WORK ON SUPERCONDUCTING LINACS IN PROGRESS IN FRASCATI

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Introduction

A research and development program in the field of RF superconductivity is in progress in Frascati, at the INFN Frascati National Laboratory, as part of a larger effort promoted by INFN in the field of superconductivity applied to accelerators, ranging from magnets to RF cavities and including basic research on the properties of superconducting (SC) materials.

The program is carried out in collaboration with other INFN laboratories (mainly Milan and Genova) and with University groups. Its aim is to establish the feasibility of high energy, high duty cycle, high peak current superconducting electron linear accelerators. As a first stage of the program, the construction of a small 49 MeV SC linac called LISA has been authorized and is under way .

We shall first present the status of LISA [1] and then give a summary of the other R&D activities in progress or planned.

The LISA project

The linear (SC) accelerator LISA is a test device aimed at studying and gaining experience on some of the problems of SC linacs and high quality, high peak current beams. The specifications are tailored to the requirements of an infrared Free Electron Laser (FEL).

The frequency is 500 MHz, a choice dictated by a compromise between high peak current capability, size and availability of designs and components. A detailed discussion on the relative merits of different operating frequencies can be found in references [2].

The energy of the machine is 25 MeV, sufficient to operate an infrared FEL. It can be doubled by recirculation to extend the FEL wavelength in the near visible.

The layout of the machine is shown in Fig. 1.

The electron beam is generated in a thermionic gun, chopped, prebunched and accelerated to 1 MeV in a room temperature preaccelerator. It is then bent through 180° and injected into the SC linac structure. This solution minimizes the machine hall size and is well suited to the design of an isochronous transport [3].

After leaving the SC linac the beam can be steered either through an FEL undulator or back to the linac entrance. In the latter case , depending on its phase with respect to the electromagnetic field, it can be either further accelerated to 49 MeV, or decelerated. In fact it is foreseen, as a further development, to bring the electron beam, after it has passed through the FEL, back to the SC linac entrance and decelerate it so as to recover part of the beam energy. The overall efficiency of the FEL would correspondingly increase and the technique could prove interesting for high power, high efficiency FEL installations.

The main parameters of LISA are given in Table I. They have been defined to match the requirements of the FEL.

The initial rather standard thermionic gun has been designed to achieve a peak current in the microbunch of 5 A, with an invariant emittance of 10^{-5} m·rad.The expected performance is adequate to test the FEL operation. The peak current performance will be improved by replacing the thermionic gun by an RF one that is currently under development and that will be compatible with the available DC and RF power supplies.

The beam structure is a succession of millisecond macropulses. The duty cycle of the machine is restricted to $\leq 2\%$ for radiation safety reasons.The microbunch repetition rate is ≤ 50 MHz.

Table I - Main parameters of LISA

Energy (MeV)	$25 \div 49$
Bunch length (mm)	2.5
Bunch charge (pC)	40
Electrons per bunch	$2.6\ 10^{8}$
Peak current (A)	5
Duty cycle	$\leq 2\%$
Average macropulse current (mA)	2
Invariant emittance (π m rad)	10^{-5}
Energy spread (@25 MeV)	$2 \cdot 10^{-3}$

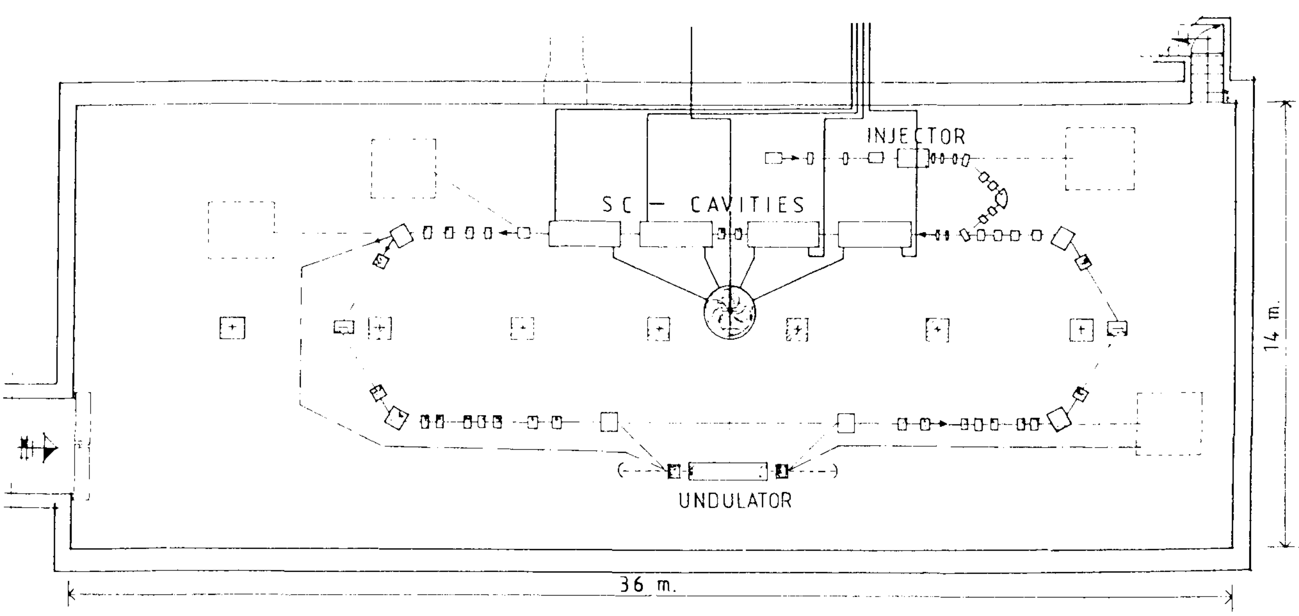

Fig. 1 - Schematic layout of LISA

Description of the machine

The injector

The injector for LISA will initially consist of a conventional thermoionic triode gun and a room temperature 1 MeV preaccelerator. This solution, that uses proven technology components, allows to speed up the design and construction schedule while still providing good quality beams. To improve on the peak current and on the emittance, studies on a RF gun with a laser-driven photocathode have been started.

The main parts of the present injector are:

- A 100 KeV, 0.2 A gun.
- Two choppers (50 MHz and 500 MHz).
- A 500 MHz prebuncher.
- A 1 MeV, 2.5 GHz preaccelerator.
- Achromatic and isochronous transport line from preaccelerator to SC linac.

The beam parameters at the injector output are given in Table II. Details about the design of the system are given in ref. [3].

Table II - Injector: output beam parameters

Kinetic energy (MeV)	1.1
$\Delta E/E$	$2\cdot 10^{-2}$
$\Delta\phi$ (@500MHz) (deg)	1.2
σ_l (mm)	1
$\sigma_{x,y}$ (mm)	3

The SC linac structure

The SC accelerating structure is made of four cavities of bulk Niobium, each placed in an independent cryostat. The design of the cavities, including RF couplers and mode suppressors is exactly that of the HERA four-cell modules [4] except for the fact that there is an independent cryostat for each cavity instead of one cryostat for two cavities. This gives more flexibility for cavity handling and for operation.

The cavities are being fabricated by INTERATOM and they will be completely tested at the factory. The main cavity parameters are given in Table III.

The accelerating voltage and Q_0 values are for normal operation and are therefore in line with the state of the art of bulk Nb cavities.

Each cavity will be fed by an an independent RF generator connected to the cavity through a circulator. This solution is somewhat more expensive than other arrangements but affords a high degree of flexibility, an important advantage for a test-bench machine. Fast phasing of the amplification chains will take place at low power level.

Table III - Parameters of the RF cavities

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

Refrigeration

The superconducting cavities are designed to operate at 4.2 °K and the expected low-temperature heat loads [5] are:

.cryostat static losses ≈ 20 W
.losses in the cryogenic distribution system ≈ 20 W
.RF power dissipated in the cavities ≈ 160 W

Intermediate temperature cooling (40 °K - 80 °K) is of course also provided.

The refrigerator is a standard model - Sulzer TCF 50 - and consists of a closed-cycle helium refrigerator operating on a modified-Claude cycle, with two turbine expanders and a Joule-Thomson final stage. The machine is reliable and equipped with an automatic control system; it is therefore expected to operate almost without supervision.

It is designed to handle 300 W at 4.5 °K and 1000 W at 80 °K, without liquid nitrogen precooling; this gives a safety margin of a factor of approximately 1.5 over the needed capacity (for the cavity parameters given in Table III.).

With liquid nitrogen precooling the cooling power can be raised to 380 W at 4.5 °K , thereby correspondingly increasing the safety factor. The efficiency of the machine is about 10% of the Carnot efficiency and corresponds to 750 W/W.

The incorporated control system automatically performs all necessary operations such as cool-down, warm up, recovery, etc. It also allows for remote manual control of the parameters, within certain safe limits, and automatically prints out a daily log of the operating conditions.

The transport line lattice

To be able to either double the beam energy or recover it after interaction with the FEL, two separate recirculation paths have to be provided.The beam energy recovery section and the energy doubling recirculator are still in the design stage [6].

The transport line from the SC Linac to the undulator has been finalized for the FEL experiment. The layout is shown in Fig. 2.

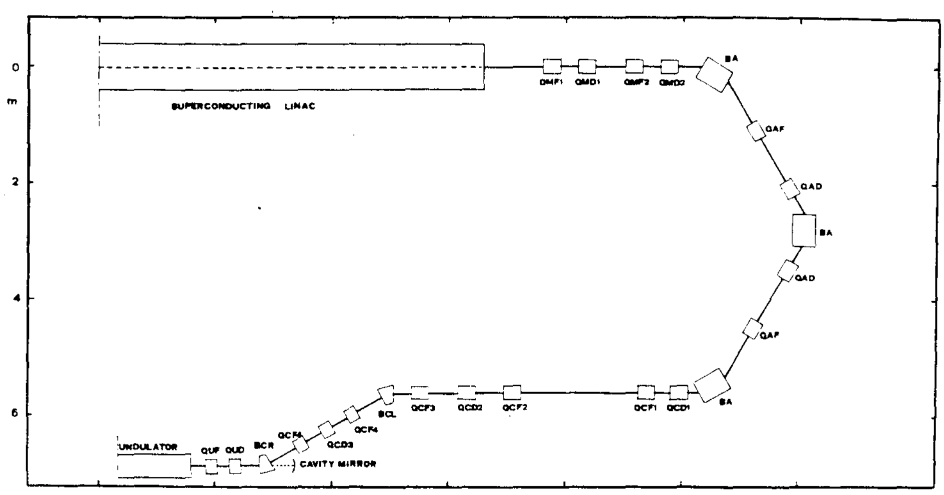

Fig. 2 - Layout of the SC Linac to the undulator transport channel

The detailed design [7] includes two additional quadrupoles in the arc to continuously vary the dispersion integral around its normal zero value (isochronicity condition). The line can thus be fine-tuned and also made non-isochronous should the need arise for a pulse compression system.

A wide angle achromatic 'chicane' takes the beam to the 2.5 m long undulator while leaving room along the undulator axis for the 6 m long FEL optical cavity. For additional flexibility, the values of the beam envelope (betatron) functions at the undulator midpoint, β^*_x, β^*_z, can be continuously varied in the range from 0.2 m to 1.3 m.

Figure 3. shows the behaviour of the optical functions along the transport line, in the isochronous configuration.

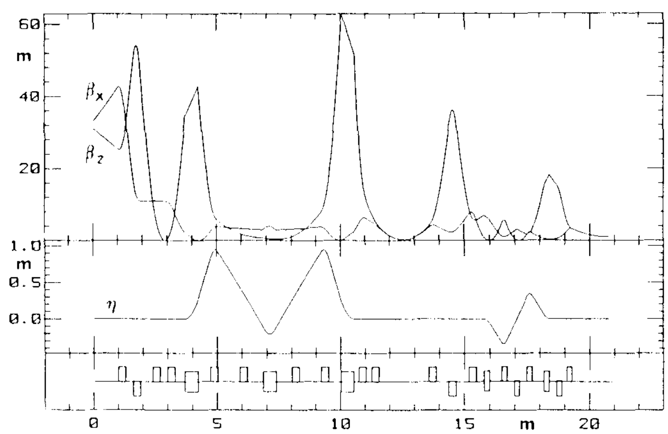

Fig. 3 - Optical functions in the transport channel in the isochronous configuration.

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 5 cm period undulator with a field parameter , K, ranging from 0.5 to 1.5, at the nominal beam energy of 25 MeV, spans the wavelength region from 12 to 22 μm. Shorter wavelengths, extending into the visible, can be covered by doubling the beam energy and working on the third harmonic emission line.

An electromagnetic undulator with a variable number of 5 cm periods, so as to optimize the radiation extraction efficiency for each operating wavelength, has been designed and a prototype is under construction [8]. A shorter period, permanent magnet hybrid undulator is also being considered [9].

The main parameters of the FEL in its present design [10] are summarized in Table IV.

Table IV - FEL: Main Parameters

Beam energy (MeV)	25
Number of undulator periods	≤ 50
Undulator wavelength (cm)	5
Radiation wavelength (μm)	12 ÷ 22
Optical cavity length (m)	6
Cavity passive losses (%)	2
Cavity output coupling (%)	3

The (maximum) radiation extraction efficiency and the laser average power during the macropulse are shown as functions of wavelength in Fig. 4.

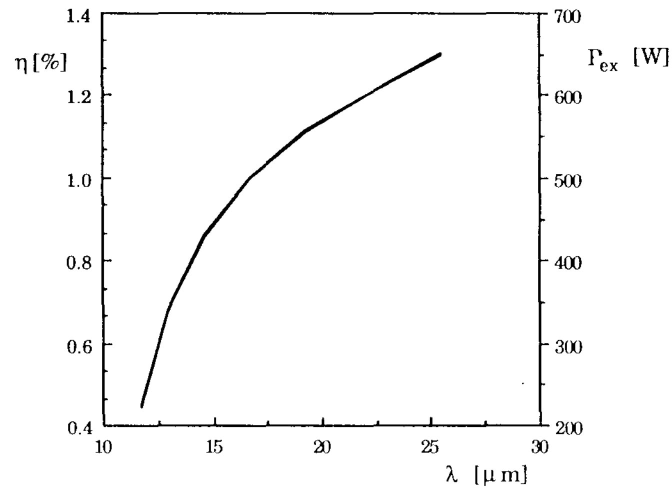

Fig . 4 - Average power and efficiency vs. wavelength during the macropulse.

Technical facilities and time schedule

The cross section of the building to house LISA and its ancillary equipment is shown in Fig. 5. The accelerator hall is underground to save on the concrete shielding. A closed circuit ventilation system ensures that no contaminated air is let out to the environment. The refrigerator, power supplies and control rooms are located alongside the accelerator.

Building activities have started and are scheduled to be completed by the summer of 1989 and all main accelerator components will have been delivered by the autumn. Installation and commissioning will proceed accordingly.

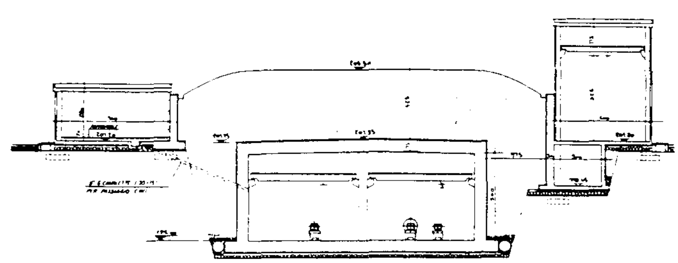

Fig. 5 - Cross section of the buildings for the LISA plants.

LNF plans beyond LISA

Superconducting linear accelerators, capable of producing high quality, continuous beams with high average current, are ideal candidates for intermediate energy machines for Nuclear Physics (NP)[11]. They also have the potential for accelerating high density, high charge beam pulses and are therefore susceptible of application to high energy and intermediate energy linear colliders and to FEL's. It is worth recalling that our choice of a 500 MHz RF frequency was a compromise between the needs of NP applications and those of high peak current pulsed beams.

All three applications have raised much interest in the INFN. The LISA project was launched at the end of 1987 as an initial step and a considerable sum has been set aside for R&D on SC linacs (Project ARES) in the INFN provisional budget for the years 1989÷1994. The budget has been approved, in its main lines, and the detailed planning is in progress.

Studies on possible developments have meanwhile been going on. In particular, a much attended workshop was held in Courmayeur, in December 1987, to study the feasibility of a $B\underline{B}$ factory and Nuclear Physics facility based on SC linacs. During the workshop a number of R&D goals, of general interest for future accelerators, were identified. They included the development of RF cavities with higher fields and Q_o values [5] and the development of electron injector systems capable of reaching rms emittances in the 10^{-6} m·rad range with bunch charges in the order of 1 nC [12]. Such values of the normalized emittance require an improvement over what is commonly achieved by a factor of the order of 3 to 10.

Another extremely interesting application of high quality, limited energy SC Linacs is that of high intensity, soft x-ray FEL's.

A collaboration between LNF (Frascati) and the INFN laboratories in Milan and Genova, has been set up, in the framework of ARES.

Specific goals have been set: to develop SC cavities with accelerating fields of the order of 10 MV/m and Q_o values of the order of $4 \cdot 10^9$, at a competitive price, and use them to build a test-bench accelerator capable of producing the kinds of beams required for colliders and FEL applications; to develop an injector capable of reaching normalized peak brightnesses in the range of 10^{11} A/(m^2 rad), with peak currents in the order of a few hundred Ampères.

The energy of the accelerator RF structure should be around 580 MeV; the exact value is still being discussed and also depends on the details of the RF system. It can be doubled by recirculation. Besides providing a 'full scale', significant feasibility test for a larger machine, including the opportunity for studying the behaviour of the low emittance high current beams as they travel through the accelerator, the test linac will become a very interesting tool for trying and extend the operating range of FEL's into the 100 to 10 nm wavelength region.

A tentative parameter list is given in Table V.

Table V - Tentative Parameter List of the Test LINAC

Energy (MeV)	580
Number of 4-cell cavities	48
Accelerating field (MeV/m)	10 (at 4.2@K)
Q_o	$4 \cdot 10^9$
RF frequency (MHz)	500
Cryogenic power (kW)	5 (at 4.2@K)
RF power (kW)	120
Total plug power (MW)	< 4

	CW	Pulsed
Current	200 μA (avg)	200 A (peak)
Repetition rate	500 MHz	≤ 1 kHz
Charge/bunch	0.4 pC	1÷2 nC
ε_n (rms)	1 10^{-6}m·rad	$2 \cdot 10^{-5}$m·rad
Bunch length	1 mm	1÷3 mm
Energy spread	< 2 ‰	< 4 ‰
Bunches/pulse	-	< 10

Cavity development is carried out in collaboration with other INFN Laboratories (mainly Milan and Genova) and with CERN. The focus is on SC films deposited on Copper or on other high conducibility materials. The technique, first developed at CERN [13], gives promise of savings (on SC material and on the cryostat), of better RF performance and of higher stability.

In the framework of the collaboration Frascati is planning to study new coating materials.

Preliminary activities on bulk Nb single cells are in progress and experimental facilities have been set up to fabricate sputtered thin films and to characterize them electrically as a function of both temperature (1.5 °K ÷ 300 °K) and magnetic field (up to 5 T) . Moreover , RF characterization of single cell cavities can be performed in a vertical cryostat. At present two single cell cavities, one made of Niobium sheet and the other by coating a copper cavity with Niobium film, are being fabricated.

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