

Multidimensional Modelling of Cross-Beam Energy Transfer for Direct-Drive Inertial Confinement Fusion

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List of Acronyms

Rad-MHD Radiative-Magnetohydrodynamics

MHD Magnetohydrodynamics

Rad-Hydro Radiative-Hydrodynamics

LPIs Laser-Plasma Instabilities

CBET Cross-Beam Energy Transfer

ICF Inertial Confinement Fusion

SBS Stimulated Brillouin Scattering

SRS Stimulated Raman Scattering

TPD Two Plasmon Decay

EPW Electron Plasma Wave

LLNL Lawrence Livermore National Laboratory

IAW Ion Acoustic Wave

EPW Electron Plasma Wave

NIF National Ignition Facility

MIT Massachusetts Institute of Technology

1 Simulations of Cross-Beam Energy Transfer for Magnetised Direct-Drive

This chapter describes a set of simulations which were conducted to understand the role of Cross-Beam Energy Transfer (CBET) in magnetised, direct-drive implosions. Magnetised Inertial Confinement Fusion (ICF) is a promising route to achieving higher target gains, due to the reduction of thermal energy loss at stagnation and additional confinement of the alpha particles responsible for burn propagation. For direct-drive implosions, magnetisation can significantly alter the coronal plasma conditions, due to the introduced anisotropy of thermal transport. The Ion Acoustic Wave (IAW) dispersion relation, which mediates CBET interactions, depends upon the background plasma and therefore significantly altered temperature and density profiles could alter the action of CBET. Before the development of SOLAS, no direct-drive suitable CBET model existed, which was integrated into a Radiative-Magnetohydrodynamics (Rad-MHD) code. Therefore, the CHIMERA-SOLAS framework has enabled the effect of magnetisation on CBET to be studied for a direct-drive implosion.

The chapter begins with a review of experimental and computational work on magnetised ICF, with a particular focus on magnetised direct-drive. Work presented in this chapter focuses on the study of *exploding-pusher* experiments. These are very different implosions to the typical *central hot-spot* ignition designs, presented in previous chapters, so a short summary of exploding pushers is also provided. Simulation results are presented of 1-D and 2-D, unmagnetised exploding pushers, both with and without the effect of CBET, which demonstrate that CBET does significantly alter these implosions. This is followed by an investigation of how various extended-Magnetohydrodynamics (MHD) terms affect the implosion, including the Nernst effect, the Lorentz force and resistive diffusion of the magnetic field. Results are given of how magnetisation affects the CBET interaction and ultimately how it changes the stagnation shape of the target. The results presented, demonstrate that redistribution of deposited power due to CBET reduced the amplitude of the stagnation asymmetry, which originated from the polar beam configuration used. However, the reduction of asymmetry was consistent for different initial seed magnetic field values, and therefore CBET was not observed to be sufficiently strongly affected by magnetisation, to lead to observable signatures in experimental measurements. The chapter concludes with a summary of the work and suggestions of additional experimental configurations, which may leave a more significant signature of magnetisation altering CBET.

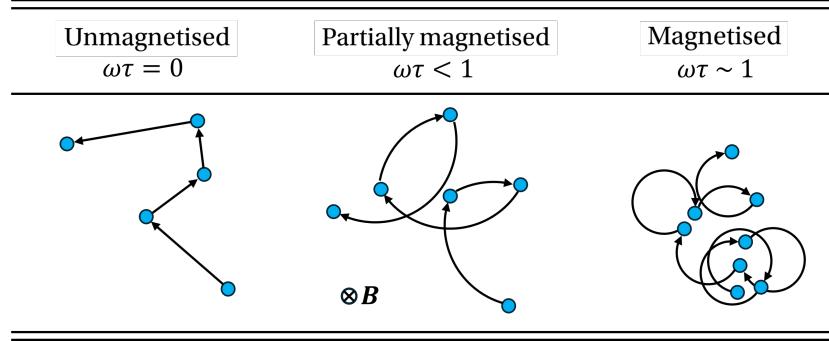


Figure 1.1: Cartoon to illustrate the effect of magnetisation on collisions, and therefore transport, of a test positive charge. Particle locations after collision are represented as blue circles and the path taken by the particle is shown by the black arrows. As the Hall parameter of the particle increases, diffusion is increasingly limited, and therefore collision transport is reduced.

1.1 Magnetised Inertial Confinement Fusion and Exploding Pushers

This chapter begins with a review of published studies of relevance to the work conducted in this chapter. Firstly, a short review of magnetised-ICF is presented, which reviews both the key concepts, existing studies and potential challenges of the design. Both work on direct- and indirect drive is summarised, alongside recent theoretical progress on understanding how magnetisation can effect Laser-Plasma Instabilities (LPIs). The exploding pusher concept is then briefly explored to aid understanding of the implosion physics, which is markedly different to conventional hot-spot ICF.

1.1.1 Potential Benefits of Target Magnetisation

Magnetisation of an ICF target has long been thought of as a potential aid to ignition [1, 2]. It is still a relevant field of study in the context of regular ignition events on the National Ignition Facility (NIF), because by relaxing the ignition threshold, magnetisation could make larger targets feasible at equivalent laser energy, and therefore lead to higher gains than unmagnetised implosions. For a central hotspot ignition targets, ignition occurs when the heat source of alpha energy deposition balances the thermal and radiative losses in the hotspot. Thermal conduction is suppressed perpendicular to magnetic field lines, therefore a magnetic field can reduce thermal losses and aid the power balance required for ignition. Fig. 1.1 demonstrates the effect of increasing magnetisation on a unit positive test charge. By constraining charged particles to orbit field lines, collisional transport terms, such as thermal conduction, are reduced perpendicular to the field direction. Fits of transport coefficients to Fokker-Planck simulations, demonstrate that in a Hydrogen plasma, thermal conductivity perpendicular to field lines κ_{\perp} , is reduced to $\sim 30\%$ of the parallel value κ_{\parallel} at Hall parameter $\omega\tau = 1$, and $\sim 1\%$ at $\omega\tau = 10$ [3]. Thus, for Hall parameters, $\omega\tau \gtrsim 10$, thermal conduction losses are almost negligible in the direction perpendicular to field lines.

Using an order of magnitude estimate for a below ignition threshold hotspot, $T_e \sim 2.5$ keV

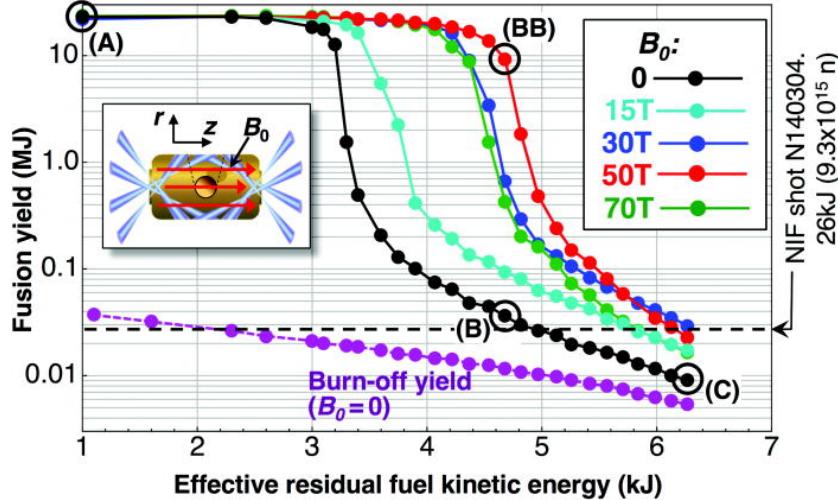


Figure 1.2: Simulated fusion yields versus effective residual fuel kinetic energy under imposed low-mode radiation flux perturbations for imposed fields in the range $B_0 = 0 \rightarrow 70$ (T). The plot demonstrates that with increasing departure from ideal compression (moving to the right on the x axis), magnetisation can enable the onset of the ignition. Reused with permission from Ref. [6].

and $\rho \sim 50 \text{ g cm}^{-3}$, a field strength $|\mathbf{B}| \sim 2.5 \text{ kT}$ is required to obtain $\omega\tau \sim 1$ [4]. This field strength cannot be produced directly, but it is possible to produce a smaller field which, assuming frozen in magnetic field and a spherical compression, is amplified by the square of the convergence,

$$|\mathbf{B}_1| = |\mathbf{B}_0| \left(\frac{R_0}{R_1} \right)^2, \quad (1.1)$$

where $|\mathbf{B}_0|$ and $|\mathbf{B}_1|$ are initial and final magnetic fields respectively and R_0 and R_1 are initial and final radii respectively. Laboratory magnetic fields can be produced from pulsed power coils with field strength $|\mathbf{B}| \sim \mathcal{O}(50)$ T [5], so even moderate convergence-ratio targets ($R_0/R_1 \sim 10$) are able to produce strongly magnetised core plasma.

Fig. ?? plots results of magnetised indirect-drive simulations, of a target on the threshold of ignition [6]. Increasing magnitude of radiation perturbation were applied to the drive (moving to the right on the x -axis), which prevent the target from achieving ignition, which is visible as the steep increase in yield, below some threshold level of perturbation. The results demonstrate that when an initial magnetic field was applied to the target, it more robustly ignited with increasing field strength due to reduced conduction losses. This simulation work, prior to the achievement of ignition on the NIF [7], motivated the development of a magnetised ICF campaign at Lawrence Livermore National Laboratory (LLNL) [8].

The CHIMERA code has been used to study a wide array of physics relevant to magnetised ICF. Simulation work has been conducted, which has shown that magnetisation can alter instability growth of magnetised laser fusion implosions. While in the deceleration phase, magnetic tension can reduce low-mode perturbation growth [9], magnetisation of directly-driven targets inhibits heatflow in the plasma corona and thus limits thermal stabilisation of short wavelength modes from laser imprint [10]. Recent work has also demonstrated that

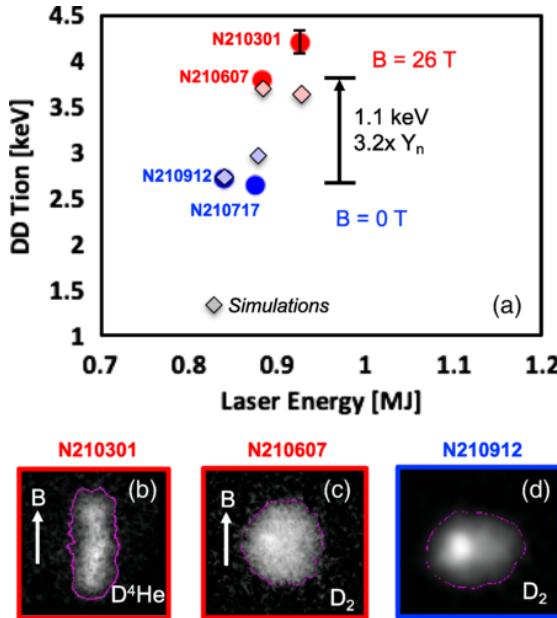


Figure 1.3: a) A 1.1 keV T_i increase was achieved by adding a 26 T B_0 field to a D_2 gas capsule implosion on the NIF. Also shown in the plot are the simulation results. b)–d) Equatorial shapes of the implosions. Reused with permission from Ref. [11].

magnetisation of high-yield, indirect-drive targets must be carefully optimised, in order to avoid significant degradation to the implosion shape, due to anisotropic thermal conduction and inhibition of burn propagation, due to α magnetisation [4].

1.1.2 Experimental Studies of Magnetised-ICF

Indirect-drive experiments have been conducted on the NIF to demonstrate the efficacy of magnetised targets, in reducing thermal conduction losses in the hotspot. Non-cryogenic, deuterium filled capsules were deployed with initial field strengths up to 26 T [11]. Results from this experimental campaign are show in Fig. 1.3.a. Fig. 1.3.b, 1.3.c and 1.3.d plot x-ray images at stagnation of different experiments, showing that a shape-tuning process had to be conducted in order to optimise the sphericity of the target, due to the field leading to anisotropic thermal conduction. The magnetised targets demonstrated significantly enhanced ion temperatures and neutron yields and work is underway to explore non-uniform field configurations to further enhance the benefits of magnetisation [12].

Magnetisation of direct-drive targets has been investigated by experiments on the OMEGA laser facility for a number of years. Initial OMEGA experiments focussed on verification of magnetic flux compression, by applying an initial seed field along the axis of a cylinder that was imploded via laser irradiation [14]. The magnetised implosions validated predictions of flux compression and demonstrated enhanced neutron yields and core ion temperatures over unmagnetised implosions. Spherical targets were subsequently fielded, which also resulted in increased stagnation temperatures and yield compared to unmagnetised targets. No noticeable degradation to the implosion shape or performance was observed in these experiments, which was assumed to be due to the high ratio of plasma pressure to magnetic

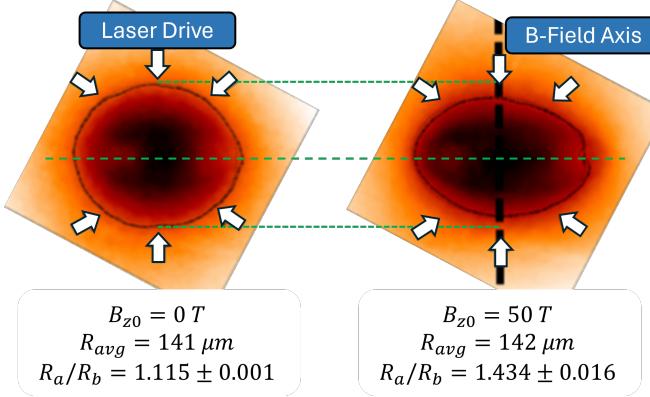


Figure 1.4: X-ray self emission images of (left) an unmagnetised and (right) a magnetised implosion. The average radius of the marked contour (corresponding to 40% of peak intensity), and the oblateness parameter R_a/R_b (ratio of major-to-minor axis) are listed below each image. The polar laser-drive is indicated by the white arrows, and the axis of the initial magnetic field by the black dashed line on the right. Applying an initial magnetic field demonstrated increased oblateness of the implosion. Adapted with permission from Ref. [13].

pressure, $\beta \gg 1$.

The most recent experimental, magnetised direct-drive work has focussed on exploring higher initial seed field values ($|\mathbf{B}_0| \sim 50$ T compared to $|\mathbf{B}_0| \sim 8$ T), to understand the saturation of performance with increasing field. A shock-driven, exploding pusher target configuration was used for these experiments, in order to create high ion temperatures and thus create a platform to study magnetised ions. Exploding pushers are significantly different implosions compared to hot-spot ignition targets discussed in previous chapters and shall be described in detail in Sec. 1.1.4. Creating these strong fields at the target necessitated reducing the radius of the equatorial field coil compared to previous experiments, and therefore a 40-beam configuration had to be used, without the 20 equatorial beams, leading to a pole heavy laser drive. The high fields of these implosions led to strongly magnetised coronal electrons, $\omega_e \tau_e \sim 50$, resulting in strongly anisotropic thermal conduction $\kappa_{\perp,e}/\kappa_{\parallel,e} \sim 10^{-4}$. This is compared to previous experiments which produced $\omega_e \tau_e \sim 1$ and therefore $\kappa_{\perp,e}/\kappa_{\parallel,e} \sim 1/3$. In direct-drive on OMEGA, laser deposition is transported to the ablation surface by electron thermal conduction, thus large electron Hall parameters led to an effective asymmetry of the implosion drive.

Fig. 1.4 shows x-ray self-emission images of an unmagnetised (left) and magnetised (right) target with an initial $|\mathbf{B}_0| = 50$ T seed field. The strongly magnetised coronal electrons led to decreased drive $\perp \hat{\mathbf{B}_0}$, markedly increasing the oblateness of the diagnostic image compared to the unmagnetised target. An ion magnetisation of $\omega_i \tau_i \sim 7$ was also reported. Previous Rad-MHD modelling of these experiments, using the CHIMERA code, did not include the effects of CBET. The development of SOLAS, and particularly the CBET model, motivated further computational study of these experiments, to explore whether CBET played a significant role in dictating the shape of these implosions. This is because CBET is known to markedly compensate global, $\ell = 1$ asymmetries [15, 16], therefore the anisotropy introduced from

magnetisation could affect the action of CBET.

1.1.3 Magnetised Laser-Plasma Instabilities

In this chapter, Sec. 1.4, aims to understand how magnetisation of a direct drive implosion anisotropically changes the hydrodynamics, and how these altered coronal plasma conditions modify the calculated CBET gains, discussed in Sec. ???. For example, magnetisation restricts thermal conduction and therefore enhances coronal electron temperatures along the initial field axis. Approximately, the fluid CBET gain, $\gamma_{ij} \propto T_e^{-1}$, therefore anisotropic changes to T_e could result in reduced CBET gains around the target and therefore change CBET scattering compared to implosions without an applied field. This modification to CBET via the altered hydrodynamic profiles is called the *indirect* effect of magnetisation on LPIs.

Magnetisation can however also *directly* modify scattering from LPIs, in a number of ways. For ICF conditions, when the field strength is sufficiently high, electron cyclotron motion can become comparable to plasma wave frequencies, and therefore alter the dispersion relation of the mediating plasma wave in LPIs. In underdense, ICF relevant plasma ($n_e \sim 10^{20} \text{ cm}^{-3}$ and $T \sim 2 \text{ keV}$), the IAW, which mediates Stimulated Brillouin Scattering (SBS) and CBET, is significantly modified when $|\mathbf{B}| \sim 100 \text{ T}$ and the Electron Plasma Wave (EPW), which mediates Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD), when $|\mathbf{B}| \sim 1000 \text{ T}$ [17]. Additionally, the (predominantly collisionless) damping of plasma waves can also be modified, because cyclotron motion of particles can affect their trapping in plasma waves [17]. Significant theoretical progress has been made in this field in recent years by Shi et al., who derived analytic formula for 3 wave coupling in the presence of a magnetic field [18, 19]. This was challenging due to the lack of simple geometries for the interaction, when a field is applied to a plasma with an arbitrary direction.

The simulation results here neglect this direct affect of magnetisation on CBET, partially because the theory is not yet deemed to be significantly mature, to implement within a reduced, ray-based model. Coronal magnetic field strengths of $|\mathbf{B}| \lesssim 50 \text{ T}$ were observed in the underdense coronal plasma so significant modifications to the IAW dispersion relation were not expected. It is noted however, that altered damping of the waves from magnetisation may affect the results, but the focus of the study was predominantly to explore how magnetisation might indirectly affect CBET.

1.1.4 The Exploding-Pusher Configuration

Exploding-pushers are considered to be a highly reproducible platform, robust to instabilities and capable of producing large neutron yields. Although historically it had a slightly different meaning [20], the term ‘exploding pusher’ is now, typically used for low convergence, thin-shell targets [21]. When irradiated with significant intensity, frequency-tripled laser light¹, the thin shell rapidly heats and then explosively ablates, driving a strong shock

¹When frequency-tripled light is not used, suprathermal electrons, rather than ablation, is the dominant driver of the strong shock [22].

radially inward, ahead of the in-falling ablated material. This shock strongly heats the ions as it propagates through gas fill to large, fusion relevant temperatures. After rebounding from the axis, the shock recompresses the infalling exploded shell material, resulting in sufficient density for a significant number of fusion reactions.

Directly-driven exploding pusher targets have the largest direct drive fusion yields recorded on the NIF, resulting in $E_{\text{fusion}} \sim 30 \text{ kJ}$ [22]. However, they are not suitable for high gain designs, as the low areal densities of the target are not sufficient to confine α particles and thus enable burn propagation. A variety of interesting physics may be studied using the platform due to the significant ion temperatures that can be achieved, such as equilibration between electrons and ions [23]. The strong shock is also highly kinetic, and thus accurate comparison to experimentally measurable variables, such as yields and ion temperatures, is expected to be difficult for Radiative-Hydrodynamics (Rad-Hydro) codes which lack a suitable model for non-local transport, such as CHIMERA. However, much of the key dynamics and results can be studied more qualitatively. !!!!!!!!!!!!!!! - Check the above sentence and get a reference - !!!!!!!!!!!!!!!

1.2 Cross-Beam Energy Transfer in Unmagnetised Exploding Pushers

This section presents simulation results, which demonstrate the effect of CBET in exploding pushers on OMEGA. Both 1-D and 2-D CHIMERA-SOLAS simulations of 40-beam, pole-heavy drive exploding pusher experiments are presented, with a focus on how CBET acts to change the implosion. The 1-D results demonstrate that CBET significantly reduced the coupled laser energy to the implosion from ... to Simulations conducted in 2-D, with a full 3-D raytrace and CBET model, clearly demonstrated that the polar drive configuration led to an oblate implosion.

1.2.1 Simulation Configuration

The simulations conducted for this chapter aimed to study experimental configurations similar to the results from Bose *et al.*, discussed in Sec. 1.1.2 [13]. Experimental data from these magnetised exploding pushers, demonstrated a clear amplification of the mode-2 due to magnetisation, which could affect CBET scattering. The beam configuration, capsule initial conditions and pulse shape are shown in Fig. 1.5. The exact pulse shape and target specifications were from a set of follow-up experiments to Bose *et al.* and were provided by C. W. Chang and J. Frenje from Massachusetts Institute of Technology (MIT) [24]. 40 beams from the OMEGA laser, delivered a total of 17.7 kJ laser energy to a $2.5 \mu\text{m}$ thick, glass (SiO_2)² capsule, filled with room temperature and pressure D_2 . All experiments removed the 20 equatorial beams from the drive, because the presence of the field coil precluded them when an axial field was applied. Magnetic fields of strength $B_{z0} = 0, 25$ and 50 T were applied along the z-axis of the configuration.

²By ion number density, the material comprised 1/3 Si and 2/3 O.

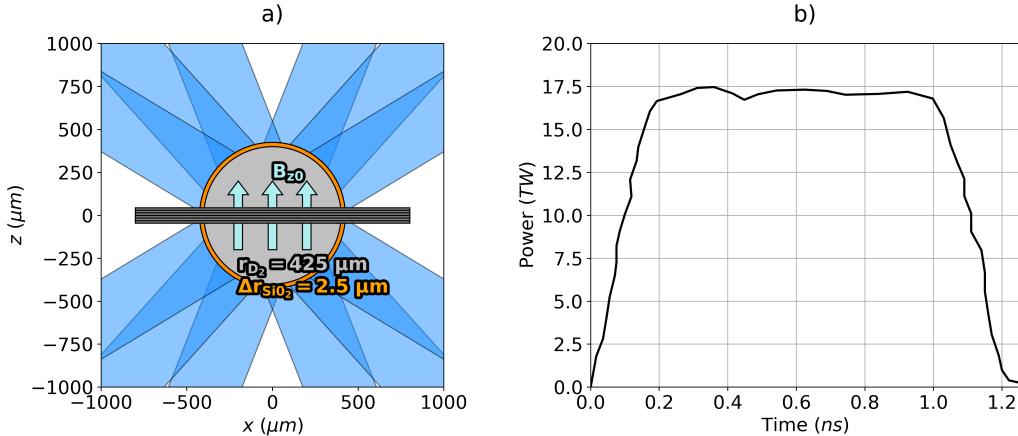


Figure 1.5: The initial conditions used for all simulations presented in this chapter. Panel a) plots the D_2 filled, glass shell capsule and direction of the initial magnetic field. An example field coil (illustrative and not included in simulations) is also shown, the presence of which necessitated the polar laser drive in experiments. Panel b) plots the laser pulse shape used, which had a total of 17.7 kJ laser energy.

An explicit $P_{1/3}$ radiation transport algorithm was used for all simulations, using tabulated opacities and emissivities from the SPK code [25]. A tabulated Sesame equation of state was used for each material [26]. The CHIMERA extended-MHD package was used, which included resistive diffusion of the magnetic field, Lorentz force of the magnetic field on the hydrodynamics, Nernst advection of the field down temperature gradients and anisotropic thermal conduction [27]. Thermal conduction was solved using a Super-time-stepping, semi-implicit algorithm [28], with flux-limited, Spitzer conductivities [29]. An electron flux limiter of $f_{lim,e} = 0.15$ was used for all simulations. Exploding pushers exhibit high coronal temperatures due to the high- Z ablator and large temperatures for the strong imploding shock, therefore simulation yields and bangtimes are highly sensitive to thermal conduction and the choice of flux limiter. Although not the focus of this work, if attempting to match simulation result to experimental yields, reducing the flux limiter value would strongly inhibit the drive and therefore reduce simulation bangtimes. In order to improve the speed of the thermal conduction algorithm, which takes small timesteps on a vacuum-plasma interface, an artificial material was placed outside the capsule, which had an enforced ionisation state of $Z = 0$. This had minimal impact on the implosion results, but significantly sped up simulation run-times. The presence of the material did create large viscous heating of the ions as the coronal plasma expanded into it which is visible in results throughout the chapter. However, this viscously heated layer was well separated from the region of interest (near critical) for the majority of the implosion and therefore did not impact upon the results.

All simulations used a spherical-polar CHIMERA mesh, with a fixed radial resolution of 0.5 μm , over the full 4π str. 1-D simulations were run from beginning to end in spherical with $r \in [0, 1400] \mu\text{m}$. 2-D, r, θ calculations assumed azimuthal symmetry of the hydrodynamics and conducted an initial ‘drive-phase’ in spherical coordinates, with $r \in [80, 1400] \mu\text{m}$, where the central cutout region was removed to avoid taking small radiation transport timesteps

due to the small cell faces close to the axis. The 2-D drive-phase grid used 120 cells in the polar direction. When the shock reached this cutout region, hydrodynamic variables were trilinearly interpolated onto a 2-D cylindrical r_{cyl}, z mesh with fixed resolution, $\Delta_{r,\text{cyl}} = \Delta_z = 1 \mu\text{m}$, and $r_{\text{cyl}} \in [0, 1200] \mu\text{m}$ and $z \in [-1200, 1200] \mu\text{m}$, for the ‘stagnation-phase’. This grid contained no singularities, unlike a 2-D spherical grid which has no cutout, and therefore excessively small radiation transport timesteps were not an issue.

All simulations used a 3-D laser ray-trace with a variety of CBET treatments. CBET was fully included for some simulations and neglected for others. Alternatively, to explore the effect that CBET *spatial redistribution* of deposited power had on implosions, some simulations were conducted without CBET, but forced to deposit the magnitude of power that was absorbed from the equivalent CBET simulation at that time. Explicitly, these simulations conducted a no-CBET ray-trace, where the power of all rays was normalised to unity. When this raytrace was complete, it read in the absorbed power from the (previously conducted) CBET simulation at that time and multiplied the (normalised) deposited power by this value. This created a hydrodynamically similar implosion to the CBET ray-trace, and via comparison of these two simulations, the impact of CBET relocation-of-deposition upon the hydrodynamics was studied. Temporally-and-spatially integrated results from all simulations are presented in Tab. 1.1 and are referred to when relevant throughout the chapter.

Several metrics have been included in the table, which are explicitly defined here. The metrics are commonly used to compare implosions in ICF, because, apart from the oblateness parameter in the last column, they can all be directly computed from experimental neutron spectra [30]. As previously stated, the bangtime is the time of peak neutron production, which for this simulation, assumes only deuterium-deuterium reactions contribute,

$$t_b = \operatorname{argmax}_t \left(\int Y_{DD}(\mathbf{x}, t) \, dV \right), \quad (1.2)$$

where Y_{DD} is the deuterium-deuterium neutron production rate, which is calculated across the CHIMERA computational grid at all locations and times throughout the simulation, using Bosch-Hale fits to the reactivity [31]. The total neutron yield is the spatially and temporally integrated neutron production,

$$Y_n = \int \int Y_{DD}(\mathbf{x}, t) \, dV \, dt. \quad (1.3)$$

The burn-width, Δ_b is the full width half maximum of the spatially integrated neutron production. One interpretation of this diagnostic, for this very two-dimensional configuration, is that a highly oblate implosion will have less temporally and spatially localised convergence. Therefore, neutron production for less symmetric implosions will likely happen over a longer timescale, because thermonuclear conditions are produced at different times in different locations. The burn-averaged ion temperature, $\langle T_i \rangle$, is defined as the ion temperature, weighted by temporally and spatially resolved neutron production,

$$\langle T_i \rangle = \frac{\int \int T_i(\mathbf{x}, t) Y_{DD}(\mathbf{x}, t) \, dV \, dt}{Y_n}, \quad (1.4)$$

Table 1.1: Results of all Simulations. In the CBET column, ‘~’ indicates CBET acted on the magnitude, but *not* spatial location, of deposition.

Run	Dim.	CBET	Note	B_{z0} (T)	t_b (ns)	$\langle T_i \rangle$ (keV)	Y_n ($\times 10^{10}$)	Δ_b (ps)	$\frac{R_{\text{equator}}}{R_{\text{pole}}} _{t=t_b}$
1	1-D	Off	-	0	0.69	14.66	11.62	87	$1.00^{+0.00}_{-0.00}$
2	1-D	On	-	0					$1.00^{+0.00}_{-0.00}$
3	2-D	Off	-	0	0.71	8.44	6.20	148	$2.96^{+0.20}_{-0.19}$
4	2-D	~	-	0	0.75	7.61	5.23	153	$3.26^{+0.25}_{-0.23}$
5	2-D	On	-	0	0.75	7.77	5.46	148	$3.23^{+0.25}_{-0.23}$
6	2-D	Off	-	25	0.74	7.26	4.73	130	$3.80^{+0.41}_{-0.33}$
7	2-D	~	-	25	0.78	6.58	4.14	125	$4.55^{+0.50}_{-0.43}$
8	2-D	On	-	25	0.78	6.72	4.44	123	$4.32^{+0.47}_{-0.41}$
9	2-D	Off	-	50	0.73	6.82	3.73	134	$4.40^{+0.43}_{-0.38}$
10	2-D	~	-	50	0.78	6.30	3.30	130	$4.92^{+0.56}_{-0.48}$
11	2-D	On	-	50	0.78	6.37	3.52	129	$4.79^{+0.55}_{-0.47}$
12	2-D	Off	No Aniso.	25	0.81	6.40	5.02	118	$3.14^{+0.68}_{-0.50}$
13	2-D	Off	No Lor.	25	0.74	7.29	4.77	131	$3.80^{+0.41}_{-0.33}$
14	2-D	Off	No Nern.	25	0.73	7.41	4.85	130	$3.74^{+0.38}_{-0.32}$
15	2-D	Off	No Resis.	25	0.73	7.07	4.59	132	$3.84^{+0.42}_{-0.33}$

It is an integrated metric, which summarises the average temperature of the regions of the implosion, which are key in producing fusion-yield. Finally, the oblateness parameter in the final column of the table, $(R_{\text{equator}}/R_{\text{pole}})|_{t=t_b}$, was obtained by fitting an ellipse (with axes orientated along $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$), to the radius of maximum density at bangtime. The fit also returned asymmetric error bars which are presented alongside the result.

1.2.2 1-D Simulations

In order to demonstrate how CBET typically affects exploding pushers, two 1-D simulations were conducted, both with and without CBET scattering included. The no-CBET and CBET simulation results are provided in Tab. 1.1 as run 1 and run 2 respectively. Note that because the simulations were 1-D and therefore spherically symmetric, the ratio of equatorial radius to polar radius at bangtime was unity. Both of these simulations used the beam configuration from Fig. 1.5, which unlike the hydrodynamics of the simulation, is not spherically symmetric. As described in Sec. ??, a sparse 3-D SOLAS mesh was created on which to compute the correct beam interaction in 3-D. For the 1-D simulations, 23 cells were used for the underlying spherical polar mesh in the θ direction and 54 cells in the ϕ direction, which were then combined to create a semi-structured SOLAS mesh.

Absorbed laser power as a function of time from these two simulations along with streak plots of hydrodynamic variables are plotted in Fig. 1.6. The left column of panels is from

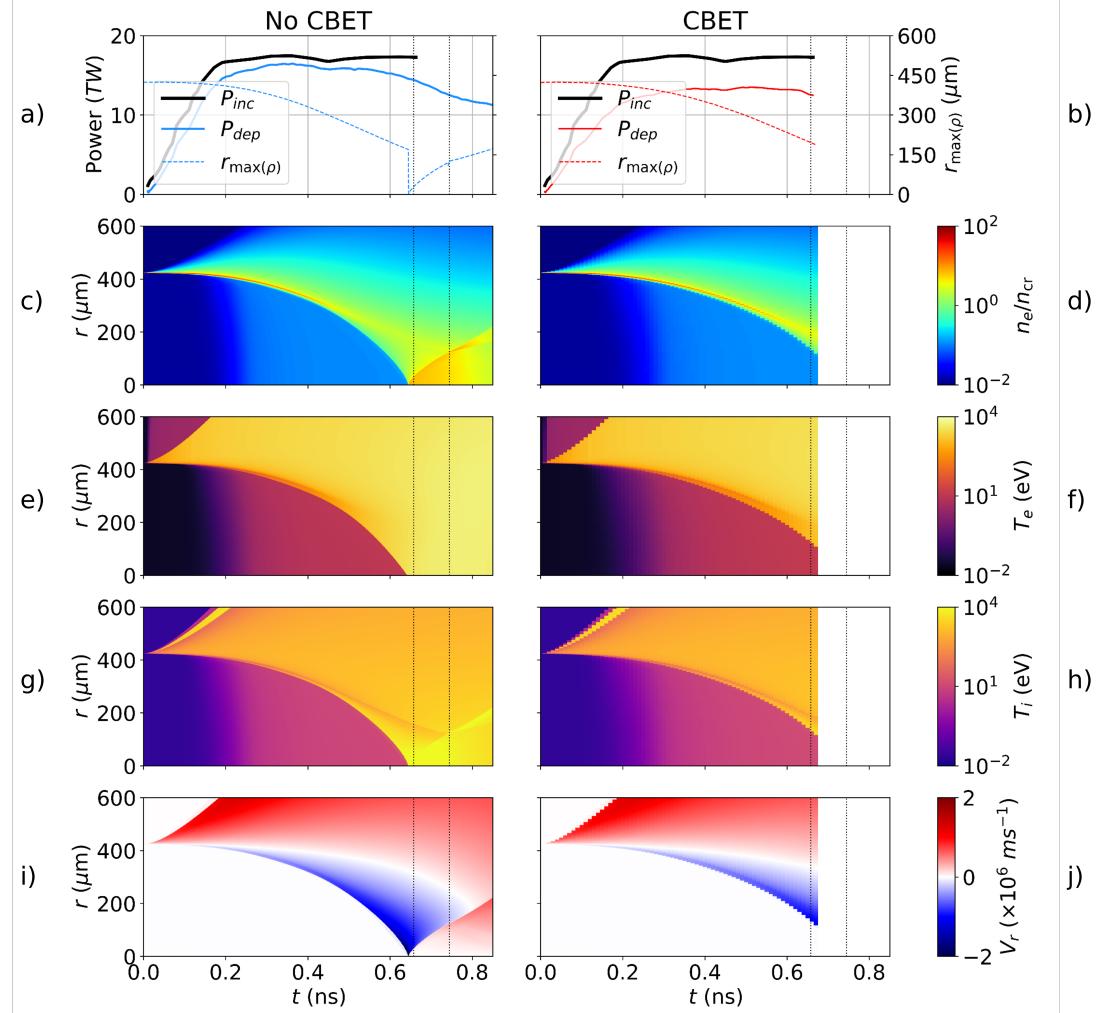


Figure 1.6: 1-D Simulation results both without (left) and with (right) CBET. The top row plots the incident and absorbed energy from the simulation on the left axis and the radius of maximum density on the right. In order, the next rows plot n_e , T_e , T_i and V_r . The full-width half-maximum times of the D₂ yield are plotted as dotted vertical black lines on all panels.

the no-CBET simulation and the right are from the CBET simulation. The top row demonstrates that CBET reduced the absorbed power by $\sim 15\%$. This reduced deposition, led to a slower and weaker shock being driven ahead of the imploding SiO₂ material, which is most clearly visible in the fourth panel, plotting T_i on a log scale. CBET reduced the speed of the shock, such that it hit the axis for the with-CBET simulation at $t \sim 0.7$ ns compared to $t \sim 0.65$ ns without CBET. Bangtime occurred for both simulations after this ‘shock-flash’, as the rebounding Deuterium fuel compressed against the in-falling shell, creating thermonuclear densities and temperatures. Note, that the effect of the fictitious, $Z = 0$ material, that was placed outside the capsule to speed up the super-time-stepping thermal conduction routine, is visible from the large T_i on the outer radius boundary of the expanding coronal plasma, which left the plot bounds at $t \sim 0.2$ ns. Simulations with vacuum outside the glass ablator initially, showed minimal difference in bangtime hydrodynamic conditions and therefore integrated diagnostics.

Compared to the streak plot of a more conventional, hot-spot ignition implosion in Fig. ??, clear differences can be seen. Firstly, the simulation presented in Fig. ?? did not include radiation transport, which is the origin of the preheat ahead of the shock³ in Fig. 1.6. Secondly, the hotspot ignition design maintained a cold dense shell throughout the implosion phase, whereas the initially thin shell of the exploding pusher simulation was approximately volumetrically heated. Therefore, relatively little mass was left in the glass shell when the re-bounding shock collided with it. Finally, the T_i increase in the exploding pusher design was predominantly from the spherical convergence of the strong shock, compared to the deceleration heating in the hotspot design, which was localised to inside the decelerating shell when it compressed on axis, at $t \sim 2.5$ ns in Fig. ?? . The lack of the cold dense shell is the reason that the exploding pusher design cannot scale to high yield, as there is insufficient areal density to confine α particles and sustain a burn wave.

!!!!!!!!!!!!!! Include more stuff here about comparing the integrated diagnostics when CBET sim works! !!!!!!!

1.2.3 2-D Simulations

Simulations of this setup were also conducted in 2-D to explore how the non-uniformity of the laser-drive affected the implosion, both with and without CBET. 2-D simulations used a 3-D SOLAS mesh to resolve the beam overlap pattern, with 58 cells in the azimuthal direction. Fig. 1.7 provides plots, which illustrate the progression of the simulation during the drive-phase. The left column plots T_e , T_i and n_e from the 2-D, $B_{z0} = 0$ T simulation without CBET. Integrated results from this simulation are given in the row labelled run 3 in Tab. 1.1. The right column plots the same for the equivalent simulation, but with the effect of CBET included, which corresponds to the row labelled run 5 in Tab. 1.1. Note that the viscous ion-heating of the fictitious material placed outside the glass shell initially, is again visible as large ion temperature in the layer immediately outside the coronal plasma expansion.

Particularly at the later times plotted in Fig. 1.7, the decreased, coronal T_e of the CBET compared to the no-CBET simulation is visible. The lower T_e was because of reduced absorption, due to CBET, and led to the shock from the no-CBET simulation imploding significantly faster than the CBET shock. Thus, the no-CBET implosion was more oblate during the drive-phase, because the shock travels primarily along the \hat{z} -axis, due to the beam-geometry. However, when including CBET, the velocity of the shock was reduced more than the velocity of the imploding portion of the glass shell, *i.e.* $|V_{r,\text{shock}} - V_{r,\text{shell}}|$ was larger for the no-CBET simulation than the CBET simulation. Therefore, the no-CBET shock, after re-bounding from the axis, collided with the shell and underwent maximal neutron production at a larger radius than for the CBET result. Thus, the oblateness parameter at bangtime in Tab. 1.1, $(R_{\text{equator}}/R_{\text{pole}})|_{t=t_b}$, is significantly larger for the CBET calculation.

Both 2-D simulations exhibited substantially reduced burn-averaged ion temperatures, compared to their 1-D equivalents. This was primarily due to the strong shock travelling mainly along \hat{z} , rather than radially inward as for the 1-D calculations. Therefore, the con-

³*i.e.* The temperature increase, which is visible in T_e and T_i plots, which hit the axis at $t \sim 0.2$ ns.

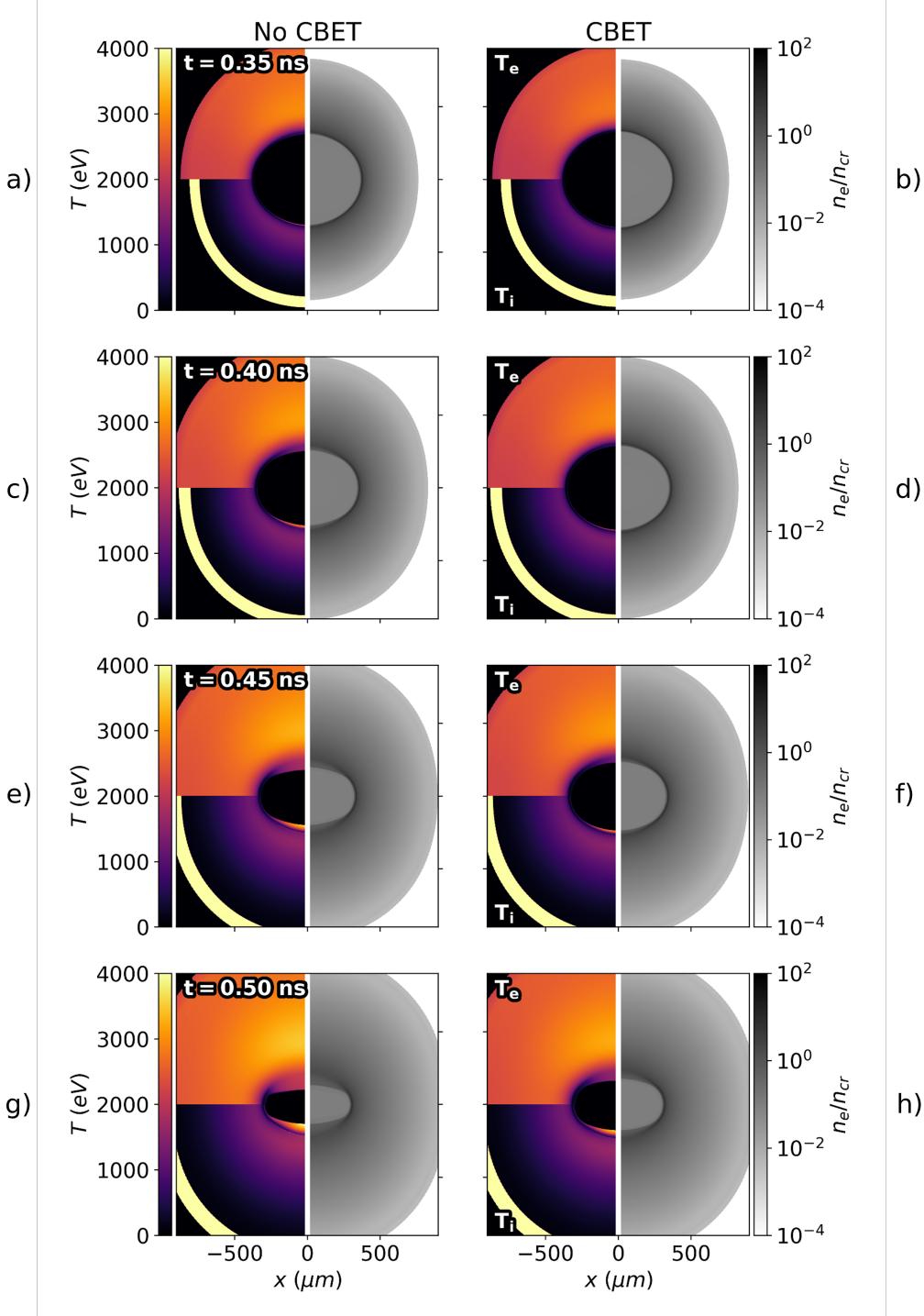


Figure 1.7: n_e (right-side), T_e (top-left-side) and T_i (bottom-left-side) plots from the 2-D, 0 T simulations without (left) and with (right) CBET at a variety of in-flight times. The decreased deposited energy due to CBET, results in lower coronal electron temperatures and therefore a slower, weaker shock being driven, which is especially evident at later times.

vergence of the shock was reduced, leading to lower temperatures, and therefore neutron yields. This interpretation is also corroborated by the increased Δ_b of all 2-D calculations compared to 1-D. The burn-width was larger, because thermonuclear conditions were pro-

duced at different times throughout the hot fuel, as the rebounding D₂ compressed against the infalling shell material, compared to the 1-D where it was spherically symmetric.

In summary of these unmagnetised implosions in 1-D and 2-D both with and without CBET, it has been shown that CBET substantially reduced the deposited power for these exploding pusher calculations. 1-D spherical calculations, which averaged the deposited power across all angles, demonstrated that this substantially reduced deposition led to a weaker shock being driven, which reduced thermonuclear yield and delayed the bangtime. When 2-D effects were included, which better reflected the geometry of the laser-drive, this resulted in an oblate implosion, which reduced the convergence of the shock, and therefore the ion temperatures. The reduced drive in the CBET calculations also slowed the shock speed more than the infalling material, so the oblateness at bangtime (when the rebounding shock collided with the in-falling material) was greater when including CBET.

1.3 Magnetisation in Exploding-Pusher Implosions

This section presents the effect that various extended-MHD terms had on the magnetised, 2-D exploding pusher simulations. Simulations were conducted with an initial field strength $B_{z0} = 25\text{T}$ and particular terms turned off, to deduce what the important physical processes were. The origin of the field structure is presented, which demonstrates that on the plasma corona, field lines are mainly radial due to the field being frozen in to highly conductive, radially outflowing plasma. Anisotropic thermal conduction in this highly magnetised coronal plasma acted to keep heat localised to the polar regions, which enhanced the drive on the pole relative to the waist. The results demonstrate that resistive diffusion and the Lorentz force have very little impact on the implosion physics, due to the bulk of the plasma being highly resistive and high- β respectively. Nernst-advection of the magnetic field acted to significantly redistribute the field in the low Hall parameter, equatorial region of the capsule, which formed a ‘divot’ in density on the capsule waist. This divot was however well separated from the region where burn was important, and thus had minimal impact on integrated neutron diagnostics.

1.3.1 In-Flight Field Structure

Initially, the development of the coronal field structure from the $B_{z0} = 25\text{T}$, no-CBET simulation, labelled as run 5 in Tab. 1.1. The top row of Fig. 1.8, plots the drive phase hydrodynamic profiles, overlaid with streamlines of the magnetic field, coloured by its magnitude, at 3 different times. Lineouts of n_e and the temperatures are plotted in the middle and bottom rows respectively, along both the polar and equatorial directions. The hot coronal plasma was highly conductive, shown explicitly in Sec. 1.3.4, and thus the field remained frozen in to the plasma. As the coronal plasma expanded outward therefore, it dragged the field lines with it, leading to $\mathbf{B} \sim \pm|\mathbf{B}|\hat{\mathbf{r}}$ in this, laser-heated region. The geometric stretching of the field lines at the target poles was less significant than at the equator, and therefore the coronal field strengths were smallest at the target equator and highest on the poles. As the target began to

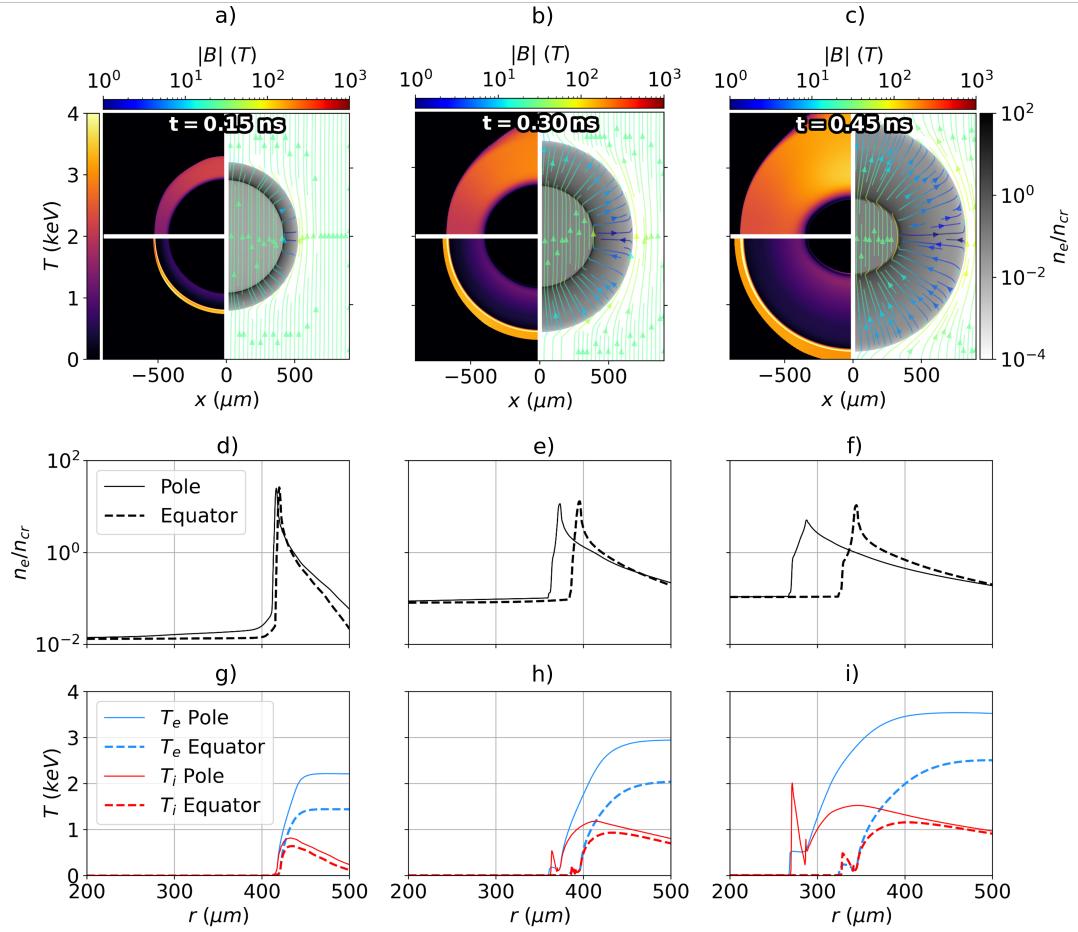


Figure 1.8: The development of the hydrodynamic variables and magnetic field structure from the $B_{z0} = 25$ T, CBET simulation. Panels a), b) and c) plot T_e (top-left), T_i (bottom-left), n_e (right) and \mathbf{B} (streamlines) at $t = 0.15, 0.30$ and 0.45 ns respectively. The approximately radially outward flowing, hot (and therefore highly conductive) ablating plasma pulled the magnetic field with it, resulting in radial \mathbf{B} field lines, which were weaker at the capsule equator. Panels d), e) and f) plot n_e lineouts along the pole ($\theta = 0^\circ$) and equator ($\theta = 90^\circ$). Panels g), h) and i) plot equivalent T_e and T_i lineouts. These all show that the increased polar temperatures, partially due to beam geometry and partially due to magnetisation, led to preferential ablation along the pole.

implode, the field compressed on the interior edge of the dense shell, resulting in non-radial field lines and an increase in field strength. This effect is most clearly visible at $t = 0.45$ ns, in Fig. 1.8.c.

The lineouts clearly demonstrate that the preferential heating of the target on the pole, led to faster ablation of the shell along this direction. This led to a much stronger shock along the pole, which is seen most clearly by the discrepancy in ion temperature between the pole and equator at $t = 0.45$ ns in Fig. 1.8.i. Increased polar electron temperature is partially due to the pole heavy drive, and also due to anisotropic thermal conduction. The field structure plotted in Fig. 1.8, inhibited equilibration of temperature via thermal conduction in the polar direction, which increased the temperature asymmetry compared to the unmagnetised

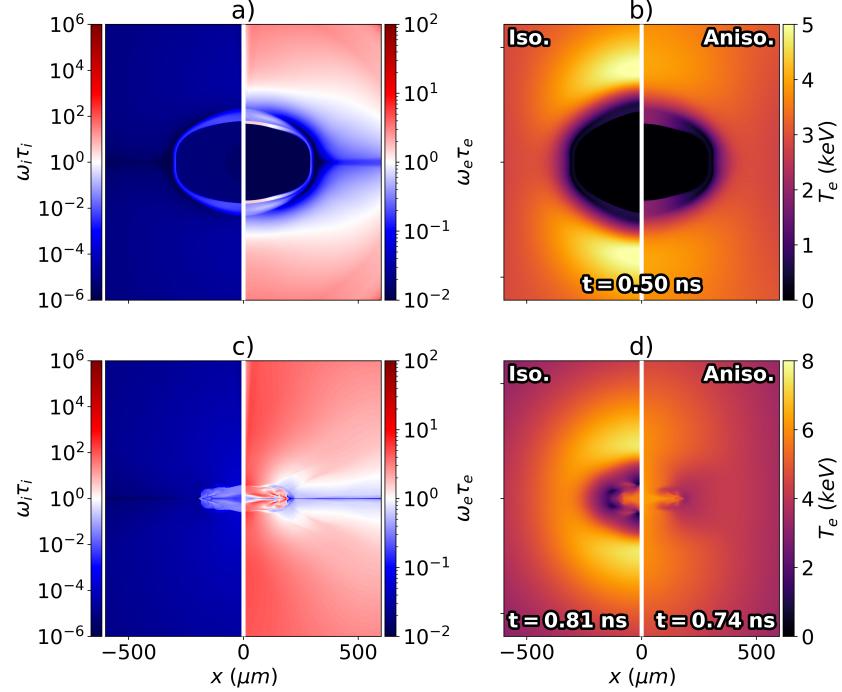


Figure 1.9: In-flight a) and bangtime c) Hall parameters, from the $B_{z0} = 25$ T, no-CBET simulation. Panel b) plots the T_e from the isotropically magnetised simulation (left-side) and anisotropic conduction simulation (right-side) in-flight. Panel d) plots the same, but at bangtime. The electron Hall parameter is > 1 at the poles due to high magnetic fields and temperatures, leading to significantly restricted thermal conduction from magnetised transport. Isotropically magnetised conduction, therefore results in a markedly different bangtime morphology, as is shown in panels b) and d). Ion hall parameters peak at bangtime, with values reaching about $\omega_i \tau_i \sim 0.1$.

simulation.

1.3.2 Anisotropic Thermal Conduction

In order to understand the effect of anisotropic thermal conduction, an additional simulation was performed, which had the same setup as the $B_{z0} = 25$ T, no-CBET, but thermal conduction was isotropically suppressed by the local magnetic field strength, regardless of its orientation. Explicitly, the parallel conductivity was forced to take the value of the perpendicular conductivity, $\kappa_{\parallel} = \kappa_{\perp}$. Comparison of this isotropically suppressed conduction simulation (labelled as run 12 in Tab. 1.1), with the $B_{z0} = 25$ T, no-CBET simulation (run 6 in Tab. 1.1), thus elucidated

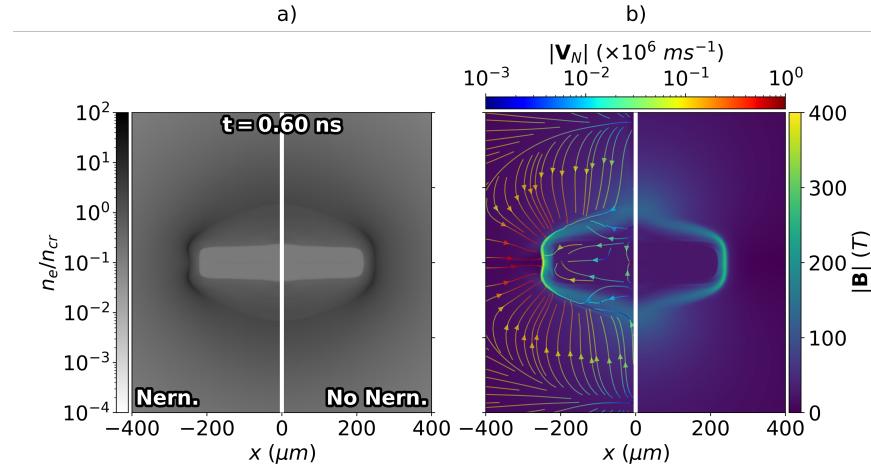


Figure 1.10: Panel a) plots in-flight electron density profiles from the $B_{z0} = 25 \text{ T}$, no-CBET simulations with (left-side) and without (right-side) Nernst advection of the magnetic field. Panel b) plots magnetic field magnitude from the Nernst (left-side) and no-Nernst (right-side) simulation. The Nernst advection velocity is also plotted for the Nernst simulation as streamlines, coloured by speed. Advection of the field is important in the low Hall parameter equatorial region, pulling \mathbf{B} down ∇T_e , into the dense wall. Altered field at the equator impacts on the magnetised thermal conduction, which ultimately imprints on the density, as is seen in panel a).

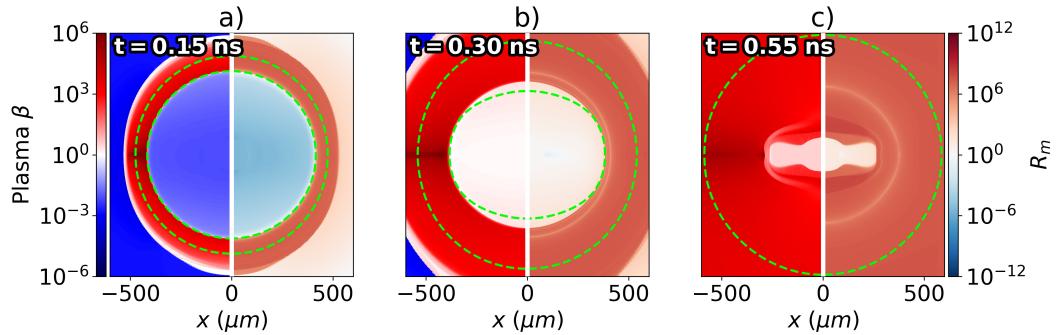


Figure 1.11: Plasma β (left-side) and Magnetic Reynolds Number, R_m , (right-side) at various in-flight times, throughout the $B_{z0} = 25 \text{ T}$, no-CBET simulation. Contours of the $n_e = n_{cr}/10$ are plotted on all panels as dashed green lines to indicate the bounding region containing a significant amount plasma. Broadly, the β and R_m values are $\gg 1$ in all regions with an appreciable amount of plasma, which demonstrate that the Lorentz force and resistive diffusion respectively, should have minimal effect on the implosion dynamics.

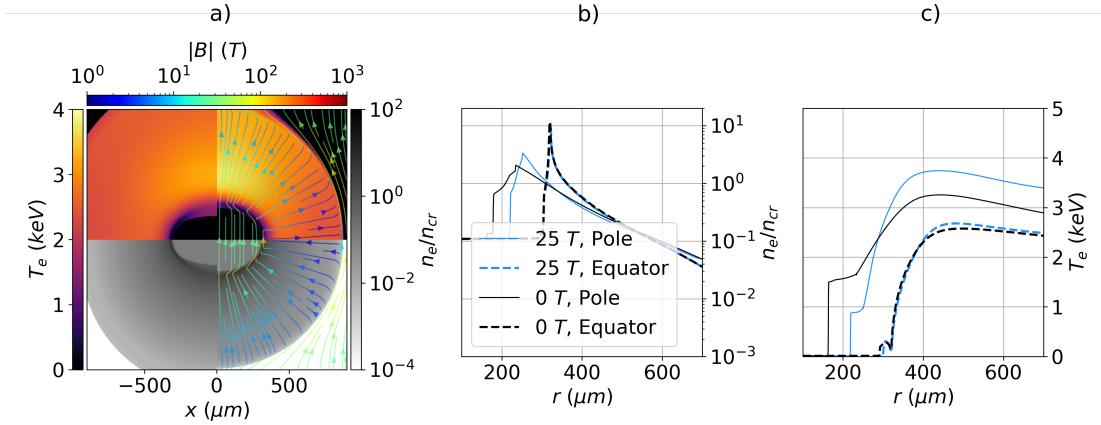


Figure 1.12: Comparison of n_e and T_e profiles from the $B_{z0} = 0$ (panel a) left-side and 25 T (panel a) right-side, with-CBET simulations, both at $t = 0.5$ ns. Panel a) also plots streamlines of \mathbf{B} for the $B_{z0} = 25$ T simulation, coloured by the field magnitude. Panels b) and c) plot n_e and T_e lineouts respectively, along both the pole and equator. It is evident from these lineouts that magnetisation anisotropically affects hydrodynamic variables, which are used to calculate the CBET gain. Therefore, it is anticipated that magnetisation could anisotropically affect the CBET scattering volume.

1.3.3 The Nernst Effect

1.3.4 Resistive Diffusion and the Lorentz Force

1.4 The Effect of Magnetisation on Cross-Beam Energy Transfer and Stagnation

This section presents results on how the magnetisation of the corona affects both CBET scattering and the stagnation shape of the implosion. As was shown in the previous sections, the laser geometry leads to a significant mode $\ell = 2$ in the coronal plasma conditions, which is significantly amplified by anisotropic thermal conduction when magnetised. This long-wavelength perturbation is slightly reduced by CBET, consistent with existing literature on how CBET mitigates $\ell = 1$ asymmetries [16]. ‘No-CBET’ simulations were conducted, for which the coupled energy was kept the same as the equivalent CBET simulation, *i.e.* so CBET only acted to redistribute the deposited power, rather than reduce its magnitude. These results showed that the increasingly anisotropic coronal plasma profiles for increasing seed magnetic field strengths did lead to changes in the CBET scattering, this was too small an effect to lead to experimentally observable changes in behaviour.

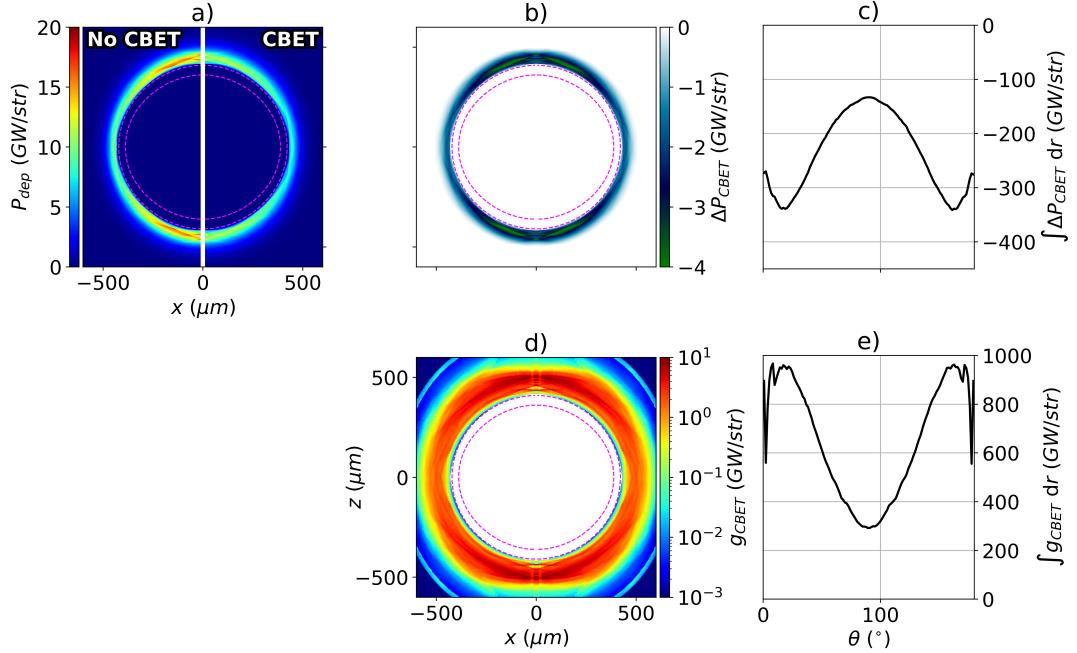


Figure 1.13: Various CBET diagnostics used in the analysis presented in this section. All plots are from the $B_{z0} = 0$ T, with-CBET simulation at $t = 0.30$ ns. Panel a) plots the instantaneous deposition with (right-side) and without (left-side) the effect of CBET. The ‘CBET-deficit’, ΔP_{CBET} , which is the no-CBET deposition, subtracted from the with-CBET deposition, is plotted in panel b). Panel c) plots the radially integrated ΔP_{CBET} , as a function of polar angle. The ‘CBET-scattering’, defined in Eq. ??, is plotted in panel d), and the radial integral is plotted in panel e). At this time, it is evident from panel e) that more CBET occurs at the capsule poles, resulting in a CBET-reduction of deposition near the poles, seen in panel c).

1.4.1 Analysis and Key Definitions

1.4.2 Spatial Change of CBET and Deposition from Magnetisation

1.4.3 Stagnation Profiles

If CBET was anisotropically affected by magnetisation, this would result in spatial differences in deposition location, between the full CBET (top row) and CBET-on-magnitude simulations (middle row), and therefore the bangtime profiles could be different. Additionally, higher initial magnetisation increases the anisotropy of the coronal plasma and therefore

1.5 Conclusions

1.5.1 Summary of Work

1.5.2 Future Work

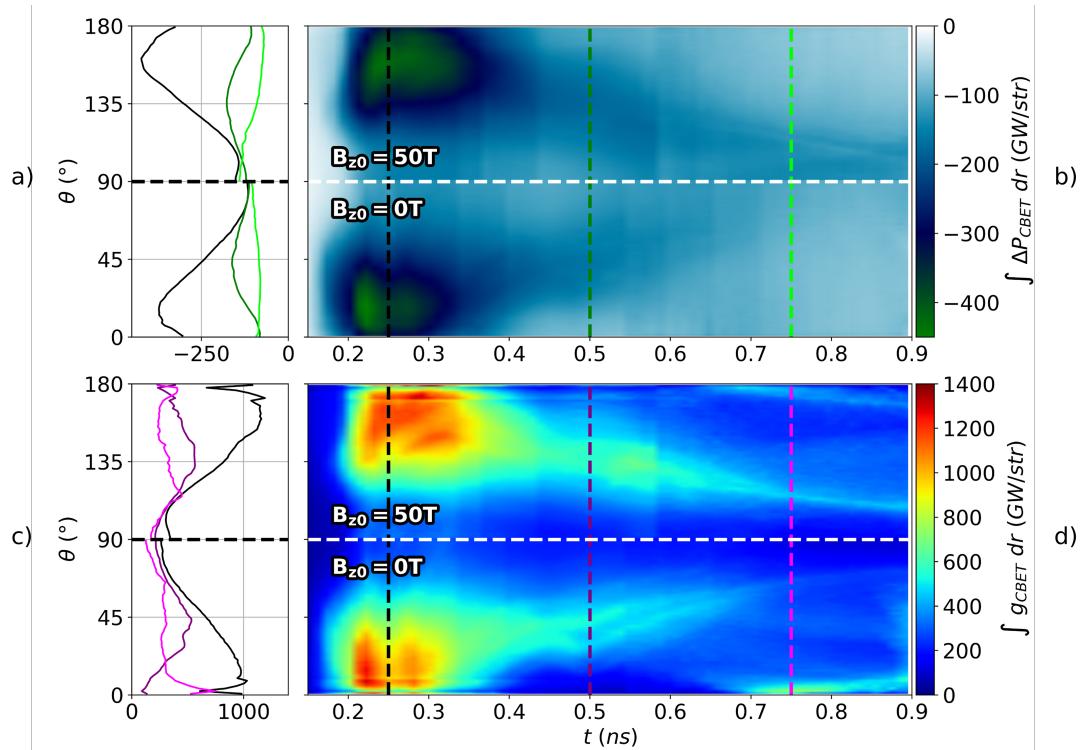


Figure 1.14: The radially integrated CBET-deficit and CBET-scattering, plotted as a function of angle and time for the $B_{z0} = 0$ and 50T , with-CBET simulations. Panel b) plots the CBET-deficit from the 50T (top-half) and 0T (bottom-half) simulations. Lineouts in θ at $t = 0.25$ (black), 0.50 (dark-green) and 0.75 ns (light-green) are plotted in panel a). The same results, but for CBET-scattering are plotted in panels d) and c). It is evident from these plots that for both simulations, as time progresses and the poles of the capsule fall in faster than the equator, the region where CBET mostly occurs, shifts in angle around the capsule. Differences are visible in all plots between the $B_{z0} = 0$ and 50T simulations, indicating that magnetisation affected CBET indirectly, via the altered hydrodynamics.

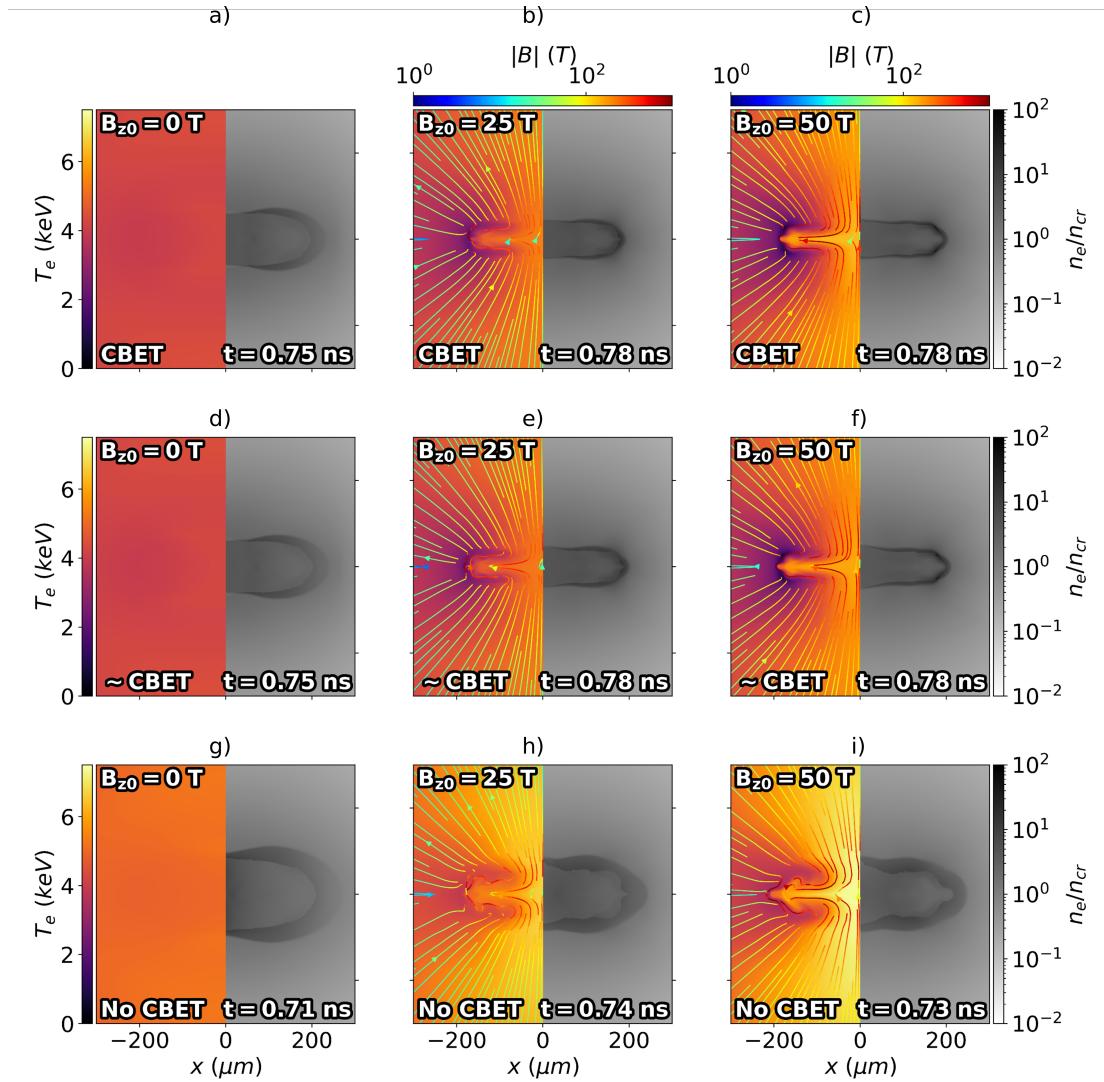


Figure 1.15: n_e , T_e and \mathbf{B} profiles from the time of peak neutron production for different initial magnetisation (columns) and CBET effects (rows). Panels a), b) and c) are from the full CBET simulations, which show that magnetisation increases the oblateness of the stagnation profile. Panels d), e) and f) are from the simulations where only the CBET effect on the magnitude, but not spatial location, of deposition was included. These simulations have identical coupled energy to the top row, and therefore have the same bangtimes. Panels g), h) and i) are from the no-CBET simulations, which have earlier bangtimes and increased temperatures due to the higher coupled energy.

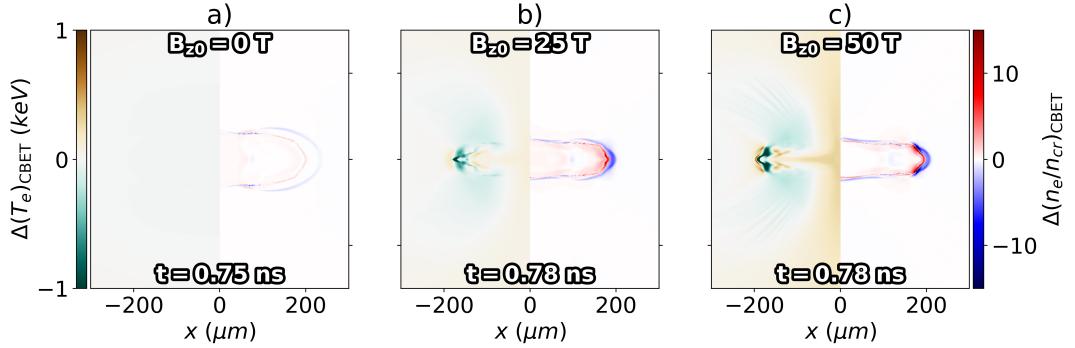


Figure 1.16: Difference in n_e and T_e bangtime profiles, between the full-CBET and CBET-magnitude a) $B_{z0} = 0$ T, b) $B_{z0} = 25$ and c) $B_{z0} = 50$ T simulations. The difference in variable ν , $\Delta\nu$ is the $\nu_{full-CB} - \nu_{magCB}$, so higher colour scale values represent regions with increased ν for the full CBET calculation. These results primarily show that CBET slightly reduces the bangtime equatorial radius, and thus reduces the oblateness, compared to simulations where the spatial redistribution of power due to CBET is neglected.

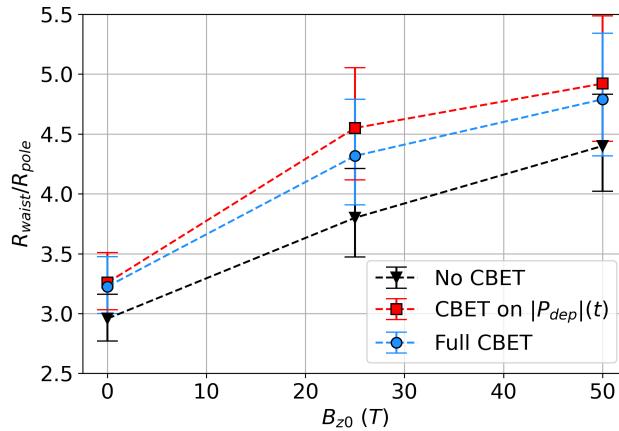


Figure 1.17: The oblateness of bangtime density profiles for different magnetisation and CBET effects. All values and errors were obtained by fitting an ellipse (with axes orientated along \hat{x} and \hat{z}), to the radius of maximum density. No-CBET simulations are consistently more round, because the initial shock is stronger and therefore travels ahead of the pusher material more quickly than the CBET equivalent. Thus, after rebounding off the axis, it meets the infalling mass and produces thermonuclear conditions at a larger radius. As was seen in Fig. 1.16, throughout the entire implosion, when including the effect of CBET on spatial location of deposition, it acts to slightly move energy from the pole to the waist and thus marginally reduces oblateness of the implosion.

Appendices

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