

Modelling Inertial Confinement Fusion Schemes Using ZEPHYROS



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Fusion energy is the future of high-yield, clean, and self-sufficient renewable energy created by fusing deuterium atoms together to form helium. Deuterium is a stable isotope of Hydrogen abundant in ocean water, making it both a massive and a renewable source of fuel. Technologies are being developed to recreate the inside of our own sun and harness the energy to power mankind while upholding environmental sustainability. Fusion energy will become necessary in the near future to avert the climate crisis caused by other polluting forms of high-yield energy.

Nuclear fusion is currently induced on earth via several methods of confining deuterium fuel until it is under enough pressure and heat to begin fusion reactions. The method being investigated is inertial confinement fusion energy, which attempts to ignite the compressed fuel core using laser pulses. Currently, ICF has yet to be produced in a way that can be considered high gain. In order to reach high gain, i.e., large energy output, different inertial confinement schemes must be investigated. One such scheme is fast ignition, which uses huge currents of electrons to heat matter compressed by lasers. A potential problem with this scheme is in the divergence of electrons which heat the compressed core.

When igniting an ICF fuel core, a 1 picosecond laser pulse is directed towards the core via a silicon cone mechanism. This cone has a tip diameter of 16 micrometres and a base diameter of 24.74 micrometres, with a gradient of 5 degrees. The silicon cone is surrounded by a carbon-hydrogen (CH^2) glue. Due to the different resistivities between the materials, when electrons are directed through the cone, a magnetic field is created around the cone and helps to collimate the electrons and prevent their divergence before colliding with the fuel core in a process called resistive guiding. The more electron divergence can be avoided, the less energy is spent on ignition, allowing for higher gain.

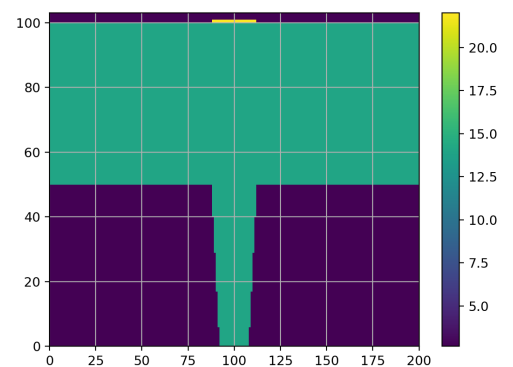


Figure 1. Diagram of a target cone used in fast-ignition ICF. Cones used in this project shared the same dimensions of 16 micrometre tip diameter and 24.74 micrometre base diameter. The CH^2 cladding is represented by the purple sections on the lower part of the graph, while the silicon cone is represented in teal.

Since a material's resistivity is related to its electron density, the question was posed whether the density of the CH^2 material would significantly affect the resistive guiding ability of the cone. This is because a material's resistivity drops as it heats up, and for the guiding characteristic of the cone to function, the resistivity of the cone must always be higher than the resistivity of the cladding. For that to happen during the laser pulse, the cladding needs to heat faster than the cone, which would require a lower density.

In order to test this hypothesis, several cones with different CH² electron densities will be simulated and compared. If a certain density was found to benefit resistive guiding, cone cladding could be made with a CH² foam of this density, rather than solid density glue, and used in future experiments.

The main way of simulating ignition sequences is through the program ZEPHYROS, a hybrid FORTRAN code that enables plasma fusion physicists to investigate if a collimating method will be successful in a fast ignition sequence before expending the resources to test it experimentally [1]. This code allows the user to submit parameters for the guiding cone and receive data that can be plotted to show graphically what the electrons are doing upon incidence with the cone. All measurements and images simulated use 2-dimensional figures of merit taken across a plane in the 3-dimensional cone, which became an issue in analysing results and will be discussed in depth later. As this project focused on investigating the effect of the density of the CH² cone cladding, only the parameters relating to the cladding were changed once the initial cone parameters were set. The ion density of the cone is the ion density of neutral silicon, and the ion density of the cladding was changed according to the g/cm³ CH² density being investigated.

For this project, electron density and background temperature were the results of importance. Monitoring the electron density throughout the cone gives a good sense of how well the electrons are being collimated through the cone and not diverging throughout it. Monitoring the background temperature allows the user to analyse the energy distribution of the electron population around the cone. Background temperature was monitored at the base of the target cone, 50 micrometres, and at the back of the target itself, 100 micrometres, to see how well the electrons were guided by the cone's cladding. A hotter temperature indicates more electrons incident on an area, and so a hotter average temperature at the base of the cone, 50 micrometres, and the back of the target, 100 micrometres, would indicate that more electrons are incident and resistive guiding was therefore more effective.

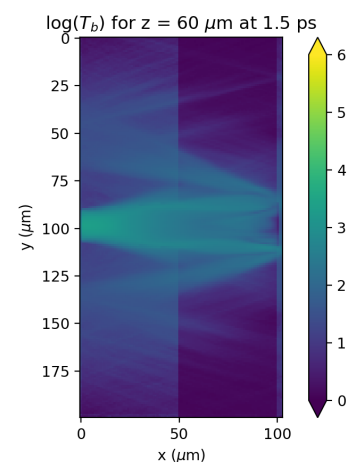


Figure 2. An example of a plot of background temperature from the z direction. Shown is the background temperature at a density of 0.3 g/cm³.

The solid density of the previously used CH² glue was determined to be 0.8g/cm³. To monitor how the density of the cladding affected guiding, a range of densities from 0.2g/cm³ to

0.5g/cm³ were assessed with ZEPHYROS, as it was previously theorised by K. Lancaster and A. P. L. Robinson in a private communication that an ideal homogenous foam at 0.4g/cm³ could provide much better resistive guiding than 0.8g/cm³. For each density, the data provided by ZEPHYROS was plotted using various routines to analyse electron density, background temperature on two axes, and at key points, the magnetic field. Every density assumes that the CH² foam is ideal and chemically homogenous.

In addition to testing multiple densities, each density was analysed at three points in time: 0.5 picoseconds, 1 picosecond, and 1.5 picoseconds. This would allow insight into how the cone and its cladding interacted with the laser pulse during and after the 1 picosecond pulse. A higher background temperature and stronger magnetic field at the 1 picosecond mark would mean that more electrons were collimated and therefore incident on the fuel core. Monitoring heat at 1.5 picoseconds would give insight into heat retention as the target and cone reach their peak temperatures at around this time stamp.

For the peak values found, these timestamps were also used to analyse the background temperature at 100 micrometres, to monitor how the back of the guiding target heated in relation to the base of the cone. This allowed an analysis of electron divergence within the target and to gain better understanding of how many free electrons were reaching the back of the target. This also displayed any filamentation of the laser beam through the target, which causes uneven heating and would be visible in any images.

Filamentation became more apparent as the temperature in the cone rose, which was expected but also indicates that average temperatures calculated at 1 and 1.5 picoseconds were subject to greater skew. This effect becomes more apparent in the graphs of average temperature values in figures 4 and 5 and is where the figures of merit that ZEPHYROS had been operating with began to be called into question. Since ZEPHYROS was using 2-dimensional figures of merit to determine values that existed in three dimensions, this sort of skew due to filamentation was likely to happen. The extent to which this affected results is discussed later in this paper.

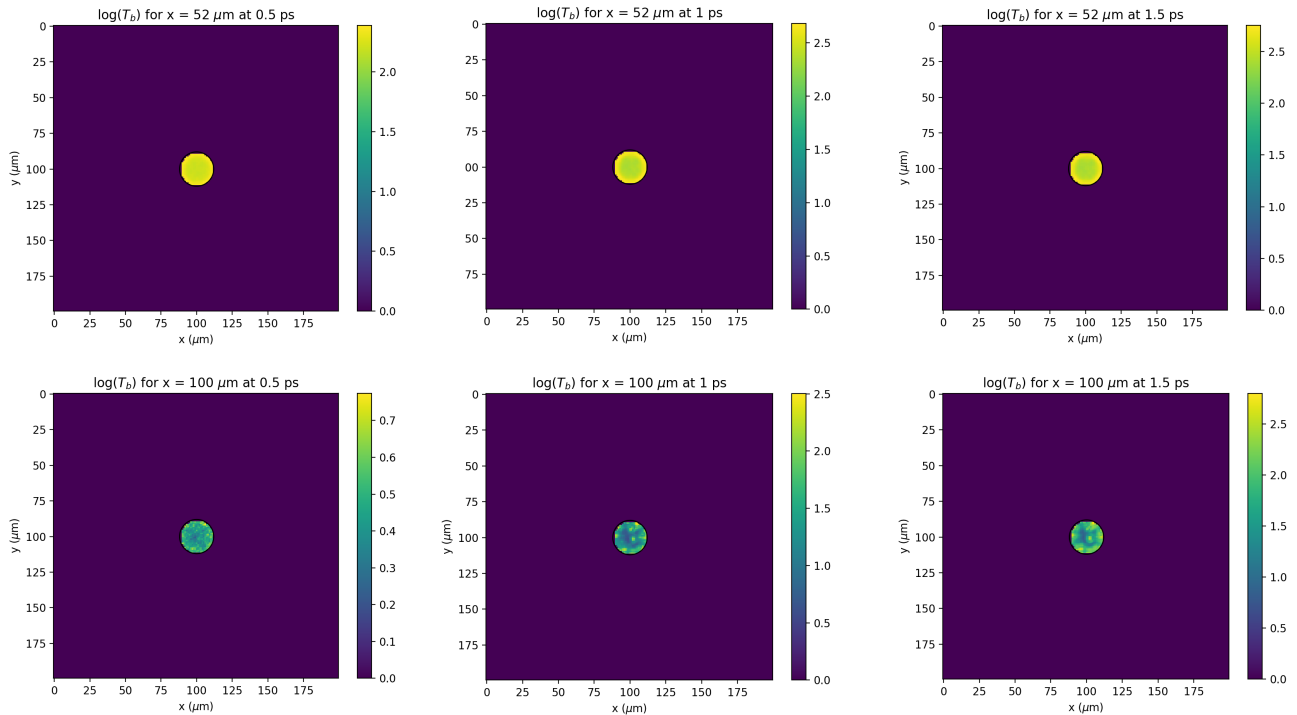


Figure 3. A time sweep of background temperature of the target cone along the x direction at both 50 (top row) and 100 (bottom row) micrometres. Temperature was taken at 0.5, 1, and 1.5 picoseconds to monitor temperature during, at the end of, and after the 1 picosecond laser pulse. This allowed for an analysis of how well the back of the target was heating, which gave information about how well the electrons were being guided. A numerical average temperature was also found and plotted in a later figure to analyse the pattern of heating throughout the distribution of cladding densities. The images simulated at 100 micrometres show significant filamentation, which can cause the average value to skew significantly.

As was theorised, the background temperature of the cone cladded with 0.4g/cm^3 material was much hotter than that of the cone cladded with solid density material. However, 0.4g/cm^3 was not a peak in the distribution of background temperatures. At 1 picosecond and 50 micrometres, all densities from 0.2 to 0.42g/cm^3 were over 100 eV hotter than solid density, but at 1.5 picoseconds, after the pulse had ended, there were two peaks of extreme temperatures, due to filamentation. These peaks were centred around 0.28 and 0.38g/cm^3 .

The background temperature averages at all three timestamps at both 50 and 100 micrometres were plotted to analyse the pattern of heating around the peaks of 0.28 and 0.38 g/cm^3 . For 50 micrometres, it was found that at 0.5 and 1 picosecond, which corresponded to the middle and end of the laser pulse, the average temperature across densities was constant, with a dip at 0.32 g/cm^3 . The peak average temperatures centres around 0.28 and 0.38 g/cm^3 appeared at 1.5 picoseconds, after the 1 picosecond laser pulse had ended. All other densities achieved a peak average temperature at 1 picosecond, and then dropped again at 1.5

picoseconds as heat dissipated. Why these densities retain heat so much more after the laser pulse has ended is due most likely to the filamentation that presented and is discussed later.

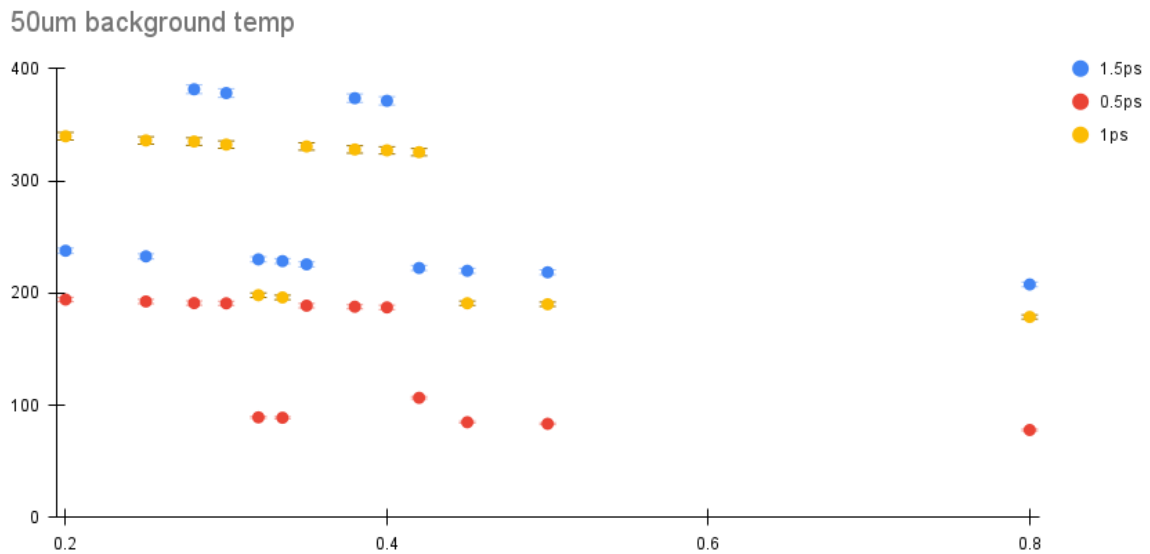


Figure 5. Pattern of average background temperatures at 0.5 (red), 1 (yellow), and 1.5 (blue) picoseconds at each CH₂ density tested. Rather than being an outlier, 0.8 g/cm³ is the solid density of CH₂ glue and was added to compare foam densities to the performance of the existing glue. While two peaks appear around 0.3 and 0.4 g/cm³ at 1.5 picoseconds, temperature was consistently high at 1 and 0.5 picoseconds across densities, with the exception of a dip at 0.32 g/cm³.

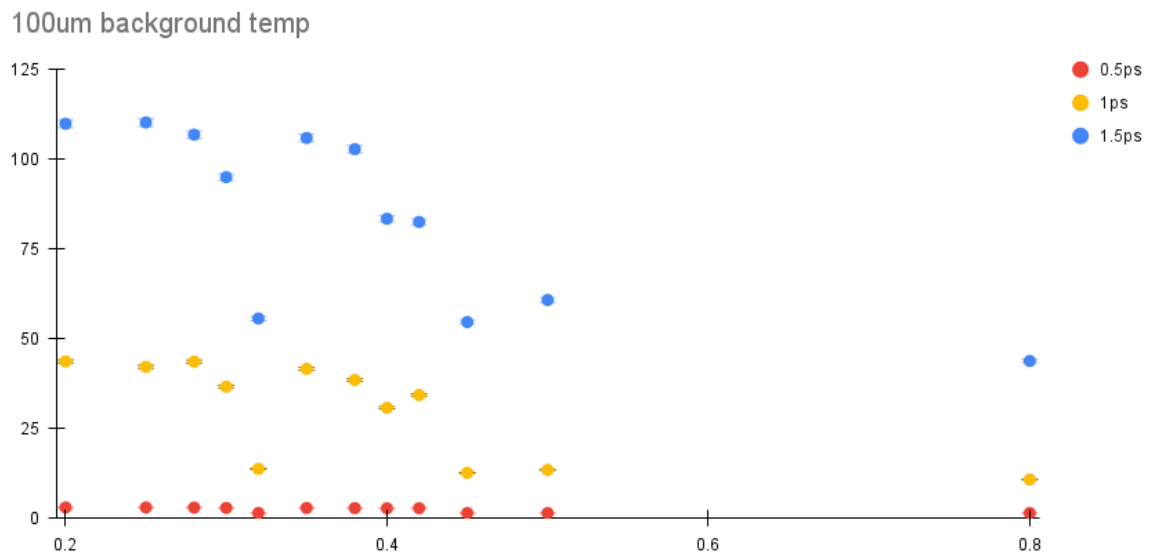


Figure 4. Pattern of average background temperatures at 0.5 (red), 1 (yellow), and 1.5 (blue) picoseconds at 100 micrometres for each CH₂ density tested. The cause behind the sharp uptake between 0.32 and 0.35 g/cm³ is currently unknown. Lower CH₂ densities were hotter at 100 micrometres, indicating that guiding was more successful at these densities.

At 100 micrometres, a different pattern was identified. There were two peaks once again, but at 0.2 and 0.35 g/cm³. There was a sharp downturn in temperature at 0.32 g/cm³, which increased dramatically at 0.35g/cm³. After the second peak, the temperature had a general decrease until reaching a minimum at solid density.

Temperature at 100 micrometres appeared to be much more affected by filamentation, as shown in figure 3. This was determined to be due to the figures of merit that ZEPHYROS operates on. Currently, ZEPHYROS generates values and images in a 2-dimensional plane in a specified cross-section of the guiding cone. Reducing the data to two dimensions makes it much harder to account for filamentation in the cone when determining an average temperature, as the temperature exists across a volume. This allows filamentation to heavily skew the average in one way or another and was determined to have accounted for the abnormalities in lower densities.

Despite the abnormalities due to filamentation, the general trend confirmed the original hypothesis that a CH² foam would be much more effective than the currently used solid density CH² glue in resistive guiding cone cladding. Data points at 1 picosecond, the end of the laser pulse, are all much higher at lower densities than at the original 0.8 g/cm³ density, dips excluded. A higher temperature indicates that more effective guiding is taking place and more electrons are hitting the back of the target.

While the results of the project confirm that a lower density CH² foam cladding would be more effective for resistive guiding cones, they also show that to more closely investigate an optimal foam density, the figures of merit that ZEPHYROS functions on must be changed. To monitor background temperature more accurately, and therefore see how well the electrons are guided to the back of the target, ZEPHYROS must be able to simulate 3-dimensional volumes where the temperature is averaged, rather than 2-dimensional planes. This modification of ZEPHYROS to operate on 3-dimensional figures of merit is currently being undertaken by K. Lancaster for the purpose of a different project, and should be completed before summer 2023, allowing further investigation into specific foam densities.

Appendix 1: Temperatures at 50 micrometres

Density (g/cm ³)	T(eV) at 0.5 ps	T(eV) at 1 ps	T(eV) at 1.5 ps
0.8	78.07	178.77	207.7
0.5	83.6	190.07	218.53
0.45	84.98	190.95	219.87
0.42	106.73	325.56	222.39
0.4	187.27	327.12	371.28
0.38	187.86	327.92	373.62
0.35	188.8	330.63	225.61
0.335	88.98	196.12	228.48
0.32	89.33	198.13	230.04
0.3	190.9	332.29	378.16
0.28	191.09	335	381.53
0.25	192.54	335.96	232.71
0.2	194.28	339.67	237.7

Appendix 2: Temperatures at 100 micrometres

Density (g/cm ³)	T(eV) at 0.5 ps	T(eV) at 1 ps	T(eV) at 1.5 ps
0.8	1.55	10.89	43.88
0.5	1.56	13.57	60.85
0.45	1.57	12.75	54.72
0.42	2.91	34.42	82.57
0.4	2.88	30.85	83.48
0.38	2.93	38.6	102.84
0.35	2.98	41.7	105.96
0.335	1.58	12.32	50.12
0.32	1.57	13.85	55.7
0.3	2.99	36.74	95.05
0.28	3.08	43.69	106.88
0.25	3.12	42.25	110.26
0.2	3.12	43.74	109.93

References

[1] A. P. L. Robinson, "ZEPHYROS User Manual", 2014.