New high power laser facility ELI Beamlines – radiation safety aspects

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Abstract

This contribution introduces a new facility, ELI Beamlines, which exploits high intensity lasers for plasma production and particle acceleration. Hereafter, radiation protection assessments and methods used for designing and implementing the radiation protection program are described. Radiation fields generated by lasers differ from conventionally generated fields in some characteristics, such as ultra-short pulse length and low repetition rates, which raise some challenges for the reliable implementation of radioprotection systems. At the moment (mid 2017), the facility is being equipped with technology and the first operations are expected at the beginning of 2018.

1. Introduction

Extreme Light Infrastructure (ELI) is a European project which benefits from the latest technical development in new generation laser technology to produce high intensity ultra-short laser pulses. ELI comprises of three pillars exploiting the unique properties of the generated laser pulses in different manner. While Hungarian "ELI Attosecond" uses pulses of attosecond length for material sciences and biology, the focus of Romanian "ELI Nuclear Physics" is on photonuclear physics. "ELI Beamlines" is the Czech Republic based pillar, which aims at the development of high-brightness sources of X-rays and the acceleration of proton, electron, and ion beams, to be used both for pure research and practical applications. Even though the pillars are totally separated legal entities as of 2017, they are expected to merge under a common ERIC (European Research Infrastructure Consortium) umbrella in 2018 and act as a single research centre further on.

The aim of this contribution is to introduce the ELI Beamlines facility and summarize the methods used for designing and implementing the radiation protection program, with emphasis on challenges raised by specifics of the ionizing radiation sources generated by lasers.

2. The ELI Beamlines Facility

ELI Beamlines shall be operated as a user facility, providing its users with laser beams of up to 10PW peak power for various experiments. Four main areas of scientific interest were identified [1], namely the development and testing of new technologies for multi PW laser systems, high field physics experiments (focused intensities of about 10^{24} W·cm^{-2}), generation of femtosecond secondary sources of ionizing radiation (XUV, X rays, gamma rays, electrons, protons), and last but not least interdisciplinary applications of the generated ionizing sources in physics, biology, medicine, and material sciences. The design of the facility started in 2009 and the first operations are expected to start at the beginning of 2018.

The ELI Beamlines facility has been built in Dolní Břežany, a small village on the south outskirts of Prague. The grounds comprises of three main buildings – offices, experimental, and technical support building. The experimental building has three floors, see Fig. 1. The top floor hosts supporting systems for the lasers, the middle floor (on the ground level) accommodates the four main laser systems, while the experimental beamlines, where ionizing radiation is generated, are located on the underground floor. Within this paper, only the installations on the underground floor are discussed, as they are of the most relevance to radiation protection.

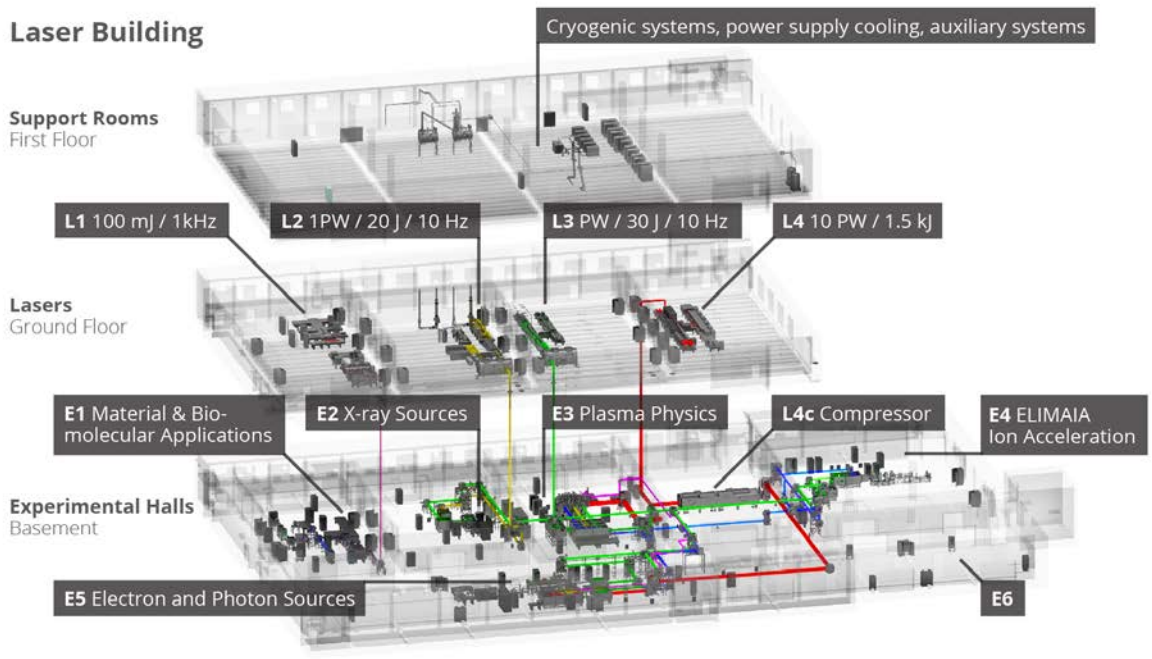

Fig.1 – Scheme of ELI Beamlines experimental building

The whole floor shall be operated in so called “clean room” regime, class 7 and 8 according to the ISO standards [2]. Considering the involved source terms, see Table 1, the area will be classified as a category III workplace and delineated as a controlled zone, in accordance with the Czech and international legislation and recommendations [3, 4]. It is expected that the maximum number of people working simultaneously on the experimental floor would be 60, mostly external users. The access will be limited to the trained workers only, as beside ionizing radiation, a number of other specific hazards including high intensity laser, high voltage, vacuum, and flammable and oxygen depleting gases have to be accounted for.

The beamlines will be operated remotely from the local control rooms, as presence of people inside the experimental halls while shooting is not possible due the life threatening conditions, especially high prompt dose rate. The only exceptions are HHG, and Plasma X ray source (PXS) beamlines, see Table 1, where a customized local shielding cabinet will be installed.

ELI Beamlines will host four major laser systems [5]. The focused ultrashort laser beams interact with targets inside specially developed end-stations, thus generating pulsed beams of ionizing radiation, and as a side effect a strong electromagnetic pulse. The combination of the different characteristics of the laser pulse and different targets will result in the production of high energy mixed radiation fields (photons, electrons, protons, neutrons, muons), with very short pulse length (order of 10^{-13} s).

In the first years of operation, the facility shall offer users 8 beamlines operated over five halls, each having area between 450 and 850 m^2. These beamlines will produce X-rays in the energy range from 1 eV to 1 MeV (frequency up to 1 kHz), electrons up to 10 GeV (frequency up to 10 Hz), and protons up to 300 MeV (frequency up to 10 Hz). A brief source term overview is provided in Table 1, summarizing both the targeted parameters and the current realistic expectations for the first years of operation for 7 of the beamlines; the last beamline will be operated purely in an optical regime and will not produce ionizing radiation.

However, it is fundamental to keep in mind that all the available source terms are indicative only, as the characteristics of the produced ionizing radiation beams is subject of research in itself. The parameters strongly depend on the experimental geometry, target material, and specifics of the particular experiment. Further, ELI Beamlines laser systems are prototypes, whose design parameters significantly exceed currently existing high-power systems. Therefore, the values used for radioprotection considerations are based on theoretical calculations using PIC simulations [6] or extrapolations of the experimental data from the existing laser systems.

Beamline	HHG	PXS	ELIMAIA	LUX	$HELL_1$	$HELL_2$	E2	P3
Targeted source term								
Primary particles of interest	X rays	X rays	protons	electrons	electrons	electrons	electrons	mixed p,e^-,e^+,γ
E max	10 keV	100 keV	250 MeV	2 GeV	10 GeV	50 GeV	1 GeV	~1 GeV
Rep rate [Hz]	1 000	1 000	1	10	1	single shot	10	1
Particles/pulse	10^9	10^{12}	10^{12}	$6x10^9$	$6x10^8$	$6x10^8$	$3x10^9$	10^{12}
Source term for 2018-2020								
E max	10 keV	30 keV	60 MeV	1.2 GeV	0.5 GeV	3 GeV	-	1 GeV
Rep rate [Hz]	1 000	1 000	1	10	10	1000 per day	-	single shot
Particles/pulse	10^9	10^{12}	10^9	$6x10^7$	$7x10^{10}$	10^{11}	-	10^{11}

Table 1 – Brief overview of ELI Beamlines source term.

3. Safety systems

To ensure a smooth operation of the facility, different systems are being used or are under development, namely building systems (fire, security, and access system), Laser control system, Management of building technologies, and Machinery safety. Beside these, to ensure safe operation of the facility, an adequate safety control system needs to be implemented. The system shall effectively integrate passive and active systems for managing ionizing radiation and other high hazards. Of course, many various hazards can be encountered in the research facility of this scale that exploits edge cutting technologies. The hazards identified during the preliminary hazard analysis include laser and ionizing radiation, electromagnetic pulse, gases (flammable, toxic, oxygen depleting), vacuum, ozone, biohazards, nanomaterials, magnetic field, high voltage, chemicals, cryogenics, pneumatics, and robotics. However, it was decided that the central safety system (Personal Safety Interlock) would cover only some of them, specifically laser and ionizing radiation, gases, and electromagnetic pulse.

At ELI Beamlines, safety management is being driven by two major safety systems: Personal Safety Interlock System and Monitoring system. While the Monitoring system detects ionizing radiation and technical gases, the Personal Safety Interlock System acts as the main integrator of safety functions that are necessary for a safe operation of the facility. The real-time information provided by the Monitoring system enables the Personal Safety Interlock system to assert an emergency and trigger an efficient early stage response.

In general, within the Personal Safety Interlock concept, several basic phases of the experiment are distinguished: preparatory phase, laser alignment, search procedure, experimental run, protective period (to allow for decay of the produced short lived radionuclides), and the end of the experiment. Each phase is characterized by different combination of hazards, which determine the level of access restriction to the experimental areas.

4. Radioprotection aspects

4.1. Simulations

As main tool for addressing the radioprotection topics and problems, the FLUKA Monte Carlo simulation code [7, 8, 9] was chosen. Ambient dose equivalent rates were evaluated within all the relevant areas in the building, occupancy limits in the experimental halls and adjacent areas were assessed, and the possible activation of the experimental equipment was estimated [10]. The simulations have also been used to adequately design the beam dumps and the local shielding to ensure personnel and machine safety. Last, but not least possible radiation damage to electronics is currently being studied.

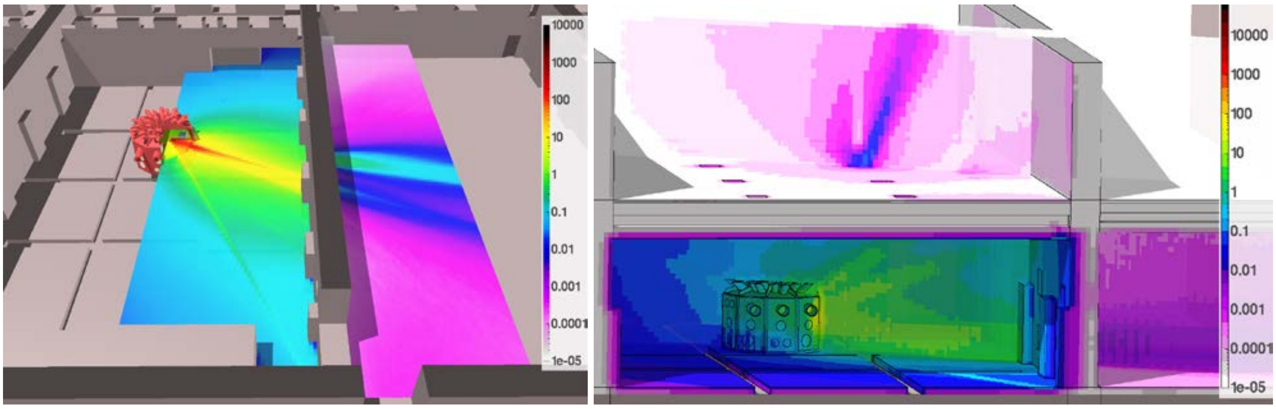

Fig.2 – H(10) rate map [mSv/shot] for P3 beamline, solid target experiment, complex source term (γ, p, e+, e-). Horizontal (left) and vertical (right) plane.*

An example of the calculated dose rate map for one of the beamlines is depicted in Fig. 2, showing the spread of radiation through the opened penetrations to the adjacent halls. Preliminary radioprotection studies for some of the beamlines were already presented elsewhere [11, 12, 13].

4.2. Passive protection - Shielding

Generally valid and well-known principles for shielding design were applied, first for the design of the civil structure, and later for the design of the beam dumps and local shielding. Given the uncertainties in the source term definition, the most conservative approach was adopted for the FLUKA calculations, and an iterative approach was implemented. First, calculations were performed for the ideal experimental conditions, i.e. the maximal possibly achievable source term and the worst geometry arrangements (e.g. all the penetrations fully opened) and only later on, for the fine-tuning of the dumps and local shielding, more realistic source term was considered.

Unfortunately, the complexity of the laser technology and demanding requirements on the properties of the internal building environment (such as temperature or humidity) resulted in a large number of penetrations for various services (about 500 in the radiation controlled zone). All the penetrations were individually assessed for local shielding, taking into account the necessity to provide measures for a combination of hazards – beside ionizing radiation also electromagnetic pulse and fire, while keeping the functionality and flexibility for the various technologies going through. Wherever feasible, the penetrations were built juggled. However, many penetrations have to be straight, typically the penetrations dedicated to laser distribution, where adding an elbow is not only extremely expensive but also strongly affects the laser beam quality. Furthermore, the penetrations are often large, with typical dimensions of 1 m x 1 m, and are effectively empty, as they accommodate vacuum or air-conditioning tubes.

Naturally, the aim of the design process was to provide efficient shielding in compliance with the ALARA principle, i.e. ensuring safety of the people whilst optimizing the shielding in terms of cost and dimensions. A driving requirement was the desire to ensure a full independence of the experimental halls, i.e. the shooting in a particular hall shall not influence work in the adjacent halls. The civil structure was designed so that the annual effective dose accrual would be lower than 1 mSv, or 50 µSv for any employee or member of public, respectively. Typical wall thicknesses between the experimental halls and other areas range between 1 m to 1.6 m. More detailed information about the process is provided in [14]

4.3. Active protection – Monitoring system

Besides the passive protective components, a well-functioning occupational radiation protection system needs access to information about the real-time dose rates. At ELI Beamlines this area is managed by the Monitoring system, which includes workplace, environmental, and personal monitoring. Workplace monitoring covers not only dose rate measurements but also concentrations of technical gases, and clean rooms' conditions (number of particles in the air). The main purpose of the Monitoring system is to provide an early warning when radiation dose rates (or gas concentration) exceed predefined limits. Additional modules take care of activated material storage, and personal dosimetry, especially administration of entries to the controlled zone, and records of obtained doses.

However, obtaining reliable dose rates measurements of the workplaces (control rooms, corridors, experimental halls) is quite challenging, due to the unique characteristics of the radiation generated by lasers – very short pulses with a low repetition rate. The detectors are expected to provide a reliable performance in the mixed radiation field of a wide range of energies, to reliably detect pulses of ~ 20 fs length, to have a good efficiency to the prompt radiation (not susceptible to saturation in high dose rate environment), to be resistant to electromagnetic pulses of few hundreds kV, to be sensitive enough to detect small fractions of legal limits, and to be able to provide on-line data. Similar concerns are valid for personal dosimetry as well. It seems to be that detection by passive systems is reliable [15, 16]; unfortunately, the time needed for dose evaluation excludes the method for on-line monitoring.

The difficulties in the radiation detection in the laser generated fields by active systems arise from the fact that the instruments available on the market are typically designed for in continuous field. As a result a low rep rate, i.e. effectively isolated, very short pulse is dismissed by the electronics as a noise and the device reading is zero. Fortunately, since the interest and the need to measure in pulsed fields are increasing, the topic is discussed within the radioprotection community and some suitable solutions already exist, such as the detectors [17] used at PETRA in DESY.

Due to the abovementioned challenges, ELI Beamlines is planning to combine active and passive systems both for workplace and personal monitoring. Environmental monitoring around the facility premises is performed by passive system only, which is acceptable thanks to justified expectations of the very low dose rates that should be indistinguishable from the background levels.

5. Conclusions

This contribution described the status of the ELI Beamlines facility, with focus on the technical radioprotection aspects associated with its operation. However, at laser facilities, social aspects need to be dealt with as well, probably due to the fact that until very recently, ionizing radiation has never been an issue at laser installations. Laser and plasma scientists are not used to radioprotection concepts and methodologies and show a wide range of attitudes spanning from the reckless to the unnecessarily scared. Therefore, the radiation protection personnel must provide an adequate guidance avoiding patronizing and authoritarian approaches that would be both counterproductive.

In terms of the future radioprotection work, it is important to improve the knowledge of the actual source term and gain better understanding of detector/dosimeter response in the fs pulse radiation fields. Hopefully, once ELI Beamlines is in operation, it will be capable to significantly contribute to increasing the knowledge of these topics.

Acknowledgements

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