# LASERLAB-EUROPE

## The Integrated Initiative of European Laser Research Infrastructures IV

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WP10 – Innovation Management and Industry Relations

Deliverable D10.2
First workshop on innovation and industry relations

Lead Beneficiary: 21 – STRATH

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| *Deliverable Type* | |
|---|---|
| R = Report<br>DEM = Demonstrator, pilot, prototype, plan designs<br>DEC = Websites, patents filing, press & media actions, videos, etc.<br>OTHER = Software, technical diagram, etc. | R |
| *Dissemination Level* | |
| PU = Public, fully open, e.g. web<br>CO = Confidential, restricted under conditions set out in Model Grant Agreement<br>CI = Classified, information as referred to in Commission Decision 2001/844/EC | PU |

**A. Abstract / Executive Summary**

As part of deliverable D10.2 we have organised a half-day Laserlab-Europe workshop on the "*Metrology of high power ultra-short lasers: user and supplier perspectives*". The event took place on the 10th of May 2017 at the Max Born Institute (Berlin, Germany) and included significant numbers of participants from across both academic and industrial sectors, with a total attendance number of about 50 people. The workshop focussed on characterisation and metrology techniques that are used to determine the parameters of high-power, ultra-short laser pulses, and discussed the need for developing metrology standards in this area. The workshop was divided into three sessions on: 1) pulse duration measurements, 2) laser intensity measurements, and 3) metrology. The two first sessions started with short presentations from both users and suppliers of lasers, which was then followed by a long discussion. The third session comprised a single talk on metrology standards followed by a discussion. A summary of the discussions and the talks is provided below.

**B. Deliverable Report**

## 1 Introduction

Recent progress in the development of high-power ultrashort pulse lasers has enabled a wide range of new physics and applications of high intensity laser technology across many areas to develop. This rapid development is driving a need for systematic and standardised characterisation of high-power lasers. Such a standardised approach would allow direct comparison between different laser systems and contribute to fully quantifying experimental results obtained at laboratories across the globe using these lasers. While the development of high-power lasers and their applications is growing rapidly, the procedures on their characterisation have not yet been standardised; they are being developed and applied independently by different laboratories. This is the main reason why we have organised a workshop on the metrology of high power few-cycle laser systems, to bring together users and suppliers to discuss the currently available techniques and procedures that are used.

## 2 Objectives

The main objective of the deliverable is to facilitate discussion through a joint workshop involving users and suppliers, to consider the primary requirements that characterise the performance of high-power ultra-short pulsed lasers. The workshop also aimed to provide an overview on metrology standards and the traceability of measurements, and considered the potential of establishing a future activity to coordinate and develop this area.

The workshop agenda included sessions to:

(i) identify the important parameters of high-power ultrafast lasers from both a user and manufacturer perspective,
(ii) promote a discussion to evaluate available and novel measurement techniques for these parameters,
(iii) establish the need and requirements for metrology standards of the high-power lasers, and
(iv) identify which measurement techniques can potentially be translated into metrology standards.

## 3 Work performed / results / description

The workshop was organised as a satellite event of the Laserlab-Europe JRA meeting held on the 10th of May, 2017, at MBI, Berlin, Germany. The event lasted for 5 hours and incorporated six talks from laser users and manufacturers and a discussion time following each session. The programme of the workshop is summarised in Table 1.

*Table 1. Programme of the Laserlab Workshop: "Metrology of high power ultra-short pulse lasers: user and supplier perspectives"*

| | |
|---|---|
| 08:00 | Registration |
| 08:30 | Welcome (Dr Roman Spesyvtsev and Prof Dino Jaroszynski) |
| | **Session 1: Duration measurements of high intensity few cycle pulses** |
| 08:35 | Dr Tobias Witting (MBI, Berlin) |
| 08:50 | Jean-Marc Heritier (Coherent Inc., USA) |
| 09:05 | Discussion with additional input from participants |
| 09:50 | Coffee/Tea break |
| | **Session 2: Intensity measurements of high intensity few cycle pulses** |
| 10:10 | Dr Fabien Quéré (IRAMIS-SPAM CEA Saclay, France) |
| 10:25 | Dr Felix Mackenroth (MPI, Dresden) |
| 10:40 | Dr Mathieu Paurisse (Amplitude Technologies) |
| 10:55 | Discussion with additional input from participants |
| 11:40 | Coffee/Tea break |
| | **Session 3: Metrology standards for high intensity few cycle pulses** |
| 12:00 | Dr Michael de Podesta (National Physical Laboratory, UK) |
| 12:15 | Discussion with additional input from participants |
| 13:00 | Lunch |

The workshop was chaired by Dr Roman Spesyvtsev and Prof Dino Jaroszynski (University of Strathclyde, Scotland). It was divided into three sessions that covered duration and intensity measurements of high-power few-cycle lasers and their metrology. The discussions were focussed on the measurement techniques used in different labs and in industry, and on how to perform a traceable measurement. Summaries of the talks and the discussions are provided below.

## <u>Summary of the talks</u>

### "Spatio-temporal characterisation of laser pulses in the single-cycle regime", by Dr Tobias Witting (Max Born Institute, Berlin)

In order to characterise ultrashort laser pulses, its time dependent electric field strength, $E(x,y,t)$, is measured as a function of time and space. Multiple techniques have been developed recently, which include autocorrelation, spectrographic, tomographic and interferometric techniques. Most of these techniques, however, ignore the space-time coupling and measure $E(x,y)$ and $E(t)$ separately, which can introduce large systematic uncertainties. A simple example of where the couplings cannot be ignored is when pulses have angular dispersion, a spatial chirp or a pulse front tilt. As result, spectral-based techniques (SEA-SPIDER and its variances) have been developed and successfully applied to direct spatio-temporal pulse characterisation. A proper characterisation of the couplings is very important in pulse front tilt measurements, hollow fibre mode (mis-)matching and for ultrafast wavefront rotation.

### "Pulse Width Measurements" by Jean-Marc Heritier (Coherent Inc., USA)

Coherent has a family of ultrafast lasers ranging in a pulse duration from several fs to ps with a repetition rate 0-250 kHz, which provide solutions for ultrafast science and nonlinear microscopy techniques. Accurate pulse measurements are required by many industries that have diverse levels of expertise and user expectations. As a manufacturer, we need simple tools that can be used by people with various levels of expertise. The single-shot autocorrelator is the most commonly used technique on a day-to-day basis because of its simplicity, wide operating range and clear interpretation of the results. More sophisticated tools such as SPIDER, SHG FROG and GRENOULINE, are also used. These tools provide more information, but they do require a higher level of expertise to use them and are often sensitive to alignment. Additionally, a common user concern is the presence of pre-pulses on picosecond and nanosecond timescales, which are measured using third-order autocorrelation techniques. We find that it is often suitable to use nonlinear conversion efficiency as a mark of quality of the laser system.

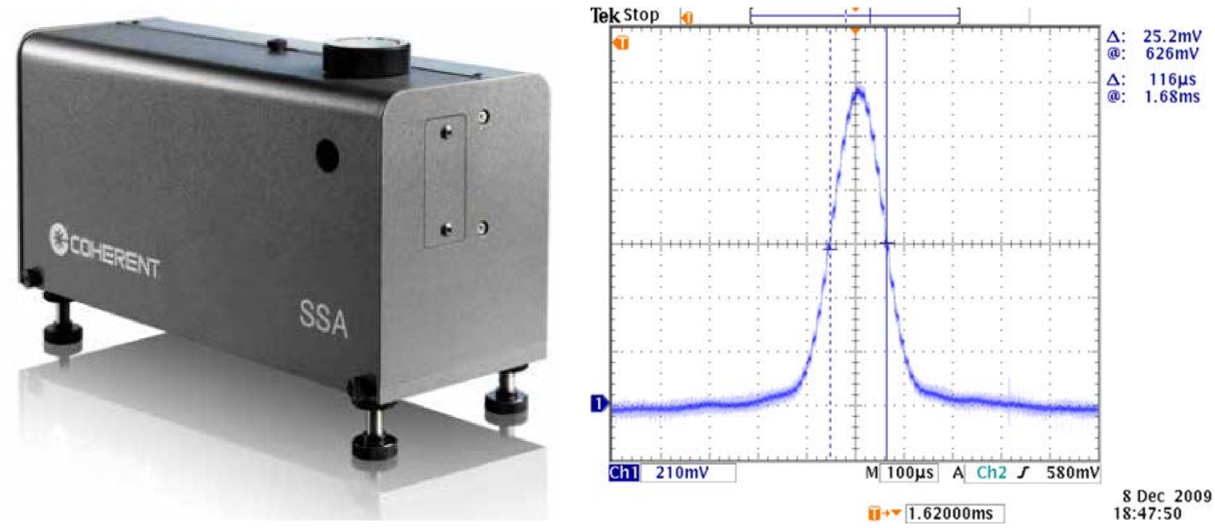


*Figure 1. Most commonly used pulse duration measurement system at Coherent. Typical example of a single shot auto-correlator device and its measurement result.*

### "Intensity measurements of high-power femtosecond lasers and their spatio-temporal metrology" by Dr Fabien Quéré (IRAMIS-SPAM CEA Saclay, France)

A basic measurement of moderate laser intensity laser radiation (up to $10^{15}$ W/cm$^2$) can be carried out using atomic ionisation, which is compared with well-established and reliable models. Such measurements, however, cannot be extended to laser intensities above $10^{15}$ W/cm$^2$. Since intensities of up to $10^{22}$ W/cm$^2$ are currently available, a new set of intensity measurement techniques have to be developed. Standard characterization routines usually separate spatial and temporal measurements of the laser pulse. This separation means that spatio-temporal couplings are neglected. Current estimation of peak laser intensity at the focus can vary anywhere between 2 and 10 times when spatio-temporal couplings are not taken into account. We have developed two techniques for spatio-temporal characterisation of the electric field for collimated (TERMITES) and focused beams (INSIGHT).

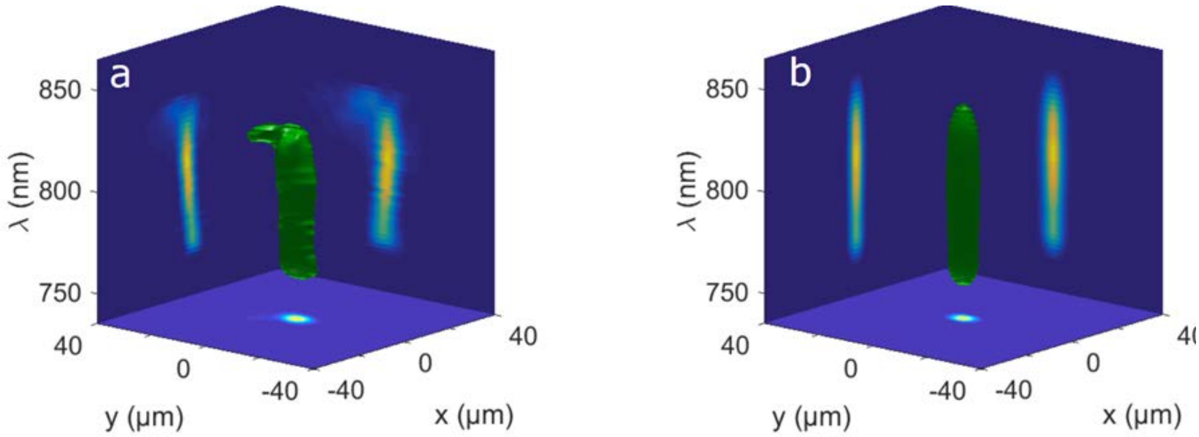


*Figure 2. Spectrally resolved focal spot with (a) and without (b) spatio-temporal coupling. Case (a) corresponds to the outcome of a measurement performed with TERMITES on a 100 TW femtosecond laser. Case (b) corresponds to an idealized case where all couplings have been suppressed on this beam.*

### "Measuring intensity and field structure in the focus of ultra-intense few-cycle laser pulses" by Dr Felix Mackenroth (MPI, Dresden)

Metrology of high-power lasers is limited by the damage threshold of the currently used measurement devices. As there is no solid material known that is capable of withstanding the electromagnetic fields at the focus of a high-power laser, measuring the properties of such a laser pulse in its focal volume is a major challenge. Any approach for overcoming this obstacle and undertaking metrology of a high-power laser focus will require highly damage-tolerant, or ideally an indestructible sensor. The role of indestructible sensors can be free, relativistic electrons. As electrons undergo strong acceleration when passing through a laser field, they radiate. The characteristics of the radiation signal are determined by the parameters of the laser responsible for the electron acceleration, and therefore can be used to characterise the laser itself. Therefore, understanding the radiation emitted by relativistic electrons promises to enable metrology even at the focus of high-power lasers. It has recently been shown that indeed the radiation signal emitted by electrons with energies of several MeV passing through a high-power laser's focus can be used to determine the laser intensity in addition to the carrier-envelope phase, thus opening up a novel approach to damage-free metrology of laser fields in the focal volume of high-power lasers.

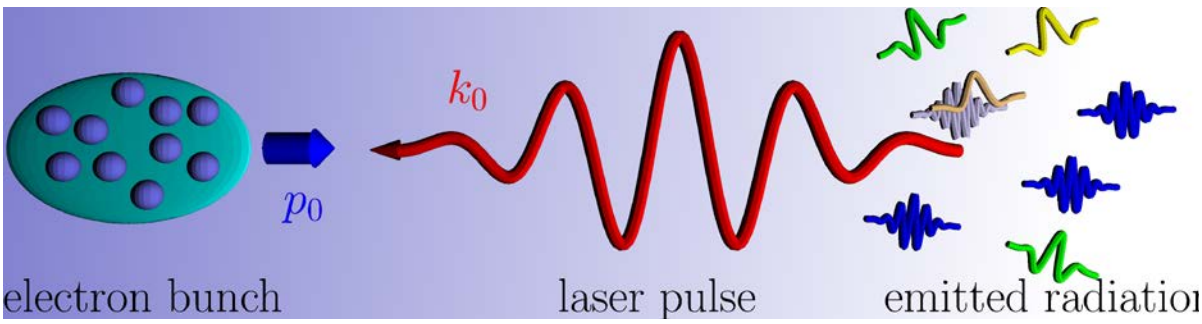


*Figure 3. Illustration of the intensity measurement of a high power laser using an electron bunch.*

### "Contrast measurements at Amplitude Technologies" by Dr Mathieu Paurisse (Amplitude Technologies)

Contrast is one of the key parameters of a high-power laser system. It requires a measurement of the temporal profile of the pulse with a very high dynamic range (> $10^{12}$) and on a large temporal window (typ. nanosecond). The contrast exhibits several features: an ASE level, a coherent pedestal, pre- and post-pulses, which can be detrimental to user experiments. The talk shows the limitation of contrast measurement when dealing with high energy ultrashort pulses. Several degradations of the contrast measurement can appear due to improper measurement conditions. The contrast degradation associated with the saturation of the nonlinear process in the third order cross correlator was discussed. The impact of the metrology bench traditionally used in high energy multi-terawatt class lasers was also discussed. Indeed, the long propagation distances in these devices can be detrimental. Finally, an experimental demonstration of the impact of B-integral on the coherent pedestal level was presented. The talk emphasised the fact that developing a high contrast laser system relies on the parallel development of a high-contrast source, a low degradation metrology bench and a high dynamic measurement device.

### "How do you make a measurement traceable?" by Dr Michael de Podesta (National Physical Laboratory, UK).

Metrological measurement is a comparison of an unknown quantity with a standard quantity. In order to achieve a metrological traceability, a measurement should be related to a reference through a documented chain of calibrations that include documented uncertainties. All physical measurements are references to the international system of units (SI), which include: Kelvin, second, metre, Ampere, kilogram, mole and candela. The calibration of the instrument produces a table of errors and can include correction factors. The errors and correction factors should be propagated through all subsequent measurements. Metrological traceability enables measurements made at different times and different places to be meaningfully compared.

## Summary of the minutes

Minutes were written by Dr Roman Spesyvtsev (University of Strathclyde) and Dr Matthew Weidman (MPI, Garching)

### Session 1: Duration measurements of high intensity few cycle pulses

#### Questions, answers and comments

1) **Company's concerns** when characterising a laser: low intensities, pre-pulses (contrast), time domain strehl ratio (second moment), conversion efficiency (as a mark of beam quality), stability under the stress and environment.

2) **Uncertainties in pulse duration measurements**

FROG as compared with SPIDER gives different results and most devices do not give the uncertainty.

@Coherent: SPIDER specifies 1% uncertainty within a 30 nm bandwidth. They look for repeatability. Perhaps it would be beneficial if multiple people used the same device to make measurements.

3) **Question: what about few-cycle pulses?**

**Answer**: Tobias – Octave or near octave spanning bandwidth make accurate FROG measurements difficult. Comparison between SEA-SPIDER and interferometric FROG for 6 fs pulses gives precision of 0.5 fs or 10%.

It is important to match the dispersion for a few cycle laser pulse in order to achieve agreement to 0.2 fs between different techniques. There is no industrial standard available for pulse duration measurement.

**Comment**: with a home-made FROG and ca. 30 fs pulses, different lab users often get different results.

**Comment**: APE (builds both FROG and SPIDER): SPIDER error margin of 1% is based on theory and simulation of the device and assumed Gaussian shaped pulses up to a bandwidth of 40 nm and 10% error for a bandwidth up to 65 nm, because of the need for thicker crystals. The error depends on bandwidth and spectral shape.

**Comment:** Need a different approach for a few cycle pulses and 30 fs pulses, regarding the development of standards.

3) **The location of the measurement** is also important: a) at the laser output; b) after the beam transport to the experimental apparatus; c) directly at the focus inside the experimental apparatus.

**Question:** when we are talking about laser output pulse duration, knowing the pulse duration at the experiment is important, especially in high-field experiments where a plasma mirror could be used.

**Comment:** this depends on the user: yet, it is often possible to see if the pulses are compressed based on the experimental results.

4) **Ioan Dancus ELI:** ELI is developing a set of common measurement procedures across the ELI consortium. Some parameters will be measured routinely (such as spectrum, energy, spectral phase, etc.), others will depend on the experiment. A clear measurement procedure will be used for every measurement.

5) **Large diameter beams** present an additional challenge. Some of the techniques require a small input beam and sample only a small part of the beam. The question is then whether the whole beam is sampled, what type of beam splitter is used, etc. This information is often omitted from publications.

6) **Carrier envelope phase measurements**

**Comments:** CEP in pulse measurements—SPIDER doesn't give absolute CE phase.

**Comments:** CEP could be calibrated using above threshold ionisation measurements of gases (for example Xe).

7) **Peak power**

**Comment:** The intensity measurements should ideally be done at full power and at the focus. The peak-power can be optimised at the sample position.

**Comment:** $a_0$ in laser wake-field experiments is often given without reference to $M^2$ of the laser. Again illustrating the importance of a Spatio-Temporal characterization.

8) **Optimization of compression**

**Comment:** The laser can be optimised in situ by monitoring the output parameters/measurements.

**Comment:** The compression of pulses can be adjusted to optimize electron generation in electron acceleration experiments.

**Comment:** Based on detailed characterization at a point (for example at the laser output), it should be possible to calculate the focal conditions.

**Comment:** Spatial beam characterization is also important.

9) **Routine monitoring**

**Comment:** The pulse duration could be measured daily to insure consistency.

**Comment:** There are perhaps two communities of laser users - those building lasers and those using them for experiments.

## Session 2: Intensity measurements of high intensity few cycle pulses

### Questions, answers and comments

1) **Questions for Felix**:

**Question:** What is the vacuum that you need to consider the electrons to be “free”?

**Answer:** The vacuum conditions have not been accounted for in the model. I assume that it should not be a problem since we need a MeV electrons in order to produce the measured signal.

**Question:** why counter propagating electron geometry?

**Answer:** Better signal to noise: however, in a sense arbitrary

**Question:** Is the ponderomotive force accounted for?

**Answer:** In that case the dynamics is dominated by laser field; however, the ponderamotive force is included in the model.

**Question:** Could you also use electrons at rest?

**Answer:** This would change the emission cone.

2) **Questions to Matthieu**

**Question:** Why is there a decrease in contrast with increase of the b-integral?

**Answer:** This corresponds roughly to the pedestal in the CPA system and a problem to re-compress the pulse.

**Question:** How about the situation where the pre- and post- pulses have different polarizations?

**Answer:** the device is sensitive to polarization: however, because the sensitivity is high, perhaps something could be detected even in the orthogonal polarization

**Question:** Do you need to scan – and + delay to account for pre- and post- pulses?

**Answer:** Yes

**Comment:** Protocol for the contrast measurement is required, including the delay range and the intensity analysis. Intensity analysis is often limited by the dynamic range of the equipment. The metrology bench should be standardised.

**Question:** how could these 3rd order auto-correlation measurements be used after a plasma mirror?

**Question:** Do the pre- and post- pulses and pedestal focus at the same place as the main pulse?

**Answer:** No

**Comment:** Plasma mirror is used more in the single shot regime, where the energy contrast is also important (not just intensity). Sequoia contrast measurement provides the intensity plot.

3) **Questions to Fabien**

**Question:** In the TERMITES Technique, is the amount of data large? How long does it take for a measurement?

**Answer:** Yes. About 40 Gb with current processing time around 40 min: however, it should be possible to reduce the data size to ca. 20 Gb. The measurement requires about 800 shots.

**Comment:** The reconstruction procedure is similar to holography.

**Question:** is TERMITES already a product?

**Answer:** Not yet.

## Session 3: Metrology standards for high-intensity few-cycle pulses

### Questions, answers and comments

1) **Michael's comments**

**Comment:** Metrological measurement is a comparison between two parameters of known and unknown values. Linking numerically the expansion of the uncertainty is important. All our measurements should be linked to SI units. The measurement procedure includes calibrations, corrections and propagation of errors.

**Comment:** It is good to have more than one way to perform a measurement. This will provide a better confidence in the result.

2) **Comment:** Some of the laser measurements are similar to calorimetry?

3) **ISO standards**

**Comment**: Current ISO standards are designed for 3 ns pulses and hence may not be relevant to ultra-short pulses. It is important to have the right standards for femtosecond and few-cycle intense pulses. The standards for high-power few-cycle laser measurements ideally have to be re-designed. Somebody could potentially be part of the ISO committee.

4) **Uncertainties**

**Question:** What would traceability look like, considering a ca. 10 % error in power measurements?

**Answer**: The measurement is perhaps more of a comparison.

**Comment**: Some of the reported results could have extremely systematic uncertainty in the intensity estimation (up to 10 times).

**Comment:** The uncertainties in the measurements should be evaluated and reported.

**Comment:** Perhaps a measure of laser intensity based on ionization would be more quantitative.

5) **Comparing to theoretical calculations**

**Question:** What about comparing with theoretical values?

**Answer:** Comparison with theoretical calculations is absolutely fine. In some cases ab initio theoretical models give more precise values than experimental measurements.

6) **Reproducibility**

**Comment:** Repeatability of the measurement and the measurement devices should be achieved.

**Question:** What is the traceability of commercial pulse measurement tools and their reproducibility? Is there reproducibility in measurements from one device to another?

**Answer:** 1% tolerance based on the assumption of Gaussian pulses.

**Comment:** Every single laser pulse is different (shot-to-shot fluctuations). Perhaps average characteristics or fluctuation range have to be defined.

7) **Metrology standards**

**Comment:** The measurements have to be done against the standard as a comparison.

**Comment: Ioan Dancus**: It is more important to agree on a standard rather than to measure absolute values. We should have the same procedures across all labs to be able to compare the results.

**Comment:** Metrology would influence the development of the devices. For metrology of FEL pulses there is a comparison with laser pulses using the time-stamp method.

**Comment:** We also should agree at which point the measurement should be taken.

**Question:** Which parameters to use for intensity measurement? Peak, RMS, spot size, etc.

# 4 Conclusions / Impact / Outlook

The workshop enabled an open discussion of LaserLab Europe participants on the metrology of high power ultrashort lasers. The event brought together laser users and laser manufacturers and created a unique opportunity for interaction between the two groups in the field of laser metrology. The talks provided a clear overview of the available techniques and procedures currently used for laser characterisation. The needs and requirements from both sides were presented. The manufacturers and facilities are keen to have standardised measurement tools and procedures across all labs. At present, no such standards exist for high-power ultrashort lasers. Measurement of laser parameters are usually performed independently by labs, using different tools. It is important to propagate and report systematic and statistical uncertainties in all the measurements, which are often omitted from publications. The discussion sessions clearly highlighted the challenges in metrology of high-power ultrashort lasers and indicated that there is a need for standardised measurement approaches and for the development of primary standards in the area. Future activities on the metrology of the high-energy ultrashort laser pulses could potentially be established with input from the standards agencies like NPL, UK.