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Control of nanosecond proton bunches in a magnetically insulated ion diode by resonant nuclear reactions of radiative proton capture

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To calibrate the detection efficiency of a plastic scintillator that detects prompt gamma quanta from the $^{19}F(p, \alpha\gamma)^{16}O$ resonant reaction of radiative proton capture and is used to control the dynamics of the arrival of protons with an energy of about 340 keV accelerated by a magnetically isolated pulsed ion diode, a change the polarity of the diode electrodes to the reverse was used, at which electron bunches were accelerated in the geometry of the Luce diode, forming virtual cathodes. The virtual cathodes in the Luce diode collectively accelerated protons to an energy of about 500 keV, the value of which was determined from the drift velocity of these virtual cathodes, while the number of such protons was determined from the activity of the ^{13}N radionuclide induced by the 457 keV resonance of the $^{12}C(p, \gamma)^{13}N$ reaction.

Keywords: intense pulsed ion beam, organic scintillator, prompt gamma spectrometry.

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Magnetically insulated ion diodes (MIIDs) with geometric ion-beam focusing [1] are used to produce high-power ion beams (HPIBs) with currents up to several hundred kiloamperes for modification of metallic [2] and ceramic [3] coatings and surfaces of metallic alloys [4–6], deposition of coatings from ablation plasma produced by an HPIB [7], nanostructure formation [8], etc. The dynamics of incidence of the primary ion component of HPIBs (protons) onto a target needs to be monitored reliably in these applications. Time-of-flight spectrometry of ion HPIB components with measurement of the ion-beam current density in the focal plane of a diode by a biased ion collector of a collimated Faraday cup (CFC) with magnetic electron cut-off [9,10] is used for the purpose. The inevitable acceleration of multicharged ions $^{12}C^{n+}$, which constitute 20−30% of HPIB ions in total, makes it significantly harder to interpret time-of-flight spectra.

It was demonstrated in [11] that the spectrometry of prompt gamma quanta emitted in resonant reactions of radiative proton capture $^{10}B(p, \alpha\gamma)^{7}Be$ and $^{11}B(p, \gamma)^{12}C$ provides an opportunity for selective proton diagnostics at proton energies starting from 200 keV in the case of summing of γ-signals in series of 25 shots of a TEMP-4M magnetically insulated diode. Gamma-quanta yield Y is proportional to the maximum of the reaction cross section at resonance σ_R and its width Γ and is determined using the following analytical expression:

$$Y = \frac{cN_0}{2A}\frac{\sigma_R\Gamma}{dE/dx}\left(\frac{\pi}{2} + \tan^{-1}\frac{E - E_R}{\Gamma/2}\right), \qquad (1)$$

where N_0 is the Avogadro number, A is the molecular mass, c is the concentration of an element in the target, and dE/dx are the energy losses of protons in the target at a near-resonance energy ($\sim E_R$), which are taken from [12].

The result of calculations show that the resonance of nuclear reaction $^{19}F(p, \alpha\gamma)^{16}O$ at a proton energy of 340.5 keV is characterized by a large cross section ($\sigma_R = 102$ mb) and a narrow width ($\Gamma = 2.4$ keV), which provide a high-energy (6.13, 6.92, and 7.12 MeV) gamma-radiation yield sufficient for the detection of 10^{13} protons with an energy no lower than 340.5 keV. Such parameters are promising for the determination of the number of protons in bunches and their energy spread and for the calibration of voltage dividers for measurements of a diode voltage no lower than 345 kV. The aim of the present study is to calibrate the γ-signal of a plastic detector in number of protons with this energy by changing the polarity and the geometry of electrodes of an ion diode to the geometry of Luce diode electrodes that provide an opportunity to accelerate electron bunches, which form virtual cathodes, thus accelerating collectively $10^{13}-10^{14}$ protons per shot to an energy of 450−700 keV, and allow one to determine this energy accurately in each shot based on the drift velocity of a virtual cathode [13].

Experimental procedures for prompt diagnostics of proton bunches of the TEMP-4M accelerator in both modes (MIID and Luce diode) were discussed in detail in [11] and [13], respectively. The accelerating MIID voltage for direct ion acceleration was set to 345 kV. This is the limit value for TEMP-4M and appeared to be sufficient to reach the maximum yield of gamma quanta in thick fluoropolymer $(C_2F_4)_n$ targets in the 340.5 keV resonance. A diode voltage of approximately 240 kV was set for collective proton acceleration in the Luce diode mode. One plastic scintillation detector type SP101 (Hangzhou Shalom Electro-Optics Technology Co., Ltd, China) Ø30 × 60 mm in size monitored a fluoropolymer target from a distance of 35 cm with solid angle $\Omega_1 = 0.0058$ (the solid angle is a dimensionless quantity here) through a 3-cm-thick lead layer, and another

similar detector monitored bremsstrahlung radiation from the cathode with the maximum energy of 380 keV through a 1-cm-thick lead layer. The FWHM time resolution of detectors in combination of PEU87 photomultipliers was 2.5 ns for individual gamma quanta. An ion beam was absorbed primarily by a fluoropolymer plate $4 \times 8 \times 0.4$ cm in size that covered the face side of a CFC and was located at a distance of 19, 26, and 33 cm from the cathode in three series of experiments. A through hole 0.5 cm in diameter was drilled at the center of the fluoropolymer plate in alignment with the CFC inlet 0.18 cm in diameter to admit a part of the proton beam into the CFC. Compared to the moment of excitation of nuclear reactions in the target located at the front CFC surface, ions drift over an additional distance of 2.5 cm to the collector.

Figure 1 presents time-resolved signals of diode voltage ($U19$, $U33$), current density ($j19$, $j33$) at the CFC collector, bremsstrahlung radiation ($B33$) from the cathode, and gamma quanta ($G19$, $G33$) at the targets averaged over two series with 20 shots in each one. Since the peak of the bremsstrahlung radiation signal of the MIID cathode marks the onset of ion acceleration (and coincides with the first diode voltage peak), time shifts (24, 31, and 39.7 ns) between the bremsstrahlung radiation peak and the peaks of γ-signals were used to estimate the energies of the fastest protons reaching the fluoropolymer target at 329, 369, and 363 keV (354 ± 22 keV on the average) for $Z = 19$, 26, and 33 cm, respectively.

No appreciable bunching of protons at targets was detected. Just as in [11], the average proton charge at the CFC collector constituted 75% of the overall ion charge, and three proton and three carbon ion components were identified in current density signals. The first proton component produced $15 \pm 7\%$ (averaged over all three series), the second one corresponded to $79 \pm 9\%$, and the contribution of the third component was $6 \pm 5\%$. The signal of high-energy gamma quanta demonstrates that protons with energies no lower than 340.5 keV are present only in the first component and are lacking in the second and the third components. The time shift between maxima of γ-peaks for series measured at distances of 19 and 26 cm, 26 and 33 cm was approximately 8.7 ± 0.2 ns. With a 7 cm shift of the fluoropolymer target, this yields an average proton velocity of 0.805 cm/ns in both cases, which is equivalent to a proton energy of 340 ± 25 keV (5 keV lower than the one predicted based on the voltage divider signal $U = 345$ kV).

Although the voltage in all shots of all three series was set to the same level of 345 kV, the accelerating MIID voltage was distributed normally within the interval from 318 to 377 kV with a mean value of 345 ± 10 kV and a FWHM of ~ 8.2 keV. Figure 2 presents the dependences of the γ-quanta yield on diode voltage for all 60 shots of the three series.

The γ-quanta yield corresponds to expression (1). Its approximation at a voltage spread equivalent to $\Gamma = 2.4$ keV (solid curve) is indicative of resonance under voltage

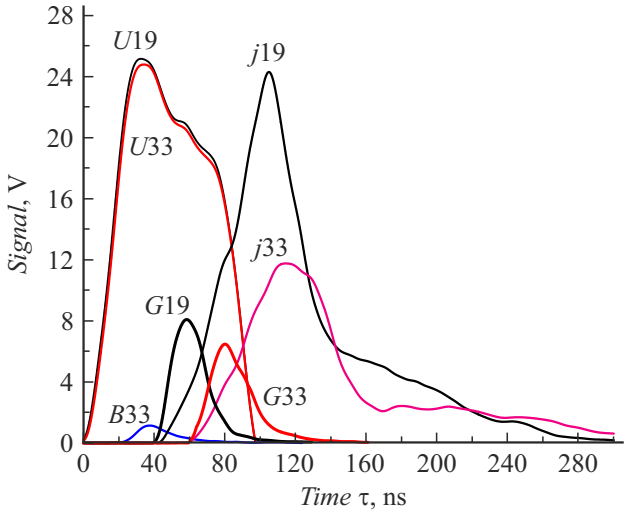

Figure 1. Time signals for the series obtained at $Z = 19$ and 33 cm.

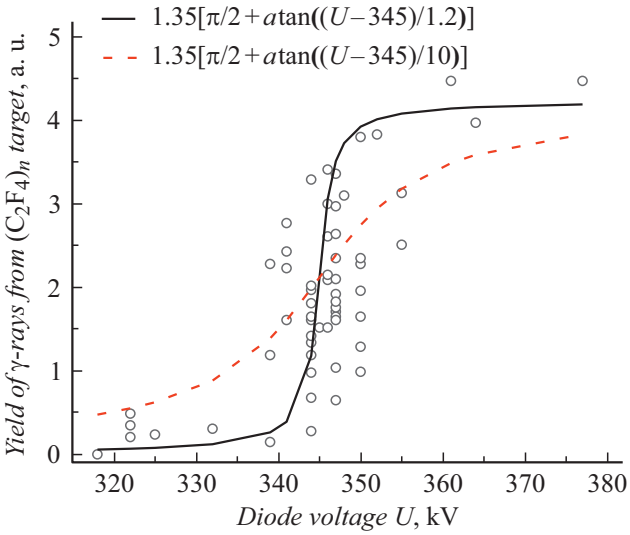

Figure 2. Dependences of the γ-quanta yield on the diode voltage.

$U_R = 345$ kV, while the least-squares method suggests that the error of approximation of curve type (1) is minimized at a voltage spread of 20 kV (dashed curve), which is an order of magnitude higher than the actual resonance width ($\Gamma = 2.4$ keV) of reaction $^{19}\mathrm{F}(p, \alpha\gamma)^{16}\mathrm{O}$ at $E_R = 340.5$ keV. Thus, the energy spread in this first and fastest proton bunch is estimated at ± 20 keV. A voltage shift of $+4.5$ kV relative to the expected resonance value of 340.5 kV implies that the diode voltage is overstated systematically by $+4.5$ kV when its magnitude is determined using the voltage divider signal. The discovered need to correct this coefficient provides support for application of the proposed method for diode voltage measurements with a higher accuracy.

Diode voltages U_i, γ-yields $Y_{\gamma i}$, and proton fluences φ_i at the CFC collector for each shot of the three series are listed

Key shot parameters

Shot/series number	U_i, kV			$Y_{\gamma i}$, a. u.			φ_i, 10^{11} protons/cm^2		
	19 cm	26 cm	33 cm	19 cm	26 cm	33 cm	19 cm	26 cm	33 cm
1	344	318	347	1.61	0.003	0.65	5.75	8.75	5.13
2	344	345	325	1.65	1.52	0.24	6.25	9.5	5.38
3	347	332	350	1.65	0.31	1.65	5	9.38	5
4	347	344	344	3.36	0.28	1.97	6.38	6.63	5.25
5	347	344	344	2.1	0.68	1.34	6.38	8	4.75
6	347	339	344	1.83	0.15	2.02	5.75	8.88	4.88
7	346	344	346	3.41	1.19	1.52	5.38	7.25	5
8	346	339	346	2.61	1.19	2.15	5.5	7.88	4.63
9	347	350	346	1.92	0.99	2.09	6	8.5	5.13
10	347	347	347	2.64	1.76	1.71	5.63	7.5	5.25
11	377	347	350	4.47	1.71	1.96	5.75	7.25	5.13
12	341	361	350	2.77	4.47	2.28	6	7.5	4.5
13	347	344	347	2.35	0.98	1.04	5.13	8.13	5.25
14	355	341	322	3.13	2.43	0.35	5.38	7.25	5.25
15	364	339	350	3.97	2.28	1.29	5.38	7.13	5
16	322	344	322	0.49	3.29	0.21	4.38	7.13	5
17	341	355	344	2.23	2.51	1.81	5.13	6.75	5
18	350	347	347	3.8	2.97	1.61	5	7.88	5
19	352	346	341	3.83	3	1.61	5.13	7	5.5
20	350	348	344	2.35	3.1	1.42	4.88	6.88	4.5
Average	348	343.7	342.8	2.61	1.74	1.45	5.51	7.76	5.03
±S.D.	10.2	8.6	8.9	0.99	1.23	0.64	0.53	0.86	0.27

in the table. Yield $Y_{\gamma i}$ of gamma quanta is expressed in arbitrary units that are equivalent to 10^{13} protons per shot. Proton fluences φ_i were determined based on the areas of proton components in the signal of the ion current density at the CFC collector. The series of shots from distance $Z = 26$ cm was performed first; it was followed by the series with $Z = 33$ cm, and the series with $Z = 19$ cm was the last one.

The gamma signal of the fastest protons, which corresponded strictly to a mean proton energy within the 318−377 keV interval and an energy spread of ±20 keV in a bunch, was detected reliably in each of the 60 shots of all three series. We managed to determine reliably the number of protons in the first (and fastest) bunch in three shots that produced the highest and approximately equal yields of gamma quanta and had the fastest protons reaching energies well above 360 keV. This was done using the results of activation calibration of the gamma spectrometer in the Luce diode geometry, wherein the proton energy in a series of ten shots was 459 ± 54 keV, and the mean number of protons per shot was $2.1 \cdot 10^{13}$ (see Table 2 in [13]). The ratio of this mean number of collectively accelerated protons to mean prompt γ-signals, which had a signal area of $129\,\mathrm{V} \cdot \mathrm{ns}$, for these ten shots (with a correction for the probable 11% contribution of the 483.6 keV resonance of reaction $^{19}\mathrm{F}(p, \alpha\gamma)^{16}\mathrm{O}$) provided a calibration coefficient of $1.63 \cdot 10^{11}$ protons/(V · ns). Gamma signals discovered in the three examined series were multiplied by the calibration coefficient to find the number of protons with energies in excess of 345 keV. The lowest measured value of Y_γ in shot No. 16 of the series with $Z = 33$ cm was equivalent to $2.1 \cdot 10^{12}$ protons with energies $\geqslant 345$ keV. This yields a detection limit for the number of protons with energies $\geqslant 345$ keV in a bunch of an individual shot.

Since the fastest proton component constituted an average of $15 \pm 7\%$ of all protons, the overall number of protons produced in a shot was estimated (based on the measured number of the fastest protons in a shot, $4.5 \cdot 10^{13}$) at $3 \cdot 10^{14}$. This value is an order of magnitude higher than the estimate based on the proton current density at the CFC: $2.7 \cdot 10^{13}$ $(\sim 9 \cdot 10^{11}\,\mathrm{protons/cm^2}) \cdot 30\,\mathrm{cm^2})$. Thus, the CFC understates the number of protons (due to strong beam density gradients over the target cross section, including the CFC collimator) and is suitable only for qualitative analysis of the dynamics of incidence of ion components on the collector and estimation of the proportions of individual ion components, while prompt γ-spectrometry of the $^{19}\mathrm{F}(p, \alpha\gamma)^{16}\mathrm{O}$ reaction provides an opportunity to characterize the fastest proton component quantitatively and estimate more accurately the overall number of protons incident on the target (based on the contribution of this component).

It was demonstrated that the proton component with an energy no lower than 340.5 keV is identified reliably and directly in individual shots via the spectrometry of prompt gamma quanta emitted by a fluoropolymer target in nuclear reaction $^{19}\mathrm{F}(p, \alpha\gamma)^{16}\mathrm{O}$, while the efficiency of the γ-spectrometer is calibrated using the same ion accelerator

operating as a Luce diode, which generates electron bunches that produce virtual cathodes and accelerate protons collectively to an energy of 400−500 keV.

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Conflict of interest

The authors declare that they have no conflict of interest.

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