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ATTRACTIVE CHARACTERISTICS OF MIRRORS

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ABSTRACT

A summary of the attractive characteristics of mirror devices is presented. Recent progress in development of axisymmetric mirror devices is described. Potentialities of mirrors as a basis for D³He fusion power generators and high-flux neutron sources for fusion material tests are discussed.

1. INTRODUCTION

Mirror devices possess a number of important attractive characteristics (see 1,2):

- They can operate at high beta without loss of equilibrium and stability;
- The possibility of steady state operation is an intrinsic property of mirror devices;
- Mirrors do not suffer from catastrophic instabilities associated with the release of the magnetic energy of axial currents (as occurs in tokamak disruptions);
- In contrast to closed systems, mirrors have a natural channel for ash and impurity removal (through the mirror throats);
- The main energy-releasing region of a mirror power plant will be a region within a simple solenoid with a homogeneous magnetic field: this is a very important engineering advantage;
- Open-ended systems are well suited for the efficient utilization of that part of the fusion energy which is released in the form of charged particles;
- Thermal and particle wall loading in the plasma dumps can be made much lower than that encountered in toroidal systems;
- Mirror devices are very flexible in their design from both engineering and physics viewpoints;

- Mirror devices constitute virtually the only class of magnetic confinement systems that are topologically different from tokamaks; this circumstance opens up new dimensions in the designing the fusion devices.

The rest of this paper contains a very brief description of a few of the recent developments in the field of mirror research. Detailed information on the progress made before 1987 can be found in survey articles ^{3,4}. The present status of mirror fusion is described in some detail in recent articles ^{5,6}.

II. DEVELOPMENT OF AXISYMMETRIC MIRROR DEVICES

A very desirable property of mirror devices is their adaptability to axial symmetry: This property eliminates problems of neoclassical and resonant transport, provides more or less automatically conditions for reaching theoretically possible values of $\beta \approx 1$ without the risk of encountering the ballooning instability limit, allows one to considerably increase the mirror magnetic field as compared to the non-axisymmetric mirrors, and makes the whole design much simpler and more reliable. However, it is well known that, if no special measures are taken, axisymmetric mirrors are unstable with respect to low-order flute instability.

During the past decade, an approach which allows the possibility of "passively" maintaining MHD stability has been suggested and tested. By a "passive" stabilization we mean an approach which relies only on the properties of a basic plasma configuration itself, without resorting to the use of any specific external agents. By "external agents" we mean, for example, resonant RF fields (as in the method of ponderomotive stabilization),

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or feedback control systems (as in the method of a feedback stabilization), or high power microwave sources that maintain the presence of high beta electron rings as employed in some other approaches.

Though "active" approaches have interesting potentialities, "passive" methods are still preferable since - if successful - they are simpler and work in a broader range of plasma parameters.

One such "passive" approach was quite successfully realized experimentally in the axisymmetric gas-dynamic trap at Novosibirsk.

The Gas-Dynamic Trap⁷ is a version of a standard simple mirror whose characteristic features are: i) a very high mirror ratio, R , in the range of a few tens; ii) a relatively large length, L , exceeding an effective mean free path, λ/R with respect to scattering into the loss cone. Under these conditions, the plasma distribution functions are almost Maxwellian in the device, and plasma losses through the ends are governed by simple gas-dynamic equations, whence the name of the device. An attractive feature of this device is that its MHD-stability can be assured even in the framework of a fully axisymmetric system. What makes this device MHD stable is the presence of a non-negligible amount of plasma in the regions beyond the mirror throats, i.e., in the regions where the magnetic field has a favorable curvature.

An experimental device of this type, called GDT, is in operation at the Novosibirsk Institute. This device, because of its remarkably simple geometry and very reliable performance, has proved to be a very convenient tool for studying various aspects of MHD stability⁸. A marked characteristic of this device is the dependence of the plasma confinement time on the mirror ratio (left panel on Fig.1): At mirror ratios below 30-35, confinement time is roughly proportional to the mirror ratio; at higher mirror ratios, a considerable decrease of the confinement time occurs. A number of diagnostics showed that at $R > 40$ the plasma decay is accompanied by the excitation of large amplitude flute-like perturbations; at $R < 40$ such perturbations do

not grow with respect to their initial values (and, instead, are somewhat subject to decay).

The interpretation of this phenomenon is as follows: At large mirror ratios, because of reduced axial losses, there is not enough plasma in the regions of favorable curvature beyond the mirrors to stabilize the unfavorable contribution of the central part. The transitional value of R found experimentally agrees qualitatively with predictions of MHD-stability analysis. Even more convincing is the result of studying the effect of intentional addition of regions of unfavorable curvature in the solenoidal part of the device (this is easily accomplished by means of a short trim coil producing a magnetic field in the direction opposite to the main field): Introduction of this "bump" shifts the stability boundary in agreement with MHD-stability theory (central panel on Fig.1). The change of the field line curvature in the end-tanks from favorable to unfavorable immediately makes the system unstable (right panel on Fig.1). All these experiments very convincingly - in an almost "textbook" fashion - show that a fully axisymmetric mirror system can indeed be made MHD stable by very simple means.

In addition to that demonstration, the GDT experiments have clearly shown that finite-orbit effects enter the problem exactly in a theoretically predicted manner: When the finite-orbit parameter is large, only the $m=1$ mode survives, while at small values of this parameter a broad spectrum of m values is excited (of course, when operating in an unstable regime). The ease of varying the FLR parameter, $\Gamma a^2/\rho_i v_{Ti}$, by a factor of 10 is, again, related to the simplicity of the geometry and the flexibility of operation that follows from it. (In this "control parameter" for the FLR stabilization, Γ is the growth rate of the flute perturbations, a is the plasma radius, ρ_i is the ion gyroradius, and v_{Ti} is the ion thermal velocity.)

III. CROSS-FIELD PLASMA LOSSES

A very attractive feature of axisymmetric mirror devices is that substantial cross-field transport in these devices cannot

arise unless turbulence is present. This circumstance arises because axial symmetry eliminates any contribution of the so-called neoclassical transport, a transport rate that can be quite large in non-axisymmetric devices. Therefore, axisymmetric mirror systems provide very favorable conditions for assessing the issues of anomalous cross-field transport (recalling that classical radial transport in axisymmetric systems is negligibly small under all realistic plasma conditions.).

Estimates of the energy confinement time in the Gas-Dynamics-Trap can be made, based on the results published in a recent article⁸. Direct bolometric measurements of the radial losses to the limiter give for the radial power flux the value of 30 kW, while the plasma energy content is 60 J. This gives for the radial confinement time a value of 2 ms. For comparison, let us then evaluate the Bohm confinement time, using the relationship

$$\tau_{\text{Bohm}} = a^2 / 6D_{\text{Bohm}}, \quad (1)$$

where $D_{\text{Bohm}} = cT/16eB$. Taking the plasma radius $a=10$ cm and, $B=0.2$ T, $T_i=50$ eV, $T_e=300$ eV, one obtains in the same manner as before that τ_{Bohm} lies between 0.02 ms (if one evaluates it for the ion temperature) and 0.1 ms (if one evaluates it for the electron temperature). Therefore, the Bohm confinement time is at least 20 times shorter than the experimentally observed energy confinement time.

Similar conclusions can be drawn regarding the radial plasma confinement in the central cell of GAMMA-10 (see⁹). This cell is axisymmetric and therefore does not suffer from neoclassical and resonant transport. The measured radial confinement time is more than order of magnitude larger than the calculated Bohm confinement time.

IV. PROSPECTS FOR MIRROR-BASED D³He FUSION POWER SYSTEMS

Mirror systems have always been considered as attractive candidates for fusion power systems burning D³He fuel (see, e.g.

10). The reasons for this are two-fold: First, mirror systems can operate at high values of β (approaching unity), taking advantage of the fact that the power density of fusion reactions scales as β^2 . This circumstance becomes crucial when fuels with a relatively small reactivity are considered. Second, almost all fusion energy in the D³He mixture is released in the form of charged particles, and the adaptability of mirror systems for the inclusion of direct energy converters in the end-tanks then comes to the fore.

The "traditional" concepts of D³He mirror reactors, such as the one described in¹⁰, are based on the assumption that both reacting components have the same temperature. As the D³He reactivity becomes significant only at ion temperatures in the range of 100 keV, this circumstance makes it difficult to keep neutron production from parasitic DD reactions at a level lower than a few percent of the total fusion power. In the papers^{2,11} it was noted that the physics of the open-ended systems makes it possible to keep the deuterium temperature well below the energy of the ³He ions, thereby maintaining a high rate of the D³He reactions while at the same time exponentially suppressing the rate of the side DD reactions. By using the special technique of "drift pumping"¹², one can keep the deuterium temperature as low as 5 keV, thereby reducing the neutron yield to as low a level as 10^{-5} of the fusion power¹³. The price paid for this extremely low radioactivity is a relatively low value of Q , barely approaching unity. Therefore, the practicality of this virtually "non-radioactive" version of a mirror fusion power system strongly depends on the development of high-efficiency direct energy converters and injectors of ³He atoms.

V. MIRROR-TYPE NEUTRON SOURCES

There exists a potential near-term application of mirror devices as a source of 14 MeV neutrons for material testing and for the evaluation of sub-components of future fusion power systems. Such a source would have two important advantages: 1) it would produce

neutrons with an energy spectrum essentially identical to that of a fusion power plant; 2) it could provide a fluence of "primary" 14 MeV neutrons in the range 10 MW/m², while consuming a very small amount of tritium (in the range of 0.4-1 kg) in reaching this fluence. The first property makes it more attractive than accelerator-based sources. These sources, in addition to 14 MeV neutrons, generate considerable amounts of neutrons with much higher energies and, thereby, may give strongly distorted results with regard to transmutations. The second property listed makes such a source preferable to tokamak-based neutron sources, which can reach the same fluence only at the expense of consuming tens of kilograms of tritium (which may prove to be unavailable in such amounts).

Several proposals for mirror-based neutron sources have been made during the recent years (see surveys^{14,15}). These proposals rely on the same data base regarding the plasma physics involved but are somewhat different in their design. We give here some details of the Novosibirsk proposal of such a source, as it has very attractive design features stemming from its axial symmetry. This source uses the GDT concept. Its schematic is shown in Fig.2. The plasma is two-component in nature: a relatively cold deuterium part and a fast deuterium-tritium part. The cold component serves two purposes: it provides an efficient trapping of the neutral beams and it stabilizes both gross MHD and microinstabilities.

The hot component produces neutrons from the collisions between fast deuterons and tritons; the contribution of reactions between cold deuterons and fast tritons is negligible. The fast tritons are injected at 80 keV and at an angle of only 30° to the magnetic axis. The plasma electrons are relatively cold, approximately 0.8 keV. Because of that circumstance the deceleration of the fast deuterons and tritons via electron drag strongly dominates over the scattering of these ions on the cold deuterons. Accordingly, the angular distribution of the fast ions remains strongly peaked around the injection angle, and the axial density distribution has very high and narrow maxima near the turning points. It is just these

zones that serve as the source of the DT neutrons, while the number of neutrons produced in the rest of the device is very small. This fact, in turn, means that, except for two narrow test-zones, all the plasma-facing components will not suffer from strong neutron damage and will survive, without replacement, throughout the 10 year period of operation. Therefore the maintenance problems in this design are much easier to contemplate than for essentially any other plasma-type neutron source (where the entire first wall will be subject to at least 1 MW/m² neutron flux).

MHD stability is provided by the flow of the cold plasma escaping through the mirrors, since the field line curvature beyond the mirror throats is favorable (cf. Sec.II of the present paper). Microstability of the fast sloshing ions was a subject of special experiments on the GDT facility at Novosibirsk. The hydrogen neutral beams were injected at an angle of 45 degrees with respect to the device axis and the injection energy was 20 keV. As the electron temperature in the device was relatively low, of the order of 50 eV, the main classical loss mechanism for the sloshing ions was electron drag. The angular distribution of the sloshing ions was found to remain very narrow in the course of deceleration¹⁷ - as it should have for a purely classical relationship between electron drag and angular scattering on the plasma ions. In fact, there was very good agreement between the measured angular distribution and one calculated on the basis of classical processes only.

The facility is a driven one, as it has a relatively low Q (in the range of a few percent). The plasma-physics parameters of the facility are as follows:

- Mirror-to-mirror length 11.m
- Plasma diameter in the midplane 14 cm
- Mirror magnetic field 28 T
- Magnetic field in the midplane 1.8 T
- Cold plasma density in the midplane $2 \cdot 10^{14} \text{cm}^{-3}$
- Sloshing ion density in the turning points $4 \cdot 10^{14} \text{cm}^{-3}$
- Electron temperature 0.8 keV

VI.CONCLUSION

The attractive characteristics of mirror-based systems listed in the Introduction should not be overlooked when undertaking long-term planning of fusion research. Potentially, the axisymmetric mirror configuration looks extremely attractive as a basis for fusion power generation. A significant increase of the Q values of such systems may occur if small-bore high field (60-80T) mirror coils were to be developed.

Mirror machines have special features that make them a very attractive candidate for developing future D³He fusion power systems: The flexibility of their governing physics allows efficient control over the distribution functions of plasma components. In particular, deuterium temperatures can be kept very low, thus exponentially suppressing neutron yield from parasitic DD reactions. Also of importance is the convenience with which direct energy conversion systems could be incorporated into the overall design of mirror fusion power systems.

In the near future mirror systems can be utilized as high-flux neutron sources for fusion material tests. The design of such a neutron source could be based on well-established theoretical results and an extensive corroborative experimental data base.

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GAS-DYNAMIC TRAP

CONTROL OF MHD STABILITY

Fig.1 MHD stability in the Gas-Dynamics Trap (after A.A.Ivanov et al⁸)

Fig.2 Schematic of the GDT based neutron source (after D.D.Ryutov¹⁴)