White Paper: The case for petawatt laser research infrastructure in Australia

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Executive Summary:

High peak-power "Petawatt" lasers drive extreme light-matter interactions to generate plasmas and particle/photon jets with conditions of temperature, electric and magnetic fields strengths only otherwise found in extreme astrophysical events (centre of stars, supernova explosions, binary star accretion, edge of black holes). They have opened the field of high-energy-density physics, including many new opportunities for scientific research and applications, from compact particle accelerators to clean fusion energy generation. The significance of these opportunities led the inventors of the key technology behind high-peak-power lasers to win the 2018 Nobel Prize in Physics.

The international scientific community has embraced this opportunity with the establishment of many petawatt laser facilities around the world (Figure 1). Some are "mission-driven" - at the centre of international collaborations focussed on the world's biggest scientific challenges, such as fusion energy generation. Facilities open to external users have seen demand far exceed laser time available and now have dedicated "network organisations" to manage them.

Unfortunately, there are no petawatt laser facilities in the southern hemisphere. This white paper proposes the establishment of such a facility in Australia which would undoubtedly be embraced by the Australian research community with key strengths in photonics, laser physics and laser engineering. It will also open the door to numerous opportunities for international collaborators, many of which were discussed during the preparation of this document.

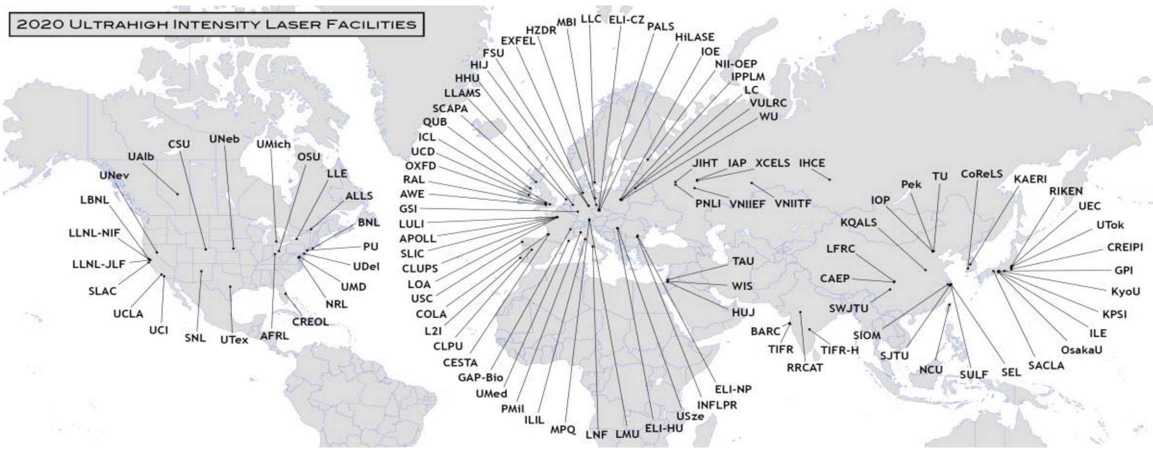

Figure 1: Ultrahigh Intensity Laser Facilities worldwide (Link to full map and list of institutions).

Background

Laser technology has progressed against key benchmarks faster than the semiconductor industry over past decades. Without this development we would not be able to rapidly sequence DNA, provide guidance for self-driving cars, manufacture microchips or transfer data at the speeds required for our Zoom calls.

High-peak-power lasers, also referred to as ultra-short pulse lasers, are a critically important niche of laser technology. They provide a very intense but short-lived pulse of light (up to petawatts or 10^{15} watts) in a single pulse typically femto- to pico-seconds (10^{-15} to 10^{-12} s) in duration. They also include lasers with longer nanosecond pulses that can produce very high energy pulses (mega-joules), albeit with sub-petawatt peak-powers.

Laser pulses at these powers provide access to physical phenomena and applications beyond what was previously accessible with large and expensive particle accelerators, such as synchrotrons. The significance of this emerging field was recognized by the **2018 Nobel Prize in Physics** to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses": chirped pulse laser amplification. This is the state-of-the-art method for achieving practical high-power output.

Developments in laser technology have provided **a rapid decline in the costs and size of laser systems**, and a major improvement in power and quality of laser pulses. This opens up the "white space" for a large swathe of applications that are on a pathway to economic viability as laser technology matures further. For high-peak-power lasers this will include new applications such as the realization of clean energy production via fusion, compact particle accelerators, novel imaging approaches, radiobiological therapeutics manufacturing.

Between the emergence of new applications and demand for lasers themselves, many new industries will be born in the coming decades from high power laser science and technological development.

Emerging fields of research, applications and opportunities to establish new industries

The range of emerging applications for high-power lasers is large. The establishment of many new industries and applications is an attractive prospect, including the manufacture of the laser systems themselves.

In analyzing the Australian setting we concentrate on specific applications of compact high peak-power laser systems cross-referencing national research groups with the specific interest in each application (see Appendix 1):

- New research capabilities:
    - to study high-energy density physics (MQP, ANU), a most famous example is breaking a vacuum.
    - Fusion energy science and quantum electrodynamics (HB11, LRG, MQP, USPL, CQD, ANU)
    - Providing more cost-effective access to frontier scientific experiments including but not limited to those only otherwise available at synchrotrons or accelerator facilities (HB11, LRG, MPQ, USPL, CQD, ANU)
- Advanced, multi-modal, dynamic and highly penetrating imaging capabilities (USPL, MQP) including:
    - High contrast X-ray imaging.

    - High-energy X-ray imaging, including biomedical imaging.
    - Imaging using terahertz radiation
    - Time resolved imaging / analysis, (in the pico- or femto-second range) enabling new analytical capabilities spanning chemistry, physics and biology.
- New technologies for advanced sensing in defence and security (ANU, USPL).
- Novel radiobiology for future therapeutic modalities, or therapies only accessible at accelerators or synchrotron (USPL, CQD, ANU). Examples include:
    - Proton therapy
    - Hadron therapy
    - X-ray therapy
    - High-energy electron beams, e.g. for intra-operative radiation therapy.
- New capabilities for the study of laboratory astrophysics (MQP, ANU)
- Clean energy research, e.g. for nuclear fusion as per HB11 Energy's mission (HB11, LRG, MQP, USPL, ANU)
- Value addition to minerals: laser enrichment of isotopes for quantum computing and energy (Silex)

Recent developments

In addition to HB11 Energy's own activities, laser fusion research will be dramatically elevated following a major breakthrough in the field. Lawrence Livermore National Laboratory (US) achieved fusion energy generation from laser pulse at the $3.5B National Ignition Facility (NIF) with a net-gain of 70%, orders of magnitude higher than previous records (link). Instrumental to the establishment of NIF was the HB11 Energy Scientific Advisory Board Member, Dr Mike Campbell (link). These results will undoubtedly lead to significant investments into laser fusion internationally. For example, US has included provisions aiming for additional investments into petawatt laser facilities and inertial fusion energy via the "Energy Science for the Future Act" (circa $US10B, link). A comprehensive review of these applications and opportunities was published in 2018 by the US National Academies of Science Engineering and Medicine in 2018 (link). As a result, the US Biden-Harris administration has begun developing a decadal vision to accelerate the viability of commercial fusion energy in partnership with the private sector (link).

As a consequence of these promised and emerging applications, the international high-power laser community is seeing:

- Very high user demand for existing petawatt laser facilities from the research community to pursue new research opportunities.
- Accelerated R&D towards the development of lasers for these specific applications.
- The availability of the first commercially available petawatt lasers from suppliers such as Thales Optronics or Amplitude (both in France).

Global perspective

There are 71 ultra-high intensity laser facilities: around 20 have a peak-power of more than 1 petawatt.

The scientific possibilities and promise of emerging industries has mobilized many governments to make big investments in these research facilities, in particular throughout the US, UK, Europe and Asia. Some examples of major research infrastructure installations include:

- UK: Ministry of Defence has recently invested £81 M into the Extreme Photonics Applications Centre – a 10 Hz, 1 PW laser facility. Australia now has a good link to this facility via recently appointed Director of the NCRIS funded ANSTO Centre for Accelerator Science, Dr Ceri Brenner. She was Innovation lead at the UK Central Laser Facility, near Oxford, with a focus on plasma accelerator physics and industry partnerships before to migrating to Australia in January 2021.
- USA: National Ignition Facility (Lawrence Livermore National Laboratory); Laboratory for Laser Energetics (University of Rochester); ZEUS (University of Michigan, link); Matter in Extreme Conditions (MEC) project at Stanford Linear Accelerator (SLAC) (details of their upgrade as a user facility here).
- Europe: Extreme Light Infrastructure - €875M investment in three major petawatt laser facilities. (link)
- Japan: Institute for Laser Energetics, Osaka University (link)
- France: Laser Megajoule project and the PETAL laser, representing a €3B investment (link), LULI-2000 (link) and the APOLLON laser (link)
- China: The most powerful being developed in Shanghai's Station of Extreme Light (SEL).
- Korea: Multi-PW laser at Gwangju Institute of Science and Technology (GIST) in South Korea (link)
- Many other smaller facilities, in the order of $20-$500M investment, such as Texas Petawatt laser (US), VULCAN at *Rutherford Appleton* Laboratory in Oxfordshire (UK), the CALA laser at Max Plank institute for Quantum Optics (Germany) and the VEGA laser at CPLU in Spain.

Most of these are run as user facilities, like synchrotrons, alongside research and engineering efforts focused on the development of the laser itself or new applications.

There is exceptional demand for these facilities which has led to the establishment of LaserLab (EU) and Lasernet (US). These consortia of laboratories focus access by scientists with the most beneficial research projects. As an example, the Omega facility at the University of Rochester's Laboratory for Laser Energetics has demand of 200-300% of available time just for basic scientific research. Similarly, within the Lasernet scheme which manages access to nine facilities across the US (and Canada), applications for laser time represent about 200% of time available. Each application represents a multi-institutional collaborative research team, of which 28% of these arise from groups outside of the USA.

During the preparation of this white paper Dr. Kramer Akli, who is the program manager for LaserNet within the Office of Sciences in the **US DOE, expressed support towards Australia to become involved with Lasernet given the establishment of a petawatt laser capability**, and offered to express this formally in a letter of support.

The need for a petawatt laser facility in Australia

Access Challenges

There are no petawatt laser facilities in Australia. Without them, Australia will miss opportunities in both the emerging fields of research and new industries that will evolve from them.

Currently, Australian access to high-peak-power laser for research is severely limited as researchers need to apply for access internationally. Like synchrotrons, access needs to be applied for on a competitive basis and often has preferred access to local research groups. If it is granted, the actual experimental time can be scheduled more than one year after the preferred application date.

Expertise and Opportunities

With respect to the research community, Australia has extensive expertise in lasers and their applications so demand for experiments in a related field will be high. Epicenters of lasers and photonics research, which include both application and fabrication/manufacturing capabilities for laser (and photonic) materials and components, can be found at the following research institutions (not an exhaustive list):

- Griffith University (Australian Attosecond Science Facility, Centre for Quantum Dynamics)
- ANU (Laser Physics Centre)
- University of Sydney (Institute for Photonics and Optical Science) ,
- University of Adelaide (link), with associated groups at:
    - The Adelaide node of the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav); and
    - The University's Institute for Photonics and Advanced Sensing (IPAS).
- University of New South Wales.
- University of Technology Sydney (Photonics - UTS Tech Lab)
- Macquarie University (MQ Photonics),
- Royal Melbourne Institute of Technology (Integrated Photonics and Applications Centre)
- Swinburne University of Technology (Ultrafast Laser labs)
- University of South Australia (Laser Physics and Photonics Devices Laboratory).
- Australian National Fabrication Facility, OptoFab Node.
- DST Group, Laser Technology Group (Laser Development and Research | DST (defence.gov.au))

Beyond academic research groups, Silex Systems is a large ASX listed company based in Sydney and employs some of the world's best laser physicists and engineers. They have expressed interest in this initiative.

Appendix 1 records the specific interest of a number of these research groups WRT high-power laser research who were consulted in the preparation of this white paper. The timescale did not permit a more extensive review of local research and innovation scope.

The establishment of a petawatt laser facility in Australia would allow the Australian research community to:

- Expand critical research in these emerging fields.
- Exploit the industrial opportunities emerging from high-power lasers, starting with a trained research community.

- Open the doors to international partnerships, potentially including laser inertial fusion energy research (NIF V2), laboratory astrophysics, or more fundamental research such as "breaking the vacuum."
- In the case of HB11 Energy, such an investment would be essential to keep scientific development and industrial exploitation of laser hydrogen-boron fusion, one of the few emerging options for truly clean, safe, low carbon energy generation, in Australia.

Beyond the research community, there will be more mature applications that have nearer term application in industry or for health, for high-brightness sources of radiation, which will be catalyzed by the establishment of such a facility.

Proposal for a petawatt laser facility in Australia

The establishment of a petawatt laser capability in Australia will benefit three groups of stakeholders:

- The scientific community, who will primarily be interested in facility access to conduct experiments. As described above, access is anticipated to be in high demand as there is a healthy photonics and laser research community in Australia. All research groups described in Appendix 1 have expressed specific interest in such access.
- The innovation community is focused on using lasers for specific applications. All research groups described in Appendix 1 have expressed specific interest in application development using lasers.
- The laser technology development community. Research groups MQP, USPL and ANU are all either already involved or interested in such laser technology development.

The international laser facilities that HB11 Energy has been in contact with in the development of this White Paper have given guidance on a likely options for the establishment for a laser facility in Australia as follows:

1. **Local competence**: Establish a sovereign research capability via procurement of a commercially available system. Discussions with vendors indicate that a 0.5-2 petawatt laser system would represent an investment in the order of $5-20M, including its building. Such a facility could be established as an open access facility to support scientific experiments within 18 months of funding. Such a facility would:
    - Establish a sovereign capability to support scientific research.
    - Train the research community, already with a high profile in lasers and photonics, to develop the field of high-power laser physics and associated applications.
    - Discussions with local stakeholders strongly suggest the upper bound investment would be fully subscribed by users
2. **International Connections and Impact:** Build an internationally benchmarked multi-petawatt laser system. This would open an opportunity to lead or become involved with international partners in projects that could address some of the world's biggest emerging research challenges. It will also open opportunities to be a leader in emerging technologies and exploit industrial opportunities that emerge from it. The investment in a multi-petawatt facility is in the order of $100M and would likely be a second-of-a-kind tailored for specific applications that could be pioneered in Australia. These could include hydrogen-boron fusion and future defence applications. To use fusion energy as an example:

- HB11 Energy is already building such international partnerships to develop and prove its aneutronic (i.e. clean) fusion energy generation concept, which will require such facilities with some degree of customization.
- The recent demonstration of a fusion burn from the National Ignition Facility has sparked planning for the next generation of experimental laser fusion facility. Such a facility could open the door to participation in such projects.

3. **Lead the world in the establishment of new applications and industries**. To use HB11 Energy as an example, (1) and (2) would be necessary for Australia to have an opportunity to lead the development of its truly clean, safe and reliable source of energy that can power the future carbon-neutral electricity grid and hydrogen generation capacity at scale.

Appendix 1: Synopsis of interest from Australian Research groups consulted in the preparation of this document.

HB11 Energy Holdings Pty Ltd (HB11)

A petawatt laser in Australia will be essential for HB11 Energy's home-grown invention for truly large-scale safe, clean energy technology to remain an Australian technology.

HB11 Energy is developing a novel approach **to large-scale clean-electricity generation** using the aneutronic fusion of hydrogen and boron-11 in a reaction that does not use any radioactive fuels nor generate intractable radioactive waste. Significantly, this reaction was discovered by an Australian, Sir Mark Oliphant, and its development led by Australian HB11 Energy founder Prof Heinrich Hora.

It is one of the few truly clean-energy sources being explored that has both the scale of a nuclear reactor and safety of traditional renewable sources. It generates electricity directly, without the requirement of a steam-cycle and is well suited for both grid electricity or hydrogen production.

HB11 Energy will require access to high-peak-power lasers for almost all experiments it conducts. As waiting times for access are long, sometimes up to two years, the pace of research will be slow. To compensate, typical experiments will be supported by months to years of theoretical and computational simulations of the experiment to maximize the useful data we can obtain in a single experiment.

HB11 Energy is currently assembling its own international consortium of research groups to support this effort. As an Australian company, it has intensions to base as much research as possible locally, but the extent of this will be very limited without a petawatt laser. Accordingly, HB11 Energy has coordinated the preparation of this white paper.

For HB11 Energy, such a facility would allow its research into its new large-scale clean energy source to remain in Australia. Without it, the development of this Australian-born invention will remain an international endeavor.

Dr Warren McKenzie FRSN
*Managing Director, HB11 Energy Holdings Pty Ltd***.**

Ladouceur research group (UNSW) (LRG)

The Ladouceur research group is focused on lasers, photonics and biomedical research. Our core interest in a petawatt laser facility is in pursuit of realizing laser fusion, although we also foresee applications in non-linear optics.

Large scale clean-electricity generation, just like any challenging engineering project, relies on sophisticated modelling. The design of a viable fusion reaction will necessarily depend on model validation through experiments that can only be conducted using realistic laboratory conditions. In that sense, access to an Australia-based petawatt laser would be crucial for the rapid development of a theoretical and computational model and, ultimately, to the success of the whole project.

We are collaborators of HB11 Energy, and as part of that effort are trying to secure laser time in other facilities around the world.

Prof Francois Ladouceur is collaborating with HB11 Energy on clean fusion energy technology development.

MQ Photonics Research Centre, Macquarie University (MQP)

The MQ Photonics Research Centre at Macquarie University has emerged from the Centre for Lasers and Applications (CLA) that was established in 1988. For the last >30 years, the centre has been at the international forefront of research into the generation and application of ultrashort laser pulses.

Many of its currently about 30 academic members are renowned experts in laser science and the prospect of being actively involved in the development of a worldwide unique laser facility represents a once-in-a-lifetime opportunity. Further, having access to a national petawatt-class laser system would open up a wide range of highly topical research directions that are perfectly aligned with the existing expertise within Macquarie University, not only at the Photonic research centre, but also at the Centre for Quantum Engineering, e.g. quantum electrodynamics experiments or attosecond physics.

In addition, Macquarie University's Research Centre for Astronomy, Astrophysics, and Astrophotonics (MQAAAstro) is one of the largest and fastest-growing astronomical centres of research excellence in Australia. "Nuclear Astrophysics" is currently one of the hottest topics in high-field research. The extreme electric and magnetic fields that can be generated by a petawatt laser match those found in neutron stars and thus allow for astrophysical models to be tested in the laboratory.

A/Prof. Alex Fuerbach from MQ photonics is collaborating with HB11 Energy on clean fusion energy technology development.

USPL Group, DST Group and the University of Adelaide (USPL)

Under the leadership **of Prof Miftar Ganija**, the USLP (Ultra Short-pulse Laser) group has recently been established as a joint initiative between DSTG and University of Adelaide. The objectives of the centre span laser design, component manufacture, laser effects and applications, and student education. Within Defence, they are already collaborating with NATO, DSTL (UK), NRL (US), AFRL (US) and Eli (EU). Within the medical field, they have established a collaboration with the Australian Bragg Centre for Proton Therapy and Research.

Instrumental in the USPL road map is the establishment of an ultra-short-pulse (high power) laser facility locally.

The USPL group is in discussion about collaboration with HB11 Energy to develop its clean fusion energy technology.

Centre for Quantum Dynamics, Australian Attosecond Science Facility, Griffith University (CQD)

Led by **Prof Robert Sang** (Dean (Academic) Griffith Sciences), the group undertakes research in what is called strong-field physics and is arguably one of the leaders in the field of using strong-field lasers to investigate atomic physics processes involving the ionisation of atoms and molecules.

The group have worked in areas such as high-harmonic generations and of course, the proposed laser systems would be of interest to us to create high energy coherent X-Rays for imaging purposes for the characterisation of materials. We are also very interested in experiments to investigate collisional induced excitation of the nucleus of atoms.

We had a project with Lockheed Martin to investigate using this process to induce a change of nuclear state for radioactive material. The concept is to make nuclear waste safe in a faster timeframe through the excitation of a nuclear state that decays faster that the steady state nuclear state. A Petawatt laser would enable us to look at a greater range of radioactive materials.

Laser Physics Centre, Department of Quantum Science and Technology, Research School of Physics, Australian National University (ANU)

Our goal is to develop and implement innovative laser systems and new laser-based techniques. Our combined perspectives and expertise can drive innovation and creativity in areas such as defence, space, energy, manufacturing, medicine and the arts. Close ties to industry need to ensure a focus on high performance and robust, affordable twenty-first century laser platforms. We aim to make cutting-edge laser technology the pre-eminent solution for new challenges in areas such as manufacturing industries, national security, health care and asset maintenance.

We aim to address the following challenges:

- Significantly reducing the current high cost of advanced high-power laser systems, which prohibits wide-spread use of new laser-based technologies.
- Targeted research and development of new high-technology laser-based products and materials, which cannot be produced by other means, for example dielectric, semiconducting and metal nanofoams, magnetic carbon, black silicon solar cells, amorphous sapphire battery separators, etc.
- Developing new laser interaction regimens for specialised applications including high throughput and/or high precision processes, for example cold ablation, laser sterilisation and surface functionalisation.

A new Petawatt laser system would be a significant component of the national innovation system supporting medium to long-term collaboration between the producers and end users of research. The Laser Physics Centre is home to much of Australia's high energy laser experience and technological expertise, and we will support the proposed Petawatt laser system both through new research and reapplying past specialist high energy laser physics knowledge to educate a new generation of physicists and engineers in this important and re-emergent field.

The aim is to build critical mass in research and education ventures between end users and researchers, which tackle clearly articulated, major challenges that deliver significant economic, environmental and/or social benefits to Australia.