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ELECTRON BEAM DIAGNOSTICS CONCEPT FOR THE ELI LUX PROJECT

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Abstract

Nowadays the popularity of Laser Wakefield Accelerators (LWFA) is increasingly growing. Although the quality of the beams produced by LWFA is still lower than provided by conventional accelerators, they have great potential to be considered as a new basis for future FELs and even colliders. Laser Undulator X-ray (LUX) source is being commissioned at ELI-beamlines in Czech Republic. The goal of this experiment is to provide photon beam in so called "water window" wavelength region for user experiments. Possible upgrade of the facility towards the LWFA based FEL is also considered. The electron beam diagnostics is absolutely crucial for achieving the aim of LUX. Specific properties of the beam produced by current LWFA, such as low charge, poor beam stability, large beam divergence and energy spread, require rethinking and adaptation of the conventional diagnostic tools and, in some cases, development of new ones. Ideally, they have to be compact, stable, non-invasive and allow measurements in single-shot mode. In this report we will present an overview and design considerations for the LUX electron beam main diagnostics. We will also discuss the hardware status and future plans.

INTRODUCTION

The beamline facility of the Extreme Light Infrastructure (ELI), located south-west of Prague, Czech Republic focuses on short pulse X-ray generation, particle acceleration and their applications using high power (PW-class) ultra-short (few fs) lasers [1]. Within this facility a dedicated Laser-Plasma Driven Undullator X-Ray Source (LUX) beamline is being commissioned. The main parameters of the LUX beamline are presented in table 1. The goal for the LUX project is to produce X-ray photons with a wavelength $\lambda = 1.9 - 6$ nm using short undulator (less that 1 m) and develop techniques to reach stable operation for user experiments. Development towards laser driven X-ray FEL is also considered.

Table 1: Expected ELI LUX Electron Beam Parameters

Parameter	Value	Units
Energy	350 – 600	MeV
Charge	1 – 100	pC
Rep. rate	up to 10	Hz
Bunch length	up to 30	fs
Norm. emittance	< 1	π mm mrad
Energy spread	< 5	%
Divergence at the source	< 5	mrad
Beam size at the source	~ 1	μm
Beam size at the undulator	~ 100	μm
Injection error	± 6	μm

In the following sections we will describe the key diagnostic systems which will be used for the LUX electron beam characterization.

TRANSVERSE DIAGNOSTICS

To measure the beam envelope (transverse size and divergence) YAG:Ce screens will be used. Although there are some resolution issues with such systems [2] this is still suitable for low intensity beams and when the beam size is large. This will be true for the first stage of the LUX commissioning where expected beam size will be a few hundreds of μm. To achieve higher resolution OTR screens [3] can be used in the future.

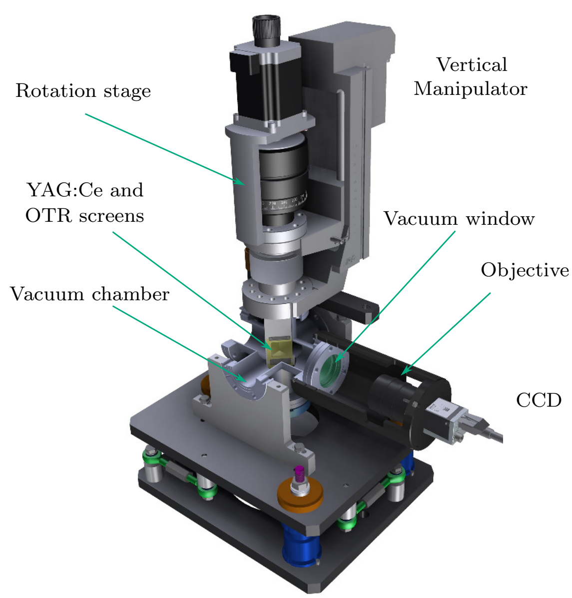

Figure 1: Model of the transverse diagnostics station.

For emittance measurements a “pepper-pot” technique will be used. This technique has been successfully demonstrated in several experiments for beams produced by the LWFA [4, 5]. Main advantage of the “pepper-pot” is the ability to measure emittance in both planes (vertical and horizontal) in a single shot.

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Other techniques, such as quadrupole scan, are also considered but their applicability is questionable due to the LWFA's shot-to-shot stability problems.

For this purpose a station for transverse diagnostics has been developed. The model of the setup is presented in Fig. 1. In general, it consists of a vacuum chamber, manipulator to insert and position the screen and optical system to image the screen. The setup is quite compact - around 120 mm flange to flange and universal - can be used for different targets. In the LUX beamline three such stations will be used in order to monitor the transverse parameters along the machine.

LONGITUDINAL DIAGNOSTICS

Due to the nature of the acceleration process in the LWFA the resulting electron bunch duration is expected to be ultrashort, $\sigma_z < \lambda_p/4 \approx 3\ \mu$m [6], where λ_p is the plasma wavelength. Conventional techniques such as transverse deflecting structures [7, 8] or electro-optical methods [9] do not have enough resolution to measure such beams. Therefore it has been decided to extract longitudinal profile of the bunch by measuring coherent transition radiation (CTR) spectrum. The CTR spectrum will be measured by custom made infra-red spectrometer based on dispersive prism - this way the spectrum and hence the longitudinal profile can be measured in a single shot. This method has already been demonstrated [10, 11] and showed very promising results.

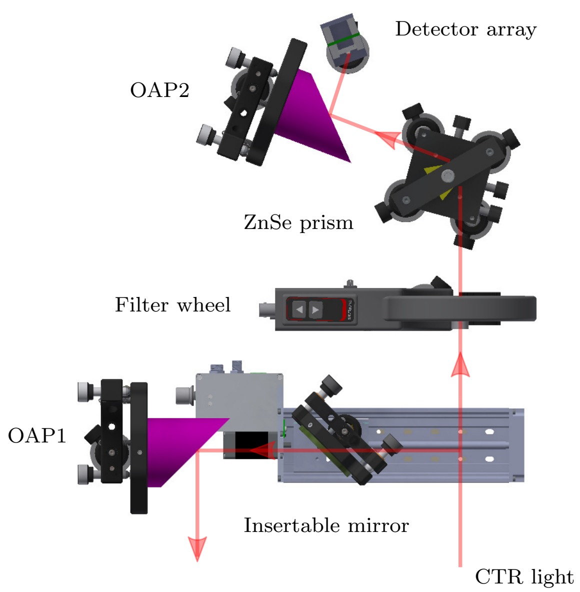

Figure 2: Schematic model of the CTR spectrometer.

The schematic of the experimental setup is presented in Fig. 2. After generation, CTR will exit the vacuum chamber through Zinc Selenide (ZnSe) viewport. ZnSe is used to limit the wavelength band to 1–20 μm. Then, CTR is collimated by means of off-axis parabolic mirror and directed to one of the two optical lines using insertable mirror. The first line is used to diagnose properties of the CTR such as number of photons, spatial profile, etc. The second optical line is an infra-red spectrometer. The spectrometer consists of a ZnSe dispersive prism a focusing mirror (OAP2) and a detector array. The geometrical shape of the prism base is isosceles triangle with apex angle of 40° and hypotenuse length of 40 mm. The height of the prism is 40 mm. To record the CTR spectrum a pyroelectric detector array manufactured by "DIAS Infrared GmbH" [12] is used. The detector array consists of 128 lithium tantalate elements with 90 μm width, 500 μm height and 100 μm pitch. The detector provides high responsivity ($S_v = 8 \times 10^6$ V/W) and low noise equivalent power (NEP = 0.15 nW).

BEAM ENERGY

Another important parameter to measure and monitor is the electron beam energy spectrum. The bunch energy distribution provides crucial information for optimizing laser–plasma parameters which are especially important during the beamline commissioning. Also, the beam energy spectrum directly affects the quality of the X-ray photons produced in the undulator, therefore monitoring of the energy spectrum is mandatory for the successful operation.

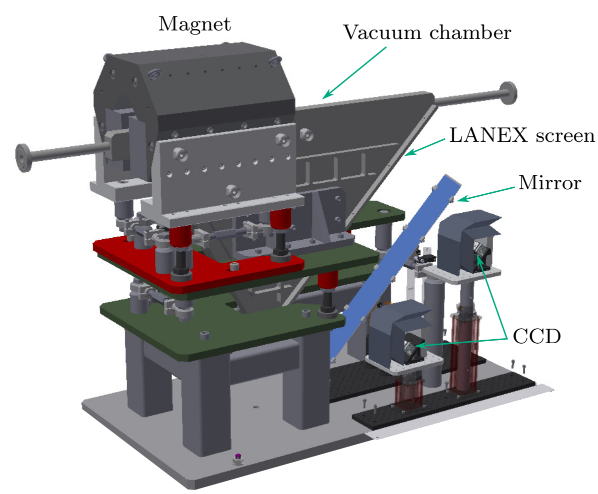

Figure 3: 3D model of the electron spectrometer.

The electron spectrometer for LUX is based on permanent magnet dipole. The dipole provides a magnetic field of 0.95 T at a gap width of 40 mm and the magnet length and height of 400 × 150 mm respectively. Once entered the magnetic field electrons are dispersed and then intercepted by a LANEX scintillating screen mounted directly to the vacuum chamber exit. The light produced by the screen is then reflected onto two CCD cameras and recorded. In order to reduce the stray light background the spectrometer is enclosed in a light-tight cover box. A schematic model of the spectrometer is presented in Fig. 3.

The spectrometer is calibrated by tracing (using GPT [13] particle tracker) simulated particle distribution through the measured field map of the dipole. This way, by knowing the geometry of the setup, the energy versus position on the LANEX screen dependence is obtained.

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BEAM POSITION

Transverse beam position measurements are important for a stable operation of any accelerator, and become crucial when it comes to reliably producing lasing in undulators. Hence, a high precision beam position monitor (BPM) system is required for LUX. The current plan includes two pill-box cavity BPMs on either side of the undulator and a re-entrant cavity BPM close to the plasma cell.

Cavity BPMs offer very high position sensitivity, which makes them able to operate with sub-μm precision even at around 10 pC bunch charge. They can work as nulling devices: even though they ultimately require a controlled beam offset, typically introduced with transverse mover stages, for calibration, once the "golden" orbit is established, it is possible to move them mechanically, so that the best orbit can later be reproduced even without any calibration by zeroing their readings. Cavity BPMs have also successfully been applied in position feedbacks, which is important for stable lasing. There is now a range of available cavity BPM designs that can be used, but the likely choice for LUX is a 6.5 GHz design currently being commercialized by FMB-Oxford [14], see Fig. 4. A suitable 8-mm aperture version of the pick-ups is now being developed for application in undulator sections of FELs.

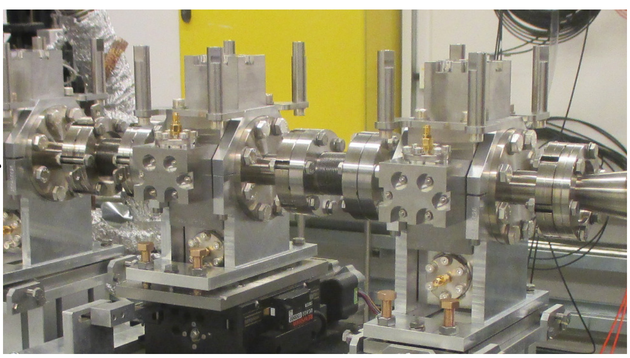

Figure 4: A triplet of position cavities and a reference cavity in a test beamline of VELA facility (Daresbury Lab., UK).

The challenging environment surrounding the plasma cell calls for a relatively narrowband BPM design. At the same time, the apertures size is relatively large, making cavity BPMs impractical, while position resolution requirements remain stringent. A possible solution to this problem is to apply re-entrant BPMs, which consist of a quarter-wavelength coaxial resonator coupled to the beampipe on the open end and to output feedthroughs on the shortened end. Re-entrant BPMs offer high position resolution while at the same time large apertures are possible without a great impact on the size of the pick-up. A design that seems nearly ideal for LUX had been developed for European XFEL [15, 16].

OTHER DIAGNOSTICS

Beam Charge Measurements

Conventionally to monitor the total beam charge a Faraday cup or current transformers are used. The latter is much more preferable since it is non-invasive, compact and commercially available. In the case of LUX beamline the integrating current transformer (ICT) produced by "Bergoz Instrumentation" [17] will be used. Recently, the company developed a special type of such transformer called "Turbo ICT" which is optimized to measure the charge in a range from 50 fC to 300 pC with a noise of 1 % [18, 19]. Moreover, such ICT is able to work in an environment with high electromagnetic pulses which are produced in the laser-plasma interaction.

Beam Loss Measurements

Knowing the amount and location of the beam losses along the beamline can be extremely helpful for the beam tuning and also allows to prevent damages caused by lost electrons, especially to the undulator magnets. It is also important to monitor the beam losses for the sake of radiation safety.

A fiber based Cherenkov beam loss monitor (BLM) has been chosen for the LUX beamline. The monitor consists of an optical fiber attached to the vacuum pipe all along the beamline. The loss is detected by recording the pulse of Cherencov radiation generated by showers of secondary particles produced when the main beam hits the vacuum pipe. The signal is then detected by photomultiplier. Knowing the speed of light in fiber the position of the loss can be determined. Such BLMs have been used in many accelerator facilities around the world and show good spatial resolution [20, 21].

SUMMARY

In this report overview of the electron beam diagnostics devices for the LUX beamline has been introduced. Most of the devices are already designed, assembled and tested. In the future the main direction of the R&D will be focused primarily on transverse and longitudinal diagnostics as the LUX beamline will be developing towards the FEL operation. In this case the efforts must be pushed to achieve higher resolution of the devices. Possible ways of upgrading towards non-invasive diagnostics are also available. This, for example, could be done by using diffraction radiation, generated when electron beam travels through a slit in a metallic screen, instead of transition radiation.

Experimental results and experience which will be obtained during proposed experimental activity might have a great interest for planning, development and optimization of diagnostics for the next generation FEL based X-ray sources driven by laser wakefield/plasma accelerators (see for example EuPRAXIA project [22]).

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