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COLLECTIVE ION ACCELERATION WITH INTENSE ELECTRON BEAMS*

Craig L. Olson
Sandia Laboratories
Albuquerque, New Mexico

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Summary

Collective acceleration methods that employ an intense relativistic electron beam (IREB) are discussed. A brief history and a classification of collective acceleration methods are given. Methods examined include IREB injection into neutral gas; IREB injection into vacuum; plasma-filled IREB diodes; and vacuum-filled IREB diodes. Accelerating fields of order 10^6 V/cm have been observed experimentally. The collective acceleration processes for IREB injection into neutral gas and vacuum are discussed. It is noted that the collective acceleration processes for IREB diodes have not been elucidated yet. A summary of present collective ion acceleration research areas that involve IREB's is given.

1. Introduction

Collective acceleration methods differ from conventional acceleration methods in that the main accelerating fields are not caused by externally applied potentials. Instead, the accelerating fields are caused by the collective effects of a large number of particles which impart acceleration to a smaller number of particles. In conventional accelerators, the effective accelerating field is ultimately limited by electrical breakdown at the accelerating gap. In collective-effect accelerators, the accelerating fields are not limited by breakdown, and accelerating fields much larger than those in conventional accelerators should ultimately be achievable. Other fundamental differences are that collective-effect accelerators can have net charge densities, and net current densities, directly in the acceleration region. In conventional accelerators, e.g., the applied accelerating fields are divergence-free in the accelerating gap region ($\nabla \cdot E = 0$), which means longitudinal phase stability and radial focusing in the gap may be mutually exclusive. In collective-effect accelerators which utilize a net charge density, the accelerating fields may have a divergence ($\nabla \cdot E \neq 0$), and longitudinal phase stability and radial focusing may occur simultaneously.

Since the introduction of several basic ideas on collective acceleration by Veksler,[1-3] Budker,[4] and Fainberg[5,6] in 1956, research on collective acceleration has grown considerably. The electron ring accelerator (ERA, concept emerged from Dubna in 1967,[7] and since that time it has enjoyed large-scale investigations at Dubna, Berkeley, Maryland, Garching, Karlsruhe, Nagoya and Moscow.[8-17] At this meeting, the latest results from Garching concerning their successful acceleration of protons and He ions will be given;[18] as will the latest results on the cusp injection ERA work at Maryland,[19] and some ring compression work at Nagoya.[20] With these brief comments on the ERA, we shall now turn to collective acceleration with intense relativistic electron beams (IREB's), to which most of this paper will be devoted.

Intense relativistic electron beams had their origins in the pulsed power technology pioneered in the early 1960's by Martin.[21] A typical IREB today has electron energies from 100 keV to 10 MeV, currents from 10 kA to 1 MA, and pulse lengths from 10 nsec to 100 nsec. Because the IREB electron density is typically high ($\sim 10^{11}$-10^{13} cm^{-3}) it is ideally suited for collective acceleration research. Interest in IREB collective acceleration research grew in 1968 when Graybill and Uglum discovered that injecting an IREB into a low pressure neutral gas could produce collectively accelerated ions with energies greater than the IREB electron energy.[22] Since that time a considerable amount of experimental[23-38] and theoretical[39-48] work has been done to investigate this process,[49-54] and recently a theory[55-59] has been developed that has been able to explain the observed acceleration.[22-38] Collective fields of order 10^6 V/cm have been inferred from the data; fields of this order are predicted by theory and are seen in numerical simulations.[60] Collective acceleration with IREB's injected into vacuum has also been studied,[30-32,61-63] and collective acceleration in the diode that generates an IREB has also been investigated.[29,30,64-90]

In part 2, a brief classification of collective methods is given. In part 3, IREB collective acceleration is discussed in regard to IREB injection into neutral gas, vacuum, and plasma; and for plasma-filled diodes and vacuum-filled diodes. In part 4, present approaches to collective ion acceleration using IREB's are discussed, and in part 5, concluding comments are given.

2. Classification of Collective Methods

Collective acceleration research at present includes a rather large area of experimental data, theoretical concepts, and proposed acceleration schemes. A brief classification of these "methods" is given in Table 1, where they are categorized as to how the main accelerating field is produced; by net space charge (of an electron beam, or a bunch of charged particles), by waves and/or instabilities (excited, e.g., by interactions between beams, plasmas, charged particle bunches and/or external structures), by inductive effects (such as those caused by envelope motion of a current-carrying beam), or by impact acceleration (a purely dynamic collisional effect). The listing is Table 1 is not meant to be exhaustive: it does, however, present a convenient summary of the major areas of collective <u>ion</u> acceleration research and collective <u>electron</u> acceleration research. In the later case, a large number of energetic electrons is used to accelerate a smaller number of electrons to higher energies; this includes electron autoacceleration effects[53,99,122-125] and the electronic ram effect.[126-130] Brief comments about each of the four categories in Table 1 follow.

(1) By *net space charge*, we mean that ion accelerating fields are produced by a simple net charge density. It should be noted that this is the only category in which accelerated ions have been produced, and explained, to date (this includes the ERA, IREB into gas, IREB into vacuum, and HIPAC).

(2) *Waves and instabilities* have been frequently proposed as possible acceleration methods, and a considerable amount of theoretical work has been done in this area, especially in the Soviet Union. Note that the listing IREB/diode was only tentatively included here, because the collective acceleration process(es) involved are not sufficiently understood at this time; the two-stream e-i instability has been suggested as a possible explanation,[76,116-118] but so have several other wave-type schemes, and space-charge and inductive-type effects.[64-72,82-90] Apart from this IREB/diode possibility, none of the wave schemes given here have been developed to date to the stage of producing accelerated ions in actual experiments.

(3) By inductive effects we mean induced fields that might be caused, e.g., by envelope motion of a beam with a net current (IdL/dt effect), or by the rise or fall of a net current (LdI/dt effect). This concept has arisen as a possible candidate for explaining certain experimental data.[64-70,44-47,83] Here we note note that recent theoretical results[56] indicate that these effects are typically not strong enough to produce useful collective ion acceleration. The electronic ram effect is tentatively included here because induced fields have been proposed[126-130] to explain the observed collective electron acceleration; however, estimates we have made tend to indicate inductive effects should be negligible, and that the acceleration mechanism is still open for further investigation at this time.

(4) Impact acceleration refers to the purely

dynamic effect caused by the collision of a relativistic (γ) heavy bunch (e.g., a dense electron bunch) with a light bunch (e.g., a small ion bunch).[1-3,131,132] Providing certain restrictions are met, each ion should receive the enormous energy $2\gamma Mc^2$ (where M is the ion mass and c is the speed of light). However, the restrictions on the heavy bunch have been shown to be prohibitive[101]--the equivalent peak current I_o of the heavy bunch must be $I_o \gg 23.4\ \beta\gamma$ MA. Since IREB peak currents today are only of the order of one MA, the impact acceleration method must apparently remain confined to the concept stage for now.

From this brief overview we note that "net space charge effects" appear to be the principle means of collectively accelerating ions to date. In regard to high energy ion acceleration in this category, we note that theoretical considerations limit the accelerating fields in an ERA to ≤ 0.45 MV/cm.[17] The HIPAC configuration[91,92] employs a stationary potential well, and it therefore cannot be used over and over again to produce very high ion energies (the HIPAC has merit principally as a high-Z ion source). IREB's, on the other hand, have already demonstrated ion accelerating fields of order 1MV/cm, and there are at present no fundamantal theoretical limitations on producing even higher fields. Collective ion acceleration research with IREB's will now be discussed.

3. IREB Collective Ion Acceleration

The basic configuration of an IREB diode and a drift tube are shown in Fig. 1. The IREB is created by a high voltage pulse from a Blumlein or transmission line which is applied across an anode-cathode gap. Cathode electrons are accelerated to the anode, which is a thin foil, and pass directly through it. Depending on what the drift tube contains (neutral gas, vacuum, or plasma), the IREB may or may not propagate efficiently in it. Collective ion acceleration has been observed in the drift tube (filled with neutral gas or with vacuum) and in the diode region (filled with plasma or with vacuum). Collective ion acceleration in a drift tube filled with plasma has not been reported.

IREB/gas: Collective ion acceleration for IREB injection into a neutral gas was discovered in 1968 by Graybill and Uglum.[22] Subsequently, many more experimental investigations were performed at Ion Physics Corporation (IPC),[23,24] at Physics International (PI),[25-28] at Sandia Laboratories,[29-32] at the Air Force Weapons Laboratory (AFWL),[33-35] at the Lawrence Livermore Laboratory (LLL),[36] at the Lebedev Physical Institute (Moscow),[37,53] and at the Physical Technical

Institute (Kharkov).[38] In the basic experiment, the metallic guide tube is filled with a neutral gas at a pressure of the order of 0.1 Torr H_2. Ions are observed to be accelerated in the same direction that the IREB propagates and to attain energies higher than the IREB electron energy. Ion detection may be accomplished by current screens, nuclear emulsions, activation analysis, and/or ion mass spectrometry. The ion energy, number of ions, and ion pulse length all have dependences on the neutral gas pressure, as well as on the electron beam energy and current. In fact, the process is controlled by at least eleven independent parameters; IREB (energy $\mathcal{E}_e$, peak current I_o, voltage risetime t_v, current risetime t_r, pulse length t_b, radius r_b), metallic guide tube (radius R, length L), and neutral gas (charge state Z_i, ion mass M, and pressure p). A summary of accelerated protons and related IREB and drift tube parameters is given in Table 2. For a summary of other accelerated ions (D, He, N, A), see ref. 32.

Originally, six theories were proposed to explain the data. These include the one-dimensional electrostatic well models of Rostoker,[39] Uglum et al.,[40,41] Rosinskii et al.,[42] and Poukey and Rostoker;[43] the localized pinch model of Putnam;[44-47] and the inverse coherent Cerenkov radiation model of Wachtel and Eastlund.[48] Thus concepts in each of categories (1) to (3) in Table 1 were originally employed to explain the data. However, in a detailed study,[56] it was found that serious questions arise concerning the validity of some of these theories, and that major difficulties occur in trying to use any of these theories to explain the date.[54,56,59] A general study of electrostatic, inductive, and wave-type accelerating fields was also made.[56] It was concluded that the mechanism responsible for the observed acceleration must be an electrostatic effect but that a new theory (different from the four earlier electrostatic theories) was needed to explain the data with all of its parametric dependences.

In a new theory developed by Olson,[55-59] substantiated by numerical simulations of Poukey and Olson,[60] ion acceleration occurs in the electrostatic fields of a time-dependent two-dimensional potential well. The acceleration process is basically a zero-order electrostatic effect, whose description depends on a complete knowledge of the ionization of the background gas and the self-consistent coupling of the beam dynamics to the ionization processes. Ion ionization and ion avalanching were shown to produce major effects while electron avalanching was shown to produce negligible effects.[57-59] The theory contains dependences on all eleven parameters mentioned earlier, and we shall now briefly summarize the basic acceleration process and the predictions of this theory.

The acceleration process depends critically on the relation of the injected current I_o to the space-charge limiting current $I_\ell = \beta(\gamma-1)\,[mc^3/e]\cdot[1 + 2\ell n(R/r_b)]^{-1}$,[54,58] where $\beta = v/c$, v is the injected electron velocity, $\gamma = (1-\beta^2)^{-1/2}$, and m and e are the mass and charge of an electron. The current I_ℓ is that current for which the potential depression φ_o caused by an unneutralized beam just equals the injected electron beam energy (i.e., $e\varphi_o = \mathcal{E}_e$). For $I_o \gtrsim I_\ell$, the injected beam initially stops at the anode, and the collective ion acceleration process occurs. For $I_o \ll I_\ell$, the beam is not slowed appreciably in the axial direction, it does not stop at the anode, and no accelerated ions should occur. For reference, the Alfvén-Lawson magnetic limiting current I for a charge-neutral, but not current-neutral, intense beam is $I_A = \beta\gamma mc^3/e$.[133,134] If there is charge neutrality, then magnetic stopping effects will occur if the net current exceeds I_A. Note that $I_\ell < I_A$ always, so whether or not collective ion acceleration can occur depends on the relative sizes of I_o and I_ℓ.

For $I_o \gtrsim I_\ell$, collective ion acceleration may occur, and the resultant two-dimensional electrostatic well effects are indicated in Fig. 2. Initially the beam stops at the anode, and a deep potential well forms of depth $\varphi_o = \alpha\mathcal{E}_e/e$, where $2 < \alpha < 3$.[43,58] The background gas is ionized (by electron impact ionization and by ion avalanching) throughout the deep well region of axial length $\approx 2R$, although the stopped electron beam is confined to a much smaller axial region.[58] At roughly the charge neutralization time, a non-adiabatic transition occurs, the beam front begins propagation, and the self-consistent well depth drops to $\varphi_o \lesssim \mathcal{E}_e/e$. Ion acceleration occurs during the deep well stage (which produces an ion distribution with energies up to $\mathcal{E}_i \approx \alpha Z_i \mathcal{E}_e$) and during the transition stage (where ions may be trapped in the propagating well). The final, propagating beam front equilibrium is shown in Fig. 3; the self-consistent front structure moves slowly ($\beta \sim 0.1$) while beam electrons stream through it ($\beta_e \sim 1$). The axial length of this structure is typically very long ($\gg r_b$).[58]

The speed at which the beam front moves out (and therefore the ion energies attainable) depends on several parameters. At sufficiently low pressures, the front speed is determined by the fastest ions created during the deep well stage. At higher pressures, the front assumes a speed about equal to $2R/\tau_n^{e,i}$ where $\tau_n^{e,i}$ is the charge neutralization time including ion ionization effects. At still higher pressures, above some "runaway" pressure p_R, the beam becomes charge neutralized during its risetime <u>before</u> the current I_ℓ is reached; in this event, the beam never sees a large potential depression, never stops at the anode, and no accelerated ions should occur. Thus for $p > p_R$, ion acceleration is effectively precluded. For $p < p_R$, ion acceleration may occur, providing that certain trapping criteria are also satisfied.[58]

A comparison of the theory, experiments, and numerical simulations (2-D) is given in Fig. 4, where the final ion velocity $\beta_i c$ is plotted against p. Note that there is reasonably good agreement between all three, and that all three show the effects of roughly constant ion energy at low pressure, increasing ion energy at moderate pressures, and beam front runaway (no ions) at higher pressures. Numerous further comparisons have also been made (concerning, e.g., beam front velocities, number of ions, etc.),[58,60] and it appears that the theory offers a reasonably-well substantiated explanation of the observed collective acceleration process. By keeping I_o fixed and varying I_ℓ (from $I_\ell < I_o$ to $I_\ell > I_o$), Straw and Miller observed the ion acceleration threshold at $I_o \approx I_\ell$, and they found ions only for $I_o \geqslant I_\ell$.[33,34] Their most recent studies with a larger IREB will be reported at this meeting.[35] Also, in earlier work recently brought to our attention, VanDevender[36] reported no ions in experiments with $I_o \ll I_\ell$ (in agreement with the theory).

Alexander et al. have also recognized the importance of ion ionization effects and have applied them to a 1-D model.[135,136] Elsewhere, Kolomensky and Novitsky have recently developed a $1\frac{1}{2}$-D computer model to study the collective acceleration process.[137] Their results tend to further substantiate the results of the 2-D theory and the 2-D simulations discussed above.

<u>IREB/vacuum</u>: Collective ion acceleration by injecting an IREB into a vacuum-filled drift tube has been reported by Kuswa,[30] Swain et al.,[31] and Olson et al.[32] The acceleration effect has been explained[31,32] in reference to the theory described above. For $I_o \geqslant I_\ell$, the beam remains stopped at the anode until a sufficient positive ion background can be created to provide some charge neutralization. In this case, the ions come from the anode foil plasma created by passage of the IREB through the foil. (The plasma may include adsorbed gas ions as well as other impurities.) When the dynamic ion background density is sufficient to

provide approximate charge neutrality, the beam may begin a "quasi-propagating" stage in which "beam propagation" is consistent with the drawn-out, dynamic ion background. Ion energies up to $\alpha Z_i \mathcal{E}_e$ $(2 < \alpha < 3)$ are predicted; ion energies up to $2Z_i\mathcal{E}_e$ have been seen experimentally, and ion energies up to $2Z_i\mathcal{E}_e$ are seen numerically.[31,32] Also, the transition between the effects of vacuum-filled and gas-filled drift tubes has been seen experimentally;[31] below a certain low pressure, anode foil ions are accelerated before the neutral gas is sufficiently ionized, and the net effect looks like a typical "vacuum shot."

Nation[61] has also reported studies on IREB injection into vacuum, as has Kim and Uhm.[62] Zorn et al. have apparently converted the Maryland ERA injector to study vacuum injection, and their results will be reported at this meeting.[63]

For $I_o \ll I_\ell$, an IREB injected into vacuum will not stop at the anode, but will propagate with radial spreading. If an axial magnetic guide field is used, then an unneutralized, propagating IREB is possible. This, in fact, forms the basis for the cyclotron-wave auto-resonant accelerator concept[119-121] to be discussed later.

IREB/plasma: For intense electron beam injection into a plasma, there have been no experimental reports of high-energy, collectively-accelerated ions to date. IREB injection into plasma is actively being studied as a means of plasma heating in relation to controlled fusion research, and the general goal is to efficiently utilize plasma instabilities to transfer beam energy to the plasma. For $n_p \gtrsim n_b$ (where n_p is the plasma density and n_b is the beam density), charge neutrality occurs quickly and the collective acceleration process discussed above (for injection into gas) is precluded. However, many of the wave and instability concepts listed in Table 1 may, in theory, be applicable in this case. However, caution is needed in applying certain theoretical calculations to experimental situations; e.g., IREB pinching to the force-neutral condition assumed in some e-i instability calculations[117,118] violates known limiting current criteria[64] for typical beam parameters. Thus, for IREB injection into plasma, waves and instabilities may eventually be used to collectively accelerate ions (to $\mathcal{E}_i > \mathcal{E}_e$), although no such experimental results have been reported to date.

IREB/diode (plasma-filled): Ions collectively accelerated in the diode region have been observed in many cases,[29,30,64-90] as summarized briefly in Table 3. Categorically there are two classes of diodes--plasma-filled and vacuum-filled. In reality, vacuum-filled diodes develope moving anode and cathode plasmas, so they too are, in some sense, plasma-filled. The physics behind anode and cathode plasma production and motion is currently an active area of IREB diode research.[138]

Collectively accelerated ions have been reported by Plyutto et al. of the Sukhumi Institute (USSR) for the plasma-filled diode configuration shown in Fig. 5a.[64-70] A spark source is used to create a plasma, which then expands through a hole in the cathode; when the cathode-anode gap is appropriately filled with plasma, the diode potential U_o is applied. A variety of phenomena are observed, including ions with energies up to many times eU_o, electrons with energies up to several times eU_o, transient current and voltage effects, and indications of time-dependent beam pinching. The process(es) responsible for the accelerated ions are apparently quite complicated. Suggested explanations have involved entries in each of the categories (1) to (3) in Table 1; i.e., space charge effects, inverse coherent Cerenkov radiation effects, and inductive beam pinching effects.[54-70] The highest energies attained are $\epsilon_i^{max}/\epsilon_e^{max} \approx 10$, and $\epsilon_e^{max} \approx 3eU_o$.[64,65] In some instances ϵ_i does not depend on Z_i;[68] in other instances ϵ_i scales directly as Z_i. A definitive explanation of the collective acceleration processes involved remains to be given.

<u>IREB/diode (vacuum-filled)</u>: Collectively accelerated ions have also been seen in "vacuum-filled" diodes at the Sukhumi Institute,[71,72] at AFWL,[73-77] at Sandia,[29,30,78-81] and at LLL.[82-90] A variety of configurations has been used, and the principle ones are summarized in Figs. 5b, c, d. The cathode usually has a small radius or is pointed. The anode is usually thick, may contain a central insert of a different material, and may have a hole on axis. Many materials (dielectrics, metal) and coatings (especially those bearing deuterium) have been used for the cathode and the anode, and frequently a CD_2 anode insert has been employed. It is evident that the time-dependent processes of the formation and motion of both anode plasmas and cathode plasmas play important roles in both the diode behavior and in the collective acceleration process.[29,30,78,80,138]

The purpose of most of the experiments in the U.S. has been to determine if thermonuclear processes were occurring. Hence the main diagnostic in the U.S. has been total neutron yield (and its isotropy or lack thereof), although in some cases ion mass spectrometry was also used.[29,30,76,78-80] The overall consensus of this work is that collectively accelerated ions produce neutrons via beam-target interactions, and that thermonuclear effects (if any) are at least not the dominant effects.

The various phenomena observed include ion energies greater than the applied gap voltage, transient current and voltage effects, and time-dependent beam pinching effects.[71-90] At Sandia, $\mathcal{E}_i$ up to 4 MeV has been reported for $\mathcal{E}_e \approx 2$ MeV.[30] At LLL, $\mathcal{E}_i$ in the range 5-13 MeV (with a possible energy tail extending to somewhat higher energies) has been reported for $\mathcal{E}_e \approx 2$ MeV.[89] The e-i two stream instability has been suggested as a possible explanation of the observed phenomena.[76,90,116-118] Several other possible explanations have been proposed by the LLL group, including inverse Cerenkov radiation, pinching effects, the electronic ram effect, the so-called Linhart effect, and several other wave type effects.[82-90] At present, however, a definitive explanation of the collective acceleration process(es) involved has not been established.

4. Present Approaches Using IREB's

A brief summary of continuing and proposed research areas involving IREB's for collective ion acceleration follows.

IREB/gas/control: Presumably more experiments will be done with IREB injection into neutral gas to further verify the acceleration mechanism, and to study even further parametric dependences (although all 11 basic parameters have already been varied.[22-34,36-38]) Kolomensky et al. (Moscow)[37] and Tkach et al. (Kharkov)[38] will apparently continue their experimental investigations. Straw and Miller (AFWL) will report new data at this meeting.[35] Also, some experiments should be forthcoming from Rostoker et al. (UCI).[139] Remaining experimental areas of interest include further studies of the effects of axial magnetic fields,[27,58,60] and possibly studies of multiple pulse phenomena[68] (which have been observed only at PI, and only in some cases[25-28]).

In regard to extending the acceleration process, the first logical choice is to consider possible passive control methods. Suggestions include axial variation of the pressure,[38,62,63,140,141] or of the guide tube radius. However, these effects have been investigated in relation to the beam-front equilibria that occurs in Olson's theory. It was found[142] that the self-consistent beam front "length," but not the beam front velocity, would vary if the pressure (or guide tube radius) were varied. Thus adiabatic theory results indicate that gradients in p or R cannot be used to control the acceleration process. It should be noted that no enhanced ion energies were seen in pressure gradient experiments at Sandia.[31] Also in experiments reported by Tkach et al.,[38] an axial variation of the pressure by a factor of 10 produced only a factor of ~ 0.5 change in the beam front velocity (instead of a change of order 10). Thus it appears that simple passive control methods cannot be used to modify the existing collective acceleration process to achieve higher ion energies.

Recently, an active control method has been proposed at Sandia, that may ultimately permit effective control of a steep beam front potential well over large distances.[59,101,102] In this scheme, the guide tube is filled with an appropriate working gas at a pressure lower than that used typically for ion acceleration, and low enough that ionization caused by the beam is negligible on the time scale of interest. An intense UV light source, e.g., a UV laser, is then used to photoionize the gas. By appropriately sweeping the UV laser, the beam front can be made to follow a predetermined motion. Estimates concerning laser powers required, and the expected ion output using modest IREB's, appear favorable.[101]

<u>IREB/transverse sweep</u>: A different concept is to transversely sweep an IREB so that ions will be accelerated by the net space charge density (of the IREB) in a direction essentially perpendicular to the IREB electron flow. Early suggestions involving highly-focused low current electron beams were given by Alfvén and Wernholm,[93] and by Johnson.[94] In the Soviet Union, suggested schemes include sweeping a long IREB "ray," and the "gyrotron."[53,95-99] The gyrotron concept involves an IREB closed on itself (a large electron ring) that is to rotate about an axis which intersects the ring and its center. Ions injected near the axis are to slip out along the ring and gain kinetic energy as the ring rotates. At present, IREB's have not been successfully recirculated on themselves to form such an intense electron ring, although many studies of this problem have been made in the U.S. for other purposes. Even if such a ring could be formed, the idea of rotating it and keeping it intact appears formidable. A different idea, proposed at Sandia, is to use a single controlled transverse sweep of an IREB that is injected transversely into a drift tube; the beam is transported to the tube (and deflected) in a region containing a charge-neutralizing plasma.[59,100,101] Inside the tube, vacuum conditions permit the full space charge of the IREB to be used for collective acceleration.

Estimates of the power required for the pulsed magnetic field for deflecting the beam, and accelerated ion estimates for existing IREB's appear favorable.[101]

IREB/vacuum: As noted above, this case has already been investigated,[29-31,61,62] and recent results from Maryland[63] will be reported at this meeting. Note, however, that peak ion energies only of the order of a few times $Z_i \mathcal{E}_e$ appear possible with this method, and that it therefore does not appear to hold promise for accelerating ions to very high energies.

IREB/cyclotron wave: The autoresonant accelerator concept is based on the assumption that a single, large-amplitude wave of the desired type (lower branch of the Doppler-shifted cyclotron mode) can be created when an un-neutralized IREB propagates in vacuum along a strong external magnetic field B_z.[119-121] The wave phase velocity is to be controlled by adiabatically decreasing B_z axially. Basic problem areas include, e.g., studies of vacuum propagation of IREB's,[143] wave excitation methods, isolation of a single large-amplitude wave, stability studies, and studies of wave-trapping of ions. Some of these investigations are already in progress and results should be forthcoming soon. It should be noted, however, that a very large IREB is needed for this method to achieve the same accelerating fields that IREB space charge methods (discussed above) should achieve using a rather modest IREB.[101]

IREB/diode: A large amount of data now exists that indicates collectively accelerated ions occur in vacuum-filled and plasma-filled diodes.[29,30,64-90] However, the acceleration mechanism(s) responsible for these results, have yet to be elucidated. More detailed diagnostics (such as time-resolved ion spectra) for various diode configurations would prove useful in isolating the acceleration mechanism(s). It should be noted that there is interest in understanding these collective acceleration phenomena in relation to controlled fusion studies using IREB diodes.[138] Also, since the "diode region" (i.e., the anode-cathode region) cannot be "extended" to a great length, it appears that IREB/diode configurations, in themselves, will not be useful for achieving very high ion energies. However, an IREB/diode configuration may prove useful as an ion source, or as an ion injector for other future collective-effect accelerators.

5. Conclusions

A summary has been given of collective ion acceleration research methods that involve intense relativistic electron beams (IREB's). Ion energies greater than the IREB electron energy have been observed (see Tables 2 & 3), and accelerating fields of order 1 MV/cm have been reported. An understanding now exists of the collective acceleration process for IREB injection into neutral gas or vacuum, whereas collective acceleration processes in IREB diodes are not currently understood. Present approaches to using IREB's for collective ion acceleration were discussed, and presumably one or more of these approaches may ultimately result in a viable working collective ion accelerator. The use of IREB's for collective ion acceleration research is still in its infancy.

REFERENCES

1. V. I. Veksler, Proc. CERN Symp. High En. Accel. 1, 80 (1956).
2. V. I. Veksler, Atomnaya Energiya 2, 525 (1957).
3. V. I. Veksler, Usp. Fiz. Nauk., 66, 99 (1958) [Sov. Phys. Uspekhi 66, 54 (1958)].
4. G. I. Budker, Proc. CERN Symp. High En. Accel. 1, 68 (1956); G. I. Budker and A. A. Naumov, ibid., p. 76.
5. Ya. B. Fainberg, Proc. CERN Symp. High En. Accel. 1, 84 (1956).
6. Ya. B. Fainberg, Usp. Fiz. Nauk. 93, 617 (1967) [Sov. Phys. Uspekhi 10, 750 (1968)].
7. V. I. Veksler, V. P. Sarantsev, et al., Proc. VI Int. Conf. High En. Accel., Cambridge (1967), p. 289.
8. V. P. Sarantsev, Particle Accel. 1, 145 (1970).
9. Symposium on ERA, Berkeley, LRL report UCRL-18103 (1968).
10. D. Keefe, Particle Accel. 1, 1 (1970).
11. J. M. Peterson, IEEE Trans. Nucl. Sci. NS-19 #2, 276 (1972).
12. G. R. Lambertson et al., Particle Accel. 5, 113 (1973).
13. M. Reiser, IEEE Trans. Nucl. Sci. NS-18 #3, 460 (1971).
14. C. Andelfinger, Particle Accel. 5, 105 (1973).
15. U. Schumacher, Max Planck Inst. für Plasmaphysik IPP 0/20, Dec. 1973.
16. G. R. Lambertson, Proc. IX Int. Conf. High En. Accel., SLAC (1974), p. 214 (and following papers).
17. D. Möhl, L. J. Laslett, and A. M. Sessler, Particle Accel. 4, 159 (1973).
18. U. Schumacher, C. Andelfinger, and M. Ulrich, Bull. Am. Phys. Soc. 20, 181 (1975) (this conference).
19. W. W. Destler et al., A. C. Greenwald and M. P. Reiser, Bull. Am. Phys. Soc. 20, 181 (1975) (this conference).
20. S. Kawasaki et al., Bull. Am. Phys. Soc. 20, 181 (1975) (this conference).
21. J. C. Martin, AWRE, private communication.
22. S. E. Graybill and J. R. Uglum, J. Appl. Phys. 41, 236 (1970); S. E. Graybill, J. R. Uglum, et al., Ion Physics Corp. Report DASA 2315 (1968).
23. S. E. Graybill, IEEE Trans. Nucl. Sci. NS-18 #3, 438 (1971).
24. S. E. Graybill, IEEE Trans. Nucl. Sci. NS-19 #3, 292 (1972).
25. J. Rander et al., Phys. Rev. Lett. 24, 283 (1970).
26. J. Rander, Phys. Rev. Lett. 25, 893 (1970).
27. B. Ecker and S. Putnam, IEEE Trans. Nucl. Sci. NS-20 #3, 301 (1973).

28. D. Drickey, B. Ecker, and S. Putnam, Proc. IX Int. Conf. High En. Accel., SLAC (1975), p. 263.
29. G. W. Kuswa, L. P. Bradley, and G. Yonas, IEEE Trans. Nucl. Sci. NS-20 #3, 305 (1973).
30. G. W. Kuswa, Annals N. Y. Acad. Sci., to be published.
31. D. Swain et al., Proc. IX Int. Conf. High En. Accel., SLAC (1974), p. 268.
32. C. L. Olson et al., Proc. Symp. Ion Sources, Berkeley (October, 1974), p. III-3-1.
33. D. C. Straw and R. B. Miller, Appl. Phys. Lett. 25, 379 (1974).
34. D. C. Straw and R. B. Miller, Bull. Am. Phys. Soc. 19, 966 (1974).
35. R. B. Miller and D. C. Straw, Bull. Am. Phys. Soc. 20, 182 (1975) (this conference).
36. J. P. VanDevender, LLL Report UCRL 50935 (1970).
37. A. A. Kolomensky et al., IV Nat. USSR Accel. Conf., Moscow (1974).
38. Yu. V. Tkach et al., Zh. Tekh. Fiz. 44, 658 (1974) [Sov. Phys. Tech. Phys. 19, 412 (1974)].
39. N. Rostoker, Proc. VII Int. Conf. High En. Accel., Yerevan (1969), p. 509.
40. J. R. Uglum, S. E. Graybill, and W. H. McNeill, Bull. Am. Phys. Soc. 14, 1047 (1969).
41. S. E. Graybill, W. H. McNeill, and J. R. Uglum, Rec. 11th Symp. Elect., Ion, Laser Beam Tech., San Francisco (1971), p. 577.
42. S. E. Rosinskii, A. A. Rukhadze, and V. G. Rukhlin, Zh. Eksp. Teor. Fiz. Pis. Red. 14, 53 (1971) [JETP Lett. 14, 34 (1971)].
43. J. W. Poukey and N. Rostoker, Plasma Physics 13, 897 (1971).
44. S. D. Putnam, Bull. Am. Phys. Soc. 14, 1048 (1969).
45. S. D. Putnam, Phys. Rev. Lett. 25, 1129 (1970).
46. S. Putnam, IEEE Trans. Sci. NS-18 #3, 496 (1971).
47. S. Putnam, Physics International Company Report PIFR-72-105 (1971).
48. J. M. Wachtel and B. J. Eastlund, Bull. Am. Phys. Soc. 14, 1047 (1969).
49. A. M. Sessler, Comments on Nuclear and Particle Physics 3, 93 (1969).
50. J. D. Lawson, Particle Accelerators 3, 21 (1972).
51. G. Yonas, IEEE Trans. Nucl. Sci. NS-19 #3, 297 (1972).
52. G. Yonas, Particle Accel. 5, 81 (1973).
53. A. A. Kolomensky, Proc. IX Int. Conf. High En. Accel., SLAC (1974), p. 254.
54. C. L. Olson and J. W. Poukey, Phys. Rev. A 9, 2631 (1974).
55. C. L. Olson, Bull. Am. Phys. Soc. 18, 1356 (1973).

56. C. L. Olson, Particle Accel., to be published.
57. C. L. Olson, Phys. Rev. A 11, 288 (1975).
58. C. L. Olson, Phys. Fluids, to be published.
59. C. L. Olson, Annals N. Y. Acad. Sci., to be published.
60. J. W. Poukey and C. L. Olson, Phys. Rev. A 11, 691 (1975).
61. J. Nation, Bull. Am. Phys. Soc. 19, 966 (1974).
62. H. Kim and H. Uhm, Bull. Am. Phys. Soc. 19, 966 (1974).
63. G. T. Zorn, H. Kim, and C. N. Boyer, Bull. Am. Phys. Soc. 20, 213 (1975) (this conference).
64. A. A. Plyutto et al., ZhETF Pis. Red. 6, 540 (1967) [JETP Lett. 6, 61 (1967)].
65. A. A. Plyutto et al., Atomnaya Energiya 27, 418 (1969).
66. G. P. Mkheidze and E. D. Korop, Zh. Tekh. Fiz. 41, 873 (1971) [Sov. Phys. Tech. Phys. 16, 690 (1971)].
67. G. P. Mkheidze, A. A. Plyutto, and E. D. Korop, Zh. Tekh. Fiz. 41, 952 (1971) [Sov. Phys. Tech. Phys. 16, 749 (1971)].
68. K. V. Suladze, ZhETF Pis. Red. 15, 648 (1972) [JETP Lett. 15, 459 (1972)].
69. V. N. Ryzhkov et al., Zh. Tekh. Fiz. 42, 2074 (1972) [Sov. Phys. Tech. Phys. 17, 1651 (1973)].
70. A. A. Plyutto et al., Zh. Tekh. Fiz. 43, 1627 (1973) [Sov. Phys. Tech. Phys. 18, 1026 (1974)].
71. E. D. Korop and A. A. Plyutto, Zh. Tekh. Fiz. 40, 2534 (1970) [Sov. Phys. Tech. Phys. 15, 1986 (1971)].
72. A. A. Plyutto et al., V Int. Symp. Disch. Elect. Ins. Vac., Poznan, Poland (1972), p. 145.
73. J. R. Kerns, C. W. Rogers, and J. G. Clark, Bull. Am. Phys. Soc. 17, 690 (1972).
74. T. E. McCann, C. W. Rogers, and D. Payton III, Bull. Am. Phys. Soc. 17, 690 (1972).
75. J. G. Clark, J. R. Kerns, and T. E. McCann, Bull. Am. Phys. Soc. 17, 1031 (1972).
76. D. J. Johnson and J. R. Kerns, Appl. Phys. Lett. 25, 191 (1974).
77. J. R. Kerns and D. J. Johnson, J. Appl. Phys. 45, 5225 (1974).
78. L. P. Bradley and G. W. Kuswa, Bull. Am. Phys. Soc. 17, 980 (1972).
79. G. W. Kuswa and L. P. Bradley, Bull. Am. Phys. Soc. 17, 980 (1972).
80. L. P. Bradley and G. W. Kuswa, Phys. Rev. Lett. 29, 1441 (1972).
81. G. W. Kuswa, Bull. Am. Phys. Soc. 18, 1310 (1973).
82. B. Freeman et al., Bull. Am. Phys. Soc. 17, 1030 (1972).
83. H. Sahlin et al., Bull. Am. Phys. Soc. 17, 1030 (1972).

84. J. Luce, H. Sahlin, and T. Crites, *IEEE Trans. Nucl. Sci.* NS-20 #3, 336 (1973).
85. B. Freeman et al., Bull. Am. Phys. Soc. 18, 1351 (1973).
86. C. B. Mills, LASL Report LA-5380-MS (1973).
87. B. Freeman, Ph.D. Thesis, LLL Report TID-4500, UC-34C (1974).
88. J. S. Luce, Annals N. Y. Acad. Sci., to be published.
89. H. L. Sahlin, Annals N. Y. Acad. Sci., to be published.
90. J. Luce, H. Sahlin, O. Zucker, and J. Wyatt, *private communication* (1975).
91. G. S. Janes et al., Phys. Rev. 145, 925 (1966).
92. J. D. Daugherty et al., I Int. Conf. Ion Sources, Saclay (1969), p. 643.
93. H. Alfven and P. Wernholm, Arkiv Fysik 5, 175 (1952).
94. R. M. Johnson, Sym. ERA, Berkeley, LRL Report UCRL-18103 (1968), p. 219.
95. Vestnik of the USSR Acad. Sci. 42, 12 (1972).
96. I. I. Logachev, Vestnik of the USSR Acad. Sci. 43, 104 (1973).
97. A. ' Kolomensky, Symp. Coll. Methods, Dubna (1972), p. 79.
98. A. A. Kolomensky and I. I. Logachev, Proc. VIII Int. Conf. High En. Accel., CERN (1971), p. 587.
99. *A. A. Kolomensky, Particle Accel. 5, 73 (1973).*
100. C. L. Olson, Sandia Laboratories Report SLA-73-0864 (1974).
101. C. L. Olson, Proc. IX Int. Conf. High En. Accel., SLAC (1974), p. 272.
102. C. L. Olson, Sandia Laboratories Report SLA-73-0865 (1974).
103. V. N. Tsytovich, Nonlinear Effects in Plasmas, (Plenum, N. Y., 1970), p. 151.
104. W. O. Doggett and W. H. Bennett, Bull. Am. Phys. Soc. 14, 1048 (1969).
105. W. H. Bennett, Annals N. Y. Acad. Sci., to be published.
106. V. N. Tsytovich, Dok. Akad. Nauk. SSSR 142, 63 (1962) [*Sov. Phys.-Doklady* 7, 31 (1962)].
107. V. N. Tsytovich, JINR, Dubna, Preprint JINR-P9-5090, 1970.
108. M. S. Rabinovich and V. N. Tsytovich, Symp. Coll. Methods, Dubna (1972), p. 92.
109. M. S. Rabinovich and V. N. Tsytovich, Lebedev Physical Institute Preprint #55 (1973).
110. J. Jancarik and V. N. Tsytovich, Nucl. Fusion 13, 807 (1973).
111. Ya. B. Fainberg, V. D. Shapiro, and V. I. Schevchenko, ZhETF Pis. Red. 11, 410 (1970) [JETP Lett. 11, 277 (1970)].

112. V. B. Krasovitskii, Zh. Eksp. Teor. Fiz. 59, 176 (1970) [Sov. Phys. JETP 32, 98 (1971)].
113. V. N. Tsytovich, Usp. Fiz. Nauk. 89, 89 (1966) [Sov. Phys. Uspekhi 9, 370 (1966)].
114. F. E. Mills, V Int. Conf. High En. Accel., Frascati (1965), p. 444.
115. K. M. Watson, S. A. Bludman, and M. N. Rosenbluth, Phys. Fluids 3, 747 (1960).
116. S. P. Gary and H. W. Bloomberg, Appl. Phys. Lett. 23, 112 (1973).
117. B. Godfrey and L. Thode, Annals N. Y. Acad. Sci., to be published.
118. B. Godfrey and L. Thode, Bull. Am. Phys. Soc. 19, 967 (1974).
119. M. L. Sloan and W. E. Drummond, Phys. Rev. Lett. 31, 1234 (1973).
120. M. L. Sloan and W. E. Drummond, Proc. IX Int. Conf. High En. Accel. SLAC (1974), p. 283.
121. V. P. Indykul et al., ZhETF Piz. Red. 20, 153 (1974) [JETP Lett. 20, 65 (1974)].
122. L. N. Kazansky, A. V. Kislatsov, and A. N. Lebedev, Proc. VIII Int. Conf. High En. Accel., CERN (1971), p. 592.
123. M. Friedman, Phys. Rev. Lett. 31, 1107 (1973).
124. R. J. Briggs, T. J. Fessenden, and V. K. Neil, Proc. IX Int. Conf. High En. Accel., SLAC (1974), p. 278.
125. V. P. Gapanovich, A. A. Kolomensky and A. N. Lebedev, IV Nat. USSR Accel. Conf., Moscow (1974).
126. W. Raudorf, Wireless Eng. 28, 215 (1951).
127. I. J. Billington and W. R. Raudorf, Wireless Eng. 31, 287 (1954).
128. N. R. Hesse and W. R. Raudorf, Brit. J. Appl. Phys. (J. Phys. D.) 2, 717 (1969).
129. A. Coutu, N. Hesse, and W. Raudorf, J. Appl. Phys. 42, 4504 (1971).
130. N. Hesse and W. Raudorf, Rev. Sci. Inst. 43, 1594 (1972).
131. V. I. Veksler and V. N. Tsytovich, Proc. Int. Conf. High En. Accel., CERN (1959), p. 160.
132. A. G. Bonch-Osmolovskii, Atomnaya Energiya 31, 127 (1971).
133. H. Alfven, Phys. Rev. 55, 425 (1939).
134. J. D. Lawson, J. Electron. Control 3, 587 (1957); J. Electron. Control 5, 146 (1958).
135. K. F. Alexander, E. Hantzsche, and P. Siemroth, Zentralinstitut für Electronenphysik Report, Berlin DDR (1973 [in German].
136. K. Alexander, E. Hantzsche, and P. Siemroth, ZhETF 67, 567 (1974) [Sov. Phys. JETP trans. not avail. yet].

137. A. A. Kolomensky and M. A. Novitsky, IV Nat. USSR Accel. Conf., Moscow (1974).
138. G. Yonas et al., Nucl. Fusion 14, 731 (1974).
139 N. Rostoker, N. Rynn, and G. Benford, private communication.
140. S. Putnam and B. Ecker, private communication.
141. N. Rostoker, private communication.
142. C. L. Olson, Bull. Am. Phys. Soc. 19, 914 (1974).
143. R. B. Miller and D. R. Straw, Bull. Am. Phys. Soc. 19, 965 (1974).

TABLE 1

Collective Acceleration Methods

	References:
(1) Net Space Charge	
ERA	7-20
IREB/gas	22-60
IREB/vacuum	30-32,61-63
HIPAC	91,92
IREB/transverse sweep	50,53,59,93-101
IREB/linear control	59,101-102
(2) Waves and Instabilities	
inverse coherent Cerenkov	1-3,48,56,103-105
EM radiation acceleration	1-3
plasma waveguide	5,6
solitons and nonlinear waves	106-112
stochastic acceleration	113
e-e two-stream instability	114
e-i two-stream instability	76,115-118
IREB/diode (?)	29,30,64-90
IREB/cyclotron mode	119-121
electron autoacceleration (e)	53,99,122-125
(3) Inductive Effects	
beam envelope motion	44-47,56
electronic ram (?)(e)	126-130
(4) Impact Acceleration	
relativistic collision	1-3,101,131,132

TABLE 2

Typical Data for Protons Accelerated by IREB Injection into Neutral Gas (H_2)

PROTONS				IREB					GUIDE TUBE			REFERENCES
$\mathcal{E}_i$(MeV)	N	T(nsec)	I_i(A)	$\mathcal{E}_e$(MeV)	I_o(kA)	t_r(nsec)	t_b(nsec)	r_b(cm)	p(Torr)	R(cm)	(cm)	
4-7	$\sim 4 \times 10^{12}$	3-10	~200	1.5	30	10	50	1.25	0.05 -0.15	7.6	50	IPC[24]
2-10	$\sim 2 \times 10^{12}$	3-5	---	1	110	10	60	2.5	0.15 -0.65	3.8	73	PI[27]
1-5	---	---	---	1.8	80	60	80	0.5	0.015-0.15	2.5	70	Sandia[29-32]
5-16	$\sim 10^{13}$	---	---	5	40	25	125	2*	0.05 -0.35	32	122	AFWL[36]
1-3,8	$\sim 10^{12}$	5-15	26	0.65	15-20	15	50	---	0.005-0.4	5	20-50	Lebedev[37,53]

(* annular beam, ~ 2 mm thick)

TABLE 3

Typical Data for Protons Accelerated in Diodes

PROTONS		ELECTRONS		DIODE			REFERENCES
$\mathcal{E}_i$ (MeV)	N	$\mathcal{E}_e$ (MeV)	I_o (kA)	U_o (MV)	A-K gap (cm)	Configuration	
4-5	10^{11}-10^{12}	--	---	0.2-0.3	----	Fig. 5a	Sukhumi[64]
0-2.5	10^{11}-10^{12}	0-0.25	1-2	0-0.1	1-10	Fig. 5a	Sukhumi[65]
0.7	10^{11}-10^{12}	0.06	1-3	0.02	1-5	Fig. 5a	Sukhumi[66]
2-7	---	--	---	0.2-1.0	2-7	Fig. 5a	Sukhumi[70]
2-3	---	--	5	0.2-0.3	1-2	Fig. 5c	Sukhumi[71]
0.08-3	$\sim 10^{15}$	--	50	5	1.8	Fig. 5b	AFWL[76]
0.1-2.5	---	--	100	2	0.6	Fig. 5c	Sandia[80]
5-13	$\sim 10^{14}$	--	30	2.5	----	Fig. 5d	LLL[84,88,89]

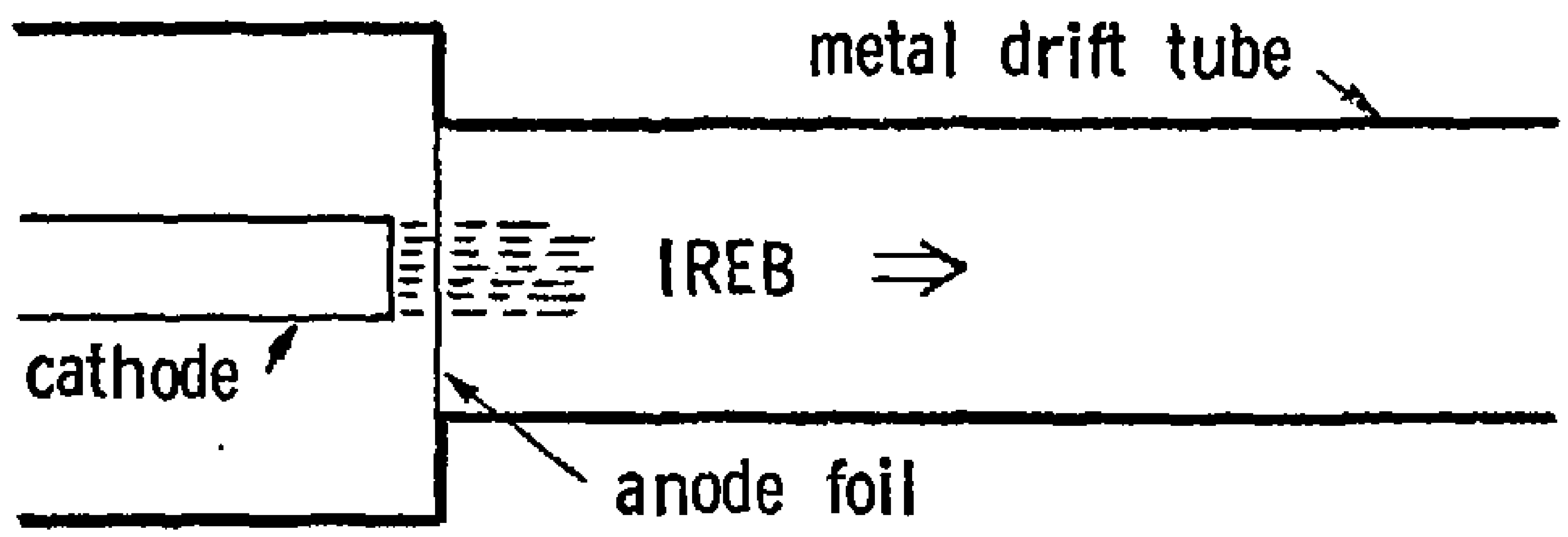
Fig. 1 Basic IREB diode and drift tube configuration.

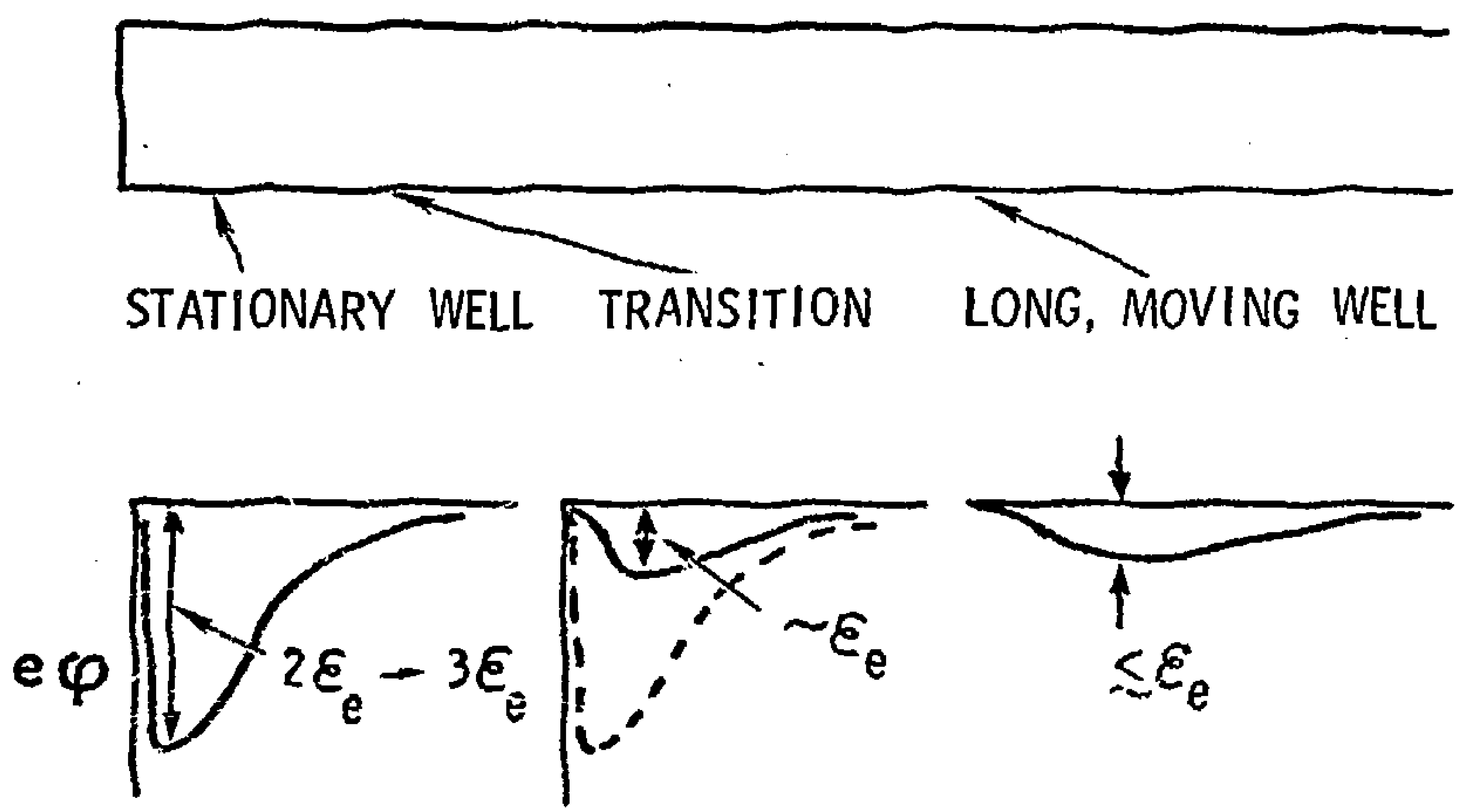
Fig. 2 Qualitative picture of 2-D potential well motion, showing $\varphi(r = 0, z)$ at successive times.

Fig. 3 Moving, self-consistent, 2-D, beam front equilibria, showing the fractional space charge neutralization f_e, the beam profile, and the resultant potential φ.[58]

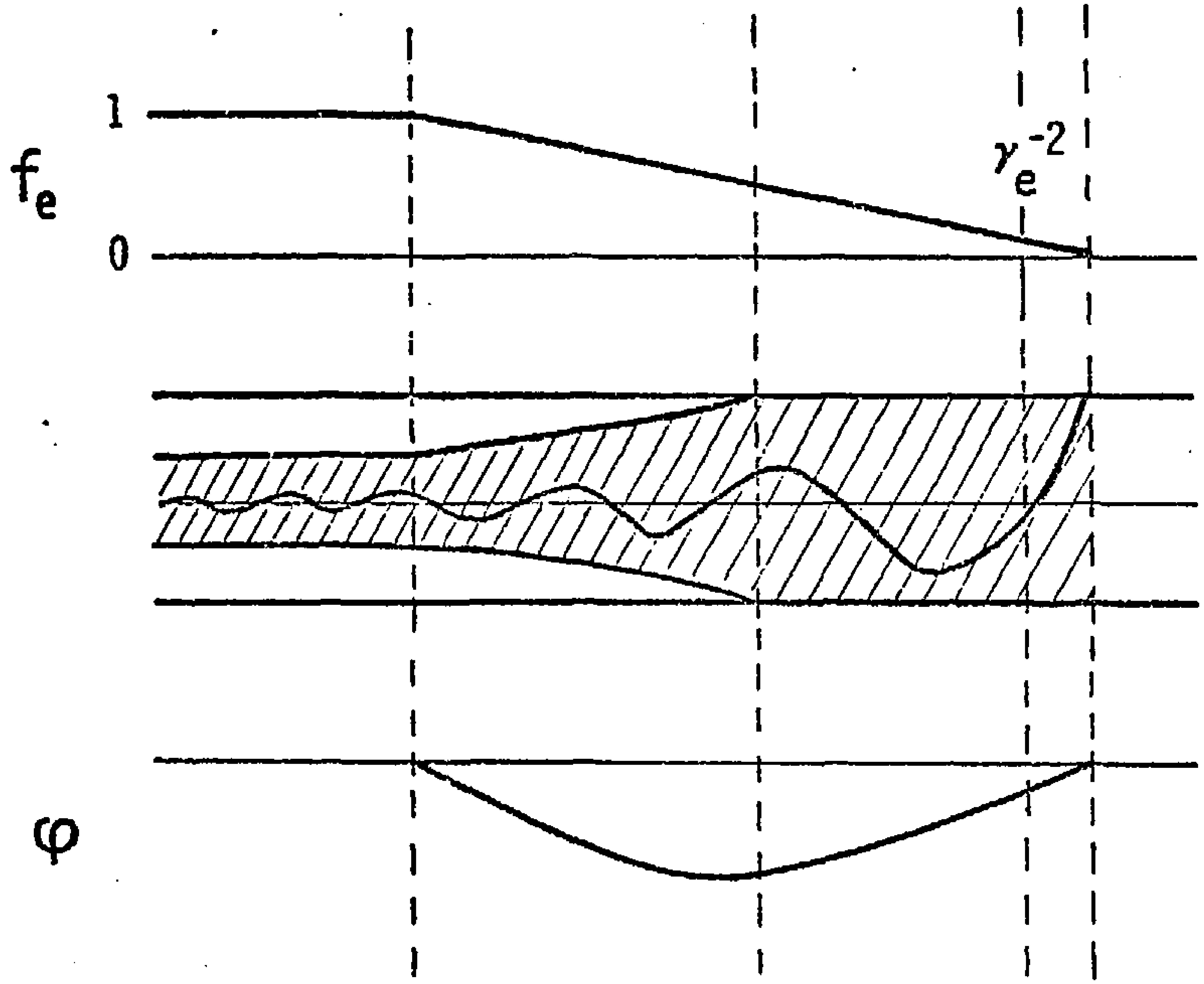
Fig. 4 Comparison of experiments (circles, shading), theory (lines),[58] and simulations (X's).[60] (a) IPC,[24] (b) PI,[27] (c) Sandia.[29-31] [The notation (X) means very few ions were seen at the indicated pressures.[60]]

Fig. 5 Diode configurations.

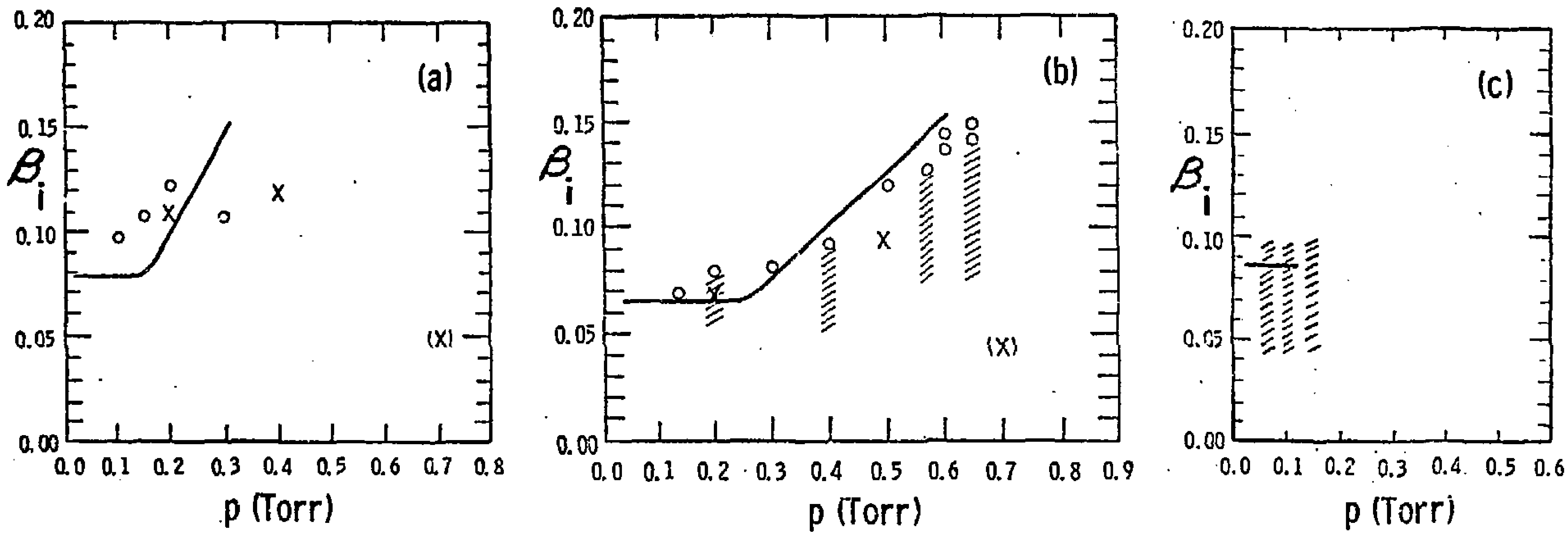

metal drift tube
IREB
cathode
anode foil



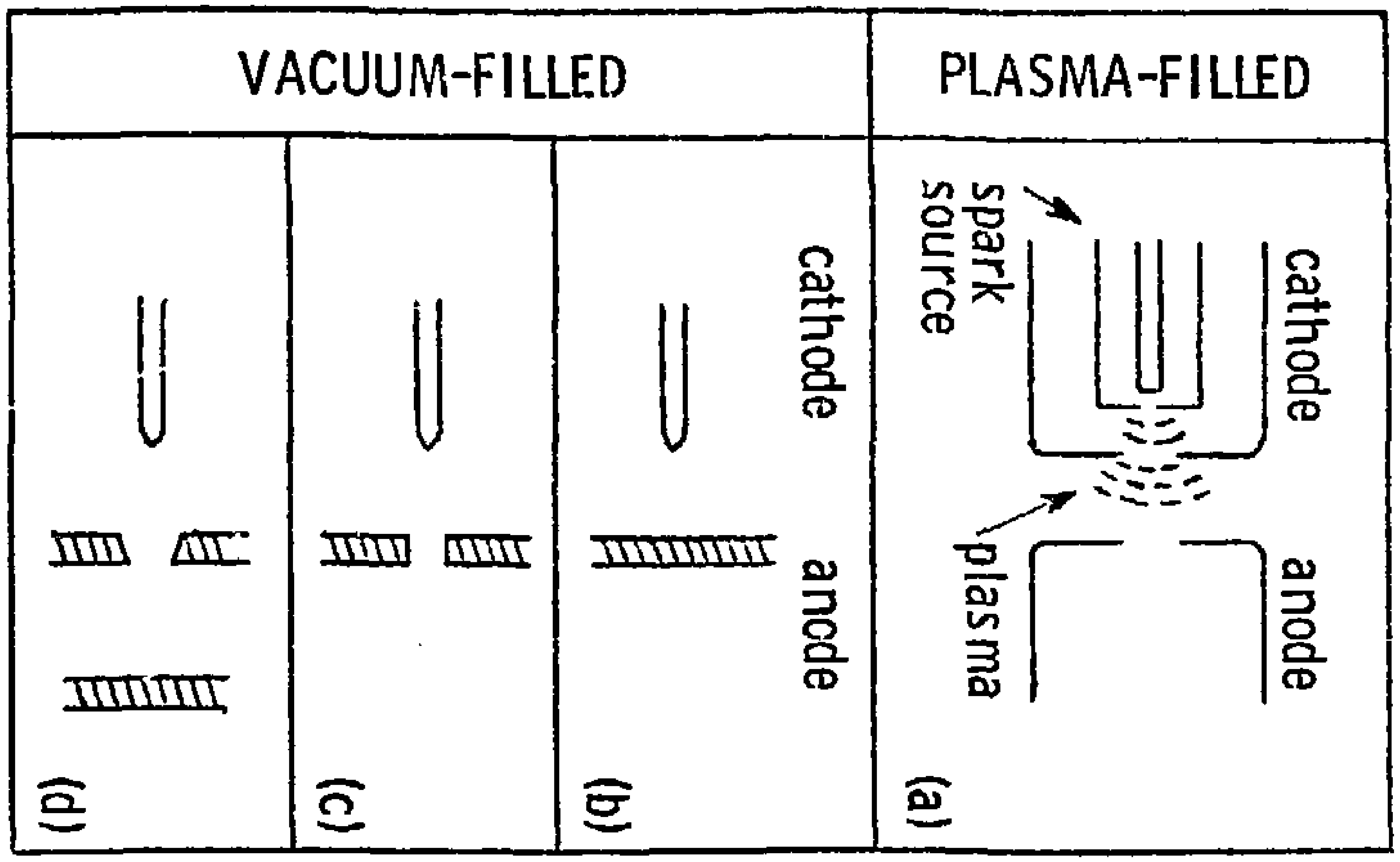
STATIONARY WELL
TRANSITION
LONG, MOVING WELL
eφ
2ε_e – 3ε_e
~ε_e
≲ε_e



1
f_e
0
γ_e^{-2}
φ



(a)
(b)
(c)
β_i
0.00
0.05
0.10
0.15
0.20
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0.0 0.1 0.2 0.3 0.4 0.5 0.6
p (Torr)
(X)



VACUUM-FILLED
PLASMA-FILLED
cathode
anode
spark source
plasma
cathode
anode
(a)
(b)
(c)
(d)