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Laboratori Nazionali di Frascati

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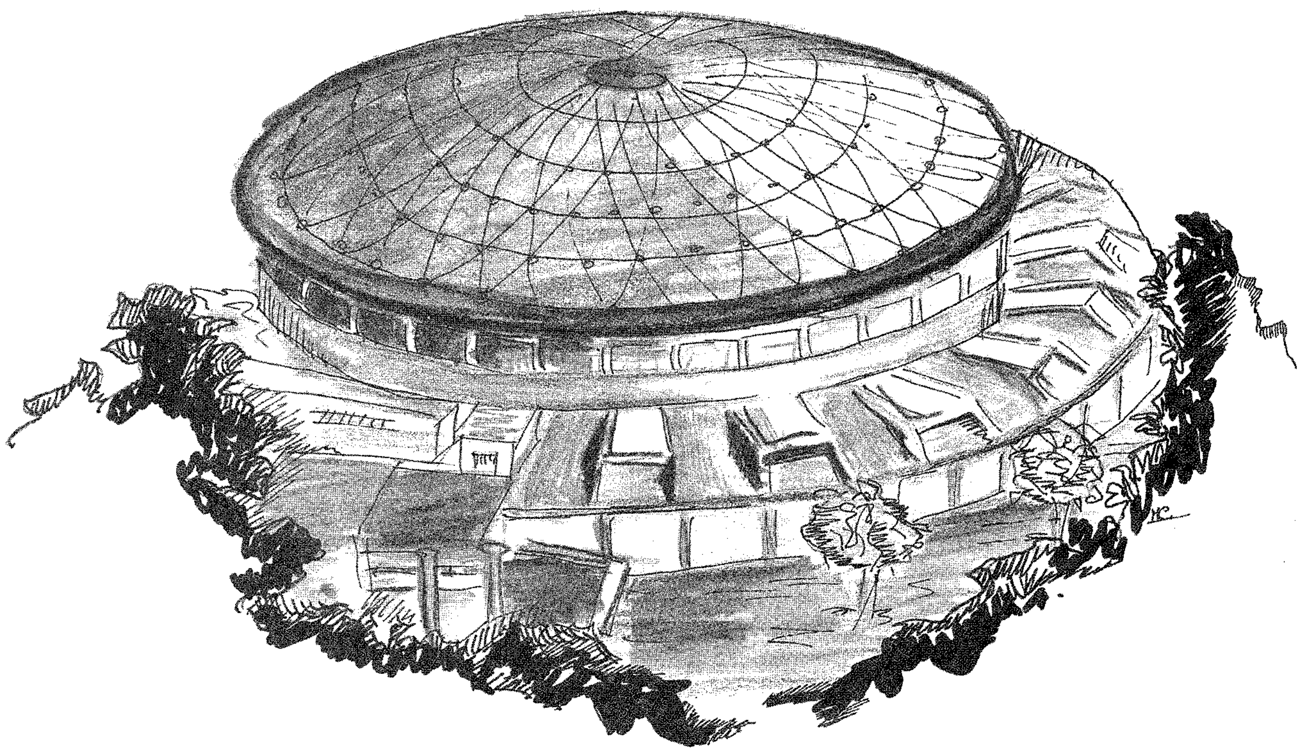
To appear in the Proc. of the
"11th International FEL Conference
Naples 28/8 - 1/9 (1989)



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ABSTRACT

A program to construct a test superconducting electron linear accelerator (LISA) is in progress at Frascati INFN National Laboratories. The electron beam will be used to realize a FEL in the infrared region (11 – 18 μm) in collaboration with a group of ENEA-CRE Frascati. The electron beam parameters and their relation to the expected performances of the FEL are discussed. Some future developments - energy recovery, energy doubling - are briefly presented.

1. INTRODUCTION

The scientific relevance of the superconducting linacs is steadly increasing despite their complexity since their performances allow experiments unfeasible with the traditional machines.

In the LNF the study of machines based on SC linacs started in 1986 [1] and a program was established to build a small accelerator to gain experimental practice in this field [2]. A FEL experiment in IR appeared the most promising choice, exploiting at the best the peculiar SC linac performances and the experience gained in the LELA experiment, carried out in Frascati in the years 1982-87 [3]. Moreover further stages of the program, requiring beam reacceleration or energy recovery after FEL interaction, would be in the current research trend in SC linac physics.

2. THE ACCELERATOR AND THE TRANSPORT LINES

The main parameters of the linac are summarized in Table I. In order to match the requirements for an infrared FEL a design of an injector providing high peak current and high brightness has been carried out.

Table I - *Main parameters of LISA*

Energy	25	MeV
Bunch length	2.5	mm
Peak current	5	A
Duty cycle	≤ 10	$\%$
Average macropulse current	2	mA
Invariant emittance	10^{-5}	$\pi m \cdot rad$
Energy spread (@25MeV)	$2 \cdot 10^{-3}$	
Micropulse frequency	50	MHz
Macropulse frequency	10	Hz

Since the design duty cycle is $\approx$ 10%, or higher in the energy recovery mode, the injector must be capable of CW operation. An RF gun with a SC cavity is the most suitable injector for this, but no one is fully operative up to now. Although an RF gun is under development in the Laboratori Nazionali di Frascati, a standard thermionic gun followed by a subharmonic chopper and an harmonic buncher will be used to speed up the realization of the machine. The layout of the machine in the experimental hall is shown in Fig. 1. The frequency of the SC linac is 500 MHz. It was chosen selecting among existing low frequency cavity designs to get a trade off between wake fields and power consumption, which decrease with frequency, and the cryogenic cost which of course increases when large cavities are used. Moreover the studies of larger SC linacs [4] included in the long term INFN program have been carried out at this frequency so the experience gained with LISA is expected to be profitable in the future.

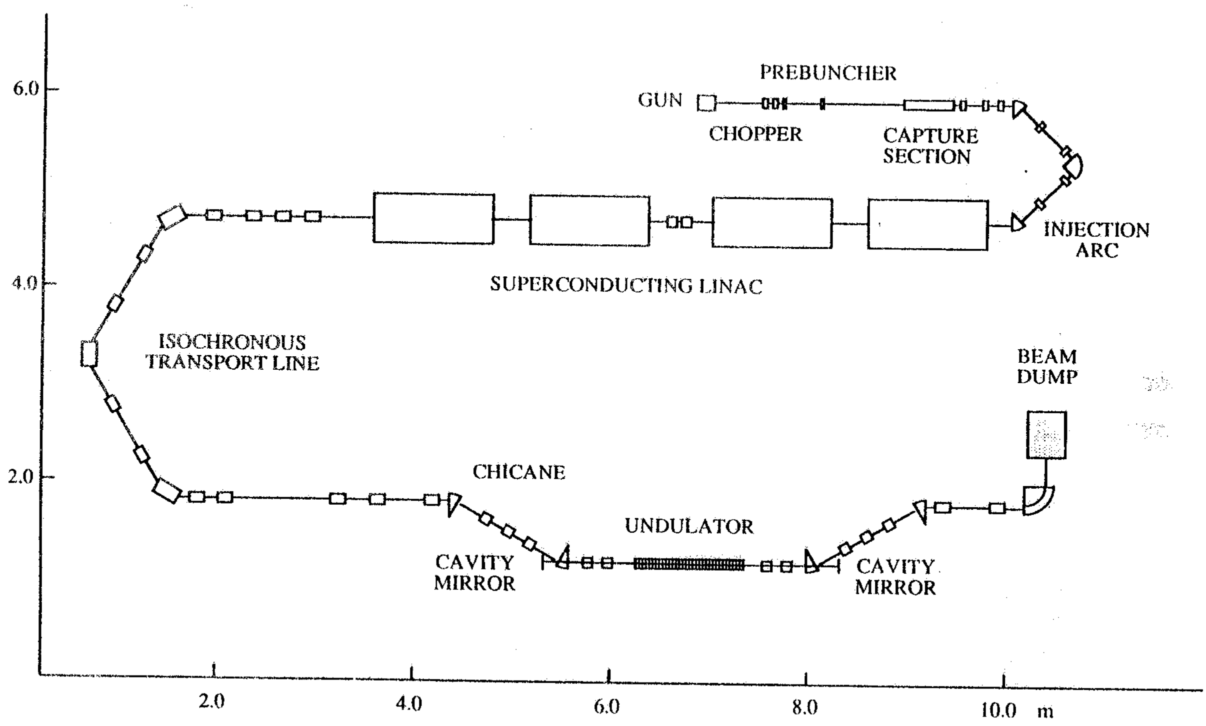

FIG. 1 - Schematic layout of LISA

1.1 The injector

The electron beam is generated in a 100 kV thermionic gun and chopped by a pair of deflecting plates at 50 MHz and then by a transverse RF field in a 500 MHz cavity, keeping 1.6% of the initial gun current. The pulse train is energy modulated in a 500 MHz bunching cavity causing $\Delta E = \pm 10\, keV$ in each pulse. After a drift space the bunching is frozen accelerating the beam to 1.0 MeV in a room temperature capture section at 2500 MHz. If the gain will be high enough to sustain FEL operation also at peak current lower than the nominal one it will be possible to operate with longer electron pulses, owing to the choice of a rather low frequency cavities, thus counteracting the gain reduction due to slippage and reducing the laser linewidth.

The beam of total energy 1.6 MeV ($\gamma = 3.1$) is injected in the SC linac after a 180° bend in the isochronous 'injecton arc'; since the electron are not fully relativistic this transport line must be carefully designed taking into account both particle velocity $\beta \approx 0.94$ and space charge effect to avoid debunching and emittance growth.

The beam structure is a succession of millisecond macropulses, the duty cycle of the machine being restricted to $\leq$ 10% for radiation safety reasons. Since the duty cycle is limited by the total beam power dispersed by losses or dissipated in the beam dump, it will be possible to extend the duty cycle when effective energy recovery will be operative.

1.2 The SC linac

The linac is composed of four cavities, each in a separate cryostat. A quadrupole doublet is placed in the 1.3 m long drift space between the cryostats 2 and 3. The connections to vacuum system and the insertion of diagnostic devices is possible also in two 0.7 m sections between cryostats $1-2$ and $3-4$.

The characteristics of the SC cavities are shown in Table II. The beam loading is ≈ 300 times the passive losses. The cavities are designed to operate at $4.2°K$ and the expected thermal load, including cryostat losses, is about 200 W.

Table II - *Parameters of the RF cavities*

Frequency (MHz)	499.8	
r/Q_0	380	Ω/m
Useful length	1.2	m
Overall length	2.5	m
Number of cells per cavities	4	
Accelerating field	5	MV/m
$Q_0(@4.2 \circ K)$	$2 \cdot 10^9$	
Q_{ext}	$6.5 \cdot 10^6$	

1.3 The tranport arc from the SC linac to the undulator

The transport line from the SC linac to the undulator is shown in fig. 1.

The 180° bending arc is normally isochronous, but the dispersion integral can be tuned and the line can be made non-isochronous if a pulse compression system will be realized to change the pulse length. A wide angle achromatic chicane, composed by two 30° magnet deflecting in opposite directions, brings the beam to the undulator, without interfering with the installation of the mirror holders of the 6 m long optical cavity. A quadrupole doublet allows the matching of the electron beam profile to the optical mode inside the cavity.

1.4 Return line for energy recovery or doubling

Preliminary study of the recirculation and related problems have been carried out. At the end of the 'transport arc' the beam will be steered either through the FEL undulator or back to the linac entrance to be further accelerated to 49 MeV; in this case a separate transport line will bring the beam to the undulator and then to the beam damp. Alternatively it is foreseen to recover part of the beam energy after the FEL interaction by recirculating it through the linac with a decelerating phase.

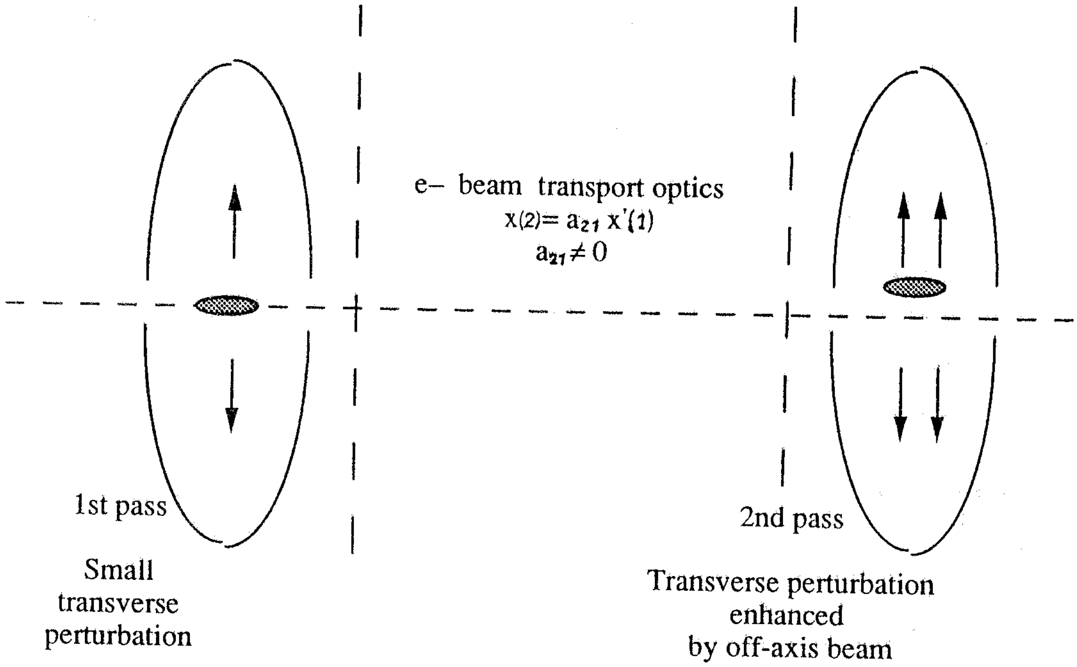

FIG. 2 - Schematic of beam break up dynamics

In both cases the main problem is the perturbation due to parasitic transverse mode in the cavity; the way a recirculated beam can excite these modes is shown in fig. 2.

Since the condition $a_{12} = 0$ cannot be obtained everywhere, a minimization must be searched along the whole linac. A satisfactory solution can be found for the energy doubling scheme since a well matched beam is to be reinjected in the linac. On the contrary after FEL interaction the beam quality is strongly degraded; moreover the deceleration makes the beam more sensitive to transverse fields and the relative energy spread increase makes the minimization more diffucult.

3. THE FEL

The beam quality of the SC linac is well suited for operating a high efficiency FEL covering the infrared wavelength region. The first harmonic wavelength obtained from a 4.4 cm period undulator, with a undulator parameter r.m.s. ranging from 0.5 to 1.0 at the design beam energy of 25 MeV, spans the wavelength region from 11 to 18 μm. Shorter wavelengths, extending into the near infrared and the visible, can be covered by doubling the beam energy and working on the third harmonic emission line. Meanwhile the region below 11 μm will be more easily accessible if the accelerating gradient will be improved over the nominal value, conservatively set at 5 MeV/m garanteed by the constructor, while current achievements approach 7 MeV/m. Of course longer wavelengths are obtainable at lower beam energy.

A NdFeB permanent magnet hybrid undulator with 4.4 cm period, to be built by Ansaldo Ricerche in Genoa in collaboration with the ENEA group [6], will be used. A 8 period long prototype has been realized and satisfactorily tested. The lower limit to the undulator period was set by the requirement of a gap of 2 cm.

The nominal small signal gain is 17.3 % at $\lambda = 15\mu m$; according to parametrization of gain given in [7] to take into account emittance, energy spread and slippage effect the gain on the fundamental harmonic is reduced to 10.0%. With the same parametrization the gain for third harmonic operation reduces to $\approx$ 2.5% which is sufficient if low losses dielectric mirrors are used for the cavity .

3.1 Small signal gain

The main parameters of the FEL in its present design are summarized in Table III.

Table III - *FEL parameters*

Beam energy	25	MeV
Undulator periods N	50	
Undulator wavelength	4.4	cm
Undulator parameter K_{rms}	$0.5 \div 1.0$	
Radiation wavelength @ 25 MeV	$11 \div 18$	μm
Linewidth @ 15 μm	0.5	%
Small signal gain @ 15 μm	17.3	%
Small signal gain @ 5 μm	2.5	%
Optical cavity length	6	m
Cavity passive losses	< 1	%
Cavity output coupling	1	%

The gain in first and third harmonic is shown in Fig. 3 and Fig. 4 for a 25 MeV beam; the three curves take into account the effect of different energy spread: $\Delta E/E = 2 \cdot 10^{-3}$ (continuous line), $1 \cdot 10^{-3}$ (dashed line), and $5 \cdot 10^{-4}$ (dot-dashed line). The normalized parameter

$$\xi = \frac{K^2}{2(1+K^2)}$$

is used on abscissa axis and the corresponding first harmonic wavelengths are reported on the top axis; the curves refer to the gain reduced by inhomogeneous broadening and slippage.

The saturation efficiency $1/2N$ is $\approx$ 1% which gives average power of 500 W during macropulses, and peak power of 1.25 MW. The energy recovery will provide a large increase of efficiency in electron to laser energy conversion which will allow longer laser

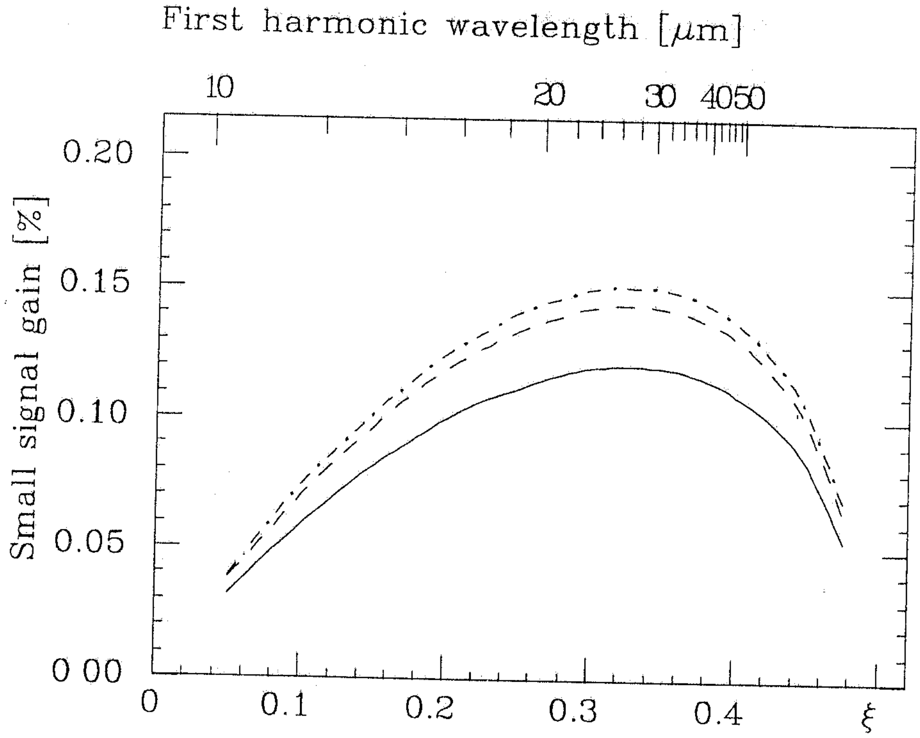

FIG. 3. - Gain vs ξ in fundamental harmonic.

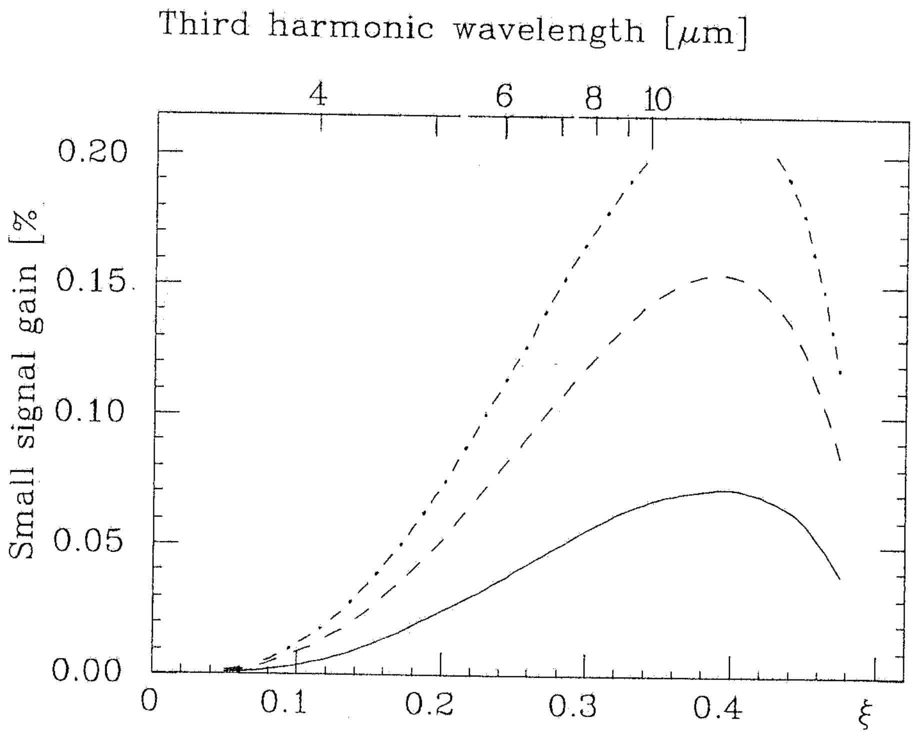

FIG. 4. - Gain vs ξ in third harmonic.

macropulses at constant average power, or higher average power by increasing the electron microbunch repetition rate. The requirement of low emittance prevents a peak power increase with the present injector scheme.

3.2 Efficiency optimization

The most favorable condition at laser start up is ν = 2.5 but at increasing laser field the peak gain moves to $\nu > 2.5$ as it is shown in fig. 5.

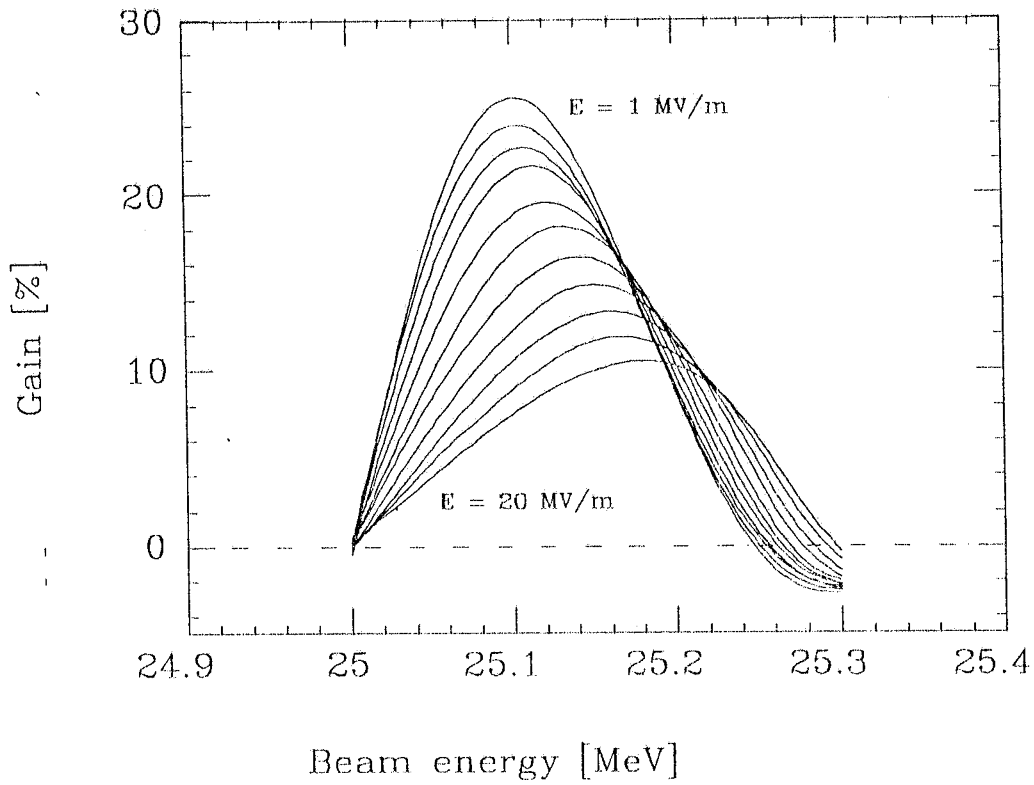

FIG. 5 - Gain curves at increasing laser field vs beam energy.

If the beam energy is set for higher gain at high field level, i.e. for maximum efficiency at saturation, the small signal gain is just larger then losses and the risetime of the laser oscillation is lenghtened. The risetime is given by

$$\tau[\mu s] = .14\frac{L_c[m]}{g - \gamma_T} \approx \frac{.84}{g - \gamma_T}$$

Assume the gain just overcomes the cavity losses

e.g. $g - \gamma_T \approx 1\%$ then $\tau = 84\,\mu s$

This risetime is $< 10\%$ of the LISA macropulse. Owing to such a long macropulse low gain $\approx 2\%$ start up is possible providing higher gain and efficiency at saturation during most of the macropulse duration. The energy extraction efficiency at beam energy optimized for small signal gain (ν = 2.5) and for high gain at $\mathcal{E} > 10\,MV/m$ (ν = 5.0) is shown in fig.6.

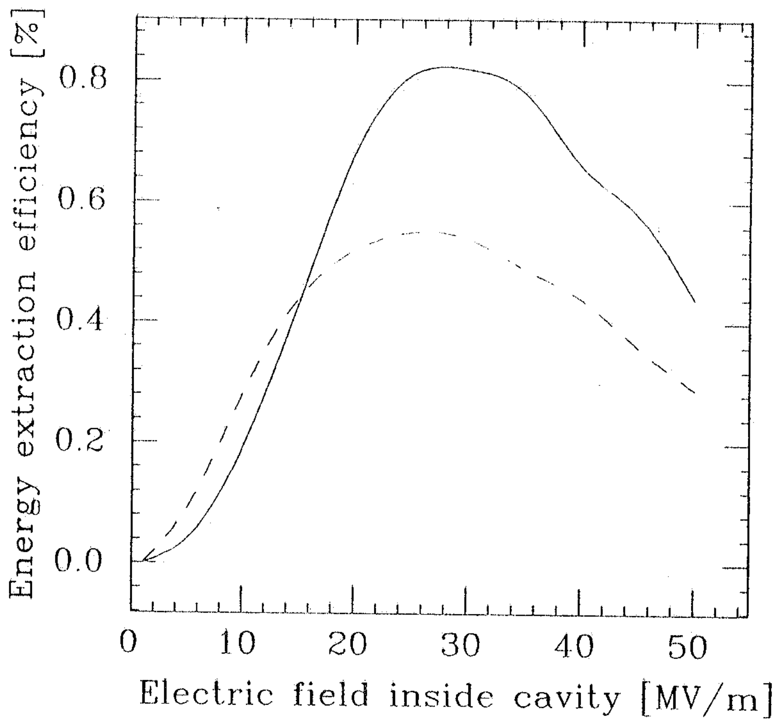

FIG. 6 - Energy extraction efficiency vs inside cavity laser field at ν = 2.5 (dashed line) and ν = 5.0 (continuous line).

The FEL efficiency with energy recovery was considered in [8]; the calculations were carried out assuming a 5 *cm* period undulator: although general considerations still hold, numerical results must be reconsidered.

The design of the optical cavity is in progress.

4. TECHNICAL FACILITIES AND TIME SCHEDULE

The accelerator hall is underground to save on the concrete shielding. Building activities started in March 89 and are scheduled to be completed by the end of the year. Commissioning of the injector is foreseen to be performed in the first half of 1990. All the main accelerator components will be delivered by Spring 1990. The undulator will be delivered by the end of 1990 closely following the commissioning of the accelerator.

Preliminary experimental activity on the FEL will be carried out in the accelerator hall. Restrictions to access - delay time after beam shut-off, limited working time, access control bureaucracy - suggest to plan an outside laboratory where the deflected FEL beam would be more accessible.

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