

ICAN: Final Report

1. Executive summary

Accelerators are today in every walk of science and life¹. High intensity lasers drive frontiers of contemporary science. Lasers in the TW and PW regime have the potential to replace conventional accelerators with the distinct advantage to be dramatically shorter by a factor of a thousand or more². For instance, electrons are accelerated to few GeV over only few centimeters, representing three to four orders of magnitude higher accelerating gradients than traditional RF-based accelerators can offer. The approach was proposed in 1979³, where a strong laser pulse⁴ moving in a plasma creates a wake in which electrons are trapped and violently accelerated. In addition, under ultra high intensity, high energy protons over 100MeV have been demonstrated as well as high energy radiation greater than MeV⁵.

Key to laser-driven accelerators, ion, X-ray or Gamma ray production are ultra high peak power lasers at the petawatt level⁶. However, current petawatt lasers exhibit low repetition rates (state-of-the-art is about 1Hz) due to thermo-optical issues in their gain medium, resulting in low average powers in the 50W range. In addition, a rather poor wall-plug efficiency (electrical power to optical power) of 10^{-3} avoids any scaling perspectives. Hence, state-of-the-art high peak power laser system cannot pretend to be tomorrow's replacement to conventional RF technology – a new class of ultrafast lasers is urgently needed.

Under the ICFA-ICUIL² initiative laser experts in the field of particle acceleration and high intensity lasers defined target parameters a future laser system should deliver to pave the way for a new kind of accelerator technology revolutionizing fundamental science and applications.

The following laser parameters are envisaged for what could be a future linear e-e+ collider: peak power in the PW regime, defined by a 10's of Joules of pulse energy and an ultrashort pulse duration below 50fs, in combination with an unparalleled average power exceeding 100kW even approaching the megawatt level, implying repetition rates of >10kHz. These extreme parameters should be contained in a beam of excellent spatial quality, featuring outstanding temporal stability and temporal contrast. An excellent wall-plug efficiency of >30% is an essential condition that such average powers are realized in a cost effective, economic and compact way. Overall, any known laser technology known today faces severe issues, with current performance orders of magnitude below these target parameters.

Inspired by these groundbreaking challenges our group combines the complementary expertise of science authorities in the field of high performance fiber amplifiers, theoretical and applied optics of optical systems and finally ultra high intensity lasers. ICAN aspires to study the fundamentals of interferometric amplification, i.e. spatially separated amplification followed by coherent addition, of ultrashort laser pulses as the underlying concept of a breakthrough in laser physics. In detail we have studied:

- 1) average/peak power and efficiency limits of coherently combined ultrafast laser systems
- 2) synchronization, spatial and temporal recombination of a large number of fibers amplifiers
- 3) temporal and spatial beam quality, combining efficiency of coherent addition, amplitude and phase stability as a function of the number of fibers and their individual performance
- 4) reduction of pulse duration and manipulation of pulse shape

In conclusion, the proposed concept offers the perspectives of a colossal improvement over existing high peak power lasers and could therefore lead to the successful replacement of RF-accelerators by laser driven accelerators. It efficaciously addresses scientific, industrial, and societal grand challenges: future colliders, vacuum physics, Higgs factories, high flux proton & neutron sources, applications such as nuclear transmutation, energy-specific gamma beams for isotope identification with high fluence as well as in medicine with nuclear pharmacology and proton therapy².

2. Project context and objectives

Introduction

The laser was demonstrated more than 50 years ago. Its ability to produce, for the first time, coherent photons at electron-Volt (eV) energy scales have been used in two almost opposite scientific directions, generally known as quantum optics and relativistic optics. In quantum optics, eV photons from the laser are used to cool down atoms to extremely low temperatures reaching nano-Kelvin temperatures (corresponding to thermal velocities of cm/s). Conversely, in relativistic optics the same eV photons are used to violently accelerate particles (both electron and ions) to relativistic velocities and energies in the MeV-GeV range over extremely short distances, in the range of millimetres to centimetres. Quantum optics generally uses extremely stable lasers, with

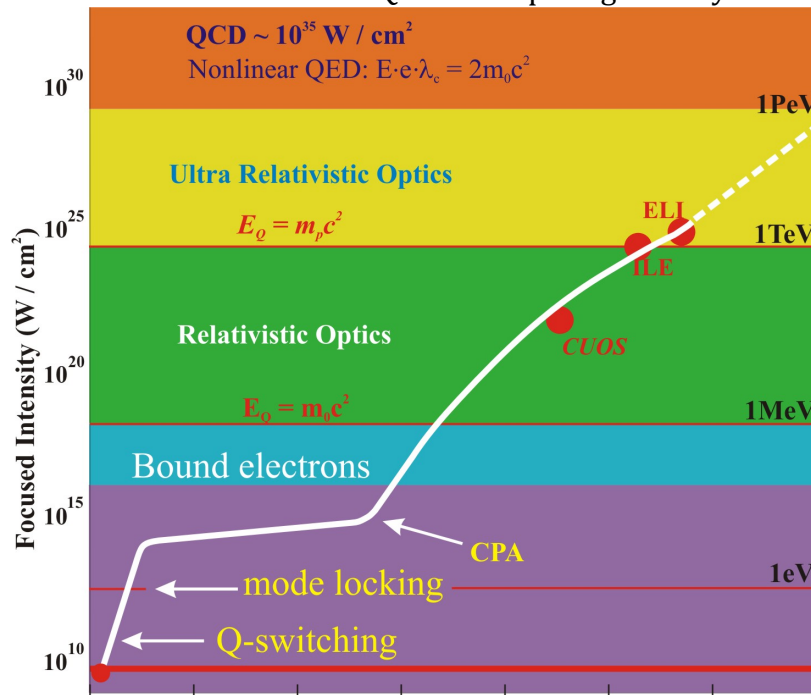


Figure 1 - Increase in laser intensity with time from its invention to present day

photon number variation down to $\Delta n/n \sim 10^{-16}$, whereas relativistic optics requires the laser to delivered its energy within ultrashort, (few cycles) ultra intense pulses.

The interaction of ultra intense laser pulses with matter in the MeV and GeV regimes defines successively relativistic and ultra relativistic laser matter interaction. In this regime, the generation of particles and radiation in the GeV-TeV range is possible; thus the field

of subatomic physics is opened up to the laser.

Figure 1 depicts the increase of the maximum possible focused intensity available from lasers over the years. We can see a rapid growth in intensity after 1985 when the technique of CPA(Chirped Pulse Amplification) was demonstrated⁴. The two regimes of interest for us are shown. The first, known as the relativistic regime, deals with light intensity between $10^{18}\text{W}/\text{cm}^2$ and $10^{22}\text{-}10^{23}\text{W}/\text{cm}^2$ for light of wavelength $1\mu\text{m}$. This regime is characterized by the possibility of accelerating electrons to relativistic energies, i.e. MeV. The second regime is called the ultrarelativistic regime, defined as intensities $>10^{23}\text{W}/\text{cm}^2$. At this intensity, the laser has the ability to accelerate protons and ions to relativistic energies, in the GeV range.

The recent increase in availability of lasers in the relativistic regime indicated in Figure 1 has opened up areas like electron and ion acceleration as potential large-scale applications. The availability of petawatt laser sources has made the implementation of ideas about using lasers for particle acceleration originally developed in the 1970s³ a reality, and progress^{7,8,9} in the area of laser plasma acceleration has produced electron beams with characteristics like high energy (GeV) and monochromaticity normally only found in traditional RF accelerators. The result is that the idea of laser-based particle accelerators has found traction within the accelerator community. The joint ICFA-ICUIL report² of 2011 looked carefully at the properties that would be necessary for a laser source in order to construct a large-scale particle accelerator based on laser plasma acceleration. At that time, no lasers existed which could come close to the specifications needed.

The principal issues facing petawatt lasers can be summarised very quickly. Firstly, the rate at which petawatt pulses can be produced by a laser source is typically very low. The state of the art at present is the BELLA laser¹⁰, at Lawrence Berkeley Laboratories, which can produce 1 pulse per second. This is a major improvement over most petawatt facilities, whose pulse repetition rate is such that only a few pulses are produced per day. Any application that requires many pulses, such as an accelerator studying rare collisions, needs to study many events, and hence requires much higher pulse repetition rates. Secondly, the petawatt sources of the present are typically based on the use of very inefficient technologies. The optical power originates in flashlamps, which have very low electrical to optical conversion efficiencies. When the laser is operation at low repetition rates and hence low average powers, this low efficiency is not particularly problematic. As an example, the BELLA laser produces ~ 40 J pulses at a rate of 1 Hz, giving an average power of 40 watts – the same as a typical household lightbulb. The input electrical power necessary to produce this 40 W output is ~ 130 kW, implying an efficiency of 0.03%. While the pulse repetition rate is 1 Hz this remains possible. If we anticipate an increase of repetition rate to, for example, 10 kHz, then the input power required would be 1.3GW, which is clearly impractical.

Thus the development of real world applications for the new science emerging from petawatt lasers requires the development of laser sources that can run at high repetition rates, and simultaneously at high efficiency. The potential applications for such a laser source are much wider than electron accelerators, although this was the original application that was envisaged. Once the average power and efficiency are increased, then many applications such as compact free electron lasers, ion sources for therapeutic applications, and even the processing of nuclear waste start to become viable.

The ICAN Project

The CAN concept was originally conceived to remove the laser's nemesis, i.e. thermal management in high peak power solid-state lasers, and their mediocre efficiency. This is the reason why we had to adopt a strategy based on massive amount of coherent efficient fibers. This strategy raises a number of questions for very large N (number of fibers) about the limit in terms of number of fiber and their overall efficiency. Another important question concerns the effect of summing large numbers of beams on the overall temporal and spatial quality. We expect that for a very large amount of channels the temporal and spatial fluctuations will average out by a significant amount. This property could be one of the most important assets of a CAN system. This needs to be studied and quantified. Finally, a CAN system has the advantage of working with independent channels that can be individually addressed, forming a digital laser where phase and amplitude can be individually controlled, leading to a very unique feature of a CAN system to be heuristic. It seems for us paramount to demonstrate also this feature.

The present ICAN project was initiated in order to look at potential technologies for high average power petawatt lasers, and in particular at the use of optical fibre-based lasers in high volumes, coherently combined to form a single beam. The project objective was to study, via a series of conferences and workshops, the possibilities for the use of multi-beam combination in this way, looking at aspects from the fundamental physical limitations to the potential manufacture of the laser.

The project beneficiaries are world experts in the fields of high intensity lasers, optical fibres, and particle accelerators: Lead beneficiary on the project is École Polytechnique, Paris, led by Professor Gérard Mourou, the inventor of the technique of Chirped Pulse Amplification⁴ (CPA) which underlies all of the high-intensity lasers used around the world. The University of Southampton and Fraunhofer IOF, Jena, are two of the leading labs in the development of high power optical fibre lasers in the world, and were responsible for the first kW average power fibre lasers. The final beneficiary, CERN, is unique in the world development of particle accelerator technology.

Together with these four direct beneficiaries, a team of experts was assembled who represented all of the major laboratories in the field, and who were funded to attend conferences and workshops. 15 laboratories contributed experts to the project, including LCFIO, Thales Research and Technology and ONERA as experts in optical beam combination, accelerator experts from KEK, Fermilab, HZDR, University of Strathclyde, and the John Adams Accelerator Institute in Oxford, and high intensity laser experts from University of Michigan, Max-Planck-Institut für Quantenoptik in Munich, LULI, and CEA. The experience provided by this team of experts is unparalleled.

Applications

Applications of very high intensity lasers are often concerned with particle acceleration, as at these intensities, the electric field of the laser is so high that no other laser-matter interaction is important. In the relativistic regime, this acceleration is provided by plasma wake field acceleration, in which the electric field of a plasma wave created by the laser pulse is used to accelerate the electrons (Laser Wake Field Acceleration, LWFA). The plasma wave is a collective oscillation of the plasma. As the laser pulse intensity increases into the ultra-relativistic regime, acceleration of electrons and ions is possible by using the laser pulse to drive electron motion directly rather than driving plasma modes. In this mode, the electrons are pushed by the laser, and the ions are

accelerated by the field created. Acceleration is by the techniques of Target Normal Sheath Acceleration (TNSA)¹¹ and Radiation Pressure Acceleration (RPA)¹².

The potential applications for the ICAN laser will be summarised in a later section.

3. Main Scientific and Technical results

Laser requirements for acceleration

This section will summarize the requirements for a laser to accelerate electrons by laser-wakefield acceleration, and for acceleration of ions and protons using ultra-intense, ultra-short laser pulses. The accelerator scheme that is the base for the calculations is shown in Figure 2. In the case of electron acceleration, most numbers will rely on the paper published by Leemans and Esarey¹³. Some information is also based upon an earlier publication by Leemans *et al.*¹⁴.

For the applications; The low intensity or relativistic regime will deal with mainly e+e- collider applications, or X-ray and γ -ray production for Higgs factory applications, whereas the ultra high intensity regime will deal more with proton acceleration and applications.

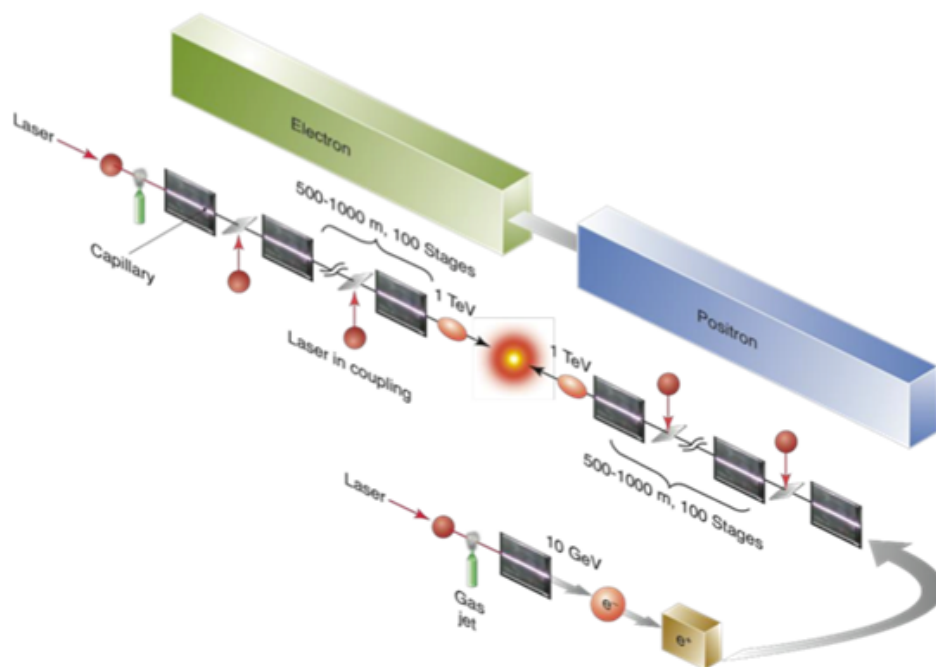


Figure 2 - A scheme for a laser-based system for an electron-positron particle collider (from ref. 13)

Laser Pulse Parameters for wake field acceleration

The amplitude of the plasma wake field created by a laser pulse is proportional to the peak intensity of the laser pulse. Higher wake field amplitudes are equivalent to larger voltages accelerating the free electrons, which implies the same velocities can be reached within shorter distances. This results in a more compact system.

To achieve high pulse peak intensities, the pulse energy should be as high as possible, the duration as short as possible and the beam quality as good as possible (more details

in the following). According to [Error! Bookmark not defined.], 32 J of pulse-energy in a pulse with the duration of sub 300 fs and a repetition rate of 15kHz, would be sufficient for an accelerator which might consist of 100 stages of 1GeV acceleration – these are the parameters taken as the starting point for the ICAN project.

Pulse Contrast

To prevent the disturbance of the plasma before the actual pulse arrives a high pulse-contrast is crucial. To give a resilient number is very hard since it depends on many parameters.

Wavelength

The chosen wavelength has multiple impacts on the final system. It seems to be desirable to have long wavelengths since the acceleration gradient is approximately proportional to the laser wavelength¹⁵. On the other hand, systems emitting at longer wavelengths usually do not deliver ultrashort pulses and typically have low efficiencies. Therefore, solid-state concepts relying on the fibre geometry at 1 μm appear to be the best compromise.

Pulse Repetition Rate and Average Power

Reference **Error! Bookmark not defined.** indicates that to achieve the desired collider luminosity, a laser-plasma collider would need a repetition rate of about 15 kHz. Taking the desired pulse-energy into account this results in average powers in the region of 0.5 MW, higher than any laser that presently exists.

Beam Quality

The beam propagation factor, M^2 , of the final beam should be lower than 1.1. This is important due to the fact that acceleration is going to happen over a certain length and therefore the high laser intensities have to be accessible over the whole length. This can either be achieved by a very low M^2 value or a large focal spot. The large spot reduces the pulse-peak-intensity at a given pulse-peak-power and is hence not the desired option.

Laser Pulse Parameters for relativistic ion acceleration

Relativistic ion acceleration requires laser intensities that are several orders of magnitude higher than those required for electron acceleration, due to their large difference in mass. Several mechanisms have been proposed for acceleration at these energies; Target Normal Sheath acceleration is shown in Figure 3. In the TNSA process, the dominant process is the heating of electrons via efficient conversion of laser radiation into kinetic energy. At the surface of the material, a cloud of relativistic electrons is formed which in turn produce a very high electric field, which then accelerates the ions left in the target. The laser intensity required is greater than 10^{18} W/cm². The issue with TNSA is that the ions accelerated have a broad distribution of energies, and the process of conversion of laser energy into ion kinetic energy is inefficient. At slightly higher laser intensities, greater than 10^{20} W/cm², acceleration is possible via the RPA process shown schematically in Figure 4. In RPA, the ponderomotive force of the laser accelerates the electrons *en bloc*, causing ion acceleration via the huge electric field produced by the electron displacement. The major advantages of RPA over TNSA are that firstly the ions produced can be monoenergetic, and also the process is predicted to be very efficient. Table 1

summarises the various intensity and polarization regimes, the type of mechanisms (TNSA¹¹, RPA¹²) and the target thickness for ion acceleration.

Table 1 - summary of parameters for relativistic ion acceleration

Acceleration mechanism	laser	Target thickness	Characteristics
TNSA (Target normal sheath acceleration)	$I > 10^{18} \text{ W/cm}^2$ Linear pol.	$\sim \mu\text{m}$	Broad spectrum Thermal electrons
RPA (Radiation pressure acceleration)	$I > 10^{20} \text{ W/cm}^2$ Linear pol. Circular pol.	$\sim \text{nm}$	Quasi-monoenergetic, collective electrons

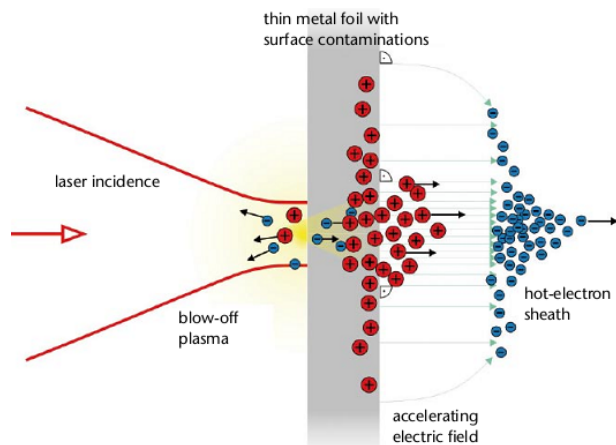


Figure 3 - Ion acceleration in the Target Normal Sheath Acceleration regime. The laser, not penetrating the target, heats electrons, which drag protons after penetrating the target (figure courtesy C.H. Nam)

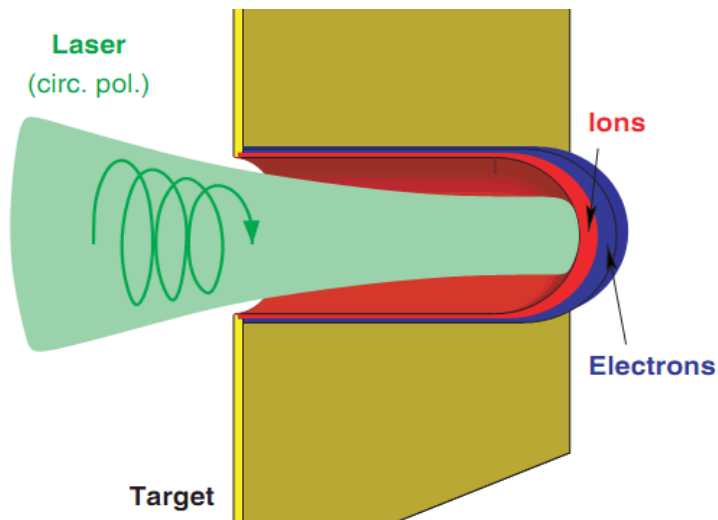


Figure 4 - Radiation Pressure Acceleration; the laser pulse pushes the electrons as a whole, which drag the protons. (figure courtesy C.H. Nam)

Target system specifications for the ICAN project

For the purposes of design within the ICAN project, different system-design proposals will be discussed that meet the following laser parameters:

- 32 J pulse energy
- 15 kHz pulse repetition rate (→ 480 kW average power)
- <300 fs pulse duration (→ >100 TW peak power)
- Near diffraction-limited beam quality
- >20% wall-plug efficiency

System designs will be discussed, and for each system design, the risk factors will be evaluated in terms of technology readiness. A detailed estimate of the potential cost of different system designs is made.

System Concepts

The ICAN optical concept is configured from components which are either presently available or close to availability wherever possible. The block design is outlined in Figure 5. Each part has one or more technology options, which each present challenges that may be resolved through refinement and engineering. Some elements are subject to further research to establish working limits for overall system design.

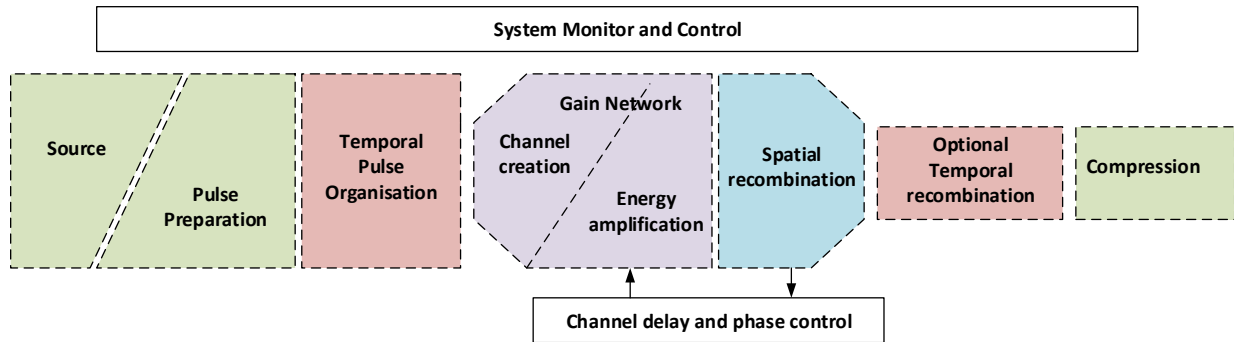


Figure 5 - optical block design for the ICAN laser

The system comprises a mode locked laser source operating at 10-40MHz, which is generally commercially available in the current market. The source may be fibre or bulk optic and its supply and performance is considered a low risk element. The source may include pulse pickers to down select the frequency and internal amplifiers to deliver the specification required for the gain network.

The pulses from the source are prepared for amplification by stretching to the order of a few ns. 10ns is challenging; four, or a few ns is moderate and perceived as readily achievable. As part of preparation, chirp and amplitude shaping is anticipated by way of a bulk optic spatial light modulation component. These are common in CPA systems, however it is expected the components will be bespoke and designed in tandem with the pulse compression. Currently two specialist suppliers are expected to be capable of manufacturing the grating and bulk optical components.

The pulse organisation stage defines the repetition rate and loading of the gain network. Three options are under consideration.

- (a) Directly picking desired pulses from the source (“parallel amplification”)
- (b) Picking desired pulses and forming into pulse trains (divided pulse amplification, “DPA”)
- (c) Retaining high repetition rate from the source and temporally stacking at the output (“stack and dump”)

In terms of overall system design, the different schemes change the average power per channel and the total number of channels needed to reform the final pulse. (b) and (c) are designed to add temporal pulse recombination as well as spatial. (c) demands high temporal pulse to pulse stability of the source and is expected to operate best with a bulk optic femtosecond laser source.

The gain medium can be split into two functions. The first is to generate the channel number retaining the input pulse characteristics, and secondly to boost the final energy per pulse per channel. The options for the gain medium include fibre and rod based waveguide technologies, depending on the desired energy per pulse per channel. Higher pulse energies reduce the number of channels, as does operating with temporal recombination techniques, which increase the operating repetition rates and average powers through the gain medium and externally amplifies the energy per pulse.

Across all schemes, the number of channels may range from 500,000 to 500. Few channels increase the thermal load per channel, whereas the many thousand channel options have the lowest thermal load per channel. The choice of channel number

depends on finding limiting parametric performance of the gain medium and the limits of each pulse recombination technique. At this stage, the options are open. Currently, the gain mediums are under consideration over repetition rates of 15–10,000kHz, with 0.1mJ – 6mJ energy per pulse per channel. Achieving the highest energies per channel and highest average powers requires validation and detailed design.

Spatial recombination schemes include polarisation combining, use of diffractive optical elements and spatial recombining of either few channels, or many thousand channels. The many thousand channels is similar to that used in beam steering phased arrays and is referred to as a digital, or tiled recombination technique with phase matching between channels processed in parallel. For overall system design, the recombination scheme defines the spatial density and the relative positioning of the channels. For the tiling technique highest spatial density are needed, and the scheme is suited to fibre delivery from each channel to a termination block.

All schemes need active delay and phase control for each channel, with live feedback and monitoring from the recombined beam.

Temporal recombination allows the energy per pulse per channel to be amplified externally to the gain medium and operation of the gain medium at higher average power, to the limit of any thermo-mechanical design. The temporal recombination schemes are paired to the pulse organisation used and the operational limits are currently under investigation.

Finally the pulse compression uses bulk optic components and is linked in design to the stretch. The compression system is anticipated to need vacuum environment to accommodate high optical intensities at focal spots within the system. Thermal management of large area components within the vacuum chamber is a complexity to be managed.

The overall system concept is rich in configuration choices from the technologies under development. Mechanical, cost, reliability and manufacturing design may contribute to the final configuration choice.

Parallel Amplification

System design

The first element of this design consists in a frontend that delivers one beam that will be divided sequentially in several beams. After the frontend, beam division and energy scaling is first carried out using single mode fiber all-integrated components. The repetition rate is decreased in two steps along the chain in order to keep the average power level high enough to limit amplified spontaneous emission and minimize nonlinear effects before the final power amplifier. The single mode fiber-based division stages are operated at hundreds of kHz, while the final power amplifiers work at the final repetition rate of 10 – 50 kHz. These power amplifiers are inserted in each of the arms to reach the final desired energy per channel.

The frontend (first line of fig. 1) is composed of a femtosecond oscillator operating at a repetition rate of e. g. 40 MHz, delivering femtosecond pulses in the 100 fs – 200 fs range. The pulses are stretched in time to a duration greater than 4 ns using a grating-based stretcher. Since the pulse duration at the output of the laser must be minimized, a spectral phase and intensity pulse shaper consisting of a zero dispersion line including a

controllable spatial phase should be inserted in the frontend. Then, the pulses are amplified, pulse picked to decrease the repetition rate by a factor of e.g. 100 (400 kHz) by a first acousto-optic pulse picker. Additional isolated preamplifiers are used to increase the power to 200 mW. This number will be the reference for the output power of a single mode amplifier, and is related to the currently available single mode pump diode power of 500 - 700 mW.

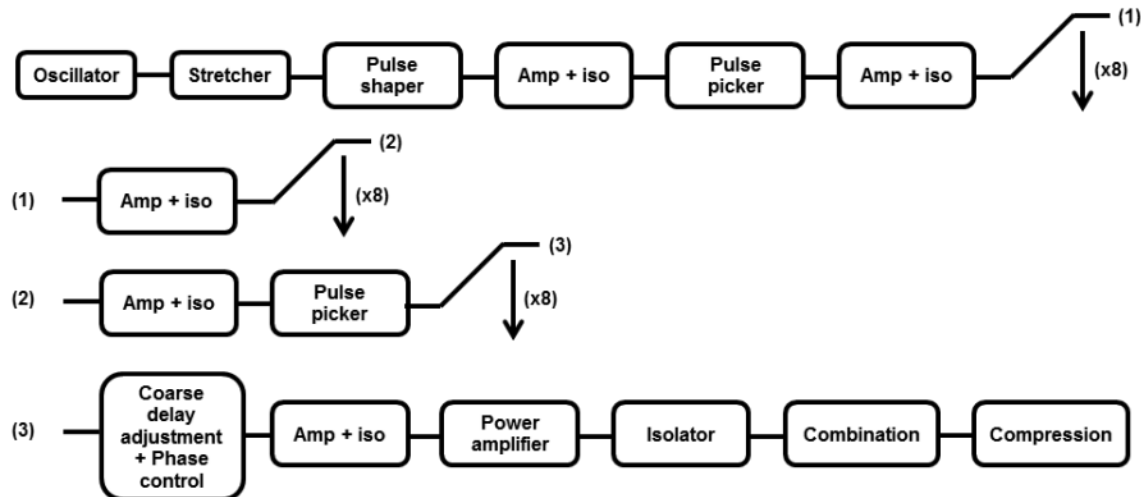


Figure 6 - Envisioned laser architecture

A number of divisions are then carried out using all-integrated single mode fiber components. As an example, Figure 6 shows three consecutive divisions in 8 beams, thereby generating 512 beams at the output. An additional step could be carried to generate 4096 beams. Divisions are made using fiber integrated star couplers, and are followed by isolated fiber amplifiers that restore the average power per channel to 200 mW.

The final repetition rate of 10 kHz – 50 kHz is generated before the last division step by a pulse picker. The optical signals are then amplified to an average power level that keeps the nonlinearity low enough (e. g. 25 to 125 mW). A second pulse picker can further be used to clean the beams from any generated ASE just before the last star coupler. After the last division step, one last low gain single mode amplifier is used to restore the average power to 25 – 125 mW, in order to seed the power amplifier. This last single mode amplifier will possibly use shared single mode pump diodes since the output average power and the gain are low. A piezo fiber stretcher and a coarse delay adjustment are used in each beam to control the optical phase and/or the group delay in each arm to be coherently combined.

To minimize the number of channels to be combined, the power amplifier are designed at the state of the art in terms of output energy per pulse. For a stretched pulse duration of 4 ns, we extrapolate from the literature that a pulse energy of 4 mJ should be achievable in very large mode area (80 μm mode field diameter) rod type ytterbium doped fiber amplifier, corresponding to average power level in the range 40 W - 200 W. The efficiency of this last step essentially drives the laser efficiency of the whole system, since the average power is scaled by a factor of ~ 1000 at this point. Given the typical optical-to-optical efficiency of 70% for this type of femtosecond amplifier, the final

stages should be pumped by 50 W – 300 W diode systems, yielding a wall-plug efficiency for the laser around 30%. This number does not take into account cooling systems.

Risk evaluation

The risk associated to the front-end and single mode fiber-based division stages is quite low since it uses established telecom-grade components and technologies. The power amplifier, although at the current state of the art, presents a moderate risk. Indeed, these systems are probably less robust than single mode fiber based systems, but they are nevertheless already included in industrial lasers used in harsh environments on a day to day basis with low failure rates.

Parallel Amplification with Divided-Pulse Amplification

The system concept employing Divided-Pulse amplification uses a combination of spatially separated combination of amplifiers and Divided-Pulse amplification. The basic idea, closing the gap between achievable average power and pulse energy of a single amplifiers compared to the desired laser parameters, is also followed here. However, in this approach, unlike in the previous one, the number of temporal pulse replicas is reduced from a few hundred to 8. This makes it necessary to increase the fibre core-diameter, resulting in more pulse energy but less average power per amplifier.

DPA - System design

The basic system design is shown in Figure 7 - schematic setup of the system concept using DPA (including indicators for risk evaluation). The oscillator does not differ across all of the systems discussed. After the stretcher, the pulses are split up into multiple pulse replicas, thus increasing the effective stretched pulse duration from 4 ns to 32 ns. This makes it possible to increase the pulse energy coming from every amplifier by the same factor. However, because the number of the pulse replicas is a lot smaller than in the Stack and Dump system concept, this has to be compensated by using fibres with a larger core. In our case, a pulse energy of 47 mJ and average power of 700 W (15 kHz repetition rate) per amplifier is assumed. Again, the same fibre type is used for the pre-amplifiers and main amplifiers. To achieve the desired laser parameters, 1024 have to be coherently combined. Due to the high channel count, even with an N to 1 beam combiner (like a DOE), this will probably require a multi-stage cascaded combiner setup. With an assumed efficiency of 85%, this results in an average power of 600 kW and a pulse energy of 40 J. After compression, the final laser parameters are achieved.

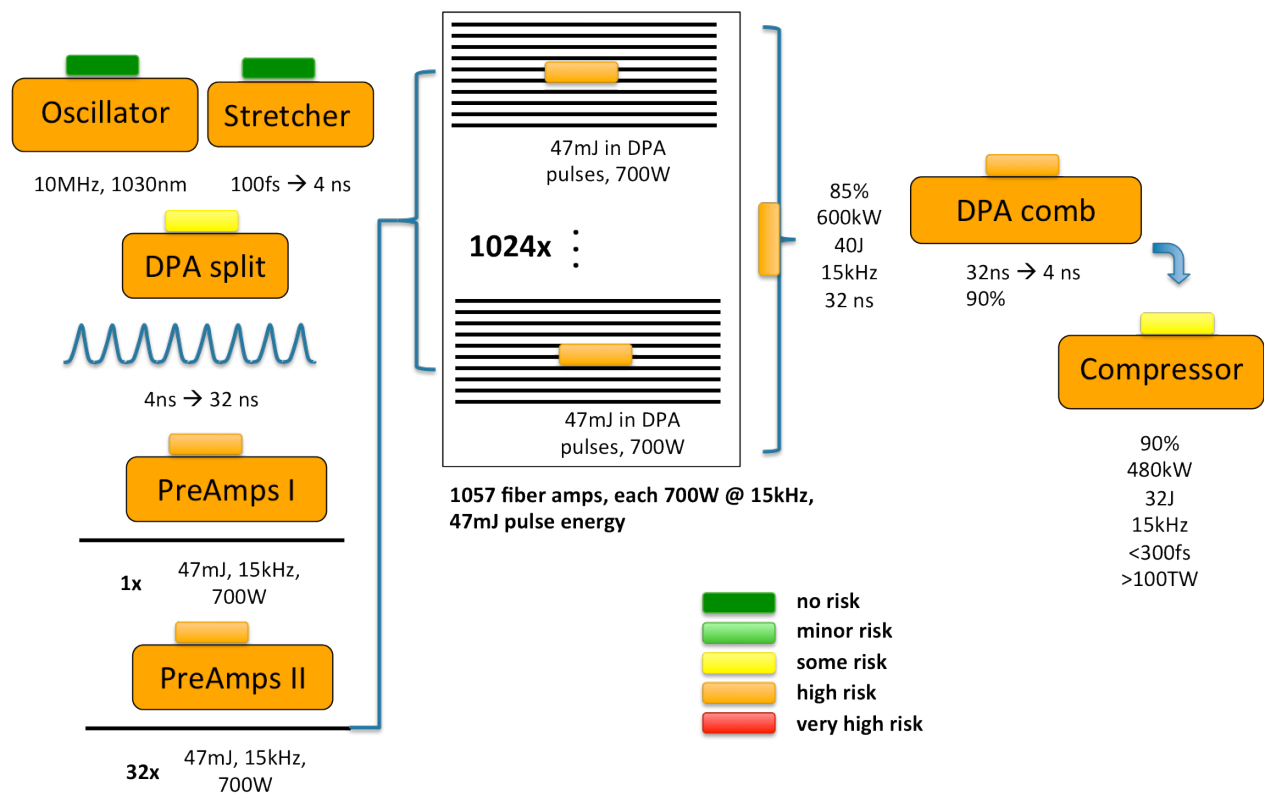


Figure 7 - schematic setup of the system concept using DPA (including indicators for risk evaluation)

Risk evaluation

The colour-coded risk indicators are shown in Figure 7. In the following table, they are described more in detail:

Table 2 - risk factors for DPA design

Component	Risk	Current status
Oscillator	None	Femtosecond oscillators with the required parameters are commercially available
Stretcher	None	Stretcher with the same parameters already used in multiple experiments
DPA split	Some	Creation of 4 pulse replicas demonstrated in multiple experiments
Fibres	High	830 W average power achieved for smaller cores in pulsed operation ¹⁶ , 26 mJ extracted from large-core fibre ¹⁷ .
Combination of 1024 fibres	High	Combination of 4 fibre amplifiers with stretched femtosecond pulses already demonstrated with a cascaded beamsplitter setup. For continuous wave operation, the combination of 15 fibres with a 2D DOE was published.
DPA combination	High	Combination of 4 pulses shown, but at average- and peak-powers magnitudes below the required values
Compressor	Some	Compressors for similar pulse energies exist in multiple Petawatt systems around the world. Average power handling

		needs to be investigated, but due to the availability of gratings with high efficiencies, thermal problems should play a minor role.
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Parallel Amplification and Stack and Dump

The stack and dump concept is based on the spatially separated combination of amplifiers in combination with the temporal combination of pulses within an enhancement cavity. The idea is based on the fact that the pulse energy gap from one fibre to the desired final laser parameters is a lot larger than the equivalent average power gap. Thus, the external cavity is used in order to close this discrepancy. Because of the high number of overlapped pulses in the cavity, fibres with smaller cores but higher average power are chosen in this design.

System design

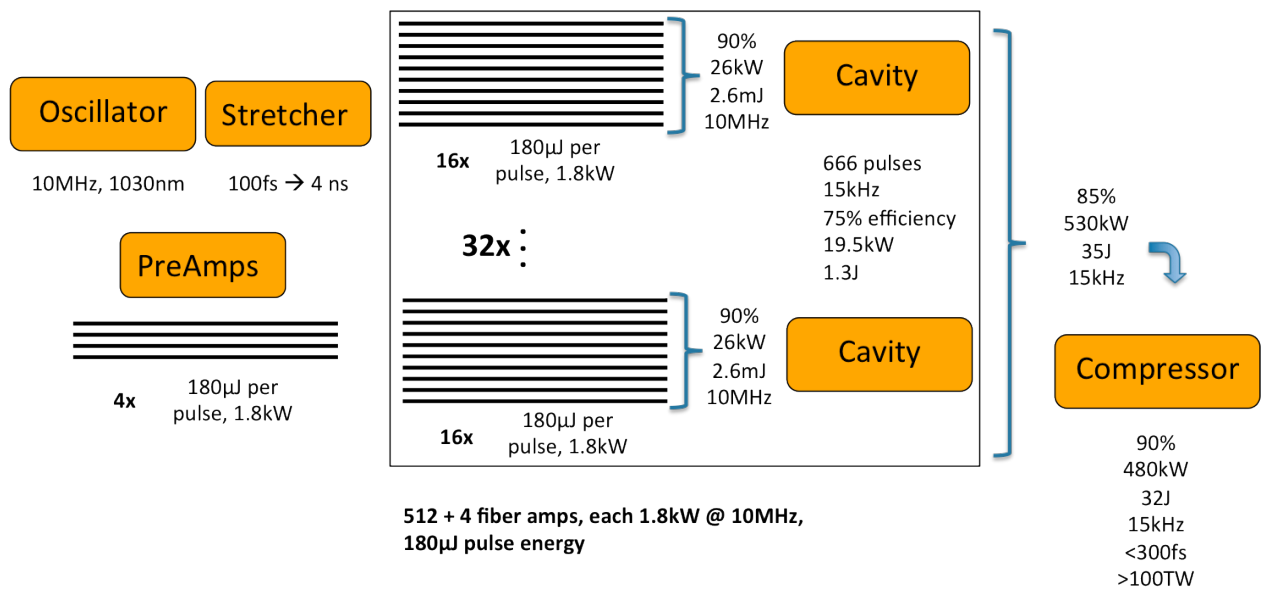


Figure 8 - system design with a combination of spatial separated amplification and external cavities

In Figure 8 **Error! Reference source not found.**, the basic stack and dump system design is shown. The pulses coming from an oscillator are stretched to the nanosecond regime and then split up into four branches for the preamplifiers. Each of them contains a fibre that is capable of generating 180 µJ pulses at an average power of 1.8 kW. The repetition is rate is set to a value of 10 MHz, and additional pulse pickers might be necessary (not shown in the figure) to reduce the fundamental repetition rate of the oscillator to this level. After pre-amplification, additional splits take place to seed 32 groups of 16 fibres. The same design and parameters are used as in the pre-amplifiers. In each groups, the output of the fibre amplifiers are combined into one beam. With an estimated efficiency of 90%, this corresponds to 26 kW power at 2.6 mJ pulse energy. The combined beam is then coupled into an enhancement cavity and designed for a repetition rate of 10 Mhz. The switching out of the cavity takes place after each 666 pulse. This reduces the repetition rate to 15 kHz and produces 1.3 J pulses (assumed efficiency 75 %). In the final step, the 32 beams coming from the 32 cavities are

combined. After compression (90% efficiency), the required parameters mentioned above are achieved.

Stack and Dump - risk evaluation

The proposed system contains a variety of different components and has high demands on many of them. However, most of the presented concepts are not completely new which simplifies the risk evaluation greatly.

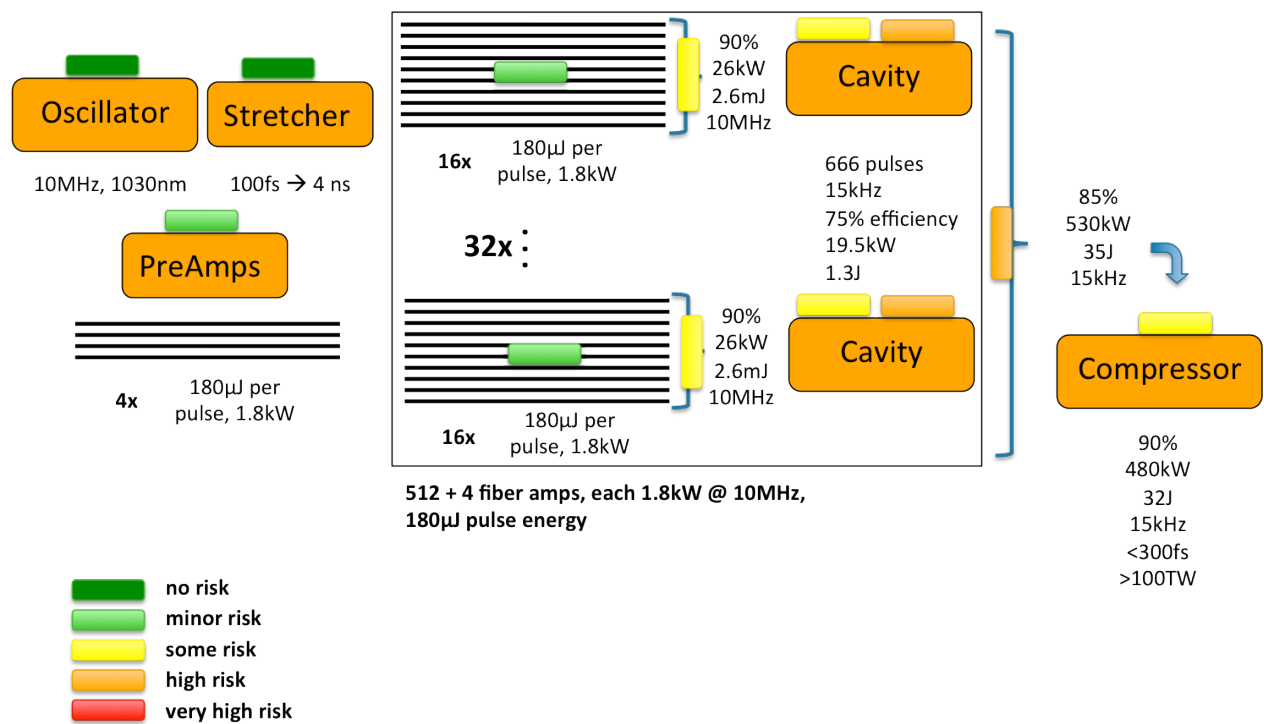


Figure 9 - risk evaluation of the stack and dump design

In Figure 9, the risks for the elements are shown with different colours. In the following table, they are described in a more detailed way and previous work on these issues is also presented:

Table 3 - risk factors for stack and dump design

Component	Risk	Current status
Oscillator	None	Femtosecond oscillators with the required parameters are commercially available
Stretcher	None	Stretcher with the same parameters already used in multiple experiments
Fibres	Minor	830 W average power achieved in pulsed operation ¹⁶ , multi kW in continuous wave operation.
Combination of 16 fibres in every group	Some	Combination of 4 fibre amplifiers with stretched femtosecond pulses already demonstrated with a cascaded beamsplitter setup. For continuous wave operation, the combination of 15 fibres with a 2D DOE was published.

Basic cavity enhancement	Some	Multiple kW average power in a cavity has already been shown ¹⁸ Pulse built-up in the stack and dump concept has to be investigated.
Cavity switch	High	Switches for the high average powers not yet tested. Multiple promising concepts exist.
Compressor	Some	Compressors for similar pulse energies exist in multiple Petawatt systems around the world. Average power handling needs to be investigated, but due to the availability of gratings with high efficiencies, thermal problems should play a minor role.

Beam combination

Coherent beam combining of fiber amplifiers provides an attractive mean of reaching high power laser by scaling up the available energy while keeping the intrinsic advantages of fibers like beam quality, reliability, robustness and compactness¹⁹. To reach the ultra-high peak power and high average power requirements for these applications, the coherent beam combining (CBC) of thousands of fiber amplifiers has to be envisaged.

Active phase locking, which is compatible with a large number of fibers, involves phase detection, calculation of the correction and compensation of the phase of each amplifier²⁰. In a far-field beam combination configuration, this technique brings additional beam forming capabilities, which can be useful to correct a wavefront distorted by a passage through atmosphere, or to address a receiver in free-space communication.^{21,22,23}

Well known phase detection methods include single-detector electronic-frequency tagging techniques,²⁴ heterodyne techniques,^{25,26} and stochastic parallel gradient descent (SPGD) algorithm phase control techniques²⁷. However, in these architectures, the complexity of the control loop (or the convergence time of the algorithm in the case of SPGD²⁸) increases with the number of fibers. To envisage the coherent combining of thousands of fiber amplifiers, a massively scalable phase measurement technique must be developed. An interferometric technique, based on the analysis of an interference pattern of the output beams recorded on a camera, performs a collective phase measurement of the beams from a single image²⁹. Interferometric methods are therefore promising candidates for very large channel counts applications. The largest reported number of combined fiber amplifiers uses this technique³⁰, but was limited to a few tens of Hz of sampling frequency due to the use of a low frame rate camera. Phase fluctuations caused by intrinsic perturbations of the fibre amplifiers and environment changes such as temperature or pressure have a bandwidth in the range of kHz²⁵.

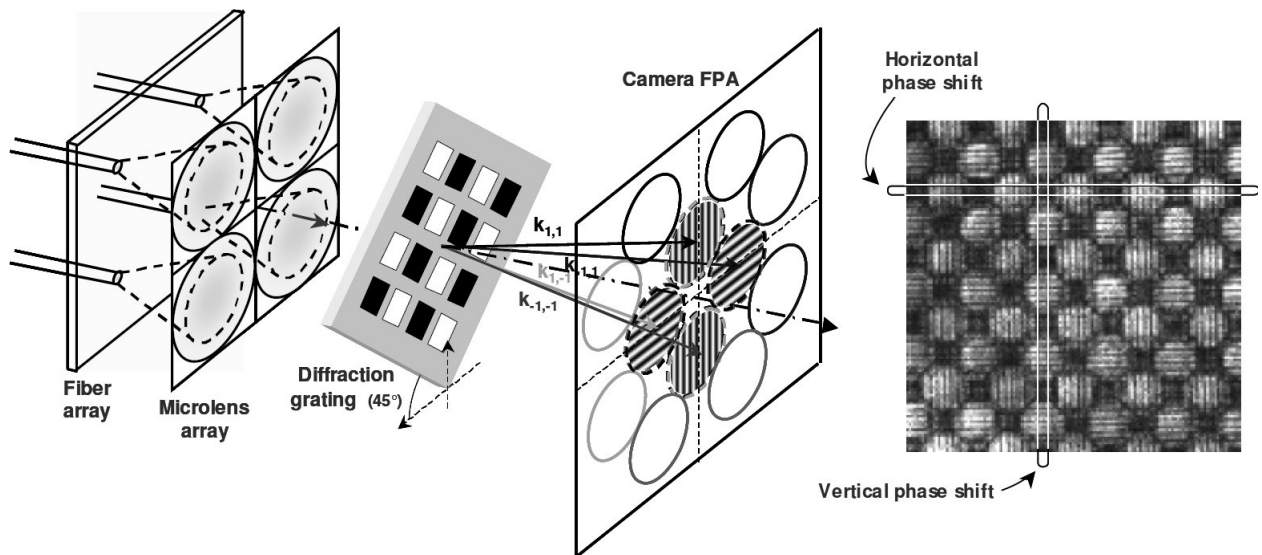


Figure 10 - Principle of the self-referenced wavefront analysis technique based on the QWLSI (on four beams in a square pattern). Right: part of an experimentally recorded interference pattern. FPA: focal plane array.

In the near field, the phase retrieval of the fibre array can be seen as the analysis of a complex segmented wavefront, which stems from the juxtaposition of subwavefronts. The Quadriwave Lateral Shearing Interferometer (QWLSI), based on a diffraction grating³¹, has proved to be an efficient self-referenced way to analyze a complex stepped wavefront^{32,33,34}. This concept has been adapted to the measurement of a periodic fibre array³⁵.

The fundamental principle is to produce interferences between four replicas of the wavefront from the square patterned beam array and to analyze the resultant interference pattern. No additional external reference wave is required. Thus, as shown in Figure 10, the incident wavefront from the collimated fibres is split into four tilted and laterally sheared replicas, thanks to a two-dimensional (2D) diffraction grating. The grating orientation is rotated by 45° with regard to the beam pattern axis, and the lateral shearing is chosen to ensure a perfect overlap between replicas of adjacent beams.

On each overlap area, we obtain a set of two-wave sinusoidal fringes, whose phase shift is in direct relation to the phase step between the considered subwavefronts. Areas with horizontal fringes lead to a measurement of the phase step between each beam and its nearest neighbour in the vertical direction, and vertical fringes give the same information in the horizontal direction. Hence, the camera records a pattern that contains sets of vertical and horizontal fringes representative of the step between the fibres in 2 directions without correlation, allowing the reconstruction of the whole segmented beam. This operation can be very fast, allowing the combination of high power fibre amplifiers with wide bandwidth. To address a hexagonal pattern, three replicas instead of four will be necessary, and the grating orientation toward pattern axis should be equal to 30° instead of 45° . This method can also be applied for pulsed regime. A two-colour version of this technique can be implemented to retrieve phase shifts higher than 2π .

Alternatively, it is also possible to use an extra reference beam to generate the interferences on the phase measurement camera, as shown in Figure 11. This approach permits further reduction of the required number of pixels per fiber. A master oscillator is divided into N polarization maintaining (PM) fibre amplifiers. In the so-called tiled

aperture configuration, the N fibres are arranged in an array and collimated in the near field of the laser output. The N beamlets then interfere constructively in the far field, and give a bright central lobe when all the beams are in phase. Active phase locking of the system involves phase distribution measurement, error signals calculation, and feedback corrections using phase modulators.

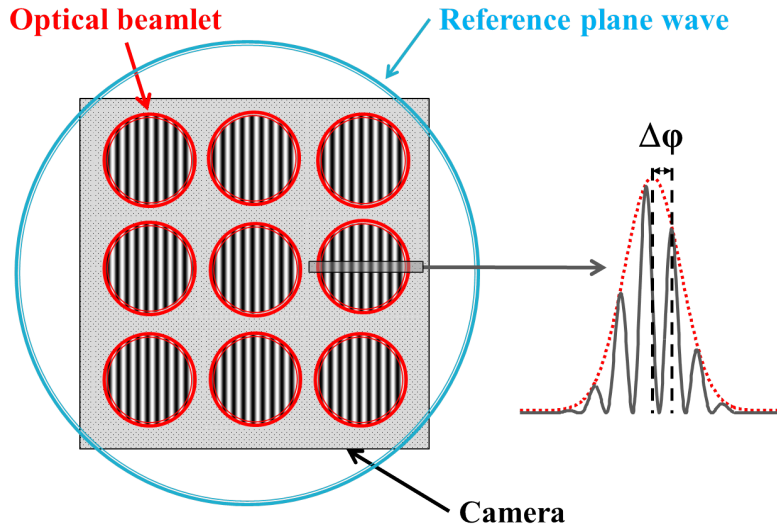


Figure 11 - Interferometric phase measurement principle. The phase shift between each fiber and the reference plane wave $\Delta\phi$ is directly derived from the position of the fringe pattern

Figure 11 shows typical fringe patterns, referred to as interlets, recorded on the camera. The position of the brilliant fringe of each interlet only depends on the phase shift, $\Delta\phi$, between the reference beam and each beamlet. The purpose of the servo-loop is to freeze the fringes positions in a configuration that gives the brightest far-field central lobe. Coherent combination of 16 amplified fibers using active phase control based on interferometric technique measurement with a sampling frequency of 1kHz has been achieved at Thales R&T. The phase shift error is $\lambda/60$ rms and the effective bandwidth of the loop is 450Hz.

The maximal number of combined fibers with this interferometric technique results from a trade-off between the number of camera pixels allocated per beamlet, and the number of pixels required for the fringe system analysis. Indeed, on one hand, the fewer pixels are used for one beamlet, the more fiber channels can be processed on a single image. On the other hand, more accurate sampling of the fringe pattern requires a minimum number of pixels. Figure 12 reports the residual phase shift error measured when the number of pixels per fibre is varied. The number of pixels per fibre is defined as the pitch between 2 fibres, and therefore includes the system near field fill factor. Each experimental point on Figure 12 corresponds to a different magnification in the imaging system of the measurement path. For each beamlet size, the number of pixels per fringe is then adjusted by changing the angle α between the reference plane wave and the beamlet. The experimental optimal number of pixels per fringe is obtained when the residual phase shift error is minimal.

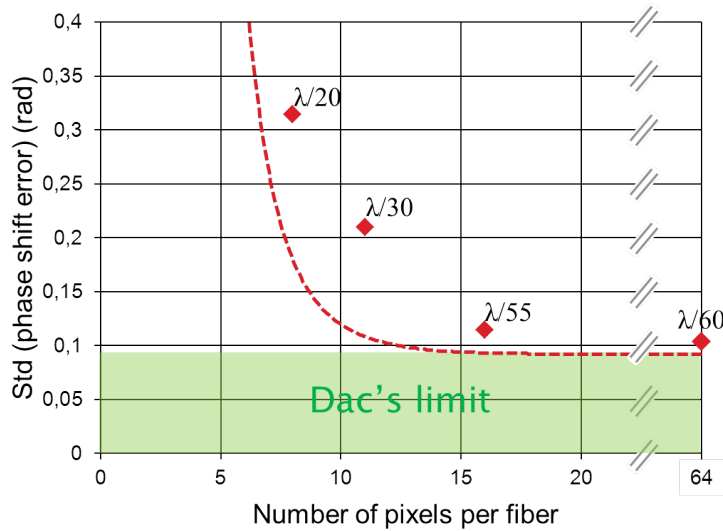


Figure 12 - Phase shift error measured for different number of pixels per fiber (red diamonds). Red dotted line shows the calculated residual phase shift error inserting our control loop noise characteristics.

A minimum of 8 pixels per fibre is needed to achieve a phase shift error of $\lambda/20$. Below 8 pixels, phase locking of our system was not achieved. Between 8 and 15 pixels per fibre, the phase shift error decreases as the number of pixels increases. Above 15 pixels per fibre, the phase shift error is clamped at $\lambda/60$. The limit of $\lambda/60$ comes from the phase corrector electronic limitations due to the analog converter and the phase modulators characteristics.

So we can now discuss the scalability of this interferometric system. Using a 1D camera we demonstrated that a line with a minimum of 8 pixels per fiber is sufficient to measure the phase error distribution and allow phase locking of the system with a residual error of $\lambda/20$. High speed 2D camera at $1.55\mu\text{m}$ are now becoming commercially available, and are already standard products at $1\mu\text{m}$, which is a usual wavelength for high energy pulsed CBC applications. A raw extrapolation of our results to 2D systems gives a minimum area of 8×8 pixels required for system operation. In this case, the coherent combining of 10,000 amplified fibres in a square of 100 by 100, necessary for a full-size ICAN system, would require a camera with a minimum of 800×800 pixels. Assuming equivalent noise properties of the control loop (including camera and modulator drivers), the closed loop phase shift error should still be $\lambda/20$. At 1kHz sampling frequency, we calculated that our algorithm performs about 5×10^5 operations per seconds per fiber. To control the phase distribution over all the 10,000 fibers, the algorithm should then operate 5Gops (Giga operations per seconds) which is still possible with a single Graphics Processing Unit (GPU). This interferometric technique can thus actively combine 10,000 fibers with conventional hardware, while reatining a good residual phase error and without any increase of the convergence time of the algorithm. This result shows that coherent combining of thousands of fiber amplifiers should be feasible with a megapixel camera.

Pulse characteristics

The output of an ICAN laser system will have different properties from those of conventional Ti:sapphire based petawatt systems. One key aspect is the digital nature of the laser – its beam is made up of the summation of $\sim 10,000$ (depending on design) separate lasers. This will influence the noise properties of the system, and also will enable some level of control of the laser via the phase feedback systems. Also, the

available bandwidth from Yb³⁺-based lasers will affect the eventual pulse length, and may require further pulse compression in some applications.

Noise properties

The reduction in beam combination efficiency produced by coherent beam combination of many noisy channels has been analysed by Siiman *et al.*³⁶. They have demonstrated that the effect of channel noise in phase and amplitude on the combination efficiency (in this case using a frequency tagging technique) shows saturation behaviour above about 100 channels – no further reduction in combination efficiency is seen on increasing channel number. The absolute reduction in this case is relatively small – efficiencies above 90% are predicted for small fluctuations.

The positive effect of combination of many channels is that noise in the beam profile and shot-to-shot variation both are decreased by the effect of combination of many channels. Traditional Ti:sapphire petawatt systems can have very large amplitude fluctuations across the beam, and significant shot to shot pulse energy variation. The nature of the ICAN systems means that both of these are much reduced, improving prospects for precise experiments using ICAN systems, which in turn may mean that constraints on the pulse energy necessary for many experiments are reduced.

Bandwidth

One of the major advantages that traditional Ti:sapphire laser have over Yb fibre lasers is the available gain bandwidth. In Ti:sapphire, amplified pulses of 30-40 fs are commonplace. For an Yb-fibre amplifier system, typical pulse widths reported can be as low as 170 fs³⁷, but for higher pulse energies, pulse durations in the region of 500 fs are more typical³⁸ for high average power, high pulse energy systems. Pulse compression of coherently combined femtosecond fibre laser pulse has been demonstrated down to 26 fs at average powers of 135W, using a hollow fibre compression system³⁹ - however, this is not practical on a system of very many fibres.

Increase of bandwidth may be possible by leveraging the multiple amplifier nature of the ICAN system. The design bandwidth of the amplifiers may be varied to give a broader total bandwidth, shortening the final pulse. This could potentially complicate the beam combination systems, but also might allow beam combination using diffractive optical elements or other wavelength-selective elements, where the wavelength difference between amplifiers could be beneficial. Recent experiments⁴⁰ have demonstrated significant shortening of the pulse from a high-power fibre amplifier using 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 19nm bandwidth with 10 W output power represents a significant step toward a solution of the problem of narrow bandwidth in Yb amplifiers.

Summary of laser concepts

Three different concepts are outlined which can achieve the target laser parameters. A straightforward parallel amplification (PA) concept and a combination of PA with either Divided-Pulse-Amplification (DPA) or Stack and Dump (SnD) Enhancement-Cavities. While the parallel amplification has the lowest risks due to medium technological challenges it also has the highest number of fibres and is hence the most expensive and least compact concept.

Parallel amplification combined with a Stack and Dump cavity offers the most compact setup at the lowest price but is also a novel technology and hence involves a higher risk. In between those two options PA combined with DPA can reduce the costs and volume significantly due to a lower count of fibres.

Costing – general comparison

Before discussing the details of cost for a large scale ICAN system that could replace conventional technology, it is important to compare its overall cost with the cost per watt of the other accelerator alternatives using conventional lasers or RF technology. Today, a state of the art PW laser system, delivering 40W average power would cost around $4 \times 10^7 \text{€}$, or 250,000€/W. We can estimate that a ICAN system delivering PW/pulse @10kHz could cost of the order of 400M€ for 400kW or 1000€ /W, which is far more economical than the previous alternative. This is very comparable to the cost per watt of an ILC (International Linear Collider) which is planned to be around $4 \times 10^9 \text{€}$ for the accelerator (tunnel not included) for a beam power of around 10MW leading to a cost per watt to around 400€/W. Table 4 gives a comparison of the costings, which although approximate, give a good idea of the scale of the different machines. We note that a PW-ICAN laser delivering 100kW would cost of the order of 100M€. Details of how the laser costings are calculated follow in a later section of the report.

Table 4 - comparative approximate costing for future RF and laser-based accelerators

Present day commercial petawatt laser	Cost of ILC (not including tunnel)	Estimated ICAN cost
1PW @ 1 Hz, 40W, 10M€	10MW, 4G€	1PW @ 10kHz, 400 kW, 400 M€
250 k€/Watt	400€/Watt	1k€/Watt

Costing - ICAN

The overall system costs of ICAN have been studied by both academic and industrial groups within the ICAN consortium. The main questions raised by the different potential system designs described above are:

- a) “Is there a balance point in cost between a large number of relatively simple telecom-type amplifiers compared to having fewer channels with more complex higher energy amplifiers?”
- b) “How do we compare the costs of the multiple technology proposals on a level footing?”

Starting with point (a): in the current cost model and system designs the overall system costs decrease with higher energy per pulse per channel, and with higher average power or repetition rate per channel. The cost is driven by channel number and the cost of per-channel power amplifiers and phase and delay controllers.

For the lowest energy per pulse designs with the highest channel numbers, the volume costs of the simple, low thermal load amplifiers decrease but within the current model the benefits are outweighed by the fixed cost of delay and phase control components and rising costs of single mode diodes. For a target cost of less than €250M, the combined cost of the energy amplifiers and the phase and delay components would need to be less than €800 per channel.

Increasing the energy per channel, the cost of the optical amplifier peak at around 0.5mJ energy per pulse per channel for the final stage of amplification; these cost peaks sit underneath the overall trend of decreased costs with higher pulse energy per channel.

Moving from 1 to 3-6mJ per pulse per channel, the system costs reduce to within the target of < 250M€. The questions arise of exactly the amplifier design in this range, its manufacturability, cost and fibre delivery. The channel number in each sub-unit may need to be reduced by thermo-mechanical design of the termination block and mechanical arrangement of the amplifiers around the head.

Overall, the costs of the low energy, high channel count systems are high, with some potential to reduce costs through design. The higher energy, lower channel count systems decrease significantly in cost. The presence of a balance point remains to be found and may emerge from reliability, thermo-mechanical design, manufacturability and parametric performance limits in practise.

Addressing point (b), a cost model has been developed that extends a flexible base design (“direct approach”) across pulse energy and repetition rate to connect with the proposals using DPA and pulse stacking. The designs are costed by functional piece part and the total channel number scaled by “sub units”.

The model focuses on the cost of the gain infrastructure. Within the amplifier cost, allowance is made for pulse energy, average power and pump type and pump costs. Two cost references are used for amplifiers, one that includes some allowance for the supporting system infrastructure, and the other from a contract manufacturer covering the cost of amplifier sub components only.

Extending the direct system to the highest energies of around 6mJ, the output of the gain medium per pulse becomes equivalent to the DPA proposal, albeit with 8x the channel number and 8x lower average power per channel. When recombined to 32J, the DPA proposal shows a 2-4x lower cost compared higher channel count direct approach.

The cost of the direct approach for a given average power reduces significantly with repetition rate, as additional pumps are added to the final amplifier stages and the channel count reduced to maintain the 480kW output power. At 60kHz, 8J, output, the direct design more than halves its cost compared to operating at 32J, 15kHz.

Further extending the direct model to 10MHz, the output from the gain medium becomes equivalent to that of the pulse stacking proposal. The gain infrastructure cost is broadly in-line between designs, with total cost of the direct approach being fractionally lower due to the use of a higher transmission efficiency through the recombination scheme and fractionally lower channel count. The gain infrastructure differs slightly between designs, with the pulse stacking using higher energy capacity components from an earlier stage.

At 10MHz, the pulse stacking approach allows rebuild of the pulse energy to 32J. Operating at the highest repetition rate and temporal recombination currently has the lowest projected cost for a 32J final pulse, although additional costs for the cavity systems will be incurred, and some technological risk in the switching schemes remains.

Comparing different component costs, the cost of the split networks are a small fraction of the total in all designs and could be interchanged should one technology be preferable.

The sources are costed as similar in all models; these differ slightly in average power, output pulse energy and frequency, so a fuller analysis may be needed, however the source is a small fraction of the total cost.

10ns pulse duration is attractive for all configurations; this significantly eases the cumulative B-integral, increasing effective optical path lengths by several multiples compared to a “few ns” pulse duration.

A challenge for all systems is overall mechanical design; for many thousand channels thermal management may be simpler but the number of piece parts and density of fibre channels is more challenging. For higher energies per channel, or higher repetition rate, compact thermo-mechanical design becomes the focus.

Overall, this simple cost model allows the technologies to be connected with some comparison across piece parts. Higher energies per pulse per channel and higher repetition rates decrease cost, and the final system will need to find the practical working limits of both for reliable manufacture, assembly and operation in the application.

These early conceptual designs focus on the power and energy requirements; spatial phase requirements and mode stability assessments will all add to the final design decisions and cost.

In terms of costs, this report provides a first step to cost evaluation across the rich choice of technologies for a smart flexible ICAN laser for high average power, high pulse energy applications. The system design and the cost model will be refined as technology limits are established in configuration of use.

4. Impact

The concept of ICAN is to take the broad range of new physics available from petawatt lasers and make it available for real-world processes, by increasing the average power available, and increasing the overall efficiency. A large number of applications become feasible with an ICAN laser. The impact of the ICAN project centres on taking these applications from lab to user. Some of the applications are predominantly science-based, for example the production of new compact accelerators and free electron lasers, or the search for dark matter. However, many applications have potentially huge societal impact, particular in areas that can be grouped under ‘nuclear photonics’. In this section, we will discuss the applications and give an overview of how they can be useful.

It is worth comment that most of the applications listed in this report are those which are new, and made accessible by the petawatt powers reached under ICAN. However, the ICAN design is intrinsically modular, with its large number of identical units making up the single beam. Thus the construction of smaller versions of ICAN, using fewer

lasers but providing very high peak and average powers will be useful in many industrial applications in materials processing – welding, cutting, etc. The use of femtosecond lasers in materials processing is beginning to become widespread, but is already limited by the availability of ideal sources. During its development, ICAN will produce demonstration systems at lower than petawatt peak powers which will be ideal for many other applications – for example, combination of a few hundred fibre lasers to produce high repetition rate, efficient terawatt-level sources. The design process will at all points consider how to retain this modularity in order to be able to construct different scales of laser source using the same basic sub-units.

Applications

The immediate applications for an ICAN source include:

- a. Laser wake field acceleration for:
 - i. Compact accelerators¹⁴
 - ii. Free electron lasers
- b. X-ray generation
- c. Nuclear Resonance Fluorescence imaging⁴¹
- d. $\gamma\gamma$ colliders for Higgs factories⁴²
- e. Accelerator-driven systems (ADS)⁴³
- f. Nuclear pharmacology⁴⁴
- g. Proton therapy⁴⁴
- h. Dark matter detection⁴⁵

These applications can be divided into groups based on their underlying physics mechanisms – LWFA is based around plasma wave generation; X-ray generation, NRF and $\gamma\gamma$ colliders are based on photon-electron scattering, and ADS, nuclear pharmacology, and proton therapy are based on relativistic ion acceleration. Each requires a different level of laser development, and each will represent steps along the way as the ICAN laser power increases.

Electron-photon scattering

Several examples of the interaction of electrons with photons have immediate applications for the ICAN laser: generation of X-rays via interaction of low energy electrons with high-intensity pulses, and also the combination of an electron beam and a high intensity photon source to produce γ radiation.

X-ray sources

For the last decade and a half, laser-driven X-ray sources have demonstrated the potential to replace conventional X-ray sources like X-ray tubes and synchrotrons. Laser-based sources often have more useful properties, being more compact, more coherent and faster. High harmonics emitted during the interaction of femtosecond laser with gas have produced⁴⁶ the shortest pulse duration ever, at about 70 as (1 as = 10^{-18} s). Also, they can exhibit full spatial coherence and diffraction-limited wavefronts around 30 nm. Both properties, spatial and temporal, open the way to many applications in metrology and coherent imaging. Soft x-ray lasers driven by intense visible laser pulses can produce very energetic X-ray pulses up to 10 mJ/pulse (to be compared to 1 μ J/pulse for high harmonic) and full coherence and diffraction-limited wavefront if seeded by high harmonic^{47,48}. Applications range from laboratory astrophysics to femto-magnetism, solid-state physics, biology and non-linear physics. X-ray sources driven by laser-accelerated electrons have shown very high photon energy

up to several 100 keV (betatron mechanism) with collimated beam and very high compactness as compared to synchrotrons^{49,50}. Several applications have been demonstrated, the most important being the phase-contrast imaging⁵¹ taking advantage of the micrometer source size (i.e. leading to μm resolution).

Currently, all these sources failed to emerge in the real market i.e. out of scientific demonstration, due to three major limitations, poor robustness, very low average power and weak efficiency, due to the old technology used for the laser drivers. ICAN has the capacity to unlock these three bottlenecks at once, leading to revolution in the development and use of laser-driven x-ray sources. The computer industry will benefit via actinic metrology and possibly mass-production with short-wavelength steppers, medicine will be dramatically changed with new 3D single-shot X-ray imaging techniques, and industrial X-ray radiography and tomography will become real possibilities.

Photon-electron beam interactions

The ICAN concept has reinvigorated the possibility of Higgs factories based on photon colliders. Producing Higgs particles by collisions between photons and electrons puts the lowest requirements on electron beam energy, and as such is an attractive option. It is proposed that the Tevatron tunnel at Fermilab could be re-used to provide the storage ring for such an electron-photon collider (HFiTT, “Higgs factory in the Tevatron tunnel”). Two counter-propagating beams collide with photons from two laser systems, and the resultant γ emission produces $\gamma\gamma$ collisions which can produce the Higgs particles. The target flux of Higgs for the Tevatron-based collider is $\sim 10\text{k}$ Higgs/year. A diagram of the proposed design is shown in Figure 14.

HFITT – Higgs Factory in Tevatron Tunnel

Goal: 10,000 Higgs/year

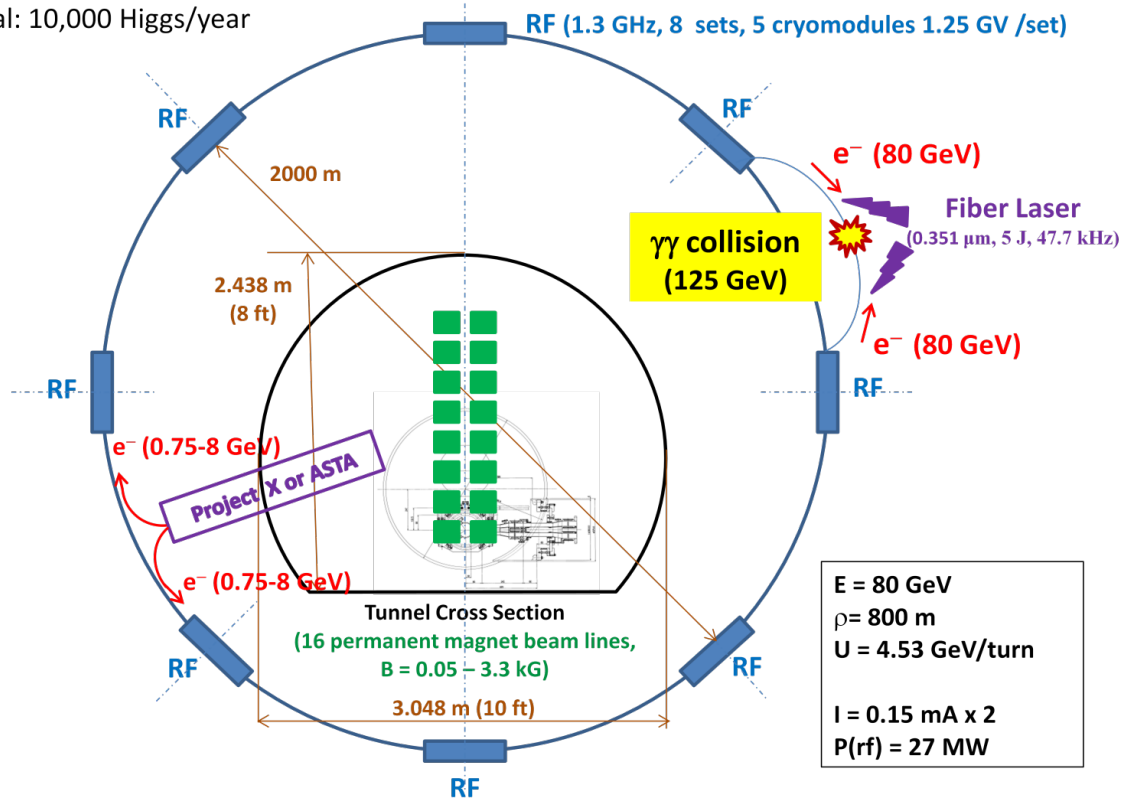


Figure 13 - The gamma-gamma collider "HFITT" based on the ICAN laser (from reference [42])

The laser requirement for a $\gamma\gamma$ collider is slightly different from that for a laser wake field accelerator – the peak power needed is lower, but the repetition rate is higher, and the wavelength is much shorter. In general, lower pulse energy and higher repetition rate is beneficial for fibre laser based systems, as the high peak power is more problematic than the high average power. According to reference 42, the laser specification needs to match the present accelerator repetition rate of 47.7kHz, at pulse energies of 5J – an average power of 240kW. Although still way beyond the reach of present laser systems, these parameters are within the design spec of the ICAN laser.

Electron acceleration

Acceleration of electrons and positron has been the initial inspiration for ICAN. Research in this area is developing rapidly with the availability of more petawatt laser systems, and since the first demonstration of monoenergetic beams^{7,8,9} in the mid-2000's, much progress has been made. Recently the first demonstration of two-stage acceleration⁵² has been achieved, which is critical to the construction of a multi-stage accelerator. Many details of the laser requirements for a large-scale accelerator have already been discussed, as they formed the original target for the ICAN project. The eventual construction of a multistage laser accelerator would require about 100 ICAN laser systems, pushing the industrial involvement to a very high level in order to manage the construction of such a large number of lasers. However, when looked at in the light of, for example, plans to construct the next generation very large hadron collider (vLHC), which may include a tunnel that is 80km long and extends underneath Lake Geneva, the construction of lasers on this scale is not insurmountable.

The effect on the laser market of constructing fibre lasers on this scale would make many other applications of electron beams much more affordable, as costs were driven down by large-scale manufacture. The production of few GeV electron beams for free-electron lasers would be well within the capacity of a single ICAN system – for comparison, the FLASH laser at DESY only uses 1.25 GeV electrons, and LCLS in the region of 10 GeV. Both systems have repetition rates that are low compared to that targeted by ICAN. Hence ICAN could provide a new generation of relatively cheap, compact FEL systems which could be much more widespread than the present few systems scattered across the world.

Ion Acceleration

High flux low-divergence proton beams accelerated to energies from a few tens to few hundreds MeV have numerous societal applications. Significant progress has recently been made in the production of low-divergence beams of MeV protons from the interaction of short high-intensity laser pulses with thin target foils in a single shot regime. The important issue remaining is to increase the number of high-energy protons and their energy. Multi-kHz repetition rate of ICAN provides a potential solution to this problem.

The main mechanism behind the highest energy protons (for ICAN parameters) is volumetric laser-plasma interaction where the foil thickness equals approximately the relativistic laser skin depth that provides increased electron heating, reduced transverse spreading of the hot electrons inside the target, and highest acceleration field. For such optimum thickness L_{opt} , current 3D PIC simulations demonstrate the efficiency in producing the maximum proton energy at the level ~ 10 MeV per 1 J of laser energy at the hundred-MeV scale of proton energy or even higher at the ten-MeV scale. This efficiency, which is derived for CH₂-foils can be somewhat increased for cryogenic pure H-targets. The higher hydrogen concentration, the more energetic protons appear. For the regime of volumetrically heated foils of optimum thickness PIC simulations predict that maximum proton energy scales as laser energy to the power 0.7 rather than a standard square root dependence.

The most severe limiting factor in experiments is the presence of weak laser pulse wings on a picosecond timescale, affecting the condition of target surviving prior to the arrival of the peak laser intensity. The thinner the target, the more sensitive it is to such non-ideality of the laser pulse. For a given peak laser intensity in the current experiments, the best target thickness is thus related to the laser temporal contrast rather than to the derived optimum thickness, L_{opt} , which is that to work for. Another limiting factor in laser based proton acceleration is a relatively small number of accelerated high-energy particles per shot. High temporal quality of the laser pulse and high repetition rate of ICAN will dramatically improve performance of laser triggered proton accelerator in terms of release from these limitations. The 30 J 10 kHz ICAN laser is able to produce up to 10^{14} protons per second in the 50 – 250 MeV energy range.

The laser requirements for relativistic ion acceleration using the RPA technique have been covered in section 3 of this document. They are typically several orders of magnitude higher than for electron acceleration, and as such will be challenging to meet even with present ICAN designs. However, the vast range of applications with huge societal benefits mean that this is a target that the ICAN consortium will aim at in the medium to long term.

Applications – medical & pharmaceutical

The application of ion beams in cancer therapy (external beam radiation therapy, or EBRT) is becoming more widespread, but is always limited by the scale of the accelerators needed to produce the ion beams. Compact, laser-based accelerators such as those possible using ICAN could make EBRT techniques more widely available. The ion beams can be more effective than more traditional chemotherapy because the beamlike nature of the source allows more precise delivery of the radiation dose, where chemotherapy usually depends on transport of the radiation within the body⁵³. The scattering dynamics of ions within the body allow precise delivery of the radiation in the region of the Bragg peak, enabling delivery to areas of tumours that may not be accessible by transport.

In particular, the availability of laser triggered high averaged flux beams of low-divergence protons with energies from 50 to 250 MeV and energy spread 1 – 5% promises innovation in particle beam therapy of cancer. Whereas laser accelerated carbon or oxygen ions, which meet the hadron therapy requirements, look like a more distant prospect for medical treatment, the laser-based proton source is likely to be developed in the course of ICAN project.

Significant progress has recently been made in the optimization simulations of low-divergence beams of ~ 200 MeV protons from the interaction of short high-intensity laser pulses with thin target foils. Based on the volumetric laser-plasma interaction scheme with semi-transparent foils, current 3D PIC simulations demonstrate reasonable efficiency in producing proton bunches with energy 200-300 MeV⁵⁴. The high temporal and spatial quality of the laser pulse, together with its high repetition rate will allow ICAN to serve as an effective source for protons with therapeutic energies. After selective collimation, energy selection (filtering), and focusing even for proton beams with broad energy spectra the number of protons with 200-300 MeV having ~ 2 -3% energy spread will dramatically decrease to $\sim 10^6$ protons per shot. However, due to high repetition rate ICAN laser is able to provide the required dose at the tumour. 3D simulations show that a therapeutic dose of ~ 100 Gy with 220 MeV protons can be delivered in few minutes with 30J 100 Hz laser. The therapeutic requirements come down to treat an eye tumor. In this case, simulations predict that 3J 100 Hz laser is enough to provide ~ 50 Gy dose by 50 MeV protons with 1% energy spread in one minute.

The key advantage of laser accelerators is their compactness. A laser accelerator can be naturally incorporated into the transport system, i.e. it need not involve a large number of magnets. In conventional accelerators, protons of 200 – 250 MeV need to be bent by magnets typically by 135 degrees. Unlike the conventional scheme, the laser accelerated protons can be generated much closer to the patient, so the typical bending angle would be a mere 10's of degrees. Whereas protons are bent by magnets, laser light is redirected in transport by mirrors. Dose control is naturally achieved with laser intensity and repetition rate change. All this should lower the cost of medical treatment. Thus, compact laser-based accelerators will make proton therapy more widely available.

The production of bright γ radiation can also be used for therapeutic applications, as the γ photons can be focused to induce photonuclear reactions, selectively generating new radioactive materials within the body at sites where their action can be short-range, and so effectively targeted. This is known as endoradiation therapy, as the radiation is

produced within the body rather than being introduced from outside. Many potential photonuclear reactions can be used for this therapeutic application, but common to all is the need for bright γ radiation.

Applications – Nuclear pharmacology

Protons and deuterons accelerated to energies at a few tens of MeV can be used for production of short lived isotopes for positron emission tomography (PET). For body-scanning applications in searching for tumour or metastatic disease the isotopes, such as ^{11}C , ^{13}N , ^{15}O , ^{18}F are in high demand these days. PET diagnostics is also essential to check brain function, diagnose heart problems and brain disorders, show areas in which there is poor blood flow to the heart, etc. In view of these diagnostics, the possibility to generate high-energy bunches of protons and deuterons with 10 kHz repetition rate is of paramount importance.

PET isotope production is conventionally accomplished with cyclotrons by bombardment of an appropriate target with protons or deuterons. Compact, laser-based accelerators such as those based on ICAN could make new laser techniques competitive to the conventional one, based on recent estimates from 3D PIC simulations⁵⁵.

Another important application for laser acceleration may be the production of isotopes such as $^{99\text{m}}\text{Te}$, which is used in Single Photon Emission Computed Tomography (SPECT) imaging. As compared to isotope production for PET, higher energy laser accelerated protons are required. Based on recent short episodes of worldwide Tc-99m generator shortage and some widely published worst-case scenarios for the long term availability of fission-based Mo-99, direct laser production of Tc-99m from the Mo-100(p,2n)Tc-99m reaction may well become a viable option. At present the main Tc-99m producer is Canada. For example, the reactor in Chalk River, Ont., produces 40 per cent of the supply of the raw materials needed to produce the isotopes. Chalk River produces the molybdenum-99. About half the North American supply of molybdenum-99, which decays into the technetium-99m isotope, is used in nuclear medicine procedures like diagnostic imaging and cancer treatments. The issue is that the era of nuclear reactors in the production of isotopes is over. The Chalk River reactor faces full shutdown in 2016. The process of developing medical technetium-99m isotope through a particle accelerator has been known for four decades, but not on a commercial scale. Non-reactor-based isotope supply is an attractive application for ICAN.

Applications – neutron sources

Protons accelerated to relativistic velocities can be used to produce neutrons via the spallation technique. Spallation can produce neutron as highly-energetic protons hit dense targets of, for example, lead. The heavy atom target will emit neutrons, which can be used for many scientific applications. Conventional proton accelerators are extremely large, and have all of the drawbacks of electron accelerators. The accelerator at the world's brightest spallation neutron source, at Oak Ridge National Labs, can accelerate protons to 1 GeV. Each proton produces 20 to 30 neutrons when it hits the target, which at Oak Ridge is a mercury reservoir. Spallation neutrons can be used for many scientific purposes, and creation of a compact spallation neutron source would be in itself a useful thing. However, the area of intense interest for this project is the use of spallation neutrons in the area of accelerator-driven systems (ADS) and in accelerator-driven reactors (ADR)

ADS are usually based around the combination of proton accelerator, a spallation neutron source, and a sub-critical nuclear reactor. The sub-critical reactor requires extra neutrons in order to maintain its reaction, as unlike a traditional nuclear reactor, the core not designed to sustain a chain reaction. Thus the progress of the reaction depends completely on the presence of the neutron beam from the spallation neutron source. If the neutron source is removed, by stopping the accelerator, the nuclear reaction cannot continue and stops. Thus an ADS is inherently much safer than a traditional critical reactor.

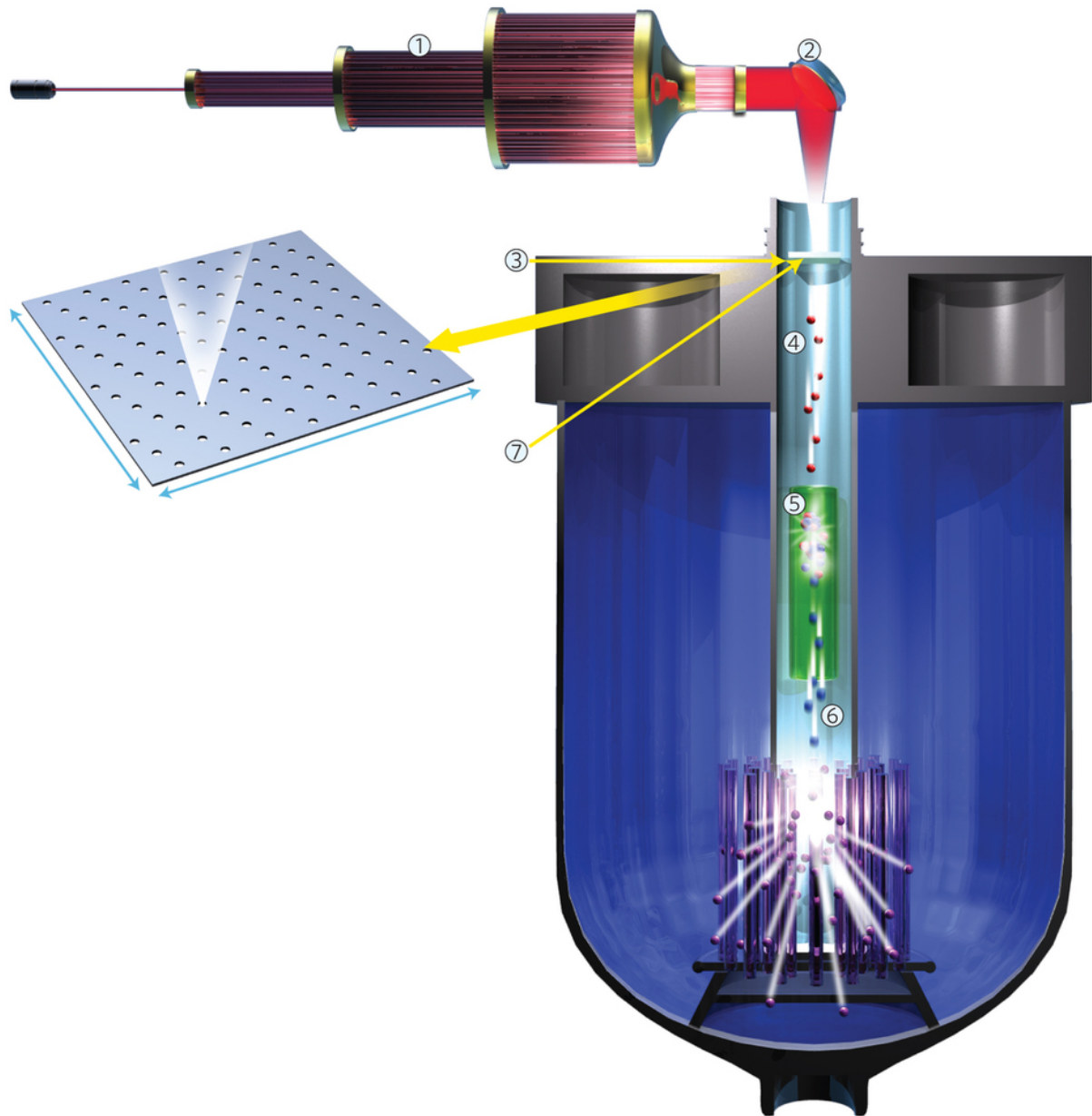


Figure 14 - schematic of laser-driven spallation neutron source for ADS (from reference 43)

At present, ADS relies on conventional technology, involving accelerators with a size that may exceed nuclear reactors. The ICAN system offers a path to more compact, more efficient and less costly proton accelerators that we could call LDT for Laser-Driven Transmutator (Figure 14). LDT would have the potential to make ADS commercially relevant.

Other applications: X-ray lithography

As the semiconductor industry moves to the next step of its roadmap⁵⁶, radiation at 13.5nm is necessary to reduce the size of features on chips below the present size of ~22nm. The major question is whether the EUV sources at 13.5 nm will be available and producing the appropriate level of power to make 13.5 nm (and later 6.X nm) lithography feasible. One approach to XUV generation is to use laser plasma sources, but the laser requirements are extreme. Although fs pulses would probably be unnecessary, the CAN concept is well-suited to producing the extreme lasers required, producing high repetition rate, high-energy pulses with average powers in the hundred kW regime, with high efficiency. The potential market for such a source is very large.

Applications – dark matter detection

While the gamma-gamma collider looks for the Higgs physics and other high-energy phenomena, copious coherent photons from the CAN lasers can provide a new opportunity to look for low energy dark fields such as Dark Matter (axion-like particles, for example) and Dark Energy⁵⁷. It has been shown that by using three distinct co-parallel lasers with huge photon numbers, one can look for sensitive detection of possible dark fields. This process is akin to degenerate four wave mixing (DFWM), well known in traditional nonlinear optics. Here we are probing the vacuum, whose possible nonlinear constituent is so weak that it looks ‘dark’ to us until now. Since the co-parallel injection of lasers can make the beat frequency of these lasers very low, the range of detectable masses is extremely low (down to neV) compared with any other high energy physics orthodox experiments. Also unusual is its extremely high equivalent luminosity; because of the coherence of these photons, the luminosity of the events is proportional to the triple products of three laser (1, 2, and 3) photon numbers, say $N_1 N_2 N_3$. If the laser has energy of 10kJ, $N_i (i=1\sim 3)$ is as large as the Avogadro number. On the other hand, the luminosity of the charged particle collider is proportional to $N_a N_b$, where a, b are species of particles such as electrons and positrons and typical $N_j (j = a, b)$ is on the order of 10^{10} . Thus the difference of these two products that determine the luminosity of each ‘collider’ is as much as by 50 orders of magnitude.

ICAN - connection to ELI

The Extreme light Infrastructure (ELI, <http://www.extreme-light-infrastructure.eu>), is a consortium effort to provide very high intensity laser sources as a pan-European infrastructure. It consists of four pillars: compact laser plasma accelerators (beamlines), Attosecond, Nuclear Physics, and Ultra High fields. ELI aims to work at the very limit of what is possible in laser intensity and time structure, and provide access to those extreme conditions to researchers across Europe.

ELI will use laser that will extend the performance of conventional petawatt laser technology to reach the extremes it envisages. The research areas covered by ELI will feed directly into ICAN projects, and provide critical information for developing applications. However, it is important to note that the applications that are opened up by research done using the lasers of ELI will in many cases only become commercially viable if a high average power source of petawatt pulses is constructed.

Communications between ICA and ELI are excellent – representatives of several pillars of ELI have attended and spoken at ICAN conferences and workshops, including the head of the Science Group for ELI-HU.

Industrial involvement

For the eventual construction of a full-scale ICAN laser system in the petawatt regime, the involvement of industry will be critical, because of the scale of manufacture necessary. ICAN is designed to take advantage of the cost savings implied by very large scale use of similar components. To this end, the ICAN consortium has made efforts to attract industry into the project at a very early stage, so that the design process can include manufacturability and other aspects such as quality control and reliability from the beginning. Representatives of 24 companies came to the workshops and conferences, including many of the major fibre laser and fibre component manufacturers in Europe. One of the major EU manufacturers of high power fibre lasers, Southampton Photonics Inc., has contributed significantly to the process of evaluating the realistic cost of an ICAN system based on industry costing techniques.

Beyond construction of the ICAN laser, applications in industry have actively been pursued by the consortium. Activities like semiconductor processing and X-ray generation are targets for ICAN as the technology develops.

Also important to consider is the impact of ICAN on the existing fibre and fibre laser industry. The scale of the project would require a significant expansion in the fibre laser industry in the EU. As an example of the scale of industrialization required, at present Southampton Photonics Inc. ships in excess of 5000 high power fibre laser systems per year. Thus even one ICAN installation would require the full output of a company the size of SPI over a period of several years. In practice it is likely that constructing ICAN will require major industry expansion, which will have many beneficial repercussions, including employment, and reduction of parts costs for future large laser projects.

Summary

The outcome of the ICAN project has been the crystallization of a design brief for an ICAN laser, based on optical fibre technology. Designs based on current and near-future technology have been proposed and costed, and the concept has been shown to be viable even with current technology. An enthusiastic and coherent community has been created who are at present working to raise funding for an ICAN demonstrator. Industrial input into the design brief from companies including Thales Research and Technology, ONERA, SPI Lasers Inc., and Amplitude Technologies has ensured that the designs are grounded in practicality, and the consideration of manufacturability early in the design process will ensure that the end product is robust and effective.

On the applications front, a large potential user base has already been established. Proposals for laser sources for a Higgs factory at Fermilab are under discussion, and CERN itself is very supportive of future ICAN development. What has become very clear during the project is that ICAN lasers are not just appropriate for laser wake field acceleration experiments. A host of applications both from within the particle physics community and also from many other areas of physics and technology will become viable with the development of ICAN. The ability to create high average power femtosecond laser systems that are modular and scalable will have widespread uses in many industrial applications where lasers are used in materials processing and manufacture. All of the applications, and the eventual success of ICAN, are based on the two key factors that the ICAN source provides – high average power, and high efficiency.

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