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THE MANY USES OF PLASMA PHYSICS

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ABSTRACT

The physics of plasmas has experienced an enormous growth during the last few decades, in its practical as well as in its fundamental aspects. It is thus no longer possible to do justice to the subject in a brief survey even if the scope were limited to cover only the most important applications. Therefore this talk will be restricted to a very cursory and superficial overview of the many uses of plasma physics, in order to demonstrate the diversity of the field. An attempt will be made to focus on the basic plasma features which the various specialties have in common. The best known and probably most challenging application of plasma physics is, of course, controlled fusion. But since this topic has already had very much attention, the emphasis this time will be placed on less well publicized although clearly also very important examples. Some of these are: a) The direct conversion of thermal into electrical energy, as for instance in the thermionic plasma diode; b) new developments in advanced laser technology; c) the production of intense X-ray and neutron bursts; and d) the acceleration of charged particles in collective fields. Many more could be cited but these should suffice to illustrate the richness of plasma physics.

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1. INTRODUCTION

Plasma physics may be defined as the study of the behavior of interacting charged-particles-in-large-numbers. The emphasis here is on the words "interacting" and "large numbers" to distinguish the subject both from ordinary particle-dynamics, as in conventional accelerators, and from atomic physics where only a few interacting particles are considered at a time. Because of the cumulative effects of overlapping long-range electric and magnetic forces plasma physics has sometimes been described as an extreme form of the many-body problem. The consequent subtleties in its statistical mechanics and kinetic theory have offered considerable challenge to physicists and mathematicians, and some fundamental questions have in fact not yet been completely resolved.

It is fair to say, however, that the spectacular growth of plasma research during the last two decades is caused not so much by interest in the field *per se* but rather by its exceptionally large range of overlap with other branches of science, and by its many applications in modern technology. In this paper a condensed survey of the many uses of plasma physics is presented, and an attempt is made to illuminate the reasons for this remarkable diversity. Since the discussion is addressed to physicists the focus is on the underlying fundamentals, and on the basic problems that still are active subjects for research, rather than on the applications themselves. The matter is given substance with the help of a few examples of current interest, selected to illustrate some of the main characteristics of plasma physics.

2. PRINCIPAL ASPECTS OF PLASMA PHYSICS

2.1 The Fourth State of Matter

In the popular press plasma is sometimes described as the "Fourth state of matter. Although experts tend to reject such terminology as improper, the concept can be shown to have some validity. Let us consider the diagram in Fig. 1 in which the energy content $\mathcal{E}$ of a fixed amount of a simple pure substance (in this example lithium) in equilibrium at constant pressure is plotted schematically as a function of the temperature T. At each phase transition extra energy in the form of potential or binding energy (sometimes called "latent energy") has to be provided to change the "state" of the substance. At the same time a dramatic increase in a particular property is noted, i.e., deformability on melting and compressibility after vaporization. When the temperature is sufficiently high for appreciable ionization, the conductivities (thermal as well as electrical) increase markedly while our curve, computed from Saha's equation, indicates something similar to a change of state. The idea was perhaps already anticipated by the ancient philosophers who conceived the universe as composed of four "elements": earth, water, air, and <u>fire</u>. Quite obviously, they must have meant the four states of matter rather than the basic substances of chemistry.

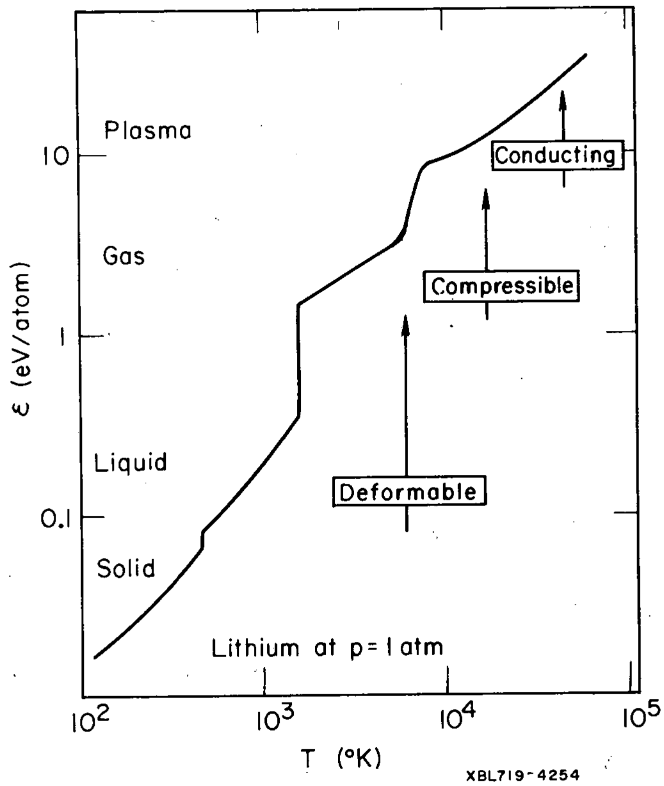


Fig. 1. Energy content in thermodynamic equilibrium as a function of temperature.

In the present context we merely note that plasma as a substance or medium is (1) very rich in physical properties, and (2) in general much too hot to be physically contained in thermal equilibrium. The former is primarily responsible for the many applications, while the latter is the cause of most of our troubles.

2.2 Collective Effects

Of all the features the most important is, of course, the electrical conductivity, or more precisely, the existence of mobile electrons. We specifically avoid the word "free" electrons because it is easily understood that, while individual charged particles are free to move with respect to each other, collectively they tend to be held together by their space charge. This macroscopic binding can be expressed quantitatively in terms of the so-called Debye length

$$\lambda_D \equiv (kT_e/4\pi e^2 n_e)^{1/2},$$

which will be recognized as the maximum displacement the bulk of the electrons can have with respect to the ions if their number density is n_e and if the resulting potential energy is not to exceed the electron random energy, denoted here by kT_e.

In line with our original definition we use the term "plasma" only for collections of charged particles whose dimensions are larger than λ_D. Only then can the cumulative effect of the long-range forces play an essential role. Figure 2 shows the domains of real plasmas in terms of n_e and kT_e, and a few lines of constant λ_D are included. It is quite apparent that ionized gases are practically always very large compared to their Debye lengths. It follows that they tend to be "quasineutral," by which we mean that $n_e - \sum_i z_i n_i \ll n_e$, where z_i and n_i denote the charge states and number densities of all the ion species present. But, furthermore, it is worth noting that in most situations the Debye length is much shorter even than the electron mean-free-path for momentum exchange, so that the collective effects are not only significant but very often they actually dominate the charged-particle dynamics. This is the primary aspect of plasma physics.

2.3 Nonequilibrium

Figure 2 also includes a curve of n_e vs T_e for 50% ionized hydrogen

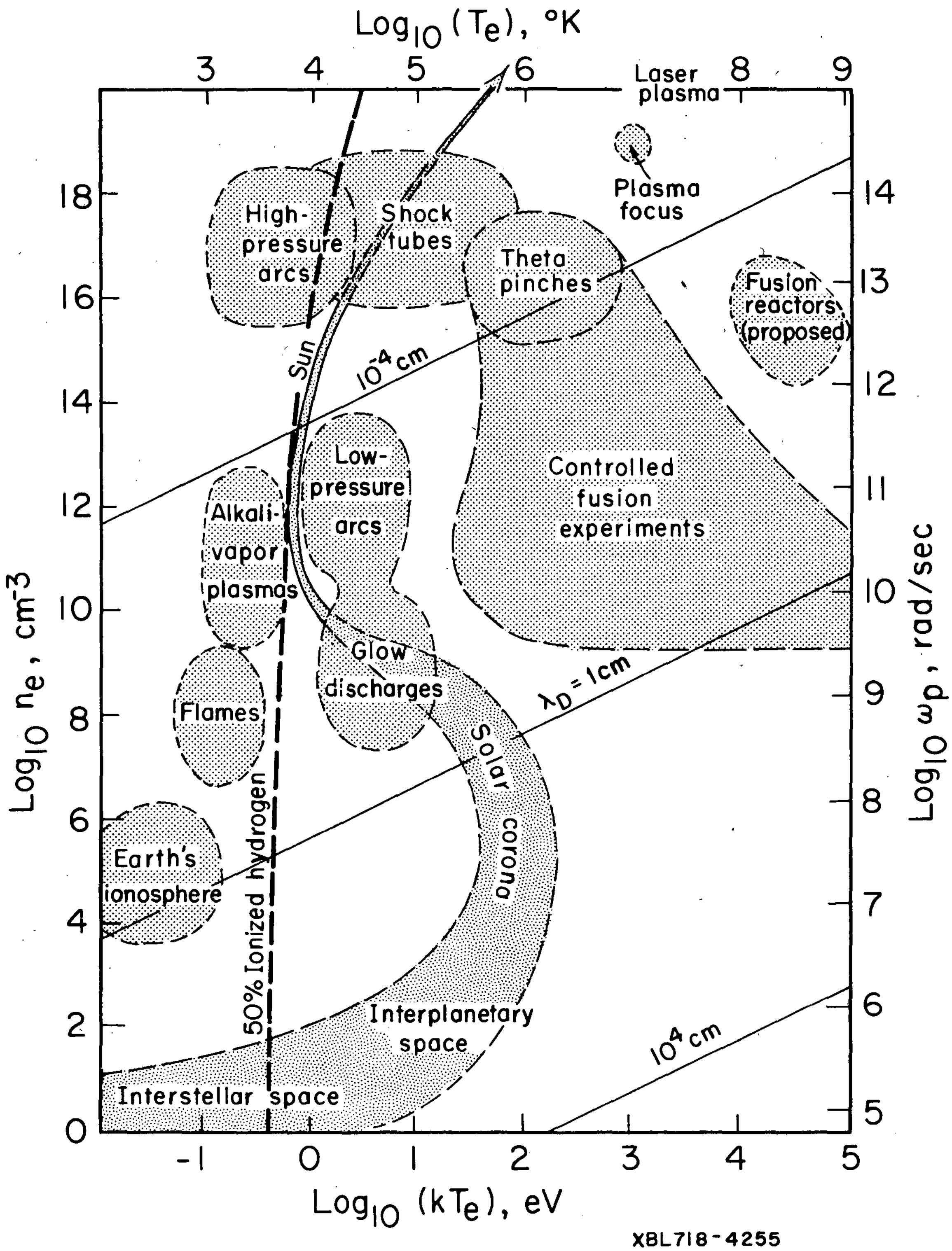


Fig. 2. Domains of gaseous plasma in terms of n_e and T_e.

according to Saha's equation. Because of the logarithmic scale used, graphs for other substances and for different degrees of ionization do not deviate grossly from this line. The curve is meant to indicate the prevalence of strong deviations from thermodynamic equilibrium, particularly for partially ionized gases at low densities. It is therefore clear that the study of ionization effects and related phenomena and of general transport processes constitutes another quite distinct and frequently essential aspect of the general field of plasma physics. Again, of course, it is the electrons which usually play the most important role as active agents because of their large interaction rate with atomic systems. In this case their presence in large numbers is demanded only for statistical reasons, however, and the collective-field effects are not essential in this context.

Thus we see that the subject of plasma physics can be divided conceptually into two rather distinct areas. As a matter of fact, a regular dichotomy seems to exist: Some investigators regard plasma physics as synonymous with "physics of ionized gases" while others prefer to reserve the term for the study of the dynamics of charged particles in self-consistent fields only. One need not insist on this distinction, however, and for our purposes this discussion merely points up again a reason for the large diversity in the applications of this field.

3. APPLICATION TO NATURAL PLASMAS

According to the definitions given above it is evident that plasma physics enters into several branches of natural science. The most obvious of these are astrophysics and space science; in fact it has been said that more than 99% of the universe is made up of plasma. Stars and stellar atmospheres, the solar wind, and, of course, planetary magnetospheres and comet tails are well-known examples of naturally occurring plasmas in one form or another. Insights into their mechanisms are closely coupled to progress in plasma physics, and considerable advances have been made in recent years. Only details, such as the heating process of the corona, or the reason for the low apparent thermal conductivity of the solar wind are still somewhat controversial. Undoubtedly certain instabilities are involved leading to turbulent behavior and resulting in anomalous ("collisionless") dissipation.

Currently, relativistic plasma physics has gained new significance in cosmological models, as for instance in Alfvén's matter-antimatter universe, and in proposed explanations for quasars and pulsars. Less speculatively, on the other hand, and closer to home, in geophysics and meteorology, we point to the existence of natural plasma such as the ionosphere and the aurorae as well as meteor trails, the lightning stroke, and St. Elmo's fire. Among these the outstanding mystery is the phenomenon of ball-lightning, which still seems to be lacking a generally acceptable explanation. The others are believed to be reasonably well understood.

Our general definition for plasma is, of course, not restricted to gaseous material. Whenever mobile charge carriers exist in sufficient density, collective effects are possible. Therefore conducting and semiconducting solids show certain plasma properties, and they must be included in this list. They often have the great advantage that they can be in the plasma state in complete thermodynamic equilibrium at reasonable temperatures, such as, for instance, the common metals. However, in order not to overload this paper, solid state plasmas will be omitted altogether.

In this section we have done little more than merely enumerate the known or assumed natural manifestations of natural plasma. Quite obviously their range and variety is much too large for a concise and yet meaningful discussion. We shall therefore dispense here with a more explicit analysis of these applications of plasma physics. Instead, we turn our attention to man-made plasmas and their practical uses, because in this case the utilitarian aspect provides a certain unifying framework.

4. MAN-MADE PLASMAS

Just as there are many different kinds of plasmas there are many different ways to produce them artificially, and there are many different reasons for doing so. One of the motivations, of course, is simply the experimental study of plasma physics as such, and of the properties of matter at extremely high temperatures. But since we are here primarily concerned with the <u>uses</u> of plasma physics, it seems appropriate to discuss man-made plasmas according to their technological applications.

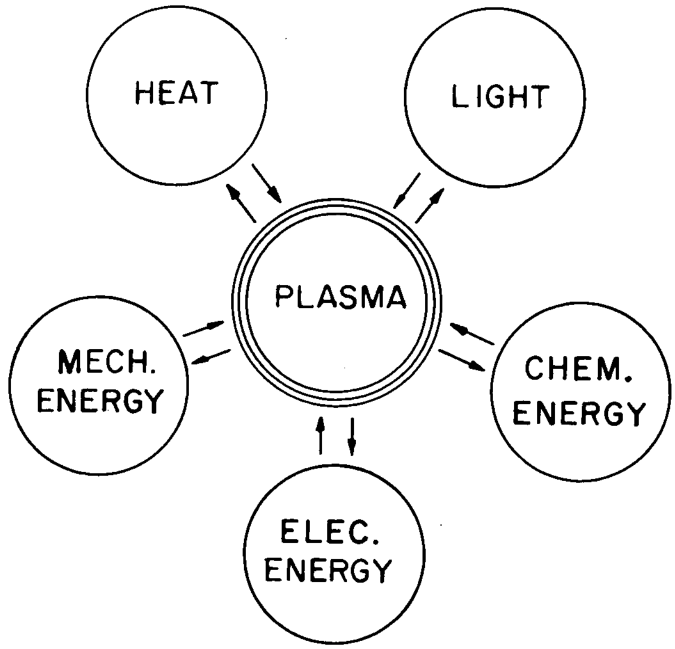


Fig. 3. Plasma as a medium for energy conversion.

It is interesting to note that the vast majority of practical applications of plasma physics can be linked to some form of energy conversion. The reason for this peculiarity presumably is the great multiplicity of physical properties discussed earlier. Particularly significant is the fact that plasma can be regarded as a conducting compressible medium endowed with enormous variability in its parameters, and which is more or less readily maintained quite far from thermodynamic equilibrium. All the forms of energy enter into consideration in plasma dynamics, as is schematically shown in Fig. 3. The arrowsare supposed to indicate that under suitable circumstances the power can flow either into or out of the particular type of energy.

By far the most common route is, of course, the conversion of electrical power into either heat or light. These are the classical applications that are discussed at length in early texts such as Cobine's "Gaseous Conductors." Therefore this review lists only some of the more important examples and concentrates on interesting or particularly useful recent developments in these categories.

4.1 Production of Heat

The old example is the well-known welding arc, but the category has gained importance through the development of the so-called "plasma torches." In these, rapidly flowing gas (usually a noble gas or nitrogen) is ionized and heated by either direct or radio-frequency current and ejected in the form of a jet with temperatures in the 10^4 $^\circ K$ range, i.e. considerably higher than obtainable by combustion. Torches can be used for cutting, melting, and even spraying of refractory materials, or for high-temperature aerodynamic research when used in a wind-tunnel arrangement. A fairly extensive treatment is given by Miklóssy in the book "Plasma Technology,"[1] and we need not go into details here.

4.2 Production of Light

The old examples are, of course, the standard glow and arc lamps, which again need not be discussed here, except perhaps for the high-intensity flash tubes recently developed for laser pumping and for photographic purposes. These are millisecond-long pulsed arc discharges in heavy gases such as krypton or xenon with peak currents in the 10^4 ampere range. Although their efficiency may be quite low their total light output is, of course, very respectable.[2] More interesting to the gas discharge physicist probably are the metal halide arcs, however. In the latter small amounts of these compounds are added to the standard gases, such as mercury vapor in helium, with the consequence of dramatic changes in emission properties.[2] In this way the usable light output, i.e. the fraction in the visible band, can be much enhanced and simultaneously the spectral distribution can be improved to give a better approximation of white light. Not all is well understood here, and the matter is still a subject for research.

The most important, or at least the most exciting items in the category of conversion of electricity into light are the electrically driven gas lasers. These depend on the fact that electronic exci-

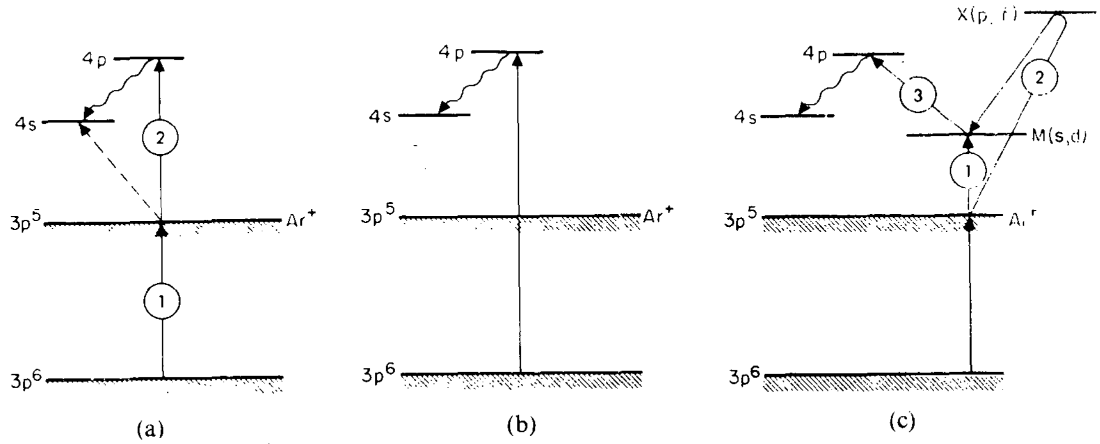
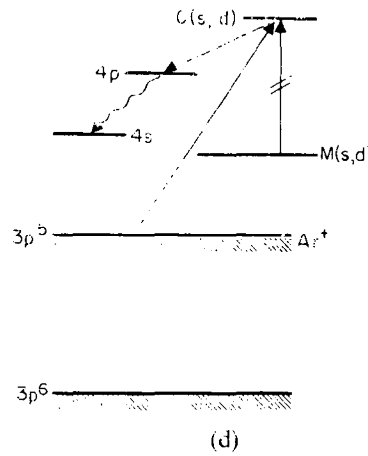


Fig. 4. Argon ion laser levels (taken from Bridges et al.[3]).



tation in gas discharges can easily lead to population inversions. As a matter of fact, the resulting phenomenon of superradiance in discharges had been known for a very long time. The application to light amplification was then only a small step, once the principle of the laser was invented.

A clean example of such a situation is found in the argon ion laser, for which the most prominent excitation levels and lasing transitions are shown in Fig. 4. Unfortunately, the processes even in this very simple case are too complicated for reliable quantitative predictions. Not nearly enough is known about the cross sections, the electron distributions, and the resulting rate coefficients for a good theoretical understanding. Therefore the progress in these matters is almost entirely experimental and empirical. There is much room for future research in the relevant plasma physics. At present the excitement about laser applications and potentialities seems to be too great to permit much deliberate and thorough fundamental study in this area. Guided by intuitive or qualitative arguments, but mostly by trial and error, many lasing transitions similar to those in argon have been found. A summary of the state of the art in 1970 is shown in Table I, which is taken from an excellent review article by Bridges et al.[3]

Table I.

ION LASER PERFORMANCE: 1970 STATE OF THE ART

Lasing Species	Lasing Mode	Strongest Wavelengths (μm)	Output Power	Output Power per Unit Length	Overall Electrical Efficiency (%)
Ar II	CW	0.4880, 0.5145	120 W[a]	105 W/m[b]	0.16[c]
Kr II	CW	0.6471	~10 W[a]	5 W/m[a]	~0.01[a,d]
Cd II	CW	0.4416	0.2 W[e]	0.14 W/m[e]	0.09[f]
Cd II	CW	0.3250	0.02 W[e]	0.014 W/m[e]	~0.01[e,f]
Ar III	CW	0.3638, 0.3511	5 W[k]	5 W/m[g]	0.01[g]
Xe IV	CW	0.4954-0.5395 (5 lines)	0.5 W[h]	1 W/m[h]	<0.01[h]
Xe IV	pulsed	0.5395, 0.5353, 0.5260	0.4 J/pulse[i] (20 kW peak)	0.14 J/m[i]	~0.3[i,j]

[a] K. Banse, H. Boersch, G. Herziger, G. Schäfer, and W. Seelig, *Z. Angew. Phys.*, vol. 26, 1969, pp. 195–200.
[b] H. Boersch, J. Boscher, D. Hoder, and G. Schäfer, *Phys. Lett.*, vol. 31A, 1970, pp. 188–189.
[c] J. R. Fendley, Jr., *Proc. 4th DOD Conf. Laser Technology* (San Diego, Calif., Jan. 1970), vol. 1, pp. 391–398 (unpublished).
[d] W. B. Bridges and A. S. Halsted, Hughes Res. Labs., Malibu, Calif., Tech. Rep. AFAL-TR-67-89, May 1967 (unpublished); DDC accession no. AD-814-897.
[e] J. P. Goldsborough, *Appl. Phys. Lett.*, vol. 15, 1969, pp. 159–161.
[f] W. T. Silfvast, *Appl. Phys. Lett.*, vol. 13, 1968, pp. 169–171. The efficiency of 9.02 percent given in Silfvast is a misprint and should instead be 0.09 percent.
[g] W. B. Bridges and G. N. Mercer, Hughes Res. Labs., Malibu, Calif., Rep. ECOM-0229-F, Oct. 1969 (unpublished); DDC accession no. AD-861-927.
[h] ——, "CW operation of high ionization states in a xenon laser," *IEEE J. Quantum Electron.* (Corresp.), vol. QE-5, Sept. 1969, pp. 476–477.
[i] W. W. Simmons, private communication, July 31, 1970.
[j] Pulse efficiency is defined as peak laser output power, divided by the product of peak tube current and initial applied voltage.
[k] J. R. Fendley, Jr., private communication, Jan. 1970.

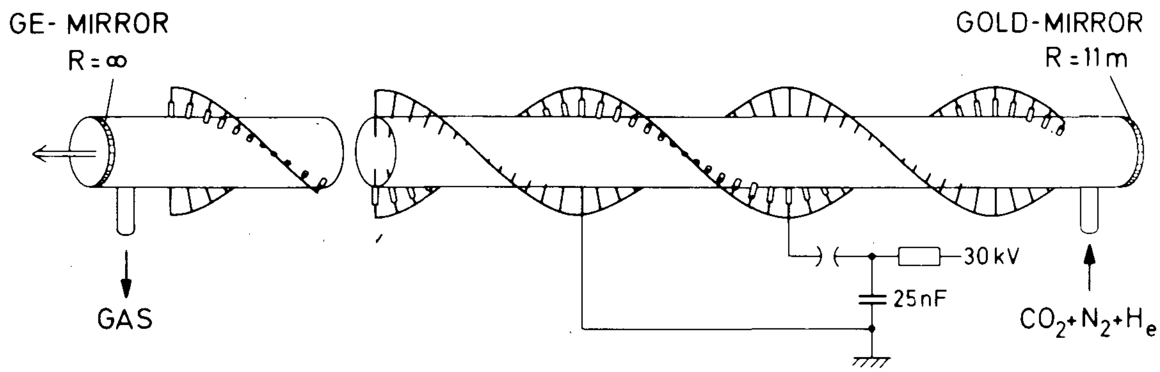
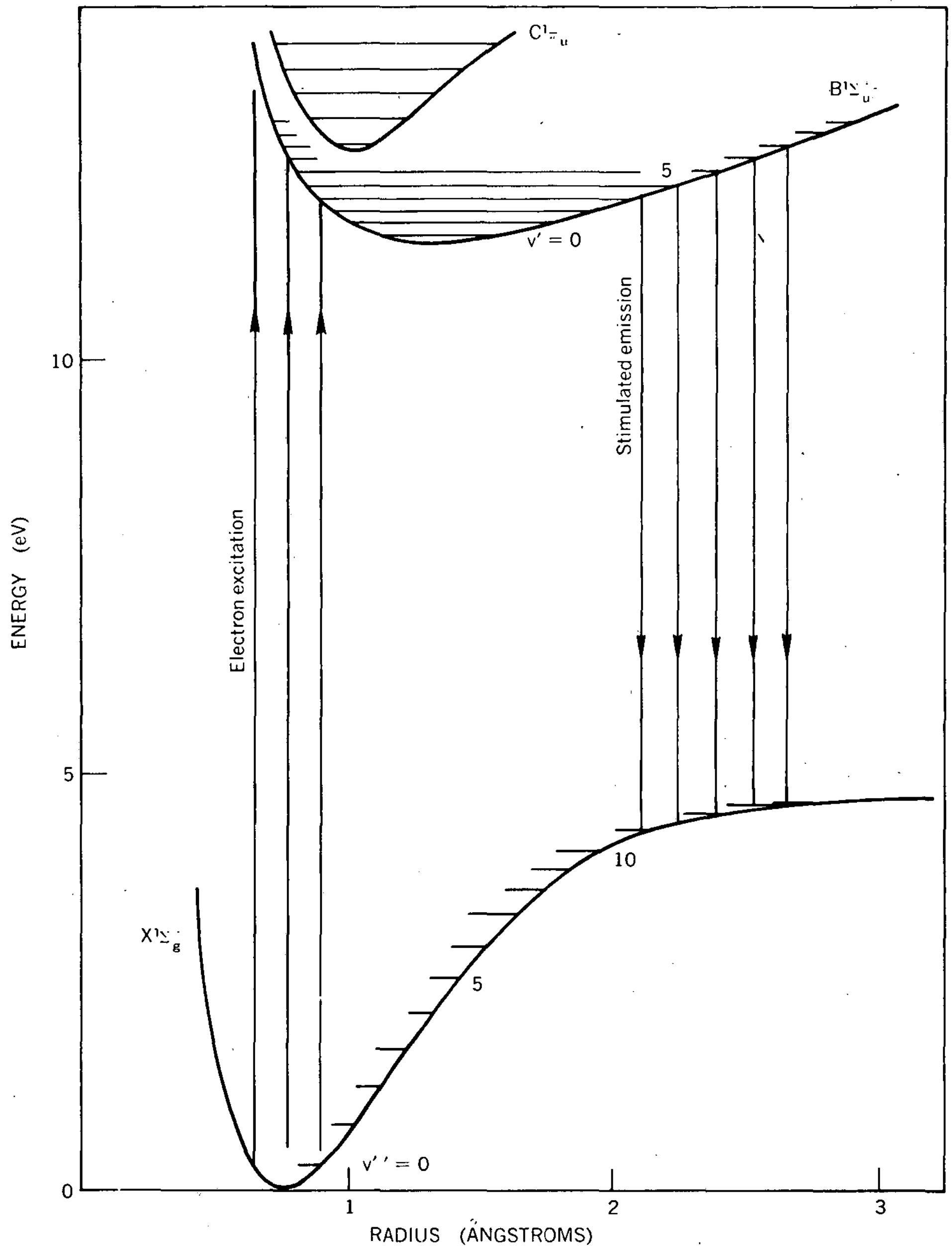


Fig. 5. Helicoidal arrangement for transverse excitation of a gas laser (taken from Büchl[4]).

Among the many new developments in this area the most spectacular is probably the high-power CO_2 laser, which seems to be capable of conversion efficiencies above 20%! There appears to be no upper limit in sight yet for the total energy that can be transformed into radiation at 10.6 μm, since it seems to be monotonically increasing with the pressure and the volume of the gas. Between 10 and 20 J/l have been achieved for pulsed operation at atmospheric pressure.[2] The problems are primarily related to intricacies in the discharges used for energizing; thus again, there is much new motivation for the pertinent gas discharge research. Ingenuity is well rewarded in this work, as displayed for instance in Fig. 5, showing an arrangement for pulsed transverse excitation at atmospheric pressure (TEA), made axially symmetric by twisting. In this manner the tube can be made arbitrarily long without need to increase the applied voltage. The sketch, which was copied from a paper by Büchl,[4] should be self explanatory.

Recently successful laser operation in molecular gases has been extended into the vacuum ultraviolet region, specifically the Lyman bands of H_2. One of the possible processes, based entirely on the Franck-Condon principle, is indicated in Fig. 6. Again, particularly clever ideas have to be incorporated. Since mirror reflections are very poor at this wavelength the amplification has to be accomplished in a single pass. In order to optimize the gain a team at the U. S. Naval Research Laboratory arranged for their excitation a transverse



Energy levels in a molecular-hydrogen laser. Groups at IBM and at the Naval Research Laboratory have observed stimulated emission in the Lyman band, corresponding to transitions from $B^1\Sigma_u{}^+$ to $X^1\Sigma_g{}^+$. $C^1\Pi_u \rightarrow X^1\Sigma_g{}^+$ has not yet been seen.

Fig. 6. Possible mechanism for an H_2 vacuum uv laser.

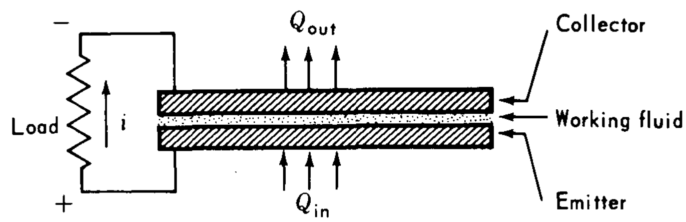


Fig. 7. The thermionic diode (schematic, taken from Blue and Ingold[6]).

electric breakdown in their laser tube that propagated along the tube at the speed of light.[2] The gain in the forward direction in this case was 10 to 100 times larger than in the retrograde direction.

4.3 Production of Electricity

In Fig. 3 it was claimed that the direction of the power flow could be reversed. In the case of light this is of course quite obvious, at least as far as absorption of radiant energy by plasma is concerned. As a matter of fact, one of the applications of high-power lasers discussed in the previous section is the production and heating of plasmas.[4] But the inversion of the other case, i.e., the use of a plasma for generation of electricity directly from heat is not quite so straightforward. In a certain sense this means that one is asking a discharge to operate in reverse; and intuitively it might be felt that such a process would violate a law of thermodynamics. In order to understand the basic physics behind direct conversion of thermal into electric energy, one must realize that mobile electrons, by virtue of their thermal energy, have a finite pressure. Under the influence of a pressure-gradient the charges can be made to move against the force of an electric field, i.e., they can be pushed towards higher electric potential energy. In other words, an electron pressure difference represents an electromotive force. Several variations and refinements of this principle are being utilized in different types of converters. A particularly extreme example is the direct energy recovery scheme that has recently been proposed for controlled-fusion reactors.[5]

Another important application, relevant to the present topic, is the thermionic diode, shown schematically in Fig. 7.[6] The temperatures here must of course be sufficiently high to cause adequate emission from the hot electrode (the emitter). Advantage is being taken of the fact that dissimilar metals have different binding energies (work functions) for electrons: Since the open-circuit voltage is given by the difference between emitter and collector work function, $\varphi_E - \varphi_C$, it is best to make φ_E much larger than φ_C. In the plasma diode ions (usually of Cs) are provided to neutralize most of the electron space charge between the electrodes, because otherwise the current density would be severely limited or the electrode spacing would have to be extremely small. Therefore an understanding of this device requires an understanding of the physics of ionized gases. Current research is concerned with studies of materials and working parameters in an attempt to optimize the characteristics and efficiency.

Plasma physicists have begun to analyze in detail not only the basic transport phenomena involving collisions and radiation effects, but also the internal fields and even the electron velocity distribution. It turns out that considerable deviations from thermodynamic equilibrium can arise, much larger than might be expected. In fact, at the highest current densities (tens of amperes/cm^2) and highest pressures, the operation can take on the character of a discharge (ignited mode). The fundamental reason for this curious effect is that discharge plasmas tend to be positive with respect to the surrounding walls. Thus in the ignited mode electrons from the emitter can gain extra (superthermal) energy. If this energy is sufficient to cause much ionization the plasma can be maintained at a "superthermal" level and hence maintain its positive potential. The process should be termed "bootstrapping." The potential distribution for this mode is shown in Fig. 8(b), in contrast to that in the normal mode in Fig. 8(a). In order to understand these phenomena quantitatively the plasma boundary layers have to be analyzed. Much progress has been made in this regard in cases where a sheath is quite distinct and separable from the body of the plasma. But in the thermionic diode the complicated transition region between the sheath and the plasma plays an important role and hence the matter is still the subject of intensive research.[7]

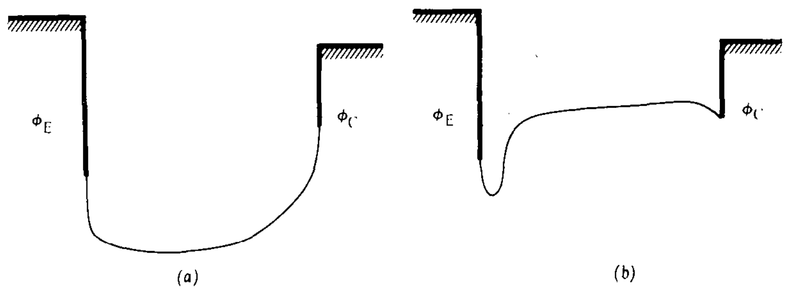


Fig. 8. Potential distributions in the plasma diode (from Blue and Ingold[6]).

The discussion of electric power production by plasma means would not be complete without reference to the so-called MHD generators. A schematic presentation of such a device is shown in Fig. 9. The principle should be apparent from the sketch.[8] The driving force here is not the electron pressure directly but the entire plasma pressure which produces a mass flow. With the help of a transverse magnetic field this mass motion is then used to induce an electromotive force, much like in a conventional generator. The method has the advantage of large scaling, obviously suited for power stations. But limitations caused by the relatively poor conductivity, and complications caused by the magnetic field have proved to be very frustrating. As a result enthusiasm among both engineers and plasma physicists, in the U. S. at least, has waned considerably. The system is seriously proposed primarily for emergency, short duration power. At the Avco-Everett Research Laboratory combustion driven generators have been operated in the MW range for many hours at a time. We mention the

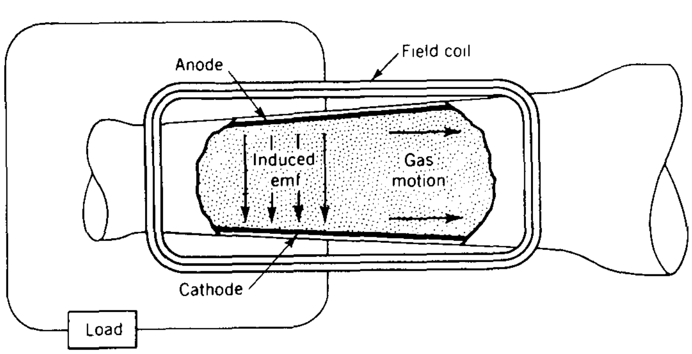


Fig. 9. Schematic of an MHD generator.[8]

method here primarily for completeness' sake, and because its inverse, in the spirit of Fig. 3, is readily recognized as another well-known application: the magnetically driven plasma thrustor proposed originally for space propulsion (cf. Fig. 10). The latter, however, belongs to the category discussed in the next section.

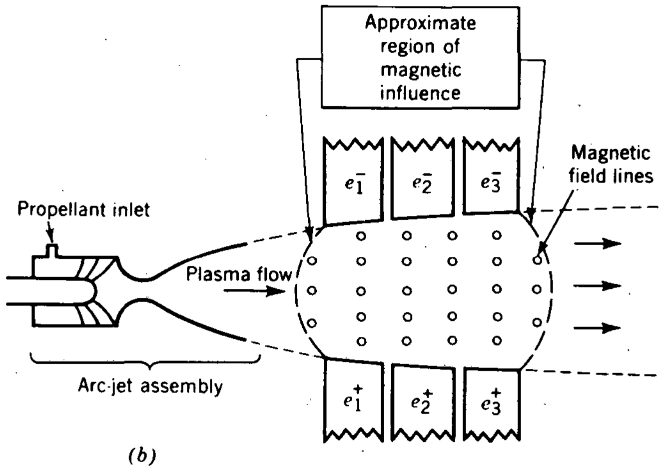


Fig. 10. A magnetic plasma propulsion engine.[8]

4.4 Production of Energetic Particles

Except for the last items mentioned, the macroscopic motion of the plasma was totally negligible, or at most played a secondary role in the applications enumerated thus far. Moreover, in all these cases we were dealing with partially ionized gases, so that ionization and recombination phenomena, and collisional effects quite generally, were of primary importance. We now take a look at the opposite extreme, i.e., at applications in which the plasma motion and collective effects are the dominant features. Plasma propulsion schemes, of which Fig. 10 is but one of many examples, obviously belong to this category. But for illustrative purposes we select the so-called dense plasma focus here because it permits discussion of a variety of effects simultaneously.

The plasma focus is essentially a very energetic and very dense transient pinch phenomenon that occurs at the end (the "muzzle") of a strongly driven coaxial plasma gun. The principle of operation is indicated in Fig. 11, which shows the location of the current-carrying "shock front" at four consecutive times. The gas, usually deuterium at a few torr pressure, is ionized and entrained by the moving current layer. The material gathered up during the axial

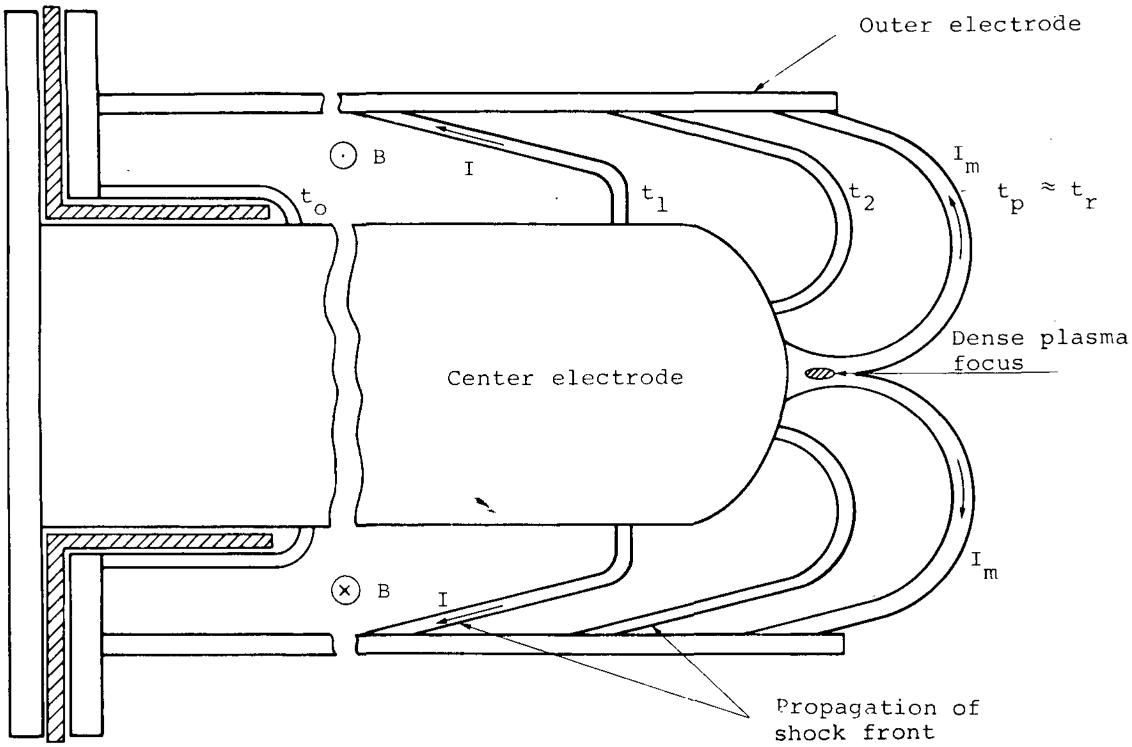


Fig. 11. Plasma focus device (schematic, taken from Gates).[10]

motion is expelled forward and does not end up in the focus. The coaxial gun is therefore often used for injection of energetic plasma into various kinds of experimental test regions, or futuristic schemes of rocket propulsion. For our pinch operation, however, the purpose of the barrel is mainly to provide time for the current to build up to a high value before the radial implosion begins. In this way radial plasma velocities in the 10^7 cm/sec range are readily achieved, i.e. corresponding to keV energies, and at the time of maximum compression the density exceeds 10^{19} cm^{-3}, while the current may reach MA levels. Under these conditions bremsstrahlung is emitted copiously and fusion reactions occur at a respectable rate,[9] so that the device is being developed as a pulsed source of X-rays and of 14 MeV neutrons. By adding tritium in a large gun driven by 500 kJ of stored electric energy the maximum yield observed was 6×10^{12} neutrons per pulse.[10]

Originally it was conjectured that the pinched plasma was thermalized at a temperature above 10^7 ^oK, but this conclusion has been called into question by later findings. At present a number of aspects of the plasma focus are not well understood or at least not agreed upon by the various research teams. In particular, the reason for the apparent stability, the cause of the pronounced axial motion at peak compression, the origin of the observed hard X-rays and of course, most of all, the detailed mechanism responsible for the fusion reactions, i.e., the character of the ion velocity distribution are all still a matter of some controversy. Recently two independent analyses showed that ions which cross the axis during the compression phase can gain considerable energy from the time-varying fields of the pinch and in this way contribute heavily to the fusion reaction rate. Figure 12 shows such an orbit schematically,[11] and in Fig. 13 a resulting distorted distribution function is plotted.[12] It is of course not yet established for certain that this "runaway" effect is important in most of the reported plasma focus experiments. The phenomenon is mentioned here because it represents a particularly clear case of the interaction of particle dynamics with plasma physics.

A multitude of other examples of energetic-plasma production could be cited here, particularly in connection with fusion research. But since the topic of controlled thermonuclear reactions has had abundant publicity, it seems preferable to omit its discussion here in favor of another application that is of primary interest in particle-physics research.

4.5 Application to High-Energy Physics

It had been realized more than a decade ago that the ability of collective fields to act on individual charged particles could probably be put to use in novel types of accelerators for high-energy physics. A number of schemes have been proposed, and developmental work on one of these, the so-called electron-ring accelerator (ERA) is being vigorously pursued at several laboratories. The principle of the ERA is indicated in Fig. 14: A large cluster of electrons creates a negative potential well when it is not completely neutralized by ions, i.e., if it is kept in good vacuum. The electrons can be forced to stay together, as is done in this case, if they are made to circulate at relativistic speeds in an external magnetic field. The major binding force, as seen in the laboratory frame of reference, is the ring's

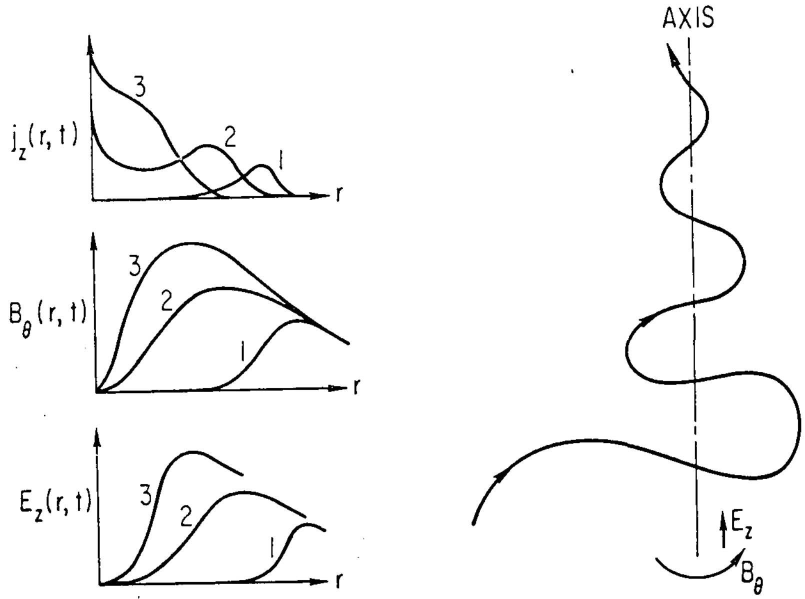


Fig. 12. "Runaway" ion orbit in a fast pinch (taken from Bernstein and Comisar[11]).

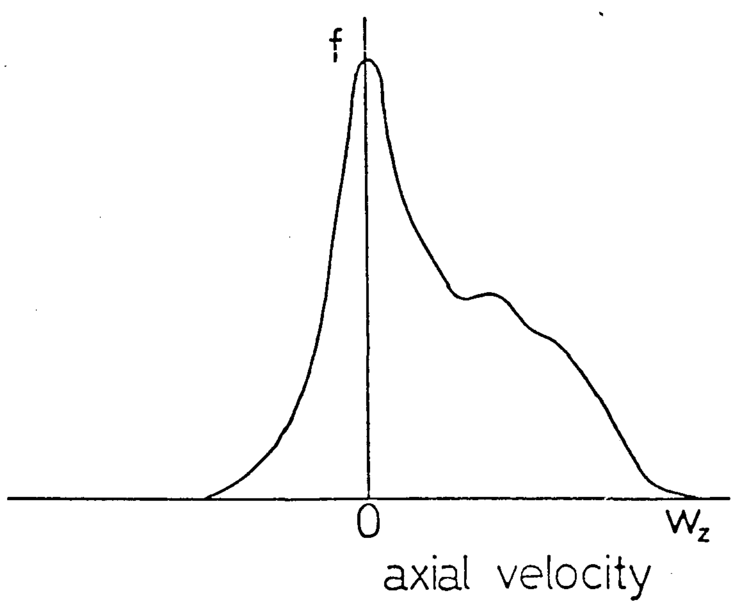


Fig. 13. "Runaway" ion velocity distribution (taken from Potter and Haines[12]).

own magnetic field (pinch effect). This electron bunch can then be accelerated by any one of a number of methods. Any ion trapped in the electrostatic potential well of the negative charges will be following the bulk motion of the ring provided the acceleration is not too large. In this way considerable gain in compactness of GeV accelerators is expected. Since the ring is a very effective ion "stripper" no separate ion source should be required, and the machine should automatically be good for all kinds of heavy ions.

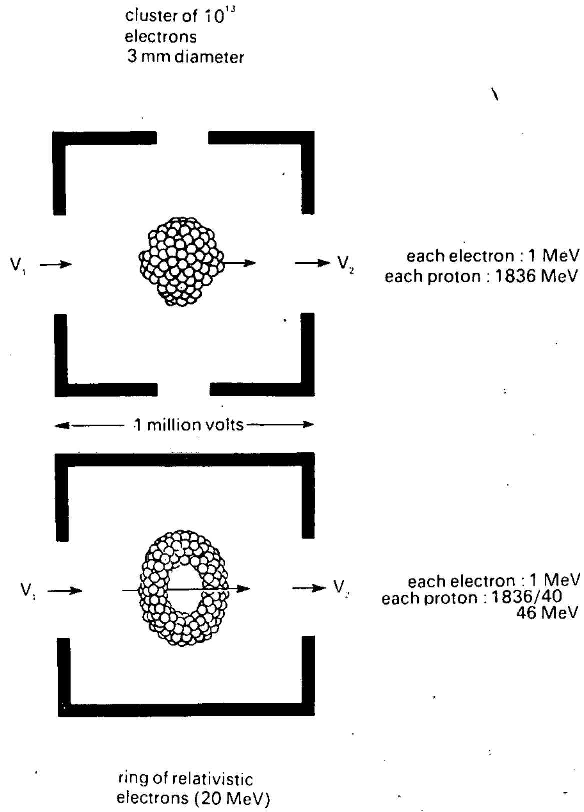


Fig. 14. Principle of collective acceleration.

A sketch of a test apparatus used at the University of California in Berkeley is shown in Fig. 15. A burst of electrons of 1 to 4 MeV energy from a special accelerator is injected and trapped in a magnetic field and compressed to a five times smaller radius with a corresponding gain in energy. The apparatus in Fig. 15 also includes provisions for acceleration of the compressed ring in the direction parallel to its major axis.[13]

Several aspects of this invention belong obviously in the realm of plasma physics. The electron cluster as a whole can be considered as a "one-component plasma." According to our primary definition quasineutrality is not a basic requirement for plasma. There are many instances where electrons in rapidly moving streams are brought

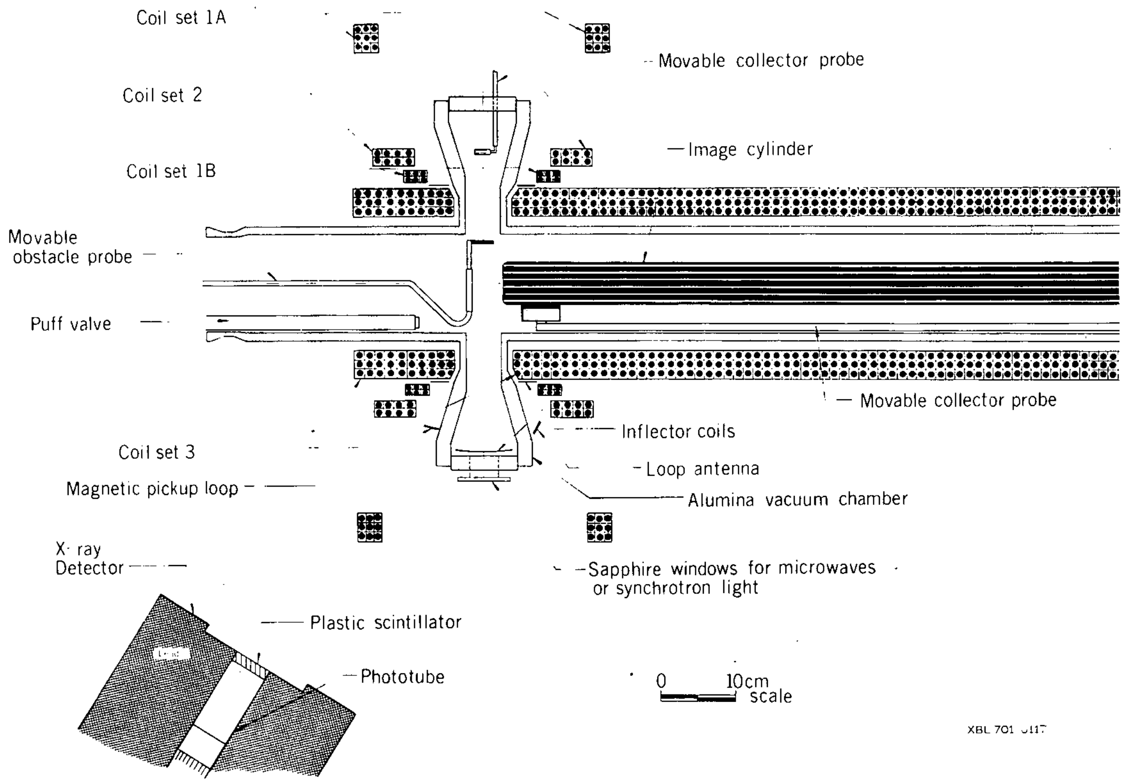


Fig. 15. Electron ring accelerator experiment at Berkeley.[13]

together in densities high enough so that collective effects are prominent. High current electron-beam tubes for the conversion of dc into high-frequency power are well-known other examples. An understanding of the ring's behavior, and particularly of its oscillations and inherent instabilities requires familiarity with the basic concepts of plasma dynamics.

A very striking application of plasma physics to the ERA problem is the so-called negative-mass instability and its cure. The instability arises because circulating relativistic electrons that are acted upon by a retarding force appear to speed up because their loss of energy decreases their relativistic mass and hence <u>increases</u> their gyrofrequency. Conversely, an accelerating force decreases the gyrofrequency. This produces a positive feedback for "bunching," i.e., it gives rise to a growing amplitude of nonuniform density distributions under the influence of space-charge forces whenever nearly monoenergetic electrons are circulating in a slender ring-shaped configuration. Much high frequency noise is generated in this way and the beam quality

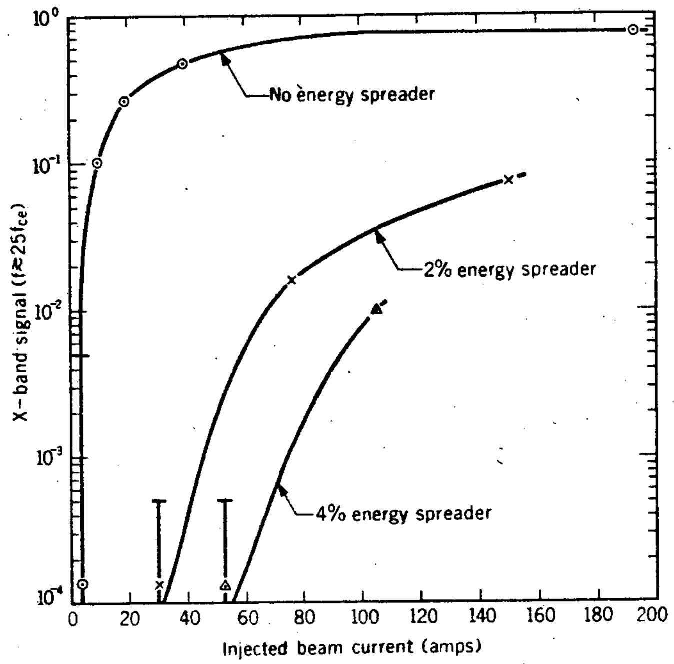


Fig. 16. Effect of energy spread on the "negative mass instability."

deteriorates rapidly. The instability can be suppressed, or at least reduced, if a small amount of energy spread is introduced from the very beginning, much like a "vaccination." The resulting spread in gyrofrequencies destroys the phase coherence of incipient bunches and thus interferes with the growth of the density modulation. If the density modulation is described by a Fourier analysis, the phase mixing caused by the energy spread appears as a damping of the wave, i.e., it looks like dissipation, although no collisions between particles are involved. This phenomenon is called Landau damping of space charge waves and is a typical example of the subject matter studied in the physics of collisionless plasmas. An experimental demonstration of the suppression of the negative-mass instability is shown in Fig. 16, which gives the results of a recent experiment at Berkeley.[14]

5. SUMMARY AND CONCLUSION

In this paper we have given a brief survey of the many uses of plasma physics in natural science and technology. We have attempted to explain the large diversity as a consequence of the broad definition of the field which includes the physics of ionized gases, in general, as well as the special study of collective interactions by charged particles. The emphasis was placed on practical applications which were characterized as various methods devised for the conversion of one form of energy into another. A few specific examples were included because of their current interest and because they seemed well suited to illustrate some of the major aspects of plasma physics. These were

1. Electrically energized gas lasers as a modern application of discharge physics, and a demonstration of severe deviations from thermal equilibrium.
2. The thermionic diode as an important case of ionization physics with self-consistent space-charge fields.
3. The dense plasma focus as an extreme version of magnetohydrodynamics, and an illustration of the interaction between particles and fields.
4. The electron-ring accelerator as an example of plasma effects in essentially unneutralized electron streams.

The coverage could not be at all complete. A major category omitted was, for instance, the entire field of plasma chemistry, or perhaps a better term would be "high temperature reactions." If we stretch the term "chemistry" to encompass nuclear reactions, then the imposing subject of thermonuclear fusion could be included under this heading. We have touched upon this topic only briefly in connection with the plasma focus.

Many other applications have been left out and it would be a hopeless task to enumerate them all. Moreover, new uses seem to be discovered almost every year. This realization should be encouraging to physicists at a time when the demand for the basic science is leveling off, or even diminishing. In short, judging by the discussions in this review it appears unlikely that the market for applied physics will decrease in the foreseeable future; certainly not in the specialty called plasma physics.

BIBLIOGRAPHY

1. The book Plasma Technology by B. Gross, B. Grycz, and K. Miklóssy (English translation: Iliffe Books Ltd., London, 1969) contains several chapters pertinent to this review.
2. The Proceedings of the IEEE, 59, 433-720 (April 1971) is devoted exclusively to atomic and molecular processes in applied plasma physics and contains most of the up-to-date information on Section 4.2.
3. W. B. Bridges, A. N. Chester, A. S. Halsted, and J. V. Parker,

Proc. IEEE, 59, 724-737 (1971). This is an excellent complete review of ion lasers.

4. K. Büchl, "Production of Plasma with a CO_2-TEA-Laser from Solid Hydrogen Targets," Max-Planck Inst. f. Plasmaphysik Report IPP IV/16 (March 1971).

5. R. F. Post, Ann. Rev. Nuclear Sci. 20, 509-588 (1970). This is a very readable, well informed summary of fusion research.

6. E. Blue and J. H. Ingold, Thermionic Energy Conversion," in Direct Energy Conversion, G. W. Sutton, ed. (McGraw-Hill Book Company, New York, 1966), pp. 239-334. This book also contains a good review of MHD power generation.

7. See, for instance, M. Clark and D. Lieb, IEEE Conf. Record 1970 Therm. Conv. Specialist Conf. (70 C 53-ED), pp. 291-298 (IEEE, New York, 1970). These conference records contain most of the recent results on thermionic conversion.

8. Figures 9 and 10 are taken from Plasma Physics in Theory and Application, W. B. Kunkel, ed. (McGraw-Hill Book Company, New York, 1966). This volume contains several chapters with extensive discussions of applications such as the MHD generators, propulsion systems, and controlled fusion.

9. See, for instance, N. J. Peacock, P. D. Wilcock, R. J. Speer, and P. D. Morgan, Third Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1969), Vol. II, pp. 51-65. These proceedings of the IAEA conferences on fusion contain several other papers on the plasma focus, as well as all the lastest reports on fusion research.

10. D. C. Gates and L. J. Demeter, "Neutron Sources and Applications," in Proc. Am. Nucl. Sci. National Topical Meetings (Conf-710402), Vol. II, paper no. 1-39 (April 1971). Figure 9 was taken from this paper because it shows the evolution of the plasma focus discharge particularly clearly.

11. Figure 13 is taken from a manuscript by M. J. Bernstein and G. G. Comisar that has been submitted to the Physics of Fluids.

12. D. E. Potter and M. G. Haines, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971), paper CN-28/D-8.

13. D. Keefe et al., Nucl. Instr. and Methods 93, 541-556 (1971).

14. G. R. Lambertson et a., IEEE Transactions on Nuclear Science NS-18, 501-504 (1971).

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