WORK WITH THE EXPERIMENTAL THERMONUCLEAR SYSTEM OGRA

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1. INTRODUCTION

BASIC information on the construction of Ogra was published in 1958 by I. V. Kurchatov.[1] The first reports concerning experiments carried out with this system were delivered at a conference at the Institution of Electrical Engineers in London in 1959.[2] We assume that the reader of the present paper is familiar with this material.

At the second Geneva Conference on the Peaceful Uses of Atomic Energy in 1958, it was found that the values of the elementary fast-ion cross sections used by us in computing the buildup of hot plasma in Ogra differed widely from the values measured at that time in laboratories in the United States. The question of plasma buildup in Ogra and magnetic-mirror systems like Ogra was discussed widely at the Conference and in succeeding years[5,9] and the cross-section measurements were repeated in England,[6] the United States,[7] and the U.S.S.R.

The second section is devoted to an analysis of buildup modes on the basis of the later measurements. In Sec. 3 we discuss possible effects of still uninvestigated factors on buildup. In Sec. 4 the results of experiments carried out with Ogra up to October 1960 are summarized briefly.

2. CRITICAL CURRENT FOR BURNOUT AND VACUUM CONDITIONS NECESSARY FOR BUILDING UP A DENSE PLASMA IN OGRA

As has already been reported,[1,2] ion capture in Ogra starts with the dissociation of the molecular ion H_2^+ on hydrogen which is formed in the chamber by the neutralization of the injected ion beam. The plasma density can increase to a limiting value determined by escape through the mirrors, and the hydrogen which is produced can be pumped away, only if certain definite conditions are satisfied. In general, the current of injected ions must exceed some definite value, which we call the critical value for burnout. If the injection current is increased gradually from a small value to the critical value, the plasma density n increases while the hydrogen density n_0 decreases. Burnout is characterized by a plasma density equal to or greater than the hydrogen density. Near burnout, dissociation of molecular ions on protons which have been captured earlier becomes important. When burnout is achieved practically all dissociation takes place on protons.

The buildup of hot plasma in Ogra depends primarily on four cross sections:

a) The cross section for dissociation of the molecular ion H_2^+ on hydrogen, σ_d.

b) The cross section for the dissociation of the molecular ion H_2^+ on protons, σ_d^*.

c) The cross section for charge exchange of protons in hydrogen, σ_{ce}.

d) The cross section for ionization of hydrogen by protons, σ_i.

The values of σ_d used by us in 1958 were measured by N. V. Fedorenko[3] at the Leningrad Physico-Technical Institute in 1957. These values were 2.5 times greater than the values of σ_d obtained by Barnett at Oak Ridge.[4] In a detailed calculation of buildup in an Ogra device carried out by A. Simon at Oak Ridge,[5] the "American" cross sections gave a burnout current which was by a factor of 40 greater than that obtained with the "Soviet" cross sections. At the present time this discrepancy has been greatly reduced. The measurements of Sweetman in England[6] and Postma and Hamblen at Oak Ridge[7] show that the old values of σ_d reported by Barnett were too low by almost a factor of 2. A check of the measurements carried out by N. V. Fedorenko in 1960 resulted in some reduction in his values. The new values of σ_d given by Fedorenko are only 20 — 30% higher than those of Sweetman and are in satisfactory agreement with the results of Postma and Hamblen. At the present time the cross section for dissociation on protons σ_d^* has still not been measured. There exists one calculation by Gerujoy,[8] which has not been verified by other authors. In the calculations carried out in 1958 we assumed that $\sigma_d^* = \sigma_d$; in the energy region of interest, however, Gerujoy reports that σ_d^* is one-half of σ_d. There are no discrepancies between the Soviet and foreign measurements of the other two cross sections σ_{ce} and σ_i.

In 1960, a group at Livermore[9] carried out another analysis of plasma buildup in a mirror system by dissociation of injected H_2^+ ions and concluded that the burnout current in Ogra should be several amperes. In order to make a complete analysis of the kinetics of plasma buildup it is necessary to solve a system of differential equations for the accumulation of ions and the loss of gas. In this paper we shall not take account of the time dependence of buildup, nor the initial conditions, but shall limit ourselves to a calculation of the critical current for burnout. For this purpose it is sufficient to consider a system of algebraic equations which describe the particle balance in the stationary state. From these we determine the critical current, the plasma density, and the hydrogen pressure at burnout as functions of the energy of the injected ions and the parameters of the mirror system. We neglect the insignificant losses due to charge exchange of molecular ions. Under the conditions which obtain in Ogra the dissociation of molecular ions on molecular ions which have been injected earlier can also be neglected. The only form of proton loss from the mirror system which we consider is charge exchange. Loss through the mirrors and diffusion across the magnetic field due to binary collisions become important only at plasma densities much greater than the burnout density. At the present time we have no experimental information concerning the role of other loss mechanisms in Ogra. In the gas balance we neglect the influx of hydrogen from the injector. Actually, in Ogra influx from the injector takes place only through the magnetic channel, at a rate of approximately 30 liters/sec. When the pressure of the residual gases in the injector is approximately 1×10^{-6} mm Hg, this value gives a flux of 10^{15} atoms/sec, which is three orders of magnitude smaller than the hydrogen flux of the ion beam.

Under these conditions, the balance equations for ions and neutrals are

$$\frac{\alpha}{\Omega} J (n_0\sigma_d + n\sigma_d^*) \mathscr{L} = n_0 n \sigma_{ce} v, \tag{2.1}$$

$$\frac{1}{\Omega} J q = n_0 n \sigma_i v \varepsilon + \frac{P}{\Omega} n_0. \tag{2.2}$$

Here, J is the injected current (ions/sec), Ω is the volume occupied by the plasma, α is the fraction of protons which do not strike the magnetic channel, $\mathscr{L}$ is the effective path length for a molecular ion in the mirror system before it is lost in the magnetic channel, n_0 and n are respectively the number of hydrogen molecules and the number of protons per cubic centimeter, v is the proton velocity, q is the number of hydrogen molecules which enter the volume with the loss of one molecular ion at the magnetic channel, ϵ is the fraction of slow ions which are captured at the pumping systems at the ends whereas $1 - \epsilon$ is the number of ions returned to the volume in the form of molecular hydrogen, and P is the rate (cm^3/sec) at which hydrogen is pumped from the volume occupied by the plasma. From Eqs. (2.1) and (2.2) and the burnout condition $dJ/dn_0 = dJ/dn = 0$ we can obtain a formula for the burnout current:

$$J_b = \frac{1}{4}\frac{q}{\varepsilon\alpha^2}\frac{\Omega}{\mathscr{L}^2}\frac{v\sigma_{ce}^2}{\sigma_d\sigma_d^*\sigma_i}\left\{1-\frac{\alpha\mathscr{L}}{q}\frac{1}{\Omega}\frac{\sigma_d^*}{v\sigma_{ce}}P\right\}^2 \tag{2.3}$$

and formulas for the plasma density and hydrogen density at burnout:

$$n_b = \frac{1}{2}\frac{q}{\varepsilon\alpha\mathscr{L}}\frac{\sigma_{ce}}{\sigma_i\sigma_d^*}\left(1-\frac{\alpha\mathscr{L}}{q}\frac{1}{\Omega}\frac{\sigma_d^*}{v\sigma_{ce}}P\right), \tag{2.4}$$

$$n_{0b} = \frac{1}{2}\frac{q}{\varepsilon\alpha\mathscr{L}}\frac{\sigma_{ce}}{\sigma_i\sigma_d}\frac{\left(1-\frac{\alpha\mathscr{L}}{q}\frac{1}{\Omega}\frac{\sigma_d^*}{v\sigma_{ce}}P\right)^2}{1+\frac{\alpha\mathscr{L}}{q}\frac{1}{\Omega}\frac{\sigma_d^*}{v\sigma_{ce}}P}. \tag{2.5}$$

The burnout current is reduced to zero at a sufficiently high pumping rate P; that is to say, the pumping rate becomes comparable with the influx of gas produced by the ion beam and plasma buildup proceeds till the density increase is limited by loss mechanisms other than charge exchange.

In Ogra the volume occupied by the plasma $\Omega = 8 \times 10^6$ cm^3. It has been found graphically that for the magnetic channel used in Ogra $\alpha = 0.7$. Measurements[10] have shown that for ion densities up to 10^7 cm^{-3} the geometric path length of H_2^+ ions (before they strike the injector) is 1.5×10^5 cm; in the first two reflections, up to 30% of the ions are lost at the channel (provided they remain guided by the channel). Assuming that this fraction of the ions does not contribute to plasma buildup, but that this geometric path length can be increased to at least 1.8×10^5 cm in the future, we take $\mathscr{L}$ to be 1.3×10^5 cm. Since there is a spread in the values of the cross sections measured by various authors, as shown in Fig. 1, we use two sets of values; the first set is least favorable for buildup, being made up of the smallest values of σ_d (for this we "combine" the Fedorenko curve with the curve of Sweetman, Postma and Hamblen by multiplying the Fedorenko values by 0.78, as shown in Fig. 1) and the highest values of the charge-exchange cross sections, corresponding to the upper limit of the hatched region in Fig. 1. The second group comprises Fedorenko's value for σ_d and σ_{ce} taken from the lower limit of the hatched region. The coefficients q and ϵ characterize the state of the surfaces in the chamber. The surface of the magnetic channel must be very carefully cleaned. After the ion

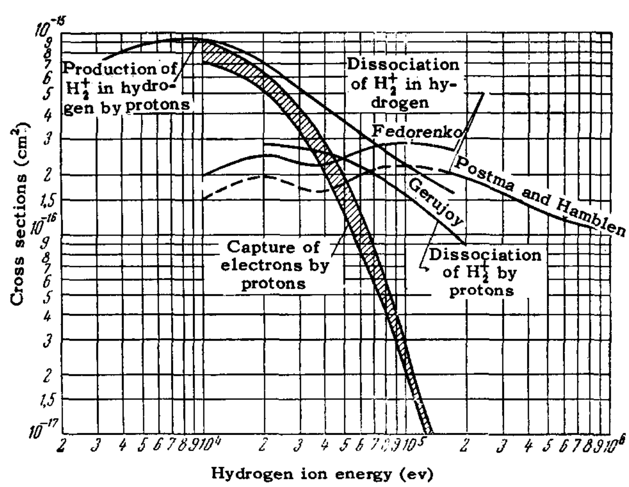

FIG. 1. Important cross sections for plasma buildup in Ogra. The hatched region encloses values of the cross sections for electron capture by protons in hydrogen obtained in reference 14. The cross sections for dissociation of H_2^+ in the energy region $10^4 - 1.5 \times 10^5$ ev are given in accordance with the correction reported by Fedorenko in 1960. The dashed curve is obtained by multiplying the Fedorenko values by 0.78 in order to join the curve obtained by Sweetman, Postma et al. The cross sections for the formation of H_2^* by protons in hydrogen are taken from the measurements of Il'in.[3]

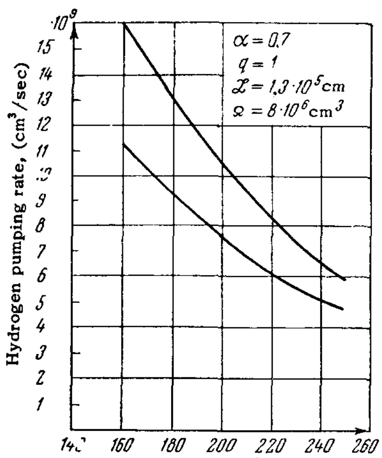

FIG. 2. Pumping rate for zero burnout current. The upper curve is for the unfavorable choice of cross sections while the lower curve is for the most favorable choice of cross sections.

beam is started the oxides are removed and the surface is saturated with hydrogen. For exposure smaller than 10^{18} hydrogen atoms per square centimeter, according to measurements of V. A. Simonov at the Vacuum Research Institute, $q < 1$. At large exposures, q approaches unity and remains equal to unity for copper, stainless steel, and gold for all exposures used by us. The cathode sputtering of these metals by hydrogen ions with energies of 100 — 200 kev amounts to less than 0.05 atoms per incident ion.

The smallest value of q measured by V. A. Simonov is 0.7. The quantity ϵ is a sensitive function of the construction of the pumping devices at the ends of the system and, in principle, can be made as close to unity as desired. To achieve this objective the collecting surface must not be "seen" from regions occupied by hot plasma. This has not been done in Ogra and for this reason the requirements on sorption are especially stringent. If we assume that the density of ion current at the end sorption surfaces is less than 10^{13} ions/cm^2-sec, it is possible to achieve a long-term value of ϵ up to 0.3. The upper value of ϵ which can be achieved depends on many factors. The measurements carried out by Simonov show that it is not impossible to obtain $\epsilon = 0.8$. For order-of-magnitude estimates we present the results of calculations carried out with $\epsilon = q = 1$.

In Fig. 2 we show the pumping rate for zero burnout current P_0 as a function of the energy of the injected H_2^+ ions. According to Eq. (4.2), the density of the accumulated plasma becomes negative when $P > P_0$. This means that the calculation has no physical meaning when $P > P_0$. When $P = P_0$ (5.2) likewise fails to yield the minimum density n_0. In any case, however, n_0 is larger than the minimum density in the chamber before the ion beam is injected.

We see that the pumping rates given in Fig. 2 are completely feasible. Actually, the minimum mean gas density in the volume occupied by the plasma is the density which obtains for a single passage of hydrogen molecules from the channel to the sorption wall. A simple calculation shows that if the walls are completely absorbing the density which is obtained is several times smaller than that which is required. For complete sorption of hydrogen on a wall section of 1.5 m on both sides of the center of the chamber it corresponds to a pumping rate of twenty million liters/sec. From Fig. 2 it follows that burnout at an ion energy of 250 kev, requires a pumping rate of no more than six million liters/sec. Consequently it is sufficient to maintain a hydrogen sorption coefficient greater than 0.3 over this wall section. This problem is now regarded as completely solved.

In Fig. 3 we show the dependence of burnout current on energy of injected H_2^+ ions at various pumping rates. It is difficult to achieve burnout at an injection energy of 200 kev. The problem is considerably simpler at an injection energy of 250 kev.

In view of the approximate nature of the calculation, we take the critical value for burnout in Ogra to be an H_2^+ current of 300 — 400 ma at a pumping rate of 4 — 5 million liters/sec at the center of the chamber.

3. STABILITY, SPACE CHARGE, AND ION COOLING BY ELECTRONS

All discussion of the possibility of building a controlled thermonuclear reactor is based on the assumption that both magnetohydrodynamic stability of a plasma as a whole and microscopic stability can be achieved; if not, it may not be possible to achieve the required magnetic thermal isolation. Many proposals have been made for obtaining magnetohydrodynamic stability. Every year new experimental verification of various aspects of this problem is reported. If the mechanisms discovered by Post et al.[11] do not operate

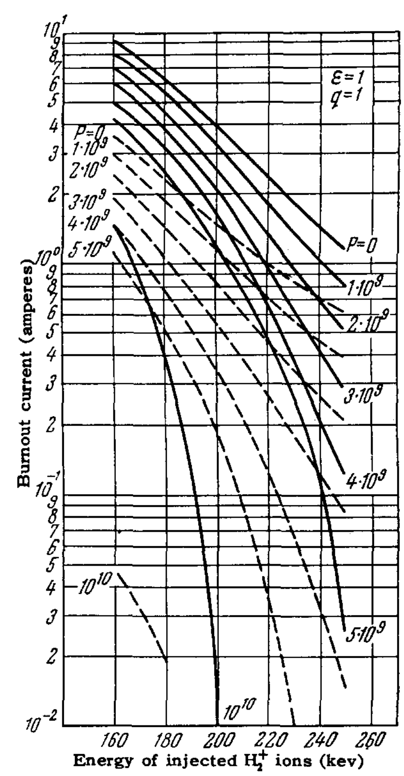

FIG. 3. Burnout current as a function of energy of injected H_2^+ ions for various pumping rates. The solid curves correspond to the unfavorable choice of cross section; the dashed curves correspond to the favorable choice of cross sections.

in Ogra at high vacuum, and if the interchange instability, investigated experimentally by M. S. Ioffe and V. G. Tel'kovskii[12] is found, it will be necessary to correct the Ogra field, making it increase in all directions from the center of the trap. This possibility can be realized, for example, by adding stabilizing turns similar to the "three-strand" winding used in the stellarator. It appears that the addition of these turns would provide magnetohydrodynamic stability of the plasma as a whole. As far as the subject of microscopic instabilities is concerned, we can say that the predictions are almost completely without experimental basis. Experiments being carried out at the present time will show whether these instabilities develop in a plasma which is produced by capture of externally accelerated particles and whether they represent danger from the point of view of plasma containment by the magnetic field.

Another possible difficulty is one which may be inherent for any machine in which ions are injected through a channel and arises because the axial symmetry of the system is disturbed. If a high current is injected the plasma space charge may be highly asymmetrical. An analysis carried out by O. B. Firsov shows that for a positive azimuthal drift, corresponding to a magnetic field which falls off in the radial direction, this asymmetry can lead to an organized flow of ions to the wall of the chamber. In a field with stabilizing turns the azimuthal drift is of the opposite sign and this danger is apparently eliminated.

To a considerable extent, the positive-ion space charge in Ogra is compensated by electrons produced in ionization of the residual gas, because the slow ions which are formed are repelled (by the space charge) along the magnetic force lines from the trap. The magnitude of the plasma space charge is determined primarily by two factors: loss of electrons through the mirrors, and plasma density oscillations. Electron loss through the mirrors means that the space charge increases with electron temperature. If, for any reason, plasma density oscillations are excited which are synchronous over the entire system, during the time in which the density increases the space charge will exceed the value which would be established in the stationary state by electron loss. Measurements carried out with Ogra show that in a number of modes of operation of the magnetic field, at injection currents which are not excessively small, the plasma potential is of the order of kilovolts and executes anharmonic oscillations. This topic is considered in greater detail in Sec. 4.

The positive space charge causes positive azimuthal drift of the ions and, for this reason, has an effect on $\mathscr{L}$, the path length of molecular ions before thay are lost at the injector. This situation may impose additional requirements on the design of the apparatus. For example, it may be necessary to reduce the potential at the end electrodes as the space charge increases; in this way the drift velocity can be controlled.

Ion cooling by electrons does not disturb buildup if the exchange of energy results solely from the Coulomb interaction between electrons and ions. However, it is possible that there are other collective mechanisms for the exchange of energy which are not described completely by theory and which will have to be investigated experimentally.

A purely theoretical investigation of the effects that can occur in the plasma in Ogra can hardly bring us closer to a prediction of these effects. We are now at a stage of the investigation in which the accumulation of experimental data must be accompanied by theoretical analyses which serve to indicate useful further experiments.

4. EXPERIMENTAL RESULTS WITH OGRA

This paper is being written at a time when elements of Ogra have been modified to increase the injected ion current and to improve the vacuum conditions. With these modifications the following results have been obtained. Whereas in the spring of 1960 we were able to inject only 30 — 35 ma of H_2^+ ions and the pressure at the center of the chamber was increased by 2×10^{-8} mm Hg for each milliampere of injected current, we are now able to inject up to 150 ma of H_2^+ current and the hydrogen pressure at the center of the chamber is increased by only 2×10^{-10} mm Hg per milliampere of injected ion current. Investigations of the plasma with these new possibilities are only in the starting stage and we shall not mention the results now being obtained, since new data are being accumulated every day. All that will be said below concerning plasma buildup is based on information obtained before the modifications were made, when the injected current was less than 30 ma and the pressure at the center of the chamber could not be reduced below 2×10^{-7} mm Hg, as has been shown by recent measurements.

The last measurements of the proton lifetime in the Ogra system[10] were carried out at an ion energy of 200 kev and injected molecular-ion currents up to 20 ma. At a pressure of 1×10^{-7} mm Hg and an injected current of 0.6 ma the proton lifetime is 10 millisec. The dependence of lifetime on the pressure of helium and the residual gas is shown in Fig. 4. On the basis of these results we can assert that within the experimental errors there are no ion losses from the system other than those due to charge exchange.

The density of the hot component of the plasma n can be computed from the relation

$$J\mathscr{L}n_0\sigma_d = \frac{n}{\tau}\,\Omega. \qquad (4.1)$$

At an H_2^+ current of 20 ma, an energy of 200 kev, and a lifetime $\tau = 3$ millisec, we find n is of the order of 10^7 cm^{-3}.

A method developed in conjunction with I. G. Goncharov and Yu. N. Dnestrovskii has been found convenient for measuring the lowest electron densities in Ogra; this method consists of the following. An elec-

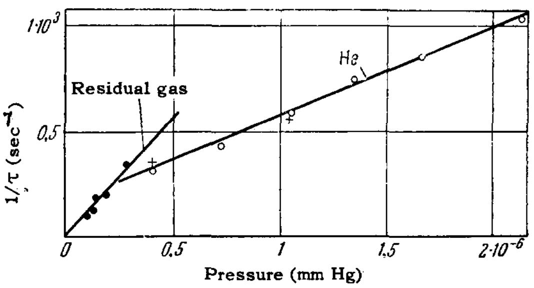

FIG. 4. The proton lifetime τ in Ogra as a function of the pressure of helium and residual gases. The energy of the injected H_2^+ ions is 200 kev. As the titanium is poisoned and the injected current is increased to 20 ma the pressure in the chamber increases; this is shown on the figure by different values of the pressure of the residual gas. The composition by components of the residual gas is not recorded.

tromagnetic generator in the meter region is used to excite characteristic oscillations of the Ogra chamber, which acts as a cavity resonator. When the plasma appears the frequencies of the characteristic oscillations of the chamber are shifted. Using perturbation theory, Yu. N. Dnestrovskii has obtained a relation between the electron density and the frequency shift. This analysis is based on the assumption that a uniform plasma occupies a cylindrical volume of dimensions different from those of the resonator. It is assumed that the plasma density is low so that the Langmuir frequency ω_0 is much lower than the frequencies of the resonator oscillations which, in turn, are much lower than the electron cyclotron frequencies in the magnetic field present in the mirror system. The magnetic field is assumed to be constant and along the chamber axis. Collisions of electrons with atoms and ions are neglected. Under these conditions, TM_{01i} modes are excited (in Ogra $i \geq 6$) and, with reasonable accuracy, the electron density n_e is related to the shift of the characteristic frequencies of the chamber Δf by the expression:

$$n_e \approx 10\Delta f.$$

The apparatus developed can measure values of Δf not less than 0.1 Mcs, so that the minimum detectable electron density is $n_e \approx 10^6$ cm^{-3}. The maximum electron density at which oscillations are excited is determined from the condition $\omega_0 < \omega$, where ω is the excited frequency. The excited frequencies lie in the range 170 — 200 Mcs so that the measured electron density $n_e < 4 \times 10^8$ cm^{-3}.

By using a swept-frequency oscillator, the authors have been able to view the oscillation spectrum on the screen of an oscilloscope and to observe the time dependence of n_e from the shift of resonance peaks. An advantage of this method is that it gives the mean value of the electron density over the plasma volume; a disadvantage is the difficulty of exciting oscillations in a chamber containing measurement devices or sorption-pumping units.

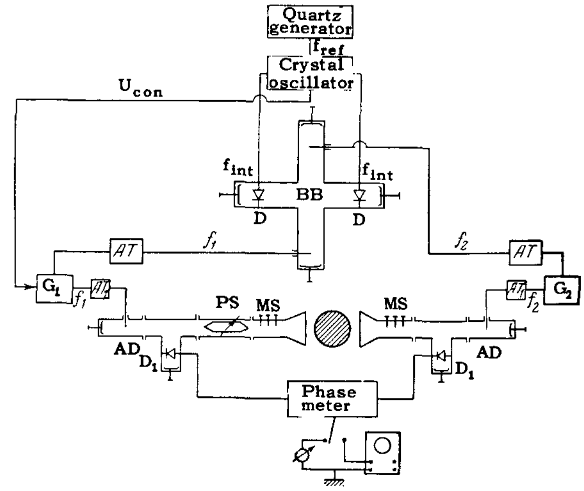

FIG. 5. Block diagram of the interferometer. The signals at frequencies f_1 and f_2 (2800.000 and 2800.345 Mc) from the generators GSS-27 (G_1 and G_2) are applied through equalizing attenuators AT_1 to the waveguide measurement system consisting of the tunable end sections AD; the tees, in the sidearms of which there are crystal detectors D_1; a phaseshifter PS (in the left branch); matching sections MS; microwave horns. The signals at the difference frequency (345 kc) from the detectors D_1 are applied to the phase meter. The phase shift is recorded by the oscilloscope or by a meter. A stable difference frequency of 345 kc is obtained from an oscillator in which AFC is used. Signals from the generators (G_1 and G_2) are applied through the attenuators AT to the detectors D in opposite arms of the balance bridge BB. In the phase detector the phase of the intermediate frequency signal f_{int} from the detectors D is compared with the phase of the reference signal (f_{ref} = 345 kc) from a crystal oscillator. The voltage from the output of the phase detector U_{con} is applied to the repeller of the klystron G_1.

In order to measure higher electron densities, V. T. Karpukhin has designed and built an interferometer which operates at 3 cm. A block diagram of this unit is shown in Fig. 5. The minimum detectable phase shift is one degree, which corresponds to an electron density of 5×10^7 cm^{-3}. The interferometer has outputs to a meter indicator and to an oscilloscope. The microwave horns of the interferometer are located at the central cross section of the Ogra chamber. Thus, the interferometer averages the density only over the cross section at which ion injection takes place. For this reason the electron densities given by this instrument may be higher than the mean density over the plasma volume.

By using both methods, it is possible to measure electron densities $n_e \geq 10^6$ cm^{-3} as well as the lifetime in the mirror system.

The measurements show that the electron density increases as the gas pressure in the chamber and the injected current are increased. For example, with 15 ma of 100-kev H_2^+ ions and an argon pressure of 5×10^{-6} mm Hg the density measured by the interferometer is greater than 1.5×10^9 cm^{-3}. At this same current but 5×10^{-7} mm Hg the density is $n_e = 1 \times 10^8$ cm^{-3}.

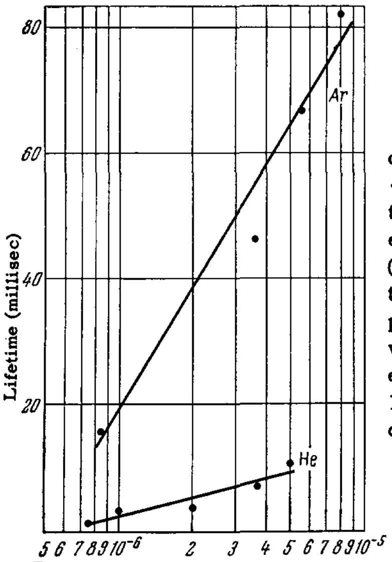

FIG. 6. Lifetime of the cold plasma component τ_{cold} measured by the interferometer. During the entire measurement time (up to 100 msec) the electron density falls off exponentially in accordance with exp (t/τ_{cold}). The energy of the H_2^+ ions is 100 kev and the injected current is 25 ma.

Thus, there are always two plasma components in the chamber, a hot component and a cold component; at residual gas pressures greater than 10^{-7} mm Hg the density of the cold component is appreciably greater than that of the hot component. At pressures below 10^{-7} mm Hg, the densities of both components tend to be equal. Switching off the ion beam shows that the cold component lives considerably longer than the hot component. Lifetimes for the cold component are shown in Fig. 6.

Magnetic radiation from ions has been observed experimentally for the first time in Ogra. Calculations showed that even at low plasma densities this radiation should be adequate for measurement. On the basis of these calculations, A. N. Karkhov[13] has constructed an apparatus to detect this radiation over the entire spectrum. In Fig. 7 we show typical ion radiation spectra. In addition to the fundamental $\omega_2 = eH/Mc$, where M is the mass of the H_2^+ molecular ion, we see other peaks, due to the harmonic frequencies $2\omega_2$, $3\omega_2$, . . . , as well as the fundamental of the proton radiation $\omega_1 = 2\omega_2$ and its harmonics $2\omega_1$, $3\omega_1$, . . . , superimposed on the molecular frequencies. At low electron densities, only the lower harmonics are observed. As is apparent from Fig. 7, the intensities of the higher harmonics increase as the electron density increases.

The theory shows that the intensity of ion radiation in a medium increases with the refractive index. The relative intensities of the higher harmonics increase while those of the lower harmonics may be reduced. Qualitative agreement holds with the experiments carried out on Ogra. In order to make a quantitative comparison it will be necessary to develop the theory further, on the one hand, and to improve the measurement apparatus on the other.

In addition to being of interest in its own right, the investigation of magnetic radiation from ions is also of value in connection with diagnostics. Even without

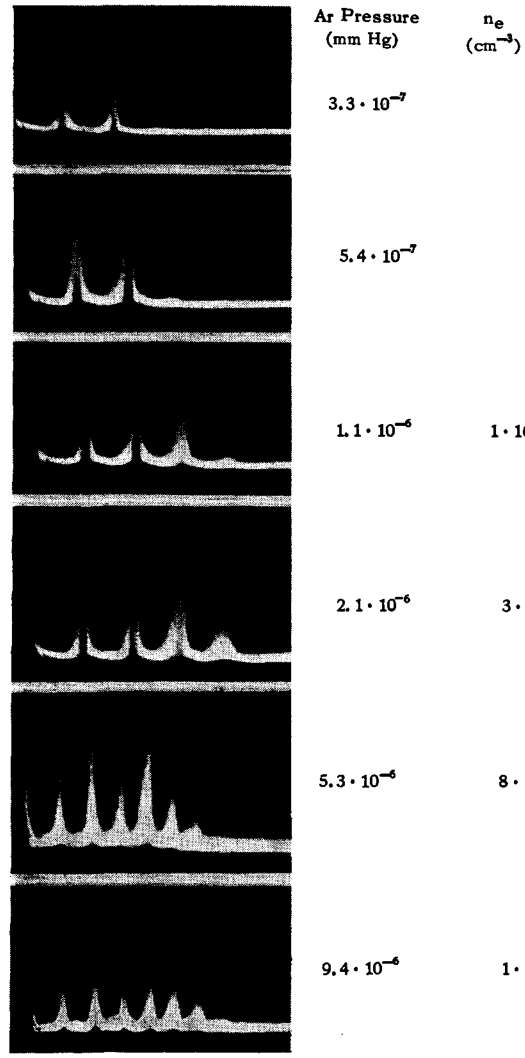

FIG. 7. Magnetic radiation from ions at different argon pressures. As the electron density n_e increases the total radiation increases primarily due to radiation from the higher harmonics. All the frames are taken with the same amplification in the detection apparatus. The injected ion current is 5 ma and the energy is 100 kev. The antenna is located perpendicularly to the chamber axis, 2 meters beyond the magnetic mirror. The frequency scale is reduced in the last two frames.

a theory for the intensity distribution over harmonics as a function of plasma density we can, using the methods described for measuring n_e, calibrate the spectrum by the electron density. The recorded spectrum can then be used for determining the electron density in the region $n_e > 2 \times 10^8$ cm^{-3}.

The radiation is detected with a rod antenna located at one of the mirrors. The antenna is simple in construction, occupies a small volume, and can be placed in the chamber without disturbing the vacuum or other measurements.

In experiments with a high vacuum, when the electron density $n_e < 10^8$ cm^{-3}, only the fundamentals ω_2 and ω_1 (cf. Fig. 7) of the molecular and atomic ions are present. From the intensity ratios for these lines

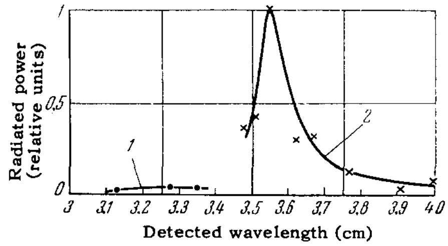

FIG. 8. Magnetic radiation and thermal radiation of plasma electrons picked up by waveguides located in the center cross section of the chamber. 1) Waveguide which transmits a mode characterized by $E \parallel H$, 2) waveguide which transmits a wave characterized by $E \perp H$.

we can approximate the density ratio for the molecular ions and protons.

At the central plane of the Ogra chamber there are microwave horns for measuring the plasma radiation at wavelengths $\lambda \leq 10$ cm. The wavelength of the magnetic electron radiation is approximately 3 cm. The intensity of this radiation is more than an order of magnitude higher than the thermal radiation of electrons at nearby wavelengths (Fig. 8). The electron temperature can be determined from the thermal radiation if the absorption of the plasma at the appropriate wavelengths is known. By measuring the intensity of the magnetic radiation together with the electron density it is possible to trace relative changes in the transverse energy of the electrons.

With the high vacuum and the plasma densities which we have obtained the radiation in the optical region is negligible. Detection of radiation from impurity lines by a high-transmission monochromator and photomultiplier is found to be much less sensitive for analyzing the residual gases than a mass spectrometer. Hence, by monitoring the composition of the residual gases with a mass spectrometer (resolution $m/\Delta m \sim 30$) we have completely avoided the need for spectral analysis.

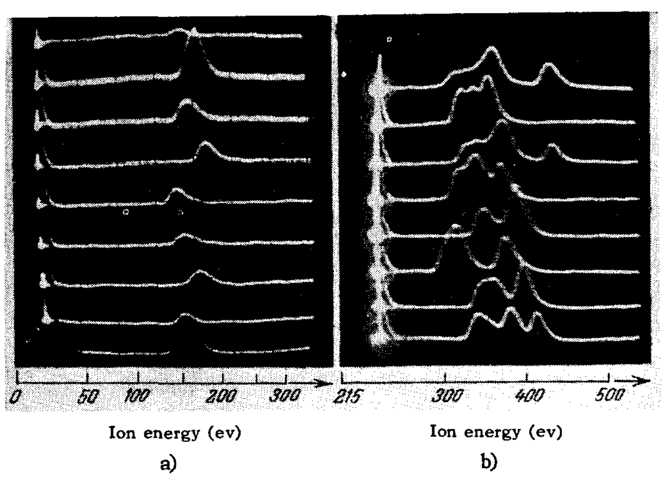

FIG. 9. Energy distribution of the slow ions which escape through the mirrors along the axis of the system. These pictures are taken with continuous injection of H_2^+ ions with an energy of 100 kev. a) injected current 15 ma, chamber pressure 1.0×10^{-6} mm Hg. The sweep length per line is 200 μsec and the distance between lines is 1 millisec. b) The injected current is 10 ma, the chamber pressure is 1.8×10^{-7} mm Hg, the sweep length per line is 200 μsec, the distance between lines is 6 msec. In both cases the energy and number of emitted ions varies in time. In b) the existence of several maxima in a line may be interpreted as the result of fast (tens of microseconds) variations in plasma potential (hundreds of volts).

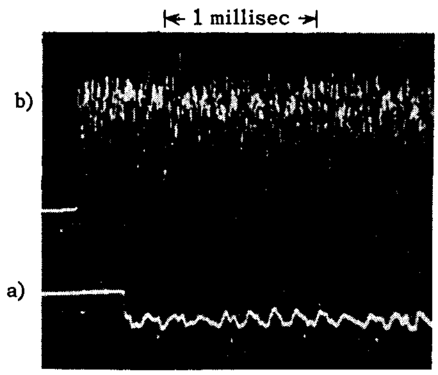

FIG. 10. a) Oscillogram of the signal from the fast charge-exchange neutrals detector. b) Oscillogram of the H_2^+ ion current detected by an electrode located at the output of the magnetic channel. In order to measure the fixed components of the signal, the inputs of the oscilloscope are shorted briefly. Clearly seen are the unmodulated noise in the injected ion beam and the modulated signal at the neutrals detector. The noise level in the second signal is appreciably lower than in the first. A current of 10 ma of H_2^+ at an energy of 100 kev is injected into the chamber. The pressure is 2×10^{-7} mm Hg.

Special spectrometers have been developed by Ya. L. Sokolov for measuring the energies of the plasma electrons by recombination radiation in the ultraviolet and bremsstrahlung in the range 1 — 1000 A.

A knowledge of the space charge in the plasma is extremely important since the radial component of the electric field causes rotation of the plasma (as a whole) about the axis of the system, while the longi-

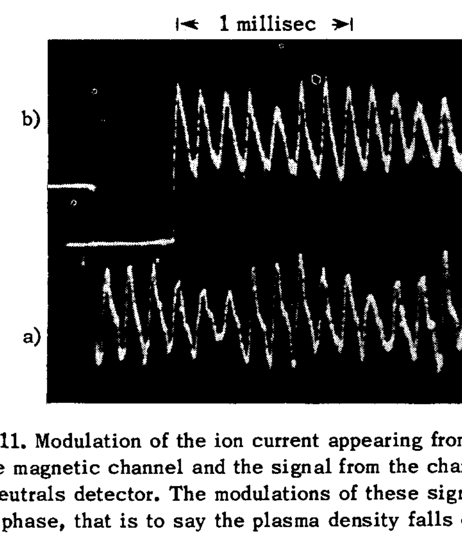

FIG. 11. Modulation of the ion current appearing from the chamber at the magnetic channel and the signal from the charge-exchange neutrals detector. The modulations of these signals is of opposite phase, that is to say the plasma density falls off when the current to the channel increases. A current of 10 ma of H_2^+ is injected into the chamber at an energy of 100 kev. The pressure is 2×10^{-7} mm Hg.

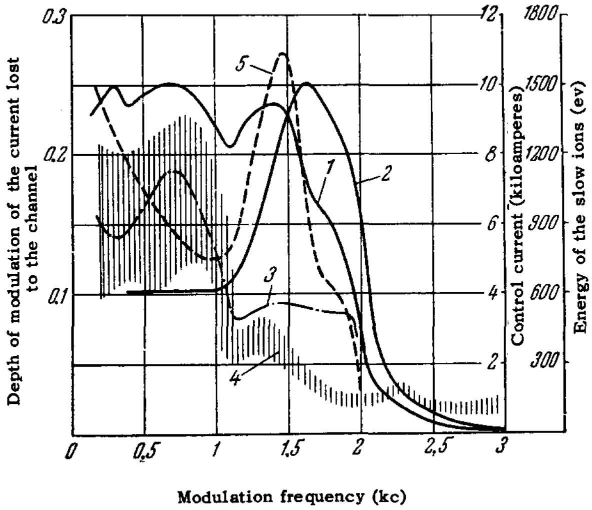

FIG. 12. 1) Flux of charge-exchange neutrals for injection of 10 ma of H_2^+ (in relative units); 2) flux of charge-exchange neutrals for injection of 1 ma of H_2^+ (in relative units); 3) modulation frequency of the currents at the detectors in the chamber; 4) energy of the slow ions ejected through the mirrors along the axis of the system. Most ions have energies lying approximately at the center of the hatched region. The edges of the region correspond to the half-widths of the energy spectrum; 5) ratio of amplitude of modulation of the mean value of the ion current moving from the system to the magnetic channel. A current of 10 ma (curves 1, 3, 4, 5) or 1 ma (curve 2) of H_2^+ with an energy of 100 kev is injected into the chamber. The pressure of the residual gases varies from 2×10^{-7} to 3×10^{-7} mm Hg.

tudinal component is responsible for ejection of ions through the mirrors. The plasma potential can be measured by determining the energy of residual gas ions ejected through the mirrors along the magnetic field lines. As is well known, an electrostatic analyzer separates ions by energy only, regardless of mass. Hence, by constructing an analyzer in which ions are detected with an open electron-multiplier, we can determine the plasma potential. Examples of slow-ion spectra are shown in Fig. 9. It is found that the plasma potential in various modes of operation ranges from tens of volts to several kilovolts. The ion energy spread is approximately 25% of the mean ion energy in a given mode of operation. The mean energy and the shape of the ion energy spectrum do not remain constant in time when the external parameters remain constant (injection current, vacuum, magnetic field), but are noticeably modulated.

The noise level in the injected current is as much as 20% of the mean value. A typical oscillogram of the noise in the injected current is shown in Fig. 10a. An oscilloscope connected to a detector of fast neutrals (produced by charge exchange) exhibits a different pattern. In Figs. 10b and 11 we see clearly defined modulation. If the oscilloscope is connected to any other detector which records the particle flux from the plasma, a similar pattern is observed.

It has been found that the depth of modulation depends on the rate of rise of the magnetic field in the mirrors. The rate of rise of the field in the mirrors is controlled by the current flowing in two sections of a winding adjacent to the mirror sections. The current flow in these sections is in opposition to the current in the main winding. At zero control current the field increases most smoothly and there is almost no magnetic drift of ions about the axis of the mirror system. When the control current is increased the slope of the field in the mirrors increases and the azimuthal magnetic ion drift is accelerated. In Fig. 12 we show the signal in the detector of fast charge-exchange neutrals, the depth and frequency of modulation of the current returning to the magnetic channel, and the energy of the slow ions (recorded by the electrostatic analyzer) as functions of the control current. When the control current is increased beyond 1900 amp the modulation breaks off suddenly and the neutral flux and the density of accumulated protons fall off rapidly. Measurements of the magnetic field show that at a control current of approximately 2000 amp the magnetic force lines passing through the magnetic channel touch the walls of the chamber in the region of minimum field in front of the mirrors. Under these conditions the molecular ions are lost to the walls of the chamber without experiencing reflection at the mirrors. This effect is undoubtedly related to the rapid reduction in the flux of neutrals which accompanies the further increase in control current.

A more complicated pattern is observed when the control current is reduced (cf. Fig. 12). The measurements show that at an injection current of 0.5 – 1 ma the longest path length $\mathscr{L}$ (before the molecular ions return to the channel) is obtained at $I_{con} \cong 1600$ amp. A reduction in I_{con} at low H_2^+ injection currents and pressures greater than 10^{-6} mm Hg causes a reduction in $\mathscr{L}$; the density of accumulated plasma, and the flux of charge-exchange neutrals, which is proportional to the density, are also reduced. At $I_{con} = 1000$ amp the azimuthal drift in the magnetic field becomes so small that all the molecular ions are lost at the magnetic channel after a few reflections from the mirrors. The flux of neutrals at $I_{con} = 1000$ amp and a small injection current is a factor of 2.5 smaller than at 1600 amp. However, at high currents and low pressures, this quantity is not reduced, as shown in Fig. 12, but can even increase slightly. This behavior can be explained by the fact that the reduction in magnetic drift is accompanied by an increased electrical azimuthal drift due to the increase in plasma potential. A simple estimate shows that with a potential of 600 volts at the center of the plasma, after one reflection from the mirror the molecular ion drifts through an angle of $\Delta\varphi \sim 1/6$ radian in the crossed electric and magnetic fields; that is to say, approximately the same amount as the magnetic drift of a single ion in a field with $I_{con} = 1600$ amp.

5. CONCLUSIONS

Investigations carried out with Ogra show that at low values of the injected current (10 — 20 ma) the ion motion is in good agreement with that predicted for the motion of individual particles; the path length of the molecular ions is greater than a kilometer, which is sufficient for effective dissociation. The path length can be increased still further by a careful choice of the magnetic field configuration. Under these conditions it is possible to accumulate a plasma with a proton density of 10^7 cm^{-3}.

The injected ion current has been increased to 150 ma but we have still not exhausted all possibilities. No apparent difficulties seem to prevent further increase of the injected current to 300 — 400 ma. Improvement of the vacuum conditions, as described in Sec. 2, so enhances the buildup conditions, that the injected current required for obtaining a high density plasma can be reduced, if necessary, to tens of milliamperes if the energy of the H_2^+ ions is increased to 250 — 260 kev.

However, it has still not been shown conclusively that the problem of building up a hot plasma with a density of 10^9 or more fast ions per cubic centimeter is solved.

We are still working at plasma densities below which the ions move as noninteracting particles, but above which the hydrodynamic properties of the plasma and the collective interaction of particles appear.

The experiments have still not adequately explained all the effects observed in Ogra. We still do not know why the plasma potential is as high as tens of kilovolts in certain modes of operation. The exchange of energy between ions and electrons by Coulomb interactions cannot transfer energies of this kind to electrons. Consequently, there may be another more powerful mechanism for the transfer of energy from ions to electrons; also there may be some form of instability, not yet understood, which results in such high electron losses to the walls that the space charge is not compensated even though the residual gas is ionized.

As the plasma density increases, conditions are satisfied for the development of all those instabilities which have been investigated in many theoretical papers in recent years.

A hot plasma is still completely unknown. Supression of the instabilities will require a great amount of work and insight.

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