Zeitschrift: Bulletin des Schweizerischen Elektrotechnischen Vereins

Herausgeber: Schweizerischer Elektrotechnischer Verein ; Verband Schweizerischer Elektrizitätswerke

Band: 51 (1960)

Heft: 20

Artikel: Plasma Containment and Radio-Frequency Fields

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DOI: https://doi.org/10.5169/seals-917069

gratings were fabricated by a photoresist etching process on milar film 0.002 inch (0.05 mm) thick which is coated with a few microns of aluminium, and evaluated at a wavelength of 4 mm. A polarizing filter for the same wavelength was constructed by stacking a series of thin conducting plates separated by 1/16 inch (1.6 mm) dielectric layers. This component also acts as a high-pass filter in the orientation in which the 4-mm waves are blocked and the third harmonic passes with negligible attenuation.

The printed Fresnel lenses and gratings have the virtue that their performance can be predicted throughout the submillimeter range where the attenuation and index of refraction of the dielectric materials is not yet known.

In Fig. 6 an optical test bench set-up is shown which is used to test components for the millimeter and submillimeter range. The particular experiment shown is part of a basic investigation of the nonlinear effects in bulk semiconductor material being conducted as an interdepartmental project at the GT&E Laboratories. If high electric fields are impressed on the semiconductor, in this case an n-type wafer of single crystal germanium 1 mil (0.001 inch = 0.025 mm) in thickness, the current density bears a nonlinear relation to the electric field. The effect arises because the mobility of carriers decreases with an increase in average energy [7]. To avoid heating of the sample, duty cycles of only 0.003 or smaller are used.

In this experiment a plastic lens concentrates the full output of a pulsed magnetron onto the germanium sample. Changes in d. c. conductivity are monitored and radiation from the backside of the crystal plate is analysed for harmonic output content.

Bibliography

[1] *Trivelpiece, A. W.* and *R. W. Gould:* Space Charge Waves in Cylindrical Plasma Columns. J. appl. Phys. Vol. 30(1959), No. 11, p. 1784...1793.

[2] *Kaufman, J.:* The Band between Microwave and Infrared Regions. Proc. IRE Vol. 47(1959), No. 3, p. 381...396.

[3] *Kapitza, P. L.:* A Method of Producing Strong Magnetic Fields. Proc. Roy. Soc. (London), Part A, Vol. 105(1924), No. 734, p. 691...710.

[4] *Furth, H. P., M. A. Levine* and *R. W. Waniek:* Production and Use of High Transient Magnetic Fields, Part II. Rev. sci. Instrum. Vol. 28(1957), No. 11, p. 949...958.

[5] *Foner, S.* and *H. H. Kolm:* Coils for the Production of High-Intensity Pulsed Magnetic Fields. Rev. sci. Instrum. Vol. 28 (1957), No. 10, p. 799...807.

[6] *Weibel, G. E.:* High Magnetic Submillimeter Wave Generators with Parametric Excitation. Proc. of the Symposium on Electronic Waveguides; Brooklyn April 8...10, 1958. Brooklyn: Polytechn. Inst. 1958. Vol. 8, p. 389...405.

[7] *Conwell, E. M.:* Lattice Mobility of Thermal and Hot Carriers in Germanium. Sylvania Technol. Vol. 12(1959), No. 2, p.30...36.

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Plasma Containment and Radio-Frequency Fields

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537.525.1 : 537.533.3

1. Introduction

The problem of plasma containment is a crucial one in controlled fusion research. For the generation of interesting amounts of controlled fusion power, plasma densities above 10^{14} ions/cm³ and plasma temperatures above 10^4 eV ($\approx 10^8$ °K) are required. The corresponding pressure of the plasma to be contained then is of the order of several atmospheres, in most cases above 10 atmospheres. Containment times of the order of a second are required [1, 2][1])[2]).

Most of the work on plasma containment so far has been concerned with the use of d-c magnetic fields, or pulsed magnetic fields behaving, from the standpoint of plasma containment, essentially like d-c magnetic fields. The reason for this is the following. The average pressure p exerted by electro-magnetic fields on a plasma is limited by the relation:

$$p \leqq 0{,}5\,(\mu_0\,H^2 + \varepsilon_0\,E^2) \qquad (1)$$

where H and E are the rms values of the magnetic and electric field respectively. Further, on the surface of a dense plasma $\varepsilon_0\,E^2 \ll \mu_0\,H^2$ in most cases of practical interest. Hence, eventually:

$$n\,k\,T = p = \beta\,\frac{\mu_0\,H^2}{2} \qquad (2)$$

where $\beta \leqq 1$. For $\beta = 1$, a magnetic flux density $B = \mu_0 H$ of 0.5 Wb/m² is required to contain a plasma pressure of 1 kg/cm². Hence, for the containment of plasmas for controlled fusion, magnetic fields between 1 and 5 Wb/m² seem required, *provided that β be not much smaller than unity.* Such orders of magnitudes, to be maintained for seconds, seem possible for d-c magnetic fields but look most discouraging for r-f fields because of prohibitive skin effect losses in the conductors associated with the generation of these fields [3, 4]. For this reason, only little attention has been given so far to the use of r-f fields for plasma containment.

There are, however, important limitations to the use of d-c magnetic fields. The most fundamental one seems to be the inability for d-c magnetic fields to provide quasi-stable plasma containment with low enough rates of plasma leakage, for finite values of β. It is illustrative for that matter to observe that after close to one decade of work, the largest time over which a dense plasma ($n \leqq 10^{14}$) has been contained by quasi-dc magnetic fields (variation of magnetic field slow compared to plasma containment time) at temperatures of interest for controlled fusion ($T \leqq 25$ keV) is of the order of 10^{-3} s only. (Typical half-life of plasma: $2 \cdot 10^{-3}$ s.) Further, the value of β in these experiments did not exceed 0.08. This rather basic limitation of d-c magnetic

[1]) Refer to the Bibliography at the end of the article.

[2]) In a proposal by *W. I. Linlor* [1959 Meeting of the American Physical Society (A.P.S.), Paper C-1] it is shown that in a plasma-target fusion machine the target temperature could perhaps be reduced somewhat below 10 keV, with a corresponding reduction of the total pressure of the plasma to be contained. Even in this case, however, the plasma pressure will most probably have to be at least between 1 and 10 atmospheres.

fields seems associated with the fact that such fields usually fail to provide a true restoring force for the charged particles which they are to contain. When a restoring force is present, like in a mirror machine [5, 6], in picket fence devices or in cusped geometries [7, 8], it is effective only for a limited velocity class of the particles to be contained. Leakage from particles outside of this privileged class still seems prohibitive. In contrast to this, r-f fields seem capable to provide restoring forces suitable for the containment of charged particles with negligibly small leakage. This is basically why in several laboratories a growing interest for the r-f containment of plasmas is evident, in spite of the severe limitations imposed by skin-effect losses.

2. Advantages and Limitations of R-F Fields for Plasma Containment

2.1 *Advantages of r-f fields*

The average force exerted by r-f fields [9] on a charged particle of charge e and mass m is given to a first approximation, in the absence of d-c magnetic fields, by:

$$\vec{F} = -\frac{e^2}{2\,m\,\omega^2}\,\vec{\nabla}\,(E^2) \tag{3}$$

where E is the rms value of the r-f electric field of frequency f, and $\omega = 2\pi f$. [It may be observed that the contribution of the r-f magnetic field, although not explicitly apparent, is properly taken into account in the derivation of Eq. (3)]. This expression shows that:

a) $\vec{F}$ is independent of the sign of the charge e;

b) $\vec{F}$ is derived from a potential proportional to the mean square intensity of the r-f field;

c) The sign and direction of $\vec{F}$ are such as to push charged particles towards the region of minimum r-f field.

The consequence of these remarks is that in a system possessing in space a true minimum E_{min} of the r-f field, all particles of energy lower than

$$W = \frac{e^2}{2\,m\,\omega^2}\,(\vec{E}^2 - \vec{E}_{min}^2) \tag{4}$$

will be contained by the r-f field if $\vec{E}^2$ is the highest mean square value of r-f field which the contained particle sees when it attempts to escape. In practice (e. g. with multipole fields) it is possible to make $\vec{E}_{min} = 0$, and $\vec{E}$ large enough to contain *without leakage* electrons up to energies of hundreds of kilo-electron-volts, with r-f fields of frequencies up to several hundred megacycles second.

In addition, because the containing force $\vec{F}$ is derived from a potential, it is of a "restoring" nature. This means that if for some reason (e. g. collision) a particle leaves the region of minimum r-f field where it is to be contained, the force $\vec{F}$ will push it back to its original place much like the force of a spring.

These considerations, although based so far on a single particle model [3]), indicate a basic difference between the containment of charged particles or plasmas by d-c magnetic fields and by r-f fields. In essence, r-f fields appear capable of the following tasks, of which d-c magnetic fields are not capable:

1. Containment of charged particles with negligible leakage.

2. Containment of charged particles by means of a restoring force independent of the velocity class of the contained particles [within the rather broad limits imposed by Eq. (4)].

The latter property is of particular interest because of the inherently stabilizing effect of restoring forces on perturbations. The importance of such a stabilizing effect becomes more evident when the momentous difficulties caused by instabilities in the containment of plasmas are fully appreciated [10, 11].

2.2 *Limitations of r-f fields*

It is clear that a heavy price has to be paid for the advantages of r-f fields indicated above. This price consists mainly in high skin-effect losses. These losses in fact set a rather straightforward limit to the maximum pressure p which r-f fields can exert in the steady state on a plasma. This limit is directly related to the maximum power P_1 which can be dissipated per unit area on the conducting surfaces necessary to support the r-f fields. The relation between p and P_1 is given by [4]:

$$P_1 = 4.15\,\kappa^2 \sqrt{f} \cdot p\,[\mathrm{kW/cm^2}] \tag{5}$$

for copper conducting surfaces at room temperature. In Eq. (5), f is the frequency of the r-f fields in Mc/s, and p the containing pressure (in atmospheres) exerted by the r-f fields on the plasma. The factor κ is the ratio

$$\kappa = \frac{H_c}{H_p}$$

of the r-f magnetic field H_c on the conductor surface to its value H_p at the plasma surface. The factor $\sqrt{f}$ arises directly from the skin effect.

Inspection of Eq. (5) indicates that to maximize p for a given maximum practical value of P_1, it is desirable:

a) To minimize κ;

b) To operate at the lowest possible frequency f.

Although values of $\kappa < 1$ are in principle possible, investigation of situations where κ is < 1 has indicated that these situations lead to plasma instabilities [12]. For this reason, at least up to this time, only situations with $\kappa > 1$ seem useful. This is not too surprising if one considers that $\kappa < 1$ means a reduction of energy density of the r-f field from the plasma surface to the walls (conductors) of the container, while $\kappa > 1$ means an increase of energy density. For this reason, the lowest useful value of κ^2 is to be taken between 1 and 2.

The lowest frequency at which r-f fields still are useful for plasma containment and possess the advantages described in Section 2.1 seems to be at best of the order of one megacycle/second. This limit is determined by a number of factors such as the rate of ambipolar diffusion in the absence of containing force, amplitude of the motion of electrons in the r-f field, rate of growth of instabilities, etc.

The maximum power per unit area P_1 which can be dissipated from a conducting surface in conventional cooling systems is of the order of several hundred W/cm². By

[3]) Self consistent solutions for dense plasmas contained by r-f fields only have been obtained for several geometries by a number of workers. Inspection of these solutions so far seems to substantiate the points of view expressed in this text.

advanced techniques such as evaporation cooling, cooling rates of several kW/cm² can be achieved.

Taking then for illustrative purpose $P_1 = 2$ kW/cm², $\kappa^2 = 2$ and $f = 1$ Mc/s, these values yield for the maximum plasma pressure p which could be contained by means of r-f fields $p \leqq 1/4$ atmosphere.

This result, approximate as it may be, is of much importance to evaluate the usefulness of r-f fields for plasma containment. It may first be observed that a plasma pressure of 1/4 atmosphere contained in steady state is far from a trivial result. This would for instance correspond to a plasma of a density of 10^{14} charged particles/cm³ at a temperature of about 2000 eV (20 million °K). For reference, it may be remembered that a conventional gas discharge tube has a plasma of a density of the order of 10^{11} to 10^{12} charged particles/cm³, at a temperature of only a few eV. By producing and containing for long times (of the order of seconds or more) plasmas of pressures of the order of 1/4 atmosphere, r-f fields would thus lead to a major step forward in the attainment of controlled fusion.

This same result, however, indicates just as clearly that for the useful generation of controlled fusion power, r-f fields alone do not seem sufficient as a practical plasma containing agent. Plasma pressures at least one order of magnitude larger than that which r-f fields can provide according to the above estimate will be required. It is true that this limit of 1/4 atmosphere could be raised, e. g. by cooling the conductor surfaces much below room temperature to reduce their resistivity. A more elegant solution, however, seems to be the combination of r-f fields with d-c magnetic fields for the stable containment of high pressure plasmas with tolerable leakage rates.

2.3 Combination of r-f fields with d-c magnetic fields for plasma containment

The idea of combining r-f and d-c fields for plasma containment arises from the observation that r-f fields and d-c magnetic fields have rather complementary properties with respect to plasma containment.

D-c magnetic fields are relatively inexpensive (no skin-effect) and can therefore provide relatively large plasma containing pressures. Devices using d-c magnetic fields alone, however, are afflicted either with instabilities (pinch; Stellarator) or with excessive leakage (mirror machine).

R-f fields are capable of reducing plasma leakage to very low levels. By providing true restoring forces, they seem capable of stable plasma containment with negligible leakage.

In a combination of d-c and r-f fields, it seems therefore reasonable to require that most of the containing pressure be provided by the d-c magnetic field, while r-f fields are used only as second-order agents to reduce leakage and improve stability.

D-c and r-f fields can be combined either in "open-ended" or "closed" configurations. Open-ended configurations are defined as configurations where the lines of force of the d-c magnetic field are not everywhere parallel to the plasma surface. Mirror machines, picket-fence and cusped geometries are examples of open-ended configurations. In these configurations, there are specific regions in space (the "open" ends) where plasma tends to leak out in a direction parallel to the d-c magnetic field when it is contained by d-c magnetic fields only. In such configurations, r-f fields are to be used at these "open ends" to reduce or prevent leakage. Because in this case the leakage tends to be parallel to the lines of force of the d-c magnetic field, it is expected that the pressure required from the r-f fields to prevent this leakage is of the same order of magnitude as the total plasma pressure. However, the area over which the r-f field has to exert this pressure can be much smaller than the total plasma surface, as it is limited to the open ends only. The relatively small area over which the r-f fields are required is one of the essential features of open-ended configurations. This may even make it economical to attempt (e. g. by cooling the conductor surfaces to liquid nitrogen temperatures or lower) to exert over these limited areas by means of the r-f fields the relatively high pressures required for controlled fusion power generations.

"Closed" configurations, like the torus or the Stellarator, are configurations where the d-c magnetic field is everywhere parallel to the plasma surface. In these configurations, the r-f field exerts its pressure in a direction perpendicular to the lines of force of the d-c magnetic field. Because in this situation the average containing forces of the r-f field are essentially in the same direction as those of the d-c magnetic field, the total pressure needed from the r-f field is expected to be only a fraction of the total plasma pressure. However, the area over which it has to be exerted to reduce leakage or improve stability is of the same order as the total plasma surface.

Preliminary investigations on both open-ended [4] and closed configurations [13] indicate so far that both appear promising for the containment of dense plasmas by means of combined r-f fields and d-c magnetic fields. Although much more work is still needed before conclusive statements can be made, it is conceivable that the possibility of stable plasma containment with negligible leakage by means of d-c and r-f field combinations could lead to a much needed break-through in the problem of plasma containment.

Bibliography

[1] *Post, R. F.:* Controlled Fusion Research—An Application of the Physics of High Temperature Plasmas. Rev. mod. Phys. Vol. 28 (1956), No. 3, p. 338...362.

[2] *Linlor, W. I.:* Plasma Target Fusion Machine. APS Meeting; Univ. of Hawaii 1959, Paper C-1. Bull. APS Ser. II, Vol. 14(1959), No. 6, p. 351.

[3] *Good, M. L.:* A Proposed Particle Containment Device. Univ. of California, Radiation Lab. Rep. No. 4146, 1953.

[4] *Dow, D. G.* and *R. C. Knechtli:* Plasma Containment by R. F. and D. C. Field Combinations. J. Electronics & Control Vol. 7 (1959), N° 4, p. 316...343.

[5] *Post, R. F., R. E. Ellis, F. C. Ford* and *M. N. Rosenbluth:* Stable Confinement of a High-Temperature Plasma. Phys. Rev. Letters Vol. 4(1960), No. 4, p. 166...170.

[6] *Post, R. F.:* Summary of UCRL Pyrotron (Mirror Machine) Program. 2nd UN Conf. on the Peaceful Uses of Atomic Energy, Geneva 1958. Vol. 32, Pap. P/377, p. 245.

[7] *Grad, H.:* Theory of Cusped Geometries, I. New York Univ. Rep. NYO-7969. New York: 1959.

[8] *Berkowitz, J.:* Theory of Cusped Geometries, II. New York Univ. Rep. NYO-2536. New York: 1960.

[9] *Boot, H. A. H., S. A. Self* and *R. B. R. Shersby-Harvie:* Containment of a Fully-Ionized Plasma by Radio-Frequency Fields. J. Electronics & Control Vol. 4 (1958),No. 5, p. 434...453.

[10] *Tuck, J. A.:* Review of Controlled Thermonuclear Research at Los Alamos. 2nd UN Conf. on the Peaceful Uses of Atomic Energy, Geneva 1958. Vol. 32, Pap. P/1860, p 3.

[11] *Ellis, R. A., L. P. Goldberg* and *J. F. Gorman:* Loss of Charged Particles in a Stellarator During Ohmic Heating. Phys. of Fluids Vol. 3(1960), No. 3, p. 468...473.

[12] *Weibel, E. S.:* Confinement of a Plasma Column by Radiation Pressure. The Plasma in a Magnetic Field. Standford, Calif.: 1958. p. 60...76.

[13] *Knechtli, R. C.* and *D. G. Dow:* Contribution of R-F Fields to the Containment of Dense Plasmas. Hughes Res. Lab. Rep. No. 137, 1960. (Available from Author on request).

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Practical Tubes for Bright Radar Displays

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621)385.832:621.396.96

1. Introduction

Radar has become an integral part of present-day activities. In particular, modern travel requires means for control, navigation, and surveillance of transportation facilities under all weather conditions and at various speeds. From fishing boats to jet aircraft, the need for safe, dependable manoeuvers is of prime interest.

Radar displays, as developed during the last two decades, were mostly dim and required either viewing in darkened areas or elaborate shielding of the screens. Furthermore, dark-adaption of the human eye was necessary in many instances.

New methods for bright radar displays have been developed during the last several years, and commercial devices are now available which allow viewing under conditions of high ambient light levels. Two distinctly different systems approaches are available. The first approach is useful when radar information is to be displayed directly on a relatively small screen and without addition of other signals. In this case, display storage tubes are most useful. The second approach incorporates the use of scan-conversion storage tubes in connection with direct-view or projection-television display devices. Such a system provides maximum flexibility in allowing the processing and mixing of signals and the arrangement of multiple displays at desired locations and in a large variety of sizes.

This paper describes the two devices used in these systems, display storage tubes and scan-conversion storage tubes, and their characteristics.

2. Display Storage Tubes

Display storage tubes have three main features which give them an advantage over conventional cathode-ray tubes as display devices. First, they have a high display brightness, 2,500 foot-lamberts (0.9 sb)[1]) for some types, which makes possible displays of high contrast under conditions of high ambient lighting. Second, they are able to present a continuous display of information for many seconds after the electrical signal containing the input information has ceased. This storage feature, combined with controlled erasure, makes possible displays in which the brightness decay of displayed information may be varied to fit individual situations. Third, they are able to integrate repetitive signals in a modulated writing beam so that repetitive information may be distinguished from random noise.

These characteristics make display storage tubes useful for the presentation of radar information. Displays of radars with slow antenna rotation rates, and displays which must be viewed under conditions of high ambient illumination, such as in many aircraft cockpits or in airport control towers, may well take advantage of these features. Display storage tubes are also suited to a variety of other applications including transient studies, data transmission including halftones, and visual communications requiring steady, non-flickering, narrow-bandwidth transmission over telephone lines.

2.1. *Principles of operation*

The writing and viewing sections of the RCA-7448, which will be used as a model for a description of the operating principles of display storage tubes, are shown in Fig. 1. The writing section contains an electrostatically focused gun that produces an electron beam which is electrostatically deflected by two sets of deflecting electrodes. The viewing section contains an aluminized screen having high visual efficiency on the inside surface of a flat faceplate, a backplate capacitively coupled to a storage grid, and a viewing gun having five grids.

Viewing operation

The viewing gun provides a low-velocity electron stream which continuously floods the electrodes (grid 5, storage grid, and backplate) controlling the storage function and the brightness of the display. A display having high brightness is possible because the very efficient phosphor is excited continuously rather than intermittently, as in conventional cathode-ray tubes, by the high-current viewing beam.

Grid 3 consists of a band of conductive coating positioned on the bulb-wall interior, as shown in Fig. 1. This figure also shows the location of grid 4, which consists of a metal cylinder. Grids 3 and 4 collimate the paths of the electrons in the stream before they reach grid 5. Collimation is required so that the lowvelocity electrons will approach the storage grid in paths perpendicular to the plane of the storage grid. This normal approach of the electrons to every point on the storage grid together with their uniform velocity, makes possible uniform control of the electrons by the storage grid.

[1]) 1 foot-lambert is the brightness of a surface emitting (or reflecting) 1 lumen(lm)/ft^2. 1 lambert = 1 lumen(lm)/cm^2 = $1/\pi$ stilb (sb).