EUROPEAN LABORATORY FOR ELECTRONS (TECHNICAL PROPOSAL)*

ELFE Machine Study Groups — presented by J.-M. De Conto

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The future 15 GeV 100% duty-cycle electron accelerator for hadronic Physics is presented. For a given set of Physics requirements, a three-pass recirculating linear accelerator has been chosen within an European collaboration. This document will explain the choice of the scenario and give a general overview of the machine.

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1. Introduction and chronology

The European Laboratory For Electrons (ELFE project) which will be presented here will be an electron accelerator dedicated to the precise study of hadron structure, quark confinement and quark dynamics for energies in the 15 GeV range. A 100% duty cycle is required to be able to select final states of several particles in coincidence, as well as a high quality beam (energy spread and emittance).

To obtain such a duty-cycle, many schemes can be and indeed, have been investigated. For final energies greater than a few GeV, the use of Radio-Frequency superconductivity is compulsory in order to keep Joule losses within acceptable values inside the accelerating structures.

In this domain, the first studies have begun as early as 1968, but progress on superconducting RF cavities has been slow and difficult. Since 1980, more successful Research and Development programs have been carried out by the collaboration between many laboratories and fields greater than 5 MV/meter have been obtained. In May 1986, in the USA, the proposal for the Continuous Electron Beam Accelerator Facility (CEBAF),

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provided a 4 GeV, 200μA, 100% duty-cycle electron beam, using 1.5 GHz Cornell superconducting cavities and a racetrack recirculating structure, was made. Presently, at the end of 1992, its construction is well advanced, with completion of all installation work anticipated in autumn 1993 [1].

In France, in 1987, the GECS (Superconducting Cavities Study Group) was set up in Saclay. In 1989, after the Ceillac European workshop on Hadronic Physics with multi-GeV electrons (1988), a first proposal was made for a 4 GeV CW machine, for a 100μA intensity [2]. At the beginning of 1990, a recommendation was issued by a group of Physicists of the French "Académie des Sciences", to propose a research program with continuous beam of energy greater than 10 GeV and to study, on an European basis, the new accelerator proposed to carry out this program [3, 4]. After discussing the Physics program during the international conferences of Dourdan in 1990 [5] and of Amsterdam in 1991 [6], for this range of energy, an European Steering Committee, an European Electron Machine Committee (EEMC) and study groups have been set up. Fundamental studies on beam dynamics and on various possible schemes were made until the end of 1991. At the beginning of 1992, after NuPECC recommendation and from precise Physics requirements, a scenario of a 15 GeV continuous wave machine was chosen. This scenario consist of a three pass, one linac recirculating machine, with a possible energy upgrade to 31 GeV.

The Steering Committee is made of four members: J. Arvieux (Laboratoire National Saturne, France), E. De Sanctis (Laboratori Nazionale di Frascati, Italy), T. Walcher (chairman, Institüt für Kernphysik, Mainz) and P. de Witt-Huberts (NIKHEF, Amsterdam). The coordination of the accelerator design and the technological choice have been made by the European Electron Machine Committee made of 18 european experts (chairman: M. Promé) and the detailed studies have been done by two study groups, a superconducting cavities group and a machine parameter group, each of them being made of accelerator physicists from Germany, Italy, Netherlands and France.

2. Physics requirements

After examining the Physics program and technological possibilities in experimental equipment, the requirements for the electron beam have been defined as follows:

$E \geq 15$ GeV for a first step — Up to 30 GeV later
$I \leq 50\mu$A at 15 GeV
100% duty-cycle
$\Delta E/E \leq 3 \cdot 10^{-4}$ at 15 GeV Full Width Half Maximum (FWHM)

$\Delta E/E \leq 10^{-3}$ at 30 GeV (FWHM)
$\varepsilon/\pi \leq 10^{-8}$ m.rad at 15 GeV (horizontal emittance, 95% of the beam particles)
$\varepsilon/\pi \leq 3\cdot 10^{-7}$ m.rad at 30 GeV (horizontal emittance, 95% of the beam particles)
3 beams (time-shared with different energies and intensities)
Beam polarization >80%, I maximum

As said before, the beam quality and the high duty-cycle are very important parameters. In addition, a high luminosity (10^{37} to 10^{38} $cm^{-2}s^{-1}$) is needed to be able to observe rare events. Such a luminosity can be obtained with a 50μA intensity ($3\cdot 10^{14}$ electrons per second on a carbon target of 1 g/cm^2 density.

3. Choice of the machine

An electron storage ring cannot be used. It has been shown [3] that the main limitation of such a solution comes from the luminosity, the maximum achievable being 10^{34} to 10^{35} $cm^{-2}s^{-1}$ only. More precisely, the luminosities that could be achieved would be $2\cdot 10^{35}$ $cm^{-2}s^{-1}$ for a Deuterium target 10^{34} $cm^{-2}s^{-1}$ for Xenon and heavier elements. This could be obtained in a ring comparable to PEP or PETRA with 800 mA circulating and a beam lifetime of only 30 minutes.

The most suited solution is the use of a linear accelerator (linac), which will permit to get the luminosity, the duty-cycle and the beam quality required. A 100% duty-cycle implies the use of RF superconductivity. In addition, a significant cost reduction can be obtained by reducing the linac length and, so, by recirculating the beam as in CEBAF. Nevertheless, the number of recirculations will be limited by the balance between beam recirculation lines cost and linac cost, but also by the effects of synchrotron radiation: the highest is the number of passes, the largest must be the radius of the recirculating system. For the same reason (synchrotron radiation), two-linac machines are larger than a single linac one, and such scenarios are not optimized for this range of energy. Studies on cost and its optimization have shown that there is a flat cost minimum for 3 or 4 passes in a linac, the simplest case being 3 passes, in terms of operability and reliability. Thus a 3 pass single linac racetrack has been chosen.

4. Machine overview

A general overview of the machine is given in Fig. 1. Three beams are simultaneously present in the linac but transported separately in the recirculation system. A 0.5 GeV beam is injected into the 5 GeV linac. At the exit, the beam is directed toward the linac entrance for a second pass and, then, for a third one, leading to a final energy of 15.5 GeV. At the linac exit, the beams are separated in the vertical plane by a magnetic system, called the spreader, according to their energy. This spreader permits also to share the beam between three users (see paragraph 6). There are two recirculating beam lines made of two identical 180° arcs and of a long straight section. Before reentering the linac, the beam are recombined on the same trajectory.

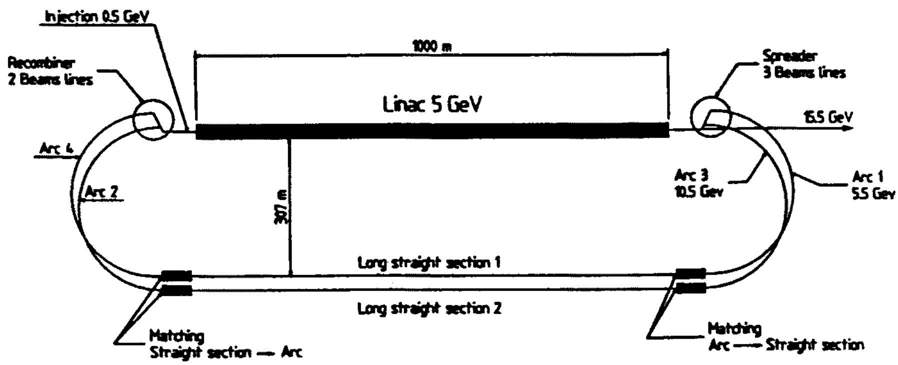

Fig. 1. General overview of the accelerator, showing the different subsystems

5. Acceleration

In order to get a good beam quality, beam dynamics issues have been studied carefully and can be summarized in two parts.

5.1. Recirculating system

In this part where the beams are transported separately, the problems concerning focusing and correction of central trajectory are quite similar to those which arise in classical beam transport systems. The main issue is here the limitation due to synchrotron radiation. Its consequences on emittance growth can be controlled by increasing the magnetic radius but also by using an appropriate focusing lattice. In our case, the dominant limitation comes from energy spread, for which the only cure is the increase of the magnetic radius. This leads to a 60 m value in the 10.5 GeV arcs for a lattice which remains simple.

General studies and simulations have been performed on the recirculator to study the effects of synchrotron radiation [7] and of misalignments of optical elements. They have shown that this design is satisfactory. Tolerances have been calculated, showing, for example, that an RMS transverse positioning error of 0.2 mm is needed for quadrupoles. This value is reasonable.

5.2. Linear accelerator

This part is different from the previous one. One must deal now with three simultaneous beams in the same 1 km long focusing structure and one has to provide:

* a good beam confinement, meaning a small enough beam size and a good acceptance (maximum acceptable emittance) for each pass. It has been shown that the choice of a constant betatron phase advance (120 degrees per FODO cell) and of a 0.5 GeV injection energy are satisfactory.
* a good stability of the central trajectory. It has been demonstrated that correction schemes exist, which permits a simultaneous and good correction of each pass. An example is given in Fig. 2.

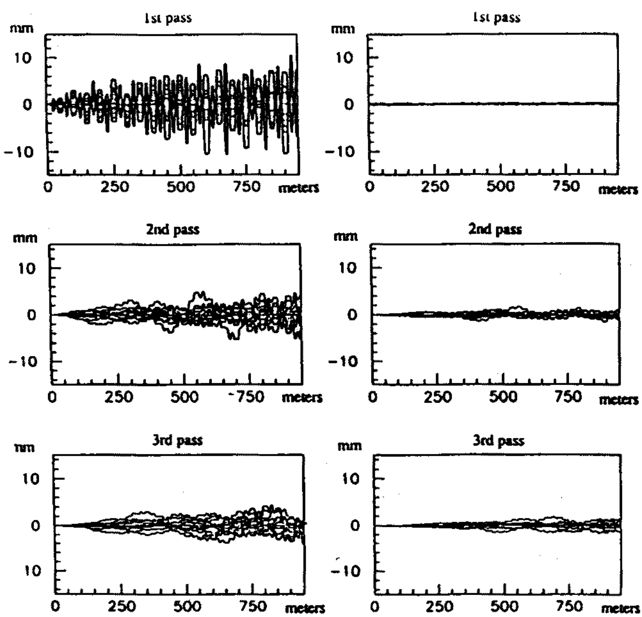

Fig. 2. Simultaneous correction of the three central trajectories inside the 1 km linac.

As it was the case for the recirculating system, the linac focusing does not lead neither to a major difficulty nor to strong constraints on some parameters.

Studies on RF superconducting cavities have been done within the TESLA worldwide collaboration. For this future linear collider, accelerating gradients of 25 MV/m are aimed, but for only 0.1% duty-cycle, which is not the case for the present proposal.

Experience gained during the building of many machines like CERN, DESY etc. shows that RF superconductivity is a mature technology, even if it is far from its limits. Much progress have been done recently. For example, figure 3 shows very encouraging results from the CEBAF cavities [8], the result being very far from the initial design value. It shows that the quality of the industrial manufacturing of such cavities is very good. Similar results have been found on nine-cell cavities at Cornell and Wuppertal. For the present project, the following choices have been done for the linac:

TABLE I

Summary of linac parameters

Injection energy	0.5 GeV
Energy gain per pass	5 GeV
Averaged accelerating gradient	5 MeV/meter
RF frequency	1.3 GHz
Filling factor	$\geq$ 50%
FODO cell length	24 m
Betatron phase advance per cell (first pass)	120 degrees
Cells per cavity	9
Frequency	1.3 GHz
Temperature	2 K
Accelerating field	10 MV/meter
Quality factor	$4 \cdot 10^9$

It is very important to note that the highest available gradient is not necessarily the optimum gradient that should be used. The RF dissipation in the cavity wall is proportional to

* The duty-cycle used.
* The wall surface resistance, which decreases when the quality factor increases.
* The square of the accelerating gradient.

Cost optimization calculations have shown that there is a flat optimum between 10 and 15 MV/m, the choice of 10 MV/m being a safe choice and preserving some margin for a future accelerator upgrade. In that case, about 20 kW losses are foreseen, leading to a 50 MW cryogenic plant, and going to higher gradients with the same duty-cycle will lead to a huge cryogenic system.

A schematic description of the linac layout is given in Fig. 4.

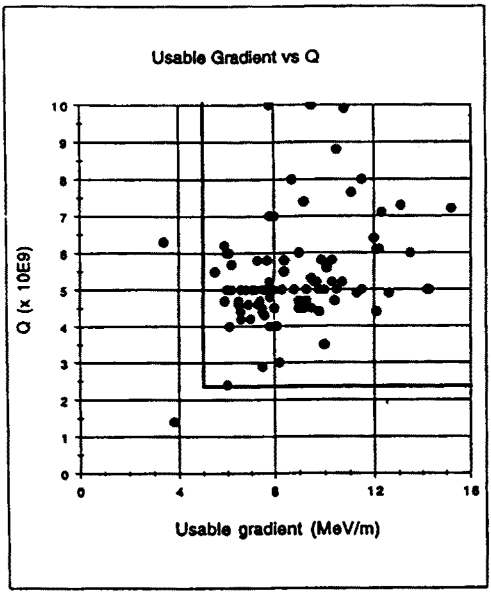

Fig. 3. Statistics on 5 cells cavities at CEBAF (vertical test) [8]

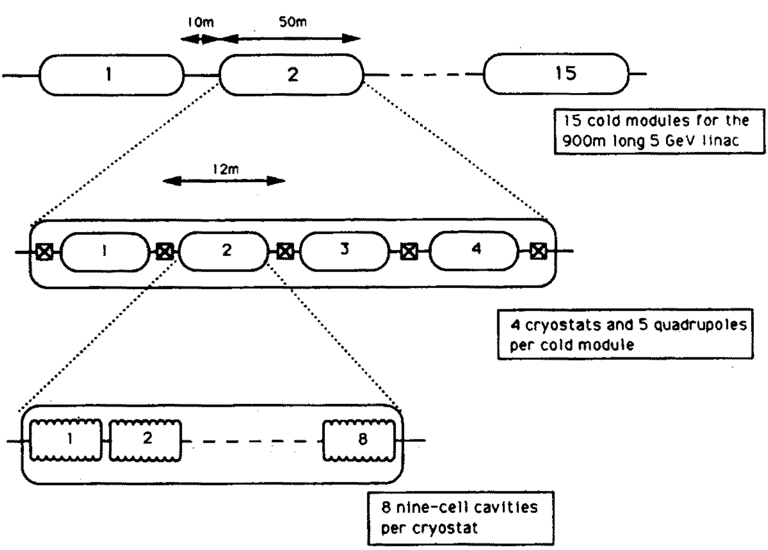

Fig. 4. Linac layout

6. Beam sharing and experimental areas

There are 3 end stations in this facility:

* End station F (for *Forward detector*) for experiments needing the detection of particles in the forward solid angle only, with an intermediate luminosity and a moderate momentum resolution:
* End station Ω (for *large solid angle*) equipped with a 4π detector for a full solid angle detection capability, at the price of a reduced luminosity and a moderate momentum resolution.
* End station S (for *Spectrometers*) equipped with a pair of high resolution spectrometers allowing high luminosity and high momentum resolution.

Beam sharing is not an obvious problem for such energies, due to the beam rigidity and the strong requirements on emittance and energy spread. As described in Fig. 5, beam sharing between two or three end stations is performed by magnetic kickers or pulsed magnets on a 1 second typical time scale. The switching occurs during >10 ms beam-off periods. The available energies are E_{max}, 2/3 E_{max} and 1/3 E_{max}.

This solution is based on the following hypotheses: An end station is in an acquisition phase, and needs the maximum available duty cycle at a well fixed energy. Another is in a testing phase, and can accept a pulsed beam (thus a reduced effective duty cycle) and an energy correlated to the previous one. The third end station is under development: free access for people is required and no beam is asked.

7. Towards 31 GeV

As said before, the main influence of synchrotron radiation is on energy spread rather than on emittance increase. The total energy spread is the quadratic sum of the contributions of synchrotron radiation, depending on the final energy and on linac fluctuations, which do not depend on the final energy. Calculations done from the Physics requirements show easily that the available margin for synchrotron radiation is in fact greater at 31 GeV than at 15 GeV and this leads finally to the same size for 31 GeV. The magnetic field in magnets has then to be doubled, from 0.6 to 1.2 T in dipoles and from 11 to 22 T/m in quadrupoles. In any case, this remain possible with a classical technology and all magnetic elements have been foreseen to be used for a 31 GeV final energy.

Doubling the linac energy is less obvious and will depend on the evolution of RF cavities technology. The gradient will have to reach 20 MV/m and keeping the same duty-cycle will increase the cryogenic power needed if the quality factor is not multiplied by a factor 4. This is not foreseen

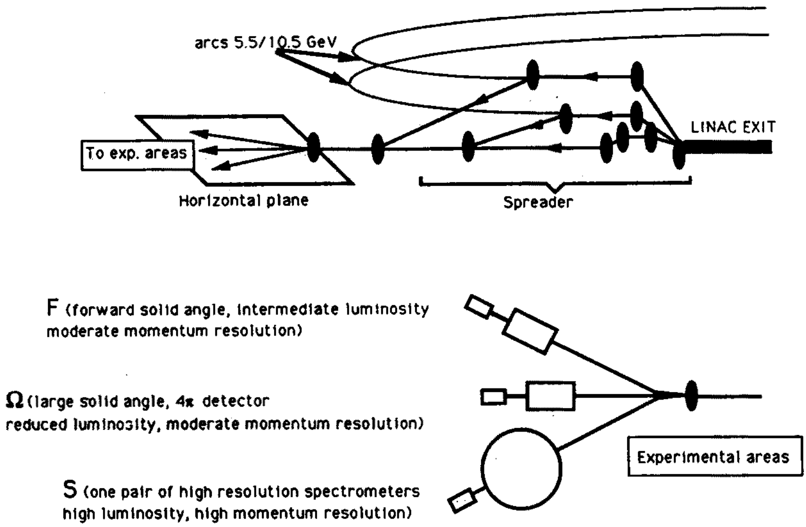

Fig. 5. Beam sharing and experimental areas

in a near future, but this machine is very flexible in terms of energy and duty-cycle. An appropriate choice has then to be done between gradient, quality factor and duty-cycle.

8. Cost (preliminary, subject to some changes)

The cost of the facility is summarized below, in Mega French Francs, taxes not included. Not included also: spare parts, contingencies, salaries, detectors, data acquisition system, cafeteria, roads etc.

The Accelerator..1481 MFF
Accelerator buildings (civil eng included).........240 MFF
Conventional facilities (cooling system etc.).....120 MFF
Exp. Areas...228 MFF
TOTAL...2069 MFF

These estimates are maximum. Three passes is a good choice (optimum is 3 or 4 passes) and nothing significant can be gained on the cost of the recirculation system, which is a well known technology. On the contrary, technical work is needed on cryomodules design and on superfluid helium technology, and one can reasonably expect a cost reduction in this part of the project.

9. Conclusion

The scheme proposed here has been chosen after careful studies concerning its feasibility and is considered as the most adequate solution after examination of a lot of alternatives. It results from intensive studies at the European level and fulfills all the Physics requirements, in terms of beam intensity, energy, quality, luminosity, and flexibility (beam sharing). It does not lead to important problems for beam transport, for which the main issues have been identified and solved.

Important progress has been done (and is expected) in the RF cavities domain. The intensity of $50\mu A$ leads neither to beam instabilities in superconducting cavities nor to an overexpensive radio-frequency system.

The scenario presents a good flexibility for future energy upgrades in the range 15–31 GeV and allows the implementation of any future technological improvement.

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