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25 May 1983

AA LONG TERM NOTE No 28

PROPOSAL FOR A SUBSTANTIAL IMPROVEMENT OF CERN's $\bar{p}p$ COMPLEX

A NEW ANTIPROTON COLLECTOR (AC)

This note outlines the research and developments needed for a more luminous $\bar{p}$-source and, if these were successful, a scheme for their incorporation into a new Antiproton Collector to be inserted between the $\bar{p}$-production target and the present Antiproton Accumulator (AA).

An appendix contains initial estimates of the resources needed in both manpower and money if such a collector were to be built at CERN in the near future. The time scale envisaged assumes that the increased luminosity made available to the SPS collider should be exploited before LEP construction ends and hopefully at about the same time as the Tevatron colliding beam facility at FNAL comes into operation.

1. Introduction

The design goal of CERN's $p\bar{p}$ complex is a peak luminosity of 10^{30} $(cm^{-2}.s^{-1})$. To-date we have achieved $>10^{29}$ $(cm^{-2}.s^{-1})$ a factor of ten away from the goal. The complexity of the operation of three accelerators in series plus their various transfer lines initially accounted for a factor of 1.3 reduction in luminosity. However, this factor of 1.3 has recently been largely compensated by the use of a better low-beta scheme than originally proposed and more protons per bunch in the SPS. The remaining factor of ten can simply be attributed to missing antiprotons either in the accumulator (AA) or in the collider (SPS).

It was originally foreseen to stack initially 10^{12} antiprotons in the AA, transfer 6×10^{11} $\bar{p}$'s per day to the SPS and reaccumulate this amount during the daily coast, to top-up the AA again ready for the next transfer. In practice the AA has only been able to stack initially $\sim 2 \times 10^{11}$ $\bar{p}$'s and reaccumulate $\sim 10^{11}$ $\bar{p}$'s per day during normal operation On average a factor of about five missing in AA performance.

Theoretical and experimental studies during this last year indicate that although one might gain perhaps a factor of two in the accumulation of antiprotons without major changes in the AA, the factor of ten is not within our grasp. Nevertheless, as a result of these studies, a way, at least in theory, to collect many more antiprotons and subsequently cool them quickly, became evident. The way is outlined in what follows and entails, the construction of an Antiproton Collector (AC). This would be a new ring interposed between a much improved $\bar{p}$-production system and the AA. The acceptance of the AC would be 6% in $\Delta p/p$ and 200π mm.mrad in both transverse phase planes. It would contain r.f. systems for bunch rotation and large bandwidth high frequency systems for fast cooling in both longitudinal and transverse planes.

In practice, some technical advances outlined below are needed. These fall into roughly two separate branches of technology; the first, related to collecting more antiprotons per bombarding proton on a target, has to do with developing extremely strong pulsed magnetic lenses. The second, has to do with cooling the much larger flux of antiprotons so produced, and consists essentially of extending the bandwidth of our present cooling equipment well into the many gigahertz range of radiofrequencies.

If these developments prove to be successful, they could be incorpo rated into the new $\bar{p}$-collecting and fast-cooling ring placed upstream of a modified AA. It is not possible to obtain the same result by modifying the AA only. Its overall acceptance is too small.

This new collector ring would be on roughly the same scale of the present AA but with magnets and vacuum chambers specially designed to accept an antiproton beam with four times the momentum spread of those captured in the AA. The new machine would also accept antiprotons which diverge twice as much as those in the AA, in both the vertical and horizontal planes. Altogether a factor of up to sixteen in antiproton flux may therefore be contemplated. This could result, after allowing for some inefficiencies, in at least a factor of ten in accumulation rate over and above the present value.

Today, the chances of detecting a Z_0 are rated at about one every few months of collider operation. With the possibility of increasing the accumulation rate of $\bar{p}$'s by a factor of ten and with subsequent improvement in exploiting more $\bar{p}$'s for longer coasting times in the SPS, it should be possible to increase the rated chances of detecting a Z_0 to one every week.

2. Technological developments in $\bar{p}$-production

The existing scheme for the production of $\bar{p}$'s in the AA is based upon the bombardment of a 3 mm diameter copper target every 2.4 s by 10^{13} protons at 26 GeV/c i.e. per PS cycle. These protons arrive at the target in bursts of five bunches, each bunch somewhat less than 35 ns in length. The five bunches of protons produce a total of 6×10^6 antiprotons circulating at 3.5 GeV/c on the injection orbits of the AA in a transverse acceptance (each plane) of somewhat less than 100π mm.mrad and a longitudinal acceptance of 1.5% in momentum spread. These acceptances are fixed by the optics and physical apertures of the magnet and vacuum systems.

The focusing of the antiprotons just after the target is accomplished by means of a pulsed magnetic horn or pulsed current sheet lens, in which the magnetic field circulates azimuthally around the longitudinal axis of the lens. Recent experiments at the AA have shown that this same focusing technique applied directly on and around the target can enhance the $\bar{p}$-yield by diverting more $\bar{p}$'s (essentially those produced at larger angles) into the fixed acceptance of the AA. The gain in $\bar{p}$-yield, however, was never more than 30%. If the same target can be designed to support a larger number of bombarding 26 GeV/c protons while at the same time being subjected to the intense magnetic pressure produced by a pulsed current through its length, the AA might improve its collection efficiency overall by up to a factor of two, namely a factor of 1.3 by pulsing the target and say a factor of 1.6 more protons from the PS.

Something more radical is obviously needed if the missing factor of ten in accumulating antiprotons is to be achieved.

The new $\bar{p}$ collector would be designed to receive 10^8 antiprotons per PS cycle within its larger transverse 200π mm.mrad, each plane) and longitudinal (6% in $\Delta p/p$) acceptance. This goal can be achieved if special technologies are developed in the domain of pulsed magnetic lenses and targets and with microwave systems operating in the 2-4 GHz frequency range for the stochastic cooling systems.

2.1. More antiprotons per bombarding proton on target

As is often the case, the improvement by more than one order of magnitude in the number of antiprotons implies the introduction of novel features, based on advanced technology.

The first one is a better match between the phase space population at the target and the acceptance of the transfer channel and the AC.

This is achieved by a pulsed target.

Pulsed target

For a long and thin target, the production diagram in the phase space looks like a "butterfly". This figure is poorly matched to the acceptance ellipse of a transfer channel. The purpose of the current pulsed in or around the target is to re-distribute the particles in such a way that they fill the acceptance ellipse more uniformly. Three configurations (at least !) can be envisaged :

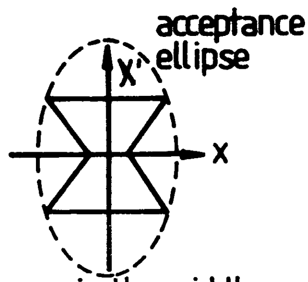
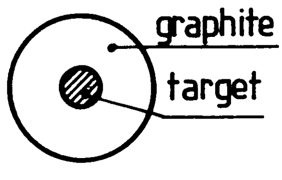
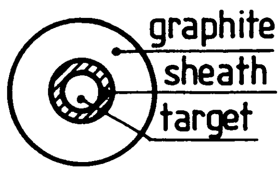


diagram in the middle of the target

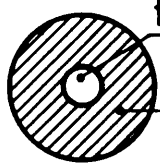
i) The current flows in the heart of the target. Particles are well confined but limitations come from proton de-focusing and antiproton re-absorption.



ii) The current flows in a sheath around the target. This sheath may be a thin conducting layer or the skin depth of a copper target. Very high fields can be reached and focusing occurs outside the target in a low absorption material.



iii) The current flows in a graphite or lithium shell. The focusing is quasi-linear.



The target is usually made of copper about 10 cm in length. Its diameter is of the order of 2 or 3 mm or less and the current intensities needed are about one to two hundred kiloampères in pulses of length 10 to 20 μs. The pulses occur every 2.4 seconds.

The second feature concerns the focusing elements both before and after the target, which should be as strong as possible.

Indeed, for a given acceptance of the AC, the smaller the proton spot on the target, the larger the angle of the cone of $\bar{p}$'s which is collected. Similarly, a very strong lens after the target limits the physical aperture of the transport system to the AC to a conventional one for CERN machines. Conceptually, very strong lenses can be obtained simply by driving a large pulse current through a conducting medium, either a solid with low atomic number, to limit the absorption of the antiprotons, or a plasma.

In such devices, which are focusing in all planes, the magnetic field rises linearly from zero at the centre to the maximum field on the outer radius.

Lithium or plasma lenses

The material of the lens must absorb the antiprotons as little as possible. This is the reason for the choice of lithium for solid lenses. A plasma is the limit case where absorption is negligible. In both cases, the current starts flowing in the outer skin of the conductor.

3. Technoligical developments in stochastic cooling

The beam produced by the target and collected by the focusing system over a very large phase space volume (large transverse dimensions and momentum spread) must be cooled by at least one order of magnitude in each of the three dimensions during the time of one PS cycle (2.4 s). The cycle is divided into two phases; betatron (transverse) cooling occurs in the first phase and is followed by momentum cooling, the cooling times being slightly in excess of one second for each phase.

3.1. Betatron (transverse cooling)

The cooling time τ for optimum gain of the system is given by :

$$\tau = \frac{2N}{W} (M + U).$$

where N = total number of particles to be cooled,
W = bandwidth of the system,
M = mixing factor,
U = noise to signal (power) ratio for the amplifier.

Clearly to obtain the minimum cooling time the bandwidth must increase proportionally to the number of particles N, while the mixing factor M should be as small (close to 1) as possible and so should be U, which depends on the "temperature" of the system. In order to achieve the goal of cooling ten times more particles, the bandwidth of the system must be extended to 1 or 2 GHz.

Pick-ups and kickers

The pick-ups are designed to balance Schottky signal and thermal noise power almost equally at the beginning of the betatron cooling. They consist of 100 sets of pairs of directional couplers of 75Ω characteristic impedance. This type of coupler is chosen for its high sensitivity. It is made of a plate whose length is tuned to a quarter of the mid wavelength (2.5 cm at 3 GHz). Its width is smaller than half the minimum wavelength (3.75 cm at 4 GHz) in order to avoid resonances. The signals from each coupler in a given position (top, bottom, right or left) are added in a combiner board using strip lines and printed circuit technology. After combination, the signals coming from opposite rows of couplers are added or subtracted in a hybrid circuit and then amplified in a low noise solid state amplifier.

The betatron system presents a peculiarity. Due to the large transverse dimensions of the beam, the gap between the electrodes of a particular pair is larger than half the cut-off wavelength and wave guide modes can propagate. The response of the system under such conditions is being studied. This situation exists at the beginning of the cooling only because the inter-electrode gaps are continuously adjusted to fit the beam size as the cooling proceeds. Thus every 2.4 seconds, the cycle time, the gaps open and close in much the same style as the shutters of the AA precooling system. The control of the electrodes is made by servo mechanisms of the type used for the AA shutters.

The kickers have the same structure as the pick-ups, also open and close each cycle, but do not require any cryogenic cooling.

Low noise preamplifiers

The number of pick-up stations is not sufficient to ensure a good Schottky to thermal noise power ratio at room temperature. This limitation is simply due to the space available in the machine. The terminating resistors of each coupler have to be cooled down to 40 K (noise temperature) and the characteristics of the best solid state amplifiers (Gallium arsenide field effect transistors, in short Ga As FET) have to be extended into our frequency range (2-4 GHz). The development is essentially in the design of input and output circuits and perhaps also in the efficient cooling of the transistor itself.

Power amplifiers

At microwave frequencies, power amplifiers with a sufficiently broad bandwidth are the so-called traveling wave tubes. In spite of all the efforts made in the design to limit the required output power, several kilowatts between 2 and 4 GHz are absolutely necessary. All the kickers need not be driven with the same tube but typical characteristics would be 1 kW maximum power and a good linearity up to 300 W. Tubes whose performances approach our requirements have been built in United States and in France for telecommunications. It seems that the technical problems can be solved but the cost of these devices is likely to be very high. For instance, a tube built in the USA having 1.5 kW output over a bandwidth of 2 GHz costs 80 kSF and its power supply 500 kSF. We would need 20 of them. The total cost would be 1 600 kSF for the tubes and 10 000 kSF for the power supplies ! Needless to say we shall try to buy the power supplies from competitive suppliers by specifying them ourselves.

3.2. Momentum cooling and very high frequency filters

For momentum cooling, the filter method is used. The essential part of the filter is a transmission line which presents notches every 1.5 MHz at each harmonic of the revolution frequency. The tolerance on the deviation of the notch centre with respect to its ideal position is about 10^{-5}. The line can work in the reflection mode with one end short circuited, its length is then one half the machine circumference (90 m), or in the transmission mode in which case its length is the whole circumference (180 m). At very high frequencies and room temperature, the attenuation and dispersion of the signal are adversely affected by the skin effect. For this reason, a superconducting cable is under study in the USA at Fermilab; it consists of a coaxial line whose inner conductor is niobium and outer conductor is lead.The cable is wound on a spool and immersed in liquid helium; it works in the transmission mode with rather good characteristics.

Other solutions can be investigated. The delay might be provided by optical or acoustic systems. The notch structure may also be built in a purely electronic way with synthesizers and mixers.

However it is done, development work is urgently needed on these devices.

4. Brief description of the AC

A detailed description of the preliminary ideas for the new $\bar{p}$-collector is given in the AA Long Term Development Note 26. The layout is outlined in the accompanying figure.

It consists essentially of a racetrack of bending and focusing magnets with a total circumference of 188 metres for a nominal momentum of 3.5 GeV/c. The two long straight sections are designed to be dispersion free and will contain all the cooling devices as well as being the injection and ejection regions. The pick-ups are in one long straight section and the kickers are in the other. Communication between pick-ups and kickers is by the most direct path across the diameter of the semicircle followed by the beam. The dimensions and strengths of the magnets and lenses are similar to the shorter bending magnets and narrow lenses of the AA. The beam optics is chosen to give the optimum phase advance between cooling devices. The frequency dispersion is both suitable for adequate unscrambling of signal information for the stochastic cooling process as well as being small enough to ensure rapid bunch compression, with a radiofrequency cavity, of the five antiproton bunches each having a momentum spread of 6%.

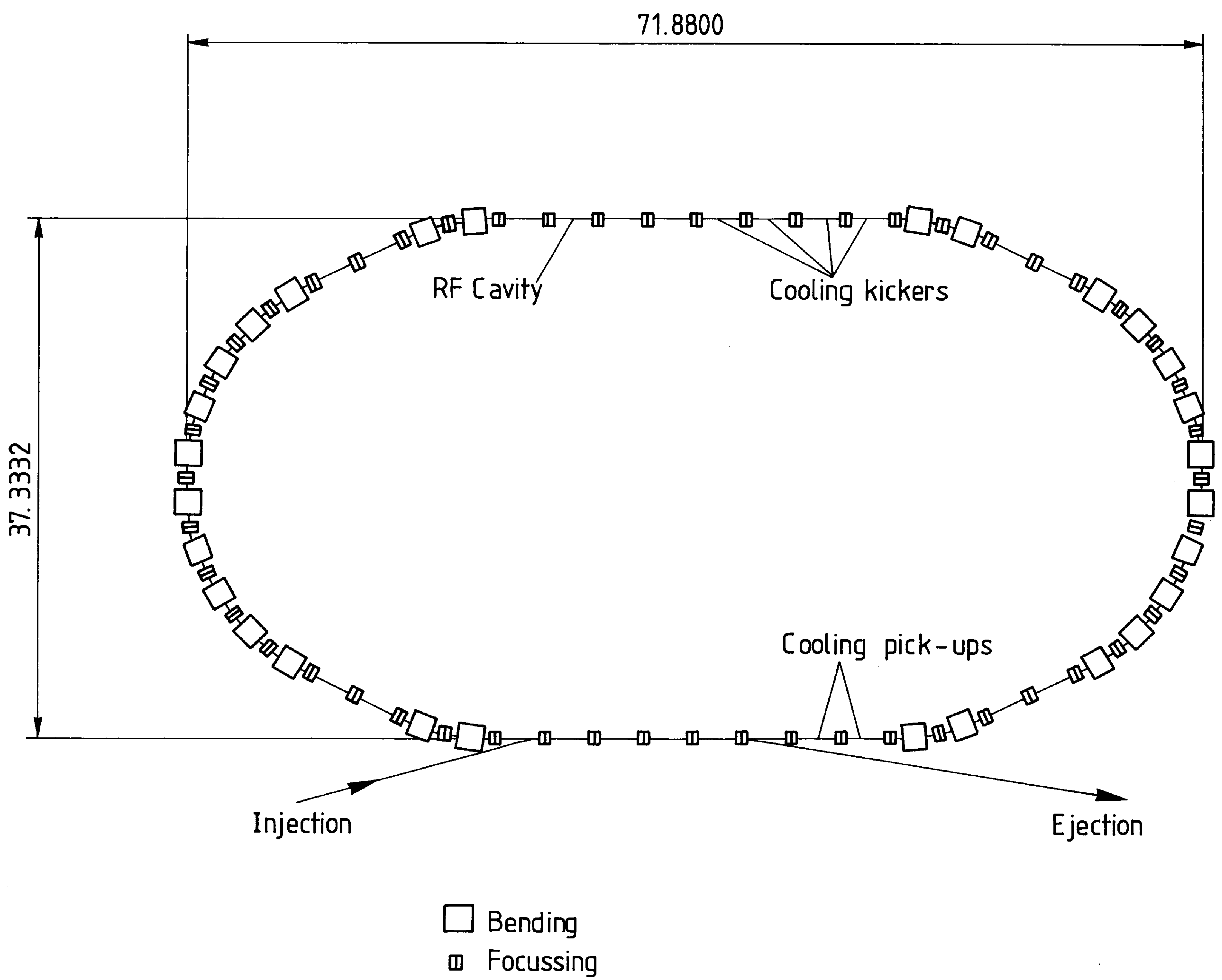
This bunch rotation is the first step in reducing the momentum spread from 6% to about 1.5%. It needs an RF cavity capable of supplying a few hundred keV per turn at around 9 MHz. Antiprotons with a transverse emittance of 200π mm.rad are injected into the five RF buckets set up by the cavity and the one sixth reduction in momentum spread occurs in less than 100 mseconds.

Next the fast betatron or transverse cooling systems are, literally, set into motion and reduce the emittances in both planes down to a few π mm.mradians. Calculations indicate that, with the developments outlined above, this can be achieved in one second. Finally, in the 1.3 seconds remaining of the 1.4 second cycle time before the next burst of $\bar{p}$'s arrive, the wideband fast momentum cooling system is switched on to attain the final momentum spread of around one per mil.

The $\bar{p}$'s are then rebunched and ejected from the AC and transferred to the AA where they are stochastically decelerated and cooled into the stack core. The much increased flux of $\bar{p}$'s arriving at the AA can only be handled by also increasing its bandwidth, presently 250 MHz for the existing stack-tail system, into the gigahertz range. The modifications to the AA are quite considerable and it is not absolutely clear yet whether in the end the real limitations to accumulation rate will in fact be in the stack tail system of the AA. This problem is being intensively studied.

The antiprotons spend only a few seconds in the collector so that requirements on vacuum are much reduced from that of the AA where bake-outs and ultra-high vacuum technology had to be used. Hopefully this should have repercussions in making the engineering of the cooling devices, and indeed the whole vacuum chambers of the collector, considerably cheaper.

B. Autin
E. Jones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37.3332
RF Cavity
Cooling kickers
Cooling pick-ups
Injection
Ejection
Bending
Focussing

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As is often the case, the improvement by more than one order of magnitude in the number of antiprotons implies the introduction of novel features, based on advanced technology.

The first one is a better match between the phase space population at the target and the acceptance of the transfer channel and the AC.

This is achieved by a pulsed target.

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For a long and thin target, the production diagram in the phase space looks like a "butterfly". This figure is poorly matched to the acceptance ellipse of a transfer channel. The purpose of the current pulsed in or around the target is to redistribute the particles in such a way that they fill the acceptance ellipse more uniformly. Three configurations (at least !) can be envisaged :

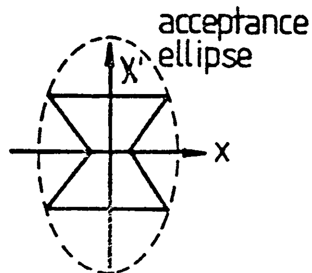
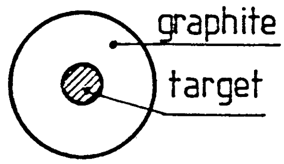


diagram in the middle of the target

i) The current flows in the heart of the target. Particles are well confined but limitations come from proton de-focusing and antiproton re-absorption.



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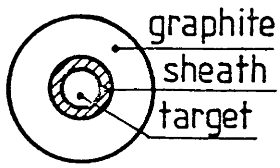

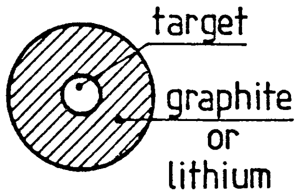

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3.1. Betatron (transverse cooling)

The cooling time τ for optimum gain of the system is given by :

$$\tau = \frac{2N}{W} (M + U).$$

where N = total number of particles to be cooled,
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Power amplifiers

At microwave frequencies, power amplifiers with a sufficiently broad bandwidth are the so-called traveling wave tubes. In spite of all the efforts made in the design to limit the required output power, several kilowatts between 2 and 4 GHz are absolutely necessary. All the kickers need not be driven with the same tube but typical characteristics would be 1 kW maximum power and a good linearity up to 300 W. Tubes whose performances approach our requirements have been built in United States and in France for telecommunications. It seems that the technical problems can be solved but the cost of these devices is likely to be very high. For instance, a tube built in the USA having 1.5 kW output over a bandwidth of 2 GHz costs 80 kSF and its power supply 500 kSF. We would need 20 of them. The total cost would be 1 600 kSF for the tubes and 10 000 kSF for the power supplies ! Needless to say we shall try to buy the power supplies from competitive suppliers by specifying them ourselves.

3.2. Momentum cooling and very high frequency filters

For momentum cooling, the filter method is used. The essential part of the filter is a transmission line which presents notches every 1.5 MHz at each harmonic of the revolution frequency. The tolerance on the deviation of the notch centre with respect to its ideal position is about 10^{-5}. The line can work in the reflection mode with one end short circuited, its length is then one half the machine circumference (90 m), or in the transmission mode in which case its length is the whole circumference (180 m). At very high frequencies and room temperature, the attenuation and dispersion of the signal are adversely affected by the skin effect. For this reason, a superconducting cable is under study in the USA at Fermilab; it consists of a coaxial line whose inner conductor is niobium and outer conductor is lead.The cable is wound on a spool and immersed in liquid helium; it works in the transmission mode with rather good characteristics.

Other solutions can be investigated. The delay might be provided by optical or acoustic systems. The notch structure may also be built in a purely electronic way with synthesizers and mixers.

However it is done, development work is urgently needed on these devices.

4. Brief description of the AC

A detailed description of the preliminary ideas for the new $\bar{p}$-collector is given in the AA Long Term Development Note 26. The layout is outlined in the accompanying figure.

It consists essentially of a racetrack of bending and focusing magnets with a total circumference of 188 metres for a nominal momentum of 3.5 GeV/c. The two long straight sections are designed to be dispersion free and will contain all the cooling devices as well as being the injection and ejection regions. The pick-ups are in one long straight section and the kickers are in the other. Communication between pick-ups and kickers is by the most direct path across the diameter of the semicircle followed by the beam. The dimensions and strengths of the magnets and lenses are similar to the shorter bending magnets and narrow lenses of the AA. The beam optics is chosen to give the optimum phase advance between cooling devices. The frequency dispersion is both suitable for adequate unscrambling of signal information for the stochastic cooling process as well as being small enough to ensure rapid bunch compression, with a radiofrequency cavity, of the five antiproton bunches each having a momentum spread of 6%.

This bunch rotation is the first step in reducing the momentum spread from 6% to about 1.5%. It needs an RF cavity capable of supplying a few hundred keV per turn at around 9 MHz. Antiprotons with a transverse emittance of 200π mm.rad are injected into the five RF buckets set up by the cavity and the one sixth reduction in momentum spread occurs in less than 100 mseconds.

Next the fast betatron or transverse cooling systems are, literally, set into motion and reduce the emittances in both planes down to a few π mm.mradians. Calculations indicate that, with the developments outlined above, this can be achieved in one second. Finally, in the 1.3 seconds remaining of the 1.4 second cycle time before the next burst of $\bar{p}$'s arrive, the wideband fast momentum cooling system is switched on to attain the final momentum spread of around one per mil.

The $\bar{p}$'s are then rebunched and ejected from the AC and transferred to the AA where they are stochastically decelerated and cooled into the stack core. The much increased flux of $\bar{p}$'s arriving at the AA can only be handled by also increasing its bandwidth, presently 250 MHz for the existing stack-tail system, into the gigahertz range. The modifications to the AA are quite considerable and it is not absolutely clear yet whether in the end the real limitations to accumulation rate will in fact be in the stack tail system of the AA. This problem is being intensively studied.

The antiprotons spend only a few seconds in the collector so that requirements on vacuum are much reduced from that of the AA where bake-outs and ultra-high vacuum technology had to be used. Hopefully this should have repercussions in making the engineering of the cooling devices, and indeed the whole vacuum chambers of the collector, considerably cheaper.

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