SOURCE OF HIGH ENERGY GAMMA RAYS ON BASIS OF STORAGE RING WITH INTERNAL TARGET AND ELECTRON COOLING

K.V. Gubin, V.A. Mashinin[1], V.V. Parkhomchuk, V.G. Shamovskij, V.A. Vostrikov
Budker Institute of Nuclear Physics, SB RAS
Lavrentiev ave., 11, 630090, Novosibirsk, Russia; E-mail:V.A.Vostrikov@inp.nsk.su

The project of a high-energy monochromatic gamma radiation source is developed. The source is based on the storage ring with an internal thin target. A limiting factor for using of the internal target is the growth of the beam phase space by multiple scattering and energy loss straggling. We consider the possibility of using the electron cooling for dumping of the beam heating by the internal target.

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1. INTRODUCTION

For generation of an intense flux of the monochromatic γ - radiation, the proton capture reactions are used. The traditional technique is an irradiation of the target by proton beam with energy up to few million electron-volts and current up to tens of milliamps.

We consider the reaction $^{13}C(p,\gamma)^{14}N$ of radiation capture of proton with the energy near resonance $E_r = 1.748$ MeV. As a result of reaction the high energy photons ($E_\gamma = 9.17$ MeV) are generated. The cross-section of the reaction is $\sigma_r = 3.5\cdot 10^{-26}$ cm^{-2}, and $\Gamma_p = 0.12$ keV is a width of resonance. The value of photons output for thick target is $Y \approx \frac{N_\gamma}{N_p} \approx 1.05\cdot 10^{-9}$.

In the storage ring with the internal thin target the beam many times pass through the target. A limiting factor for using of the internal target is the growth of the beam phase space by small angle multiple scattering and energy loss straggling. Therefore, the compensation of the energy loss at every turn is required. At papers [1,2] the compensation by using the RF resonator are considered. It allows one to increase significantly the nuclear reaction output and reduce the power consumption. We consider the possibility of using the electron cooling in combination with betatron inductor for dumping of the beam heating by internal target.

2. KEY PHYSICAL PROCESSES

2.1. BEAM HEATING BY INTERNAL TARGET

Moving in the target, the protons ionize the target atoms. This results in the beam transverse emittance degradation by Coulomb scattering on target nucleus and systematic loss of the particle energy as well as in an increase in the beam energy spread [3,4]. For the particle with the energy $E_p = \gamma m_p c^2$, the cross-section of the Coulomb scattering on the nucleus of target is

$$\sigma_s = \frac{4\pi r_p^2 Z_A^2}{\gamma^2\beta^2\theta^2_{max}}, \tag{1}$$

where Z_A is the atomic number of the target material, r_p is a classical proton radius and θ_{max} is defined by an angular aperture limitation.
Then the beam lifetime is

$$\tau_s = \frac{1}{f_0\sigma_s t_A}. \tag{2}$$

The average proton energy loss for one turn is

$$\Delta E = -m_e c^2 \frac{4\pi r_e^2 Z_A t_A}{\beta^2} ln\left(\frac{E_{max}}{I}\right). \tag{3}$$

Here, t_A is the target thickness, r_e is the electron classical radius, $E_{max} \cong 2m\gamma^2 v^2$, I is the mean ionization potential of the target atoms. The dispersion of energy can be estimated as

$$\left\langle \Delta E^2 \right\rangle = m_e c^2 \frac{4\pi r_e^2 Z_A t_A}{\beta^2} E_{max}. \tag{4}$$

2.2. ELECTRON COOLING

For compensation of the energy loss and emittance degradation we consider to use the combination of the electron cooling and induction module. The betatron inductor must compensate the average energy loss during one injection cycle. The electron cooling is needed for dumping of the emittance dilution due to multiple scattering and space charge forces, and for decreasing energy spread.

In this paper, we estimate the electron cooling force using the following phenomenological expression which has been proposed in .[5]

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e V\tau}{m_e\left(\sqrt{V^2+V_{ef}^2}\right)^3}\ln\left(1+\frac{\rho_{\max}}{\rho_L+\rho_{\min}}\right). \tag{5}$$

This simple expression is in a reasonable agreement with available results of the measurements of the cooling force as well as with computer simulations. All parameters in Eq.5 are taken in the beam reference system, n_e is the density of electron beam, V is the proton velocity $V^2 = V_\perp^2 + V_{||}^2$, $\tau = l_c/\gamma\beta c$, l_c is the length of the cooling region, $\rho_L = m_e c v_T/eB$ is the Larmour radius of the electron beam, $m_e v_T^2$ is the transverse temperature of the electron beam, B is the

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magnet field in the cooling section. The value $m_e V_{eff}^2$ is an effective temperature of the electron gas. Generally, we shall write

$$V_{ef}^2 = V_{\Delta\theta}^2 + V_{E\times B}^2 + V_e^2 , \qquad (6)$$

where $V_{\Delta\theta}$ is the effective velocity induced by the curve of the magnetic field lines, $V_{E\times B}$ is the electron drift velocity in the crossed the space charge fields of the beams and the guiding magnetic field of the cooling device, $m_e {V_e}^2$ is the longitudinal temperature of the electron beam $V_e = \sqrt{2e^2 n_e^{1/3}/m_e}$. As the maximum impact parameter ρ_{max} we take the value:

$$\rho_{max} = \frac{V \cdot \tau}{1 + \omega_{pe} \cdot \tau} , \qquad (7)$$

where ω_{pe} is the plasma frequency of the electron. The minimal impact parameter reads are:

$$\rho_{min} = \frac{e^2}{m_e V^2} . \qquad (8)$$

2.3. INDUCTION MODULE

The induction module provides an accelerating voltage for compensating average energy losses during operation cycle $U = -\frac{1}{c} S \frac{\Delta B}{\Delta t} , \Delta t < \tau_s$, where S is a core cross-section area, ΔB is a flux swing [6]. An inductance of the core and a leakage current can be estimated as

$$L = \frac{\mu}{2\pi} l \, ln \left(\frac{R_0}{R_f} \right), I = \frac{S}{L} \Delta B . \qquad (9)$$

2.4. PROTON ENERGY SPREAD

The proton energy spread created by the internal target will not result in the decreasing on the flux of photons if the total power of the cooling force and accelerating voltage exceeds the power of the ionization losses. We take calculations follow paper [7]. If F is the longitudinal component of the cooling force, the equilibrium energy of a particle is defined by the following balance equation

$$v\left[F(\Delta E) + eU \right] = -mc^2 \frac{4\pi t_A {r_e}^2 c^2}{v\Pi} ln \frac{E_{max}}{I} . \qquad (10)$$

Due to decrease in the value of the cooling force with an increase in the value of the energy spread Eq.10 has two roots. The vicinity near the first root at the decreasing slope of the curve $F(\Delta E)$ corresponds to stable solutions. During the cooling the protons will collect near this energy. The second root corresponds to the unstable solution and defines the momentum aperture of the ring. For calculations of the systematic variations of the particle energy due to cooling force the power $F(\Delta E)$ is averaged over the periods of the betatron oscillations. For simplicity we take that the dispersion function in the cooling section is zero and neglecting the variations of the betatron functions of the ring along the cooling section. Inspecting dependencies $Q(\varepsilon, \Delta E) = \frac{vF(\varepsilon, \Delta E)}{(dE/dt)_t - veU}$ we can find out, for a taken electron beam density, the roots of the Eq.10 ($Q(\varepsilon, \Delta E) = 1$) corresponding to the stable fixed point and the momentum aperture θ_a . The lifetime of the beam can be estimated calculating the average frequency of ionization events with the energy loss exceeding $\Delta E_{ap} = \gamma m_p \beta^2 \theta_a$. Then, we write

$$\tau_{ion}^{-1} = 2 \frac{m_e}{m_p} \frac{4\pi Z_A t_A {r_e}^2}{\gamma \beta^3 \theta_a} \frac{c}{\Pi} . \qquad (11)$$

The numerical solutions of the Eq.10 for chosen ring and beam parameters will be done below.

3. STORAGE RING DESIGN

The source based on the storage ring with internal thin target, betatron inductor and electron cooling was designed. In Table 1 the main ring parameters are listed. In Fig.1 the layout of the storage ring are shown.

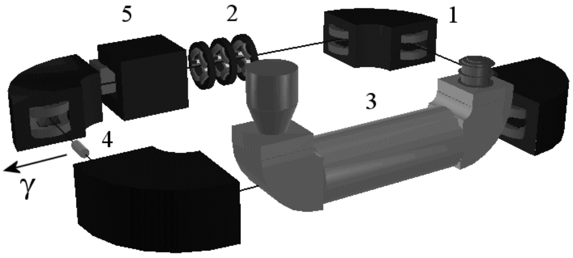

Fig.1. Layout of the storage ring: 1-dipole magnets; 2-quadruple triplet; 3-electron cooler; 4-internal target; 5-induction module

Table 1. Main parameters of storage ring

Energy, MeV	1.748
Circumference, m	9.29
Betatron tunes ν_x/ν_y	1.47/1.68
Transition factor	1.31
Momentum compaction factor	0.584
Revolution frequency, MHz	1.967

The magnet system of storage ring consists of four magnets with edge focusing and quadruple triplet. In drifts the internal target, electron cooler and induction module are located. In Fig.2 the optics functions of the ring are presented, solenoid is switch on [8]. The solenoid of the electron cooler creates a coupling of the transverse betatron oscillations. The length and magnet field of the solenoid are selected so as the rotation angle of the proton equal to 2π. Therefore the transverse coupling beyond the bounds of the solenoid defaults. As the dispersion function in the cooling region is nonzero, the vertical dispersion in the cooling region is appeared. The maximal value of the vertical dispersion is 0.69 m.

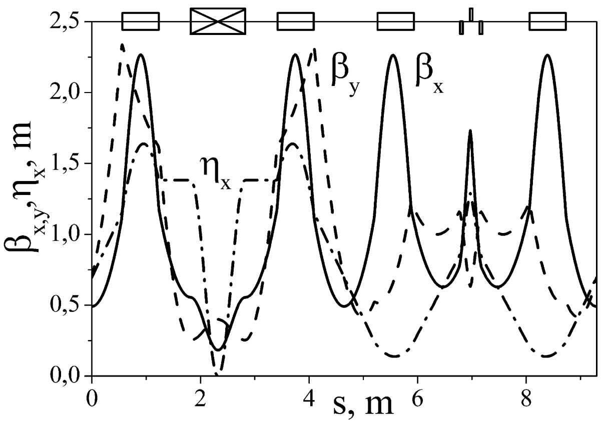

Fig.2. Optic functions of the storage ring

Table 2. Main parameters of subsystems

Electron cooler	
Energy, keV	0.952
Length of the cooling region, m	1
Electron current, A	0.5
Beam radius, cm	0.63
Magnet field in the cooling region, T	1.2
Internal target	
Material	carbon C^{13}
Thickness, cm^{-2}	$3 \cdot 10^{15}$
Average energy loss per turn, eV	9.5
Gain of energy dispersion, eV	97
Single scattering beam life time, ms	37
Induction module	
Voltage, V	9.5
Pulse duration, ms	25
Core cross-section, cm^2	600
Inductance, Hn	10^{-6}
Leakage current, A)	300

The main parameters of the subsystems are listed in Table 2.

The electron cooler consist of superconducting solenoid with accuracy of straightens magnetic field line about 10^{-5}, electron gun immersed in the magnetic field, collector and toroids.

The vapour internal target (carbon C^{13}) is used as a stripper for the H^- charge exchange injection also. At energy 1.75 MeV H^- charge exchange cross-sections are $\sigma_{-10} = 35 \cdot 10^{-17}$ cm^2, $\sigma_{01} = 16 \cdot 10^{-17}$ cm^2, the optimal target thickness is about $\delta \approx 6 \cdot 10^{15}$ cm^{-2} [9]. The injection can be as a single-turn as a multi-turn.

The duration of an operational cycle is 27 ms. H^- ions are injected to reference orbit and stripped on the carbon target. The storage proton beam many times passes through the target and creates the output flux of γ-radiation. The average beam energy losses are compensated by induction module during pulse duration 25 ms. The multiple scattering and space charge emittance dilution, and energy loss fluctuations are dumped by electron cooling device. The next 2 ms reserved for reverse part of the induction module cycle.

The numerical solution of Eq.10, assuming the beam and target parameters described above and inhomogeneous of field derivative about 5% give the next results. As is seen from Fig.3 for the beams with emittances less 1 cm·mrad the cooling using the electron beam with $n_e = 1.4 \cdot 10^9$ cm^{-3} successfully suppresses the ionization energy losses in the target. The roots of the equilibrium equation on the increasing slopes of $Q(-\Delta p)$ occur in the regions which are well below the value of $\Delta p/p = 7 \cdot 10^{-5}$ corresponding to $\Delta E = 120$ eV. The roots of Eq.10 on the decreasing slopes of the curve $Q(-\Delta p)$ give the momentum aperture of the ring in such operation. According to data given in Fig.3, for all three curves these roots occur at approximately $\theta_a = 10^{-2}$, and $\tau_{ion} = 43$ ms. This lifetime does not limits the operation performance.

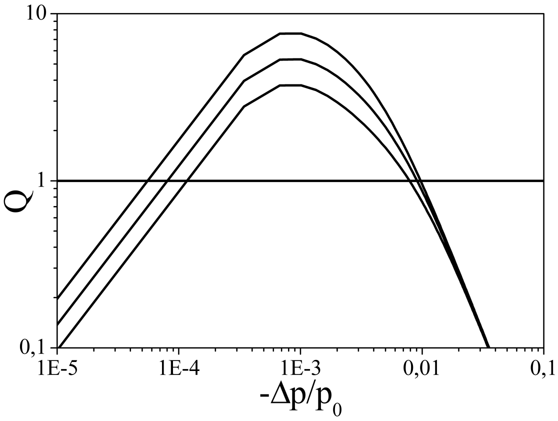

Fig.3. Dependence of the factor Q in Eq.10 on $-\Delta p/p$. From top to bottom $\varepsilon = 0.5,1,2$ cm·mrad

The maximal space charge tune shift $\Delta\nu = 0.1$ allows one to estimate the maximal storage beam intensity $N_p = 5 \cdot 10^{11}$ particles per pulse.

Let's estimate the output flux of γ-radiation for the described above target parameters and beam intensity $N_p = 5 \cdot 10^{11}$ particles. The effective current of the proton beam passing through the target is $I_0 = eN_p f_0 \cong 0.16$ A and the output flux of γ-radiation is $N_\gamma \approx N_p f_o Y = 1.1 \cdot 10^8$ photons per second. In assuming, that the proton beam is completely replaced after $5 \cdot 10^4$ turns in the storage ring ($\tau = 25$ ms), the injection current needed from the ion source is only $I_{inj} = eN_p \tau^{-1} \cong 0.32$ μA.

4. CONCLUSION

The project of high energy gamma radiation source is discussed. The source is based on the storage ring with internal thin target and electron cooling. The design of the storage ring and main parameters of the subsystems are developed.

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ИСТОЧНИК ВЫСОКОЭНЕРГЕТИЧНОГО ГАММА-ИЗЛУЧЕНИЯ НА ОСНОВЕ НАКОПИТЕЛЬНОГО КОЛЬЦА С ВНУТРЕННЕЙ МИШЕНЬЮ И ЭЛЕКТРОННЫМ ОХЛАЖДЕНИЕМ

К.В. Губин, В.А. Машинин, В.В. Пархомчук, В.Г. Шамовский, В.А. Востриков

Разработан проект высокоэнергетичного монохроматического источника гамма-излучения. Источник основан на накопительном кольце с внутренней тонкой мишенью. Лимитирующим фактором для использования внутренней мишени является рост фазового объема пучка из-за многократного рассеяния и разброса энергетических потерь. Рассматривается возможность использования электронного охлаждения для уменьшения нагревания пучка внутренней мишенью.

ДЖЕРЕЛО ВИСОКОЕНЕРГЕТИЧНОГО ГАММА-ВИПРОМІНЮВАННЯ НА ОСНОВІ НАКОПИЧУВАЛЬНОГО КІЛЬЦЯ З ВНУТРІШНЬОЮ МІШЕННЮ Й ЕЛЕКТРОННИМ ОХОЛОДЖЕННЯМ

К.В. Губін, В.А. Машинин, В.В. Пархомчук, В.Г. Шамовський, В.А. Востриков

Розроблено проект високоенергетичного монохроматичного джерела гамма-випромінювання. Джерело засноване на накопичувальному кільці з внутрішньою тонкою мішенню. Фактором, що лімітує використання внутрішньої мішені, є ріст фазового об’єму пучка через багаторазове розсіювання і розкид енергетичних втрат. Розглядається можливість використання електронного охолодження для зменшення нагрівання пучка внутрішньою мішенню.