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THE CERN PROTON-ANTIPROTON COLLIDING BEAM FACILITIES

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Introduction

The technique of beam cooling using electrons as a means of collecting large numbers of antiprotons was first proposed by Budker and Skrinsky in 1966. This idea indicated the possibility of achieving high luminosity in colliding $p\bar{p}$ beams.

In 1968 van der Meer proposed a very different cooling technique, known as Stochastic Cooling. Experimental and theoretical studies of electron cooling continued at Novosibirsk and of stochastic cooling at CERN.

Following the news of successful tests of electron cooling at Novisibirsk and the continuing progress in stochastic cooling at CERN, interest was revived in $p\bar{p}$ colliding beam systems and in 1976 Rubbia proposed a variety of schemes using electron or stochastic cooling to collect antiprotons, inject them into the SPS, accelerate them together with protons and collide the beams at energies up to 270 GeV.

During 1976, working groups examined the technical aspects and the physics possibilities. As a result, CERN decided to pursue two courses of action in parallel. One was to construct a small experimental ring (ICE) to study both electron and stochastic cooling; the other was to set up a study group for a complete facility to provide antiprotons in the SPS.

Initially, the study group produced a proposal using two separate rings based on electron cooling. Meanwhile, however, many experimental runs in the ISR together with further theoretical development 1)-5) and a more efficient method of momentum cooling (filter method) indicated the possibility of a solution based on stochastic cooling with a single d.c. operated ring 6). The resulting reduction of cost and complexity induced us to adopt this scheme even though the cooling would have to be a thousand times greater than in the best ISR experiments. Subsequently, this design was confirmed by the outstanding results of stochastic cooling tests on ICE 7) which have reduced the extrapolation factor to 15.

Design Criteria

The project which was approved in July 1978 is to extend the CERN facilities to provide for proton-antiproton colliding beam experiments in the SPS at centre of mass energies up to 540 GeV with a luminosity of 10^{30} cm^{-2} sec^{-1}. This includes the construction of a 3.5 GeV/c antiproton cooling ring, three new beam transfer lines and the excavation of a large underground experimental hall. Subsequently, it was decided to construct a second experimental hall on the SPS ring and another beam line which will allow for transfer of antiprotons to the ISR. The overall site layout is shown in Figure 1.

To achieve a design luminosity of 10^{30}cm^{-2} sec^{-1} at 270 GeV/c it is necessary to collect, cool and stack antiprotons for many hours. Studies of lifetimes showed that, with a factor of ten improvement to the average vacuum in the SPS, a luminosity lifetime of about 24 hours could be expected at 270 GeV/c. Consequently, the design is based on collecting sufficient antiprotons in 24 hours to reach the design luminosity.

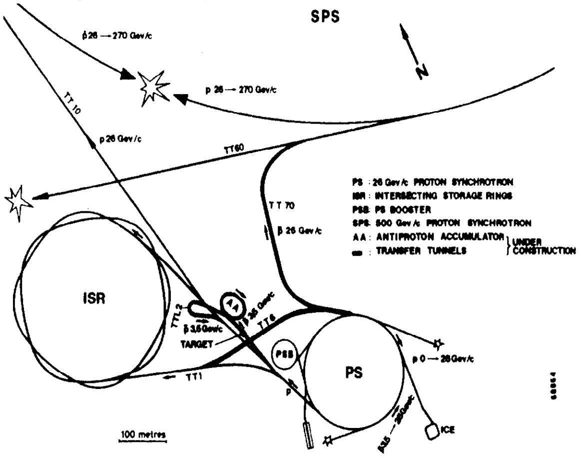

Figure 1. Overall Site Layout

The RF system of the SPS should be able to contain bunches of up to 10^{11} antiprotons with the estimated emittance from the cooling ring. In this case, and by introducing a low-beta insertion at the interaction region, the required luminosity can be achieved by having six bunches each of antiprotons and protons. Thus, we require to accumulate 6 x 10^{11} antiprotons.

Antiproton Production

To permit the production and accumulation of antiprotons during either mode of operation of the SPS, they will be produced in a target by 26 GeV/c protons coming from the PS. After acceleration to 800 MeV in the PS booster synchrotron, the 4 beams each containing 5 bunches will be ejected in pairs, combined in vertical phase space and injected into the PS. Here the two sets of 5 "double" bunches will be accelerated to 26 GeV at which time the two halves of the RF cavities will be operated at slightly different frequencies so that one set of bunches is accelerated slightly while the other is decelerated. When the two sets of bunches overlap, thus filling one quarter of the PS circumference they will be ejected.

The beam thus formed, containing 10^{13} protons will then be focussed onto a tungsten target of a few mms diameter and 10 cm long. The $\bar{p}$'s produced will be focussed by a small horn-type lens to collect as wide an angular range as possible. A spectrometer like arrangement then provides momentum selection so that the ring will not be subject to much radiation and little shielding is needed in the ring building. Antiprotons will be accepted around a momentum of 3.5 GeV/c, near the production maximum.

Cooling Ring

The cooling ring, (Figure 2) is a large aperture fixed field machine having one quarter the circumference of the PS. With a momentum of 3.5 GeV/c, this allows a design with adequate straight section space to accommodate the equipment for injection, extraction and stochastic cooling as well as a RF cavity and diagnostic devices.

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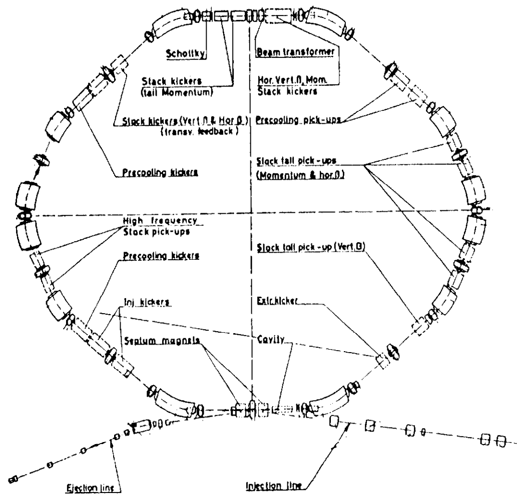

Figure 2. Antiproton Accumulator General layout

The unusual shape of the ring is a consequence of its use for stochastic cooling, which requires a strong dependence of revolution frequency (and hence orbit circumference) on momentum. This implies an average value of the momentum dispersion (α_p) of 4.2 m, whereas the injection of large emittance, large momentum spread beams requires α_p close to zero at the septum. For this reason the bending magnets are distributed so as to make $\alpha_p = 0$ in the two long straight sections.

To avoid disturbing the stack, pulses will be injected at a slightly higher momentum so that they are horizontally separated at the injection kicker. The stack is then protected from the kicker field by a moveable eddy current screen or shutter. After injection the momentum spread of the pulse is reduced from 1.5% to 0.2% in about 2 seconds by a high-gain pre-cooling system using the filter method. In this case, the pick-ups must be shielded from the much higher levels of the stack and the latter must be shielded from the high level signals of the pre-cooling kickers. Thus the 200 pick-ups and kickers will be closed off by moveable ferrite shutters.

After pre-cooling the shutters will be opened, the beam decelerated by the RF cavity and deposited at the top of the stack. The stack will be cooled continuously both in momentum and transversely so that particles slowly migrate to the dense bottom of the stack, where the density will be four orders of magnitude higher than at the top. In total, 32 pick-ups and about 100 kickers are foreseen for the stack cooling system.

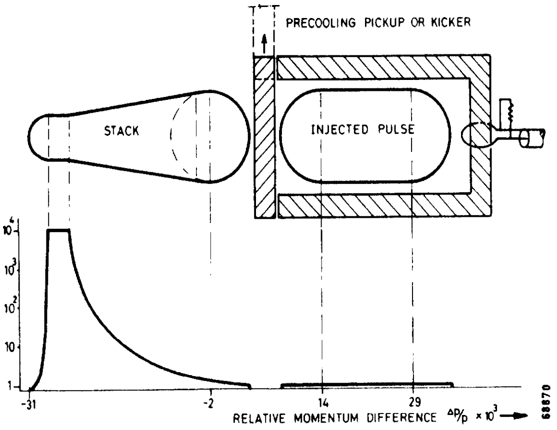

Figure 3 Schematic cross section in cooling ring

The overall machine acceptance (shown schematically in Figure 3) corresponds to a 6% momentum spread and transverse emittances of 100 $\pi\mu$rm, which results in radial apertures of up to 70 cm. Special wide quadrupoles are required in these positions, which must provide the radial aperture whilst limited to a steel length of 54 cm. In addition, they must incorporate one of the three sets of sextupole fields which are needed to make the betatron tunes independent of momentum whilst preserving zero momentum dispersion in the long straight sections.

To provide a sufficient beam lifetime in the cooling ring a vacuum pressure of less than 10^{-10} Torr is needed. Consequently, all components in the vacuum system must be bakeable to about 200°C including the large quantity of ferrite in the pre-cooling system. Since the negative space charge of the stored beam will attract positive ions, clearing electrodes must be provided to maintain the neutralization factor below 0.03.

After 24 hours of stacking, we expect to obtain a circulating beam of 6×10^{11} antiprotons (180mA) whose final density will be limited by intra-beam scattering. This limitation, together with the RF power available in the SPS requires that the antiprotons be extracted in 12 batches.

The RF system will capture one twelvth of the stack and accelerate it out to the injection/extraction orbit where it will be extracted, transported to the PS and injected couter-clockwise.

Acceleration in the PS and transfer to the SPS

In order to contain the rather large momentum spread, the PS RF system will be operated at a harmonic number of 6, which is within the tuning range of the cavities and will give a larger bucket area than the usual harmonic number of 20. No difficulty is anticipated in passing through transition in the PS, since the charge per bunch when normally accelerating 10^{13} protons is about ten times that for the antiproton acceleration.

To avoid the difficulties which have been experienced in trying to accelerate intense bunches through transition in the SPS, the antiprotons will be accelerated to 26 GeV, above the SPS transition energy, in the PS.

When a bunch of antiprotons has reached 26 GeV in the PS, it is necessary to reduce its length from 6.5 m to about 1.2 m to permit its capture into one bucket of the SPS rf system. The compression will be achieved by the well known bunch rotation technique which has already been carried out with protons in the PS.

The bunch is then extracted from the PS and directed along a new transfer line, shown as TT70 in Figure 1, which bends the extracted bunch round and down to meet the TT60 extraction beam line.

After the junction with the TT60 beam line, the bunch is injected into the SPS magnet ring through the same channel as protons are new extracted, and circulates in an anti-clockwise direction, the magnetic fields being kept steady at the 26 GeV level.

This process is repeated twelve times, an antiproton bunch being extracted from the cooling ring, accelerated in the PS and then transferred to the SPS, the relative timings being adjusted to give twelve equally spaced bunches.

Before this transfer of antiprotons starts, twelve bunches of protons would have already been accelerated in the PS and transferred to the SPS in the normal way down TT10 and injected to circulate in a clockwise direction.

Acceleration in the SPS

The SPS has four travelling-wave structures for acceleration, each with a nominal input power of 1 MW. Two of the structures, fitted with change-over switches so that the power can be reversed will be used to accelerate antiprotons when the SPS is being used in the colliding-beam mode. Two structures will be able to provide enough voltage at 200 MHz to capture the single bunches, each containing 5×10^{10} protons or antiprotons , and accelerate them to 270 GeV at an average rate of 80 GeV/sec.

Having arrived at 270 GeV, which is the highest energy at which the magnet system of the SPS can be run in a d.c. mode without exceeding the specified dissipation, we wish to reduce the twelve bunches of each type to 6 by combining the adjacent bunches, to reach the required luminosity. Since there is a gap of 2 microseconds between bunches, and the rise time for the RF system is a little over 1 microsecond, it is possible to change the RF phase between bunches, so that alternate bunches are accelerated and decelerated, putting them on slightly different orbits having different revolution frequencies. Thus, the alternate bunches will drift towards each other until they coincide. During the drifting, a bunch can be contained in the bucket produced by one travelling-wave structure, operating at the appropriate frequency, so the two structures used for acceleration of the antiprotons can be used separately to contain the alternate bunches. Once they coincide, both structures are switched to the mean frequency, providing a bucket large enough to contain the combined bunches.

VII Low beta section

The design of the low beta section, which consists essentially of two doublet lenses to focus the beam down in both planes, has to respect two main constraints. First of all, it is necessary to avoid moving the existing quadrupoles from their present positions otherwise too much time would be lost in changing from normal fixed target operation to $p\bar{p}$ and vice versa. Secondly, as much as possible of the space between the two quadrupoles on either side of the intersection point should be left free for the experiment.

A design which fits in with these requirements is shown in Figure 4. Ten quadrupoles have to be added to the straight section, each element of the doublet requiring three quadrupoles of an existing design. The existing machine quadrupoles form part of these, two of them having the current reversed from the normal direction. Ten other machine quadrupoles have to have their currents modified to match the low beta section into the rest of the SPS, and this can be done by fitting separate power supplies to these elements. It will be seen that beta values of 5 m in the horizontal plane and 1 m in the vertical plane can be achieved, giving a gain in luminosity of about 20 compared with the normal lattice, in which the beta midway between quadrupoles is 48 m.

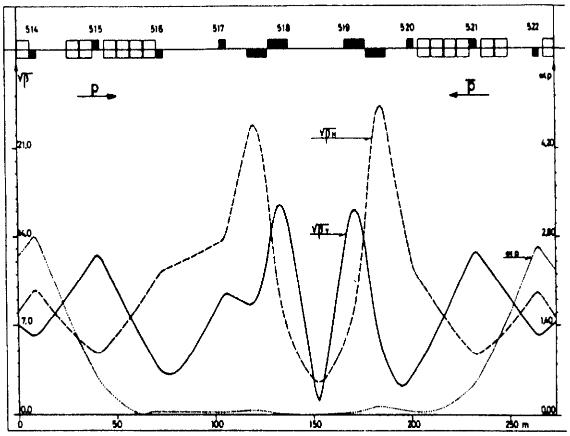

Figure 4. Low Beta section

The experimental areas

Although the original idea was that it might be possible to mount an experiment within the confines of the present SPS tunnel, it soon became evident that a considerable enlargement of the tunnel would be necessary. It also became evident that it would be impractical to leave the experiment in position during normal running of the SPS, for two reasons. One was that the radiation level during normal operation was likely to damage some of the experimental equipment if left in position for long periods, and the other was that the experimenters would have little possibility of access to the equipment in these periods, just when they would be most likely to want to make changes and improvements. Therefore, it seems essential to provide a means of moving the experiment, with minimum loss of time, out of the tunnel to an area where work can go on while the SPS is running normally.

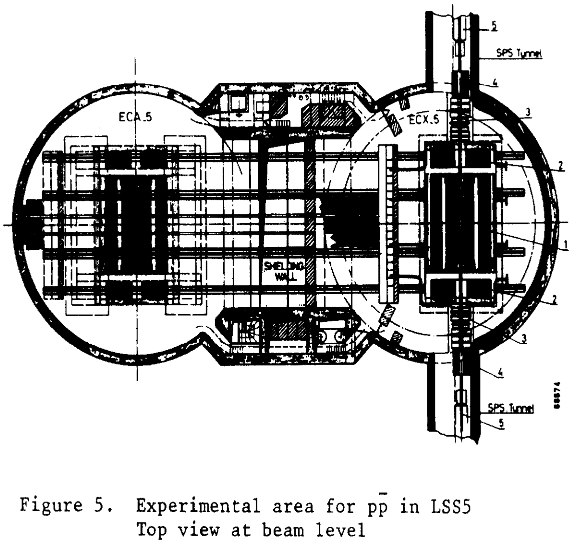

Figure 5. Experimental area for $p\bar{p}$ in LSS5
Top view at beam level

Since the proposed experiments weigh up to 1000 tons, the only feasible method is to translate the experiment horizontally, on rails or other means, into an adjacent area, and build up shielding between this area and the tunnel, after transfer of the equipment.

After examining the various proposals, it seemed clear that if the more ambitious experiments were to be accommodated, the tunnel could need to be enlarged to about 20 m diameter, with a similar size for the assembly area. Taking into account the civil engineering requirements that the underground parts must be strong enough to resist the pressure of the sourrounding molasse rock, we arrive at the layout shown in Figure 5 for the first experimental area in LSS5, consisting of two circular pits connected together by a concrete "picture frame" to take the stress resulting from the opening between the two. The experiment is shown mounted in the collision region, with the alternative position shown dotted.

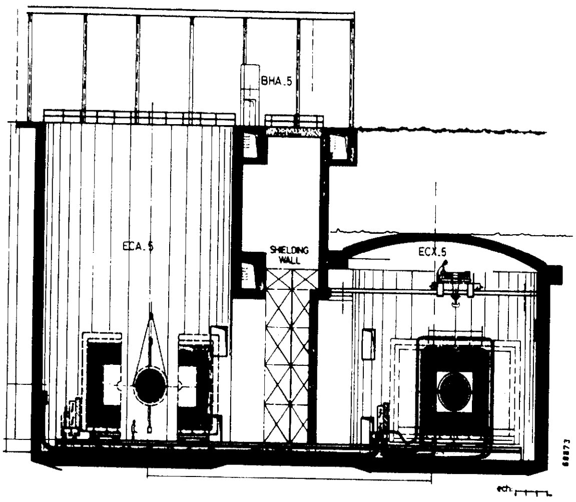

Figure 6. Experimental area for $p\bar{p}$ in LSS5 Vertical section at crossing point perpendicular to the beam

The vertical cross-section in Figure 6. shows how the experimental area is covered over after construction, to give the shielding needed for normal operation, while the assembly area is open to the surface, where it is covered by the building BHA5 fitted with a 75 ton crane. The shielding wall between the two is made of concrete blocks which can be lifted out by this crane when it is required to move the experiment.

A second experimental area is also to be provided in LSS4, but here the tunnel is 60 m below the surface, too deep for open excavation to be used. Therefore, two access pits have to be made and tunnelling techniques employed for the excavation of the experimental and assembly areas, as shown in Figure 7.

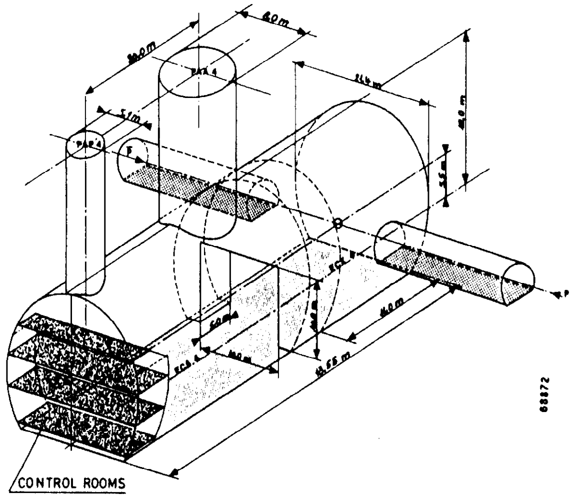

Figure 7. Design Concept for underground Experimental area No. 2

Time scale

The building work for the AA ring started last November, and all the main components are now on order. The first tests are expected to take place in the second half of 1980.

Work will start this spring on the transfer tunnels and the LSS5 experimental area, and on the LSS4 experimental area this summer. As much as possible will be done before shutting down the SPS in the middle of 1980 and this shutdown is expected to last for about 8 months. After this, the SPS will be started up for fixed target physics periods, interspaced with tests of the new equipment for accumulating, accelerating and storing the antiproton bunches. Operation for physics with colliding beams is expected later in 1981.

Acknowledgement

This paper is a summary of the work of a large number of CERN staff who make up the $p\bar{p}$ project teams.

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