Prospects for high gain inertial fusion energy: an introduction to the second edition.

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ABSTRACT

Part II of this special edition contains the remaining eleven papers arising from a Hooke discussion meeting held in March 2020 devoted to exploring the current status of inertial confinement fusion research worldwide and its application to electrical power generation in the future, via the development of an international inertial fusion energy programme. It builds upon increased co-ordination within Europe over the past decade by researchers supported by the EUROFusion Enabling Research grants, as well as collaborations that have arisen naturally with some of America's and Asia's leading researchers' both in the universities and national laboratories. The articles are devoted to informing an update to the European roadmap for an inertial fusion energy demonstration reactor, building upon the commonalities between the magnetic and inertial fusion communities' approaches to fusion energy. A number of studies devoted to understanding the physics barriers to ignition on current facilities are then presented. The special issue concludes with four state of-the-art articles describing recent significant advances in fast ignition inertial fusion research.

In Part I of this special issue devoted to the prospects for high gain for inertial fusion energy[1], compelling arguments were put forward to study the underlying physics of inertial confinement fusion from both the fundamental physics perspective[2] as well as for underpinning the two nations' (the United Kingdom and the United States of America) independent nuclear stockpile stewardship programmes, in the absence of underground testing[3]. A review of the current day electricity market in the United States of America then followed, indicating smaller-scale fusion devices are more likely to be compatible with future power needs in order to supplement those provided by renewable sources[4]. The requirement for high gain in order to drive down the capital infrastructure costs of future inertial fusion power plants (and therefore the costs of electricity) when these reactors are ready for market delivery were also reinforced[5]. Following discussions of the welcome formation of a fusion industry advocacy group[6] as well as discussions on the elements required for constructing future roadmaps[7], a number of research articles devoted to understanding obstacles to ignition on current-day devices were then presented[8-12]. Part I concluded with a fascinating discussion of the benefits of deploying the Naval Research Laboratory's argon-flouride (ArF) driver, operating at a wavelength of 193 nm, for direct drive of inertial fusion targets. Their work suggests that a significant saving on drive energy (and capital costs) might be realised using this approach[13].

In Part II of this special issue, Norreys *et al.*[14] in their article "Preparations for a European R&D roadmap for an Inertial Fusion Demo Reactor" present a brief summary of the current status of the indirect drive approach on the National Ignition Facility. They argue that, on current evidence, ignition will be achieved for a drive energy of between 5 MJ and 7 MJ delivered into the hohlraum targets. They go on to summarise the world-wide research into the underpinning physics for the fast ignition inertial fusion concept. While both the compression and ignition drive energy requirements for fast ignition are somewhat higher than initial experiments indicated, this approach remains intrinsically high gain. Current evidence is that a laser driver of 0.5 – 1.0 MJ is needed for compression and a similar sized short pulse laser is needed for ignition. Fast ignition therefore still promises substantially reduced drive and ignition pulse energy requirements compared with the indirect drive approach. Following that discussion, an exploration of the new idea of auxiliary heating is made, as a route to minimise the drive energy requirements for isobaric compression. Auxiliary heating was inspired by the magnetic fusion community's requirement for additional heating of tokamak plasma using RF, ion-beam, neutral beam heating *etc*., as a finishing stroke to reaching ignition temperature in the plasma, a key obstacle also in inertial fusion research. The idea builds upon two concepts. The first is the performance of indirectly driven, low convergence ratio wetted foam capsule implosions that exhibit remarkable agreement with radiation hydrodynamic simulations on the National Ignition Facility. The second is the encounter of two fast electron beams generated by petawatt laser pulses in the central hot spot. At the point of beam-beam collision in the central hot spot, the beams drive-up Langmuir (electron plasma) waves over a short distance to high amplitude that then crest and break, resulting in a cascade of energy into the background plasma and causing a large fraction of wave energy to be transformed into turbulent kinetic energy, thus raising the temperature to ignition conditions. The first estimates of the increased fusion performance for absorbed energy is presented in the article. Norreys *et al.*'s then goes on to discuss the benefits of investing in an inertial fusion energy programme for the photonics industry and the associated societal spin-offs, before concluding with a discussion on the remaining obstacles to ignition from a scientific and technological viewpoint. The article discusses the technological challenges to ignition and high gain and concludes that the timescales are likely to be multi-decadal to realise these goals.

These timescales are reinforced in the useful and interesting paper by Ian Chapman and Nick Walkden[15]. They present compelling evidence that the common issues associated with fusion power plants, whether they are based upon magnetic or inertial confinement – such as radiation hardened materials, large-volume tritium handling, blanket technologies, robotics, reactor control systems, diagnostics etc. – are highly complex and require multi-decade sustained effort that spans national boundaries.

Fortunately, the modular nature of inertial fusion research and development, where target physics is decoupled from both the driver and power-plant technologies, allows the field to continue to make progress in parallel on all fronts. The latter point is reinforced in Mark Koepke's article[16]. First, he summarises the results of the 2013 review on inertial fusion energy[17] before going on to outline the technology challenges for mass manufacture of targets, blankets for neutron capture, heat exchange and tritium breeding as well as the laser and/or pulse power drivers. He advocates for promoting industry awareness of the complexity of the technology (a perceived barrier) and of the availability of complementary resources (a perceived driver) for technology commercialization by small and medium enterprises (SME). SME interest in forming bid consortia for a demonstration IFE fusion power plant and establishing the requisite supply chains becomes valuable leverage in realising the fruits of an IFE roadmap.

The article by Mike Campbell *et al*. builds upon the research undertaken at the University of Rochester's Laboratory for Laser Energetics (LLE) over the past six decades and provides an up to date overview of the academic programme in the United States for direct drive inertial fusion[18]. Their article describes the current status of LLE's extensive studies into cryogenic implosions, fundamental materials properties, and hydrodynamics, along with laser-plasma interactions. The University of Rochester is the leading institutional advocate of the so-called 'polar- direct-drive' configuration on the National Ignition Facility where the 192 laser beams are repointed directly onto the surface of a spherical capsule in order to provide a more uniform drive pattern. LLE's stated goal is to achieve a burning plasma in the laboratory and the University of Rochester team's proven capability to conduct forefront studies over a wide range of energy, power and scale size suggests that they are likely to make strong headway towards realising this goal.

In the article by Paddock *et al*., "One-dimensional hydrodynamic simulations of low convergence ratio direct-drive Inertial Confinement Fusion implosions" a computational study of the performance of wetted foam targets that are directly driven is presented. Albeit limited at this stage to one dimension, they indicate that it might be possible to approach energy breakeven on the National Ignition Facility using a novel four-pulse shape design, reinforcing the conclusions of higher adiabat studies of directly driven targets presented earlier by Riccardo Betti *et al*.[20] who showed 500 kJ of fusion energy for polar direct drive on the National Ignition Facility (corresponding to 74% of the Lawson criterion). Paddock *et al*., work indicates that 4 MJ of drive energy might provide a gain of 24, and fusion reactor gains ($G \geq 50$) with 8.5 MJ on target. It is interesting to note that these results provide a route to minimise the energy budget in future studies for auxiliary heating. They also provide the areal densities required for fast ignition with the added advantage of a larger compressed target on which to form the hot spot on the side of the fuel.

The limited energy budget currently available on the National Ignition Facility has largely restricted implosion studies to those with higher convergence ratios to maximise the pressure. The principle limitations to ignition are mix of the residual shell materials with the DT fusion fuel, raising the temperature requirement in the central hot spot to account for the increased bremsstrahlung radiation losses. A nice overview of international efforts to understand, mitigate and control the Rayleigh-Taylor and Richtmyer-Meshkov instabilities are given in the Alexis Casner article "Recent progress in quantifying hydrodynamics instabilities and turbulence in ICF and High Energy Density experiments”. These include the use of picket pulses that smooth out laser beam imprint for direct drive, as well as hybrid indirect-direct schemes that enable the suppression of hydrodynamic instabilities via the ablation of the shell material via more penetrating X-rays before the laser pulses hit the outer surface of the shell[22].

The article by Christopher Ridgers “The inadequacy of a magnetohydrodynamic approach to the Biermann Battery” discusses a key microphysics element associated with inertial fusion – that of the self-generation of magnetic fields[23]. These fields are associated with crossed density and temperature gradients in plasma and have, until recently, been incorporated into radiation hydrodynamics codes using flux-limited heat flows in order to calculate the magnetic field growth. This is important both in the coronal plasma during the acceleration phase of the implosion, as well as the stagnation phase where the magnetic fields that arise in the mix layer can have a big influence on the overall heat flow and thereby the hydrodynamic response. They argue that more accurate descriptions using kinetic treatments for the magnetic field growth are now required.

The final four papers in this special issue are related to the physics of fast ignition inertial fusion. The article by Ben Spiers *et al.* “Whole beam self-focusing in fusion-relevant plasma” provides conclusive evidence for straight-channel formation in the large-scale-length plasma (several hundred microns) using the Orion laser facility at AWE, Aldermaston[24]. They present a systematic study of the plasma expansion using a variety of optical and particle diagnostics. These are supported by three-dimensional particle-in-cell and radiation hydrodynamic simulations. The experiment confirms that a combination of relativistic self-focusing and relativistic induced transparency – the Habara-Kodama-Tanaka mechanism – provides straight channels, overcoming a critical barrier on the path to realising fast ignition.

Fabrizio Consoli and colleagues’ paper “Sources and space-time distribution of the electromagnetic pulses in experiments on inertial-confinement-fusion and laser-plasma acceleration” provides a succinct overview of experiments to quantify the scale of electromagnetic pulses in current day experiments[25]. This is needed when these devices are scaled up to those that will be required for full scale tests of fast ignition.

Farhat Beg and colleagues’ article “Fast electron transport dynamics and energy deposition in magnetized, imploded cylindrical plasma” provides benchmarking simulations and experiments using the OMEGA EP facility at the University of Rochester on the energy transport in cylindrical plasmas. The advantage of this geometry is the transverse access to the plasma to interrogate the plasma conditions.

The Special Issue concludes with Elisabetta Boella and colleagues’ fascinating article “Fast ignition using shock accelerated ions from the target corona” [27]. The paper indicates that there is the possibility of using collisionless electrostatic shocks to accelerate particles into the hot spot where they deposit their energy via collisional stopping in the dense fuel. The article demonstrates that younger scientists can still make a significant contribution to inertial fusion science, despite the field’s relative maturity and that there is still space for innovative ideas and novel concepts. The concluding article confirms that new approaches to inertial fusion ignition, and the associated reductions in the drive energy requirements, deserve attention and consideration.

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