Modelling Inertial Confinement Fusion Schemes Using ZEPHYROS

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Inertial Confinement Fusion (ICF) & fusion energy

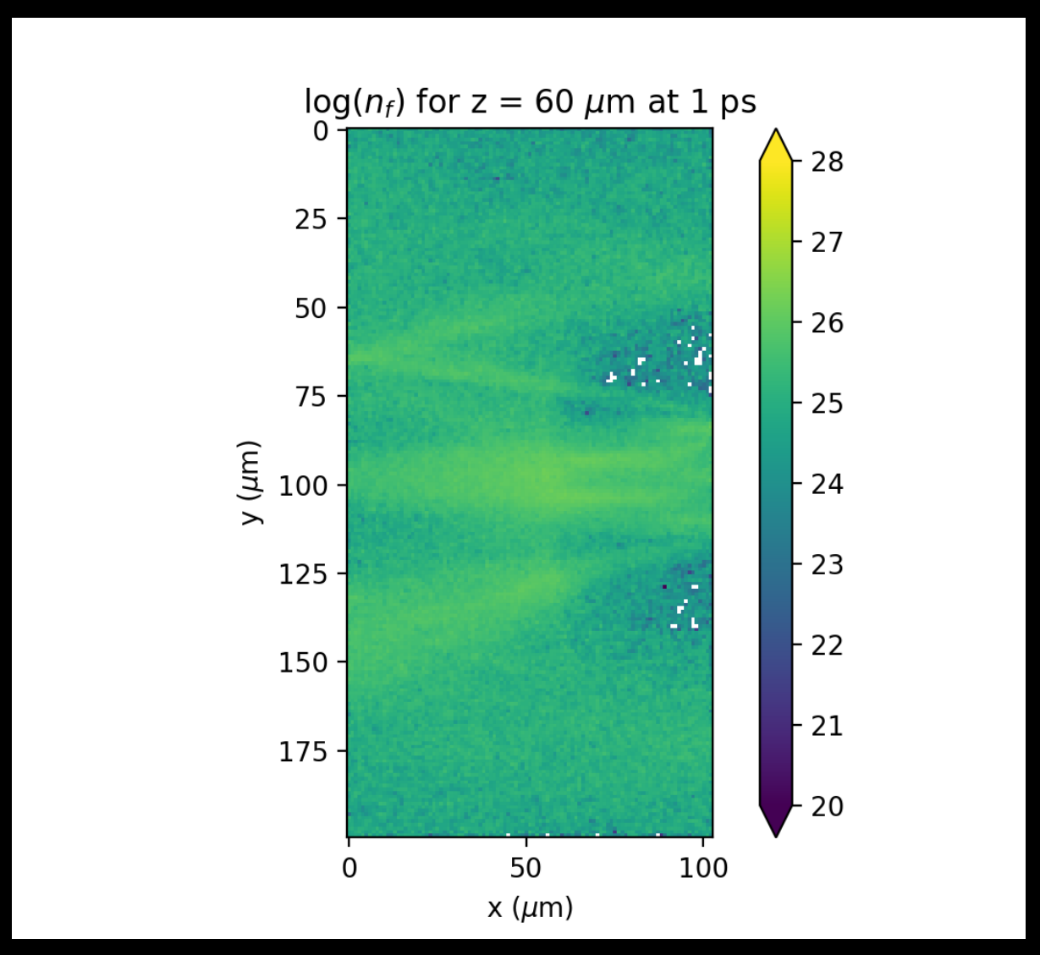
Fusion energy is the future of high-yield, clean, and self-sufficient renewable energy that will become necessary in the near future to avert the climate crisis caused by other polluting forms of high-yield energy. The energy is created by fusing Deuterium, an isotope of Hydrogen found abundantly in the ocean, into Helium. Fusion is a much safer nuclear energy process than the more well-known fission, as there is no risk of a meltdown, and any ignition failure would simply result in the unfused plasma cooling.

As fusion is the nuclear process that powers stars, schemes must be investigated to produce the conditions of the sun on Earth. One such scheme is Inertial Confinement Fusion (ICF). ICF, specifically a process called fast ignition, involves directing a high-energy laser at a fuel core made mainly of Deuterium in order to trigger a chain reaction throughout the fuel that would become self-sustaining fusion. At present, a self-sustaining reaction has not been achieved, and ICF is being researched as to how an ignition process can become high-yield.

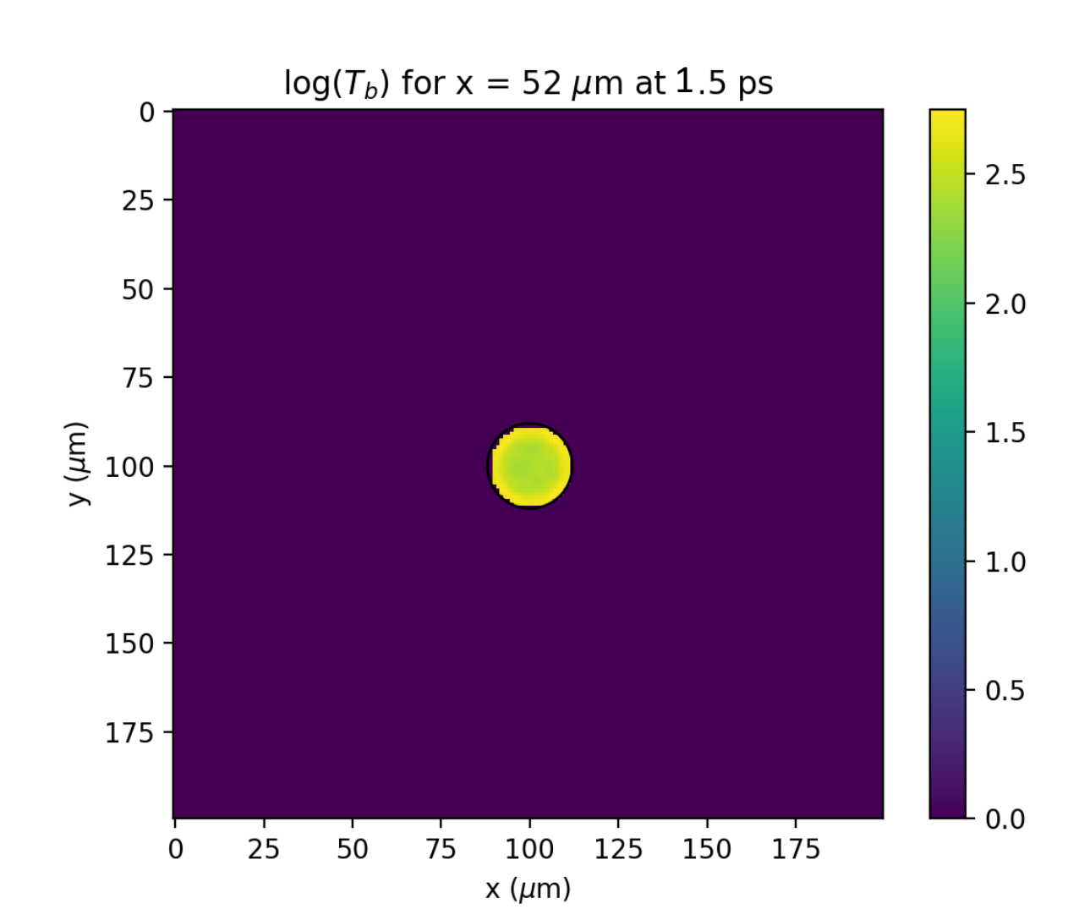
ICF fast ignition resistive guiding cones

A main obstacle in the energy yield of fast ignition fusion is the divergence of electrons in the laser before incidence with the fuel core. Simply put, the less electrons that are incident on the core, the less ionisation and heating can take place, and the less fusion that will occur. This can be overcome by guiding the electrons via a magnetic field. This magnetic field is created with an inverted cone target placed in front of the fuel, shown to the right. The cone is made of Silicon, and the tip is clad in a CH^2 foam or glue. The difference in electrical resistivity between the Silicon and CH^2 creates a magnetic field, which guides the electrons. This effect is known as resistive guiding.

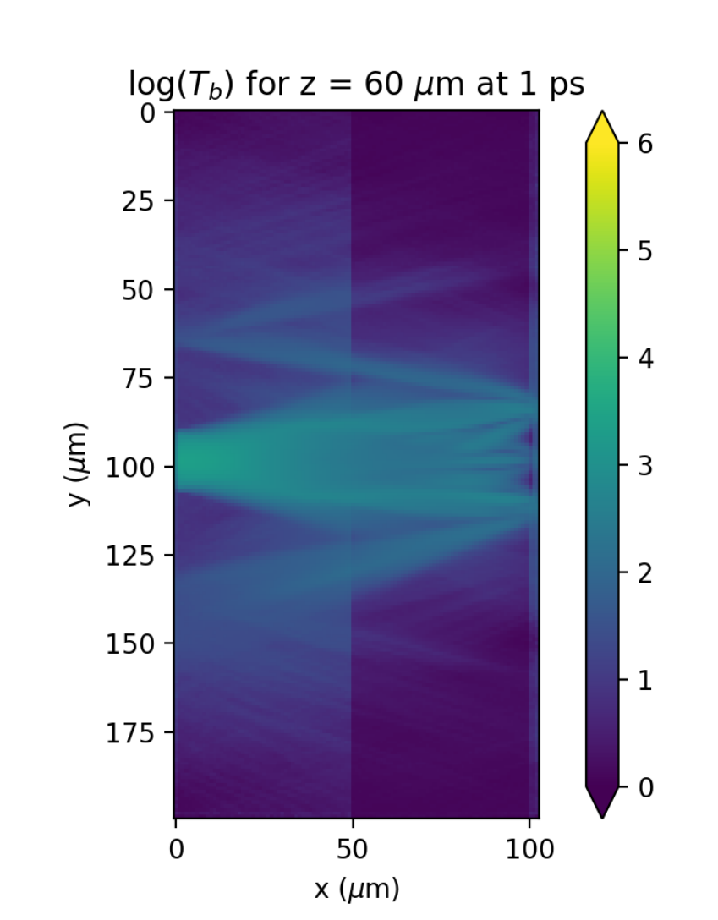
This project focused on how the density of the CH^2 cladding affected the resistive guiding of the cone target and how the heating and ion density of the fuel were affected by the change in density. Currently, resistive guiding cone targets use a solid density CH^2 glue cladding of 0.8 g/cm^3.



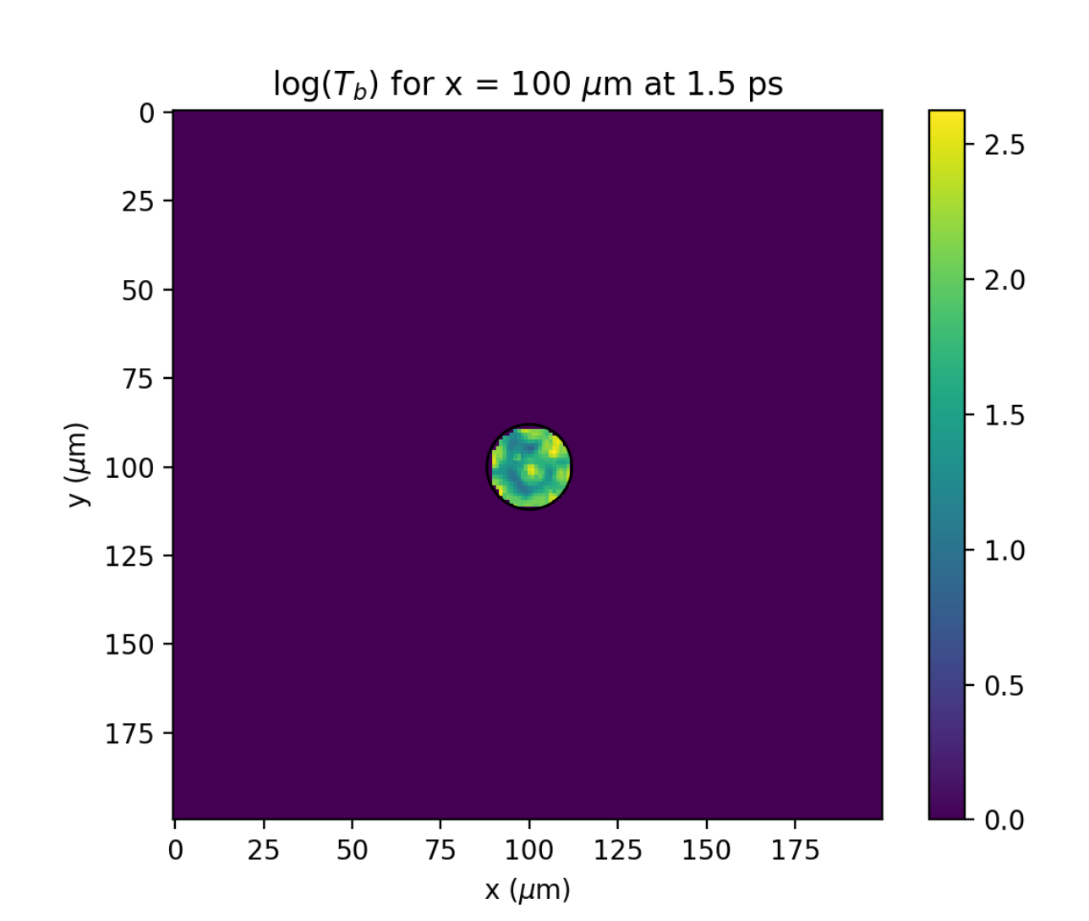
Electron density plot for 0.4 g/cm^3 CH^2 cladding. Brighter regions towards the middle of the back of the target indicate that successful guiding is taking place.



Average background temperature at 50 micrometres looking at the target cone head-on. The material surrounding the cone in the centre is the CH^2 cladding, which heats slower and allows for resistive guiding.



Background temperature plot for 0.4 g/cm^3 CH^2 cladding. Brighter regions around the shape of the cone indicate successful guiding taking place, as well as give a clearer view of reflux.



Average background temperature at 100 micrometres looking at the target cone head-on. Cooler temperatures at the back of the target are to be expected as some electrons diverge, and given that this plot shows the cone after the laser pulse has ended and hit the fuel.

Findings & future areas for research

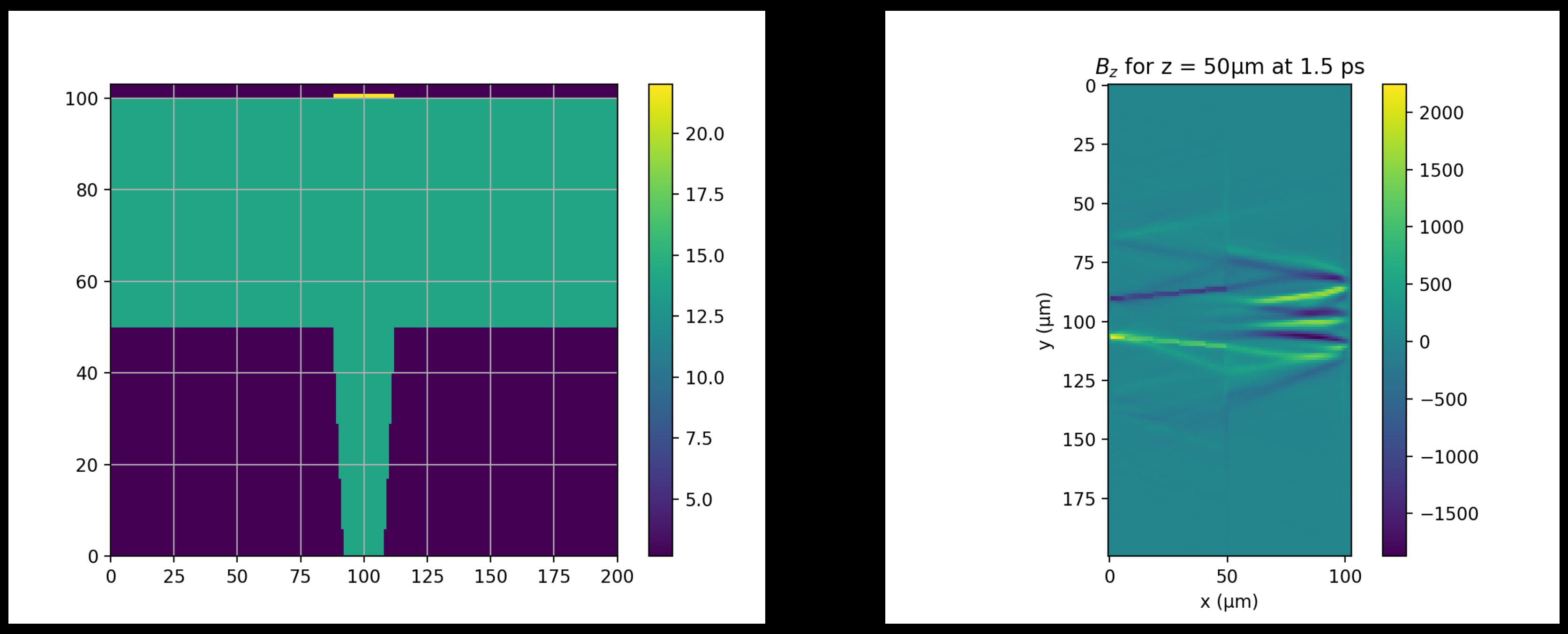
The results of primary importance were the average background temperatures for each density at 50 micrometres. While it was expected that lower densities would be better at guiding the electrons, therefore making the target hotter, the pattern of average temperatures observed was unexpected. Two temperature peaks appeared after the 1 picosecond laser pulse ended around 0.3 and 0.4 g/cm^3. Another abnormality found was the significant dip in temperature around 0.32 g/cm^3. Average temperature was also monitored at 100 micrometres, and the pattern found was also unexpected. The back of the target reaching a peak temperature at 1.5 picoseconds was expected, but the dip at 0.32 g/cm^3 was abnormal once again.

While the individual temperatures for each density were abnormal, the general trend shows that using a CH^2 foam for cone cladding rather than solid density CH^2 glue. With the exception of the unexpected dips, all temperatures at 0.5 and 1 picosecond are higher at lower densities than at 0.8 g/cm^3. This trend is consistent at both 50 and 100 micrometres. This confirms the original hypothesis that a foam of 04.g/cm^3 would guide an electron beam better than solid glue when used on a resistive guiding cone.

When investigating the abnormal results, it was determined that the figures of merit being inputted into ZEPHYROS were inherently flawed. ZEPHYROS was taking 2-dimensional slices of a 3-dimensional cone at 50 and 100 micrometres. Because of the way that the laser filaments, uneven heating is caused as shown in the figures above. This can skew the average temperature at that infinitesimally thin slice, because it does not consider a full volume. In order to further investigate specific foam densities, ZEPHYROS would need to be modified for a 3-dimensional analysis of temperature throughout a volume rather than a plane, which would account for the filamentation.

This modification required for ZEPHYROS is currently being undertaken by K. Lancaster, and could be used next summer for further research on the results determined by this project.

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



Shown are visual simulations of the resistive guiding cone target (left) and the magnetic field generated by the cone during a laser pulse (right). All visualisations on this poster use a CH^2 density of 0.4 g/cm^3. The cone is rotated 90^o anticlockwise for the diagram on the left.

The green and purple lines on the image of the magnetic field indicate the edges of a magnetic field moving towards and away from the viewer, respectively. The magnetic field exists in the z direction and surrounds the cone.

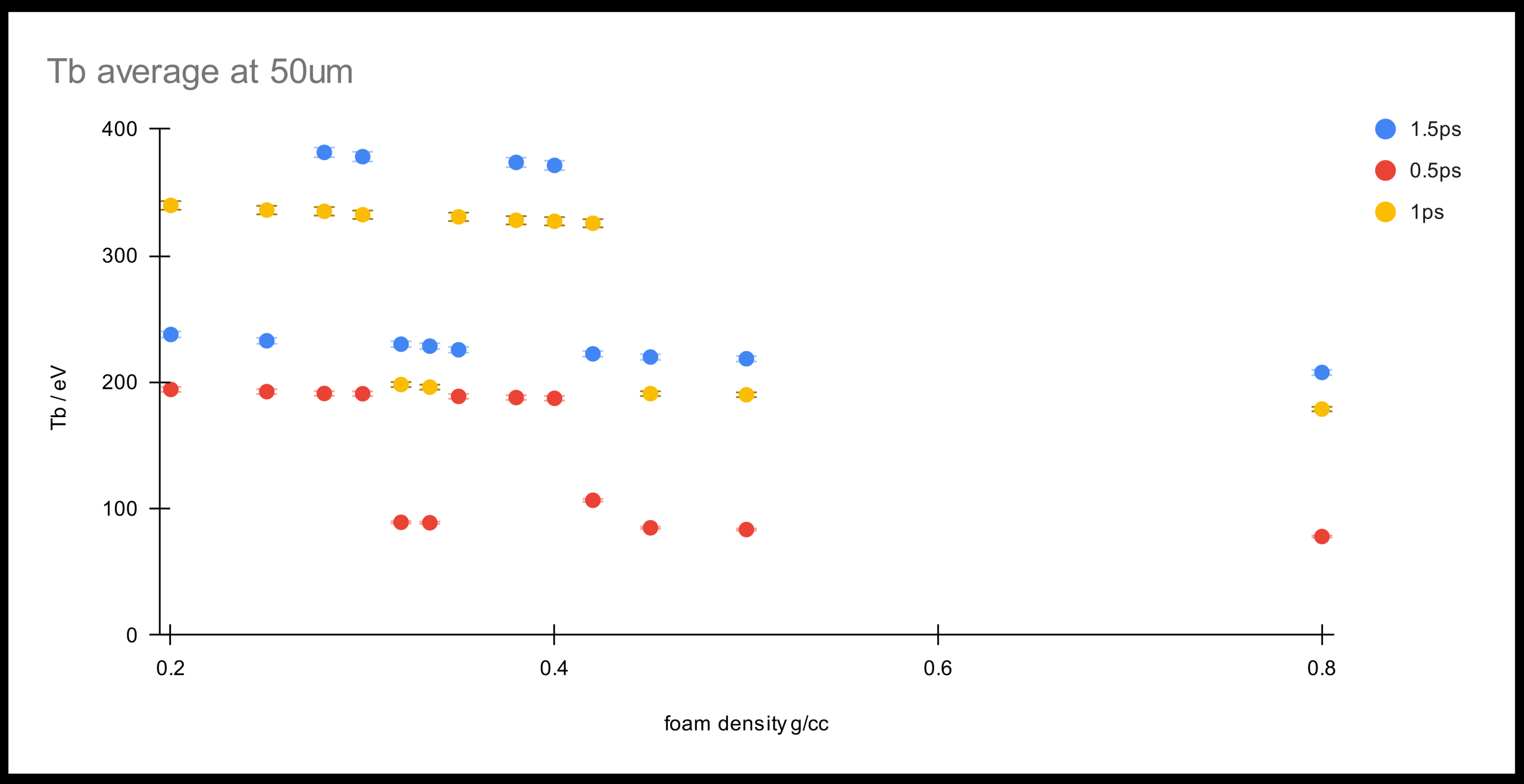
Simulated images of background temperature were taken from 2-dimensional plane slices at 50 micrometres and 100 micrometres on the cone, which correspond to the base of the cone itself and the back of the entire target, respectively.

Using ZEPHYROS to investigate cone cladding

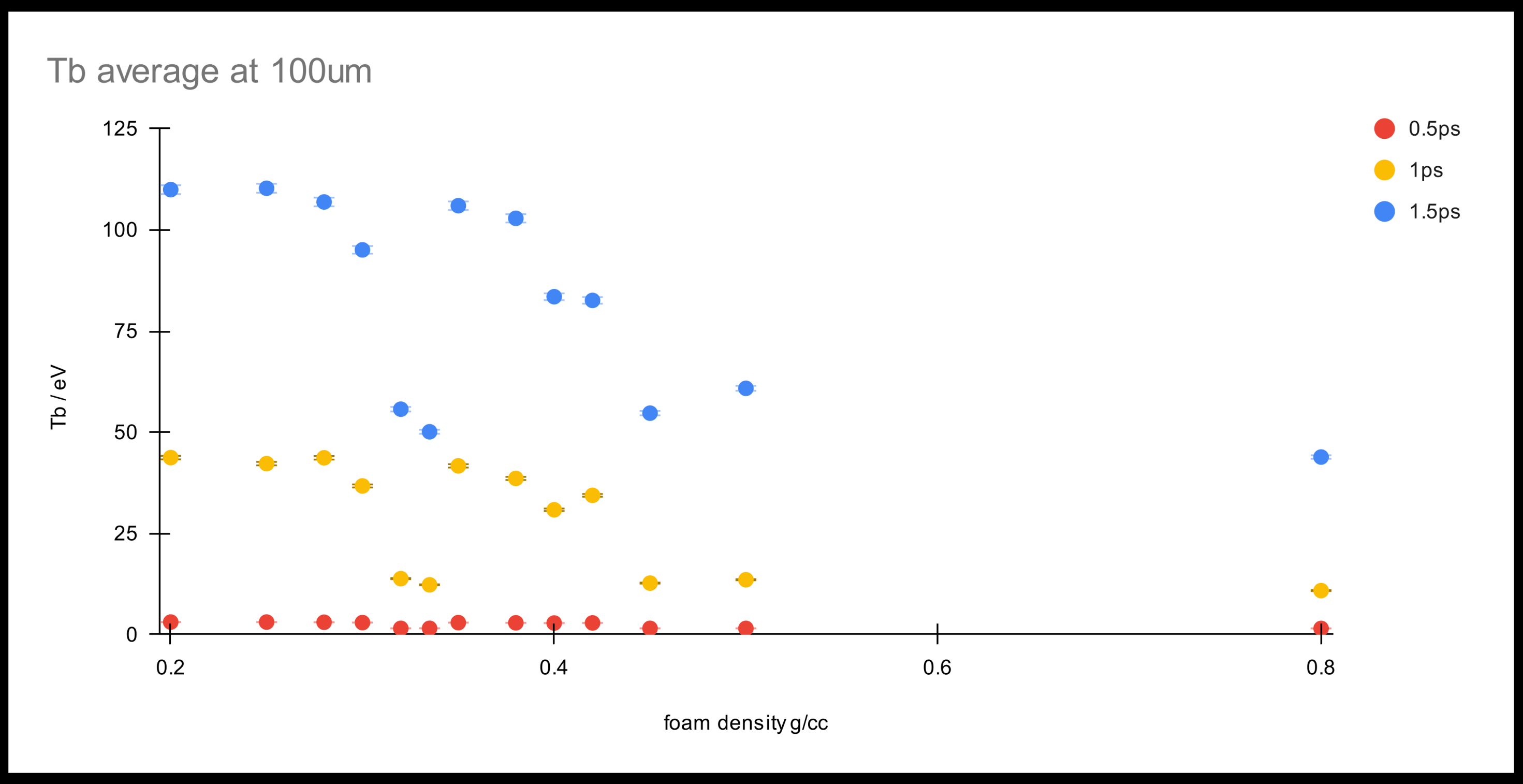
ZEPHYROS is a FORTRAN hybrid code that can be used to simulate fast ignition ICF by inputting target cone parameters [1]. These parameters can include cladding ion density, cone diameter, cone gradient, cone height, and cone ion density. As this project focused on investigating the effect of the density of the CH^2 cone cladding, only the parameters relating to the cladding were changed once the initial cone parameters were set. Every cone used in simulation had a total depth of 100 micrometres from tip to back of the target, with a cone height of 50 micrometres. Every cone also had a tip diameter of 16 micrometres and gradient of 5 degrees. 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/cm^3 CH^2 density being investigated.

0.8 g/cm^3 is the solid density of CH^2 glue, but it was hypothesised via private communication between K. Lancaster and A. P. L. Robinson that a CH^2 foam with a density of 0.4 g/cm^3 would produce better guiding effects. A range of densities from 0.2 to 0.5 g/cm^3 were simulated. Fast electron density and background temperature from the z and x directions were monitored. In the x direction (facing the cone head-on), temperature was monitored at both 50 and 100 micrometres to understand how the back of the target was heating, as well as the base of the cone. This provided a sense of how well the electrons were guided to the back of the target by the cone.

In addition to monitoring the numerical value for the temperature, the magnetic field, fast electron density, and background temperature were plotted using Python scripts. Images of the simulated ignition can give a better sense of filamentation and reflux, which both show the efficacy of the cone's guiding ability as well as influence further parameter changes.



Plot of average background temperatures at 50 micrometres for every CH^2 density simulated. Temperature was measured at 0.5 (red), 1 (yellow), and 1.5 (blue) picoseconds to monitor how the resistive guiding functioned during, at the end of, and after the 1 picosecond laser pulse. Abnormal peaks were found at the 1.5 picosecond mark around 0.3 and 0.4 g/cm^3, and an unexpected dip was found around 0.32 g/cm^3 for all timestamps. Solid density 0.8 g/cm^3 is shown for comparison.



Plot of average background temperatures at 100 micrometres for every CH^2 density simulated. Temperature was measured at 0.5 (red), 1 (yellow), and 1.5 (blue) picoseconds to monitor how the resistive guiding functioned during, at the end of, and after the 1 picosecond laser pulse. The peak pattern, as well as the dip and sudden spike between 0.32 and 0.35 g/cm^3 was unexpected and is not fully understood. Solid density 0.8 g/cm^3 is shown for comparison.