)$$

Finally the total losses are, using (21) (23) and (24)

$$P = P_{iron} + P_{ec} + P_{je} \approx 11.3 \text{ KW} \quad (25)$$

The energy lost in every shoot is

$$\Delta E = P T \approx 110 \text{ joules}$$

Therefore the switching power supply has to charge the capacitor up to a voltage

$$V_C = \sqrt{\frac{2(E + \Delta E)}{C}} \approx 257 \text{ V}$$

2.5 DLS features summary

- **Mode of operation:** ON LINE. One measured bunch every fifty.
(The DAΦNE-LINAC repetition rate is 50 Hz)
- **Measurable beams:** Energy up to 800 MeV
Emittance up to 10 mm mrad

The hodoscope allows two different resolution modes

- **High resolution mode.** Used with beams with emittance up to 1 mm mrad (DAΦNE-LINAC electron beam)

$$\delta E/E = \pm 0.1 \% \qquad \text{max energy spread} = \pm 1.3 \%$$

- **Low resolution mode.** Used with beams with emittance in the range 1÷10 mm mrad (DAΦNE-LINAC positron beam)

$$\delta E/E = \pm 0.2 \% \qquad \text{max energy spread} = \pm 2.8 \%$$

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