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INTRODUCTION

The experiments[1,2,3] in which low energetic protons were cooled by a "cold" electron beam have proved that this method is a very powerful technique to improve low energy beams and to increase their phase space density by several orders of magnitude in short times. The theoretical understanding of the cooling process is well advanced[4,5,6]. The applications of this technique, which was invented and developed in Novosibirsk, are manifold[7]. It seems to be clear that its main domain is the cooling of non-relativistic ions. However, also at extremely high energies, cooling of protons and antiprotons with stored electrons (cooled themselves by synchrotron radiation) can be contemplated[8,9].

The main virtue of this method is its high rate of phase space compression. It enables the stacking and accumulation of "hot" ion beams and provides a powerful counteraction against beam blow-up due to residual gas and intrabeam scattering. Its application allows the operation of thin internal targets even at low energies. The achievable high phase space densities enable loss free deceleration to very low energies.

After the initial experiments to study and understand the cooling process, this method can now be considered as a conventional accelerator technique complementing the stochastic cooling[10]. In the following we discuss its use[11] in LEAR[12].

APPLICATION OF ELECTRON COOLING IN LEAR

The strongest case for electron cooling in LEAR is its use during internal target operation[13]. An enormous gain in efficiency and beam properties can be achieved by compensating the beam blow-up and the energy loss due to repeated passages through the target. These effects increase with decreasing energy, which makes electron cooling even more important. Of further advantage is the small interaction vertex, the high energy resolution and the high luminosity that can be obtained by combining electron cooling and internal target operation. This is of extreme importance for experiments below 200 MeV/c. In this case experiments with external $\bar{p}$ beams suffer very much from the low efficiency and the bad resolution.

The use of electron cooling in the stretcher mode is also of advantage in the low energy region of LEAR operation and would complement the stochastic cooling in an efficient way[10]. The small emittances and the low momentum spread achievable with electron cooling would facilitate the LEAR operation down to 100 MeV/c and possibly allow further deceleration to even much lower momenta. This is of great importance for stop experiments, since it would enable the use of very small and thin targets. The simultaneous operation of electron cooling and ultra slow extraction has not yet been studied in detail and electron cooling is envisaged to operate only before extraction, possibly intermittently. However, there exist some ideas to realise this operation. During ultra slow extraction only transverse cooling is required and longitudinal effects should vanish. Continuous transverse cooling during extraction would prevent the increase of beam emittances and retain the small beam size during the full spill. One possible way to achieve this is to fit the electron velocity profile to the momentum dispersion of the $\bar{p}$ beam in the cooling section. We are studying the possibility of extracting the $\bar{p}$ beam slowly by means of electron cooling, using the drag force to pull the antiprotons in the extraction resonances.

Moreover, the use of electron cooling in the co-rotating beam mode[14] is of importance in order to decrease the H^- losses and to increase the formation of $\bar{p}p$ atoms.

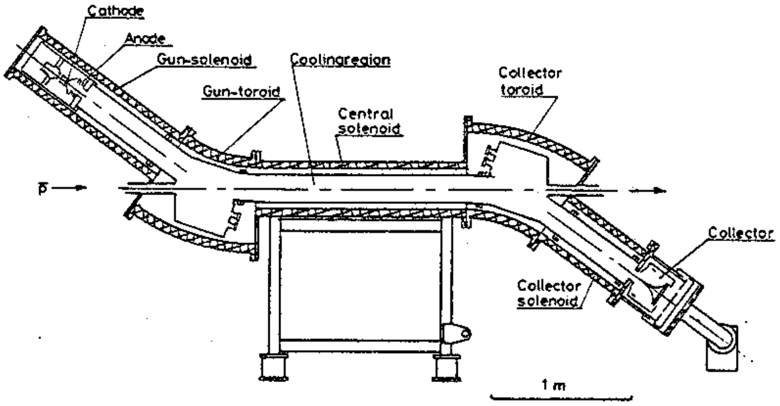

Fig. 1 - LEAR Electron Cooler

THE LEAR ELECTRON COOLER

The electron cooling apparatus for LEAR is shown in Fig. 1. It is an improved version of the ICE experimental set-up[2] adapted to the requirements[11] of LEAR. The 2" cathode, which is at negative high potential is situated on the axis inside the gun solenoid magnet. Electrons emerging from the hot cathode (1350°K) are accelerated by five ring shaped electrodes of increasing potential to their nominal energy which they reach at the entrance of the gun drift tube (Fig. 2). The electron beam is prevented from blowing-up by the solenoid field and retains its size of 5 cm diameter with a practically homogeneous density distribution. The electrons follow magnetic field lines through the adjacent toroidal section, where they are bent into the antiproton beam, through the central solenoid and the collector toroid to the collector solenoid. At the end of the section the electrons are decelerated to a few keV and distributed over the collector pot (Fig. 3) in the rapidly decreasing magnetic field with the help of an axial deflector. The electron trajectories were calculated with the help of the SLAC trajectory program[15]. In this way up to 98% of the beam current is recovered. The principles of the electron gun and collector are retained from the ICE set-up. They are described in detail in Ref. 2 and 11. There are, however, slight changes in the final design for LEAR.

Initially the cooler will be operated in the range between 3 and 40 kV ($\beta = 0.1 \div 0.36$) with space charge limited electron emission. The cooling length of 1.5 m is a factor of two lower than in the ICE experiment. This fact focused our attention to the improvement of the electron beam quality and in particular to the form of the magnetic field at both ends of the cooling section. Special correction coils were made to reduce the "end effects" to a tolerable level. At

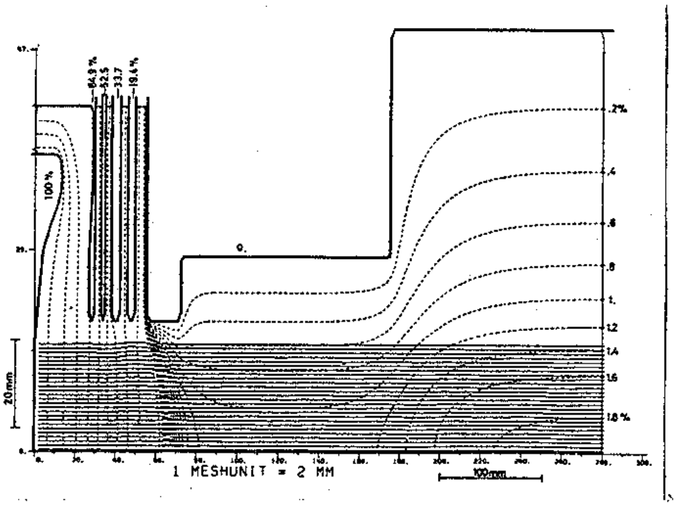

Fig. 2 - The LEAR Electron Gun. Calculated electron trajectories (full), and electric potential lines (dashed) in a constant longitudinal magnetic field. Potentials are given in percent of the cathode high voltage.

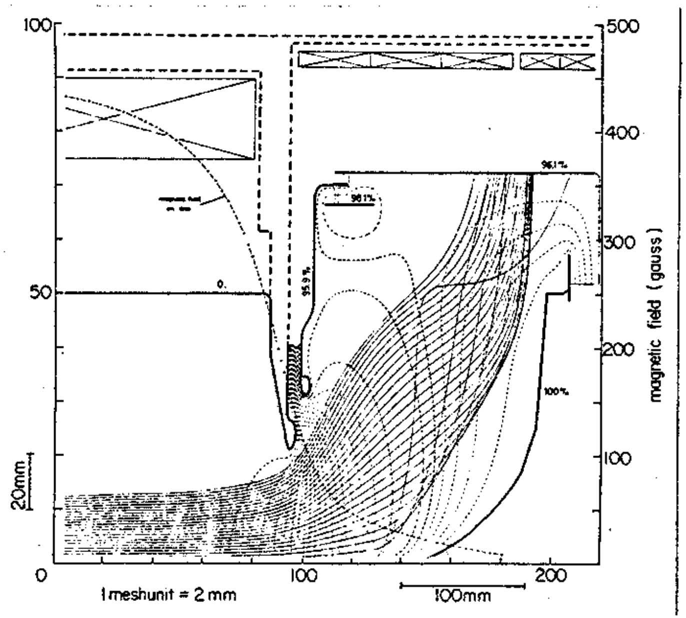

Fig. 3 - The LEAR Electron Collector. Calculated electron trajectories (full), electric potential lines (dashed, percentage of cathode high voltage) and the magnetic field on the axis (dashed-dotted).

present a highly stabilized HT power supply is been built to meet the requirements[16] for efficient cooling.

The stringent vacuum conditions in LEAR require a redesign of the cooler vacuum system which is in progress. The cooler will be equipped with improved old and additional new diagnostic systems to allow an efficient control of the electron beam in the cooling process.

During electron beam studies and performance tests outside LEAR the apparatus will be manipulated with a computerized control system. After installation in LEAR it will be linked to the LEAR serial control highway.

A computational simulation of the electron cooling process in LEAR, taking into account intrabeam and residual gas scattering and the effect of an internal target, is in preparation[17]. This will allow us to anticipate the evolution of beam properties and to optimize cooling.

EXPECTED OPERATIONAL PERFORMANCE

Initially it is intended to operate the cooler in the low energy region where it is most urgently needed. Operation will be possible in the momentum range between 100 MeV/c and 370 MeV/c. Depending on the history of the injected beam (injection energy, stochastic pre-cooling), electron cooling could be applied first at the highest electron energy followed by deceleration to the working energy and further cooling of the adiabatic blow-up. In many cases cooling at the working energy might be sufficient.

STRETCHER MODE

Electron cooling in this mode facilitates the achievement of lowest extraction energies with beams of small emittances. If ever LEAR is operated in shorter cycles than 10^3 s the fast cooling times of electron cooling are of great benefit.

Initially electron cooling will be switched off during ultra slow extraction by stepping away the gun high voltage. As mentioned before, however, schemes are investigated to have continuous cooling.

From the experience gained in ICE we expect to achieve e-fold emittance cooling times of the order of 2 to 5 s at 300 MeV/c. The momentum cooling should be faster by a factor of about 4. This estimate depends somewhat on the initial beam size and the number of stored particles and assumes that the reduced cooling length can be compensated by a correspondingly higher electron current. As equilibrium emittances we expect values of at least 1 π mm mrad. The momentum spread should be cooled down to approximately 10^{-4}. The cooling times increase at lower energies as β^{-2} for a constant perveance gun which is easy to operate during the deceleration procedure. However, if necessary, we could change the perveance at low voltage to obtain a higher electron current. Equilibrium emittances should be rather independent of the beam momentum. With these prospects, it should be clear that electron cooling is of particular importance for the extraction of a cold antiproton beam at 100 MeV/c and eventually for a further deceleration in LEAR or any other device[18-20] to even much lower energies.

INTERNAL TARGET OPERATION

For the operation of an internal target at low energies, the use of electron cooling is of vital interest to compensate multiple scattering and energy loss of the beam in the target. Small beam sizes leading to a high brilliance and a long beam lifetime can be obtained.

The optimum target thickness for a maximal duty cycle is given when equality between antiproton consumption and accumulation rate is reached. This criteria fixes only the product of target thickness and beam intensity. It is shown in Fig. 4 for various acceptance angles at the target position[21]. Other constraints, however, determine the optimum combination of these two values. There are, for instance, the maximum feasible target densities (presently few 10^{-10} g/cm^2 for continuous molecular cluster beams), the desired beam size and the momentum spread of the beam. The beam size is determined by the equilibrium between multiple scattering and cooling rates. The required cooling time had been calculated[22] for various energies and a target density of 2.10^{-10} g/cm^2 and is shown in Fig. 5. The equilibrium emittance for various combinations of cooling times and target densities are plotted in Fig. 6[21]. The equilibrium momentum spread depends mainly on the stored beam intensity and the counteracting of cooling against intrabeam scattering. Hence for small interaction volumes a low target density and a high beam current should be chosen, while for ultimate momentum resolution lower beam intensities should be combined with thicker targets. A more detailed estimate can only be given when the exact operation conditions are known. However, it is clear that extremely short cooling times are needed for the operation at lowest energies.

A typical operation scheme[21] could be as follows :

- Injection of $\bar{p}$ beam and stochastic precooling,

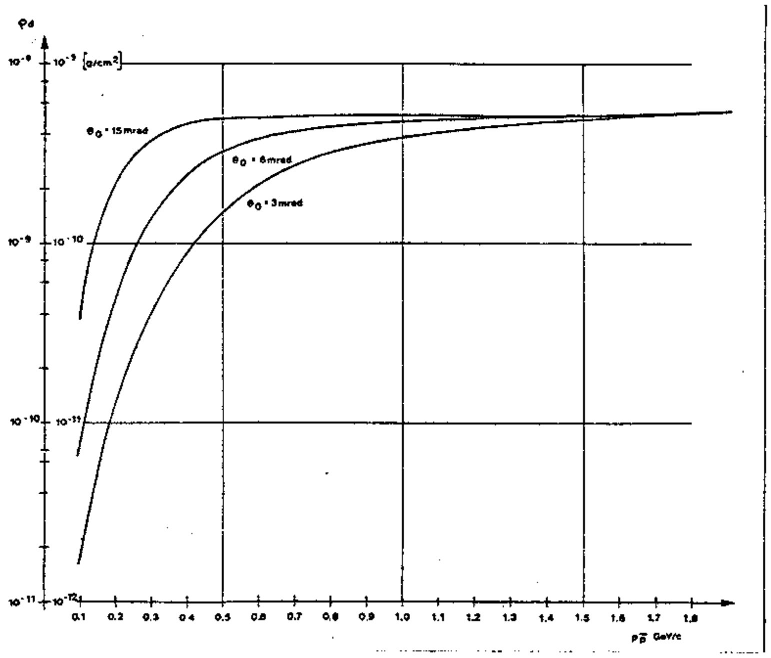

Fig. 4 - Optimal internal target density for an antiproton consumption rate of 10^6 $\bar{p}$/s and for three machine acceptance angles at the target position (Ref. 21). Left ordinate (thick target): number of stored $N_{\bar{p}} = 10^9$, beam decay time $\tau = 10^3$ s. Right ordinate (thin target): $N_{\bar{p}} = 10^{10}$, $\tau = 10^4$ s.

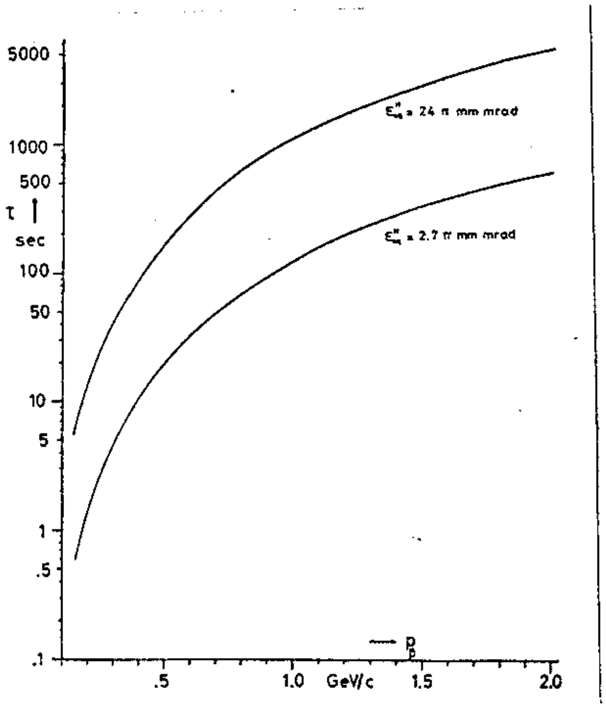

Fig. 5 - Required cooling times to obtain a horizontal equilibrium beam emittance of 24 π mm mrad and 2.7 π mm mrad respectively when operating with a 2.10^{-10} g/cm² thick internal target (from Ref. 22).

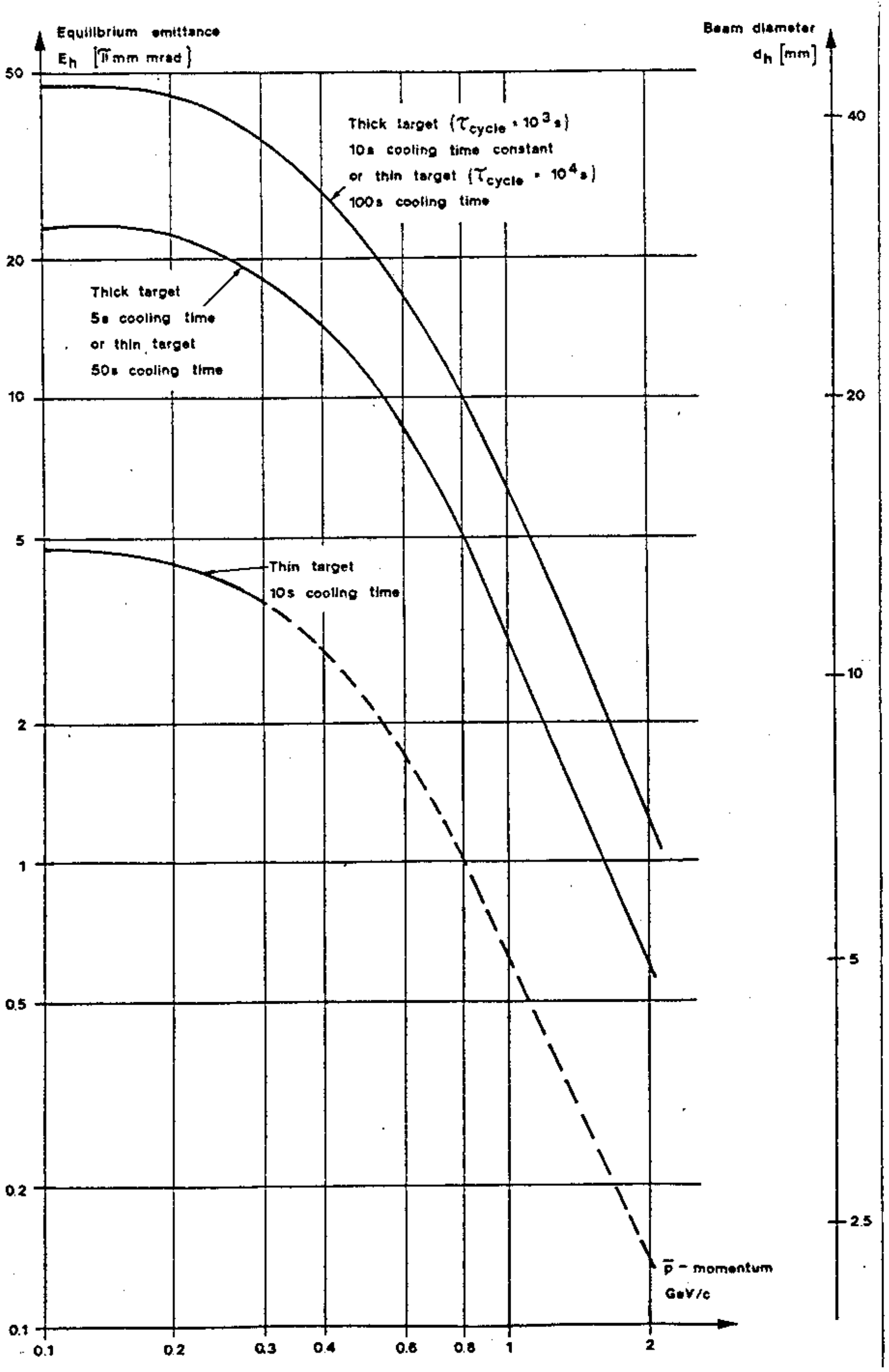

Fig. 6 - Equilibrium horizontal $\bar{p}$ beam emittance (left ordinate) and diameter (right ordinate) for "thick" and "thin" targets and various cooling times (from Ref. 21).

- Deceleration to the working energy and cooling of the adiabatic blow-up,
- Turning on of the internal target and continuous electron cooling.

At the end of the cycle the target is switched off and the new fill is prepared. For the whole operation the electron cooler can be kept always at the working energy. It should be noted that by means of acceleration and deceleration with the electron beam at a rate of 100 keV/s scans around a certain momentum can be performed with high accuracy. Moreover, the $\bar{p}$ beam momentum can be determined very accurately from the electron gun high voltage.

CO-ROTATING BEAM MODE

In this operation H^- and $\bar{p}$ beams can be cooled simultaneously by electrons. Loss free cooling of H^- is possible if the energy difference between H^- ions and the electrons is below the H^- neutralisation threshold (0.75 eV). Hence initially the hotest part of H^- beam will be stripped and the remaining core will be cooled. In addition stripping of H^- ions by other H^- or by antiprotons leads to very rapid beam losses[23]. They can be strongly suppressed if the beams are cooled down below 10^{-4} in $\Delta p/p$ and well synchronised in energy such that their velocity difference does not exceed 10^{-3}. Although H^- and $\bar{p}$ beams will intersect the electron beam at slightly different positions for a non-vanishing dispersion in the cooler, provision can be made that the velocity difference between the two cooled beams does not exceed 10^{-4}. The high cooling rates of electron cooling enable these limits to be passed in rather short time. Furthermore, the small achievable emittance enables a complete spatial separation of the cooled beams except at the achromatic points. The equalisation of the velocities would considerably increase the $\bar{p}p$ formation rate[24].

BUNCHED BEAMS

Electron cooling of bunched beams is possible. This has been demonstrated in experiments in Novosibirsk[1,7] and ICE[2]. Cooling times and equilibrium values may slightly increase. For the cooling of bunched beams, however, a very good matching of electron cooling and RF is required to prevent instabilities. The reliable operation in this mode needs certainly further experimental study.

FURTHER APPLICATIONS

Electron cooling may also be of advantage for the LEAR operation at high energies. Prior to acceleration to high energies the beam could be decelerated to low energy, cooled by electrons to high phase space density and then be reaccelerated, profiting from the adiabatic shrinkage.

With electron cooling of protons the formation of neutral hydrogen through recombination can be studied in detail and the optimal conditions for this process can be determined. This knowledge would be of great importance, if antihydrogen is to be formed by recombination of positrons and antiprotons[25].

Furthermore, electron cooling of $\bar{p}$ and H^- beams gives the possibility of determining the $\bar{p}p$ mass difference with high accuracy[26].

DIAGNOSTICS FOR COOLING

The most important diagnostics during cooling of coasting $\bar{p}$ beams is the observation of the Schottky spectrum, which allows the matching of machine and cooler parameters. Of advantage will be a beam profile monitor to control the beam emittances. When cooling H^- ions, the neutral atoms emerging from the cooling section give an excellent means of diagnostic. Machine developments in conjunction with electron cooling and performance tests are best done with protons circulating clockwise in LEAR. This gives the possibility of using the recombination of electrons and protons as diagnostics for cooling.

OPERATION OF THE ELECTRON COOLER AT HIGHER AND LOWER ENERGIES

A later increase of the gun high voltage to 100 kV (630 MeV/c) is possible but requires some improvement on gun and collector and an upgrading of the HT-power supply. These improvements are partially of technical nature (HT capabilities, insulations, feedthroughs, etc.). The main problem, however, is the required high electron recovery efficiency in the collector. Losses should then be considerably lower to keep the load on the vacuum and on the HT supply at a tolerable level. To achieve this goal the collector probably has to be redesigned. Electron cooling at $\bar{p}$ injection energy would then be possible and a smaller cathode could be used. All other parts of the cooler can remain unchanged.

The operation of the cooler at voltages below 3 kV is straightforward and is much easier than at higher voltages. If LEAR can operate at momenta below 100 MeV/c the electron cooler can be used also there. It should be noted that electron cooling at 0.8 kV gun high voltage (53 MeV/c) had been performed in Novosibirsk and all features of electron cooling had been observed[7].

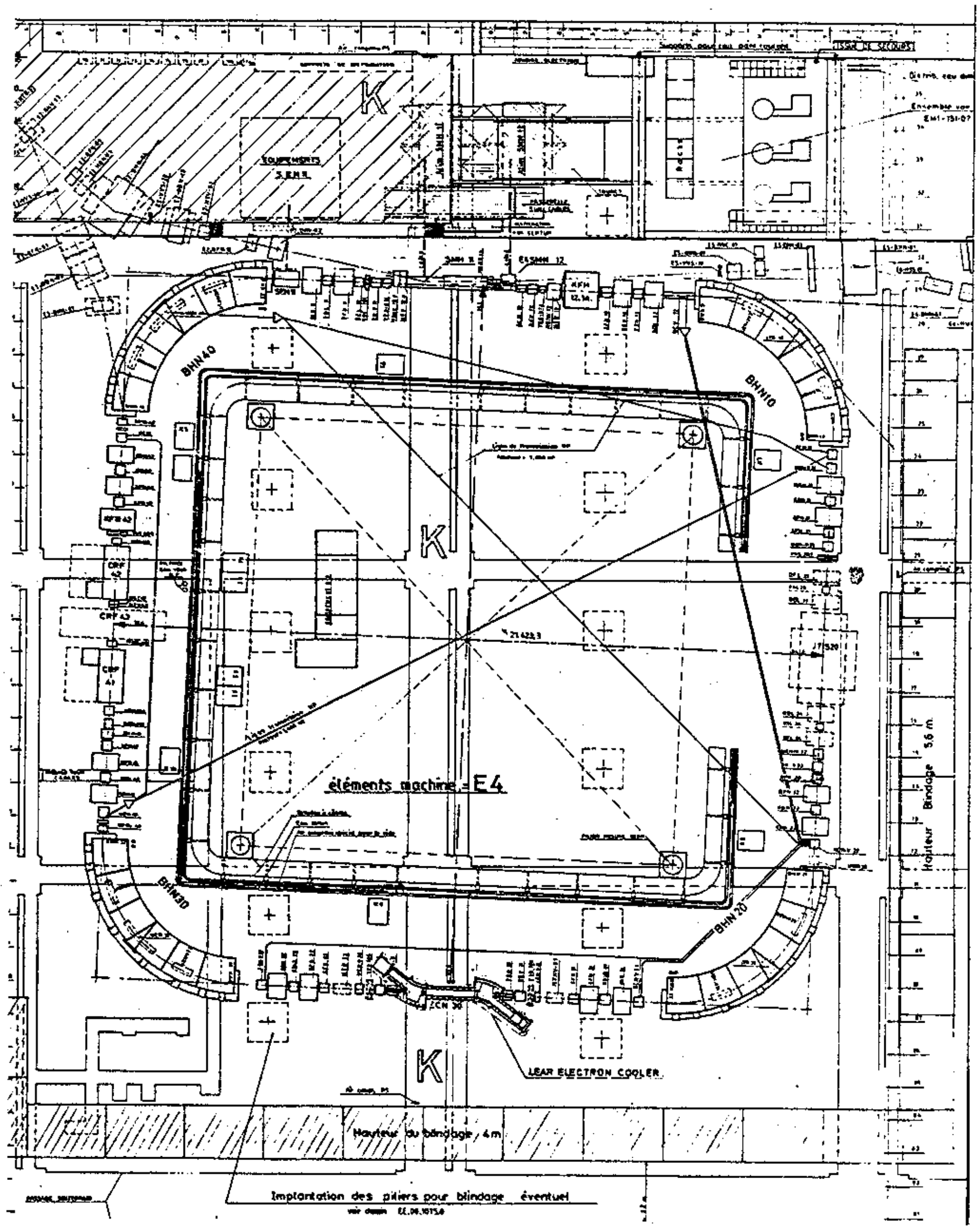

Fig. 7 - The LEAR ring

PRESENT STATUS

Presently the vacuum system of the electron cooler is dismantled and the necessary vacuum improvements are in preparation. The changes of the mechanical set-up have been executed. The main magnetic field system is assembled and the field measurements are completed. A considerable improvement of the magnetic field at the end of the cooling section has been achieved.

The rest of the year will be dedicated to vacuum studies, setting-up of the power supplies and the development of the control hard- and software. We aim at the generation of a first electron beam in a reduced set-up for the end of the year. In the next year the effort will be concentrated on the achievement of the required vacuum conditions for LEAR and the investigation of the electron beam properties. The installation of the cooler in the long straight section 3 of LEAR (Fig. 7) is foreseen around 1985.

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