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# DESIGN STUDY OF THE ANTIPROTON DECELERATOR: AD

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## Abstract

This Design Study reports on a simplified scheme for the provision of antiprotons at 100 MeV/c in fast extraction. The physics programme is largely based on capturing and storing antiprotons temporarily in Penning traps. The physics goals are the production and spectroscopy of antihydrogen to study fundamental symmetries, and the study of the interaction of antiprotons at ultra-low energies with atoms and nuclei. The scheme uses the existing $\bar{p}$ production target area and the modified Antiproton Collector Ring in their current location. The modifications necessary to deliver batches of $1 \times 10^7$ antiprotons every minute at 100 MeV/c are described and details of the machine layout and the experimental area in the existing AAC Hall given.

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# Contents

# FOREWORD

The Antiproton Decelerator Design was prepared by a working group from PS Division with the help of other CERN Divisions.

We would like to take the opportunity of thanking all those who made helpful contributions, in particular

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In addition we would like to make special mention of the devoted assistance of A. Molat who patiently prepared the many drafts of this report.

## 1. INTRODUCTION

Following the decision to close the LEAR antiproton programme, there were strong requests from the user community to continue certain experiments. Simplified schemes for the provision of antiprotons of a few MeV were presented at the Antihydrogen Workshop in Munich, in July 1992 [1]. This study has been updated [2], taking new developments into account:

1) The momentum favoured for transfer to the traps, for antihydrogen production, is now 100 MeV/c (i.e. about 5 MeV kinetic energy), instead of 60 MeV/c (~2MeV) as assumed in [1].
2) The use of LEAR as a heavy-ion accumulation ring is now part of the LHC design proposal [3].

A scheme, compatible with these boundary conditions, is the use of the AC [4] (appendices 1 and 2) alone as an antiproton cooler and decelerator ring. The feasibility of this scheme was studied in Ref. [5] and estimates of the resources necessary to build and to run it were subsequently made [6,7].

A large reduction of the operational costs results from the use of only one antiproton machine, whereas the scenario in operation today involves four machines (AC, AA, PS and LEAR) to 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 $1\pi$ 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, using the modified AC, is called AD (Antiproton Decelerator). It is the subject of the present design report.

## 2. AD OVERVIEW

The existing target area and the AC ring in its present location (Fig.1) are used and 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 $5\pi$ 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 $33\pi$ 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 $5 \times 10^7$ $\bar{p}$ are injected at 3.57 GeV/c and with an estimated overall efficiency of 25%, $1.2 \times 10^7$ $\bar{p}$ are available at low energy.

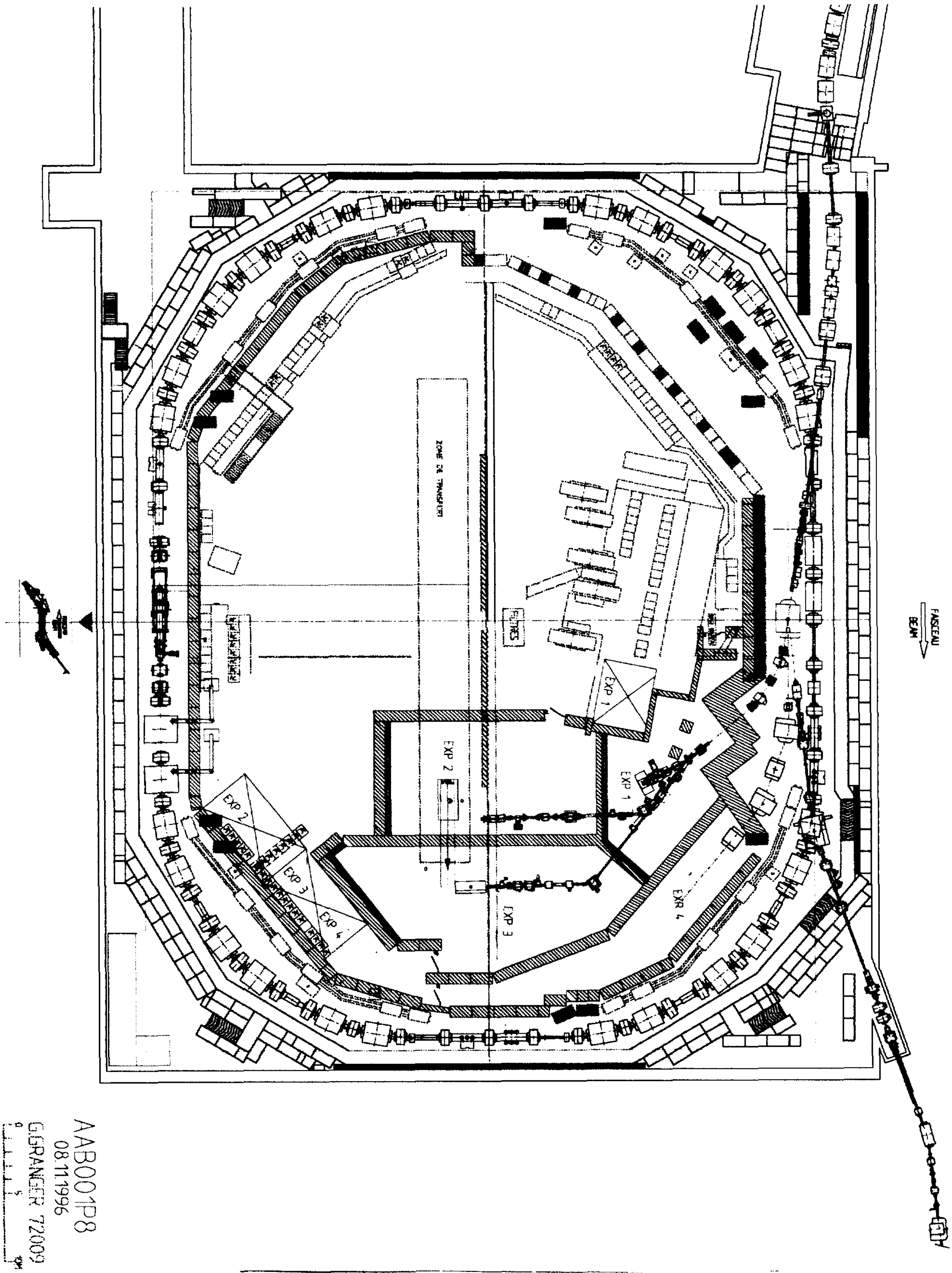


*Fig. 1*

*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 | $\varepsilon_i$ | $\varepsilon_f$ | $\Delta p/p_i$ | $\Delta p/p_f$ | $t$ | Cooling process |
|---|---|---|---|---|---|---|
| [GeV/c] | [$\pi$ 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 | - | |

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 $1.2 \times 10^7$ $\bar{p}$ 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.

**Basic AD deceleration cycle**

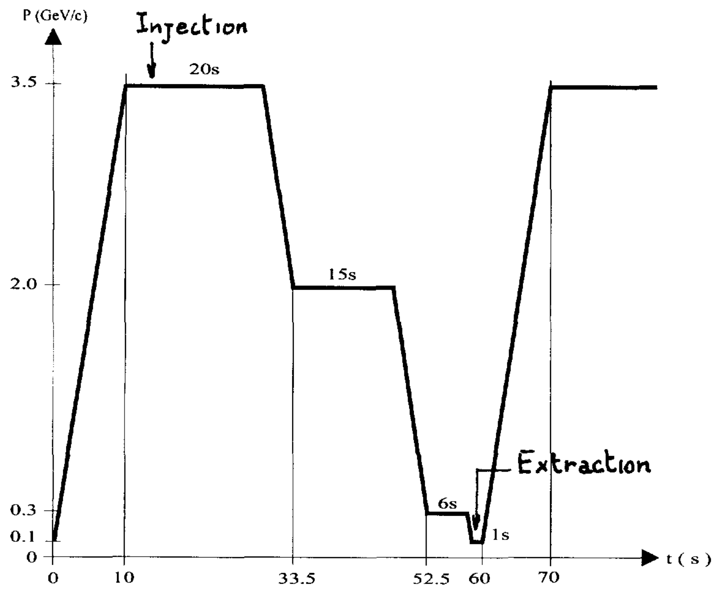


*Fig. 2*

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

## 3. AD LATTICE

The present AC lattice [4] 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.

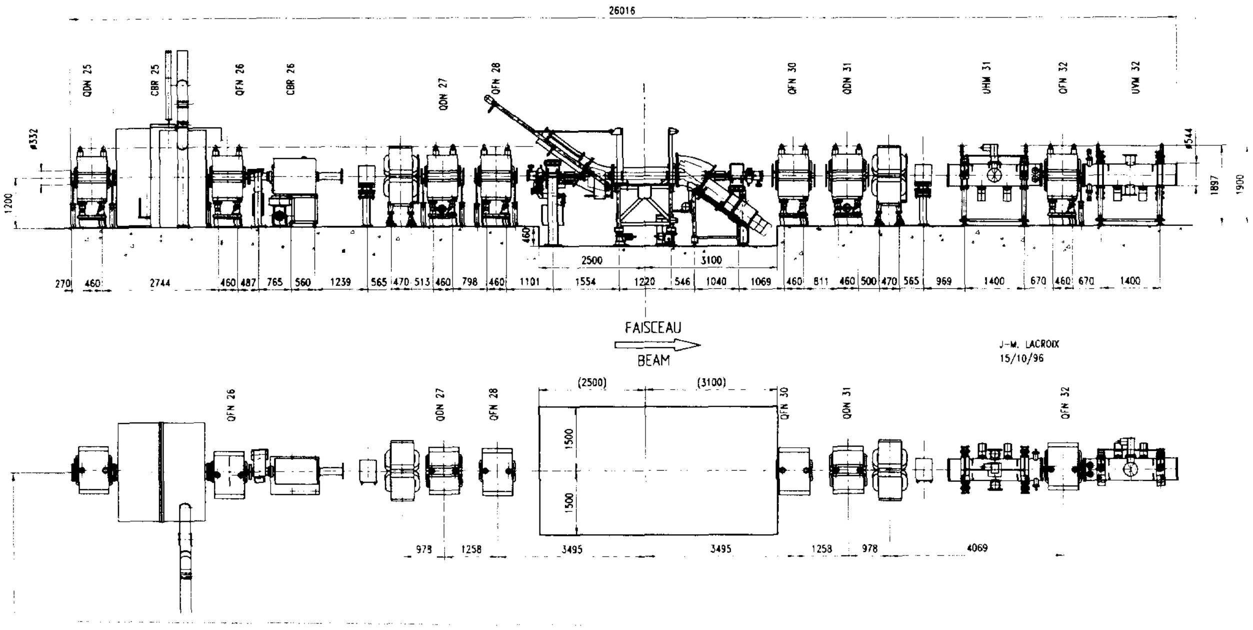


*Fig. 3 - Layout of the electron-cooling section*

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 $\Delta Q$ 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.

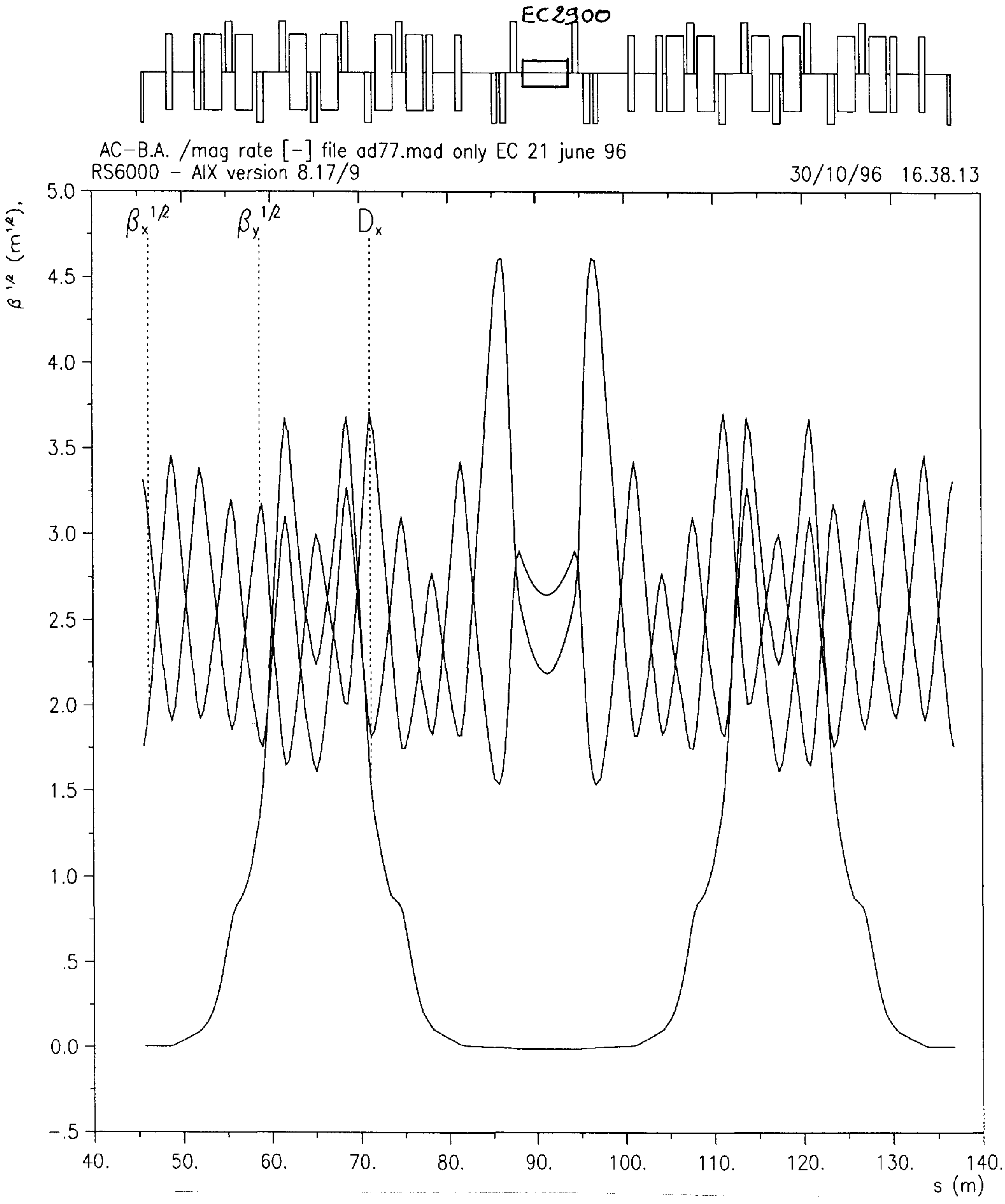


*Fig. 4 - The lattice functions of the Antiproton Decelerator*

The vertical $\beta$ -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

## 4.1 Antiproton Production Beam

A 26 GeV/c production beam of $10^{13}$ protons is necessary in order to inject the required $5 \times 10^7$ antiprotons into the AD.

The present method for producing the proton beam will be replaced by a more efficient technique [8], profiting from developments required in view of the LHC. In particular, protons will be accelerated on the harmonics $h = 1$ and 2 in the PS Booster, and on $h = 8$ and 16 in the PS. The purpose is to fill half the PS ring with bunch to bucket transfer of the beam from the 4 PS Booster rings.

Acceleration in the PS of the production beam will take place on $h = 8$ up to 26 GeV/c, where a compression scheme similar to the present one [9] is applied. The harmonic number is increased stepwise from 8 to 20, keeping the beam in 4 adjacent bunches. On the flat top, at 26 GeV/c after the synchronisation of the PS beam frequency with the AD rf driving the bunch rotation cavity, bunches are shortened by a non-adiabatic rf manipulation, and the beam is ejected and sent onto the production target.

For the stacking option, the PS beam needs to be synchronised at the third subharmonic of revolution frequency, and the plateau of the PS magnetic cycle at 26 GeV/c will probably be lengthened by about 50 ms.

## 4.2 Antiproton Production

The production beam is focused on the target with two pulsed quadrupoles (QDE 9050, QFO 9052) (Fig. 5). The high density target made of a thin iridium rod (3 mm × 55 mm in diameter and length) embedded in graphite and enclosed in a sealed, water cooled, titanium container, remains unchanged. Antiprotons emerging from the target are focused and matched into the injection transport line by a magnetic horn used as collector lens. This 60 mm diameter biconical aluminium horn [10] operating at 400 kA peak is a simple and cheap device to build and operate. During the last 4 years, a consolidation programme of the target area has been carried out [11]. For the AD era, only some overhauling and the provision of some spare components is needed.

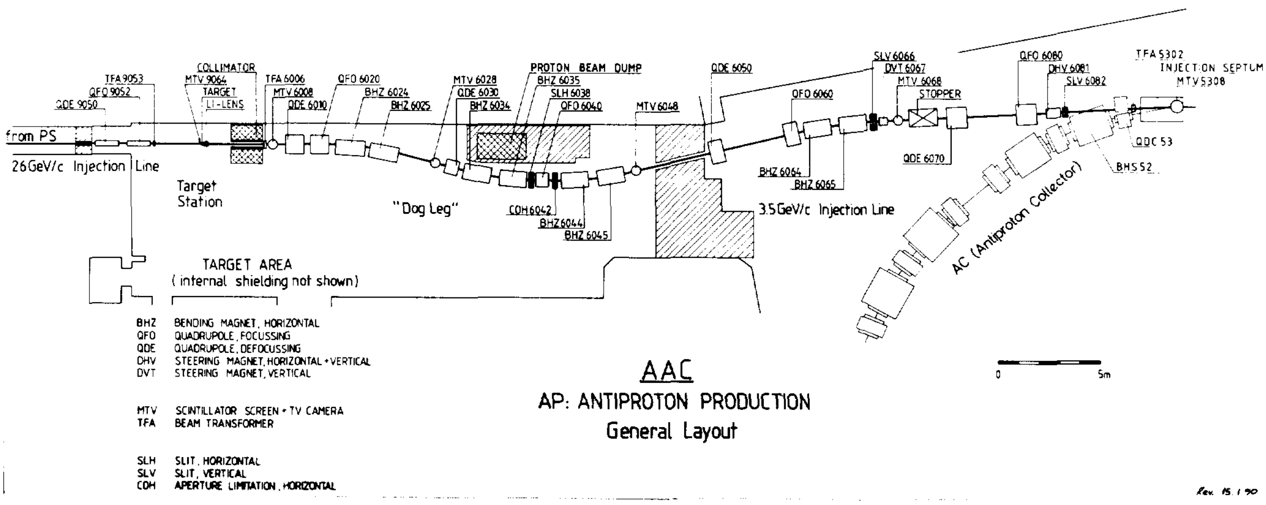


*Fig. 5*

# 5. RADIOFREQUENCY SYSTEMS

## 5.1 Bunch Rotation rf System (9.586 MHz)

To free the present rf zone, required for the AD Experimental Area, the equipment situated in the hall will be moved towards the concrete shielding. The bunch rotation system will undergo some modifications mainly due to the relocation of the equipment but also for consolidation. This should not affect the performance of the system.

The transmission line connecting the final amplifier to the cavity is composed of a 16 Ω half-wavelength section followed by a 60 Ω, $\lambda/8$ section. The latter plays a fundamental role in the accelerating cavity discharge process and cannot be avoided, while the 16 Ω sections can be suppressed if the amplifier can be put closer to the cavity.

In the new layout the concrete shielding will be moved closer to the ring and the 16 Ω ($\lambda/2$) section will be completely removed such that the present $3\lambda/4$ transmission line is replaced by a $\lambda/4$ line.

The final amplifiers with only the 60 Ω sections have to be installed closer to the cavity and at about 120 cm above the floor level. A platform allowing the installation of all the equipment racks, except the high voltage supplies, will therefore be built.

The consolidation of some elements of the system is required to improve reliability and ensure an easier servicing. It will mainly consist of the installation of new, standard interlocks and replacement of the 1 kW pre-drivers with 4 kW units.

## 5.2 Deceleration rf System

The present 1.6 MHz ($h$ = 1) rf system with a 3.5 $kV_p$ peak produced in a single ferrite loaded cavity will be modified to cover a frequency range of 0.50 – 1.59 MHz. The present gap capacitor will be increased from 880 pF to 3 300 pF, and the bias current range increased from 300 A to 1 000 A (bias supply recuperated from the AA $h$ = 1 rf system). In addition, a relay switched capacitor of the order of 25 nF will be connected to the gap prior to fast extraction to lower the resonant frequency to 174 kHz to create a single antiproton bunch of less than 300 ns at 100 MeV/c.

This rf system serves four distinct purposes:

- Deceleration of antiprotons,
- Bunching of the already cooled antiprotons at 3.5 GeV/c when several production pulses are being accumulated,
- Bunching and bunch rotation of the cooled antiproton beam at the extraction momentum of 100 MeV/c,
- Capture and deceleration of proton test beams ($10^9$ to $2 \times 10^{10}$ protons per pulse) for setting up.

With a ramping time of 10 seconds from 3.575 GeV/c to 100 MeV/c the $dB/dt$ becomes -0.146 T/s, which corresponds to an energy loss per turn of 212 eV. The required rf voltage is therefore determined more by longitudinal acceptance than by deceleration rate. Deceleration takes place at $h = 1$ from 3.575 GeV/c to 300 MeV/c, and on $h = 3$ from 300 MeV/c to 100 MeV/c. A voltage of 3 $kV_p$ at high energy and a voltage of 1.5 $kV_p$ at low energy is sufficient. For the bunching and bunch rotation prior to extraction 500 $V_p$ at 174 kHz is required. It is likely, however, that deceleration will be limited to much slower ramping rates due to limitations in the magnet power supplies and eddy currents in magnets and vacuum chamber.

The low level rf system will be converted from the present analogue to a digital system using standard modules already being used in the PSB and PS rf systems. A B-train generator based on a coil in one of the bending magnets is required to drive the rf frequency program.

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.

### 5.3 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. Alternatively, the cooled stack bunched at $h = 1$ could be further compressed adiabatically with the $h = 6$ system prior to injection. The cooled bunch will then be slightly diluted by the bunch rotation, but this is easily compensated for by cooling. The newly injected antiproton beam will thus be debunched to a $\Delta p/p$ of 1.5% (compared to 6% in the previous scheme) and the full bandwidth of both band I and II can be exploited resulting in a much shorter stacking cycle. Some modifications to the power supply of the $h = 6$ rf system will be required to implement the adiabatic voltage rise.

## 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. The performances are given in Table 2 with an additional blow-up factor of 2.5 at low energy and they are derived from measurements made on LEAR.

*Table 2 - Characteristics of the cooler*

| | | | |
|---|---|---|---|
| Antiproton momentum, $p$ | [MeV/c] | 300 | 100 |
| Cooling length, $L_{cool}$ | [m] | 2.2 | 2.2 |
| *$L_{cool}$/circumference, $\eta_c$* | | 0.0116 | 0.0116 |
| Electron energy, $U_{ecin}$ | [keV] | 25.48 | 2.894 |
| Electron current, $I_e$ | [A] | 3.5 | 0.5 (0.1) |
| *Perveance of electron beam, $p_g$* | [$10^{-6}$ $AV^{-3/2}$] | 0.58 | 2.6 (0.52) |
| Electron beam radius | [mm] | 25 | 25 |
| Space charge potential, $U_{Sp}$ | [kV] | 1.034 | 424.6 |
| Cathode voltage, $U_{cath}$ | [kV] | 26.52 | 3.318 |
| *Betatron functions at cooler, $\beta_{HV}$* | [m] | 6.0 | 6.0 |
| *Initial, final emittances $\varepsilon_i/\varepsilon_f$* | [$\pi$ mm·mrad] | 33/2 | 15/1 |
| *Cooling time constant, $\tau_c$* | [s] | 2.2 | 0.05 (0.3) |
| *Total cooling time, $t_c$* | [s] | 6.3 | 0.14 (0.7) |

To accumulate lead ions for the LHC, a strong cooling device is needed. It is foreseen to construct a "state-of-the-art" cooler for this purpose. The series of experiments on LEAR to test ion accumulation will be finished in 1997, in time to allow the transfer of the present cooling system. 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 is located in a straight section where the dispersion of the orbit ($D$) is zero. The insertion of the electron cooler induces perturbations to the antiproton beam:

- a closed orbit distortion due to kicks induced by the toroids ,
- coupling of the horizontal and vertical betatron motion due to the solenoid,
- a tune shift due to the electron beam and residual coupling from the solenoid.

The U-shaped arrangement (where gun and collector point to the same side) has advantages for the electron beam optics compared to the S-shaped arrangement (where gun and collector point to the opposite side) but needs a more elaborate compensation scheme. The present LEAR correction dipoles are well suited for this compensation, but the vertical acceptance at high energy could be limited in the horizontal dipoles. Another restriction could exist in the toroids, where, the maximum $\beta$ functions allowed are 8 m. The U-shaped or S-shaped arrangement installed vertically or horizontally needs more studies.

Horizontal-vertical coupling will be compensated by the same type of solenoids installed on LEAR. They will be connected in series with the main solenoid.

The tune shift due to the electron beam is in the order of $10^{-3}$ and therefore does not require any special form of compensation.

For the high voltage power supplies, a Faraday cage can be mounted, adjacent to the electron cooling device on the inside of the hall.

## 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.

Typical vacuum conditions measured in the present AC are summarised in Fig. 6. For these conditions one calculates:

i) a single scattering lifetime of 0.75 min at 100 MeV/c (taking a horizontal and vertical acceptance of $50\pi$ mm·mrad for the AD at low energy),

ii) a blow-up of the emittance $(2\sigma^2/\beta)$ at 100 MeV/c of $d\varepsilon/dt \approx 20\pi$ mm·mrad/s

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 $\sim 20\pi$ 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 $<1\pi$ 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 $3 \times 10^{-10}$ torr).

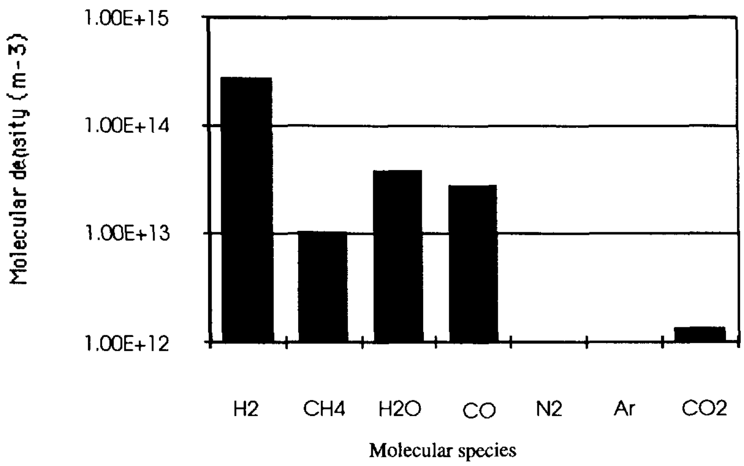


*Fig. 6 - Residual gas composition typical for the present AC ring and for a total average pressure of 8 pbar*

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 AREA

## 8.1 Kicker Magnets

### *8.1.1. Injection of protons at 3.57 GeV/c coming from the PS*

The injection of protons into the AD from the PS will be done as at present. The exception is that only three kicker modules will be available, and there is just enough kick strength. The parameters for this operation are given in Table 3.

*Table 3 - Parameters for the AD 3.5 GeV/c proton injection kicker*

| | | |
|---|---|---|
| Kick strength ∫Bdl | [Tm] | 0.1173 |
| Deflection $\theta$ | [mrad] | 9.84 |
| Kick flat top duration | [ns] | variable 0-500 |
| Flat-top ripple | [%] | ±1 |
| Kick rise time (10-90%) | [ns] | ~207 |
| Kick fall time (90-10%) | [ns] | ~207 |
| Number of pulse generators/magnets | | 3 |
| Pulse generator Pfn voltage | [kV] | 74.3 |
| Magnet tank position | | K35-1, K35-2, K50-1 |

### *8.1.2. Ejection of antiprotons at 100 MeV/c from the AD*

One pulse generator and one terminated magnet of the existing AD ejection equipment, working at 13.4 kV, will provide sufficient deflection for ejection of the $\bar{p}$ beam from the AD. The termination will be recovered from the AA injection system and minor circuit adaptations must be made to obtain a good kick flat top. The important data are shown in Table 4 and a simulated kick waveform is given in Fig. 7.

*Table 4 - Parameters for the AD 100 MeV/c ejection kicker*

| | | |
|---|---|---|
| Kick strength $\int Bdl$ | [Tm] | 0.00328 |
| Deflection $\theta$ | [mrad] | 9.84 |
| Kick flat top duration | [ns] | variable 0-500 |
| Flat-top ripple | [%] | ±1 |
| Kick rise time (10-90%) | [ns] | ~93 |
| Kick fall time (90-10%) | [ns] | ~93 |
| Number of pulse generators/magnets | | 1 |
| Pulse generator Pfn voltage | [kV] | 13.4 |
| Magnet tank position | | K50.2 |

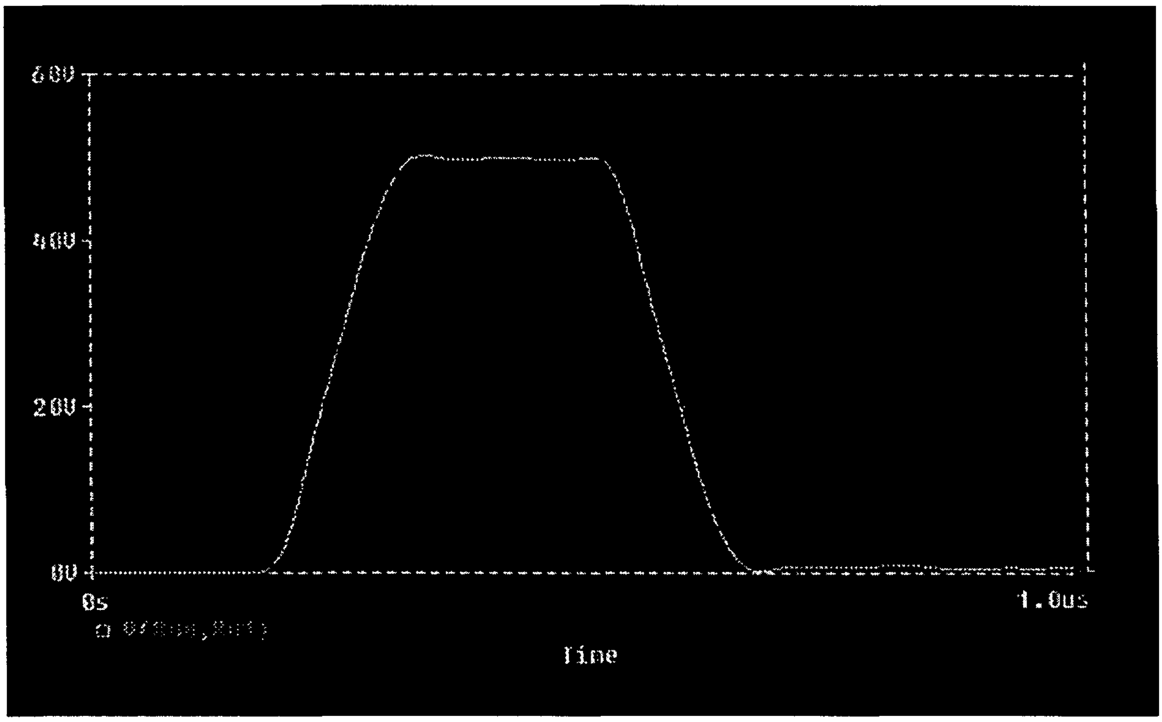


*Fig. 7 - Calculated kick waveform*

## 8.2 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.

### *8.2.1. 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 PS M2 type solid core magnet which has a sufficient horizontal aperture and bending power can be used for this purpose.

To match the beam to the AD (Table 5) it is necessary to add a quadrupole magnet upstream of the new bending magnet in order to correct properly the quadrupolar effect of the fringe field and the dispersion introduced by this magnet. Another possibility is to move the quadrupole QFO 7040 which is not very useful at its actual location. The optics of the AD 3.57 GeV/c proton test beam line is shown in Fig. 8.

*Table5 - AD parameters at the quadrupole QDC 53.*

| Horizontal Plane | | | | Vertical Plane | | | |
|---|---|---|---|---|---|---|---|
| $\beta_x$[m] | $\alpha_x$ | $D_x$ [m] | $D'_x$ | $\beta_y$[m] | $\alpha_y$ | $D_y$ [m] | $D'_y$ |
| 4.98 | -1.189 | 0.11069 | 0.13276 | 9.401 | 2.102 | 0 | 0 |

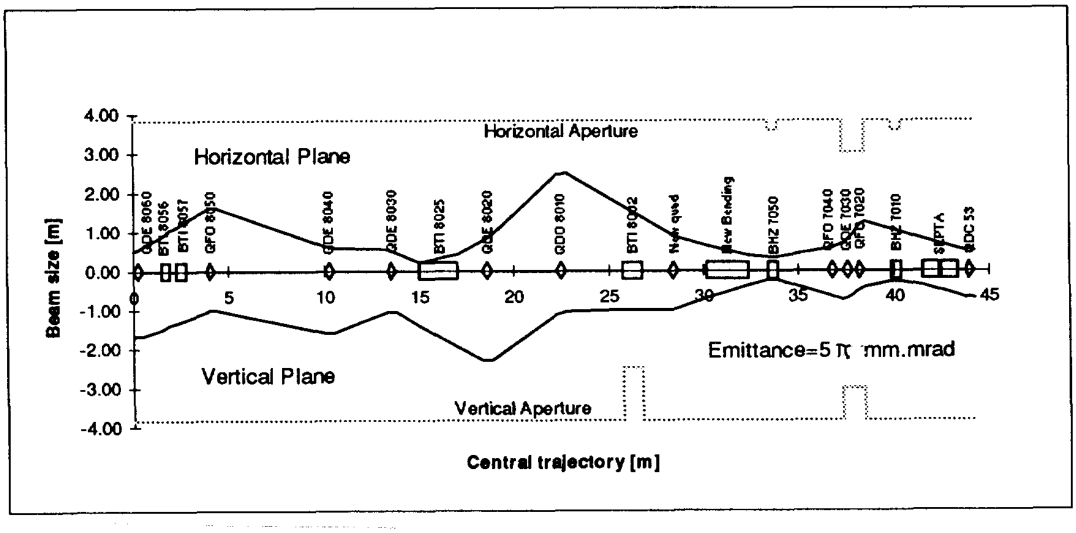


*Fig. 8 - Optics of the 3.57 GeV/c injection line*

### *8.2.2. 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. A possible layout for the beam transfer lines to the experimental areas is shown in Fig 9.

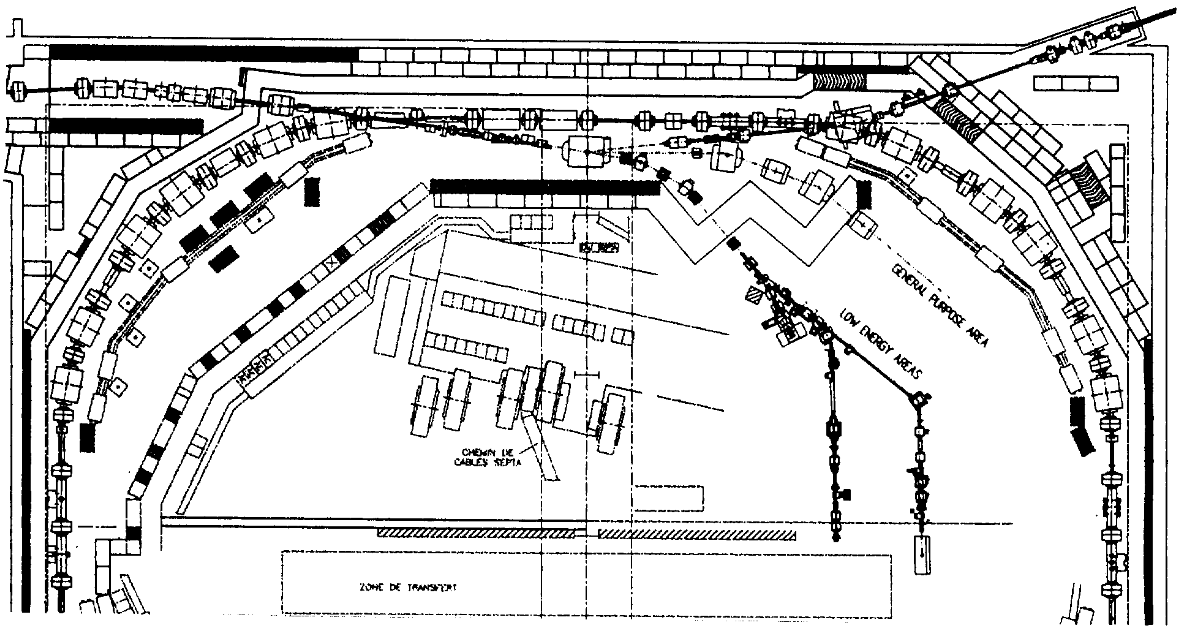


*Fig. 9 - Possible layout for the beam transfer lines to the experimental areas*

## 8.3 Experimental Area

### *8.3.1. Experiments in the AD hall*

The beam lines installed in the South Hall will be dismantled and remounted in the AD hall [12]. The difference of beam height between LEAR and AD does not cause a problem since most of the equipment has adjustable supports.

### *8.3.2. Shielding*

The installation of experiments requires a new configuration of the shielding.

The shielding currently in place would not allow sufficient floor space for the experiments foreseen, and future removal of the heavier sections (concrete beams of 17 m × 1.5 m × 0.5 m of weight 37 t) would be difficult. Therefore, a new layout is proposed. The outer support wall must stay in place whereas the inner support wall is brought as near to the AC machine as possible. This would make sufficient space available for the experiments. The roof shielding would have to be changed accordingly.

The second layer of roof shielding, and any extra side shielding can be made from existing blocks and beams. The existing shielding above stochastic cooling kickers can be retained, the first layer of roof shielding will require a series of reinforced concrete beams. These beams would be made of standard section (80 cm × 80 cm) with various lengths to suit the proposed configuration.

The rf amplifiers for the bunch rotation system will be mounted on a platform adjacent to the shielding. This platform will be of a simple but sturdy steel construction.

Experimental huts will be put on platforms on top of the shielding where dose rates are low. Below the hut a Faraday cage can be mounted for the high voltage power supplies of the electron cooler.

All the AA ring will be dismantled.

*8.3.3. Gas distribution*

The gas installation is made on the assumption that inert gases ($N_2$, $CO_2$, He) can be stored and distributed from within the hall. As much as possible of the distribution system presently in use in the South Hall will be transferred and re-adapted to the experiments in their new location.

Flammable gases must nonetheless be stored in specific conditions on the outside of the building. This means that a suitable storage shed has to be constructed in the area adjacent to the cooling tower. Such a siting would facilitate delivery of the gas bottles.

## 9. CONTROLS

The AD Control System is based on the new PS control system [13], with workstations, servers and VME embedded processors (PowerPC processors) linked by an Ethernet sub-network.

The workstations, servers and front-end processors run UNIX operating system (AIX version on IBM RS/6000, LynxOS RT UNIX on front end). The user interface consists of a console manager and a set of generic programs (set of operational parameters, Knobs, Alarms presentation); specific application programs can be called from this console manager. Generic and specific programs use the X-Windows package, and the specific application programs are built in C/C++ language, inside frameworks specially developed to facilitate the production of some classes of application programs. The programs interact with the accelerator parameters through the Equipment Access interface; in the front-end processors the Equipment Modules (EM) and Real Time tasks (RT) control the different equipment, by means of drivers when necessary. The front end configuration (hardware and software) as well as the operator interface are centrally managed by means of an Oracle Data Base. The Beam instrumentation devices are controlled using specific software which handles the particular needs of the instrument.

A controlled bridge between the CPS control system and PC office network provides programming facilities to access under Windows 95 the accelerator parameters in the frame of machine studies or equipment prototyping.

The different equipment will be interfaced through few field buses (CAMAC and mainly MIL 1553), as well as VME modules. For the power converters, rf systems, kickers, vacuum, water cooling and magnetic horn, all the standard control software will be used and adapted to the AD. CAMAC crates will be kept for the power converters of the part of the transfer line between the PS and AD (FT16 loop). The control of the electron cooling may require a dedicated control and is under study.

The timing, based on VME counter modules, and the synchronisation between the AD and the CPS needs to be studied in more detail.

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 have a control system which will be radically different in concept from the existing AAC complex control system. Hence, significant effort has to be foreseen for commissioning the control system and its routine use for this machine. Furthermore, all beam measurement and diagnostics devices will run under this new control environment needing dedicated studies and commissioning; this is particularly true for very low intensity (few $10^7$ particles) beams whereby the measurement systems would be stretched to their limits of capability, not seen in the current AC ring.

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. In addition to renovation, a major part of the work involves migrating CAMAC-Norskdata computer-based equipment to the standard PS Controls environment of VME-based front-ends and workstation-based applications. Some interfaces may be reusable and even kept in CAMAC, controlled through VME front-ends to minimize costs. However, Norskdata computer-based software has to be re-written. The higher-level applications can use new programs running in the control room workstation environment. The new application programs will use the concepts and ideas from the current high-level application programs so as to minimize effort [14].

### 10.1 Injection Line and Injection into AD

Scintillation screens and TV cameras will continue to be used to help steer the beam onto the target. The existing stations, four before the target and four after the target are suitable both for 26 GeV/c high intensity production beam ($10^{13}$ ppp) and the 3.57 GeV/c low intensity test beam ($10^{10}$ ppp).

The four beam current transformers routinely used today will continue to be used with the same requirements and conditions, but with major adaptations to the new acquisition system implying modifications to electronics and interfaces to the new control system.

### 10.2 AD Ring

A scintillation screen and TV camera measure the beam position at the entrance to the injection septum and kicker of the current AC Ring. This will remain unchanged. Similarly, a screen which also acts as a beam stopper after nearly one turn will continue to fulfill the same function. For the beams ejected to the experiments, a screen is also available at the exit of the septum magnet. This screen permits the observation of cooled antiproton beams ejected as well as proton test beams.

The current AC closed orbit measurement system consists of 32 horizontal and 28 vertical pick-ups and measures orbits at 3.57 GeV/c with test proton beams of few $10^9$ particles. These pick-up stations will not be changed; however, 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 measurement will require a bunched beam, kept at a constant energy whilst the sum and difference signals are scanned by a multiplexer and the difference to sum ratios determined by a network analyzer. The time required to scan the 60 pick-ups will be not more than 6 seconds for $10^7$ particles. Most likely, new amplifiers will be required to optimize the signal-to-noise ratio.

The existing or upgraded Schottky pick-up will be used to measure the antiproton yield, and the beam intensity and emittance. It will also be used to monitor the performance of the various processes of rf bunch rotation/debunching, and cooling through different stages of deceleration. 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, where the present 50 MHz Schottky pick-up fails. The FFT-based system used in LEAR will be upgraded for use with the Schottky signals in AD (faster FFT processing, more memory, larger dynamic range). Similarly, a beam ionization profile monitor of the type used in LEAR will be installed in AD to measure beam profiles in horizontal and vertical plane.

The existing dc beam current transformer TRA4105 is adequate to make measurements with test protons beams. However, for low-intensity antiproton beams, it has certain limitations. The transformer has a resolution of 2 to 3 microamperes while the routine antiproton injected intensities of $5 \times 10^7$ particles correspond to about 1.4 microamperes at 100 MeV/c. Hence for accurate low-intensity measurements, a Schottky pick-up will be used for intensity measurements, calibrated using the TRA4105 with proton beams of sufficient intensity.

The existing destructive transverse scrapers in the zero-dispersion region of the AC ring will continue to be used in AD for machine aperture and acceptance studies. These 4 blades permit the exploration of betatron phase space. The acquisition and control of the scrapers will be upgraded to the new controls standard.

For measuring and correcting the injection coherent oscillations for test proton beams, the existing system of 100 MHz sample-rate digitizers will be used. To correct the energy mismatch between PS and AD, the synchronising rf phase will also be digitized using another low sample-rate ADC. For correction of coherent oscillations of injected antiprotons, special low-frequency resonant pick-ups will be used as in AC, coupled with the fast digitizer system and a digital oscilloscope. All these systems will be upgraded to work under the VME based front-end systems.

### 10.3 Ejection from AD to Experiments

The ejection transfer line to the experiments is composed of 2 parts: the first part is used at high energy with protons from the PS and at low energy with antiprotons, the second part is only used with antiprotons at low energy.

Scintillation screens with TV cameras are already used to adjust the first part of the line using test proton beams from the PS. These stations, currently existing in this transfer line will also serve the purpose of steering the ejected antiproton beam. The beam current transformer works adequately for the test of proton beam intensities but is close to the resolution limit for antiproton intensities. Possible methods of measuring low intensities and profiles are being studied.

In the second part of the transfer line at low energy the existing MWPC's can be used.

### 10.4 Proton Test Beams from PS

The TTL2 line which injects currently into the AA Ring will be modified to inject directly into the AD ring. The existing scintillation screens and TV cameras will be used to adjust the line with minor relocation if necessary. The beam current transformers TRA8084 in TTL2 and TRA7012 just before AD injection will be used to measure the test beam intensities.

## 11. POWER CONVERTERS

### 11.1 AD Machine

The range between 3.57 GeV/c and 100 MeV/c is large. In order to guarantee a current stability of about $5 \times 10^{-4}$ at low energy, active filters must be added on the main power converters [15]. 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 actual precision of the power supplies is listed in Table 6. Table 7 shows the parameters of the new trim supplies.

*Table 6 - Present $\Delta I/I$ precision of the power supplies*

| Power supplies | 3.57 GeV/c | 100 MeV/c |
|---|---|---|
| Bending | $\sim 10^{-4}$ | $10^{-3}$ |
| Quadrupole | $2 \times 10^{-4}$ | $\sim 3 \times 10^{-3}$ |
| Trimming ($B$+$Q$) | $10^{-3}$ | $10^{-2}$ |

*Table 7 - Parameters of trim-supplies*

| Power converter | Number | Current/Voltage rating |
|---|---|---|
| B-Trim | 1 | ±20 A/±450 V |
| Q-Trim | 3 | ±100 A/±250 V |

The power supply of the ejection septum magnet needs a consolidation in order to achieve the low current values at 100 MeV/c and the replacement of the electronics due to the new control system.

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.

## 11.2 Transfer Line

All the power supplies of the transfer lines will be equipped with new controls electronics based on a G64 bus in order to be consistent with the new controls systems.

With some modifications, the 4 pulsed power converters of the AD ejection line which should work at 3.57 GeV/c and 100 MeV/c can cope with the smaller current required at low energy. Three dc power converters used in this line cannot work at low energy and must be replaced by new ones. Their characteristics are listed in Table 8.

*Table 8 - Characteristics of transfer line dc power converters*

| Power converter | Current/Voltage rating |
|---|---|
| AI.DVT 7013 | ±10 A/±60 V |
| AI.QFO 7040 | 100 A/30 V |
| AI.DVT 7042 | ±10 A/±60 V |

The rest of the line which is used to transfer the proton beam from PS to AD only works at 3.57 GeV/c. Six steering magnet power converters will be replaced by new standard low power supplies, and the other six already equipped with standard low power supplies need to be upgraded.

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.

### 11.3 Experimental Areas

Some of the 30 power supplies used at low energy for the experiments are recuperated from the LEAR experimental area and will be installed in the hall and partly in the equipment room close to the AAC control room. A new low voltage distribution is needed for these power converters.

## 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 $3 \times 10^{10}$ protons per 2.4 s may be injected into the AD through the TTL2 loop, a side and roof shield of 3.4 m of concrete would be needed to keep the dose rate due to local full loss of the beam below 25 μSv/h. Assuming local losses to be below 10% will still require a roof and side shield of 2.4 m thickness. In the forward direction, which concerns the outer shield of the ring, the shielding needed would be at least 4 m of concrete.

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.

Radiation dectectors will be installed to monitor the radiation level and produce an alarm in case unexpected levels are encountered.

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.

### 12.3 Water Cooling System

As the AA is not running, the activity of the cooling tower is reduced in spite of the requirements of the experiments. A minor consolidation of this old installation is needed.

## 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. COST, MANPOWER AND TIME SCALE

The cost estimated of 6 MCHF after the feasibility study of the Antiproton Decelerator is shown in Appendix 3, the manpower in Appendix 4 and the time scale in Appendix 5 (AD commissioning could start in September 1998). After the deeper detailed studies done for the

Design Report, it appears that the cost will be somewhat higher than expected due to items which were not foreseen in the feasibility study (new power supplies for the quadrupoles of the electron cooling insertion, new trim supplies for the orbit correctors at low energies...)

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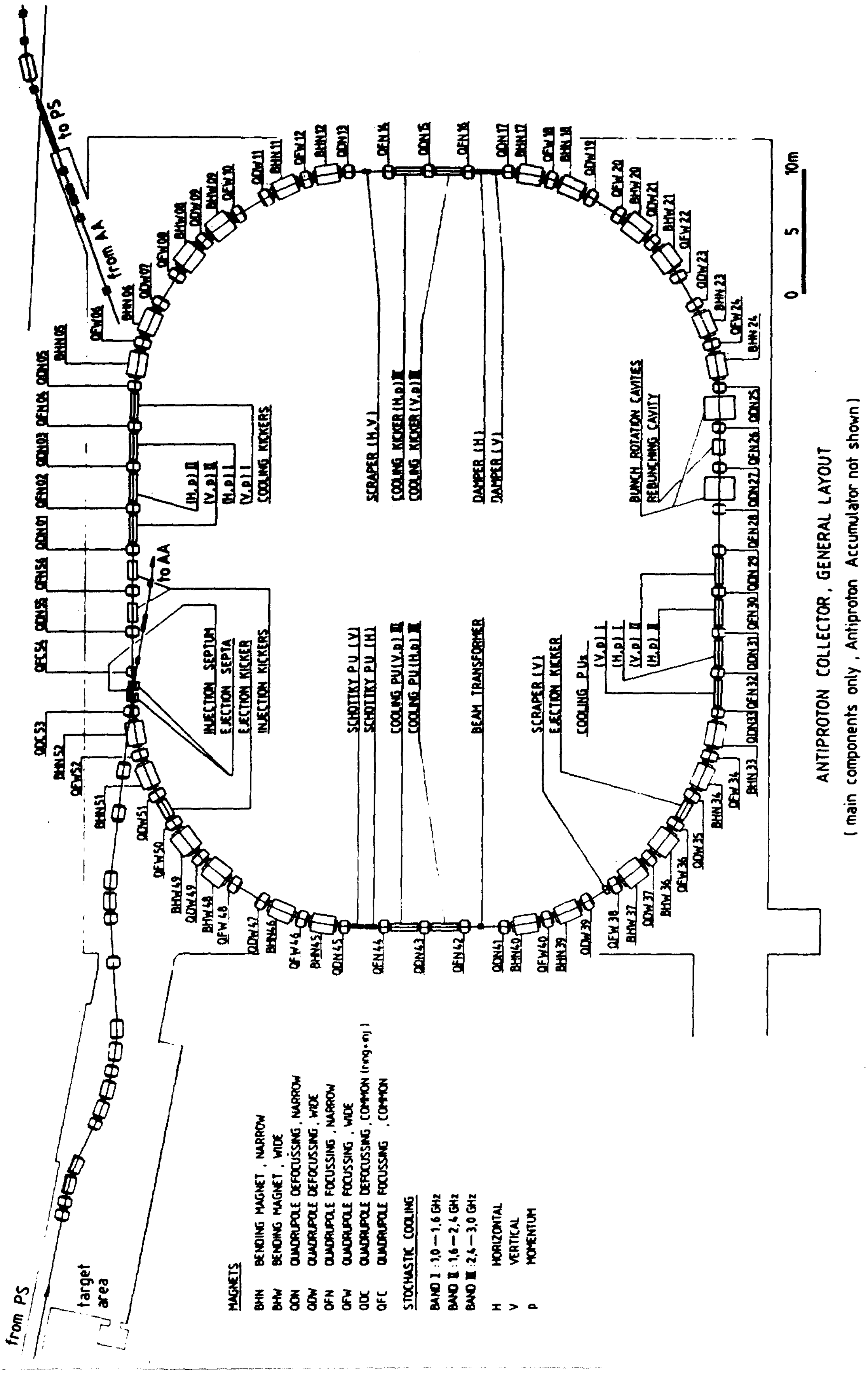
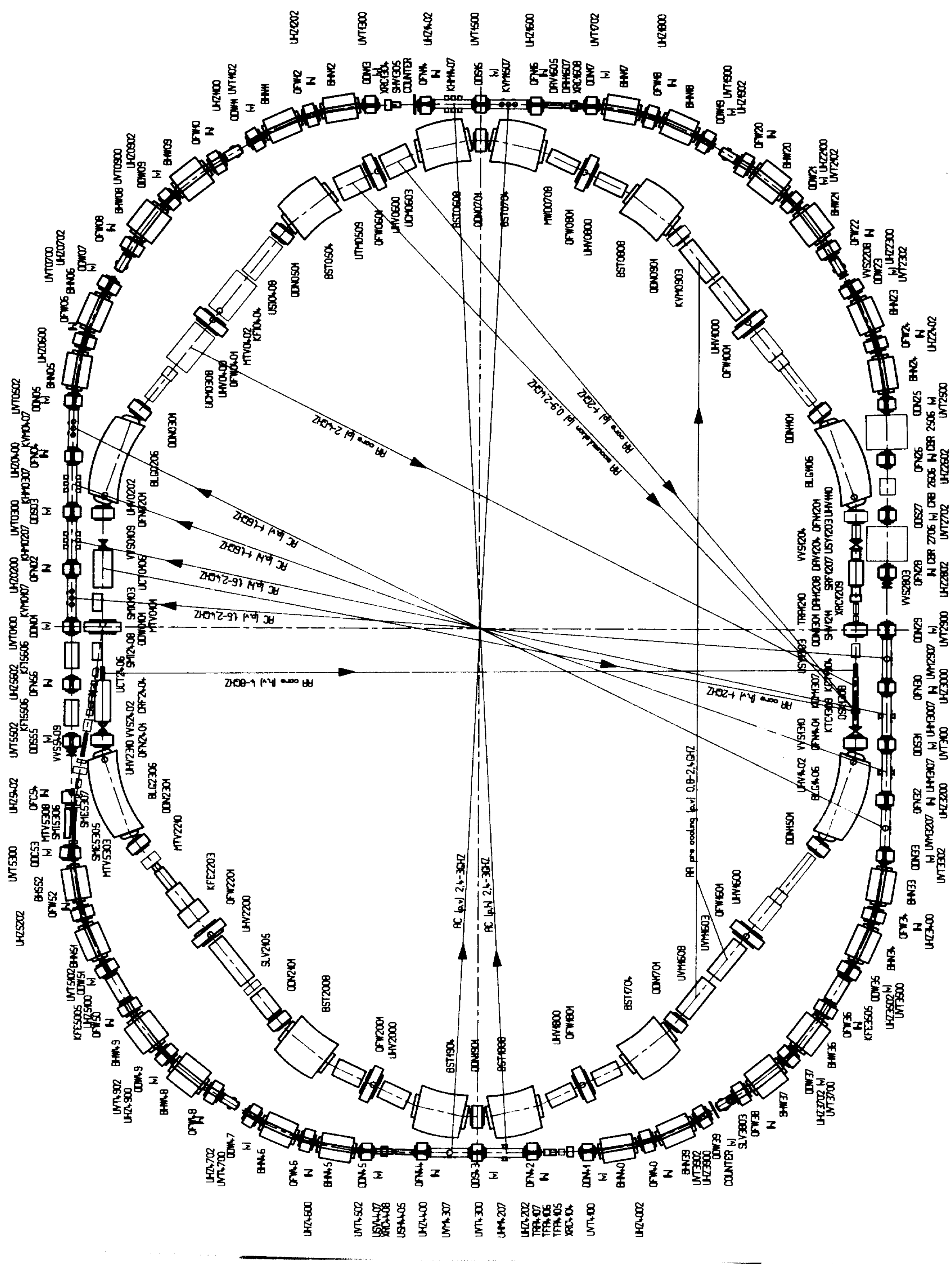
# APPENDIX 1: AC LAYOUT




ANTIPROTON COLLECTOR, GENERAL LAYOUT

( main components only, Antiproton Accumulator not shown )

# APPENDIX 2: AAC LAYOUT



# APPENDIX 3

## COST OF THE ANTIPROTON DECELERATOR (AD)

| | Investments (kCHF) |
|---|---|
| Production beam | 200 |
| Target area. | 150 |
| RF (h=6) modif. | 170 |
| AC rf | 70 |
| Stochastic cooling | 400 |
| Electron cooling | 500 |
| Experimental area | 790 |
| Vacuum | 1150 |
| Controls | 1300 |
| Experimental area access | 190 |
| Instrumentation | 450 |
| Kickers | 50 |
| Power supplies | 570 |
| Water cooling | 65 |
| Application programme | |
| TOTAL | 6055 |

## APPENDIX 4: MANPOWER

| | Ind. Support (m. y.) | CERN (m. y.) | External help (m. y.) |
|---|---|---|---|
| Prod. Beam | 1 (or money) + 1 | 2.0 | 1 |
| Target area | | 0.5 | |
| Bunch Rotation cavity | 1.2 | 1.2 | |
| AC rf | 0.5 | 0.5 | 0.5 |
| Stochastic Cooling | | 2.5 | 1.0 |
| Electron Cooling | 1.0 | 3.0 | |
| Exp. Area | | 3.5 | 1.5 |
| Vacuum | 2.5 | 2.0 | 1.0 |
| Controls | | 5.0 | 1.0 |
| Instrumentation | 0.5 | 3.5 | 1.5+1.5 |
| Kickers | 0.6 (or money) | | |
| Power Convertor | 1+1 (or money) | 3.0 | 1.0 |
| Appl. Prog. | 4.0 | 1.0 | |
| Design* | 0.5 (money) | | |
| Physics Acc. | | | 1.0 |
| **Total** | 14.8 | 27.7 | 11.0 |

* Money (equivalent to 0.5 man.year) is requested by the CERN EST Group for design work concerning AC modifications.

APPENDIX 5

# Possible AD Availability Time Scale