STORING NONRELATIVISTIC NUCLEI OF HYDROGEN ISOTOPES

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The paper shows that in cyclic magnetic systems the particle stopping losses provide the damping of both the betatron and synchrotron oscillations of hydrogen isotope ions in the energy range 20-80 keV/nucl. Parameters of the storage ring magnetic system and the circulating beam are estimated. Some aspects of such a storage ring application are discussed.

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For the first time the influence of ionization energy losses on particle dynamics in a cyclic magnetic system was considered in [1]. It was shown, that "the ionization losses lead to a swing of oscillations if $\beta=v/c<2^{-1/2}$ ", since in this case $\langle\Gamma_x\rangle+\langle\Gamma_s\rangle= 1/2\langle\Gamma(1+\partial\ln P/\partial\ln E)\rangle<0$; here $\langle\Gamma_x\rangle$ and $\langle\Gamma_s\rangle$ are decrements of the respective oscillations; E is the full particle energy; P is the instantaneous power of stopping losses; $\Gamma=P/\omega E$, ω is the angular frequency of particle circulation. To obtain this result it was assumed that, according to the Beta-Bloche formula [2], $P \sim 1/\beta$.

Later the authors of [3] have showed that the sum of transversal and longitudinal oscillation decrements for $\beta \leq 0.7$ case is positive. They suggested introducing the connection between radial and vertical oscillations, providing the damping of longitudinal oscillations to suppress a swing of radial oscillations.

The results of experimental research on the stopping power of hydrogen and helium for protons [4,5] are essentially differ from theoretical estimation used in [1, 3].

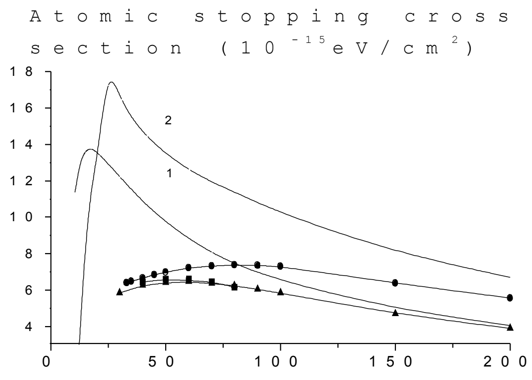

Fig. 1. *Atomic stopping power of hydrogen and helium vs the incident proton energy. 1, 2 – hydrogen and helium stopping power calculated according to the Beta-Bloche formula;● - helium stopping power for protons measured experimentally in [4];▲- hydrogen stopping power for protons measured experimentally in [4,5].*

Fig. 1 shows the stopping power of helium and hydrogen as a function of proton energy measured in [4,5] in comparison to that calculated by the Beta-Bloche formula. One can see the principal difference between experimental and calculated curves in the energy range 30-80 keV: as for the calculated curve in this energy range $\partial/P/\partial E$ is negative, for the experimental one the same magnitude is positive.

This fact has decisive significance for consideration of hydrogen isotope ion dynamics in a storage ring. The expressions for decrements of betatron and synchrotron oscillations look like [3]:

$$\Gamma_z=\langle cF/2\beta E\rangle, \quad (1)$$

$$\Gamma_x=\langle cF/2\beta E*[1-\psi R_0(K+\partial\ln F/\partial x)]\rangle, \quad (2)$$

$$\Gamma_s=\langle cF/2\beta E*[\beta^2\partial\ln F/\partial\ln E+\psi R_0(K+\partial\ln F/\partial x)]\rangle. \quad (3)$$

Here <…> means averaging over the installation perimeter, F is the stopping losses per unit of the path, R_0 is mean radius of installation, ψ is dispersing function of magnetic system, $K(\theta)$ is local curvature of particle trajectory, θ is generalized azimuth, E is full particle energy. From expression (3) it is clear that for ensuring the synchrotron oscillation damping for the case $\partial\ln F/\partial\ln\gamma<0$, as it was assumed in [1,3], it is necessary, firstly, to provide $\psi>0$ at the place of stopping losses location and, secondly, either to install the stopping target in the magnetic field ($K\neq0$), or to create the stopping target inhomogeneous on radius ($\partial \ln F/\partial x>0$). The first circumstance causes the additional increase of beam transversal sizes, and other two complicate a technical realization of installation.

In Fig. 2 the rough scheme of such an installation is shown. As for the mentioned energy $\partial\ln F/\partial\ln\gamma$ is positive, the damping of all oscillation types is ensured under condition $\psi=\partial\ln F/\partial x=K=0$ at the place of target location. It makes the easier operational mode of the storage ring and simplifies the stopping target design.

We shall evaluate probable parameters of a magnetic system, RF replenishment system and parameters of a beam circulating in such an installation.

The time of betatron and synchrotron oscillation damping for tritium ions was evaluated from expressions (1) - (3) for the case $\psi=\partial\ln F/\partial x=0$. It was assumed that $\partial\ln F/\partial\ln\gamma=d\ln F/d\ln\gamma=\gamma/F*dF/d\gamma=\gamma/F*dF(E_{kin})/d\gamma=\gamma/F*dF/ /dE_{kin}*E_0$; here E_0 is the particle rest energy. The magnitudes F and dF/dE_{kin} were determined from the respective graphs of Fig. 1 for the case E_{kin} = 50 keV.

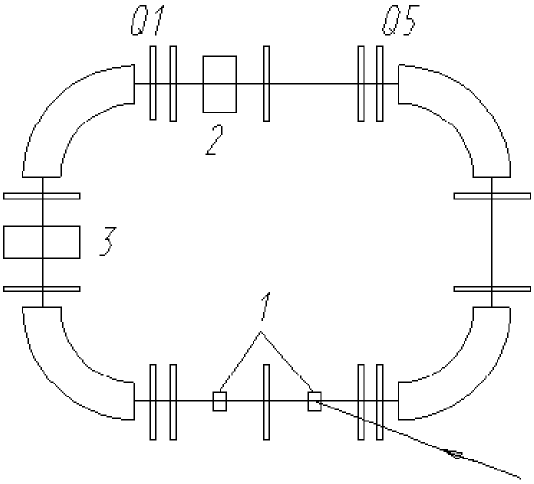

Fig. 2. *The rough scheme of the tritium ion storage ring. Q1,...,Q5,… – quadruple lenses; 1 –kicker magnets; 2– block of targets; 3– RF – cavity.*

The steady sizes of ion beam in the storage ring. The beam steady sizes are determined by quantum fluctuations of beam energy losses and by multiple Coulomb scattering. As the dispersion function at the place of stopping target location is equal to zero, the quantum fluctuations of stopping losses do not affect the steady beam sizes. In this case the mean square of the betatron oscillation amplitude is equal:

$$\langle |a_{x,z}|^2\rangle=R_0/8\Gamma_{x,z}*\langle\theta^2\rangle_t\,|f_{x,z}(\theta_0)|^2, \quad (4)$$

where $\langle\theta^2\rangle_t=4\pi\beta c r^2 nZ(Z+1)E_e^2/E\beta^4*\ln(183Z^{-1/3})$ is the meansquare angle of multiple scattering in time unit.

The steady beam energy dispersion. To find the steady energy dispersion we have used the equation for synchrotron oscillation [6]:

$$d(\Delta E)^2/dt=1/2\dot{N}\,\overline{\varepsilon^2}-(2\Gamma-1/2*\dot{E}/E)(\Delta E^2). \quad (5)$$

Here $\dot{N}\,\overline{\varepsilon}=d(\Delta\overline{E})/dt*\varepsilon_s$, where ε_s is the mean quantum of stopping losses taken equal to the mean ionization energy of the target atom ($\varepsilon_s\approx 25$ eV), $d(\Delta\overline{E})/dt=e_a\langle n\rangle\beta c$. For the stationary case, $d(\Delta E)^2/dt=0$:

$$(\Delta E)=\dot{N}\,\overline{\varepsilon}/4\Gamma=e_a\varepsilon_s(2\partial e_a/\partial E_{kin})^{-1} \quad (6)$$

i.e. the steady energy dispersion does not depend on the target density.

The lifetime of stored particles. The lifetime of stored particles is determined by the single and multiple processes. The single processes involve: the Coulomb scattering through large angles; the collisions with a large momentum transfer; the nuclear interactions; the charge transfer.

The Coulomb scattering through large angles. The lifetime due to the single elastic scattering on atoms of the ionization target by the angle larger then θ_m is equal to ([6]):

$$\tau_{el}=\beta c\langle n\rangle 2\pi(2zZe^2/pv)^2\int_a^b\theta(\theta^2_{min}+\theta^2)^{-2}d\theta. \quad (7)$$

Here θ_m is the maximum scattering angle with which the particle does not leave the vacuum chamber; Z and z are the charges of target nucleus and beam particle, respectively, p is the particle momentum; m is the electron mass; $a=tg\theta_m$; $b=tg\theta_{max}$;

$\theta_{max}\approx 274*A^{1/3}(mc/p)$; $\theta_{min}\approx Z^{1/3}(mc/p)\,(192)^{-1}$.

Collisions with large momentum transfer. As it was noted in [3], here it is enough to take into account those collisions with nuclei, which occur with scattering by an angle smaller then θ_m, since the losses due to collisions with $\theta>\theta_m$ are taken into account earlier. In the nonrelativistic case the relation $\Delta p/p<\langle\theta_m^2/2A$ is true. (A is the atomic weight of target substance). As $\Delta p/p\cong\Delta E/2E$, the collisions with large momentum transfer will affect the lifetime under condition $\theta_m^2>A(\Delta\bar{E}^2)^{1/2}/E$, where $(\Delta\bar{E}^2)^{1/2}$ is the tritium ion energy dispersion, E is the particle kinetic energy.

The nuclear interactions. The cross section of $^3H(\alpha,\gamma)^7Li$ -reaction which can take place under interaction of the tritium ion beam with the helium target in the mentioned energy range makes ~ 10^{-30}см^2 [8]. The cross sections of other reactions with protons, deuterons and tritium nuclei are much smaller. Thus, the influence of this process on the stored beam lifetime is extremely insignificant.

The charge transfer. Under interaction of hydrogen isotope nuclei with the jet targets the following charge transfer processes can occur:

$(p,d,t)+{}^4He\rightarrow{}^{1,2,3}H+{}^4He^+$

If the velocities of T^+, D^+ and H^+ ions are the same then these processes are reduced to

$H^++{}^4He\rightarrow H+{}^4He^+$,

respectively. One can reduce the influence of these processes by taking steps to neutral atom ionization.

The possible parameters for the hydrogen isotope nuclei storage ring were estimated and are given in Tables 1 and 2.

Table 1. *Rough parameters of the magnetic and RF system of the tritium ion storage ring*

Type of a magnetic structure	Strong focusing with achromatic straight sections
Mean radius R_0, cm	~ 95
Vacuum chamber aperture, cm	$A_x=\pm5$; $A_z=\pm4$
Product of maximum and minimum value of focusing functions, $\beta_{x,z\,(max)}*\beta_{x,z\,(min)}$, cm^2	~130
Frequency of betatron oscillations, $Q_{x,z}$	~ 4 … 5
RF frequency multiplicity, q	20
Magnitude $U_0/\|K\|$, where U_0 is the RF voltage amplitude, $K=(\alpha\gamma^2-1/(\gamma^2-1)$,($\alpha$ is the factor of orbit compression)	3.3*

The focusing functions of magnetic system are chosen so that, at first, the beam lifetime due to multiple processes be significantly more then the lifetime due to single processes and, secondly, the particle capture to the circulation mode after their scattering by an angle ≤ 0.3 be ensured.

Table 2. *Parameters of hydrogen isotope ion beams with the hydrogen or helium jet target*

Parameter			p	d	t
1	Particle kinetic energy (keV)		50	100	150
2	Stopping losses per turn (eV)$*[R_0(cm)*\langle n\rangle]^{-1}$	H	$4.0*10^{-14}$	-	-
		He	$4.4*10^{-14}$	-	
3	Damping time of transverse oscillations (s)$*\langle n\rangle$;	H	$9.7*10^{10}$	$1.9*10^{11}$	$2.9*10^{11}$
		He	$\sim 9.*10^{10}$	$1.8*10^{11}$	$2.7*10^{11}$
4	Damping time of longitudinal oscillations (s)$*\langle n\rangle$;	H	$\sim 10^{12}$	$\sim 2*10^{12}$	$\sim 3*10^{12}$
		He	$2.6*10^{11}$	$5.1*10^{11}$	$7.8*10^{11}$
5	Steady beam energy dispersion (keV)	H	2.54	3.6	4.4
		He	1.7	2.4	3
6	Mean square angle of multiple scattering in time unit$*\langle n\rangle^{-1}$	H	$8.8*10^{-14}$	$2.2*10^{-14}$	$9.9*10^{-14}$
		He	$2.6*10^{-13}$	$6.7*10^{-14}$	$\sim 3*10^{-14}$
7	Mean square of betatron oscillation amplitude $*\beta_{x,z}^{-2}(\theta_{min})$, cm	H	$\sim 10^{-3}$	$\sim 5*10^{-4}$	$\sim 3.6*10^{-4}$
		He	$2.9*10^{-3}$	$1.5*10^{-3}$	10^{-3}
8	Lifetime due to the single Coulomb scattering by an angle >1 rad$*\langle n\rangle$	H	$\sim 1.7*10^{15}$	$\sim 7.3*10^{15}$	$\sim 1.8*10^{16}$
		He	$\sim 4.3*10^{14}$	$\sim 1.9*10^{15}$	$\sim 5.1*10^{15}$
9	Lifetime due to the single Coulomb scattering by an angle >0.3 rad.$*\langle n\rangle$	H	$\sim 6.8*10^{13}$	$\sim 2.6*10^{14}$	$\sim 6*10^{14}$
		He	$\sim 1.7*10^{13}$	$\sim 7*10^{13}$	$1.7*10^{14}$
10	Limiting number of particles which is determined by forces of space charge (R_0=100cm, $\lvert\delta\nu\rvert \approx 0.25$, $\nu \approx 5$)		$3.6*10^{11}$	$\sim 7*10^{11}$	$\sim 10^{12}$

The stored beams of nonrelativistic ions of hydrogen isotopes can find quite wide application both for applied purposes and in fundamental investigations.

For instance, by application the deuterium jet target in the tritium ion storage ring one could to generate a rather intensive neutron stream ($\sim 10^{13}$ neutr./s) with lesser, in comparison with other methods, specific expenditure of energy. Using the deuterium ion beam interaction with the deuterium jet target one can investigate rather intensively the D(d,t)T and D(d,n)^{3}He reactions which are promising from the standpoint of controlled thermonuclear synthesis [9]. Moreover, we think that there are many other problems where such installations will find its application.

REFERENCES

1. A.A. Kolomensky. The oscillation decrements in accelerators in presence of arbitrary energy losses // *Atomnaya Energia.* 1965, v. 19, p. 534 (in Russian).
2. B. Rossi. *High-Energy Particles*. M.: GITTL, 1955 (in Russian).
3. Yu.M. Ado, V.I. Balbekov. The possibility of ionization friction using for heavy particles storing // *Atomnaya Energia.* 1971, v.31, No.1, p. 40 (in Russian).
4. J.A. Phillips. The energy loss of low energy protons in some gases // *Phys. Rev.*, 1953, v. 90(4), p. 532.
5. H.L. Reynolds, D.N.F. Dunbar, W.A. Wantzel, W. Whaling. The stopping cross section of gases for protons, 30-600 keV // *Phys. Rev.* 1953, v. 92(3), p. 742.
6. G. Bruk. *Cyclic Charged Particle Accelerator.* M.: "Atomizdat", 1970, 311 p. (in Rusian).
7. J. Jackson. *Classical Electrodynamics.* M.: "Mir", 1965, 701 p. (in Russian).
8. *Tables of physical notation.* Reference book by Ed. I.I. Kikoin. M.: "Atomizdat", 1976, 1005 p. (in Russian).
9. V.I. Khvesyuk, Yu.A. Chirkov. Burning parameters of deuterium-based fuels in tandem mirror reactor // *VANT, Ser.: Thermonuclear Syntheis.*1999, No 2, p. 82-88 (in Russian).