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Electron cooling of magnetized positrons

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Abstract

Electron cooling of positrons is the essential peculiarity of the method of antihydrogen and positronium fluxes generation, which is based on low-energy positron storage ring. The design of the positron ring equipped with an electron cooling system is discussed. The positron beam circulates in a longitudinal (quasitoroidal) magnetic field. Electron drift inside special "septum" coils and toroidal sections is used for superposition and separation of the cooling electron beam and the circulating positron one. The working cycle of the ring is described. Peculiarities of the electron cooling of magnetised positrons are discussed. The general parameters of the Low-Energy Positron Toroidal Accumulator (LEPTA), which is under construction in the JINR, are presented. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Proposed in Ref. [1], the method of the positronium generation based on low-energy positron storage ring equipped with an electron cooling system gives a possibility to obtain monochromatic positronium fluxes with small angular spread. With positronium fluxes in vacuum one can perform new original setting up of the experiments without the distortion caused by medium in the traditional methods of the positronium generation in a target. The measurements of the positronium lifetime, the probability of decays with momentum conservation and charge invariant violation (CPT violation), fine structure of the positronium spectrum, Lamb shift measurements can be done at much higher precision than in traditional methods [2].

General aims of the LEPTA construction are experimental investigation of the particle dynamics in the focusing structure with longitudinal magnetic field, investigation of the electron cooling of positrons and positronium flux generation.

It has to be pointed out that the low-energy positron storage ring together with small antiproton ring can be used for a high-intensity antihydrogen atom flux generator [1,2].

2. Lepta

The low-energy positron storage ring (Fig. 1, Table 1) has 2 toroidal solenoids and 2 straight

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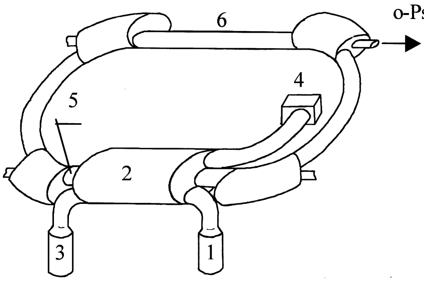

Fig. 1. The schematic representation of the LEPTA: (1) electron gun, (2) septum, (3) electron collector, (4) positron injector, (5) kicker, (6) cooling section.

Table 1
General parameters of the Low-Energy Positron Toroidal Accumulator

Circumference	m	18.12
Positron energy	keV	10
Revolution period	ns	300
Longitudinal magnetic field	G	400
Major radius of the toroids	m	1.45
Bending magnetic field	G	1.75
Positron beam radius	cm	0.5
Positron energy spread at injection		10^{-3}
Initial positron angular spread	mrad	15
Number of positrons		10^9
Residual gas pressure	Torr	10^{-10}
Electron cooling system		
Cooling section length	m	4.53
Electron current	A	0.5
Electron beam radius	cm	1
Electron transverse temperature	meV	100

ones, connected together as a racetrack. The first of straight solenoids, the so-called "septum", is used for superposition and separation of the cooling electron beam and the circulating positron one by the horizontal displacement of the electron beam in transverse magnetic field, which is produced by special coils. Beams superposition and separation in the vertical plane are produced by centrifugal drift of electrons in the toroidal solenoids.

At the first stage of the ring working cycle the electron gun is switched off. The positron beam from injector is directed into septum coil and moves in horizontal direction to the equilibrium orbit. After that, it is displaced in vertical direction by the field of special kicker coil, which is placed in the straight solenoid near the septum. At the exit of the kicker coil the positron beam has to reach the equilibrium orbit. Applying of bending magnetic field of the corresponding value compensates centrifugal drift of the positrons inside the toroidal sections. The field of the septum coils does not act on the particle moving along the equilibrium orbit due to septum design. When the positron beam fills the total ring circumference, the kicker coil is switched off and electron gun of the cooling system is switched on. The electron beam after travelling through the septum coil is placed below the median plane of the ring. Inside the first toroidal section electrons drift up in the longitudinal toroidal field and bending one which compensates the drift of the positrons. Total displacement of the electrons in the vertical direction is equal to:

$$\Delta = \pi(\rho_p + \rho_e) \tag{1}$$

where ρ_p, ρ_e are the positron and electron Larmor radii. Inside the cooling section both beams travel together (in the same direction), and both beams are overlapped. To provide the equality of the positron and electron velocities some potential is applied to the vacuum chamber wall isolated from the ground in the cooling section. Inside the second toroidal section the electrons displace up again and to the left in the septum coil and come to the collector (Fig. 1).

3. Electron cooling of positrons

The choice of the positron injector parameters and the ring design is significantly limited by the relation between characteristic times of the processes accompanying the positron storing. The first among them is the electron cooling of positrons, which was investigated only theoretically up to now [3].

Maximal angular spread of positrons in the ring is determined by the relation:

$$\tau_{ee} \ll \tau_{ms} \tag{2}$$

where τ_{ee} is electron cooling time and τ_{ms} is characteristic time of increase of the positron beam angular spread due to multiscattering in collisions with residual gas atoms. This maximal angular spread determines the choice of vacuum conditions in the ring necessary to obtain required positron lifetime, which is restricted by the single scattering on residual gas atoms on big angles.

And, finally, equilibrium positron temperature, when the cooling process is completed, determines the positronium generation rate.

In order to test analytical estimations of the cooling time and to calculate positron dynamics in the ring, taking into account the action of the friction force, a special computer code is under development now. First results of the calculation of the transverse component of the friction force are presented below.

4. Friction force calculation

An essential peculiarity of electron cooling of positrons is magnetisation of both interacting particles. In this case, an impact parameter of the collision can be determined as a distance between magnetic field lines crossing the centres of positron and electron Larmor cycles (Fig. 2).

Numerical calculation of the friction force is performed in terms of binary collisions and the calculation algorithm includes the following steps:

1. Calculation of the positron momentum losses for given impact parameter and electron velocity components. It is made by numerical integration of the motion equations along the longitudinal coordinate and averaging over initial phases of positron and electron Larmor rotation.
2. Averaging of this value over the electron velocity distribution function.

$$\Delta\bar{p} = \int \Delta p(v_\perp, v_\parallel) f(v)\, \mathrm{d}^3 v \tag{3}$$

In the case of flattened distribution of electrons the distribution function can be approximated

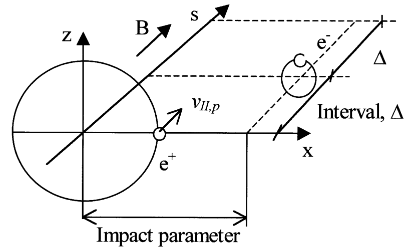

Fig. 2. Schematics representation of binary collision.

by the following formula:

$$f(v)\, \mathrm{d}^3 v = \left(\frac{m}{2\pi}\right)^{3/2} \frac{1}{T_\perp \sqrt{T_\parallel}} \times \mathrm{e}^{-mv_\perp^2/2T_\perp - mv_\parallel^2/2T_\parallel} 2\pi v_\perp \, \mathrm{d}v_\perp \, \mathrm{d}v_\parallel \tag{4}$$

3. Integration of the momentum losses over the impact parameter.

$$F_\perp = n_e v_\parallel 2\pi \int_0^{\rho_{\max}} \Delta\bar{p}\rho \, \mathrm{d}\rho \tag{5}$$

where maximum impact parameter $\rho_{\max} = \min(R_D, a_e)$, R_D and a_e are radii of Debye screening and electron beam, respectively.

Motion equations are solved in the particle rest frame using dimensionless variables: the particle coordinates are normalised on positron Larmor radius, all velocities are normalised on positron transverse one and independent variable – time is measured in units of $\omega \cdot t$, where ω is the cyclotron frequency. Integration, is performed in the symmetric interval and the distance between particles before and after collision is the same. After integration, the variations of the particles velocity components $(\Delta v_\parallel, \Delta v_\perp)$ due to collision are calculated as a difference between their final and initial values. The accuracy of numerical algorithm was tested using energy conservation law and is determined by integration step. In the presented calculations, the accuracy of velocity variation after collision was $\Delta v \approx (1\text{–}4) \times 10^{-9}$ depending on initial conditions.

Calculation shows (Fig. 3), that the change of longitudinal momentum of each particle has zero

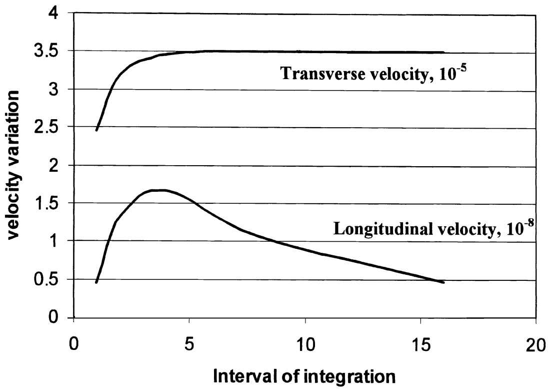

Fig. 3. Dependence of electron velocity variation on integration interval.

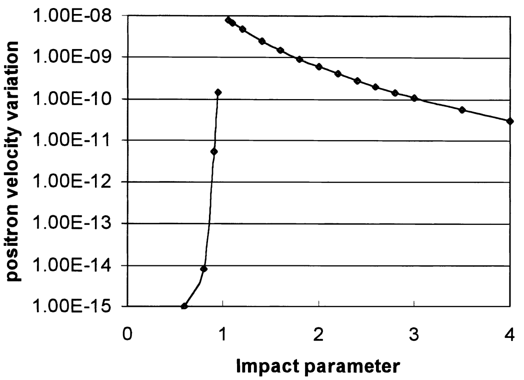

Fig. 4. Dependence of the positron transverse velocity variation on impact parameter (the initial electron velocity is equal to zero).

value, when the interval of relative motion extends from minus infinity to plus infinity as it follows from collision symmetry. For calculation of transverse velocity variation integration can be performed in the interval of about 5 Larmor radii of positron.

Figs. 4 and 5 present the dependencies of positron velocity variation on the impact parameter value and initial value of transverse component of electron velocity (initial values of positron velocity components correspond to parameters from Table 1). The region of impact parameter near

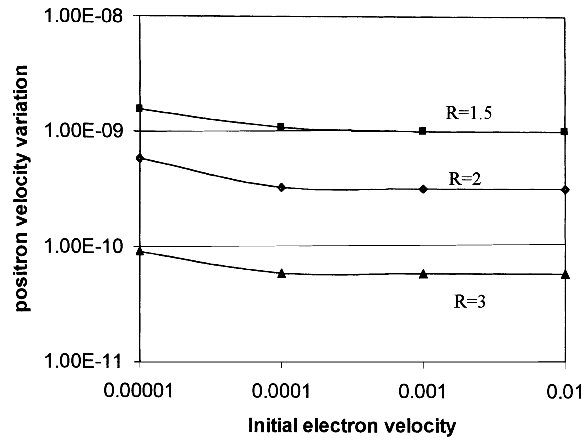

Fig. 5. Dependence of the positron transverse velocity variation on the initial electron velocity (R is impact parameter).

1 corresponds to fast collision between particles, when the magnetization does not play a significant role, and numerical simulation of the particles motion in this region is difficult enough for practical realisation. Influence of the collision with such parameters can be taken into account by using analytical formula for nonmagnetized friction force [4]. The accuracy of presented calculation does not permit one to calculate the positron transverse velocity variation directly (the magnitude lies in the range from 10^{-15} to 10^{-8}). Therefore, this value is calculated from electron velocity variation using energy conservation:

$$\Delta v_{\perp,p} = -v_{\perp,\mathrm{e}0}\Delta v_{\perp,\mathrm{e}} - \Delta v_{\perp,\mathrm{e}}^2/2. \quad (6)$$

In accordance with Figs. 4 and 5 the transverse component of the friction force, which acts on positron inside "cold" electron beam ($v_\mathrm{e} < 0.01 v_\mathrm{p}$), has a value of about 5 meV/cm, that corresponds to cooling time of about 50–100 μs.

The obtained magnitude of the cooling time is less by about an order of magnitude compared to the estimation made in Ref. [1] using formulae for nonmagnetized friction force, but higher than the analytical estimation made using the same model of particle collision in Ref. [3]. Such a value of the friction force is big enough to suppress multiscattering process at positron injection.

Acknowledgements

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