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Experimental evidence of energetic neutrals production in an ion diode

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ABSTRACT

The paper presents several experimental proofs of the formation of energetic charge-exchange neutrals in a self-magnetically insulated ion diode with a graphite cathode. The energetic neutrals are thought to be produced as a result of charge exchange process between accelerated ions and stationary neutral molecules. The experiments have been carried out using both a diode with externally applied magnetic insulation (single-pulse mode: 100 ns, 250–300 kV) and a diode with self-magnetic insulation (double-pulse mode: 300–500 ns, 100–150 kV (negative pulse); 120 ns, 250–300 kV (positive pulse)). The motivation for looking at the neutral component of the ion beam came when we compared two independent methods to measure the energy density of the beam. A quantitative comparison of infrared measurements with signals from Faraday cups and diode voltage was made to assess the presence of neutral atoms in the ion beam. As another proof of charge-exchange effects in ion diode we present the results of statistical analysis of diode performance. It was found that the shot-to shot variation of the energy density in a set of 50–100 shots does not exceed 11%, whilst the same variation for ion current density was 20–30%; suggesting the presence of neutrals in the beam. Moreover, the pressure in the zone of ion beam energy dissipation exceeds the results stated in cited references. The difference between our experimental data and results stated by other authors we attribute to the presence of a low-energy charge-exchange neutral component in the ion beam.

1. Introduction

Some previous studies [1] were looking into the formation of a large flux of energetic neutrals in the ion beam produced by magnetically insulated diodes with flashover anodes. The neutrals are produced though the effect of charge exchange between the ions and background neutrals in a thin gas layer onto the anode surface. The density and thickness of the neutrals layer formed above the anode are not well known. The formation time of one monolayer of molecules on the surface is ~1 ms at a pressure of 0.65–6.5 mPa [2]. Based upon evidence that several monolayers of neutrals are initially present on the anode surface (adsorbed layer), the areal density is thought to be approximately 10^{16}–10^{17} cm^{-2}. The anode plasma expansion velocity is typically a few cm/μs so in a 400–500 ns pulse, the thickness increases to a few millimeters at most. This implies a neutrals density of ~10^{16} cm^{-3} or even higher [1]. Energetic neutrals are produced as a result of charge exchange process between accelerated ions that have energy of 10–50 keV and stationary neutral molecules. Therefore, the charge exchange neutrals have kinetic energy of much higher than thermal velocity of molecules of residual gas in vacuum chamber. When the ion current density is 40–80 A/cm^2 and an accelerating voltage is 250 kV, the ions density is equal to (2–3)·10^{13} cm^{-3}. This value is significantly lower than the density of neutral particles in the anode–cathode (A–C) gap. Therefore, the acceleration of the ions is accompanied by intensive interaction with the neutral gas and charge exchange. Since each ion can create many fast neutrals, the neutrals flux can be much larger than the ion flux.

Prono et al. [3] proposed charge-exchange effect to explain anomalously early impedance collapse in an ion diode experiment. This idea has also been proposed as a possible explanation for the observation of unusually rapid expansion of the anode plasma across the magnetic field in a magnetically insulated ion diode [4]. Additional confirmation that charge exchange neutrals are present in the beam is the spot formed by undeflected charge exchange neutrals in the center of Thomson spectrogram registered by the Thomson parabola spectrometer [5–7].

However, there is no experimental data on the generation of neutral beams in diodes with explosive emission cathode operating in double pulse mode. The presence of a time interval between a moment of desorption of molecules from the anode surface and a moment of ions generation increases the thickness of a layer of desorbed molecules. This leads to an increase in the number of

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charge-exchange acts for an ion. The purpose of the work is to study production of charge-exchange neutrals in an ion diode with self-magnetic insulation operating in double-pulse mode.

2. Experimental set-up and diagnostics

The experiments were carried out using the TEMP-4M ion accelerator [8]. Powerful ion beam (PIB) was generated by a self-magnetically insulated diode with a graphite potential electrode. Diode connection, diagnostic equipment arrangement and the calibration of the TEMP-4M accelerator are considered in our papers [9,10]. The waveforms of accelerating voltage, total diode current and ion current density are shown in Fig. 1.

The generator was operated in double-pulse mode: the first pulse is of negative polarity (300–500 ns, 100–150 kV), and this is followed by a second pulse of positive polarity (120 ns, 250–300 kV). The first pulse is used for formation of the explosive-emission plasma on the surface of the potential electrode (cathode). The second pulse is used for the extraction of ions from the plasma and acceleration. The ion beam was composed of carbon ions (80–85%) and protons, the ion current density was 50–70 A/cm^2, and the pulse repetition rate was 5–10 pulses per minute. To analyze the composition of the ion beam formed by our diode, a time-of-flight diagnostic, based on a magnetically insulated Faraday cup was

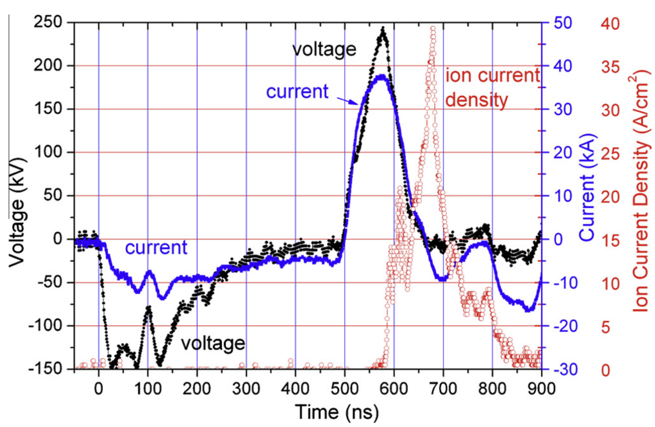

Fig. 1. Waveforms of the accelerating voltage, total diode current, and ion current density measured by a magnetically insulated Faraday cup at 10 cm downstream from the diode.

used [11]. The shot-to shot repeatability of acceleration voltage for a set of 100–200 pulses was good with the standard deviation not exceeding 6–7% [12].

The diode current and voltage were measured by a Rogowski coil and a high-frequency voltage divider respectively. The ion current density was measured using a magnetically insulated Faraday cup (B = 0.4 T). For measuring the cross-sectional energy distribution of the beam we used an infrared imaging technique of targets intercepting the beam [13]. Fig. 2 shows a photograph of the strip focusing diode and the beam energy density distribution in the focus.

To increase focusing efficiency and prevent the loss neutralizing electrons from the beam during transport to the target, we used a metal shield installed on a grounded electrode of the diode [14].

3. Measurement of the ion beam energy density

The motivation for looking at the neutral component of the ion beam formed by the diode came when we compared two independent methods to measure the energy density of the beam: (1) by multiplying the measured current density with the voltage at the diode, and integrating the product over time; (2) using the infrared imaging of the target. First, we compared the results of two methods (current density + voltage, and using the infrared imaging) for the beam formed by an applied B_r magnetically insulated ion diode [15]. The experiments were carried out using the TEMP-4M accelerator configured in single pulse mode suitable for this diode. The results of the measurements are shown in Fig. 3.

The ion current density and the accelerating voltage allow one to evaluate the energy density of the ion beam by multiplying the measured current density from Faraday cup with the voltage at the diode, and integrating the product over time. During beam transport from the diode to Faraday cup the shape of ion current density waveform can change as the pulse duration of ion current density changes. The latter is determined by the velocity of ions and depends on beam composition, energy spectrum and the distance from the diode to Faraday cup. To restore the initial shape of ion current density pulse we used the following procedure. For each data point of the accelerating voltage (sample interval of 0.4 ns), we calculated the delay of arrival of ions to the Faraday cup and the plotted the original curve of ion current density. The ion beam energy density calculated for the applied B_r diode was

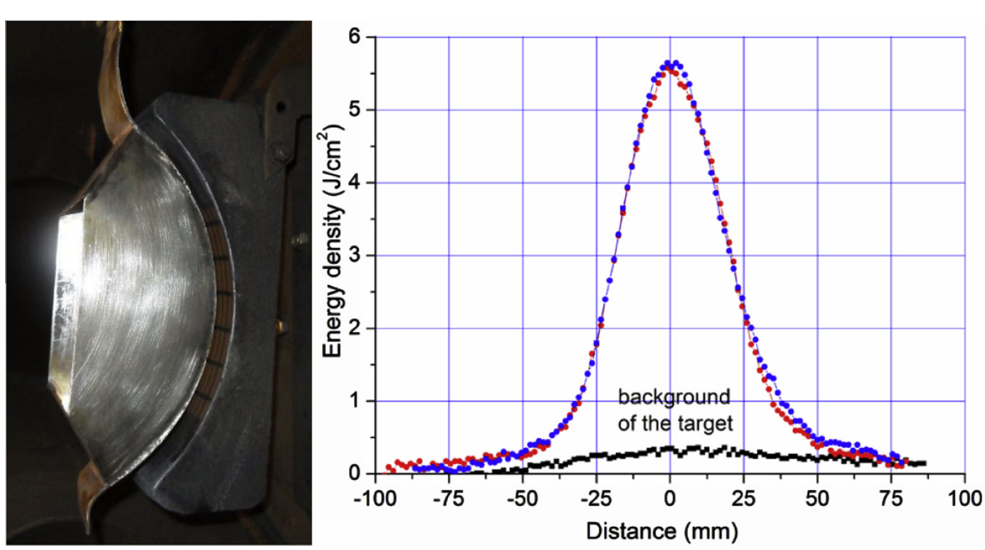

Fig. 2. Photo of the focusing diode and ion beam energy density distribution over the cross section.

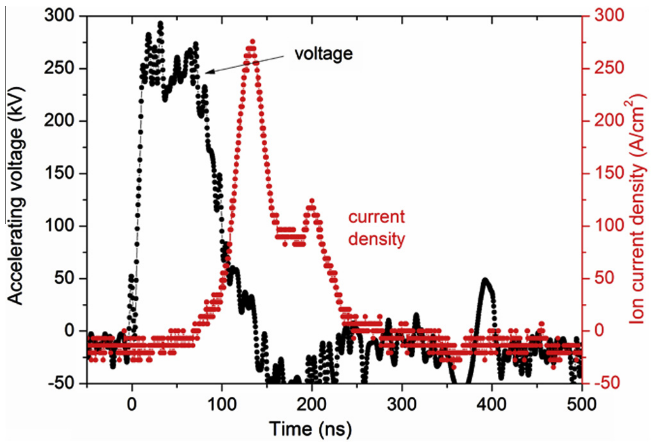

Fig. 3. Waveforms of accelerating voltage and ion current density for the applied B_r-magnetically insulated diode.

3.5–4.0 J/cm^2, which coincides with the values of the energy density as measured with the infrared imaging technique (see Fig. 4).

The IR imaging diagnostics for measuring ion beam energy density distribution is described in details elsewhere [16]. After exiting the diode the ion beam is intercepted by a thin metal target (100 μm stainless steel), the rare surface of the target is viewed with the Fluke TiR10 thermal imager (spectral range of 7–14 microns). To increase its emissivity the rear surface of the target was sprayed with the flat black paint (ε = 0,90). The distribution of temperature on the target is then converted to energy density units using well-knows formulas, provided that ablation of target material is not significant. For experimental determination of the ablation threshold for our target we used an approach with stainless-steel wire-mesh filters (transparency of 50%), placed in the path of the beam several centimeters upstream of the target. The mesh transparency was about 50% so that in the absence of target ablation, the unfiltered beam produced a temperature rise twice that of the filtered beam. When the unfiltered beam temperature rise was less than twice the filtered beam temperature rise, ablation is significant. The temperature rise on the target for filtered and unfiltered beam we measured using infrared camera. In our conditions incident beam energy is less then ablation threshold for the stainless steel target, so the ablation is not significant for

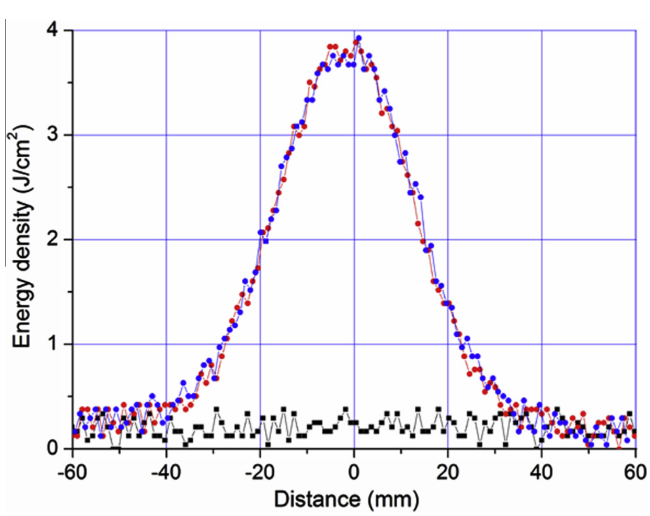

Fig. 4. Energy density distribution of the PIB for the applied B_r-magnetically insulated diode.

the ion beam energies below 4 J/cm^2. This corresponds to the results obtained by Davis et al. [17] for a diode with an external magnetic insulation of similar design. As stated in [18] the Faraday cup data agree with the infrared data up to 3 J/cm^2. Similar results were obtained for a diode with magnetic self-insulation for single pulse mode [18]. Ion current density measurements near the anode 50–100 A/cm^2, which corresponds to the total ion current of 13–27 kA, provided that ion beam is uniformly generated. Calorimetric measurements give the beam energy of 0.4–0.7 kJ which is in agreement with ion current density readings.

We compared the results of these two methods for the beam formed by the focusing self-magnetically insulating diode, which is configured in double pulse mode. The energy density derived from ion current density and accelerating voltage measurements (Fig. 1) was found to be 0.4–0.5 J/cm^2 whereas energy density calculated using infrared data was 5–10 times higher as shown in the Fig. 2. The difference in the results can be explained by the presence of charge-exchange neutral component in the beam which cannot be registered by the Faraday cup but still contribute to the heat of the target measured by infrared camera.

4. Shot-to-shot reproducibility of the PIB parameters

Our study shows that the reproducibility of ion current density (pulse amplitude in Fig. 1) in the self-magnetically insulated diode in double pulse mode is very poor, the standard deviation is 20–25% in a set of 50–100 shots, whilst at the same time variations in the output parameters of the Blumlein generator do not exceed 10% [12]. Time interval between measurements was 10 s. However, the reproducibility of PIB energy density for the same diode is much better. The results of a statistical analysis are shown in Fig. 5 and summarized in Table 1.

For measuring of the energy density of the beam we used an infrared imaging technique. Time interval between measurements is 120 s to allow temperature on the target equalize before the next shot. The total number of shots in each set was 35–40.

A possible reason for a relatively good reproducibility of the energy density compared to ion current density for the same diode is the target ablation which can affect the results of the measurements. When the beam energy density exceeds the ablation threshold of the target, the energy absorbed by the target is less than the incident beam energy, because some energy is carried away in the ablated material. This leads to an underestimation of the beam energy density when measured by infrared imaging diagnostic, which also affects the results of statistics. We expect that reduction in the energy density on target so that it does not exceed the ablation threshold of the target would increase the variation in energy density. However, the measurements (see Table 1, sets 3

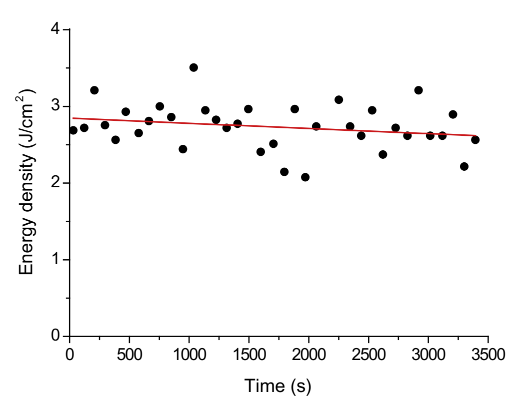

Fig. 5. The shot-to shot variation in the maximum PIB energy density.

Table 1
Statistical analysis of the PIB parameters.

	Mean value and standard deviation	
	Energy (J)	Energy density (J/cm^2)
Set 1	103 ± 11%	4.2 ± 8%
Set 2	100 ± 8%	3.8 ± 10%
Set 3	83 ± 10%	3.8 ± 9%
Set 4	66 ± 9%	2.7 ± 11%

and 4) show that reduction in the beam energy density did not increase standard deviation. The results suggest that good reproducibility of the energy density is not due to underestimation of the beam energy density measured by infrared imaging diagnostic.

The infrared imaging diagnostics allows one to measure the full energy and energy density distribution of the ion beam with a high space resolution, but a time interval between the measurements of 100 s is unavoidable. The shot to shot stability of the ion current density [12] was measured with the time interval of 9–10 s, which corresponds to normal pulse repetition rate of the TEMP-4M accelerator.

For measuring PIB energy density we used additionally acoustic diagnostics [19]. For the acoustic diagnostic set up the target was placed 14 cm downstream from the diode, which corresponds to the focusing distance for the strip focusing diode. As a target we used a copper strip with a rectangular cross section measuring 2 × 7 mm^2; the length of the strip was 5 m. A piezoelectric transducer (PZT) was fixed at one end of the strip, while the other end was placed in the diode chamber and subjected to PIB irradiation. Fig. 6 shows typical signal measured by PZT.

Determination of the dependence of the PZT signal amplitude on the input energy was made using the thermal imaging diagnostics [13]. The target was placed in the diode chamber downstream the copper strip, with the infrared camera focused on the back surface of the target. Fig. 7 shows the correlation between piezoelectric transducer signal (the amplitude of the second positive half-wave in Fig. 6) and ion beam energy density.

A typical feature of the obtained calibration dependence is the stabilization of the piezoelectric transducer signal amplitude with the PIB energy density over 2 J/cm^2. To explain the reason for non-linearity of the calibration curve, we made simulation of carbon ions interaction with copper target. The simulation shows that melting of the surface layer of a copper target becomes with the beam energy density over 2 J/cm^2, which leads to uncertainty in

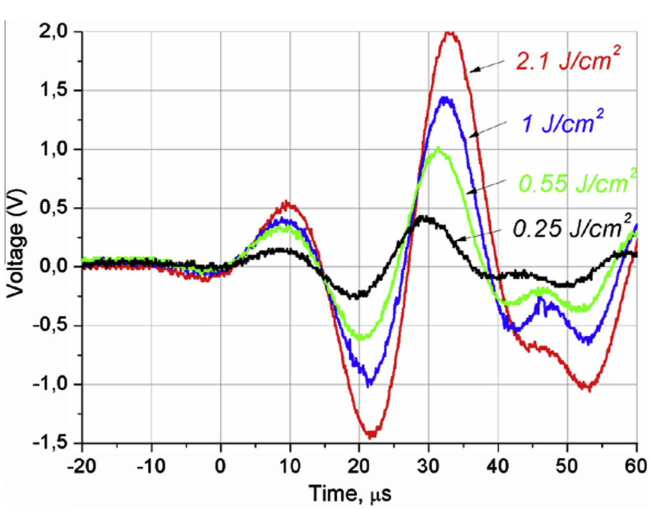

Fig. 6. Waveforms of the signal measured by piezoelectric transducer on the different ion energy density.

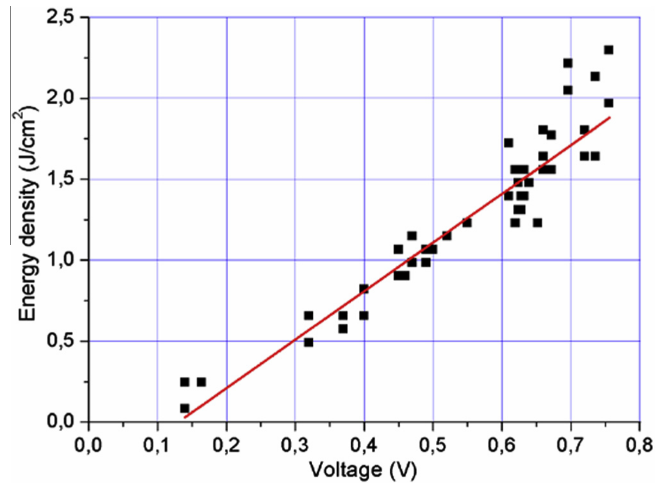

Fig. 7. Piezoelectric transducer signal amplitude dependence on PIB energy density.

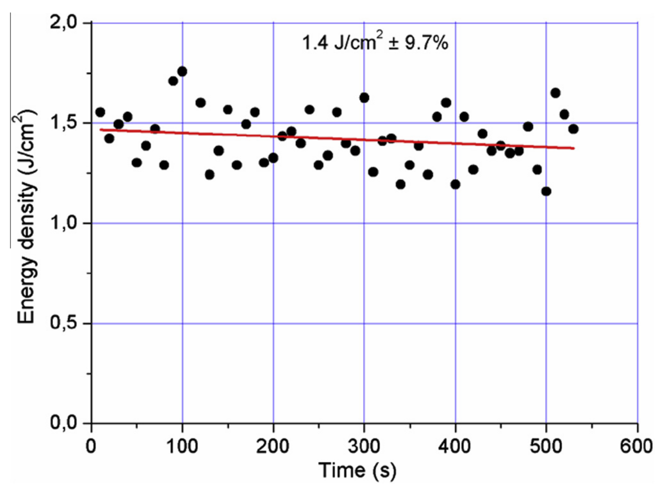

Fig. 8. The shot-to shot variation in the energy density. Acoustic diagnostics.

measurements using acoustic diagnostics for beam energy above melting threshold and thus limits the use of acoustic diagnostics to lower energy density. Fig. 8 shows the results of shot-to-shot variation in the energy density of extracted beam with measurements performed using acoustic diagnostics. The statistics was derived according to 53 shots with a 10 s time interval between shots.

The results of statistical analysis of the beam energy density reproducibility in a self-magnetically insulated ion diode showed that the standard deviation of the energy density at a high repetition rate (time interval between measurements of 10 s) does not exceed 11%, which is close to that obtained with infrared imaging diagnostics (time interval between measurements is 120 s).

5. Correlation of the PIB energy

Our research shows that the ion current density correlation with the output parameters of the TEMP-4M accelerator, such as accelerating voltage, total diode current and first pulse duration is low; the determination coefficient *R* (adj. *R*-square in the program Origin 8) does not exceed 0.3 with a 10-s pause between pulses.

The results of a statistical analysis are shown in Fig. 9 and summarized in Table 2. The total number of shots each set was 100.

The correlation of the ion current density with the TEMP-4M output parameters is also low, when the time interval between pulses increases, Fig. 9b. The determination coefficient does not exceed 0.1 for a set of 25 pulses with a 120 s interval between shots.

Further observations showed a good correlation between total beam energy (or energy density) and some output parameters of the TEMP-4M accelerator (Table 3). The total number of shots in a set was 37 with 120 s between each shot. In Table 3 the coefficient of determination is used for quantitative expression of the correlation strength between the parameters.

Unlike the ion current density, the PIB energy density and the total beam energy are the integral parameters, reflecting the beam formation during the whole process of generation. Therefore, it is more correct to compare them with the accelerating voltage integral or the total charge transferred in the A–C gap during the beam generation. Fig. 10 shows PIB energy dependence on the total charge (the total current integral during the second pulse, Fig. 1) for different diodes.

For all the examined diodes, besides spiral diode [20], the dependence of the total beam energy on the total charge is described by the relation $E = -35 + 22Q$ at the standard experimental data deviation from the calculated ones no more than 10%. The unclosed electron drift is typical for these diodes. The dependence of the total beam energy on the total charge in the spiral diode differs considerably from the data for the other diodes. It confirms the implementation of a new PIB generation mechanism in the spiral self-magnetically insulated diode – the closed electron drift [21].

The preliminary research showed the insignificant correlation of the ion current density, formed in different parts of the strip planar diode simultaneously [12]. We measured the ion current density by two separate Faraday cups, installed at the equal distance from the planar diode, but at the distance from each other. Fig. 11 shows the correlation dependence of ion current density measured by two Faraday cups (at a 5-cm distance between them).

Our observations show that the correlation between ion current density measurements at different positions along the length of the diode decreases with increased distance between the Faraday cups. The coefficient of determination for the current density at the points distant from each other of more than 5 cm does not exceed 0.1. This indicates that ion beam is formed non-simultaneously along the length of the diode. At the same time, PIB energy density changes from pulse to pulse in different points of the diode synchronously, Fig. 11b. The determination coefficient of PIB energy density in the points, distant from each other for 10 cm along the beam cross-section, exceeds 0.9.

Table 2
The correlation analysis of the ion current density with the accelerator output parameters.

Parameter	Mean value and SD	Determination coefficient
Diode voltage (second pulse)	262 kV ± 4.5%	0.3
Diode current (second pulse)	61 kA ± 10%	0.19
Duration of the first pulse	480 ns ± 11%	0.34

Table 3
The correlation between total beam energy/energy density and electrical parameters of the TEMP-4M accelerator.

Parameter	Total energy of PIB	Energy density of PIB
Diode voltage (second pulse)	0.09	0.30
Diode current (second pulse)	0.98	0.94
Duration of the first pulse	0.95	0.97

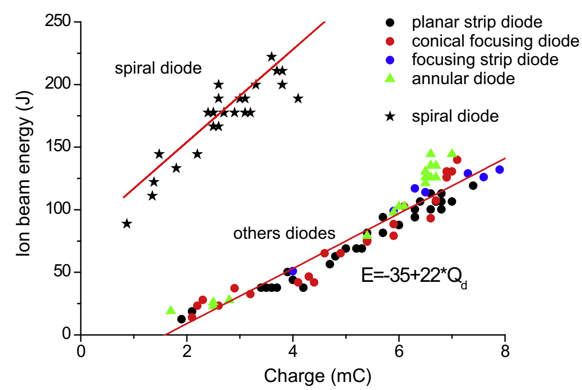

Fig. 10. Dependence of total PIB energy on the total charge for the strip focusing and planar diodes, a conical focusing diode, a spiral diode.

The analysis of the energy transfer efficiency in the diode shows a good correlation between the total energy of extracted beam and the energy supplied to the diode (the integral of the product of diode current and accelerating voltage during the second pulse) [21]. The determination coefficient for the strip focusing and spiral diodes is 0.95.

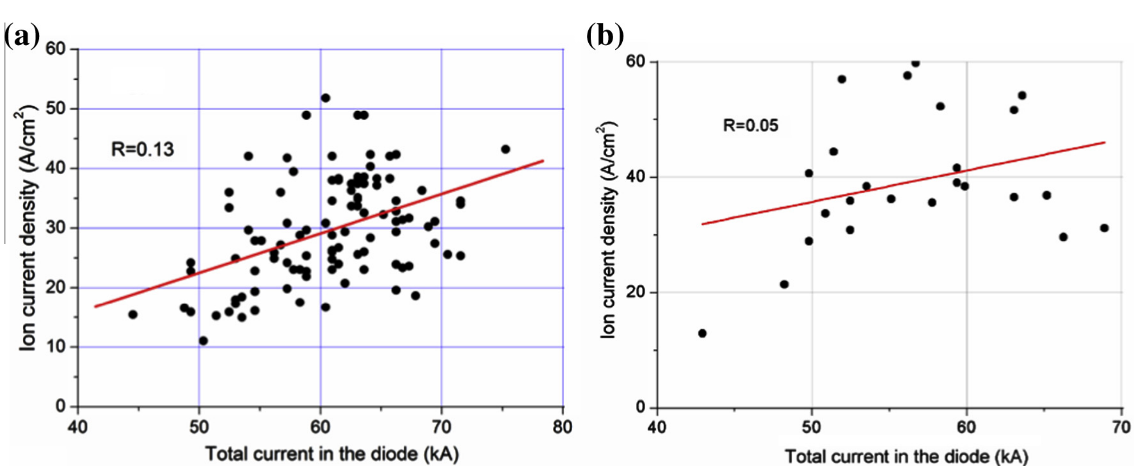

Fig. 9. The correlation between the ion current density and total diode current. 10 s (a) and 120 s (b) time interval between shots.

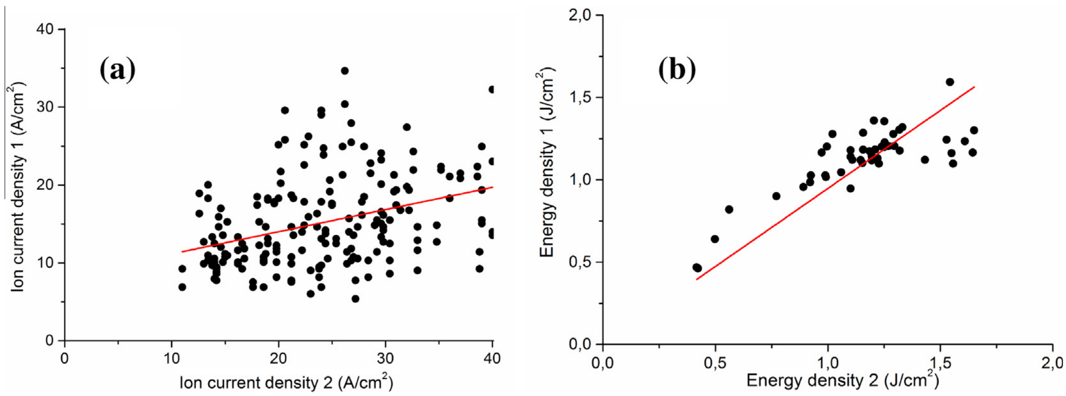

Fig. 11. Correlation of ion current density from two Faraday cups (a) and the energy density in the different points of a beam cross-section (b).

6. Determining the ion beam generated pressure in target

Ion beam irradiation of the target causes an increase in pressure which forms stress waves. Fig. 12 shows the dependence of the pressure on the PIB average power density for our case and other studies.

One can see that the data on the beam generated pressure obtained in our experiments exceed the simulation results obtained by Boyko et al. [22]. They studied an ion beam (660 kV, 120 ns), containing C^+ ions (40%) and protons. The simulations were performed using a target made of aluminum. It was shown that beam interaction with the target forms thermoelastic waves due to a rapid increase in the surface temperature. When the beam power density exceeds the ablation threshold (67.5 MW/cm^2) ablation of the target material takes place, which leads to a sharp increase in the pressure. Fig. 12 also shows the experimental data on pressure in a titanium target irradiated with a proton beam formed by a diode with an external magnetic insulation [23]. The authors studied a beam with the following parameters: the peak accelerating voltage of 350 kV, ion current density ranging from 200 A/cm^2 to 400 A/cm^2 and pulse duration of 150 ns. The pressure formed in copper irradiated with ions having a maximum energy of 660 keV and pulse duration of 120 ns is shown in Fig. 12 [24].

The difference between our experimental data and results stated by other authors we attribute to the presence of a low-energy charge-exchange neutral component in the beam, formed by the TEMP-4M accelerator. Neutrals with lower energy have a smaller range in materials, thus they release the energy in a thinner surface layer than ions. This leads to a sharp increase in the portion of energy released in the near-surface layers which leads to the earlier "start" of the ablation mechanism. Notice that the wavelength of the recorded signal increases with energy density. However, this did not occur during calibration, which suggests that the increase in the wavelength observed in Fig. 6 is due to another effect; we attribute this to ablation. Similar results were obtained by Boyko et al. [22] where it was shown that the material ablation and plasma formation caused a significant increase in the duration of acoustic signal.

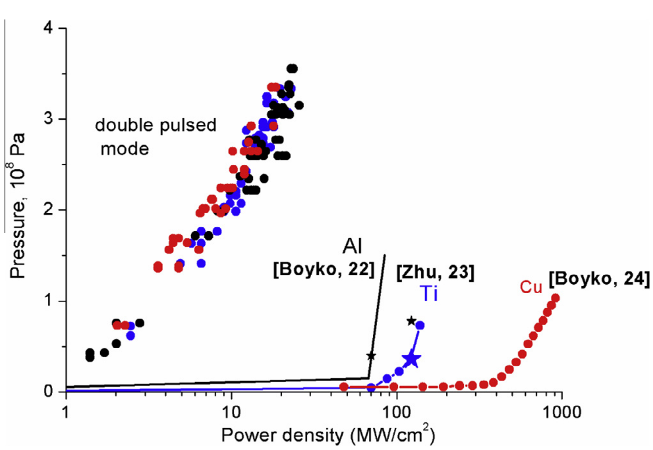

Fig. 12. Dependence of maximum beam generated pressure in the target on the PIB power density.

7. Discussion

A disagreement between experimental and calculated values of the beam energy density was found only for a case with the self-magnetically insulated diode in double pulsed mode. The ion beam energy density measured and calculated for the applied B_r diode was in a good agreement, whilst the measured results (infrared camera method) for the self-magnetically insulated diode in double pulsed mode exceed by a factor of 5–10 the calculation (waveforms of ion current density and accelerating voltage).

Statistical analysis has shown that the shot-to shot reproducibility of ion current density is poor (*sd* of 25–30%), whilst that for total energy and energy density is much better (*sd* of 10–11%). If a beam is composed entirely of ions, then variations in energy density must be due to variations in the fluence of ions (or ion current density) and their kinetic energy (or accelerating voltage). Based on this consideration, with a *sd* of 20–30% for ion current density, and *sd* of 5–7% for accelerating voltage, the *sd* of the energy density should be around 25–30%, much higher than the 10–11% found by experiment.

We found that ion current density is only weakly dependent on the accelerating voltage and other output parameters of the accelerator, $R < 0.3$. At the same time, we have identified that the total energy and the energy density of the beam is strongly dependant on the accelerator output parameters, $R > 0.9$.

These results can be explained by the presence of charge exchange neutral atoms which are produced through a charge exchange process between beam ions and molecules in a neutral layer near the anode. In the diode with self-magnetic insulation, operating in a double pulse mode, the charge-exchange processes proceed more effectively compared to the applied B_r filed diode, operating in a single pulse mode. The presence of a time interval (in double pulse mode) between a moment of desorption of molecules from the anode surface and a moment of ions generation increases the thickness of a layer of desorbed molecules. This leads to an increase in the number of charge-exchange acts for an ion.

It is well known that anode plasmas created by explosive emission on graphite cathode have substantial fractions of carbon, and the cross sections for the charge exchange reactions:

$$C^{n+} + H \rightarrow C^{(n-1)+} + H^{+}$$

has a much higher-energy cutoff than for protons on hydrogen [1]. It also strengthens the process of the charge exchange.

During the charge exchange process the initial quantity of ions which take part in charge exchange acts does not change and therefore the correlation between the energy density of the combined beam (ions + neutrals) and the output parameters of the accelerator should not be better than the correlation between ion beam charge density and other accelerator parameters because of the additional instability of accelerating voltage. High correlation between the energy density of combined beam with the accelerator output parameters while the ion current density is only weakly dependent on total diode current indicates that there exists a feedback between ions formation and charge exchange processes in the diode. If the quantity of atoms, which can participate in charge exchange process with accelerated ions is limited then the charge exchange process will stabilize the reproducibility of the total beam energy. When the total quantity of ions increases, the number of charge exchange acts decreases by one ion and vice versa. The total energy of the accelerated neutrals in the combined beam considerably exceeds the total kinetic energy of ions, therefore, the correlation of total beam energy with accelerator output parameters is higher than the correlation of ion current in the diode.

A study using Raman spectroscopy and electron paramagnetic resonance showed that short-pulse ion implantation of carbon ions into a silicon target results in formation of *nc*-diamond clusters with the of size 5–15 nm [25]. The maximum volume fraction of *nc*-diamonds was found when the target was treated with 10 pulses at the ion current density of 70–80 A/cm^2. The formation of diamond structure in the implanted layer occurs at high temperature and pressure in the silicon substrate after treatment by intense pulsed ion beams. The experiments were performed on the TEMP-4M accelerator. It can be treated as an indirect confirmation of a large flux of atomic carbon in the ion diode operated in double-pulse mode.

8. Conclusion

Complex research was conducted into PIB generation process in the magnetically insulated diodes. The experiments have been carried out using both a diode with externally applied magnetic insulation and a diode with self-magnetic insulation. Investigations are performed into diodes of different design: strip focusing and planar diodes, a conical focusing diode, a spiral diode. The total beam energy was measured by means of the infrared imaging diagnostics and a calorimeter, the beam energy density was measured by the infrared imaging and acoustic diagnostics. It was also calculated using the waveforms of ion current density and accelerated voltage. For diode in double pulse mode infrared measurements exceed the ion current density measurements. It was found that the standard deviation of energy density does not exceed 11%, whilst the same variation for ion current density was 20–30%; suggesting the presence of neutrals in the beam. This idea is further supported by the fact that ion current density is only weakly dependant on the accelerating voltage and other output parameters of the accelerator (coefficient of determination <0.3); whist the correlation between the energy density of the beam and the output parameters is strong (coefficient of determination >0.9). This discrepancy is typical for all studied types of diodes operating in the double-pulse mode. It may be due to production of energetic neutrals though charge exchange processes between accelerated ions and molecules of the residual gas in the A–C gap.

The main factor determining the change in the properties of the metal target under the influence of pulsed ion beams at gigawatt power is the thermal effect rather than implantation of ions. The heating of the material is the same for ions or neutrals at the same velocity. For a material with high thermal conductivity the heat penetration depth exceeds the depth range of ions within 100–150 ns. Therefore, the charge exchange process does not reduce the possibility of technological application of the combined high-power beam (ions + neutrals).

Charge exchange effects in an ion diode are actually rather beneficial since it allows for the limitation of space charge effects in the A–C gap, which can significantly increase the energy density of the complex beam (ions + neutrals). The realization of charge exchange provides an increase in energy density by a factor of 25–30 times compared to space-charge-limited current density (Child-Langmuir limit).

The ability of production of large fluxes of energetic neutrals in an ion diode with self-magnetic insulation is shown. With the energy of neutrals of 10–50 keV, the fluence can reach up to (2–4)$\cdot 10^{15}$ cm^{-2} per pulse. A big operating resource of the self-magnetically insulated ion diodes with the explosive-emission cathode (more than 10^6 pulses), and high stability of PIB energy density in the pulse train make them prospective for various technological applications.

Acknowledgement

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