

Transient and Steady State Thermal Modeling of Pulsed Inductive FRC-Based Thrusters

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Abstract: Due to the high power requirements of electric propulsion systems, thermal management can pose serious problems. This paper covers the development of a finite element thermal model (FEM) for the 1 kW ElectroMagnetic Plasmoid Thruster (EMPT). Simulations are built in the finite element program ANSYS® and help illustrate problematic areas in the EMPT thruster design. Different methods, such as a cooled baseplate, are modeled to help lower the temperature of components such as the plasma formation coils. The conclusion is reached for EMPT to be designed with high temperature components to mitigate these problems. A functional test model is built that is used to calibrate thermal convectivities and emissivities. This test model is then used to validate the results of the ANSYS® simulation compared to experimental results.

Nomenclature

m	= mass
I_{sp}	= specific Impulse
g_o	= gravitational constant at sea level
ΔV	= velocity change
h	= thermal convectivity
Ra	= raleigh number
Pr	= prandtl number
k	= thermal conductivity
L	= characteristic length of vertical wall – thruster heat shield
t	= time
T	= period of transient FRC heat flux wave
τ	= pulse width

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I. Introduction

Due to the rising importance of space based infrastructure, long-range robotic space missions, and the need for active attitude control for spacecraft, research into Electric Propulsion is becoming increasingly important. Electric Propulsion (EP) systems utilize electric power to accelerate ions in order to produce thrust. Unlike traditional chemical propulsion, this means that thrust levels are relatively low. The trade-off is that EP thrusters have very high specific impulses (Isp), and so require far less onboard propellant than cold gas, monopropellant, or bipropellant thrusters. Due to the large power consumption and waste heat from electric propulsion thrusters, accurate measurements and predictions of thermal losses are necessary. Excessive heating of sensitive components of a thruster may lead to premature failure of vital components. As such, reliability is critical in EP systems, both during ground testing and on-orbit operation. This paper illustrates work that has been done regarding the usage of Finite Element Analysis (FEA) modeling in the program ANSYS® Academic Research Version 13.0 and experimental tests on the thermal characteristics of the ElectroMagnetic Plasmoid Thruster (EMPT) and the Electrodeless Lorentz Force (ELF) thruster made by MSNW LLC.

A. FRC Propulsion

The primary method for thrust production used by the EMPT and ELF thrusters is the Field Reverse Configuration (FRC) plasmoid. An FRC is a self-contained, stable plasma structure that can be accelerated through the use of the Lorentz force ($\mathbf{J} \times \mathbf{B}$). An FRC is formed through the use of a Rotating Magnetic Field (RMF) which ionizes the injected gas by inducing a strong azimuthal current. A magnetic field that results from this current helps to form and confine the plasma. This plasmoid is stable enough that it will not decay in the time that it takes to accelerate it out of the thruster. However, by its very nature, the function and behavior of the thruster is transient. Gas must be injected, ionized, and then formed into an FRC before being accelerated. In order to make an efficient thruster, this formation must occur at a fairly high frequency. The EMPT thruster normally operates at approximately 1-3 kHz.¹⁵

The process of creating an FRC may be difficult to visualize and will be shown in slightly more detail. In Fig. 1 the formation of an FRC is illustrated as a four step process.

- In step (a), bias coils are used to create a steady axial B field.
- In step (b), lightly ionized gas is injected into this magnetic field. Two pairs of antenna coils oriented 90 degrees from each other and operated 90 degrees out of phase from one another then start to drive an oscillating current. This causes a rotating magnetic field (RMF) to be generated. The electrons in the injected gas are attached to the magnetic field lines and fully ionize the plasma.
- This rotation also generates the azimuthal current shown in step (c). As a result, this creates a second (blue) toroidal magnetic field around the current that confines the plasma.
- As the plasma becomes fully ionized and the electrons become fully attached to the RMF, the structure known as the Field Reverse Configuration plasmoid shown in step (d) is formed. During this process aluminum conducting rings around the thruster act to conserve flux and provide a radial pressure balance to the FRC.

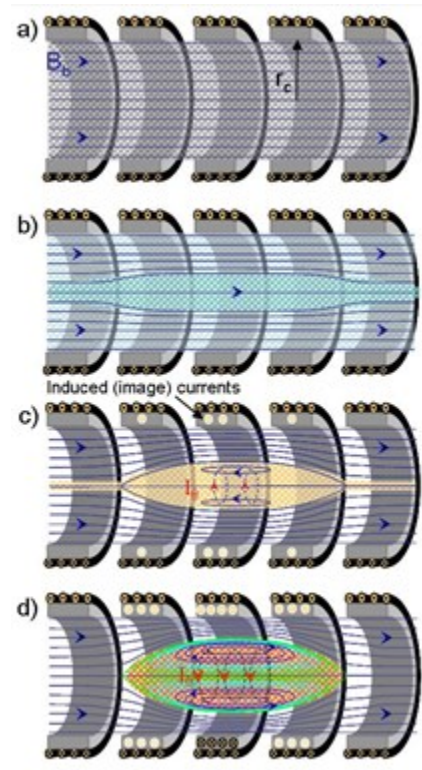


Figure 1. FRC formation in a cylindrical geometry²⁵

The plasmoid is then ejected via the electromagnetic Lorentz force caused by the cross product between the

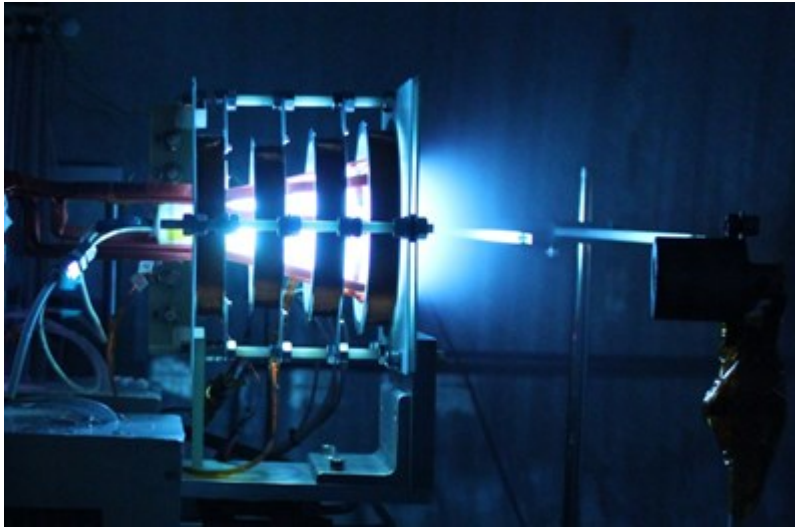


Figure 2. Ejection of an FRC from EMPT, showing the conical geometry of the thruster

azimuthal plasma current and radial component of the bias field. When combined with a magnetic field gradient force from a conical thruster geometry, the FRC is expanded out of the cone to produce thrust. The ejection of an FRC from an EMPT thruster variant is shown as Figure 2.

Using MSNW's methods for generating FRC plasmoids as propulsion can alleviate some of the problems that trouble traditional thruster development. Because of the plasma interaction with the walls of the thruster, most engine types require exotic materials to withstand the high temperature loading. Since the FRC is magnetically confined, the plasma does not interact with or

transfer heat to the walls directly. This ensures that heat loading to the inside of the cone is far less than that of the traditional EP thrusters. The main sources of heating in EMPT are therefore:

- Radiative energy from the FRC on the inside of the cone
- Ohmic heating in the rotating magnetic field (RMF) antenna coils
- Ohmic heating in the bias coils
- Induced heating in the aluminum flux conservers
- Heat generated by the integrated power supply system components

For the EMPT Power Processing Unit (PPU), the heat generated by most of the electronic components is relatively small compared to the heat sinkable area of the thruster and the primary concern is heating in the coils. However, the high frequency switching requirement of the thruster leads to significant heating within the PPU's Insulated-gate bipolar transistors (IGBTs).

B. The ElectroMagnetic Plasmoid Thruster (EMPT)

EMPT, as it is currently being tested and manufactured, is designed to run at variable power from 1-3 kW. Using xenon propellant, this would correspond to a variable specific impulse of 800-5000 seconds. An FRC is formed from an ionized gas as detailed previously, but there is no restriction to what that gas is composed of. Therefore, EMPT is not strictly confined to using solely xenon as its primary propellant. EMPT has been run on alternative fuels such as argon, nitrogen, air, ethylene, and vaporized water. This gives it versatility of use in flexible path and Near Earth Orbit (NEO) style missions. It also enables a possible mission focus on in-situ resource utilization for spacecraft propellant.¹⁵

Fig. 4 shows a working laboratory test model of the EMPT thruster, with several important components detailed. The heat produced by these components is designed to be shunted through the aluminum flux conservers and radiated away. In non-vacuum conditions, natural convection from the surrounding air cools the thruster as described by standard convection equations. The heat also conducts through whatever material is used to support the thruster during testing and is essentially lost for the purposes of examining the system. This leads to the conclusion that if the thruster is thermally isolated enough from the supporting structure and in a vacuum, most of the heat will radiate away according to the Stephan-Boltzmann law. However, modeling this is difficult. Radiation is based off of emissivity values which can be estimated, but are difficult to precisely measure due to their dependence on quantities like surface roughness. The same applies for conduction values, as exact values depend on the manufacturing process and impurities in the final product. A table of emissivities and conductivities compiled from various sources is listed in Appendix 1. For the same reasons that have already been detailed, convection is also

difficult to estimate. Currently, a vertical wall convection model is used for EMPT. That is, a model of still air that becomes less dense with increasing heat and rises, with only cooler air and gravity opposing it. In reality, a detailed fluid simulation would be needed to accurately model the air, taking complex geometry and chaotic (turbulent) fluid motion into account. As approximations must be made to reduce the complexity of the examined system, some accuracy is lost. However, as will be seen later, the changes in the final temperature values due to these approximations are not significant. For the following simulations, the empirical vertical plate correlation for convection in Eq. (1) by Churchill and Chu was used.³⁰

$$h_{laminar} = \frac{k}{L} \left(0.68 + \frac{0.670 Ra^{1/4}}{\left[1 + \left(\frac{0.492}{Pr} \right)^{9/16} \right]^{4/9}} \right) \quad (1)$$

One other difference between experimental setups and theoretical models is thermal contact resistance between parts. In actuality, there is an interstitial gap between two objects which is filled with the fluid of the surrounding medium. This is caused by the fact that solid materials do not have perfectly flat surfaces. There are microscopic hills and valleys formed by imperfections in the material or by polishing processes during manufacturing. Thus, two rough surfaces pressed up against each other have a significant gap “resistance” regardless of the conduction values of the surrounding materials. This resistance is heavily based off of the conductivity of the interstitial fluid (air, in most cases). In many instances, the resistance of the gap can be greatly reduced by the use of thermal paste. This thermal paste will generally consist of a non-electrically conductive ceramic that fills the microscopic gaps between materials. This paste is also a much better thermal conductor than air, and so can improve the heat flux across a surface greatly, making it invaluable for cooling purposes.

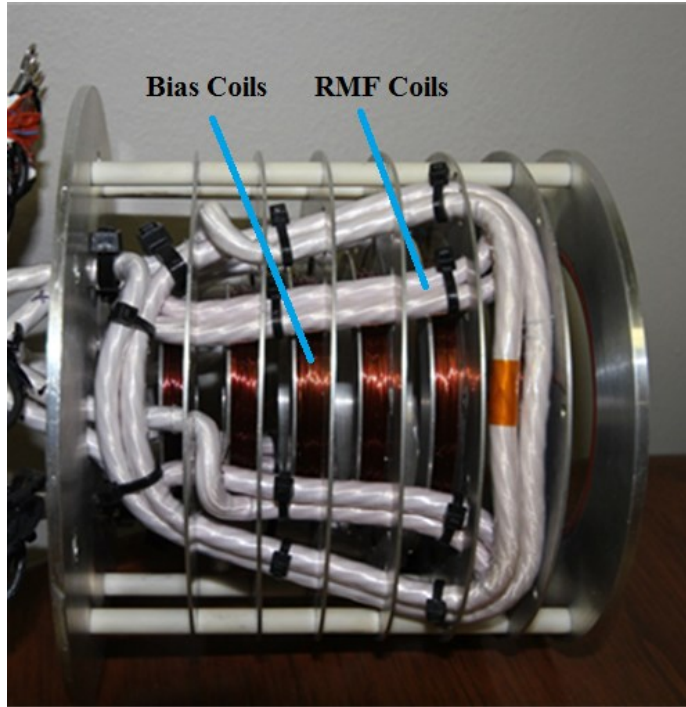


Figure 3. Laboratory model of EMPT Mark III, Version 2

C. Pulsed vs. Steady Approximations

Since FRC plasmoids are transient by their very nature, the heat flux due to radiation that raises the temperature of the thruster cone wall is also transient. This heat flux would essentially be a pulsed rectangular wave, consisting of a high heat flux against the wall for the duration of the FRC’s formation and acceleration out of the thruster. Due to the time-stepping nature of FEM simulations, an approximation needed to be found to prevent the need for timesteps on the order of tens of microseconds to capture this pulsed behavior. Two short simulations were performed to compare a true pulsed environment to an averaged heat flux one. The first input was a pulsed rectangular wave, representing a pulse of 150,000 W/m² heat flux against the quartz thruster cone. This pulse would have a pulse width of 50 microseconds, followed by a 450 microsecond quiescent period before the next pulse was fired. This input was represented in ANSYS® as a 30th place Taylor Series approximation represented by Eq. (2).

$$f(t) = \frac{\tau}{T} + \sum_{n=1}^{30} \frac{2}{n\pi} \sin\left(\frac{2\pi n}{T}\right) \cos\left(\frac{2\pi n}{T}t\right) \quad (2)$$

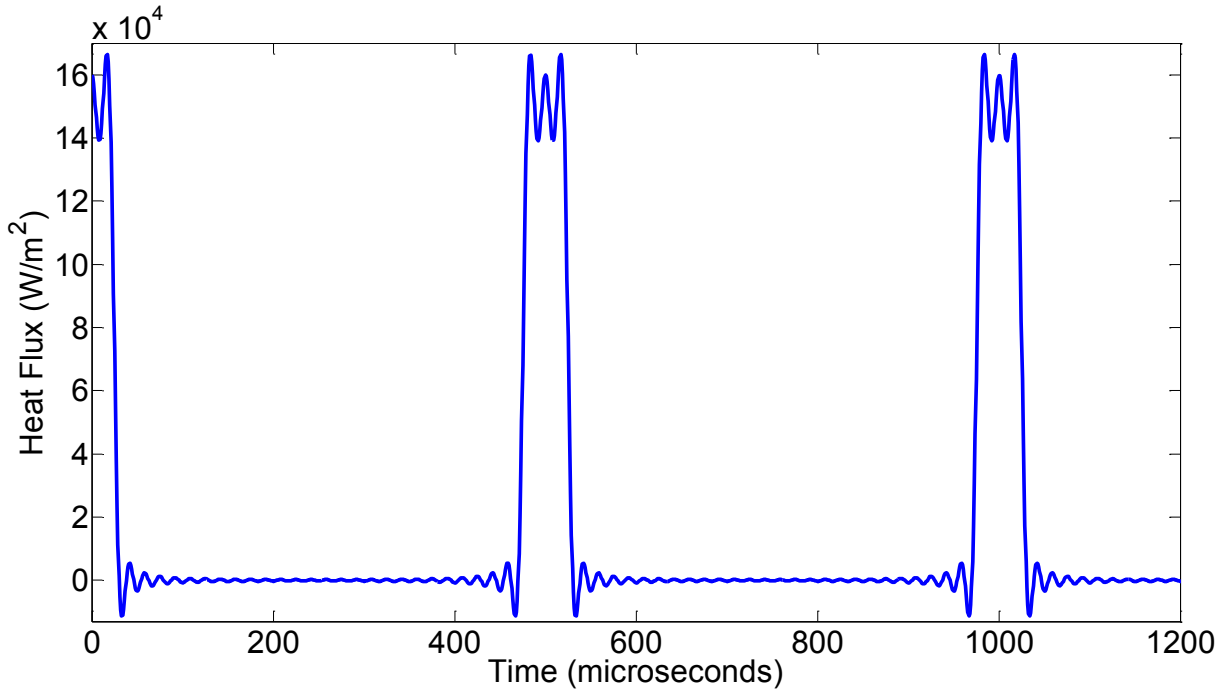


Figure 4. Rectangular wave input into ANSYS® describing FRC heat pulse against thruster wall

The output into ANSYS® would then be described by Fig. 4. The simulation was run for 15 seconds of simulated time using timesteps of 40 microseconds. This ensured that at least one data point at the peak heat flux would be caught for each pulse in addition to all of the zeros used during the quiescent period. This was very resource intensive, and required approximately 8 hours to run on a Intel i7 quad core 3.33 GHz CPU.

The second type of input used was simply a constant 15000 W/m². In comparison, this simulation took only several seconds to solve over the same 15 second simulation time duration as the pulsed version. When plotted, shown in Fig. 5, the results show that the difference between the two methods was negligible, only 0.01 K, and so averaging the heat flux over the entire duration of the pulse is an acceptable alternative.

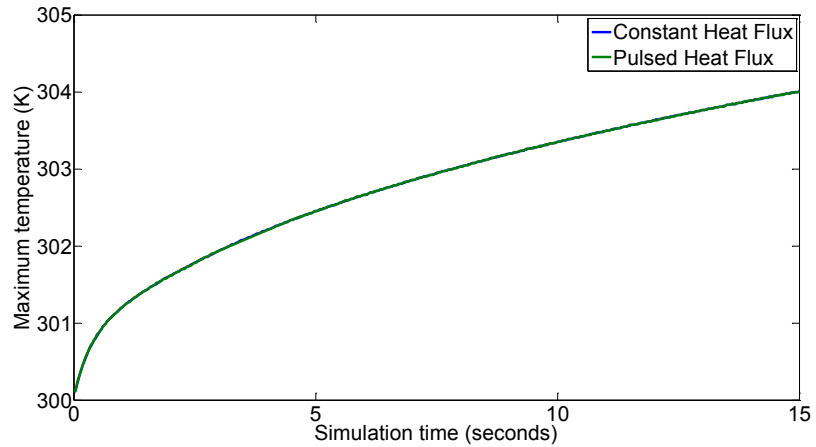


Figure 5. Maximum temperature of thruster wall plotted vs. simulation time - Results are essentially identical

D. Validation of Testing Method and Model

In order to validate the results from ANSYS®, extensive testing with an experimental setup needed to be performed to marry the theoretical vacuum models to the experimental air tests. During extensive electronics testing of the thruster outside the vacuum chamber, measurements were taken to determine the steady state temperature of different components of EMPT. To determine both the ohmic heating of the IGBTs and the natural/forced convection cooling of the thruster, a small heat sink plate with attached heat sources was created and modeled. These heat sources consisted of 12 HSA50 resistors, placed to emulate the point source nature of the heat-emitting IGBTs in the actual EMPT electronics. This setup, shown in Fig. 6, is isolated from the workbench by a low thermal conductivity block of fiberglass. Six resistors are connected together for each two power supplies.

Running the full transient heating simulation for the same 120 minutes as data was taken for the laboratory experiment yielded a maximum temperature of 106.3°C. This is well within the $\pm 3^\circ\text{C}$ error of the thermocouples used. Thus, it was determined that the emissivities in Appendix 1 were accurate representations of the laboratory model and that the vertical plane wall convection formula was applicable.

The second phase of the electronics validation was to remove the fiberglass base of the setup and replace it with an actively cooled baseplate so as to match experiments performed in the laboratory with the actual EMPT electronic platters. This baseplate used local tap water flowing through channels within the base to provide a constant temperature reference for the resistor's heat sink.

During the course of the EMPT platter testing, Jim Pihl of Raven Technologies took temperature data that could be used as a base comparison to the simulation model in order to determine the power dissipated by the IGBT's. An accurate model of the electronics boards tested in the laboratory was created in Solidworks and imported into

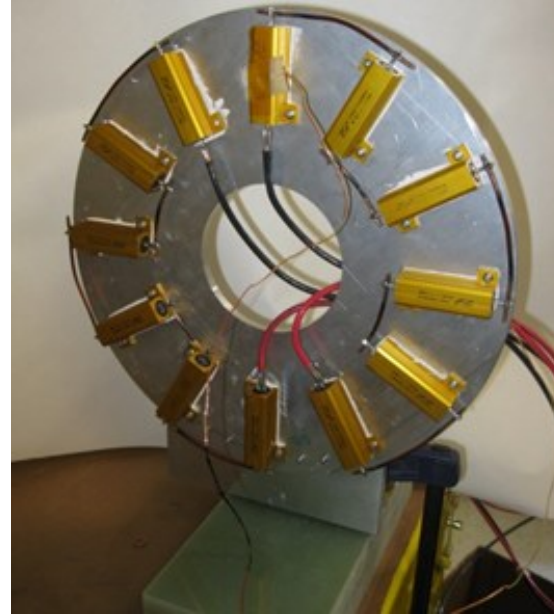


Figure 6. The validation test setup with 134.4 Watts (11.2 Watts/IGBT) running

ANSYS®. Using the knowledge in regards to emissivity and convection that was acquired through the previous test, a sweep of power levels were run through the modeled IGBT's to determine which best matched up with the experimental results. Table 1 shows one such sweep.

The sweep was run with 9.0 amperes through each pair of 6 resistors. This led to a power per resistor of 12.2 Watts. When this was replicated

in ANSYS®, the following readings in Table were acquired. For reference, the ambient temperature was measured to be $31^\circ\text{C} \pm 3^\circ\text{C}$ and the water temperature (base temperature) was $19.5^\circ\text{C} \pm 3^\circ\text{C}$.

Table 1. Comparison of readings from experimental test setup and theoretical ANSYS® values at 12.2 Watts/IGBT

	Theory [$^\circ\text{C}$]	Experimental [$^\circ\text{C}$]
Top Resistor Temp	93.5	91.5
Behind Resistor Temp	92.9	91.0
Top Footer Temp	36.5	44.5
Bottom Footer Temp	19.5	26.4

These results show that, while thermocouples reading close to the resistor were still in agreement to within the uncertainty of the probe, the footer values were not. This was attributed to differences between the ANSYS® model and the experimental model, as well as small effects from contact resistance between the different components of the system. However, as different power sweeps found that the top resistor values consistently agreed with the theoretical values, the final step to finding the power in the IGBT's could be made.

Earlier testing by Jim Pihl had found that the heat sink temperature behind the top IGBT would reach a steady state value of 96°C after two hours, and so an effort was made to match this final temperature in ANSYS® by using different IGBT power levels. In this way, the unknown exact power level of the IGBTs could be backed out from the thermal tests. The simulation results in Fig. 7 show that the temperature behind the IGBT would come to 96°C using an input of 12.6 Watts/IGBT. This number agreed with the EMPT simulations of the previous section. Thus, a reliable estimate for the IGBT ohmic heating due to power loss was found and put into the primary EMPT model.

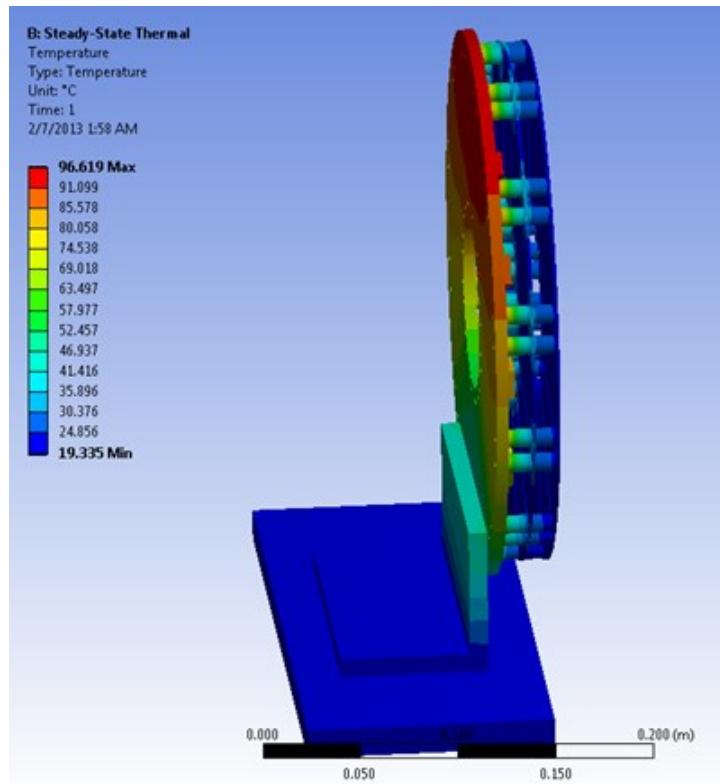


Figure 7. Full model of EMPT electronics as tested by Jim Pihl. Input power of 12.6 Watts/IGBT

E. Examination of the EMPT Thruster Design

At the same time that the EMPT thruster was being developed, so were the electronics to be used for the power processing unit. Once these electronics were completed, they were integrated with EMPT to make the complete thruster shown in Fig. 8. For the thermal analysis, it was assumed that the thruster would be operating at the ideal total power usage of 1 kW. Different ohmic heat losses and heat generation were estimated from the circuit characteristics of the electronics boards and coupling between the RMF coils and bias coils. A simplified CAD model of the electronics boards was then made to prepare the system for analysis. This model is illustrated in Fig. 9. While most of the electronics components on the boards produced heat, the majority of the ohmic heating in the system came from the IGBT switches controlling the high frequency switching current in the RMF coils. Thus, 12 point sources of internal heat generation were used on the primary circular heat sink attached to the footer. Another 12 were placed on the surface of the secondary heat sink located behind the first.

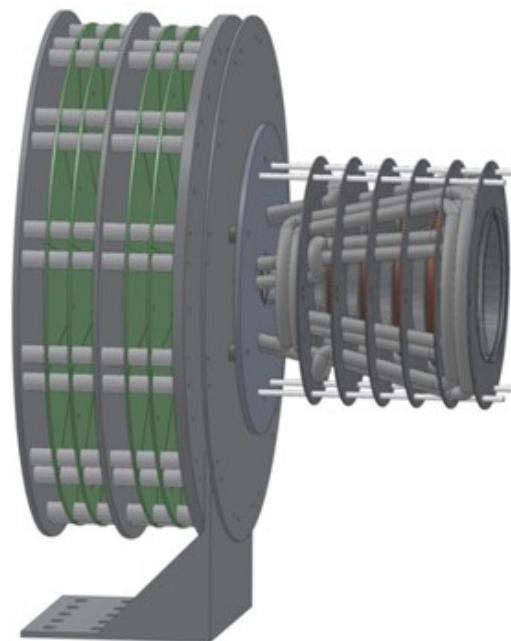


Figure 8. Assembled Solidworks CAD representation of EMPT

An equivalent circuit resistance for the plasma load was determined by comparing a model of the electronic circuit with the electrical response from an experimental FRC pulse and adjusting the model parameters accordingly. For a proxy plasma load with a resistance of 0.018 ohms and coupling to the RMF coils, the heating power levels of the various thruster components are estimated below in Table 2. It should be noted that the bias coils were omitted due to being small relative to the other power levels. Also, since there was no plasma in the cone, only a proxy load, no heat flux was experienced by the inside of the quartz cone.

Similarly, the emissivities of the different components in EMPT also needed to be estimated, in absence of a reliable thermal imaging system to

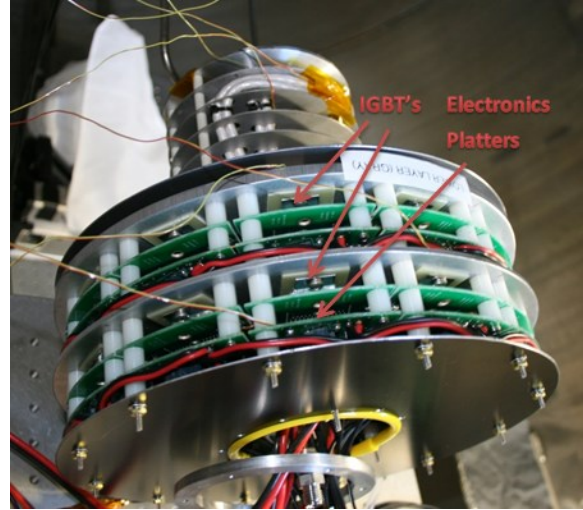


Figure 9. Fully assembled laboratory model of EMPT

Table 2. Power losses in the EMPT thruster for an 0.018 ohm plasma

	Power Loss (Watts)
RMF Coils (Inner)	132.0
RMF Coils (Outer)	132.0
Bias Coils	-
Flux Conservers	60.0
Quartz Cone Absorption	-
Electronics (Per IGBT)	12.6

determine them independently. The values used in the following analyses were taken from the sources in Appendix 1. Unlike in previous examinations of the thruster, this time PCB electronics plates, nylon electronics spacers, and various aluminum surface coatings were also considered.

The first simulation of an 0.018 ohm plasma used the basic emissivity values for aluminum on both the structural plate heat sinks and flux conservers. The large un-anodized baseplate was used as the primary conductor of heat for the system. As this simulation took was for the vacuum case,

there was no additional cooling from convection. The only power transfer out of the model came from radiative cooling to the surrounding chamber at 25°C. The model shown in Fig. 10 illustrates the primary problem with the EMPT thruster at these power levels; that the maximum temperature reached on the thruster will destroy certain components. Although the quartz cone is capable of withstanding temperatures in excess of 725°C, the Litz wire that the RMF coils are composed of will begin to fail around 200°C.²¹ Likewise, the Tefzel® Teflon tubing surrounding the Litz has a maximum operating temperature of 150°C.⁹ In addition, the PCB boards and attached IGBT's have reached approximately 205°C,

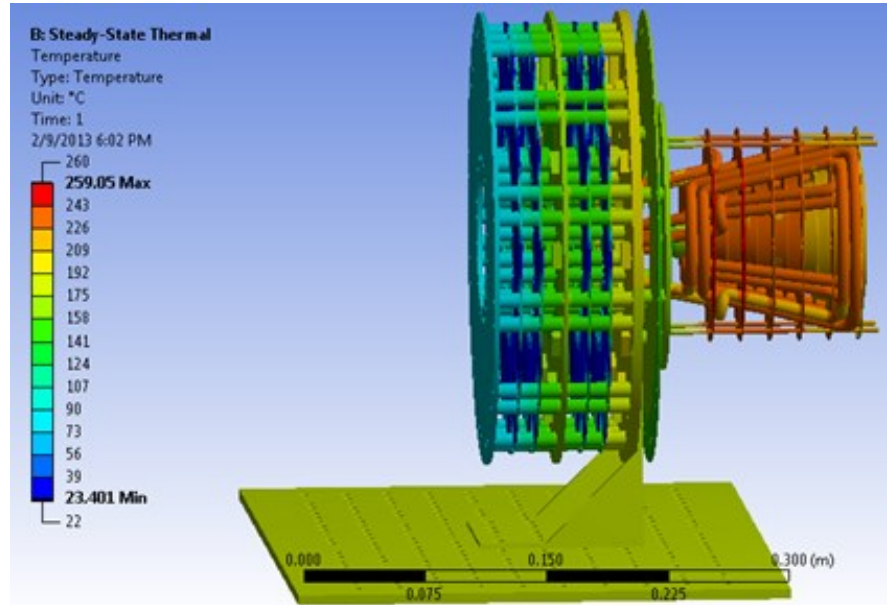


Figure 10. 0.018 ohm plasma, large baseplate, radiatively cooled with 0.105 emissivity value for aluminum

which is far above their maximum temperature of 150°C. These are clearly unacceptable operating temperatures, and so work proceeded on attempts to mitigate them.

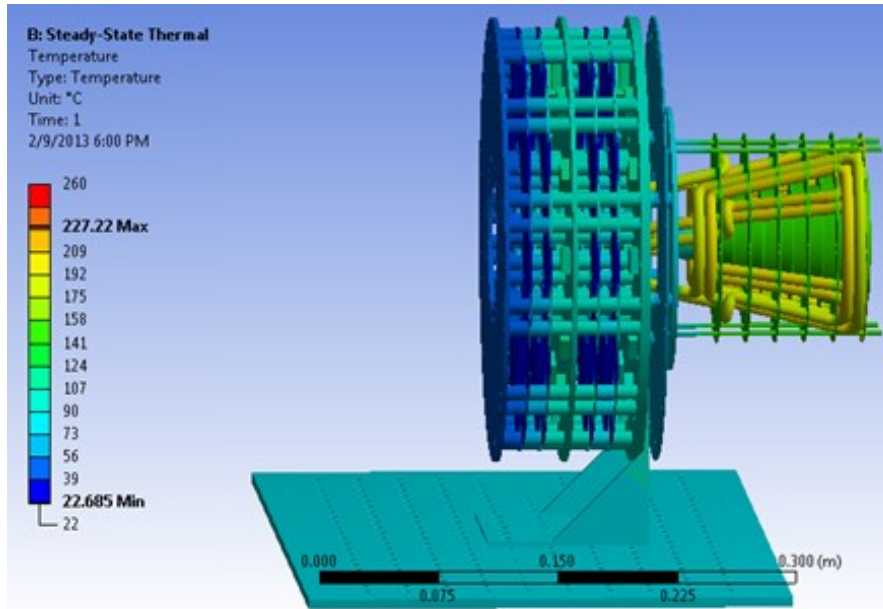


Figure 11. 0.018 ohm plasma, large baseplate, radiatively cooled with 0.900 emissivity value for aluminum

The simulation in Figure 11 shows an 0.018 ohm plasma with anodized heat sink plates and flux conservers. Using a commercial black anodized aluminum surface as a base, the temperatures on the different thruster components were reduced due to the increase of radiation emissivity from 0.105 to 0.900. However, it was found that even though the IGBT's might be within an acceptable temperature range, the heat from the thruster was simply not conducted well enough to the heat sinks to cool the RMF coils to 150°C.

A third simulation was performed in order to determine the efficacy of a water cooled baseplate on

the thruster. The primary aluminum baseplate was replaced with one set at a constant temperature of 22°C. However, as Fig. 12 shows, the conduction through the thruster was again not sufficient to allow the RMF coils to be cooled to a satisfactory temperature.

The fourth simulation is similar to the first, which is with a non-anodized and non-cooled base plate, but with the RMF power levels reduced to 35.7 Watts each. This represents a better case scenario, in which a 0.055 ohm plasma load would be used instead of a 0.018 ohm plasma. As a higher equivalent circuit resistance represents a more efficient coupling between the RMF coils and the plasma, less energy would be dissipated as ohmic heating in the coils.

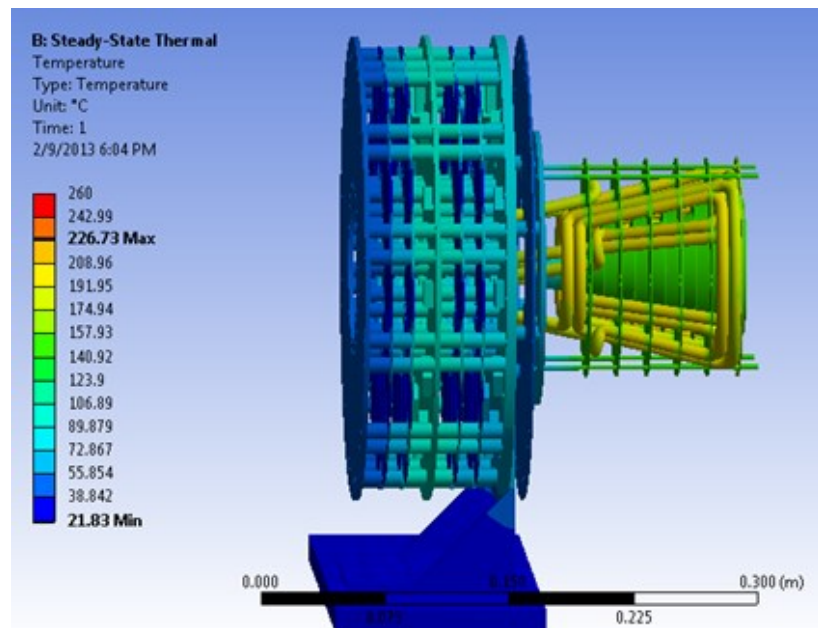


Figure 12. 0.018 ohm plasma, large baseplate, actively cooled (to 22°C) with 0.900 emissivity value for aluminum

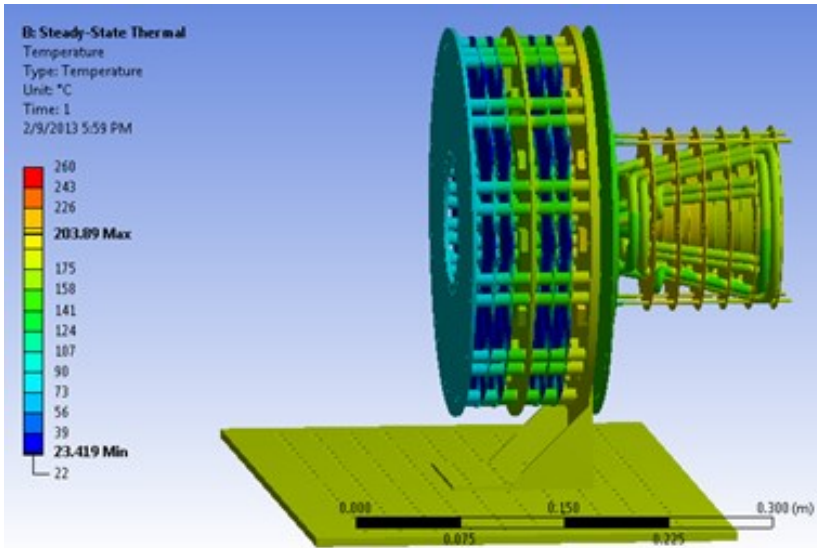


Figure 13. 0.055 ohm plasma, large baseplate, radiatively cooled with 0.105 emissivity value for aluminum

high frequency current one skin depth into the coil, and so would result in higher resistance. The redesigned thruster with solid copper RMF coils is shown in Fig. 14. It was found through laboratory testing that the RMF coils in the previous versions of EMPT tended to couple electrically to the aluminum flux conservers situated beneath them. This was mitigated by moving the flux conservers outside the RMF coils. This also allowed them to be used as simple structural supports, shown by the tabs and Macor supporting rods in Fig. 12.

The changes made to EMPT did have several advantages that outweighed the increase in electrical losses. First, the copper strips bent into shape for use as coils would retain their shape as a rigid body, unlike the flexible RMF coils used before. This allowed for a far lighter and less complex structural system to hold the RMF coils in place over the thruster cone. Second, since the coils were made out of copper alone, they could easily withstand temperatures past 429°C. Since 429°C represented the most pessimistic view of the thruster heating, this was deemed to be an acceptable alternative.

II. Conclusion

This paper has shown the process by which the EMPT thrusters and the future higher-powered Electrodeless Lorentz Force (ELF) thruster have been thermally simulated using the program ANSYS®, and how the EMPT analysis was validated. During simulations, it was found that both the Litz wire and Teflon composing the RMF coils would fail under the heat loads predicted for steady operation. This remained true for a variety of favorable and cooler conditions, and so the EMPT thruster was changed to operate with high temperature materials that will not be affected by its most pessimistic predicted steady operating temperature. It was then shown that the same convection models and emissivities used in the EMPT computer analyses were valid for a controlled laboratory environment test, and would agree within a reasonable margin of error. Thus, the EMPT simulations could be understood to represent a reasonable prediction of laboratory operating temperatures.

The resulting picture in Fig. 13 shows the thruster in steady state with these new power values. Even with a more conservative estimate for the plasma resistance, it is still obvious that both the Litz wire RMF coils and their Tefzel coating are exposed to undesirable temperatures. As a result of these models, and to similar experiments conducted in the vacuum chamber with thermocouples, the decision was made to redesign the EMPT thruster antenna in order to prevent failure within the RMF coils.

This redesign resulted in a next generation EMPT thruster composed of solid copper RMF coils rather than Litz wire. This would, unfortunately, only support

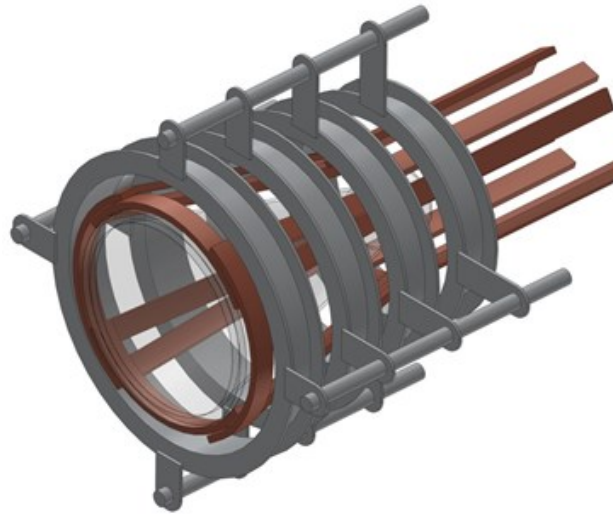


Figure 14. Free floating (unsupported) representation of EMPT Mark IV

Appendix

Material	Emiss.	Therm. Cond. (W/m-K)	Elect. Cond. (ohm-cm)	Max Temp. (°C)
Alumina ^{1, 18}	0.900	35.00	1.00E+15	1500
Aluminum (Anodized) ^{11, 21}	0.900	0.70	1.00E+12	100
Aluminum (Dull) ^{18, 31}	0.105	180.00	3.66E-06	582
Aluminum (Shiny) ^{18, 31}	0.069	180.00	3.66E-06	582
Copper ^{18, 26}	0.830	400.00	1.72E-08	1010
Fused Quartz ^{12, 18}	0.750	1.40	7.00E+07	1683
G-10 Fiberglass ²⁶		0.29	4.27E+15	140
Macor ^{2, 7}	0.940	1.46	1.00E+16	800
Nylon ^{6, 23}	0.730	0.23	1.00E+15	100
PCB (Circuit Board) ¹³	0.800			273
Sil-Pad 2000 ²⁷		3.50	1.00E+09	392
Tefzel ^{8, 16}	0.950	0.24	1.00E+17	255

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