Proposed Target Area 2 work-plan in preparation for EPAC

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Introduction

The Extreme Photonics Applications Centre (EPAC) will provide a major upgrade of high-power laser capability in the UK. The main differences from Gemini are a higher laser energy (30 J), a higher repetition rate (10 Hz), and better machine stability. The latter is achieved by the housing of EPAC within a customised building, and an emphasis on beam stability through design choices and the integration of active stabilisation systems.

Many new systems are being developed for EPAC including EPICS-based control software [1], high frame rate radiation detectors, specialist gas cells and jets, and electron beam transport components. It is important that a programme of iterative design and prototyping is implemented in the period leading up to commissioning of the EPAC experimental areas in 2025.

For this reason, Target Area 2 was closed to open application in February 2022 so that it could be dedicated to specific experiments needed to prepare for EPAC. In this report we describe our proposed work-plan to address the challenges and confirm that our design is robust and suitable. All of these activities will be carried out collaboratively with our user community.

Laser stability

The commercialisation of chirped pulse amplification laser technology brought a huge improvement in the measurement [2], monitoring and stability of high-power laser parameters. For example, the 1 PW Thales Quark 1000 laser [3] offers 1.2 microradian beam pointing stability and < 1% rms pulse to pulse energy stability. Gemini is housed in an old building (R7), making improvements to infrastructure very difficult. Therefore, to achieve better stability we will need to retrofit stabilisation systems that actively respond to beam measurements.

The first step will be a thorough characterisation of the performance of the TA2 main beam. We will diagnose the pulse before the compressor using near-field and far-field cameras, a wavefront monitor, an energy meter, and a spectrometer. The quality of the focus can be further investigated with a scanning M-squared diagnostic [4]. By analysing jitters and drifts in the laser parameters we will attempt to identify the causes within the laser system and/or laboratory environment. As far as possible, these will be eliminated passively, for example by damping vibrations and enclosing optical layouts.

We will then implement stabilisation systems, which will act as prototypes for the EPAC laser. While shot-to-shot fluctuations are very difficult to eliminate, drift correction should be relatively straightforward, provided that constant measurement is possible. Gemini already operates with an auto-alignment system through the amplifier chain. This will be extended into TA2, using motorised mirror mounts (Newport 8824-AC), GigE POE cameras (Allied Vision Manta), and the EPICS system under development for EPAC. The pulse energy can be stabilised using the waveplate/polariser energy control in LA2 in a feedback loop with an energy measurement in TA2 (integrated near field signal). By running the system at below maximum energy (90% output for example), it should be possible to compensate for degradation of performance over extended periods (> 1 hour). The quality and position of the focal spot may prove more challenging to stabilise. We will try several methods using measurements of the far field and/or wavefront (Imagine Optic HASO4). Correction could be applied using the adaptive optic in LA2 or a lens on a motorised stage [5].

With these stabilisation systems in place, we expect to achieve consistent pulse compression. However, if we find that the post-compression pulse-shape and spectrum are not stable, we will need to find methods to also stabilise these directly (for example with a feedback loop to the Dazzler).

Compressor operation at high repetition rate

Many CPA systems, including commercial products, have found issues with the compressor when ramping up to full energy at high repetition rate (> 1 Hz). Because of the high average power, a significant amount of energy is deposited in the grating substrates leading to deformation and spatio-temporal errors in the pulse compression. The problem was highlighted in a study of the ANGUS 200 TW laser system at DESY [6]. This system originally used Pyrex grating substrates and suffered from a degradation of the focal spot at average powers above 5.6 W (compared to 30 W at full specification).

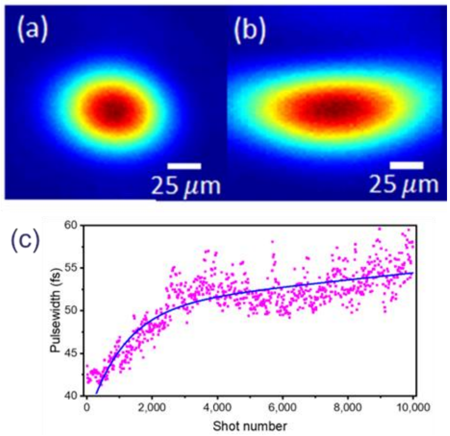

Figure 1. Focal spot (a) after initial optimisation; (b) after 10,000 shots; (c) evolution of the measured pulse duration.

We have previously characterised the TA2 performance at 5 Hz repetition rate and observed an elongation of the focal spot and an increase in pulse duration (Figure 1). This was unexpected at the relatively low average power of 5W. We attempted to apply the model of heat-induced spatio-temporal couplings published by DESY [7], but our results were inconclusive. Therefore, we plan to repeat these measurements in a more detailed study. We will measure pulse duration (APE LX-Spider), focal spot, pulse tilt ([9]), and compressor throughput (ratio of pre- and post-compression energy) during multiple heating and cooling cycles. By using a small pick-off (5 mm diameter) to measure the pulse duration, we can scan through the beam (55 mm diameter) to determine any spatial dependence of pulse duration [9]. We can also carry out spatio-temporal metrology of the compressed pulse using an INSIGHT device [10].

One solution to grating heating is to use high-reflectivity dielectric rather than gold coated gratings to reduce the amount of energy deposited in the substrate. We have procured dielectric gratings for TA2, so we can perform testing with both sets. A further advantage of the dielectrics is an enhancement of compressor efficiency enabling higher laser energy onto target.

Optimisation of laser wakefield acceleration

Stabilising the laser parameters will bring about an improvement in the electron beam stability. Studies on the DESY LUX system measured the correlations of the electron energy with laser energy, longitudinal focus position, and pointing [11]. The effect of pointing fluctuation is not obvious, because it is coupled to changes in pulse compression. By fitting a model to the electron energy drift, they show that active correction of the laser should lead to beam consistency.

Another source of instability can arise from poor target reproducibility. We will concentrate effort on producing higher quality targets than have previously been used in the CLF, and characterising them through non-destructive inspection (eg x-ray tomography) and offline neutral gas interferometry [12]. Target design will be guided by fluid simulations carried out by members of the Scientific Computing Department (SCD) at STFC Daresbury Laboratory. Where necessary, precision engineering methods will be used to manufacture components.

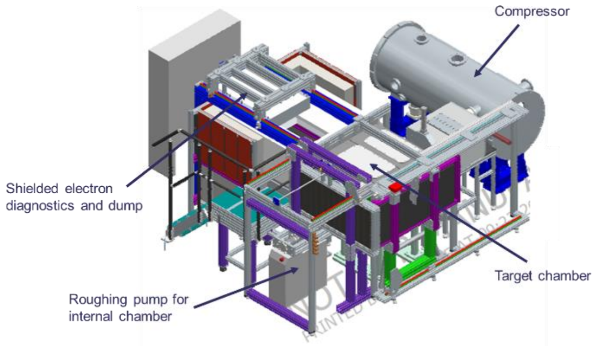

Figure 2. Experimental arrangement in TA2 for producing high repetition rate 100 MeV electron beams.

The arrangement for laser wakefield acceleration will be based on a previous TA2 experiment led by the John Adams Institute at Imperial College [13]. This demonstrated the application of Bayesian optimisation to LWFA (subsequently achieved at DESY as well [5]) operating at 1 Hz. As shown in Figure 2, the interaction chamber and electron spectrometer and beam dump were surrounded by shielding suitable for high repetition rate. Our starting point will be to repeat this experiment, but with the superior beam stability resulting from the improvements to the laser and target. With dielectric gratings we should be able to increase the repetition rate to 5 Hz. Further experiments with machine-learning algorithms should allow us to find robust, stable operating conditions [14]. Our aim is to produce 10 pC bunches with <5% energy spread at 100 MeV and good shot-to-shot and long-term stability.

Electron beamline component testing

To progress from LWFA R&D to a fully functioning beamline for experiments and applications using the laser-driven secondary sources, electron optics are required to control and condition the beam. This also improves diagnostic capabilities to confirm low energy spread [15] and emittance [16]. Several beamline configurations are being designed for EPAC by the Accelerator Science and Technology Centre (ASTeC) at STFC Daresbury Laboratory. These include permanent magnet quadrupoles, electromagnet quadrupoles, and possibly active plasma lenses [17]. Because of time constraints, electron focusing components are usually not used on Gemini experiments, meaning CLF staff are not experienced in their use. The test beamline in TA2 will allow training of staff and users under the guidance of accelerator experts.

Another objective is to develop new diagnostic techniques for ultrashort (~ 10 fs) electron bunches. There is no established method for directly measuring the bunch duration in this regime. (The longitudinal profile can be indirectly measured by characterising transition radiation from a foil [18,19].) A proposal by ASTeC is to use a dielectric streaker in which the beam is passed off-axis through a dielectric lined waveguide. This imparts a kick to the electrons that increases from the head to the tail of the bunch and can be observed on a downstream screen. In theory this device should have sufficient resolution to measure EPAC electron bunches. We plan to test this diagnostic using ~50 MeV electron beams in TA2.

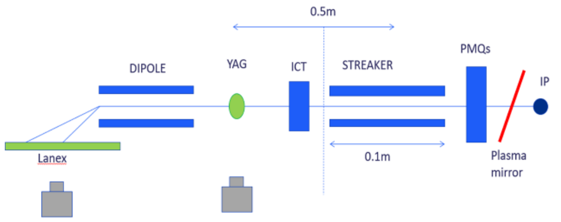

Figure 3. Schematic of the LWFA arrangement for testing permanent magnet quadrupoles (PMQs) and the dielectric streaker. The streak is measured on the YAG screen and the energy spectrum on the Lanex screen. An integrating current transformer is used to measure the beam charge.

Optimisation of laser-driven x-ray sources

The electron beams can be used to generate x-ray beams through betatron oscillations within the wakefield, bremsstrahlung by impact in a metal foil, and inverse Compton scattering (ICS) of the drive beam reflected from a plasma mirror [20]. The optimisation strategies used for electron beams can also be applied directly to optimise x-ray properties (see Figure 3 in Ref [13]). Numerous demonstrations of imaging using laser-driven sources have been published [21–24], but to achieve the image quality and short scan times demanded by industrial users requires extensive source optimisation.

We will start by determining the best parameters achievable in TA2 for each x-ray generation scheme. We expect broadband emission with critical energy ~3 keV from betatron [13] and 1 – 10 MeV bremsstrahlung radiation [25]. We should be able to reproduce the tunable 50% energy-spread self-reflection ICS beams reported by Tsai *et al* [26], and may be able to improve on these results using machine learning.

We will then choose suitable samples to develop imaging capability in each energy region. Provided we achieve good enough image quality (i.e. signal-to-noise ratio) with single-shot or few shot imaging, we should be able to demonstrate fast (of order 1 minute) x-ray tomographic scanning (XCT) with high spatial and temporal resolution. It is important to engage with the XCT community [27,28] to verify that our image quality is acceptable for industrial and medical applications. Because synchrotrons and commercial scanners are very well established, their users have high expectations that are currently not met with LWFA-based sources. We have ongoing collaborations with several XCT groups (WMG, NPL, UCL [29–31]) who can apply industry-accepted source characterisation methods to rigorously validate our performance.

Solid target interactions

In parallel with the LWFA work, we will develop equipment to be able to deliver high repetition rate solid target interactions. Tape drive targets produced by the Target Fabrication group have been extensively tested on experiments at the CLF and elsewhere. Now the design is mature enough that it can be sold as a commercial product. Alongside this, a liquid sheet target is under development in collaboration with the SLAC National Accelerator Laboratory and Queen's University Belfast. The SLAC target [32] was used in a TA2 experiment applying Bayesian optimisation to ion acceleration [33]. A modified version of this apparatus is currently being built and tested. When complete, this will be housed in a vacuum chamber with a dedicated diagnostic suite. We aim to be able to carry out experiments in TA2 during 2024, after the highest priority LWFA work has been finished. Using a separate interaction chamber means that the LWFA beamline can be maintained and thereafter high-repetition rate gas and solid target experiments can both be supported.

Conclusions

We have outlined here a work-plan that uses prototyping experiments to address some of the concerns we have about increasing laser repetition rate, in order to de-risk the EPAC project. A combination of software and engineering improvements and emerging machine learning techniques should lead to the production of stable, high-quality laser-driven secondary sources. We emphasise that while these activities are led by the facility, we intend to fully involve our user community at all stages.

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