THE PHYSICAL BASES OF LOW-ENERGY HYDROGEN ISOTOPE IONS STORAGE RING

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The idea of a nonrelativistic hydrogen isotope ion storage ring is proposed. The influence of different factors on the main parameters of circulating beam is considered. The principal possibility for construction of such installation is shown.

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1. INTRODUCTION

The main factor, which for a long time prevented the proton storage ring construction, was lack of betatron and synchrotron oscillations damping that is caused by negligible quantity of proton energy losses for synchrotron radiation.

The offer an electron [1], and then stochastic [2] method of oscillation damping has allowed to construct proton storage rings with energies from several tens to several thousands of MeV [3,4].

Rather earlier it was offered to use the proton energy losses for internal target ionization as a braking force for ensure the oscillation damping [5]. However, as it was shown in [6], it is impossible to ensure the damping of all oscillation modes in this case.

In paper [7] it was shown that the use of the non-elastic energy losses of charged particles passing through the substance allows one to provide in some range of velocities ($\upsilon_p \le 4*10^8$ cm/s) the damping of all oscillation modes. This fact was put as a base of proposals on designing the hydrogen isotope storage ring, which were suggested in papers [8,9].

This work is dedicated to investigation in single particle approximation the influence of neutral and plasma target on the main parameters of circulating beam.

2. THE MAIN PARAMETERS OF CIRCULATING BEAM

1. The energy. The following factors were taken into account for choice the energy of accumulating particles:

a) close by the operating energy value the necessary and sufficient condition of all modes of oscillations damping must be satisfied [6,7]:

$de_a/dE_P>0$,

here e_a is the atomic stopping ability of a target substance for protons; E_p is the proton kinetic energy;

b) the energy of hydrogen isotope ions must be close to 53 keV/a.m.u. This condition is connected with that the maximum cross-section of T(d,n)^{4}He reaction takes place at the energy range ~53 keV/a.m.u.

The measurement data of the atomic stopping ability of different elements for protons, that were obtained in many experiments and are adduced in [10a], points that the condition $de_a/dE_P>0$ is valid for energies $E_P \le 50$ keV. This corresponds to the proton velocity $\upsilon_p=3.1**10^8$ cm/s. The energy E_P=46.97 keV corresponds to $\upsilon_p=3*10^8$ cm/s ($\beta=10^{-2}$).

2. The time of oscillation damping. For the case the stopping target is installed in achromatic straight section, the expressions for the damping time (refer to. [6]) may be transformed to the form

$$\tau_{x,z} = \left(\frac{c\, dE/dx}{2\beta E_t} * \frac{l}{\Pi}\right)^{-1}$$

$$\tau_s = \left(\frac{c\beta\gamma}{2E_t} * \frac{\partial (dE/dx)}{\partial\gamma} * \frac{l}{\Pi}\right)^{-1}.$$

Here dE/dx is the particle energy losses on the path unit in the target; N_s are the target atomic surface density; E_t is the total particle energy; Π is the perimeter of the installation; γ is the particle relativistic factor; l is the target thickness.

After substitution of numerical values, with taking into account if $E_p \approx 50$ KeV, dE/dx for protons in hydrogen [11] is equal to $\sim 6.4*10^{-15}*N$ eV/cm (N is the volume density of the target), one obtains:

$$\tau_{x,z} \approx 10^{11} \frac{\Pi(cm)}{N_s\left(\frac{at}{cm^2}\right)}, s \qquad (1)$$

$$\tau_s \approx 4*10^{11} \frac{\Pi(cm)}{N_s\left(\frac{at.}{cm^2}\right)}, s \qquad (2)$$

3. The settled energy spread. This value is defined by the expression [12a]:

$$\overline{\Delta E^2}^{1/2} = \left(\frac{\dot{N}\overline{\varepsilon^2}\tau_s}{4}\right)^{1/2} \qquad (3)$$

here: $\overline{\varepsilon^2}$ is the mean square of the energy that the particle loses in a single act of scattering, N is the mean number of collisions, which the particle subjects at one pass through the target.

So far as we do not dispose the data about the spectral density of non-elastic energy losses, we shall evaluate the settled energy spread in suggestion that dispersion of energy losses spectrum is equal to the mean value of losses i.e. $\overline{(\varepsilon - \bar{\varepsilon})^2} = \bar{\varepsilon}^2$ or $\overline{\varepsilon^2} = 2\bar{\varepsilon}^2$.

$$\bar{\varepsilon} = \frac{\overline{\Delta E}}{\overline{n_{col}}} = \frac{e_a N_s}{\pi R_{\text{int}}^2 N_s} = \frac{e_a}{\pi R_{\text{int}}^2}. \quad (4)$$

Here $\overline{\Delta E}$ is the mean energy, that the particle loses of one pass through the target; $\overline{n_{col}}$ is the mean number of collisions, subjected by the particle at one pass through the target; R_{int} is the maximum distance between the particle and the target atom nucleus, beginning from which the particles are non-elastically scattered.

R_{int} value is defined from the expression:

$\varphi_i(r_1) = \varphi_a(r_2)$; $R_{int} = r_1 + r_2$

where

$\varphi_i(r) = er^{-1}$ is the potential of the particle field;

$\varphi_a(r) = e(r^{-1} + a_0^{-1})\exp(-2ra_0^{-1})$ is the potential, which is created by the hydrogen atom [10a];

a_0 is Bohr orbit radius of hydrogen atom.

After substitution the corresponding values in (3), taking into account expressions (2) and (4), we obtain:

$$\overline{\Delta E^2}^{1/2} = \frac{2^{1/2} e_a}{4.7\pi\ a_0}(\pi\ \beta\ c * 1.11 * 10^{11}, s * cm^{-3}) = 1183\ eV \quad (5)$$

Thus, the settled energy spread in the storage ring depends only from the braking target substance (e_a) and is independent neither from its density, nor from the perimeter of the installation.

4. The particle lifetime due to fast processes. The fast processes, that quit the particles out during one turn, are: a) the particle scattering on the angle that is greater than the permissible one for a given magnetic structure; b) the circulating particle neutralization (the charge exchange) on the target atoms.

We shall consider both these factors one after another.

a) The lifetime due to particle scattering through an angle that is greater than the most permissible. The numerous experimental studies [10a] have showed that in the energy range from 60 keV/a.m.u. up to 0.1 MeV/a.m.u. the interaction of hydrogen isotope nuclei with a substance is defined by the non-elastic scattering. Since the number of collisions during one particle pass through the target is much greater than one, it is necessary to consider the process of multiple non-elastic scattering. The comparisons with experimental study results have shown that multiple scattering is described the best by the distribution function of following type [10a]:

$$f(\theta, d, E) = \frac{1}{4\pi} * \frac{1 - \exp(-2\bar{p})}{[1 + \exp(-2\bar{p}) - 2\exp(-\bar{p})\cos\theta]^{3/2}} \quad (6)$$

Here

$$\bar{p} = \frac{2.05 Z_1 Z_2 e^2 a_0 (M_1 + M_2)}{M_2} * N \int_{E_1}^{E_0} E^{-1} \left(\frac{dE}{dS}\right)^{-1} dE,$$

$M_{1,2}$ is the mass of bombarding and rest particle respectively; $E_{0,1}$ is the particle energy before and after passing the target, respectively; N is the target volume density.

For the case of protons (or deuterons) on hydrogen scattering $\bar{p} \approx 2.35(3.8) * 10^{-19} N_s$. From Fig.1 one can see that in the region where $\bar{p} << 1$ $\overline{\sin^2\theta} \approx 0.2\bar{p}$. Here θ is the deflection angle of a bombarding particle in the coordinate system, where the scattering particle rests.

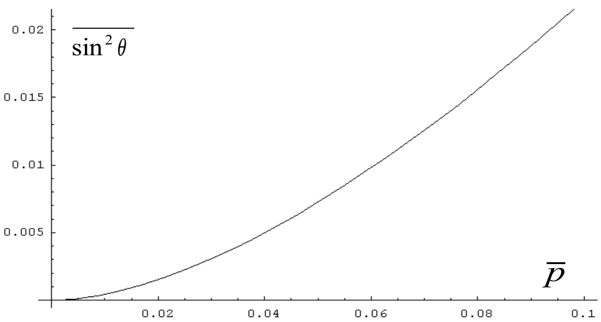

Fig. 1. *The mean-square scattering angle vs parameter $\bar{p}$ in the region $\bar{p} << 1$*

In the laboratory coordinate system the mean-square angle of proton on hydrogen atoms scattering is equal to $1.2*10^{-2}$ rad. and $3.5*10^{-2}$ rad. for the target surface density 10^{16} cm^{-2} and 10^{17} cm^{-2} respectively. The same value in the case deuterium scattering on hydrogen under the same target surface densities is equal to $8.3*10^{-3}$ rad and $2.6*10^{-2}$ rad respectively.

The angular particle distribution after the target passing is close to Gaussian with the dispersion $D = \overline{\sin^2\theta}^{1/2}$. For ensuring the lifetime due to scattering on the internal target be more than the damping time by a factor of one hundred (not less), the magnetic system of the storage ring must provide the capture of particles scattered through an angle $\vartheta \sim 5*D$ into the circulating mode. This angle is equal ~0.15 rad. (for protons) and ~0.12 rad. (for deuterons) at $N_s = 10^{17}$ cm^{-2} and, 0.06 rad and 0.04 rad at $N_s = 10^{16}$ cm^{-2} respectively.

The atomic hydrogen as a target is proposed.

b) The lifetime due to ion neutralization (the charge exchange) during passing through the atomic target. In case of heavy charged particles interaction (for instance, protons with an energy $E_p \sim 47$ keV) with the atomic or molecular target, two types of reactions can exist: a) the reactions with nuclei redistribution between interacting particles (nucleus conversions); b) the reactions with the excitation of electron levels in atom or the electron redistribution between interacting particles (the reactions of ionization, neutralization, the charge exchange).

At a mentioned energy the first type reaction cross sections do not exceed 10^{-24} cm^2 while cross section of the second type reactions can reach to 10^{-16}-10^{-15} cm^2.

Since these reactions are determining for low energy protons let us consider them in detail.

The proton interaction with atomic target can occur by the following channels:

p+A→H+A$^+$ (7)

p+A→p+A$^+$+e (8)

p+A→H*+A$^+$ (9)

p+A→p+A* (10)

p+A*→p+A$^+$+e (11)

p+A*→H+A$^+$ (12)

The reactions (7), (9), (12), which describe the neutralization of bombarding protons, are characterized by the cross section σ_{10}. The reactions (8) and (11) describe inverse ionization and are characterized by cross section σ_{01}. In the reactions (8) (10) the charge beam composition does not change.

The equations, which describe the time evolution of charged and neutral beam components, have the following form:

$$\frac{dn_0}{dx} = \lambda_0 n_+ - \lambda_+ n_0$$

$$\frac{dn_+}{dx} = \lambda_+ n_0 - \lambda_0 n_+ . \qquad (13)$$

Here

$\lambda_0=\sigma_{10}n_m$;

$\lambda_+=\sigma_{01}n_m$ n_m is the target volume density;

n_0 and n_+ are respectively the number of neutral and charged particles in the beam, n_++n_0=const.

Solution of system (13) gives:

$$\frac{n_0}{n_+} = \frac{\lambda_0 + \lambda_+}{\lambda_+ + \lambda_0 \exp[-l(\lambda_0 + \lambda_+)]} - 1 . \qquad (14)$$

Finally one obtains:

$$\frac{n_0}{n_+} = \frac{\sigma_{10}(1 - \exp[-n_{sm}(\sigma_{10} + \sigma_{01})])}{\sigma_{01} + \sigma_{10}\exp[-n_{sm}(\sigma_{01} + \sigma_{10})]} . \qquad (15)$$

For a "thick" target ($n_{sm}(\sigma_{01}+\sigma_{10})>>1$, where n_{sm} is the surface target density) we obtain:

$$\frac{n_0}{n_+} \approx \frac{\sigma_{10}}{\sigma_{01}} . \qquad (16)$$

For $\sigma_{10}\approx\sigma_{01}=\sigma$ and $n_{sm}(\sigma_{01}+\sigma_{10})<<1$ ("thin" target):

$$\kappa = \frac{n_0}{n_+} \cong n_{sm}\sigma . \qquad (17)$$

From expression (17) one can see the inefficiency of the target thickness reduction for decrease the beam neutralization degree, since as neutral target thickness decreases the beam damping time increases. The ratio of the lifetime due to the beam neutralization to the oscillation damping time remains constant.

In the table are presented interaction reactions of 50 keV protons with hydrogen and their cross sections according to [13]. These reactions can be divided into four groups: i) (4) - direct ionization reaction; ii) (1)→(5), (6)→(4), (2)→(5) - reactions of ionizing through the intermediate state; iii) (6), (7), (8) - reactions of direct charge exchange, iv) (1,2)→(9,10) - reactions of charge exchange through the intermediate state.

The reactions of groups i) and ii) are characterized by the general cross section σ_{01}; the reactions of groups iii) and iv) are characterized by the general section σ_{10}. At E_p=50 keV $\sigma_{10}\approx\sigma_{01}\approx10^{-16}$ cm^2 and $n_+/n\approx n_0/n=0.5$ [14] that means practically complete beam loss after several the target passing.

№	Reaction	Cross-section σ , cm^2
1	p+H(1s)→p+H*(2p)	~4∗10^{-17}
2	p+H(1s)→p+H*(2s)	~2∗10^{-17}
3	p+H*(2s)→p+H*(2p)	~2∗10^{-14}
4	p+H(1s)→p+H$^+$+e	~3∗10^{-16}
5	p+H*(n)→p+H$^+$+e	~3∗10^{-16}
6	p+H(1s)→H(1s)+p	4∗10^{-16}
7	p+H(1s)→H*(2s)+p	~10^{-17}
8	p+H(1s)→H*(2s)+p	~10^{-17}
9	p+H*(n)→H*(n)+p (n=2,3)	~10^{-16}
10	p+H*(n)→H*(n)+p (n≥4)	5∗10^{-15}

In this connection we have considered possibility of ionization the neutral beam component immediately after the braking target passing.

Since the potential of hydrogen ionization is equal to ~14 eV, its photoionization in laser field can occur by to multiphoton absorption. The velocity of multiphoton ionization *w* is connected with the electromagnetic field strength *F* by expression [15]:

$$w \propto F^{2k} ,$$

where $k=\langle E_i/h\nu+1\rangle$ is the number of absorbed photons; *E* is the potential of ionization.

From this expression it is clear that for efficiency of multiphoton ionization the large values of the laser field strength are required that, in one′s turn, causes significant technical difficulties.

Therefore we have considered a possibility of the hydrogen atoms ionization by means of plasma target.

c) Ionization in plasma jet. The passing of two-component (neutral atoms and protons) beam through the quasi-neutral plasma is accompanied by the following conversions:

H+p→H$^+$+p+e (18)

H+p→p+H (19)

H+e→H$^+$+2e (20)

p+e→H*+hν (21)

Here the velocity of hydrogen atom in reactions (18)-(20) is approximately equal to the proton velocity in reaction (21) and formers ~3*10^8 cm/s. In reactions (21) one can shifts to proton rests. In this case the electron energy equals E_e≈25 eV (v_e~3∗10^8 cm/s). The reactions (18) and (19), describe the atomic hydrogen beam ionization when it passes through the plasma.

The complete cross sections of ionization σ_i and neutralization σ_0, according to the data of [13], are 7.5∗10^{-16} cm^2 and ~6.7∗10^{-23} cm^2, respectively. Since $\sigma_i>>\sigma_0$, then in the subsequent calculations the proton neutralization was not taken into account. From the adduced values it is seen that the plasma target with a surface density of ~1.7*10^{16} cm^{-2} is "thick" and provides almost full ionization of the neutral beam component.

The energy loss of the particle passing through plasma is described by expression [10e]:

$$-\frac{dE}{dx} = -\frac{dE}{dt} * \frac{1}{v} = \frac{4\pi Z_1^2 Z_2^2 e^4 M_1}{\mu (M_1 + M_2) v^2} nL . \qquad (22)$$

Here M_1 and M_2 are the masses of the test and field particles, respectively; v is the velocity of the test particle; n is the volume atomic density of the target; L is the Coulomb logarithm (for proton-electron collisions under $n \sim 10^{16}$ $L \approx 5$).

For protons with an energy of ~47 keV

$$-dE/dx \approx 2.5 * 10^{-14} * n, eV/cm .$$

From this relation and expression (22) one can see that, firstly, the main particle energy losses occur by the particle collisions with plasma electrons, secondly, specific energy losses in the plasma target are approximately by a factor four higher than the similar value for atomic hydrogen target and, thirdly, the value of specific losses decreases with test particle energy increasing.

The plasma target density must be sufficient to provide full beam ionization and, at the same time, such that the synchrotron oscillation increment is not higher than the decrement that is caused by the neutral target.

These requirements both may be satisfied if the neutral target density $n_{sa}=1.7*10^{17}$ cm^{-2} and the plasma one $n_{sp}=1.7*10^{16}$ cm^{-2}. Under these conditions $\tau_s = 1.6*10^{-2}$ s. For the case without plasma target $\tau_s \approx 4*10^{-3}$ s.

3. CONCLUSIONS

The given above considerations and results of numerical estimations allow one to do the following conclusions:

it is possible to realize the installation for nonrelativistic ($\beta \cong 10^{-2}$) proton (deuteron) accumulation;

preliminary parameters of such installation may be following: $\Pi \cong 15$ m, $N_s \sim 10^{16}$–10^{17} cm^2, the capture angle ~0.15 rad;

for particle accumulation one must provide the device for ionization of neutral atoms, which are formed after the beam passing through the braking target.

To construct such installation it seems to be expedient with the following considerations:

as far as in none of the installation the energy loss of nonrelativistic particles in the neutral target is not used for damping of all oscillation modes it would be useful to investigate in detail such principle of damping ensuring;

such installation may be used for perfection of some units and systems necessary for applying the installation in other fields of investigations, in particular, as a neutron source or in studies on plasma physics and controlled fusion.

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