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LNF-90/024(R)
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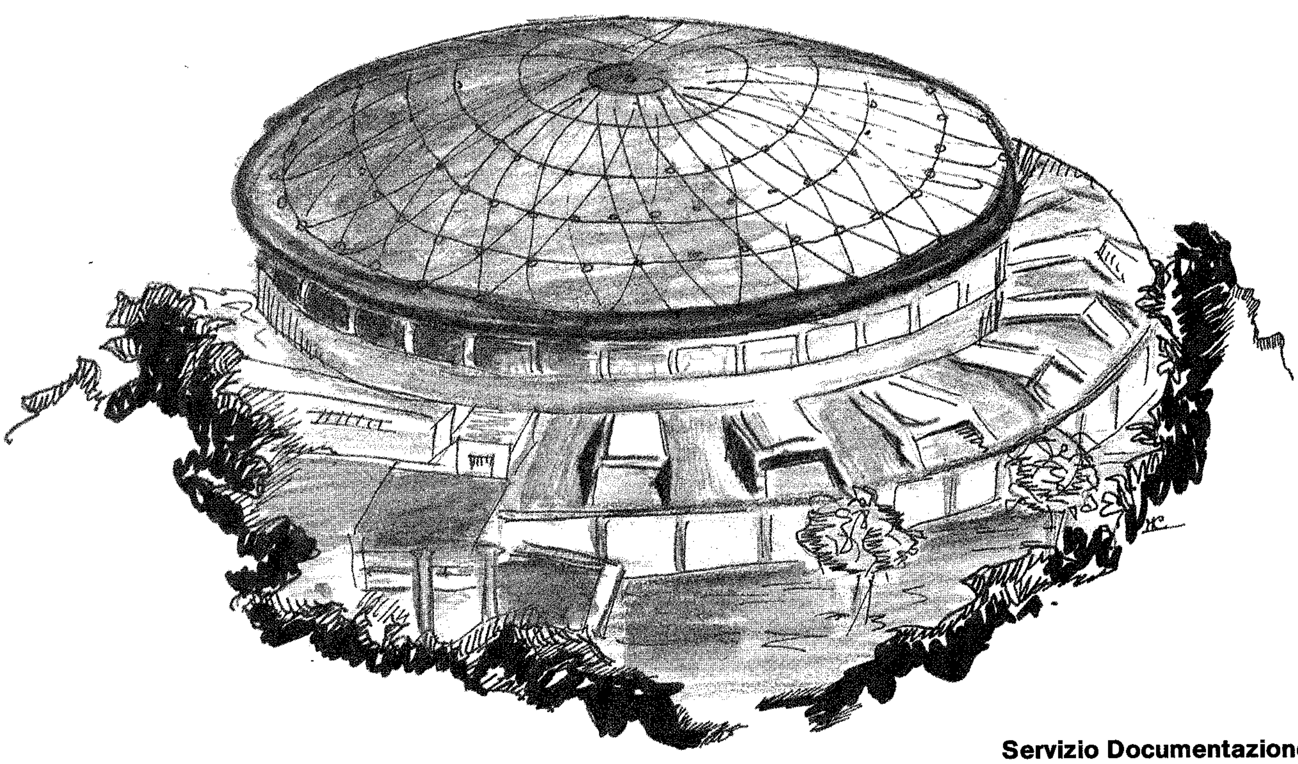

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BUNCH LENGTH MEASUREMENT SYSTEM IN THE INJECTOR SECTION OF THE SC LINAC LISA

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ABSTRACT
The possibility of measuring the length of the electron bunch (of the order of 3 mm) in the low energy spectrometer channel of the SC Linac LISA is considered. A RF cavity with vertically deflecting field has been designed which maximizes the ratio between deflecting angle and RF power. The result of a simulation shows the effectiveness of this solution as a diagnostic tool for the correct setting of the injector elements.

1. - INTRODUCTION

The bunch length in a RF electron Linac is normally very short due to the requirement of reducing the energy spread induced by the accelerating field change along the bunch itself. This is even more true when the beam must be used for the production of coherent electromagnetic radiation in a Free Electron Laser. In this case the optical gain which can be achieved in the passage of the beam through a magnetic undulator is proportional to the electron peak current, and much care has to be taken to keep the electron bunch as short as possible along all the acceleration stage. Although a magnetic compression is in principle possible at the final energy, it would introduce an unwanted energy spread and would require an additional large RF power. This is the main reason why the bunch length compression is normally performed at low beam energy.

The bunch length being one of the most critical and easily degraded parameters, it is important not only to measure it, but also to keep it under constant periodic control.

In the LISA superconducting linac [1], a 25 MeV accelerator in construction in the Frascati National Laboratory, whose aim is the implementation of an infrared high power, high efficiency, Free Electron Laser, the bunch compression required to obtain the desired peak current is performed in the injection section [2].

The bunch length measurement is done along the transport channel to the SC linac, exploiting the presence of a spectrometer line through which the beam can be deflected by means of a pulsed magnet.

A vertically deflecting RF cavity gives an angular kick to the electrons depending on their position along the bunch, causing a vertical widening of the electron spot on the spectrometer screen proportional to the bunch length.

In Section 2 we give a brief description of the injector and of the transport channel. In Section 3 we discuss the variation of the optical element values required by the bunch length measurement. In Section 4 the design of the deflecting cavity is fully described, while in Section 5 the simulated performance of the whole system is presented.

2. - THE LISA INJECTOR

The electron beam is produced in a DC 100 kV thermionic gun, in 10 Hz, 1 ms long macropulses during which the emitted current is 120 mA.

A double chopper system cuts the beam in micropulses, lowering the average current (along the macropulse) to 2 mA, distributed in bunches of 50 MHz repetition frequency.

A prebuncher (a 500 MHz cavity) gives to the bunches the energy spread necessary to shrink the bunch length to a few millimetres before the injection in the capture section, a 2500 MHz normal conducting graded β linac.

In this linac the beam is accelerated to 1.1 MeV, and then π-bent to be injected into the superconducting linac (SC) .

A schematic layout of the injector from the gun to the capture section is shown in Fig. 1, while the optic of the arc to the SC linac is shown in Fig. 2.

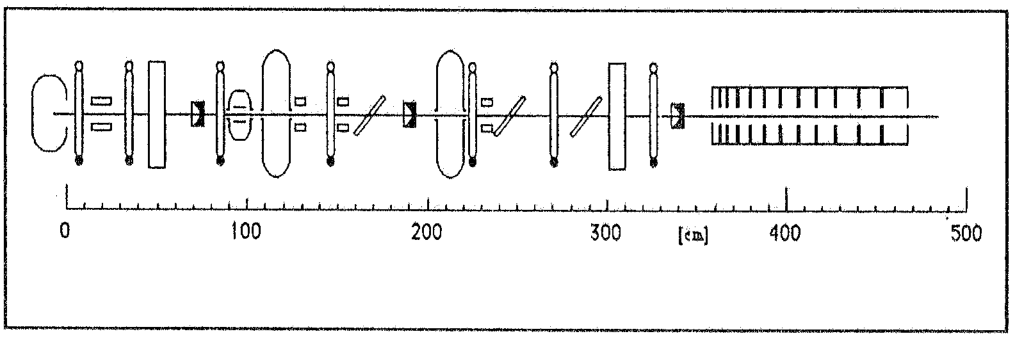

FIG. 1 - Layout of the low energy injection section.

The transport line from the capture section to the SC linacs is achromatic and isochronous. The bending is obtained with three bends ($\pi/4$, $\pi/2$, $\pi/4$) and two symmetric quadrupole doublets which adjust the dispersion function to the isochronism condition; two quadrupole triplets in front and after the arc take care of the matching between the linacs and the arc itself.

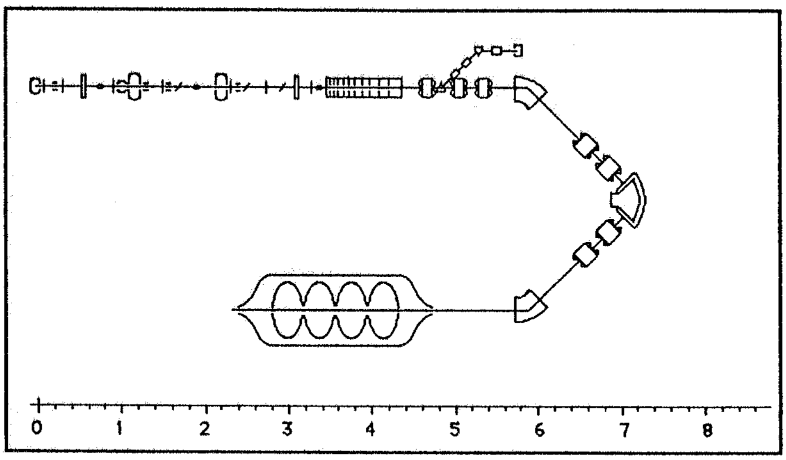

FIG. 2 - Layout of the whole injection system.

In the matching line between the capture section and the arc, a pulsed magnet can deviate the beam to the spectrometer. The pulse timing is such that a single macropulse can be extracted, or the whole beam derived to the spectrometer arm.

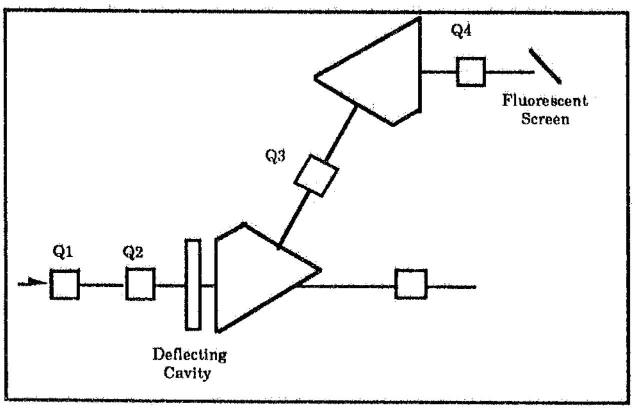

FIG. 3 - Spectrometer layout.

As is shown in Fig. 3, the spectrometer consists of two 60° sector bending magnets and two defocussing quadrupoles. The beam dimensions are analyzed on a fluorescent screen.

In the normal running condition, in which the beam is carried to the SC, and only a sample periodic macropulse is derived to the spectrometer for survey purpose, the first two quadrupoles in the transport channel and the two ones in the spectrometer are set at the values of Table I.

Table I - Quadrupole setting for the standard optics.

Quad	K^2
Q1	-35.14
Q2	30.88
Q3	- 6.08
Q4	-24.57

This setting is designed to satisfy the conditions required by the transport channel and to optimize the energy resolution of the spectrometer.

The behaviour of the optical functions along the transport channel is shown in Fig. 4.

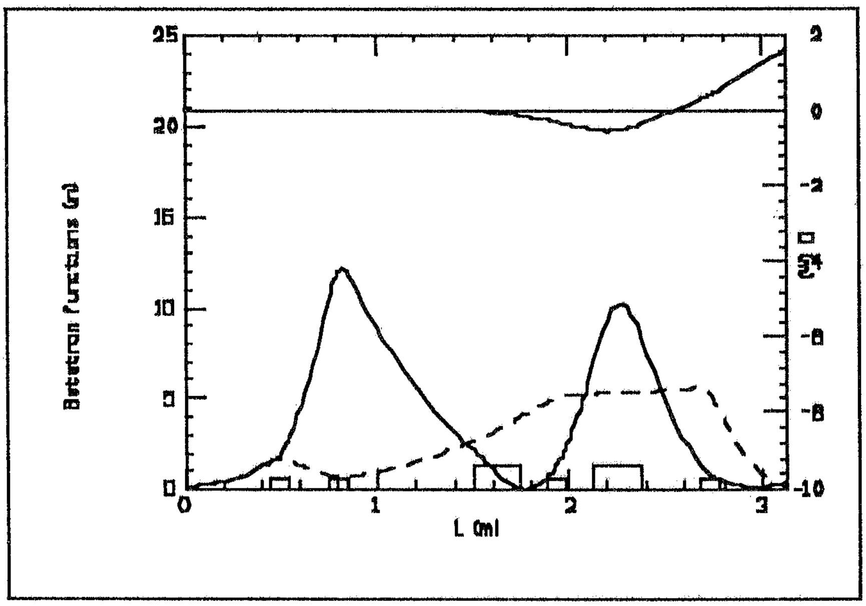

FIG. 4 - Vertical Optical Functions along the transport channel.

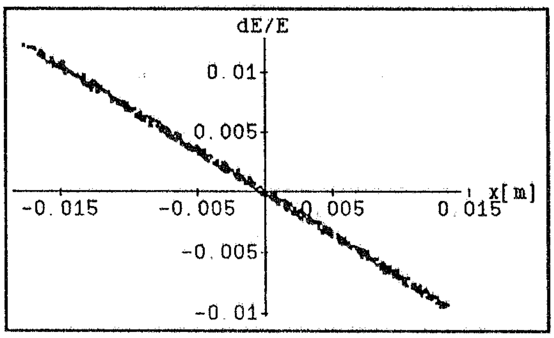

FIG. 5 - Horizontal position on the spectrometer screen versus energy spread.

Table II - Beam parameters at the capture section output; the optical functions are equal in both planes.

α	0
β	.1 m
ε_n	10^{-5} m rad
$\Delta E/E$	2%
l	3 mm

The result of a simulation, in which a number of particles with energy spread and transverse phase space as foreseen at the capture section output (see Table II) is tracked along the spectrometer, is shown in Fig.5 where the horizontal position on the screen for each particle is plotted versus its energy deviation from the nominal one.

3. - TRANSPORT CHANNEL OPTICS FOR THE BUNCH LENGTH MEASUREMENT

The use of a deflecting cavity to measure the bunch length is effective only if the cavity itself is inserted before the pulsed magnet. In fact after this magnet the different length of electron paths due to their energy spread will dominate over the original position along the bunch, making the length measurement impossible.
The cavity has been thus inserted just before the pulsed bending magnet, as shown in Fig.4.

The performance of this measurement is also strongly conditioned by the transverse phase space distribution of electrons inside the deflecting cavity, and by the optics of the spectrometer channel. Indeed the head-tail angular spread induced on the bunch in the cavity must be much larger than the natural beam divergence, and the spot size on the spectrometer target due to this angular spread must be larger than the natural spot size of the beam (i.e. without the deflecting cavity).

The maximum head-tail angle which can be realized on a bunch of 3 mm length, which is the value foreseen at the output of the capture section, is limited by the RF power that can be injected into the deflecting cavity. As it will be shown in more detail in next paragraph, for practical reasons the maximum deflecting angle realistically obtainable on a bunch of 1.1 MeV is of the order of ± 2 mrad.

With the standard optics setting of Table I, this angular spread is not large enough to make possible the bunch length measurement. In fact a particle tracking simulation, supposing the deflecting cavity inserted just before the pulsed magnet, gives the result of Fig. 6, in which the vertical coordinate of each particle on the spectrometer screen is plotted versus its original position along the bunch.

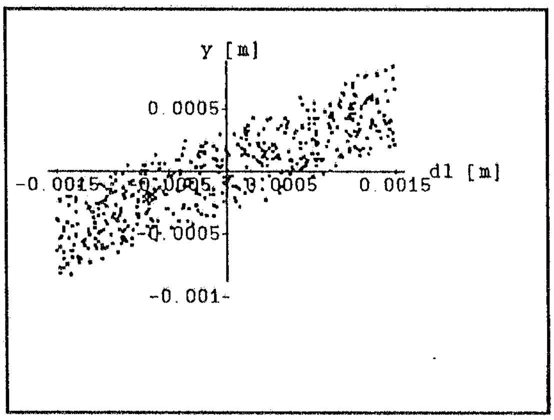

FIG. 6 - Vertical displacement on the spectrometer screen as function of position along the bunch with standard optics

Although a correlation between position along the bunch and vertical coordinate on the screen is visible, the signal to noise ratio is too small to make the length measurement possible. Indeed, according to the simulation, the rms vertical width of the spot, with and without the deflecting cavity, is respectively .35 mm and .18 mm, to be compared to the horizontal rms width of 8.4 mm. Because the whole spot must be focalized on the CCD matrix that performs the data acquisition, the precision of the vertical dimension measurement would result intolerably low.

On the other hand, if we give up the requirement of an on line diagnostic tool, and we accept that with the deflecting cavity operating the beam will be always derived into the spectrometer arm, we can change the setting of all quadrupoles, even the ones of the transport channel.

Table III - Quadrupole setting for the new optics.

Quad	K^2
Q1	25.42
Q2	-19.89
Q3	-10.10
Q4	19.68

In this way a new optics can be designed, reducing the sensitivity to the energy spread, but allowing a much higher sensitivity in the bunch length measurement. This new set of quadrupoles values are shown in Table III, while the behavior of the optical functions can be seen in Fig. 7.

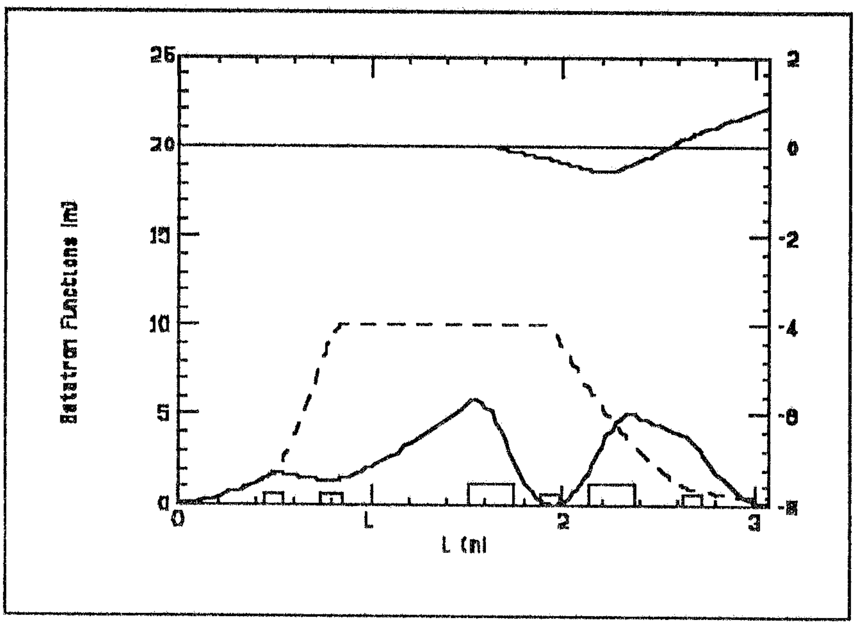

FIG. 7 - Vertical Optical Functions along the spectrometer channel.

As already stated, with this optics the sensitivity of the energy spread measurement is slightly decreased, as can be seen in Fig. 8, but the correlation between the position along the bunch and the vertical coordinate on the spectrometer screen is largely increased. The vertical spot width becomes also larger, making the measurement of the whole spot much easier.

The result of the simulation with the deflecting cavity on is shown in Fig. 9.

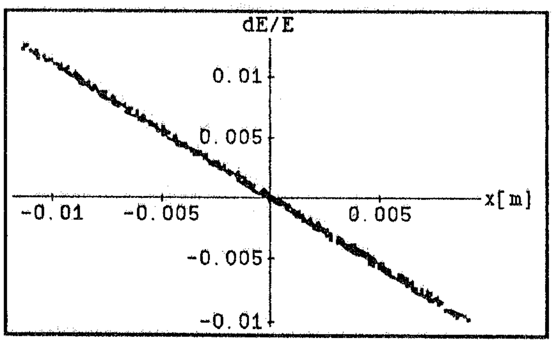

FIG. 8 - Horizontal position on the spectrometer screen versus energy spread with the new optics

In this case the rms vertical width of the spot on the screen with deflecting cavity on or off is respectively 2.2 mm and .54 mm, to be compared with the horizontal rms width of 5.4 mm. It is thus clear that the bunch length is measurable with a good accuracy.

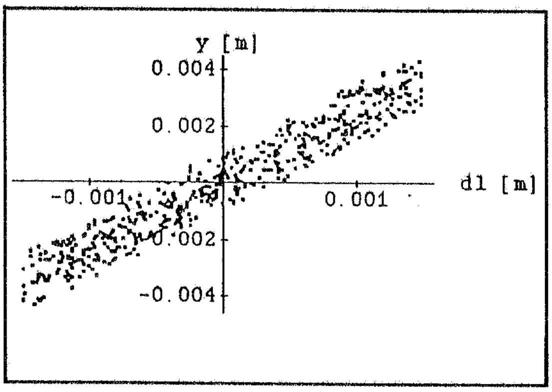

FIG. 9 - Vertical displacement on the spectrometer screen as function of position along the bunch with the new optics

4. - DEFLECTING CAVITY AND PROPOSED RF SYSTEM

A sketch of the deflecting cavity is shown in Fig. 10. It is a rectangular resonator operating in TM_{210} mode as the 500 MHz chopper of the LISA injector. TM_{210} configuration shows a maximum deflecting magnetic field and a vanishing electric field on the beam axis and therefore is the best suitable mode to achieve the required beam deflection.

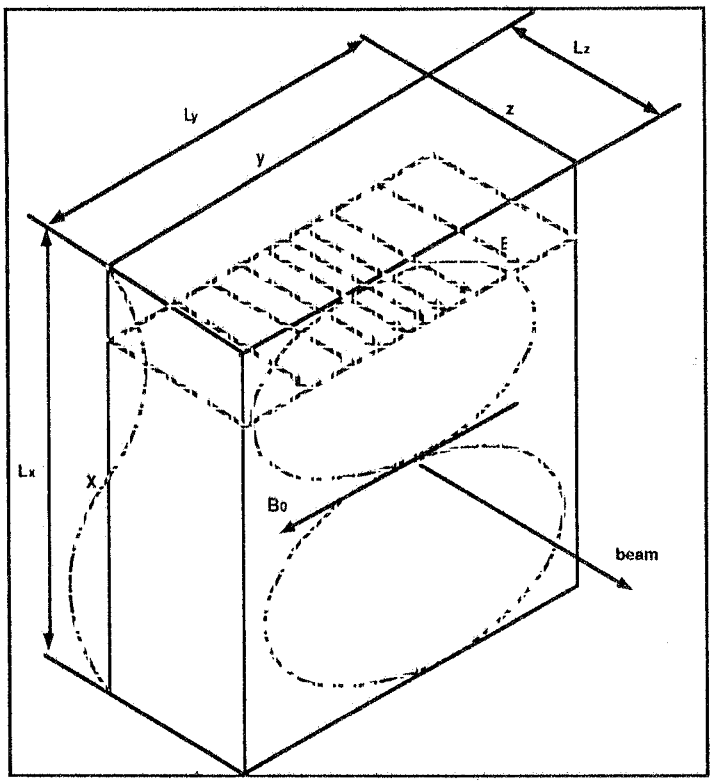

FIG. 10 - TM210 mode in a rectangular resonator.

If the centre of a bunch particle crosses the centre of the cavity gap with a null deflecting field, the head and the tail of the bunch will be deflected by equal and opposite angles, accordingly to the following formula:

$$\Delta\phi_B = \left(\frac{v_x}{\beta c}\right)_{out} \approx \frac{eB_0}{m\beta c} L_B \sin\left(\frac{\pi L_z}{\beta\lambda}\right) \qquad (1)$$

where $\Delta\phi_B$ is the bunch head deflection with respect to the bunch centre, v_x is the transverse velocity of the bunch head at the end of the gap, L_B is the bunch length, e is the electron charge, m is the electron relativistic mass (at 1.1 MeV energy), βc is the electron velocity (at 1.1 MeV), L_z is the gap length and λ is the RF wavelength.

For a given cavity geometry, eq. (1) shows that the maximum magnetic field needed to obtain the required head-tail deflection does not depend upon the choice of the operating frequency. Therefore we firstly optimized the geometry of the deflecting cavity in order to minimize the input RF power and consequently we chose the most convenient operating frequency.

By combining eq. (1) with the usual expressions of the electromagnetic fields [3] one can obtain the RF power needed to produce the required deflection :

$$W_L = \frac{R_s}{2}\frac{\beta^2}{1-\beta^2}\left(\frac{m_0 c\lambda}{\mu e L_B}\right)^2 f_\eta(L_z/\lambda)\Delta\phi_B^{\,2} \qquad (2)$$

where Rs, which scales as the square root of the frequency, is the surface resistance of the resonator inner surface, μ is the vacuum permeability, m_o is the electron rest mass, $\eta = L_x/L_y$ is the ratio between the transverse dimensions of the cavity and $f_\eta(L_z/\lambda)$ is a function defined as follows:

$$f_\eta(L_z/\lambda) = \frac{\eta^2+4}{4\eta^2} \frac{1}{\sin^2\left(\frac{\pi L_z}{\beta\lambda}\right)} \left[\frac{2\eta}{\sqrt{4+\eta^2}} (1+\eta^3/4)(L_z/\lambda) + \frac{1}{2}\eta(1+\eta^2/4) \right] \quad (3)$$

The required RF power is then proportional to the square of the deflection angle by means of a coefficient that depends on resonant frequency (by Rs and λ) and cavity geometry (by $f_\eta(L_z/\lambda)$).

The optimum geometry is defined by the values of η and L_z/λ corresponding to the minimum of the function $f_\eta(L_z/\lambda)$ (i.e. the minimum of the RF power for a given deflection) which occurs for $L_z/\lambda = 0.43$ and $\eta = 1.15$.

We remark that the Linac will operate at 500 MHz while the Capture Section of the injector will run at the 5th harmonic of the linac frequency. 500 MHz and 2500 MHz are then two possible working frequencies for the deflecting cavity.

The dimensions of a rectangular resonator for the minimum power dissipation are:

$$(L_x, L_y, L_z)_{500\ MHz} = (69\ cm,\ 60\ cm,\ 25.8\ cm)$$

at 500 MHz and :

$$(L_x, L_y, L_z)_{2500\ MHz} = (13.84\ cm,\ 12\ cm,\ 5.16\ cm)$$

at 2500 MHz.

In both cases the maximum required magnetic field is:

$$B_0 = 32.4\ Gauss$$

In conclusion, for an aluminium resonator, the dissipated RF power is respectively:

$$W_L(500\ MHz) = 11.9\ KW \quad W_L(2500\ MHz) = 1.06\ KW$$

In fact, as shown in eq. (2), the power losses scale as the frequency to -3/2.

A RF system operating at 2500 MHz is therefore cheaper (about a factor 4) then an equivalent 500 MHz system. We then propose the first one as deflecting device to measure the length of LISA bunches.

The RF power to produce the requested magnetic field (32.4 G) at 2500 MHz is 1 KW, but a margin should be available because the resonator will certainly dissipate more power then that calculated. Moreover a power margin will allow a more accurate bunch length measurement.

A block diagram of the proposed system is presented in Fig. 11. The power can be derived from the waveguide which connects the 2.5 GHz Capture Section with the 50 kW klystron source.

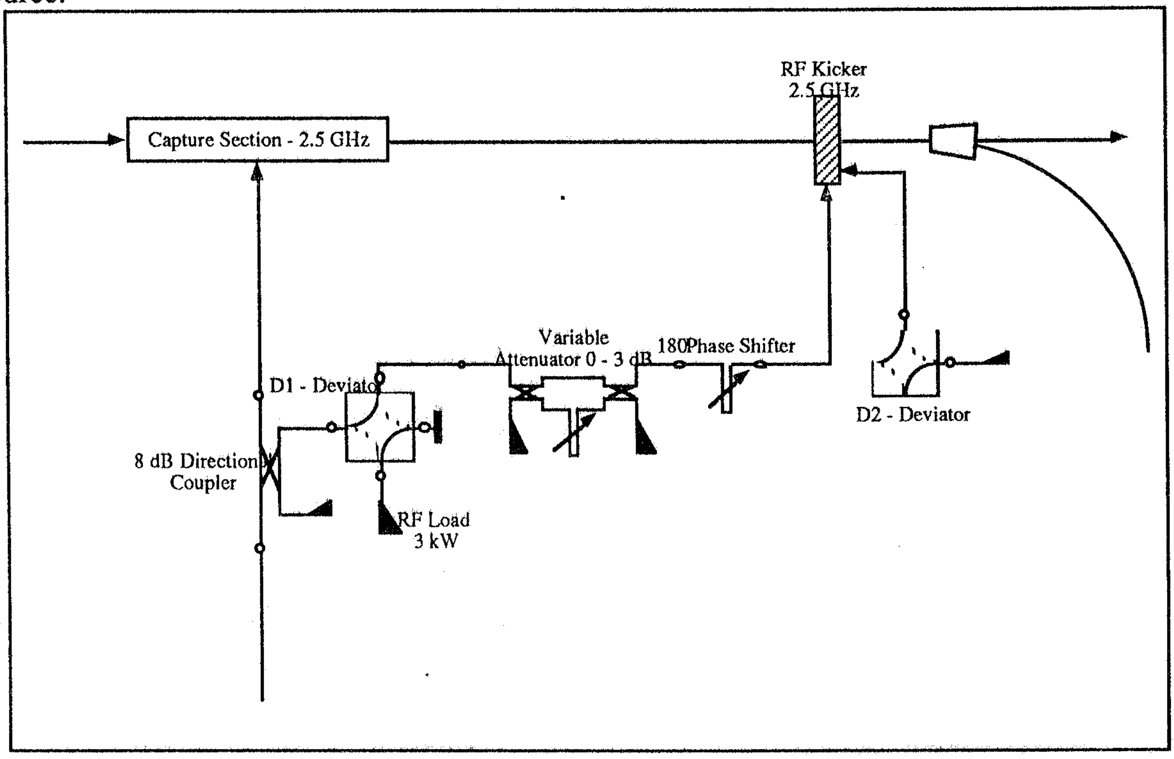

FIG. 11 - The deflecting cavity RF system.

An 8 dB directional coupler derives a suitable fraction of the power addressed to the Capture Section and a variable attenuator (0 to 3 dB) allows to vary the power flow to the deflecting cavity from 1.5 to 3 KW.

A half-wavelength continuously variable phase shifter is needed in order to set the correct phase relationship between the cavity and the other parts of the injector.

The switch D_1 will feed a 3 KW dummy load as long as the bunch length measurement will not be required and the linac will operate for the FEL. If necessary, an additional switch D_2 could be installed in the feeding chain to connect an external load through a low Q_{ext} port of the deflecting resonator for damping the wakefields induced by the bunches when the cavity is off to avoid possible and unwanted multibunch interactions.

Low power coaxial transmission lines (i.e 1-5/8" standard) can be used to connect the directional coupler with the deflecting cavity because of the short distances between them. This choice allows an additional reduction of the costs.

A pulsed operation is foreseen (2 msec on, 2% duty cycle) in accordance with that for the capture section. The average power flow to the cavity is therefore very low. The main cavity coupler will be a small antenna coupling to the electric field, like the 500 MHz Chopper cavity.

A tuning system is also foreseen, unless we'll decide to cool the cavity with the same water used for cooling the Capture Section to 38°C constant temperature.

In the following table the main parameters of the cavity are reported for a maximum deflecting magnetic field $B_0 = 40$ Gauss and two different metals that could be used for the cavity construction:

Table IV - main cavity parameters.

	Q_0	β_{loaded}	W_L
Al	17000	300 KHz	1650 W
Cu	22000	230 KHz	1200 W

5. - CONCLUSIONS

The results of the numerical simulation, although based on rather simplified assumptions, indicate the effectiveness of the described technique for the bunch length measurement at the end of the LISA injection system.

In this paragraph we will illustrate some more results of the simulation, supposing a deflecting angle in the cavity of 1.33 mrad/mm, and in particular the diagnostic capability of the whole system.

In Fig. 12 it is shown the rms vertical plane projection width of the beam spot on the spectrometer screen as function of the bunch length.

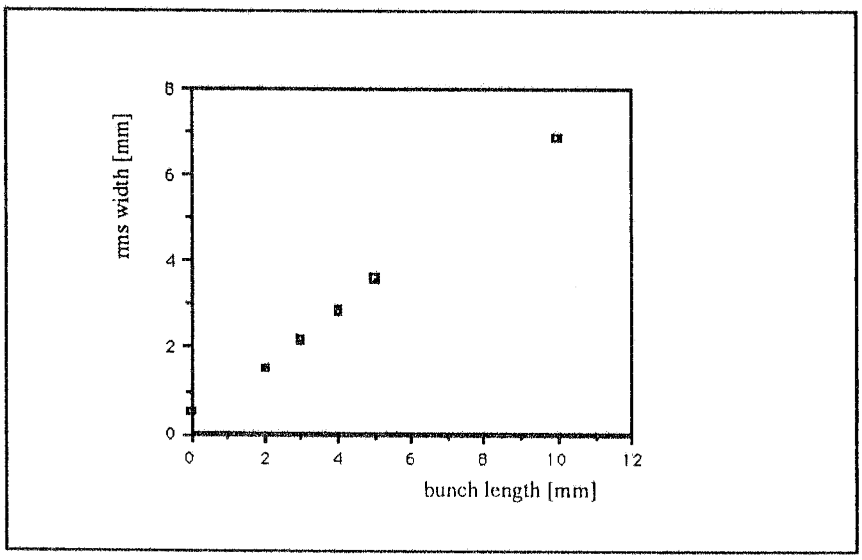

FIG. 12 - Rms vertical spot width versus bunch length.

For small longitudinal bunch dimension the correspondence between measurement and length is not linear due to the beam vertical emittance. The measured quantity is the quadratic mean between the width due to bunch length and the zero length width.

After the quadratic subtraction of this offset value, the measured width is a linear function of the bunch length, as shown in fig. 13.

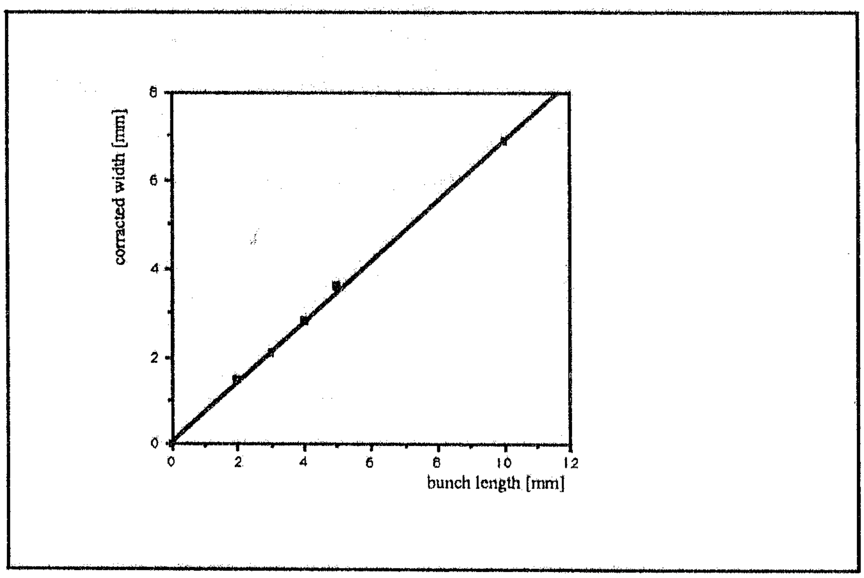

FIG. 13 - Vertical spot width after emittance correction versus bunch length.

The slope of this line is easily obtained by measuring the vertical position of the spot centre as function of the deflecting cavity phase. In this way we can have an absolute calibration of the bunch length measurement.

With the nominal optics used in the simulation, the results in Fig. 13 give the following relation between bunch length and rms width on the screen:

$$\frac{l_b}{w_{rms}} = 1.45$$

The full visualization of the longitudinal beam phase space in the spectrometer channel is also a powerful diagnostic tool for the correct phasing of the capture section with reguard to the prebuncher cavity. In fact an error in the phase angle of the capture section results in a reduced final beam energy, but only the longitudinal phase space analysis can give the sign of the phase angle error, as it is shown in Fig. 14.

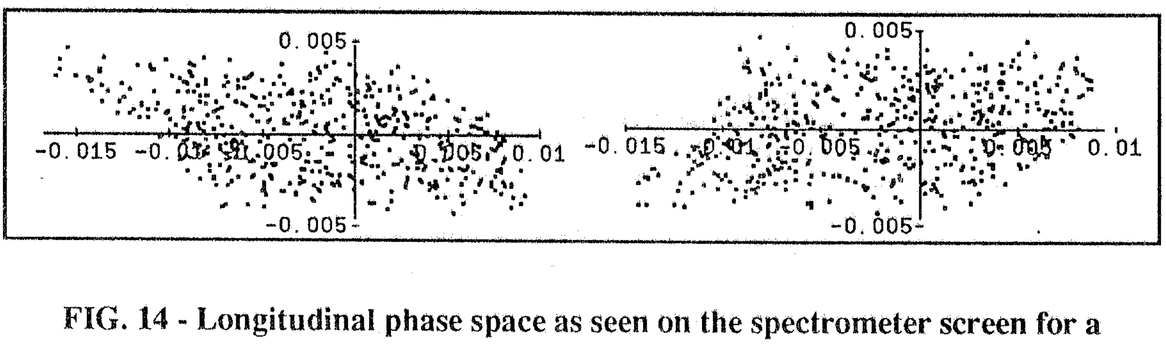

FIG. 14 - Longitudinal phase space as seen on the spectrometer screen for a phase error of ± 3° in the capture section.

In this figure, which is the representation of the beam spot on the spectrometer screen, both the coordinates units are meters, and while the horizontal axis is proportional to the energy spread (larger energy with larger x value), the vertical coordinate is proportional to the longitudinal position along the bunch (head of the bunch with more positive y value).

The two situations correspond to a phase error in the capture section respectively of +3° and -3°. The energy distribution of the whole bunch is identical in both cases, but the analysis of the complete longitudinal phase space shows that in the first case the bunch head received a smaller energy, while the inverse is true for the second case.

On the other side, it is obvious that the measurement of the longitudinal bunch charge distribution has a fundamental role in the diagnostics of the correct setting of the prebuncher cavity, which must be operated in such a way to give the highest possible peak current for the FEL operation.

All the previous simulation results have been obtained supposing a fully relativistic beam. In particular the bunch length has been assumed constant along the drift path between the capture section output an the deflecting cavity. But a 1.1 MeV kinetic energy beam has $\beta = .95$, so that a bunch length increase proportional to the energy spread will take place.

If no correlation between energy and longitudinal position is present at the end of the capture section, the bunch lengthening due to the energy spread combines quadratically with the natural length. With the beam parameters used in the simulation we obtain a 17% bunch lengthening. This number, which is already small enough to make the measurement effective, can be reduced taking advantage from the fact that higher energy electrons are less deflected than slower ones by the same magnetic field. A faster electron will reach a slower one started in an advanced position, but will be deflected by a smaller angle, partially compensating the speed difference.

To fully exploit this possibility, the phase of the deflecting cavity must be slightly changed in such a way that the whole bunch will encounter the magnetic field with the same sign, being deflected in the same direction.

In Fig. 15 is shown the spot on the spectrometer target either in the normal phase condition and with the required phase shift. It is clear that in the last case the correlation between energy and position is reduced, in fact the numerical results give a bunch lengthening of less than 8 %.

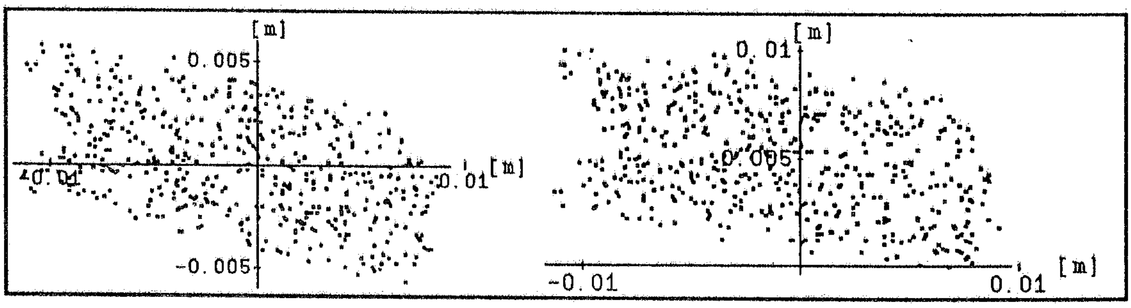

FIG. 15 - Spot on the spectrometer target without and with phase shift in the deflecting cavity.

In conclusion, the bunch length measurement performed along the spectrometer channel after the capture section is a unique diagnostic instrument for the correct phasing of all the RF elements of the injection system.

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