High-power pulsed ion sources

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The current status of the experimental work on the development of high-current accelerators, ion diodes, and anode-plasma sources is reviewed. The main areas of research on increasing the power of the output high-voltage pulse of accelerators are discussed. Various ion-diode schemes with their advantages and disadvantages are reviewed along with possible ways of raising the efficiency of using them to generate high-power ion beams. The problems related to the generation and use of a homogeneous, dense anode plasma as an ion source are analyzed. The characteristic features of various types of passive and active anode-plasma sources are given.

INTRODUCTION

The physics and technology of high-power pulsed ion sources became an independent area of research in the mid-1970s as a result of the advanced development of the pulse technique of attaining high powers and the corresponding development of direct-action accelerators operating in the nano- and microsecond pulse-duration range.[1,2] The great advances in this area during the ensuing period were also a consequence of the possibilities of using high-power ion beams (HPIBs) to solve some important physical problems: inertial thermonuclear fusion,[3] generation of intense neutron bursts with fluxes above 10^{13} neutrons/pulse, which exceeds the level attainable in ordinary setups of the plasma-focusing type,[4] and the behavior of solid media under extremal conditions when a dense, focused HPIB interacts with them.[5]

During this period the power level of HPIBs rose by more than three orders of magnitude, and the range of accelerated ions came to include a significant part of the periodic table, although most of the experiments were carried out in beams of protons and the lightest ions (see Sec. 3). For example, whereas in the first experiments on HPIB generation in 1974, carried out at the Laboratory of Plasma Studies at Cornell University, USA, the power of the ion beam was 6×10^9 W (Ref. 6), by 1989 at the unique thermonuclear accelerator PBFA-2 at Sandia National Laboratory, USA, an ion beam was obtained with pulsed power of order 10^{13} W with maximum current $I = 2$ MA and maximum voltage $\varphi = 5$ MV (Ref. 7). Naturally, this remarkable progress is the result of a great amount of experimental and theoretical work by many leading laboratories around the world on the development and modification of all aspects of high-power pulsed ion accelerators, including primary and intermediate energy storage devices, self ion diodes, anode-plasma sources, commutators, HPIB transport systems, and so on.

In the present review we attempt to give a brief analysis and the main results of the development of the physics and technology of high-power pulsed ion sources during the last decade for some of the ion acceleration systems listed above.

1. ENERGY STORAGE DEVICES

Voltage pulse generators (VPGs) of the Arkad'ev–Marx or Fitch capacitative type are widely used as the primary energy storage devices of nano- and microsecond accelerators. These have characteristic rise times of the output voltage on the order of a fraction of to several microseconds and amplitude of several to tens of megavolts.[8]

The modular principle is used to provide generators with an energy supply of several megajoules and higher. Here the VPGs are made in the form of parallel sections, each with an energy supply of order 10^4–10^5 J and with operating-time spread of about 10 nsec. For example, the primary storage device PG-4 with a maximum energy supply of 2.5 MJ is constructed of four parallel VPGs, each containing nine sections with an energy supply of 69 kJ per section.[9]

The further transformation of the energy stored in the VPG with subsequent compression to form a high-voltage nanosecond pulse occurs in the intermediate and forming elements, which, as a rule, are low-inductance coaxial capacitors with dielectric liquid insulation, usually deionized water with resistivity $\rho \approx 10^6$–10^7 Ω·cm. A scheme for such a line sequence at the SNOP-3 accelerator is shown in Fig. 1 (Ref. 10). The high dielectric strength of water (up to 300 kV/cm), its large dielectric constant ($\varepsilon = 81$), and the rapid restoration of the electrical conductivity after breakdown have led to widespread use of deionized water in a wide range of accelerator powers from 10^9 to 10^{14} W. For example, the volume of the water insulation used at the accelerator PBFA-2 amounts to more than 100 m^3 (Ref. 11). It should be noted that during the last decade there has been a trend to higher output voltages of 5–10 MV at pulsed accelerators, which is related to the preference for using high-energy HPIBs for solving the practical problems listed above. In addition, when the output power of the accelerator is fixed, this trend corresponds to decreased current level in the diode load and, consequently,

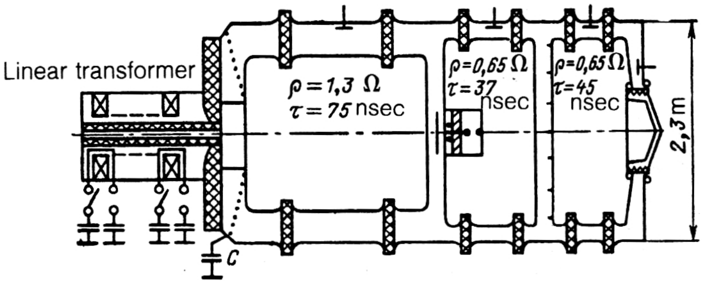

FIG. 1. Line-shaper system of the accelerator SNOP-3.

weakening of the defocusing effect of the self magnetic field of the beam in the diode, and also of the role of the burst-emission plasma formed, the motion of which in the gap leads to rapid collapse of the impedance of the latter when working with the small anode–cathode (AC) gaps needed for low operating voltages.[12]

In connection with the fact that the construction of a primary storage device of the capacitative type with voltage $\varphi \geqslant 10$ MV is a very complicated technical and engineering problem, not to mention the awkwardness of such a VPG owing to the low energy density ($\leqslant 0.1$ J/cm^3) and the requirements on the dielectric strength, the advance to the range $\varphi \geqslant 10$ MV requires certain modifications or alternative methods of forming high-voltage pulses on the diode load. Examples of these are the following.

1. *Use of the time-isolation regime, where the electrical length of the water transmission line is significantly larger than the duration of the shaped pulse.* In this case several transmission lines parallel at the input are connected in series at the load. The engineering solution is the use of cross-leads and transformation of the cylindrical coaxial line into two flat lines connected in series to the load. A typical illustration of this solution is the scheme for the four-fold voltage multiplication in the system for the energy flow from intermediate storage devices to the diode of the PBFA-2 accelerator shown in Fig. 2 (Ref. 13). It involves splitting of the coaxial transmission line into two flat lines with spatial inversion of the electrodes in one of the strips by means of rod cross-leads with subsequent connection of the four flat lines to the common insulator of the diode vacuum junction. This summation method can be realized only in the generation of nanosecond pulses. A defect of the method is the need to keep the total voltage ($\varphi \geqslant 10$ MV) on the common water–vacuum dividing insulator, which tends to increase the size of the latter. For example, to keep the final voltage on the central insulator of the PBFA-2 accelerator, the total height of the insulator had to be 4 m. Because of this, the method becomes impractical in going to voltages > 20 MV.

2. *Induction multiplication of the voltage using a linear transformer (LIT) with a single secondary winding and a large number of primary windings connected in series (Ref. 14).* The scheme of the primary storage device based on an LIT is shown in Fig. 1. The secondary winding of the transformer is made in the form of a coaxial cable (with grounded housing and central high-voltage wire). In the engineering realization of the magnetic circuit of the LIT this is a set of coaxial toroidal cores made of steel (permalloy, Metglas, ferrite) separated from the electrodes of the coaxial cable by a vacuum or electrical insulation suited to the operating voltage of the LIT.[15] Pulse capacitors[14] and line shapers[15] are used as the power supply for the primary windings of the LIT. In the first case the typical duration of the generated pulses is hundreds of nanoseconds to a few microseconds and the typical output voltage is hundreds of kilovolts to a megavolt, and in the second case they are tens of nanoseconds and tens of megavolts. For example, the LIT of the accelerator SNOP-3 contains 24 single-winding transformers, connected in series to the primary windings by means of six parallel transmission cables of the KVIM type and two gas discharger arresters via two heteropolar IK-50-3 pulse capacitors (3×10^{-6} F, 40 nH, 50 kV). At the output the LIT provides a pulse [voltage $\varphi \simeq 2$ MV, duration $\simeq$ 1.5 μsec

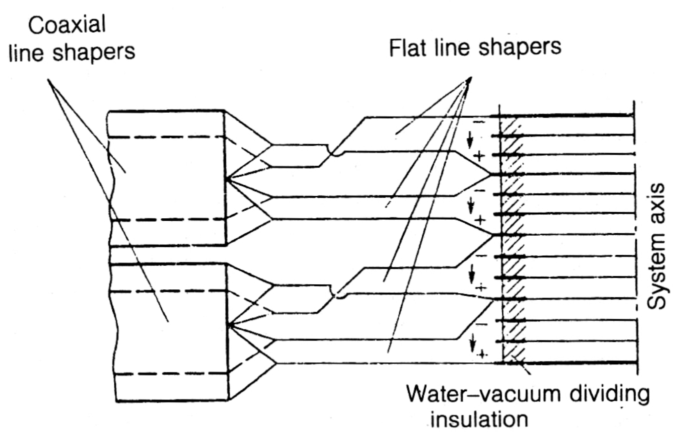

FIG. 2. Scheme for voltage multiplication on the line shapers lines of the accelerator PBFA-2 (Ref. 13).

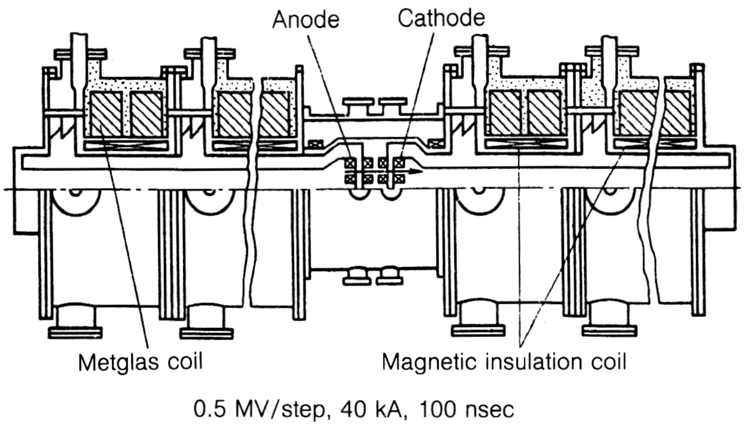

FIG. 3. Vacuum high-voltage section based on inductor modules (Ref. 16).

(for operation on a matched load), and stored energy 100 kJ] charging an intermediate water storage device. In this example the LIT performs the function of the primary storage device itself.

Another example in which the LIT plays the role of the final storage device is that of the REIDEN-IV–SHVS setup (Ref. 16), a standard nanosecond accelerator (1.5 MV, 1 Ω, 50 nsec) incorporated as a power source in an auxiliary vacuum superhigh-voltage section of an LIT (Fig. 3). The LIT has eight inductor cores made of Metglas with operating voltage of the primary windings (the output voltage of REIDEN-IV) equal to 0.5 MV. The LIT shapes an output pulse with the following parameters (for a matched load): 4 MV, 40 kA, 100 nsec. In the SHVS vacuum breakdown of the coaxial line related to the low current level is suppressed by using an external magnetic field produced by an auxiliary solenoid, and the vacuum coaxial line is loaded directly at the diode generating the HPIB. This solution eliminates the need to keep the total output voltage on the dividing insulators (the LIT–line shaper), and the electrical insulation must be strong enough only for the operating voltage of the primary windings ($\leqslant 1$ MV). At the present time the largest LIT with inductors based on Metglas cores is used in the accelerator GERMES-III, ensuring an output pulse on the diode with parameters $\varphi = 20$–22 MV, $I = 800$–720 kA, $\tau_c = 40$ nsec (Ref. 15), which was put into operation in 1988. In the GERMES-III there are 20 intermediate water storage devices, each charging four line shapers, each of which operates for one primary winding of the inductor. The step-like rise of the line impedance as the line voltage is added ensures that the total current along the whole length of the LIT is practically constant at a level of 800 kA and that the output voltage applied directly to the high-voltage diode of the accelerator is constant at 20 MV. The main advantage of the super-terawatt (about 15 TW) GERMES-III accelerator is the possibility of further increase of the final voltage by the addition of more induction sections.

Comparing a nanosecond accelerator of this type with the traditional linear induction multigap accelerator (LIA), we can see the advantages of the former. Among them are the absence of problems related to beam injection and capture into the acceleration mode, to the existence of a succession of acceleration gaps and the resulting buildup of various instabilities, and so on. The working experience gained so far with auxiliary acceleration of ion beams in multigap ion LIAs is all for final energies of up to 1 MeV (Ref. 17). The specific features of powerful ion beams—their high degree of charge and current neutralization, close to 100%—make it necessary to impose a transverse magnetic field (of the cusp type) on the region of the induction acceleration gaps in the LIA to block the acceleration of the accompanying electron beam, which otherwise would lead to a sharp drop in the ion acceleration efficiency. The use of such gaps together with the suppression of the electron component of the induction current ensures stability of the voltage when a fairly large initial distribution in the longitudinal velocities of the beam ions is introduced.[18]

3. *Induction multiplication of the voltage by means of a plasma opening switch (POS).*[19,20] In this scheme the transmission line of the accelerator in the immediate vicinity of the load–diode (from several to tens of centimeters; in the case of microsecond pulses these can be distances on the order of tens of centimeters) is overlapped by a plasma flux of density 10^{12}–10^{13} cm^{-3} and velocity 10^7 cm/sec. Owing to the high plasma conductivity, the accelerator current at the leading edge of the pulse is short-circuited through the plasma with finite drop of the voltage at the following edge of at most hundreds of volts to several kilovolts. The plasma fluxes in the coaxial vacuum line are created by special plasma sources operating in advance of the shaping of the high-voltage pulse. A magnetic energy equal to $LI^2/2$ is stored during the current rise front in the line. When a certain level of the current through the plasma is reached, called the critical current I_{cr}, the plasma conductivity falls sharply, leading to the generation of a vortex emf and, over a period of several to tens of nanoseconds, switching of the energy flux to the input of the load–diode with voltage amplitude greater than the initial value. Theoretical analysis and experiments for the nanosecond POS interpret this phenomenon as the following sequence of processes[21] (Fig. 4).

(a) Rise of the current through the POS for high conductivity of the latter up to the critical level

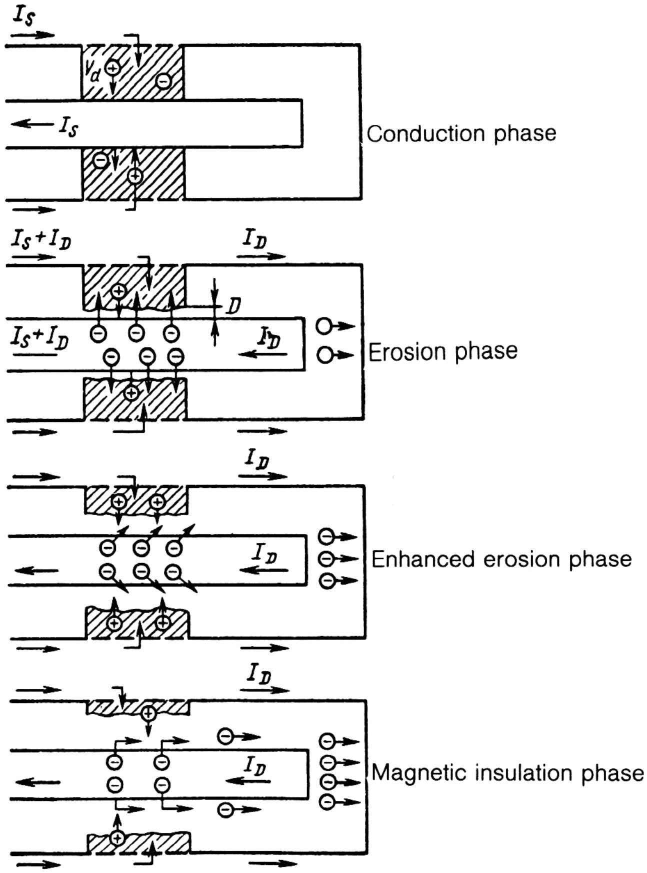

FIG. 4. The four phases of operation of nanosecond plasma opening switches.

$$I_{cr} \geqslant 0.4 n_e e \sqrt{kT_i/m_e} S, \tag{1}$$

where n_e is the plasma density, T_i is the ion "temperature," m_e and e are the electron mass and charge, and S is the plasma contact area of the cathode. Here the current has a predominantly radial direction in the channel, and diffusion of the current channel into the plasma occurs at a rate considerably (up to a factor of ten and more) exceeding the classical rate.

(b) Decrease of the emission capability of the plasma, onset of growth of the POS resistance, and formation of a double layer at the cathode, at which a voltage considerably greater than the ion flux velocity appears.

(c) Penetration of the electric field into the plasma, rise of the ion current accompanied by plasma breakdown and decrease of the electron component of the current owing to misalignment of the electron trajectories in the self magnetic field of the full current, and onset of switching of the energy flux to the load.

(d) Complete cutoff of the electron component in the POS. In this phase the POS impedance is determined by the ion currents of the losses. The energy flux in the form of a short and intense pulse is switched to the diode.

It has been shown in numerous experiments with POSs performed at nanosecond accelerators in front of ion diodes with a very wide range of voltages, powers, and currents that at best POSs ensure a 1.5–2-fold increase of the power at the diode and a 1.5–2.5-fold increase of the pulse voltage for the corresponding reduction of the duration.[22,23] In addition, in the case of POS installation in multimodular accelerators (the PBFA-1,2) based on a single central ion diode, there is a significant decrease of the current losses at the diode input owing to the spread in the arrival times of pulses reaching the diode via different lines because of the symmetrizing role of the POS. By the middle of 1989 the use of two POSs at the PBFA-2 accelerator with a current of up to 2 MA in each ensured the effective switching of the energy flux to the load–ion diode.[24] In the case of the microsecond POSs used directly after the primary storage device in schemes without intermediate and shaping nanosecond lines, on the whole, like the nanosecond POSs, they also ensure switching of the energy flux to the load during a time of the order of or less than the initial pulse for a 2–5-fold increase of the shaped pulse voltage over the voltage of the primary storage device.[25] This scheme appears promising for the generation of short-pulse ion beams in schemes without traditional shaping lines, and the first experiments in this area are very encouraging.[26]

Summarizing the above, it can be stated that at the present time for the generation of powerful pulsed ion beams there exists a developed energy base of generators in a wide range of voltages (from hundreds of kilovolts to tens of megavolts), powers (up to 10^{14} W), and pulse durations (10^{-6}–10^{-9} sec) using various methods of energy storage and transformation, for which in the intermediate and shaping elements there is a tendency to go from capacitative to inductive storage modes and to higher voltages for various areas of application (inertial thermonuclear fusion, neutron pulse generation, new types of shortwave lasers, and so on).

2. DIODE SYSTEMS

The problem of ion beam generation in a diode system involves the need to suppress the lighter electron component, which in an ordinary Child–Langmuir diode makes up more than 97% of the total diode current. Here the specific form of the ion source in the anode–cathode (AC) gap of the diode is not specified, and the most common characteristics of such a diode are charge-limited emission (the E-field strengths on the surface of the electrodes are zero), and also the presence of collinear countercurrents of electrons and ions. The first property is ensured by electron burst emission and formation of a dense plasma at the electrodes ($E=0$ inside the plasma) characteristic of the power range under consideration,[27] and the second is ensured by the absence in the Child–Langmuir diode of significant external (and self) magnetic fields capable of changing the nature and geometry of the electron fluxes. The value given above follows from the well known nonrelativistic equation for the current density of a planar diode in the case of charge-limited emission:

$$j_{eC\text{-}L} = \alpha \left(\frac{2}{9\pi}\right)^{1/2} I_0 \frac{U_A^{3/2}}{d^2}, \tag{2}$$

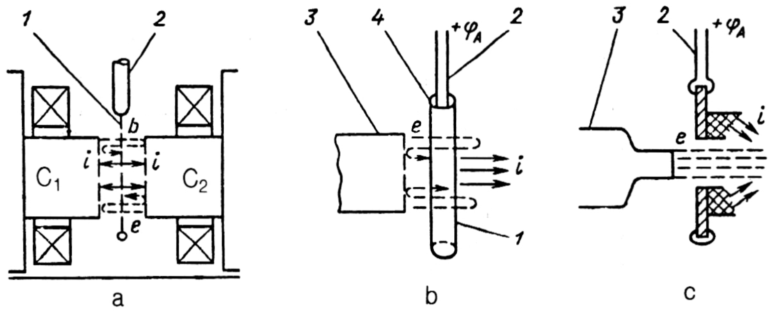

FIG. 5. Reflection-system schemes (Ref. 29): (a) symmetric double diode, (b) tetrode, (c) asymmetric triode with indestructible anode; 1—film, 2—anode, 3—cathode, 4—metal grid.

where $\alpha = 1.86$ is a coefficient related to partial neutralization of the AC gap by the electron–ion fluxes $I_0 = (4\pi/\mu_0)(m_e c/e) = 17$ kA, $U_A = e\varphi_A/m_e c^2$, φ_A is the accelerating voltage applied to the AC gap, and d is the AC gap.

The known methods of electron-current suppression in diodes amount to increasing the time the electrons stay in the AC gap by arranging to have multiple oscillations of the electrons through the anode transparent to them in reflection systems (RSs), the electron flux radially converging to a pinch or diverging in the self magnetic field in pinch diodes or inverse pinch diodes, respectively, or cutoff of the electron flux from the anode by means of external or self magnetic fields or a combination of these in magnetically insulated diodes (MIDs).

In reflection systems (Fig. 5) when certain conditions are met multiple oscillations of the electrons through the anode lead, owing to energy loss and scattering at an angle, to smearing of the electron energy and thus to effective neutralization of the entire AC gap and sharp increase of the electron–ion fluxes, which is referred to as "collapse" of the diode impedance. As a rule, this is observed at low-impedance accelerators when the critical number of electron oscillations through the anode and the effective formation of an anode plasma as an ion source are ensured.[28] For diode systems of this type it is also possible to operate in a weak-current regime (use of a high-ohm generator, ineffective neutralization of the AC gap) without impedance collapse.[29] The development of the technique of RS with electron oscillations in the laboratories at BMC (USA), the Institute of Nuclear Physics, Tomsk, USSR, the Nuclear Physics Institute, Novosibirsk, USSR, and Cornell, USA has led to the design of several different types of RS (the symmetric double diode, triode, tetrode, asymmetric triode, inversion tetrode). Some of the general characteristics of these devices are the following.

1. As a rule, the ion source in an RS is a plasma formed on the anode surface as a result of both the heating of the latter by the oscillating electrons and surface electrical breakdown (see Sec. 3).

2. On the RS is imposed a fairly strong longitudinal magnetic field (from a few to ten kOe) which suppresses the losses of oscillating electrons to the anode mount, the induction of which can be estimated from the expression[30]

$$B_{\min} \geqslant \mu_0 I_0 (2U_A + U_A^2)^{1/2}/4\pi d. \quad (3)$$

This determines the geometry of the ion beam generated by the RS, since this beam is extracted along the magnetic field, which makes it practically impossible to focus the HPIB in the immediate vicinity of the RS. There are some proposals for HPIB compression using a mildly sloping magnetic mirror[31] or a short magnetic probe with subsequent charge transfer and ballistic focusing.[32]

3. As a rule, the operating regime is single-stage, owing to the destruction of the thin anode. This defect is eliminated by individual modifications of the RS using massive indestructible anodes,[33] but these RSs have low efficiency ($\lesssim 20\%$).

4. The efficiency of HPIB generation in "classical" RSs is greater than 50–60%. It can be estimated from the expression[34]

$$I_i/I_e \sim 0.5[1 + (m_i/m_e)^{1/2}(2\eta + 1)^{-1}], \quad (4)$$

where η is the number of electron oscillations through the anode.

5. Reflection systems generate HPIBs with large energy spread. Here, owing to collective effects (especially in RSs with a moving virtual cathode in the realization of the gas dynamical-acceleration scheme), the spectrum contains ions with energy exceeding the working voltage by a factor 2–5 or more, the fraction of which can reach several percent of the total number of ions.[35,36]

6. The half-angles of divergence of the HPIB which can be generated in RSs depend significantly on the strength of the leading magnetic field and on the type of ion, and they lie in the range of several degrees (4–6°).

7. The largest values of the current amplitude and power of HPIBs obtained in RSs are 1 MA and 1 TW, respectively.[12] The main characteristics of several reflection systems and of the HPIBs generated by them are given in Table I.

To conclude this brief review of RSs, it should be noted that although they were chronologically the first intense pulsed ion sources,[30] in recent years RSs have lost their leading position. Now studies on RSs are carried out mainly with plasma-filled modifications of them at the Institute of Nuclear Physics, Tomsk.[37]

In contrast to the vacuum diode, a plasma-filled diode, under certain conditions depending on the parameters of the plasma prepared earlier and the generator, can operate in the growing-impedance mode, which ensures generation of an HPIB with increasing energy and, accordingly, in-

TABLE I. Characteristics of some reflection systems.

Generator and its parameters	Type of diode system	Ion type	Ion energy, MeV	Ion current, kA	Generation efficiency, %
Tonus (1 MV, 24 Ω, 50 nsec)	reflex triode	H^+	0.4–0.5	25	40
	reflex tetrode	H^+	1.0	15	50
	reflex triode	H^+	1.0	1.0	10
VERA (450 kV, 7 Ω, 80 nsec)	reflex triode	H^+	0.15–0.25	30	40
	reflex triode	H^+	0.25	5–10	30
INAR (1 MV, 50 Ω, 50 nsec)	reflex triode	H^+	0.7	3–4	50
Akvagen (1 MV, 4 Ω, 50 nsec)	reflex triode	C^+	0.5	20	10
GAMBLE I (1 MV, 1 Ω, 50 nsec)	reflex triode	H^+	1.0	200	40
GAMBLE II (1.5 MV, 1 Ω, 50 nsec)	inversion reflex tetrode	H^+	0.6–1.4	380	80
VODA 1-10 (1 MV, 5 Ω, 80 nsec)	reflex triode	H^+	0.5	16	14

crease of the power, owing to the space–time compression occurring as the HPIB is transported to the interaction object.

Yet another interesting modification of RSs is the tetrode filled asymmetrically with a plasma in only one half, which operates in the POS mode. In order to reach the critical value of the current in this half of the reflex tetrode there is an abrupt drop of the current with increasing impedance and switching of the energy flux to the other half with HPIB generation.[38]

Pinch diodes, in which the ratio I_i/I_e is increased by an electron flux converging toward the diode axis, are essentially low-impedance diodes (the impedances are from several to a fraction of an ohm). This follows from the expression for the working impedance of the disk line $\rho = 60\ kd/R_C$, where d is the AC gap of the diode, R_C is the cathode radius, and k is a factor less than unity characterizing the degree of loading of the AC gap by ion–electron fluxes. The experimentally established values for voltages in the MV range lie in the range $0.25 \leqslant k \leqslant 0.6$. The corresponding values of the total current of the pinch diode can be determined with acceptable accuracy ($\leqslant 20\%$) using the equation for the parapotential current:[39]

$$I_{pp} = 8.5\gamma(R_C/d)\ln[\gamma + (\gamma^2 - 1)^{1/2}], \tag{5}$$

where $\gamma = (e\varphi_A + m_e c^2)/m_e c^2$, and the corresponding value of the ion current amplitude is given by[40] $I_i = I_{pp}/[1 + 2(d/R_C)(\beta_e/\beta_i)]$. It follows from (5) that already for moderate values of γ the total current of the pinch diode turns out to be less than the Child–Langmuir current, and it does not obey the Child–Langmuir law. This is due to the self-limitation of the current owing to the presence of the self magnetic fields of the established electron and ion fluxes.

The typical construction of a low-impedance diode designed for HPIB generation is shown in Fig. 6. It is characterized by use of a full ring cathode, usually covered by a thin film, and also by the filling of the space behind the cathode with a neutral gas at low pressure (several pascals).[41] Both the film and the neutral gas ensure the current neutralization of the ion beam, starting from the anode surface, in the drift region beyond the cathode, which makes it possible to have controllable ballistic focusing of the HPIB with resulting densities $j_i \geqslant 10^5$ A/cm^2. In the first approximation the ratio I_i/I_e in pinch diodes can also be found from the expression

$$\frac{I_i}{I_e} \cong \frac{t_e}{t_i} = 0.5\frac{R_C}{d}\left(\frac{m_e}{m_i}\right)^{1/2}(2U_A)^{1/2}, \tag{6}$$

which for sufficiently large R_C/d and U_A can amount to tens of percent. Comparison of the experimental results with the estimates from Eq. (6) shows that when an auxiliary thin anode transparent to electrons is used, the ion yield is considerably higher than estimated. This is due to the decreased electron beam loss at the large radii occurring for a solid, opaque anode, the resulting increase in the space-charge density in the pinch, and also the considerable increase in the time for finding the electron in the AC gap owing to multiple oscillations around the thin anode. The oscillation mechanism in this case is related to the self azimuthal magnetic field of the diode, in contrast to the oscillations in reflection systems. The available statistics on HPIB generation in this type of pinch-reflex diode with low-impedance generators indicate that its efficiency generally grows with increasing generator power. For example, in HPIB generation in the pinch-reflex diode at the GAMBLE II generator ($P = 1.5$ TW, $\rho = 1\ \Omega$, $\tau = 50$ nsec) it was 60%, at the PITHON generator[40] ($P = 10$ TW, $\rho = 0.5\ \Omega$, $\tau = 100$ nsec) it was 70%, and at the PBFA-1 generator[41] ($P = 15$ TW, 18 modules, $\rho = 0.27\ \Omega$, $\tau_c = 40$ nsec) it was 80%. In the last case a pinch-reflex diode of the keg type with auxiliary anode in the form of a

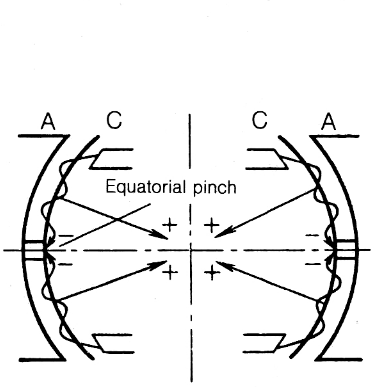

FIG. 6. Low-impedance ion diode of the keg type with pinching of the electron current (Ref. 41).

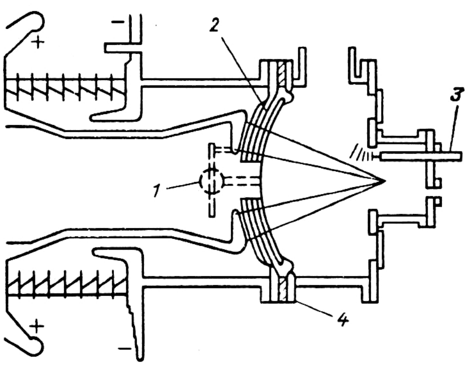

FIG. 7. Scheme of the diode AMPFION (Ref. 45): 1—electron diode, 2—helical cathode, 3—plasma guns, 4—insulator.

dielectric film transparent to the oscillating electron flux converging toward the equatorial plane was used.

In connection with the fact that pinch diodes operate without an external magnetic field in the so-called self-insulation mode, the characteristics of the HPIBs generated by them can be significantly affected by such factors (especially at powers in the terawatt range) as the self magnetic field of the HPIB and the shape and behavior of the anode plasma moving toward the cathode. It is its surface instabilities (plasma ejections) after 40–50 nsec which cause the HPIB divergence angles to increase significantly to values of 40–60 mrad (Ref. 45). Another modification of the pinch diode is AMPFION (automatic plasma-filled ion diode), which has been studied both in the classical variant with anode in the form of a spherical sector, and in the form of a "keg" used in the installation at the accelerator PBFA-1 (Ref. 45). In contrast to ordinary pinch diodes, the AMPFION has the following characteristics: 1) preliminary plasma filling of the AC gap; 2) creation of an auxiliary self radial magnetic field ensuring that the total field is constant over the entire cathode area, which is attained by using an auxiliary helical cathode connect in series to the circuit carrying the full current (Fig. 7). This is achieved by having the same rate of plasma erosion when the critical current is exceeded and the high-voltage stage of the diode starts. AMPFION operates in the growing-impedance mode, and, as experiments show, the emitting surface of eroding plasma effects a certain selection of the accelerated ions in Z/M, which is related to the presence of the potential barrier in it.

Pinch diodes have passed the stages of development and study at practically all the terawatt accelerators (except perhaps the PBFA-2). Their operating characteristics are the following.

1. The maximum ion current densities are considerably larger than in RSs. In the region near the axis they reach 10–15 kA/cm^2 at superterawatt levels.

2. There is significant convergence of the generated HPIB (owing to the large self magnetic fields in the AC gap itself).

These features make it possible to use diodes of this type to obtain dense focusing of extracted HPIBs at a short distance from the anode with subsequent transport of the beam in a gaseous or plasma current-carrying channel.[46] We conclude this review of pinch diodes as a source of HPIBs by giving the characteristics of the ion beams generated in them in Table II.

Magnetically insulated diodes (MIDs) with an external magnetic field have become widely used during the last decade. MIDs have been used for HPIB generation in a very wide range of powers beginning with the first experiments at the laboratory of R. Sudan at Cornell University at the level of several gigawatts[47] to the experiments at PBFA-2 at the level of tens of terawatts.[48]

MIDs have been the subject of the largest number of experimental and theoretical studies, and various types of MIDs have been developed for specific applications. The work on MIDs focuses on cutoff of the electron flux in the AC gap from the anode using an auxiliary external magnetic field.[47]

When working at low power levels (10^9–10^{10} W) the effect of the self magnetic field of the current in the AC gap can be neglected, and the induction of the critical external magnetic field needed to effect the electron cutoff can easily be calculated in the one-particle approximation from the expression

$$B_{\rm cr} = \frac{\mu_0 I_0}{2lh_2} g(U_A^2 + 2U_A)^{1/2}, \tag{7}$$

where h_2 is the Lamé coefficient in the curvilinear coordinate system used for the specific diode geometry cor-

TABLE II. Characteristics of pinch diodes.

Generator	Ion energy, MeV	HPIB current, MA	Ion type	Pulse duration, nsec
BLACKJACK-I	1,3	0,3	H^+	50
GAMBLE-II	1,7	0,6	H^+	60
PITHON	1,8	1	H^+	70
PROTO-I	0,8	0,8	H^+	40
PROTO-II	1,4	1,4	H^+	50
PBFA-1	1,9	2	H^+	40
REIDEN-IV	6,3	0,16	H^+	50
BLACKJACK-V	3	2	H^+	50

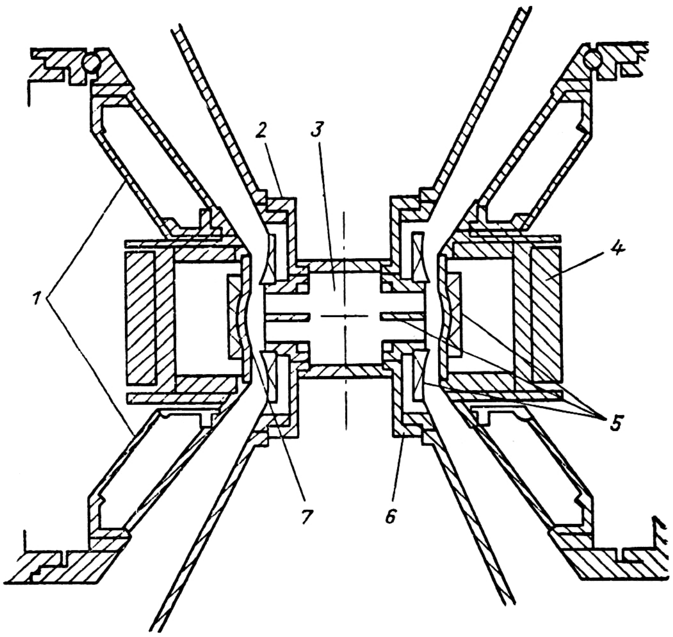

FIG. 8. Scheme for a magnetically insulated diode at the PBFA-2 accelerator: 1—plasma release of the current, 2—upper cathode, 3—gas cell, 4—anode, 5—pulse coils for magnetic field generation, 6—lower cathode, 7—anode plasma.

responding to the magnetic field direction, l is a quantity depending on the diode geometry and the length of the integration contour at the anode, and g is a geometrical factor. In particular, for a coaxial cylindrical diode with axial magnetic field $l = R_A$, $\eta_2 = 1$, and $g = R_A^2/[\pi(R_A^2 - R_C^2)]$ with azimuthal magnetic field $l = 2\pi$, $\eta_2 = R_A$, $g = \ln(R_A/R_C)$ (Ref. 49). This expression was obtained from the equation for the conservation of the cylindrical component of the canonical electron momentum $P_y = P_y(A) = \gamma m_e v_y - eA_y = \text{const}$ in the AC gap when the requirement $v_\perp(A) = 0$ is met, where $v_\perp$ is the component of the electron velocity normal to the anode. When a pulsed current appears in an MID, there is redistribution of the magnetic flux in the AC gap of the diode with conservation (or partial nonconservation) of the latter owing to the diamagnetism of the electron flux.

The various MIDs can be classified into several types according to the type of magnetized electron flux shaped in them. These can be closed or open in the $\mathbf{E}\times\mathbf{B}$ drift direction, and also of the Larmor or Brillouin type (laminar along the equipotential of the electric field). Theoretical analysis of the conditions for the existence of a stationary magnetized electron flux depending on the form of the latter and on various assumptions about the ideality of its boundary ($v_\perp = 0$) leads to widely divergent conclusions about the characteristics of such a diode and the HPIB generated by it.

For example, when studying a Brillouin electron flux and assuming that its boundary is absolutely "cold" ($v_\perp = 0$), the authors of Refs. 50 and 51 concluded that the electron and ion currents diverge for every chosen value of U_A for a given value of Bd. This corresponded to filling of the entire AC gap by the electron flux (i.e., actually violation of the magnetic insulation) and divergence of the electron density near the anode, which, in turn, led to the theoretical divergence of the ion current in disagreement with experiment. The study of the magnetized Larmor electron flux in the AC gap carried out by Bergeron in Refs. 52 and 53 showed that there was no current divergence and that the currents significantly exceeded the Child–Langmuir limit by up to an order of magnitude only near the critical value of the magnetic field induction depending on the diode geometry. Experiment at moderate power levels (up to 1 TW) confirmed the prediction of the Bergeron model. However, owing to the motion of the electron plasma during the high-voltage pulse and the corresponding change in the effective interelectrode gap, the value of B corresponding to the maximum excess of the current over the Child–Langmuir limit was shifted to large $B/B_{cr}\geqslant 1.3$–1.5.

Meanwhile, in going to superterawatt power levels the cathode in an MID is, as a rule, not a metal surface, but an electron cloud completing the closed drift and, owing to strong diamagnetism and conservation of the total magnetic fluxes in the AC gap, experiencing a "lift" to the anode. On the basis of these assumptions, Desjarlais in his model[54] obtained a similar result: "collapse" of the impedance observed for values of B/B_{cr} far from unity, and final voltage at the diode due, in contrast to Refs. 50 and 51, to the vanishing of the effective value of the AC gap owing to the "lift" of the electron layer. Depending on the thickness chosen for this layer, assuming a uniform electron density distribution in it, the value of this limiting voltage is given by

$$3.5B_0d\leqslant U^*\leqslant 4.4B_0d, \tag{8}$$

where d is the AC gap in centimeters and B_0 is the external magnetic field induction in tesla. The analysis of the experimental dependence for MIDs of this type at terawatt and superterawatt accelerators carried out by Miller[55] demonstrates this impedance collapse and is in good agreement with the model predictions. As an illustration, in Fig. 8 we show the spherical focusing scheme of an MID installed at the PBFA-2 accelerator, including the ion-beam diagnos-

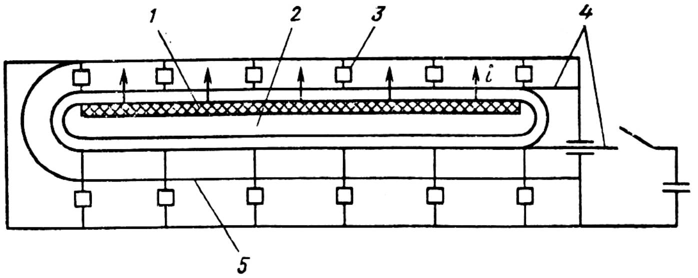

FIG. 9. Scheme for a diode with a single-loop cathode and magnetic field inclusion (Ref. 57): 1—dielectric, 2—anode, 3—avalanche diodes, 4—cathode, 5—magnetic screen.

tics. This diode is at present a record-breaker in the parameters attained among focusing MIDs with an external meridian magnetic field and zero magnetic flux traversed by the ion beam. It incorporates a number of modifications allowing the optimization of the focusing properties, such as aspherical shape of the anode surface for correcting the effect of the self magnetic field of the HPIB in the AC gap, introduction of auxiliary anode magnetic coils compensating for the residual magnetic current on the path to the focus and thus constricting the calculated position and shape of the separatrix, depending on the type of accelerated ions (H^+ or Li^+, which undergo stripping in the film that they pass through), and guaranteed high degree of neutralization in the basic segment along which they drift in a low-pressure gas to the focus in the region behind the cathode.

In the shaping of HPIBs extracted from a diode of this type, the AC gap, like the electrodes themselves, is planar, and the magnetic field has radial geometry.[56] At high current levels the effect of the self field of the latter can be taken into account as a correction of the flat surface of the anode. In MIDs of this type the electron drift is closed in the azimuthal direction.

Another example of an MID with azimuthal drift is the diode with the inclusion of a magnetic field, which is created in the transmission of a current along the surface of the cathode made in the form of a loop surrounding the anode[57] (Fig. 9). In this case the continuity of the $\mathbf{E}\times\mathbf{B}$ drift of the electron flux can be ensured for constant ratio E/B at all points in the AC gap. When an MID of this type is extrapolated to large loop lengths (up to 1 m and more), it becomes necessary to correct E, owing to the significant inductance of the cathode loop. This can be done by using nonlinear elements shunting the cathode on the main pulse (for example, the diodes of Ref. 58).

Among the MIDs with nonclosed drift are not only diodes with an external magnetic field, but also diodes operating in a self-insulating mode, without anode shaping of the dense focus of the converging electron beam, i.e., a pinch. An example of the first type is the diode with current-carrying cathode—a squirrel cage—and azimuthal magnetic field created in the transmission of the current through it.[59]

An example of the second type is a flat or focusing MID with azimuthal self field created by currents passing through the cathode loop surrounding the anode in the radial direction,[60] or a flat diode with self-insulation of the strip type[61] (Fig. 10). The very diversity of MIDs and the considerably larger number of experiments carried out using them are an indication of the advantages of MIDs compared with reflection systems and pinch diodes. Among these are (1) long operating life, (2) controllability of the HPIB parameters, and (3) the large range of MID powers and diversity of MID geometries, which broaden the application of MIDs as ion sources.

To illustrate this, in Table III we give the characteristics of several MIDs developed in the last ten years for various studies and applications.

3. ION SOURCES IN DIODES

In all the diodes discussed above, except for the plasma-filled ones, the ion source is a plasma generated by some method at the anode surface. In the case of plasma-filled diodes the plasma is created either directly in the AC gap of the diode (for example, by ionization of the residual gas), or it is injected into it from external sources. Let us briefly consider the main methods of obtaining such a plasma and the characteristics of the HPIB extracted from it, and also the problems encountered in optimizing these characteristics (homogeneity of the beam composition, spatial uniformity, low temperature) related to the parameters of the plasma itself. In an RS, where oscillating electrons repeatedly intersect the thin anode, plasma formation on the anode surface occurs primarily owing to Joule heating (in the case of conducting anodes) because of electric-charge storage in it. Here the plasma which is generated is, as a rule, a multicomponent one, and its composition is mainly determined by the molecules adhering to the anode surface, which undergo electron-stimulated desorption and avalanche ionization in the electric field when primary and

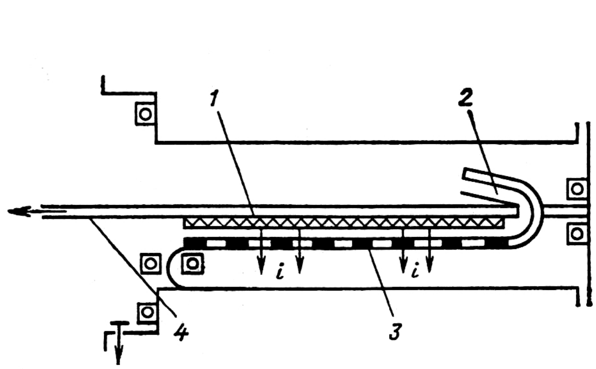

FIG. 10. Planar strip diode with self-insulation (Ref. 61): 1—dielectric, 2—electron flux stripping region, 3—cathode, 4—strip anode.

TABLE III. Characteristics of magnetically insulated diodes.

Generator	Ion energy, MeV	HPIB current, MA	HPIB energy, kJ	Ion type	Generation efficiency, %
ETIGO	0,9	0,015	0,5	H^+	20
ВЕРА	0,7	0,03	1	H^+	80
ВОДА-10	1	0,1	100	H^+	80
PROTO-2	1,7	2,4	100	H^+	80
PROTO-1	2	0,4	150	H^+	90
GERMES-III	4	0,02	12	H^+	13
PBFA-1	5	7,2	180	H^+	80
PBFA-2	6	8	240	Li^+	90

secondary electron fluxes are present. Passive plasma sources, which have actually been studied at all the attainable MID power levels, are chronologically the first plasma sources in MIDs, and they are still important. They are mosaic-dielectric covering of the anode surface made in the form of separate elements,[62] dielectric-filled grooves, a system of holes in the dielectric, and so on.[63,64]

In spite of the lack of a complete understanding of all the processes and their interrelationship in plasma formation on such a surface, the essential situation is that surface breakdowns occur at points where the electric field is nonuniform as a result of buildup of the electron-current leakage charge, secondary-electron knockout, and stimulated desorption of gases from the anode surface followed by their breakdown in the electric field. The anode-plasma formation process and the onset of HPIB generation altogether take 5–10 nsec (in the case where the electron losses to the anode are small the plasma can operate for longer time intervals[58]). The materials most widely used for obtaining proton beams are polyethylene (CH_2), polystyrene (CH), and an epoxy compound ($C_8H_{11}O$). Mass-spectrometer analysis of the composition of HPIBs generated with these types of coatings has shown that they generate multicomponent beams whose content is to a significant degree determined by the adhesed gases. Here it should be noted that for the working vacuum used, $P \simeq 10^{-4}$ mm Hg, the anode surface is coated with a multilayered film of molecules of the residual gases and oil vapors from the vacuum system. Here the use of special cleaning methods (glow discharge into a different atmosphere), as a rule, has little effect if they are not performed during the high-voltage pulse itself and directly ahead of it. This is illustrated by the data given in Table IV, which were obtained at the accelerator Nereus.[65] Roughly the same results were obtained using a passive lithium-containing source $LiNO_3$, LiF, or LiI at room temperature, except perhaps that the Li^+ yield was a bit higher for the simultaneous use of glow discharge into Ar and anode heating to 200 °C.

Therefore, these sources cannot ensure that the HPIB contains only a single component. Their second main defect is the time delay of the plasma formation itself and, accordingly, the start of the ion-beam generation. Nevertheless, cryogenic passive anodes coated with solid pure H_2, N_2, Ar, and so on, prepared directly in front of the operating accelerator are certainly of interest. The integrated current amplitudes of hundreds of amperes with nearly 100% single-component content presently attainable are very promising.[66] A large number of studies in this area have been carried out by groups of Japanese physicists at the Tokyo Technological Institute.[67]

A fundamentally new class of passive sources of intense ion beams is that of liquid-metal sources using ion-field emission from micropoints (microbursts) formed from instabilities of the liquid surface of the anode in a strong electric field.[68] The time for such microbursts to be formed at the anode ($\tau \sim E_0^{-3}$) and the characteristic distance between them ($\lambda \sim E_0^{-2.5}$) are shown as functions of the E field in the AC gap in Fig. 11. For example, for the diode at the PBFA-1 accelerator the formation time for microbursts of liquid lithium is 3 nsec, the average total density on the surface is about 5 kA/cm^2, and the microdi-

TABLE IV. Characteristics of anode-plasma sources.

Type	Anode backing material	Temperature, K	Li^+	N^+	$C^{+,2}$	$N^{+,2}$	$O^{+,2}$
Epoxy compound	Al	293	—	71	13	12	2
ETEG 4	Cu	505	82	—	—	4	12
ETEG 5	Cu	442	82	1	2	2	12
$LiNO_3$	Stainless steel	544	90	—	—	2	7
$LiNO_3$	Cu	564	69	—	—	4	27
Li	Stainless steel	414	96	—	—	—	3

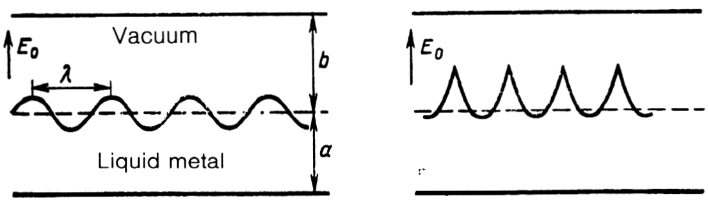

FIG. 11. Scheme for development of a surface instability of liquid metal in strong electric fields (Ref. 68).

vergence of the beams is about 6 mrad. Owing to the local rise of the E field at the tip of the microburst, its amplitude reaches 10^8 W/cm, which is sufficient for the appearance of ion-field emission with average current amplitude of up to several kiloamperes per unit area. This method is applicable in working with AC-gap voltages of order 10^7 V/cm, i.e., only at superhigh-voltage generators (PBFA-2, GERMES-III, Aurora, and so on).

In a control experiment carried out at a lower voltage, the formation of micropoints on a liquid surface of area 600 cm^2 with density agreeing with the linear analysis of Ref. 69 was confirmed.

The first experiments with lithium-containing anodes (surface deposition of a lithium layer, or saturation of a porus surface layer by lithium) confirmed the possibility of attaining very nearly one-component HPIBs with lithium content of up to 90% and higher,[70] and also the possibility of constructing a vertically oriented liquid anode surface maintained by the forces of molecular binding to the porous backing.

Such passive plasma sources are designed for obtaining beams of positively charged ions. Naturally, the plasma generated by a passive source also contains some number of negative ions, the concentration of which depends primarily on the temperature, the degree of equilibrium, and the density. The possibility of using diodes to obtain pulsed beams of negative ions with power level of the same order as in the case of positive HPIBs (when the negative-ion content in the plasma at the electrodes is sufficiently high, 2–5%) was first demonstrated in Ref. 71. The basic idea is to impose on the AC gap of an MID a very strong magnetic field [$B \geqslant (5\text{–}10) B_{cr}$] which squeezes the electron flux toward the cathode, so that the main contribution to the space charge comes from the negative-ion flux ($E_C = 0$).[72] The results of experiments on the measurement of the fluxes of negative ions emitted from the plasma of the cathode electrode in coaxial diodes (lines with self-insulation) carried out at several laboratories are ambiguous and indicate that the state of the intradiode plasma significantly affects the characteristics of an electrically negative HPIB.[72–75] The measured values of the current density lie in the range from a fraction[73] to tens[75] of amperes per square centimeter and strongly depend on the state of the plasma in the AC gap before the arrival of the main high-voltage pulse, i.e., on the shape and amplitude of the prepulse, its duration, the vacuum conditions, and so on. The goal of using intense H^- beams in various problems stimulates further studies in this area, primarily to understand the mechanisms of H^- ion formation in the cathode plasma and the optimization of this process.

Turning now to a brief description of active plasma sources, which ensure the appearance of a plasma in the AC gap before the arrival of the high-voltage pulse from the generator, we note that above we have already mentioned some studies on plasma-filled diodes, in particular, AMPFION, a plasma-filled diode with magnetic self-insulation. The two types of plasma source most widely used in practice at present are coaxial or helical plasma guns[76] or surface multispark devices.[77] Among their drawbacks are the large divergence and nonuniformity of the plasma (in the first case) and the large content of neutral atoms and low plasma density (in the second). Another type of plasma source in the form of a ring-like spark gap located in a composite anode of a reflection system has been tested in experiments.[78] This construction with a practically indestructible anode is superior to traditional RSs in its long operating life. Analysis of the HPIB content shows that there is a broad mass spectrum, including the heavy materials of the spark electrode. The same is true for active plasma sources made in the form of an exploding foil located on the anode.[79] The explosion of the foil and subsequent plasma generation can be effected both by an external power source and by the shunting of the main generator current through the foil. The resulting ion-current density levels are quite high (200 A/cm^2 for H^+ and 500 A/cm^2 for heavier gas ions). The possibilities offered by these plasma sources for obtaining heavy ions significantly depend on preliminary outgassing of the electrodes and oil-free pumping to a high vacuum (10^{-6}), which significantly diminishes their prospects. In connection with this, ion sources made from a gaseous anode layer produced in pulsed admission with subsequent ionization by means of vortex fields may prove very interesting. A scheme for such a plasma source is shown in Fig. 12. The development of plasma sources of this type at Cornell University[80] and at the Institute of Nuclear Physics, Tomsk at a power level of 10^{10} W gave proton and nitrogen beams in MIDs with a current density of 100 A/cm^2, good reproducibility, and long operating life. Here it should be noted that, as these studies have shown, it is necessary to perform an additional ultraviolet irradiation of the gas layer to prepare a plasma with a high degree of ionization.

Actually, intense UV irradiation (10–100 MW/cm^2) can also be used as an independent method of plasma generation on a solid surface. Experiments with UV irradiation performed at Sandia[81] and Osaka[82] on passive anodes with LiF and Na coatings, respectively, demonstrated a several-fold increase in the ion current and decrease of the "delay" time in switching on the anode from 25 to 10 nsec in the first case, and in the second they made it possible to obtain HPIBs containing 90% Na^+. An alternative to UV irradiation of the anode surface is provided by laser plasma

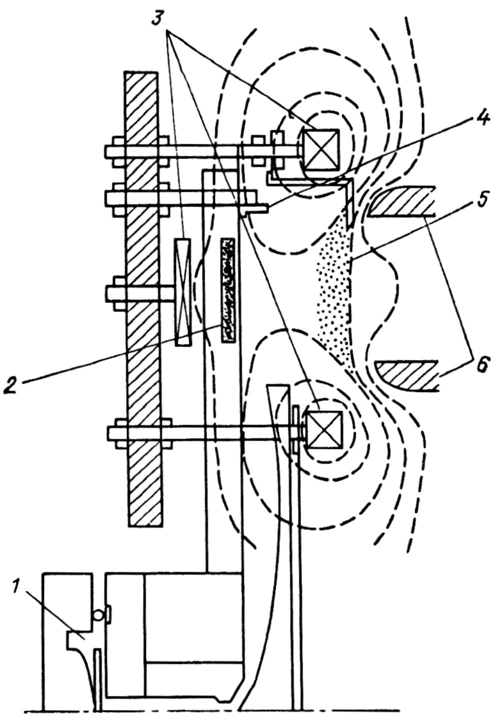

FIG. 12. Construction of an active plasma source with pulsed gas admission: 1—gas valve, 2—fast magnetic-field coils, 3—slow magnetic-field coils, 4—preionizer, 5—plasma anode, 6—cathode.

sources. Such a plasma source was used in a neutron source made in the form of a coaxial MID with titanium anode saturated by deuterium at high concentration (up to 0.5 deuterium atoms per lattice atom[83]). The plasma cloud with density up to 10^{15} cm^{-3} formed under the action of the laser pulse contains both deuterium ions and ions of the absorber material. The average neutron yield is 10 neutrons/pulse. A laser source of a pure lithium plasma was developed in Ref. 84 using a 20-nsec pulse of a ruby laser ($\lambda = 670.8$ nm) or a dye laser. Experiments with these lasers showed that the generation of a plasma of density 10^{16} cm^{-3} requires 40 MW/cm^2 and 1 MW/cm^2 for a ruby and a dye laser, respectively. In the latter case, the considerable decrease in the required power level is a reflection of the resonance nature of the ionization of the lithium cloud formed at the initial stage of bombardment of the lithium target by the laser beam. It should be noted that to ensure constant impedance of the diode, good matching between it and the generator, especially at terawatt levels, and good reproducibility of the dynamical MID parameters it is preferable to have a dense plasma ($\geqslant 10^{16}$ cm^{-3}) with a high degree of ionization occupying a small region near the anode. The preliminary creation of such a plasma can be accomplished by several methods. For example, the use of a two-pulse accelerator mode in which the first high-voltage pulse has opposite polarity ($-$) ensures the formation of a burst-emission plasma at the anode, and the second pulse ($+$) is the working pulse.[85] Analysis of the HPIB content shows that it contains many fractions, including a large number of ions of the adsorbed gases.

Variation of the pause between the pulses and the amplitude of the first pulse makes it possible to control the HPIB parameters within certain limits. The method requires the use of oil-free vacuum pumping and the corresponding preparation of the anode surface.

A two-stage method of generating a dense layer of lithium plasma (10^{15} cm^{-3}, 1 mm) (BOLVAPS/LIBORS), including in the first stage anode heating with formation of a thin film of lithium vapor with subsequent laser ionization using resonance absorption, is being developed at Sandia Laboratory.[86] The active anode is in the form of a sandwich containing a ceramic substrate, a heating element in the form of a metal film, and a surface layer containing lithium (LiAg). The thin layer of Li vapor is also formed in two stages via a phase of LiAg fusion using a slow (longer than 1 msec) and a fast (longer than 1 μsec) pulse. The ionization process occurs with a very large cross section via an excited resonance level at the wavelength 670.8 nm. Small-scale test experiments have confirmed the formation of an almost completely ionized plasma with density 10^{16} cm^{-3}. These data were used as the basis for constructing an active Li plasma source for the PBFA-2 accelerator, where a radiation power of about 60 MW at this wavelength is required to obtain the calculated plasma density of 10^{17} cm^{-3}.

CONCLUSION

Let us conclude this review by listing the main results and trends in the further development of high-power pulsed ion sources.

1. The voltage and energy-storage levels presently reached in primary storage devices of the capacitative type amount to tens of megavolts and megajoules, and the modular principle is typically used for them. Further increase of the voltage on a capacitative storage device is inadvisable, and it is more promising to use inductor sections fed in parallel from micro- and nanosecond sources with voltages of up to hundreds of kilovolts to a megavolt.

2. The use of plasma releases directly in front of an ion diode is promising for decreasing the pulse front and duration, and also for increasing the pulse voltage and power.

3. Ion diodes with external magnetic insulation are the most promising from the viewpoint of HPIB generation. Their advantages are (a) the possibility of operating without replacement of the anode block after each triggering of the accelerator at power levels of up to 10^{13} W, (b) a high degree of transformation of energy transferred to the diode into energy of the generated HPIB when the electron drift orbits in the AC gap of the diode are closed, (c) the possibility of reaching 100% HPIB extraction in the transport and focusing region, owing to the absence of a real cathode surface, the role of which is played by the virtual cathode formed by the drift electron cloud, (d) controllability of the diode parameters by choice of the corresponding magnetic field distribution in the AC gap, (e) simplicity of the realization of ballistic focusing of the HPIB for the corresponding choice of shape of the anode surface, and (f) the possibility of realizing HPIB generation with current den-

sity an order of magnitude larger than the Child–Langmuir value, owing to neutralization processes in the interelectrode gap.

4. For plasma sources in diodes there is a tendency to go from passive to active types in connection with the fact that the former generate multicomponent beams whose composition depends on the state of the electrode surfaces. Therefore, in all active plasma sources control of the state of the anode surface and its cleaning immediately before the "shot" (use of oil-free pumping) become particularly important for obtaining a one-component beam.

5. Laser plasma sources, including the creation of a gas layer or control and preparation of the anode surface state (its heating and evaporation), are quite efficient and offer good possibilities for obtaining pure beams of light ions (H^+, D^+, Li^+, and C^+).

6. It is very important to extend the range of plasma sources to intermediate and heavy ion masses. Liquid-metal, cryogenic, and capillary plasma sources with large total area are the most promising for this. Plasma sources of the burst-emission type (the "two-pulse mode") require further modification to obtain effective control of the anode surface state.

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