

Spherical Cusp for High Energy Density Plasma Confinement

Plasma Power Systems

Introduction

The spherical cusp is an innovative confinement concept that has the potential to create and maintain the densities and temperatures necessary for controlled fusion. This project involves the design and construction of a set of low resistance coils for installation inside a large diameter vacuum chamber. The coils will be designed in a spherical array with the coils extending away from the center in the radial direction. The motivation for the spherical cusp configuration is the potential for stable magnetic confinement of high energy density plasma.



Figure 1. This image shows the structure of the spherical cusp with each concentric layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.



Figure 2. This image shows a cross section of the spherical cusp with each concentric layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.



Figure 3. This image provides a rough sketch of the magnetic field for the spherical cusp with the magnetic field lines illustrating the magnetic contour as a result of positive and negative current flow in the blue and red coils.

Confinement Stability

In the majority of configurations used to confine plasma, there is a tendency toward instability due to the fact that the corresponding magnetic field lines can shorten themselves causing a disruption. The exception, in terms of configurations, is when the magnetic field lines curve away from the plasma, or in other words, when the configuration is a magnetic cusp. This configuration is inherently stable due to the fact that an instability requires an expenditure of energy to stretch the lines of force to fill the volume previously occupied by the plasma.

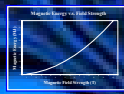


Figure 7. This graph shows the magnetic energy stored in the plasma per unit volume versus the magnetic field strength. In general, a diamagnetic plasma with no current flow can provide improved plasma stability.

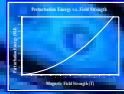


Figure 8. This graph shows the magnetic energy required for a small perturbation in the plasma per unit volume versus the magnetic field strength. In general, a magnetic cusp can provide improved plasma stability.

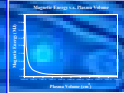


Figure 9. This graph shows the magnetic energy per unit volume versus the unit volume of constant density or the volume with an equal number of particles. In general, a stronger field can provide improved plasma stability.

Confinement Strategy

The strategy for improving confinement time is based on three objectives: a significant reduction in charge exchange, a significant reduction in the loss of particles and a significant reduction in surface interactions. Charge exchange can be reduced by maximizing the ionization fraction and minimizing the impurities in the plasma, particle losses can be reduced by increasing the ratio of perpendicular to parallel velocities and surface interactions can be reduced by surrounding all surface structures with sufficient magnetic field insulation.

Figure 13. This image shows the structure of two concentric spherical cusps with each layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.



Figure 14. This image shows a cross section of the concentric spherical cusps with each layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.



Figure 15. This image provides a rough sketch of the magnetic field for the two concentric spherical cusps with the magnetic field lines illustrating the contour based on positive and negative current flow in the blue and red coils.



Discussion

Energy demand is at an all time high, and if alternatives are not found in the very near future, world economies will decline. With a 3% growth in world energy consumption, the use of fusion energy will be absolutely necessary in the very near future. This project will require an investment of \$4,000,000 dollars leading to the development of a power system capable of producing electricity at less than 1% of wholesale. It is estimated that this power system will be capable of producing energy at a rate of roughly one megawatt leading to revenue of \$1,000,000.

Figure 19. This graph shows the plasma density versus the magnetic field strength for the spherical cusp based on the power output efficiencies of two continuous wave gyrotrons each with a net power output of one megawatt.

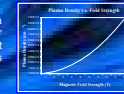


Figure 20. This graph shows the electron temperature versus plasma density for the spherical cusp based on the power output efficiencies of two continuous wave gyrotrons each with a net power output of one megawatt.

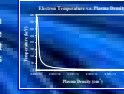
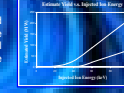


Figure 21. This graph shows the estimated yield versus injected ion energy for the spherical cusp based on the use of a spherical array of particle accelerators housed inside the coils of the outer spherical cusp.



Overview

The spherical cusp is an innovative confinement configuration designed to provide sufficient confinement time to maintain a high energy density population of particles in order to reach ignition conditions. This confinement configuration involves electron cyclotron resonance heating with the use of a pair of very high frequency (~200 GHz) gyrotrons along with a very strong magnetic field (~7.2 T) to operate in a regime that allows the microwaves to penetrate into the plasma with very little power loss. This operating regime, which is on the order of 5×10^{14} electrons per cubic centimeter, along with an ideal ignition temperature of 4 keV and 36 keV for D-T and D-D reactions, respectively, could produce breakeven conditions for steady state confinement times on the order of one second.



Figure 4. This image shows the contour of the magnetic field for a spherical cusp with three concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.



Figure 5. This image shows the contour of the magnetic field for a spherical cusp with ten concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.



Figure 6. This image shows the strength of the magnetic field for a spherical cusp with ten concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.

Confinement Time

In experiments involving a magnetic cusp, sufficient energy confinement on the order of tens of milliseconds have been achieved, and where there was a large ratio of perpendicular to parallel velocity, hundreds of milliseconds have been achieved.

For the case of $\alpha \approx 1$, the confinement time is proportional to the magnetic field strength, the square of the radius and inversely proportional to the temperature, and with a radius on the order of 50 cm and a magnetic field strength on the order of 7.2 T, a confinement time on the order of one second can be achieved for very low temperatures. For temperatures on the order of 4 keV and 36 keV for D-T and D-D reactions, confinement times of 4.5 ms and 0.5 ms can be achieved.

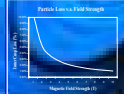


Figure 10. This graph shows the end loss percentage for particles in the inner spherical cusp versus the magnetic field strength based on a finite sheath thickness related to the skin depth and the refilling of the loss cone.

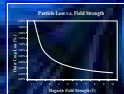


Figure 11. This graph shows the end loss percentage for particles in the outer spherical cusp versus the magnetic field strength based on a finite sheath thickness related to the skin depth and the refilling of the loss cone.

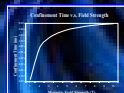


Figure 12. This graph shows the energy confinement time for the spherical cusp versus the magnetic field strength based on the end loss percentages and the power requirements to maintain the conditions in the plasma.

Confinement Structure

The structure for sufficient confinement of a thermonuclear plasma in a spherical cusp involves the use of radial reverse field supports, concentric spherical cusps, electron cyclotron resonance heating, ion particle injection and a large chamber.

In this configuration, the magnetic field coils are shaped in a conical form with radial support posts that have reverse field coil windings that extend from the outer portion of the coils with an inner spherical cusp that serves as the central plasma source, an outer spherical cusp that serves as an array of ion particle injectors and a middle cusp region that serves as the fusion reaction zone. Sufficient confinement will be obtained by creating a trapped population of energetic electrons.

Figure 16. This image shows the structure of two concentric spherical cusps with reverse field support posts attached to each coil with the supports posts designed to reverse the field to provide sufficient magnetic insulation.



Figure 17. This image shows a cross section of the concentric spherical cusps with reverse field support posts attached to each coil with the supports posts designed to reverse the field to provide sufficient magnetic insulation.



Figure 18. This image shows the structure of a single magnetic cusp with a set of reverse field support posts attached to each coil to illustrate the structure of the support posts and the orientation of the reverse magnetic field.



Parameters

Gyrotron Power	1 MW – 3 MW
Gyrotron Frequency	40 GHz – 240 GHz
Inner Magnetic Field	2 Tesla – 8 Tesla
Outer Magnetic Field	1 Tesla – 2 Tesla
Chamber Diameter	3 meter – 4 meter
Chamber Pressure	1 mTorr – 100 mTorr
Electron Temperature	1 keV – 100 keV
Injected Ion Energy	10 keV – 100 keV
Plasma Density	$10^{14} \text{ cm}^{-3} - 10^{16} \text{ cm}^{-3}$

References

Controlled Thermonuclear Fusion by Samuel Glasstone and Ralph H. Lovberg; Krieger Publishing Company, 1975.
 Principles of Plasma Discharges by Michael A. Lieberman and Allan J. Lichtenberg; Wiley, John and Sons, 2005.
 Plasma Confinement by R.D. Hazeltine and J.D. Meiss; Dover Publications, 2003.
 Introduction to Electrodynamics by David J. Griffiths; Benjamin Cummings, 1998.

Acknowledgement

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