Ion acceleration mechanism in mega-ampere gas-puff z-pinches

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Abstract

Acceleration of high energy ions was observed in z-pinches and dense plasma foci as early as the 1950s. Even though many theories have been suggested, the ion acceleration mechanism remains a source of controversy. Recently, the experiments on the GIT-12 generator demonstrated acceleration of ions up to 30 MeV from a deuterium gas-puff z-pinch. High deuteron energies enable us to obtain unique information about spatial, spectral and temporal properties of accelerated ions. In particular, the off-axis ion emission from concentric circles of a ~1 cm diameter and the radial lines in an ion beam profile are germane for the discussion of acceleration mechanisms. The acceleration of 30 MeV deuterons can be explained by the fast increase of an impedance with a sub-nanosecond e-folding time. The high (> 10^13) impedance is attributed to a space-charge limited flow after the effective ejection of plasmas from m = 0 constrictions. Detailed knowledge of the ion acceleration mechanism is used with a neutron-producing catcher to increase neutron yields above 10^13 at a current of 2.7 MA.

1. Introduction

The study of ion acceleration in z-pinches commenced with the beginning of the controlled thermonuclear fusion research and was closely related to the study of neutron production mechanisms [1, 2]. Already in 1952, compressional z-pinches produced significant neutron yields from the nuclear fusion of two deuterons. At first, it was assumed that deuterons were accelerated to fusion energies by multiple elastic collisions in high-temperature plasmas. However, in 1956 at Harwell, Kurchatov pointed out that ‘acceleration of ions in the longitudinal electric field is possibly the explanation for the appearance of neutrons’ and that ‘some types of instability… may play an important role in accelerating particles’ [3]. In a typical compressional z-pinch, deuterons were accelerated up to 200 keV energies and produced 10^6 beam-target neutrons at a 150 kA current [1].

Since the 1960s, fast ions have been extensively studied in dense plasma foci (DPFs) [4, 5]. It was shown that, even though more than one acceleration mechanism might play a role, the principal acceleration occurs at the time of m = 0 instabilities [6]. During the past 60 years, a lot of hypotheses were proposed to explain physical processes connected with m = 0 instabilities. However, the exact acceleration mechanism has remained the source of controversy [6–8]. Recently, state-of-the-art numerical codes have opened up new possibilities to solve this very old problem in plasma physics. The dynamics of deuterium gas-puff z-pinches and DPFs was simulated by the fully kinetic particle-in-cell LSP code [9–12] as well as by 3D-MHD GORGON code [13]. Most of these
simulations attempted to explain a high DD neutron yield of \(4 \times 10^{13}\) in a deuterium gas-puff on the Z machine [14, 15]. In our opinion, it would be useful to have more experimental data to validate numerical codes with respect to ion acceleration. For this purpose, we have carried out deuterium gas-puff experiments on the GIT-12 generator at \(~3\) MA current and \(~\mu\)s rise time. In our previous experiments, the emphasis was put on neutron production [16, 17]. On the one hand, neutrons carry the information about accelerated ions [18]. On the other hand, neutron production is influenced also by target deuterons. Therefore, our recent experiments have been focused on direct diagnostics of fast ions on GIT-12. GIT-12 is unique in the use of a novel z-pinch configuration [19] that is able to accelerate deuterons to an unprecedented energy exceeding 30 MeV. This is fifty times the ion energy provided by the GIT-12 driving voltage. An advantage of higher energies is smaller influence of a given magnetic field on ion trajectories. Another advantage is that multi-MeV deuterons can be analyzed by many techniques, including several novel (to z-pinches) diagnostic methods.

In this paper, we present angular, spatial, spectral and temporal characteristics of ion emission from the deuterium gas-puff z-pinch. An important result for the discussion of ion acceleration mechanism is the off-axis emission of \(>20\) MeV deuterons from concentric circles of a large diameter. The acceleration of \(>20\) MeV deuterons is explained by the increase of the z-pinch impedance with a sub-nanosecond \(e\)-folding time. The high impedance and the generation of \(>\text{GV m}^{-1}\) electric fields could result from a breakdown of quasi-neutrality and a gap formation after the ejection of plasmas from \(m = 0\) constriction.

The paper is organized as follows: section 2 describes the z-pinch load used in our experiment on GIT-12. Section 3 presents the experimental data on the ion emission. Section 4 discusses the experimental results and provides some conclusions on the ion acceleration mechanism. Section 5 describes how our better knowledge of the ion acceleration mechanism was used to increase neutron yields above \(10^{13}\). Finally, section 6 summarizes the most important points of this paper.

2. Hybrid deuterium gas-puff on GIT-12

Our z-pinch experiments on the GIT-12 generator are carried out with a hybrid deuterium gas-puff [17]. In this configuration, an inner 8 cm diameter annular deuterium gas-puff is surrounded by an outer hollow cylindrical plasma shell of 35 cm diameter. The main idea behind using the plasma shell is to form a homogeneous, uniformly conducting current sheath prior to implosion (see [17, 20] for more details). A hollow cylindrical plasma shell consisting of hydrogen and carbon ions is injected between electrodes by 48 polyethylene cable guns. The optimal conditions for high deuteron energies and large neutron yields are achieved when the cable guns are triggered 1.7–1.8 \(\mu\)s before the main z-pinch current. This timing provides a \(~5\,\mu\text{g cm}^{-2}\) mass loading of the plasma shell inside the anode–cathode region. A total linear mass of the deuterium gas-puff is about 100 \(\mu\text{g cm}^{-1}\). Both the anode and cathode are formed by a stainless-steel (SS) mesh with a transparency of about 70%. Due to multiple reflections of a fraction of the gas onto the mesh electrodes, the gas is spread out over a large area. A schematic diagram of our experimental setup together with a simulated gas distribution is illustrated in figure 1.

The pinch forms between the anode and cathode wire meshes separated by \(~25\) mm. During implosion some mass can be lost through the meshes. An implosion lasts 700 ns, and a maximum velocity reaches \(6.5 \times 10^5\) m s\(^{-1}\). Stagnation occurs at a 2.7 MA current. At stagnation, a constriction is formed near the anode as shown in figure 2. Accurate time measurement shows that high energy (\(>2\) MeV) bremsstrahlung radiation and the principal neutron pulse are generated immediately after the plasma ejection from the neck (see also the increase of x-ray background radiation between \(~1\) and \(4\) ns). An average neutron yield is \(2 \times 10^{12}\) per shot.

3. Experimental results

3.1. Angular, spatial and spectral properties of ion emission

The information about ion emission is obtained by a detector placed on the axis (see figure 3(a)). This detector measures simultaneously angular, spatial, and spectral properties of ion emission. The angular distribution is measured by large samples of HD-V2 GafChromic films at about 10 cm below the cathode mesh. Figure 3(b) shows a typical beam profile of \(>20\) MeV hydrogen ions. The effective area of the detector is reduced by a shielding mask and 3 cutouts. At the center of each cutout there is a pinhole, thereby providing a spatial distribution of the ion source. Three pinholes are used to estimate ion emission anisotropy.

Figures 3(c) and (d) show pinhole images of deuterons with energies above 2 and 6 MeV, respectively. Evidently, fast ions produced a radiograph of the cathode mesh. (Note: it is the first ion radiograph produced by a z-pinch. A point pinhole acts as a point source used, for example, in laser-driven proton radiography.) The marks in the cathode mesh enabled us to identify the radial position of the ion emission in each shot. Analyzing tens of shots, we found out that the ion emission center was in the center of the cathode within a \(2\) mm accuracy.
As shown in figure 3(d), a very characteristic feature of the pinhole images is the detection of concentric circles. These circles were also observed in DPFs [21, 22] and Ar gas-puff z-pinches [23]. However, the data from those experiments were not sufficient to answer a key question: does the annulus represent a real spatial distribution of an ion source or is it created by magnetic fields after ion acceleration?

To differentiate between these two hypotheses, we take advantage of high ion energies and the comprehensive ion diagnostics on GIT-12. If the circle is created by azimuthal magnetic fields which bend ions emitted from a divergent point source [24], then the observed diameter will depend on the deuteron energy because the Lorentz force depends on the deuteron velocity as shown in figure 4(a).

From this point of view, a very important result is that the circles seen by various detectors in the stack of the pinhole camera are of comparable diameters (see figures 3(c) and (d)). It indicates that the circles are formed by ions with various energies. To confirm this, we used a so-called radiochromic film (RCF) stack spectroscopy [25, 26]. This method is based on the fact that each RCF in the stack has a different sensitivity to deuterons (see figure 5(b)). If there is a high number of RCFs in the stack, the ion energy spectra can be unfolded as in the shot presented in figure 5. The spectrum depends on the region which is selected for analysis. Figures 5(c), (d) show that the part of the ring at a 1 cm diameter is formed by deuterons with a very broad energy spectrum. It rules out the hypothesis that the circle was produced by magnetic fields focusing ions from one divergent central point source towards a pinhole (see figure 4(a)). Thus a more plausible explanation is that the circle in pinhole images somehow reflects the spatial distribution of an ion source. Of course the diameter of a circular source at its origin may differ from that observed in the plane of the cathode mesh. The difference between these two diameters, i.e. the original diameter and the diameter observed by the pinhole camera, depends on the position of an ion.
Figure 3. Measurement of angular, spatial and spectral properties of ion emission. (a) Scheme of the axial ion detector. (b) An image of the beam profile detected at 10 cm. Images from a three-pinhole camera (magnification of 0.55 and a pinhole diameter of 0.4 mm) recorded by the first (c) and third (d) layer of a stack of HD-V2 films. Spatial scales correspond to the plane of the cathode mesh.

Figure 4. Detection of ions by the pinhole camera. (a) A divergent point source. (b) Collimated ion beams emitted from a circle. Because of the charge and current neutralization of ion beams in a low pressure gas, we assume the ballistic transport below the cathode mesh.
source above the cathode mesh and on the strength of magnetic fields. A simple case occurs if there is no magnetic field along ion paths. However, it seems more likely that magnetic fields play some role.

The model shown in figure 4(b) illustrates how the non-monoenergetic circle can be detected even in the presence of magnetic fields. The non-monoenergetic annulus could be explained by time-variable magnetic fields and by collimated ion beams emitted from a circle (likely near the anode). As shown in figure 4(b), off-axis ions can be focused towards on-axis pinholes for a specific combination of magnetic fields and ion energies. If the ion source has a broad energy spectrum and if the magnitude of the magnetic field is changing (but the 'topology' remains the same), the annular ion source will be detected by the on-axis pinhole camera as a non-monoenergetic circle. In this case, the detection of ions through pinholes is a function of time and ion energy.

The role of magnetic fields is supported by the ion emission anisotropy observed with the pinhole camera along a different line of sights (see differences between individual pinhole images in figure 5(c)). We are able to reproduce the most important features observed in three-pinhole images by an appropriate choice of initial radii, ion beam divergences and magnetic fields. The pinhole images were reconstructed with the product of magnetic field and ion trajectory length \( \tau \int B \times dl \approx B_0 \cdot Z \) between 10 and 20 T cm. Further details on the reconstruction go beyond the scope of this article and will be the subject of a future paper. Here, we only mention that 20 T cm is not a high value considering the total current of 2.7 MA. On the one hand, this shows how the current is concentrated near the axis. On the other hand, it should be taken into account that the magnetic field during the ion acceleration might be decreasing and that the on-axis pinholes detect preferentially less deflected ions, i.e. provide the information about a relatively weak magnetic field.

The influence of magnetic fields on ion trajectories is more apparent in the radial lines observed by the beam profile detector in figure 3(b). Experimental results suggest that radial lines can be produced by collimated ion beams which are deflected by azimuthal magnetic fields (see figure 6(a)). To provide a clear evidence of this hypothesis, we analyzed the shots where the intersection of radial lines was close to one pinhole. In these cases, it was possible to assign radial lines to individual sources. As shown in figure 6(b), the number and position of individual spots in the ion pinhole image seem to correlate with the radial lines detected by the beam profile detector. This correlation is an important result because it enables one to determine not only the initial position of emitted ions but also to estimate the azimuthal magnetic field \( B_0 \) along the ion trajectory. In other words, we can use, for the first time, z-pinch driven ion deflectometry to evaluate the magnetic field near the z-pinch axis.
where $d$ and $n$ are the deuteron charge, mass and final kinetic energy after acceleration, respectively. Interestingly, the deflection angle depends neither on the way how ions are accelerated nor the way how the azimuthal magnetic field is distributed in the z-pinch. The radial lines displayed in figure 6(b) were near the endpoint energy (33 MeV in this particular shot). Equation (1) therefore shows that the relatively long radial lines in figure 6(b) were not caused by a broad ion energy spectrum, but mainly by the variability of the integral $\int B_y dz$. To obtain quantitative results, we simulated trajectories of off-axis ions. The radial lines in the beam profile detector and individual spots in the pinhole camera could be easily reproduced with the azimuthal magnetic field partly justified the model described in the previous paragraphs and displayed in figure 4(b).

3.2. Time of ion emission
Our three-pinhole camera can be used with small semiconductor detectors providing some spatial and temporal information. However, due to a strong bremsstrahlung pulse, we measure the time of ion emission mostly by the method described in [19]: a small piece of a LiF sample is placed below the cathode mesh (see figures 7(a), (b)). This way, >500 keV deuterons are converted to neutrons by the $^7$Li(d, n) reaction. The nuclear reactions of deuterons with $^7$Li isotopes produce the radial neutron peak at about 12 MeV as shown in figure 7(c). The production time of this neutron peak is measured by our neutron time-of-flight (nToF) detectors [17]. Because of the temporal dispersion of neutrons, one of nToF detectors should be placed as close to a neutron source as possible. In our case, the nearest nToF detector is placed at 2 m. At this distance, the dispersion of the neutron peak of about 7 ns is on the order of temporal resolution of our detectors [27]. The neutrons and gammas from the nToF detector at 2 m are displayed in figure 7(d). In figure 7(d), the neutron signal was shifted by the time-of-flight of 12 MeV neutrons, i.e. the energy of $^7$Li(d, n) peak. In order to take into account the finite width of the energy peak and neutron scattering on GIT-12, we used the Monte Carlo N-particle (MCNP) code [28] and we simulated the neutron signal at 2 m. The best fit of the MCNP simulation to the measured signal was obtained for the neutron spectrum calculated from the nToF detector at 25.7 m (see figure 7(c)) and for the neutron emission that was simultaneous with >2 MeV photons (see red line in figure 7(d)). It means that the emission of >500 keV deuterons lasted for ~10 ns and its start corresponded to the onset of bremsstrahlung radiation.

We were also interested in the spatial dependence of the ion emission time. For this purpose, we placed LiF samples at various radial positions ranging from 0 to 26 mm from the z-pinch axis. Even though the number of neutrons from the LiF catcher depended on the radial position of the sample, we did not observe any significant radial dependence of neutron energy spectra or the rise time of neutron signals at 2 m. It indicates that the onset of on-axis ion emission was simultaneous (within 1 ns precision) with the onset of off-axis ions.
3.3. Axial position of ion acceleration

In the previous section, we have shown that the ion emission started simultaneously with the $>2 \text{ MeV}$ bremsstrahlung radiation. If we consider the correlation of the bremsstrahlung radiation with the plasma dynamics shown in Figure 2, we can conclude that deuterons are accelerated immediately after the plasma ejection from the constriction. At this moment, the plasma column is faintly visible only near the cathode. There is no significant emission at the original position of the neck. It is therefore natural to expect that ions are accelerated in this region with a dramatic change of plasma emission, i.e., in the gap formed near the anode.

The vertical (axial) position of ion acceleration is studied by two independent methods. The first method relies on the analysis of images from the pinhole cameras observing the ion source along a different line of sights. Because of the magnetic field effects, the analysis of the pinhole images is not straightforward and will be described in another paper. Here we want to present the results from a more direct measurement. In the second method, we place a pyramid from four wires 1 cm above the cathode mesh (see Figure 8). The main idea is not to change the dynamics in the region where the gap is formed. If the ions are accelerated in the gap near the anode, the ions can go through the Al wires and can record the pyramid in ion pinhole images below the cathode mesh. To confirm this idea, we carried out 3 shots with the Al pyramid. The neutron yields remained at about $2 \times 10^{12}$. As shown in Figure 8(a), the soft x-ray emission above the cathode mesh was significantly influenced by the Al wires, however, the plasma dynamics near the anode seemed to be similar as in the shots without an Al pyramid. In particular, the gap was formed near the anode after the implosion of a deuterium gas-puff onto the axis. The pinhole image of the deuterons with energies above 2.1 MeV is shown in Figure 8(c). Here, we can see the shadow of the top of the pyramid, namely the aluminum wires crossed at 10 mm above the cathode mesh. This suggests that on-axis ions were really accelerated above the pyramid, i.e., in the low-emission region after the plasma ejection from the necks.

Figure 7. (a) Photo and (b) ion pinhole image of the cathode mesh and the on-axis LiF sample in shot no. 1840 with $2.1 \times 10^{12}$ neutrons. (c) Radial nToF signal at 25.7 m from the deuterium gas-puff with the LiF sample. (d) Experimental (black line) and simulated (green line) neutron signal measured by the radial nToF detector at 2.00 m. Red line represents the signal of high energy bremsstrahlung radiation above 2 MeV. High energy photons and neutrons were detected by the same detector and recorded on the same waveform. The MCNP simulation revealed how the neutron ToF signal was affected by spectrum broadening and by the neutron scattering in 20 cm thick lead shielding.
4. Discussion of ion acceleration mechanism

4.1. Most important experimental results

The most important experimental facts on the ion emission can be summarized as follows: first, maximum energies of hydrogen ions exceed 30 MeV. Second, ions are emitted not only from the axis but also from concentric circles. Third, the ≈ cm diameter of circles is larger than the diameter of compressed necks. Fourth, high energy ions are emitted from many sub-millimeter spots rather than from a dispersed source (see figures 5(c) and 6(b)). Fifth, the ion beam profile at >20 MeV consists of radial lines which are produced by a variable magnetic field deflecting collimated (≤ 10 mrad) microbeams. Finally, ions are accelerated in a gap which is formed after the plasma ejection from a neck. All these facts together rule out many hypotheses on ion acceleration mechanisms.

In most of the previous works on ion and neutron emission, experimental results allowed more than one interpretation, mainly because of low ion energies. In fact, there are several mechanisms which can accelerate ∼ MeV deuterons on MA devices. However, it is difficult to explain all the above experimental results by any of the existing theories. In order to show these difficulties, we will provide a brief discussion of the most frequent hypotheses in what follows.

4.2. Acceleration mechanisms not based on the generation of axial electric fields

In this section we consider the mechanisms which are not primarily based on the generation of large axial electric fields. Historically, there has been interest in the thermonuclear mechanism, i.e. in ions accelerated to fusion energies by multiple elastic collisions in high-temperature plasmas. In our case, however, the ion acceleration by elastic collisions in a compressed z-pinch [8, 29–31] cannot explain 30 MeV deuteron energies, ion emission originating outside a neck, and high ion emission anisotropy observed in our experiment (small anisotropy of ion emission could arise even from initially isotropic distribution because of the influence of azimuthal magnetic fields on ion trajectories [32]). The latter two observations also rule out the gas-dynamic model of a neck [8, 33] and the Coulomb explosion of hot spots [34]. Another hypothesis is the formation of energetic ion tail by microturbulences [7, 35–37]. Current-driven turbulences favor the ion acceleration in the direction of the electron flow. This is inconsistent with an intense ion beam collimated towards the cathode. A similar argument can be used against collective ion acceleration mechanisms [38]. Further, one can speculate that the ion acceleration is a gradual process, such as the Fermi mechanism [3, 39]. However, in that case, we would expect a poorly collimated ion flow from a dispersed on-axis source rather than well collimated emission from many sub-mm off-axis spots.

It seems difficult to explain high ion energies and collimated ion beams without acceleration in electric fields. In what follows, we will therefore focus on another group of the acceleration mechanisms which are based on the generation of axial electric fields.

4.3. Acceleration of high energy deuterons by axial electric fields

Our experimental observations, particularly the occurrence of collimated microbeams at high energies, indicate that high axial electric field is generated in a low-density region. The acceleration of ions observed in our experiment requires the peak voltage \( V \) above 30 MV. This voltage is fifty times the GIT-12 open-circuit voltage.
of 0.6 MV and, therefore, needs to be explained. The voltage is likely driven by the inductive energy stored around the \(z\)-pinch during the decrease of a current. The decrease of a current \(\frac{dI}{dt} = -\frac{V}{L}\) should last for a sufficiently long period to accelerate finite-inertia particles. The acceleration of deuterons by a 30 MV voltage takes time \(\Delta t\) of 400 ps for a 1 cm gap. However, since \(\Delta t\) is very short (comparable with an electromagnetic transit time inside the chamber), it is difficult to estimate the inductance \(L\) precisely. Therefore, we calculate the current drop and other conditions required for the acceleration of 30 MeV deuterons directly from the Maxwell equations with the displacement current.

In our simple model, we use the Gaussian profile of an axial current density and we let it exponentially decrease with the decay time \(\tau\) as

\[
j(r, t) = j_0 \left(1 - \frac{r^2}{2w^2}\right) \cdot \exp \left(-\frac{t}{\tau}\right).
\]

The drop of this conduction current generates electric fields. In a cylindrical geometry we have

\[
\frac{\partial E_z}{\partial t} = \frac{1}{\mu_0 \tau} \left[\frac{\partial}{\partial r} (rB_\rho)\right] - \frac{1}{\tau} j_z,
\]

\[
\frac{\partial B_\rho}{\partial t} = \frac{\partial E_z}{\partial r}.
\]

Knowing \(\mathbf{E}\) and \(\mathbf{B}\), the single-particle motion of deuterons can be calculated for various initial radial positions using a relativistic equation of motion and the Lorentz force

\[
\frac{d(\gamma v_z)}{dt} = \frac{q}{m} (E_z + v_z B_\rho),
\]

\[
\frac{d(\gamma v_\rho)}{dt} = \frac{q}{m} (-v_z B_\rho).
\]

This way, we can obtain the velocity and the kinetic energy of deuterons accelerated in the gap of a length \(l\). The results for the initial current of 2.7 MA and the gap length of 1 cm are shown in figure 9. Figure 9(a) shows the maximum energy gained by on-axis deuterons with various decay times \(\tau\) and current diameters \(w_{\text{FWHM}}\) of a 2.7 MA current column. (b) Trajectories of deuterons emitted from a \(\sim 1\) cm diameter and accelerated to 26 MeV during the decrease of the current with the diameter \(w_{\text{FWHM}} = 1\) cm. Color indicates the product \(B_\theta \cdot Z\) ranging from 10 to 25 T cm.

We also study trajectories of off-axis deuterons during acceleration. In order to reproduce the radial lines in figure 6, we are interested in the path of the deuterons originating from \(\sim 1\) cm radius and accelerated to \(\sim 26\) MeV. Several exemplary paths of deuterons emitted at different times during the generation of an
electron-magnetic pulse are displayed in figure 9(b). Evidently, because of the decreasing magnetic field, the deflection of ions is falling from 250 to 100 mrad with the product \( B_0 \cdot Z \) ranging from 25 to 10 T cm. This is in agreement with the radial lines observed in the shot presented in figure 6. Even though the results mentioned above are derived from the simplified model which describes only 1 cm of the total z-pinch length, our model provides illustrative information on spatial and temporal scales that could explain the acceleration of deuterons at a 3 MA current.

The acceleration by a current drop, sometimes called ‘a current disruption’, was suggested decades ago [41–43] and later modified by the effects of peripheral plasmas [44] and electron magnetohydrodynamics (EMHD) [45]. Nevertheless, we should note that the current drop is only the response to a rapid change inside the z-pinch. Therefore we have to ask: what is the primary cause of electric fields and voltages in the z-pinch? From the point of view of an equivalent circuit, we have to find the source of the impedance \( Z > 10 \, \Omega \) causing the current drop and the voltage generation according to \( V = Z I \approx -L di/dt \approx 30 \, \text{MV} \). From the fluid point of view, we have to explain the electric field above 3 GV m\(^{-1}\) along 1 cm. The latter will be the subject of the following section.

4.4. Acceleration mechanisms based on the generation of axial electric fields

The origin of axial electric fields in a z-pinch can be discussed on the basis of the individual terms in a generalized Ohm’s law. In what follows, we will use Ohm’s law in the form

\[
E = -\mathbf{v} \times \mathbf{B} + n\mathbf{j} + \frac{1}{ne} j \times \mathbf{B},
\]

where \( \mathbf{v} \) is the fluid velocity, \( n \) is the electron density and where the pressure gradient and inertia terms are neglected.

Large electric fields in z-pinches are often ascribed to the \( \mathbf{v} \times \mathbf{B} \) term during global [46–49] or local [2, 9, 13, 50–53] implosions. (Note: mechanisms based on explosions [54, 55] should produce electric fields towards the anode.) However, to generate \( >3 \, \text{GV m}\(^{-1}\) \) fields at 3 MA, high implosion velocities or small diameters of a current-carrying column are needed. In fact, for the case of a \( <6 \times 10^7 \, \text{m s}\(^{-1}\) \) velocity, a magnetic field should be \( >5 \, \text{KT} \) which means a pinch radius below 100 \( \mu \)m. When we take the finite acceleration time into account, the minimal radius should be below 30 \( \mu \)m to generate an average field above 3 GV m\(^{-1}\) for 400 ps. It is not easy to imagine such a small diameter of a still-imploding, 1 cm long plasma column carrying the current of almost 3 MA. Especially when we do not observe any implosion during the ion emission. But most importantly, a sub-mm diameter would lead to high deuteron energies mainly on the axis whereas we detect similar ion energies also at a cm diameter. To explain our observations, one could hypothesize many current filaments at a large radius. In this case, however, the current in each individual filament would be lower and consequently the diameter of imploding filaments should be even smaller, likely less than one micrometer. The problem with very small diameters also occurs in the case of mechanisms based on the magnetic reconnection during the evolution of individual current filaments [24, 56, 57]. These mechanisms with astrophysical relevance do not intrinsically require implosion. However, they need a fast change of a very complex topology of high magnetic fields to explain our observations mentioned in section 3. As a result we have not been able to obtain \( >3 \, \text{GV m}\(^{-1}\) \) fields along a 1 cm gap with reasonable parameters. Therefore we should consider other terms in the generalized Ohm’s law.

As for the Hall term, the axial acceleration of ions by the \( \mathbf{j} \times \mathbf{B} \) force was considered by Haines [51] and partially also by Gribov [58] in the form of EMHD resistance [59]. In our case of reasonable fields \( B_0 \lesssim 100 \, \text{T} \), the \( \mathbf{u}_e \times \mathbf{B} \) term will reach \( 3 \, \text{GV m}\(^{-1}\) \), if the relative electron–ion velocity \( u_e \) is \( 3 \times 10^7 \, \text{m s}\(^{-1}\) \approx 0.1 \) c. It is difficult to see how such a velocity could occur in the radial direction along the whole gap of 1 cm.

As for the resistive term \( \eta \mathbf{j} \), an anomalously high value is usually explained by current-driven microinstabilities that are triggered in low-density plasmas during a disruption. In z-pinches, lower-hybrid or ion-acoustic turbulences have been supposed to be the most important [7, 60, 61] and their influence on ion acceleration was discussed [40, 58, 61, 62]. The strength of this hypothesis is that (i) anomalous resistivity does not require a sub-mm current diameter, (ii) turbulences might occur after sweeping up the plasma from a neck, (iii) their onset could be fast, and (iv) they were observed experimentally in DPFs [63]. The most problematic issue is that a sufficiently high resistance requires large values of effective collision frequencies and fluctuation electric fields. For instance, based on the energy-density consideration, the saturation level of fluctuation fields is given by [64]

\[
\frac{1}{2} \epsilon_0 E_{sat}^2 \lesssim \frac{1}{2} m_e u_e^2 = \frac{1}{2} \frac{m_e}{e} j u_e,
\]
A high impedance gap is the main principle of plasma- and gap formation in pulsed power devices is not unusual. In fact, the transition from a low impedance plasma to be con of quasi-neutrality could occur and the collisionless gap could be formed. Of course, the gap formation should be confirmed by simulations. However, from the experimental point of view, the occurrence of plasma erosion and gap formation in pulsed power devices is not unusual. In fact, the transition from a low impedance plasma to a high impedance gap is the main principle of plasma-filled diodes [65–69]. In the following section, we will therefore consider the formation of a gap where an impedance is determined by space-charge limited bipolar flow and/or by self-magnetic insulation.

4.5. Ion acceleration in collisionless gap

The impedance of a gap can be roughly estimated from the experimentally modified formula [70, 71] for parapotential flow in pinched-electron-beam diodes

\[
E_{\text{sat}} \lesssim \sqrt{\frac{n_e m_e u_e^2}{\varepsilon_0}} = \sqrt{\frac{m_e u_e}{\varepsilon_0 e}}.
\]

These equations show that it is difficult to support 3 GV m\(^{-1}\) fields by current densities \(j\) of the order of MA cm\(^{-2}\) even with relativistic electron drift velocities \(u_e\).

As shown above, there is a difficulty to justify \(>3\) GV m\(^{-1}\) electric fields and \(>10\) \(\Omega\) impedances in plasma loads. Therefore, instead of invoking anomalous collisions, attention could be drawn to another phenomenon connected with sweeping up the plasma from a neck. In necks, the line density is decreasing whereas the current density, voltage, electron drift velocity and magnetic field are increasing. Under these conditions, the breakdown of quasi-neutrality could occur and the collisionless gap could be formed. Of course, the gap formation should be confirmed by simulations. However, from the experimental point of view, the occurrence of plasma erosion and gap formation in pulsed power devices is not unusual. In fact, the transition from a low impedance plasma to a high impedance gap is the main principle of plasma-filled diodes [65–69]. In the following section, we will therefore consider the formation of a gap where an impedance is determined by space-charge limited bipolar flow and/or by self-magnetic insulation.

4.5. Ion acceleration in collisionless gap

The impedance of a gap can be roughly estimated from the experimentally modified formula [70, 71] for parapotential flow in pinched-electron-beam diodes

\[
I \ [\text{KA}] = 5.5 \frac{R}{D} \gamma \ln (\gamma + (\gamma^2 - 1)^{1/2}),
\]

where \(R\) is the (plasma) cathode radius, \(D\) is the anode–cathode gap, and \(\gamma = 1 + eV/m_e c^2\). For \(V = 30\) MV and \(R/D \approx 1\) we obtain the total current of about 1.5 MA and the impedance of 20 \(\Omega\). This impedance and the significant current drop mean that 30 MV voltages can be generated by our z-pinch if the transition from a collisional current in unstable plasmas to a beam current in a collisionless gap occurs. Such dynamics is actually analogous to the main principle of plasma-filled diodes and plasma-opening switches where the gap formation in plasma is used for power and voltage multiplication [72–74]. Several plasma-filled diode experiments, e.g. [74], even have geometry and results similar to ours. The main differences seem to be higher plasma and current densities in our experiment.

The gap formation explains not only the impedance needed for the generation of 30 MV voltages but also other observations such as ion acceleration in a tenuous region after plasma ejection from a constriction. An important counter-argument against the diode-like mechanism was raised by Haines who emphasized the role of the conservation of a momentum [61]. It is really difficult to reconcile a macroscopic momentum conservation law with MA ion currents estimated in [63]. However, if the ion current forms only a fraction of the total current (as in [19]), the total momentum is conserved as shown by Adler for various configurations of ion beam systems [75]. From this point of view, it seems more relevant to study the most intriguing result, i.e. the formation of rings in our ion pinhole images. Interestingly, similar ion pinhole images were observed in pinched-beam diodes (see figure 7 in [76]). The ring-like structures were also observed in the electron beam imprint in a plasma-filled diode [74]. The latter experiment suggests that the circular ion source might be connected with the electron flow at the anode. Even though it is still not clear how the rings are created, the similarity between our experiment and pinched-beam diodes could support the hypothesis on the gap formation. Of course, there are significant differences between our z-pinch and ion diodes. However, taking into account temporal and spatial characteristics of our ion emission and the need for the high impedance, we wonder whether the similarity of the ion pinhole images could be a pure coincidence. In our opinion, the connection of ion diodes with ion acceleration in z-pinch should be studied in more detail. We believe that it could facilitate the interpretation and simulation of physical processes in both devices.

5. Generation of \(10^{13}\) neutrons with a large neutron-producing sample

The knowledge gained in our experiment has significant implications for future research. For instance, the spatial and spectral information about the ion source helps us to increase neutron yields. As shown in figures 3, 5(c) and 7(b), many ions are accelerated at large radii. At the periphery, the number of target deuterons is low and thus off-axis deuterons cannot produce a significant neutron yield. To increase the number of neutrons, we use the following neutron-producing catcher. Below the cathode mesh, we place a 0.4 mm thick deuterated-polyethylene (CD\(_2\)\(_n\)) disk. Its diameter of 35 mm is large enough to catch most of the ions. On the axis, we use a small 1 mm thick LiF sample which is more suitable for \(>2\) MeV deuterons. The photo of the sample together with results is displayed in figure 10. The pinhole image in figure 10(b) shows a SS holder as well as the LiF sample (CD foil is not seen due to a small contrast between the SS foil and the SS foil with the CD sample). An
intense central ion beam with the end-point energy above 21 MeV hit the LiF sample. Also deuterons from the circle of a 1 cm radius interacted with the CD catcher. As a result, in the shot presented in figure 10, we achieved a high yield of \((1.1 \pm 0.3) \times 10^{13}\) neutrons. In order to be confident with absolute yields, the number of neutrons is measured by several independent techniques\(^7\). The significant neutron yield increase with a large neutron-producing sample can be seen in figure 10\((c)\) which shows the comparison of nToF signals in 3 different configurations at the same current. The black curve shows the shot with a standard D\(_2\) gas-puff z-pinch\(^8\). The blue curve displays the shot when a plasma shell is injected around a gas-puff\(^1\). Evidently, neutron energies are increased significantly, and the yield is higher by an order of magnitude. Finally, the red line represents the last improvement, i.e. \(10^{13}\) neutrons when the large neutron-producing sample is placed on the axis.

6. Conclusions

In conclusion, we have been interested in the ion acceleration mechanism in deuterium gas-puff z-pinches. High energy deuterons generated in our experiment enable us to obtain unique information for z-pinch physics (e.g. about magnetic fields during the ion emission) and to discuss various hypotheses of ion acceleration. In z-pinches, more than one mechanism might play a role. However, the comprehensive results from GIT-12 indicate that the dominant mechanism, which is able to accelerate 30 MeV deuterons, could be connected with transition of MHD unstable plasmas to space-charge limited bipolar flow. In this case, the 30 MV voltage is driven by the inductive energy which is stored around the z-pinch and which is extracted during a sub-nanosecond current drop. This behavior can be characterized as a high-density plasma-filled diode with a microsecond conduction time, nanosecond opening switch and fifty-fold voltage multiplication. The suggested mechanism could explain the time and space of ion acceleration, a high (>10 \(\Omega\)) impedance, the generation of a 30 MV voltage and the radial lines in the beam profile detector. The connection of ion diodes with particle acceleration in pinches would justify the usage of the terms ‘diode mechanism’ and ‘mini-diode’ in DPF and x-pinch papers, respectively.

The similarity between our z-pinch and ion diodes is supported by the rings observed in pinhole images. Unlike the previous works, we show that the observed rings reflect both the spatial distribution of an ion source and the influence of magnetic fields. The origin of rings of a particular diameter has not been identified but will be the subject of our future research. Since similar circles have been observed in various z-pinch configurations and in pinched-beam diodes, they seem to be suitable benchmarks of numerical codes simulating ion acceleration after the ejection of plasmas from constrictions.
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