PS/AA/Note 78-3 22.6.78
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PROTON-ANTIPROTON COLLIDING BEAMS IN THE SPS

Production and accumulation of antiprotons

1. History

The use of beam cooling for collecting large numbers of antiprotons was first proposed by Budker and Skrinsky in 1966. At that time electron cooling looked quite difficult and as a consequence, the idea was not taken up outside Novosibirsk. However, during 1973, we heard the news of the successful cooling tests by Budker's team and in the meantime, stochastic cooling had been developed at CERN to the point where it also showed some promise. Rubbia at CERN then revived the old idea and worked out various schemes using either electron or stochastic cooling. He showed that a reasonable $p\bar{p}$ luminosity could be obtained in the SPS.

During 1976, two working groups examined the technical aspects and the physics possibilities. As a result, an experiment on stochastic and electron cooling was started (ICE) and in parallel a study group was formed to prepare a detailed design.

First, we assumed electron cooling and produced a proposal using two separate rings. Meanwhile, however, stochastic cooling had become more respectable after further theoretical development and many experimental runs in the ISR. A more efficient method of momentum cooling - the so-called filter method - showed promise of making the stochastic solution possible with a single d.c. operated ring. The resulting reduction of cost and complication induced us to go for stochastic cooling even though the cooling would have to be a thousand times faster than it had been in the best ISR experiments. We expected to reduce this large extrapolation factor by the results from ICE.

2. ICE experiments on stochastic cooling

ICE (for Initial Cooling Experiment) is a storage ring of 24 m diameter constructed largely from existing components. In particular, the magnet of the last g-2 experiment was used after some modifications. The machine has four straight sections (fig. 1), most of which are filled with cooling and diagnostic equipment. The mean vacuum pressure is 2 x 10^{-9} Torr, sufficient to reach a beam lifetime of 40 minutes at 1.7 GeV/c.

ICE was started at a time when we still planned to use electron cooling. An experiment similar to the Novosibirsk one was therefore prepared, mainly to get some experience with the special techniques needed for producing low-temperature electron beams. We also foresaw some stochastic cooling tests and these, of course, became more important when we decided to use this technique for the $\bar{p}$ accumulator.

As it happens, cooling in ICE can be much faster than in the ISR for reasons that are well understood, such as ring size, particle intensity, spread of revolution frequency, etc.

We used three independent systems for cooling in the three degrees of freedom: horizontally and vertically (betatron oscillations) and longitudinally (momentum spread). The momentum cooling in particular, was done by the filter method, which we tried out for the first time.

The results were encouraging. They agreed with the theory and reduced the gap between previous experience and what is needed for the $\bar{p}$ ring to a factor 15.

Fig 2. shows an example of momentum cooling. It represents a spectrum analysis of the noise signal from a longitudinal pick-up electrode ("Schottky scan"). The horizontal axis represents frequency, the vertical signal is proportional to the square root of the particle density. The frequency distribution is similar to the momentum distribution because the revolution frequency varies linearly with momentum.

The flat, wide curve represents the initial distribution; after four minutes of cooling, the peaked curve shows how the momentum spread has been reduced and the peak density increased. The shortest initial cooling time obtained was 15 seconds.

Simultaneous cooling in the three degrees of freedom worked without showing any perturbations of one system by the others. The lifetime of the beam was increased to twenty hours, showing that the cooling is stronger than the heating by multiple scattering on the rest gas.

These tests provided useful experience in the techniques needed for the $\bar{p}$ ring design. In fact, it now seems evident that with the parameters foreseen (larger bandwidth, higher power, more pick-up electrodes, etc.) the remaining factor 15 can be obtained.

3. General design features of the $\bar{p}$ accumulator

Antiprotons will be produced in a target by 26 GeV/c protons coming from the PS. They will be focussed by a small horn-type lens (fig. 3)that will do most of the matching between the narrow, large-angle beam at the target and the wide, small-angle beam in the ring. A spectrometer-like arrangement then provides momentum selection so that most of the protons and other unwanted particles are removed from the beam in a collimator (fig 4.). In this way, the ring will not be subject to much radiation and little further shielding is needed in the ring building. The $\bar{p}$ momentum will be 3.5 GeV/c, near the production maximum.

Only a fraction of the antiprotons produced in the target can be caught in the ring, even though its acceptance is made as large as possible. Since the available acceptance is filled up, multiturn injection is out of the question. The ring must therefore have at least one quarter of the PS diameter. This is enough to profit fully from the PS intensity, since techniques exist to concentrate all protons in a quarter of its circumference.

As it happens, a ring for 3.5 GeV/c of this size will just provide sufficient straight section space to locate equipment for injection, extraction and stochastic cooling as well as a RF cavity and diagnostic devices.

The somewhat unusual shape of the ring is a consequence of its use for stochastic cooling. This technique uses the fact that the beam consists of a finite number of particles whose phase-plane density is therefore subject to random fluctuations. The cooling exploits these fluctuations, but also reduces them. To get efficient cooling, it is necessary to reestablish randomness by mixing the particles as well as possible. The mixing is due to the different revolution frequencies of particles with different momentum. It is this spread of revolution frequencies that must be as large as possible for efficient cooling.

To get a large spread of revolution frequencies for near-relativistic particles with nearly equal velocities, the mean orbit circumference must depend strongly on momentum. Techniques exist for obtaining this, but clearly the horizontal beam width due to the momentum spread will be large as a consequence. A wide aperture is then needed; even more so, because we also want a large acceptance.

With such a wide aperture, the injection becomes quite difficult because the injection kicker must produce a large deflection. To avoid this problem, the bending magnets are distributed around the ring in such a manner that while the average dependence of horizontal position on momentum is large, its local value in the two long straight sections becomes zero, so that the beam is small in those regions. The septum magnets for extraction are placed there, as well as the RF cavity. The shape of the ring is the consequence of this.

The 24 focussing quadrupoles are distributed regularly, and will all have the same strength, but those in the regions of small beam size are smaller than the others. The large ones have an aperture of 70 cm whereas they are only 54 cm long. The bending magnets will also be of two types: wide and short, where the beam is wide, long and relatively narrow near the long, straight sections.

In general, the large apertures and the high field precision that is required are offset by the fact that this ring will work at a constant excitation, so that shimming may be used to obtain the required field shapes.

4. Vacuum system

A vacuum pressure of 10^{-10} Torr is needed to provide a sufficient beam lifetime. The negative space charge in the beam will attract positive ions and the resulting neutralization should be kept low. This is because with a fully neutralized beam of the final size the density of the positive ions would be a few hundred times the rest gas density. This would increase the scattering effect by the same factor and might even be the cause of beam heating due to coupled ion-proton oscillations.

Clearing electrodes will therefore remove these ions and provide a sufficiently low neutralization factor (<0.03). The low pressure will be reached by baking techniques as used in the ISR and no problems are foreseen.

5. Stacking and unstacking

To inject each successive pulse, it must be kicked by the injection kicker without influencing the particles already in the ring, in the so-called "stack". This is done by injecting the new pulse at a momentum slightly above the stack momentum. The new pulse and the stack overlap in the long, straight sections, but are horizontally separated at the extraction kicker. The stack is protected from the kicker field by a moveable eddy current shield, or shutter.

After injection the momentum spread of the injected pulse is reduced from 1.5% to 0.2% by a precooling system. This will be similar to the systems used in ICE, but faster; the whole process will take about 2 seconds.

The shutter will then be opened and the beam will be decelerated by the RF cavity and deposited at the top of the stack. Continuous momentum cooling is applied to the stack by a separate system. The particles will slowly migrate to the dense bottom of the stack, making place for the next pulse to be deposited. At the same time, the horizontal and vertical betatron oscillations will be cooled.

After 24 hours of stacking, we expect to obtain a circulating beam of 6×10^{11} antiprotons, representing an anticurrent of 180 mA. The final density will be limited by intra-beam scattering. This effect will transfer energy between the longitudinal and transverse planes in such a way that a general heating is the result. It is strongly dependent on beam size. Fortunately, the theory predicts a final size that is small enough for the purpose although not by a wide margin. In fact, it is this limitation combined with the RF power available in the SPS that will force us to extract the antiprotons in 12 separate batches.

One batch at a time will be captured by the RF system that will superimpose a small bucket upon the stack and accelerate the required amount of particles up to the extraction orbit, which is the same as the injection orbit. This batch can then be extracted without influencing the remaining stack. The process is the inverse of stacking and might perhaps be called "unstacking".

After extraction the antiprotons will be returned to the PS, accelerated to 26 GeV/c and transferred to the SPS. The original design assumed direct transfer to the SPS at 3.5 GeV/c. The present solution was preferred because it reduces the amount of extra construction and machine development needed in the SPS and also avoids some of the problems associated with high-density beams at these low energies.

6. Precooling

Stochastic momentum cooling can be understood as a feedback action by each single particle upon itself, disturbed by the other particles. The disturbing or heating effect varies with the square of the feedback gain because of its random nature, whereas the single-particle or cooling effect varies linearly with the gain. It is therefore always possible to find a gain value low enough to make the cooling predominant.

The feedback is obtained by passing the signal from a longitudinal pickup through an amplifier into a wideband longitudinal cavity called kicker (fig 5.) The cable length is adjusted so that the signal produced by a particle passing the pickup will arrive at the kicker together with the particle. Each particle will then, by its own signal be systematically decelerated or accelerated, depending on the signal phase. The other particles will have a random effect, whose average is zero.

The signal from a single particle is a repetetive series of delta functions. These can be considered as a sum of sine waves, each a multiple of the revolution frequency. As many sine waves as fit within the passband are present.

By inserting a filter into the feedback chain it is possible to make the systematic accelerations dependent on the revolution frequency, i.e. on the momentum. All that is needed is a filter that causes a sudden 180° phase shift at each harmonic of the revolution frequency for the central momentum. Particles on either side of this frequency will then be pushed towards it and the momentum spread will be reduced. Such a filter can be made by using transmission lines with an electrical length equal to half the ring circumference and whose far end is either open or short-circuited. These will present an impedance that is a periodic function of frequency, with a period equal to the revolution frequency.

The feedback gain needed depends on the particle density. At high density the perturbing signal from the other particles is worse and therefore a lower gain is needed. For the precooling system the density is still low and the gain must be high (with a correspondingly high cooling rate). This means a high power wide-band amplifier for the final stage, together with many kicker gaps. To protect the high density stack bottom from this strong feedback system, the precooling pickups and kickers should only see the newly injected beam; they will be separated from the stack by shutters (fig 6).

Of the order of 200 pickups and kickers each 2.5 cm long are foreseen. Partial tests of these devices have already been made in the ICE ring.

Fig 7. shows calculated cooling curves. In 2 seconds, 80% of the particles should be within the required momentum width.

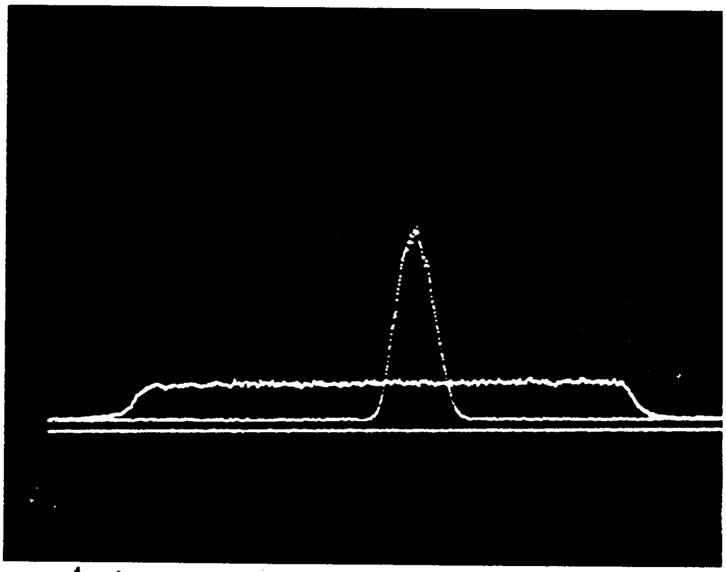
7. Stack cooling

The density at the bottom of the stack will have to be four orders of magnitude higher than at the top, where each new pulse is added. The feedback gain must vary correspondingly with momentum, or with frequency. This cannot be done with filters; the theory predicts instabilities if this were tried. Instead, the dependence of gain on momentum will be obtained by using pickups with a gain depending strongly on the horizontal orbit position. Such pickups would not be suitable for the precooling system because their sensitivity per unit length is low and therefore the signal to noise ratio would be too low. For the stack, this is less important because of the higher particle density.

In total, 32 pickups and about 100 kickers are foreseen. Fig 8. shows the expected density distribution and its development with time as new particles are added to the top of the stack.

The final stack width needed will only be about 1/7 of the width shown in fig 8. At extraction time, the tails of the distribution will contain many particles at densities too low to be used. However, as unstacking goes on at the stack bottom, these particles will not be lost; they will be moved into the stack by the accelerating buckets and will form the beginning of the next stack.

S. van der Meer



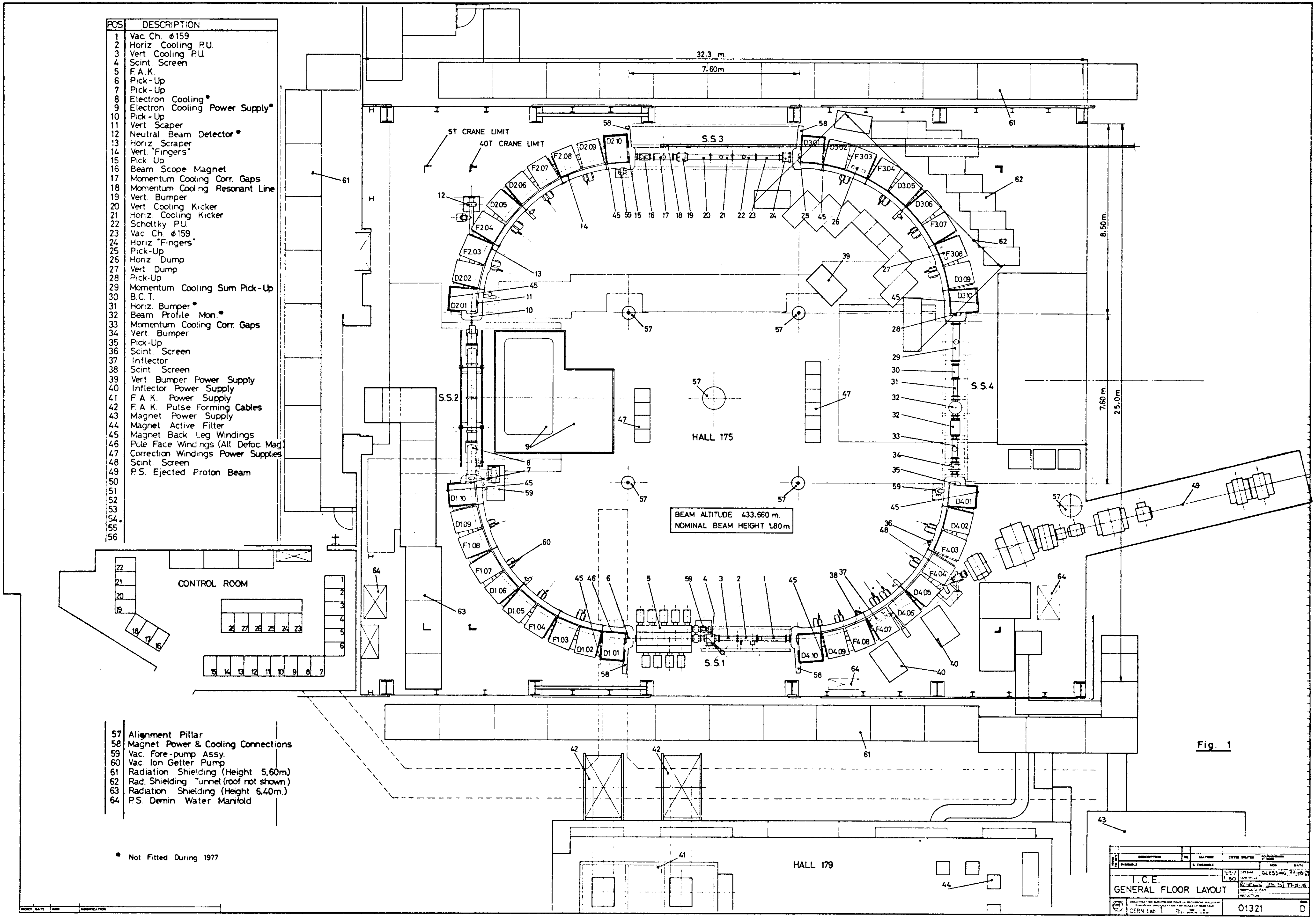
factor 20 in 4 min. $4 \cdot 10^7$

Fig. 2.

Momentum cooling in ICE

Underlined Horizontal scale: 1 cm represents $\frac{\Delta p}{p} \approx 2 \times 10^{-4}$

Vertical scale: proportional to the square root of the particle density $\frac{dN}{dp}$



POS	DESCRIPTION
1	Vac. Ch. ϕ159
2	Horiz. Cooling P.U.
3	Vert. Cooling P.U.
4	Scint. Screen
5	F.A.K.
6	Pick-Up
7	Pick-Up
8	Electron Cooling •
9	Electron Cooling Power Supply •
10	Pick-Up
11	Vert. Scaper
12	Neutral Beam Detector •
13	Horiz. Scraper
14	Vert. "Fingers"
15	Pick Up
16	Beam Scope Magnet
17	Momentum Cooling Corr. Gaps
18	Momentum Cooling Resonant Line
19	Vert. Bumper
20	Vert. Cooling Kicker
21	Horiz. Cooling Kicker
22	Schottky P.U.
23	Vac. Ch. ϕ159
24	Horiz. "Fingers"
25	Pick-Up
26	Horiz. Dump
27	Vert. Dump
28	Pick-Up
29	Momentum Cooling Sum Pick-Up
30	B.C.T.
31	Horiz. Bumper •
32	Beam Profile Mon. •
33	Momentum Cooling Corr. Gaps
34	Vert. Bumper
35	Pick-Up
36	Scint. Screen
37	Inflector
38	Scint. Screen
39	Vert. Bumper Power Supply
40	Inflector Power Supply
41	F.A.K. Power Supply
42	F.A.K. Pulse Forming Cables
43	Magnet Power Supply
44	Magnet Active Filter
45	Magnet Back Leg Windings
46	Pole Face Windings (All Defoc. Mag.)
47	Correction Windings Power Supplies
48	Scint. Screen
49	P.S. Ejected Proton Beam
50	
51	
52	
53	
54	
55	
56	
57	Alignment Pillar
58	Magnet Power & Cooling Connections
59	Vac. Fore-pump Assy.
60	Vac. Ion Getter Pump
61	Radiation Shielding (Height 5,60m)
62	Rad. Shielding Tunnel (roof not shown)
63	Radiation Shielding (Height 6.40m.)
64	P.S. Demin Water Manifold

• Not Fitted During 1977

BEAM ALTITUDE 433.660 m.
NOMINAL BEAM HEIGHT 1.80 m

I.C.E.
GENERAL FLOOR LAYOUT

CERN Lab 1

1:50

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FIG 1

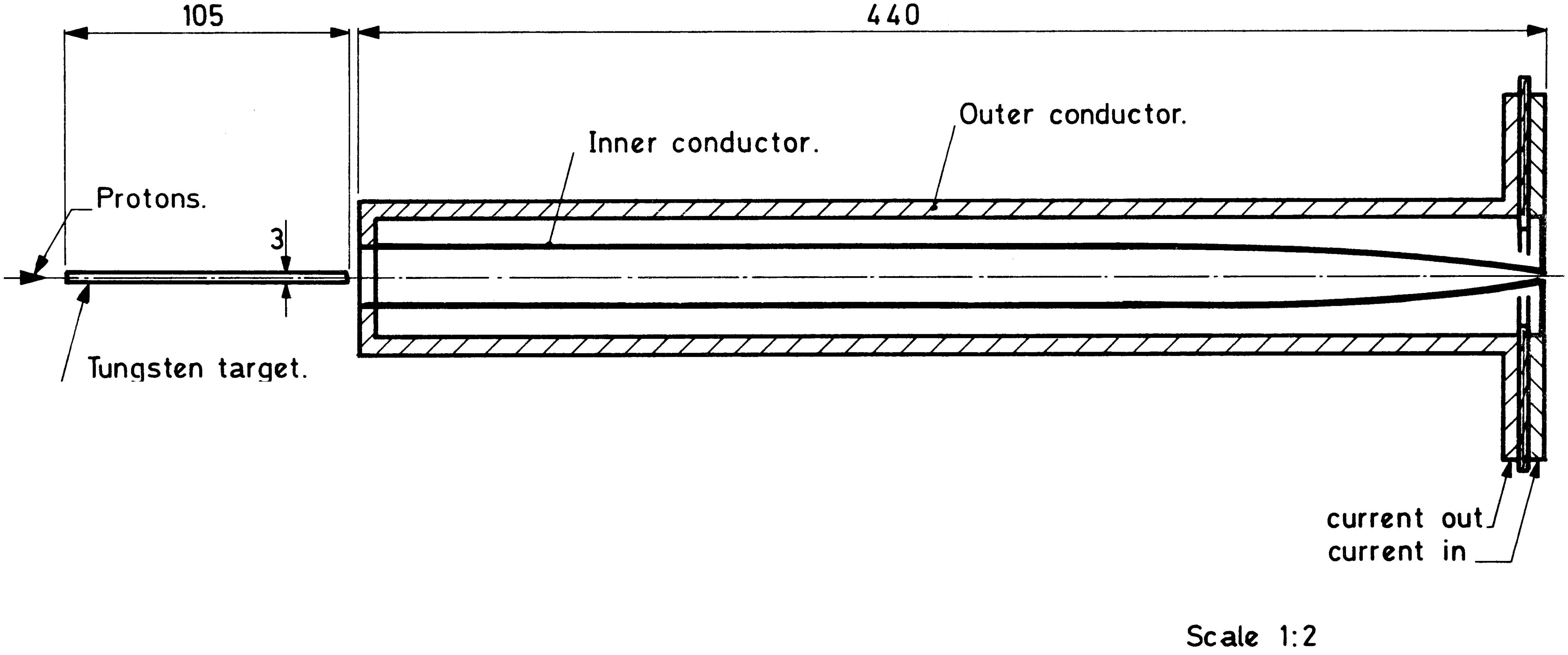

Fig. 3 Cross section of focusing horn.

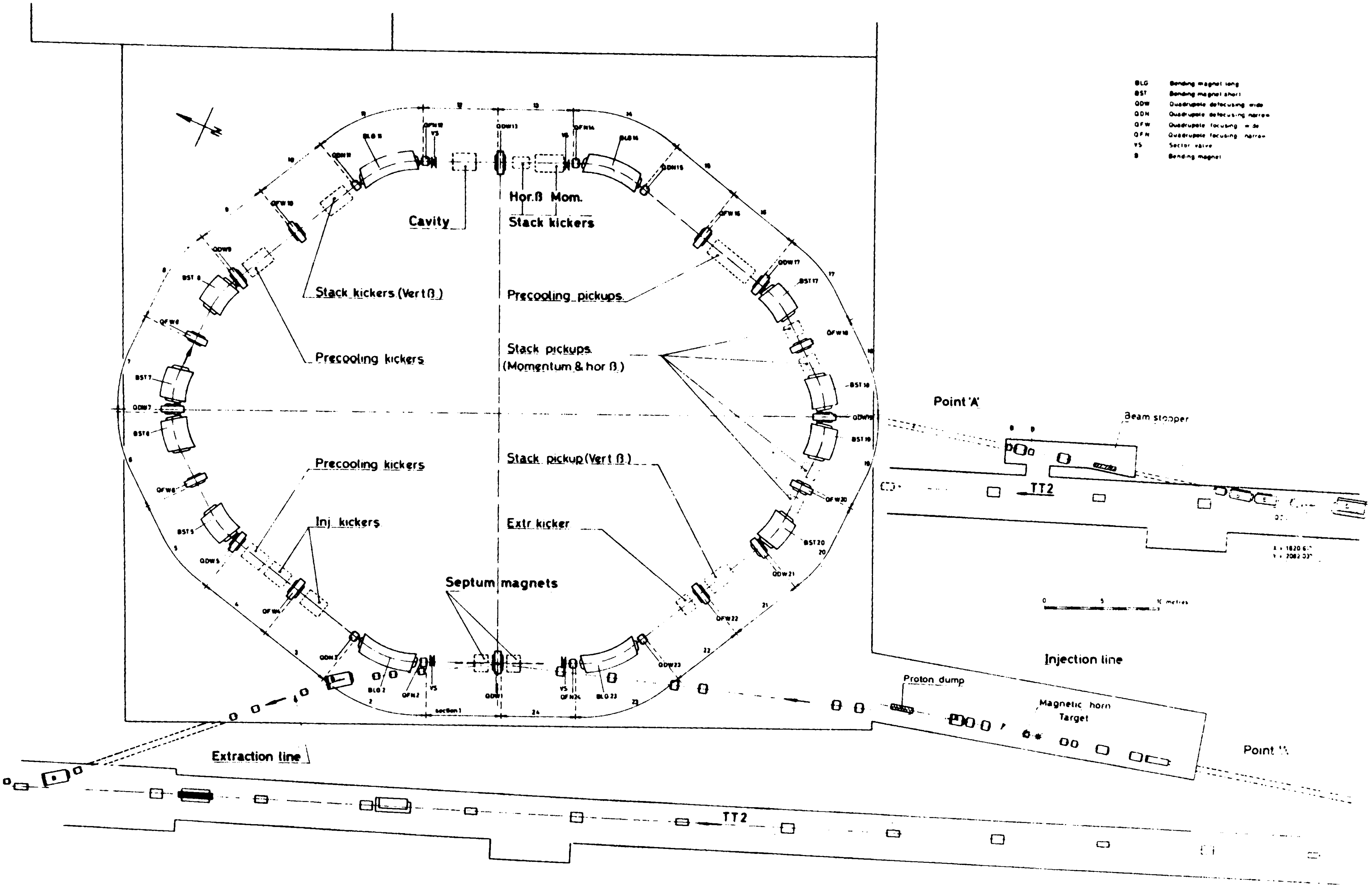

Fig. 4 General Layout Of The Antiproton Accumulator

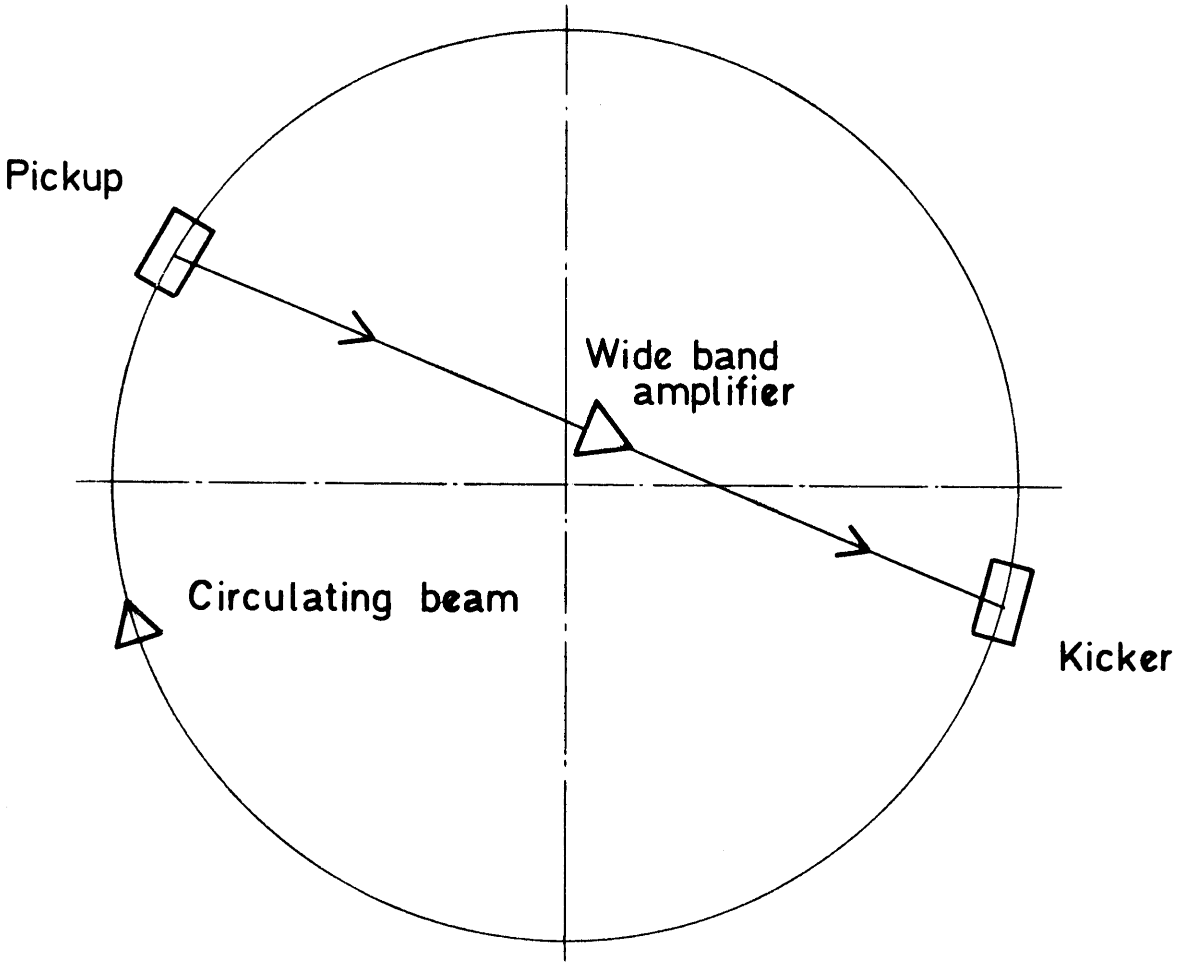

Fig. 5 Schematic representation of a storage ring with momentum cooling.

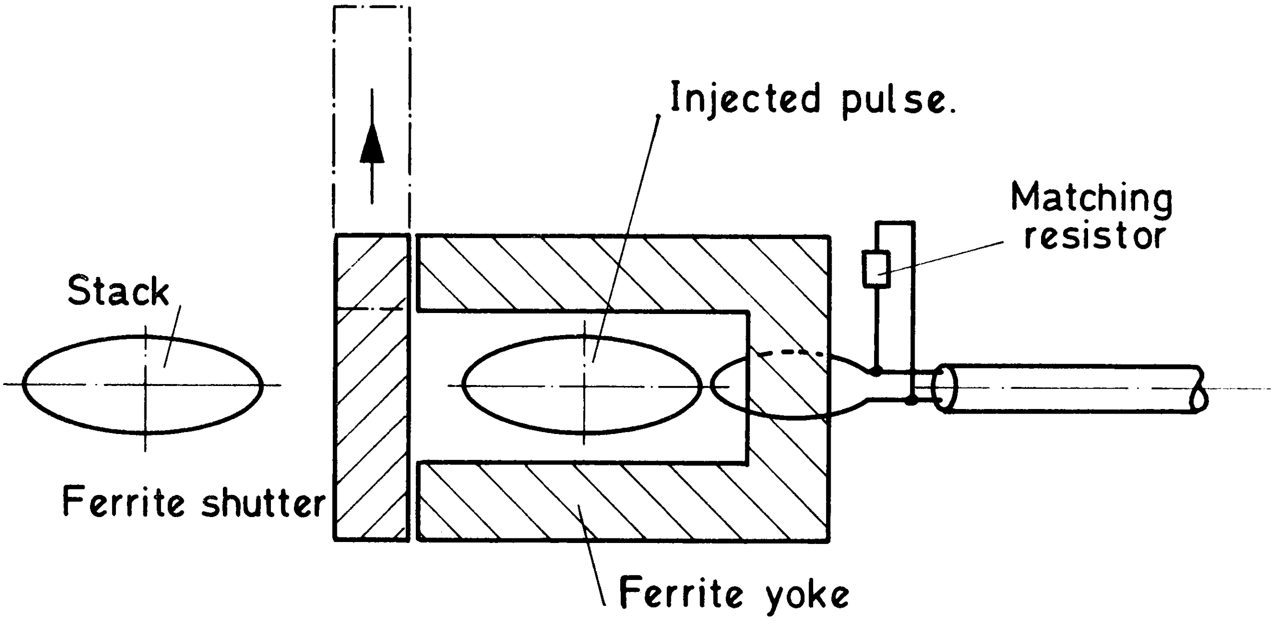

Fig. 6 Schematic cross section of precooling pickup or kicker.

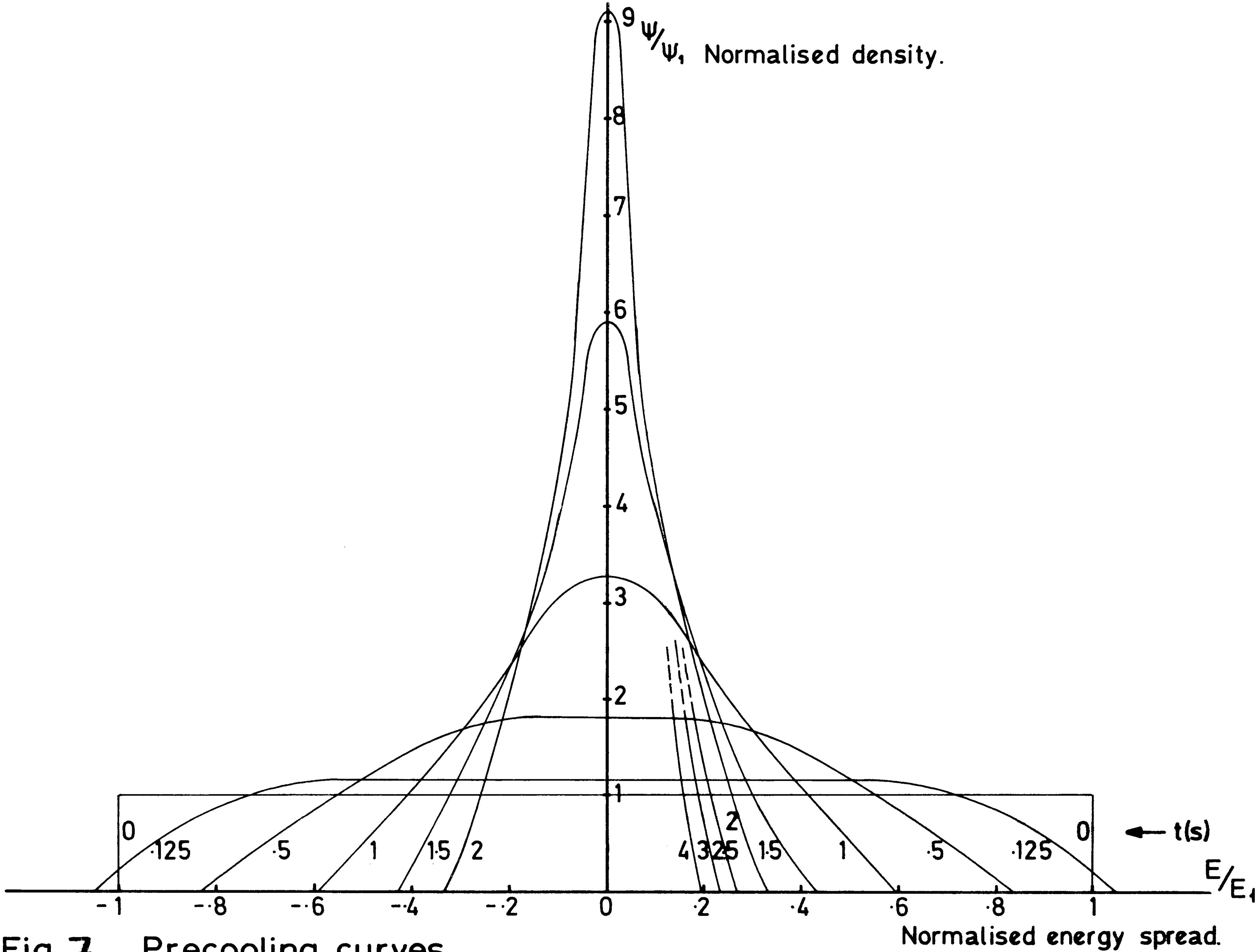

Fig. 7 Precooling curves.

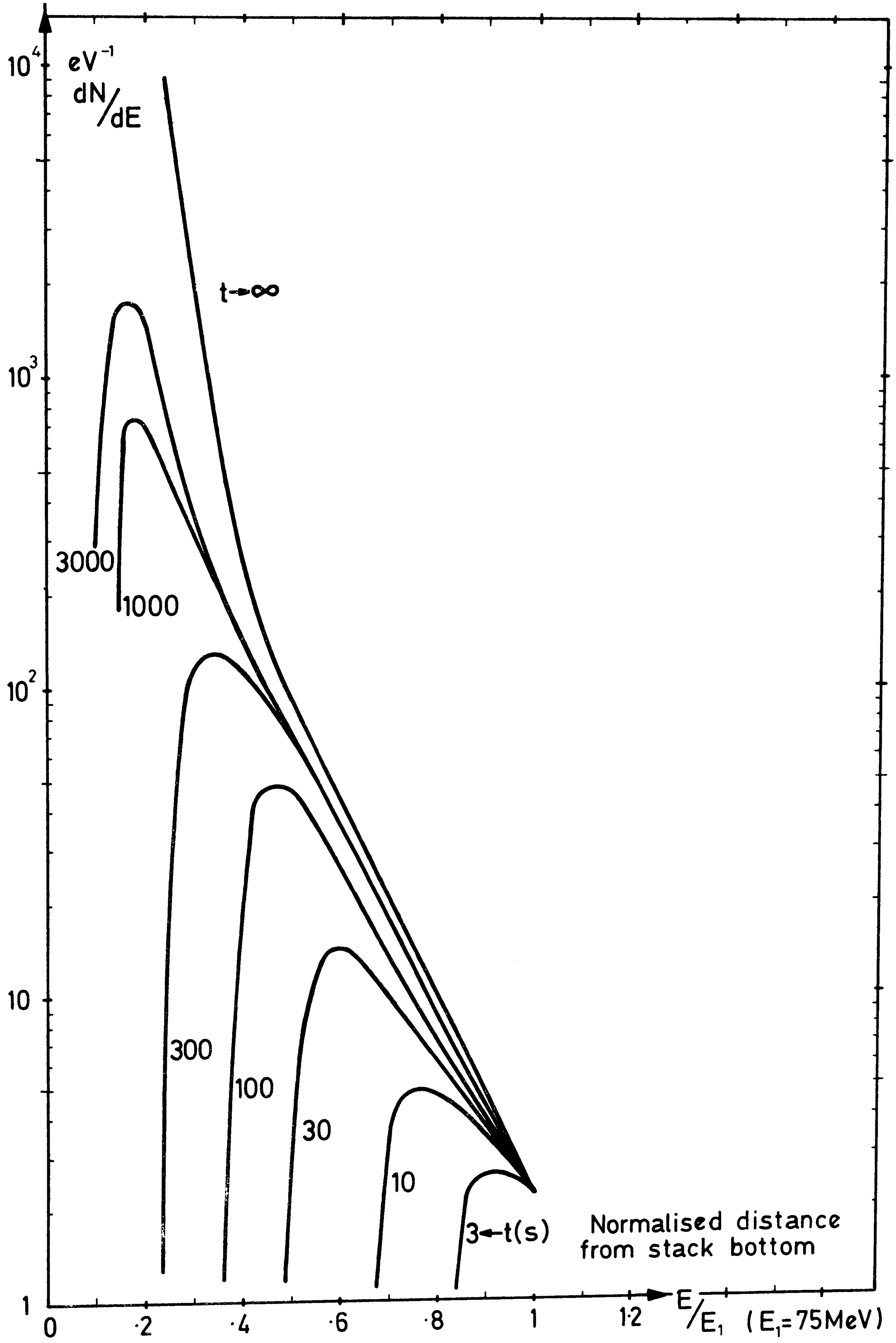

Fig. 8 Density profile of the stack for a constant particle flux towards the stack bottom.