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LLNL-TR-408176

The Axisymmetric Tandem Mirror: A Magnetic Mirror Concept Game Changer Magnet Mirror Status Study Group

T. Simonen, R. Cohen, D. Correll, K. Fowler, D. Post, H. Berk, W. Horton, E. B. Hooper, N. Fisch, A. Hassam, D. Baldwin, D. Pearlstein, G. Logan, B. Turner, R. Moir, A. Molvik, D. Ryutov, A. A. Ivanov, J. Kesner, B. Cohen, H. McLean, T. Tamano, X. Z. Tang, T. Imai

October 24, 2008

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

The Status of Research Regarding Magnetic Mirrors as a Fusion Neutron Source or Power Plant

Workshop held in

Berkeley, California on September 8-9, 1008

December 9, 2008

Forward

A workshop to assess the status of magnetic mirror research was held in Berkeley, California on September 8-9, 2998. Two dozen active and former mirror researchers participated (see below). Members came from 6 laboratories and 5 universities. The workshop consisted of formal and informal presentations some of which are posted on the web. (http://www.mfescience.org) Following the workshop several teleconference meetings were held to discuss the conclusions of the workshop.

Workshop Participants

David Baldwin, LLNL/GA
Herb Berk, University of Texas
Bruce Cohen, LLNL
Ron Cohen, LLNL
Don Correll, LLNL
Nate Fisch, Princeton University
Ken Fowler, LLNL
Adil Hassam, University of Maryland
Wendel Horton, University of Texas
Bick Hooper, LLNL
Tsuyoshi Imai, Tsukuba University Japan
Alexander Ivanov, INP, Novosibirsk Russia
Jay Kesner, MIT
Grant Logan, LLNL/LBNL
Harry McLean, LLNL
Ralph Moir, LLNL
Art Molvik, LLNL
Don Pearlstein, LLNL
Gary Porter, LLNL
Dick Post, LLNL
Dmitri Ryutov, LLNL
Tom Simonen, LLNL/GA
Teruo Tamano, GA/Tsukuba University Japan
Xianzhu Tang, LANL
Bill Turner, LLNL/LBNL

1. Introduction and Executive Summary

Experimental results, theory and innovative ideas now point with increased confidence to the possibility of a Gas Dynamic Trap (GDT) neutron source which would be on the path to an attractively simple Axisymmetric Tandem Mirror (ATM) power plant. Although magnetic mirror research was terminated in the US 20 years ago, experiments continued in Japan (Gamma 10) and Russia (GDT), with a very small US effort. This research has now yielded data, increased understanding, and generated ideas resulting in the new concepts described here.

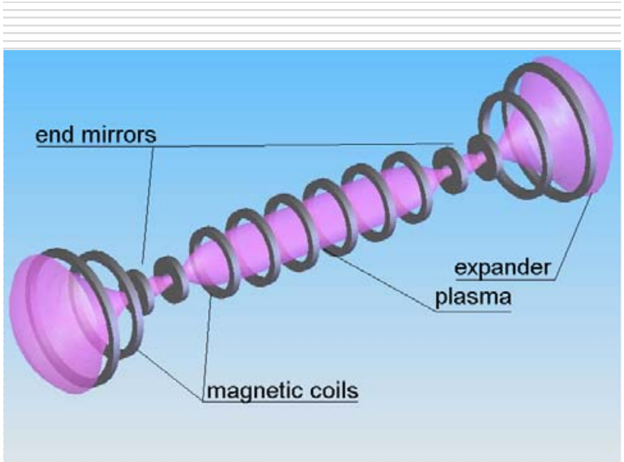


Figure 1.1. Illustration of an axisymmetric mirror system. The GDT Neutron Source would employ only a single mirror coil at each end. The simple tandem mirror ATM power plant would employ two mirror coils at each end to confine a small high density plasma to provide axial confinement.

Early mirror research was carried out with circular axisymmetric magnets. These plasmas were MHD unstable due to the unfavorable magnetic curvature near the mid-plane. Then the minimum-B concept emerged in which the field line curvature was everywhere favorable and the plasma was situated in a MHD stable magnetic well (70% average beta in 2XII-B). The Ioffe-bar or baseball-coil became the standard for over 40 years.

In the 1980's, driven by success with minimum-B stabilization and the control of ion cyclotron instabilities in PR6 and 2XII-B, mirrors were viewed as a potentially attractive concept with near-term advantages as a lower Q neutron source for applications such as a hybrid fission fuel factory or toxic waste burner. However there are down sides to the minimum-B geometry: coil construction is complex; restraining magnetic forces limit field strength and mirror ratios. Furthermore, the magnetic field lines have geodesic curvature which introduces resonant and neoclassical radial transport as observed in early tandem mirror experiments.

So what now leads us to think that simple axisymmetric mirror plasmas can be stable? The Russian GDT experiment achieves on-axis 60% beta by peaking of the kinetic plasma pressure near the mirror throat (where the curvature is favorable) to counter-balance the average unfavorable mid-plane curvature. Then a modest augmentation of plasma pressure in the expander results in stability. The GDT experiments have confirmed the physics of effluent plasma stabilization predicted by theory. The plasma had a mean ion energy of 10 keV and a density of 5e19m-3. If successful, the axisymmetric tandem mirror extension of the GDT idea could lead to a Q~10 power plant of modest size and would yield important applications at lower Q.

In addition to the GDT method, there are four other ways to augment stability that have been demonstrated; including: plasma rotation (MCX), diverter coils (Tara), pondermotive (Phaedrus & Tara), and end wall funnel shape (Nizhni Novgorod). There are also 5 stabilization techniques predicted, but not yet demonstrated: expander kinetic pressure (KSTM – Post), Pulsed ECH Dynamic Stabilization (Post), wall stabilization (Berk), non-paraxial end mirrors (Ryutov), and cusp ends (Kesner). While these options should be examined further together with conceptual engineering designs. Physics issues that need further analysis include: electron confinement, MHD and trapped particle modes, analysis of micro stability, radial transport, evaluation and optimization of Q, and the plasma density needed to bridge to the expansion-region. While promising all should be examined through increased theory effort, university-scale experiments, and through increased international collaboration with the substantial facilities in Russia and Japan

The conventional wisdom of magnetic mirrors was that they would never work as a fusion concept for a number of reasons. This conventional wisdom is most probably all wrong or not applicable, especially for applications such as low Q (DT Neutron Source) aimed at materials testing or for a Q ~ 3-5 fusion neutron source applied to destroying actinides in fission waste and breeding of fissile fuel.

The following addresses past concerns about mirrors in light of more recent research:

- Concern: Complex minimum-B magnets are required.
    - No, axisymmetric magnets are feasible as discussed above and below and demonstrated 60% beta in the axisymmetric GDT device. Several other axisymmetric methods providing MHD stability are described in Section 2.
- Concern: Complex thermal barriers are required.
    - No, from the outset Q = 2 to 3 was projected without thermal barriers. Q increases with smaller and higher field axisymmetric magnets which reduce the plug volume and power. Thermal barriers were introduced to increase Q with large and low magnetic-field minimum-B end plugs.
- Concern: Particles leak too rapidly out the ends.
    - No, circular coils enable higher mirror ratio and magnetic fields reduce leakage and reduce the end plug volume, and thus reduce the power demands to create potential confinement without thermal barriers.

- Concern: Electron temperature is intrinsically low due to conduction to ends.
  - No, expansion of the magnetic field in large end tanks decouples confined plasma from end walls when the mirror ratio from mirror to end walls is sufficiently large, > 100 to 300. Successive improvements in electron temperature were achieved in 2XIIB, TMX, TMX-U, GDT, and Gamma 10.
- Concern: Classical radial transport is overwhelming.
  - No, For axisymmetric mirrors neoclassical and resonant transport arising from minimum-B anchors is eliminated.
- Concern: Energetic neutral beam injected ions are lost by micro-instabilities.
  - No, warm plasma suppresses loss cone modes (PR6, 2XIIB, TMX,…) Skew injection suppresses Alfven ion cyclotron modes (TMX-U).
- Concern: Drift wave instabilities will cause excessive radial transport.
  - No, without toroidal curvature, drift wave drive is weak plus sheared ExB rotation suppresses drift waves (HIEI, Gamma 10)
- Concern: Toroidal systems suffer from wall interactions, why not mirrors?
  - Mirrors have no plasma current so they have no current driven disruptions. Also power and particle exhaust are handled in large end tanks at low power density outside the main magnet system. Direct energy conversion of the exhaust power is even an option.
- Concern: RF-heated mirrors necessarily suffer from RF pump-out
  - No, not when waves are properly controlled.
- Concern: Mirror systems will require developing exotic technologies (superconducting magnets, negative ion beams, microwave gyrotrons)
  - No, the technologies being developed for ITER are adequate

In summary, an attractive magnetic mirror concept has been identified and many basic principles have now been demonstrated in experiments, most recently in Russia and Japan. This progress opens up a range of new options that warrant further investigation. This optimized magnetic configuration, simpler than previous mirrors, if developed further, could lead to an attractive Q~10 fusion system with an ignited central cell and include advanced features outlined below.

- Simple circular magnets in a linear array that is easy and fast to construct and maintain.
- Taming of the plasma material interface is achieved by expanding the power and particle exhaust to low levels in large end tanks outside the magnet system.
- The opportunity of direct energy conversion of the plasma exhaust.
- The possibility of liquid molten salt breeding blankets to harness fusion power.
- The possibility of alpha channeling and D-He3 with low nuclear activation.

2. ATM Stabilizers

An axisymmetric mirror system has excellent single particle-confinement (e.g. the Argus ionosphere experiment confined particles for over 10 years). However, a simple mirror is MHD unstable as demonstrated by many experiments in the 1960's. As illustrated in Fig. 2.1 when the field-line radius of curvature center is in the direction of the plasma, the plasma is unstable. The simple mirror shown on the upper right panel of Fig. 2.1 has both unstable and stable curvature. When averaged over a field line its plasma is unstable requiring additional stabilization.

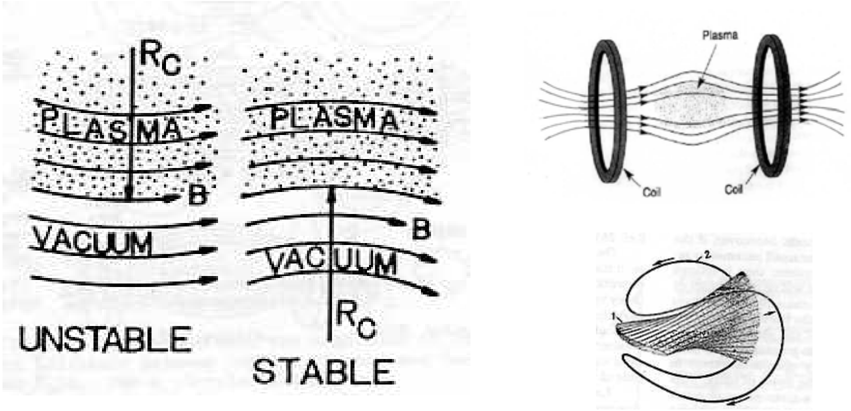


Figure 2.1. Illustration of stable and unstable curved magnetic field lines as well as a simple and minimum-B baseball mirrors.

The common way of stabilizing a magnetic mirror has been to create a minimum-B magnetic well with Ioffe bars or a baseball shaped coil. Minimum-B provides MHD stability (as demonstrated by the achievement of 70% average beta in 2XIIB), but introduces significant degradation of single particle confinement. As in stellerators, resonant transport results from resonances between the bounce motion and the azimuthal drift in the Ioffe-bar structure. In addition neoclassical transport is introduced as in toroidal systems. Thus it is highly desirable to employ mirror stabilizers that are axisymmetric. Previous work followed this line, but was overshadowed by the minimum-B method. For example TMX had minimum-B end cells. Gamma-10's end region consists of a minimum-B anchor between the central cell and the axisymmetric end plug. Tara had an axisymmetric plug adjacent to the central cell followed by a minimum-B anchor at both ends. Only the Ambal device design in Russia was fully axisymmetric, but its construction was never completed. Consequently we know a lot about the advantages and disadvantages of minimum-B systems but relatively less about axisymmetric stabilizers. Below we discuss a number of stabilization methods, some of these concepts have been explored in experiments.

For paraxial (long-thin) axisymmetric mirror systems, the Rosenbluth-Longmire stability criterion can be presented in a particularly simple form:

$$\int (p_{\|} + p_{\perp}) a^3 \frac{d^2 a}{dz^2} dz > 0, \qquad (2.1)$$

where $a(z)$ is a radius of the plasma boundary that lies on one of the flux surfaces. This criterion is written for the case of a radially uniform plasma, with a sharp boundary, but it contains all the substantial features of a general criterion. Note that larger plasma radii (i.e. smaller magnetic fields) zones make a stronger contribution to the integral (2.1).

2.1 Stabilization by Pressure Profiling

Figure 2.1 illustrates that simple mirrors have both unstable and stable curvature. Experiments with an angular velocity distribution peaked near 90 degrees will have the plasma pressure peaked near the midplane where the curvature is unstable. If the pressure profile is broadened (e.g. by neutral beam injection at a skew angle), then the line-averaged, pressure-weighted curvature includes stable curvature near the mirror throats. However, due to the a^3 dependence, the average is still unstable, although less so. As a result it is necessary to augment the stability by additional means. Note that skew injection would seem to inject particles near the loss cone. Compared to 90 degree injection this is true. However, with simple circular coils much higher magnetic fields can be produced, and thus very high mirror ratio can be achieved so the loss cone is very much smaller.

2.2 Stabilization by Plasma Exhaust

Note that the curvature is stable beyond the mirrors, in the expander region. Thus, plasma pressure in the expander can stabilize the system. Of course this plasma exhaust is of relatively low pressure, but due to the a^3 weighting of the stability integral, the contribution to stability is significant. This concept has been demonstrated in GDT experiments where the mirror ratio and curvature were varied and GDT achieved central betas as high as 60%.

One of the benefits of the GDT concept is that skew injection avoids AIC modes driven near the mid-pland. Also, due to the large amount of warm plasma present, the Drift Cyclotron Loss Cone (DCLC) mode is suppressed. GDT experiments also show that self-generated ExB shear additionally suppresses drift-wave turbulent structures.

One of the limitations of the GDT concept is that the required plasma exhaust drains energy from the mirror cell. However, the large expansion of the exhaust decouples electron thermal conductivity from the mirror cell to the end walls. As a result, GDT has achieved electron temperatures up to 230 eV. This value is well above 50 eV range expected if electron thermal conduction to the end walls is dominant.

The GDT concept with modest electron temperature (Te<1 keV) is envisioned as an attractive fusion-spectrum neutron source operating at high beta, with Q<<1 unless the device is extremely long (e.g. L~1 km). The neutron flux of ~2 MW/m2 to an area of ~1 m2 is well suited for material testing. It has a fusion neutron spectrum and operates with low tritium consumption at efficiencies equaling or exceeding other non-fusion spectrum options. A fusion reactor based on GDT would, however, be quite long. Thus we envision the GDT concept as a DT neutron source but the ATM concept which employs simple tandem mirror end plugs is a candidate for a power plant.

2.3. Stabilization by Plasma Rotational Shear

Sheared plasma rotation is predicted to stabilize unstable MHD modes. Experiments in the PSP series of experiments [2.3.1] in Novobirsk explored this technique for several years and reached ion temperatures ~10 keV at a plasma density ~ 10^{12} cm^{-3}. More recently the MCX experiment at the University of Maryland has shown that stability is achieved when the shearing rate of the ExB rotation exceeds the MHD growth rate. In addition, the Gamma-10 experiment has shown that with sufficient shear (generated by end electrodes, ECH, or spontaneously) vortex structures and drift type modes are suppressed.

[2.3.1] A.D. Beklemishev, M.S. Chaschin, Plasma Phys. Repts, 34, 422 (2008).
[2.3.2] R. Ellis, APS DPP (2008).

2.4. Stabilization by a Divertor

The Tara experiment at MIT demonstrated that a divertor attached to the axisymmetric mirror can augment stability. Stability of the Tara axisymmetric mirror cell was believed to derive from a combination of divertor and pondermotive stabilization effects. It was demonstrated that increasing the divertor current increased the limit on heating power [2.4.1]. The stabilization was attributed to a change of field line curvature and to the magnetic seperatrix at the plasma edge which enables electron cross field access to short out MHD modes [2.4.2].

[2.4.1] Casey et al, Physics of Fluids, v 31, n 7, 1988, p 2009
[2.4.2] Lane, et al Nuclear Fusion, v 27, n 2, 1987, p 277.

2.5. The Kinetic Stabilizer

The concept of MHD stabilization of axisymmetric mirror cells, accomplished by the presence of a low-density plasma on the field lines in the expanding magnetic field lines outside the mirror cell, is a seminal one for mirror systems. Predicted theoretically by Ryutov and demonstrated conclusively in the Gas Dynamic Trap experiment at Novosibirsk, this stabilization concept is employed in the Kinetic Stabilizer studied theoretically by Post and others [2.5.1 - 3]. In the original Kinetic Stabilizer concept, as applied in an ATM, the stabilizing plasma is created by injecting ion beams into the "expander" region at a small angle to the local direction of the field lines. These ions move up the field gradient until they are reflected and return to the end. These ions, plus accompanying electrons, form the "stabilizer" plasma. By optimizing the field line curvature in the expander region so as to enhance the stabilizing effect, and by using heavy ions (e.g. Cesium) to form the stabilizer plasma, Post calculates that a total stabilizer beam power of 10 MW would be sufficient to MHD-stabilize an ATM generating 500 MWe. In further studies the creation of the stabilizer plasma by the use of transversely injected gas jets located just outside the mirror in the expander region was studied with similar results with respect to the small power drain associated with the formation of the stabilizer plasma relative to the electrical power output of the ATM. Also, in one preliminary study, where both the expander field-line shape and the field configuration of the ATM mirror cells were highly optimized, it was found that a sufficiently large ATM could become “self-stabilized” in the same manner as the GDT is “self-stabilized, ” namely solely by its own emergent plasma. These various ways in which Ryutov’s stabilization technique might be employed in an ATM are yet another illustration of the inherent adaptability of open-ended systems for the adoption of a variety of effective stabilization means.

A central important issue in the application of Ryutov’s stabilization technique is that there should exist adequate “communication” along the field lines between the confined plasma and the stabilizer plasma. As has been shown, both by experiment (the GDT) and by theory (Ryutov), this “bridging” plasma can be several orders of magnitude lower in density than that of the confined plasma and still be able to provide the necessary link. However, this requirement, and that of assuring the avoidance of possible related “trapped-particle” modes, needs further elucidation.

[2.5.1] R. F. Post, “The Kinetic Stabilizer: a Simpler Tandem-Mirror Configuration?” Fusion Science and Technology, **39,** 25 (Jan. 2001)

[2.5.2] R. F. Post, “”The Kinetic Stabilizer: Further Calculations and Options,” Fusion Science and Technology, **43**, 195 (Jan. 2003)

[2.5.3] R. F. Post, T. K. Fowler, R. Bulmer, J. Byers, D. Hua, and L. Tung, “Axisymmetric Tandem Mirros: Stabilization and Confinement Studies,” Fusion Science and Technology, **47**, 49 (Jan 2005)

2.6 Cusp End Cells

Rather than employing simple mirror coils to plug the center cell, Ryutov [2.6.1] described the use of axisymmetric cusps. Kesner [2.6.2] considered a neutron source that consisted of an axisymmetric central cell bounded by cusp anchor cell (i.e., with no plugging). MHD stability is derived from the good curvature of the cusp in combination with compressibility in the vicinity of the cusp-field null.

[2.6.1] D.D. Ryutov, Sov. Phys. Usp. 31, p300 (1988).
[2.6.2] J. Kesner, S.F. Horne, and V.P. Pastukhov, J. of Fusion Energy, 4, p401 (1987).

2.7 Wall Stabilization

MHD theory predicts that at sufficiently high beta conducting wall stabilization can be used to provide MHD stability for a symmetric mirror system. Indeed this mechanism is intimately related to the conducting wall stabilization proposed and achieved by Christoflis [2.7.1] for the E-layer where the current induced in the wall due to plasma displacement provides the stabilization effect. Within MHD theory the effect was first shown by Haas and Wesson [2.7.2] and the connection to the effect of Christofilis to MHD theory of mirror machines was demonstrated by Berk, et. al [2.7.3]. Pearlstein and Kaiser [2.7.4] derived the arbitrary beta relation in the long thin limit and studies for implementing wall stabilization in mirrors were performed by Li et. al. [2.7.5].

It is found that if one can maintain an axially localized distribution where $\left(\frac{p_{\perp h}}{p_{\| h}}\right)$>>1, a rather modest beta criterion needs to be fulfilled to obtain MHD stability. It is likely sufficient to have the conducting wall just near the plug regions and not throughout the central cell plasma. There is a need for active feedback due to wall receptivity, but as the instability growth rates are then quite low (of order the L/R time of the wall) feedback techniques, which are related to issues with tokamak resistive wall modes, are feasible.

[2.7.1] Christofilis, N. A. et.al. UCRL # 14282 (1967)
[2.7.2] Haas F.A. and Wesson, J. A. Phys. Fluids **10** 2245 (1967)
[2.7.3] Berk H.L., Rosenbluth, M.N., Wong H.V. and Antonsen T.M. Phys. Fluids **27** 2705, (1984)
[2.7.4] Kaiser, T.M. and Pearlstein L.D. Phys. Fluids **28** 1003 (1985)
[2.7.5] Li, X.Z., Kesner, J., and Lane B., Nuclear Fusion, **25**, 907 (1985)

2.8 Pondermotive Stabilization

The Phaderus axisymmetric tandem mirror experiment at the University of Wisconsin and the Tara axisymmetric tandem mirror experiment at MIT both found that the central cell could be stable without the use of MHD anchors due to pondermotive stabilization.

However the pondermotive effect requires large RF fields. High RF fields were present in these experiments because of weak end cell plugging which required relatively strong heating for relatively low density plasmas. Also, near fields played an important role. It is not believed that pondermotive forces above can stabilize reactor-grade plasmas. However, pondermotive stabilization could be combined with other methods.

2.9. Non-paraxial End Plugs

A non-paraxial stabilizer [2.9.1] with a properly chosen field structure (with “stability ring” present) stabilizes the first several MHD modes (m=1, 2; n=1, 2, 3), with the rest of the modes stabilized by FLR effects.
It has a “natural” shape and does not affect the simple connectivity of the mirror plasma It is created by a simple set of coils and can be incorporated into any of the mirror designs It does not require control over the distribution functions (entirely passive: no sloshing ions, drift pumping, etc)

[2.9.1] D.D. Ryutov, G.V. Stupakov. JETP Lett., 26, 186 (1985); Sov. J. Plasma Physics, **12**, p.815 (1986).

2.10 End Wall Shaping

End wall shaping [2.10.1] can stabilize an axisymmetric mirror. Magnetic field lines in the expansion tank should intersect the wall in such a way that the length of the flux tube decreases when the flux tube moves radially outward. This is a purely passive technique; it does not require installing any additional subsystems and requires only a proper choice of the shape of end-wall

Only a very low plasma density in the expander tank (as little as 0.001% of the main plasma) is needed for stabilization. Note that direct contact of the plasma with a conducting wall *does not mean that the line-tying is present!* [2,10.2 - 3].

For the plasma parameters of interest for fusion research, the sheath voltage effectively decouples the plasma from the conducting wall [2.10.3 - 4]. For a complete description of the wall effect, one needs to formulate boundary conditions for the sheath in the tilted field [2.10.5-9].

This stabilization technique can be used in Q~1 mirror facility for nuclear waste burning. The natural plasma loss is sufficient to maintain a required amount of stabilizing plasma. No specific additional systems are needed – just a properly shaped plasma absorber.

Recently a dedicated experiment to study this technique was carried out at Nizhni Novgorod in a small mirror machine that was used as an ion source [2.10.10].

[2.10.1] D.D. Ryutov. “Axisymmetric MHD stable mirrors.” In: Physics of Mirrors, Reversed Field Pinches and Compact Tori (Proc. of the Course and Workshop, Intern. School of Plasma Physics, Varenna, Italy, Sept. 1-11, 1987, S. Ortolani and E. Sindoni, Eds.) v.2, p. 791, Editrici Compositori, Bologna, 1988.

[2.10.2]] W. Kunkel, J. Guillory. In: “Phenomena in Ionized Gases” (Proc. &th Conf. Belgrade, 1965) Vol. 2, p. 702, Belgrade, 1966

[2.10.3] B.B. Kadomtsev, ibid, p. 610.
[2.10.4] H.Berk, D. D. Ryutov, Yu. A.Tsidulko JETP Lett., **52**, 23 (1990).

[2.10.5] D.Farina, R.Pozzoli, D. Ryutov. Plasma Phys. Contr. Fusion, **35**, 1271 (1993).

[2.10.6] D.Farina, R.Pozzoli, D.D. Ryutov. Phys.Fluids, **B5**, p.4055 (1993).

[2.10.7] R.H.Cohen, D.D. Ryutov. Phys. Plasmas, **2**, 2011 (1995).

[2.10.8] D.Farina, R.Pozzoli, D. Ryutov. Nuclear Fusion, **33**, 1315 (1993).

[2.10.9] D.D. Ryutov, R.H. Cohen, Contributions to Plasma Physics, 44, 168 (2004).

[2.10.10]. (V.G. Zorin, V.A. Skalyga, et al. “Method of MHD Stabilization of Plasma in Magnetic Mirror Trap of ECR Ion Source by a Stabilizer with End-Wall Special Shape.” Inst. Appl. Phys., Nizhni Novgorod, 2007).

3. ATM System Studies

A number of system studies have been carried out on the Gas Dynamic Trap and Axisymmetric Tandem Mirror concepts. These have been carried out with differing applications in mind and with differing assumptions and models. These studies ranged from a low tritium consumption 2 MW/m2 neutron source with Q ~ 0.1 to a 1000 MWe fusion power reactor with Q > 10.

The study of Ryutov, Baldwin, Hooper and Thomassen [3.1] was for a high-flux source of fusion neutrons for material and sub-component testing. It was a modest extrapolation from present GDT experimental results (see Fig. 3.1 below) with MHD stability provided by the plasma outflow in the expander. It would operate at a low electron temperature (0.75 keV) and low Q (0.07). It would produce a neutron flux of 2 MW/m2 over an area of ~ 0.5 m2 and a volume of ~ 100 liters at each end. Because the source strength is only 2 MW, the tritium consumption would be less than 200 grams per year of continuous operation.

Pratt and Horton [3.2] considered a conventional tandem mirror and evaluated the consequences of radial transport by employing a range of drift-wave models describing toroidal systems. They considered that their models were conservative and calculated Q values in the range of 1.5 to 5.

Hua and Fowler [3.3] developed a code called SYMTRAN to evaluate the ATM. Their code includes an electron temperature gradient radial transport model and self-consistently calculated the axial confinement by the end plugs which employed 1 MeV ITER-like neutral beams. MHD stability was achieved by Post’s Kinetic Stablization concept. They sized the center cell to have a length of 30 m (the circumference of ITER) but a smaller 1.5 m radius. The 3 T magnetic field equals ITER’s confining poloidal magnetic field established with a plasma current of 20 MA. Because of the 40% beta the power output was 250 MWe. The cost was expected to be considerably less than a comparable toroidal system due to the ATM’s higher beta and simpler magnet configuration.

Moir and Rognlien [3.4] considered a more advanced concept with direct energy conversion and a thick liquid molten salt first wall and breeding blanket. They assumed radial transport was negligible because of ExB shear suppression so their design was for a smaller radius center cell which reduced the required end plug power. Thus they estimated a Q of 40.

		Ryutov	Pratt	Fowler	Moir
L	m	10	30	30	95
a	m	0.08	1.5	1.5	0.42
B-min	T	1.3	3.0	3.0	3.0
B-max	T	20	18	-	26
NBI	keV	70	70	1000	
NBI	MW	30	70		30
Ne	1e20 m-3	2.0	1.0		2.2
Ti	keV	-	30-60	22	30
Te	keV	0.75	50-150	66	
Beta	%		30	40	60
P-neut	MW	2	100-500	-	960
Flux	MW/m2	2			2.7
Area	m2	1.5x0.6			
Q		0.07	1.5 to 5	10	40

[3.1] D.D. Ryutov, et.al., J. Fusion Energy, 17, p253 (1998)
[3.2] J. Pratt & W. Horton, Phys. Plasmas, 13,042513 (2006)
[3.3] D.D. Hua & T.K. Fowler, LLNL Report UCRL-ID-204783 (June 14, 2004)
[3.4] R.W. Moir & T.D. Rognlien, Fusion Sci. & Tech 52, p408 (2007)

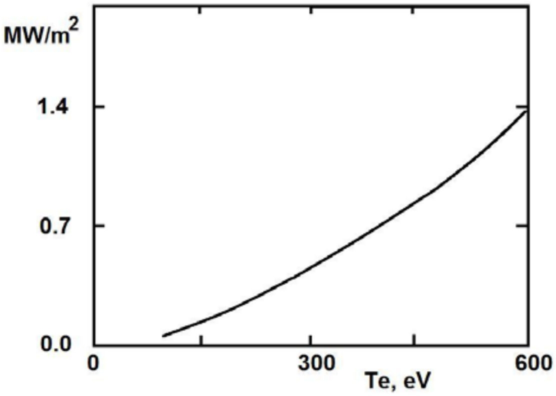


Figure 3.1. The neutron flux of a GDT type neutron source depends on electron temperature (Ivanov). To generate a neutron flux of 1 MW/m2 requires 500 eV electron temperature. Several experiments have operated up to 250 eV. Thus the extrapolation is a factor 2. It is expected that this would be achieved with the 10-fold higher injection power in the DT Neutron Source according to the established electron temperature scaling (see Fig. 4.10.3). A 1 MW minimum-B neutron source that requires an electron temperature of only 200 eV has been described by Coensgen, et., al. Nuclear Science and Engineering 106, p138 (1990).

3.1 Mirror neutron sources

Fusion has the advantages of a large supply of fuel, the promise of passively safe operation, the hope of power-plant construction materials with long lifetimes and the possibility of low-activation. Converting these promises, hopes, and possibilities to reality requires a neutron source in order to develop materials with long lifetimes (at least 10-15 $MW_e yr/m^2$, which corresponds to ~100 displacements of every atom (dpa)) and minimal activation under neutron bombardment, and to develop components needed in a fusion power plant.

The characteristics of magnetic-mirror plasma-confinement devices make them particularly appropriate for neutron sources [1-3, 5, 6]:

1. Mirrors are inherently steady-state, but can be modulated at a few kHz if desired.
2. An extensive international data-base has been developed for pulsed magnetic mirrors. The needed steady-state data-base could be generated during hydrogen operation of a neutron source, before completing the shielding and nuclear-technology portions of the facility, or in a separate facility.
3. Mirrors provide high beta confinement, $\beta \sim 1$(i.e., the plasma pressure is equal to the magnetic field pressure). This enables a high flux of neutrons to be created in small volumes of a few liters.
4. Mirrors can also provide 1-2 MW/m^2 neutron flux over the larger volumes (~100 liters to 1 m^3) needed to develop tritium-breeding blankets.
5. Electron temperatures can now reach classical values, using techniques that are understood theoretically, and demonstrated experimentally, to suppress secondary emission [4]. This reduces the heating power for a given neutron production.
6. Low tritium consumption [≤0.2 kg/yr so that tritium can be purchased and is not required to be bred in situ] and a low tritium inventory for safety. Tritium breeding can be developed in this facility.
7. High neutron flux (>2 MW/m^2) in test zones, allows accelerated testing of materials in volumes exceeding 1 liter.
8. Much lower neutron flux at the facility walls (≤0.1 MW/m^2) and low heat (≤0.6 MW/m^2), so the facility is not being “tested”.
9. The primary neutron spectrum is that of deuterium-tritium, with no high-energy tail, as in accelerator-based neutron sources (spallation or D-LI IFMIF type).
10. Simple, hence inexpensive, magnets.

11. Can use well-tested positive-ion neutral beams, extended from current operation to steady state.
12. Only fusion-relevant technologies used: neutral beam or possibly rf-heating, superconducting magnets, tritium handling, steady-state power plant operation (with Q<1).
13. Cost is ~10% of ITER.
14. Hydrogen operation allows commissioning without radiation issues.

References

1. D. D. Ryutov, D. E. Baldwin, E. B. Hooper, and K. I. Thomassen, "A High-Flux Source of Fusion Neutron for Materials and Component Testing," J. Fusion Energy **17**, 253 (1998).
2. A. A. Ivanov, et al., Phys. Plasmas **1**, 1529 (1994).
3. F. H. Coensgen, et al., "High Performance Beam-Plasma Neutron Sources for Fusion Materials Development," Nuclear Science and Engineering **106**, 138 (1990).
4. D. D. Ryutov, "Axial Electron Heat Loss from Mirror Devices Revisited," Fusion Science and Tech. **47**, 148 (2005).
5. R. F. Post and D. D. Ryutov, "Mirror Fusion Research: Update and Prospects," Comments Plasma Phys. Controlled Fusion **16**, 375 (1995).
6. D. E. Baldwin, Rev. Modern Phys. **49**, 317 (1977).

4. Mirror Experiments

In this section we describe present and recent past mirror experiments. We emphasize results relevant to the gas Dynamic Trap Neutron Source (DTNS) and the Axisymmetric Tandem Mirror (ATM) concept. Several review articles [4.1-6] describe features and results of earlier experiments as well as underlying theory.

[4.1] R.F. Post, Nuclear Fusion, v27, p1579 (1987)
[4.2] R.F. Post & D.D. Ryutov, Comments Plasma Phys. Cont. Fusion, v16, p375 (1995)
[4.3] D.D. Ryutov, Sov. Phys. Usp., v31,p300 (1988)
[4.4] D.D. Ryutov, Plasma Devices and Operation, v1, p79 (1990)
[4.5] T.C. Simonen, Proc. IEEE, v69, p935 (1981)
[4.0.6] T.J.Dolan, Chapter 11 in "Fusion Research" (available on the internet, Google Fusion Research Dolan)

4.1 Gamma-10 at Tsukuba University in Tsukuba Japan --- operating since 1980

Gamma-10 [4.1.1-2] is a thermal barrier tandem mirror device 27 m in total length. It has a central cell bounded by minimum-B MHD anchors which are connected to axisymmetric thermal barrier end plugs. A unique feature of Gamma-10 is the use of high power (0,5 MW) 28 GHz gyrotrons to generate high plasma potentials (2.5 kV) and electron temperatures of several hundred eV. Many students have produced fine theses at the Plasma Reseach Center. Gamma-10 has carried out extensive studies of plasma potential profile variations with other plasma and device parameters. Experiments with end-wall electrodes to suppress neoclassical transport, as well as with ECH have shown that sheared ExB flow stabilizes central cell drift-type turbulence. Like TMX-U, Gamma-10 operates at rather low densities of a few e18 m-3. Future plans are to incorporate ITER related divertor and plasma-wall interaction studies to complement plasma potential experiments by adding a divertor coil configuration to the central cell is being considered.

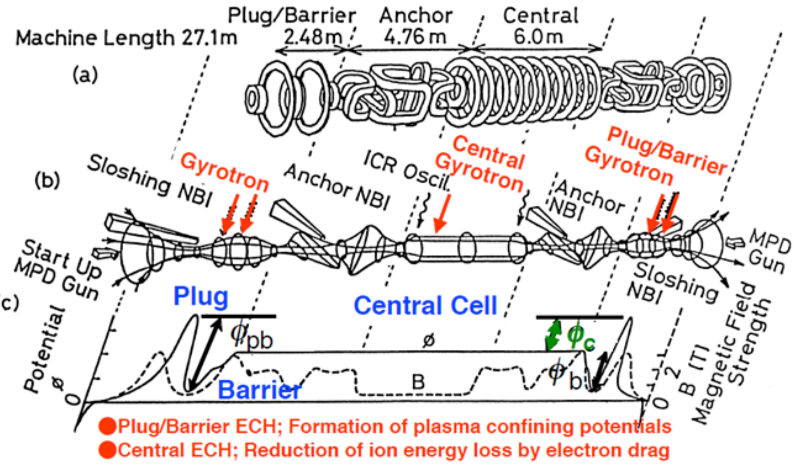


Figure 4.1 Gamma 10 magnet and power systems are shown with a typical axial potential profile.

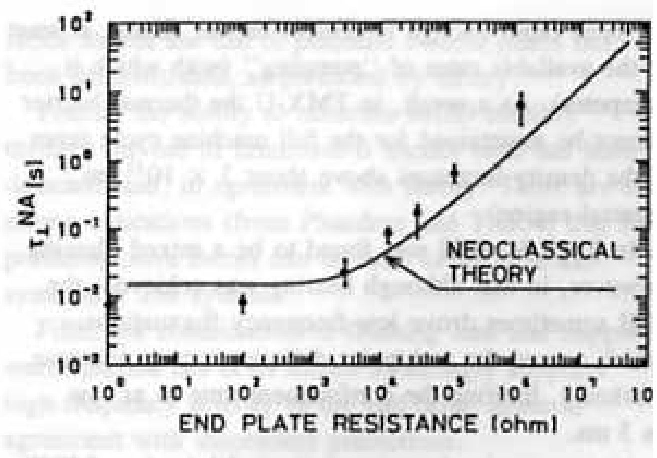
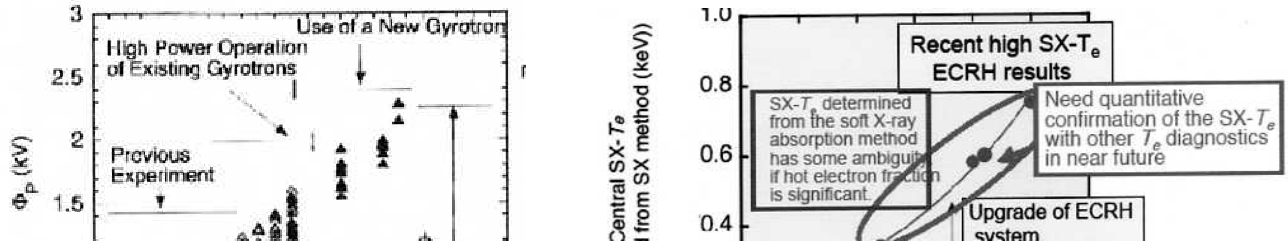


Figure 4.1.2 Gamma 10 neoclassical radial confinement time increases from 15 msec to 6 sec. when segmented end plates are floating by high resistance. Neoclassical transport is eliminated in the ATM concept.



References -------list a few key ones

Figure 4.1.3. Gamma 10 employs high power gyrotrons to increase the plasma potential and unofficial soft xray determinations of electron temperature that will be checked by Thomson scattering in the future.

[4.1.1] T. Cho et. al., IAEA Fusion Energy Conference, Chengdu, China, 16-21 October 2006, paper IAEA-CN-149/EX/P7-14.

[4.1.2] T. Cho et. al., Physics of Plasmas 15, 056120 (2008).

4.2. GDT at Budker Institute of Nuclear Physics, Novosibirsk, Russia

The Gas Dynamic Trap device [4.2.1-2] is a version of a standard simple mirror whose characteristic features are a very high mirror ratio, R, in the range of a few tens; a relatively long length, L, exceeding an effective mean-free-path, λ_{ii} lnR /R, with respect to scattering into the loss cone.

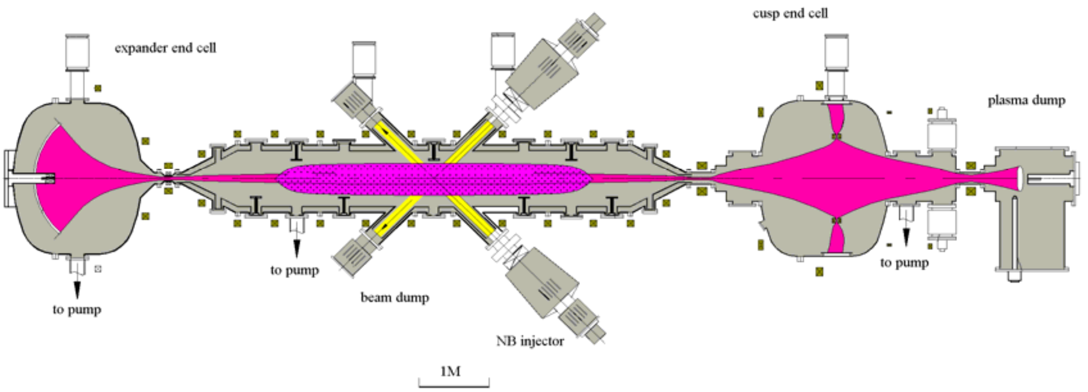


Figure 4.2.1. Conceptual layout of GDT. Currently the right end is like the left end.

The warm target plasma contained between the end mirrors is almost Maxwellian and behaves like an ideal gas in a container with a pinhole leak. It is MHD-stable even though it is fully axially symmetric. This stability is provided by non-negligible amount of plasma in the regions beyond the mirror throats, where the magnetic field has favorable curvature. MHD ballooning/interchange modes limit stability at $\beta = 40\text{-}60\%$

The electron heat flux to the end walls is suppressed by a potential drop in the expanders which develops if B(mirror) / B(wall) ~ 100 to 300. Several issues have been studied in the recent years at the Gas Dynamic Trap experiment.

1. Factors controlling the plasma electron temperature when heated by 18-20keV neutral beams with a power of up to 4.5MW. It was shown that the electron temperature is determined by gas dynamic losses through the mirrors as expected. In the operational regime of GDT when plasma steady state was reached using gas puff from periphery, electron temperatures of 150-160eV were obtained with 3MW beam power. Higher temperatures ~230eV were obtained in a transient regime without gas puff. These results confirm that with higher power (5MW) electron temperatures of ~250eV should be achievable when the plasma is sustained in steady state by gas puff at a density about $3\ 10^{19}\ m^{-3}$.
2. MHD stabilization of high-β plasma is achieved by different mechanisms including favorable pressure-weighted curvature provided by expander or cusp remote end cells and arrangement of plasma vortex flow using biased end electrodes and radial limiters.
3. Radial pinch of fast ions is observed as fast radial compressing of energetic injected ions in a time less than the slowing down time.
4. Ambipolar plugging was studied in experiments with one end cell. Injection of focused neutral beams with high power density builds up the plug density considerably higher than the center plasma density. In this case a strong reduction of axial losses was observed due to development of an ambipolar potential peak in the end cell.
5. AIC instability of fast ions in the end cell was observed when the beta and anisotropy exceeded the instability thresholds. Measurements of characteristics of unstable perturbations showed reasonable agreement with theory and previous results obtained in the TMX device.

Near-term plans in GDT include completion of neutral system upgrade reaching 4-5 MW injection power for 5ms pulses and increase of electron temperature up to ~250eV.

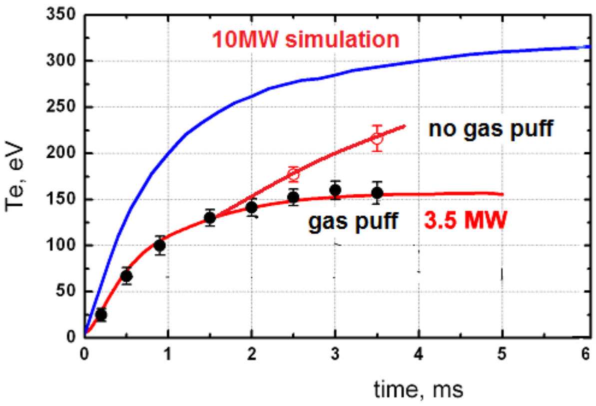


Figure 4.2.2. The electron temperature of the GDT reaches 150-230 eV with 3.5 MW of neutral beam heating power.

[4.2.1] A.A.Ivanov, et al, Steady-State Confinement of Anisotropic Hot Ion Plasma in the Gas Dynamic Trap, 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, Oct. 13-18, (2008), paper EX/P5-43
[4.2.2] A.V.Anikeev, et al, Confinement of strongly anisotropic hot-ion plasma in a compact mirror, Journal of Fusion Energy, v.26 (2007), pp.103-110

4.3. GOL-3 Multiple Mirror, Budker Institute of Nuclear Physics, Novosibirsk, Russia

Recent findings in study of multi-mirror confinement and their implications for reactor are also being investigated in the GOL-3 facility [4.3.1-3]. It was experimentally observed that plasma turbulence excited by an electron beam results in reduction of electron heat conduction to end walls by ~ 3 orders of magnitude compared to Spitzer conductivity. When very steep axial gradients of plasma pressure and electron temperature are developed (especially near local maxima of magnetic field) in the cells then high speed plasma flows are generated. Relaxation of these flows leads to an increase of ion temperature to 2-4 keV within several microseconds. Additionally, interaction of axial plasma flow with ions localized in individual cells gives rise to plasma oscillation in the cells. Transiting ions are scattered by these oscillations and subsequently trapped. These observed effects substantially increase the time of plasma axial expansion when plasma density is relatively low (of order of $10^{21}m^{-3}$) and when the mean free path of scattering of ions strongly exceeds the mirror-to-mirror distance. Realization of this regime enables reaching plasma confinement time relevant to reactor conditions for plasma beta smaller then unity thus avoiding application of radial plasma confinement by material walls, which was assumed originally.

[4.3.1] Burdakov, A.V. et al, Advances in Plasma Heating and Confinement in the GOL-3 Multiple Mirror Trap, 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, Oct. 13-18, (2008), paper EX/P5-27
[4.3.2] Burdakov, A.V. et al, Plasma heating and confinement in GOL-3 multimirror trap, Fusion Science and Technology, Vol.51, No.2T, 2007, p.106-111.
[4.3.3] Arzhannikov, A.V.et al, Study of the Mechanism for Fast Ion Heating in the GOL-3 Multimirror Magnetic Confinement System. Plasma Physics Reports, Vol. 31, No. 6, 2005, pp. 462–475.

4.4. LDX Dipole Experiment, a joint Columbia/MIT Device at MIT

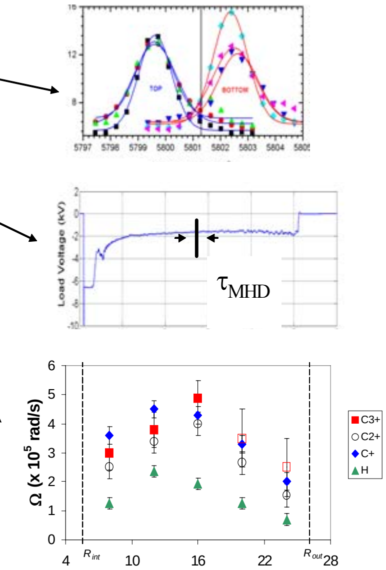
Although not strictly a mirror device, the LDX [4.4.1]floating ring experiment has shown the importance of compressibility for MHD stability. This bodes well for utilizing paraxial (short-fat) end plugs and for stabilization with shaped end walls.

[4.4.1] D.T. Garnier et. al., Phys. Plasmas 13, 056111 (2006).

4.5. MCX Rotating Mirror Experiment at the University of Maryland.

The MCX device [4.5.1] is an axisymmetric mirror with a central rod to which a high voltage is applied to generate a strong radial electric field. This causes an ExB force which causes the plasma to rotate at speeds up to mach 1 to 3. The rotating plasma has shear which stabilizes the MHD activity when the shearing rate is sufficiently large compared to the MHD growth rate. This experiment demonstrates the important role that rotation can play as an axisymmetric stabilizer.

[4.5.1] R. Ellis, Bul. Am. Physical Soc., v. 53. No. 14, p75 (2008) papers CP6 92 to 97.



1. ***Supersonic rotation demonstrated, Mach 1 to 3***
2. ***Discharge quiescent for 1000's of instability growth times***
3. ***Rotation shear rate exceeds that theoretically required for suppression of flutes by upto ×5***
4. ***Discovery of High Rotation (HR) Mode: critical velocity exceeded in bifurcation phenomenon***

Figure 4.5.1. Results from MCX show that with supersonic rotation, the discharge is stable and when the ExB shearing rate exceeds a critical value then high confinement is achieved

4.6. Phaedrus at the University of Wisconsin 1986-92

Phaedrus had a 3 m long central cell with 0.06 T magnetic field and 0.2 m radius. The end cells were minimum-B with both neutral beam and ICRF heating. Phaedrus introduced and developed the use of ion-cyclotron heating in tandem mirrors [4.6.1]. Axisymmetric operation was achieved and stabilized with pondermotive forces generated with 0.4 MW of ICRF power [4.6.2]. Pressure-weighted curvature-stabilized mhd stability limits were observed that agreed with theory [4.6.3]. Typical Phaedrus plasma parameters were density few e18 m-3, ion temperature ~ 200 eV, and electron temperature 60 eV. Phaedrus experiments indicate that pondermotive stabilization does not scale well to a reactor, although it could be used to augment stability.

References:
[4.6.1] R. Breun, et al., “Experiments in a tandem mirror sustained and Heated solely by rf,” Phys. Rev. Lett. **47**, 1833 (1981).
[4.6.2] J. Ferron, et al., [ponderomotive stabilization of effectively axisymmetric mirror], PRL
[4.6.3] A. W. Molvik, R. A. Breun, S. N. Golovato, N. Hershkowitz, et al., “Observation of macroscopic stability limits in a tandem mirror,” Phys. Rev. Lett. **48**, 742 (1982).

4.7. **TARA at MIT**

Tara (also operated in Korea as Hanbit) was built at MIT in the 80's to study axisymmetric tandem mirror confinement. Tara had an axisymmetric central cell bounded by axisymmetric plugging cells with outboard minimum-B anchors. Although the experiment was prematurely terminated it operated for a few years (86-88) and a lot was learned. Findings included divertor and pondermotive stabilization of the central cell [4.7.1], m=1 stability in the central cell (Irby et al, PF 88), radial transport in the central cell (Brau et al, NF 88) and trapped-particle-mode limitations on stability [4.7.3-4]. Tara also had very innovative antenna designs for the heating of axisymmetric plasmas (Golovato et al, PF 89). The central-cell density was relatively high (mid 10^{12} range) and they did not succeed in creating sufficient plugging to observe operation in which the radial transport dominated the central cell plasma loss.

Tara provided some observations of trapped particle modes with axicell plugging of tandem mirrors with outboard anchors. Although an axicell permits the incorporation of strong choke fields (Tara had central cell and plug (choke field) fields of Bcc =0.2 T & Bp=5 T respectively) the restriction on passing particles from trapped particle theory limited the ability to increase the mirror ratio much above 10. The central cell and the plugging cell can be independently unstable. Importantly, while central cell instability is limited by FLR to m=1, the axicell can support higher-m unstable modes. Tara observed both m=1 central cell and m>1 axicell modes in Tara. Therefore, with any end stabilizer there must be sufficient passing particles bridging both the axicell and central cell in order to stabilize modes with m>=1. Tara found that a central cell divertor added stability to the central cell.

Experience from Tara suggested the desire to skew injection in the axicell to generate sloshing ions to stabilize micro-instabilities like the DCLC. This makes the axicell longer than would be possible with perpendicular injection and also creates a challenge in designing coils with sufficient access for angled beams. Alternately beams could be injected at 90 degrees, but not at the midplane.

[4.7.1] "Experimental studies of divertor stabilization in an axisymmetric tandem mirror" Casey, J.A., Lane, B.G.; Irby, J.H.; Brau, K.L.; Golovato, S.N.; Guss, W.C.; Kesner, J.; Post, R.S.; Sevillano, E.; Zielinski, J., Physics of Fluids, v 31, n 7, July 1988, p 2009-16

[4.7.2] "Axisymmetric sloshing-ion tandem-mirror plugs", Kesner, J.,Nuclear Fusion, v 20, n 5, May 1980, p 557-62

[4.7.3] "Observation of trapped particle modes in a tandem mirror"
Gerver, M.J., Golovato, S.N.; Irby, J.H.; Kesner, J.; Casey, J.A.; Guss, W.C.; Horne, S.F.; Lane, B.G.; Machuzak, J.S.; Post, R.S.; Sevillano, E.; Zielinski, J. Source: Physics of Fluids B (Plasma Physics), v 1, n 3, March 1989, p 608-14

[4.7.4] "Stabilization of MHD modes in an axisymmetric plasma column through the use of a magnetic divertor", Lane, B., Post, R.S.; Kesner, J. Source: Nuclear Fusion, v 27, n 2, Feb. 1987, p 277-86

4.8. 2XIIB Experiment at LLNL in the mid 1970's

2XIIB was a single-cell minimum-B ying-yang magnet and was the first mirror experiment with high power neutral beams (20&40 keV injectors with a total power of 5 MW). The plasma parameters reached average beta of 70%, mean ion energy of 10 to 20 keV, electron temperature up to 160 eV. 2XIIB experiments demonstrated the stabilization of the drift-loss-cone instability with warm plasma fueled either by plasma guns or gas injection. Results from 2XIIB were incorporated into the design of the TMX end plugs.

F.H. Coensgen, et. al., "Stabilization of a neutral-beam-sustained mirror-confined plasma", Phys. Rev. Lett., 35,1501 (1975).

B.G. Logan, et. al., “High-beta Gas-stabilized Mirror-confined plasma”, Phys. Rev. Lett., 37,1468 (1976).

D. L. Correll Jr, et al., “PRODUCTION OF LARGE RADIUS HIGH BETA CONFINED MIRROR PLASMAS,” Nuclear Fusion, Vol. 20, 655, 1980.

4.9. TMX Tandem Mirror Experiment at LLNL, 1979-81

The TMX tandem mirror experiment with baseball coil end plugs demonstrated principles of the tandem mirror concept. The center cell was 5.3 m long, with a 0.2 T magnetic field and a radius of 0.3 m. The 5 MW neutral beam system per end cell utilized 24 injectors operating at 20 kV.

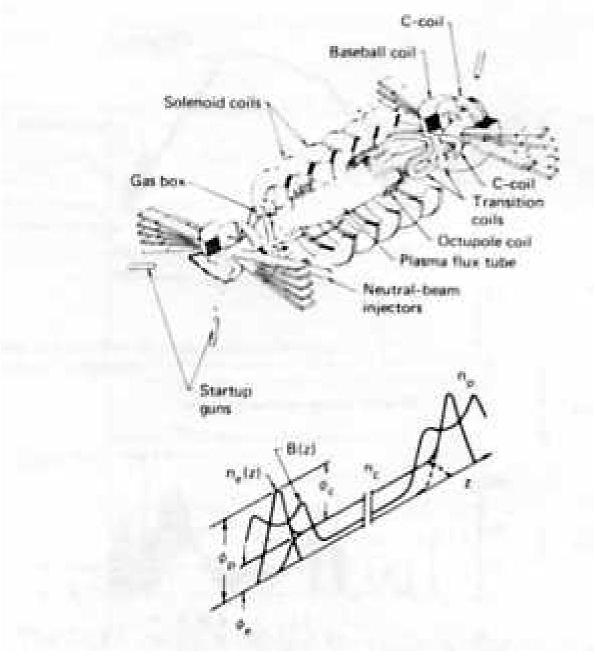


Figure 4.9.1. Tht magnet configuration and axial plasma profiles of TMX. The ATM would have similar profiles except with all axisymmetric magnets.

When the end plug densities exceeded that of the center cell then the particle confinement of center cell ions improved dramatically, resulting from an axial confining potential as high as 0.3 kV. As predicted, the central-cell ion confinement was two orders of magnitude above that of a single mirror at the same temperature, due to the confinement of low energy ions by the end-plug potentials and higher electron temperature. TMX also observed neoclassical radial transport of center cell ions. It also discovered the Alfven ion cyclotron instability driven by excessive perpendicular ion energy in the end plugs when the end plug beta was sufficiently high.

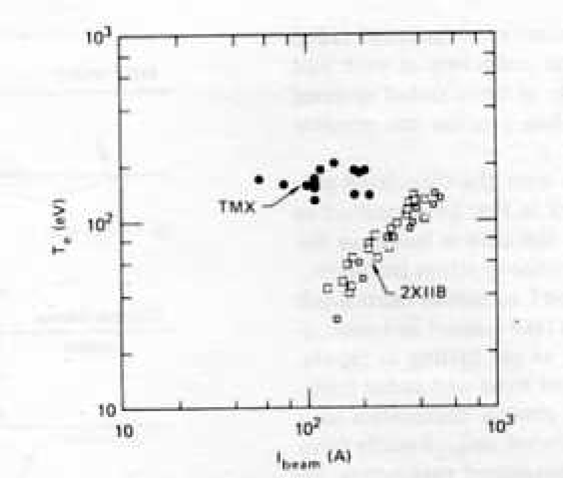


Figure 4.9.2. TMX achieved higher electron temperature than the single cell mirror 2XIIB because warm plasma fueling for microinstability suppression was in the center cell rather than from the ends.

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F. H. Coensgen, C. A. Anderson, T. A. Casper, J. F. Clauser, W. C. Condit, D. L. Correll Jr, et al., “ELECTROSTATIC PLASMA CONFINEMENT EXPERIMENTS IN A TANDEM MIRROR SYSTEM,” Phys. Rev. Letts, Vol. 44, 1132, 1980.

T.C. Simonen, Proc. of the IEEE, v69, p935 (1981)

R. P. Drake, E. B. Hooper Jr, S. L. Allen, T. A. Casper, J. F. Clauser, F. H. Coensgen, R. H. Cohen, D. L. Correll Jr, et al., “A DETAILED STUDY OF RADIAL TRANSPORT IN THE TMX CENTRAL CELL,” The Physics of Fluids, Vol. 25, 2110, 1982.

D. L. Correll Jr, et al., “AMBIPOLAR POTENTIAL FORMATION AND AXIAL CONFINEMENT IN TMX,” Nuclear Fusion, Vol. 22, 223, 1982.

D. P. Grubb, S. L. Allen, T. A. Casper, J. F. Clauser, F. H. Coensgen, R. H. Cohen, D. L. Correll Jr, et al., “ENERGY CONFINEMENT STUDIES IN TMX: POWER FLOW,” The Physics of Fluids, Vol. 26, 1987, 1983.

T.C. Simonen, Nuc. Fusion, v25, p1205 (1988)

4.10. TMX-U Thermal Barrier Experiment at LLNL 1982-87

The TMX-U central cell was 8 m long with a field of 0.3 T and a radius of 0.25 m. The TMX-U end cells incorporated skew beam injection at 45 degrees in a minimum-B end plug with mirror ratio of 4:1. Heating and potential generation utilized 24 neutral beams with 20 kV injection energy and four 28 GHz 200 kW gyrotrons   One gyrotron in each end cell midplane (to generate a mirror trapped electrons to form a thermal barrier) and one at each end cell heating at a mirror ratio of 2:1 (to generate a potential peak at the turning point of sloshing ions) generated the thermal barrier potential profile

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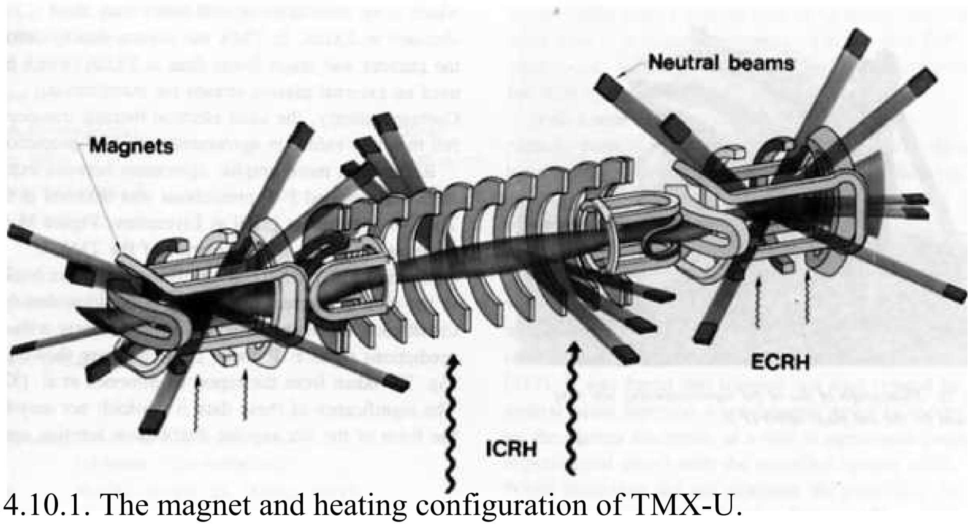

Figure 4.10.1. The magnet and heating configuration of TMX-U.

These features enabled TMX-U to create the thermal barrier configuration, with confining potential exceeding 1 kV, three times higher than that achieved in TMX. Likewise the center cell electron temperature reached 260 eV, double that of TMX and with the aid of ICRF heating or low-energy neutral beam heating in the central cell the parallel ion temperature reached 0.4 keV, four times higher than TMX. However the central cell density was limited to ~ 3e18 m-3. Due to the inability to operate at higher densities and due to a shortage of funds within the US fusion program, tandem mirror experiments ceased.

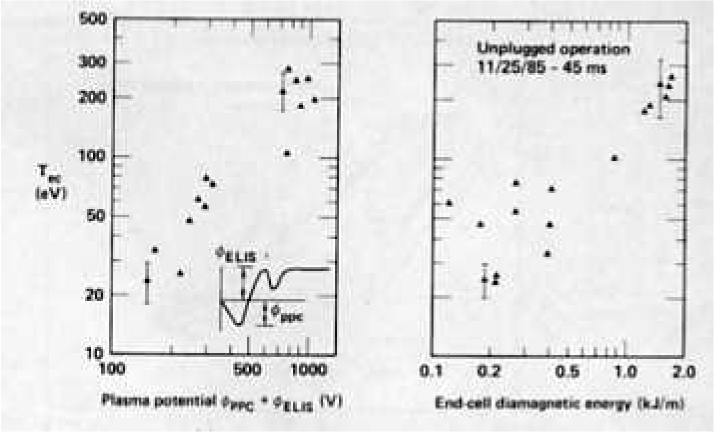

Figure 4.10.2. Central cell electron temperature as a function of plasma potential (left) and end cell diamagnetic energy (right).

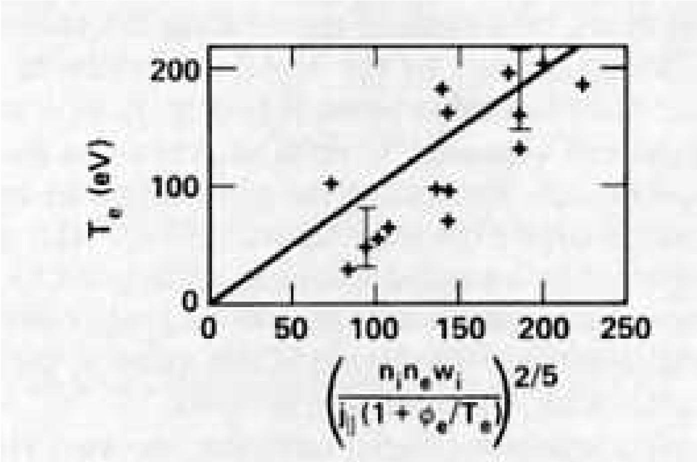

Figure 4.10.3. An illustration that the TMX-U electron temperature is determined by a simple balance of heating by energetic ions and end losses.

References

T. C. Simonen, S. L. Allen, T. A. Casper, J. F. Clauser, C. A. Clower, F. H. Coensgen, D. L. Correll Jr, et al., “OPERATION OF THE TANDEM MIRROR EXPERIMENT (TMX-U) WITH SKEW NEUTRAL BEAM INJECTION,” Phys. Rev. Letts, Vol. 50, 1668, 1983.

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G.D.Porter, Editor, LLNL Report UCID-20981, February 1, 1988.

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D.L. Correll, LLNL Report UCRL-96666, August 1, 1987

T.C. Simonen et. al., IEEE Transactions on Plasma Science, v16, p1, (1988)