25

ИНСТИТУТ
ЯДЕРНОЙ ФИЗИКИ СОАН СССР

ПРЕПРИНТ И Я Ф 111 - 73

G.I.BUDKER

THERMONUCLEAP FUSION IN INSTALLATIONS WITH A DENSE PLASMA*

Новосибирск

1973

In my present talk I will speak about, so called, systems using a dense plasma. At various times different people put the quite different meanings into the words "dense plasma". We shall call the plasma "dense" if the mean free path of charged particles is comparable with the length of the device.

For the thermonuclear temperature range $T \approx 10^4$ eV it means that the plasma density should satisfy the condition

$$n\ (\mathrm{cm}^{-3}) > \frac{3\cdot 10^{20}}{L\ (\mathrm{cm})}$$

and its length should satisfy the condition

$$p\ (\mathrm{atm}) > \frac{10^{7}}{L\ (\mathrm{cm})}$$

(see Fig.I).

We shall be interested in traps with a dense plasma, that is in systems for which the magnetic fields are of great significance. Therefore I will not be concerned with ideas abcut thermonuclear reaction realization in microparticles of condensed matter about which there is much talk at present (despite the fact we are certainly dealing with a plasma which is dense in our sense of the word: $L \leq 0.I$ mm, $P > 10$ atm).

The maximum pressure for which one can still speak of a plasma confinement in a trap is of the order of millions of atmospheres. This pressure is obtained by means of explosive compression of a liner. The corresponding density of the plasma is of the order of $3\cdot IO^{19}\mathrm{cm}^{-3}$ and the mean free path is about IO cm. The final dimensions of a reactor after implosion are approximately I cm in the radial direction and

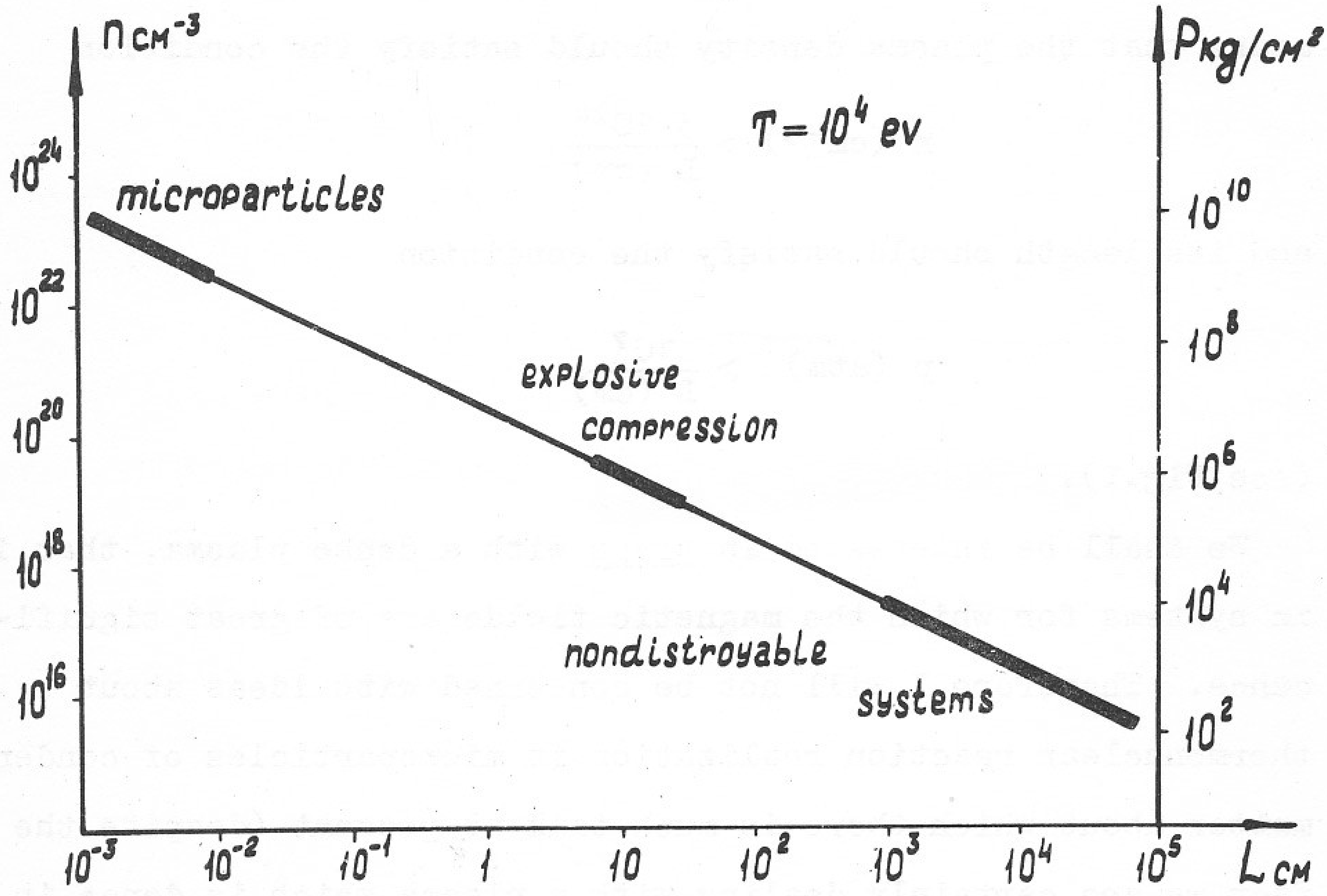

Fig.1. Graphs of n and p versus L with double logarithmic scale.

several meters in length. The length I speak of here is determined from the condition that the time of the plasma longitudinal expansion should be on the order of a Lawson time:

$$\tau\ (\mathrm{sec}) \sim 10^{14}/n(\mathrm{cm}^{-3})$$

Work in this field has been carried out at the Institute of Nuclear Physics [I] and in the Laboratory of Linhart in Italy[2]. At Novosibirsk the possibility of preliminary storage of the necessary energy as the kinetic energy of a liner was considered. The liner was accelerated by means of a magnetic field of about IOO kG. Magnetic compression of a liner has obvious advantages over the implosive compression both from an experimental standpoint and from the point of view of the final aim, since in the case of magnetic compression only the part of the D-T mixture which is actually put into the reaction of one experiment is used up (and all the rest is not wasted). In order to make it possible to carry out many cycles of a reaction with the same fraction of the mixture, we considered MHD-compression of a liquid metal liner located on top of a heavier insulating liquid and which is restored by centrifugal forces after each working cycle.

In fact, in our experiments of I965-66 the liner compressed not the plasma but the magnetic field. In this way magnetic fields up to 2 MG and corresponding pressures of several hundred thousands atmospheres were obtained. In the purely thermonuclear aspect this set of works was unsuccessful. It was unsuccessful not in the sense that negative results were obtained, but in the sense that the complexity and the cumbersome size of experiments as well as the defficiency in the staff, that were required to overcome the difficulties which we met, undermined the hope for obtaining conclusive results in forseeable future. And we are very pleased that physicists of other laboratories have returned again in recent years to this question[3].

The next step along the descending curve shown in Fig.I is the attempt to obtain a high pressure plasma within an unbreakable rigid vessel ($P < IO^4$ atm). Such systems were considered in particular by Morozov, Tuck and others[4,5]. Since in a dense plasma in the longitudinal direction neither thermal insulation nor confinement was assumed, the resulting length of the installation was getting to be on the order of several hundred meters. One can agree that a thermonuclear reactor length of several hundred meters is not hopelessly great. More than that, I would say that it is quite appropriate for a thermonuclear power station with power of commercial interest. However, in order to confine a plasma along this whole length, it is necessary to produce a magnetic field of the order of several hundred kilogauss. And when the device has a length of about I km this task becomes really complicated and very expensive. In addition, it is very difficult to model this machine and an <u>immediate</u> start with the construction of a full-scale installation would require exeptional boldness on the part of experimentalists and their financing institutions.

Therefore we considered another possibility which may seem unconventional at the first sight, namely: plasma confinement in the transverse direction not by a magnetic field but by the installation walls. The only role that is left for the magnetic field is to decrease the transverse heat conduction and this requires a considerably smaller magnetic field and the problem of stability is solved in a new way. In this way a system with $\beta \gg 1$ appeared. The technical feasibility of designing a cylinder capable of withstanding internal pressure of tens of thousands of atmospheres as compared to that of designing a solenoid for a corresponding field is clear.

A bit later I will dwell on the physics of the processes occuring in a thermonuclear plasma under the condition of plasma confinement by the walls.

Since a length of I km is still cumbersome even in the case of confinement by the walls, we attempted to find a solution corresponding to an installation with more conventional dimensions. A few years ago we found such a method. The essence of the method is that at the ends of the installation a multiple mirror configuration of a magnetic field is produced[6,7](see Fig.2).

The work on dense plasma confinement by a multiple-mirror magnetic field is carried out in the laboratory headed by Ryutov and Kruglyakov. This work is a little more that half the whole CTR-program of the Institute. The other half involves investigations of the feasibility of thermonuclear reactor based on a mirror machine with the plasma rotating in crossed fields. These investigations are carried out in the laboratory headed by Volosov and Zel'nik. In spite of the

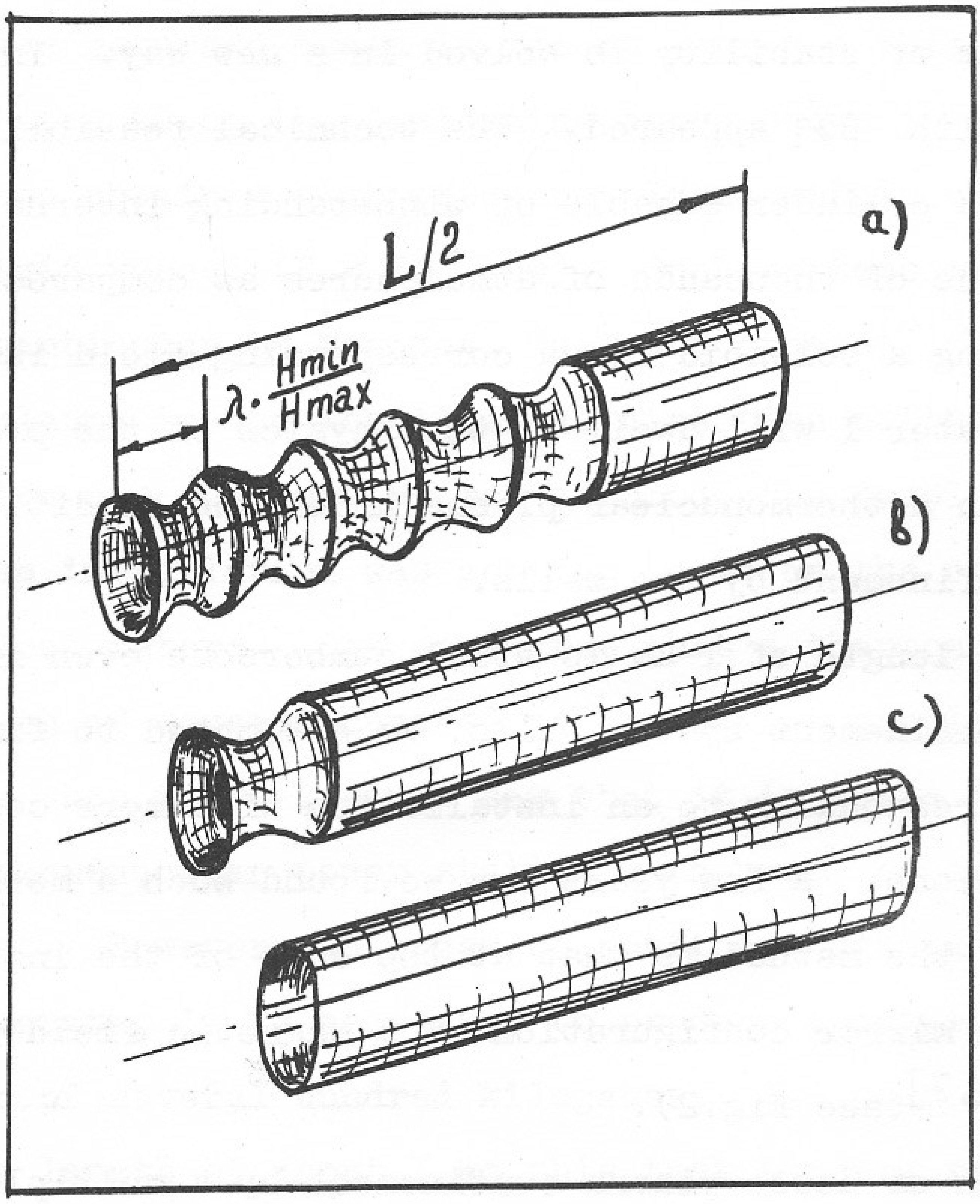

Fig.2. Magnetic surface for: a) corrugated system; b) mirror machine; c) straight system.

the lack of success of the previous experiments on the "Ixion" and "Homopolar"[8,9], carried out at the Los-Alamos Lab, we maintained an interest in this field since we succeeded in getting a stable plasma due to special distribution of the potential[10]. But I am not going to speak about this now, since the topic of my report today concerns a dense plasma.

The essence of the multiple-mirror confinement of a dense plasma is that at the end of the machine the multiple-mirror is installed which sharply decreases the plasma output at a given mirror ratio in comparison to a machine of the same length but having one mirror or no mirror at all.

If one chooses the length of every mirror so as to cause the particles passing through this mirror to be scattered at an angle $\Delta\Theta \sim \sqrt{H_{min}/H_{max}}$ then the particles within the mirror length will be captured. Some subsequent scattering events will cause the particle to leave the trap but with equal probability that the exit will be in the forward or backward direction. Thus, a particle will move diffusively between the mirrors and its lifetime will become proportional to the square of the system length and increased many times in comparison to that of a homogeneous field.

It is interesting to note that the positive effect disappears both at very low and at very high densities of a plasma. At lower density the particle passed through the first mirror will also pass freely through all the others mirrors. And at higher density due to the viscosity decrease the conventional gasdynamic flowing through the corrugated tube will occur which differs only slightly from the flowing through the smooth tube. Thus, we have only specific parameter range where our effect is occured.

From the macroscopic viewpoint the picture looks as follows. At any given moment the plasma is a mixture of two gases: a gas of untrapped particles and a gas of trapped ones. The transport of matter along the axis of a system is naturally provided only by untrapped particles. Due to collisions the utrapped particles transmit their momenta to trapped particles and those in turn transmit them to the magnetic field of the mirror thus, the plasma behaves as if it experiences friction against the magnetic field and the character of the longitudinal motion of a plasma is qualitatively altered. Inertial expansion is transformed into a slow leakage of plasma through the system of mirrors similar to that through a porous medium. The leakage velocity in comparison to that of a homogeneous field is decreased by a factor of $k^2\frac{L}{\lambda}$ where k is the mirror ratio. L/λ appears due to diffusive character of the motion. One power of k appeares due to the fact that the number of untrapped particles is $1/k$ of the total number of particles; the second one due to decreasing in the scattering length with respect to capture into mirror. The general gain is so high that it is impossible to pay no attention to this effect.

From the exact mathematical equations the system of macroscopic equations was analytically obtained by Ryutov and Mirnov (junior). This system of equations takes quantitatively into account all these effects mentioned above as well as the role of the polarization electric field[11, 12]. The results of the investigation of the system confirm the simple estimates I mentioned above.

Despite the self-evident nature of these estimates they were not immediately accepted by the scientific community. We have even heard statements to the effect that our estimates contradict the momentum conservation law. I think that this was the effect of a certain psychological barrier connected with many years of experience in work with plasma, where $\lambda \gg L$. The situation is similar to that of about twenty years ago when great efforts were needed to overcome the opposite barrier for specialists in gasdynamics who joined thermonuclear investigations.

In order to overcome this barrier and to be assured that there were no major mistakes in the theory we have done a model experiment with an alkali plasma[13,14]. This work was presented at this Conference by Kruglyakov in his report.

The idea of the experiment is based on the fact that due to the large Coulomb cross-section in a low-temperature plasma one can manage to satisfy the condition $\lambda < L$ at low values of plasma density and at relatively small dimensions of the device. In the installation shown in Fig.3 of 3 m length the process of diffusive motion of a plasma with an average density of $\sim 10^{10}\,\mathrm{cm}^{-3}$ through a system comprised of 14 mirrors is investigated. The results given in Fig.4 are in full agreement with the theoretical predictions: at the transition from a homogeneous magnetic field to a multiple-mirror field

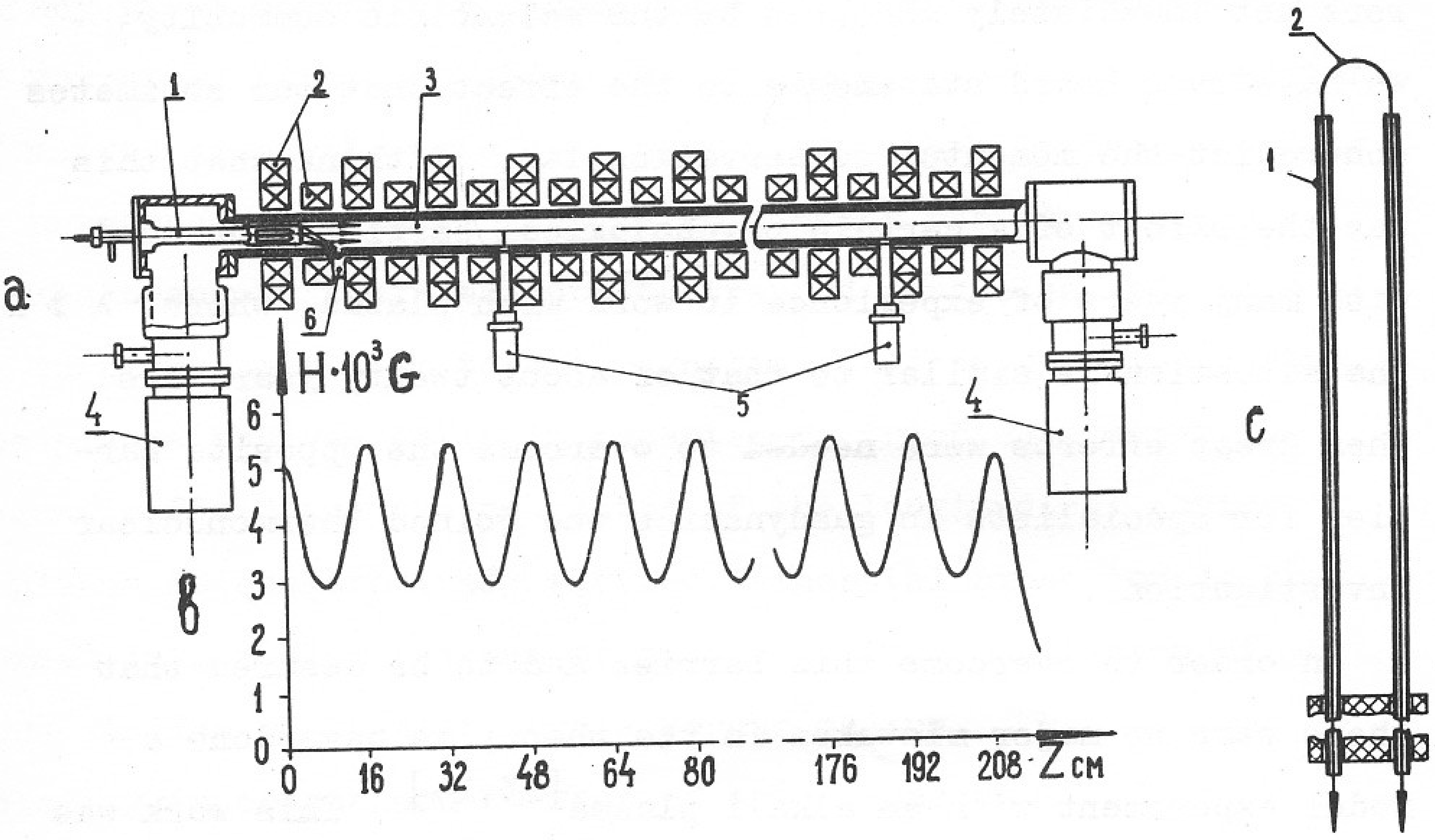

Fig. 3. The model experiment with cesium plasma.
a - diagram of a device: 1-hot plate;
2-coils of magnetic field; 3-vacuum chamber;
4-pumps; 5-probes; 6-cesium vapour inlet.

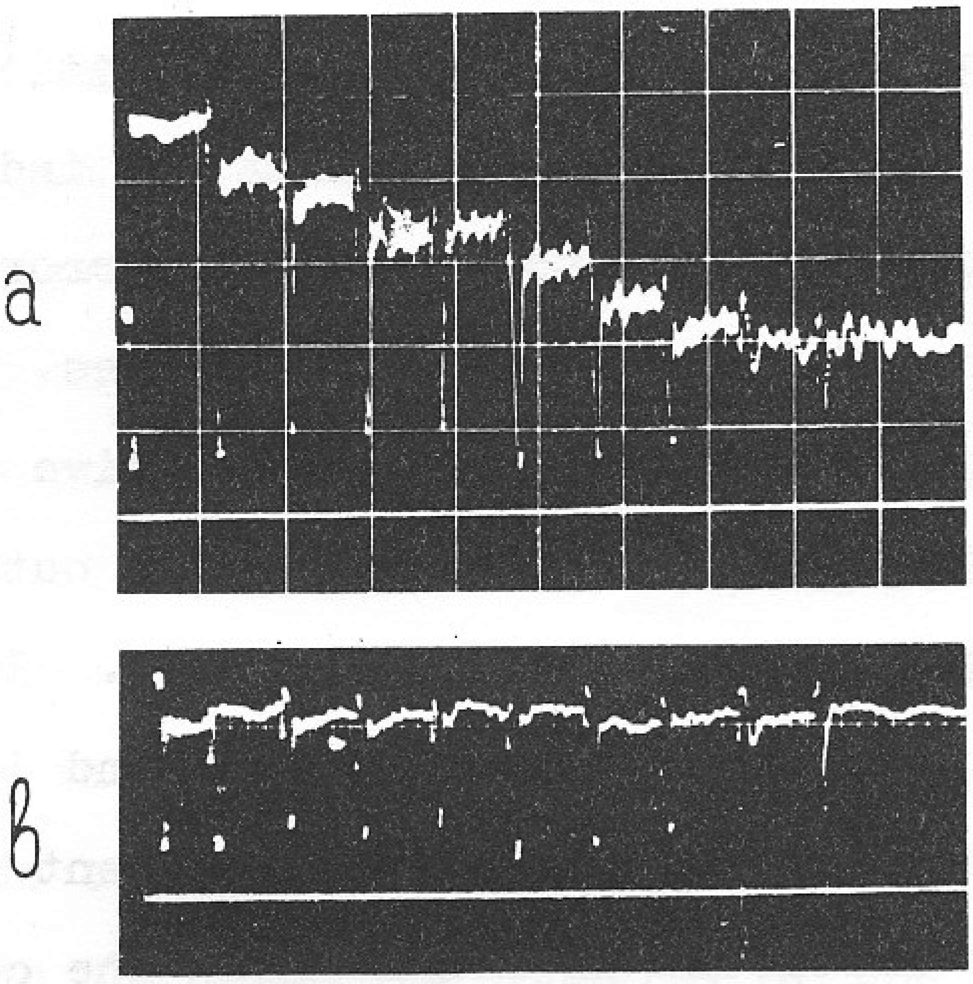

Fig.4. Distribution of plasma density along the system axis: a - in a currugated magnetic field; b - in a uniform magnetic field.
Sensitivity is $3,2\cdot10^{9}\,\mathrm{cm}^{-3}$ per division.

the plasma density near the sources sharply increased, the increase being just the required amount.

Simultaneously with our group and independently the idea of dense plasma in multiple mirror magnetic field was proposed by B.Logan, M.Lieberman, A.Lichtenberg and A.Makijani[I5]. They have done numerical calculations concerning the individual charged particle motion through the multiple-mirror magnetic field in the presence of fixed scattering centres. By this the authors predetermined in advance the diffusive character of the motion and were able in essense to "fish out" only the mirror ratio dependence of the confinement time. This same group has carried out a set of experiments on and installation with 3-5 mirrors and obtained results in agreement with ours[I6].

At present in our Institute we are nearing the complition of an installation for studying multiple-mirror confinement of a hydrogen plasma with a density of $n \sim 10^{15} cm^{-3}$ and a temperature of I00 eV. We have chosen I00 eV since at this temperature value the requirements for the imparted energy became comparatively moderate. Then imparted energy increases as a high power of a temperature and in the thermonuclear region is becoming of the order of tens megajouls. The installation length is 6 m and the average intensity of the magnetic field is up to 20 kG. Plasma will be prepared with the aid of a high current relativistic electron beam.

Now I will return again to the problem of the transverse plasma confinement. As I have already said there are two substantially different possibilities: namely the well known magnetic confinement ($H^2 \ll 8\pi nT$) and plasma confinement by the chamber walls when the magnetic field serves only for suppressing the transverse heat conduction.

The first possibility has been fully studied and I will not dwell on this case. I will only note that in the case of an axially-symmetric multiple-mirror field the plasma is unstable relative to flute perturbations and therefore it proves necessary to use a nonaxial symmetric configurations which provide a magnetic well[I7]. The well known disadvantage of such configuration is the difficulty in getting a high mirror ratio. In spite of this, the strong magnetic field has advantages: since in this field plasma may be removed from the wall it turns out be reasonable to make movable mirrors (Fig.5) which provide the quasistationarity of the longitudinal confinement. The waves shown in the Figure on the left and right hand sides continuously "dash against" the region of homogeneous magnetic field and because of the frictional effect described above between the plasma and magnetic field they provide a constant force which opposes longitudinal expansion of the plasma. The velocity of these waves is not large. It is equal to the plasma flow velocity, i.e. much less than the ion velocities and the technical feasibility of such a moving field is of no difficulty. However, the previously mentioned difficulties in obtaining strong magnetic fields in large volumes justify our paying attention to systems with plasma confinement by the walls.

For simplicity let us consider first the problem of plasma

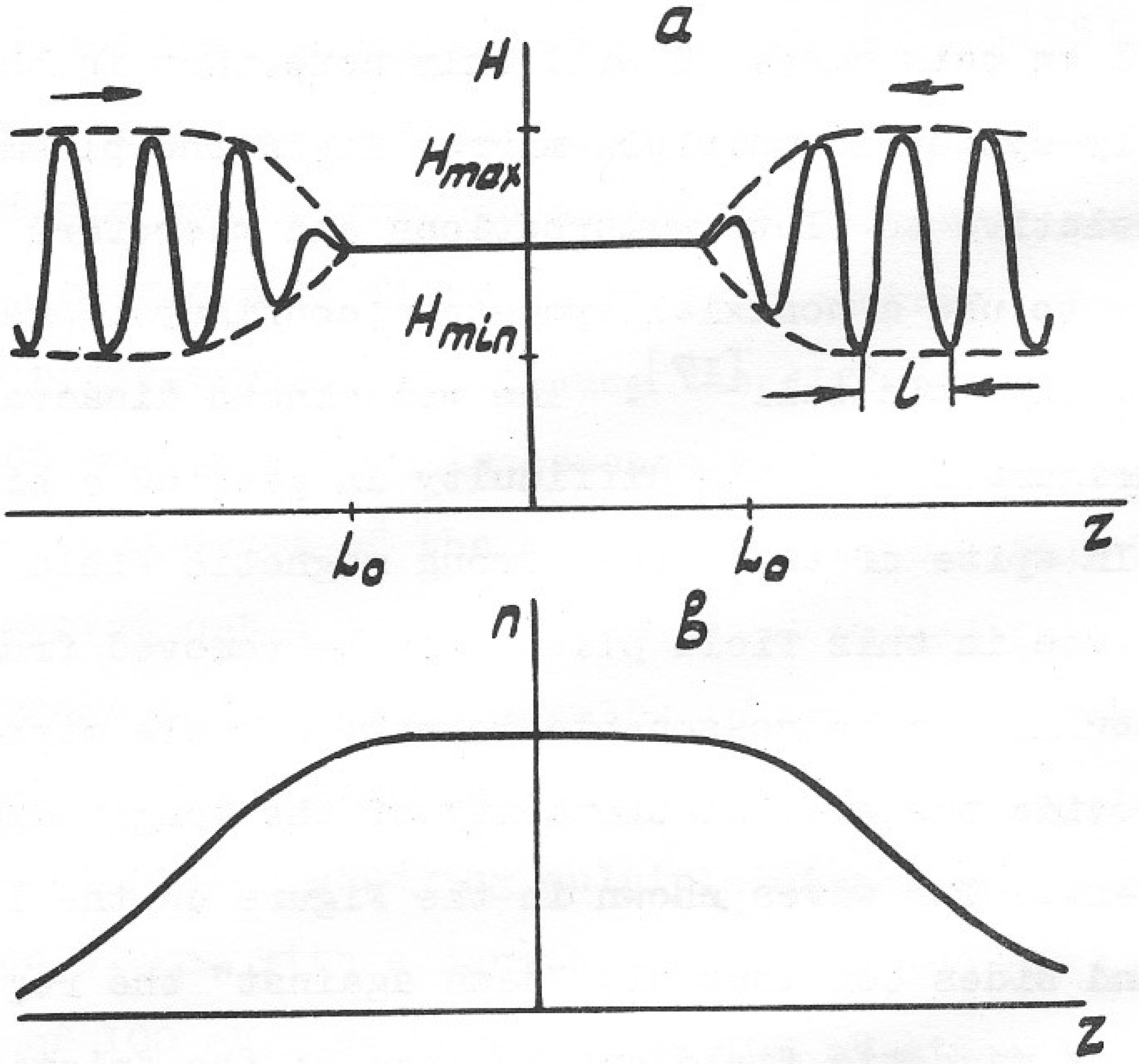

Fig. 5. Stationary confinement of the plasma.

a) Profile of a magnetic field (waves shown in the Figure, on the left and right hand sides, continuously "dash against" the region of homogeneous magnetic field; points-L_0 and L_0 are fixed.

confinement in a cylindrical tube (with no corrugation). Even in this case the physics of nonmagnetic confinement is somewhat more complicated than it seems at first sight. The reason for these complications is connected with bremmstrahlung. Really, the bremmstrahlung power, per unit volume of hot plasma is proportional to $n^2 \cdot \sqrt{T}$ But under the condition $nT \gg H^2/8\pi$ the equilibrium condition has the form $n \cdot T = \text{const}$, i.e. the power of the radiation is altered in proportion to $T^{-3/2}$ and in the layer of cool plasma attached to the chamber walls the radiation power becomes very large. The radiation is so strong that even the weakened magnetic field does not provide the flux required for the compensation of radiation losses. This has predetermined our lack of success in searching for stationary solutions in the works during 1967-69[18,19]. Recently quasistationary solutions were found by Chebotaev, Ryutov, Spector and Vekstein that were presented at the Conference by Ryutov. The meaning of this is the following:

While they are cooling, the external layers of plasma are pressed against the wall and are in some sense "eaten up" by the wall. As a result there develops a plasma flow toward the wall. The plasma flow velocity is determined by the velocity of the plasma "eating up" which in turn depends upon the heat conduction processes and the radiation in the layer near the wall. In particular, the presence of plasma flow causes the lifetime of plasma to increase not as R^2 as it does with ordinary heat conduction but only linearly with R.

At the same time the calculations showed that the lifetime of a plasma turns out to be sufficient enough for obtaining positive energy output even in the case of very modest transverse dimensions of the reactor and in the case of comparatively low fields ($R \sim 5$ cm and $H = 2 \cdot 10^4$G in the case of classical heat conduction and $H = 10^5$G in the case of Bohm heat conduction). I would also like to underline again that $\beta \gg 1$ and that energy losses in the coils even when H = 100 kG can be neglected.

In the course of calculations the distributions of T and H were obtained along the installation radius at various moments in time. A typical example of the corresponding results is shown in Fig.6. One can easily see the layer near the wall where the density is two orders of magnitude higher than that in the centre.

It is necessary to take into account the corrugation because of two new problems. First is the problem of the deformation of force lines during the plasma expansion. In order that the desired magnetic field configuration be preserved in a plasma with $\beta > 1$, it is necessary to have the wall conductivity high enough (to prevent the penetration of the magnetic field through the wall during the processes of deformation and to maintain the shape of the field lines at least near the wall). Under these conditions the various alterations of the radial profile of plasma density during the processes of heating and cooling cannot lead to substantial of the magnetic field profile in the main part of the trap volume. Here the field intensity may be altered by not more than on amount of order unity. Numerical calculations

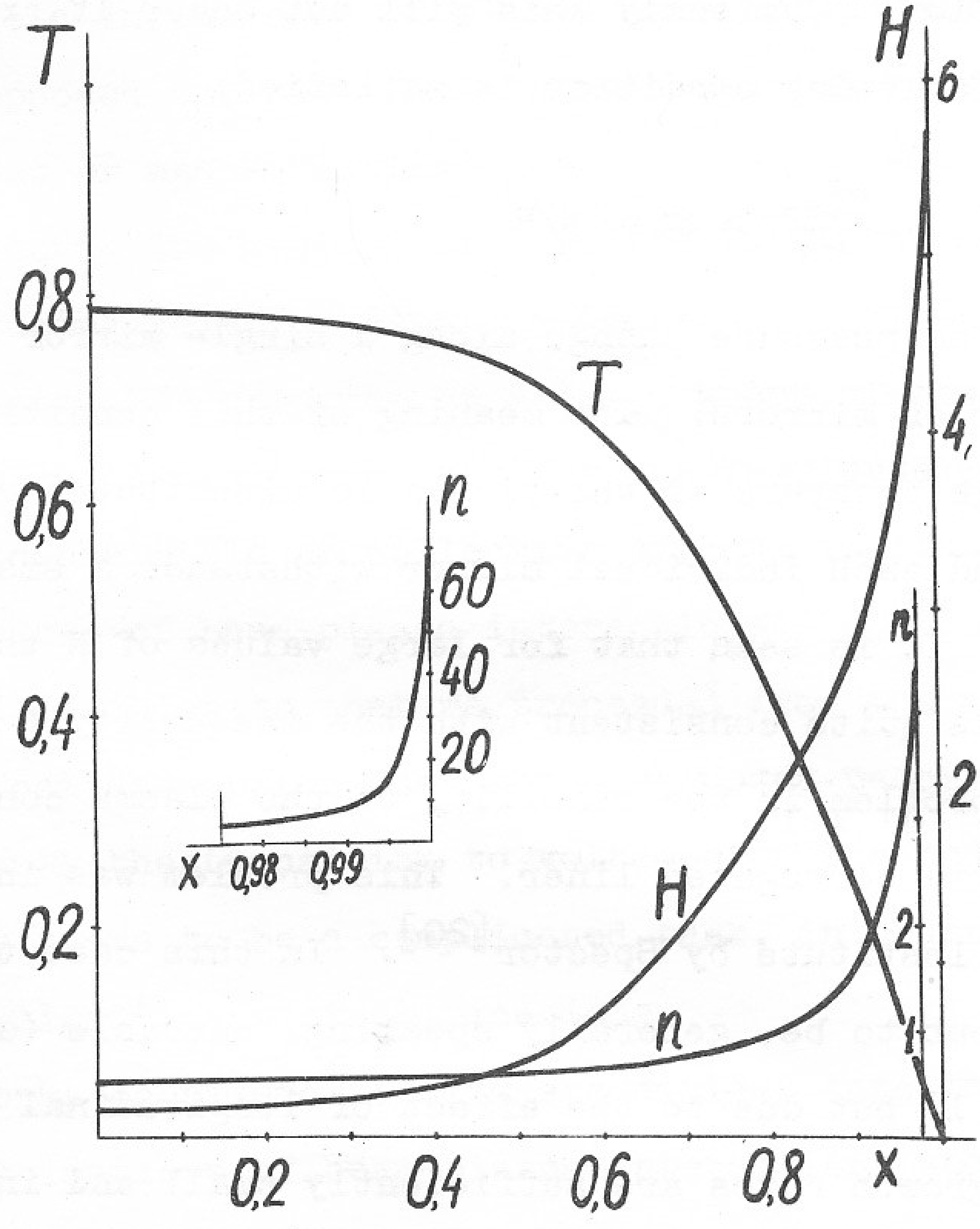

Fig. 6. Radial distributions of concentration n, temperature T and magnetic field H (dimensionless units) at the moment of time when the temperature in the centre is maximum.

confirm this conclusion.

More substantial may be the field line deformations connected with the longitudinal pressure gradient. If the magnetic field is too weak, it may be smashed and carried away by the plasma flux. Obviously this will not occur if, roughly speaking, the following condition is satisfied:

$$\frac{H^2_{max}}{8\pi} > \delta p \sim p/N$$

where δp is the pressure change along a single mirror and N is the number of mirrors. The meaning of this condition is that the high pressure of the plasma is distributed among many mirrors and each individual mirror withstands a small pressure drop. It is seen that for large values of N the last equation is quite consistent with the inequality $\beta \gg 1$.

The second problem is the stability of the plasma confinement by the rigid corrugated liner. This problem was investigated at our Institute by Spector[20]. In this case the plasma turned out to be, generally speaking, unstable (as in the case of $\beta < 1$) but due to the effect of longitudinal ion viscosity the growth rates are sufficiently small and in the case of $\beta > N^2/2\Lambda$ there is no time for the instability to develop during the time of plasma confinement (where Λ is logarithm of the ratio of the allowed fluctuation amplitude to the initial amplitude). In the task under consideration in addition to the problem of plasma confinement and plasma thermal isolation the problem of plasma heating is also of decisive significance. Of all the possible methods of plasma heating (with the configuration taken) we have chosen the method of plasma heating by a powerful relativistic electron beam. For this choice there were the following grounds.

First. The absence of substantial distortions of the magnetic field in the case of plasma heating by relativistic beams (as opposed to, say, Joule plasma heating by a longitudinal current or shock heating).

Second. The availability at the Institute of experience in producing powerful electron beams.

Third. The presence of a large group of physicists (theorists and experimentalists) at our Institute whose interests lay in the field of collective effects in plasmas and the processes of beam-plasma interactions.

In addition to that we proceeded from the general philosophical assumption that the high power requires high voltage. Although the transition to voltages of the order of a million volts seems to be a complicated task, in practice it will give significant simplifications.

Works on plasma heating are divided into two parts: the investigations of beam-plasma interactions and the production of the corresponding electron beam sources.

First experiments on the relativistic beam-plasma interactions have been carried out in 1970-71 at our Institute by the Kurtmullaev group[21]. These experiments showed that in the case of plasma density of $\sim 10^{12} cm^{-3}$ the beam can impart to plasma 10-15 per cent of its initial energy. The energy transfer from beam to plasma cannot be connected with Coulomb collisions since the Coulomb mean free paths of the beam particles and the plasma exceed the device length by several orders of magnitude. The only reasonable explanation is the excitation of microscopic fluctuations in the plasma with the subsequent scattering of the beam on these fluctuations. A corresponding theory was made by Breizman and Ryutov[21-23]. This theory enabled the qualitative understanding of many experimental results. Recent results were reported in the paper presented by Breizman at this Conference. In new experiments carried out at our Institute during the last two years[24] also reported here by Koydan we have obtained a significant advance to higher plasma densities: effective beam-plasma interaction was observed for densities $n \sim 3 \cdot 10^{14} cm^{-3}$.

Extrapolation of the data, taking into account the available experimental and theoretical findings, makes us believe that the problem of plasma heating up to thermonuclear temperatures will be overcome in case when we solve the problem of producing beams with voltages of $\sim 10^6 V$, total currents $\sim 10^6 A$ and lifetimes of $\sim 10^{-4} sec$.

The second part of our program is connected with the production of powerful beams. First beams with currents up to 30 kA with the particle energies up to 4 MeV were obtained at our Institute in 1969 with aid of a Tesla transformer in compressed gas. Financial means do not allow us to construct installation as big as "Hermes" or "Aurora" and therefore we keep our attention on the design of relatively small low impedance lines with insulation provided by super pure water. This work was set up in 1969. Now we have at our disposal a water line of 2 m length and 40 cm in diameter with the impedance 2,3 Ω. The current obtained is up to 110 kA with 700 keV particle energy.

The strengthening of the water gap due to the production of conducting diffusive layers in the vicinity of the electrode surface was recently investigated by Ryutov[25]. The results obtained give us hope of success in raising the break-down intensity of electric field by a factor of 4. This will permit a substantial decrease in the resistance of the water line.

In conclusion I would like to draw your attention to what would be a thermonuclear reactor designed on the principles I have previously described. The reactor is a strong conductive shell (see Fig.7) of about 10 m length with an internal diameter of about 10 cm; the average intensity of the magnetic field is 10^5G; and the mirror ratio is 3. The number of mirrors is about ten on both sides of the shell. Plasma with a density of about 10^{18}cm^{-3} is prepared in the central part of the device with the aid of an electron beam which is injected from the one end of the shell. The thermal energy of the plasma is about 10^8J; and the lifetime of the plasma of about 10^{-4}sec is sufficient to obtain a positive energy output.

I do not dwell on the engineering problems since in general they are common to the other systems using dense plasmas (like θ pinch with a liner) which are being

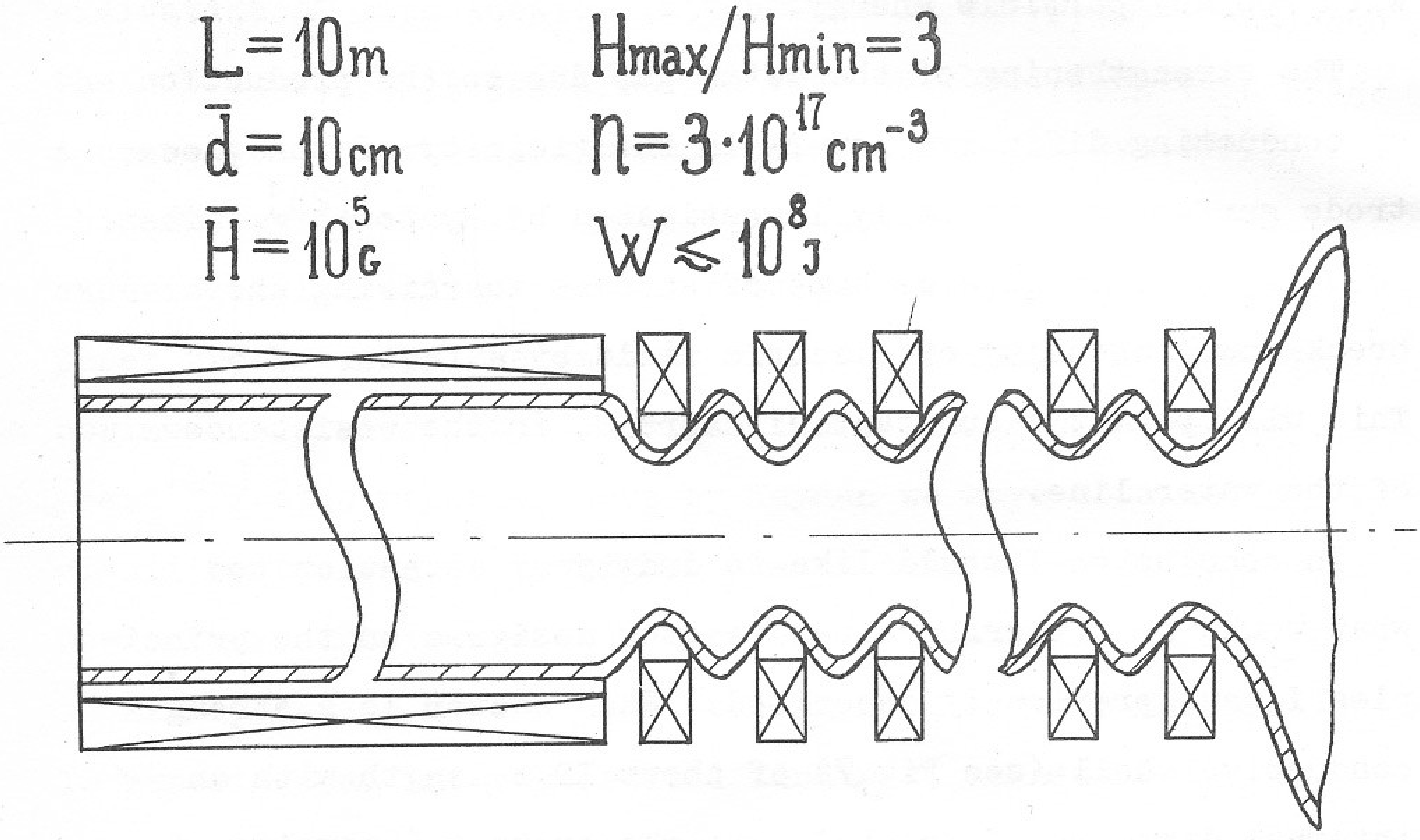

Fig. 7. The diagram of hypothetical thermonuclear reactor with the multiple-mirror magnetic field (Bohm diffusion).

discussed at this Conference.

Of course, the design of such a system under the conditions of the successful solutions of all the principal problems is still a very complicated task. Nevertheless these difficulties are on the order of the aim advanced and lie within the limits of modern technological potential.

I would like to return again to that viewpoint I have already expressed at the closing of the Conference which was held in Novosibirsk in 1968, namely that the data accumulated in plasma physics investigations are enough to start on the realistic design of thermonuclear systems.

We have undertaken a reorganization at our Institute, having left only the plasma physics investigations which are directly connected with the design of thermonuclear machines. I was very pleased to be convinced here at the Conference that this my point of view became to be well approved and now it is not regarded as indecent to talk about realistic thermonuclear systems.

REFERENCES

1. Alikhanov S.G., Budker G.I., Komin A.V., Polyakov V.A., Estrin B.S., Proceedings 7th Intern. Conf. on Ioniz. Events in Gases, Beograd, 1966.
2. Linhart J.G., Proc. Conf. MGauss Field-Gener., Euratom Publ. EUR 2750e (1965), 387.
3. Boris J.P., Shanny R.A., Vth European Conf. on Contr. Nuclear Fus. and Plasma Phys., Grenoble,1972,V.1.,p.20.
4. Morozov A.I., Report CN-24/G-1 on 3rd Intern. Conf. on Plasma Physics and Controlled Thermonuclear Fusion, Novosibirsk, 1968.
5. Tuck J.L., Report CN-24/K-5 on 3rd Intern Conf. on Plasma Physics and Controlled Thermonuclear Fusion , Novosibirsk, 1968.
6. Budker G.I., Mirnov V.V., Ryutov D.D., JETP Letters 14, 320, 1971.
7. Budker G.I., Mirnov V.V., Ryutov D.D., Proc. Intern. Conf. on Plasma Theory, Kiev, 1971, p.145.
8. Baker D., Hammel J., Ribe F., Phys. Fl., 4, 1534 (1961).
9. Halbach K., Baker W., Layman R., Phys. Fl., 5, 1482(1962).
10. Konstantinov S., Miskin O., Sorokin A., Zel'nik F., JTP, 41, 2527 (1971).
11. Mirnov V.V., Ryutov D.D., Nucl. Fus., 12, 627, 1972.
12. Mirnov V.V., Ryutov D.D., Proc. 5th Europ. Conf. on Plasma Physics and Controlled Thermonuclear Fusion, Grenoble, 1972, p.100.
13. Budker G.I., Danilov V.V., Kruglyakov E.P., Ryutov D.D., Shun'ko E.V., JETP, 65, 320, 1973.
14. Budker G.I., Danilov V.V., Kruglyakov E.P., Ryutov D.D., Shun'ko E.V., JETP, 65, 562, 1973.

15. Grant Logan B., Lichtenberg A.J., Lieberman M.A., Makhijani A., Phys. Rev. Lett., 28, 144 (1972).

16. Grant Logan B., Brown I.G., Lieberman M.A., Lichtenberg A.J., Phys. Rev. Lett. 29, 1435 (1972).

17. Furth H.P., Rosenbluth M.N., Phys. Fluids, 7,764(1964).

18. Alikhanov S.G., Kichigin G.N., Konkashbaev I.K., Preprint N 140, Novosibirsk, Inst. of Nucl. Phys., 1967.

19. Alikhanov S.G., Konkashbaev I.K., Chebotaev P.Z., Preprint N309, Novosibirsk, Inst. of Nucl. Phys., 1969; Nuclear Fusion, 10, 13, 1970.

20. Spector M.D., PMTF (Journal of Applied Mathematics and Technical Physics), N 6 , 1974.

21. Altinzev A.T., Breizman B.N., Es'kov A.G., Zolotovsky O.A., Koroteev V.I., Kurtmullaev R.Kh., Masalov V.L., Ryutov D.D., Semenov V.N., Proc. IV Intern. Conf. on Plasma Phys. and Nucl. Fus., V.2, p.309, 1971.

22. Breizman B.N., Ryutov D.D., JETP, 60, 409, 1971.

23. Breizman B.N., Ryutov D.D., Chebotaev P.Z., JETP, 62, 1409, 1972.

24. Koydan V.S., Lagunov V.M., Lukyanov V.N., Mekler K.I., Sobolev O.P., Proc. V Europ. Conf. on Plasma Phys, and Contr. Nucl. Fus., Grenoble, 1972, p.161.

25. Ryutov D.D., PMTF (Juorn. of Appl. Math. and Techn. Phys.), 1972, N 4, p.186.

Ответственный за выпуск С.Н.РОДИОНОВ
Подписано к печати 17.XII-73 г. МН 17065
Усл. 0,9 печ.л., тираж 200 экз. Бесплатно.
Заказ № 111.

Отпечатано на ротапринте в ИЯФ СО АН СССР