# Laser science and development

## Stable high-energy, high-repetition-rate, frequency doubling in a large aperture temperature-controlled LBO at 515 nm

**J.P. Phillips, S. Banerjee, K. Ertel, P. Mason. J. Smith, T. Butcher, M. De Vido. C. Edwards, C. Hernadez-Gomez, J. Collier** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

We report on frequency doubling of high-energy, high-repetition-rate ns pulses from a cryogenically gas cooled, multi-slab Yb:YAG laser system, using a type-I phase-matched lithium triborate (LBO) crystal. Pulse energy of 4.3 J was extracted at 515 nm for a fundamental input of 5.4 J at 10 Hz (54 W), corresponding to a conversion efficiency of 77%. However, during long-term operation, a significant reduction of efficiency (more than 25%) was observed owing to the phase mismatch arising due to the temperature-dependent refractive index change in the crystal. This forced frequent angle tuning of the crystal to recover the second-harmonic generation (SHG) energy. More than a five-fold improvement in energy stability of SHG was observed when the LBO crystal was mounted in an oven, and its temperature was controlled at 27°C. Stable frequency doubling with 0.8% rms energy variation was achieved at a higher input power of 74 W when the LBO temperature was controlled at 50°C.

*Reproduced from Phillips, Jonathan P. et al., Stable high-energy, high-repetition-rate, frequency doubling in a large aperture temperature-controlled LBO at 515 nm, Opt. Lett. 45, 2946-2949 (2020) ©2020 Optical Society of America, under the terms of the OSA Open Publishing Agreement. doi:10.1364/OL.383129*

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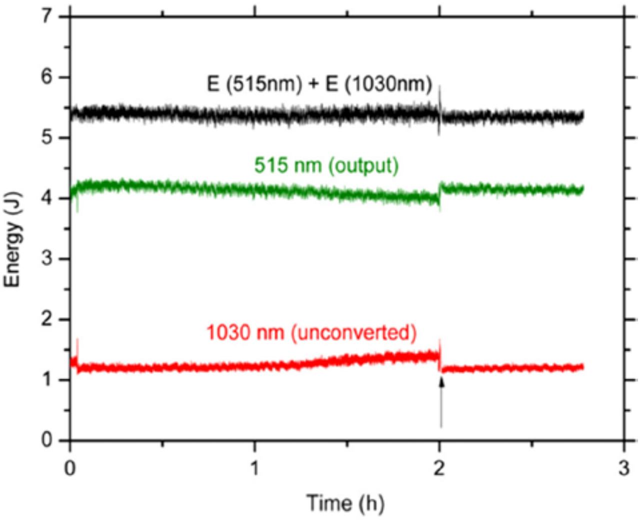
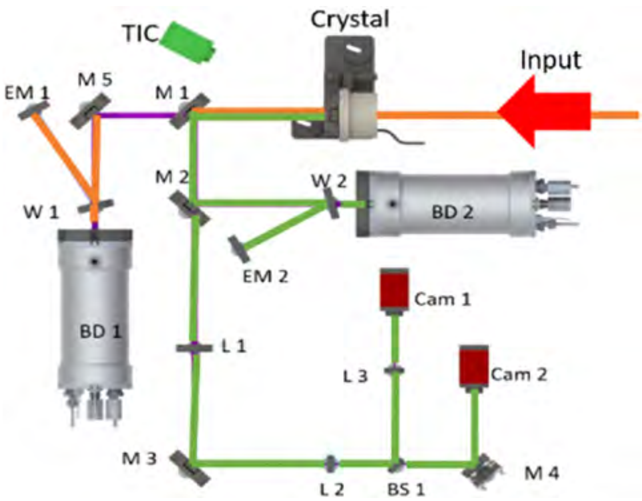
*Photographs of LBO crystal oven components. The photo on the left shows the spring-loaded metallic crystal holder with the crystal in place. This is placed inside the oven unit (the photo on the right). The oven is then connected to a separate temperature control unit.*



*Long-term energy stability of type-I SHG in LBO in an oven set to 27°C using a 1 cm$^2$ beam. Total input energy of 5.4 J (black line) and average power of 54 W, 515 nm energy 4.1 J (green line) and unconverted fundamental energy 1.1 J (red line).*



*Schematic of the experimental setup used for frequency doubling energy stability experiments.*

# Pushing the boundaries of diode-pumped solid-state lasers for high-energy applications

**S. Banerjee, P.D. Mason, P.J. Phillips, J.M. Smith, T.J. Butcher, J.L. Spear, M. De Vido, D. Clarke, K.G. Ertel, C. Hernandez-Gomez, C.B. Edwards, J.L. Collier** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

**G. Quinn** *(School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK)*

We report on the successful demonstration of a 150 J nanosecond pulsed cryogenic gas cooled, diode pumped multi-slab Yb:YAG laser operating at 1 Hz. To the best of our knowledge, this is the highest energy ever recorded for a diode-pumped laser system.

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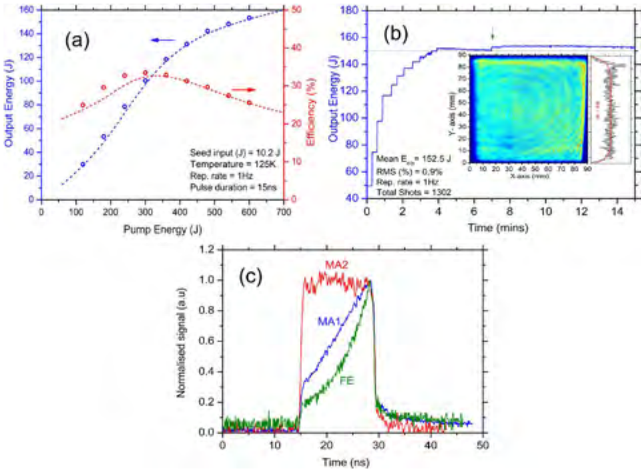

*Right: a) Output energetics, experimentally measured (circle) and numerically calculated (dotted lines); (b) long-term operation at 150 J, 1 Hz, and the inset shows the near-field profile at 150 J, 1 Hz operation; (c) temporal profile of the front end (FE), main-amplifier 1 (MA1) and main-amplifier 2 (MA2) during 150 J, 1 Hz operation.*

*Figure reproduced from Banerjee, S. et al. Pushing the boundaries of diode-pumped solid-state lasers for high-energy applications. High Power Laser Science and Engineering, 8, E20, under the terms of the Creative Commons Attribution 4.0 International License. doi:10.1017/hpl.2020.20*

# High-resolution absorption measurement at the zero phonon line of Yb:YAG between 80K and 300K

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**A. Wojtusiak** *(Loughborough University, UK; Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
**K.G. Ertel** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

We present measurements of the temperature dependence of the absorption cross-section of Yb:YAG at the zero phonon line (ZPL) near 969 nm. Experiments were carried out on a 1.08 mm thick, ceramic, 1.1 at-% Yb-doped YAG sample over a temperature range between 80 K and 300 K. Results show that the ZPL characteristics strongly depend on temperature. The absorption cross-section increases from 0.8 x $10^{-20}$ cm$^2$ to above 49 x $10^{-20}$ cm$^2$ as temperature is decreased from 300 K to 80 K. The full-width at half maximum of the absorption line decreases with temperature, from 2.38 nm at 300 K to 0.05 nm at 80 K. The absorption peak shifts from 969.04 nm at 300 K to 968.39 nm at 80 K. To the best of our knowledge, this is the first time that the ZPL of Yb:YAG has been characterised with enough resolution at cryogenic temperatures and we expect that this data will assist in the design and optimisation of Yb:YAG lasers pumped on this absorption line.

*Reproduced from M. De Vido, A. Wojtusiak, and K. Ertel, High-resolution absorption measurement at the zero phonon line of Yb:YAG between 80 K and 300 K, Opt. Mater. Express 10, 717-723 (2020), under the terms of the Creative Commons Attribution 4.0 International License. doi:10.1364/OME.386436*

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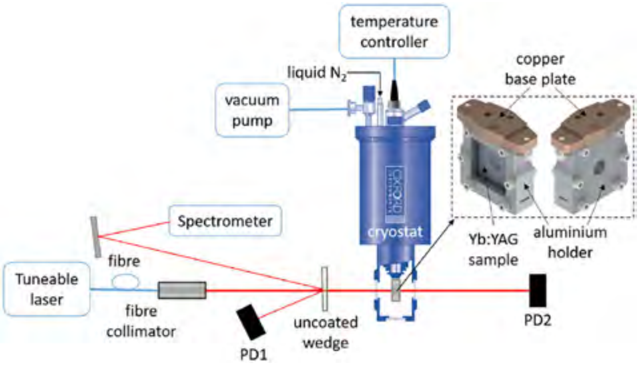
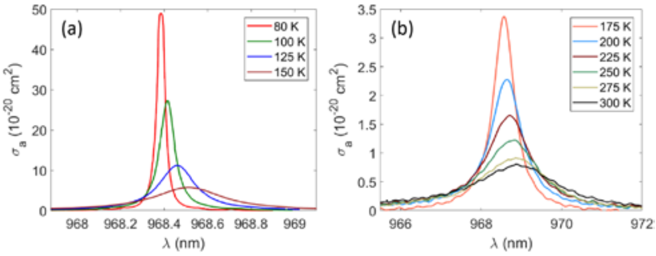


*Experimental setup used to characterise absorption at the ZPL of Yb:YAG (PD1, PD2 = photo-detectors). The insert shows frontal and rear views of the holder in which the Yb:YAG sample is mounted.*



*Absorption cross-section at the ZPL of Yb:YAG at temperatures between 80 K and 150 K (a) and between 175 K and 300 K (b).*

# Double rotating angled flanges for adjustable diagnostic pointing

**B. Matthews** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

It is relatively common for diagnostics and optics on high-power laser experiments to need to be mounted onto the outside of the target chamber at an angle. This is generally achieved by manufacturing a custom angled flange to hold the device at the correct angle. This practice is extremely wasteful, however, as these flanges are usually large, difficult to store, and only usable by a particular diagnostic at a specific angle (preventing them from being reused). It also limits the ability for users to adjust and fine-tune their setup. A new design of flange is presented, comprising two counter-rotating 'wedges' that allow for the angle of orientation of an attached diagnostic or optic to be continuously varied within a range.

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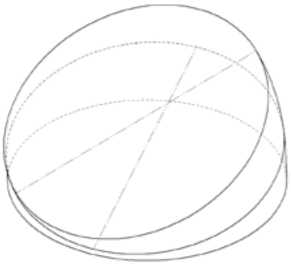
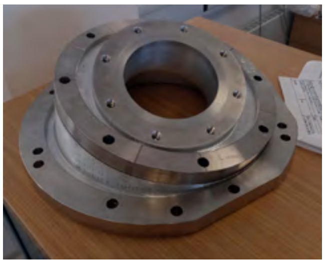




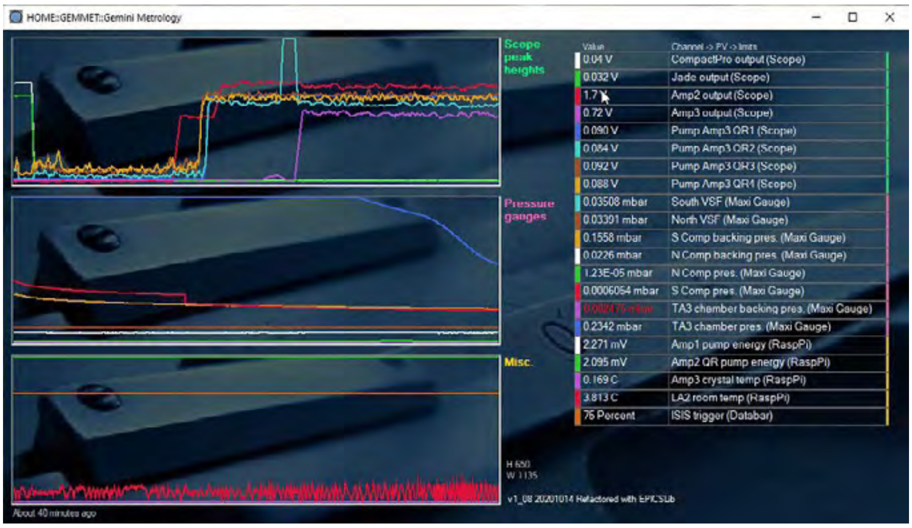
*Left: Schematic diagram of the operating principle of a double-rotating flange.*

*Right: The manufactured low-profile double-rotating flange.*

# Software developments in Gemini

**V.A. Marshall** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

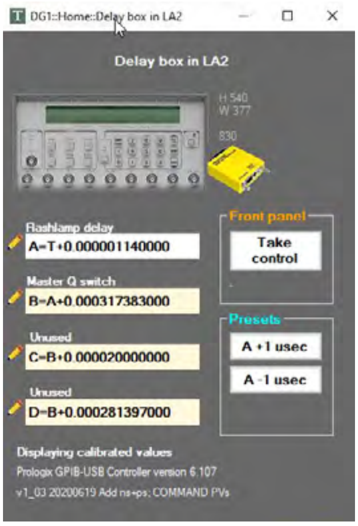
Over the last year there have been significant updates to the Gemini facility metrology system. The system is now based on EPICS, following the trend of other control and diagnostic software in the CLF, and monitors nearly a hundred parameters of the Gemini beam and its environment. There have also been improvements connected to remote operation of the facility, namely an application to adjust timings on a critical Stanford delay box, improvements to the interface of the main Control System to allow the operator to move the Amp3 beam-dumps, plus the installation of a webcam to check that they are indeed in the expected position.



| Value | Channel -> PV -> limits |
|---|---|
| 0.04 V | CompactPro output (Scope) |
| 0.032 V | Jade output (Scope) |
| 1.7 V | Amp2 output (Scope) |
| 0.72 V | Amp3 output (Scope) |
| 0.090 V | Pump Amp3 QR1 (Scope) |
| 0.084 V | Pump Amp3 QR2 (Scope) |
| 0.092 V | Pump Amp3 QR3 (Scope) |
| 0.088 V | Pump Amp3 QR4 (Scope) |
| 0.03508 mbar | South VSF (Maxi Gauge) |
| 0.03391 mbar | North VSF (Maxi Gauge) |
| 0.1558 mbar | S Comp backing pres. (Maxi Gauge) |
| 0.0226 mbar | N Comp backing pres. (Maxi Gauge) |
| 1.23E-05 mbar | N Comp pres. (Maxi Gauge) |
| 0.0006054 mbar | S Comp pres. (Maxi Gauge) |
| 0.002475 mbar | TA3 chamber backing pres. (Maxi Gauge) |
| 0.2342 mbar | TA3 chamber pres. (Maxi Gauge) |
| 2.271 mV | Amp1 pump energy (RaspPi) |
| 2.095 mV | Amp2 QR pump energy (RaspPi) |
| 0.169 C | Amp3 crystal temp (RaspPi) |
| 3.813 C | LA2 room temp (RaspPi) |
| 76 Percent | ISIS trigger (Databar) |

v1_08 20201014 Refactored with EPICSLib

*The Gemini Metrology application (formerly Mon&Cont). There was a spike on Amp3 output as the system was brought up, the TA3 Target Chamber is being pumped-down, and the ISIS trigger is holding steady.*



Flashlamp delay: A=T+0.000001140000

Master Q switch: B=A+0.000317383000

Unused: C=B+0.000020000000

Unused: D=B+0.000281397000

Displaying calibrated values

Prologix GPIB-USB Controller version 6.107

v1_03 20200619 Add ns+ps; COMMAND PVs

*Screenshot of the DG535 control software showing the settings of the four channels (only two of which are in use), preset timing adjustment buttons, and physical control override button.*

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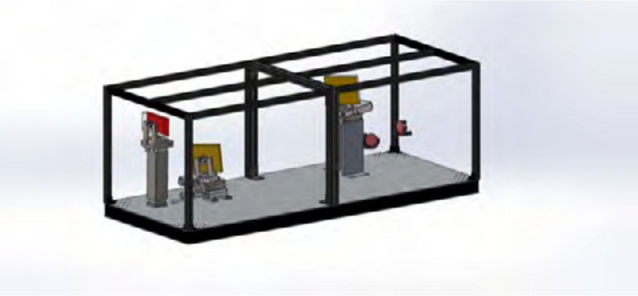
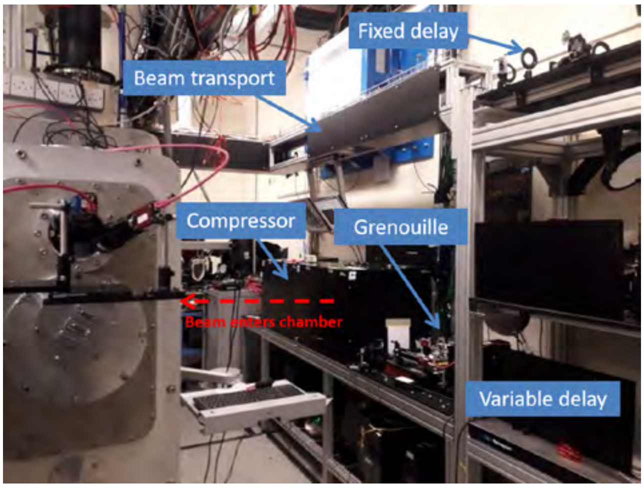
# Installation of an independent probe beamline in Gemini TA3

**M.M. Alderton** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; School of Physics, University of Bristol, UK)*
**B.B. Boyde** *(Department of Physics, Imperial College London, UK)*
**N.C. Bourgeois, S.J.D. Dann, S.J. Hawkes, E. Raptodimos, D.R. Symes** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

A third beamline has been introduced to Gemini Target Area 3, to provide a short-pulse probe beam independently of the two main beams. The beam is derived from a leakage of the Gemini North beam after the fourth amplifier in LA3, and is compressed in the target area using a commercial compressor. This probe is designed to deliver up to 15 mJ in a pulse length < 50 fs with 25 mm beam diameter. Preliminary alignment of the probe compressor achieved a sub-100 fs duration that has been used for several user experiments.



*Design drawing of Crunch Technologies quadruple pass compressor installed in TA3 to provide a short-pulse independent probe beam.*



*Photograph showing the location of the probe beam within Target Area 3. The beam is transported in an overhead gantry to fixed and variable delay lines. It passes through the compressor and is directed into the vacuum chamber from the East side.*

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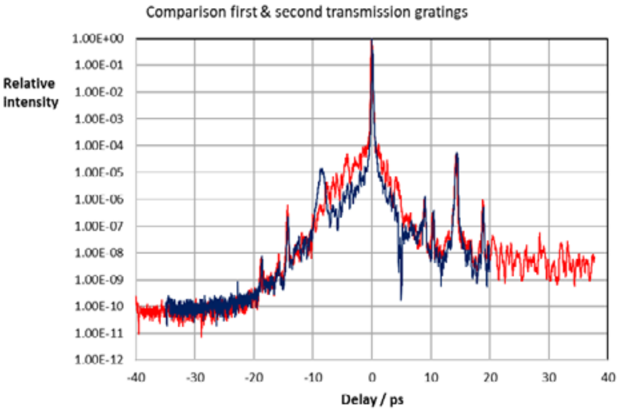
# Replacement of the transmission grating in the Gemini pulse stretcher

**C.J. Hooker, Y. Tang** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Precision measurements of the surface profiles of diffraction gratings used in the pulse stretcher of the Gemini laser facility have been analysed. Detailed modelling showed that the surface roughness of a reflection grating, and refractive index non-uniformities in the substrate of a transmission grating, both introduced spectral phase noise into the pulse. This leads to a reduction of contrast ahead of the compressed pulse, known as the pedestal, which can potentially cause problems with experiments. The existing transmission grating was replaced in 2020 with a new grating, fabricated on a higher grade of fused silica with 5x lower inhomogeneity. Contrast scans of the compressed pulse following the change show a tenfold reduction in intensity of the pedestal near the main pulse. The pulse duration is also slightly shorter than before, which is believed to be due to greater uniformity in the grating groove structure resulting from improved fabrication techniques.



*Comparison of Sequoia scans taken with the original transmission grating (red) and the new grating (blue). The level of the pedestal just before the main pulse is almost a factor of 10 lower with the new grating. The origin of the broad pre-pulse at -8.8 ps has not yet been identified.*

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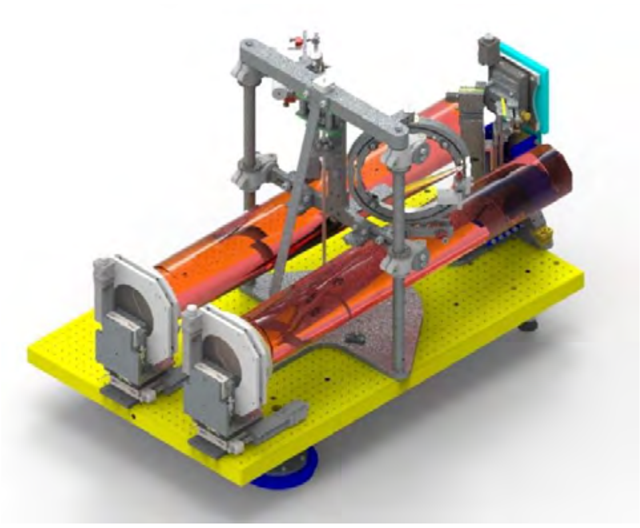
# Redesign of Gemini double plasma mirror system

**T.W.J. Dzelzainis, D. Treverrow, K. Fowell, B. Matthews, Y. Katzir, M. Alderton** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Since the original plasma mirror system was installed in the Gemini target chamber in 2008, there have been many changes to the layout and modes of operation. The use of support frameworks and extension chambers now allows more efficient use of the space, which prompted a redesign of the plasma mirror system. The new layout is horizontal rather than vertical, and fits on a breadboard in a standard TA3 extension chamber. This allows more flexible use of alignment devices, and provides options for future upgrades. The parabolas are mounted on translation stages for focusing, with manual adjustment in the other axes. The plasma mirrors are mounted on a common vertical stage with separate horizontal stages to allow for rastering and independent selection of the spot sizes on each substrate. New debris shields have been designed with rotation and translation adjustments for accurate positioning, and kinematic mounts to allow easy replacement.

Contact: T.W.J. Dzelzainis (thomas.dzelzainis@stfc.ac.uk)



*CAD render of the new Gemini plasma mirror system, shown mounted on a standard extension chamber breadboard.*

# Characterisation of duration-tuneable heavily-chirped pulses from the Gemini beamline using a streak camera

**T. de Faria Pinto, M. Notley, S. Hawkes, R. Clarke** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

In this paper, we report on a recent experiment where a streak camera was used to characterise long pulses from the Gemini beamline, creating a calibration curve between pulse duration and grating position. Using this calibration, the experimental scientists could easily change the pulse duration in a reproducible way between 20 ps and 39 ps, using only automated translation stages, with minimal impact on compressor alignment.

We evaluated the lower limit of operation of the streak camera by measuring a compressed 45 fs pulse, which was measured as having a duration of 7.2 ps. While a more thorough characterisation is needed for the streak camera to be used accurately for pulses of similar duration, this value can be used as an indicator for the suitability of this diagnostic for future experiments.

The timing jitter of the trigger signal was measured to be 165 ps over a period of 12 minutes.

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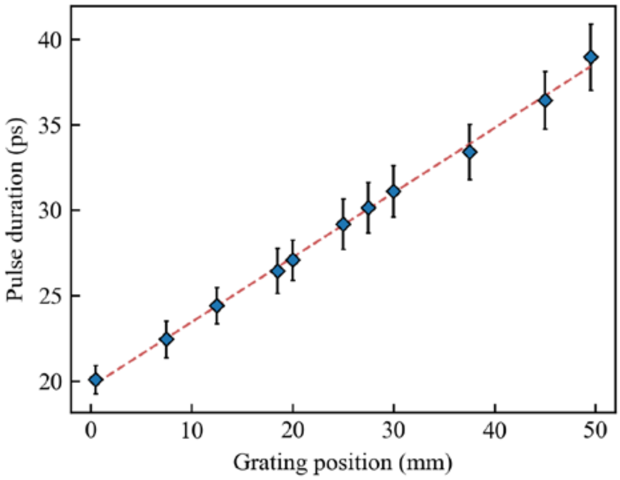

*Pulse duration calibration curve, ranging from 20 ps to 38.9 ps, used by the experimental scientists to set a desired pulse duration using the G2 automated stage position.*

## Upgrading the kHz pump laser for the Gemini front-end

**Y. Tang, T. de Faria Pinto, S. Hawkes** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

After many years of operation, the kHz Jade 2 pump laser in the front end of the Gemini facility has been replaced with a modern Ascend 40 laser. The Ascend is an industrial diode-pumped solid-state Q-switched laser manufactured by Spectra-Physics, which can deliver more than 25 W of average output power at a wavelength of 527 nm and a repetition rate of 1 kHz. The kHz pre-amplifier was also given a full service and re-optimised. The average output of the amplifier increased by a factor of 2.2x, the shot-to-shot stability was greatly improved and a high-amplitude slow drift with a period of ~200 s is no longer present. Overall, the RMS stability of the system improved from 19 % to 0.9%. This has led to a reduction in pump power required for the early amplifiers, and better stability throughout the amplifier chain.

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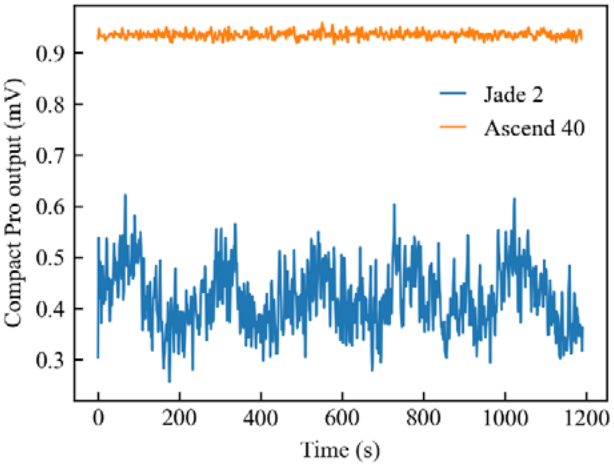

*Stability measurement of the FemtoPower Compact Pro output before (blue) and after (orange) the pump laser upgrade and system maintenance.*

## Development of low-density sine wave targets for high-power laser experiments

**P. Ariyathilaka** *(Scitech Precision Ltd, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

**C. Spindloe, A. Hughes** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Methods are described for the production of a low-density foam target incorporating a sine-wave textured, brominated plastic disk. The targets were used in high power laser experiments to study Rayleigh-Taylor instabilities. Modifications to production processes giving target quality improvements are discussed.

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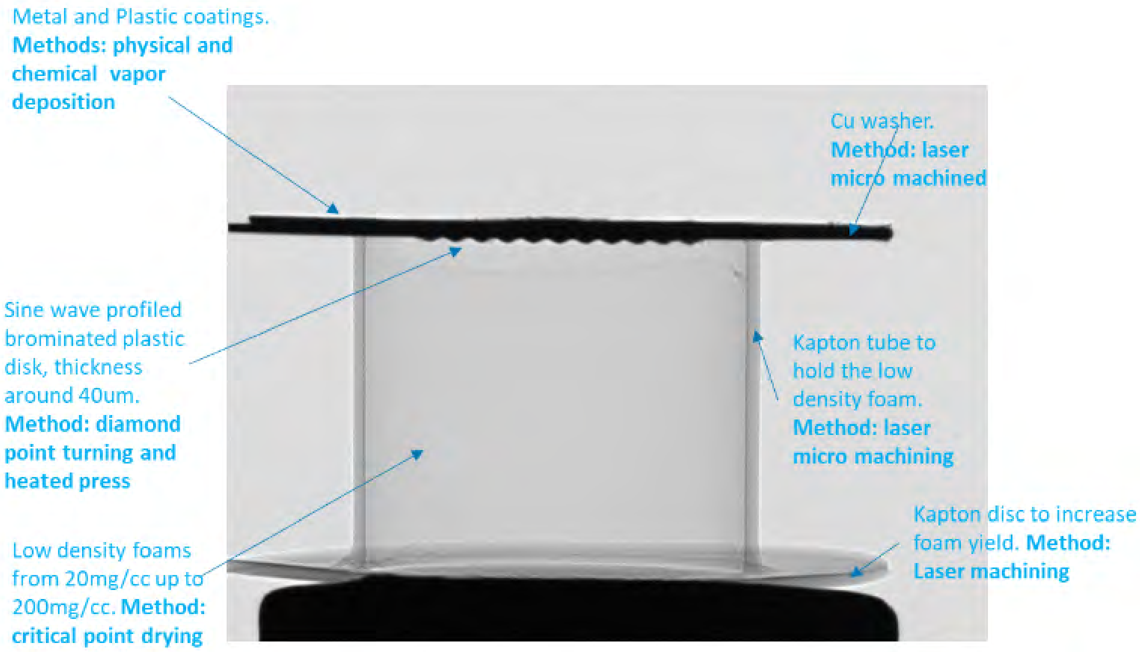
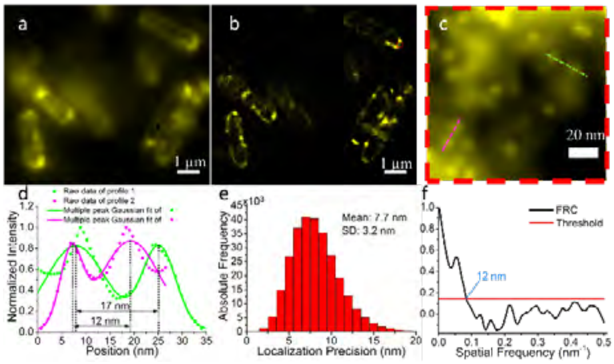


*Computer tomography (CT) image of sine-wave target showing major components.*

# Super-resolution cryogenic correlative light and electron microscopy reveals protein organisation in the context of intact cellular ultrastructure

**L. Wang, B. Bateman, L.C. Zanetti-Domingues, M.L. Martin-Fernandez** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

To understand how cells work, we need elucidate how proteins interact inside cellular ultrastructure. Super-resolution microscopy, e.g. stochastic optical reconstruction microscopy (STORM), underpins our understanding of interacting molecular networks in cells at the resolution of dozens of nanometres. However, to ascertain protein structure and function relationship, cryogenic correlative light and electron microscopy (cryo-CLEM) is highly sought after because it combines the functional information from molecular tagging in light microscopy with the intact ultrastructure information in electron microscopy. The challenge is the discrepancy in resolving power and imaging volume between cryo-EM and conventional cryo-FM. To address this challenge, we developed cryogenic STORM (cryo-STORM) to achieve sub-10 nm localization precision, and 3D Double Helix STORM with extended imaging volume to a few microns in a single shot. We are developing super-resolution cryo-CLEM workflow, aiming at unravelling the structure-function relationship of proteins and their partners throughout the cells with unprecedented precision.



*Cryo-STORM of Escherichia coli cells. (a) Wide-field and (b) STORM image of a field of cells. (c) The enlarged image of the region of the cell indicated by the red dashed border box in (b). (d) Line profiles of the cross-section of two adjacent single molecules. (e) Localization precision histogram. (f) FRC curve.*

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# Improving signal to noise ratios for transient absorption spectroscopy using an alternative referencing method

**A. Edmeades, G.M. Greetham, M. Towrie, P.M. Donaldson** *(Central Laser Facility,STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Improvements to signal-to-noise ratios in transient spectroscopies have been enabled by recently published schemes for better calculation of laser noise from reference measurements. In this article we describe the principles of these schemes and show them implemented on the CLF-Ultra transient spectrometers.

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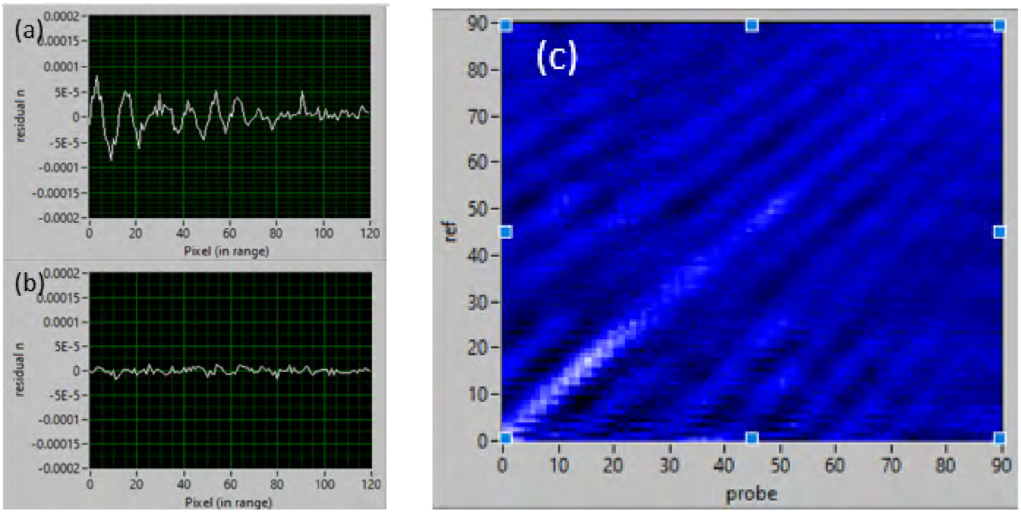


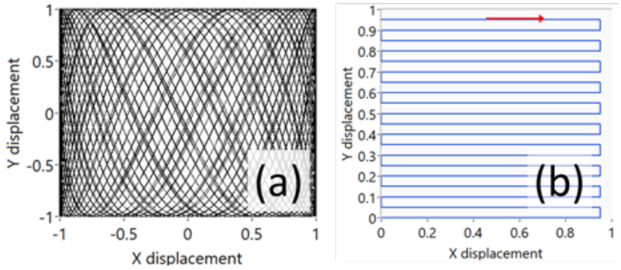
*Pump on–off difference spectrum dispersed across 120 pixels of a Si photodiode array from a spectrally unstable WLC probe, referenced. (a) conventional referencing; (b) spectrum from same data as (a), but with B correlation referencing applied; (c) the correlation matrix.*

# Synchronised sample movement and pump laser timing in Time Resolved Multiple Probe Spectroscopy (TRMPS)

**P.M. Donaldson, G.M. Greetham, M. Towrie** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

**R.L. Owen** *(Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, UK)*

Transient absorption spectroscopy often requires the sample studied to be moved in the laser beams to ensure measurement of a pristine sample. This is typically done unsynchronised to the measurement lasers, which convolutes the motion of the sample into the measured data and adds noise. Here we explore a rapid sample translation scheme which can be triggered from the lasers and demonstrate its operation in a transient infrared setup.



*Position of a focussed laser spot in a moving sample for (a) 'Lissajous'-type sample motion and (b) 'Serpentine' motion.*

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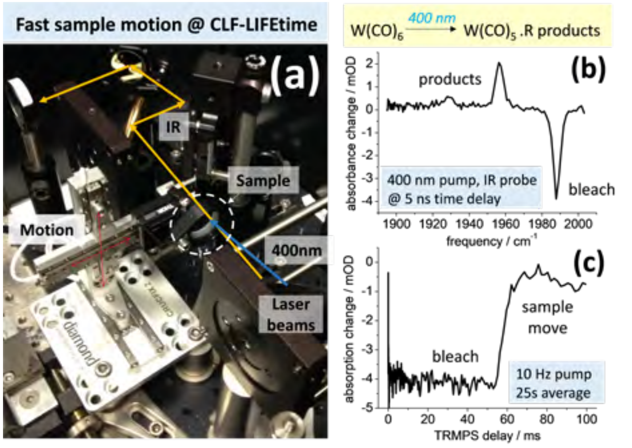

*TRMPS-IR spectroscopy on a sample moving in synchronisation with the pump laser (a). The sample is $W(CO)_6$ in heptane. The effect of its permanent bleaching by a 400 nm laser pulse is clear in the transient infrared spectrum (b). Tracking the absorption change of the bleach (c), 50 ms after the photoproducts are created, the sample is moved 100 µm, exposing fresh sample for the next laser shot. (c) is an average of 250 pump laser / move events.*

# Development of a single-shot third-order cross-correlator for Vulcan

**A.C. Aitken, P. Oliveira, L.E. Bradley, E. Dilworth, M. Galetti, B. Parry, M. Galimberti, I.O. Musgrave** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

In this paper we present the development of a near-field single-shot third-order cross-correlator (TOCC). We present measurements of sub-ps pulses at $\lambda$ = 1055:5 nm demonstrating the device has a temporal window of $\Delta T$ = 36:4 ps and a resolution of $\delta t$ = 91 fs. We also discuss the spectral acceptance and the minimum required operational conditions.

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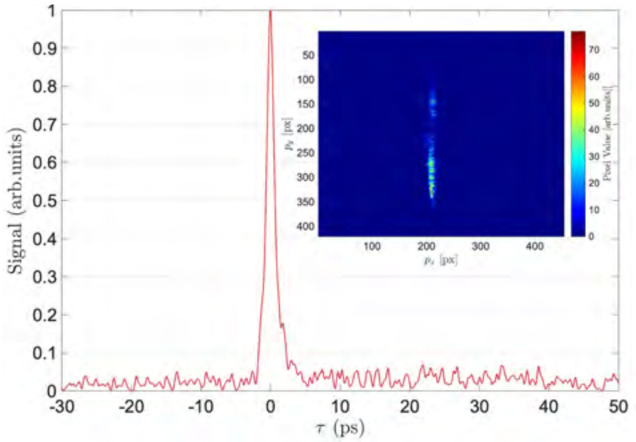

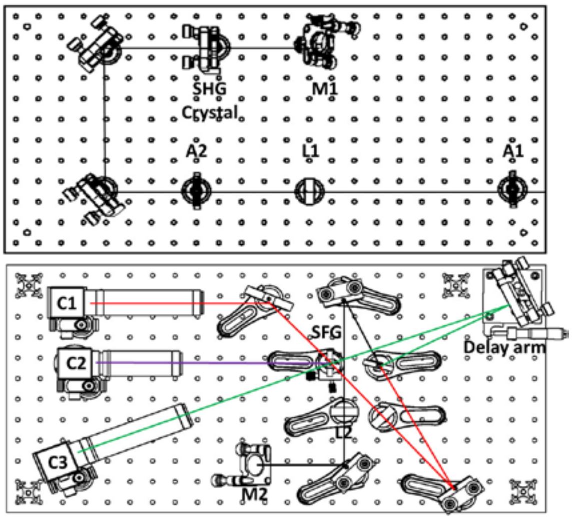

*Above Schematic showing a top-down view of the upper (top) and lower (bottom) decks of the single-shot TOCC*

*Left: TOCC profile of the pulse retrieved through the lineout of the trace image. The signal in arbitrary units, normalised to the maximum value, is plotted against time in picoseconds from the point of maximum signal. (Inset) Single-shot measurement of the 2 Hz ns OPCPA*

# Comparing temporal contrast measurements taken in the Vulcan front-end and target area petawatt

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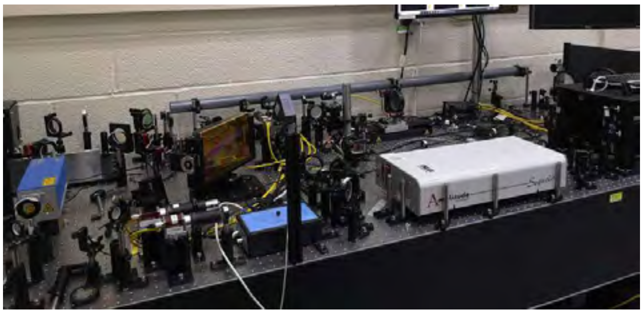
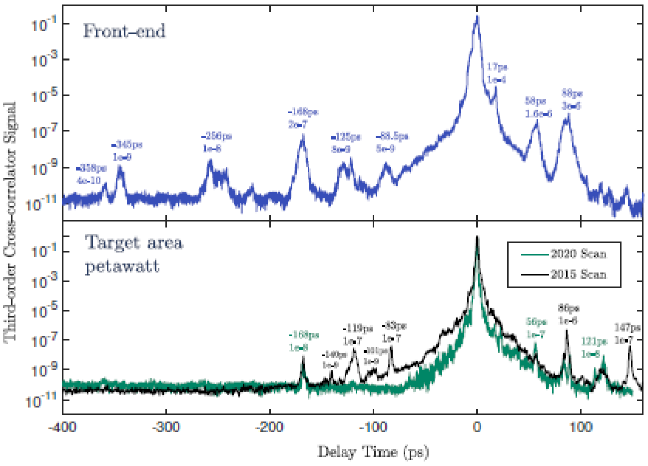
Producing high-intensity laser pulses with a high temporal contrast is essential to establishing the mechanisms that drive particle acceleration at petawatt class laser facilities. Here we present measurements taken in both the Vulcan front-end and target area petawatt (TAP) using a third-order cross-correlator giving a contrast of $10^{10}$. Comparing these measurements with an historical scan demonstrates that changes to the front-end can have a significant effect for the pre-pulses arriving in TAP.



*Setup showing the third-order cross-correlator in TAP.*



*Third-order cross-correlator measurements from the Vulcan front-end and TAP compared with an historical 2015 scan. A single pre-pulse is left at time -168 ps at $10^{-8}$ in the target area after changing various optics in the front-end.*

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# Progress on improving stability of the short picosecond pulse by fast stabilisation in Vulcan

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Energy stability of the short picosecond CPA pulse in Vulcan can vary over time. This creates operationally dynamic conditions, as the energies between shots can deviate from user requested energies. We present progress in stabilising the beams near-field, while identifying future interventions to improve stability.

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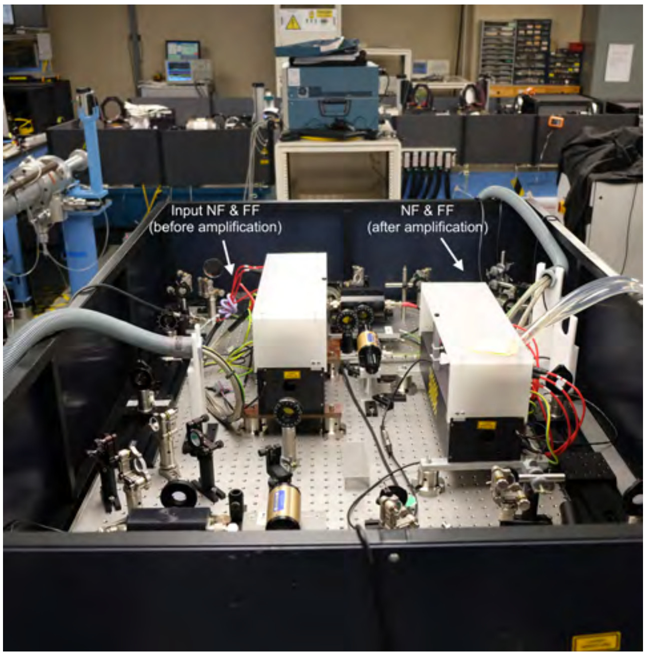

*Right: Near-field and far-field diagnostics installed before and after the short pulse is amplified through the two double pass 9 mm amplifiers*