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Fusion: Doing it With Mirrors

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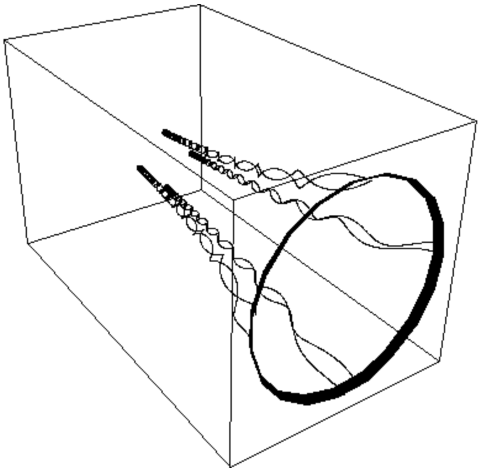
Summary: This paper is about a new approach to magnetic fusion, one that could give new life to an old fusion approach and could shorten the time to develop fusion power by decades.

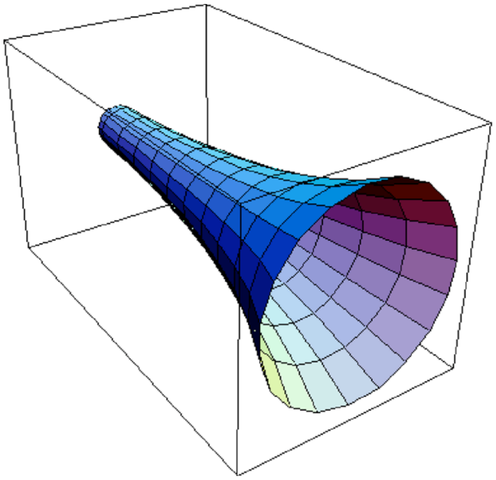
When research on the magnetic confinement of plasmas for fusion power began, over fifty years ago, there were two kinds of "magnetic bottles" being studied. One was the doughnut-shaped variety, which in time evolved to the tokamak, today's front-runner in fusion. The second was the "mirror machine," with a shape resembling a "party popper." That is, the configuration or “magnetic field-line pattern” resembled a long cylinder squeezed in near its ends. These two very different shapes represented different responses to a fundamental problem of magnetic containment: "The problem of the ends."

The problem: containing plasma in a magnetic field resembles the "containment" of water in a hose. A hose is effective at "containing" the water within itself, but is ineffective in keeping it from flowing out the ends.

A cylindrical bundle of magnetic field lines resembles a water hose as follows: if the magnetic field is strong it will curl the paths of the charged ions and electrons of a hot plasma into corkscrew-shaped orbits, thereby "containing" the ions and electrons. But such a field will do nothing to keep the plasma from escaping out the ends. The tokamak, and other similar "closed" fusion systems, solve this problem by closing the ends on themselves, thereby enclosing the field lines within a doughnut-shaped region. Now the only way a plasma ion or electron can escape to the fusion chamber wall is to cross the magnetic field lines. So far, so good. However, as fusion researchers found early on, things are not that simple. Before describing the problem they encountered we will discuss "open" systems, the subject of this paper.



Computer-generated plots of the orbits of ions injected, reflected, and returned along the (invisible) converging magnetic field lines outside a mirror machine. The ions are launched at positions 12 noon, 3 pm, 6 pm and 9 pm on the ring-shaped region at the near end.



Computer-generated depiction of the surface on which the magnetic field lines lie, along which the ions (with accompanying electrons) are injected in the manner shown in the first figure.

In their simplest form, "open" magnetic confinement systems, or "mirror machines," solve the problem of the ends by taking advantage of the "magnetic-mirror" effect. That is, a region of increased magnetic field (the "mirror") will tend to reflect and turn back tight-spiraling ions or electrons that approach that region. Thus a "magnetic bottle" can be formed by adding coils that increase the field strength at the ends of a long cylindrical bundle of magnetic field lines. This was the form of the first mirror machines that were studied. So far, so good. But, again, problems arose.

For closed systems, such as the tokamak, the problem was and is chaotic plasma motion, i.e., plasma turbulence. Turbulence causes the plasma in a tokamak to escape across the magnetic field to the chamber walls at a much more rapid rate than it would if the plasma were quiet. Though means have been found to diminish the level of the turbulence somewhat, the only satisfactory answer to this problem remains the "brute force" one: scaling up the size of the tokamak so that the plasma particles have a longer distance to go before reaching the wall. This accounts for the unwieldy size of fusion-relevant tokamaks, such as ITER.

For the mirror machine early experiments and theory showed the way to avoid the turbulence problem almost completely. However, there remained two problems: a "slow leak" out the ends and, in its cylindrical form, a tendency for the plasma to slide sideways across the field and end up on the wall, like a log rolling off the top of a hill. By the mid-1970s, an answer had been found to both these problems, but at a price.

The answer to the sideways drift was found through a classic experiment in Russia, the "Ioffe experiment." Ioffe reshaped the magnetic field of a mirror machine to form a "magnetic trough" (or “magnetic well”). This severe reshaping cured the drift but made the field complex and tended to degrade the confinement.

The concept devised to control mirror end leakage, called the "tandem mirror", was put forward, in 1976, by Dimov in Russia, and Fowler (co-author) and Logan at Livermore in the U. S. By adding short "plug" mirror cells at the ends of a mirror machine electric barriers are generated in such a way as to plug the losses. By the mid 1980's tandem mirror experiments proving the effectiveness of this plugging had been built in the U. S., Japan, and Russia. However, owing the need for magnetic-well type fields, these tandem-mirror systems became very complex. Then a severe budget cut in Washington led to the cancellation in the U. S. of all approaches to magnetic fusion but the tokamak. As of today the world effort on tandem-mirror systems is minimal. Only in Japan, Russia, and South Korea are there tandem mirror experiments.

This paper addresses a way that the mirror machine, like the legendary Phoenix, might arise from the ashes. The huge advantage that mirror machines (such as the tandem mirror) have is the possibility of containing the plasma in a non-turbulent state, with major gains, both in simplification and in economics. These gains can only be realized if the tandem mirror is reconfigured to the original simple cylindrical form. This implies that new means must be found to prevent the sideways drift that plagued mirror machines before the invention of the magnetic well. An answer was found in theory put forth in the 1980s by co-author Dmitri Ryutov (formerly of Novosibirsk, Russia, now at the Lawrence Livermore National Laboratory). Ryutov's insight was that plasma contained in a mirror machine could be stabilized against sideways drift by insuring that a small amount of plasma, acting as a plasma “anchor,” is present on the diverging field lines outside the mirrors at the ends of the machine. Ryutov's theory was then confirmed, beautifully, by experiments at Novosibirsk.

It remains, then, to find a practical way to implement Ryutov's idea in a tandem-mirror machine. This paper addresses our studies at Livermore of a novel solution to the problem. By injecting ion beams, aimed into the mirrors nearly parallel to the direction of the field lines the magnetic mirror effect acts to slow down and stop the forward motion of the ions before they reach the mirrors. In this way a plasma is formed, so to speak “in mid air”. This plasma then stabilizes the interior plasma, and at a power "cost" that is small compared to the total fusion power output. Computer simulations and theoretical analyses have been performed that bear out our optimistic predictions. It is our hope, indeed our conviction, that the venerable mirror machine can take on new life and could become the answer that fusion has so long been waiting for.

Reference:

Post, R. F., The Kinetic Stabilizer: Further Calculations and Options, Transactions of Fusion Science and Technology, American Nuclear Society, Vol. 43, Pages 195-202, The Fourth International Conference on Open Magnetic Systems for Plasma Confinement, Jeju Island, Korea, July 1-4, 2002, LLNL Report Number UCRL-JC-148763

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