

A PULSED SOURCE OF NEUTRON FOCUS FOR FUNDAMENTAL AND APPLIED RESEARCH IN HIGH-ENERGY ELECTRON ACCELERATOR CENTRES

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ABSTRACT: Hard magnetic bremsstrahlung radiation of relativistic electrons is suggested to be used according to the idea [1] to generate pulsed neutron fluxes by photonuclear reactions. The spectral and integral characteristics of the corresponding source have been determined by multigroup calculations for several targets as applied to present-day electron accelerators with an energy of more than 7 GeV. It is shown that the beam parameters of the accelerators allows one to generate the pulsed neutron fluxes of unprecedented space, time and spectral densities.

I. INTRODUCTION

Over many years leading research centres have exhibited an unremitting attention to improving the parameters of neutron sources based on charged particle accelerators. This is explained by both some unsettled fundamental problems and demands of applied investigations of practical importance.

The known methods allow the generation of pulsed fluxes of thermal and resonance neutrons which do not exceed $5 \cdot 10^{16}$ n/cm² · s at a pulse duration of much more than 10^{-6} s. To a great extent, these limits are dictated by a considerable exothermicity of the processes used and a high average energy of the spectrum of neutrons produced. The stage of slowing down features a significant neutron leakage and a strong dispersion of the originally short neutron pulse. For these reasons the source quality parameter defined as a ratio of the average the intensity $\langle N_n \rangle$ to the square of the pulse duration falls by 3 to 6 orders of magnitude during slowing down. For the methods using acceleration of charged particles restrictions on the current and the energy release in a target are also of basic importance.

The approach proposed in this paper is free from the above short-comings to a considerable degree. It was described for the first time in [1].

II. THE METHOD OF NEUTRON FOCUS

The method is based on the (γ, n) reaction producing neutrons from the nuclei of a target placed in a beam of directed hard magnetic bremsstrahlung ("synchrotron") gamma radiation formed by a current of ultrarelativistic electrons in a spatially periodic magnetic field. The fundamental features and advantages of the method are due to a set of the following properties of magnetic bremsstrahlung (MB) radiation:

(a) a high spectral and spatial density of MB resulting from a high energy, a great averaged current and a very small electron beam cross-section in up-to-date accelerators;

(b) the pulsed nature of MB allowing the ultrashort neutron pulses with a typical duration of 10^{-9} s to be produced;

(c) a specific shape of the MB spectrum falling exponentially in the high-energy range and a relatively low energy of γ -quanta in the basic part of the spectrum.

Properties (a) and (b) provide a high space-time and spectral density of neutron generation and flux. Property (c) allows the optimization of the process with respect to radiation losses in the target.

A radically new property consists in a possibility to produce low-energy neutrons *without slowing down*. For this purpose light nuclei *with an anomalously low neutron binding energy*, such as Be and D, should be used as a target. These nuclei are characterized by not only the minimum value of the (γ, n) reaction threshold equal to 1.665 and 2.225 MeV, respectively, but also an abrupt growth of the reaction cross-section near the threshold. The latter dictates the specific shape of the photoneutron spectrum with a great density in the low-energy range. When the moderating stage is absent, there are no reasons for the loss of intensity and the pulse broadening mentioned above. This increases drastically the quality of the source of slow and resonance neutrons.

In the case of a space-periodic magnetic field H_w , when the values of the horizontal and vertical divergences of MB differed insignificantly, the geometry of the neutron production region would be considered approximately as axially symmetrical. Because the MB divergence and the area of the MB source are small, the radial dimension of the region should be much less than the longitudinal one determined by the path length of γ -quanta in the target. Such an axially symmetrical source with a high generation density was proposed in [1] to be named the "neutron focus" (NF).

The spectral density of photoneutrons producing in the NF is determined by the expressions:

$$N_n(E_n) = N_\gamma \frac{A}{A-1} \cdot \Theta_{\gamma, xn}(E_\gamma) \Phi_\gamma(E_\gamma), \quad (1)$$

$$\Phi_\gamma(E_\gamma) = k \cdot \eta(E_\gamma/E_c) \frac{1}{E_\gamma}, \quad (2)$$

$$\Theta_{\gamma, xn}(E_\gamma) = \frac{\sum \nu_x \sigma_{\gamma, xn}(E_\gamma)}{\sigma_\gamma(E_\gamma)} (1 - e^{-\Sigma_\gamma l}), \quad (3)$$

$$E_n = \frac{A-1}{A} (E_\gamma - E_{\gamma n}), \quad (4)$$

where N_γ is the integral intensity of the MB radiation; A is the mass of the target nucleus; E_γ , E_n and $E_{\gamma n}$ are the energies of γ -quantum, photoneutron and the (γ, n) reaction threshold, respectively; $\Theta_{\gamma, xn}(E_\gamma)$ is the spectral neutron-yield function; $\sigma_\gamma(E_\gamma)$ and $\sigma_{\gamma, xn}(E_\gamma)$ are the total cross-section and the cross-section of the (γ, xn) reactions for γ -quanta of energy E_γ , respectively; Σ_γ is the macroscopic cross-section of attenuation for γ -quanta in a target of length $l \simeq 3/\Sigma_\gamma(E_{\gamma n})$ along the MB beam; ν_x is the yield of neutrons in the γ, xn processes

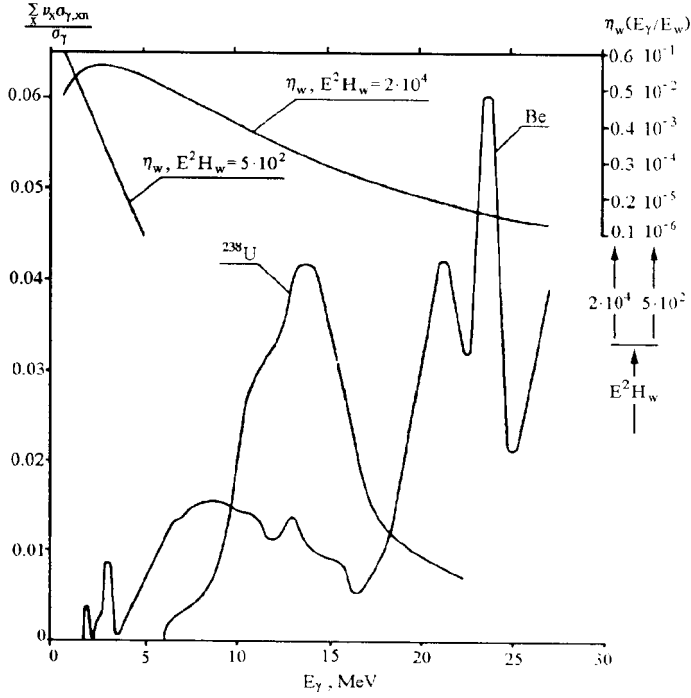


Figure. 1. The dependences of the ratio $\sum_x \nu_x \sigma_{\gamma, xn} / \sigma_\gamma$ on an energy of γ -quanta for Be, U-238 and the MB spectral function for $E^2 H_w = 5 \cdot 10^2$ ($E_c = 340$ keV) and $2 \cdot 10^4$ ($E_c = 13.3$ MeV).

($\nu_x = 1, 2$) and photofission ($\nu_f = 3$); $\eta(E_\gamma/E_c)$ and E_c are the MB spectral function and the parameter determining the position of its maximum; k is the factor normalizing the MB spectrum to unity.

The spectral and integral intensities of photoneutrons produced are determined by the yield function $\Theta_{\gamma, xn}(E_\gamma)$ and the values of the parameters E_c and $E_{\gamma n}$. The energy dependence of the ratio $\sum_x \nu_x \sigma_{\gamma, xn} / \sigma_\gamma$ are shown in Fig.1 for Be and U-238.

The MB spectral functions $\eta(E_\gamma/E_c)$ are given in the same figure for $E_c = 340$ keV and 13.3 MeV, corresponding to $H_w = 8$ T and the electron energy $E = 8$ GeV and 50 GeV, respectively. It is seen that for $E = 8$ GeV the value of η near $E_{\gamma n}$ for Be is as small as $10^{-2} - 10^{-3}$. It grows exponentially as the parameter $E^2 H_w$ increases to approach at $E = 50$ GeV the maximum values in the wide range of the γ, n resonances.

The photoneutron spectrum for the Be target calculated for $E = 8$ GeV and normalized to one γ -quantum is shown in Fig.2. The data of the precision measurements of the cross-sections for Be from [2] were used for the calculation. The spectrum exhibits a high density of neutrons in the resonance range and low values of the mean and boundary energies.. The extrapolation of the results of [2] to zero shows that a considerable density of neutrons should persist in the region below $E_\gamma - E_{\gamma n} = 0.5$ keV by virtue of the recoil of nuclei emitting photoneutrons. The kinematic corrections to the neutron energy E_n at angles of more than 90° for Be amount to 200 – 400 eV to be sufficient to shift the zero of the E_n scale to the region of the noticeable values of $\sigma_{\gamma, n}$ in the $E_\gamma - E_{\gamma n}$ scale. It should be noted that for D this effect must

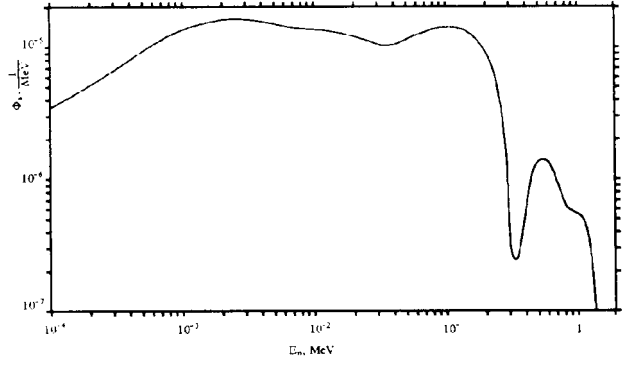


Figure. 2. The spectrum of photoneutrons emitted from the Be target at $E_c = 340$ keV.

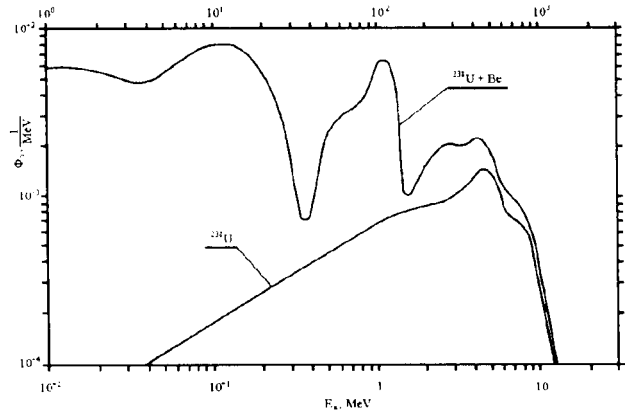


Figure. 3. The photoneutron spectra for the U-238 target and for the combined target of U-238 and Be enveloping it.

be considerably stronger.

The photoneutron spectrum for the Be target have been calculated too for $E = 50$ GeV.

The above results have been obtained under condition that the cross-sectional dimensions of a target are much smaller than the path length for γ -quanta scattered from the incident MB beam. Results for the opposite case are shown in Fig.3. The calculations were fulfilled for the U-238 target and for the same target enveloped by Be. The partial (γ, xn) cross-sections of U-238 were taken from [3], [4]. The allowance for the contribution of photoneutrons produced in the scattered gamma field have been made in the manner similar to [5]. Account was taken of the Compton scattering of γ -quanta and the bremsstrahlung of Compton electrons and electron-positron pairs. It is seen that the spectral density of resonance neutrons in the spectrum increases in the U-Be target almost by an order as compared to the "thin" Be target. In the case one should expect no broadening of a neutron pulse because the time of the scattering act do not exceed the MB pulse duration.

The integrated characteristics of the NF have been determined for the above cases and for a MB formed in a wiggler of a length $L_w = 7.5$ m and a field period $2d_w = 15$ cm by an electron beam with the average current $\langle I \rangle = 0.01$ A at a pulse duration $\tau = 10^{-9}$ s and a circulation frequency 10^5 1/s. These parameters

are typical for modern storage rings such as APS, ESRF, Spring and TRISTAN in a single bunch regime. The results obtained are listed in Table. The table symbols are as follows: q_n^γ is the yield of photoneutrons per γ -quantum; q_n^e is the same per single electron passage through the wiggler; P_γ^w and $P_{\gamma n}^w$ are the integral flux of γ -quanta incident on a target for the exit channels length of 10 m and 20 m for $E = 8$ GeV and 50 GeV, respectively, and the same in the energy range $E_\gamma > E_{\gamma n}$ of Be; N_n and P_n are the integral intensity and the flux of photoneutrons, respectively; $\langle \dots \rangle$ are the same averaging over time; $\langle N_n \rangle / \tau^2$ is the source quality parameter; Q_γ is the specific MB power released in the target and estimated approximately.

It is necessary to note that for the U – Be target allowance was made approximately for neutrons produced in the $(n, 2n)$ processes in Be and U. Therefore, the pulse duration is assumed to be equal to $\sqrt{\tau^2 + t_m}$, where t_m is the moderation time of neutrons with an average energy of the spectrum slowing down to the $(n, 2n)$ reaction threshold.

Parameter	$E_c=340$ keV	$E_c = 13.3$ MeV	
	Be	Be	U + Be
τ, s	10^{-9}	10^{-9}	$2.0 \cdot 10^{-9}$
$q_n^\gamma, n/q$	$1.4 \cdot 10^{-6}$	$4.7 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$
$q_n^e, n/e$	$1.0 \cdot 10^{-4}$	0.49	0.81
$\langle P_\gamma^w \rangle, \frac{q}{cm^2 \cdot s}$	$1.4 \cdot 10^{18}$	$5.0 \cdot 10^{18}$	$5.0 \cdot 10^{18}$
$\langle P_{\gamma n}^w \rangle, \frac{q}{cm^2 \cdot s}$	$7.3 \cdot 10^{14}$	$2.2 \cdot 10^{18}$	$2.2 \cdot 10^{18}$
$N_n, n/s$	$1.4 \cdot 10^{17}$	$4.7 \cdot 10^{20}$	$1.3 \cdot 10^{21}$
$P_n^*), \frac{n}{cm^2 \cdot s}$	$8.2 \cdot 10^{13}$	$1.6 \cdot 10^{18}$	$5.0 \cdot 10^{17}$
$\langle N_n \rangle, n/s$	$1.4 \cdot 10^{13}$	$4.7 \cdot 10^{16}$	$2.5 \cdot 10^{17}$
$\langle P_n^* \rangle, \frac{n}{cm^2 \cdot s}$	$8.2 \cdot 10^9$	$1.6 \cdot 10^{14}$	$1.0 \cdot 10^{14}$
$\langle N_n \rangle / \tau^2, \frac{n}{s^2}$	$1.4 \cdot 10^{31}$	$4.7 \cdot 10^{34}$	$6.2 \cdot 10^{34}$
$Q_\gamma, n/MeV$	$1.2 \cdot 10^4$	480	180

*) P_n is the neutron flux on the target surface.

III. CONCLUSION

It is evident from the data presented that the neutron source proposed has considerable promise for the use in fundamental and applied investigations. This results from the NF properties such as a great pulsed flux in combination with an ultrashort duration, a specific shape of the spectrum with a maximum in the resonance neutron energy range, a possibility to change simply the spectral end point in the wide energy region by varying the electron energy and a minimum radiation loading the target as compared with the known methods.

The method can be best realized on SLAC and present-day storage rings with electron energies of at least 7 – 8 GeV, such as APS, PEP, PETRA, Spring and TRISTAN, using superconducting wigglers with a field amplitude of at least 5 T.

The variant with an uniform magnetic field, ranking below the NF in the flux and the space density, is superior to it in higher intensity which is achieved at the expense of the increased horizontal angle of MB ejection and in essentially less energy loading on the target. One can expect that this variant will turn out to be more promising for technological applications (see, for example, [5]).

References

[1] I.P. Ereemeev. JETP Lett., Vol. 27, No 1, p. 10, 1978.

[2] B.L. Berman, R.L. van Hemert, C.D. Bowman. Phys. Rev., Vol.163, p.958, 1967.

[3] J.T. Caldwell, E.J. Dowdy, B.L. Berman et al. Phys. Rev., Vol. C 21, p. 1215, 1980.

[4] A. Veysiere, H. Beil, R. Bergere et al. Nucl. Phys., Vol. A 199, p. 45, 1973.

[5] I.P. Ereemeev. Paper to be presented to this Conference.