THE CERN $\bar{p}p$ COLLIDER

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INTRODUCTION

At the 1976 Neutrino Conference C. Rubbia suggested to convert the CERN SPS machine into a proton-antiproton collider to search for the intermediate vector bosons[1].

The idea was followed up at CERN in the Initial Cooling Experiment ICE. The very encouraging results[2] led to the approval in July 1978 of a Proton-Antiproton Colliding beam facility[3] see also Fig. 1. based on stochastic cooling[4] which was first proposed by S. van der Meer from CERN.

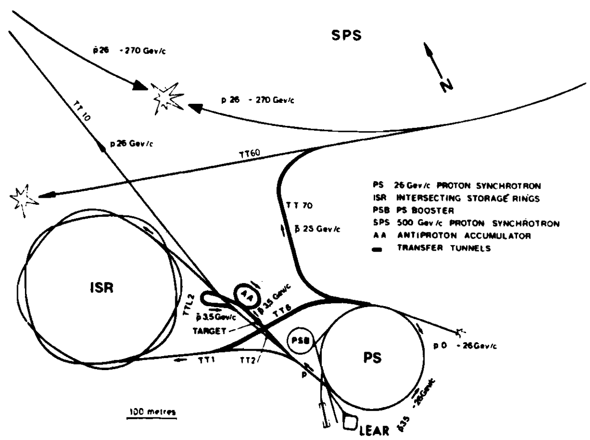

Fig. 1. Over-all site layout.

This project has been described in detail previously[5][6]. Therefore only major features will be reported here, stressing the present performances and showing evidence of the first collisions at $\sqrt{s}$ = 540 GeV observed by the UA1 experiment.

STOCHASTIC COOLING

The most unusual feature of the $\bar{p}p$ complex is the stacking mechanism of the antiprotons in the $\bar{p}$ accumulator using stochastic cooling. This allows to increase the phase space density of the $\bar{p}$-beam in the accumulator by a very large factor.

Stochastic cooling can be understood as feed-back action of individual particles upon themselves disturbed by other particles. The disturbing effect varies with the square of the feed-back 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 cooling predominant.

Cooling can be achieved in the transverse motion (betatron cooling) and longitudinally (momentum spread). For betatron cooling, deviations from the nominal orbit are measured (Fig. 2) and a correcting kicker pulse is applied to the same particles on the same turn. For momentum cooling, the

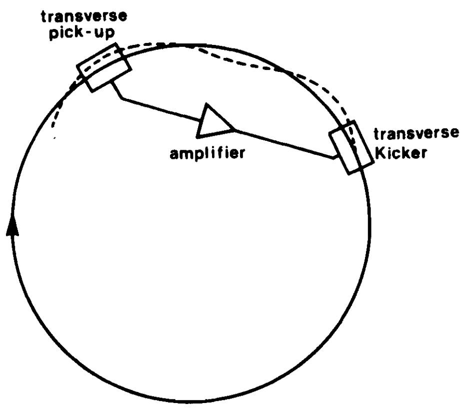

Fig. 2. Stochastic cooling of the transverse or betatron motion.

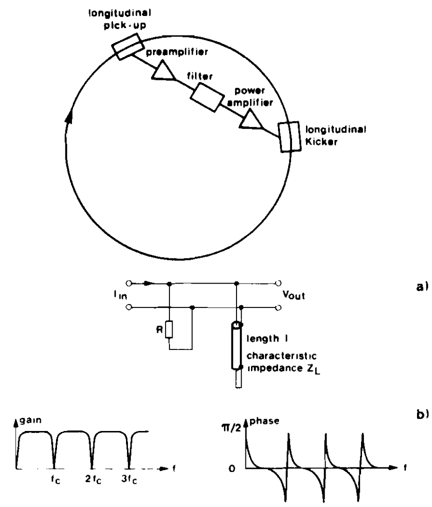

Fig. 3a),b). Stochastic momentum or longitudinal cooling and filter network and performance.

"filter method" is used (Fig. 3a),b) : a reflecting transmission line is introduced into the feed-back chain, its electrical length being equal to half the ring circumference. It causes a 180^0 phase shift of the pick-up signal for the nominal momentum and produces a gain which is zero for the nominal frequencies larger/smaller than the nominal revolution frequency.

ANTIPROTON ACCUMULATION

A high intensity CPS beam of 1×10^{13} protons filling longitudinally one quarter of the CPS circumference is ejected at 26 GeV/c and focussed on a tungsten target followed by a magnetic horn. Of the emerging antiprotons 2.5×10^7 $\bar{p}$/CPS-pulse can be collected into the acceptance of the antiproton accumulator AA.

The AA (Fig. 4) is a large aperture fixed field machine. The egg like shape of the ring was chosen to obtain long straight sections (top and bottom in Fig. 4) with zero dispersion for injection/ejection (bottom in Fig. 4) and for stack momentum cooling (top Fig. 4).

In other parts of the ring the vacuum chamber is as wide as 70 cm to accomodate a total momentum spread of 6%. Half of this is used for the stack and 1.5% is needed for the injected beam before precooling. The gap between these regions is necessary for the movable shutters of the injection kickers, the precooling pick-ups and the precooling kickers.

In Table I a short parameter list of the AA is given.

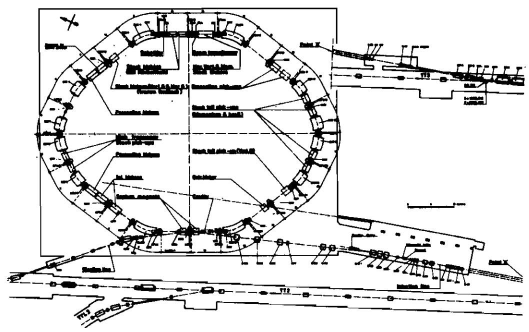

Fig. 4. General Layout of the Antiproton Accumulator.

TABLE 1. AA PARAMETERS

PARAMETERS	
CENTRAL MOMENTUM	3.5 GeV/c
CIRCUMFERENCE	151.08 m at injection (CPS/4) 155.84 m at stack centre
WORKING POINT	Q_x = 2.284 Q_y = 2.276 at stack centre
TOTAL $\Delta p/p$	$\pm 30 \times 10^{-3}$
VACUUM PRESSURE	10^{-10} Torr
TARGET	Tungsten rod 110 mm long, 3 mm Ø followed by magnetic horn
PROTON/PULSE ON TARGET	1×10^{13} every 2.4 sec
ANTIPROTON/PULSE	2.5×10^{7} in AA acceptance
ACCEPTANCE (INJECTION)	100 hor., 100 vert. πmm mrad at $\Delta p/p = 7.5 \times 10^{-3}$
(TRANSFER TO CPS)	7.6 hor., 4.5 vert. πmm rad at $\Delta p/p = 1.1 \times 10^{-3}$
FIRST FILL (1×10^{12} $\bar{p}$)	50 000 pulses, 33 hrs
REFILL (6×10^{11} $\bar{p}$)	30 000 pulses, 20 hrs

The stacking procedure[7)] is described in Fig. 5. After injection, the momentum spread of each pulse is reduced rapidly from 1.5% to 0.17% by a high gain precooling system using the filter method. The movable shutters shield the pick-ups from the much higher signals from the stack and the latter must be shielded from the intense signals of the precooling kickers. The precooled pulse is then decelerated by the RF cavity across the opened shutter and deposited at the top of the stack. The stack itself is cooled continuously both in momentum and transversely by the stack tail and the stack core cooling systems (Fig. 5). The stack momentum cooling requires a gain that varies approximately as the inverse of the particle density over momentum (or frequency). Two low frequency systems (150 to 500 MHz) cover the top of the stack (fast removal before the next bunch is deposited) and the high momentum tail. The third, high frequency system, cools the high density part of the stack, 0.3% wide in momentum, and compensates intra-beam scattering. The location of these cooling systems is indicated in Fig. 6. After more than 30 hours of stacking and cooling, 10^{12} antiprotons should be accumulated. One twelveth of the high density core of the stack is then collected in an RF bucket accelerated to the ejection (injection) orbit and sent to the CPS for acceleration to 26 GeV/c and transfer to the SPS. This is repeated twelve times and then a new acceleration cycle starts.

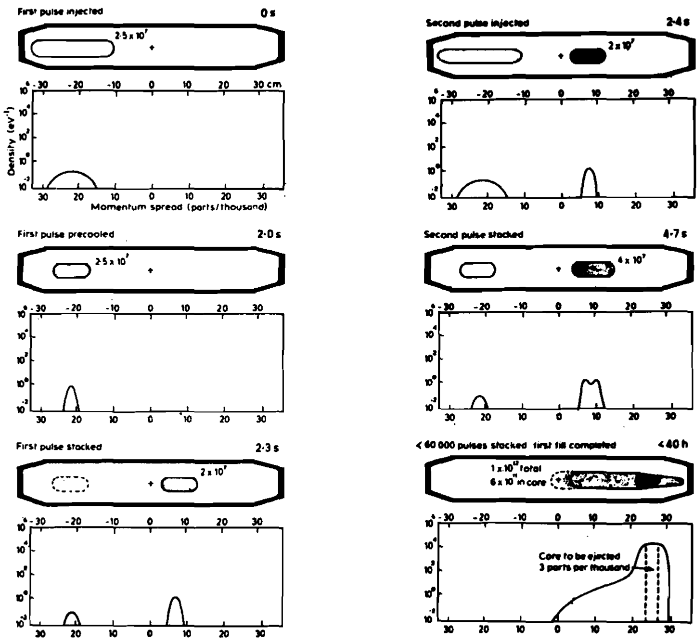

Fig. 5. Stochastic stacking in the Antiproton Accumulator.

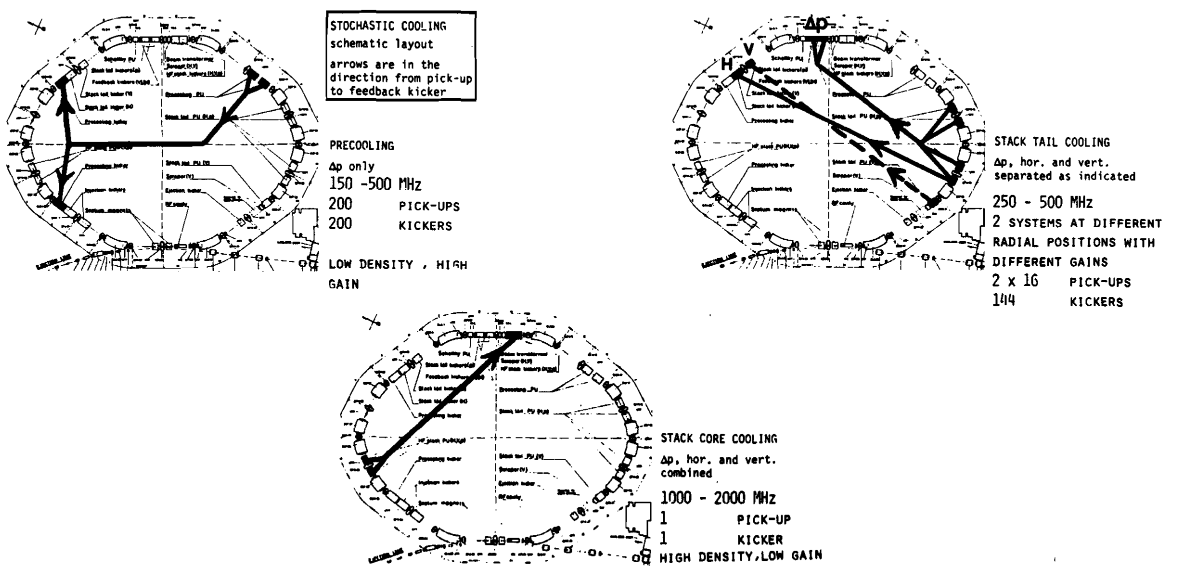

Fig. 6. The Antiproton Accumulator beam cooling systems.

THE SPS AS $\bar{p}p$ COLLIDER

The key parameter of the SPS used as a $\bar{p}p$ collider is luminosity which can be expressed as follows :

$$L \propto \frac{N_p N_{\bar{p}} f}{n_b \sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}} ,$$

where $N_p(N_{\bar{p}})$	total number of (anti-)protons/beam
n_b	number of bunches (equal for both beams)
$\varepsilon_x(\varepsilon_y)$	horizontal (vertical) emittance
$\beta_x^*(\beta_y^*)$	horizontal (vertical) beta value in the crossing region
f	revolution frequency .

In order to obtain a high luminosity, the number of particles per bunch $N_{p,\bar{p}}/n_b$ should be large and the beam dimensions $\sqrt{\varepsilon_{x,y}^* \beta_{x,y}^*}$ small. However N_p/n_b or $N_{\bar{p}}/n_b$, whichever is larger, determines the beam-beam tune shift which limits the luminosity ultimately by setting a limit to the maximum number of particles per bunch which can circulate and cross oncoming bunches in the machine without emittance blow-up. Maximum luminosity with a given maximum beam-beam tune shift and charge per bunch have resulted in the following parameters for the SPS as $\bar{p}p$ collider.

TABLE II. SPS COLLIDER PARAMETERS

INJECTED BEAM (26 GeV/c)		p	$\bar{p}$	
PARTICLES/BUNCH		1	0.5	10^{11}
NB OF BUNCHES		6	12 merge to 6	
HOR. EMITTANCE	πmm mrad	0.8	0.2	0.8
VERT. EMITTANCE	πmm mrad	0.4	0.2	0.4
270 GeV/c START OF STORAGE				
HOR. EMITTANCE	mm mrad	0.08		
VERT.EMITTANCE	mm mrad	0.04		
BUNCH LENGTH	nsec	2		
BEAM BEAM TUNE SHIFT		0.003		
β_x^*	m	2		
β_y^*	m	1		
TUNE		$Q_x = 26.89$	$Q_x = 28.87$	
LUMINOSITY	$cm^{-2}\ sec^{-1}$	1×10^{30}		

There are six proton bunches injected at 26 GeV/c spaced equidistantly around the machine, followed by the injection of 12 antiproton bunches, the antiproton bunches being recombined two by two horizontally on their arrival in the SPS. The bunches are then accelerated by two groups of travelling wave cavity structures. For each kind of particles, the corresponding two structures can provide 5 MV at 200 MHz with maximum output power of 2 MW, which is enough to capture bunches of 10^{11} particles and accelerate them at an initial rate of 40 GeV/sec.

At 270 GeV/c, the momentum given by the available power for running the SPS magnets in dc-mode, the low beta quadrupole settings are altered to achieve the final focussing in the crossing region with beta values of 1 m and 2 m in the vertical and horizontal planes respectively. Then with the given emittances and an assumed beam-beam tune shift limit of 0.003 the luminosity should reach $10^{30}/cm^2$ sec. In order not to limit the beam life time by multiple and nuclear scattering the average vacuum level in the SPS will be lowered to $\sim 2 \times 10^{-9}$ Torr. In the experimental straight sections the pressure will be as low as 10^{-10} Torr. Finally two large experimental halls have been provided to accomodate the 5 approved experiments.

PRESENT STATUS OF THE $\bar{p}p$ MACHINES AA, CPS, SPS

The $\bar{p}$ target station, the AA, the new transfer tunnels, the modifications to CPS and SPS, and the experimental areas all are in different running-in stages. The first "production run" of the SPS collider is scheduled for end November/December.

To give an impression of the present performance of the collider complex a review of a machine development session of AA, CPS and SPS devoted to $\bar{p}p$ storage (8-1981) is given. However, one should keep in mind that machine development sessions are not aimed at obtaining the best possible performance for experiments but to test out specific features and problems. Therefore conclusions cannot be drawn easily as to what the experimental conditions will be at the end of the year.

The AA with the antiproton target and its transfer tunnels was realized in a very short time. 2 years after approval, the first antiprotons were accumulated in summer 1980.

Today's performance can best be seen in Fig. 7 showing the accumulation of a stack exceeding 10^{11} antiprotons.

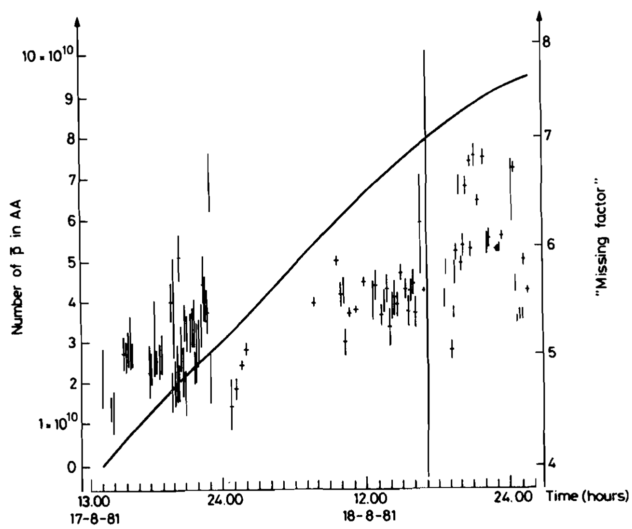

Fig. 7. The number of antiprotons accumulated and the development of the "missing factor" with time of accumulation.

Plotted are the number of antiprotons (right scale) versus accumulation time and "missing factor" averaged over periods ranging from minutes to one hour, again versus time. The "missing factor" describes the fraction of antiprotons really accumulated in the AA compared to the number of antiprotons which should be accumulated according to the design study, both normalized to the same number of protons incident on the antiproton target. It contains the focussing of the CPS beam on the target, yield of antiprotons, the transfer and injection efficiency into the AA, the acceptance of the AA and the performance of all AA cooling systems. Note that the missing factor does not seem to depend on the number of $\bar{p}$'s in the machine as it comes down to almost the initial value of ~ 5 at the end of the storage (better adjustment of the stack core cooling). In Fig. 8 a Schotty scan of the same stack in the AA is shown, the vertical scale being proportional to $\sqrt{N_{\bar{p}}}$ and the horizontal scale to revolution frequency or momentum of the antiprotons. Precooled antiprotons are deposited at the lower left edge of the stack and then cooled towards the peak.

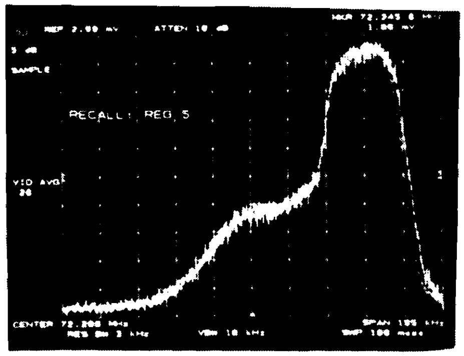

Fig. 8. Schottky Scan of a Stack of > 10^{11} Antiprotons in the AA.

From this stack, antiprotons were ejected several times to the CPS, accelerated to 26 GeV/c, transferred to the SPS and accelerated together with a proton bunch to 270 GeV/c and stored. The proton bunches contained typically 3×10^{10} p and the antiproton bunches a factor of 10 less. The overall transmission for the whole procedure was on the average 50%, however there was a considerable blow up of the emittances because of some deficiencies in the settings of injection, ejection and the transfer tunnels. In this specific machine experiment no attempt was made to switch on the low beta quadrupoles. Under these conditions the luminosity obtained was of the order of $1\text{-}3 \times 10^{25}/\text{cm}^2$ sec. However, the lifetime of the stored proton and antiproton bunches was short, less than one hour. The lifetime of intense proton bunches was studied in great detail already in 1980 and lifetimes exceeding 10 hours were recorded[6]. The problem was longitudinal diffusion out of the stable RF-bucket area due to RF noise. At present a very low noise RF central loop is installed. Unfortunately it not only failed to improve the lifetimes, but they are even shorter than last year. Very probably however the problem is trivial and will be solved in the next machine development sessions.

What can experiments hope to see under these adverse conditions, characterized by high loss rate, low luminosity, rather poor vacuum in the straight section? Surprisingly the conditions were found quite liveable. In Fig. 9 is demonstrated the separation obtained between beam-beam events at $\sqrt{s}$ = 540 GeV and "beam-gas" events using a simple time of flight measurement between two counter hodoscopes of the UA1 experiment and the machine gate. By a simple tight coincidence between both hodoscopes, most of the machine background can be excluded.

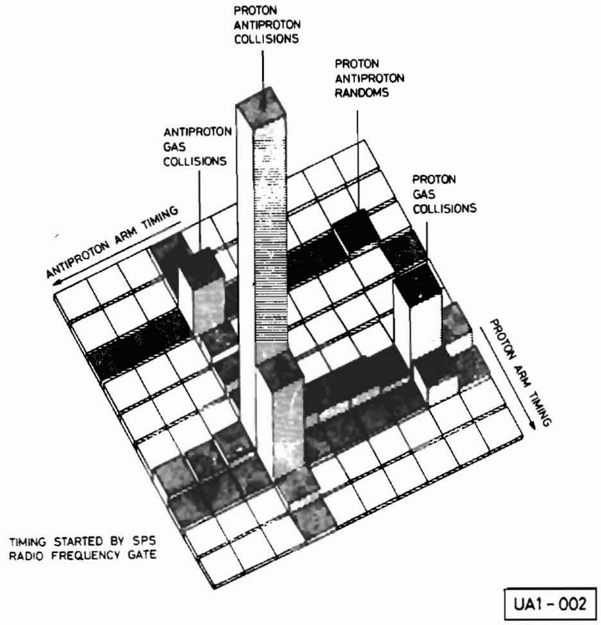

Fig. 9. On-line timing plot of coincidence rate between forward hodoscopes.

To summarize , it can be said that no limit has yet been found which could prevent the SPS collider from reaching its design performances, specifically its design luminosity of $10^{30}/cm^2$ sec.

For the long physics run scheduled for November/December, several straight-forward improvements in luminosity are to be expected, namely low beta (factor 7-30), multiple bunch operation (factor 3), better emittance control (factor 2-3) and higher intensity proton and antiproton-bunches (factor > 10), together with improved lifetimes.

EARLY PHYSICS PROSPECTS AND CONCLUSIONS

The operation of the SPS collider opens the possibility to study very high energy interactions at centre of mass energies exceeding those of all other machines by an order of magnitude. There are both theoretical considerations and experimental facts which suggest that new and fundamental phenomena will emerge at these very high energies.

For the early physics runs of the SPS collider a luminosity of $10^{29}/cm^2$ sec is in reach. As this is not the place to discuss the physics at the collider in detail, in the following only some expected rates for significant reactions will be given, based on the above luminosity.

An extrapolation of the total pp and $\bar{p}p$ cross-sections as function of cm-energy gives a total $\bar{p}p$ cross-section of 60 mb or 6000 events/sec. There is evidence from cosmic ray data that the charged multiplicity will well exceed the one which can be extrapolated from the ISR. There may also be a kind of threshold at collider cm energies from where on the penetration of particle cascades increases dramatically. As these hints come from cosmic ray data, cross-sections should be large and these effects - if existent - visible from the start.

The study of events with large transverse momenta is of great interest. At collider energies high p_T phenomena will provide a sound testing ground for QDC, since the $\bar{p}p$ collisions will be an ample source of quark and gluon jets, both produced with large and comparable cross-sections. Jets with p_T exceeding 20 GeV/c can be expected at a rate of more than 250/hour[8].

Most importantly, the intermediate vector bosons $W^{\pm}$ and the Z^0 expected by unified gauge theories should be produced with reasonable cross-sections at collider energies. A recent estimate[9] based on the leading order calculation for W production for a 100% acceptance of electrons and 80% acceptance of muons with a p_T cut for the leptons at 10 GeV/c finds the following rates for electrons and muons combined :

$$W^+ \text{ and } W^- \rightarrow e \text{ or } \mu \qquad 10/\text{day}$$
$$Z^0 \rightarrow e \text{ or } \mu \qquad 1/\text{day} \quad .$$

The background of these leptonic decays of the intermediate vector bosons should be small.

Five experiments (UA1,...,UA5)[10][11][12][13][14] have been approved to study very high $\bar{p}p$ collisions the first two being very large detectors aimed at a general coverage of the physics expected at the collider. The others are smaller and more specialized experiments. Some details are listed in Table II and an impression of the large experiments can be obtained in Fig. 10 and Fig. 11. At present only the largest of these experiments is installed in the SPS machine. It consists of a dipole magnet weighing 1400 tons with a useful field volume of 80 m^3 at 0.7 T enclosing the large drift chamber which contains 6000 sense wires with 3-dimensional and dE/dx readout. The return yoke of the magnet acts as a hadron calorimeter while the electromagnetic calorimeters are placed inside the coil. A similar sequence of drift chamber, e.m. calorimeter and hadron calorimeter is repeated in the forward directions down to the very small angles. The whole central part is surrounded by 8 layers of drift tubes for the μ-detection (Fig. 12). In Fig. 13 finally one of the first events with very large multiplicity and transverse momentum is shown, indicating all cells of the electromagnetic and hadronic calorimeters hit.

Clearly there is new and exciting physics at hand.

TABLE III. APPROVED $\bar{p}p$ EXPERIMENTS AND THEIR STATUS

Experiment	Collaboration	Detector	Physics Aims	Status	Intersection Region
UA1	Aachen-Annecy-Birmingham-CERN-CdF Paris-QMC,London-Riverside-INFN,Rome-Rutherford-Saclay-Vienna	Large drift chamber with image read-out, large dipole magnet, e.m. and hadronic calorimeters covering 4π,large solid angle μ-detection	$W^{\pm}$,Z^0;all aspects of $\bar{p}p$ events at high energies	Has observed the first collisions in LSS5	LSS5
UA2	Bern-CERN-Copenhagen-Orsay-Pavia-Saclay	Vertex detector,e.m. and hadronic calorimeters covering a large solid angle forward toroidal magnets	$W^{\pm}$,Z^0;hadronic physics	Setting up for Nov/Dec run	LSS4
UA3	Annecy-CERN	Kapton foils	Monopole search	Installed in LSS5	LSS5
UA4	Amsterdam-CERN-Genova-Naples-Pisa	Small angle "Roman Pots"	Elastic scattering and total cross-sections	Setting up,tests in October	LSS4
UA5	Bonn-Brussels-Cambridge-Stockholm	Streamer chamber	High multiplicity events	Has taken $\bar{p}p$ data at the ISR,will run in October	LSS4

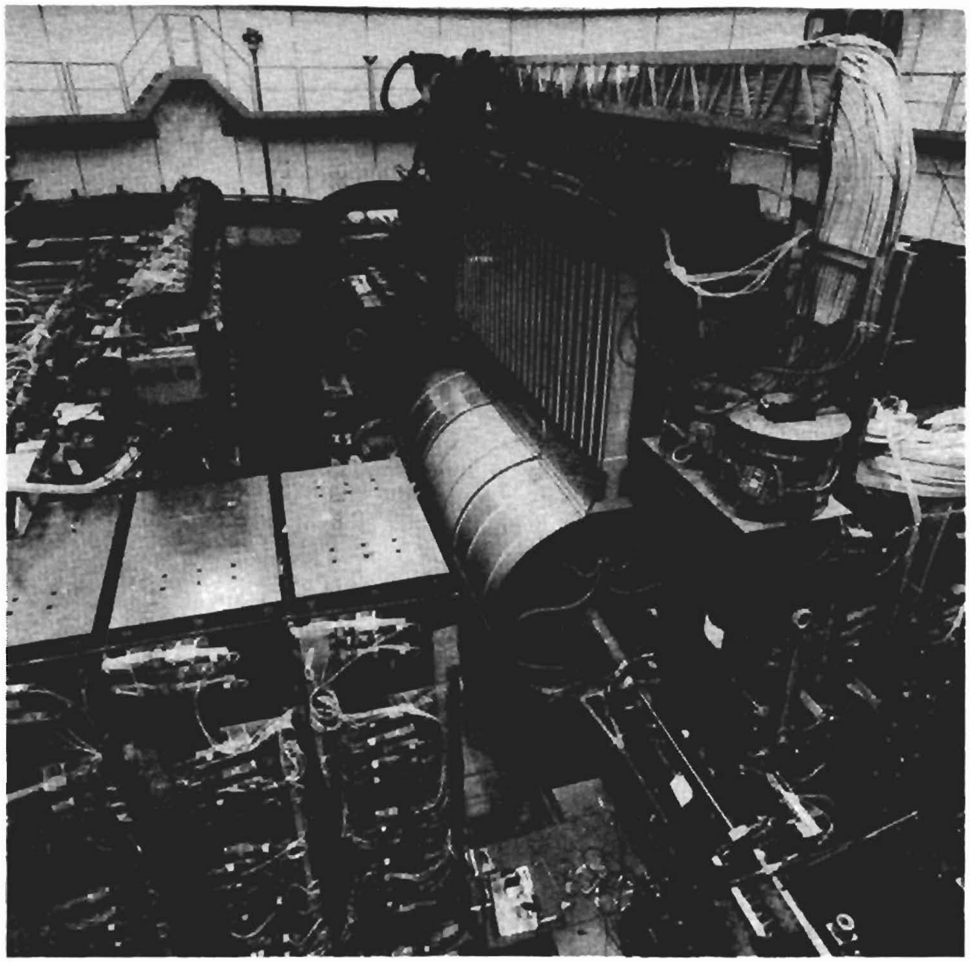

Fig. 10. The UA1 Detector installed in the SPS machine
(CERN 607-07-81)

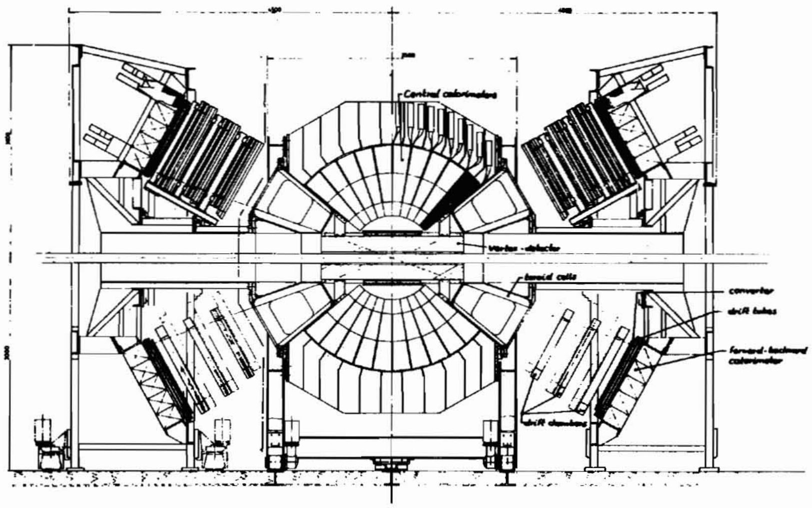

Fig. 11. Schematic cross-section along the beam line of the UA2 detector.

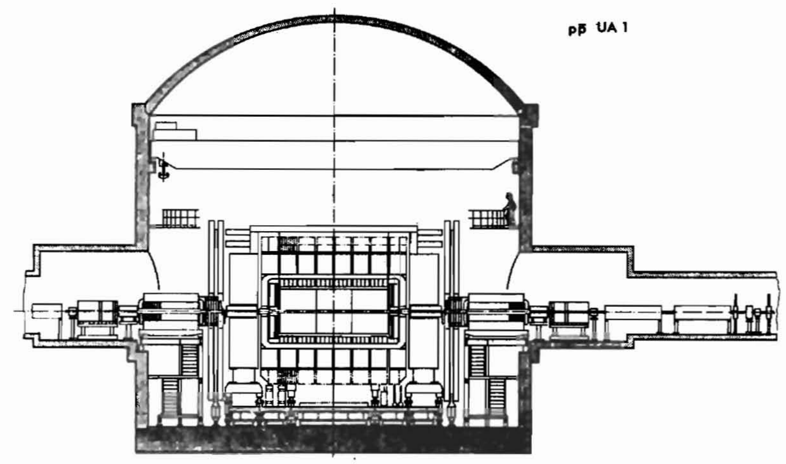

Fig. 12. Longitudinal Section of the UA1 experiment along the beam.

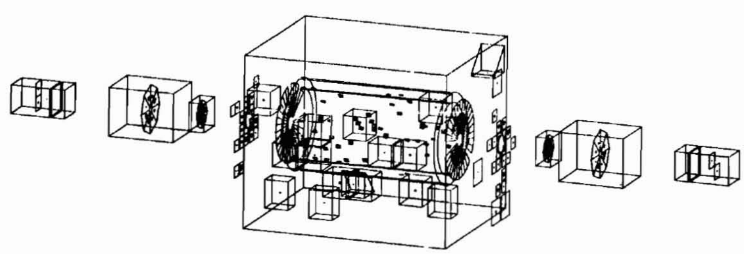

Fig. 13. A high multiplicity high transverse momentum proton-antiproton event at $\sqrt{s}$ = 540 GeV.

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