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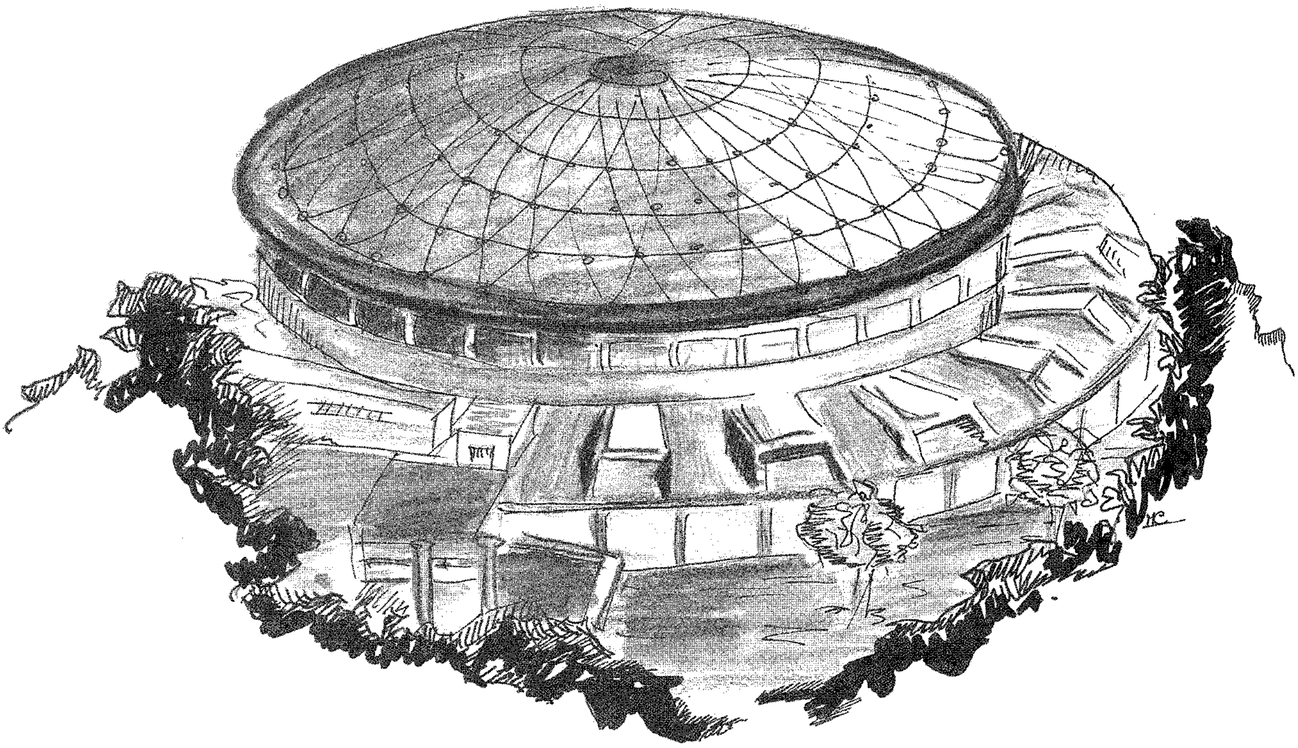

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STUDY OF LISA FEL OPERATION WITH PREBUNCHED BEAM

P. Patteri, M. Castellano, A. Ghigo
INFN, Laboratori Nazionali di Frascati, P.O. Box 13, 00044 Frascati (Italia)

ABSTRACT

A technique exploiting the high quality beam of the SC linac LISA to provide Coherent Harmonic Generation (CHG) at variable wavelength is presented. The wavelength shifting is obtained with pulse compression applied to an optically modulated beam. This technique provides also a gain enhancement both at the fundamental and harmonic wavelengths when a FEL is operated with prebunched beam.

1. INTRODUCTION

Superconducting linacs provide beams with low emittance and low energy spread, comparable with a storage ring beam. This performance can be exploited in a FEL whose operating mode resemble the Optical Klystron (OK) configuration [1] or in un Up Converter (UC) to provide CHG [2].

It is noteworthy that both OK and UC have been realized on storage rings [3] [4] while less attention has been paid to their operation on single pass devices. We presume this was due to the unsuitable performances of the standard linacs, but owing to recent improvements in linac beam quality, these configurations deserve more careful consideration. Moreover, few constraints apply in the design of the transport optics for single pass devices, so uncommon layout are feasible [5].

We present a Distributed Optical Klystron (DOK) in which the modulator and the radiator undulators are far apart, allowing separate optimization of the interaction regions. This disposition allows the insertion of a Pulse Compressor (PC), exploiting the dispersive section between the modulator and the radiator obtaining at the same time the onset of the longitudinal density modulation and the stretching (or shrinking) of its period. In this way the modulation is produced at fixed wavelength by an external high power laser, and then shifted at the required wavelength before entering the radiation undulator. The final period of the modulation is controlled by the slope of the RF field in the PC, allowing fast wavelength chirping.

2. PREBUNCHED VS UNIFORM BEAM

The dynamics of a single electron in the pendulum-like phase space of FEL is described by the Colson equations [6]

$$\dot{\gamma} = -\frac{e\mathcal{E}K}{m_0 c\gamma}\sin\psi \tag{1a}$$

$$\ddot{\psi} = -\Omega^2 \sin\psi \tag{1b}$$

where

$$\Omega^2 = \frac{2\pi e\mathcal{E}K}{m\gamma^2\lambda_q}$$

and

$$\psi = (k + \frac{2\pi}{\lambda_q})z - \omega t - \psi_0$$

In this paper we follow the notation used in [7]; noticeably the r.m.s. value of K is used. The energy variation of one electron through the undulator is

$$\delta\gamma = \frac{\lambda_q\gamma}{4\pi c}\Delta\dot{\psi} \tag{2}$$

and the corresponding amplification of the intensity of the e.m. field is

$$G = -\frac{8\pi^2 r_0 c^3 K^2}{\lambda_q\gamma^3 V}\frac{\Delta\dot{\psi}}{\Omega^4} \tag{3}$$

The amplification with a real beam is obtained averaging $\Delta\dot{\psi}$ over the electron pulse. At first order

$$\Delta\dot{\psi} = -\left(\frac{\Omega L}{c}\right)^2 \frac{c}{L}\frac{\sin(\nu/2)}{\nu/2}\sin(\nu/2 + \psi_0) \tag{4}$$

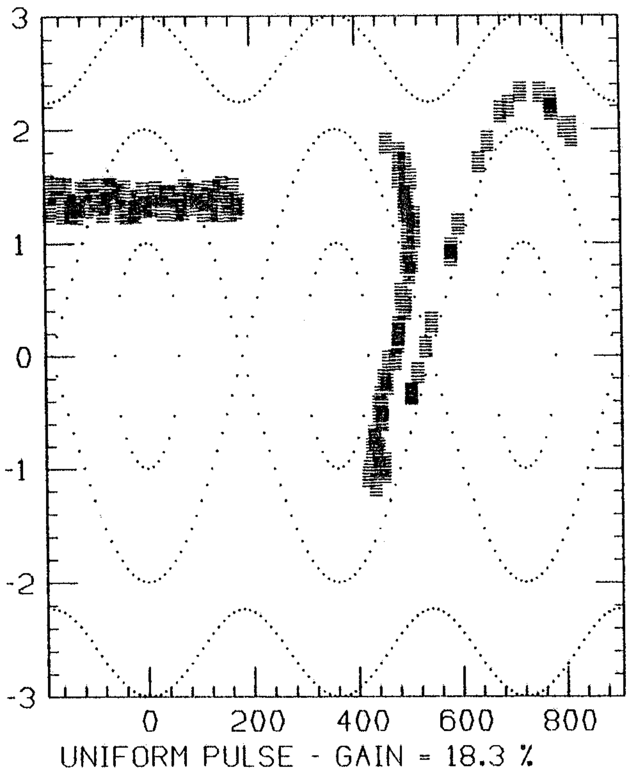

FIG. 1a - Phase space motion of a uniform beam during FEL interaction: initial $\psi, \dot{\psi}$ distribution in the left bucket, final $\psi, \dot{\psi}$ distribution in the right buckets.

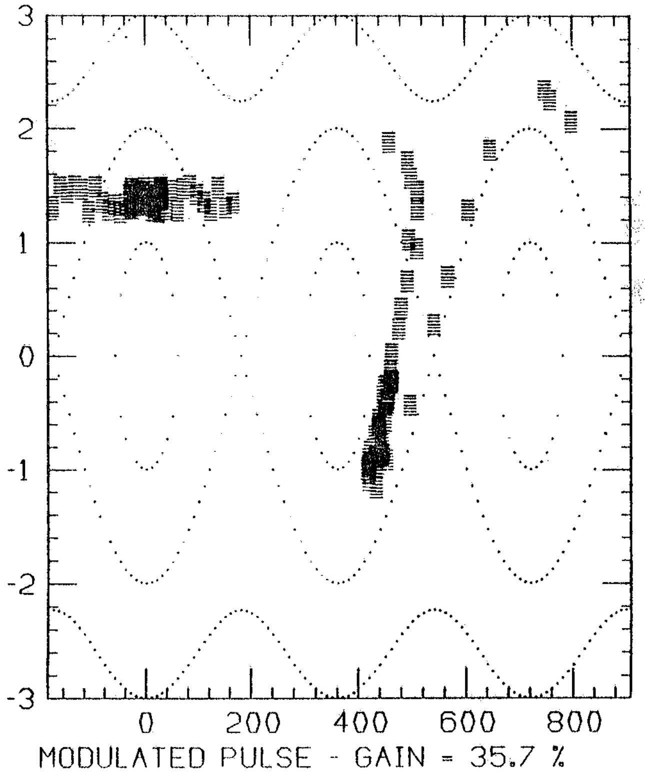

FIG. 1b - Phase space motion of a prebunched beam during FEL interaction: Initial $\psi, \dot{\psi}$ distribution in the left bucket, final $\psi, \dot{\psi}$ distribution in the right buckets.

and a uniform pulse in ψ_0 gives zero amplification. On the other hand if prebunching has been obtained at optical wavelength, a first order amplification is possible. The physical meaning is clearly shown in the plot of particle motion in the phase space.

In uniform pulse (fig. 1a) the amplification is given by the difference between the energy lost by electrons with phase $\psi_0 > 0$ and the energy gained by electrons with phase $\psi_0 < 0$. Positive gain is possible because a second order bunching effect slightly increases the number of electrons loosing energy with respect to the others. Moreover large energy spread comes out too. In prebunched beam (fig. 1b) all electrons have the right phase and loose energy contributing to the amplification. Since all starting points are concentrated in a small volume in the phase space, the final distribution also will be concentrated providing smaller energy spread. This behaviour may simplify the recirculation in the linac for energy recovery and make the operation with a tapered undulator more efficient.

An estimate of the gain increase obtainable in fundamental harmonic is given by the ratio of $\Delta\Psi$ averaged over the phase distribution of a uniform and a modulated pulse (see eq. 8)

$$\frac{G_m}{G_u} = \frac{\langle\Delta\Psi\rangle_{mod}}{\langle\Delta\Psi\rangle_{unif}} = \frac{4i_1c^2}{L^2\Omega^2} \frac{\frac{\sin^2\nu/2}{\nu/2}}{\frac{d}{d\nu}\left(\frac{\sin\nu/2}{\nu/2}\right)^2} \approx 4\frac{mc^2}{e}\frac{\lambda_q\gamma^2}{L^2\mathcal{E}K} \tag{5}$$

The ratio G_m/G_u is plotted in fig. 2 at two wavelengths.

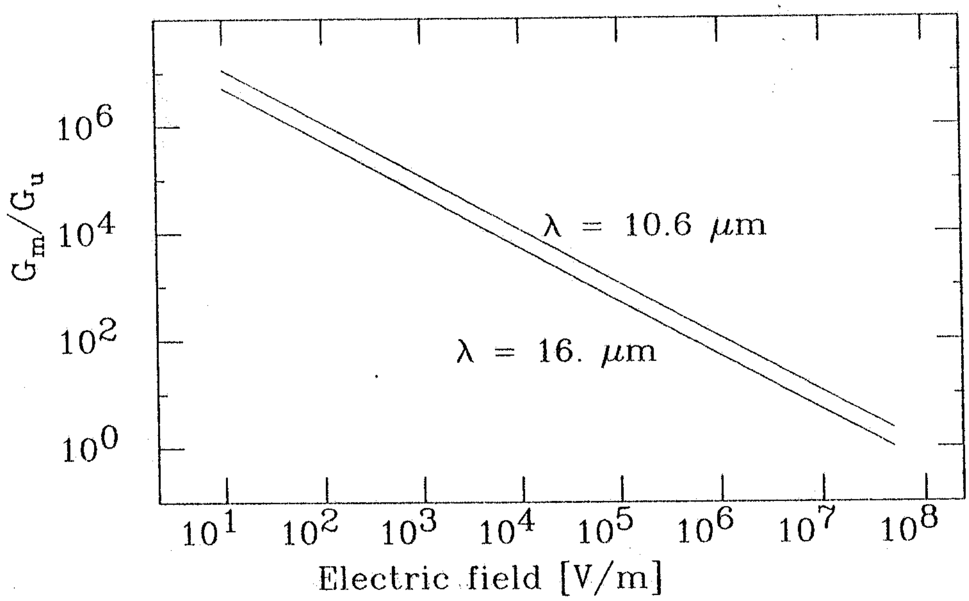

FIG. 2 - Plot of the gain ratio G_m/G_u vs inside cavity field $\mathcal{E}$ at $\lambda = 10.6\ \mu m$ and $\lambda = 16\ \mu m$.

At increasing field, i.e. approaching saturation, the gain ratio decreases since the second order FEL mechanism is strong enough to produce bunching; of course the simple estimate given by (5) fails when the small signal approximations are no longer valid.

3. ENERGY MODULATION AND BUNCHING

Consider the schematic of the DOK shown in fig. 3.

In the modulating undulator (MU) a periodic energy modulation

$$\delta\gamma(\psi_0) = \delta\gamma_{mod}\sin\psi_0 \tag{6}$$

is impressed to the electron pulse by an external laser. A large modulation depth is possible if $\delta\gamma_{mod} \geq \Delta\gamma_{spread}$. It is maximized when γmc^2 is chosen to give $\nu = 4\pi N(\gamma - \gamma_r)/\gamma_r = 0$ at the laser wavelength λ_0. The modulation depth derived by eqs. 2 and 4 is then

$$\delta\gamma_{mod} = \frac{e\mathcal{E}KL}{2m\gamma c^2}$$

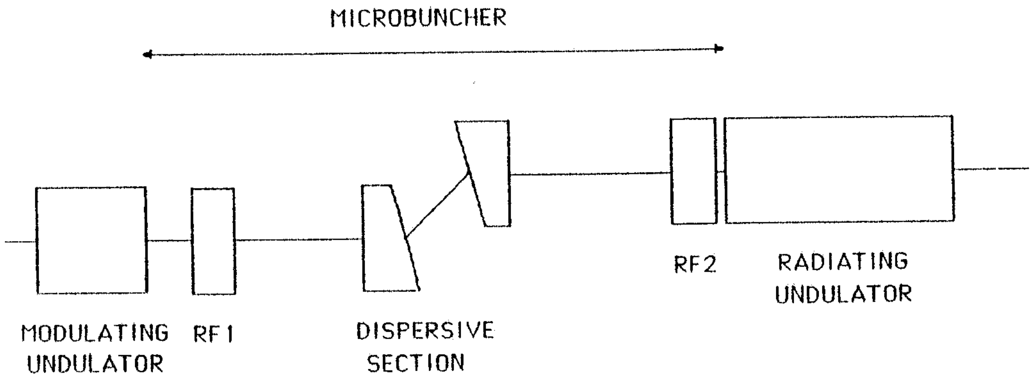

FIG. 3 - Layout of pulse compressor for wavelength shifting.

Going through a dispersive path (free space + magnets) the relative electron phases lead or lag with respect to the phase of the electrons with $\delta\gamma = 0$. Neglecting the phase shift in the modulating undulator, the dispersive effect of the transport line to the radiating undulator (RU) is given by

$$\frac{ds}{d\gamma} = (\frac{\alpha_t}{\gamma} - \frac{z}{\gamma^3}) \tag{7}$$

In the rhs of the above equation the terms

$$\frac{\alpha_t}{\gamma} = \frac{1}{\gamma}\int_0^z \frac{\eta}{\rho} ds \qquad \text{and} \qquad \frac{z}{\gamma^3}$$

account respectively for the path length variation due to the magnetic dispersion and for the delay due to the velocity modulation. The evolution of longitudinal density modulation in a wavelength λ_0 along z is described by

$$I(\psi) = I_0 \left(1 + 2\sum_{m=1}^{\infty} i_m \cos(m\psi)\right) \tag{8}$$

where

$$\psi = \psi_0 + \Psi \sin\psi_0 \tag{9}$$

and

$$\Psi = \frac{2\pi}{\lambda_0}\left(\alpha_t - \frac{z}{\gamma^2}\right)\frac{\delta\gamma_{mod}}{\gamma} \tag{10}$$

The m^{th} harmonic amplitude growth in the path from the modulator to the radiator is given by

$$i_m(z) = J_m(m\Psi)$$

The emittance causes path length variations uncorrelated with the energy modulation so the bunching will be smeared after a long drift space. The path lengthening due to emittance is given by

$$\delta l(\epsilon) = \int_0^z dl - z \approx \int_0^z \frac{\epsilon}{2\beta} \sin^2\left(\frac{z}{\beta}\right) dz \approx \frac{\epsilon z}{4 < \beta >} \tag{11}$$

where the simplifications

$$\beta = < \beta > \qquad \text{and} \qquad < \sin^2\left(\frac{z}{\beta}\right) > = \frac{1}{2}$$

have been used.

The harmonic components of order n of the bunching are smeared when $n \cdot \delta l(\epsilon) \approx \lambda_0/2$.

4. WAVELENGTH SHIFTING

Exploiting the distance between the modulator and the radiator an RF cavity can be inserted to add a linear energy variation to the beam already affected by the periodic energy modulation as shown in fig. 3. Assume a pulse of length l_p; its center passes the RF cavity when the field is zero; the energy variation at the ends of the pulse is

$$\delta\gamma_{lin} \equiv \Gamma \delta\gamma_{mod} = e\hat{V} \sin\left(\frac{\omega_{PC} l_p}{2c\beta_0}\right) \approx \frac{e\hat{V}\omega_{PC} l_p}{2c\beta_0} \tag{12}$$

The energy modulation along the pulse is

$$\delta\gamma_T = \delta\gamma_{mod}\left(\Gamma\frac{\lambda_0\psi_0}{\pi l_p} + \sin\psi_0\right) \tag{13}$$

In this case the dispersion of the chicane causes pulse lengthening or stretching while keeping the periodic modulation. A second RF cavity inserted after the chicane cancels the energy shear impressed by the firs one.

Assume that the RF cavities are just aside the undulators so that in the bunching process described in sect. 3 it is possible to replace $\delta\gamma_{mod} \rightarrow \delta\gamma_T$; then

$$\psi = \psi_0 + \Psi\left(\Gamma\frac{\lambda_0\psi_0}{\pi l_p} + \sin\psi_0\right) \tag{14}$$

The final wavelength of the density modulation is

$$\lambda = \lambda_0\left(1 + \frac{\Psi\Gamma\lambda_0}{\pi l_p}\right) \tag{15}$$

In order to cancel in the cavity $RF2$ the energy shear given by $RF1$ before the pulse compression the fields of the cavities must be in the ratio

$$\frac{\hat{V}_{RF2}}{\hat{V}_{RF1}} = \frac{\lambda_0}{\lambda} = 1 - \frac{\Psi\Gamma\lambda_0}{\pi l_p + \Psi\Gamma\lambda_0} \tag{16}$$

The evolution of a periodically + linearly energy modulated beam in the phase space $\psi,\delta\gamma$ is shown in fig. 4; a different modulation wavelength is clearly seen after the PC.

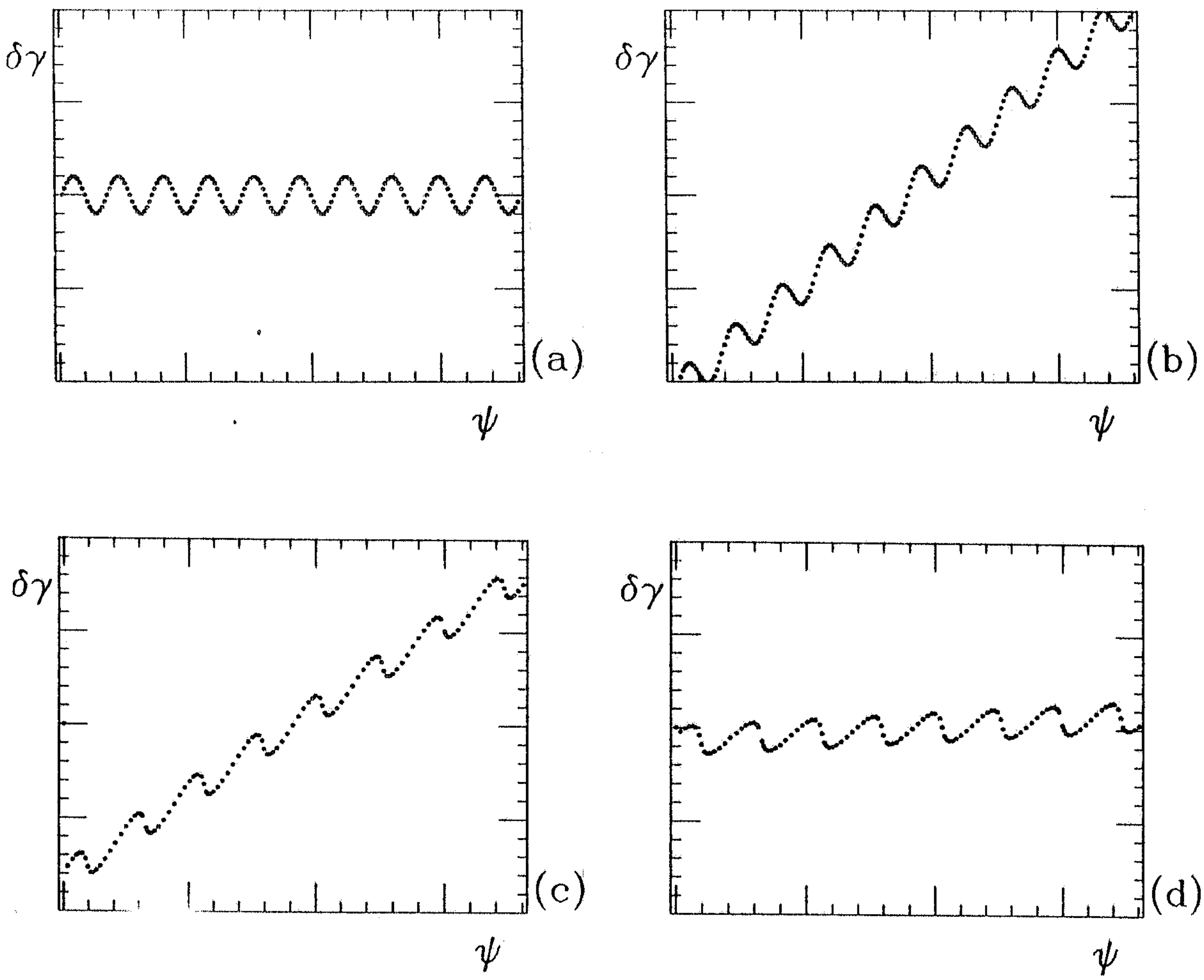

FIG. 4 - Evolution of a periodically + linearly energy modulated beam in the phase space $\psi,\delta\gamma$.

The arriving time distributions for beams linearly modulated at $\Gamma = 200$, $\Gamma = 0$ and $\Gamma = -200$ are shown in fig. 5.

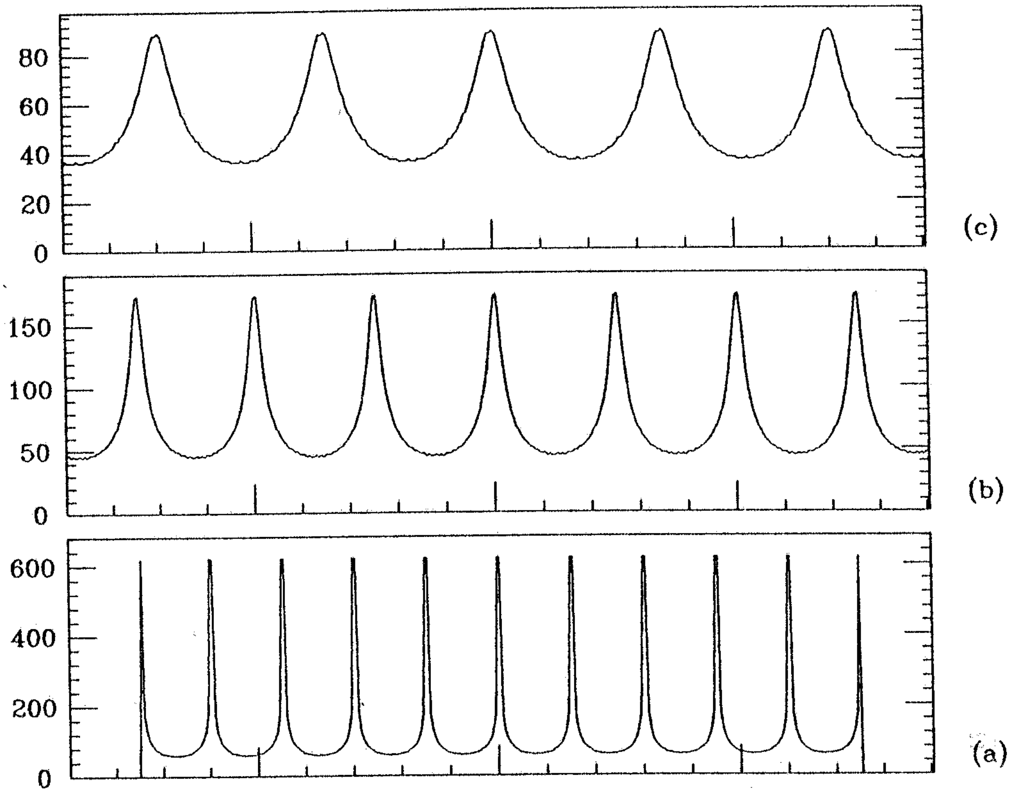

FIG. 5 - Longitudinal density modulation at $\Gamma = 200$ *(a),* $\Gamma = 0$ *(b) and* $\Gamma = -200$ *(c).*

These distributions correspond to the longitudinal density distributions for a initially uniform beam.

5. THE LAYOUT OF THE LISA DOK

The main parameters of the beam and of the transport line from the MU to the RU are listed in table I.

Table I - *Machine and undulator parameters concerning LISA operation with prebunched beam.*

LISA parameters			Undulator parameters		
Energy max	25	MeV	Modulator		
Horizontal emittance $\gamma\epsilon_x$	10^{-5}	$m \cdot rad$	Period λ_q	36	mm
Vertical emittance $\gamma\epsilon_y$	10^{-5}	$m \cdot rad$	K_{rms}	0.64	
$\Delta E/E$	$2 \cdot 10^{-3}$		Poles N	8	
Micropulse length	2.5	mm	Radiator		
Peak current	5	A	Period λ_q	44	mm
$\langle\beta_x\rangle$ in transport line	10	m	K_{rms}	$0.5 \div 1.$	
$\langle\beta_y\rangle$ "	3	m	Poles N	50	

The layout of the LISA FEL includes a chicane at both ends of the undulator to allow the insertion of a short optical cavity [8]. The modulating undulator is placed before the chicane in a straight section where the electron beam can be squeezed to interact with a focused laser beam and gain periodic energy modulation $\delta\gamma = \delta\gamma_{mod} \sin\psi_0$. In the path to the radiating undulator both the free space drift and the dispersion in the chicane cause the onset of longitudinal bunching at the laser wavelength λ_0.

In the layout shown in fig. 3 the distance between the modulator and the radiator is $z \approx 8\,m$, $< \beta_x > \approx 10\,m$ and $< \beta_y > \approx 3\,m$. The LISA emittance is $\gamma\epsilon = 10^{-5}\,m \cdot rad$ in both planes and the nominal energy is $25\,MeV$. The path length variations are

$$\delta l(\epsilon_x) = 4 \cdot 10^{-8}\,m \qquad \text{and} \qquad \delta l(\epsilon_y) = 13 \cdot 10^{-8}\,m$$

so their effect is always negligible in the IR range.

6. HARMONIC COMPONENTS OF THE MODULATION

The profile and the harmonic components of the optical modulation of a pulse stretched or shrinked respectively at $\Gamma = -200$ and $\Gamma = 200$ are shown in fig. 6. The bunching parameter

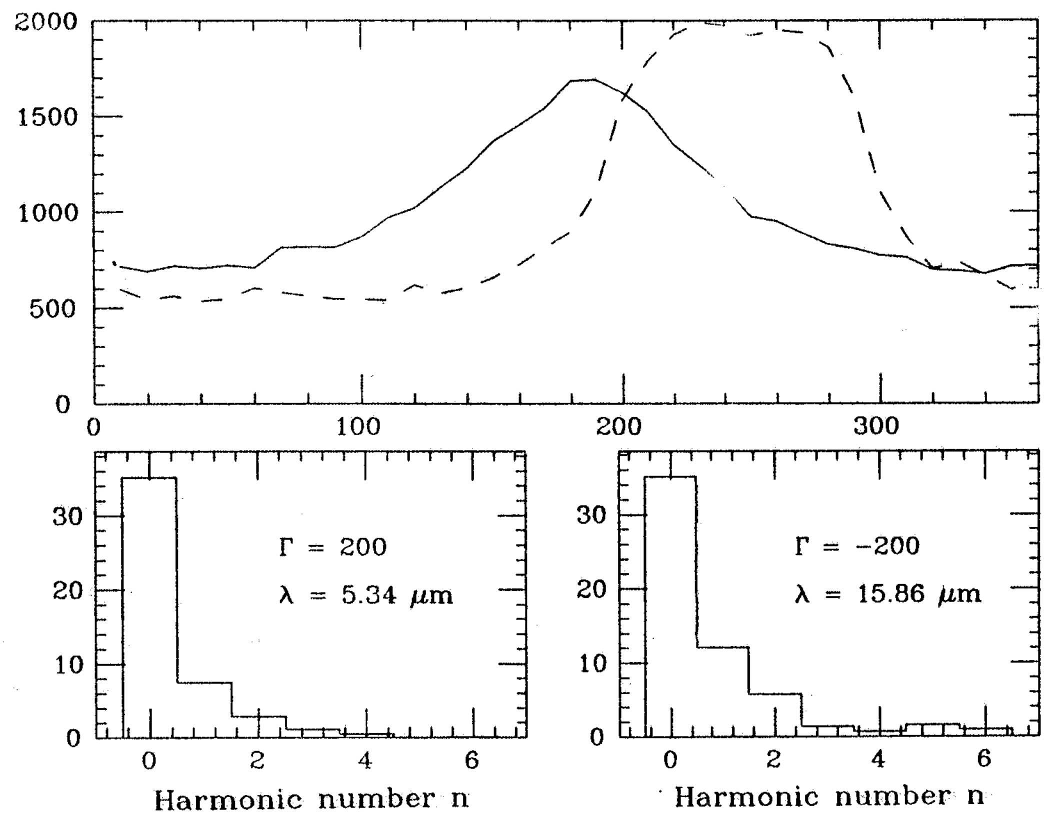

FIG. 6 - Profile and harmonic components of a pulse with $\delta\gamma_{mod} = \Delta\gamma_{spread}$ shrinked at $\Gamma = -200$ (dotted line) and stretched at $\Gamma = 200$ (dashed line).

Ψ is kept fixed at the value which maximizes the fundamental harmonic of the modulating laser.

An estimate of the harmonic amplitudes has been obtained with a simple Montecarlo propagating along the buncher a pulse with an energy modulation depth $\delta\gamma_{mod} = \Delta\gamma_{spread}$ folded with the initial uniform energy distribution. The spectrum obtained at $-100 < \Gamma < 100$ is shown in fig. 7; the spectra around the harmonics $n < 5$ are also shown. The amplitudes reported are the ratio a_n/a_0 of the n^{th} harmonic component to the constant term.

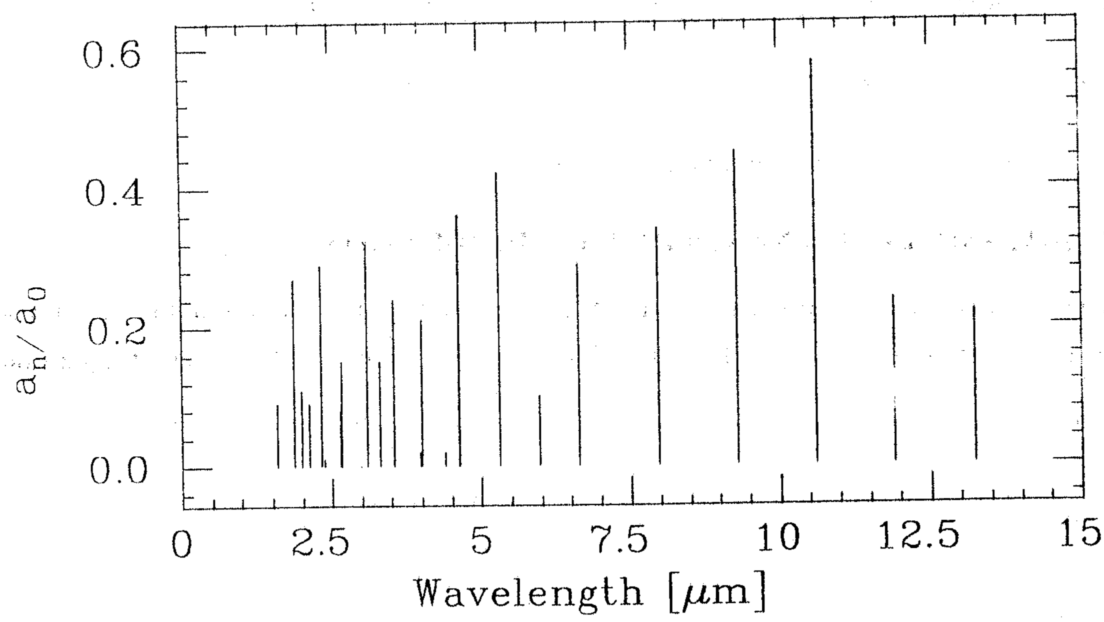

FIG. 7 - Spectra of the modulation and its harmonics shifted at $\Gamma = -100, -50, 50, 100$.

7. CONCLUSIONS

It has been shown that a high quality SC linac beam is suitable to realize unconventional FEL configuration.

Since in the IR region conventional sources and FEL schemes already provide high gain and high efficiency, the best application of this capability will be found in devices were a careful control of the final beam state is required, such as a recirculated linac, and in FEL's requiring a very high gain at start up to ensure fast frequency variation.

Moreover the frequency shifting is a peculiar feature that allows the realization of coherent harmonic generation over a virtually continuous band.

REFERENCES

[1] N.A.Vinokurov and A.N.Skrinsky, preprints INP 77.59 and 77.67, Novosibirsk 1977

[2] I.Boscolo and V.Stagno, '*Coherent emission from a bunched electron beam in a wiggler*' in *Free electron Lasers* S.Martellucci and N.A.Chester eds. Ettore Majorana International Science Series vol.18, Plenum Press, New York 1983

[3] M.Billardon et al, Phys. Rev. Lett. 51 (1983) 1652
V.Litvinenko, '*Results of the USSR storage ring FEL*', invited paper at the 11^{th} FEL Conference, Naples 1989

[4] R.Prazeres et al., Nucl. Instr. and Meth. A272 (1988) 68

[5] P.Patteri,'*Un Optical Klystron per LISA*'- Adone int. memo LIS-38, and '*Tunabilità della micromodulazione dell' OK di LISA*' - Adone int. memo LIS-39 (in Italian)

[6] W.B.Colson, Phys. Lett. 59A (1976) 187

[7] G.Dattoli and A.Renieri, '*Experimental and theoretical aspects of the free-electron laser*' in Laser Handbook vol. 4, Amsterdam 1985

[8] M.Castellano et al., '*The LISA project in Frascati INFN Laboratories*', presented at the 11^{th} FEL Conference, Naples 1989