Eur. Phys. J. Special Topics **223**, 1189–1195 (2014)

DOI: 10.1140/epjst/e2014-02172-4

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

ICAN as a new laser paradigm for high energy, high average power femtosecond pulses

W.S. Brocklesby[3], J. Nilsson[3], T. Schreiber[2], J. Limpert[2], A. Brignon[6], J. Bourderionnet[6], L. Lombard[5], V. Michau[5], M. Hanna[4], Y. Zaouter[7], T. Tajima[8], and Gérard Mourou[1]

[1] Ecole Polytechnique [Coordinator], Palaiseau, France
[2] Fraunhofer IOF Jena, Germany
[3] ORC – Optoelectronics Research Centre, Southampton, UK
[4] Laboratoire Charles Fabry, Institut d'Optique, Palaiseau, France
[5] ONERA – The French Aerospace Lab, France
[6] TRT-Fr – THALES Research and Technology, Palaiseau, France
[7] Amplitude Systèmes, Pessac, France
[8] University of California – Irvine, USA

Received 13 March 2014 / Received in final form 24 March 2014
Published online 4 June 2014

Abstract. The application of petawatt lasers to scientific and technological problems is advancing rapidly. The usefulness of these applications will depend on being able to produce petawatt pulses at much higher repetition rates than is presently possible. The International Coherent Amplification Network (ICAN) consortium seeks to design high repetition rate petawatt lasers using large scale coherent beam combination of femtosecond pulse amplifiers built from optical fibres. This combination of technologies has the potential to overcome many of the hurdles to high energy, high average power pulsed lasers, opening up applications and meeting societal challenges.

1 Introduction

Petawatt science and technology is becoming widespread as more and more large laser systems are built. It brings lasers into areas of physics previously reserved for large-scale RF accelerators – electron acceleration [1], ion acceleration [2], X-ray and γ-ray generation [3]. In these areas, lasers can have significant advantages of scale and cost. However, in order to take these applications from single-shot experiments to useful electron or ion sources, the nature of petawatt lasers must be changed completely.

Present petawatt lasers are almost all based on chirped pulse amplification in titanium-doped sapphire laser amplifiers. Chirped pulse amplification [4] (CPA) was developed nearly 30 years ago, in order to solve the problems of amplifying very high intensity laser pulses. CPA uses frequency chirp to stretch the pulses temporally in a reversible manner, so that the peak intensity can be greatly reduced during amplification, mitigating degradation from nonlinearities and material damage. After amplification the pulses can be recompressed to their original duration, producing very high peak intensities.

At petawatt peak powers, several factors combine to reduce the rate at which high-energy pulses can be produced. The Ti:sapphire crystals are pumped using a Nd-based nanosecond pulsed laser, which itself is pumped by flashlamps. These are intrinsically low efficiency and low repetition rate. In addition, the energy mismatch between pump laser and output laser photon energies in Ti:sapphire is as large as 30%, meaning at least 30% of the pump energy is deposited into the sapphire crystal. This causes optical distortion due to thermal lensing, which in high energy systems is commonly reduced by cryogenic cooling of the laser material.

Several new designs of laser are attempting to use alternative technologies to overcome the repetition rate and efficiency issues limiting present lasers. Flashlamps excel in converting short pulses of electrical energy from capacitor banks into flashes of pump light, but the efficiency is rarely better than fractions of a percent and they are only suitable for low repetition rates. Changing the pump source from the highly inefficient flashlamps to laser diodes has a huge effect on overall system efficiency. Laser diodes can be 60–70% efficient and are particularly attractive for higher repetition rates. For example, the DiPOLE project [5] at Rutherford Appleton Laboratories, UK aims to use face-cooled Yb^{3+}:YAG ceramic amplifier slabs pumped with laser diodes to produce petawatt pulses at 10 Hz, and has demonstrated 7.5 J pulses at 10 Hz. The use of Yb^{3+} instead of Ti^{3+} as an active medium reduces the heat load into the laser material, as the energy mismatch between pump and output photons in Yb^{3+} is very small, a few percent rather than over 30%. Furthermore the fluorescence lifetime of Yb:YAG is at the ms-level, which is considerably longer than that of Nd:YAG and Ti:sapphire. This further benefits direct diode-pumping. The ICAN project aims to change petawatt laser design even more radically, aiming to do in the spatial domain what CPA did in the frequency domain – thus mitigating nonlinear and damage limits even further, and simultaneously providing a way to control thermal effects by spatially separating the beam into many individual channels, each amplified to high energy by optical fibre amplifiers. Although this increases complexity, in that it requires coherent pulse combination to re-form a single output beam, the degree of control allowed by this separation produces a laser system with unparalleled properties.

The Yb^{3+}-doped optical fibre amplifier system is technologically very well-developed. Output powers greater than 1 kW from a single optical fibre were demonstrated in 2004 by two groups, and since then, the use of very high average power Yb-doped fiber lasers has become widespread within industry as a source of high power, because of the very high efficiency – the fiber laser itself can be >90% efficient – combined with low complexity. In the fibre laser, thermal problems are much reduced because of the very high surface to volume ratio of the core gain medium, a result of its shape. Thus the Yb-fibre amplifier is an efficient, simple, and relatively cheap source of very high power laser light.

The adaptation of the Yb-fibre amplifier to ultrashort pulses is straightforward, using CPA in a similar manner to bulk lasers. However, ultrashort pulses bring with them one significant issue. The propagation of pulses in an optical fibre can rapidly become nonlinear at high peak powers, and nonlinear propagation can produce phase shifts in the chirped pulse that are not removed by the recompression process, meaning that short pulses cannot be recovered. This limits the peak power available from a single fibre, and given current pulse stretching technology limits the output of each fibre to the mJ range. The state of the art at present for high-energy pulses in a fibre amplifier is the production of 2.2 mJ pulses [6], with peak power of 3.8 GW. Thus to produce a pulse with energy in the 10 J range necessary for petawatt peak powers, a very large number of fibres must be used – in the range of 10,000 – and their output

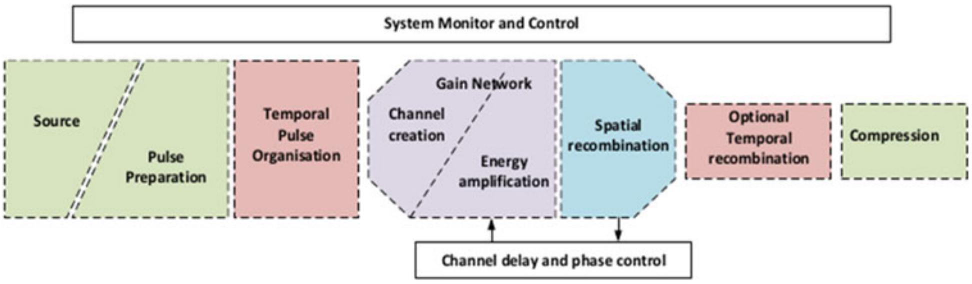

Fig. 1. Optical block design for the ICAN laser.

beams combined into a single pulse. The ICAN concept is based on the ability to produce and recombine this large number of fibre channels in a cost-effective and reliable way.

2 Large-scale optical fibre amplification

The use of 10,000 separate amplifiers using bulk laser technology would be extremely difficult to engineer, because of the huge complexity involved. However, the use of optical fibres is a major advantage, because of the infrastructure already present to produce complex networks of fibres for telecommunications. Instead of using bulk components to split and manipulate each channel, fiberized components can be used which do not require alignment. This technology has been perfected in communications networks, which commonly use huge numbers of channels. The ICAN laser is based on this idea of a "coherent amplification network", or CAN, which uses many channels starting from a single seed laser, and splitting, amplifying and controlling each channel using components based on those used for telecoms. This reduces cost, and reduces complexity enough that creating 10,000 channels is still economically viable. The current drive towards telecom systems with coherent control and highly parallel multicore fibers and elements reinforces this trend.

The block design for an ICAN laser is shown in Fig. 1. The source of femtosecond pulses can be a fibre or a bulk laser, and after the source the pulse must be stretched temporally (CPA), and its initial repetition rate adjusted. After the source, a 'gain network' is used to create the correct number of channels by repeated splitting and amplification of the low-energy pulses. Once the required channel count has been reached, each channel is amplified up to the mJ level using high average power fibre amplifiers – these amplifiers represent the bulk of the cost and complexity of the CAN, as up to this point all the pulses are low energy. After amplification, the pulses must be spatially recombined into a single chirped pulse, which can then be emporally recompressed to produce the final pulse. The technology for stretching and recombination of petawatt pulses is well developed, although the addition of high average power will require careful engineering design in these more conventional components.

The final amplifiers represent a significant part of the complexity of the CAN. In the simplest ICAN design, each must be able to produce $\sim$ mJ pulses at the chosen final repetition rate, which is $\sim$10–15 kHz. Thus each channel needs to handle tens of watts of average power, which is moderate for a fibre amplifier. The key issue is keeping nonlinearity low. The measure of this is given by the total nonlinear phase shift at the centre frequency of the pulse, known as the B integral. To keep this at a value compatible with temporal recompression, large core fibres must be used, and as fibre cores increase in size, problems associated with multimode propagation and thermal power handling start to arise. This area is a key issue for ICAN's development.

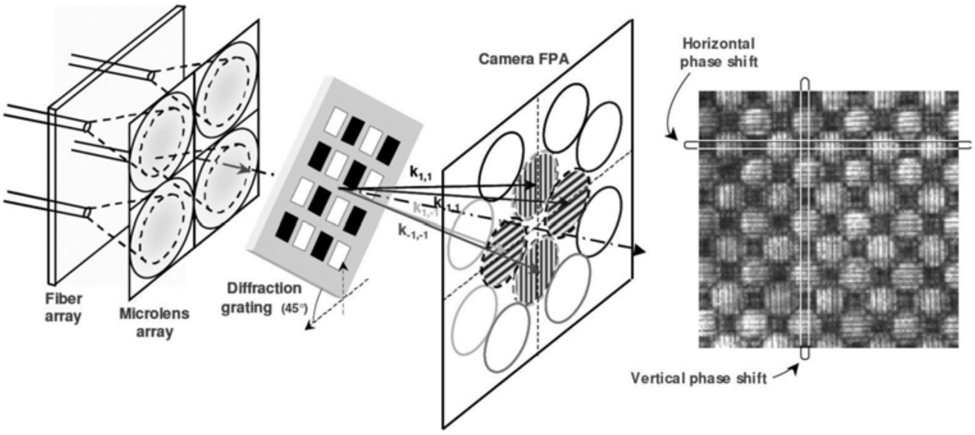

Fig. 2. (Left) principle of self-referenced wavefront analysis technique based on QWLSI; (right) part of an experimentally-recorded interference pattern (from A. Brignon J. Bourderionnet, C. Bellanger and J. Primot [9]).

Coherent spatial recombination of many fibre channels is a key ingredient of the CAN laser. Two routes are possible: (1) filled aperture techniques, which often use beamsplitters to combine two beams at a time, and (2) tiled aperture techniques, which combine many beams at once. At present, the state of the art in femtosecond pulse recombination is the coherent combination of four fibre amplifiers using a filled aperture technique, to produce 1.3 mJ pulses at a 550 kHz repetition rate [7]. For very large channel numbers, tiled aperture techniques look more feasible. Coherent combination of 64 fibre amplifier channels was demonstrated several years ago [8] using quadriwave lateral shearing interferometry (QWLSI). The principal noise components in the phase errors between channels are at acoustic or lower frequencies, so that phase control loops at frequencies of less than 1 kHz are required. Recent work has shown that QWLSI is scalable to 10,000 channels using current detector and computer technology at loop frequencies up to 1 kHz, while retaining a phase error of less than $\lambda/20$. A schematic of the recombination technique is shown in Fig. 2.

Several new technologies may provide a way for ICAN to increase its average power and reduce the number of channels necessary, decreasing system cost. Divided pulse amplification (DPA), which is a further extension of CPA in which the pulse is split into several temporal copies each delayed by tens of nanoseconds, has been shown [10–12] to allow total pulse energies of up to ~50 mJ to be extracted from each single fibre rather than a few mJ. If these temporally-split pulses can be coherently recombined, the use of DPA will reduce total channel count in the CAN by more than a factor of 10, with resultant reduction of cost.

Temporal recombination on a much larger scale can be used to produce high energy pulses at kHz repetition rate using a resonant enhancement cavity [13]. In a slightly different ICAN design, the overall repetition rate of the network is set at a higher value, for example 10 MHz, and the output pulses reduced in energy by a factor of 500–1000. This plays to the strength of the optical fibre amplifier, because for the same average power, peak power is reduced by a factor of 1000, reducing issues with nonlinear propagation significantly. The pulses then need to be temporally recombined on a large scale using an enhancement cavity. The cavity has a round-trip time equal to the pulse separation, so pulses build up inside the cavity until the circulating pulse has perhaps 500–600 times the original pulse energy. This pulse is then rapidly switched out of the cavity for use in experiments. The pulse repetition rate is thus reduced, but could still be around 15 kHz. The cavity adds system complexity, but also reduces channel count very significantly if suitable fast intracavity switches can be produced.

3 Costs

Estimation of the total system cost for such a new type of laser is not trivial, but within the ICAN consortium cost models have been developed based on information from the manufacture of present day commercial high power fiber laser systems. The comparison with the present state of the art in petawatt lasers is instructive. For a 1 PW laser (40 J, 40 fs) running at 1 Hz, the present cost is (to an order of magnitude approximation) ∼10 M€, giving a unit cost of €250 k/W. The projected component cost of an ICAN system with output of 32 J at 15 kHz (∼500 kW average power) is between 100 and 200 M€, or around € 400/W, i.e. almost three orders of magnitude cheaper than the total cost of a conventional petawatt systems.

4 Efficiency

The key comparison between present petawatt systems and the ICAN system is in its efficiency. The best present-day systems have wallplug efficiencies in the region of 0.03%. For a 1 Hz system with average power 40 W, this is acceptable. For a 15 kHz system, this would require an input electrical power of ∼ 2 GW, which is clearly unacceptable. The ICAN system should reach efficiencies of ∼30–50%, giving a total power requirement for a 480 kW system of 1–2 MW, which is technically feasible.

5 Bandwidth & pulse duration

One drawback of Yb-doped fibre vs Ti:sapphire as a gain medium is the available gain bandwidth. In Ti:sapphire, amplified pulses of 30–40 fs are not difficult to achieve. In Yb-fibre amplifiers, pulse durations down to 170 fs have been reported [14] but pulse durations of ∼500 fs are more typical [15]. However, the multiple nature of the ICAN amplifier system may provide help toward a solution to this issue. Recent experiments [16] have demonstrated significant shortening of the pulse from a high-power fibre amplifier using coherent spectral beam combining, where each amplifier acts on part of the bandwidth of the input seed pulse, and the two pulses are coherently combined to increase the total bandwidth. Demonstration of 130 fs pulse, with 19 nm bandwidth with 10 W output power represents a significant step toward a solution of the problem of narrow bandwidth in Yb amplifiers.

6 ICAN – Applications

The immediate applications for an ICAN source cut across many branches of physics and engineering. ICAN's initial goal, and still one of the very important applications is in laser wake field acceleration (LWFA). LWFA was the original focus of the ICAN project, aiming for the production of 10 GeV electron acceleration per stage at a repetition rate of ∼13 kHz. Multistage acceleration could be used to produce colliders, as detailed in the ICFA-ICUIL report [17] of Leemans et al., with the cost and wallplug efficiency making a laser-based accelerator an attractive option compared to next-generation RF accelerators. Single stage acceleration to 10 GeV could provide electron

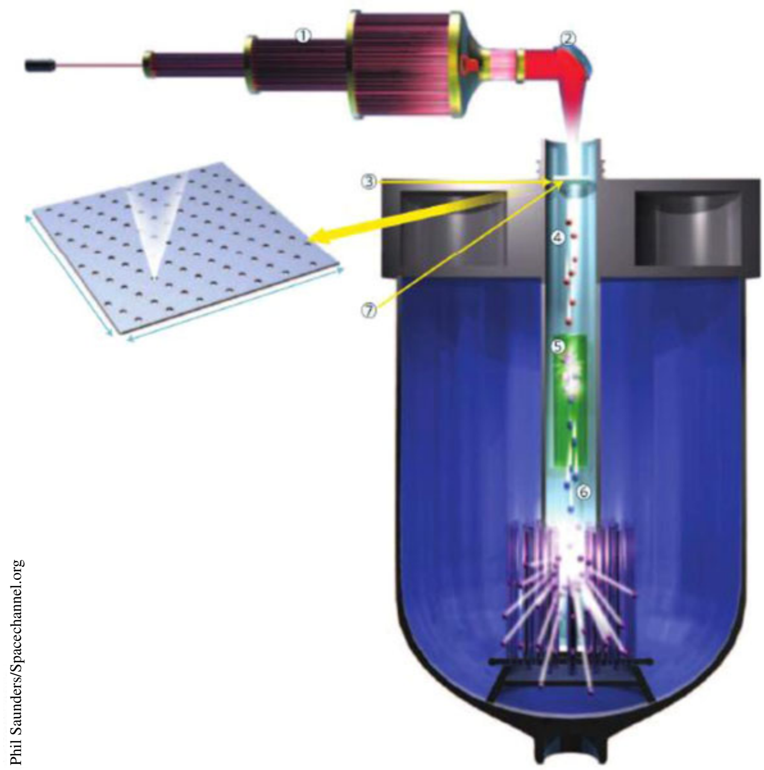

Fig. 3. Transmutation via ADS schematic – the ICAN front end laser (1) is focused (2) onto a proton-rich target (3). The GeV protons produced (4) are incident on a Pb-Bi target (5), and the high energy neutrons produced by spallation are used in nuclear transmutation (6). Maintenance of the entrance window to the chamber (7) is critical to safe operation (from Ref. 19).

beams suitable for use in free electron laser applications in a much more compact form than present linear accelerators.

As the ICAN technology develops, higher laser intensities will allow relativistic proton generation. The possibility of generating intensities $>10^{23}\,\mathrm{W/cm^2}$ will enable the use of the Light Sail mechanism [18] for efficient generation of relativistic protons, which have many applications with relevance outside of basic science. Examples include:

- Spallation neutron sources
- Nuclear pharmacology & proton therapy [19]
- Transmutation of nuclear waste via accelerator-driven systems (ADS) [20] as shown in Fig. 3.
- Nuclear resonance fluorescence imaging [21], for detection and identification of radionuclides in security applications and nuclear waste cleanup.

The ICAN laser in combination with a conventional electron beam is an ideal candidate for the large-scale production of Higgs bosons. In one example of this application, HFiTT [22] (Higgs Factory in the Tevatron Tunnel), 3 eV photons produced by frequency tripling the CAN laser undergo Compton scattering from 80 GeV electrons from a storage ring, producing γ photons at 62.5 GeV. Subsequent $\gamma-\gamma$ collisions will create Higgs bosons at a projected rate of 10,000 Higgs particles per year.

The ICAN laser alone can provide a pathway to dark matter detection, based on laser-induced nonlinearities in vacuum. This application relies heavily on the high intensities and high repetition rates provided by the CAN laser, and demonstrates the range of applications that can be considered once a high repetition rate petawatt laser is achievable.

In conclusion, ICAN represents a route to high average power, high peak power laser systems with unparalleled efficiency. Many of the fundamental technical challenges in building a large-scale ICAN system have been overcome in other experiments, and at each stage of development, the ICAN concept will provide lasers which will have important applications. Costs will reduce with the very high volume of manufacturing which will be necessary. The next stage of ICAN, a hardware demonstrator, is planned for the period 2014–2018.

References

1. W.P. Leemans, et al., Nat. Phys. **2**, 696 (2006)
2. T. Esirkepov, M. Borghesi, S. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. **92**, 175003 (2004)
3. K. Ta Phuoc, et al., Nat. Photonics **6**, 308 (2012)
4. D. Strickland, G. Mourou, Opt. Commun. **56**, 219 (1985)
5. K. Ertel, et al., DiPOLE: a scalable laser architecture for pumping multi-Hz PW systems, edited by J. Hein, G. Korn, L.O. Silva 87801W–87801W–5 (2013), doi: 10.1117/12.2021330
6. T. Eidam, et al., Opt. Exp. **19**, 255 (2011)
7. A. Klenke, et al., Opt. Lett. **38**, 2283 (2013)
8. C. Bellanger, et al., Opt. Lett. **35**, 3931 (2010)
9. A. Brignon (ed.), *Coherent Laser Beam Combining* (Wiley-VCH, 2013), p. 481
10. M. Kienel, et al., Opt. Exp. **21**, 29031 (2013)
11. M. Kienel, et al., Opt. Lett. **39**, 1049 (2014)
12. Y. Zaouter, et al., Opt. Lett. **38**, 106 (2013)
13. I. Pupeza, et al., Opt. Lett. **35**, 2052 (2010)
14. J. Prawiharjo, et al., Opt. Exp. **16**, 15074 (2008)
15. F. Stutzki, et al., Opt. Lett. **36**, 689 (2011)
16. F. Guichard, et al., Opt. Lett. **38**, 5430 (2013)
17. W. Leemans, ICFA Beam Dyn. Newslett. **56**, 10 (2011)
18. S. Steinke, et al., Phys. Rev. Spec. Top. Accel. Beams **16**, 011303 (2013)
19. D. Habs, T. Tajima, U. Köster (2011), Laser-Driven Radiation Therapy, Current Cancer Treatment – Novel Beyond Conventional Approaches, Prof. Oner Ozdemir, ISBN: 978-953-307-397-2, InTech, doi: 10.5772/24190
20. G. Mourou, B. Brocklesby, T. Tajima, J. Limpert, Nat. Photonics **7**, 258 (2013)
21. T. Hayakawa, et al., Rev. Sci. Instrum. **80**, 045110 (2009)
22. W. Chou, G. Mourou, N. Solyak, T. Tajima, M. Velasco, "HFiTT – Higgs Factory in Tevatron Tunnel" Fermilab-TM-2558-APC (2013)