THE LOW ENERGY POSITRON STORAGE RING FOR POSITRONIUM GENERATION

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Abstract

The design of the low energy positron storage ring is discussed. The positron beam circulates in longitudinal (quasitoroidal) magnetic field. The electron cooling of positrons is the essential peculiarity of this system. 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 positronium is generated by recombination of the positrons with electrons in the electron cooling section of the ring. With positronium flux 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 creation of the low energy positron storage ring will give a possibility to design a high intensity antihydrogen atom generator.

The general parameters of the low energy positron toroidal accumulator (LEPTA) are presented. The ring circumference is about 18 meters. Positron energy can be varied from 5 to 20 keV.

1 INTRODUCTION

The precision measurement of the ortho- and parapositronium characteristics is one of the fundamental problems of the modern quantum electrodynamics.

Proposed in [1] 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 to 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 life time, 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].

Presently the positron ring dedicated to the positronium generation and called Low Energy Positron Toroidal Accumulator (LEPTA) is under construction at the JINR. At the first stage of the experiments an injector of low energy positrons based on radioactive isotopes will be used. At the second stage we plane to use an injector based on electron linac in order to increase the positronium flux intensity.

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].

An electron storage rind with similar magnetic structure is proposed as the base of electron cooling system with circulating electron beam, which permits to cool down the ions at energy of several GeV [3-5].

2 LEPTA

The low energy positron storage ring (Fig. 1) has 2 toroidal solenoids and 2 straight ones, connected together as a racetrack. The first of straight solenoids, so called "septum", is used for superposition and separation of the cooling electron beam and the circulating positron one by the horizontal drift 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. Such a design of the ring is preferable because of technical reasons, mainly: this is a problem to construct a solenoid of the diameter of less then 30 cm and the beams superposition can not be performed only by the centrifugal drift, which gives the displacement about a few cm. The long term stability of the positron beam is provided by additional spiral coils, which form a quadrupole magnetic field, similar to the "stellarator" one[1].

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 drifts in horizontal direction to the equilibrium orbit. After that, it is displaced in vertical direction by drift in 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 haas to be reach the equilibrium orbit. Centrifugal drift of the positrons inside the toroidal sections is compensated by applying of bending magnetic field of the corresponding value. 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, after that, the injected positron beam circulates inside the ring.

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 vertical direction is equal to:

$$\Delta = \pi(\rho_p + \rho_e), \qquad (1)$$

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).

The spiral quadrupole coil is placed inside the septum solenoid. The choice of its parameters is provided by numerical simulation of the positron dynamics [6].

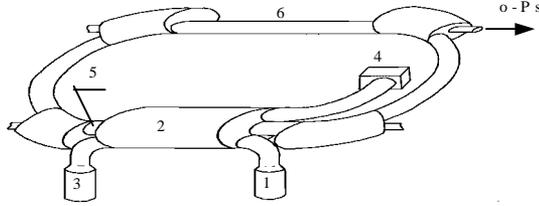The general parameters of the LEPTA are listed in the Table 1.

Fig 1. The schematics 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	nsec	300
Longitudinal magnetic field	G	400
Major radius of the toroids	m	1.45
Bending magnetic field	G	1.75
Gradient of quadrupole magnetic field	G/cm	5
Positron beam radius	cm	0.5
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

3 THE POSITRONIUM GENERATION RATE

The rate of the positronium generation is describe by the formulae:

$$R = \frac{dN}{dt} = \alpha_r n_e n_p V , \qquad (2)$$

where α_r is recombination coefficient:

$$\alpha_r = \frac{80 \alpha r_e^2 c^2 L_c}{v} , \qquad (3)$$

$n_{e,p}$ are the electron and positron beam densities, $\alpha = 1/137$, $v = \sqrt{v_p^2 + v_e^2}$, $v_{e,p} = \sqrt{T_{e,p}/m}$, $T_{e,p}$ - electron and positron velocities and temperatures in particle rest frame, r_e, m are the electron classical radius and mass

respectively, $L_C = ln(\alpha c/v)$, $V = l_{rec} \pi a^2$, l_{rec} – the length of the recombination section, a – minimal of the electron and positron beam radii. For the parameters from the Table 1 and beam temperature of 0.2 eV the positronium generation rate is about $1.2 \cdot 10^{-4} \cdot N_p$ sec^{-1}, N_p – the number of positrons in the ring.

One should note, that parapositronium life time is very short and flight length is about 1 cm. Orthopositronium life time is about 0.14 μsec and it leaves the magnetic system of the ring and can be used for physical experiments. The orthopositronium generation rate is 0.25 of the total value.

Taking into account the decay of the orthopositronium inside the cooling section, to obtain the positronium flux of 10^4 sec^{-1} the number of the positrons in the ring has to be of the order of magnitude of 10^9.

The longitudinal temperature of the positron beam is determined by equilibrium between electron cooling and microwave coherent instability. The threshold of the instability can be estimated by formulae:

$$\frac{\Delta p}{p} \geq \sqrt{\frac{eI_e \left| \frac{Z_n}{n} \right|}{mc^2 \gamma \beta^2 |\eta|}} , \quad \eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2} \qquad (4)$$

at positron energy of 10 keV the impedance $\left| \frac{Z_n}{n} \right| = \frac{377}{2 \beta \gamma^2} \left(1 + 2 ln \frac{b}{a} \right)$ is about 5 kΩ, where b and a are radii of vacuum chamber and positron beam, γ_{tr} is equal about 2. The positron number $N_p = 1 \cdot 10^9$, which is necessary to obtain generation rate of about 10^4, corresponds to positron current of 500 μA. The equilibrium momentum spread lies near the threshold value (4) and is about $3 \cdot 10^{-3}$. Longitudinal temperature of the positron beam is equal to

$$T_{II} = \frac{T_{Cathode,eff}^2}{2E} , \qquad (5)$$

where $T_{Cathode,eff} = \Delta E$, ΔE is the positron energy spread and E is the positron energy. In our case $T_{II} = 0.15$ eV and the recombination rate is determined mainly by transverse temperature of the electron and positron beams. For the positron beam at a higher intensity the equilibrium longitudinal temperature of the positrons limits the recombination coefficient, and maximum value of the positronium flux achievable with such a ring is of the order of 10^5 sec^{-1}. But, in practice, the positronium flux value is limited by the intensity of a low energy positron source and by the choice of an injection scheme.

4 THE POSITRON INJECTOR

The choice of the positron injector parameters 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 characteristic time can be described with the following formula [1]:

$$\tau_{ee} \approx \frac{\beta^4 \gamma^5}{8\pi c r_e} \frac{mc^3}{e} \frac{1}{\eta_e J_e L_c N_{col}} (\theta)^3 . \qquad (6)$$

Here J_e is electron beam current density, L_c - Coulomb logarithm, θ - the angular spread of the positron beam, η_e - the ratio of cooling section length to positron ring circumference, N_{col} ~5-8 is an effective number of electron- positron collisions due to their rotation in magnetic field.

The second process is positron multiscattering in collisions with residual gas atoms. This increases the angular spread of the positron beam with characteristic time

$$\tau_{ms} \approx \frac{\beta^3 \gamma^2}{4\pi Z(Z+1)} \frac{(\theta)^2}{c r_e^2 n_0 L_z} , \qquad (7)$$

$L_z = ln(183*Z^{1/3})$, n_0 is residual gas density, Z - atomic number of residual gas atoms. This effect is negligible, if $\tau_{ee} \ll \tau_{ms}$, or the positron angular spread is small enough:

$$\theta_{max} \leq \frac{2 N_{col} L_c \eta_e J_e}{\beta \gamma^3 \frac{mc^3}{e} Z(Z+1) L_Z r_e n_0} . \qquad (8)$$

The 3d process is positron singlescattering in residual gas , which limits the positron life time in the ring:

$$\tau_{life} \approx \frac{\beta^3 \gamma^2}{4\pi Z(Z+1)} \frac{(\theta_{max})^2}{c r_e^2 n_0} . \qquad (9)$$

If the positron energy lies in the range of 5 - 30 keV the positron life time is about 100 sec at vacuum pressure of 100 pTorr.

The initial angular spread of the positron beam has to be small enough, therefore only positrons moderated inside a solid or gas target can be used for injection into the ring. All methods of production of such positrons give poor intensity of positrons and one needs to use a storing of positrons.

Assuming a multiple single turn injection application and positron storing in the longitudinal phase plane[1] we obtain obvious limitation of characteristic times: the injection repetition period is to be longer of the electron cooling time and the number of stored positrons is proportional to the number of injection cycles, which, in its turn, can not exceed the ratio of the positron life time (9) to the injection period. For such an injection scheme the positron source with pulsed intensity in the range of 10^5 -10^6 positrons per injection cycle is necessary. The injection pulse duration is to be about 200 nsec, and injection repetition rate is about 10 - 100 Hz. An appropriate positron source is one based on electron linac with energy about 40-100 MeV[7]. Such a linac is available, in principle, at the JINR [8], but final decision depends on progress of the IREN project.

Another injection scheme presumes storing of the low energy positrons in an additional magnetic trap

during a long time duration and using of the single pulse injection into the ring. This scheme allows to obtain positron beam of approximately required parameters even when an electron linac of relatively low energy (~10 MeV) either a radioactive source are used.

In this scheme positrons from the electron linac or radioactive source after slowing down in a solid target accelerate up to some energy (of the order of several keV) and are injected into an additional magnetic trap. In there the positrons are thermolized once again in collisions with the residual gas atoms and are accumulated during several tens of seconds. For injection into the storage ring the positrons are to be extracted from the trap by an electric field pulse and are accelerated up to required energy.

The positron flux from the electron linac based source can be estimated by the following formulae:

$$\frac{dN}{dt} = \frac{W k_{eff}}{e\varepsilon} , \qquad (10)$$

where W is the average power of the electron beam at the target, ε is the energy of primary electrons, $k_{eff} = N^p/N^e$ is the conversion efficiency, which is about 10^{-8} at electron energy of 10 MeV[7]. At the average power of the electron beam of the order of 100 W the positron flux is about 10^6 sec^{-1}. Available flux of the slow positrons with radioactive isotope based source is about the same value. The number of positrons injected into the ring after storing in the trap is about 10^8, that permits to achieve the positronium generation rate of about 10^3 sec^{-1}.

ACKNOWLEGEMENTS

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