Intense ion beams

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INTRODUCTION

The past decade in accelerator physics has been characterized by the invention and intensive development of a fundamentally new class of direct-action electron accelerators that allow powers in a pulsed regime up to 10^{14} W with corresponding current amplitudes up to units of a MA and voltages up to 10 MV.[1] These accelerators employ the principle of gradual accumulation of energy in a primary accumulator (usually an Arkad'ev-Marx pulsed-voltage generator, a pulsed transformer, or an inductive accumulator) with fast transfer of the energy to the accelerating gap of a diode system, or accelerator gun employing a shaping element (single or double shaping lines). In turn, they have led to the development of a new field: generation of intense ion beams (IIBs) in diode systems.[2-4] Application of these beams offers promise in many fields of science and technology: pulsed energetics [controlled thermonuclear fusion (CTF) of the inertial or stationary type],[5,6] nuclear physics (design of high-power pulsed neutron sources),[7] and quantum electronics (pumping of high-power lasers with stored energy per pulse up to tens of kJ).[8]

The fundamental problems of designing an efficient diode system include the need to suppress the electron component of the diode current and the provision of an unlimited ion-emissive capacity of the anode.

As the well-known Child-Langmuir (CL) formula implies,[9] the maximum densities of electron and ion beams that flow in a diode when a potential difference V_A is applied to it are determined in the nonrelativistic approximation by the expression

$$j_{e,i,\,\mathrm{CL}}=\frac{\alpha\sqrt{2e}}{9\pi}\left(\frac{Z_{e,i}}{m_{e,i}}\right)^{1/2}\frac{V_A^{3/2}}{d^2},$$

Here $m_{e,i}$ is respectively the rest mass of an electron or an ion, $Z_{e,i}$ is the charge of the electron or ion in units of the electron charge, d is the distance between the anode and the cathode, and α is a factor that depends on the character of the electron-ion fluxes in the anode-cathode (AC) gap: $\alpha=1$ in electron or ion regimes of the diode, and $\alpha=1.86$ in a bipolar regime in which the electron-ion beams in the AC gap reach their limiting values.

The expression for $j_{e,i,\mathrm{CL}}$ implies that the ion beam in the best case amounts to 2.3% of the magnitude of the electron beam. Thus, the efficiency of generating it without suppressing the electron component proves very low.

Suppression of the electron component of the diode current can be achieved by several methods: multiple reflection of the electrons, which increases the time that the electrons and the space charge stay in the AC gap of reflex systems[10]; magnetic electron cutoff in magnetically insulated diodes[11]; and increase of the transport distance of the electrons from the cathode to the anode by a factor of about r_c/d in diodes with a pinched electron beam, where r_c is the radius of the cathode.[12]

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The problem of providing a practically unlimited ion-emissive capacity of the anode is no less important, since, as is known, ion autoemission does not suffice for obtaining the required ion currents. This problem can be solved by generating a sufficiently dense plasma (10^{17}–10^{18} ions/cm^3) at the surface of the anode by electron bombardment[10] or by surface electrical breakdown,[11] or finally, by an auxiliary plasma source.[13] Here one must take into account the motion of the anode plasma, which diminishes the efficiency of generation of the IIB owing to mismatch of the diode system with the shaping element. The final temperature of the plasma determines the minimum emittance of the beam and the possibility of focusing and transporting it. This article is devoted to the problems listed above.

Section 1 treats the problems of generating IIBs in different modifications of reflex systems and the dynamics of accumulation in them of charge fluxes and of the formation of the anode plasma. Section 2 treats magnetically insulated diode systems, their fundamental characteristics and those of the ion beams that they generate. Section 3 is concerned with problems of shaping of IIBs in diodes having a high aspect ratio r_c/d. Section 4 discusses problems of neutralization, transport, and focusing of IIBs. Some fields of application of IIBs, both at present and in prospect (laser-beam generation, high-power neutron pulses, i-layer formation, inertial controlled thermonuclear fusion) are presented in Sec. 5. The Conclusion will try to formulate the fundamental lines of further studies of IIBs from the point of view of their promise for the stated fields.

1. GENERATION OF INTENSE ION BEAMS IN REFLEX SYSTEMS

The idea of employing reflection of the electrons to suppress the electron flux in an ion beam was advanced and first realized in the studies of Sudan and Humphries.[10] Its essence is as follows. An anode sufficiently transparent for electrons is placed between two cathodes (Fig. 1a). The entire system is placed in a homogeneous longitudinal magnetic field that prevents the electrons from reaching the anode holder. When a high-voltage pulse is applied to the anode, the electrons emitted by the cathodes perform multiple oscillations passing through the anode and spending their energy in

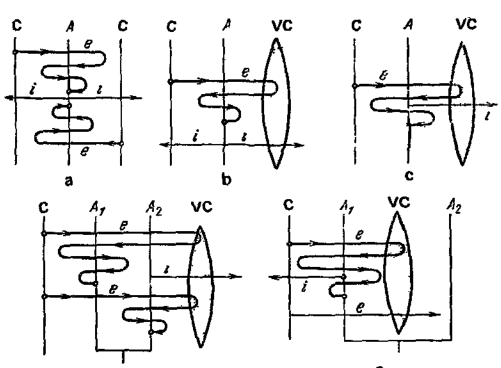

FIG. 1. Diagrams illustrating principles of design of reflex systems.

heating it and forming a surface plasma, which is the source of the ions. The ions, which are extracted toward the two cathodes, form two ion beams. When there is only one cathode, the role of the second cathode is played by the virtual cathode formed by the oscillating electrons. An analysis of the operation of reflex systems enables one to classify them on the basis of the number of ion beams generated as symmetrical (two ion beams—Fig. 1a,b) or asymmetrical (one ion beam, Fig. 1c,d). Let us examine these groups in further detail.

a) Symmetrical reflex systems

Chronologically the first scheme proposed was a double diode with a highly transparent grid anode.[10] In the one-dimensional approximation neglecting scattering at this anode, the oscillating electrons are characterized by a constant total energy $\mathscr{E}_{\text{tot}} = \mathscr{E}_K + eV = 0$ (where $\mathscr{E}_K$ is the kinetic and eV is the potential energy). The corresponding distribution function of their currents $f(\mathscr{E}_{\text{tot}})$ can be represented in the form of the δ-function $\delta(\mathscr{E}_{\text{tot}})$. This allows us directly to write expressions for the electron and ion components j_e and j_i of the current in terms of the corresponding magnitudes of the currents of the bipolar Child-Langmuir regime $j^{BP}_{e,i,CL}, j^{BP}_{i,CL}$ [see (1.1)]:

$$j_e = \frac{2 j^{BP}_{e,CL}(1-T)}{1+T}, \quad j_i = j^{BP}_{i,CL} = \sqrt{\frac{Z_i m_e}{m_i}} \cdot j^{BP}_{e,CL}. \tag{1.1}$$

Here T is the transmission of the anode.

When there is only one real cathode, the electrons oscillate between the real and virtual cathodes. In this case the corresponding expressions have the form:

$$j_e = \frac{j_{e,CL}(1-T^2)}{1+T^2}, \quad j_i = j^{BP}_{i,CL}. \tag{1.2}$$

As these relationships imply, when T is large enough, the efficiency of generation of the ion beam in the triode can approach unity, while the quantity j_i/j_e substantially exceeds it. However, here the absolute values of the ion current do not exceed the corresponding values of $j^{BP}_{i,CL}$, which lie in the range of units and tens of A/cm^2 in the employed region of voltages and sizes of AC gaps.

Within the framework of the approximation under study, one can get a certain increase in the absolute values of the currents (up to fivefold) upon going to ultrarelativistic electron energies (but, as before, with nonrelativistic ions). In this case the magnitude of the ion current density is determined by the expression[14]

$$j_i = \sqrt{\frac{Z_i e V_A}{2 m_i c^2}}\, j_e. \tag{1.3}$$

Here we have $j_e = \pi c V_A / 8d^2$.

In the more general case in which the oscillating electrons undergo scattering and energy losses in the thin anode, the distribution of their total energies ceases to be monochromatic. The corresponding Poisson equation (nonrelativistic variant) is written as follows:

$$\frac{d^2V}{dx^2} = 4\pi \left[\frac{j_e}{\sqrt{2eV/m_e}} - \frac{j_i}{\sqrt{2Z_i e (V_A - V)/m_i}} + 2\int_{-eV}^{0} f(\mathscr{E}_{\text{tot}}) \left(\sqrt{\frac{2(eV + \mathscr{E}_{\text{tot}})}{m_e}} \right)^{-1} d\mathscr{E}_{\text{tot}} \right]. \tag{1.4}$$

This has the boundary conditions: $V_C = (dV/dx)_C = (dV/dx)_A = 0$. The first two terms in the square brackets represent the local charge densities created by the opposing primary electron and ion currents, while the integral corresponds to the charge density created by the fluxes of oscillating electrons whose total energy $-eV < \mathscr{E}_{tot} < 0$. The form of the distribution function of these fluxes with respect to the energy $\mathscr{E}_{tot}$ depends on many parameters (thickness, material, fabrication, and geometry of the AC gap, V_A, etc.), and is not known in the general case. However, as analysis shows, the qualitative behavior of j_e and j_i of the triode proves not to depend on the specific form of $f(\mathscr{E}_{tot})$, and is characterized by divergence under certain conditions. Such conditions can include certain values of the contribution of the fluxes δ of scattered electrons at the anode,[14] the mean number η of transits of the anode by the oscillating electrons until they are absorbed in it,[15] or the root-mean-square scattering angle $\Delta\theta$ of an electron in passing through the anode,[16] which enter as parameters into the integrand expression for j_i and j_e. The stated divergence arises in the repeated integration of Eq. (1.4). As an example, Figs. 2a, b show the relationships of $j_i/j_{e,CL}$ and $j_e/j_{e,CL}$ to the parameter η, which is the mean number of transits of the anode, as obtained for several model distribution functions. We see from the diagram a sharp rise of the currents j_e and j_i at certain values of η. The corresponding potential pattern in the AC gap is characterized by a decline in a narrow region near the anode and the presence of a plateau over the major part of the AC gap. All this indicates complete charge neutralization in the AC gap and a sharp decline in the impedance of the diode. Analogous results were obtained upon introducing a distribution function that depends on the scattering angle. Divergence of the currents was observed at $\Delta\theta \lesssim 9°$.[16] One could continue these examples.

The specifics of the distribution of the potential and of the charge fluxes in the AC gap of the triode, together with the character of the energy losses of the electrons in the anode in the studied energy range $(d\mathscr{E}_K/dx) \lesssim V_A^{-0.4}$ gives rise to the relationship $J_i \approx PV_A^{2.5-3.5}$. This differs from the well-known CL 3/2 law for a bipolar regime of the diode.[17]

Thus, in all stationary models having a nonmonochromatic distribution function of the electrons in the AC gap of a symmetrical triode or double diode, certain conditions exist (mean number of transits of the anode, relative number of scattered electrons, mean scattering angle) for which no stationary solutions exist. That is, they correspond to divergent currents and zero impedances of the triode.

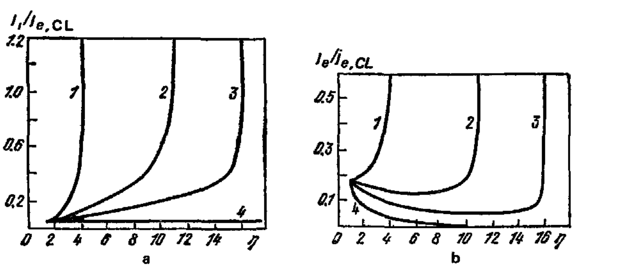

FIG. 2. Dependence of $j_i/j_{e,CL}$ and $j_e/j_{e,CL}$ on η, the mean number of transits of the anode by the electrons for various distribution functions of the electron fluxes[15] in a symmetrical triode. 1—$f(\mathscr{E}_{tot})$.

b) Asymmetrical reflex systems

A reflex triode in which only one side of the anode is a good source of ions correspondingly generates one ion beam (Fig. 1, c). A modification of the asymmetrical triode is the tetrode (Fig. 1, d), whose anode consists of two thin foils or a foil A_2 and a grid A_1 facing the cathode, so that only one ion beam is generated.[18,20]

In the tetrode geometry, the electric field of the cathode does not penetrate to the surface A_2 that emits the ions. Consequently an ion beam is extracted only in the direction of the virtual cathode. The treatment of the established regime of the asymmetrical triode[37] amounts to a simultaneous solution of the Poisson equation for the left-hand (pure electron fluxes) and right-hand (electron and ion fluxes) parts of the triode. Figure 3 gives the results of numerical solution for $j_i/j_{e,CL}$ and $j_e/j_{e,CL}$ for several assumed distribution functions of the electrons analogous to those employed above. The fundamental distinguishing features of the asymmetrical triode being discussed are:

1. The lack of divergence of the electron and ion currents for any number η of transits.

2. A corresponding lack of "collapse" of the potential in the asymmetrical triode.

We find that $j_i \to j_e$ in the asymptotic behavior as $\eta \to \infty$, with an efficiency of generating an ion beam that reaches 100%. The stationary solutions for any finite η yield values of j_e and j_i smaller than $j_{e,CL}$. This is due to the large space charge of the pure electron half of the asymmetrical triode.

In contrast to the triode, the tetrode contains three groups of oscillating electron fluxes: two of them having total energies $-eV_A < \mathscr{E}_{tot} < -eV^*$ oscillate about one of the anodes (A_1 or A_2), and one group having total energy $-eV^* < \mathscr{E}_{tot} < 0$ oscillates about both anodes. Here V^* is the minimum potential in the interanode space. Analysis of the derived solutions for $j_e/j_{e,CL}$ and $j_i/$

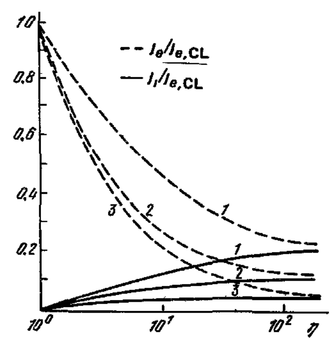

FIG. 3. Dependence of $j_i/j_{e,CL}$ on the mean number of transits of the anode by the electrons for distribution functions of the electrons in an asymmetrical triode analogous to those of Refs. 15 and 37.

$j_{e,\,\mathrm{CL}}$ shows that, just as in the case of the asymmetrical triode, the currents do not diverge, and correspondingly the impedance does not collapse.

The stationary character of the presented models restricts their field of applicability to rather long potential fronts. In this regard we note that a numerical simulation of the transition processes in the symmetrical triode or diode has shown the absence of a stationary regime for times of the order of 50–100 ns or longer (Fig. 4).[22] On the whole, the behavior of the triode proves very sensitive to the absolute magnitude of the uncompensated electron charge in the AC gap, which increases with increasing dimensions of the triode. And, while one observes self-limitation of the triode current and reaching of a stationary potential (owing to the finite impedance of the generator) for ordinary dimensions of the AC gap and areas of the electrodes, a stationary state is not reached for small dimensions (units or fractions of a millimeter). Then the densities of the electron and ion components increases exponentially. These results are of great interest with regard to obtaining superdense ion beams ($\gtrsim 10^7$ A/cm^2) at acceptable power levels of the generators. The analytical treatment of the processes of space-charge accumulation and shaping of the ion fluxes in triode configurations[23] agrees with the cited calculations.

c) Reflex triode with a massive dielectric anode

As we have noted above, the generation of an ion current stems from the processes of plasma formation at the surface of the anode. The employment for this purpose of oscillating electrons that heat a thin anode has some substantial defects, namely:

1) the need of a considerable specific energy input to the anode for generating a dense anode plasma of the order of 1 kJ/g,[24,25] and a corresponding delay time (20–30 ns) of the onset of generation of the ion beam after the high-voltage pulse has been applied to the triode[26];

2) the short working life of film anodes, which restricts reflex systems to a single-pulse regime.

An alternative is to employ surface breakdown of a massive anode with generation of a thin layer of dense plasma (10^{17}–10^{18} ions/cm^3) at the front of the high-voltage pulse. This method is widely applied in ionic magnetically insulated diodes[11] (for more details, see Sec. 3). In this case the generation of the ion beam begins considerably earlier than when the anode is heated by the oscillating electrons, and it is carried out in a few nanoseconds.

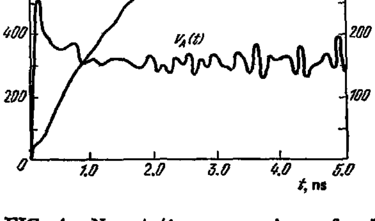

FIG. 4. Nonstationary regime of a double diode.[22]

In a reflex triode with a massive dielectric anode, the electrons emitted by the cathode move through apertures in the anode in a strong guiding magnetic field that enables suppression of losses of electrons at the anode.[27,28]

d) Comparison with experiment

Under real conditions, if special measures are not taken, the ion beams are mainly composed of protons. This results from the maximal mobility of protons and the high content of hydrogen in the employed dielectrics and vacuum oils of the accelerators. Use of special materials, coatings of the electrodes, or of an auxiliary plasma source, etc., enables one to get ion beams of the heavier elements.[13,29–31]

On proceeding to the basic experimental results, we note the specificity and complexity of the diagnostics of high-current ion beams. This arises from their considerable charge and current neutralization and the high energy deposition of the beam upon interacting with the contact measuring electrodes. This process evaporates the surface layer of the latter at ion current densities $j_i \gtrsim 30$ A/cm^2. The situation is also complicated by secondary electron emission from the surface of the transducer, which can exceed the value of the ion current. The problems of IIB diagnostics have been treated in a number of studies.[31–33]

Apart from the first case, a unifying feature of the stationary models of symmetrical triodes is the divergence of the ion and electron currents and the corresponding "collapse" or the impedance. In actual instruments having a finite impedance of the generator and a self-inductance of the triode, the decline in impedance of the triode causes a mismatch with the shaping element and limits the current level. On the basis of what has been said, one can expect experiments to yield values of $j_i/j_{i,\,\mathrm{CL}}$ substantially larger than unity, which increases with decreasing impedance and with increasing voltage in the system, as is actually observed. In an apparatus having an internal resistance of the order of 1 ohm,[29] the values of $j_i/j_{i,\,\mathrm{CL}}$ reached 30 as η increased, with a corresponding fall in the impedance of the triode. Yet in experiments in accelerators having an internal resistance of ~7 ohms,[26,34] this quantity did not exceed 6. Studies of the dynamics of formation and movement of the plasma in the AC gap have established the fact that the sharp decline in impedance is due to neutralization processes, rather than to decrease in the equivalent gap of the diode $d = d_0 - v_p t$, where v_p is the velocity of the plasma.[35] At the same time, in agreement with Ref. 21, generation of an IIB in an experimental asymmetrical diode is not accompanied by a fall in impedance.[35,36] Analogous results have been obtained for a tetrode.[18,37]

Depending on the time of formation of the anode plasma after the onset of the voltage pulse, the operation of actual reflex systems is classified into two regimes[37]:

1) the regime of late plasma formation, in which processes of accumulation of space charge of the oscillating electrons prevail, and one observes an increase in the total current in the system with increasing thickness of the anode;

2) the regime of early plasma formation, in which neutralization processes prevail, and one observes a decrease in the total current with increasing thickness of the anode.

The former regime is characteristic of systems having conducting anodes and moderate current amplitudes, in which the plasma is generated 25–30 ns after the onset of the pulse, owing to heating of the anode.[26]

The latter regime is observed in systems having an anode made of a dielectric or in systems having a conducting anode at large current amplitudes.[29,35]

The IIB extracted on the side of the virtual cathode proves to be considerably underneutralized (up to 50%).[24,28] In this connection, it seems interesting to employ inverted tetrodes in which the IIB is extracted through the real cathode (Fig. 1, d). This scheme of a reflex system permits higher levels of ion currents and better match with the accelerator in the low-impedance mode.[39,40]

On the whole, experiment indicates a substantial nonstationary character of the intratriode processes. Depending on the particular experimental conditions, this can be manifested in oscillations of space-charge density and concomitant UHF generation,[41,42] in periodic generation of the ion beam,[43] and in collective processes that accelerate a small fraction of the ions to an energy that exceeds by a large factor the voltage applied to the system.[38,44] The largest obtained efficiencies of actual reflex systems remain somewhat smaller than the calculated. They are as much as 40% and 70% for symmetrical and asymmetrical triodes (or tetrodes), respectively. The maximal attained values of currents in IIBs in reflex systems at present amount to $\lesssim 1$ MA at a power level $\lesssim 1$ TW.

2. GENERATION OF INTENSE ION BEAMS IN MAGNETICALLY INSULATED DIODES

The idea of employing magnetic insulation in ion diodes was first proposed by Winterberg.[45] The essential point in magnetic insulation consists of applying an external (or intrinsic) magnetic field to the region of the AC gap perpendicular to the electric field, of a magnitude that will suppress the passage through the diode of the electron component of the current (Fig. 5, a, b). Here the electron fluxes turn out to be confined to a layer next to the cathode whose thickness depends on the external parameters: the potential difference, and the magnitudes of the AC gap and the magnetic field. Owing to their considerably larger mass, the ions that transit the AC gap suffer only a small deflection in the transverse magnetic field. The minimal magnetic field at which cutoff of the electron current sets in, B_{cr}, depends on the geometry of the magnetically insulated diode (MID) itself and on the applied potential difference, on the geometry of the insulating magnetic flux, on whether it is conserved in the AC gap, on its rise time, and on the character of the rise. In particular, if we treat a stationary external field with magnetic flux conserved in the AC gap, B_{cr} is determined by the following relationships[46,47]:

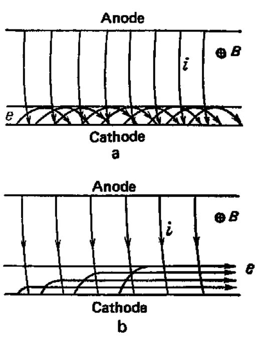

FIG. 5. Diagram illustrating the principle of ion-electron fluxes in a magnetically insulated diode.[13] a) Drift electron flux; b) Larmor electron flux.

a) for a planar MID:

$$B_{cr} = \frac{J_0\sqrt{2U_A+U_A^2}}{cd}; \qquad (2.1)$$

b) for a coaxial MID with an azimuthal direction of the insulating magnetic field[49]:

$$B_{cr}(A) = \frac{J_0\sqrt{2U_A+U_A^2}}{cr_A \ln (r_A/r_C)^i}; \qquad (2.2)$$

c) for a coaxial MID with an axial direction of the insulating magnetic field[49]:

$$B_{cr} = \frac{J_0}{c}\cdot\frac{2\sqrt{2U_A+U_A^2}}{ir_A[1-(r_C/r_A)^2]}. \qquad (2.3)$$

Here we have $J_0 = m_e c^3/e$, $U_A = eV_A/m_e c^2$, r_A, and r_C are the radii of the anode and the cathode, and $i=1$ for $r_A > r_C$, while $i=-1$ for $r_A < r_C$, respectively.

A treatment of the established regime of an MID yields different results, depending on the assumed form of the electron fluxes in the layer next to the cathode: a Brillouin drift flux or a flux with Larmor orbits. Let us examine these regimes.

a) Magnetically insulated diodes with a drift electron flux

Some necessary assumptions for establishment of this type of flux are an increase in the electric field intensity that is slow in comparison with the cyclotron period, together with closed orbits of the drift flux, so that subsequent emission of electrons at large values of the electric field will be suppressed. A simultaneous solution of the equations of motion of the ions and the electron drift with the Ampere and Poisson equations yields a system of equations that enable one numerically to determine the diode potential difference and the corresponding amplitude of the ion current for a certain value of Bd:[14]

$$j_i = \frac{9}{4}(kd)^2\frac{j_{i,CL}}{U_A^{3/2}}. \qquad (2.4)$$

Here k is a parameter that is determined from the system of equations, and which depends on the magnitude of Bd.

Analysis of (2.4) shows that a certain value of the anode potential exists for each value of Bd at which divergence of the ion current sets in. This value corresponds to complete overlap of the diode gap by the electron layer, i.e., actually the condition of magnetic insulation breaks down.

b) Magnetically insulated diodes with Larmor electron orbits

In contrast to the approach in which one postulates establishment of a Brillouin flux upon slow increase in the diode potential, Refs. 46–49 have treated an established motion of the electrons in the AC gap in orbits of Larmor radius when the total potential V_A is suddenly applied.

The finding of the electron and ion components of the diode currents for assigned values of Bd and V_A (for a planar diode[46–48]), or of B, r_C, r_A, and V_A (for a coaxial diode[49]) is reduced to numerical integration of a system of two second-order differential equations in the potentials V and A. The results of the solution for the planar case are given in Fig. 6, a, which shows the relationship of the ion and electron currents to the magnitude of the insulating magnetic field B/B_{cr} for several values of the diode potential for two models: in the approximation of a strong magnetic field[47] ($B \gg B_{cr}$) and for $B \approx B_{cr}$.[48] In contrast to the results of Ref. 14, the model of Ref. 48 predicts a finite increase in the ion current at $B/B_{cr} \approx 1$ by a factor from 3 to 6. Qualitatively this can be explained by the filling of the AC gap with electrons moving in Larmor orbits, whose length is larger by a finite factor than the AC gap (and correspondingly, the time they spend in the AC gap is longer than in the case $0 \leq B \ll B_{cr}$). Upon taking the limit of $B \to 0$, $j_i/j_{i,\,CL}$ approaches the value 1.86 characteristic of a bipolar flux. Upon increase of the external magnetic field to $B/B_{cr} \gg 1$ the results of the models of Refs. 48 and 47 agree, and they yield the value $j_i/j_{i,\,CL} = 1$. A treatment of the coaxial geometry of a MID[49] shows that, in contrast to the planar geometry, there may be no stationary solutions for diodes having $r_A > z_C$ for values of the insulating magnetic fields $B > B_{cr}$, and which are greater than some value that depends on U_A and r_C/r_A. Figures 6, b, c show the relationship of $j_i/j_{i,LB}$ to the parameter R_w for some values of r_C/r_A with the cathode lying outside or inside; here $j_{i,LB}$ is the Langmuir-Blodgett[50] limiting ion-current density for a one-component ion flux in a coaxial configuration, while the quantity R_w is defined by the expression[49]

$$R_w = \frac{W_A}{\sqrt{2U_A + U_A^2}}. \tag{2.5}$$

Here we have $W_A = eA/m_e c^2$. In the case of a conserved magnetic flux, the parameter R_w is equal to $R_w = B/B_{cr}$.

Figures 6, b, c imply that stationary solutions do not exist for $r_C/r_A < 1$ for values $R_w > R_{w,\,lim}$. This involves the discontinuous character of the behavior of the potential at the edge of the electron layer and the thickness of the layer itself at certain values of j_e and j_i. Of course, this does not imply impossibility of obtaining magnetic insulation in actual MIDs, which exhibit a velocity distribution of the electrons in the region of the layer near the boundary. That is, the fundamental condition of the model being treated is not satisfied that a cold flux exists at the boundary: $v_r = 0$. When the given limiting requirement is removed, integration of the stated equations yields solutions for all regions of B/B_{cr} including $B/B_{cr} \gg 1, j_i/j_{i,LB} \approx 1$.

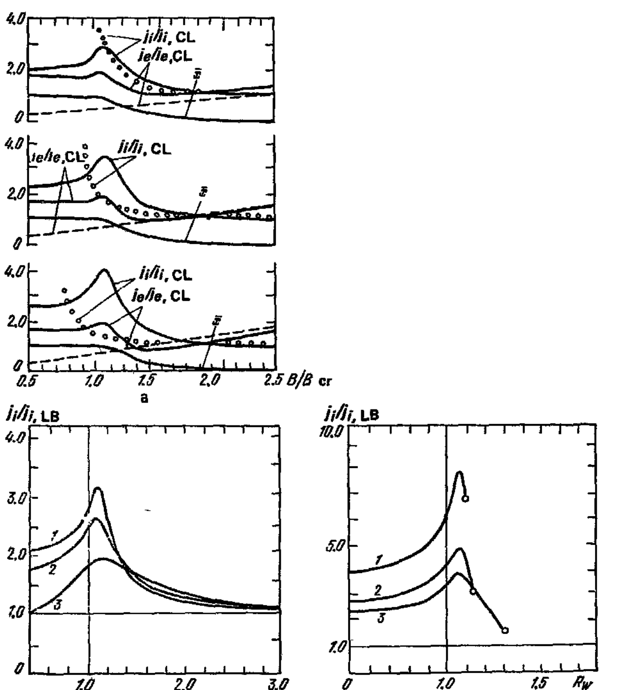

FIG. 6. Dependence of j_i/j_{iCL} and $j_e/j_{e,CL}$ for a planar magnetically insulated diode on the quantity B/B_{cr} (solid curves—model of Ref. 48, dotted curves—model of Ref. 47); b) dependence of $j_i/j_{i,LB}$ for a coaxial magnetically insulated diode on the quantity $R_w = B/B_{cr}$ for the arrangement with the cathode outside: $r_C > r_A$[49]; $U_A = 1$; insulating magnetic field is azimuthal, $r_C/r_A = 1.5$ (1), 3.0 (2), and 9.0 (3); c) the same with the cathode inside: $r_C < r_A (r_A/r_C = 1.5$ (1), 3.0 (2), and 9.0 (3).

c) Comparison with experiment

In the first experimental studies on MIDs,[51,52] a fundamental difficulty was the problem of creating an efficient source of the anode plasma. This source must generate a homogeneous and dense plasma over large areas in times short in comparison with the pulse durations (~1 ns). Originally filament anodes made of hydrogen-containing material were employed for this purpose. Subsequent modification led to design of a composite massive anode in which the plasma is generated at the surface of insulated regions of the anode as surface breakdown develops in them.[11] Just as in the case of the filaments, the onset of surface breakdown arises from the transition potentials that develop over the surface of the insulated regions of the anode as a high-voltage pulse is applied to it. Anodes of this design have been widely used in MIDs, owing to a number of advantages over nonrigid filament anodes. They make possible:

1) "colder" ion beams, i.e., beams with a smaller emittance;

2) rigid geometric adjustment of the entire system;

3) an effective yield of ≈100% of the ion beam, since the plasma-generating regions (the insulated inserts) can be positioned at the necessary sites opposite the corresponding apertures in the cathode;

4) employment of rigid-type cathodes (not grids), which can withstand the magnetic pressure of fast pulsed fields.

The experiments that have been performed[51–55] have shown that an MID generates ion beams with current amplitudes up to $(2-5)J_{i,\,CL}$. We must note that, as a rule, the insulating magnetic fields have considerably exceeded B_{cr} (by a factor of 2 to 3). At the same time, when operating at $B \gtrsim B_{cr}$, large electron leakages were observed. However, the divergence of the ion current predicted by the model[14] was absent. The difference between the calculated results[14] and the real situation involves the fact that the pattern of an initial Brilluoin flux formed on a slow voltage front is altered as the drift electrons leak out into a pattern of movement of electrons in large Larmor orbits. This corresponds to the treatment in Refs. 48–49, which agrees rather well with the experimental results. The efficiency of generation of an IIB depends on the character of the drift of the electron flux in the crossed E, B fields in the AC gap and the overall magnitude of the electron leakage. The latter comes to dominate when lines of force exist in the AC gap that simultaneously intersect both electrodes. This arises from the passage along them of an electron current that loads the diode. The drift along the unclosed trajectories leads to breakaway of the near-cathode electron flux at the edge of the cathode, accompanied by local oscillations of the electron density and UHF generation.[51] The stated high conductivity along the magnetic force lines in the vacuum for plasma or cold electrons makes possible the creation of a pseudocathode surface along them. In connection with this, nonparallelism of the surfaces of the MID electrodes to the magnetic force lines can lead to breakdown of the homogeneity of the ion flux and to local density variations in it by a factor of 2–5.[11,51] In the light of what we have presented, a high efficiency of ion-beam generation in an MID is possible if we provide for:

a) parallelism of the magnetic force lines to the electrode surfaces;

b) absence within the AC gap of lines of force that intersect both the anode and the cathode; a maximal length of the lines of force that intersect these electrodes outside the AC gap, and a minimal field intensity at the surfaces of the electrode that emit electrons in the region of intersection with these lines;

c) closure inside the AC gap of the trajectories of drift $(E \times B)$ of the electron magnetized flux. Figure 7 gives an example of an MID that satisfies the fundamental requirements.[55] The insulating magnetic field of the diode is created by passing a current directly through the cathode, which has the form of a θ-loop with slits. The fast risetimes of this field (units or tens or microseconds) ensure that the massive anode and cathode will be impenetrable to it and that the magnetic force lines will be "layered" parallel to their surfaces. The corresponding field geometry leads to an azimuthal closed drift of the electrons inside the AC gap, while the magnetic force lines that intersect the anode and the housing (emitting surface) have a maximal length together with a minimal electric field intensity at the site where they intersect the housing. The efficiency of ion-beam generation in the cited MID is as much as 80%, or $\gtrsim 50\%$ when corrected for output losses.

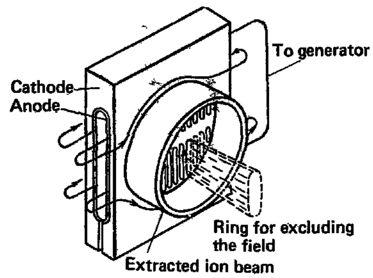

FIG. 7. Diagram of an MID with a θ-loop-type cathode.[55]

In contrast to triode systems, the plasma movement in an MID, which leads to reswitching of the diode, occurs transverse to the magnetic field. It has been established experimentally that application of a magnetic field to the AC-gap of an MID hinders the movement of the anode plasma.[53,60] The measured plasma velocities lie in the range 0.3–0.5 cm/μs. This makes it possible to generate IIBs with microsecond durations.[53,61]

Thus, on the basis of comparing the entire set of experimental data with the theoretical predictions, one can conclude that they agree well in the region $B \gg B_{cr}$ and satisfactorily in the region $B \approx B_{cr}$. In spite of the moderate values of the ion current density (up to hundreds of amperes per cm^2), the possibility of employing large anode areas (≈2000 cm^2) has made it possible to generate in an MID an IIB with a current amplitude ≈0.4 MA at a power level 0.4 TW with an efficiency up to 80%.[57–59]

3. GENERATION OF INTENSE ION BEAMS IN DIODES WITH A PINCHED ELECTRON BEAM

a) Analytical and numerical models

The possibility of using pinching of electrons to generate IIBs stems directly from the results of experimental and theoretical studies on shaping of electron fluxes in diodes having a large aspect ratio r_C/d. An important characteristic of such a diode is the magnitude of the critical current that creates at the periphery of the electron beam in the diode a magnetic field sufficient to return the outer electrons to the axis of the diode, i.e., to pinch the beam. From simple considerations of equality of the Larmor radius of the electron to the size of the AC gap, one can find an expression for the critical current of the diode[62]:

$$J_{cr} = \frac{J_0}{2}\,\frac{(\gamma_A^2-1)\,r_C}{d}. \quad (3.1)$$

One can treat this value as a lower estimate of the diode current at which an electron flux is shaped that converges toward the axis of the diode. In this regime we have $J < J_{CL}$. In this geometry of the flux, the time of crossing the AC gap by the electrons is increased approximately by a factor of r_C/d over the case of a planar CL flux. When the condition of charge-limited emission $E_A = E_C = 0$ is satisfied, i.e., when the charges of the ions and the electrons in the AC gap are equal, the ratio J_i/J_e is defined in the first approximation by[63]:

$$\frac{J_i}{J_e} = \frac{r_C}{cd}\sqrt{\frac{Z_i e V_A}{2m_i}}. \tag{3.2}$$

This formula implies that J_i/J_e can be comparable with unity for a large enough value of r_C/d. Here the absolute magnitude of the ion current depends on the value of the current J_e in the convergent electron flux.

The intradiode processes that shape this flux include the increase in the intrinsic magnetic field, the formation and motion of the electrode plasma, and also the motion of the ions. All these factors are interrelated and nonstationary, which makes an exact analysis impossible. Intensive experimental, theoretical, and numerical studies on the movement of the anode plasma and its effect on the pinching of the electron beam have led to a sufficiently complete understanding of all the processes that occur here.[64-68] Numerical calculations showed the possibility of strong pinching of the beam in the layer of plasma next to the anode having a density of 10^{15} cm^{-3}, which screens the electric field of the electron beam. However, the established velocities of movement of the anode plasma (a few cm/μs) do not make possible the needed thickness of the plasma anode layer for turning the electrons toward the cathode in the shaping time of the pinch.

Further studies have led to an understanding of the important role played here by the ions.[63,69,70] Qualitatively the sequence of the transition to a focused flux appears to be the following:

a) establishment of a CL charge-limited flux in the diode;

b) transition under the action of electromagnetic forces to the stage of a weak pinch when the current reaches a value close to the critical;

c) Generation of an anode plasma at the periphery of the anode, where the direction of motion of the electrons near it is mainly radial, which leads to a more intense local heating of the anode;

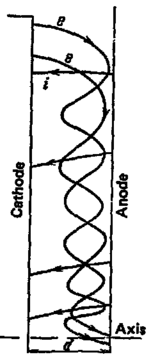

FIG. 8. Diagram illustrating principle of the electron-ion fluxes in a diode with a pinched electron beam.[63]

d) appearance of a charge-limited flux of ions from the plasma toward the cathode;

e) repeated turns of the electrons toward the cathode under the action of the intrinsic magnetic field of the beam in the ion sheath that compensates the Coulomb field, which leads to rapid constriction of the electron flux toward the axis of the diode;

f) establishment of a radially-convergent flux of electrons with an axial flux of ions.

Whenever hollow cathodes with a small wall thickness are employed, the weak-pinch stage does not precede the shaping of the ion current, but follows it. This is associated with the small magnitude of the current for these cathodes in the CL stage.[70]

Figure 8 shows the trajectories of the electrons and ions in the established regime of the pinch. These trajectories agree with the results of the numerical calculations[69] and amount to a much more complex motion than a simple radial flux.

One can determine the total current of the diode in the stationary phase by several analytical approaches[71-74] that employ certain assumptions about the character of the established flux, or by direct numerical experiments[69] that employ no special assumptions. An idea fundamentally new at the time was the introduction of the concept of a parapotential electron flux in the AC gap of a planar diode as a flux along conical equipotential surfaces whose vertices lie on an axis near the anode.[71] An equilibrium state of this flux without neutralizing ions is made possible by an auxiliary magnetic field arising from the neutralized axial current, whose value determines the angle of inclination of the equipotential surfaces and is an input parameter.

In the model that employs the assumption of parapotentiality: $\mathbf{E} = -\mathbf{v}\times\mathbf{B}$, $\mathbf{p} = \text{const}$, $\mathscr{E}_e = \text{const}$, under the condition $J > J_{cr}$ the simultaneous solution of the Poisson and Ampere equations yields the following expression for the diode current[72]:

$$J_{pp} = J_0 \gamma_A \ln[\gamma_A + \sqrt{\gamma_A^2 - 1}]\frac{g}{2}. \tag{3.3}$$

Here g is a geometric factor, which for planar diodes is equal to $\approx r_C/d$. The defects of the model include the impossibility of emergence of the electrons toward the anode, which is implied in the condition itself of parapotentiality of the flux.

Almost the same expression follows from the approximation of a cold focused flux[73] without using the assumption of parapotentiality and without consideration, as in Ref. 72, of the ion current and the movement of the plasma in the AC gap. In the studied model of a planar diode, the equipotentials differ only slightly from planes, and the resulting electron flux is characterized by weak pinching.

A joint treatment of the ion and electron fluxes allows one to employ the parapotential approach without assuming the presence of an axial neutralizing current. As has been shown in Ref. 74, the self-consistent analytical solution in this case can be obtained for a diode with a smooth variation of the quantity $r/d(r)$ where r and $d(r)$ are the current radius and AC gap, respectively, as characterized by the presence of a minimum. In the cited models,[63,74] the ion current density increases with decreasing radius as $1/r^{1-2}$.

Numerical calculations[69] give a pattern of the distribution of equipotentials and established electron-ion fluxes far from confocality in the studied models.[72,74] Nevertheless, such integral characteristics as the magnitude of the predicted total currents and of the ion current of the diode and the radial dependence of the ion current density agree satisfactorily enough with one another.

b) Comparison with experiment

An analysis of the entire set of experiments over broad ranges of variation of the voltage from 0.1 to 2.5 MV, currents up to 2 MA, aspect ratios $r_C/d=6$ to 23, and varying degrees of conicity of the cathodes allows one to conclude that the model of a Brillouin parapotential flux is preferable for calculating the overall diode current $J_{pp}=J_e+J_i$, if they do not employ corrections for the variation of the AC gap caused by plasma movement. Attempts to approximate the experimental results with hollow cathodes by an empirical expression yield the formula $J=0.65J_0[r_C/(d-\Delta)]\gamma_A\ln(\gamma_A+\sqrt{\gamma_A-1})$, where Δ has the form of a constant coefficient equal to 0.15 cm.[70] This can indicate a substantial deceleration of the cathode plasma by the magnetic field.[64,72] At the same time, in a number of other experiments[75] that assumed constant velocity of motion of the plasma, the results are well approximated by the empirical formula

$$J_i+J_e=J_{cr}\left(1+\frac{r_C}{d}\sqrt{\frac{eV_A}{2m_ic^2}}\right). \tag{3.4}$$

The magnitudes of the ion currents show good agreement with Eq. (3.2) throughout the set of experiments with a massive anode and with different cathodes. Here the onset of IIB generation follows exactly 10 ns after the transition to the pinch phase.

The experimentally determined densities of energy deposition in anode materials up to the moment of pinching of the beam amount to ≈1 kJ/g. They are attained 20–35 ns after the onset of the pulse.[76,77] The results of calculations of the energy input necessary for desorption of the surface layer of gases and material to form a dense plasma agree with the corresponding experimentally observed values and with the time for appearance of an ion current. The fact has been experimentally established that an IIB is generated earlier when the anodes are made of heavy materials.[76] The latter corresponds to the higher energy-deposition density in heavy materials, which corresponds to greater local heating of the anode and early plasma formation.

In line with the fact that the ions are related to the desorbed gases (water vapor, organic molecules of oil, carbon dioxide, hydrogen atoms), the motion of the front in the initial stages of shaping of the ion beam arises from the most mobile H^+ ions.

Experiments[77] have confirmed the increase in the beam density in the near-axis part of the anode, which involves the increase in this region of the axial electric field as predicted by numerical calculations and models[63,74] (Fig. 9).

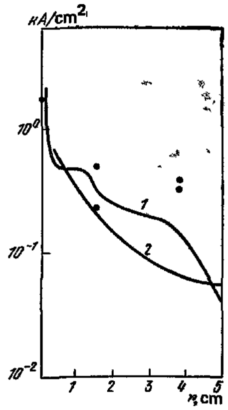

FIG. 9. Radial dependence of the ion current density in a diode with a pinched electron beam. 1—results of numerical calculations[69]; 2—curve corresponding to the model of Ref. 63; solid circles—experimental results.

We must note that, in experiments that have employed a thin, electron-transparent anode[78] instead of a solid anode, the obtained values of the ion currents considerably exceeded those calculated by Eq. (3.2). This stems from the reduced losses of the electron beam at large radii in a thin anode and the resulting increase in space-charge density of the electrons in the pinch. Moreover, the oscillations of an electron about the anode in its movement toward the axis of the anode increase the time that it spends in the AC gap and correspondingly increase the ratio J_i/J_e. This pattern possesses the characteristic traits of the reflex systems. By using such a pinch-reflex diode set up in the accelerator "Python", IIBs have been obtained with a mean current density at the anode of $\gtrsim 10$ kA/cm^2 and an amplitude of the order of 1 MA at a voltage of 2 MV. This corresponds to an efficiency of 60%.[106]

In summing up what we have presented above, we can note that up to now the pattern of shaping of an IIB in a diode with a pinched electron beam seems clear enough in general outline. In spite of the stationary character of the parapotential models, they yield integral characteristics of the IIB that agree with experiment.

4. TRANSPORT AND FOCUSING OF INTENSE ION BEAMS

One of the most important problems involved with the use of intense beams of both electrons and ions is the problem of focusing and transporting them. As we know, several factors exist for intense electron beams that restrict their transport to large distances. They include, first of all, the effect of various instabilities and the existence of a critical current that prevents transporting currents above this limit. From this standpoint, intense ion beams must have considerable advantages, since their critical currents are larger by a factor of $\approx(m_i/m_e)^{1/2}$ than those for electron beams, and they amount to several megaamperes. Thus instabilities will not exert a substantial effect on the stability of ion beams. Let us examine in greater detail the problems of transport and focusing of ion beams.

The high density of intense ion beams of 10^{11}–10^{13} ions/cm^3 has the result that, if the beams are not neutralized, the sag of potential in them can reach hundreds and thousands of kilovolts. The corresponding field intensities of 10^5–10^6 V/cm cause such a beam to dissipate at distances of the order of its transverse dimensions. This entails the need of complete charge neutralization of ion beams for extracting them from diode systems. One must also take into account the fact that all ion beams produced in diodes have an intrinsic temperature that is determined by the temperature of the generating plasma. This leads to an additional broadening of the drifting beam. The experimentally established temperatures of the anode plasma, which depend on its method of formation, lie in the range of from a few to tens of electron volts.

a) Mechanisms of neutralization and transport of intense ion beams

The drift of the cold electrons and the plasma electrons along the magnetic force lines determines the fundamental mechanisms of neutralization of IIBs in a diode system, which depend on the magnitude and the mutual directions of the magnetic field and the IIB. In reflex systems, in which the ion beam is extracted along the magnetic lines of force, its charge and current neutralization is provided by electrons drawn from the virtual or real cathodes, depending on the direction of extraction of the IIB. The corresponding energies of the neutralizing electrons lie in the range $\mathscr{E}_e \sim AeV_A(m_e/m_i)$,[13] where A is a coefficient of the order of unity.

In the AC gap of a MID, the ion beam propagates perpendicularly to the magnetic lines of force, and is not accompanied by cathode plasma electrons. In this case, the charge neutralization of the IIB when extracted from the diode is brought about by cold electrons extracted by the electric fields of the beam from the walls along the magnetic lines of force, or by plasma electrons from an auxiliary source. Such an auxiliary source can be a dielectric surface on which a part of the ion beam falls and generates a plasma over it.[11] Analysis shows that neutralization of the space charge of the IIB by cold electrons remains incomplete in the case in which their motion is symmetric in the trans-cathode space with respect to the ion beam. Introduction into this geometry of scattering centers, and also a diminution of the angle between the magnetic-field direction and that of the ion beam, etc., result in breakdown of symmetry and "tangling" of the trajectories of the cold electrons. They make possible a sufficiently complete charge neutralization of the IIB within a time of the order of fractions of a nanosecond.[80,81]

In the case in which fast magnetic fields are employed in an MID that do not succeed within the duration of the pulse in penetrating through the cathode into the trans-cathode space, the charge and current neutralization of the ion beam by cold electrons occurs when they are extracted from the exit windows of the cathode along the direction of motion of the ion beam.[57,82]

Alternative possibilities of neutralization of an IIB in the systems under study are ionization of the residual gas in the drift region or preliminary production of a plasma. This method is highly effective for extracting an IIB from a pinch diode in which the large magnetic self-fields can lead to current decompensation of the IIB.[83]

Propagation of a charge-neutralized IIB along a line having a finite inductance gives rise to a retarding inductive emf. Its magnitude, as determined by the well-known formula $\mathscr{E}_{\text{ind}} = [1 + 4\ln(R_{\lim}/r_b)]J_i/\tau_{\text{ph}}$ considerably exceeds the kinetic energy of the beam for the megaampere range of the IIB. Thus, in spite of the fast neutralization of the space charge of the IIB by cold or plasma electrons, its propagation becomes possible upon complete current neutralization. In this regard, it is promising to use preformed plasma channels with a high enough density (10^{17} ions/cm^3) and conductivity ($\sigma > 2\times10^4\,\Omega^{-1}\text{m}^{-1}$), in which the vortical fields arising from the established current will be of the order of kV/cm.[83] The diffusion time of the magnetic field in such a channel is $\tau_{\text{dif}} \approx 4\pi r_c^2\sigma/c^2 \approx 10^{-6}$ s, and the IIB will be transported in force-free equilibrium with an angle of divergence determined by its initial emittance.

In order to increase the distance of transport of an IIB, it is expedient to employ longitudinal and azimuthal magnetic fields created by auxiliary sources or by passing an axial current along the plasma channel.[83] The needed value J_c of the current for confining the IIB in such a channel can be determined from the condition of conservation of the canonical angular momentum of an ion injected into a channel of radius r_c with an angle of injection θ, radial coordinate r_{inj}, and energy $\mathscr{E}_i$[84]:

$$c\sqrt{2m_i\mathscr{E}_i}\,(1-\cos\theta) = Z_i e\int\limits_{r_{\text{inj}}}^{r_c} B_\theta\,dr. \tag{4.1}$$

In the special case of an ideal channel having a homogeneous current distribution, one can derive from Eq. (4.1) the following expression for J_c:

$$J_c = \frac{c^2\sqrt{2m_i\mathscr{E}_i}\,(1-\cos\theta)}{Z_i e\,[1-(r_{\text{inj}}/r_c)^2]}. \tag{4.2}$$

As an example, for a proton beam of energy $\mathscr{E}_i = 2$ MeV and $\theta = 10°$, we have $J_c = 30$ kA, while for a C^{+4} ion beam of the same energy, $J_c = 100$ kA.

Under actual conditions, the channel is created by passing a slowly increasing current along it. Here the conductivity of the channel remains low, while the current distribution over the cross-section is homogeneous. Injection of the IIB into the channel is accompanied by intense heating of the latter by the return current and by ionization losses. It is also accompanied by fast local increase in the conductivity of the channel (breakdown) and transition to a state having a "frozen-in" field. The heating of the channel and the electrodynamic interaction with the IIB expand the former. The beam pushes the channel apart upon penetrating into it and squeezing the magnetic field to the periphery. Estimates of the attainable expansion of the channel within the time of passage through it of the IIB give the following relationship between the parameters of the channel and the IIB:

$$J_c J_i < \frac{3c^2 r_C^4 \rho}{\tau^2}. \tag{4.3}$$

Here ρ is the density of the channel and τ is the duration of the IIB.

Numerical and analytical studies of the interaction of an IIB with a nonideal channel under conditions of development of various types of instabilities[85–87] have shown a good efficiency of transport of IIBs with a current up to 1 MA. In particular, a plasma channel makes possible the effective confinement of an Hb as sausage instabilities develop in it with a wavelength much smaller than the corresponding wavelength of betatron oscillations of the ions in the channel. At greater values of the current, the losses of ions at the periphery of the channel become unacceptably large.

The first experiments on transport of IIBs in plasma channels have been performed at a current level $J_i \lesssim 0.3$ MA and voltage $V_A \sim 1.4$ MV. The corresponding efficiency of transport attained values of $\gtrsim 50\%$.[88]

b) Ballistic focusing of intense ion beams

Whenever complete current and charge neutralization exist, the ion beams propagate in force-free equilibrium with an emittance determined only by their temperature. This enables one to employ the so-called ballistic focusing inside or in the immediate vicinity of the diodes. In the case of reflex systems, these conditions can be satisfied most simply in a spherical or coaxial reflecting triode (or tetrode) without an external magnetic field.[89]

The application of ballistic focusing in magnetically insulated diodes is attractive in connection with the possibility of shaping the needed surface of the plasma while allowing for the divergence of the IIB owing to Coulomb repulsion in the AC gap and aberration in passing through the cathode windows. This possibility is based on the use of fast magnetic fields whose diffusion time inside the conducting electrodes of the system considerably exceeds the pulse duration. An analogous magnetic "cushion" can be created upon passing a current that generates an insulating magnetic field through the electrodes of the diode[55,56] or in self-insulated diodes.[90] The use of fast magnetic fields limited to the AC gap can enhance the degree of ballistic focusing of an ion beam by a factor of $r_A/2d$ compared with the case of fields that penetrate into the trans-cathode space. This is associated with a considerable decrease in the distance of transport of the ion beam in a transverse magnetic field.

The application of a compensating magnetic field that fills the trans-cathode space and which is reversed with respect to the main field enables one completely to eliminate the limitation on focusing imposed by the deflection of the ions in the magnetic field B. The corresponding value of the compensating field is $B_{comp} = (2d/r_A)B$. One can get this same result by applying a field of closed configuration, so that the total magnetic flux intersected by the ions in moving toward the focus also proves to be zero.[3]

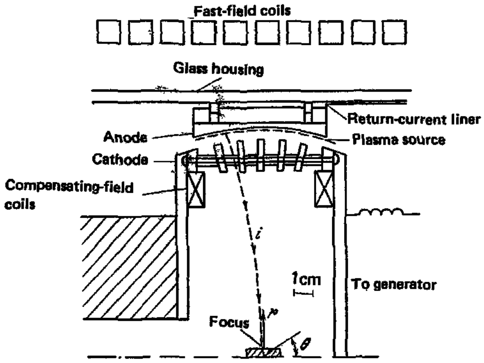

FIG. 10. Diagram of a spherical MID with a compensating magnetic field.[91]

When one employs massive electrodes and fast fields, the latter inevitably sag into the exit cathode windows to give rise to a wavy surface of the virtual cathode, and correspondingly, a hotter ion flux. This fault can be eliminated by shifting the pseudocathode surface out into a region of smaller distortions of the field inside the AC gap.[91] Use of the indicated types of magnetic fields and methods of correcting them has made it possible to increase the density of the IIB in an MID by a factor of 90,[91] and to elevate it to the level of ≈ 100 kA/cm^2.[59,92] Figure 10 shows a diagram of an experimental MID with spherical focusing.

The absence of external magnetic fields in diodes involving pinching of an electron beam presupposes a high efficiency of ballistic focusing. Experiments on a pinch diode having a spherical anode and hollow cylindrical cathode have confirmed this.[2,88] The density of the ion beam at the focus was as much as 0.3 MA/cm^2. This corresponded to an 80-fold increase over the density at the anode. These results were obtained by bringing about complete charge and current neutralization of the IIB in the trans-cathode gas-filled region, which was separated from the AC gap by a thin film (Fig. 11). The absence of a gas region or thin film covering the hollow cathode impaired the charge neutralization, and correspondingly also impaired the focusing (down to 20 kA/cm^2). We must note that the intense magnetic self-fields of the IIB in this geometry make possible an effective self-focusing (up to 0.1 MA/cm^2) in the vacuum region of the diode with subsequent ballistic focusing in the gas region.[88]

Thus the only restriction on the maximum attainable degree of ballistic focusing remains the finite tempera-

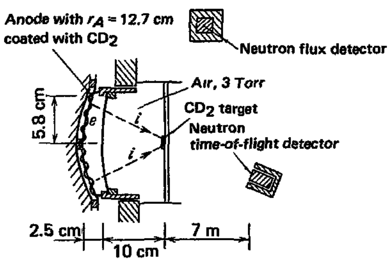

FIG. 11. Diagram of a spherical pinch diode with ballistic focusing.[88]

ture of the IIB, which leads to a mean divergence of the beams in the range 1–3° for energies at the level of a few MeV.

c) Electromagnetic focusing of intense ion beams

The employment of electromagnetic optics is of undoubted interest for transport and focusing of IIBs by analogy with the electrostatic and magnetic dipole and quadrupole lenses in classical accelerator technology. This would enable the transport of an IIB through accelerating AC gaps arranged in succession. That is, it would extend the region of generation of pulsed IIBs to tens and hundreds of MeV, as is especially important for heavy ions. A possible scheme for this has been discussed in Ref. 80, which employed electrostatic focusing of a tubular IIB in sequential MIDs (Fig. 12). The optical properties of these AC gaps are determined by the shape of the surfaces of the virtual cathode and anode formed by the cold electrons. The curvature of these surfaces corresponds to that of the magnetic lines of force, and it provides the needed focusing. Here the focal length of the nth gap is determined by the relationship

$$f_n \approx \frac{2R_n \mathscr{E}_n}{eV_n}. \tag{4.4}$$

Here R_n is the radius of curvature of the median line of force in the nth gap, $\mathscr{E}_n$ is the kinetic energy of the ions in the nth gap, and V_n is the potential difference applied to the nth gap. The problems of transverse and longitudinal stability of an IIB during sequential acceleration in a system of n MIDs requires further study. The first experiments on auxiliary acceleration (to 200 keV) of a C^+ ion beam of 2 kA current in a coaxial-type MID have confirmed the promise offered by this line of study.[59]

When an IIB passes through magnetic lenses, one should expect breakdown of the established pattern of charge and current neutralization, and consequently, a breakdown of the focusing properties of the lenses. Numerical experiments performed in the self-consistent non-relativistic approach have shown that current neutralization exists in the rx plane of the lens, but not in the $r\theta$ plane. This leads to an increased defocusing of the IIB as its current increases. Comparative experiments show that this defocusing becomes substantial when the IIB current reaches the value of J_α, i.e., a few MA.

The experimental results on focusing of IIBs with vacuum dipole lenses agree with the numerical calculations.[93] A tenfold-increased density of the IIB was obtained at the focus, which corresponds to the single-particle approximation, with an IIB current at the level of units or tens of kiloamperes.

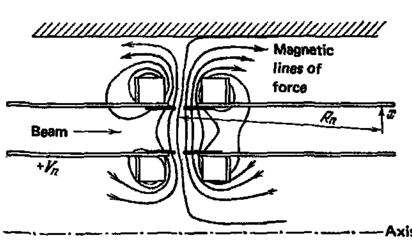

FIG. 12. Diagram of an accelerating magnetically insulated gap with focusing. R_n is the radius of curvature of the median line of force.[80]

One can also employ other suggestions for electromagnetic focusing of beams. Interesting alternatives are plasma-filled lenses, vacuum lenses having a toroidal magnetic field, and also lenses having an electron space charge (with magnetic mirrors, or of the Gabor lens type).[94,95] As the estimates show, the optical strengths of space-charge lenses ($1/f_g$) whose density lies below the threshold of magnetron instability ($n_e < B^2/20\pi m_e c^2$) exceed by a factor of 10^2–10^3 the optical strength of magnetic lenses ($1/f_m$) for the same values of the magnetic fields:

$$\frac{f_m}{f_g} \approx \frac{4v_i^2/L\omega_{i,n}^2}{v_i^2/L\omega_{i,l}} \approx \frac{2m_i}{5z_i m_e}. \tag{4.5}$$

Here we have $\omega_{i,l}^2 = 2\pi n_e Z_i e^2/m_i$, and $\omega_{i,n}$ is the ion Larmor frequency.

The first experiments on accumulation of electronic space charge in such lenses yielded the value $n_e \approx 10^{11}$–10^{12} cm^{-3}. This enables effective focusing of the IIB by the electrostatic forces of this charge.[95]

The possibility of sharp focusing of an IIB by employing stationary magnetic fields that vary slowly in space has been studied in Refs. 96 and 97. In particular, the passage of a cold charge- and current-neutralized IIB through a magnetic mirror of small gradient that conserves the temperature of the beam compresses the latter when the condition is satisfied that $L \gtrsim (3r_{ib}^2 A v_i/\omega_{i,n})^{1/3}$, where A is the magnetic-mirror ratio. The degree of compression r_{ib}/r_{fb} (r_{fb} and r_{ib} are the final and intial radii of the beam) proves to be a highly sensitive function of the initial transverse energy of the IIB. It can become as large as 5–10 with acceptable field values (tens of kilogauss) and distances L (several meters). As has been shown in Ref. 97, injection of a nonparaxial IIB into such a magnetic mirror and the concomitant processes of nonadiabatic radiation losses can jointly lead to sharp focusing of the IIB to a diameter of 10^{-1} cm.

In closing the presentation of the problems of focusing and transport of IIBs, we must point out the dearth of experimental results, which does not allow any long-term prognoses. The only indubitable point is that the pace of the studies that have been performed, which is especially graphically seen in the advances in ballistic focusing and transport in plasma channels, will soon make it possible for this lag to be overcome.

5. APPLICATION OF INTENSE ION BEAMS

a) Ion-beam-driven controlled thermonuclear fusion

Among all the promising applications of ion beams, controlled thermonuclear fusion is the most tempting. We briefly recall the fundamental ideas and relationships of the current approaches to CTF.[98] The well-known Lawson relationship $n\tau > 10^{14}$ s/cm^3 defines the minimum product of the density n in cm^{-3} of the hot plasma of temperature 10^8 K (or 10 keV) multiplied by the time τ of confining it for initiation of thermonuclear fusion with a relative energy yield η_t of the order of unity:

$$\eta_t = \frac{W_t}{W_i} \gg 1, \tag{5.1}$$

Here W_t and W_i are respectively the thermonuclear energy and the energy input into the plasma.

There are two fundamentally different approaches for achieving this: the stationary approach (in devices like the tokamak, stellarator, "Astron", etc.)[99–102] and the inertial approach, in which the deuterium-tritium D-T target is irradiated with laser, electron, or ion beams.[98] As the calculations show, the power of the energy release per unit volume of a stationary thermonuclear reactor can exceed the analogous characteristics for the existing reactors at a plasma density of 10^{14}–10^{15} cm^{-3}. The corresponding confinement time of this plasma and the magnetic field needed for this amount to tenths of a second to several seconds and tens of kilogausses. This is a complicated, but realizable problem at the current technological level.

In inertial thermonuclear fusion, the confinement time of the plasma is determined by its dimensions and velocity of dissipation ($v_{pl} \approx 10^8$ cm/s). It amounts to several nanoseconds. The density of the plasma in this case should be $\approx 10^{23}$ cm^{-3}. The corresponding energy input needed to heat a D-T target of this density exceeds 10^8 J, which lies outside the limits of current technology. The cited value can be substantially diminished (down to a few MJ) by fast compression (several nanoseconds) of the target to a density level in the central region of $\gtrsim 10^{26}$ cm^{-3}. This exceeds the density of solid D-T by a factor of more than 10^3. The adiabatic heating of this region by compression to the ignition temperature ($\gtrsim 5$ keV) of CTF and the fast subsequent heating to several tens of keV leads to stable thermonuclear burning ($\rho \cdot r \approx 1$ g/cm^2) that propagates outward. The corresponding relationship between the needed energy input and the degree of compression C_{comp} of the target is determined by:

$$\frac{W_{i,1}}{W_{i,2}} \sim \left(\frac{C_{2,\,comp}}{C_{1,\,comp}}\right)^2. \tag{5.2}$$

The cited densities of the hot plasma $n_{pl} \gtrsim 10^{26}$ cm^{-3} can be attained at pressures of the order of $\approx 10^{12}$ atm, which develop upon irradiating the target with a beam of the appropriate power ($\approx 10^{14}$ W), owing to ablation (vaporization) of the outer layer and implosion of the target.

The use of IIBs for purposes of inertial CTF has a number of advantages over the electron approach, namely: 1) the absence of bremsstrahlung, which causes deleterious preheating of the D-T plasma and carries away a considerable fraction of the energy; 2) the small scattering of the ions by the target; 3) the substantially larger ionization losses together with the peaked character of the energy deposition at the end of the range, which increases the efficiency of transfer of the energy of the beam to the envelope of the thermonuclear target; 4) the fact that one can compress an IIB longitudinally during transport owing to the nonrelativistic character of the IIB, so as to increase its power at the target.

Numerical calculations performed for various designs of D-T targets show that the advantages cited above for ion beams enable one to diminish the threshold energy input to the target by about an order of magnitude as compared with electron beams.[5] Figure 13 shows the results of these calculations for targets of different designs, masses, and dimensions. They illustrate the decrease in the energy input needed to initiate CTF when one employs ion beams. As we see from Fig. 13, this requires electron currents $\gtrsim 100$ MA. The corresponding ion-current levels lie in the range of tens of megaamperes. We can foresee attaining the latter in the next several years.

The main obstacle to attaining the required degree of compression is the Rayleigh-Taylor instability, which develops at the boundary of two media when a less dense medium (the plasma) moves toward a more dense one (the target material). Numerical analysis has shown that the most dangerous instabilities are those having a wavelength of the order of the thickness of the envelope of the target, since they grow within the implosion time to amplitudes comparable with the envelope, and they can lead to breakdown of the envelope before completion of the implosion and onset of CTF.[104,105] Here the implosion under the action of an ion beam proves somewhat less stable than that under the action of an electron beam. This is due to the peaked character of the energy deposition of the ions, and correspondingly, to the smaller thickness of the zone that can be imploded as compared with the case of implosion in an electron beam. An approximate estimate of the limiting attainable value of r_i/r_f (where r_i is the initial radius and r_f is the final radius of the target) caused solely by the initial asymmetric loading of the target yields the expression $r_i/r_f \approx (\mathscr{E}/\delta\mathscr{E})/c$ (here $\delta\mathscr{E}/\mathscr{E}$ is the relative asymmetry of the energy loading of the surface of the target, and c is a coefficient of the order of unity).[105]

Performance of the first experiments on ion-beam CTF has already been included in the current programs of various laboratories.[88,106] Figure 14 shows a diagram of a planned demonstration experiment on CTF using IIBs generated by pinch-reflex diodes. Owing to the nonrelativistic nature of the IIBs, the employment of a time profiling of the voltage on the diode close to the form $V_A(t) = V_A(0)/(1-\beta_i ct/L)^2$ enables a longitudinal compression of the beam and a considerable increase

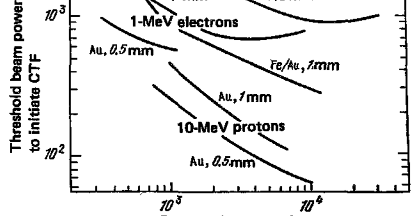

FIG. 13. Results of numerical calculations of the energy input (TW) needed for initiating CTF in a target as a function of the radius C_{comp} and the design of the target for electron and ion beams.[104]

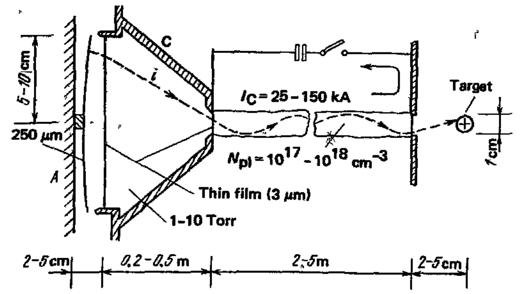

FIG. 14. Diagram of an experiment of CTF with an IIB generated by using a pinch-reflex diode.[88]

(by a factor of 5-6) in the power of the IIB applied to the target. The optimal transmission of the plasma channel (<1 MA) with account taken of the longitudinal compression of the IIB determines the number of beams needed to attain a power of $\approx 10^{14}$ W to be 30-50. One can employ MIDs for these same purposes.[59]

At present, regardless of the concrete type of diodes, all the schemes of accelerators for CTF include two fundamental features: multimodularity and energy transfer to the load (the diode) by magnetically self-insulated vacuum lines. These fundamental principles were first proposed and theoretically and experimentally substantiated in the studies of the group at the Kurchatov Institute.[107]

In closing this section, we note as a more remote prospect the realization of fusion with a yield $\eta_t > 1$ in direct nuclear reactions of a deuterium beam of energy 200 keV with a tritium target of density $n_T \approx 10^{23}$ cm^{-3}. The needed IIB current in this case exceeds that attained at present by less than two orders of magnitude.[103]

b) Ion rings for "Astron"-type devices

High-power ion beams are also of interest from the point of view of creating a magnetic field of closed configuration with reversal of its direction—an ion analog of the electronic E-layer that is known under the name of "Astron".[101] The undoubted advantages of ion rings include the absence of synchrotron radiation losses, which are unavoidable in electron rings,[108,109] and absence of collective-type instabilities. On the other hand, due to the large mass of the ions, the number of them required for reversing the field $\xi = 1 = \delta B/B$ must be $\approx b m_i/\gamma_e m_e Z_i^2$ times larger than for the E-layer, since $N_i \gtrsim r_L/r_i$, where $r_i = (Z_i e)^2/m_i c^2$, and r_L is the Larmor radius of the ion. For actual ion rings with allowance made for possible loss of ions by capture, this quantity lies in the range $\lesssim 10^{17}$.[110] The ion fluxes obtained recently have already attained these values.[89]

As the presented expression implies, one can attain a decrease in the quantity of ions needed to reverse the field by adiabatic compression of the ring, which leads to a decrease in r_L, generation of a divergence-free E_θ, and a corresponding faster rise in the self-field of the ring.[110,112] A necessary condition for this is the absence of current neutralization of the ring by electrons.

An ion ring, being considerably heavier than its electron analog, is not subject to various collective effects. This enables a rather rigorous analysis of its equilibrium configurations and corresponding distribution functions. In treating a thick charge-neutralized ion ring, the equilibrium distribution functions of the rigid-rotator type for a rotating thick cylindrical tubular beam lying inside a conducting cavity[113] are of undoubted interest:

$$f_i(H-\omega P_\theta) = \frac{m_i n_i}{2\pi}\delta(H-\omega P_\theta - k_i). \quad (5.3)$$

Here H is the total kinetic energy of an ion, ω is the frequency of rotation of the layer, and P_θ is the canonical angular moment of an ion. For such a rotating layer, one can write an expression for ξ in the form[111]

$$\xi = \frac{2\nu_i|\omega|}{\omega_{i,\,\mathrm{init}}}.$$

Here ν_i is the ion analog of the Budker parameter. Hence we have $\nu_i \gtrsim 1/2$ for $|\omega| \approx \omega_{i,\,\mathrm{init}}$ and $\xi \approx 1$.

Study of the stability of equilibrium configurations of intense ion rings with respect to low- and high-frequency perturbations has enabled a determination of the corresponding criteria for their stability.[114-116] In particular, for the case of a thin ring immersed in a plasma, the criterion for stability with respect to the kink mode has the form

$$\frac{4\pi n_i m_i v_i^2}{B^2} < 2g^2. \quad (5.4)$$

Here g is a factor of the order of unity.

The corresponding criterion with respect to high-frequency perturbations has the form $T/(m_i v_i^2) > (n_i/n_{pl})^{2/3}$, where n_i and n_{pl} are the densities of the ring and of the plasma, T is the temperature of the beam, and v_i is the azimuthal velocity of the ions.

The most attractive method for shaping an ion ring is injection of a tubular ion beam along the magnetic field through a so-called "cusp", or magnetic field of acute-angle geometry.[112] This stems from the far smaller axial velocities of the rotating ion layer when it has passed through the "cusp" as compared with the electron velocity. This facilitates its further retardation, effective capture, and constriction by the self-fields. Moreover, the large mobility of the cold or plasma electrons along the magnetic lines of force makes possible charge neutralization of this layer without current neutralization. The axial velocity of the ionic rotating layer after passing through the "cusp" is determined to be $v_{i,x} \approx v_i(a/R)$, where R and a are respectively the large and small radii of the ion layer. In connection with the spread of the longitudinal velocity, which is of the order of the velocity itself, the condition for constricting the beam into a thick ring can be written in the form $\delta v_{i,x}/v_i < (\xi)^{1/2}$, where $\delta v_{i,x}$ is the spread in the longitudinal velocity. Since ξ increases in proportion to B as the beam moves along the increasing magnetic field, this condition can be satisfied.

Numerical studies of the shaping and capture of rings under initial conditions that are maximally close to the actual conditions (currents of the order of hundreds of kiloamperes, finite transverse dimensions of the ring $a/R \sim 1-0.25$), have shown the possibility of stable transport of a rotating tubular ion beam after it has passed through a "cusp" and has been captured in a magnetic trap. They have also shown the absence of axial and radial losses of ions during the entire time of confinement.[117,118] The calculations showed that using cavity walls with a finite conductivity enhances the efficiency of deceleration of the ring if one makes an optimal choice of the conductivity of the material of the walls.

Experimental studies on ion rings were begun in 1977 with the employment of a planar magnetically insulated diode with the IIB extracted perpendicular to the magnetic field.[51] The experiments confirmed the high effectiveness of charge neutralization along the magnetic lines of force and the absence of current neutralization of the rotating ion beam. The first-measured diamagnetic effect of the ion beam amounted to 1.5%. Further development along this line in magnetically insulated systems has involved ring MIDs and a radial insulating field[55] following a scheme of injecting the ion beam through a "cusp."

An analogous approach using a ring reflex triode has permitted, even in the first experiments, the authors to obtain rotating ion beams with record-setting parameters ($J_i \gtrsim 200$ kA, $V_A = 0.6-1.2$ MeV, current density 1 kA/cm^2, $\tau_p = 55$ ns) and with a diamagnetic effect of the order of tens of percent.[4,119] In subsequent experiments using an inverted tetrode set up at the accelerator "Gamble-II" with a power of 1.5 TW, a rotating ion layer 20-cm long was obtained with the parameters: $V_A = 1.4$ MV, $J_i \approx 0.4$ MA, $\tau_p = 50$ ns, and a corresponding field reversal at $\xi = 1.25$.[111] Estimates of the quantity of protons in the layer yielded the value 6×10^{16}, which agrees with $\nu_i \approx 1/2$.

An interesting method of generating high-energy ion beams by using current-neutralized compressed ion rings has been proposed in Ref. 120. In this proposal, owing to the mechanisms of current neutralization, the magnetic self-field of the ring remains considerably smaller than the external field, and the compression of the ring (with an explosive liner) is accompanied by a preferential increase in its kinetic energy. In the subsequent stages, the stored azimuthal energy of the ring is converted into translational energy upon passage through an inverted "cusp" to form a dense, high-energy ion beam.

In closing this subsection, we note a high-energy variant of ion rings ($\mathscr{E}_i \approx 300$ MeV) with strong diamagnetism $\delta B/B \approx 50\%$ in an assembly with a breeder reactor treated in Ref. 6. Such rings do not give rise to CTF, but the high-power neutron fluxes that they generate can be effectively used for operating with subcritical blankets.

c) Neutron sources based on intense ion beams

Another field of application of high-power ion beams that is closest to realization is in intense pulsed neutron sources.[7] Experiments have been performed with magnetically insulated diodes and diodes with electron-beam pinch, in which deuterium and tritium coatings on the anode and cathode were used.[3,78] They showed that one can generate neutron fluxes with an integral intensity per pulse at the level of $10^{12}-10^{14}$ neutrons, depending on the power of the generator employed and the nuclear reactions in which the neutrons are produced. These results pertain to a one-shot regime of operation. In this regard it is of great interest to generate neutron fluxes in diode systems operating in a frequency regime (10–100 pulses/s).

The main difficulty blocking the construction of these neutron sources is the small working life of the electrodes of the diodes when acted on by a high-power ion beam, together with the problems associated with the frequency regime of commutation of the energy stored in the shaping element.[121,122]

d) Laser pumping by intense ion beams

In closing this section on application of IIBs, we shall examine the problem of using them to pump gas lasers. In this regard, ions possess a certain advantage owing to their high ionization losses compared with electrons of the same energies. The fact that one can compress an ion beam longitudinally enables one to increase the pumping power and to employ inverted levels having a short lifetime, extending to the soft x-ray region. Moreover, the efficiency of the laser is increased in operating with self-limited transitions in which the lower laser level is metastable or sufficiently long-lived. It is promising to employ IIBs also for pumping metal-vapor lasers, which possess the highest efficiencies among the monatomic gases,[123] or excimer lasers.

Already the first experiments with modest values of the parameters of the ion beams (≈ 0.5 J) have confirmed the possibility of effective pumping.[8,124,125] Upon employing as the source the proton beam of a reflex tetrode[8,125] or a MID,[124] laser action was obtained in an Ar-N_2 mixture in the 2^+ transitions of the system $N_2 C^3\Pi_u \to B^3\Pi_g$, $v = (0,1), (0,2)$, which correspond to wavelengths of 357.7 nm and 380.5 nm, with an output of the order of several mJ and an efficiency $\lesssim 2\%$. Figure 15 shows a diagram of the experimental arrangement.[8] An interesting continuation along this line is the pumping of gas lasers by using multiply-charged ions. In Ref. 19, intense bunches of helium and nitrogen ions (several amperes), which had been collectively accelerated in a relativistic electron beam, were used for this purpose. The efficiency of generating laser

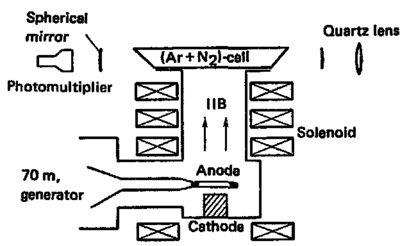

FIG. 15. Diagram of an experimental setup for pumping a laser with a proton beam.[8]

radiation lay in the range of $\lesssim 1\%$, owing to the known nonoptimality of the experimental conditions. These first results on pumping gas lasers with IIBs are very encouraging, especially from the point of view of applying coaxial focusing geometries without extracting the IIB from the diode system. In this case one can work at a level of efficiency of the diode $\gtrsim 50\%$. This enables one to generate laser pulses with a stored energy of several kJ.

CONCLUSION

This review of the current state of the theory and of the experimental results on generating intense ion beams allows us to draw certain conclusions on the problems and the further development along this line. On the whole, the physical processes that occur in diode systems in shaping ion beams have been studied rather fully. The stationary analytical models that have been studied give good qualitative agreement with experiment, while the numerical calculations without simplifying assumptions even give quantitative agreement. At the same time, such individual problems as the features of motion of the electrode plasma in the AC gap and the role of the electrons scattered by the anode, etc., require further refinement. As regards the problems of focusing and transporting intense ion beams, as we have noted, this field has been as yet poorly studied. Undoubtedly it is expedient to concentrate scientific efforts along this line.

The presented information convincingly indicates that intense ion beams are of interest in many fields of science and technology, and primarily in thermonuclear fusion in devices for stationary and inertial confinement of a plasma. Intense ion beams are also promising for solving other problems, including the generation of neutron beams and pumping of shortwave lasers.

Thus, intense ion beams are a new field of high-current relativistic electronics that substantially expand the sphere of application of this fast-developing field of modern physics.

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