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Status of the Antiproton Decelerator: AD

Reported by S. Maury for the AD Team:

S. Baird, D. Berlin, J. Boillot, J. Bosser, M. Brouet, J. Buttkus, F. Caspers, V. Chohan, D. Dekkers, T. Eriksson, R. Garoby, R. Giannini, O. Grobner, J. Gruber, J.Y. Hémery, H. Koziol, R. Maccaferri, S. Maury, C. Metzger, K. Metzmacher, D. Möhl, H. Mulder, M. Paoluzzi, F. Pedersen, J.P. Riunaud, C. Serre, D.J. Simon, G. Tranquille, J. Tuyn, and B. Williams

Abstract

A simplified scheme for the provision of antiprotons at 100 MeV/c in fast extraction is described. The scheme uses the existing $\bar{p}$ production target area and the modified Antiproton Collector Ring in their current location. Some modifications necessary to deliver batches of 1×10^7 antiprotons every minute at 100 MeV/c are described, details of the machine layout and the experimental area in the existing AAC Hall are given.

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CERN, 1211 Geneva 23, Switzerland

A simplified scheme for the provision of antiprotons at 100 MeV/c in fast extraction is described. The scheme uses the existing $\bar{p}$ production target area and the modified Antiproton Collector Ring in their current location. Some modifications necessary to deliver batches of 1×10^7 antiprotons every minute at 100 MeV/c are described, details of the machine layout and the experimental area in the existing AAC Hall are given.

1. INTRODUCTION

The actual scenario of providing low energy antiprotons to physics experiments involves 4 machines downstream the antiproton production target: the Antiproton Collector (AC), the Antiproton Accumulator (AA), the Proton Synchrotron (PS) and the Low Energy Antiproton Ring (LEAR). They will collect, cool and decelerate antiprotons in the following sequence:

1) Antiprotons, produced by 26 GeV/c protons on the production target, are collected and precooled at 3.57 GeV/c in the AC.
2) They are then transferred to the AA where they are accumulated and further cooled.
3) A bunch of a few 10^9 $\bar{p}$ is taken from the AA and sent to the PS every 30 minutes to several hours.
4) This bunch is decelerated in the PS from 3.57 to 0.6 GeV/c.
5) It is then transferred to LEAR, where cooling (at 3 or 4 intermediate momenta) and deceleration alternately to bring the full intensity to low energy. With electron cooling, typical emittances at 100 MeV/c are 1π mm·mrad and $\Delta p/p = 5 \times 10^{-4}$.

This scheme was designed as an annex to the antiproton source for the Sp$\bar{p}$S. The simplified solution proposed [1], using the modified AC, is called AD (Antiproton Decelerator). It is the subject of this present paper.

2. AD OVERVIEW

The existing target area and the AC ring [2] in its present location (Fig.1) are used whereas the AA is unused and totally dismantled. The basic AD cycle with the different intermediate levels is shown in Fig. 2. The 26 GeV/c production beam coming from the PS remains the same and the antiprotons produced in the target are collected at 3.57 GeV/c. After the injection of the antiprotons into the AD, bunch rotation is applied to reduce the momentum dispersion from ±3% to ±1.5%. Then, the antiprotons are stochastically cooled to 5π mm·mrad in the transverse planes and 0.1% in $\Delta p/p$. They are decelerated to 2 GeV/c where band I (0.9 to 1.6 GHz) of the present transverse and longitudinal stochastic cooling system is used to compensate the adiabatic beam blow-up due to the deceleration. Then, the beam is further decelerated in several steps. Below 2 GeV/c the next intermediate cooling level is at 300 MeV/c where the transverse emittances have grown to 33π mm·mrad and $\Delta p/p$ = 0.2%. Now electron cooling can be applied. The beam characteristics and the cooling times are shown in Table 1. Two or three intermediate levels at low momenta are also necessary for the change of the rf harmonic number. This avoids excessive frequency swings. About 5×10^7 $\bar{p}$ are injected at 3.57 GeV/c and with an estimated overall efficiency of 25%, 1.2 × 10^7 $\bar{p}$ are available at low energy.

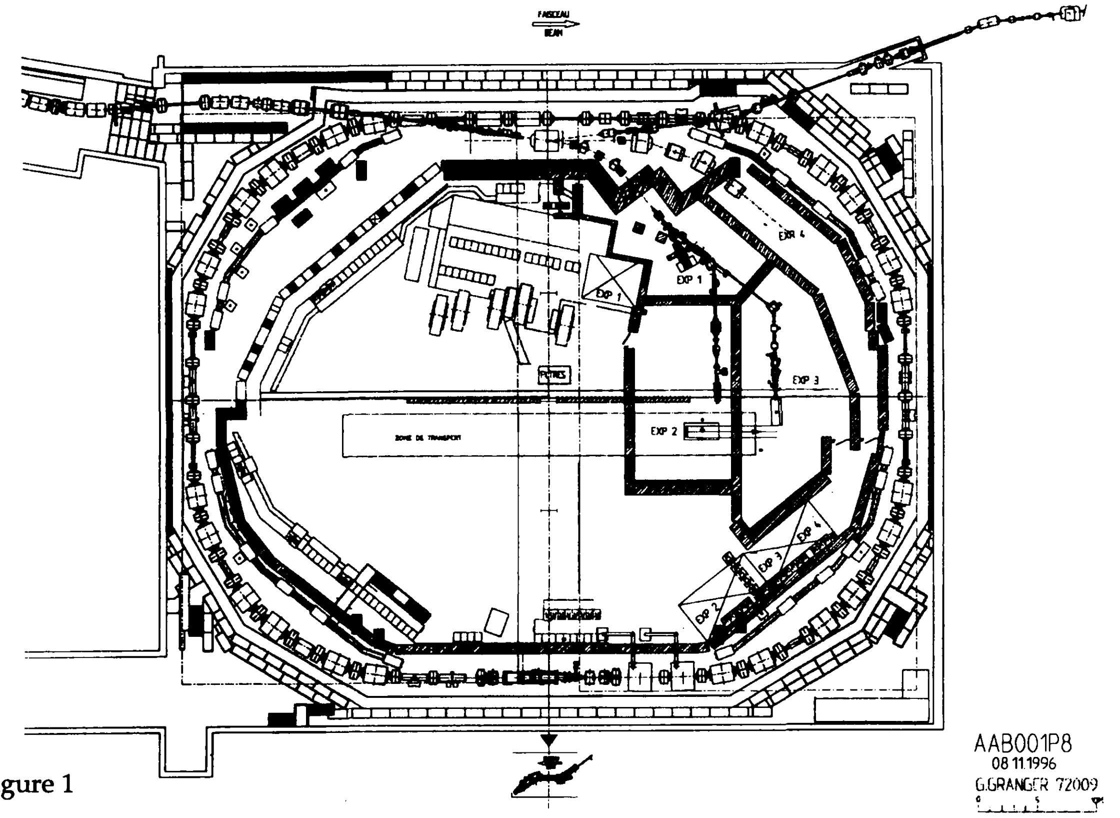

Figure 1

Table 1

Transverse emittances and momentum spread before (i) and after (f) cooling, and cooling times. Only adiabatic increase due to deceleration is considered[*].

p	ε_i	ε_f	$\Delta p/p_i$	$\Delta p/p_f$	t	Cooling process
[GeV/c]	[π mm.mrad]		[%]		[s]	
3.57	200	5	1.5	0.1	20	Stochastic
2.0	9	5	0.18	0.03	15	
0.3	33	2	0.2	0.1	6	Electron
0.1	6	1	0.3	0.01	1	
0.1 bunched	–	1	-	0.1	-	

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[*] 2σ-emittances [$\varepsilon = (2\sigma)^2/\beta$] and $4\sigma_p$-momentum spread [$\Delta p = 4\sigma_p$] are used throughout in this report.

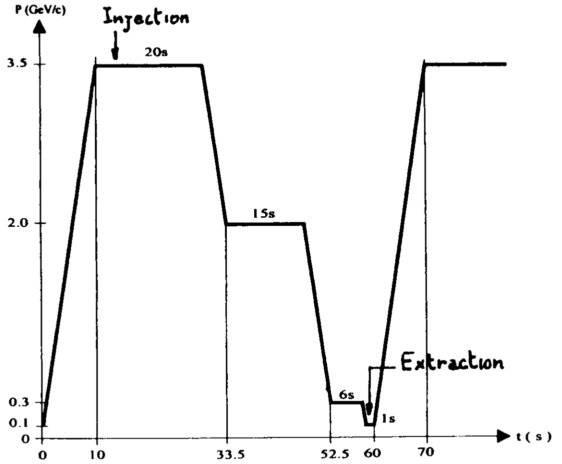

Figure 2 - Basic AD deceleration cycle

The new experimental area will be inside the AC ring. By adding some shielding, the users are allowed to access the experimental area during $\bar{p}$ production and deceleration.

Only minor modifications of the present ejection system are necessary for fast extraction at low energy. With the addition of electron cooling, 10^7 $\bar{p}$ can be ejected in one pulse of 0.2-0.5 µs length, with a repetition cycle of about 1 minute. In standard operation a pulse of about 1.2 × 10^7 $\bar{p}$ is available at 100 MeV/c once per minute and can be ejected in one or several bursts with a length ranging from 200-500 ns. A stacking mode where up to 10 production cycles are cooled and accumulated prior to deceleration is described in section 5.

3. AD LATTICE

The present AC lattice [2] is made of 28 FODO cells with two straight sections of ~28 m length, two of 15 m length and 4 densely packed arcs. The 28 m straight sections have no orbit dispersion, whereas the 15 m sections have a small orbit dispersion as they contain combined-function magnets which provide a small bending angle. This is necessary to satisfy the topology imposed by the injection and ejection lines. In fact special quadrupoles (half-quadrupoles) are used in the injection/extraction section and some quadrupoles are transversely displaced in the other "straight" sections of the lattice in order to maintain symmetry.

The electron cooling device should be located in a straight section where the orbit dispersion is zero. To gain space the central quadrupole has to be removed and the re-matching of the optics is done by changing the position and the strength of the two adjacent quadrupoles.

A detailed study has led to the conclusion that the location for the cooling device EC 2900 is a long straight section opposite to the injection section. Then the quadrupole QDN 29 has to be removed. To reduce the strength of quadrupoles used for the matching, it is proposed to add an additional quadrupole from the Antiproton Accumulator ring at the upstream and downstream end of the cooling insertion. The new layout of this section is shown in Fig. 3.

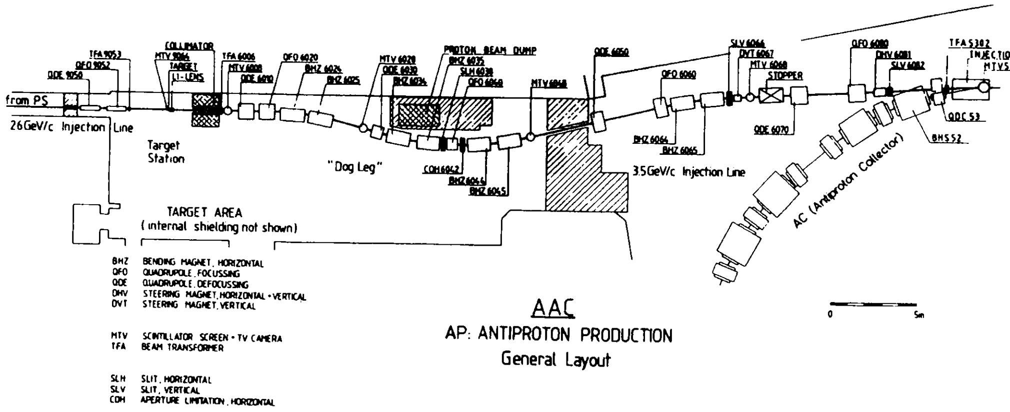

Figure 3 - Layout of the electron-cooling section

Phase advances between the pick-ups and kickers of the stochastic cooling, 89° and 80°, respectively in horizontal and vertical planes, are close to optimum of 90°. These phase advances have been adjusted by modifying the strength of other AD quadrupoles outside the cooling insertion. The tunes $Q_h = 5.482$, $Q_v = 5.236$ do not take into account the ΔQ given by the solenoids of the electron cooler. Further study is needed to compensate this tune shift taking into account the presence of high order resonances. Calculations of the dynamical aperture are also foreseen. The AD lattice functions is shown in Fig. 4.

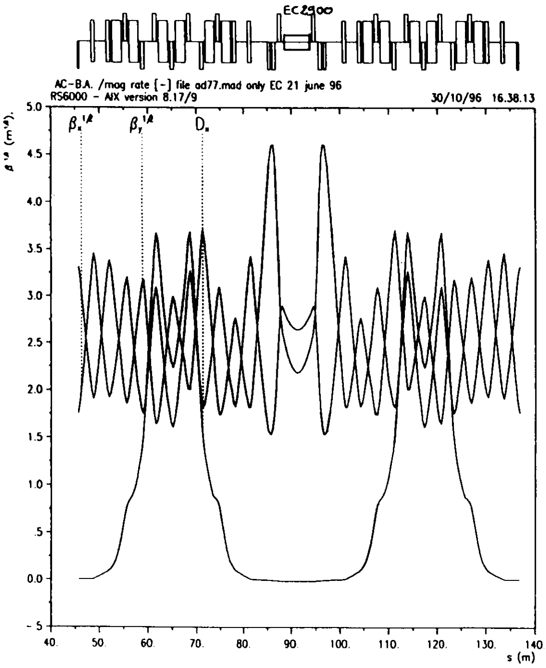

Fig. 4 - The lattice functions of the AD

The vertical β-function in one of the quadrupoles (QDS27 and QDS31) used for the matching of the optics is increased from 10 to 21 m. An enlarged vacuum chamber is therefore needed. Another consequence of inserting the electron cooling device is that the bunch rotation cavity (CBR2706) has to be moved.

4. ANTIPROTON PRODUCTION

The primary beam of 10^{13} protons at 26 GeV/c hitting the antiproton production target will be similar to the present one. It will, however, benefit from developments carried out in view of the use of the PS complex as part of the LHC injector chain [3]. They consist mainly of new acceleration systems in the PS Booster and in the PS itself, and of the transfer energy between these two machines increased from 1 to 1.4 GeV.

Antiprotons emerging at 3.5 GeV/c from the target will be focused and matched to the transport line acceptance of 200π mm·mrad by a magnetic horn [4] pulsed at 400 kA. During the last 4 years a consolidation programme of the target area has been carried out, therefore only minor overhauling and provision for some spare parts are needed.

5. RADIOFREQUENCY SYSTEMS

The 5 × 10^7 antiprotons injected in the AD will be trapped by the existing 9.5 MHz (h=6) rf system, as in the present scheme, and a bunch rotation will be applied in the longitudinal phase space in order to reduce the beam energy spread. The beam will then be decelerated with the present 1.6 MHz (h=1) rf system whose frequency range will be extended down to 0.5 MHz. As this frequency range will not be wide enough to allow deceleration of the beam down to 100 MeV/c with h=1, changes of harmonic numbers at intermediate energy levels will be performed.

This rf system, on top of its basic use for antiproton deceleration, will also be used to shorten the vunch at 100 MeV/c prior to extraction and to capture and decelerate proton beams coming from the PS and circulating counter-clockwise, during setting-ups.

A phase pick-up is essential to achieve efficient deceleration. The sensitivity of this phase pick-up and its shielding from rf parasites determine the lowest antiproton intensity that can be decelerated.

5.1. Stacking Option

In the accumulation mode, up to 10 PS production cycles could be accumulated at 3.57 GeV/c to increase the number of antiprotons per cycle by up to an order of magnitude. The cooled antiprotons are bunched with the $h = 1$ system to a bunch length of less than 100 ns obtained with the bunched beam cooling or bunch rotation. The PS production beam of 3 consecutive bunches (instead of 4 in the standard operation without stacking) is synchronised to fall in the gap left free by the stack. The AD injection kicker is shortened to a flat top length of 235 ns (two PS rf periods plus the bunch length) to avoid disturbing the stack. The rf voltage is adiabatically reduced and a new stochastic cooling cycle at 3.57 GeV/c takes place on the longitudinally merged beam. The Band I (0.9 - 1.6 GHz) of the present stochastic cooling would require a modification of its notch filter in order to have a momentum acceptance of up to ±3% and not heat the stack on the central orbit.

6. BEAM COOLING SYSTEMS

6.1. Stochastic Cooling

Stochastic cooling is needed at 3.57 GeV/c and 2 GeV/c (Fig. 1), for which band I (0.9 to 1.6 GHz) and band II (1.6 to 2.4 GHz) of the present systems will be employed. The pick-ups and kickers of band I remain in their present location. The band II system will be located in the present band III location. Band III (2.4 to 3.2 GHz) is not used as the gain in the cycle time would not be significant and space is needed for the electron cooling system.

For use at 3.57 GeV/c there will be no modification except for electronically controlled variable attenuators for the longitudinal and transverse cooling systems and phase shifters (new dynamic phase compensators) for the transverse systems. They should allow continuous adjustment of optimum conditions and thus reduce the cooling time.

At 2 GeV/c we can still use the band I pickup but its sensitivity is reduced by a factor of about 2. The kicker consists of modules, individually accessible, such that their phasing can be adjusted by means of relays on the drivers of the rf power amplifiers. Switchable delays in the signal transmission have also to be added for commutation from 3.57 to 2 GeV/c.

If the bunch rotation cavity is not used, band I (0.9 - 1.6 GHz) of the present stochastic cooling system could collect the full 6% momentum spread with a reasonable efficiency. This can be realized by an extension of the present system. The modification consists in disabling the notch filter of the band I momentum cooling and placing an inverter in the signal transmission path. A cooling time of about 30 s per injected pulse is needed in this case.

6.2. Electron Cooling

Electron cooling will be applied at low momenta, especially at 300 and 100 MeV/c (Fig. 2). The requirements of AD are met by the present LEAR device. It is therefore proposed to transfer the existing LEAR cooler with only minor modifications.

It is foreseen to have the electron cooling at 300 and 100 MeV/c but, as in LEAR, additional cooling at 200 MeV/c is possible if needed.

The cooler with its correctors is located in a straight section where the dispersion of the orbit (D) is zero.

7. VACUUM

The different effects of the residual gas which have an influence on the quality of the antiproton beam are:

- losses caused by nuclear scattering and single Coulomb scattering with an angle larger than the acceptance,
- blow-up of the beam emittance due to multiple Coulomb scattering.

Both the single scattering loss and the blow-up scale with beam momentum as $(p^2\beta)^{-1}$ and thus become very important at low momenta. The nuclear scattering has a much weaker energy dependence and can be neglected at low momenta.

Without electron cooling the emittance increase would lead to beam loss within a few seconds making deceleration from 300 MeV/c to 100 MeV/c impossible with a reasonable *dB/dt*. In the presence of cooling, with a time constant of 1 s for the large beam, an equilibrium emittance of ~20π mm·mrad would be reached.

Loss rates and emittances much smaller than these values are needed to be able to decelerate and to adjust the electron cooling and to satisfy the needs of the users. In fact, for efficient capture of antiprotons in a Penning trap, equilibrium emittances <1π mm·mrad at 100 MeV/c are important. Therefore, an improvement of the present vacuum conditions by about a factor 20 is required (leading to a nitrogen equivalent pressure for multiple scattering of about 3×10^{-10} torr).

A sizeable improvement can be obtained by adding titanium sublimation pumps and ion pumps. In addition, some baking can be applied with the aim of reaching a pressure in the low 10^{-10} torr region.

8. AD EJECTION LINE AND EXPERIMENTAL

8.1 AD Ejection Line

The part of the beam line between the AD extraction point and the common switch to the transfer lines for the 3 or 4 experiments serves a dual purpose:

- to connect the AD to the present AA ejection line by adding one extra dipole. This new transfer line will be used to take protons at 3.5 GeV/c from the PS via the TTL2 loop for the AD setting-up.
- To match the beam from the AD to the transfer lines for the experiments. This can be done once the experimental areas are defined.

8.1.1. Injection of 3.57 GeV/c proton beam coming from the PS

It is foreseen to use the existing AC-AA and AA-PS transfer lines but, due to the fact that the antiproton accumulator will be dismantled, the two lines have to be linked. This could be done by means of a 280 mrad bend at the intersection of the two lines.

The optics of the AD 3.57 GeV/c proton test beam line is shown in Fig. 5.

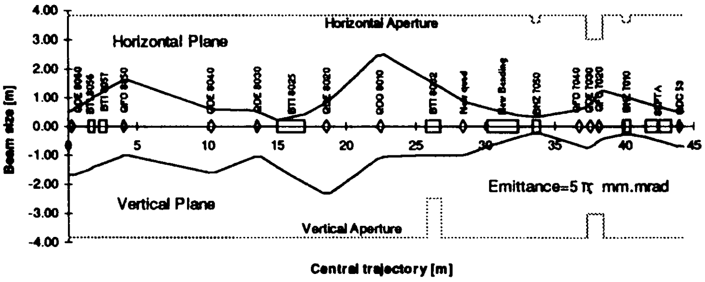

Fig. 5 - Optics of the 3.57 GeV/c injection line

8.1.2. Beam line to the experimental area

The experimental areas are not yet defined. A senario with three low energy experimental areas and a general purpose area to accommodate a number of small experiments in a rapid succession and the use of this last area at high energy is under discussion.

A preliminary study has been done, on the basis of the AC beam optics parameters, to make sure that both low energy and general purpose areas could be housed inside the hall and that the optics of the low energy transfer line is feasible (Fig 1).

8.2 Experimental Area

Experiments will be housed inside the AD ring. Shielding currently in place in the AAC hall does not allow sufficient floor area, therefore a new shielding configuration is proposed, where the inner support wall is brought as close to the AD ring as possible.

9. CONTROLS

The Nord 100 computer presently installed for the controls of the AC and the AA cannot be used in the future. The AD Control System is based on the new PS control system, with workstations, servers and VME embedded processors (PowerPC processors) linked by an Ethernet sub-network.

The workstations will be located in the PS Main Control Room (MCR) and the AD Control Room (ACR) for the normal operation; workstations will also be provided to the experimental teams.

In order to simplify the conversion to the new control system, some of the existing programs could be used as a base for writing new applications. As considerable effort has been invested in the current AC setting-up and measurement programs, the experience accumulated in these programs will significantly reduce the effort to get the new software working. A new set of application software is required for deceleration, electron cooling and ejection.

10. INSTRUMENTATION

The AD will use the existing beam diagnostics and measurement devices installed in the AC and its injection and ejection lines, including the Antiproton Production area. For some of the devices, a renovation has to be carried out.

The pick-up stations of the current AC closed orbit measurement system need some upgrading. For the AD, it is foreseen to measure the closed orbit over the complete momentum range, and for beam intensities down to 10^7 antiprotons.

The Schottky pick-up will also be used for tune measurements with test proton beams. For tune measurements during deceleration, the existing low frequency resonant pick-ups will be upgraded for larger tuning range and lower noise to be able to measure the tune by bunched beam Schottky signals at low energy.

11. POWER CONVERTERS

The range between 3.57 GeV/c and 100 MeV/c is large. In order to guarantee a current stability at low energy, active filters must be added on the main power converters. The trimming power supplies will have to run below the present minimum controllable current. It is proposed to build new power converters which will be stable down to a very small current. The present unipolar converters must be replaced by bipolar trim supplies.

The insertion of 2 quadrupoles, recuperated from the AA ring, for the electron-cooling section requires 3 additional trim converters with similar characteristics to the present ones.

The electron-cooling power converter, recuperated from LEAR machine, needs some upgrade due to the new control system.

The horizontal and vertical closed orbit correction is under study in order to define the number of power supplies and trim supplies needed.

Due to modifications of the AC-AA and AA-PS transfer lines, new bending and quadrupole magnets are required, the power converters are still to be found or built.

12. OTHER SERVICES

12.1. Radiation Safety Aspects

Studies and measurements have been done to evaluate the safety measures necessary to allow user teams to be present inside the AD hall during operation. There are two operation modes:

- setting-up of the machine with protons,
- operation with antiprotons.

12.1.1. Operation with protons

Assuming that 3×10^{10} protons per 2.4 s may be injected into the AD through the TTL2 loop, the radiation level is too high to allow access to the hall during the setting-up.

In order to limit the amount of shielding necessary it is therefore recommended not to allow access to the hall during operation with protons. Consequently, during proton operation, the hall and the ring will be considered as a primary beam area. The entrance to the hall (existing door 301) will be electrically locked and controlled by the operation crew from the Main Control Room.

12.1.2. Operation with antiprotons

Measurements have been carried out inside the AC hall to determine the present dose equivalent rate arising from muons and neutrons. The detectors were placed at beam height level and they were exposed for a period of operation. Taking into account that future operation will be at 1 pulse/minute the average dose rates are still too high for permanent occupancy in experimental huts. It is therefore recommended to add a layer of 80 cm of concrete in the injection region over a length of 18 m. This will locally reduce the dose rates by one order of magnitude and keep the radiation level in the huts, on top of the shielding roof, at a very low level.

During the operation with antiprotons, the door 301 will be open, and the hall is considered as an experimental hall. The antiproton experimental beam areas will be equipped with the new access system similar to that of the PS East Hall.

12.2. Ventilation

A minor modification of the ventilation system of the AC hall will be necessary to improve the release system for activated air from the target area. At present this air is entering the AC hall which may cause unwanted background in the installed experiments.

13. OPERATION

13.1. AD Commissioning

The initial running-in will require the participation of the system specialists, plus a small number of "dedicated" accelerator physicists. In addition, it is hoped that each of the main experiments will supply at least one physicist/engineer to help with all phases of the running-in. These experts, 4 or 5, will then form the basis of the team of AD machine supervisors for routine operation. Some experienced operation technicians will be needed to help full time with the commissioning of the facility. They would be temporarily detached from their other duties in the PS operation structure. These new qualified AD operators will be part of the regular PS/PSB operation team foreseen for the MCR Operation crew after the end of 1996.

13.2. Routine Operation

We assume that the facility will run continuously from Monday morning to Friday evening, but not over weekends, for about 3000 h each year between April and October avoiding the PS start-up after the shutdown and the critical day period in November and December. The initial start-up for each running period will be performed by the team of the AD machine supervisors assisted by the qualified AD operators. Each week of regular operation will be supervised by an AD machine supervisor. The existing PS Operation crew will continue to be responsible for the primary production beam up to the production target, but the routine facility operation will be left to the users themselves, along the lines currently followed for ISOLDE and the EAST Hall secondary beams. This implies a high degree of automation. However, the AD will be a complex installation with $\bar{p}$ production, injection, deceleration and extraction; therefore, in order to assist the users with the day-to-day problems, a technical supervisor will be available to help them during normal working hours. For operational problems that the users encounter outside normal working hours, they will be able to contact the MCR operation crew or the machine supervisor, but as a rule, other specialists will not be called until the following working day. This means that in case of serious breakdowns the AD will be off until the following working day.

14. CONCLUSION

Using the modified AC as an antiproton decelerator to deliver dense beams of 10^7 $\bar{p}$/min at 100 MeV/c with bunch lengths between 200 and 500 ns seems possible. This simplified scheme opens the possibility for a new antiproton physics programme based on fast extracted beam. However, taking into account the lack of CERN's resources, the cost and manpower for the project must be supported by external laboratories who will also be required to help with the operation.

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