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ANTI-PROTON INTENSITY LIMITATIONS

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ABSTRACT

The recent developments on antiproton rings are reviewed. They cover the new focusing methods used in the vicinity of the production target, various functions of a collector and the way they are implemented, the accumulation and the intensity limitations.

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1. INTRODUCTION

Since the first beams of antiprotons were stored in the CERN Antiproton Accumulator in 1980, interest in collecting and storing antiprotons has increased exponentially. They have been used in the SPS and ISR for high-energy colliding beam experiments, and now support a community of almost 400 users at LEAR in a very wide variety of experiments. Recently a two-ring collector/accumulator has been successfully completed at Fermilab and CERN has added a separate collector ring to its existing accumulator to increase the supply of antiprotons to 10^{12} per day. In other fields, interest is focused on collecting antiprotons at rates of "a few grams per year" for use as a propulsion fuel. However, before embarking on an improvement programme to gain the necessary factor of 10^9 , we will describe some of the features of the existing antiproton collector rings and discuss some of the limitations.

2. PRODUCTION

The antiprotons are produced by conversion of the kinetic energy of a proton beam into the creation of proton-antiproton pairs. The process takes place in the collision of the primary beam with the nuclei of a long and thin cylindrical target. Among the vast amount of secondary particles, only less than one percent are antiprotons. In absolute value, the total number of antiprotons per second, the "flux", is of the order of 10^{10} every second, which is more than two orders of magnitude below the routine production of protons. More astonishing is that actual flux of an antiproton source which is almost four orders of magnitude lower in the CERN Antiproton Accumulator. It is really a miracle that the discovery of the W and Z particles has been made possible with so tenuous

beams. After six years of successful operation, one has almost forgotten the formidable bet at the origin of the antiproton project but each time one reconsiders the design of an antiproton source, one is faced with these tremendous orders of magnitude.

Since the protons are so abundant, one may and one does increase the number of particles on the target as much as possible. The limitations do not come from the synchrotron but rather from the target which cannot withstand an energy deposition larger than 200 joules/gramme typically, and from the radiation levels which have to be maintained below a tolerable threshold. Therefore, the main effort has to be put on the collection efficiency.

A very smart idea consists of pulsing a high-intensity current in the target to increase the transverse phase space density as it can be understood in an elementary test case which can be generalised:

The particle 1 emitted at the origin of the target is bent by the magnetic field associated with the current and its exit trajectory coincides with the particle 2 emitted at the exit of the target and thus unaffected by the field.

The beauty of the process is a little tarnished by the adverse effect of the field on the primary protons which are defocused. An extra-focusing lens has then to be added on the proton line or the field must be confined at the periphery of the target. Harder to solve than the optics problems are the technological difficulties due to current densities

in excess of 10^4 A/mm² in so hot an environment. For the time being no reliable systems exist in spite of promising developments and the present trend consists of using short and dense passive targets.

3. INITIAL FOCUSING

Once produced, the antiprotons have to be captured in the largest solid angle downstream to the target. This is the realm of exotic lenses; they have in common a revolution symmetry permitting an overall focusing of all the particle rays as in geometrical optics but in contrast with conventional magnetic quadrupoles which have to be grouped in doublets or triplets to have a net focusing effect. In all cases, the magnetic field is due to a current which flows along the axis of the particle beam. The differences lie in the support of the current which may be a low density and therefore weakly absorbing metal like lithium, a plasma or a coaxial structure whose inner conductor is a thin metal sheet of appropriate shape (magnetic "horn"). The horn is very reliable, it has been used extensively in neutrino physics and gave full satisfaction for the AA. Its extension to very high focusing strengths (>50 mrad at 3.5 GeV/c) is limited by mechanical stresses exerted on the conductor. The lithium lens has been retained for the Tevatron project and for the start-up of ACOL; its field is linear, its parameters are thus easy to optimize and it was tested with currents as high as 400 kA; its reliability in a hot target environment is not yet fully proven. The plasma lens may turn out to be the solution for the future because its transparency has basic advantages; it is the object of an active research at CERN, its main characteristics (shape and nature of the electrodes, wall material, electrical circuit) are defined, but the physics of the z-pinch is not sufficiently known: a 400 kA current can indeed be routinely discharged,

the field inside the pinch, however, has not yet the correct time structure.

4. THE COLLECTOR RING

Once the particles have been produced and focused, they are transported towards a large acceptance storage ring. The name of this type of ring is not yet firmly supported by a well established tradition. It is called "collector" at CERN and is at the origin of the ACOL acronym which stands for Antiproton Collector, "debuncher" at Fermilab, whereas the outer part of the CERN Antiproton Accumulator is anonymous.

4.1 Acceptance

The acceptance is the volume of phase space in which the particles are accommodated; it is the product of the longitudinal, horizontal and vertical sub-phase spaces:

$$A = A_L A_H A_V$$

with

$$A_L = \Delta p \cdot T$$

$$A_H = \pi \Delta x \cdot \Delta p_x$$

$$A_V = \pi \Delta y \cdot \Delta p_y$$

Δp is the momentum bite, T the revolution period, x and y the transverse coordinates, p_x , p_y the transverse momenta, and the symbol Δ denotes the amplitude of the interval containing all the values of a variable. The transverse positions and momenta are not independent for a given particle; it is a known property of linear optics that the image of (x, p_x) or (y, p_y) describes an ellipse of constant area when a particle turns

around the ring, the acceptance is precisely the area of the ellipse and this is the reason of the π coefficient. Any machine is limited by its geometrical aperture which is fixed by the maximum field on the magnet pole (< 2 T for conventional magnets). To accept large emittances implies large beam divergences which lead to strong focusing structures in which the quadrupoles are tightly packed. This feature is very apparent in the Fermilab debuncher and in the CERN Antiproton Collector. The measure of the focusing is given by the betatron tune Q . A direct consequence of a high Q value is a high chromaticity, the Q dependence with the momentum, which must be compensated by strong sextupole magnets for beam stability reasons. The field in a sextupole is represented by a quadratic polynomial in x and y . The chromaticity is not, in general, difficult to control but the presence of non-linear fields has a secondary effect on the behaviour of large amplitude oscillations and may lead to substantial aperture reductions. The problems of non-linear dynamics have been intensively studied in the recent years, some of their aspects have been clarified, and ACOI which has a record nominal acceptance of 200π mm.mrad in each plane is equipped with diagnostics and correction systems. Similar developments are being pursued for LEAR and the Tevatron.

The aperture is not only defined by the betatron oscillations but also by the momentum bite. More precisely, it is the momentum relative error $\Delta p/p_0$, where p_0 is the central momentum, which comes in the aperture evaluation. It is therefore interesting to operate at a high nominal momentum. Another advantage of creating antiprotons at high energy is the narrowing of the production cone. In this respect, the Fermilab machines take advantage of their high-energy synchrotron to get an initial phase-space density much higher than for the CERN machines.

4.2 Beam Dynamics

In addition to the storage function, a collector performs a compression of the beam in order to get a density compatible with the accumulation process which takes place in the second ring of an antiproton source, the "accumulator" (next section). In other words, it acts as a buffer between the target and the accumulator. Its duty cycle is equal to proton synchrotron's one (~ 2 s). Several operations occur sequentially: debunching, betatron cooling, momentum cooling, rebunching, and ejection.

The antiproton bunches are first coherently debunched. As we have mentioned it, the number of particles is proportional to the momentum bite. The antiproton bunches are therefore short and of large momentum spread ($\Delta p/p_0 < 6\%$) at the exit from the target. In the collector, they are stretched until the beam becomes continuous; the momentum spread reduction is thus equal to the bunch lengthening. After a few turns, the beam is ready for a further momentum spread reduction by momentum stochastic cooling.

Before momentum cooling, it is preferable to achieve a compression of the transverse phase space by betatron cooling in order to be in the best conditions of sensitivity. Whereas the debunching is a conservative process, stochastic cooling increases phase space density. In a collector, the cooling must be fast (~ 1 s), it is dominated by two key parameters: a characteristic time τ

$$\tau = N/W$$

where N is the total number of particles and W the frequency bandwidth of the system, and the correction power delivered to the beam in order to compress it

$$P = F \cdot v_{\text{cooling}}$$

where F is the combination of the electrical and magnetic force applied to the particles and v_{cooling} the reduction of betatron amplitude per unit of time. At Fermilab, the characteristic time is the e-folding time and the power is of the order of a few hundreds of watts applied in a 2-GHz bandwidth. At CERN, the beam emittances are an order of magnitude higher and a new type of betatron cooling was invented. The emittances decay linearly and not exponentially as in classical cooling. This type of variation is obtained by maintaining the electrodes against the beam during the cooling using sophisticated mechanisms to displace the detection and correction electrodes. The minimum gap between the electrodes is fixed by the capacitive coupling which diminishes their impedances. As a rule, the electromagnetic couplers must have dimensions in proportion to the beam size. For ACOL, the beam size has been reduced to a minimum by using a strong focusing lattice; nevertheless, it reaches 10 cm and the 2-GHz bandwidth has been split into three equal subbands so that efficiency moves progressively from the low towards the high-frequency band during the cooling process.

Momentum cooling comes next. It is based upon the "filter" method which has been inaugurated in the ICE ring. The particle revolution frequency depends on momentum:

$$\frac{\Delta f}{f_0} = \eta \frac{\Delta p}{p_0} .$$

The η parameter is a function of the lattice. The best momentum resolution is obtained with a high η value. In a collector, there is a conflict between debunching and cooling for the choice of η because the RF

increases with n and an overlapping occurs when Δf exceeds f_0 . Until now, there was no reason to diminish $\Delta p/p$ below $10/100$ and a bandwidth of 2 GHz is quite adequate for this purpose.

At the end of the cycle, the beam is rebunched and ejected towards the accumulator with all the precautions requested to avoid a dilution of density.

5. ACCUMULATOR

At the exit of the collector, the antiproton density may have been increased by three orders of magnitude but the number of particles is equal, say with optimism, to 5×10^7 . The final intensity of a beam delivered to physics experiments must be ten thousand times higher. The increase of intensity cannot be obtained by superimposition of pulses in momentum space as it was the case in the Intersecting Storage Rings since such a method would lead to the absurd momentum spread of 10. The stochastic techniques are thus essential.

5.1 Accumulation

The accumulation can be regarded as a generalised momentum cooling in which the equilibrium or "core" momentum is no longer the central momentum. The method has been tested the first time on the Antiproton Accumulator without any prior experimentation. It was initially intended to apply the filter method but, as the cooling operates over many turns, the observation is affected by the corrections ("feedback" effect) and an instability may blow the beam up when the number of particles increases beyond a certain threshold. For this reason, another method not prone to instability is used; the momentum is detected via the particle position

$$x = D \cdot \Delta p/p$$

where D is the orbit dispersion. A good momentum resolution requires a high dispersion value (~ 10 m). As a consequence, the accumulators have a smooth focusing and a loose quadrupole lattice with long straight sections in which the many equipments can be accommodated. The accumulation is characterised by the particle flux which can be handled and it is mainly determined by the square of the system frequency bandwidth. The difficulty of the accumulation is due to the large spread in particle density, the four orders of magnitude which have been mentioned at the beginning of this section. The core signal tends to dominate the signal of the particles which are deposited at the bottom of the stack. The core and bottom frequencies are chosen to be distant enough from each other and any cross-talk between the signals is very carefully controlled by a set of filters. Furthermore, the accumulation process is assisted by an independent core cooling system whose design is classical but incorporates record bandwidths (up to 4 GHz) to deal with the high particle density. This way, when the stack signal is observed on the screen of a spectrum analyser, it presents an exponential ascent in the accumulation region followed by narrow peak in the core region and an abrupt descent beyond the core. The accumulation lasts several hours, a time during which the betatron cooling is perfected.

5.2 Intensity Limitations

The record intensity obtained so far in the Antiproton Accumulator is $5 \cdot 10^{11}$, it has been reached after four days of operation and has revealed a number of space-charge related instabilities, some of them are well known and others are more peculiar to antiproton beams.

A basic limitation is the Brownian motion of the particles inside the beam also called "intra-beam scattering". It is a hard limit which can barely be overcome by existing cooling techniques and fixes the theoretical limit to the core intensity.

All the instabilities which have been observed affect the transverse phase space. The first one was a vertical coherent instability due to the resistivity of the vacuum wall-chamber. It belongs to a well-known type which can be rather easily cured by a feedback system.

The others are due to the residual gas or to impurities. In a relativistic beam, electrical and magnetic force between particles are almost balanced. The cancellation of the forces can be broken by positive ions which neutralise the electrical field of the antiprotons.

When the neutralisation is distributed, a $\bar{p}$ -p coherent instability shows up for a number of particles in excess of 2×10^{11} . It has been christened "hiccup" to recall the sudden and limited amplitude blow-up of the beam. It happens when the bouncing frequency of the proton in the negative potential well of the antiproton beam coincides with a natural betatron frequency of the antiprotons, it is a resonance effect analogous to the e^- -p instability observed in the ISR and it can be cured by a dedicated feedback tuned at the resonance frequency.

The neutralisation can be localised. In that case, the beam potential is quasi-gaussian inside the ion "pocket" and thus a source of a very non-linear field which excites high-order resonances. The beam blow-up is incoherent and of the same nature as the beam-beam effect in a collider. One has then to choose a "quiet" region in the working diagram of the betatron tunes and, better, suppress the ion pocket by extracting the ions using the field of "clearing" electrodes.

Last comes a strange beam blow-up, nicknamed "ghost" because it is fugitive and unpredictable. The emittance increases violently in a time which ranges from minutes to hours. It is interpreted as due to a minute dust grain suspended in the beam. The speculation is based on the ion microscope theory. Due to some external cause like the shock of a shutter, dust would be projected into the beam and there heavily bombarded by the antiprotons. Under the action of repeated collisions, the dust is stripped of electrons which escape easily the beam negative potential and is covered of a multitude of positive charges. The electrostatic field which surrounds the dust can reach gigantic values (many GV/m) and thus produce a strong coulomb scattering of the antiprotons. The lifetime of the ionised dust is determined by the various discharging processes. There are always low-energy electrons resulting from the ionisation of the residual gas by the antiprotons, these electrons are attracted by the dust. Above 20 GV/m, the dust field itself ionises the residual gas and the number of captured electrons is enhanced. Near 40 GV/m, the electrostatic pressure is so high that the dust surface is disaggregated and evaporates. As in the case of ion pockets the dust can be eliminated by a clearing field should the dust not stay still in a secluded potential well; for a while, the beam is fully neutralised by increasing the residual pressure artificially so that the dust can drift towards regions where it is extracted.

6. CONCLUSION

The industrial production of antimatter is a science fiction topic. However, antimatter physics may take advantage of further developments in the antiproton sources based upon stochastic cooling. Using gallium arsenide technology, ever higher frequency and broader band systems are

being developed; moreover, new couplers adapted to that very high frequencies have promising features. As a consequence, fluxes of 10^9 antiprotons per second, a factor 40 over present sources design values, may be contemplated as a very ambitious but still accessible goal for a source which would combine a high repetition rate proton synchrotron with several sets of collector-accumulator rings.

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