EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-ISR-VA/70-48

THE SCHEME OF ANTIPROTON PRODUCTION FOR THE PROTON-ANTIPROTON COLLIDING BEAM FACILITY IN NOVOSIBIRSK

by

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(Paper to be presented at the Soviet National Particle Accelerator Conference in Moscow, November 1970)

Translated at CERN by E. Fischer
(Original : Russian)

Geneva - September 1970

The project which is to obtain an intense antiproton beam in the storage ring VAPP-4 for experiments with colliding proton and antiproton beams at an energy of 2 × 25 GeV includes the intermediate storage of antiprotons at an energy of 1.8 GeV in a storage ring with electron cooling[1].

In the present paper we consider the following problems: the focussing of the primary protons onto a target, hence the production of an antiproton beam and its injection into the 1.8 GeV storage ring.

The antiprotons are produced in an external target by a proton beam, which is accelerated up to 25 GeV in the main storage ring, ejected from it and then focussed onto the target. The ratio of the energy of antiprotons (1.8 GeV) to the energy of the primary protons (25 GeV) is so chosen that one is near the maximum of the antiproton production rate in a target of heavy material, as one can conclude from published experimental data for lead[2].

The angular distribution of the antiprotons at the energy of 1.8 GeV can be assessed from the data of the quoted reference by extrapolation into the region of small energies of secondary particles. It must be expected to be close to a Gaussian distribution with a root mean square angle

$$\sqrt{\overline{\theta^2}} = 0.15 \text{ rad} .$$

The total number of antiprotons leaving the target, under the assumption that the antiprotons remain inside the target while traversing its length, depends on this length ℓ according to

$$F(\ell) = f_o \, \ell \, \exp \, (-1/\sigma_A n \, \ell) \, ,$$

where f_o is the production probability of antiprotons with a momentum in the given interval per cm path length, σ_A the inelastic cross-section of protons and antiprotons with the nuclei of the target and n the number of nuclei per cm^3. This function has a maximum of

$$f_m = f_o/e\ \sigma_A n$$

at

$$\ell = 1/\sigma_A n$$

that means at the inelastic collision length.

The root mean square emittance of the antiprotons $\overline{\Phi}$ under the assumption of a infinitely thin proton beam increases proportionally to the target length

$$\overline{\Phi} = \overline{\theta^2}\ \ell$$

and at the length of ℓ = 10 cm, which is approximately the inelastic nuclear scattering length in tungsten, its value is 225 mradcm (π included) and has a shape which is shown on Fig. 1. It is clear that an antiproton beam of such an emittance cannot be efficiently captured into a storage ring.

In an attempt to increase the capture efficiency a method has been worked out in our institute in which the secondary beam is produced in a target through which runs a very high electrical current ($\sim 10^6$ A). The magnetic field generated by the current does not permit the particles to run away from the axis of the system and forces them to oscillate within the dimension

$$r_{max} = \theta_{max} \sqrt{\frac{pcr_o}{eB_o}}\ ,$$

where r_o is the radius of the target, B_o the magnetic field strength on its surface and where θ_{max} can be regarded as the root mean square production angle of the antiprotons.

The emittance of the beam depends thus not on the target length and is determined only by the gradient of the magnetic field and the original angular spread of the antiprotons. In comparison to a target without magnetic field the emittance of the beam is reduced. This is not in contradiction to Liouville's theorem since the secondary particles are produced inside the magnetic field. The influence of the magnetic field on the primary protons can be neglected (in first approximation) because of the large difference in energies and the smallness of the emittance of the proton beam which makes it possible to focus it to small dimensions over the full length of the target.

In the case considered the root mean square emittance of the antiproton beam is reduced to 50 mradcm if it is produced in a target with a magnetic field of a gradient

$$\text{grad } B = 1.3 \times 10^7 \text{ G/cm} .$$

This requires a current density inside the target of 220 kA/mm^2 and makes it impossible to use a target several times.

It is consequently proposed to use each target only once and to exchange it automatically against a new one between two cycles. The cycle time is determined by the speed of the electron cooling and will be 100 sec. It is essential only that the destruction of the target occurs not before the first current maximum. This can be obtained by using a sufficiently small current pulse time, since the build-up of deformations in the target is a process having inertia.

From the experimental results which we have until now achieved we can mention a magnetic field strength of 1.3 MG on the surface of a tungsten rod of 2 mm diameter at a current pulse length of 1.35 µsec. Under these conditions the target is fully evaporated; but this happens only after the current maximum, as one can judge from oscillographic observation. At a magnetic field of 1 MG one observes only a partial destruction of the target at the places where it is supported.

At present a new test set-up is being assembled which should give a current pulse of about 0.75 µsec (the anticipated length of an antiproton bunch is 0.1 µsec). With this pulse length we hope to obtain on the surface of a rod of 2 mm diameter a magnetic field of 1.7 to 2 MG before it explodes.

The short duration of the current pulses provokes inevitably the question of the inhomogeneity of the current distribution over the cross-section of the target. In fact, at a pulse duration of about 1 μsec the skin depth in tungsten is only about 0.2 mm. However, the heating of the target up to a temperature close to the melting point causes the specific resistivity of the target material to increase so that the skin depth becomes comparable to the radius of the target.

The task of focussing the protons onto a small target over the full length of it is complicated by the defocussing of the proton beam inside the target with a high current and requires a very strong lens. In our case it is possible to focus a proton beam of an emittance of $\Phi = 0.5$ mradcm to a root mean square dimension (over the full length of the target) of $\pm$ 0.35 mm by a lens with a focal length of about 25 cm.

Such a lens for protons of 25 GeV energy can only be made by using the axially symmetrical focussing action of the field of a direct current in a rod. The lens, which we have calculated, consists of a rod of beryllium or titanium of 1 cm diameter and a length of 6-8 cm with a magnetic field on its surface of up to 300 kG.

In the described lens 15% of the protons are lost by nuclear reactions and scattering. But this is inevitable for the optimal focussing of a proton beam of about 0.5 mradcm emittance. If, however, the emittance will be about 0.1 mradcm, then optimal focussing will already be obtained by a lens of $\sim$ 100 cm focal length. Such focussing is possible with a triplet or quartet of magnetic quadrupole lenses of 100 to 150 kG/cm field gradient. At present we are installing on a test bench a pair of quadrupole lenses with an aperture 2a = 1.5 cm and a maximum field strength of 100 kG at the edge of the aperture (gradient 150 kG/cm). The length of each unit is 10 cm.

For the collection of the antiproton beam originating from the target with an angular spread of $\pm$ 0.15 rad and a momentum spread of a few percent, a lens is required not only of large aperture but also of sufficiently small focal length, so that the angular spread at its end caused by chromatic aberration does not exceed the angular spread for a given momentum. For this purpose we are designing a lens with a focal length of about 20 cm with field strength of 200 - 250 kG and a special profile (see Fig. 2a). This lens, which we call "linear" lens is so designed that its principal plane coincides with its plane of symmetry, in contrast to a parabolic lens which has no principal plane. The lens provides linear focussing of the beam and has a minimum aberration in the angular range we are interested in[3]. Figure 2b shows a sectional view of a model of such a lens.

For the focussing of a beam with large energy spread (for instance, for the collection of pions with $\Delta p/p \simeq \pm 10\%$) another lens is needed with a focal length $F \leq 10$ cm and a current of 1.5 - 2 MA. Such a lens can generate in its neck a field strength of 600 kG and it will not be possible to use it more than once. The lens has the shape of a "half-lens" with a special profile of the first surface and a flat second surface. A prototype of such a lens is at present in operation with a current of 1.5 MA. For the time being the electrodes are changed manually, but a scheme for the automatic change of electrodes is in preparation.

The antiproton storage ring consists of a race track with four long straight sections of 7 m length and four quadrants with a radius R = 3 m. One of the long straight sections is reserved for the injection and ejection of antiprotons and the other three for electron cooling and an RF cavity. The magnets of the quadrants have zero gradient and edge focussing, symmetrical with respect to the centre of the quadrants. This gives a constant momentum compaction function in the long straight sections, which is necessary for successful electron cooling of the antiprotons.

The aperture of the storage ring is $A_Z \times A_R = 8 \times 32$ cm^2 and allows the capture of a particle beam with an emittance of up to 70 mradcm and a momentum spread of $\Delta p/p = \pm 2.5 \times 10^{-2}$.

One of the conditions for electron cooling is that the apparent energy spread for a given closed orbit due to horizontal betatron oscillations covering neighbouring closed orbits is small. The injected beam is therefore made to undergo a chromatic dispersion in correspondence to the values of the momentum compaction function in the long straight sections of the storage ring. As the result of this the apparent energy spread for a given closed orbit is not higher than $\Delta p/p = \pm 0.6\%$.

The chromatic dispersion of the injected beam is realized by the bending magnet M_1 (see Fig. 2) and the lens Λ_1. The focal length of this lens is connected with the bending angle φ, the field gradient of the magnet n and the momentum compaction function Ψ of the storage ring by the relationship

$$F = \Psi \frac{\sqrt{1-n}}{\sin \varphi \sqrt{1-n}} .$$

The injection of the particles into the storage ring takes place at the beginning of the injection straight section and vertically upwards by means of the magnets M_2 and M_3 (see Fig. 3). The magnet M_2 plays the role of a septum magnet with a septum of not less than 1 cm thickness. Injection in front of a quadrant, which would be the best if one aims at the smallest possible inflector voltage would require twice as much vertical aperture in the storage ring because the emittance of the injected beam is practically equal to the admittance of the storage ring*).

The existence of the long straight sections makes it possible to inject the beam under a small angle with respect to the medium plan directly into an inflector which is placed at the end of the same long straight section. The bending angle of the inflector must in this case be larger by a factor of 1.7 with respect to the conventional scheme of injection[4]. Furthermore the distance between the inflector electrodes must be twice as large as the aperture of

*) The capture of the beam with such an emittance is possible if one synchronizes the pulse of the inflector with the moment of passage through the inflector of the previously stored beam, so that the latter one is not destroyed in the field of the inflector.

the circulating beam which increases still more the voltage on the electrodes, in fact, up to ± 500 kV for a travelling wave in the direction opposite to the beam.

It has been proposed in order to reduce this voltage to inject through one of the electrodes of the inflector in the following way: The space between the two electrodes can be divided into two regions, the region of the aperture of the storage ring, where the stored beam circulates and where the field of the inflector must be pulsed with a pulse length shorter than the revolution period and with a very short rise time - which presents exactly the main difficulty - and a region beneath the main aperture where one can produce a quasi-stationary magnetic field of about 300 G bending the lower part of the injected beam. These two regions can be separated by a thin wall of a thickness of a few tenth of a millimeter through which the beam passes practically without losses. This wall is the upper part of a box like electrode of the inflector and the "knife" of some sort of a septum magnet, placed inside of the box. This type of injection reduces considerably the difficulties connected with the design of a high voltage generator for the inflector.

The described scheme of production and injection of antiprotons allows the collection of all particles within the root mean square production angle and in the given momentum interval and the achievement of a capture efficiency in the storage ring of up to 10^{-5} defined as number of captured antiprotons divided by the number of primary protons.

The realization of this requires the design of several complicated pulsed electro-optical devices and is a part of the development programme of the Institute of Nuclear Physics directed towards the application of powerful and superpowerful pulsed magnetic fields in particle accelerator techniques.

References

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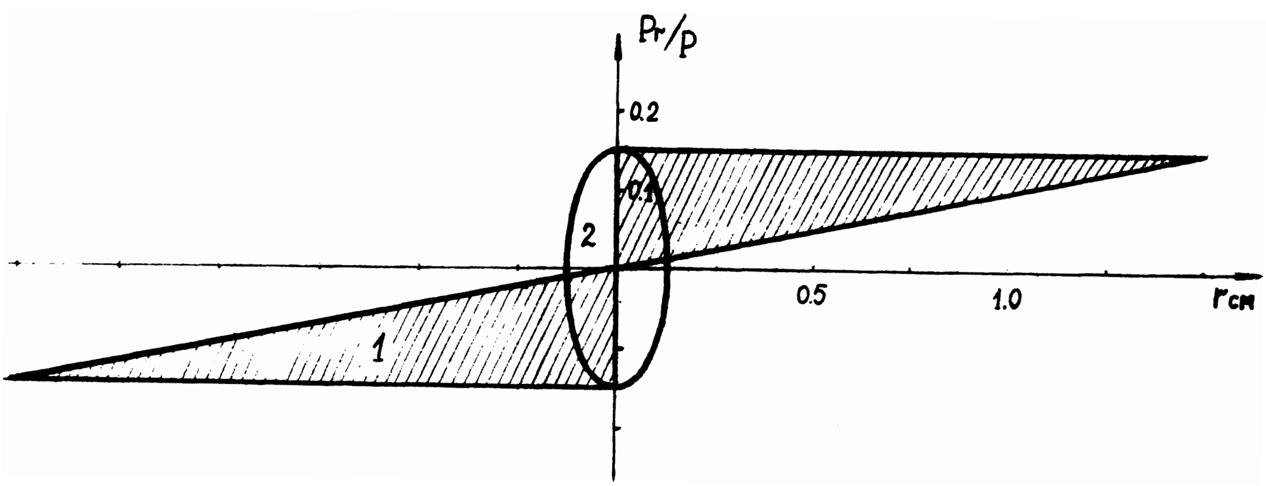

Fig. 1 The emittance of the antiproton beam at the end of a target of 10 cm length

1) without magnetic field in the target

2) with magnetic field of a gradient of grad B = 1.3×10^7 gauss/cm.

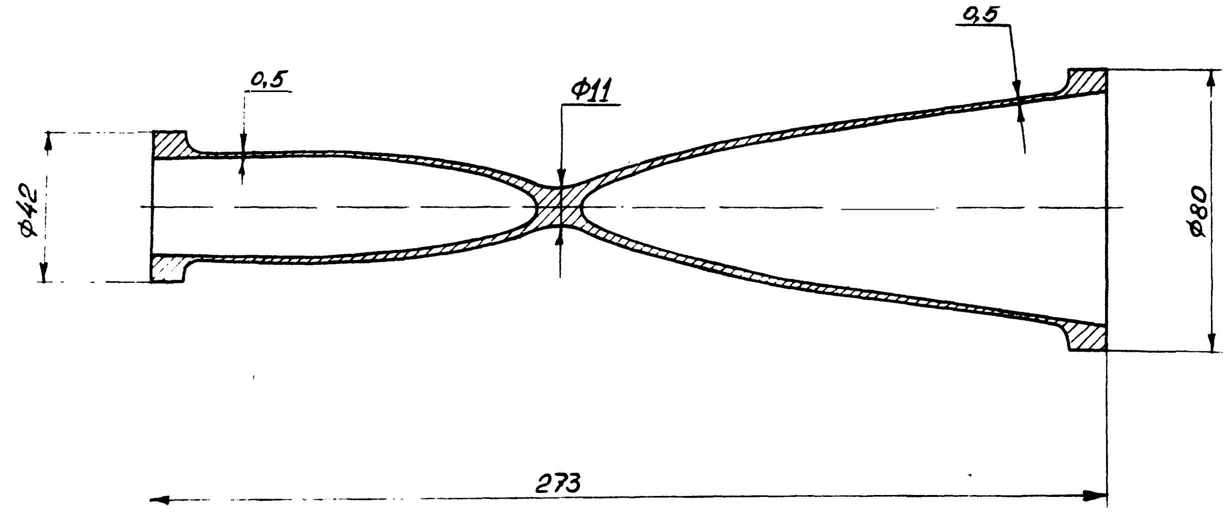

Fig. 2a Special profile of the "linear" lens.

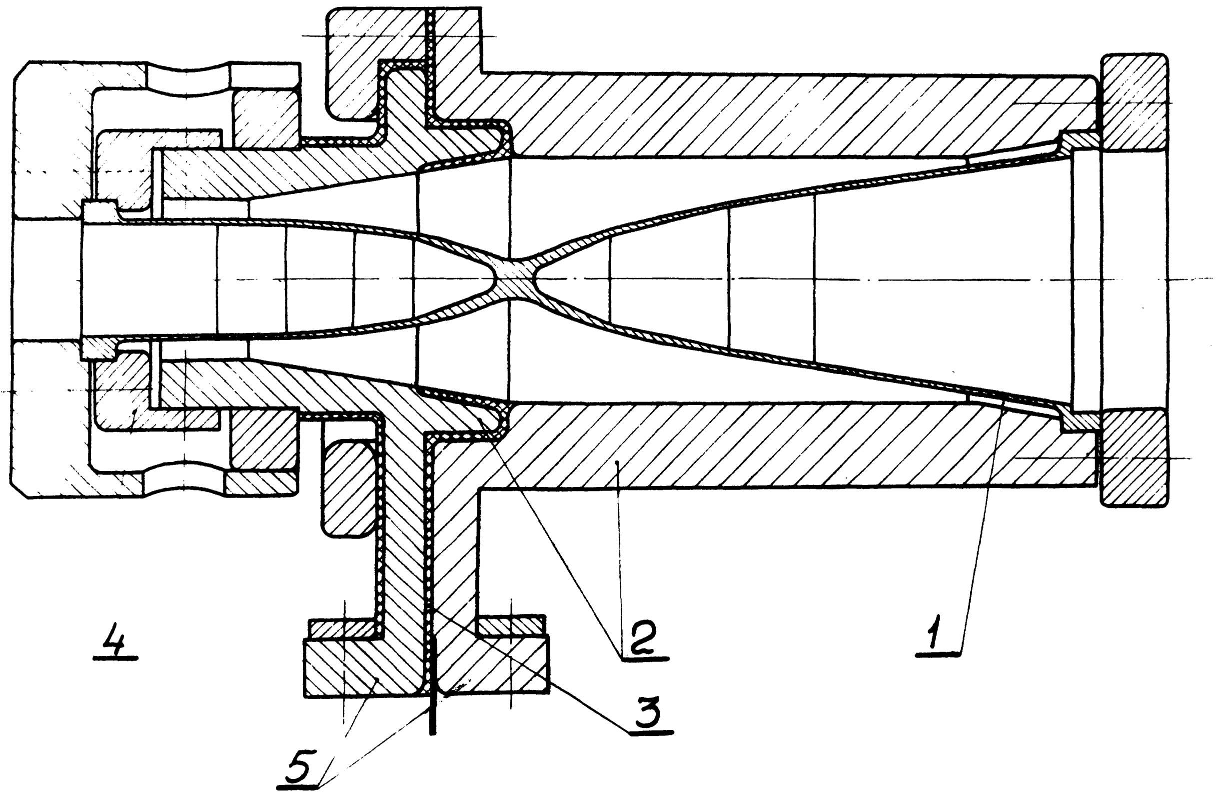

Fig. 2b Sectional view of the "linear" lens

1 - lens body
2 - coaxial conductor
3 - insulation
4 - damping device for demountable contact
5 - flat conductor for connection to the transformer.

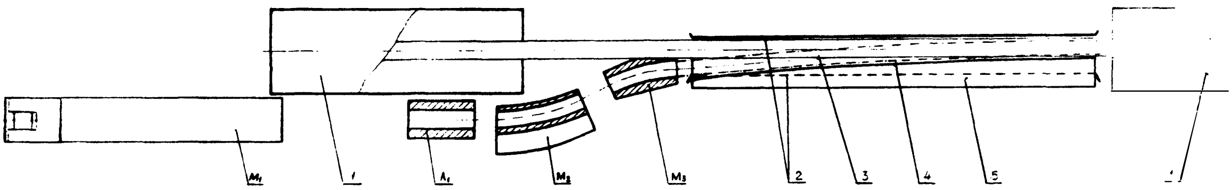

Fig. 3 Scheme of the injection of antiprotons into the storage ring.

M_1 and M_2 - bending magnets

A_1 - lens

M_3 - septum magnet

1 - storage ring magnets

2 - top electrode of the inflector and position of the bottom electrode (dotted line) for injection with double distance between the electrodes

3 - conducting foil

4 - conductor bar of the septum magnet

5 - thick bottom electrode in the case of injection through the foil.