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REVIEW PAPER

# Laser plasma session: AAPPS-DPP Conference, 12–17 Nov 2018, Kanazawa

**Amita Das**[1]

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**Abstract**
This is a summary of presentations made at the second Asia Pacific Conference on Plasma Physics, AAPPS-DPP (12–17 Nov. 2018) held at Kanazawa, Japan, in the laser plasma physics session.

**Keywords** Laser plasma Interaction · Particle acceleration · Inertial confinement fusion · Giant magnetic fields · Magnetic reconnection · Laser facilities · Ultra relativistic electron physics

## 1 Introduction

There was an overwhelming participation in the laser plasma session of the AAPPS-DPP conference, 2018 at Kanazawa. There were 4 plenary talks, 12 semi-plenary talks, 24 invited talks and 12 oral presentations. Two evening lectures and 28 posters were the other highlights of the session. One of the main attractions of the entire conference this year was the Chandrasekhar Prize lecture delivered by Tajima in the opening session (Mourou et al. 2006; Tajima et al. 2017; Tajima 2009, 2003). This had a special importance and relevance, as this year's Nobel prize was shared by Gerard Mourou (2019), Donna Strckland (2019) on their pioneering work on developing CPA technique for lasers to generate high-intensity ultra-short laser pulses. The CPA technique in fact opened up the flood gates for a variety of ingenious applications related to lasers specifically in the context of laser plasma interaction. The AAPPS-DPP conference bore testimony to the richness of the field and the frontier aspects of research in this particular area carried out all over the world. Interesting reviews on ongoing activities in Japan, India and National Ignition facility (NIF) of USA were covered in the plenary talks of R. Kodama, G. Ravindra Kumar and Bruce Remington, respectively.

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✉ Amita Das
amita@iitd.ac.in

[1] Physics Department, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

The research conducted by the laser plasma community has over the years branched out in many directions. The presentations in the conferences represented most of the major themes that include laser fusion, particle acceleration, radiation sources, warm dense matter, magnetic field generation, etc. The talks broadly touched upon them from the perspective of (i) application-oriented studies(ii) facility developments defining new research directions and (iii) addressing frontier physics issues with cutting edge technologies in these areas. The presentations and deliberations during the conference in these directions have been summarized in the sections below.

## 2 Laser fusion

Nuclear fusion using lasers has continued to remain a prominent goal for the laser plasma research community. The idea of compressing and heating the fusion pellet of DT fuel by laser to achieve the required Lawson criteria, defined in terms of fusion triple product, is attractive. However, despite appearing to be well within reach during the early days of the discovery of lasers in 60s, careful investigations have underlined and brought to fore many difficulties which need to be overcome for fusion to be realised and be commercially viable. There has been considerable progress over the years towards this goal. However, the gap in attaining the commercial viability continues to remain.

Many different approaches towards achieving laser fusion have been adopted. Some prominent schemes amongst them are the direct drive (DD) (Craxton et al. 2015; Campbell et al. 2017) and the indirect drive (ID) (Lindl 1995) inertial confinement approaches. In the DD drive, laser is used directly to implode a low-Z capsule. On the other hand, in ID scheme the the X-rays produced by the laser falling on the a high-Z hohlraum are employed.

The parametric processes in the laser plasma interaction, wherein the laser light gets scattered to another electromagnetic wave with a different frequency results in a major loss of energy and has proved to be one of the serious impediments for laser fusion. This was realised as far back as in the late 60s (Kaw 2017) when the parametric processes were extensively researched upon. It was pointed out in the plenary talk (P23) by Robert Bingham (University of Strathclyde, UK) that even now the appearance of these parametric processes continues to pose a serious concern for both direct and indirectly driven schemes (Montgomery 2016). It was also shown that the cross beam energy transport (CBET) (Myatt et al. 2017) is another important issue concerning laser fusion. To preserve the symmetry of target compression, multiple beams impinge the target from various directions. The CBET concerns the energy transfer amongst the various laser beams (incoming and those refracted from the plasma corona) and it proves to be one of the major loss mechanisms. It was shown that while it has been a major concern in the DD scheme, for indirect drive the CBET is instrumental in providing the required symmetry and is beneficial to some extent. The energy transfer process amongst the incident and refracted beams, however, is not smooth and can often be very bursty, which is of major concern. The outgoing laser beam from the target can thus have properties which are wildly different than that of the incoming laser pulse. This has inspired many modelling and simulation activities.

The National Ignition facility (NIF) in the USA has been engaged on laser fusion research studies. The progress and status of NIF for the indirect drive experiments was summarized in the talk (L-I2) by Landen Hurricane et al. (2019), Merritt et al. (2019), Clark et al. (2019), and Kline et al. (2019). He presented experiments showing the best neutron yield (of $2 \times 10^{16}$) with 3 times increase in alpha heating (Kline et al. 2019). This was achieved with increase in velocity and smaller fill tube. In the presence of asymmetries, the yield was observed to drop by a factor of 1.5 to 2. It has, however, been possible to fix these asymmetries. The compression ratio in the experiments was observed to be dependent on the shock merge depth. New techniques were being designed at NIF to study fuel compression, uniformity and mixing properties.

Progress in the fast ignition concept of DD laser fusion was reported from many laboratories. The fast ignition concept (Tabak et al. 1994) relies on separating the task of compression and heating of the fusion target, as compression of a cold fuel is easier. A long nanosecond laser pulse is employed for the task of compressing the fuel which is followed by a short sub pico-second laser pulse to create a hot spot for ignition. The compressed fuel being overdense for the ignitor laser pulse, the challenge here is the transport of energy from the fast laser pulse in the overdense plasma region of the target for creating a hot spot for ignition. One typically relies on the transport of energetic electrons, created at the critical density surface of the target by ignitor laser pulse, to the core region and its stopping at appropriate location to heat the target. The divergence in electron transport and the low value of the collisional cross section of energetic electrons have been considered as major challenges to overcome.

Many ideas to overcome some of these challenges have been proposed. For example, one method is to utilize the inhomogeneity of plasma density to guide as well as ensure energy dissipation of the electron current at appropriate location (Yadav et al. 2008, 2009; Yadav and Das 2010; Yabuuchi et al. 2009). Other ingenuous ways of addressing this complex issue were presented in the talks by Fuzioka (ILE, Osaka, LPL-13), Sakata (Osaka University, L-I4) and Mori (The graduate school for the creation of new photonics industries, L-I3). The FIREX experiments at ILE osaka employed magnetic field of the order of kilo Tesla to help guide the energetic electrons. They could achieve about 20 GBar of energy density at 2 KeV temperature with the density of 16 g/cc. Plasma density profile was measured by X-ray backlighting at about $0.72n$ s. The quasi-mono-energetic image from He (alpha) clearly showed the heated region. Temperature was estimated from FLYCHK runs which reproduced the photon spectrum. A factor of two enhancement of laser to core energy coupling was reported (Sakata et al. 2018).

The experiments conducted at GPI Hamamatsu were reported by Mori. Their laser system HAMA is unique and provides freedom and flexibility for beam configuration. The counter-beam configuration was chosen in their experiments. An increase in coupling efficiency was observed. In contrast to single beam case where the coupling efficiency is about 7%, counter-beam experimental configuration showed 10% coupling (Mori et al. 2017). Simulations on the other hand suggested the possibility of achieving even higher coupling efficiency up to 28% for counter-beam configurations. Their experiments also observed mega-Gauss class Weibel magnetic field generation in the core region which was indicative of collective processes at work, suggesting the possibility of having anomalous heating.

Observations from Indirect drive experiments conducted at Shenguang-III prototype laser facility were reported by Yuqiu Gu (SJTU, Shangahai, L-O1) which showed that the anomalously large energy spread in neutron yield from the corona plasma could only be interpreted by taking account of kinetic effects (Shan et al. 2018). This provided an evidence of the presence of kinetic effects which is supposed to have significant impact on energy transport and intrinsic plasma behaviour.

An overview talk (LPL-7) by Peter Norreys summarized the activities at University of Oxford and the Central Laser Facility (CLF), STFC Rutherford Appleton Laboratory on inertial fusion experiments and simulation activities on the topic. A new concept of heating the central hot spot with the help of crossed Relativistic Electron Beam (REB) was developed (Ratan et al. 2017). An increase in ion temperature and fusion yield was reported. Conclusive experimental observations were reported showing the mitigation of hosing instability leading to a stable channel formation in coronal plasma. Results from experiments performed at Omega EP facility showing the formation of plasma channelling. The role of plasma channelling in several applications with the help of high-intensity lasers were also presented (Olson et al. 2016; Ceurvorst et al. 2018).

## 3 Particle acceleration

The issue of particle acceleration is another important area where lasers are playing a very critical and important role. The high-power laser interacting with plasma provides a compact alternative to the conventional schemes of particle acceleration. As the laser pulse propagates in the underdense plasma medium, it disturbs the medium and produces a wake electric field behind it. The electric field in the wake produce acceleration gradients which can be about 1000 times higher than the conventional accelerators, thereby providing a compact set up for the acceleration of charged particles. Studies in the last few decades have shown significant progress both in physics understanding and experimental demonstrations (Malka et al. 2008; Faure et al. 2019; Pukhov et al. 2004; Bingham et al. 2004). The enhancement of beam energy and improvement in its quality, in terms of low-energy spread, reduced emittance, etc., are now being investigated. The de-phasing length and the pump laser depletion are the main difficulties which limit progress towards achieving these goals. The acceleration of heavy high-Z ions is also attracting attention lately. There were many talks in the conference which highlighted the ongoing research carried out worldwide in this particular field. Some novel concepts were also presented.

An extensive review on this topic was provided in the Chandrasekhar lecture delivered by T. Tajima (UC Irvine) in the inaugural session. He pointed out that the requirement for laser acceleration scheme has in fact driven major innovations in laser technology such as Chirped Pulse Amplification (CPA) (Mourou 2019; Strckland 2019) in 1985, coherent amplification network (CAN) laser in 2013 Soulard et al. (2015) and thin film compression (TFC) in 2014 Mourou et al. (2014), ever since the concept of laser plasma acceleration was put forth as a theoretical idea in 1979 by John Tajima and Dawson (1979). He put forth an interesting physics analogy by viewing wakefield as a robustly elevated energy state of plasma having relativistic coherence and termed it as the Higgs state of the plasma (Tajima et al. 2017). He compared it with the field reversed configuration of plasma which can be viewed as the elevated state of the Landau–Ginzburg potential. Many examples of wakefield prevalent in nature were also pointed out by him, such as AGN accretion disks and jets, and gamma ray bursts in blazers.

Recent developments involving multistage laser wakefield acceleration was discussed in the talk. This is a compact and efficient scheme of coupling various laser wakefield accelerators with specially designed curved plasma channels wherein fresh laser pulses are fed. This leads to acceleration in multiple stages to beat the limitations posed by de-phasing and pump depletion of a single stage wake field acceleration. This is the basis of the coherent amplification network (CAN) lasers (Soulard et al. 2015) which have a promise of achieving energy gain in the TeV range. The CAN laser will be helpful for building the laser collider (Nakajima 2018) (similar to the concept of particle colliders of CERN). It would also make possible the seamless coupling between laser and particle beams to seek future explorations of the energy-frontier with considerable reduction in size and cost. The miniaturization and achievement of better beam quality in laser acceleration was also emphasized in the plenary talk given by R. Kodama from ILE Osaka. More discussions on Kodama's talk will appear later.

Laser-driven ion acceleration is perceived as the future of a new generation of compact accelerators which can provide high-quality ion beams for many applications in nuclear fusion, medicine, industry, high energy density science, etc. It is noteworthy that ion acceleration through lasers has interesting properties which can be exploited for strongly localised energy deposition. The energy conversion efficiency is found to be high from laser to ions. The proton numbers are high and they can be focussed easily by suitably shaping the target rear. Ion acceleration by lasers has thus attracted immense interest lately (Macchi et al. 2013).

There are many ways to accelerate ions to produce hot ion beams. Some examples are the target normal sheath acceleration (TNSA) (Passoni et al. 2010), radiation pressure acceleration (RPA) (Robinson et al. 2010), cluster explosion (Mathur and Krishnamurthy 2006; Rajeev et al. 2013), etc. Newer mechanisms of ion acceleration with lasers are also being proposed. The topic of ion acceleration and various novel schemes to achieve the same were covered in many talks in this conference.

Experimental and simulation activities in Japan on high-Z ion acceleration with intense lasers were presented in talks by Nishiuchi (Kansai Photon Science Institute, QST) (Nishiuchi et al. 2015) and Sentoku (ILE, Osaka) (Sentoku et al. 2003), respectively. The experiments were conducted at the J-KAREN-P laser system at the Kansai Photon Science Institute. The laser pulse with energy of 10J, duration of 40fs was focused down to a diffraction limited spot size to have a maximum peak intensity of $3 \times 10^{21}$ W/cm$^2$ onto the 500 nm silver target. The experimental work was aimed at controlling the target normal sheath acceleration (TNSA) scheme. The charged ion states were used as a diagnostic to measure the sheath potential. The experiments showed the dominance of sheath ionization with charge states upto 40 ± 2. PICLS and FLASH2D hydrodynamic simulations reproduced the experimental situation. The results of high-Z ion acceleration with the help of PIC simulations from the PICLS code for a laser with intensity ($10^{20}$ W/cm$^2$) falling on a thin target was presented by Sentoku. It was shown that the strong sheath field produced high-Z ions on the target surface and was mainly responsible for acceleration of ions. While there were evidences of collisional impact ionization competing with the field ionization in the bulk region, the rapid ionization of ions at the rear surface was again governed by the evolution of the sheath field.

Farhat Beg (UCSD) in his talk (LPL-17) discussed about the slow scaling of accelerated ion energy as a function of laser intensity in the TNSA mechanism. He presented results on ion acceleration for various laser parameters for different materials (Ti, Si, Ti, Cu and Au) for ultra-thin targets of size varying between 35 and 500 nm. The interaction of high-contrast laser pulses with such ultra-thin targets produced quasi-mono-energetic Ti ions of energies in excess of 100 MeV for 100 nm thickness. Nearly collimated and quasi-mono-energetic titanium ions having two distinct populations were produced. The physics leading to the production of such ions was discussed. Results from 2-D Particle-In-Simulation (PIC) with EPOCH confirmed these observations (McGuffey et al. 2016).

Radiation pressure acceleration (RPA) (Robinson et al. 2010) is another promising approach for ion acceleration to obtain high-quality ion beams. The experiments on RPA scheme are, however, impeded by the dramatic growth of the multi-dimensional Rayleigh-Taylor-like (RT) instabilities. Such instabilities lead to heating and loss of co-moving electrons from the accelerating plasma sheet. The ion acceleration then terminates as a result of Coulomb explosion. In the talk (L-I7), Bin Qiao (IAPCM) presented recent progress on theoretical and numerical studies of stabilization of laser-driven ion RPA at Peking University (PKU). A novel scheme to achieve stable RPA of ions from laser-irradiated ultrathin foils was proposed, where a high-Z material coating is used (Shen et al. 2017a, b) at the target front. The coated high-Z material acts as a moving electron repository which continuously replenishes the accelerating ion foil with comoving electrons in the light-sail acceleration stage due to its successive ionization under laser fields with Gaussian temporal profiles. As a result, detrimental effects such as foil deformation and electron loss induced by the Rayleigh-Taylor-like and other instabilities in RPA are suppressed and stable acceleration of heavy ions is maintained. Two- and three-dimensional particle-in-cell simulations were used to show mono-energetic $Al^{13+}$ beam with peak energy of 3.8 GeV and particle number $10^{10}$(charge > 20 nC) at laser intensity of $10^{22}$ W/cm$^2$. The experimental verification of this scheme is being proposed at the Petawatt laser facility of China.

It was pointed out in the talk by Fukuda from Kansai Photon Science Institute, QST (L-I16) that experiments with thin targets which normally have good energy conversion efficiency were not suitable for producing pure proton beams. Protons from surface contaminants and high-Z impurities are accelerated together making it unrealistic to produce impurity-free proton beam by this process. It was shown that experiments with the PW class J. KAREN laser using micron sized hydrogen cluster targets, generated impurity free, highly reproducible and robust multi-MeV proton beams. This happens as the electrons inside the target get fully stripped off, resulting in Coulomb explosion of the cluster (Jinno et al. 2018).

Experiments on structured target with varying thickness and/or with nanostructures were carried out in India at IIT Hyderabad and RRCAT. The observations were presented by Ramakrishna (L-I8) who showed that the structured sandwich targets were helpful in suppressing large divergence and filamentary structures of ions accelerated up to MeV energies (Ramakrishna et al. 2015).

A novel mechanism of ion heating was presented from the group of Amita Das from India (L-I12 and L-O5) (Vashistha et al. 2020). The technique depends on the application of an external magnetic field on the target. The magnitude of the applied magnetic field is chosen such that the lighter electron species is magnetized, whereas the heavier ion species remains un-magnetized at the laser frequency. As a result there is a difference between the $\mathbf{E} \times \mathbf{B}$ drift of the electron and ions at the oscillating laser electric field. The difference in the drifts produces charge density oscillations and excites electrostatic ion waves. The laser energy thus gets transferred to the ions leading to the generation of energetic ions. This was demonstrated using Particle-In-Cell (PIC) simulations using OSIRIS4.0 framework. For the lower frequency pulsed CO2 lasers, the requirement of magnetic field turns out to be of the order of about 15 kilo tesla. Magnetic fields of the order of kilo tesla have already been produced in laboratory and it is likely that in near future the required magnitude of magnetic field will be produced for this mechanism to be tested out in the laboratory.

## 4 Radiation sources

Particle acceleration is accompanied by emission of radiation. Thus, laser-driven acceleration also proves to be a novel and compact source of radiation which is employed for many applications such as imaging, screening, and characterization (Schlenvoigt et al. 2008). There were many presentations which covered possible radiation sources that the laser plasma interaction can produce.

Radiation at THz frequency was one of the main attractions of the conference. In fact, the Under 40 (U40) and Under 30 (U30) awards were both given for studies on THz radiation sources this year. The Under 40 award winning paper by Wei-Min Wang from Institute of Physics, CAS, (L-I11) presented the experimental work on producing THz radiation with a two-color laser scheme (Zhang et al. 2017). Conventionally, in this scheme, the ratio of laser frequencies is fixed at $\omega_2/\Omega_1$ = 1:2. Experimental observations were presented which showed that even at new ratios of laser frequencies viz., $\omega_2/\Omega_1$ = 1:4, 2:3 the energy of THz generation peaked. The experimental results were in contradiction to the multi-wave mixing model which predicts different scaling for different frequency ratios. Their experimental results on the other hand agreed with the plasma current or gas ionization models. The under-30 winning presentation given by Zhelin Zhang from SJTU, Shanghai (L-O6) discussed ways of controlling the THz radiation (Zhang et al. 2016). Ye Tian (LP-8) from Shanghai Institute of Optics and Fine mechanics presented the novel scheme of THz radiation by irradiating a wire with laser. The instantaneous radial electric field leads to helical electron motion giving rise to THz radiation. They could produce well collimated and intense THz source with a conversion efficiency of 1% in their femtosecond laser facility. The THz frequency was shown to be tunable by adjusting the diameter of the wire. A. Kuratov from Center of Fundamental and Applied Research (VNIIA) (L-P21) provided a comparative evaluation of the various surface and volumetric schemes of producing the THz radiation from laser plasma sources. In a semi-plenary talk (LPL-9), Yutong Li from Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, (CAS) presented experiments with laser-foils for THz generation using a multi-TW femtosecond laser system at Shanghai Jiao-Tong University and the Vulcan PW laser system at the Rutherford Appleton Laboratory (Liao et al. 2016). Different types of targets were used in the experiment, including mass-limited metal targets with different sizes, polyethylene (PE)-metal double-layered targets and single-PE targets. The energy conversion efficiency from the laser pulse energy on targets to THz radiation is $2 \times 10^{-4}$ for the femtosecond laser system. The experiments with the Vulcan pico-second laser system showed much enhanced conversion efficiency of 0.1%.

Interestingly, in the plenary talk by G. Ravindra Kumar of the Tata Institute of fundamental Research (TIFR) in India ,the observation of THz acoustic wave in dense laser plasma experiments were reported. Pump–probe reflectometry and pump–probe Doppler spectrometry diagnostics were used to identify the terahertz acoustic disturbance. Hydrodynamic simulations were performed to offer insight into this process. The relevance of these observations to astrophysical phenomena was highlighted (Adak et al. 2015).

The water window (WW) soft X-ray have important technological implications. They can be employed for observing nano-meter scale structure of living cells with high spatial resolution. The Kakunaka from Graduate School of Engineering, Hiroshima University (LP-24) and C. John from Graduate School of Engineering, Hiroshima University (LP-25) presented experiments on the generation of WW soft X-ray by a picosecond laser falling on the Au target. The enhancement of emission in the presence of nitrogen gas environment was shown and plausible atomic physics reasons were presented to explain this.

With upcoming laser facilities promising to deliver intensities of the order of $10^{23}$ W/cm$^2$ novel radiation sources can be expected. One such example was provided in the talk by A. Arefiev (L-I21) from UCSD. The relativistically induced transparency in this regime allows the laser pulse to propagate through denser region of the material. The dense population of electrons produces magnetic field of the order of mega Tesla which can be comparable to the magnetic field of the laser pulse itself. This magnetic field in turn enhances the energy gain of the accelerated electrons. The strong acceleration and high energy leads to a strong emission of energetic photon. The computational and theoretical studies presented in the talk showed multi MeV gamma ray photon generation with an efficiency of around 3% with such lasers (Jansen et al. 2018a). The dense beam of gamma-ray photon source will have important applications in advanced nuclear and radiological detection.

## 5 Magnetic fields in laser plasma interaction

The lighter electron species of target plasma is the species which suffers the direct onslaught of the laser pulse. When the laser falls on the plasma medium its energy gets transferred to the electrons at the critical density surface. The concept of fast ignition laser fusion relies on the transport and deposition of energy to create hot spot for ignition by these energetic electrons. It is, therefore, of extreme importance to understand the transport and stopping of these energetic electrons through the plasma medium. Some issues of major concern are (i) whether the transport is governed by classical processes and/or influenced by instability driven anomalous processes, (ii) what is the role of inhomogeneous plasma density in the energetic electron propagation, (iii) how much is the divergence of electron beam and how can it be controlled. Research studies are being conducted to attain an understanding of these questions. The electron transport in plasma is a source of current which has magnetic fields associated with it. Thus, the behaviour of electron transport in the plasma gets suitably mapped by the magnetic fields and hence can be understood by studying the generation and evolution of magnetic fields.

The plenary talk by G. Ravindra Kumar (P17) from Tata Institute of Fundamental Research, India, covered this area extensively. The recent experimental and theoretical studies of the instabilities encountered by the energetic electron as it propagates in the plasma was discussed in the talk. The experiments were conducted with the help of 100 TW laser at TIFR. The creation and turbulent evolution of giant magnetic fields was captured and tracked in time using a pump–probe polarimetry (Mondal et al. 2012; Chatterjee et al. 2017). The observations showed the presence of long scale magnetic fields transverse to the laser propagation direction at very early times. The Weibel and Kelvin–Helmholtz modes considered to determine the electron propagation account for scales of the order of electron skin depth. The presence of longer scales right from the very beginning could be accounted for by a novel effect arising due to finite size of the laser laser spot. This was confirmed by the OSIRIS4.0 PIC (Particle-In-Cell) simulations (Das et al. 2017). In addition, the ultra-fast mapping of the electron transport was carried out by monitoring the emission from these electrons in the experiments. The lifetime of intense-laser ($2 \times 10^{19}$ W/cm$^2$) generated relativistic electron pulses in solids was measured by tracking the time evolution of their Cherenkov emission (Shaikh et al. 2018). A picosecond resolution optical Kerr gating technique was employed to show that the electrons remain relativistic for about 50 picoseconds or more which is about 1000 times longer than the incident light pulse. Numerical simulations of the propagation of relativistic electrons and the emitted Cherenkov radiation were carried out with Monte Carlo GEANT4 package which reproduced the striking experimental findings.

In the talk L-I13, Romagnani from Ecole Polytechnique presented experimental investigations of the propagation of laser-induced fast electron currents in near solid-density medium. The growth of filamentation instabilities was temporally resolved and the net currents were reconstructed from the experimental data. Comparison with hybrid simulations and analytical models were made to explain the magnitude, topology and growth rates of the observed field distributions.

Studies on Weibel instability leading to magnetic field generation were covered in some presentations. The evolution and nonlinear saturation of Weibel instability in electron-ion relativistic plasma was studied with the help of fully 3D PIC simulations and was presented in the talk LPL-3 by Matsumoto from Chiba University. It was shown that the ion Weibel filaments were stable to secondary instabilities and the consequent magnetic fields were sustained for a long time after the ion Alfven current limit was reached. The oral talk by M. Garasev from Institute of Applied Physics RAS (L-O9) considered long-term evolution studies of Weibel instability in a plasma with temperature anisotropy.

The reconnection of magnetic field leading to energetic particle generation has remained an outstanding issue in the context of astrophysical scenarios. The dissipative processes have been inadequate for understanding rapid release of energy in reconnection processes. Lately, however, laser experiments have been designed to understand the mechanism in a controlled laboratory set up. There were talks dedicated towards understanding astrophysical observations of magnetosphere and magnetosheath. The talk by Seiji Zenitani from Jyoto University (LPL-4) presented the reconnection at the dayside magnetopause using 2-D PIC studies. The electron scale physics signatures in region surrounding the X line were explored (Zenitani et al. 2017). The characteristics features of electron velocity distribution function were observed to be similar to the magnetosphere multiscale spacecraft (MMS) observations by NASA.

The experimental observations on reconnection processes with lasers were presented by Fox from PPPL (L-I17). The experiment was conducted with two colliding magnetized laser-produced plasmas obtaining long extended current sheets ($L/di \sim 100$) and low dissipation (high Lundquist number $S = \mu_0 L V_A/\eta \sim 1000$, where $V_A$ is the Alfven speed). The current sheet was observed to break up into a chain of a large number of magnetic islands. Proton radiography and optical shadowgraphy were employed to directly observe the size and temporal growth of island structures. The possibility of particle energization relevant to heliospheric and astrophysical plasmas using the laser experiment was also discussed.

An interesting possibility of employing magnetic fields to control the high-power laser pulse propagation in plasma was proposed by Weng (L-I18) from Shanghai Jiao Tong University, wherein the extreme Faraday effect could be employed to split a linearly polarised laser into two opposite circularly polarised lasers (Weng et al. 2017).

## 6 New technologies and facilities

The plenary talk by R. Kodama (P9) from the Institute of Laser Engineering Osaka covered a comprehensive review of High Energy Density Science research activities carried out at ILE Osaka and other laboratories using high-power lasers. He touched on the topic of a variety of extreme states of matter such as warm dense matter (WDM), high-pressured plasmas, radiative plasmas, fusion burning plasmas, relativistic plasmas and electro-positron plasmas. These states enable a lot of applications in areas as diverse as particle acceleration, laboratory astrophysics, material science, nuclear photonics and laser fusion. It was shown that the studies on these applications were in various stages of progress. Facilities like XFEL and related plasma devices are employed for these studies. ILE Osaka in Japan is exploring the HED science by developing high-power lasers as center of excellence (COE) in the field. The promotion of certain topics as projects and project initiatives for HED science were outlined in the talk. For instance research activities on fast ignition in laser fusion with kJ-PW lasers are carried out in the FIREX project, laser-driven ion acceleration and neutron source development in the Laser Nuclear Engineering project (LANE), laser-wake field electron acceleration in the LAPLACIAN project, high-pressure condensed matter and material science with high-power lasers and XFEL in the HERMES project, high average and high-power laser development for HED science in the J-EPoCH project, and laser astrophysics research such as collisionless shock in the Laser Astrophysics project initiative. He presented recent progress in these projects and discussed the prospect of HED science in Japan. He also elucidated some of challenging frontier problems including vacuum quantum optics and talked about the EPOCH millennium goals. The generation of strong magnetic fields using laser-driven coil targets and their use to collimate and guide MeV range relativistic electrons in solid targets is another important frontier development which was highlighted in his talk (Iwata et al. 2018; Bailly-Grandvaux et al. 2018; Yogo et al. 2017; Albertazzi et al. 2017; Huntington et al. 2015).

Discovery science program at the National Ignition Facility (NIF) in the USA was summarized by Bruce Remington. This program offers outside users access to the world's largest lasers to perform basic science experiments in an environment which has never been achieved before in any laboratory. The experiments conducted under this theme involve diverse topics of equation of state (EOS), studies of matter in extreme states, investigation of supernovae such as shock phenomena, hydrodynamic instabilities and turbulence, plasma-based nuclear reactions, X-ray Thomson scattering in dense plasmas, magnetic field and plasma wake field acceleration experiments. The discovery science program of NIF issues calls for proposal every year during May.

Yabuuchi talked about other experimental facilities such as XFEL at SACLA in Japan which have also been opened up for international users from 2018 onwards for combined experiments. It will provide an experimental platform for the usage of high-intensity laser and X-ray free electron lasers. The current experiments in this facility involve 200 TW, 8 Joule, 40 fs pulse laser coupled to the XFEL.

Similarly the Gekko XII laser, a national facility of Japan is also open for International collaboration. Mitsuo Nakai (Osaka University) presented a detailed description of the facility which involved a recent upgrade in terms of installation of fibre oscillator to obtain arbitrary pulse shape, spherical plasma mirror to increase the contrast ratio and the illumination direction. Experiments involved generation of strong magnetic field to the tune of 10 kilo Tesla by the novel technique of magnetized fast isochoric laser heating. The system is essentially a high-power laser facility for the study of high-energy density science.

It is thus clear that in the upcoming laser facilities offer major advancements in terms of laser power, pulse duration, repetition rate, etc., for exciting experiments to be conducted at the frontiers.

## 7 Frontier physics issues

With steady progress in the intensity of lasers, new physics regimes of radiation reaction (RR), quantum electrodynamics (QED) will come within reach of laboratory investigation. Radiation reaction in fact appears to be well within reach as the upcoming laser systems are expected to have intensity around $10^{23}$ W/cm$^2$. Quantum electrodynamic effects require higher intensity as one has to reach the typical Schwinger electric field $E_s = 1.32 \times 10^{16}$ V/m which translates to an intensity of about $10^{29}$ W/cm$^2$. The Schwinger limit represents the field at which the laser generates electron positron pairs in vacuum. It is, however, possible to have QED effects such as photon–photon scattering in vacuum using intensities below the Schwinger limit. Furthermore, with increasing laser power, new regimes of warm dense matter (WDM), high energy density (HED) science can be studied in the laboratory. Theoretical and simulation studies are being carried out for the understanding and investigation of these new frontier physics areas. There were many presentations in the conference which addressed these issues.

The talk by Esirkepov (L-I20) from National Institutes for Quantum and Radiological Science and Technology identified the various regimes where classical radiation reaction and QED effects will become important, in terms of two dimensionless parameters $a_0$ and $\chi_e$. While $a_0$ is the ratio of the quiver velocity of electron in the electric field of the laser to the speed of light, $\chi_e$ represents the ratio of laser electric field to the Schwinger field. It was shown that the laser intensity for observing radiation reaction $I_{RR} = 10^{23}$ W/cm$^2$ would be soon achieved by the high-power lasers. An interesting technological feasibility of achieving high irradiance with the help of multiple beam has been put forth. The cumulative irradiance would increase N fold at the focus of N colliding laser beams. The standing wave pattern in space will have strong fast oscillating RR effect leading to interesting phase space trajectories of electrons (Esirkepov and Bulanov 2017; Bulanov 2017). In oral presentation Liangliang Ji from Shanghai Institute of Optics and Fine Mechanics (L-O10) talked about the possibility of observing QED effects at intensities lower than required to reach the Schwinger limit, by colliding laser and energetic electron beams. The possibility of producing a dense beam of gamma rays in the high-intensity regime approaching $10^{23}$ W/cm$^2$ through self-generated magnetic field which couples relativistic transparency, direct electron acceleration and synchrotron photon emission, was illustrated in the talk by Arefiev (UCSD) (Jansen et al. 2018b).

The production of warm dense matter (WDM) in laser experiments carried out with the Trident laser facility at the Los Alamos National Laboratory was presented in the invited talk (L-I6) by Bang from GIST. They used a beam of laser-driven quasi-mono-energetic aluminium ions to heat solid density gold and diamond foils uniformly and rapidly above 10,000 K. The expanding warm dense gold and diamond particles were observed with an optical streak camera (Bang et al. 2016). The initial temperatures of the heated samples were estimated from the measured expansion speeds of gold and diamond. The creation of such a uniformly heated solid density target will allow for direct quantitative measurements of many properties such as equation-of-state, conductivity, opacity, and stopping power of warm dense matter.

The production of WDM and HED through lasers opens up the possibility of investigating phenomena associated with astrophysical objects and planetary interiors. These were covered in the talks by Casner from CELIA, (L-I9) and Ravasio from LULI (L-I10). The experiments with the help of MJ class laser in the HED regime to explore hydrodynamic instabilities have been carried out at the LULI2000 and NIF facilities (Casner et al. 2015, 2019; Remington et al. 2006). The talk by Casner (L-I9) presented studies on Rayleigh Taylor instability (RTI) at the ablation front. The scaled single and multimode RTI (relevant to young supernova) and their nonlinear evolution were investigated in laboratory. Transverse radiography diagnostics were employed to observe the evolution. The system and diagnostics were updated for quantitative study of turbulent hydrodynamics and mixing in HED system.

## 8 Concluding remarks

It is clear that the field of laser plasma interaction has progressed rapidly over the last couple of decades. The fundamental physics questions have pushed the technological advancements of lasers. The technological advancements in lasers have in turn led to further explorations of challenging frontier areas in Physics. The developments in the field of laser plasma interaction explicitly show interdependence of technological advancements and fundamental curiosity for exploring frontier areas of physics. These developments have simultaneously led to many discoveries of applied nature for the benefit of human society. Applications in areas as diverse as medicine, imaging, materials, security etc., have sprouted from these discoveries. The presentations in the conference bore testimony to the rich advances in frontier physics, technological advancement and many associated applications.

An important application is the area of energy through nuclear fusion. While steadfast progress is being made both in the inertial confinement fusion (ICF) scheme through lasers, and magnetic confinement fusion (MCF) which rely on strong magnetic field, we are still away from satisfying the required condition for its commercial viability. Recent experiments, however, have shown the production of strong quasi-static magnetic field of the order of kilo Tesla in the laboratory. This suggests an interesting possibility, wherein these strong quasi-static magnetic field could be utilized to come up with a smart design of plasma confinement which relies on the best of both ICF and MCF concepts. It will also open up new areas of interest in terms of heating and absorption of energy by magnetized plasmas experimentally in a much simpler and smaller setup of plasma (Tokamak and other MCF devices are burdened with complex geometry and huge size). It, therefore, appears quite likely that in future, this generation of strong quasi-static magnetic field in laboratory, will bring together the MCF and ICF concepts for building smarter fusion devices/reactor.

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