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DESIGN CONSIDERATIONS FOR A MIGMA ADVANCED FUEL FUSION REACTOR

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Summary

The migma concept is being pursued at Fusion Energy Corporation as a means of achieving controlled fusion.[1-4] The features which distinguish this concept from other controlled fusion concepts may be summarized as:

1. High energy
2. Ordered motion
3. Use of advanced fuels
4. Small physical size

Beams of ions are injected into the field of a superconducting magnet at MeV energies. The resulting motions of trapped ions have a high degree of order in phase space compared with a thermalized gas. At MeV energies the two major ion loss mechanisms, charge transfer and multiple Coulomb scattering, are greatly suppressed compared with thermonuclear energies (1-100 keV), because the cross section for multiple Coulomb scattering falls off as $T^{-1.5}$ and that for charge transfer approximately as T^{-5}.

Because ions are injected at nearly the average energy of the migma, it may also be said that, as a practical matter, the use of ordered motions facilitates the attainment of colliding energies in the MeV range. The ion motion is essentially that of precessing orbits which all intersect within a central core that is small compared with a gyrodiameter. Motion along the magnetic field lines is confined by a non-adiabatic focusing.

The high collision energies obtainable enable the use of what are called "Advanced Fuels," that is, fuels other than the deuterium-tritium (D-T) mixture planned for, e.g., the tokamak fusion reactor. These fuels require higher collision energies for useful reaction rates. The advantage of advanced fuels is that they do not produce the 14 MeV neutron that the D-T reaction does. Thus, the problems of neutron activation are less, and, since most or all of the energy is released as kinetic energy of charged particles, the use of direct conversion to electricity is possible with its benefit of reduced heat rejection. In addition, advanced fuels do not have the problem of maintaining an inventory of a radioactive gas which diffuses extremely readily--tritium.

Helium-3–helium-3 is proposed for the next series of experiments because it releases no neutrons on reacting. Helium-3 might also be used for practical power generation in cases where cost was not a prime consideration. The cost of producing electricity using the helium-3–helium-3 reaction was estimated to be 4 to 6 cents per kilowatt-hour in 1976 dollars. This cost includes direct and indirect fixed costs, fuel, mantenance, and profit.[5] Another promising fuel is deuterium by itself. The deuterium-deuterium reaction releases one approximately 3 MeV neutron in 50% of the reactions and so requires some neutron shielding and thermal conversion of energy. The cost of producing electricity using the D-D reaction was estimated to be from 4 to 14 cents per kilowatt-hour on the basis quoted above.[5] The variation in cost is due to assumptions about the power level of an individual migmacell. The larger cost is for cells producing 100 kW each, and the smaller cost is for cells producing 1 MW each. The injection energy for helium-3 would be approximately 4 MeV while the deuterium injection energy would be slightly less than 1 MeV.

Another advanced fuel reaction, which is very desirable is $p + {}^{11}B \rightarrow 3\alpha + 8$ MeV. Because the energy is released as 3 alpha particles of approximately equal energy, there would be no appreciable neutron activation problem, and direct conversion would be easier than for the other reactions. The $p^{11}B$ reaction, however, suffers from an expremely high multiple scattering rate and so remains speculative at this point.

Because the ion motion is highly ordered, the active reaction volume is relatively small, that is, less than or on the order of one cubic meter in volume. This implies some savings in magnet costs over what would be needed for a randomized distribution.

The near-term consequence of the small size of an individual migmacell is that the principle can be tested more quickly and for less money than schemes in which the individual reacting volume is much larger, as, for example, the tokamak.

A more long-term advantage is reflected in economic considerations as is discussed in reference 5. A multi-megawatt central power station would contain a large number of identical migmacells. Thus, if any given cell failed, the total capacity of the plant would be only minimally affected. This is to be contrasted with present-day fission power plants where failure of one reactor may reduce the plant capacity by 50%. Recently projected fusion power plants based on the tokamak have had even larger capacities for single reactors.

Since a central power plant would be composed of small units, producing approximately a megawatt each, the capacity of the plant could be matched closely to the demand and could be increased by small amounts to allow for growth. Thus, it would not be necessary to install and pay for overcapacity to allow for future growth. This is a substantial economic advantage.

Recent experience appears to indicate that 1000 megawatt power plants are somewhat beyond the optimum size, particularly if the community total energy concept is developed. In this concept, relatively small power plants are placed close to the consumer, be it a residential community or an industrial complex. Transmission costs are thereby reduced; the probability of regional power outages is reduced; and the heat produced in the generation process can be used as space or process heat thereby converting a potential pollutant into a product.

Power Balance

The operation of a migmacell may be thought of as power amplification. A beam of high energy fuel ions is injected into a migmacell and unburned fuel ions and fusion products emerge carrying more power than the injected beam. This power is then converted directly to electricity by deceleration or possibly by other processes. If the injection and conversion efficiences are high enough the resultant power is sufficient to power the injector with net power remaining for distribution. The direct conversion efficiences must be from 60% - 90% for net power production, depending on the power level and efficiency of confinement, which are the subjects of the research and development program. Power is also emitted from the cell in the form of radiation and hot electron leaks. This power would most likely be converted into electricity thermally and therefore with lower efficiency. With this power included in the power balance calculation, the heat rejected becomes approximately equal to the net power produced, as compared to a ratio of two for fission power plants and the proposed D-T fusion schemes.

The determination of the fusion power gain as well as the important classical loss processes is made using a Monte-Carlo collisional transport code. The transport code provides a means of obtaining the equilibrium ion distribution function, f(r,v), as a function of r, z, v_p and v_z, where $v_p = (v_x^2 + v_y^2)^{1/2}$ at z=0. This distribution function is obtained by considering the following processes:

1. Ion-ion Coulomb scattering
2. Ion-ion nuclear elastic scattering
3. Electron-ion Coulomb scatteirng (energy transfer only)
4. Charge transfer with background gas, and
5. Fusion

The electron temperature is determined self-consistently by equating the rate of energy gain by electrons, through ion-electron collisions, to the rate of electron radiation (bremsstrahlung and synchrotron) and leakage of electrons. The determination of synchrotron emission involves the determination of the self absorption of synchrotron radiation by electrons.

The absolute fusion power level is important not only for economic reasons, but also because synchrotron radiation losses are dominant at lower power levels and become relatively less important at high power levels (megawatt). At high power levels diamagnetic effects become dominant and so have to be explicitly included. We have proposed a five-year research and development program leading to a demonstration migma reactor producing approximately 1 KW of fusion power. At this power level diamagnetism has been calculated to be signigicant but not yet dominant, which was a major consideration in selecting this power level as a goal.

At higher power levels the diamagnetic field produced by the ions significantly affects the motion of the ions, which in turn affects the diamagnetic field produced. An accurate calculation of diamagnetism must therefore be self-consistent, that is, the ion density distribution, the total magnetic field (external and diamagnetic), and the ion motion must all predict each other. The result of such a calculation shows that a one megawatt reactor can be attained if an external magnetic field of 5 to 7 Tesla can be provided in a volume of something less than a cubic meter.

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