CONCEPT OF FUSION REACTOR BASED ON MULTIPLE-MIRROR TRAP

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The paper summarizes recent advances in physics of multiple-mirror confinement. GOL-3 in Novosibirsk is the only existing large-scale device of this type. Achieved plasma parameters are: $n \sim 10^{21}$ m^{-3}, $T \sim 2$ *keV,* $\tau_E \sim 1$ *ms. Intense experimental and theoretical studies revealed several new collective phenomena that radically change plasma behavior in the trap as compared to simple classical theory. These phenomena are intrinsically linked to the second major feature of GOL-3, namely, fast plasma heating by a high-power relativistic electron beam. Collective beam-plasma interaction delivers energy to plasma through strong Langmuir turbulence and changes other plasma properties as well. In particular, the turbulent plasma in GOL-3 features suppressed axial heat transport, fast collective heating of ions, limitation of axial particle loss, and MHD stabilization by a magnetic shear. Mentioned phenomena greatly improve prospects of multiple-mirror confinement for fusion reactor applications. An outlook for possible fusion-scale device is presented.*

I. INTRODUCTION

Early fusion history brought a vast collection of confinement schemes, some of which were successful and the rest was rejected. Magnetic mirrors invented almost simultaneously by G. I. Budker in USSR and R. Post in US in early 1950s were popular in fusion research at that time. Unfortunately, mirror machines suffered from large axial heat losses, so this branch of fusion research gradually shrank despite the fact that world's first real 10-keV plasma was achieved in 2XIIB baseball trap. Attempts to improve confinement in open systems resulted in invention of several advanced mirror confinement schemes including tandem mirrors, multiple-mirror confinement, rotating plasma devices, gas-dynamic confinement, etc.

Two teams almost independently introduced the idea of multiple-mirror confinement.[1,2] This approach utilizes effective "friction force" between the magnetic field and plasma particles that arises in the corrugated magnetic field. As a result, plasma axial expansion becomes diffusion-like. Since $\beta >> 1$ is required in this scheme, transverse plasma equilibrium and stability can be provided by a rigid conducting wall. The main advantages of the multi-mirror-based fusion reactor are technical simplicity, absence of density and β limits. First tabletop proof-of-principle experiments followed soon.[3,4] Further advances that were mainly in theory and were summarized in Ref. [5].

The next period of progress in physics of multiple-mirror confinement started following commissioning of GOL-3 in Novosibirsk which is the only existing trap of this type.[6] This device was built for verification of theory of multiple-mirror confinement at much larger scales and temperatures as compared to first experiments. Several new physical phenomena that determine plasma behavior in the trap were discovered. Main conclusion from data is that plasma heating and confinement in the multiple-mirror trap are of essentially turbulent nature in contrast to the original theory based on classical binary collisions. Collective relaxation of a high-power electron beam leads not only to effective plasma heating but also to 1000-fold turbulent suppression of axial heat losses during the beam pulse. The turbulent beam relaxation also creates sheared magnetic field that provides MHD stability. New class of plasma oscillations in the cells of multiple-mirror trap is observed. The oscillations are identified as bounce instability that can decrease axial particle losses.

These new experimental findings will be briefly reviewed in the paper. Then a new look to a fusion-scale device that incorporates mentioned new physics will be presented. Effective plasma confinement in a multiple mirror can be achieved at more reasonable plasma parameters as compared to initial proposals.

II. MULTIPLE-MIRROR CONFINEMENT

The idea of multiple-mirror confinement is quite simple. In a corrugated (periodically-modulated) magnetic field with plasma of high enough density collisions provide effective momentum exchange between populations of transiting and locally-trapped particles. This exchange acts as an effective friction force that reduces expansion rate of the plasma along the magnetic field. Corrugated magnetic field acts as a medium which receives momentum from expanding plasma and slows it down. Optimal conditions for the confinement are achieved if the mean free path of ions, λ_i, is much shorter than the device length L, but is comparable with the corrugation scale length l (see Fig. 1). Then the transiting ions are moving via random walk between corrugation cells rather than directly escape the trap. The expansion becomes a diffusion-like process. A simple estimate of the confinement time is

$$\tau \sim R^2 \frac{L^2}{\lambda_i v_{Ti}} = R^2 \frac{L}{\lambda_i} \tau_0 \gg \tau_0 ,$$

where $R = B_{\max} / B_{\min}$ is the mirror ratio, and $\tau_0 = L / v_{Ti}$ is the plasma lifetime in a simple solenoid. Figure of merit $R^2 L/\lambda_i$ can be made large enough for a competitive fusion reactor system.

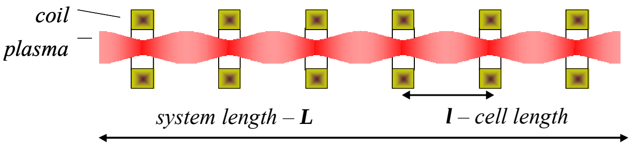

Fig. 1. Scheme of multiple-mirror confinement.

First experiments demonstrated improved confinement in a corrugated field.[3,4] However, if particle scattering is provided by classical binary collisions, then the scaling of this system to a reactor resulted in very challenging plasma parameters. The first estimate of reactor parameters was as follows:[7]

Total length	100 m
Plasma radius	5 cm
Plasma density	10^{24} m^{-3}
Central temperature	about 10 keV
Mean magnetic field	10 T
Mirror ratio	3
Plasma β	>>1
Stored plasma energy	100 MJ
Energy confinement time	0.1 ms

At such plasma density the β value is much greater than unity. That means that the magnetic field cannot stop transverse plasma expansion. Therefore a wall confinement was discussed at the time, in which the magnetic field is used only for suppression of radial heat losses, and the plasma pressure is confined by a conducting material wall.[1]

Operation with wall confinement means that such reactor can work in a short-pulse mode with very high power of plasma heating, very high load of the first wall, and very high power output. These are clear disadvantages for commercial applications of such systems.

The above text of this section reflects knowledge of 1970s. No new experimental information appeared prior to beginning of experiments at GOL-3. Lack of new experiments was partially caused by absence of a high-power heating system suitable for the dense, hot and short-lived plasma. Plasma heating by injection of a high-power electron beam along the magnetic field is possible due to linear axisymmetric geometry of the system. Such heating technology was developed in BINP.

Experiments at GOL-3 in Novosibirsk demonstrated that the plasma heating by an electron beam radically changes plasma properties and confinement regimes. Requirement of high beam power means a high-current relativistic beam. Requirement of good power deposition efficiency means that the regime of collective beam-plasma interaction is necessary, with a typical relaxation length of about 10^{-6} of the classic scattering length of relativistic electrons. Collective interaction also means turbulence, which dramatically changes plasma properties as compared to classical multiple-mirror confinement.

In general the GOL-3 experiments demonstrated that under proper conditions the best plasma confinement can be realized for considerably smaller plasma density as compared to the classical estimate. The condition $\beta \gg 1$ is not necessary for a multiple-mirror reactor anymore. This means that such reactor can be made steady-state that is physically, technically and commercially attractive.

III. GOL-3 EXPERIMENT: PLASMA HEATING BY RELATIVISTIC ELECTRON BEAM

General layout of GOL-3 is shown in Fig. 2.

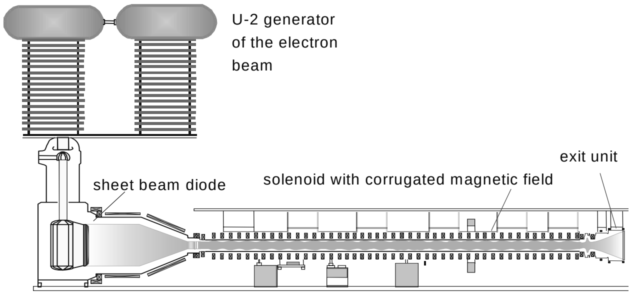

Fig. 2. Layout of GOL-3.

In basic configuration of GOL-3 the deuterium plasma with density of $10^{20} \div 10^{22}$ m^{-3} is confined in a 12-meter-long solenoid, which comprises 52 corrugation cells with mirror ratio $B_{\max}/B_{\min} = 4.8/3.2$ T. The plasma in the solenoid is heated up to ~2 keV temperature by a high power relativistic electron beam (~0.8 MeV, ~20 kA, ~1.5 kA/cm^2, ~12 μs, ~120 kJ) injected through one of the ends.[8]

Primary physical process in this system is excitation of high-level Langmuir turbulence by the electron beam. Theoretical analysis of GOL-3 parameter space is quite complicated because of gradients of magnetic field and plasma density, close electron cyclotron resonance and possible high-level ion sound turbulence that was directly observed in beam-plasma interaction experiments.[9] Nevertheless good understanding of main features of turbulent phenomena in the beam-heated multiple-mirror trap exists.

Beam electrons lose up to 50% of their initial kinetic energy during the beam-plasma interaction – see Fig. 3.[10] A fraction of this energy stays in the plasma and the rest is lost along the magnetic field with fast electrons.

Turbulent Langmuir waves of high amplitude are excited by the beam in the plasma, if the increment of two-stream instability exceeds the electron collision rate. Therefore, high beam current density and good beam quality are required. Microwave emission at double plasma frequency is observed during the beam injection into the plasma – see Fig. 4.[11] Such emission is a good marker of non-linear Langmuir turbulence. Fine temporal structure of $2\omega_p$ signal meets expectations for plasma with small-scale depletions of density.

Effective heating of plasma electrons occurs in turbulent fields. In GOL-3 we observe two phenomena typical for beam-plasma experiments. The first one is non-Maxwellian electron distribution function – see Fig. 5.[12] The second is non-uniform plasma heating along the device length. The resulting pressure profile depends on initial density profile, features of energy deposition from the beam and energy transport processes. Due to strong turbulence the axial electron heat transport is suppressed by ~3 orders of magnitude.[13,14] This allows buildup of high pressure gradients along the magnetic field. Such suppressed heat transport exists while the beam injection maintains strong Langmuir turbulence and then it is restored to near-classical values. Typical pressure distributions along the axis are shown in Fig. 6.[8]

Observed scalings of beam-plasma interaction are reasonably reproduced by a numerical model that was developed for plasma in uniform magnetic field.[15] The saturation level of the two-stream instability in the model agrees with the condition $\nu^* \sim \Gamma$, where Γ is the linear growth rate, and ν^* is the anomalous electron collision frequency[13] responsible for suppression of electron thermal conductivity along the magnetic field.

In a linear system like GOL-3 most energy losses occur along the magnetic field. Therefore we can extrapolate predictions of the numerical model to reactor conditions.

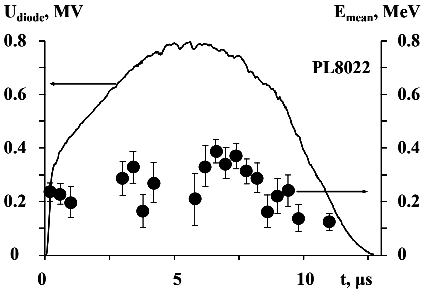

Fig. 3. Beam energy losses in plasma.[10] Solid line is for initial energy (diode voltage), dots are mean energy at exit measured by miltifoil analyzer.

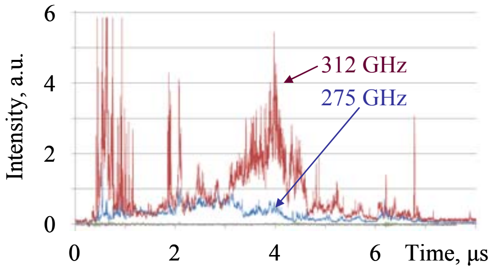

Fig. 4. Microwave emission at double plasma frequency.[11] Two spectral channels are shown.

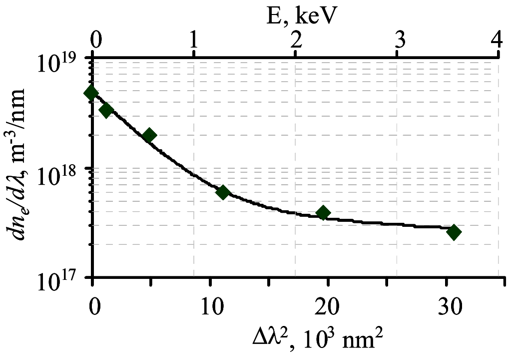

Fig. 5. Electron distribution function for shot PL10217 at $Z = 2.15$ m and $t = 7.5$ μs; $n_e = 0.67 \cdot 10^{21}$ m^{-3}, $<E> = 2.7$ keV.[12]

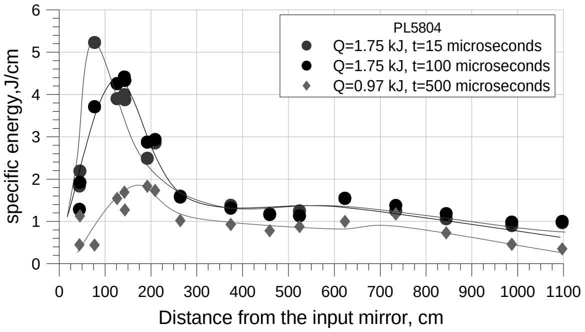

Fig. 6. Axial distribution of plasma energy at different time moments.[8] Heating is stopped at 10 μs.

IV. FAST HEATING OF IONS

Previous section described only features of beam-plasma interaction that results in energy transfer from the electron beam to plasma electrons. The ions were supposed to gain energy from electrons by binary collisions. Collisional heating of ions is slow, therefore in beam-plasma experiments the ion temperature usually stays below few tens of eV.

Addition of multimirror magnetic field dramatically changes physics of ion heating. All three ion diagnostics of GOL-3 (namely: charge exchange particles analyzer, neutron detectors and H_α spectroscopy) revealed fast growth of ion temperature up to 1÷2 keV at time scales much shorter than expected.[6] Figure 7 shows typical data from spectroscopy at $n_e = (3.5\pm0.5)\cdot10^{20}$ m^{-3}.

The second parameter that strongly differs in the multiple-mirror regime (from its behavior in the simple solenoid) is the dynamics of electron temperature. During the beam injection the plasma electrons reach almost the same mean energy (word 'temperature' is not good here because of strongly non-Maxwellian distribution) in both cases. But just after the beam injection stops the electron temperature in corrugated field very fast decreases down to 100÷200 eV. This occurs simultaneously with fast heating of ions.

The explanation of both phenomena is quite simple.[17] It takes into account the following: a) a non-uniform plasma heating (which depends on the $n_{\mathrm{beam}}/n_{\mathrm{plasma}}$ ratio, i.e. on the local magnetic field); b) suppression of heat transport during the beam-plasma interaction that enables one to create high pressure gradients; c) collective acceleration of plasma flows from the high-field part of corrugation cells to cell's 'bottom'; d) thermalization of the opposite ion flows. The model predicts strong modulation of density and velocities of ions in cells of the trap after several microseconds of beam injection. Such modulations were found in the experiment – see Fig. 8.[18]

Collective mechanism of ion heating via electron pressure allows obtaining high ion temperatures in GOL-3 and makes this process competitive with energy losses along the magnetic field by cooling of electrons.

V. BOUNCE OSCILLATIONS NEAR ENDS

The next interesting feature of multiple-mirror confinement was first observed by local detectors of D-D neutrons as periodic oscillations of neutron flux – see Fig. 9. Period of these oscillations corresponds to time of transit of thermal ion through the corrugation cell. Further studies demonstrated that oscillations are produced by a small group of ions.[8]

These oscillations were explained by theory as excitation of bounce oscillations in cells of the trap.[19] Plasma flow through a cell causes a 'bump' on ion distribution function for a group of marginally trapped ions – see Fig. 10. Such bump is unstable to oscillations of electric potential at $\omega \sim v_{Ti}/l \propto \sqrt{T_i}$, that give additional scattering to weakly transiting and weakly trapped ions. Hot passing ions are reflected near $B_{\max}$ and then propagate counter-flow, thus effectively generating spikes of neutron flux.

This effect is spectacular and important. It is observed within high-pressure-gradient zones. Interaction between trapped and transit ions there increases momentum exchange between two mentioned particle groups and suppresses axial plasma flow. Physics of multiple-mirror confinement relies on fast particle exchange between trapped and transit ions. Such

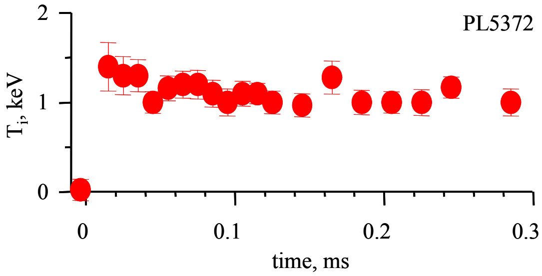

Fig. 7. Dynamics of ion temperature by H_α spectroscopy.[16]

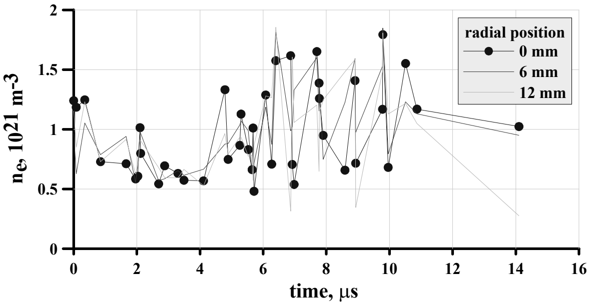

Fig. 8. Shot-by-shot measurements of radial profile of the plasma density by Thomson scattering.[18]

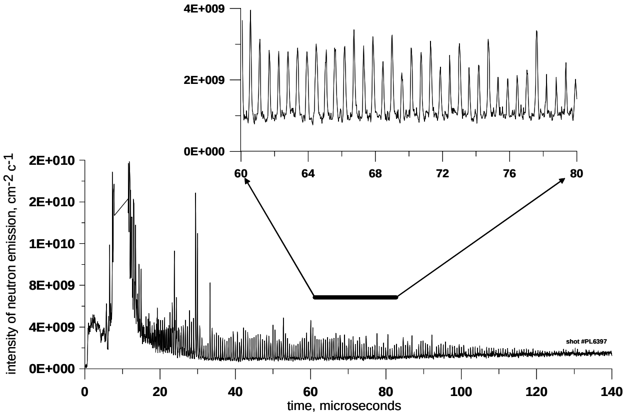

Fig. 9. Periodic oscillations of neutron flux due to bounce instability. [8] Steady background is from thermal plasma.

exchange is good within central section of a device but degrades to its ends due to decreasing plasma density. This additional mechanism which provides limitation of axial particle flux is beneficial for confinement because makes the end sections of a trap more effective as end plugs.

VI. CONFINEMENT SCALINGS

The change of magnetic configuration from a simple solenoid to the multiple-mirror significantly improves the energy confinement time in GOL-3 – see Fig. 11.[16] This confirms that the multiple-mirror confinement works.

The list of collective phenomena shows that the plasma dynamics in multiple-mirror traps is mainly determined by turbulent processes. Turbulent scattering of electrons increases the effective collision rate up to some level. Enhanced collision rate can saturate the two-stream instability that determines efficiency of the beam relaxation in the plasma. In the case of bounce instability the mean free path of transit ions decreases, and the momentum exchange between transit and trapped ions occurs more effectively in the end cells of the trap.

Confinement in multiple-mirror trap is also improved by collective effects.[8] Best energy confinement time in the multiple-mirror trap GOL-3 (~1 ms) corresponds to predictions of classical theory[20] but it is achieved at much lower density (Fig. 12). Good confinement at low density indicates that the effective collision frequency in the plasma exceeds the classical value by a factor of few tens.

This fact is beneficial for multiple-mirror fusion reactor concept. The usual fusion paradigm is that any turbulence in a system will degrade confinement. This is true for toroidal devices, where parallel transport plays small role in confinement. In linear systems the main energy losses come through electron heat transport along the magnetic field. Therefore, additional scattering due to strong turbulence, like that observed in GOL-3, will reduce axial losses and improve confinement. Transverse confinement will surely degrade at the same time, but currently such losses are small in GOL-3.

Considering scalings of GOL-3 data to higher plasma parameters, we will interpret Fig. 12 in the following way. The experimental τ_E dependence on density is weaker than can be expected from theory, and thus the multiple-mirror confinement works in broader density domain. This could mean that the effective scattering length for ions, λ^* , is close to the optimal condition, $\lambda^* \sim l$. Such relation arises since λ^* is of turbulent nature and self-organization of plasma adjusts it for optimal confinement in the same way as self-organization adjusts canonical radial profiles in tokamaks.

If this conjecture is true, then the confinement scalings can be re-written for $\lambda^* \sim l$, and instead of classical dependence, $\tau \propto R^2 L^2 n T^{-5/2}$, one will get $\tau \propto L^2 l^{-1} T^{-1/2}$. Such change of the scaling law enables operation with reasonably turbulent high-temperature plasma of much lower density than required by formal condition $\lambda \sim l$. This opens the way to reactor-grade multiple-mirror plasma with $\beta < 1$ that is far more feasible than the original proposal, featuring wall confinement at ultrahigh β.

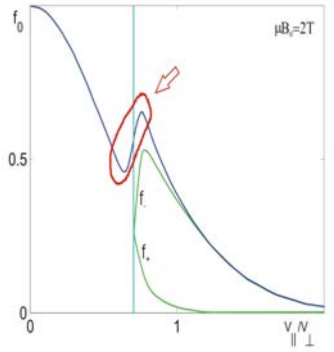

Fig. 10. Distribution function of ions in a cell of the trap.[19]

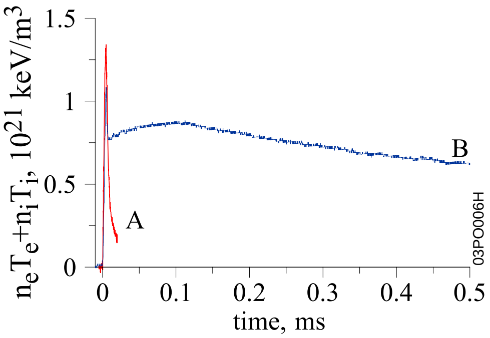

Fig. 11. Evolution of plasma pressure in uniform magnetic field (A) and in the multiple-mirror system (B). [16]

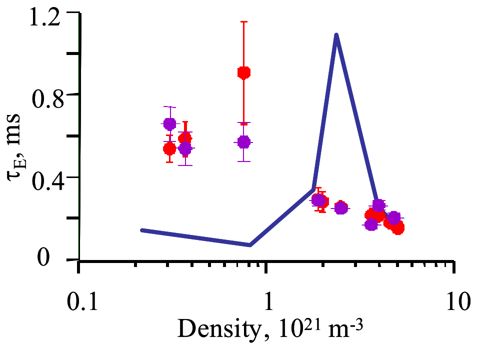

Fig. 12. Energy confinement time *vs.* initial density (dots).[8] Solid line shows prediction of the classical theory for R = 1.5 and $L / l = 55$.[20]

VII. MHD STABILITY

Another class of collective phenomena is connected with formation of helical magnetic field by axial currents. Complex radial structure of currents is formed in the plasma with turbulent resistivity. Main results are as follows:[21]

- Rotational transformation factor was directly measured (Fig.13). Sheared helical magnetic field is formed in GOL-3 by axial currents, while the zero-azimuthal-field magnetic surface is inside the plasma.
- Magnetic shear is shown to be the important factor for achievement of stable operation and good confinement in GOL-3. However, computations show that tearing-like instability could exist inside the plasma column.
- Global plasma stabilization in GOL-3 can be achieved by control of the magnetic shear.

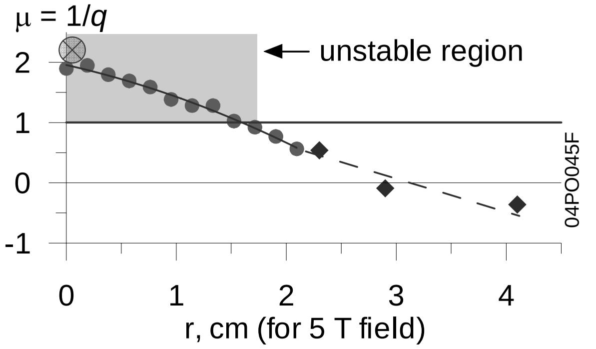

Fig.13. Measured rotational transformation at $t = 3.5$ μs after beam injection start. Dots are measurements via X-ray footprint[21], the cross corresponds to current density at the axis, diamonds are set according to current measurements with entrance limiters.

The safety factor can be written for a linear system as $q = 2\pi(r/L)(B_z/B_\phi)$, where B_z and B_φ are longitudinal and azimuthal components of the magnetic field, r and L are plasma radius and column length. It is above unity except for the central beam-heated zone, where it falls below one and can reach values of 0.4÷0.3.

Observed role of the magnetic shear is extremely important. If we consider a multimirror trap as a reactor, then the magnetic shear can provide stability at $\beta < 1$, if the Mercier condition (which reduces to the Suydam criterion in cylindrical geometry) is satisfied. Sheared magnetic field does not completely eliminate the interchange modes. Instead it decreases growth rates of interchange modes down to values typical for Mercier modes in tokamaks – see Fig. 14.[22] Suppression of interchange modes in some radial area with significant shear may provide an effective thermal barrier. Observed influence of q profile on confinement,[21] could indicate existence of such thermal barrier at some conditions.

Corrugated magnetic field is not a minimum-B configuration, so MHD stabilization should be provided by other means. Stabilizing role of magnetic shear can partially solve this problem. On the other hand, large axial currents that are required to create sheared magnetic field can initiate sawtooth-like tearing processes in the core.[23] So some tradeoffs in parameters will be necessary for a next step device. Simulations show that the MHD stability can be realized at reactor parameters as well.

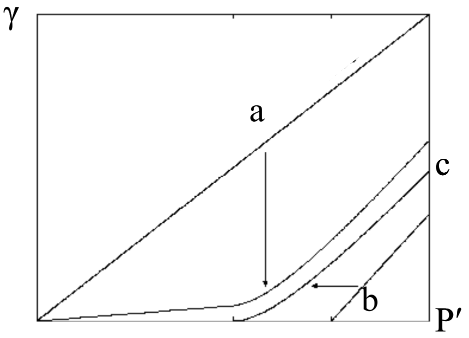

Fig. 14. Growth rate of convective mode vs. pressure gradient in a sheared field of open trap. Starting from pure interchange modes (a) and ballooning modes (b) the instability is modified closer to Mercier modes (c) as the trap length is increased.

VIII. FEASIBILITY OF MULTIPLE-MIRROR FUSION REACTOR

Features of confinement discussed in previous sections indicate that the effective axial plasma confinement in a multiple-mirror trap can be obtained with lower plasma density as compared to original theory and such trap can be made stable at $\beta < 1$.

A simple 1-D numerical model for fusion-grade linear device with multiple-mirror end plugs was made. Changes in physics with respect to older projects include all discussed turbulent phenomena. We impose two severe additional constraints. The new device must operate at $\beta < 1$ for pure magnetic confinement without necessity of direct plasma contact with the wall. It must also be steady-state in underlying physics. The second requirement means that the current and power of the electron beam should be decreased to minimal level at which the beam-plasma interaction still maintains the required level of turbulence. Decreased beam power means that the plasma heating cannot be provided by electron beams alone and additional heating source will be required.

General layout of a reactor-grade device is shown in Fig. 15. It consists of main central section where most fusion power will be produced, magnetic null divertors, multiple-mirror end plugs, and end magnetic expanders with plasma dumps. Plasma in the central section will be heated by distributed NBI. Two electron beams will be injected through the ends, providing turbulent suppression of electron heat transport and the sheared magnetic field. The currents will return back into electron beam injectors through periphery of the plasma, in the same way as in GOL-3.

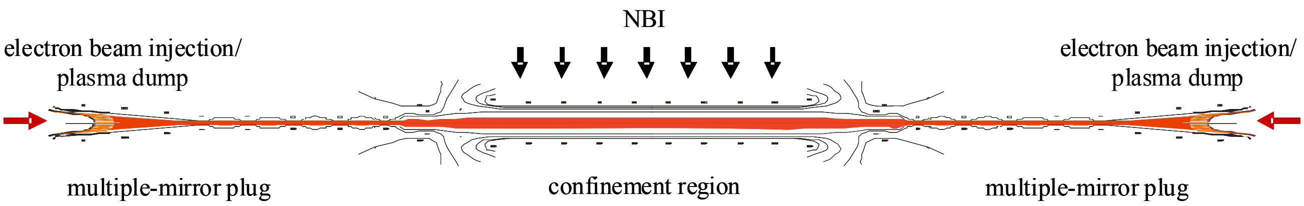

Fig. 15. Layout of steady-state reactor based on long solenoid with multiple-mirror end plugs. Vertical scale is stretched for convenience.

Technology of electron beams required for a true steady-state system is far beyond the current state-of-the-art. Hence, we list below conceivable parameters of simpler version of pulsed reactor.

Total length	150 m
Length of central section	50 m
Plasma density	$2{\cdot}10^{21}$ m^{-3}
Temperature	12 keV
Central β	0.9
Energy confinement time	0.09 s
Plasma radius	6 cm
Central/plug/mirror field	5/10/20 T
Stored plasma energy	7.2 MJ
Energy in neutrons	40 MJ
Peak neutron power	360 MW
Energy content in heating beams	7 MJ
D-T NBI energy	100 keV

Several mechanisms of MHD stabilization are considered including biased end electrodes, sheared magnetic field, magnetic null divertors. The electron energy end losses can be further reduced by large magnetic expansion from the end mirrors to the end walls like that demonstrated in GDT experiments.[24]

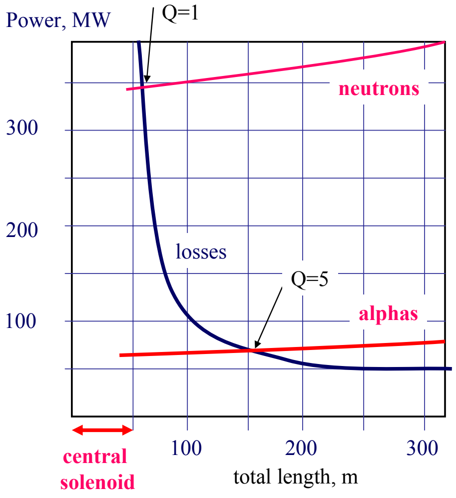

Fig. 16. Energy balance in reactor depending on total system length with a fixed 50 m length of central confinement section.

Figure 16 shows estimates of fusion power and losses in such a system. At total length below 100 m the device will have Q near unity. These estimates may be too optimistic because many important 3-D effects are neglected, especially transverse energy and particle losses and enhanced losses of NBI particles. On the other hand, current 1-D model is similar in this respect to old models of multiple-mirror reactors. This allows reasonable comparison of the new system with older approaches.

Feasibility of the proposed system will depend not only on underlying physics but also on advances in fusion technology. First of all it is the technology of steady-state high-power electron beams with good quality and high power, capable of operating in plasma-filled environment. High-field superconducting magnets and effective heat removal systems are required, albeit the simplest circular shape make the magnets less challenging than the equal-field magnets for toroidal systems. And finally, traditional for fusion problems of plasma-facing materials are there. As for the NBI injection, the situation is better, because the relatively low injection energy allows operation with positive ions in ~1 MW modules. Such technology is already available.

IX. DISCUSSION AND SUMMARY

High plasma parameters were achieved in GOL-3 experiments, including ion temperature up to 2 keV at $\sim 10^{21}$ m^{-3} density, and energy confinement time ~1 ms. Such parameters are provided by several collective effects in the electron-beam-heated plasma confined in corrugated magnetic field.

Importance of these mechanisms is that optimal plasma density for the best confinement significantly decreases with respect to the classical model and therefore becomes more suitable for a feasible fusion reactor. Conceptual reactor which includes collective effects can have significant advantages over the classical concept. It can be stationary, operate at β less than unity, and be more compact. New concept of fusion reactor based on experimental results is presented in the paper.

Reactor research includes development of required fusion technologies. First steps on a long-pulse electron beam technology and on development of focused high-brightness neutral beams can be made at the existing GOL-3 in near term.

In general, the achieved plasma parameters support our vision of a multi-mirror trap as the alternative path to fusion reactor with $\beta\sim1$ and $10^{21}\div10^{22}$ m^{-3} plasma density.

ACKNOWLEDGMENTS

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