DEVELOPMENT OF A HIGH-SPEED DIAGNOSTICS PACKAGE FOR THE 0.2 J, 20 fs, 1 kHz REPETITION RATE LASER AT ELI BEAMLINES*

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Abstract

The ELI Beamlines facility aims to provide a selection of high repetition rate terawatt and petawatt femtosecond pulsed lasers, with applications in plasma research, particle acceleration, high-field physics and high intensity extended-UV/X-ray generation. The highest rate laser in the facility will be a 1 kHz femtosecond laser with pulse energy of 200 mJ. This high repetition rate presents unique challenges for the control system, particularly the diagnostics package. This is tasked with measuring key laser parameters such as pulse energy, pointing accuracy, and beam profile. Not only must this system be capable of relaying individual pulse measurements in real-time to the six experimental target chambers, it must also respond with microsecond latency to any aberrations indicating component damage or failure. We discuss the development and testing of a prototype near-field camera profiling system forming part of this diagnostics package consisting of a 1000 fps high resolution camera and FPGA-based beam profile and aberration detection system.

INTRODUCTION

ELI Beamlines will be the first high-power laser research facility fully dedicated to public users. It must be multifunctional and highly adaptable to accommodate the needs of scientists from many different fields. There will be four high repetition rate, femtosecond-pulse laser sources ranging from TW to PW peak power and incorporating some of the latest laser technology to reach high wall-plug efficiency and excellent beam quality.

The four laser sources (L1-L4) are currently under development and will be installed in the facility in time for a 'first light' demonstration in 2016 and open to users from 2017. L1 is the highest repetition rate at 1 kHz and the lowest energy at 200 mJ for a peak power target of >2 TW. L1 is aimed at experiments based on high harmonic generation (XUV), X-ray and keV betatron radiation in the molecular, biomedical and materials sciences.

The L1 laser is the first to be developed and is an ideal test-bench for the ELI facility control system. One crucial aspect of the control system is beam diagnostics. We discuss our plan for beam diagnostics in L1 and the results of our evaluation and prototype of a diagnostic system for high speed, real-time (RT) camera-based beam profilometry at 1 kHz repetition rate.

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DIAGNOSTICS OVERVIEW

Requirements

For L1 and the target stations using it, the repetition rate is a challenge for the collection of individual pulse diagnostics. These must be available for use in processes such as stabilisation feedback loops and condition monitoring. Control system support for these must therefore be compliant with the 1 kHz RT criterion. These RT diagnostics include:

- Pulse energy and power;
- Pulse contrast (ratio of pulse power to background);
- Beam centroid and beam width;
- Beam spatial profile;
- Detection of aberrations that might cause or signify damage to optical components.

In addition to these fast pulse-to-pulse diagnostics, there are many others that need to be measured at reduced rate with less strict RT constraints, including:

- Pulse temporal profile;
- Average power and pulse contrast;
- Beam wavefront;
- Pulse optical spectrum.

Diagnostics Package

To minimise hardware/software diversity, a modular diagnostics package (DP) design was chosen. The DP has a simple, flexible optical layout (Fig. 1) combined with in-house solutions for the most commonly required diagnostics listed above. It will be deployed in a number of key locations in L1, providing detailed information on each major sub-system (Fig. 2).

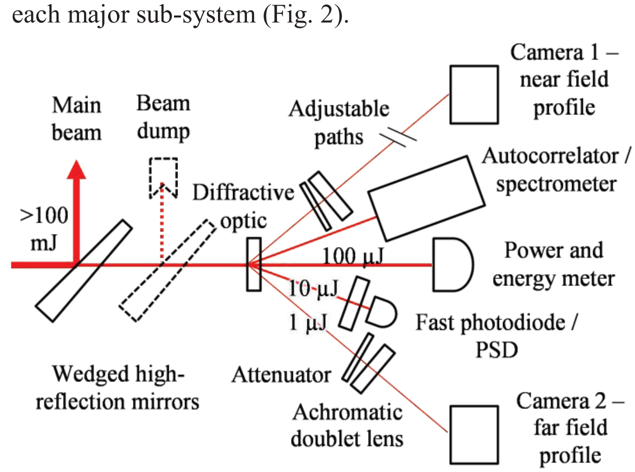

Figure 1: Conceptual layout of the modular high speed diagnostics package.

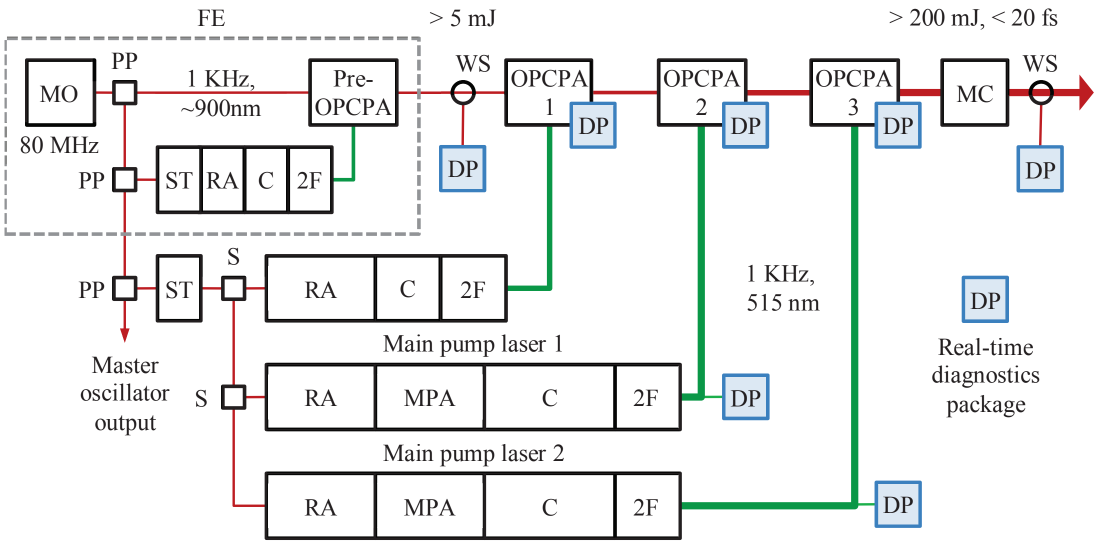

Figure 2: Overview of the main features of the L1 laser showing the locations of the diagnostics packages. DP diagnostics package, FE laser front-end, MO master oscillator, PP pulse-picker, ST pulse stretcher, S splitter, WS wedge beam sampler, RA regenerative amplifier, MPA multipass amplifier, C grating compressor, 2F frequency doubling, OPCPA optical parametric chirped pulse amplifier, MC mirror compressor.

The DP samples the beam using mirror leakage. Two mirrors in series provide sufficient attenuation at all L1 energies. The mirrors are wedged to minimise ghosting and interference. A transmission diffraction optic is used to provide multiple, low-power copies of a main beam with low distortion [1]. Details such as filters, optic diameters and focal lengths can be readily changed to accommodate requirements, and devices will be on guide rails to facilitate quick adjustment.

Other Diagnostic Systems

The laser systems at ELI Beamlines are being designed for a high degree of availability; essential to our goal of being a user-driven facility. For this reason, L1 includes extensive process automation to optimise performance and rich condition monitoring to protect key assets and minimise down-time.

Therefore, as well as these DPs, L1 will also have ~50 low-cost GigE cameras for optical component inspection and monitoring. These will be linked to a RT camera server with change detection and analysis algorithms, as well as logging and remote streaming services. A prototype system based on LabVIEW Real-Time (LVRT) on a standard industrial single-board PC with four 100 fps VGA CMOS cameras is being evaluated currently. A similar number of low-cost calibrated photodiode calorimeters are also required. These will use in-house analogue electronics interfaced to a standard high-density DAQ system. A combined position-energy-power sensor based on a calibrated commercial PSD chip and custom electronics is being development.

Many specialist laser measurement instruments, from femtosecond pulse autocorrelators to spectrometers, will also require evaluation and integration with the L1 SCADA system. These systems, together with the DPs, form the backbone of the L1 beam diagnostics system

1000 FPS CAMERA DIAGNOSTICS

The most challenging aspect of the L1 DP requirements listed above is the measurement of beam width, spatial profile and the detection of aberrations. For these a camera directly images the laser beam, usually at both near-field (imaged from a critical plane, such as the laser gain medium or from a compressor grating) and far-field (usually approximated by focussing the beam). These measurements give vital information about the operation of amplification or compression processes and how the beam from that process will propagate to downstream components.

Beam centroid and width are defined in the ISO 11146 standard [2] and are based on the moments of the image data after careful baseline calibration. This is extended with eccentricity and angle for ellipsoidal beams.

Beam profile is simply the camera image. This data can be compressed and streamed over a dedicated network. For this we propose a parallel ‘fast controllers network’ for low-level, high-bandwidth data streaming outside of the confines of SCADA system but coupled to it with a rate-reducing bridging server.

By comparison, the detection of aberrations is an open-ended and potentially difficult challenge. A combination of simple techniques aimed at FPGA analysis is proposed, which through experimental trials and real-life data analysis can be honed and adapted over the coming years of L1 development. These are:

- RT histogram analysis (distribution of pixel intensity values);
- Whole-frame change detection based on a sliding median filter ‘reference image’;

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- Orthogonal spatial transforms (e.g., pseudo-Zernike polynomial transform, the first few Fourier coefficients, *etc*.). [3]

These methods all produce a reduced set of information that can be alarm thresholded or put to a simple classifier to determine the presence of problems such as bright/dark spots, diffractive or absorptive contaminants, optical coating damage, amplifier instability, beam clipping, etalon and interference fringes, *etc*.

If an error is detected, the next pulse from the L1 FE is blocked, giving the best possible chance of damage prevention. This is done using a PIN-diode switch controlled by a hard-wired connection. The switch interrupts the trigger signal to the pulse-pickers (Fig. 2). This stops any seed pulses reaching the amplifiers and prevents pulse emission. For this process to take place in less than a millisecond is a challenge (Fig. 3). With the majority of the time taken up by the transfer of pixel data from the camera, predominantly on-line, parallel processing in an FPGA must be used to for the µs latencies required.

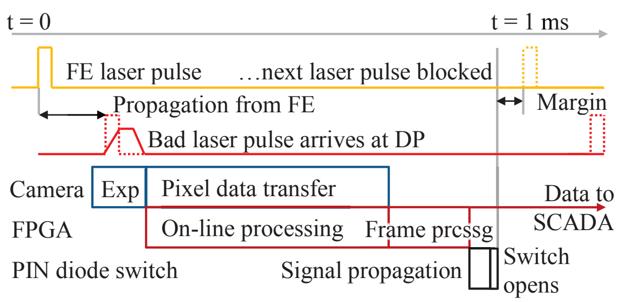

Figure 3: Timing diagram for a next-pulse laser interlock scheme based on FPGA analysis of profile aberration indicators on the 1000 fps camera diagnostics system.

Choice of camera and interface

Most 'high speed' cameras on the market are recording cameras that are not suitable for RT control. Only a few are capable of streaming data from a significant region of interest (ROI) at 1 kfps. All are CMOS at this speed, with dynamic range ≤10 bits. For imaging short pulses, a global shutter is essential. To stream an ROI of 500 × 500 pixels (1/4 MP – our target specification) at 8 bits per pixel and 1 kfps requires a bandwidth of 2 Gb/s before any encoding or control.

Until recently, the only standard interface for such cameras was Camera Link (CL) [4], offering 6.8 Gb/s with the 80-bit (10-tap, 8-bit) extension. CL suffers from bulky, expensive cabling and a 10 m limit without repeaters. In 2011, CoaXPress (CXP) became a standard and is available on a few cameras and frame grabbers. A 75 Ω coaxial cable link provides 6.125 Gb/s over 40 m, and 4× parallel links are common [5]. Other planned interfaces include Camera Link HS and a GigE Vision derivative based on 10 GbE [6].

Due to the wider availability of cameras and frame grabbers (particularly National Instruments' R-series), the mature CL interface was selected for this initial test. By the time of L1's final installation, a more optimal and cost-effective interface may be fully supported.

A survey of cameras was carried out (Table 1). Some caveats are necessary in this comparison. For instance, the Bonito 400 needs two 10-tap CL frame grabbers to capture both left and right halves of the sensor data (making setup difficult and expensive). The JAI camera could be cheaper than the others (and comes with either CL or CXP ×4), but it is currently pre-release so numbers here are estimates. For the DP, active area is important as well as pixel resolution, so larger pixels are preferable. The older Basler A504k and the EoSens CL were thus chosen for testing on a prototype system.

Table 1: Camera Comparison

Manuf.	**Basler**	**AVT**	**AVT**	**Eo Sens**	**Eo Sens**	**JAI**
Model	A504k	Bonito 400	Bonito 200	3CL	CL	SP-5000
Res, w, h (pixels)	1280 1024	2320 1726	2320 1726	1690 1714	1280 1024	2560 2048
Pixel size (um^2)	12 × 12	7 × 7	7 × 7	8 × 8	14 × 14	5 × 5
Clock (MHz)	67	80	80	85	80	70.5
ROI at 1 kfps, h, w (pixels)	480 480	660 2320	330 2320	**820** **820**	760 760	~500 500
h, (mm)	5.8	4.6	2.3	6.6	**10.6**	2.5
Est. price (k€)	8	5.8	~5	6.7	6.1	**~3**

TESTING AND RESULTS

We used a NI PCIe-1473R frame grabber in a desktop running LabVIEW RTOS (to be replaced by an industrial single board computer). An FPGA design (Fig. 4) was developed for computation of the centroid, D4σ beam width, and real-time histogram analysis on the incoming pixel data. The measurements are streamed to the RTOS and relayed to the Windows development PC. Most of the rest of the design was adapted from an existing demo project.

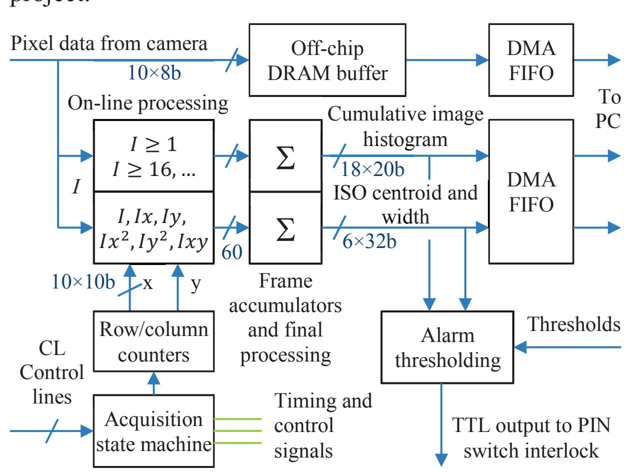

Figure 4: Block diagram of the FPGA design for on-line beam centroid, width and RT histogram analysis.

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The system is synchronously triggered by the L1 timing system. For the test, the output of the FE pump laser (~1.5 ps at 515 nm) was imaged in the far-field. Exposure time has no effect for single-pulses, so brightness was controlled with attenuators and camera gain settings. The background offset feature was used to calibrate to the point where all pixels are zero with the beam blocked.

The performance of both cameras was compared to a commercial beam profiler (Ophir Spiricon) using a partly reflecting optic. Beam profile quality and centroid-based pointing stability measurements were compared.

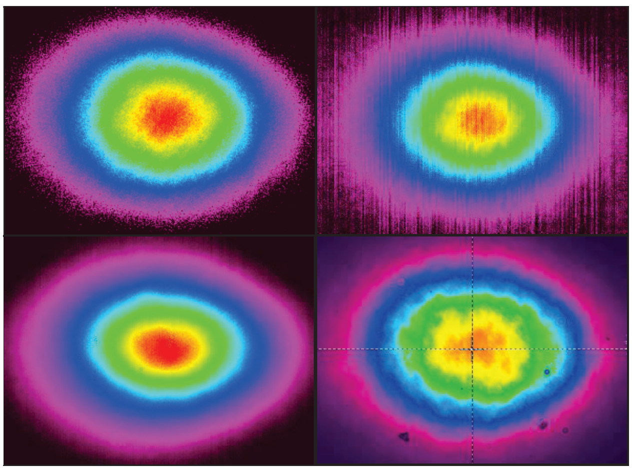

Figure 5: Single-shot beam profile measured with EoSens camera with (top left), and without (top right) FPN correction. Single-shot profile measured with Basler camera (bottom left). Many-shot reference profile measured with commercial beam profiler (bottom right).

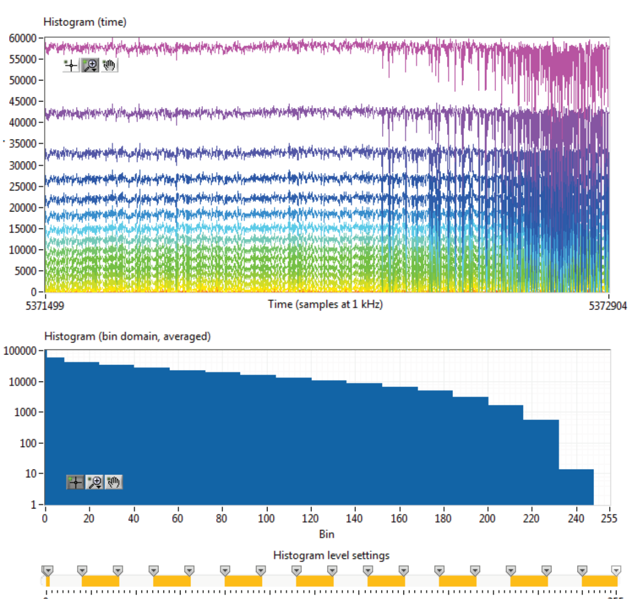

Figure 6: Screen-shot from the LabVIEW histogram analysis panel. The top graph plots cumulative pixel value counts against time and the lower shows the cumulative log pixel value counts against pixel value. The onset of chaotic behaviour is seen in the time plot by isolated occurrences of 'dim' pulses. The time frame here is 1.4 s.

Although comparable, the cameras showed small differences in performance (Fig. 5). The Basler camera suffered slightly from blooming. The EoSens camera was sharper but had residual fixed pattern noise (FPN) that was not fully removed by its correction algorithm. With correction off, it is clear that FPN is inherently worse than the Basler (which has no automatic correction). To correct this fully would require additional FPGA processing. Both are quite different from the commercial profiler; however, this is partly due the many pulses per frame (exposure time ~100 ms) combined with the movement of the beam (the long path length here magnifies the pointing jitter). This is an advantage of single-pulse profiling. The higher resolution (10 bit) of the commercial profiler does reveal more detail in beam structure, however. A more quantitative comparison would require an adjustable telescope, due to the differing pixel sizes.

The potential for aberration detection was also demonstrated (Fig. 6), when a sudden transition to a chaotic operating regime is clearly visible in the data captured by RT histogram analysis. A photodiode might not distinguish this from a change in beam position, propagating mode or baseline power in-between pulses.

CONCLUSION

The plan for diagnostics provision in the L1 beamline has been discussed. A prototype 1 kfps camera-based beam profile analysis system has been built and two commercial cameras compared. The prototype demonstrated that beam centroid, width, profile and histogram data can be measured and collected in real-time at 1 kHz. The camera system has also been shown to be suitable for operating a next-pulse interlock system to block seed pulses at the laser front-end within a 1 ms window. The next-pulse interlock will be developed further and tested in the near future. FPGA algorithms for change detection based on a sliding median of past frames and simple orthogonal spatial transforms will also be developed. We will also monitor developments in high speed camera technology and evaluate new cameras as they are released.

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