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SELF COLLIDING BEAMS ("MIGMA") AND CONTROLLED FUSION

B. Maglich, M. Mazarakis, R. A. Miller,
J. Nering, S. Channon, and C. Powell
Fusion Energy Corporation, Princeton, N.J. 08540

and

J. Treglio*
Stevens Institute of Technology, Hoboken, N.J. 07030

While much of the early work on colliding beams was done in the U.S., the lead in the development of this technique is now held by Europe. The most spectular being the only colliding beams of nuclei in the Intersecting Storage Rings at CERN. It may be for this reason that the idea of using colliding beam technology as a means of achieving fusion has not reappeared until just recently. The idea of using colliding beams for fusion is nearly as old as is the interest in fusion as a source of power, but the problems of low reaction rate and high coulomb scattering initially seemed insurmountable. This work describes recent work done at Fusion Energy Corporation which attempts to overcome these problems.

Before turning to our own work, let us examine the well know facts about CERN ISR in a manner suggesting comparision with traditional plasma thermonuclear machines. The confinement time of the ISR is 235 days, that is, a beam stored in the morning has decreased by less than a percent in intensity by evening. The parameter, $n\tau$, density times confinement time can easily be found to be about 10^{17} cm^{-3} sec compared with present plasma values of no better than 10^{13},"Lawson Criterion" (see below) values of 10^{14}, and values of 10^{17} required when the Lawson Criterion is corrected by a number of realistic considerations (see below). Another parameter of interest to plasma researchers is $\beta = 8\pi\ nkT/B^2$, which is the ratio of kinetic energy density to magnetic energy density. In magnetically confined plasmas, this ratio must be less than 1. At ISR the ratio is 36 in the curved sections and as much as 10^8 in the straight sections. The difference may be attributed to the high degree of order of the motion in a beam compared with a plasma.

Figure 1 shows another advantage of beam technology simply in the higher energies attainable. In this figure we have plotted the reaction parameter $\langle\sigma v\rangle$ as a function of beam energy for several processes, assuming head-on collisions (which will be shown to be a good approximation in a migma). The processes shown are charge transfer (CT), multiple coulomb scattering (MS), elastic scattering, which includes synchrotron radiation $dd \to pt$ or nHe^3, and the fusion reaction $dHe^3 \to pHe^4$. Also indicated are the equivalent energy ranges of present and future plasma devices and present and future migma devices. A more detailed description of this curve appears in reference 1. It is possible to operate a net energy producing reactor in regions where loss rates exceed gain rates, but this requires, for example, extremely good confinement, and the difficulty involved probably plays a large part in the slow progress experienced by plasma research programs. Those of us used to ordinary physics, where experiments are planned and executed in some fraction of a professional lifetime, are naturally drawn to the region near 1 MeV, where losses fall below gains. The basis of the migma principle of controlled fusion can be explained by referring to Fig. 2. If the hypothetical two storage rings of deuterons shown were constructed, multiple coulomb scattering would destroy the beam long before any significant fusion had occurred. If instead, the colliding beams were placed in the axially symmetric single volume as shown, a particle scattered in the horizontal plane would be returned to the central

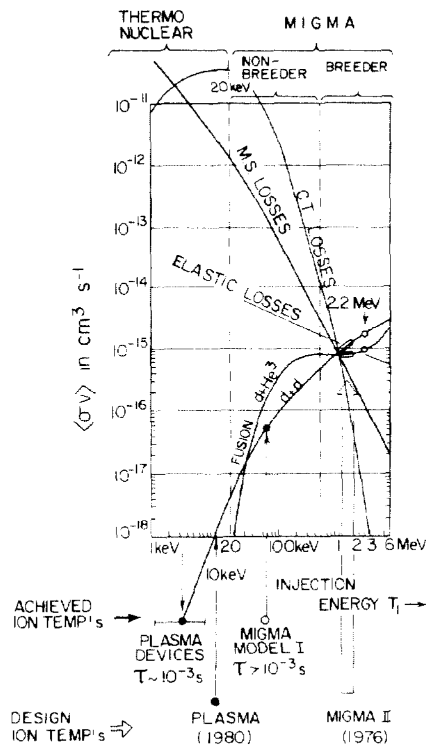

Fig. 1. Reaction parameter $\langle\sigma v\rangle$ for various losses and gains as a function of beam energy for head-on collisions.

region. If, in addition, the field is given a shape of the form: $B_z = B_0(1 - kr^2/R^2 + kz^2/R^2)$, the particles will precess about the center in the horizontal plane and be focussed to the midplane vertically[2,3] as shown in the lower two diagrams in Fig. 2. This configuration is called "migma" from the Greek word for "mixture". The migma configuration naturally results in a very sharply peaked central density and consequently in a very sharply peaked reaction rate. Fig. 3 shows the result of a Monte Carlo simulation of fusions in a migma; 95% of the fusions take place in 2.5% of the radius.

The central region of a migma is equivalent to an infinite number of colliding beams at all crossing angles. However, the flux is largest for beams meeting head-on, and, further, the fusion rate increases strongly with relative collision energy. As a consequence, the fusion rate is the same as if all collisions were between deuterons with a relative crossing angle of about 165° or nearly head-on.[3]

It is known that in focussing machines the mean squared beam spread increases linearly with time rather than cubically with time as in a nonfocussed situation. Multiple coulomb scattering is similarly suppressed in a migma. The exact calculation is given in reference 4.

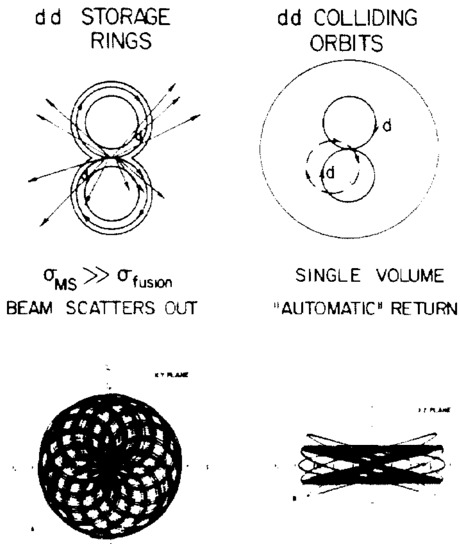

Fig. 2. Comparison of migma with a hypothetical pair of intersecting storage rings.

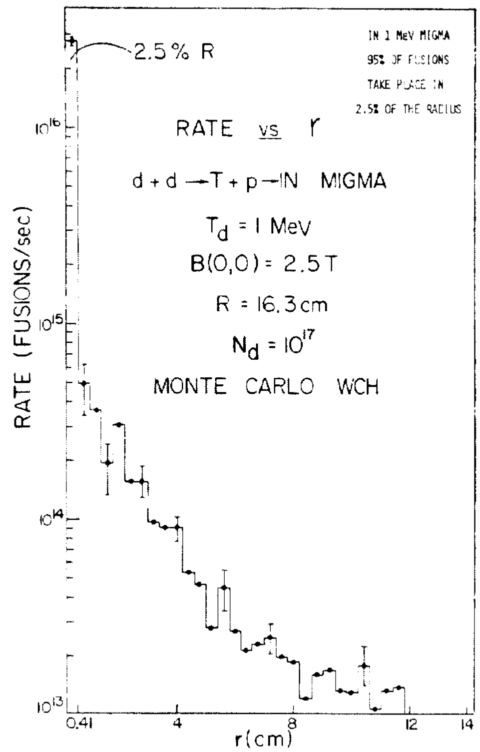

Fig. 3. Monte Carlo calculation of relative fusion rate as a function of radius in a migma.

For reasonable vertical confinement the scattering time is found to be longer than the fusion time.

Migma has some superficial features in common with mirror-confined plasmas, including the DCX series which was an attempt to heat a mirror-confined plasma by a beam of up to 600 keV. The differences are actually many and important. To begin with, migma is highly organized, resulting in the high central density and predominance of near head-on collisions already mentioned. The gradient of the magnetic field is large across a migma orbit, while it is essentially zero across the lower energy plasma orbits. Among other things, this means that migma is focussed rather than confined by magnetic pressure. Because migma is focussed, a ratio of kinetic to magnetic energy density, β, greater than 1 can be achieved. Because ions are injected directly, MeV energies can be attained, compared with roughly 1 keV in present plasmas. In addition to the advantages discussed in connection with Fig. 1, higher energies also allow the use of non-polluting advanced fuels. [5]

A graphic demonstration of the difference between migma and plasma is shown in Fig. 4. The two sets of lines plotted are flux lines and migma energy envelopes are obtained from the requirement of conservation of canonical angular momentum and are the boundaries of migma ions of given energy. Plasma, on the other hand will be bound to the flux lines. One consequence of this is that migma does not obey the Alfven mirror relation that plasma does.

As mentioned earlier, Fig. 1 seems to indicate that around 1 MeV is the favorable energy region for dd fusion. However, dd plasma reactors were targeted for about 100 keV. This difference is puzzling and is rooted in the "Lawson Criterion". [6] The Lawson Criterion was developed by J. D. Lawson almost 20 years ago. It is derived from a simple energy balance equation and includes a single conversion efficiency for

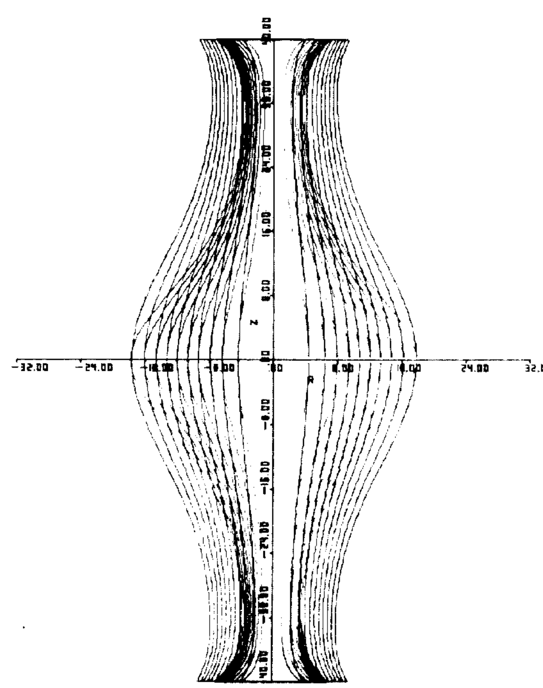

Fig. 4. Magnetic flux lines compared with the more sharply curved migma energy envelopes for the same magnetic field. (See text).

all forms of energy emitted by the reacting medium. Lawson clearly stated that this criterion was "idealized" and "by no means sufficient for the successful operation of a thermonuclear reactor."[6] Reference 1 includes 18 effects not in the original Lawson Criterion used to derive a more realistic criterion. Fig. 5 shows the resulting values of $n\tau$ for energy break-even for a set of parameters representative of plasma

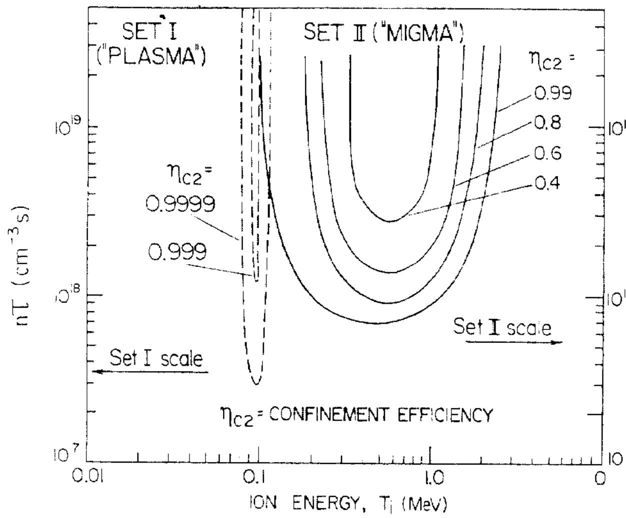

Fig. 5. Plot of $n\tau$ as a function of energy from reference 1.

and a set representative of migma for the dd reaction. Reference 1 should be consulted for a discussion of the choice of parameters. Note that the minimum value of $n\tau$ for plasma is more than 10^{17} cm^{-3}sec compared with approximately 10^{15} cm^{-3} sec given by the Lawson Criterion for the dd reaction. This minimum, however, requires a confinement efficiency of 99.99%; that is, for every 10,000 deuterons scattered through 90°, only 1 can escape. The migma curves, however, show a minimum of about 10^{15} cm^{-3} sec at about 600 keV for a confinement efficiency of only 60%.

It should be noted that there is no serious plan to build a dd plasma reactor; all present plans call for the dt reaction. It is an advantage to be able to use the dd reaction, because tritium is rare, radioactive, and expensive. More importantly the dt reaction has as a product a 14 MeV neutron which carries most of the energy. These neutrons pose serious technological problems of activation, radiation damage and thermal pollution because their energy can only be converted thermally.

If only positive ions are injected into a migmacell, their density is limited by the space charge limit to about 10^{13} cm^{-3}. At that density the fusion power is a small fraction of a watt. In order to achieve useful power densities it will be necessary to neutralize the positive charge with electrons. Two schemes have been proposed to accomplish this. The first scheme is simply to impregnate the migma with a thermal electron gas. It is shown in reference 7 that the electrons will be limited to about 100 keV by radiation and that at that temperature they will be only weakly coupled to the ions by multiple coulomb scattering. The second scheme is to have ordered electron motions as well as ion motions by inducing vertical oscillations of electrons along the magnetic field lines.[8]

In order to develop these ideas the experimental set-up shown in Fig. 6 was constructed.[9] A 108 keV D_2^+ beam is accelerated, analyzed, and focussed in the migma chamber, which is shown in more detail below. By means of differential pumping and cryosublimators a vacuum of 10^{-12} torr was obtained in the chamber. A

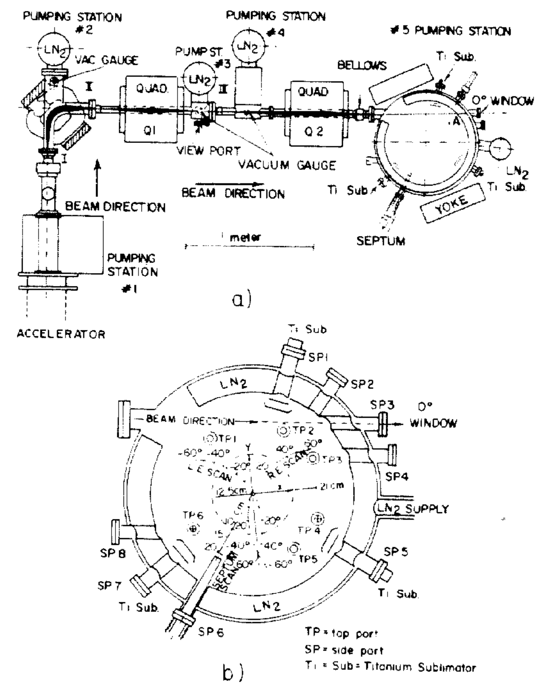

Fig. 6. Experimental set-up at Rutgers.

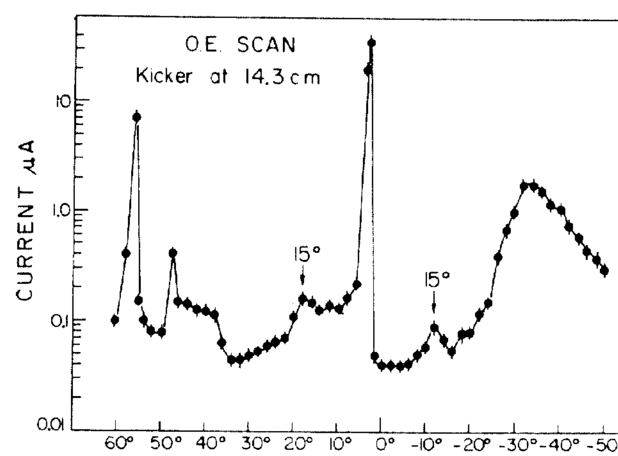

Fig. 7. Typical scan with one of the movable probes.

non-linear electrostatic kicker was used to inject the beam into the chamber. Two curved scans with tungsten probes shown in Fig. 6 intercepted the beam at a number of points and the path of the beam could then be reconstructed by computer. Fig. 7 reproduces a typical scan by one of the movable probes. Fig. 8 shows a typical computer fit to a scan, but not the scan of Fig. 7. The kicker injects the beam into the self-colliding configuration we call "figure of 8". In this configuration the D_2^+ molecules dissociate and form atoms which are then well confined by the magnetic field. The 15° peaks in Fig. 7 are at exactly the location and have the symmetry expected of atomic migma orbits. Solid state counters were placed near the interaction region and the proton and triton peaks from the dd re-

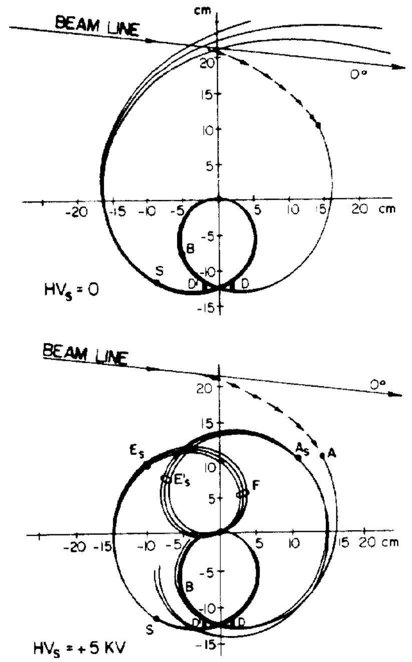

Fig. 8. Computer generated orbits fit to observed interceptions of beam by probe. Upper and lower plots are for non-linear kicker off and on, respectively.

action were observed. However, proof that these come from beam-beam interaction by showing quadratic dependence, will be obtained with the new experimental set-up.

Fig. 9 shows the new experimental installation at Fusion Energy Corporation, which is now nearing completion. A 3 MeV van de Graaff accelerator will allow experimentation in the MeV region as is suggested by Fig. 1 and Fig. 5. Provisions are made for differential pumping to reach ultra-vacuum. A special superconducting magnet has been designed and built which produces 50 kG at the center and 60 kG on the windings. Data taking will be semi-automated through the use of digital drive scanning probes. Electrostatic quadrupoles will be used exclusively for beam transport.

Instabilities that may develop in a neutralized migma will be more akin to those in accelerators and storage rings than those in plasmas. Studies of instabilities are under way but are beyond the scope of this brief report.

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* Reserach supported by Fusion Energy Corporation.

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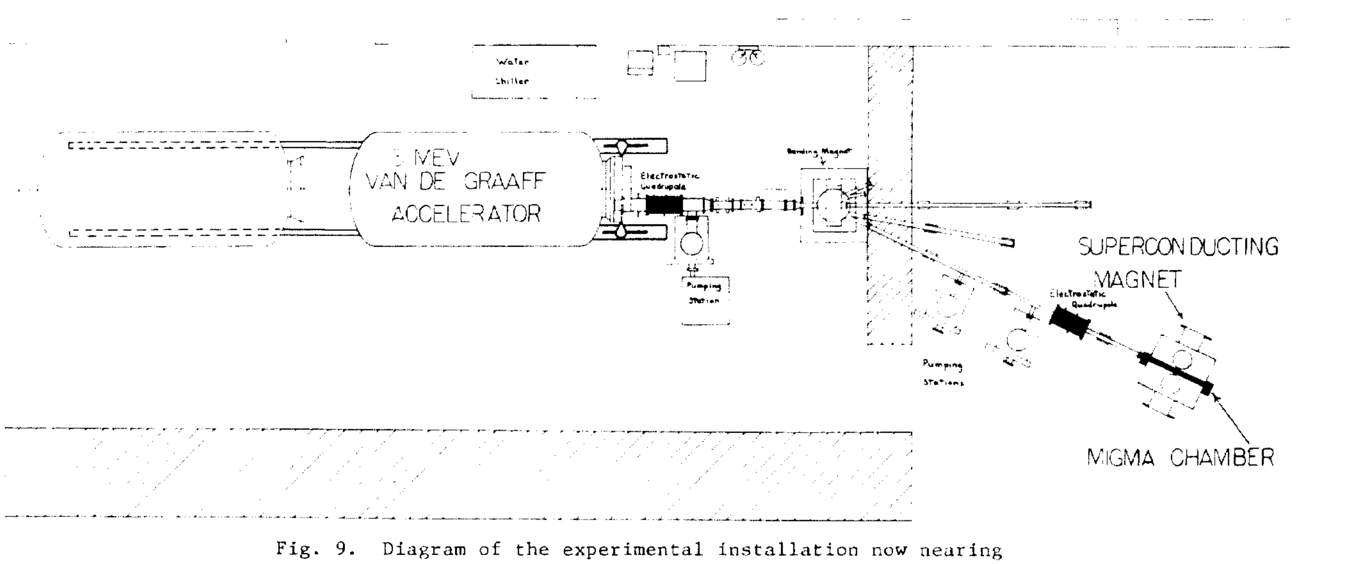

Fig. 9. Diagram of the experimental installation now nearing completion at Fusion Energy Corporation, Princeton, N.J.