Wall Protection for the MICF Fusion Propulsion System

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Abstract. A preliminary design of a reaction chamber for the Magnetically Insulated Inertial Confinement Fusion (MICF) propulsion system is presented. Special emphasis is placed on protecting the walls of the chamber from the debris of the micro-explosion, which takes place at the end of the fusion burn. The protection in question is provided by an externally applied magnetic field which becomes compressed under the pressure from the plasma and the fusion reaction products such as the alpha particles. It is shown that an external field of about 3 kilogauss provides the needed protection from a chamber of about 3 m radius made of a carbon composite material. The total mass (field coils, and chamber walls) of the reactor is found to be 10 mtons.

INTRODUCTION

The Magnetically Insulated Inertial Confinement Fusion (MICF) system has been shown to possess propulsive capabilities that render interplanetary and some interstellar missions achievable in a human's lifetime. The system makes use of spherical pellets whose inner walls are coated with a fusion fuel such as Deuterium-Tritium (DT) that can be ignited by a laser or particle beam that enters the target pellet through a hole. This fusion scheme combines the favorable aspects of both magnetic and inertial fusion in that physical containment of the hot plasma is provided by a metallic shell e.g. tungsten, while its thermal energy is insulated from that wall by a strong, self-generated magnetic field. With the self-generated internal magnetic field compressing the fusion reaction we get much longer burn times, and as a result much larger energy gains per pellet. The use of laser or particle beams generally results in massive vehicle, and though currently considered not feasible, the use of anti-protons to ignite these pellets can lead to *smaller* mass systems. As a propulsion device, MICF makes use of a reaction chamber into which the pellets are dropped at a pre-determined rate and zapped by the appropriate driver. At the end of the burn the pellet (or the ionized debris) is guided by a magnetic nozzle to generate the thrust. One of the important technological problems facing this propulsion system is protection of the walls of the reaction chamber. This can be achieved with the use of an external magnetic field that can be designed to include the magnetic nozzle. We address the issue of wall protection of this method and calculate the field strength, chamber size, coil characteristics, and overall mass.

TECHNICAL CONSIDERATIONS AND RESULTS

We provide in this paper the reasoning and the calculations supporting the use of a simple magnetic field to protect the inner wall of the reaction chamber against the products of an MICF, DT pellet of several hundred megajoules yield. The reason that simple field geometries are adequate for such particle beam (antiproton) induced thermonuclear reactions lies in the short plasma confinement time needed. In fact, the magnetic field need not even confine the exploding plasma but need only decelerate it sufficiently to prevent wall damage. However, our preliminary calculations indicate actual cylindrical confinement, thus protecting the first wall for times beyond a plasma recoil back towards the axis. Our geometry is the simplest, a micro-explosion occurring on the axis of a long solenoid with constant (long the length) initial magnetic field. Our objective it to protect the wall of the solenoid, yet allow the plasma to stream toward the nozzle on one end to generate the thrust.

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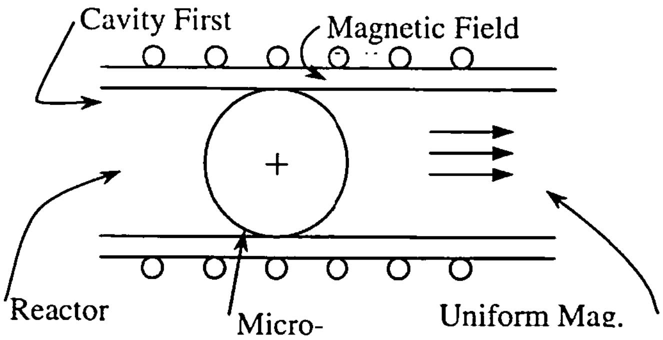
In keeping with the philosophy of worst-case investigation we calculated the equatorial containment of the plasma by applying equatorial parameters to spherical geometry. In our case the actual geometry is cylindrical, which will relieve pressure axially, thus imposing a lesser containment burden than indicated from spherical geometry calculation.



If we assume that solenoid resistance is negligible and that coil windings are arbitrarily light, a compressed magnetic field cannot penetrate the coil winding. We invoke the conservation of magnetic flux to calculate the compressed field B.

$$B = \frac{Bo}{1 - \frac{R^2}{Ro^2}} \tag{1}$$

This allows us to calculate the magnetic pressure, Pm, which resists the plasma expansion.

$$P_M = \frac{B^2}{8\pi} \tag{2}$$

The work done by expanding the plasma, W, is that done on the magnetic field, Wm, plus that compressing the residual gas W_{RG}. We choose Ro to be coil radius and Bo the initial uniform magnetic field.

$$\int P_m dV = W_M = \frac{Bo^2 R_0^4}{2}\left[\frac{R}{2\left[R_0^2 - R^2\right]} - \frac{1}{4R_0}\ln\left[\frac{R_0 + R}{R_0 - R}\right]\right]$$

$$\int P_{rg} dV = W_{RG} = \frac{4}{3}\pi PgR^3$$

$$W = W_{MagneticField} + W_{ResidualGas} = \frac{Bo^2 R_0^4}{2}\left[\frac{R}{2\left[R_0^2 - R^2\right]} - \frac{1}{4R_0}\ln\left[\frac{R_0 + R}{R_0 - R}\right]\right] + \frac{4}{3}\pi PgR^3$$

So this gives us the stopping power of the magnetic field in terms of Ro, Bo, and the final stopping radius, R, given the residual gas density (ρ_g) and an initial total energy of the plasma. We consider two different cases of expanding plasmas (because of the decay times of each of the "waves"), the alpha particles and the pellet and shell debris plasmas.

The energy of the alpha particle plasma is given by:

$$E_\alpha = n_\alpha \overline{n}$$

$$E_\alpha = 7MJ$$

The energy of the debris plasma can be determined knowing its mean temperature and number density :

$$E_p = 15MJ$$

From here we can find for a given plasma parameter the distance at which the debris is no longer traveling radially (I will refer to this as "stopped' from now on).

I will now consider 3 cases for the residual gas density.

- $\rho_g=0$
- $\rho_g=10^{12}\ {}^{DT}\!/_{cm^3}$
- $\rho_g=10^{17}\ {}^{DT}\!/_{cm^3}$

Any gas density larger than this seriously affects the operation of the driver (laser or particle beam) to ignite the pellet. However it should be noted that although our current analysis does account for the reversal of the debris, it does not account for the effect the expanding plasma has on the residual gas. For the first two cases it is a good approximation to say that there is very little effect, however for the high residual gas density we must account for the effect the expanding plasma has on the residual gas. To do this we use conservation of momentum and assume that the magnetic field is the only force that can affect the momentum of the initial plasma.

$$p_m = \int_0^R F(R)\frac{dt}{dR}dR$$

$$v = \frac{dR}{dt} = \frac{c}{m_o + m_r(R)}$$

c is a constant, m_o is the initial mass of the debris plasma, and m_r is the mass of the residual gas.

$$F(R) = P_m A = \left(\frac{B_0^2}{2}\right)\frac{R^2}{\left[1-\left(\frac{R}{R_o}\right)^2\right]^2}$$

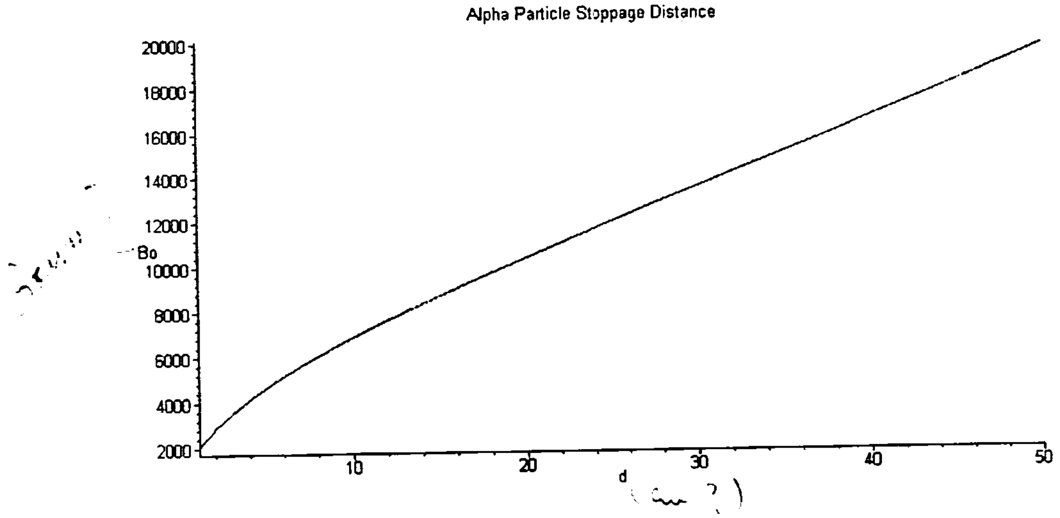
Now plugging into p:

$$p_m = \frac{B_0^2 R_0^4}{2c}\int_0^R \frac{R^2 m_{o+}\rho_0(\frac{4}{3}\pi R^3)R^2}{\left(R_o^2 - R^2\right)}dR$$

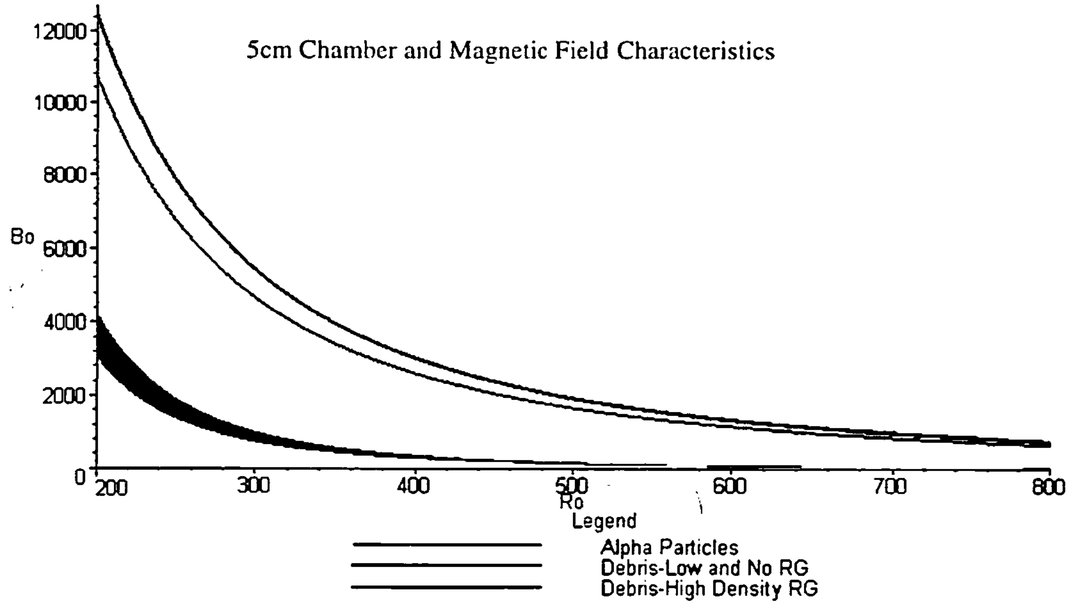
which solves to:

$$p_m = \frac{B_0^2 R_0^4}{2c}\left[m_0\left(\frac{R}{2\left[R_0^2 - R^2\right]} - \frac{1}{4R_0}\ln\left[\frac{R_0+R}{R_0-R}\right]\right) + \rho_0 \frac{4}{3}\pi\left(-\frac{1}{2}R_0^2R^2 - \frac{R^4}{4} - \frac{1}{2}R_0^4\ln\left(R_0^2 - R^2\right)\right)\right]$$

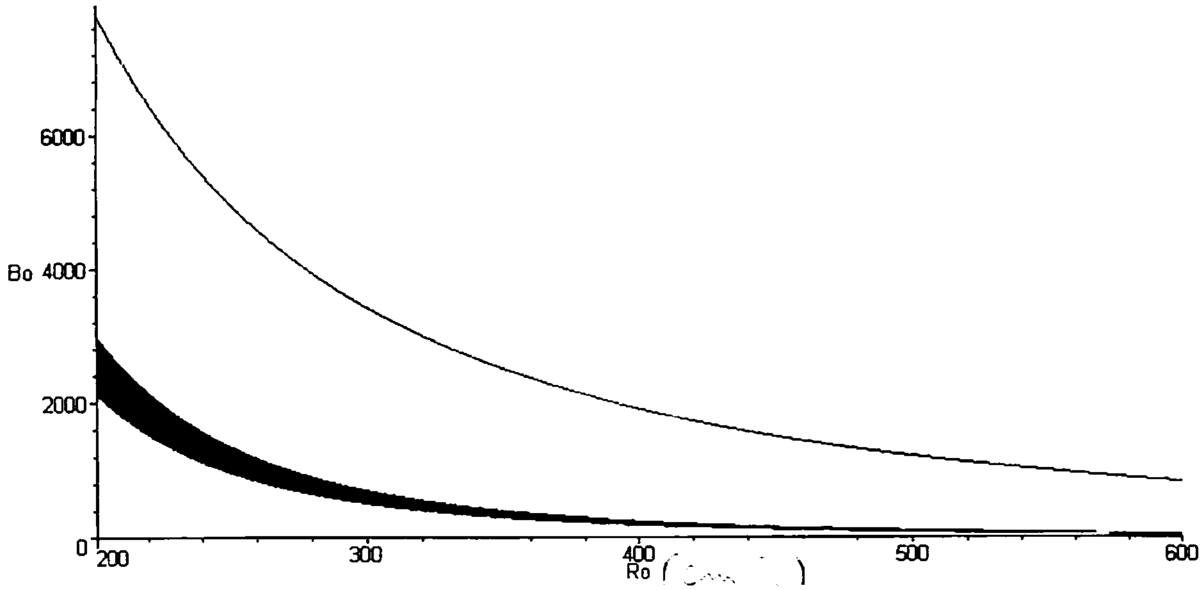
If we arbitrarily (at this point in the analysis) assume a chamber radius of 3 meters, we can determine the stoppage distance from the wall as a function of the initial magnetic field for each of these three cases. Once caveat to this analysis is that we must define how much of the energy in the expanding plasma is kinetic energy, so I'm going to continue on in this analysis by saying 50%-100% of the energy is kinetic (the actual value is close to 100%. but for now a rough approximation is sufficient).



Using the debye length for this temperature/density plasma we can determine that a distance of 2.8 cm is sufficient to prevent significant damage/heat transfer to the chamber wall. Two cases for the stopping distance will be considered, 2.8cm and 5 cm (for a large safety margin). Then it is a matter of simple algebra to find the initial magnetic field versus the initial chamber radius for a specified separation distance.



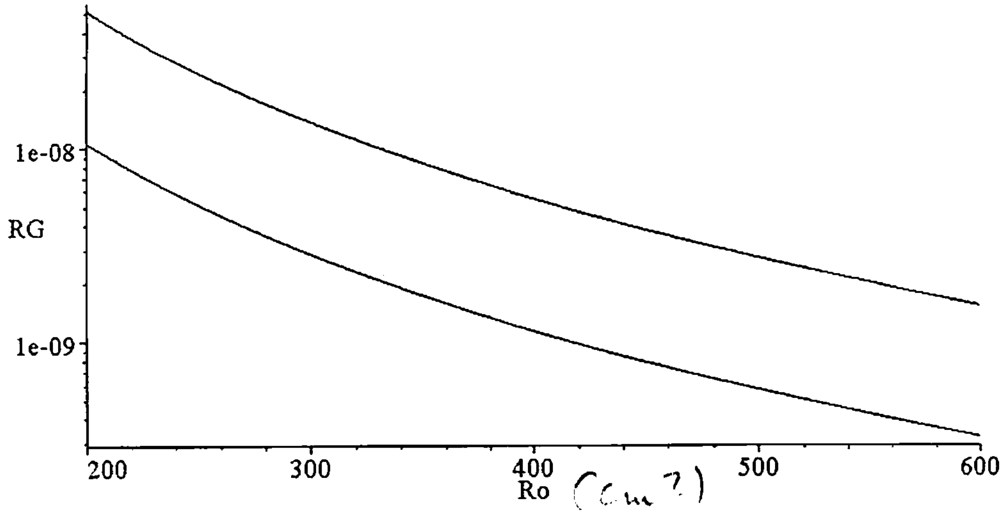
Comparison of Alpha Part. and Plasma with a high RG density for 2.8cm



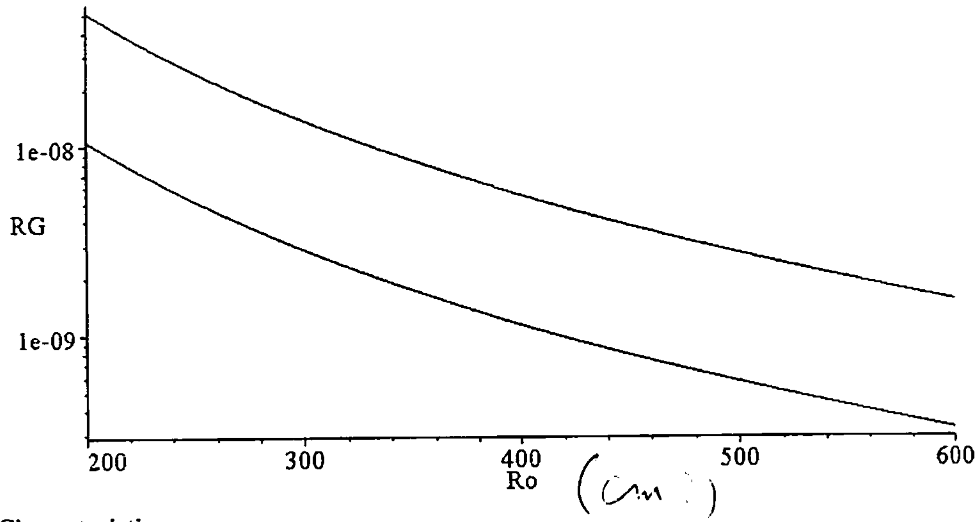
Physical Technical Considerations

Now we need to find the actual density of the residual gas that would benefit us most. For the high density case the alpha particles (not affected by the residual gas) are stopped , for a typical radius, with a significantly higher magnetic field. Ie, for Ro=300cm, Bo=100kG. This indicates that if the residual gas is over-utilized, a chamber of the specified size is still needed to stop the alpha particles, so using more mass (higher gas density) to stop the plasma debris is not efficient in a spacecraft system (mass is paramount). So, if we solve for $\Delta B_o \rightarrow 0$ we can calculate the optimal residual gas density.

Optimal RG Densities (Best and Worst case) needed for Ro at 2.8cm



Optimal RG Densities (Best and Worst case) needed for Ro at 5cm

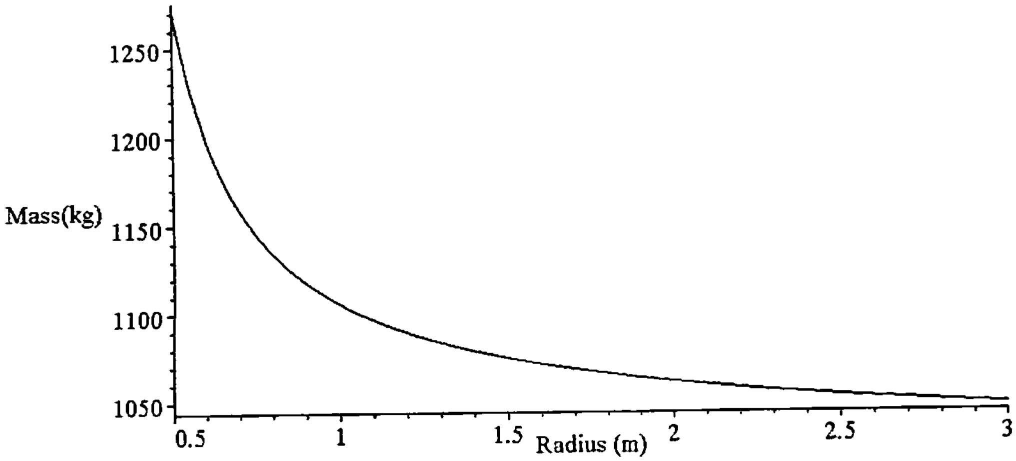


Field Coil Characteristics

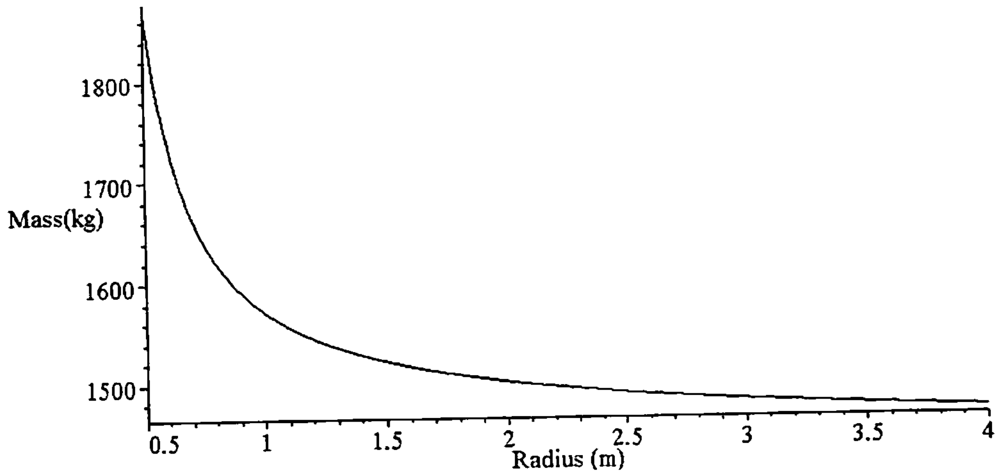
Once a relationship between the field strength and the chamber radius is found it is straight forward to determine the coil thickness, and therefore the coil mass.

$$B_{GeneratedbyCoil} = \tfrac{1}{2}\mu J \phi L \frac{a + \left(a^2 + \frac{L^2}{4}\right)^{1/2}}{b + \left(b^2 + \frac{L^2}{4}\right)^{1/2}} \equiv B_{NeededtoStopDebris}$$

Coil mass for 10cm wall thickness and Alpha Particles



Coil mass for 10cm wall thickness and Plasma Particles



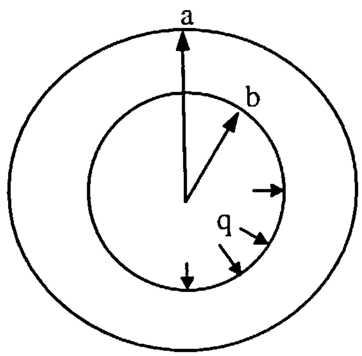
$$M_{coil} = A(R_o + (t/2))\rho_{coil}$$

where $\rho_{coil}=7\ \frac{kg}{m^3}$. We now must assume a length to determine the total mass. This is where we must continue with our cylindrical/spherical assumption, even though that would grossly over-estimate our mass for both the coil and chamber masses.

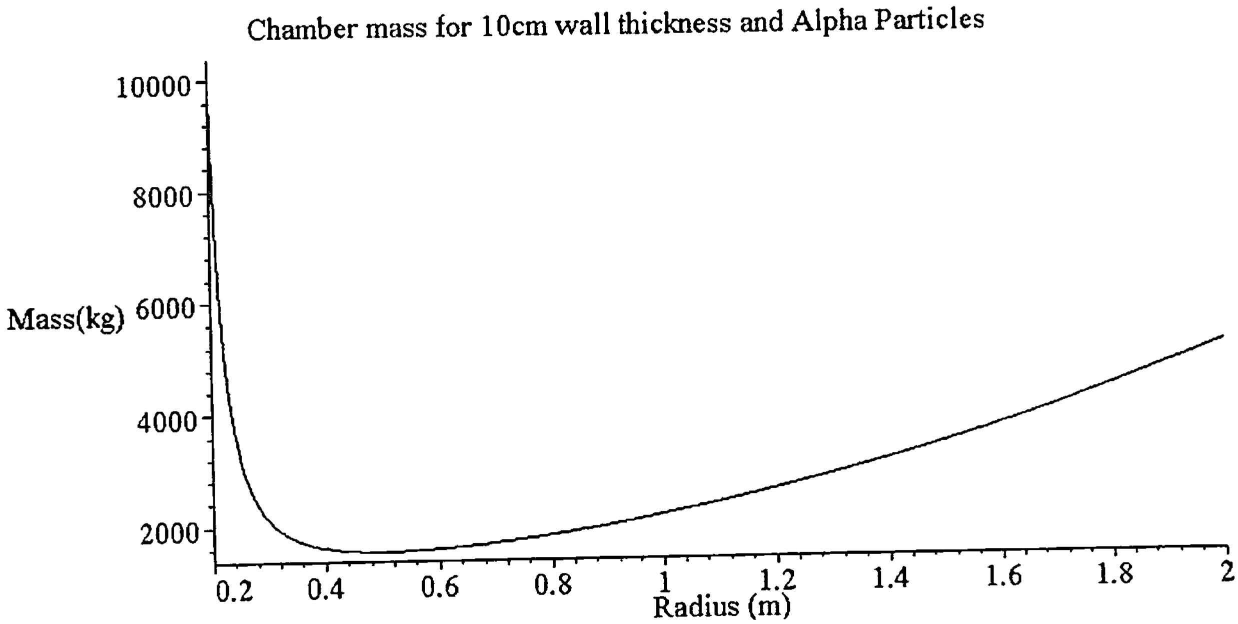
L=2R

The mass of the cooling system, injection system, residual gas management system, and the neutron shielding will be ignored in this analysis, as they are projected to be minor mass considerations. The mass of the chamber is primarily dependent upon the thickness of the chamber walls, which are in turn dependent on the pressure, q, on the inside of the chamber (structural stability). The maximum stress, σ, that the chamber can handle is given by:

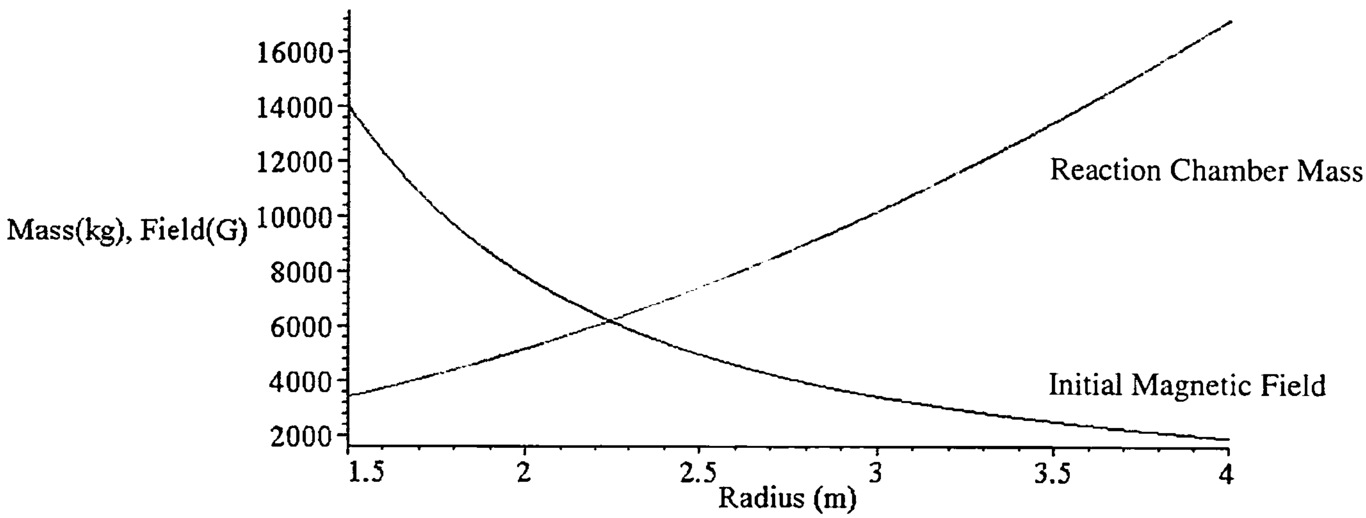
$$\max \sigma = q \frac{a^2 + b^2}{a^2 - b^2}$$



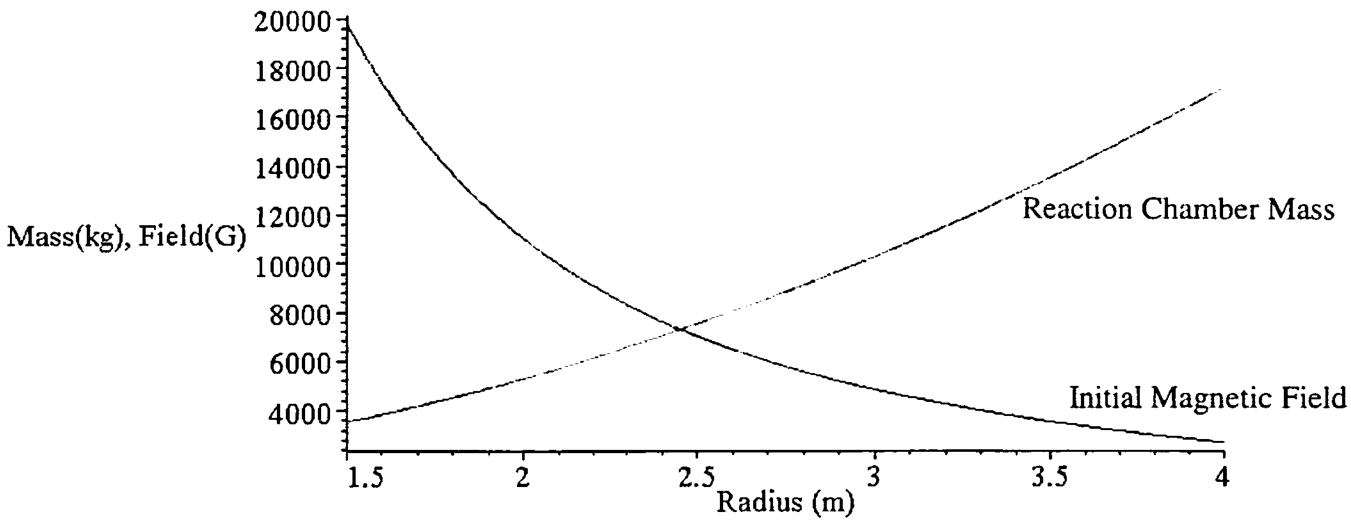
where a-b is the thickness of the chamber wall. If we assume that the pressure on the walls is the magnetic pressure due to the magnetic field on the coils, Pm, we realize that we need a chamber thickness of about 15cm for 3m radius chamber. We can then calculate the chamber and coil masses as functions of initial magnetic field strength, and therefore chamber radius.



Chamber mass and field strength for 10cm wall thickness and Alpha Particles



Chamber mass and field strength for 10cm wall thickness and Plasma Particles



Conclusions and Recommendations

The goal for this research was to flesh out a rough design of a reaction chamber to contain and utilized the Magnetically Confined Inertial Fusion propulsion system. I have laid out generalized forms of the coil thickness, initial magnetic field strength, chamber (coil and structure) masses, and the residual gas densities that we would need as functions of the internal radius of the chamber. However, now I will discuss the relative merits of chamber sizes and give an overall recommendations as to were to start further analysis on the reaction chamber (approximations that were made in this analysis).

For space travel, the primary limiting factor is mass; Mass is expensive to get to space and costly to propel through space. And the second limiting factor is energy; Solar Cells are inefficient and powerless far from the sun and nuclear reactors are heavy and complicated. If we look for the optimal mass of this system we find that at between 50cm and 60cm chamber radii we get the optimal mass necessary to contain the debris, both alpha and plasma debris. However, if we then look at the field strength and therefore the energy necessary to run this system we find that a initial magnetic field of over 100 Teslas would be necessary to prevent the debris from damaging the walls of the chamber! This is nowhere near the 0.5 Teslas that I was we were aiming for when beginning this investigation. For chamber radii larger than 0.6m the mass increases, magnetic field decrease, and the density of residual gas decreases. For this analysis I chose configuration for our system to have the following values.

	Best Trade-Off	Optimal Mass	Example 3m	Example 2m
Inner Radius	2.9m	0.5m	3.0m	2.0 m
Internal Field Strength	0.5T	>100T	0.56T	1.1T
Residual Gas Density	$\sim 10^{-8}$	$\sim 10^{-6}$	$\sim 10^{-8}$	$2e^{-8}$
Coil Mass	1.5mT	~0.3mT	1.5mT	-
Total Chamber Mass	10mT	1.5mT	10.5mT	5.1mT

The "Best" case has a mass less than 10mTons and a field strength of 0.5T, that would enable us to use less complicated superconducting materials and cooling devices.

Further Considerations

Some of the details of this analysis that need to be looked into further. The actual shape of the chamber will not be cylindrical shaped, and this analysis needs s to be done in more detail with a properly shaped (almost spherical) containment system. A more detailed analysis of the magnetic fields needs to be done, including looking at the mirror part of the magnetic field (ends) and the magnetic nozzle. Also how this system reacts in time is still a big concern, as this analysis was done separately for the alpha particles and the plasma debris, and they will be interacting with the field at the same time in the real system. In this analysis I ignored the effects of heat and radiation on the coils, as well as the contributing effect that the coils act in regards to structural stability (the chamber does not need to be as thick as I made it in the real system). Perhaps the most vital part for further analysis is in the residual gas, i.e. were does it come from and how do we control its density within the chamber.

Constants and System Values

$E_{\alpha}=N_{\alpha}*e_{\alpha}$ = (4/3π*4.10*10^20)(1465keV*1.6*10^-19 J/eV*10^7 erg/J)=4.02*10^16 erg
$E_{plasma}=N_p*e_p$=(4/3π*5*10^22)(16.71keV*1.6*10^-19 J/eV*10^7 erg/J)=5.44*10^16 erg

$M_p= N_p*m_D$=(4/3π*5*10^22)(3.34*10^-24g)=0.6995gm
Po=initial momentum=Mp*sqrt(E_{plasma}/1/2c_kMp) where c_k is the kinetic energy ratio->1 (all kinetic energy) or 1/2

$\mathbf{P}_{oupper}$=8.72825*10^7
$\mathbf{P}_{olower}$=6.1718*10^7

$\rho_{\text{High Density Case}}$=4.15*10^(-7)

Safety Factor=2
Magnet Density=6000 kg/m3
Chamber Structural Density=2500 kg/m3 carbon-carbon composite
C-C Max Yield Stress:=1000 Mpa
mu=Pi*4*10^(-7)
Current Density=250 MA/m2
Current Fraction~1

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