Modelling burning thermonuclear plasma

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***Abstract*—Considerable progress towards the achievement of thermonuclear burn using inertial confinement fusion has been achieved at the National Ignition Facility (NIF) in the USA in the last few years. Other drivers, such as the Z-machine at Sandia, are also making progress towards this goal. A burning thermonuclear plasma would provide a unique and extreme plasma environment; in this paper we discuss a) different theoretical challenges involved in modelling burning plasmas not currently considered, b) the use of novel machine learning based methods that might help large facilities reach ignition, and c) the connections that a burning plasma might have to fundamental physics, including QED studies, and the replication and exploration of conditions that last occurred in the first few minutes after the Big Bang.**

Demonstrating controlled nuclear fusion burn in the laboratory is a critical milestone in the pathway to nuclear fusion as an industrial power source. One of the key potential pathways to this goal is *inertial confinement fusion* (ICF), in which deuterium-tritium fuel is compressed to extremely high temperatures and pressures very quickly. The world's premier ICF facility is NIF, in California, USA, at Lawrence Livermore National Laboratory, although ICF is a worldwide endeavour with facilities around the world working towards this goal (see [1] for a recent summary of ICF work on the NIF).

In addition to NIF, the Laser Mégajoule (LMJ, [2]) in France is currently undertaking ignition-class experiments and other facilities are being considered that may reach ignition through using an even larger driver energy (see section 3b).

The amplification of energy density that a burning thermonuclear plasma will produce will result in macroscopic plasma conditions that have never been achieved in the laboratory before. Although the physics taking place in a burning plasma is probably well enough understood and described in current models to allow the design of capsules that achieve ignition (given enough driver energy), there are still significant uncertainties in our current modelling. Burning plasmas offer the prospect of developing new, more complex plasma models that better describe these extreme conditions and also offer the possibility of experimentally testing those models.

I. Theoretical challenges for modelling burning plasmas

A burning plasma will provide unique conditions of extreme temperature and density and also extreme fluxes of energy and particles. Although not yet achieved in the laboratory, a burning thermonuclear plasma such as has been predicted to be achieved on the National Ignition Facility is expected to involve electron and ion temperatures of many tens of keV with densities of hundreds of g/cc. Radiation fields, although not Planckian, in terms of photon number density are predicted to have an equivalent radiation temperature of several keV. More advanced burning plasmas have been predicted to reach even more extreme conditions ([3] and references therein). Fig 1a shows the flow of energy between the microscopic components of a DT plasma according to current modelling in ICF simulation codes, where both the electrons and ions have a Maxwellian distribution of energies whereas other components are allowed to have a non-thermal description. Allowing the electrons and ions to be non-Maxwellian would potentially provide a better description of current ignition schemes as well as allowing the opportunity to consider other burning scenarios. For example, injection of high-energy DT ions into a burning DT plasma will produce energy gain and could allow for residual, unburnt DT to be burnt (a 'plasma afterburner' [4]). The large α-particle flux in a burning DT plasma may also drive a non-Maxwellian distribution of ions [5]. These, and many other areas of physics could be tested using burning plasmas on NIF.

Doping of a burning DT plasma with a small amount of a higher-Z material should provide information on the temperature and density conditions in a burning plasma. Current NIF experiments have already employed such techniques [6], although it should be noted that uniform doping in targets involving DT ice is not yet possible. However, the current models found in ICF simulation codes (see Fig 1b) have several issues that need to be addressed. Experiments with doped DT would potentially allow validation of those improved models as well as allowing better experimental diagnostic interpretation. The modelling uncertainties arise in several areas including the description of continuum lowering of the dopant ion which has never been tested at the extremely high densities and temperatures involved ([7] and references therein), as well as the description of line radiation transport in the presence of intense bremsstrahlung broadband radiation from the burning gas (photo-exciting and photo-ionising the dopant). At the electron temperatures obtained in burning plasmas it is necessary to consider the effect of relativity on the electron distribution that alters electron collisional rates [8] as well as other collisional processes [9]. In addition, there is the complication of coupling that physics self-consistently to a description of the spatial and temporal evolution of the burning plasma in a computationally tractable way.

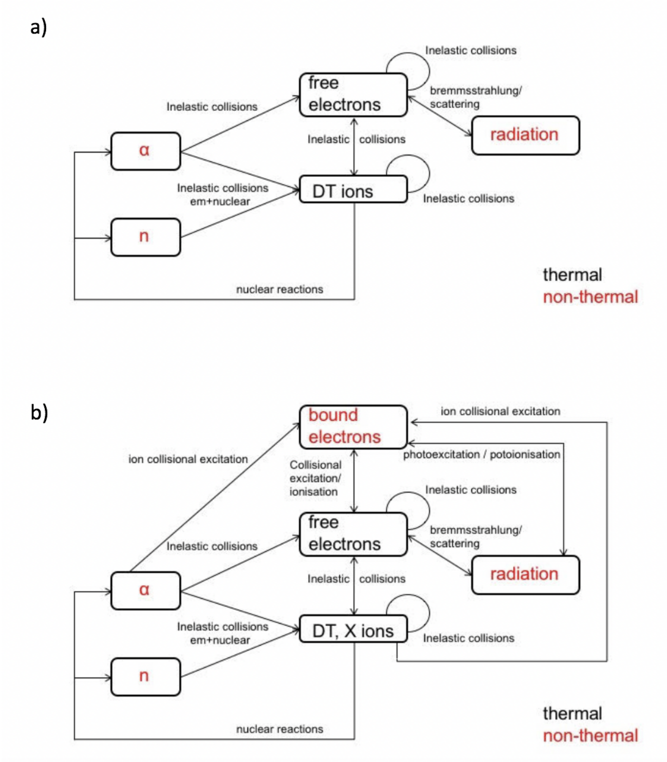

Fig. 1. Different physical processes relevant for a burning plasma: a) Microscopic physics of burning DT plasma, b) Microscopic physics of burning DT with higher-Z dopant

II. Data science challenges for reaching a burning plasma

In the last few years researchers have started using contemporary data science and machine learning tools to help design ICF experiments, as well as make the most of the data resulting from the experiments; [10] described a way to find robust designs using machine learning, [11] have considered the use of neural networks for hohlraum shape design, [12] gave ways to find plausible designs in very large parameter spaces, [13] presented a way to combine data with simulations to give improved predictions, [14] gave a way of choosing the optimal new experiment to do and [15] developed ways of making machine learning based models obey physical laws. [16] have started for the first time to use data driven methods in real ICF experiments, and AI-controlled high powered lasers are now common-place in other areas of high energy density physics e.g. [17], [18].

A. Automated Design

Recently genetic algorithms have been considered for the goal of constructing a NIF indirect drive experiment from scratch [12]; very limited assumptions were made on what both the drive and the capsule were to look like. Here we use a genetic algorithm again, but consider a slightly different problem; i) the context of direct drive on the Omega facility (rather than indirect drive on NIF), ii) assuming the starting position of a reasonably good design that one seeks to improve upon, rather than starting very agnostic about what the design should look like and trying to find a plausible experiment.

We use an computational setup very similar to what was used in the previous application of genetic algorithms [12]; simulations were performed using the radiation-hydrodynamics simulation code Hyades [19], again on SCARF at the Central Laser Facility at Rutherford Appleton Laboratory (see [12] for other details of how the simulations were performed). We leave the capsule design unchanged; 430μm of DT gas at 0.62mg/cc surrounded by 50μm of DT ice, surrounded by 8μm of CH. The genome now, rather than describing the drive, describes a 'correction' to the pulse; a sum of Gaussians, (which can now be positive or negative), that multiply the original pulse to find a new pulse. Figure 2 shows the original pulse, and the improved pulse found after 50 generations of a population of 600 designs. The total energy within the pulse was constrained to be unchanged (<20kJ), and for the peak pulse to be within what is achievable on Omega (<21.5TW, when crossed-beam energy transfer is accounted for). This represented an improvement (in simulation) from $Y = 2 \times 10^{14}$ neutrons to $Y = 3 \times 10^{14}$ neutrons with no additional human effort, within the same design constraints. Expert knowledge can be incorporated e.g. if it is wished to keep the pulse below 16.6TW in order to reduce the impact of laser-plasma instabilities, a different pulse can be found (using the same sized population and number of generations), which reaches $Y = 2.4 \times 10^{14}$ neutrons.

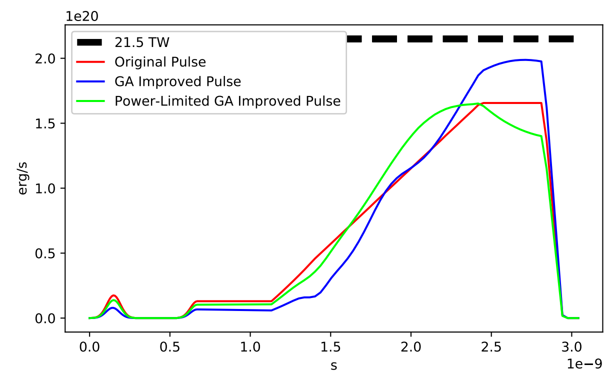

Fig. 2. Improvements found to a direct drive pulse. Red shows the original pulse produced by a human designer, and blue the improvement found with Omega's power limit, and green the improvement found with the more conservative power limit.

B. Unknown Unknowns

There has been increased interest in understanding uncertainty in HEDP in recent years e.g. [20], [21], [22]. The approaches described in these papers give realistic uncertainties, within a given model. But what if the model is wrong - what if there is an 'unknown unknown' that modelling failed to account for? This form of unknown systematic is very hard to quantify, and it is likely impossible to completely account for all such uncertainties. Going from a non-burning plasma to a burning plasma would be a move into a novel regime, where, despite our best efforts, there is likely to be new physics not considered (for example section I). Making conservative predictions in the face of this radical uncertainty is intrinsically hard. However there are some methods in the literature that seek to quantify this uncertainty; in particular here we focus on the method of [23], although [24] considers similar issues. [23] considers the problem of what a conservative scientist should believe in the face of multiple independent probes of some physics . Their model ('BACCUS') essentially assumes that each probe is receiving an unknown systematic error sampled from a distribution with unknown parameters. It then uses Bayesian inference to simultaneously estimate both the parameters of interest, as well as the 'nuisance' parameters that describe the possible unknown systematics. MCMC is used to first draw samples from the resulting posterior, and then marginalise over all the nuisance parameters, to get a final conservative posterior for the parameters of interest, that accounts for the fact that there are likely unknown systematics. In particular this approach is able to give realistic long thick tail probabilities, to account in a systematic way for the fact that there may be 'unknown unknowns'.

We show in figure 3 a simple implementation of the methodology, in the context of estimating how energetic a laser system must be to achieve ignition. Suppose i) three different independent estimates give $E_1 = 5.0 \pm 0.5$MJ, $E_2 = 5.5 \pm 0.2$MJ and $E_3 = 8.0 \pm 0.2$MJ (arbitrary numbers chosen to illustrate methodology) and ii) one is agnostic as to which method is better. What should a sceptical scientist believe is the true value, given that there are likely unknown systematics? Figure 3 shows i) the pdfs of the three estimates, ii) an overall estimate naively multiplying the pdfs together and iii) an estimate combining the pdfs using BACCUS. In particular, although the energy of maximum likelihood is not dramatically changed, BACCUS gives quite thick tails to high laser energies. We propose such a methodology might be useful for making very conservative predictions. In particular, if you wished to know the laser energy that would have a 99% chance of reaching ignition, conventionally you might either i) take the 99th percentile of the conventional combination of the pdfs (6.9MJ) or ii) take the maximum of the three 99th percentiles (the three 99th percentiles are 6.1MJ, 6.0MJ, 8.5MJ, so 8.5MJ). Conservatively accounting for unknown systematics with BACCUS however would suggest that 11.5MJ would be needed for 99% confidence.

We note this approach requires the different estimates to not be correlated; if all different probes of the physics have the same systematic, then likely no method can correctly quantify the unknown unknowns. The method does of course require some specification of priors (e.g. uniform prior on laser energy in linear or log space), but this is true of all Bayesian methods. Other contexts that might benefit from an approach similar to this could include scenarios of multiple different classes of experiment measuring some microphysics (e.g. iron opacity, combining data from both [25] and [26]), situations where some parameter had been inferred independently from both astronomical observations as well as laboratory astrophysics experiment etc.

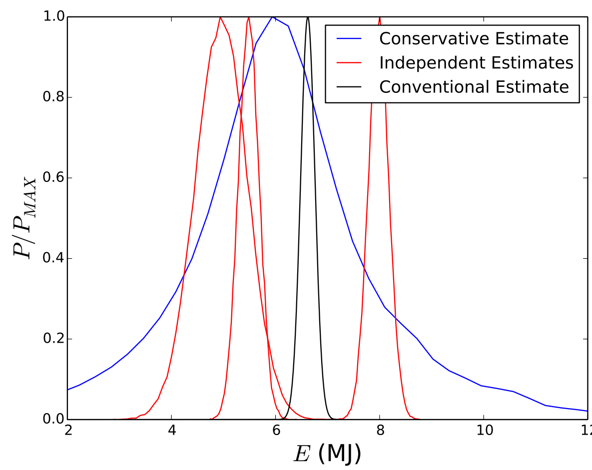

Fig. 3. Different pdfs in our toy model of characterising uncertainty of ignition laser energy scale: i) red distributions are three hypothetical separate estimates of what energy is required for ignition in MJ, ii) black is a naive multiplication of the probability distributions and ii) Blue is the conservative estimate from BACCUS accounting for unknown unknowns.

III. Fundamental physics and cosmology connections to burning plasmas

Looking further to the future, burning tritium-poor DT or even pure deuterium would allow even more extreme conditions to be achieved [3]. This would be attractive for energy generation (as less tritium would be used) but would also be attractive for scientific experiments by allowing investigation in the laboratory of intense broadband quasi-isotropic radiation fields of higher intensity than could otherwise be reached [3]. For NIF the peak intensity of the radiation field is expected to reach of order 10^{20}Wcm^{-2}, whereas for pure deuterium burning capsules the intensity would be greater than 10^{22}Wcm^{-2}. Such high intensities potentially allow experimental access to several areas of physics that can either not otherwise be accessed or can only be accessed on other international facilities:

- The study of photoionised plasmas of uniquely high photoionisation parameter relevant to the understanding of X-ray spectra from compact objects [27], [28]
- The study of double-Compton scattering of relevance to the generation of the Cosmic Microwave Background in the early Universe [29], [3]
- The study of the Breit-Wheeler process and photon-photon scattering of relevance to the investigation of physics beyond the Standard Model [30]
- The study of extreme-field QED such as the thermal Schwinger process [31]

In particular, both Bremsstrahlung and Double Compton scattering are responsible for the fact that the CMB is an almost perfect black-body, by providing absorption and emission of photons, rather than scattering by the Compton process.

Double Compton scattering is faster than Bremsstrahlung and the rates put a constraint on the injection of photons into the early Universe by a variety of possible processes - decay of primordial black holes, decay of primordial particles, even radiation transfer from non-uniformities. More generally, as experiments like CMB-S4 and the Simons Observatory come online, the need to understand CMB spectral distortions is becoming more important [32] - a burning plasma may be the only way to understand much of the physics behind these observations.

IV. Conclusion

Burning plasmas would provide access to the most extreme macroscopic environment ever created in the laboratory. There are many challenges to modelling such extreme conditions, and much of the necessary microphysics is not included in current rad-hydro codes. There remain many milestones before reaching a burning plasma; it may be that augmenting the human designer with AI and modern advanced statistical techniques might be one way to make advances towards this goal. Finally, experiments using burning plasmas could potentially test our understanding of the early Universe, the physics of compact objects and probe physics beyond the Standard Model. Creating a burning plasma would be an achievement in the same category as detecting gravitational waves or finding the Higgs boson - it would open up a whole new regime and give a new way of understanding the Cosmos. The justification for continuing to work towards achieving thermonuclear burn by ICF should be the immense amount of science that it will unlock - of equal importance to the drive to make inertial fusion energy a reality.

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