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DELIVERABLE 4.3

Detailed analysis of users targets needs to implement mitigation strategies of EMP protection and debris shielding

Work Package #	4.2
Deliverable leader:	ELI-NP
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Abstract:
ELI experimental stations work as user facilities and supply of targets is mission critical. The same is valid for protection from Electro-Magnetic Pulses and Debris Shielding strategies. User workshop analyzing user requirements for key target types was organized and its output together with previous works of the task group was summarized in this document. The EMP generation modes, its mitigation possibilities and the current best practices and measurements were described. The requirements and possibilities for protecting optics and detectors by debris shields and their current implementation experiences were described.

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5/4/22	1.1	DK	Minor corrections, WHshop info added, summary
11/4/22	1.2	MOC	Small corrections
13/4/22	1.3	MOC, DK	Extended introduction and conclusions
18/04/22	1.4	MOC	Small corrections, extended conclusions
26/04/22	1.5	DK	abstract
6/05/22	1.6	MOC	Small corrections
17/5/22	1.7	MOC, DK	Fig. 26 redacted, other corrections

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Table of Contents

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
EC	European Commission
ELI	Extreme Light Infrastructure
ELI-ALPS	ELI Attosecond Light Pulse Source Facility
ELI-NP	ELI Nuclear Physics Facility
EMP	Electro Magnetic Pulse
CLPU	Centro de Láseres Pulsados (Spain)
HZDR	Helmholtz-Zentrum Dresden – Rossendorf (DE)
DS	Debris Shield

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1. Introduction

The objectives of IMPULSE Work Package 4 – "Key technologies & enhanced experiments" are described as follows: *The risk mitigation of the routine operation of research infrastructures as ELI, based on state-of-the-art high peak power, high repetition rates laser systems requires the understanding and control of a few key technologies.*

Task 4.2 implements within WP4 these objectives in the field of targets, debris shields and EMP generation. The main challenge was set as "*A standard and joint approach to the target supply and debris shielding for relevant ELI user experiments, efficient and cost-effective, in the continuity of the ELITRANS work on ELI target standardization and manufacturing capabilities*."

2. EMP and DS Workshop

In order to understand the requirements of the user community and learn about the current EMP and debris mitigation solutions, an online workshop was organized. This document summarizes the information gathered during the workshop and combines it with the work done by the working group of Task 4.2.

The workshop took place between 24-25 February 2022 and was focused on:

- specific EMP and debris challenges encountered in the laser – matter experiments,
- recent theoretical and experimental results on EMP and
- damages induced by debris.

A series of strategies, solutions, requirements and open questions for EMP and debris shielding with respect to target types and materials, their geometry and laser parameters were also discussed. 45 participants were registered and 9 talks were presented during the first day. The discussions on the presented topics were continued the second day, during a 90 min round table.

The link to the workshop agenda with presentations can be found online:
https://indico.eli-np.ro/event/159/

3. Scope of document and structure

During the laser – target interaction with high intensity laser beams like the ones available in the ELI facilities, emission of strong electromagnetic pulses and debris in the form of plasma plume and shrapnel is often generated. The particular problem of EMP and debris especially during the interaction of high power laser pulses with solid targets require protective measures in order to overcome the potential damages induced to the detectors, general electronic equipment and expensive optics. Also, specific tools are required to diagnose the

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electromagnetic pulses and understand the physics of the EMP that will enable better control of electromagnetic fields of high intensity.

The main purpose of the report is to provide requirements, strategies and technical solutions for mitigation of the EMP and debris for an efficient and cost-effective user operation.

The report focuses in the first section on the overview of target requirements in the ELI pillars that have potential in generating EMP and debris. Further on, details are provided on the measurement tools to characterize the electromagnetic pulses and the results obtained for the two typical target types – solid and gaseous. A short resume of the EMP theoretical modelling and simulations is done in Chapter 5 while sections 6 and 7 focus on protective measures implemented for mitigating the EMP and debris generation respectively. Other requirements and future possibilities conclude the report.

4. Target types required by ELI pillars

An extensive survey was done on the targets required by the facilities and their users and is presented below in Table 1

Facility	Material	Target type	Purpose	Applications	Specifications
ELI-NP	**Solid**	**Thick**	Primary and secondary target	1PW& 10 PW laser primary target Gamma beam secondary target	Rep rate: 1/min and 1 Hz Material: Metal, polymers, CH Thickness: microns, Mounting: Frame, wafer or stalks Estimated maximum number/year, by ramping up no of campaigns and shots/day: ~6000
		Thin	Primary target	1PW& 10 PW laser primary target	Rep rate: 1/min and 1 Hz Material: Metal, polymers, CH Thickness: hundreds nm Mounting: Frame, wafer or stalks Estimated maximum number/year, by ramping up no of

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					campaigns and shots/day: ~4000
		Ultrathin	Primary target	1PW & 10 PW laser primary target	Rep rate: 1/min and 1 Hz Material: Metal, polymers, CH Thickness: nm – tens of nm Mass limited also Mounting: Frame, wafer or stalks Estimated maximum number/year, by ramping up no of campaigns and shots/day: ~4000
		Micro/ nano structured	Primary target	1PW & 10 PW laser primary target	Rep rate: 1/min and 1 Hz Mounting: Frame, wafer or stalks Estimated maximum number/year, by ramping up no of campaigns and shots/day: ~1000
		Tape	Primary target Laser beam dump	1PW & 10 PW laser experiments	Rep rate: 1/min and 1 Hz Material: metallic and dielectrics
		Dielectric	Laser pre-conditioning	1PW & 10 PW laser experiments	Rep rate: 1/min and 1 Hz Size: 10-30 mm Diam Estimated max number/year: 18000
		3D	Primary target	1PW & 10 PW laser experiments	Experiment specific Estimated max number/year: 1000
		Foams	Primary target	1PW & 10 PW laser experiments	Experiment specific Low density Rep rate: 1/min and 1 Hz.

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					Estimated max number/year: 1000
		Multilayermulti component	Primary target	1PW & 10 PW mixed particle beams generation	Rep rate: 1/min and 1 Hz Mounting: Frame, wafer or stalks Estimated max number/year: 1000
		Isotopical enriched		Gamma beam	Rep rate MHz, target doesn't need replacement
		Cryogenic	Primary	1 PW and 10 PW	Rep rate: 1/min and 1 Hz Experiment specific Type: Layers, ribbons
	Liquid	**Sheet and jet**	Primary target and plasma mirror	1PW & 10 PW laser experiments	Rep rate: 1/min and 1 Hz Liquid crystal type, CH based – plasma mirror Liquid jet/droplet hi-rep as primary target part of mixed particle beams generation
	Gas	**Jet and cell**	Primary target	0.1, 1 and 10 PW	Rep rate: 10Hz, 1/min and 1Hz Different lengths and geometries
	Biological targets		Secondary target	1 PW	Rep rate 1Hz Experiment specific

Facility	Material	Target type	Purpose	Applications	Specifications	
ELI-ALPS	**Solid**	**Thick**	Plasma Mirror (PM) Interaction	Higher Harmonic Generation EMP	Material Operational Mode	AR coated glass (silica) 1 kHz, 10 Hz Single Shot

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			Secondary Source (Seso)			Size 20 CM dia circular
		Foil	SeSo Interaction	THz (Generation, Samples) Particle Acceleration X-ray, XUV EMP	Material	Al, Au, Ta, Ti, PE, Deuterated PE Diamond like Carbon Nano and micro structured Targets Aerosol Targets (Foam)
					Thickness	50 nm -> 12 um
					Target Holder	Matrix Elements
					Operation Mode	High Rep-rate (>= 1Hz); Single Shot
					Maximum laser Energy	34 J
	Liquid	**Sheet**	SeSo Interaction	Particle Acceleration X-ray, XUV PM	Material	H_2O, D_2O, Molecular Liquids
					Thickness	100 nm to 12 um
					Operation Mode	Ultra High Rep-rate (1 kHz), single shot
					Maximum laser Energy	100 mJ -> 34 J
		Shaped	SeSo Interaction	Particle Acceleration	Material	H_2O, D_2O, Molecular Liquids

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				X-ray, XUV XUV induced ionization studies in water solved samplse (Task 4.4)	Thickness	100 nm à 12 um
					Operation Mode	Ultra High Rep-rate (1 kHz), Single Shot
					Maximum laser Energy	100 mJ à 34 J
	Gas	**Static**	Seso Interaction	Electron Acceleration XUV, atto-second	Backing pressure: 0 —2 bar Gas: He – Ne, … Operation Mode: Single Shot, kHz	
		Pulsed	Seso Interaction	Electron Acceleration XUV HHG	Backing Pressure: 0 – 100 bar Gas: He, Ne, H2, … Operation Mode: Single Shot, kHz	

Facility	**Material**	**Target type**	**Purpose**	**Applications**	**Specifications**
ELI-Beamlines	**Solid**	**Thick**	Primary target if requested by users	1 PW laser	Rep rate: single shot and 1 Hz Material: metallic Thickness: microns Mounted in our frame holder Estimated max number/year: 1000
		Thin	Primary target if requested by users	1 PW laser	Rep rate: single shot and 1 Hz Material: metallic Thickness: sub-micron Mounted in our frame holder Estimated max number/year: 1000

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		Ultra-thin	Primary target if requested by users	1 PW laser	Rep rate: single shot and 1 Hz Material: metallic, polymers, CH Thickness: 10 nm Mounted in special frame holder Estimated max number/year: 10000
		Micro-nano structured	Primary target	1 PW laser	Rep rate: single shot and 1 Hz Mounted in our frame holder Estimated max number/year: 1000
		Tape	Primary target	1 PW laser	Rep rate: up to 10 Hz Material: metallic and dielectric Qty: 10s of meters
		Cryogenic	Primary target		Rep rate: up to 10 Hz Solid H2/D2 ribbon Cryogenic liquid jets TBC

5. EMP generation in high power laser experiments

Intense broadband electromagnetic pulses (EMP) in the GHz to THz range are generated in the interaction of high intensity laser pulses and matter, in particular solid targets. When the laser pulse hits the sample energy is transferred to electrons which can be accelerate to relativistic energies. The result is broad emission (from GHz, THz to Xrays) of radiation due to the recirculation of hot electrons in the sample. A fraction of these electrons is ejected from the target. The resulting positive space charge drives return currents in the target holder structure that acts as an antenna and emits EMP in the GHz range.

The vacuum chamber acts as a resonance cavity and its geometry therefore defines resonant frequencies of the emission. EMP properties depend on a number of factors, including target geometry and composition, holder structure and material, chamber geometry and laser pulse properties (energy, pulse duration and temporal laser contrast).

Both return currents and radiated EMP can cause severe problems in electronic systems electrically connected to the target or located close to the vacuum chamber. The operation of sensitive components can be compromised or even damage can occur.

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Current techniques for damage prevention include shielding electronic components with Faraday cages; using shielded cables; turning off and electrically decoupling devices during the laser shot; placing any sensitive equipment far away from the interaction area; and ensuring a good isolation to the sample.

Many plasma diagnostics, e.g. time-of-flight techniques rely on the measurement of fast, amplified or non-amplified signals with fast electronic detectors (photo-diodes, photo multipliers etc.) and fast oscilloscopes. The optimization of the signal-to-noise ratio of these techniques is highly complicated by the plasma induced EMP and often deserves special mitigation strategies.

5.1 EMP measurement tools

When a high-power laser beam is focused onto a small solid or gaseous target, secondary particles such as high-energy electrons, ions and neutrons and X – rays, γ-rays and electromagnetic fields of tens or hundreds of kV/m typically flood the target chamber. The region of EMP in a band from several MHz to several GHz is generated mainly by the space charge fields induced by impulse of charged particles, voltage pulses emanating the interaction region and return currents towards the discharged target.

The EMP is generated mainly by the impulse of charged particles, which excites the chamber and equipment within it [M J Mead, D Neely & P Patel, Review of Scientific Instruments, Vol. 75, No 10 Oct 2004]. This causes the chamber and equipment within it to resonate at its natural frequencies, which can extend from MHz for the chamber cavity up to THz for smallest target structures. Also, the EMP is emitted from the chamber through ports and wiring into the surrounding room, where it is modified by reflection and absorption from equipment and the walls of the room. The EMP is also propagated down the beam tube to the laser components, as through a waveguide. It can be concluded that EMP of various spectrum and spectral energy distribution is present at all locations in target areas of high-power laser systems. Thus, EMP can be coupled into measurement devices and have a wide range of possible effects, from an increase of noise to a full system failure.

There are various cases where EMP plays a role and application-case tailored known mitigation strategies can be:

- Semiconductor devices in equipment within the target chamber and surrounding rooms are susceptible to damage and malfunction by EMP induced voltages. These need to be protected by shielding or moved away from the source of EMP.
- Signals from target diagnostics are degraded by EMP pick-up.
- There is also a need to ensure that the level of EMP in occupied areas outside the target area must be safe for personnel within the exposure limit values established by Directive 2013/35/EU. Even though there is no known case where limits designated to the mobile phone standards (GHz frequency band) are exceeded, constant monitoring could be a valued feedback to facility staff, guests and users. Further, research on

biological effects of EMP is a hot topic in the laser-plasma community, attractive for potential users.

It becomes thus obvious that in such a harsh environment, detecting unique physical phenomena specific for high power laser-driven experiments should not be hampered by EMP pick-up by susceptible semiconductor-based diagnostics. Designing a proper EMP shielding on different levels, from the interaction chamber as root to the full target area, and especially for individual diagnostics represents, consequently, a high priority at high-intensity laser facilities. Note that EMP mitigation is not only limited to shielding but can also involve structural changes to the targetry [P. Bradford et al., DOI:10.1017/hpl.2018.21].

The ELI lasers operate at high repetition/shot rates which implies increased stress levels for equipment and operators if no shielding measures are undertaken.

Using passive diagnostics inherently immune to EMP, is not viable mitigation option, as they cannot be used at high repetition rates. This raises significant engineering challenges for the teams involved in the development of the instrumentation for experiments. A good understanding of the magnitude and frequency range of the EMP helps establish the source terms of EMP, the strict control of unwanted conducted and radiated EMP emission, developing of models and developing the efficient EMP shielding system. Consequently, a significant effort for developing EMP measurements installations has been made by the scientists from ELI pillars and the respective partners.

The appropriate sensors for measurement of EMP produced in laser experiments are the conductive probes [https://www.montena.com/system/measurement-technique-and-tools/] for electromagnetic fields and the electro-optical sensors [F. Consoli et al., Scientific Report, 6:27889 | DOI: 10.1038/srep27889, 2016]. The electro-optical sensors are still under development and are not the subject of the current study. Nevertheless, as they do not disturb the fields and are immune to ionizing radiation, they can be installed very close to the laser targets. These can be considered an advantage over conductive probes which are usually deployed far from the interaction region. Their use opens up new perspectives for measuring EMP and especially for understanding the physics of laser-target interaction. For this project. However, deployed conductive sensors should still be installed inside and outside the target chamber; they will also remain in operation after future electro-optical metrology is available as an engineering tool. The conductive probes are simple dipolar antennas and inductive resonating loops, improved by manufacturers to increase the upper-frequency limit for differential mode operation.

Usually, the conductive probes are symmetrical differential structures, so, they are also immune to ionization radiation coming from the laser when placed far enough away from the target, because the output generated by ionizing radiation appears as a common-mode signal, which is rejected by the balun. This converts the differential output signal to a single-ended signal. Due to their simplicity, they are often built locally as well [P. H. Duncan, IEEE Trans. on Electr. Comp. 16, 83-89, 1974]. The sensors are usually made of low atomic number materials to reduce electron emission, they are vacuum compatible and therefore can be positioned both inside and outside target chambers.

The basic principles of these antennas are the simple shape and radiation pattern, the sensitivity to one component of the field and the ease of use. They are narrowband and the operational frequency strongly depends on their physical dimensions.

Measurement in the target chamber

The source of EMP is located in the interior of the target chamber. A complete characterization of the EMP produced in the target chamber involves the measurement of electric and magnetic fields in a location within the target chamber, in the widest practicable range of frequencies. In other words, several probes of the same type (magnetic or electric) are needed to cover a wider range of measurements. It is also necessary to simultaneously measure the electric and magnetic fields, considering that the intrinsic impedance of the chamber cavity does not match the value of the impedance for free space, and the conversion between the two fields is not possible.

Measurement in the experimental area

The target chamber is not a perfect Faraday cage, even if its walls are metallic. The presence of vacuum ports for alignment and diagnostics, and the electrical feedthroughs allow radiative and conductive emissions from the chamber. Measurements in the exterior of the target chamber are usually simpler because EMP fields generated in the chamber are reduced due to the shielding effectiveness of the vacuum enclosures. The sensors can be placed at reasonable distances from other objects and only one field, magnetic or electric, is enough to be measured. The conversion between the physical quantities can be done using the relationship: **H**=**E**/Z, where **H** is the magnetic field strength, **E** – is the electric field strength and Z is the impedance of free space. The region of interest is occupied by electronic equipment, which is exposed to the still very high magnitude of EMP. These fields can still produce major damage to susceptible electronics and this is why it is important to make accurate measurements.

The EMP measurements are polluted by background EMP fields acting as high-intensity noise on the full readout system. Thus, the background field can be directly coupled with the digitizers or can penetrate within the transmission lines (usually coaxial cables), where the measured signals are travelling, and then added to them. Therefore, special attention shall be paid to the choice of shielded coaxial cables and the shielding of the readout system. The readout shall be enclosed in shielded cabinets and placed far away from the EMP source. The bandwidth limitations of digitizers, cables, feedthroughs, connectors and attenuators used to diminish the input signal in the readout system is an issue that shall be carefully considered in the design of EMP monitoring tools. Considering all the above, an EMP measurement tool shall be able to measure both electric field and magnetic field in the frequency range from a few MHz to many GHz [Mihail Cernaianu and Marius Gugiu, EMP and Debris Mitigation Challenges in Commissioning Experiments at 1 PW level in ELI-NP, EMP and Debris mitigation workshop, 24-25 February 2022], [Stanislav Stancek, ELIMAIA system commissioning 2021/11 - EMP measurement and mitigation, EMP and Debris mitigation workshop, 24-25 February 2022].

The role of the EMP measurement tools (Figures: 1-3) shall be to:

- Measure the EMP produced inside and outside the target chambers;
- Verify the effectiveness of the EMP shielding around the target chambers, experimental areas and the shielded enclosures;
- Study the generation of EMP to find how to reduce or mitigate its effects.

The EMP measurement tool shall be capable of being set up to capture waveforms when triggered by trigger signals coming from the laser. It shall include all the following elements, which are:

- Sensors (ELI-NP used B-dot, D-dot probes and homemade Moebius loop magnetic fields probes, positioned inside and outside the target room and on the technical corridor; ELI-Beamlines used D-dot probes, H-field probes, omnidirectional antenna and double ridged Horn antenna, positioned inside and outside the target chamber, inside and outside shielded racks, in the control room),
- Cabling (shall be used good quality cables, shielded, with low insertion loss, large operating frequency and with proper connectors, attenuators, etc.)
- Electronics rack (shall be chosen shielded cabinets fitted with power lines filters for electronics)
- Trigger equipment (Trigger signals mediated via optical cables, delay generators, etc.)
- Acquisition equipment (large bandwidth oscilloscope and fast digitizers with large sampling frequencies).

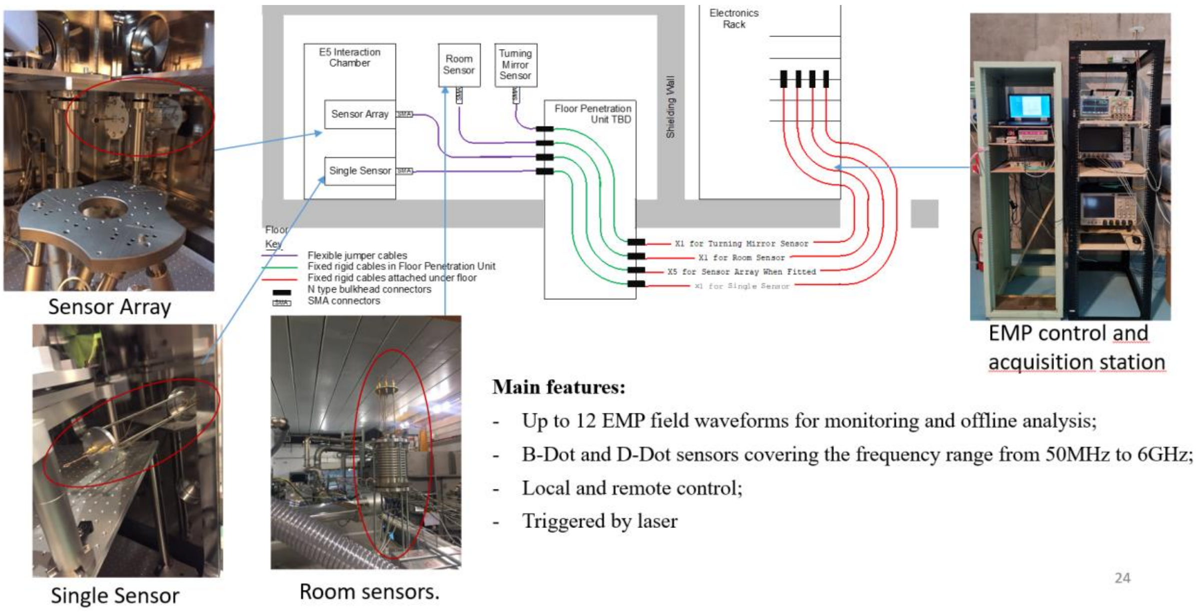

Figure 1 Overview of EMP measurement tool developed by ELI-NP for commissioning experiments at 1PW level [M. Cernaianu]

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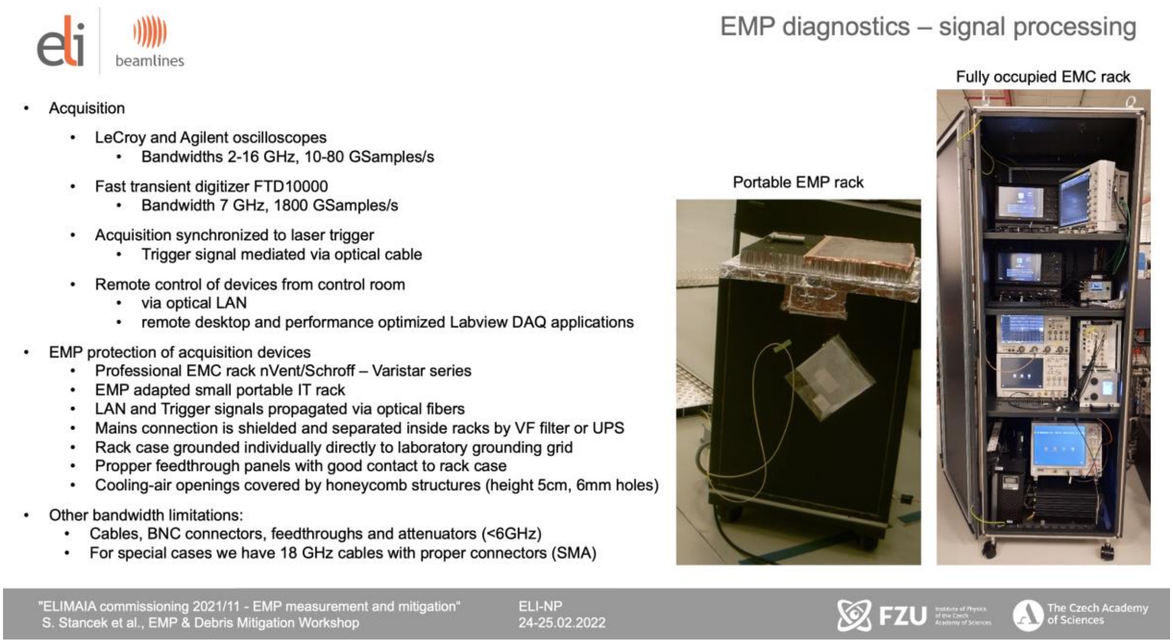

Figure 2. Overview of EMP measurement tool developed by ELI-Beamlines for ELIMAIA commissioning experiment [S. Stancek]

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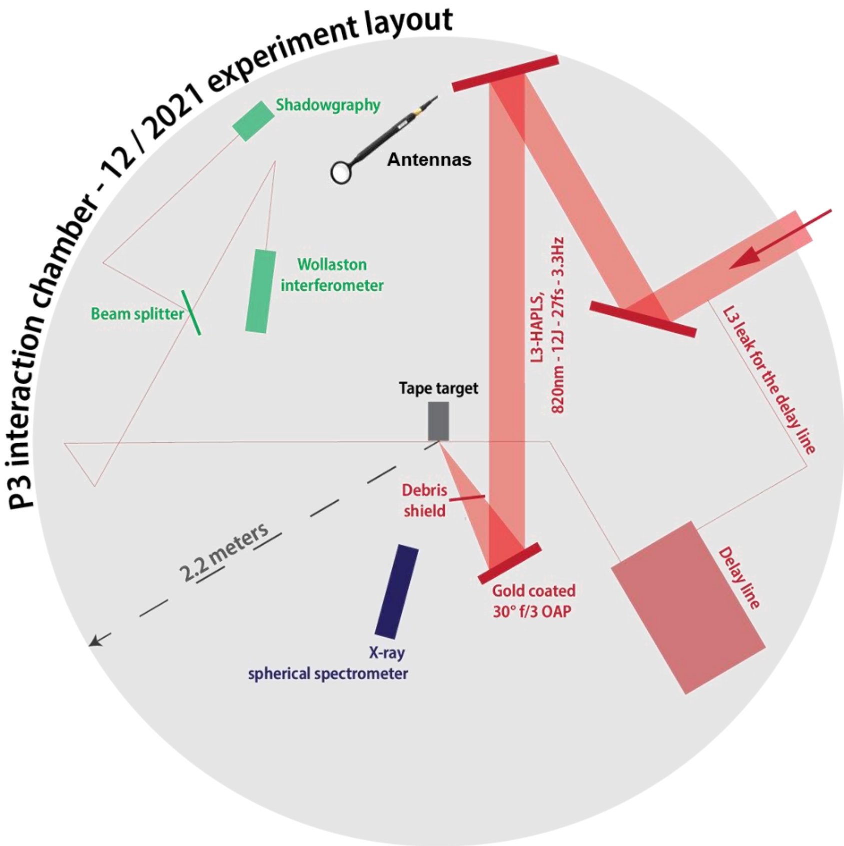

Figure 3. Sketch of the experimental setup iin P3 chamber at ELI Beamlines [T. Lastovicka, EMP monitoring and debris mitigation in the P3 chamber at ELI-Beamlines, EMP and Debris mitigation workshop, 24-25 February 2022]

5.2 EMP Measurement results: Solid and Gas targets

5.2.1 EMP measurements ELI-Beamlines L3-HAPLS

Figure 3 presents the Short Focal Length (SFL) experimental setup used for the high power commissioning of the L3-HAPLS laser inside the P3 chamber. Due to dimensional and spatial restrictions, tested debris shields were placed between the f/3 OAP and the tape target.

The level of EMP was monitored by two passive H-probes (Rohde & Schwarz RSH400-1) installed inside the P3 chamber approximately 1.8 m from the focal spot in two orientations (in the vertical and the horizontal planes), see **Error! Reference source not found.**. The signals were attenuated by 18 GHz, 20 dB attenuators and digitized by a fast oscilloscope KeySight DSO-S 604A (6 GHz, 20 GSa/s). Additional cable shielding braids were not used. The EMP signal was used during the commissioning to address the relative intensities of laser-plasma interaction and, particularly, the impact of the debris shield transparency deterioration.
The measurement of EMP RMS is shown in Figure 4 for single shots and bursts. Each day, a new debris shield was used. **Error! Reference source not found.** (left) shows a continuous

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decrease in the EMP RMS over the whole day for both 5 J and 10 J shots with approximately the same slope. The level of EMP went down by about 12.5% over one day. It is assumed that this decrease was due to the debris shield, which became partially coated by debris and partially imprinted by the laser beam, see Figure 27.

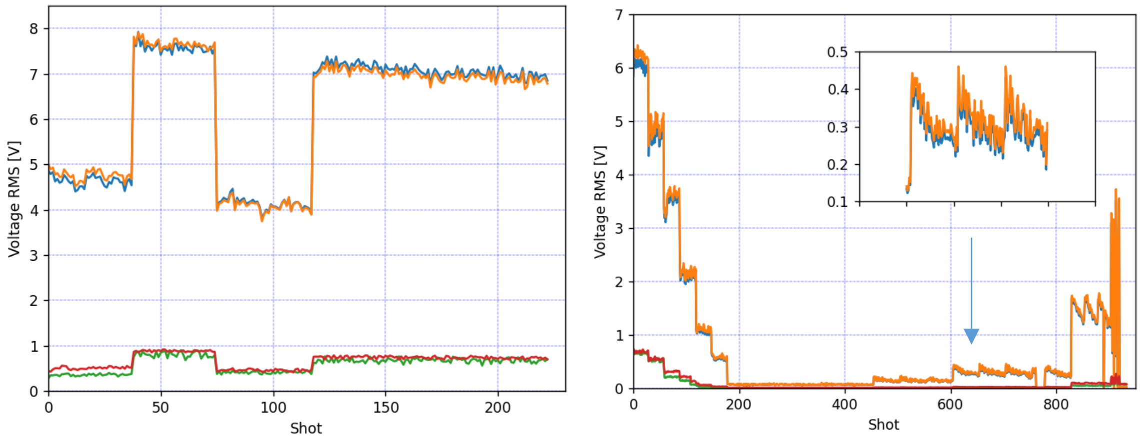

Figure 4. The EMP RMS for two H-probe orientations (orange, blue) is shown for 5 J and 10 J single shots on Thursday 16/12 (left) and single shots (<200 shot on the X-axis) and burst shots (>450 shot number on the X-axis) on Friday 17/12 (right). The red/green lines correspond to the cable noise levels due to the EMP. The antenna cables picked up this noise both inside and outside the P3 chamber.

Figure 4 (right) shows another effect, which can be observed by monitoring EMP levels. The EMP RMS level goes quickly and sizeable down during each burst. Then, with the new burst, it is restored and drops down again in the same manner. This effect is expected and is assumed to be caused by the laser beam wavefront changing during bursts and consequently defocusing due to changing thermal conditions. The bursts were 50 shots long at a 3.3 Hz rate and various energies, from 0.3 to 2 J. At the end of the day, when the laser beam energy was 4J, the tape target ran out of the tape (see the rightmost side of **Error! Reference source not found.** (right)).

Although no calibration was done, we theoretically estimate the absolute EMP levels to be on the level of 7-8 kV/m RMS inside the chamber when using 25 um thick iron foils as targets.

When no additional shielding braid was used, the EMP level picked up by the shielded RF antenna cables (Figure 4, red and green lines) is about 10% of the whole signal on an absolute scale. However, it affects the measurement much less (approx. 0.5%) since the antenna and cable signals add in quadrature. Nevertheless, ELI-BL plans to use additional braids to shield antennae cables and shielding racks to shield electronics in the future.

5.2.2 EMP measurement CLPU (ELI-ALPS)

CLPU reported on the characterization of EMP driven by relativistic fs-laser pulses both on solid as on gas targets. Concerning solid targets the EMP measurements were reported on 10 um Au targets with an intensity on target of 10^{20} Watt/cm^2. The amount of charge was

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estimated based on the model of A. Poye, et. Al. Phys. Rev. E 98 (2018). The reconstruction of the spectrum was obtained by finite element modelling with the commercial software COMSOL

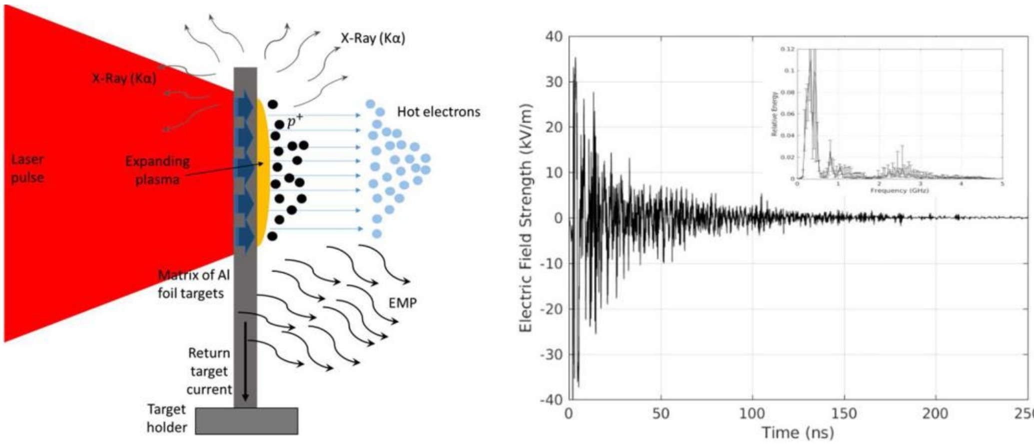

Figure 5(a) Conceptual scheme of laser-solid target interaction with EMP generation. (b) Typical EMP signal detected at 30 cm from the target. Inset: normalized spectrum averaged over 23 shots. K. Nelissen et. al, Sci. rep. 10, 3108 (2020)

More recently, measurements were performed on gas targets using both VEGA-2 and VEGA-3 as driver laser. VEGA-2 has a pulse energy in the range 3-5J, a maximum intensity on target of 10^{19} Watt/cm^2 with focusing parabola of F/13. Vega-3 has pulse energy in the range 10 -30 J, a maximum intensity on target of 10^{20} Watt/cm^2 with focusing parabola of F/10. A schematic of the experimental setup is shown in the figure below were the left figure represents the VEGA-2 setup and the right figure VEGA-3.

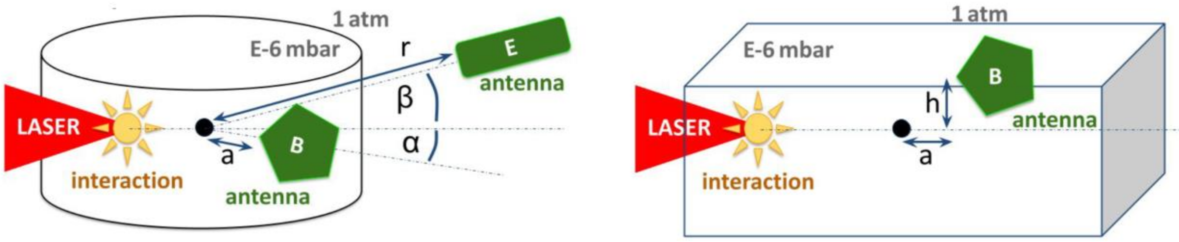

Figure 6

The eigenmodes were modelled with COMSOL. Example modes are shown in the figure below [E. Jensen, RF Basics & TM Cavities (2017)].

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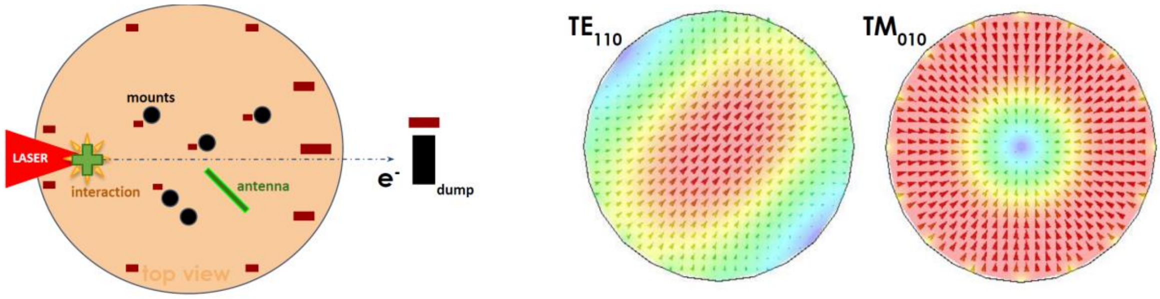

Figure 7

For the measurements, commercially available calibrated magnetic- and electric-field antennas are used to capture electromagnetic waves inside and outside the interaction chamber. For the following, the magnetic field antenna MDF-9400 (9 kHz – 400 MHz, Aaronia AG) and the electric field antenna OmniLOG-30800 (300 MHz – 8 GHz, Aaronia AG) were used. The out-gassing of both antennas was tested before use, see fig. 4. Regular immersion into the main interaction chamber should not degrade the vacuum to values above 1e-6 mbar, thus antennas are suited for measurements. Nevertheless, they can contaminate higher cleanliness chambers. Antennas are oriented vertically, their coordinates are given in the following with respect to the center of the cavity. The horizontal holding stalks of antennas are from segments of 1/2" diameter plastic cylinder. This mounting via insulators is intended to reduce the noise.

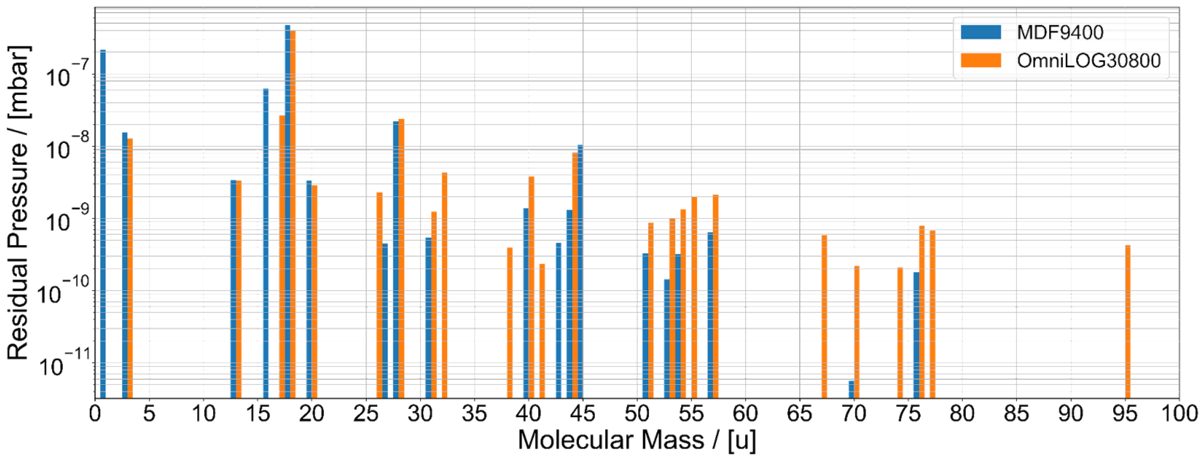

Figure 8 The residual pressure of detected molecules in a high vacuum chamber for two commercial antennas. [M. Ehret, EMP a the VEGA experiment stations at CLPU, EMP and Debris mitigation workshop, 24-25 February 2022, TBD picture and permission]

In a first experiment the VEGA-2 laser at CLPU (Salamanca, Spain) is focused into a gas target aiming at laser-wakefield acceleration of electrons, such as in [L. Volpe et al., doi:10.1017/hpl.2019.10]. The laser pulse with on-shot laser energy in the range from 3 – 5 J is focused by a f/13 off-axis parabola to 1e19 W/cm2 at best compression with 30 fs pulse duration. The radially Gaussian gas jet is set to attain the peak electron density of 1e18 /cm3 at full ionisation, with a full-width-half-maximum (FWHM) of 8 mm. The used gas is Helium.

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The interaction point is 30 cm off-centre with respect to the cylindrical vacuum chamber of radius 60 cm. The magnetic field antenna is positioned inside the cavity at polar coordinates (a = 8 cm, α=π/4). The signal of antennas is transported via calibrated double shielded SMA cables and through floating feed-throughs to an oscilloscope with 2 GHz bandwidth and 10 GS/s sampling rate (Rohde&Schwarz DPO64). Conductive connection of SMA cables and ground is avoided completely.

As observed for solid targets [K. Nelissen et al., doi:10.1038/s41598-020-59882-8], the EMP spectrum during laser shots reveals the pill-box cavity mode structure of the interaction chamber, see fig. 5.

The cavity modes are directly related to the geometry of the target chamber and the experimental setup within. Prediction of free bands prior to experimental campaigns can be based on the geometry of the experiment. Such free bands can be used for experiment-specific inductive measurements of fields.

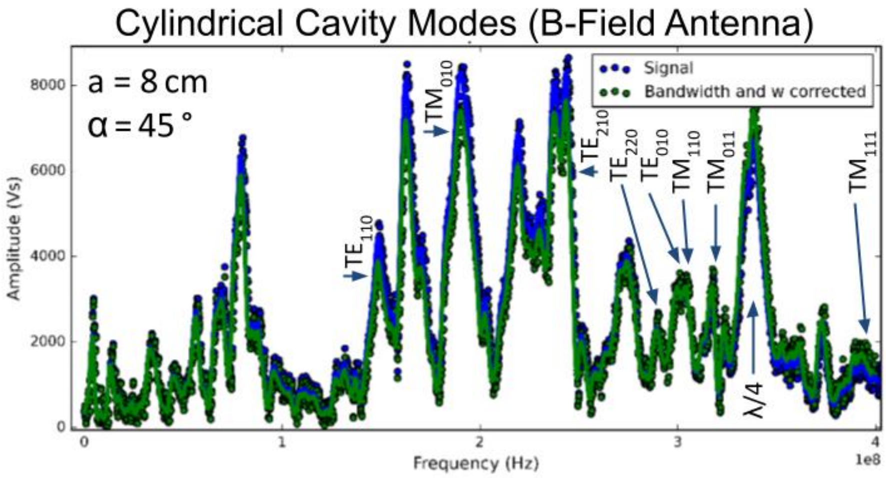

Figure 9: Time integrated spectrum of the magnetic field measured in the VEGA-2 interaction chamber for a shot on an under-critical density gas jet target, with indication of identified pill-box cavity modes (TM and TE) and the resonance of the vertical stalks that hold optics (λ/4). [M. Ehret, EMP a the VEGA experiment stations at CLPU, EMP and Debris mitigation workshop, 24-25 February 2022]

At last, the EMP was characterized in the experimental hall. The maximum Electric field strength measured at various locations in the experimental hall are shown in the figure below.

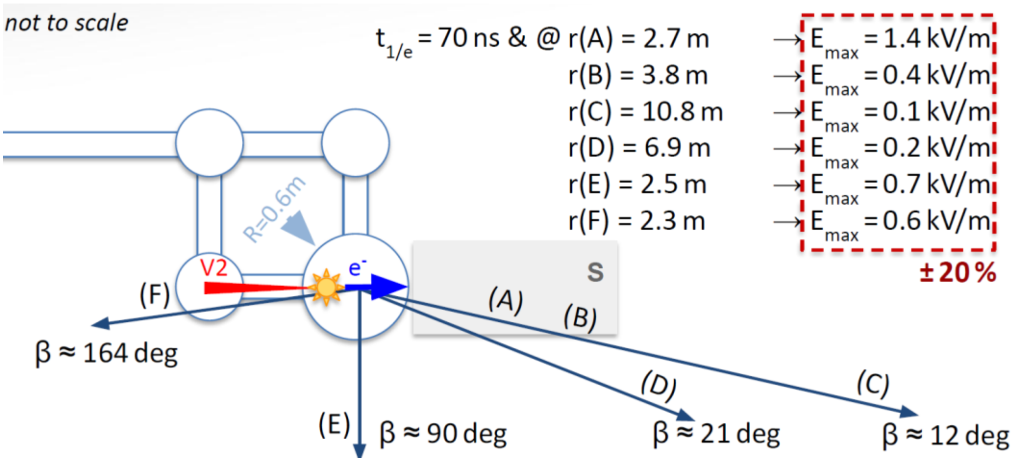

Figure 10

The scaling of maximum electric field strength as function of the distance to the interaction chamber was obtained by fitting the experiment results shown in the figure below:

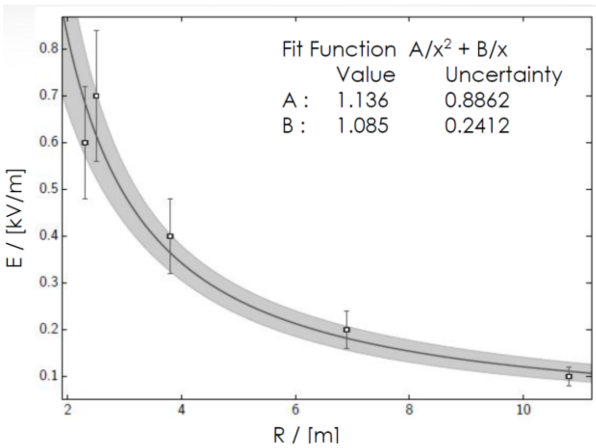

Figure 11

5.2.3 EMP measurement at ELI-Beamlines ELIMAIA

EMP measurement results during the ELIMAIA commissioning 2021/11.
Contributing authors: S. Stanček, L. Giuffrida, F. Schillaci, F. Grepl, M. Tryus, A. Velyhan, V. Kmetík, D. Margaron.

Experimental setup:
During the experimental campaign the following probes were used:
Probes used:

- Montena: SFE3_5G double D-dot, Bandwidth 3.5GHz, D-field probing
- The Rohde-Schwarz H-probe RSH400-1, Dloop = 25mm, Bandwidth 3.5GHz, H-field probing
- Omnidirectional antenna I-ATO5 380/6000, Bandwidth 6GHz
- Double ridged Horn antenna Rohde-Schwarz HF-907, Bandwidth 18GHz

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The positioning of the probes are shown in the figure below:

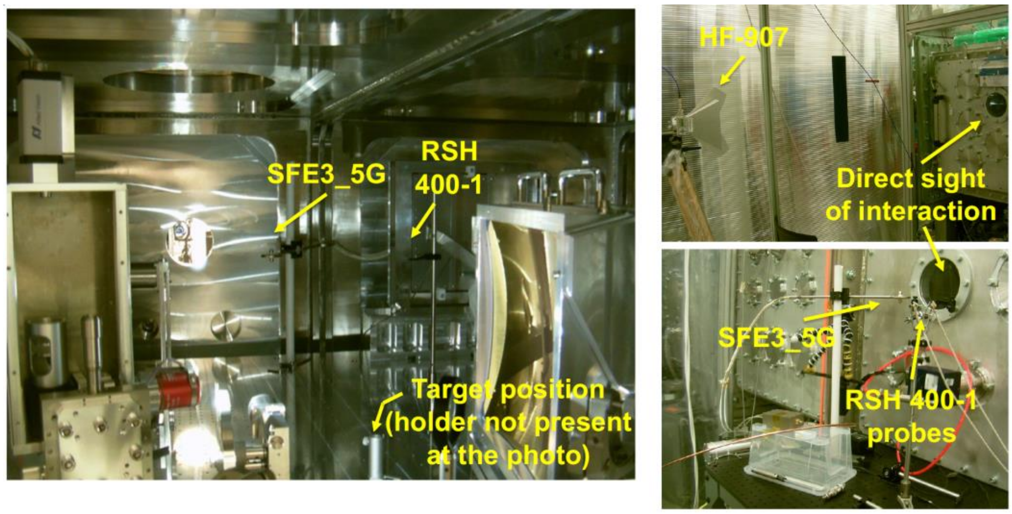

Figure 12

The measured H-field measured inside and close to the EMC rack is shown in the figure below:

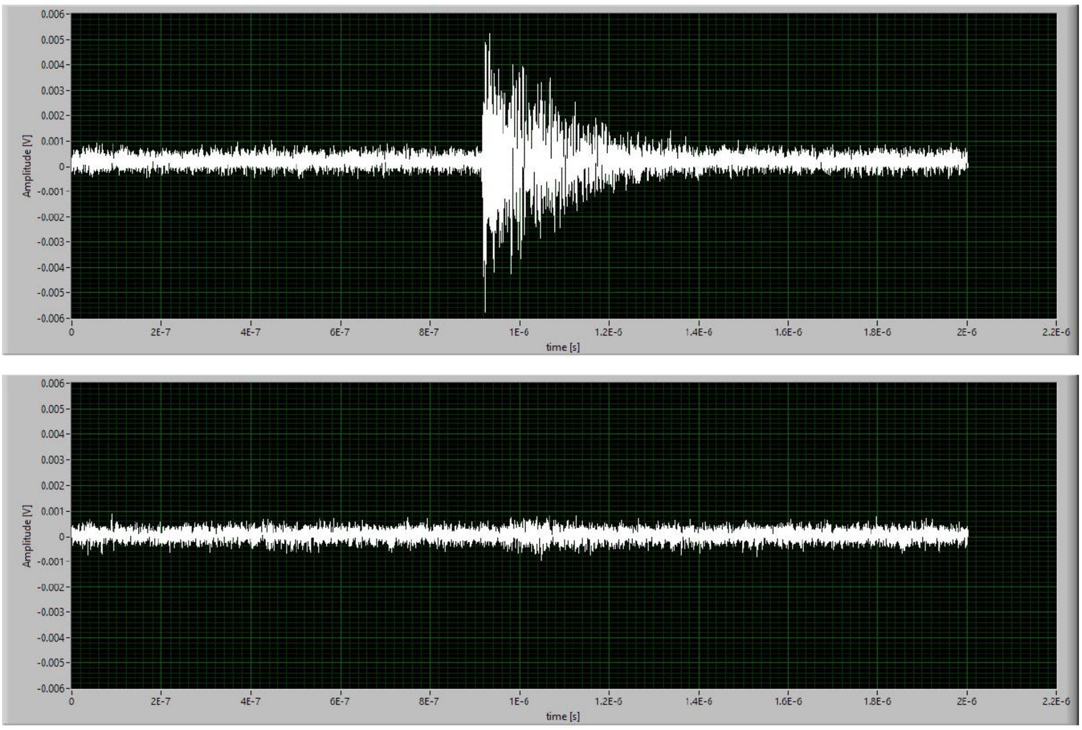

Figure 13: Measurements outside and inside the EMC rack

The laser energy on target was 12 J, the target was made of 13 um thick Mylar, the EMC rack was placed 5 m from the interaction chamber.

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The following figures compare the EMP level inside and outside of the interaction chamber. In figure below on can observe that frequency below 0.6-0.8 GHz are cut-off. The upper figure show the EMP amplitude inside the chamber while the lower figure show the amplitude outside the vacuum chamber. This is visualized by the red marking in the figure below. This frequency correspond to the cur-off frequency of a waveguide with dimensions 25-18.75 cm which is matching with the size of the viewport.

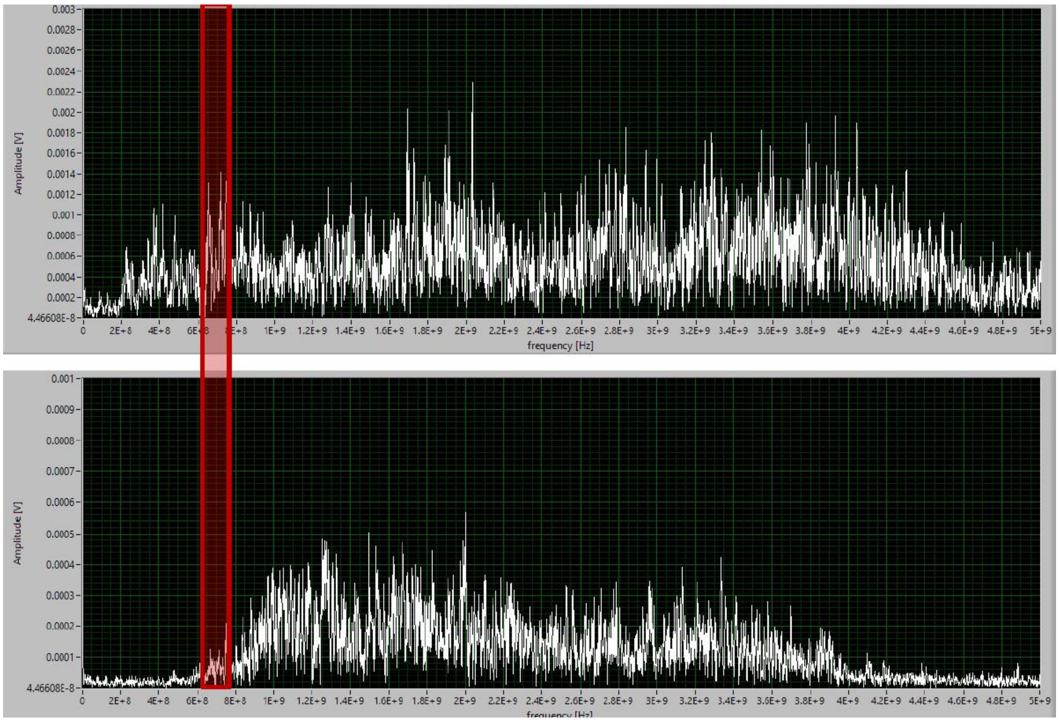

Figure 14: EMP spectrum measured inside and outside the vacuum chamber.

From this one can conclude the all frequencies higher than the cut-off frequency of the viewports can escape the chamber. The results above were obtained with a laser energy of 10 J on a Nickel foil target of 7.5 um thickness.

5.2.4 EMP measurement at ELI-NP

Contributors: Mihail O. Cernaianu and Marius Gugiu

In the figure below an EMP sensor array in an interaction chamber is shown

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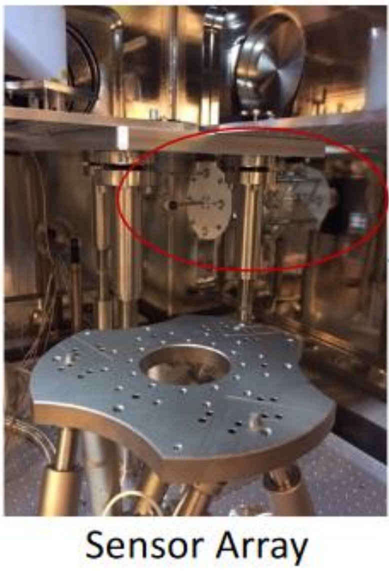

Figure 15 Sensors array mounted inside the vacuum chamber at ELI-NP in the 1 PW chamber

Three different mechanisms for producing EMP are identified:

- First component: Chamber ringing at its natural frequency in the MHz domain
- Second component: Antenna radiation excited by the transient return current in holder in GHz domain
- Third component: Emission of THz radiation due to a very short duration jet of hot electrons produced in the target

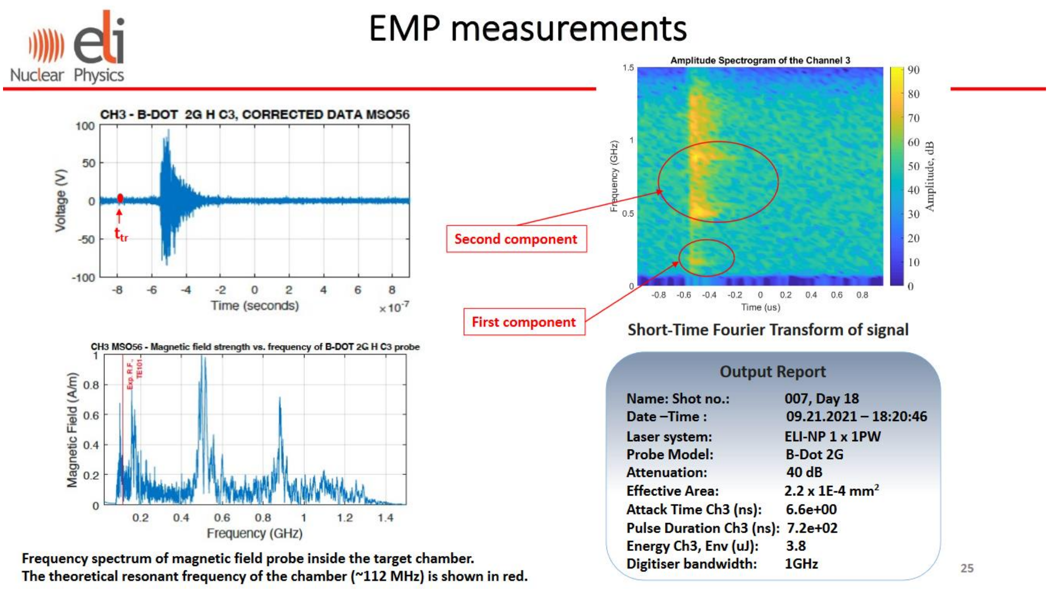

Figure 16 EMP time domain and frequency spectrum obtained at 1 PW at ELI-NP. The first and second component are encircled in red in the upper right figure.

IMPULSE has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161.

5.3 EMP theoretical modelling and analysis

The simulation of the laser-generate electromagnetic field is challenging because the EMP combine various effects related to laser-matter interaction, particle diffusion and collision in the target, with the electromagnetic circuit aspects, such as current flows in conductors and dielectrics, and only a few codes can handle this. A suitable candidate for this kind of simulation is CST Studio Suite, a commercial software [https://www.3ds.com/products-services/simulia/products/cst-studio-suite/] that has the combined circuit and PIC capability to model the resulting electromagnetic fields. Likewise, we have to deal with a multitude of disparate length scales, such as laser-plasma interaction scales, target size, stalk size and target chamber size. This involves many time scales from tens of fs for laser-target interaction to hundreds of ns for EMP oscillating within the target chamber. Often, to simplify the EMP generation model, a small region in the vicinity of the target and a short time after laser-target interaction is considered [Piotr Raczka, On the nature of laser-generated electromagnetic pulse emission and the possible mitigation methods, EMP and Debris mitigation workshop, 24-25 February 2022]. In this approximation, the majority of EMP reverberating inside the target chamber is generated in the microwave frequency domain [J. L, Dubois et al. Phys. Rev. E 89, 013102, 2014] by fast electrons escaping from the target [C. J. Brown et al. Journal of Phis: Conf. Series 112, 032025, 2018]. The evolution of the hot electron cloud generated within the ionized laser target and the evolution of escaped electrons from the target can be treated according to the simple method developed by A. Poye and his collaborators [A. Poye et al., Phy. Rev. E 91. 0433106 (2015)]. This can be used to estimate the target charge and to assess the spectrum and the density of the electrons emitted from the target and can be introduced as input in the numerical simulations.

To assess the possibilities of mitigating the EMP at the source two simple concepts were considered: controlling the target stalk impedance and inductance by optimizing the material it is made of [P. Bradford et al. High Power Laser Science and Engineering, vol 6, e21, 2018] and confining the EMP field in a finite volume of a birdhouse [J. L. Dubois et al., Rev. Sci. Instrum. 89, 103301, 2018]. The origin of the EMP is in the ejection of high-energy laser-accelerated electrons. The model assumes the EMP is generated by the return current in the target, flowing to compensate for the deficit of charge created between target and chamber by laser-target interaction and exciting the target stalk, which acts as a monopole antenna.

The preliminary numerical simulations performed by IFPILM [Piotr Raczka] and independently, by ELI-NP, on the influence of the target mount on EMP magnitude by changing the material of the stalk that supports the target, from metal to dielectric, predict a substantial reduction in peak magnetic field. These predictions are in agreement with the measurements performed at RAL, where a factor two reduction in peak magnetic field was observed, as can be seen in Figure 17, taken from the reference [F. Consoli et al., High Power Laser Science and Engineering, vol 8, e22, 2020]. For the current study, only the cylindrical stalk was considered. The preliminary results of the simulations above mentioned, show that if the target is closed in the metal birdhouse [D. C. Eder, Lawrence Livermore National Laboratory LLNL-TR-411183 (2009)] or in a birdhouse with a dielectric crossbar, the level of the magnetic signal decreases considerably, especially in the second case. These are in

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agreement, too, with the measurement performed at LLNL, where a reduction of the EMP magnitude by a factor of 3 was obtained. This is depicted in Figure 18, captured from reference [D. C. Eder]. The simulated frequency spectrums present large contributions in very broadband frequency for the metal stalk. For dielectric stalk, there is an obvious tendency for broadening the frequency spectrum toward higher frequencies, compared to the previous case studied. For the two birdhouse configurations simulated, the frequencies are shifted at higher values. The birdhouse with a dielectric crossbar has very small contributions to the frequency spectrum. This seems to be an appropriate design approach for EMP mitigation, when it can be integrated into the experimental setup.

An interesting aspect noticed is a clear evidence of the leakage of information contained in the simulated signals, if a high-pass filter above 6 GHz frequency, the typical bandwidth of the oscilloscopes used in experiments, is applied. A more laborious analysis of the simulation results is required, but extending the ability to measure EMP over a broadband (DC-20 GHz, at least) is worth considering.

In summary, the experimental results obtained at PW class laser facilities and preliminary numeric simulations performed predict that one can mitigate EMP by using a dielectric stalk and birdhouse concepts, when applicable in experiments.

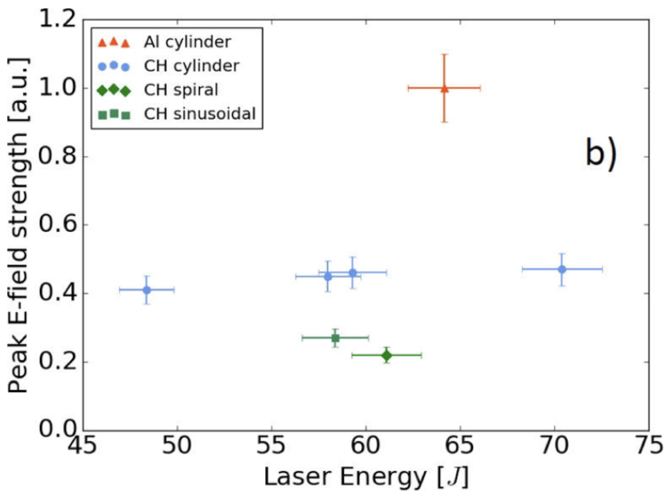

Figure 17 Normalized peak electric field strength plotted as a function of laser energy for aluminium and CH stalks with cylindrical, spiral and sinusoidal geometries. Data is taken from the D-dot east probe and presented as a fraction of the peak electric field for the aluminium stalk [F. Consoli].

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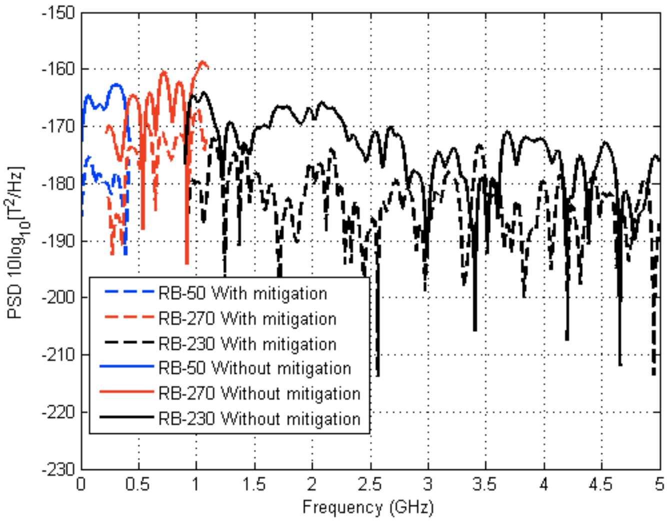

Figure 18 The EMP power spectral density measured by 3 B-dot probes for a target with and without a mitigation sphere surrounding the target [D. C. Eder].

5.4 EMP mitigation techniques

5.4.1 Mitigation strategy at ELI-NP

Several techniques and solutions were employed at ELI-NP to protect the EMP effect on general electronics and detectors during the shots:

- Fiber bundles inside vacuum chamber for online imaging diagnosis. Readout was placed in air.

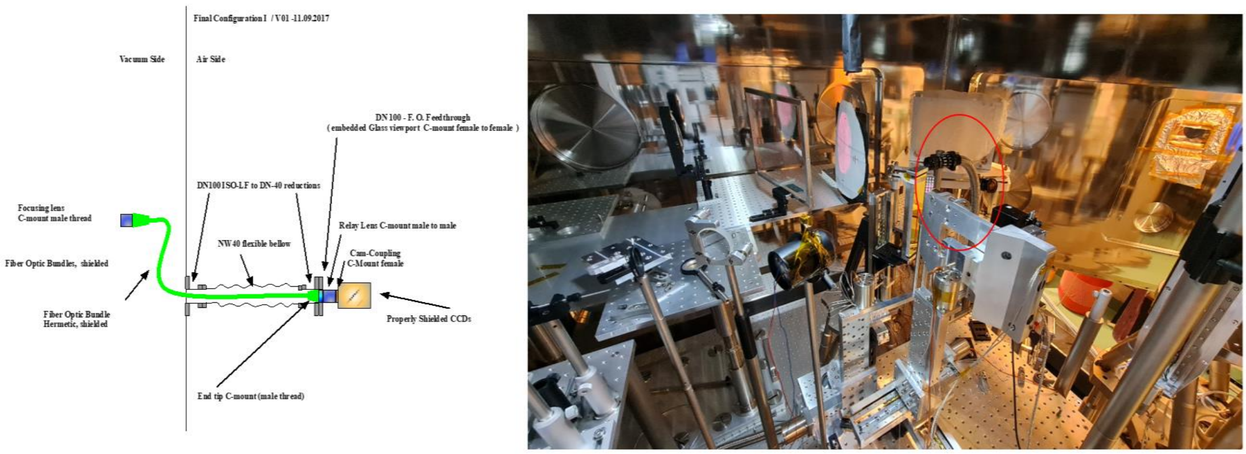

Figure 19. Design for imaging inside the vacuum chamber using fiber bundles and implementation in the ELI-NP 1 PW experimental area on a solid target experiment [Mihail Cernaianu and Marius Gugiu, EMP and Debris Mitigation Challenges in Commissioning Experiments at 1 PW level in ELI-NP, EMP and Debris mitigation workshop, 24-25 February 2022]

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- Typically low-frequency control and instrumentation is placed into vacuum (CCD cameras for visualizing moving equipment, focal spot camera, etc).
- Use of remote controlled relays to turn off equipment (e.g. motorized stages, visualizing CCDs inside vacuum) during shots.
- Shielded cables inside vacuum and outside (air), shielded connectors, control units installed in shielded cabinets, very good grounding.
- Second EMC gasket on the vacuum flanges to provide SE of at least 60dB over the frequency range of interest
- Vacuum feedthroughs with EMP shielded plugs, MIL-C connectors, shielded cables & overall braided copper screen, Twisted pair cables to minimize EMP pick-up

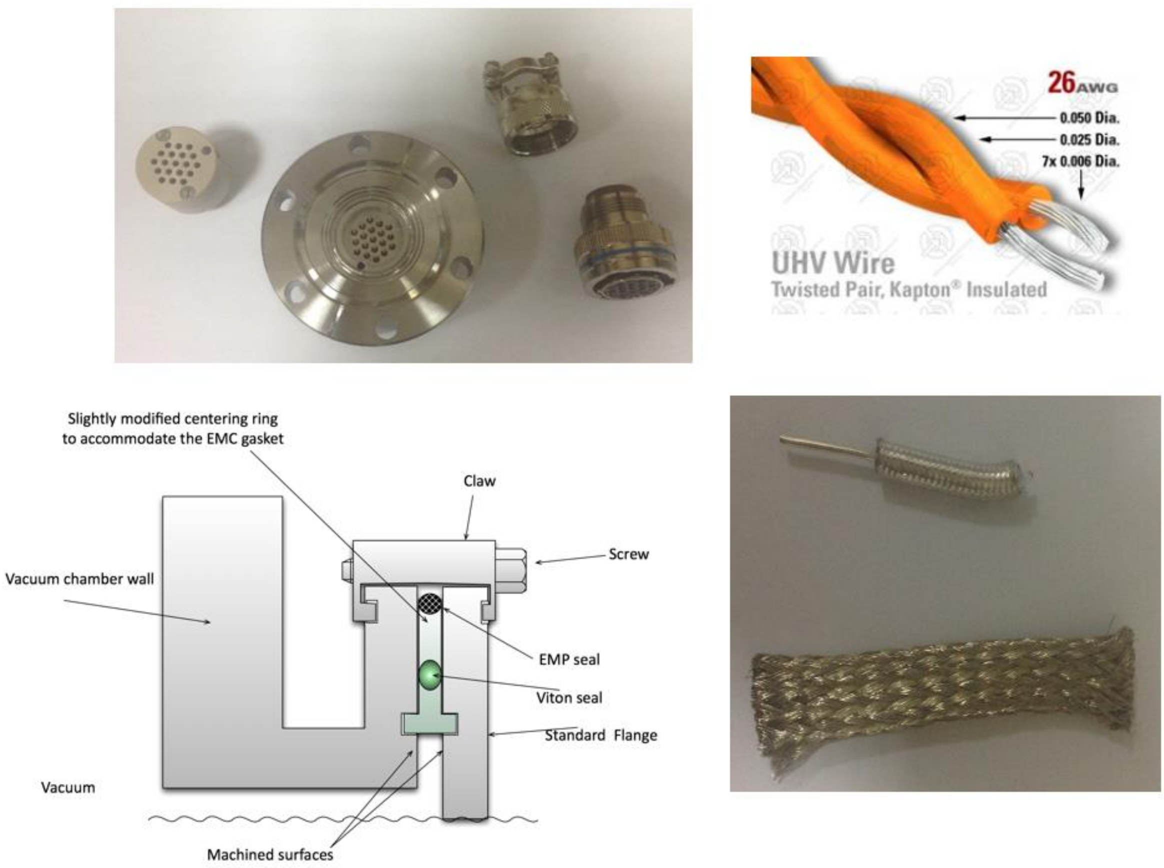

Figure 20 Examples of MIL-C connectors, twisted cables, EMC flanges with EMP seal and cables shielding used in the experimental setups at ELI-NP [Mihail Cernaianu and Marius Gugiu, EMP and Debris Mitigation Challenges in Commissioning Experiments at 1 PW level in ELI-NP, EMP and Debris mitigation workshop, 24-25 February 2022]

- To the largest possible extent, use of fiber optics for communication
- Control units and electronics placed outside the experimental area installed in shielded enclosures and fitted with EMP filters
- Control and instrumentation wiring outside shielded racks in the experimental shall follow good EMC practice as:

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- Shielded twisted pair cable shall be used for low frequency control and instrumentation.
- Coaxial cables shall be used for high frequency signals. Cables shall have an overall braided copper screen.
- Cables shall be terminated by cable glands or connectors providing 360° shield connection to metal enclosures.
- Connector types shall be chosen to allow connector filters to be added to overcome EMP problems found during operation.

5.4.2 Mitigation strategy at HZDR

A few general methods applied during experiments at the Draco PW laser facility to minimize the influence of EMP are listed in the following. Cables and sensitive electronic components inside and outside the chamber need to be shielded appropriately. Al foil, Cu cloth, braided sleeves or Faraday cages were implemented successfully. Cable loops should be avoided and perfect grounding improves EMP shielding.

Cameras and network switches turned out to be sensitive to induced EMP leading to problems while data acquisition. As the EMP distribution is very non-uniform, a simple strategy turned out be relocation of the devices or to increase their distance to the chamber. Oscilloscopes directly collect EMP even if strong shielding is applied and should, if possible, be operated outside the hutch. Optical decoupling of signals should be considered whenever appropriate. As the main source of EMP is the laser irradiated target inside the vacuum chamber, electrical isolation (e.g. ceramic posts) of the target frame has reduced EMP influences significantly. This measure reduces the return currents into the target stages and enables more robust operation. For experiments with large EMP generation, e.g. if low temporal contrast is applied or huge target pre-plasma is present, additional relays can be used to decouple the sensitive target stages from the controller during the shot.

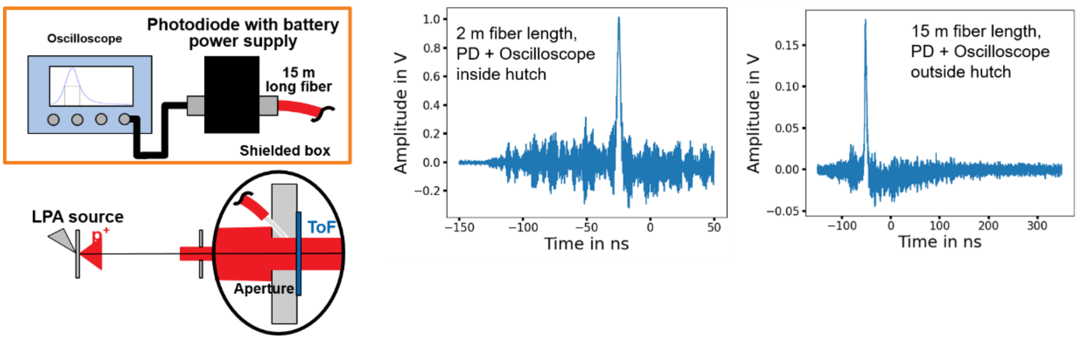

Figure 21 EMP mitigation example 1: Proton time-of-flight measurement using an optical fiber coupled scintillator and a photo diode read out with an oscilloscope. Increasing the length of the fiber from 2m to 15m and relocating the oscilloscope outside the hutch reduced the EMP noise down to 10 %. The signal level reduction is due to additional dispersion in the fiber.

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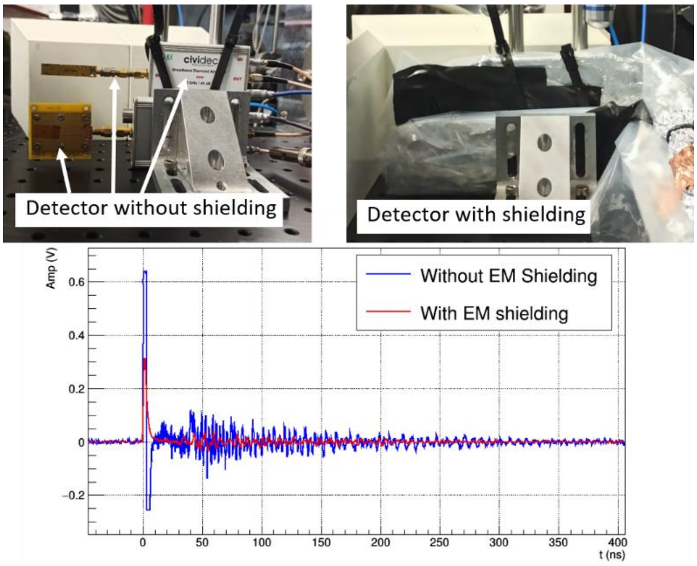

Figure 22 EMP mitigation example 2: Neutron time-of-flight measurement with diamond detector. Pre-amplifier is closely connected to the sensitive detector.

Signal improvement after appropriate shielding is shown on Figure 22 (cables, separate power supply, avoiding cable loops etc.).

6. Debris mitigation solutions

During high intensity and high power laser-target experiment a considerable amount of debris can be generated which can contaminate final focusing optics. Over multiple target shots, accumulated debris on the optics will lead to performance drops or even failure. Furthermore, neighboring targets on the target frame can be damaged or unintentionally modified. For high intensity lasers, optical elements can be very large and expensive to replace or the refurbished. This issue is becoming even more important on the advent of large user facilities, such as the ELI pillars, facilitating high repetition rate experiment combined we a large power and intensity on target. Former mitigation techniques included maximizing the angle of incidence, i.e. the angle between laser incidence and target normal, placement of debris shields and pellicles.

The thickness of the pellicle is however limited by the non-linear phase that is accumulated in the transmission. This can be expressed by the B integral given by:

$$B = \frac{2\pi}{\lambda} \int_0^L I n_2 dl,$$

Where I is the laser intensity, Gamma is the laser wavelength, n_2 the nonlinear index of the material, and L the thickness of the Debris shield. This means for petawatt-class experiments the thickness of the pellicle is limited to micrometers.

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6.1 Debris mitigation strategies at HZDR

The main strategy to mitigate the influence of debris to neighboring targets is the design of special target frames intrinsically shielding nearest neighbors or to keep sufficient distance between the targets. The protection of optics, in particular the main focusing off-axis parabolic mirror is achieved by implementing additional debris shields in front of the optics. They are based on thin plastic pellicles or glass plates coated with anti-reflection layers on both sides. The quality of the anti-reflection coating is continuously reduced during operation due to the accumulation of material. Besides simple reflectivity changes also other optical properties (spectral amplitude and phase) of the transmitted laser pulse could be disturbed. Also, shielding of targets or other optics by additional mechanical parts may cause unwanted side effects or diagnostic artefacts as illustrated in the following examples.

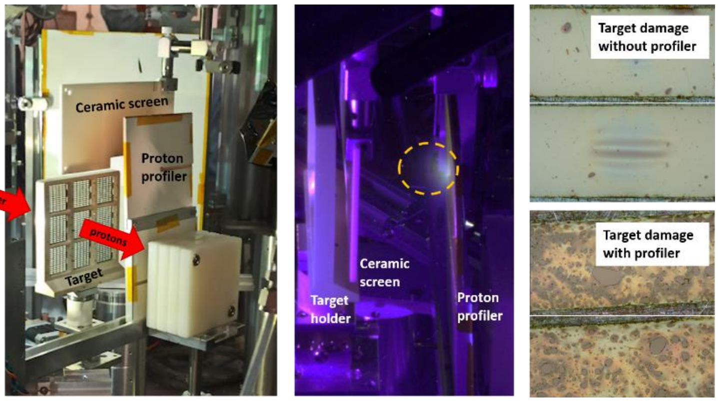

Figure 23 Debris mitigation example 1: Target damage induced by laser light transmitted through the target. This light component is still intense enough to damage neighboring targets when scattered off the proton profiler in a few centimeters distance. Ablated material from the proton profiler screen might be emitted, too. Additional shielding with ceramic plates behind the target frame helps to mitigate secondary damage.

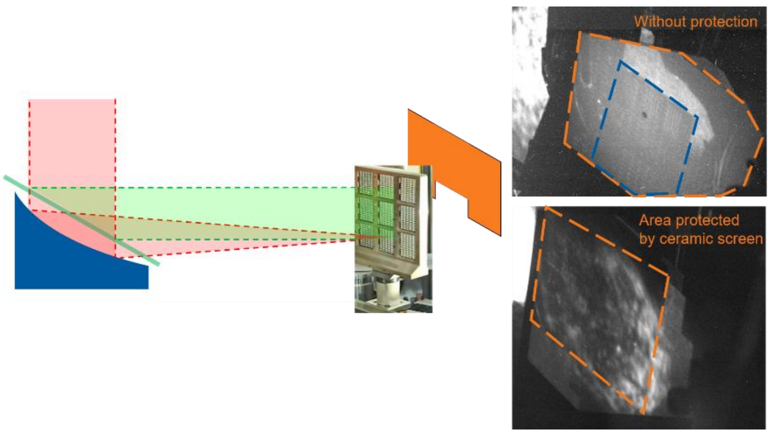

Figure 24 Debris mitigation example 2: Unfocused reflection from the debris shield in front of the main focusing optics compromises the characterization of the transmitted target profile. Additional ceramic screens (illustrated in orange) behind the target can block this light.

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Debris free hydrogen jet target developments at HZDR within IMPULSE

The ideal solution to mitigate the generation of debris from the target is to develop so-called debris-free targets. Several laboratories have been developing cryogenic systems for in-situ target formation based on extrusion, casting or condensation. Recently, HZDR implemented cryogenic hydrogen jets for the generation of high energy proton beams. There, hydrogen liquefies in a source cooled by liquid helium and then solidifies at the moment it exits the nozzle into the vacuum due to evaporative cooling. After the laser shot, no debris potentially coating neighboring optics is produced as the material is gaseous at ambient temperatures and removed by the vacuum pumps. Due to the replenishing nature of the jet, a fresh target is provided for every shot.

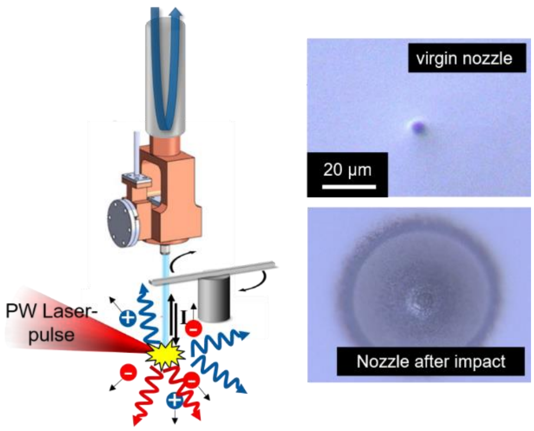

Figure 25: Schematic view on the cryogenic hydrogen target. Strong photon and particle emission from a plasma driven by a PW class laser impacts the nozzle aperture and destroys it after a single shot (comparison of right images taken of the aperture before and after a shot). A rotating mechanical blade can protect the nozzle from the impact by blocking the direct line of sight if synchronized to the main pulse interaction.

However, in the harsh environment of the high-power laser plasma interaction particles and radiation are generated which can damage the fragile nozzle apertures (see figure). The laminar flow of the material through the nozzle gets disturbed and the jet operation stops. To mitigate this effect a concept based on a rotating mechanical chopper plate was tested. If correctly synchronized to the main laser pulse arrival, the plate blocks the direct line of sight between the laser-plasma interaction and the nozzle, preventing any damage resulting from direct impact of radiation coming from the plasma. Crucial for the error-free operation is a minimal jitter of the plate position in time and space with respect to the laser pulse arrival. However, the synchronization of this proof-of-principle device was limited by the driving electronics as well as the influence of EMP.

Within the IMPULSE project, a new chopper assembly utilizing direct position feedback by hall sensors will be developed and tested in the experiment running at full laser energy. The goal is to design a compact assembly to clear the space around the target interaction point best as possible. The hall sensors guarantee a strongly improved timing jitter of the rotating blade in the order of few µs. However, the introduction of electronic feedback for the

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synchronization from close proximity of the laser-plasma interaction requires development of effective countermeasures like shielding and insulation against the EMP.

As an interesting alternative beyond the rotating device, compact piezo driven chopper systems will be investigated. The significantly smaller size and the much simpler synchronization to the laser pulse arrival of piezo designs allow much more flexible on-demand operation. The close proximity of the sensitive piezo crystals to the laser-plasma interaction again poses significant challenges on the EMP shielding and reaching sufficient blade velocity in the order of meters per second with piezos is another difficulty.

6.2. Debris mitigation solutions ELI-ALPS

In the current design of the PW target holder a debris shield is implemented to avoid debris propagation within the chamber and on the different optics. Next, the debris is continuously monitored by imaging the laser target surface.

The z-direction of the target surface is monitored in order to allow fine tuning of the focal spot. A smaller spot size as a result will consequently lead to lower debris emission from the target surface.

Figure 26 (figure redacted due to confidentiality)

Mitigation on the kHz 120 mJ plasma mirror

In order to mitigate the debris from the plasma mirror an R&D project was initiated replacing the solid target plasma mirror by a liquid leaf target.

6.3 Debris mitigation solutions ELI-NP

During the commissioning experiments at ELI-NP with the 1 PW laser beam on solid and gaseous targets, debris was generated inside the interaction chamber. The laser energy was ramped up to 23 J and the pulse compressed down to 23 fs.

Several solutions were employed to limit the damages induced by the debris depending on the target type.

Solid target experiments:

- Target generated debris

During the campaign on proton acceleration via TNSA, to limit the back-reflection and debris generation the target was placed at AOI greater than 30˚. Additionally a protective AR coated nitrocellulose pellicle (~8µm thickness) with large aperture was placed in front of the OAP.

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This proved effective in protecting the optics against plasma plume and was used with success for more than 300 shots. However, this solution is not available in very large size, for instance as needed for the 10 PW optics. Where possible, baffles were also placed to shield other small optics and vacuum components from the plasma plume.

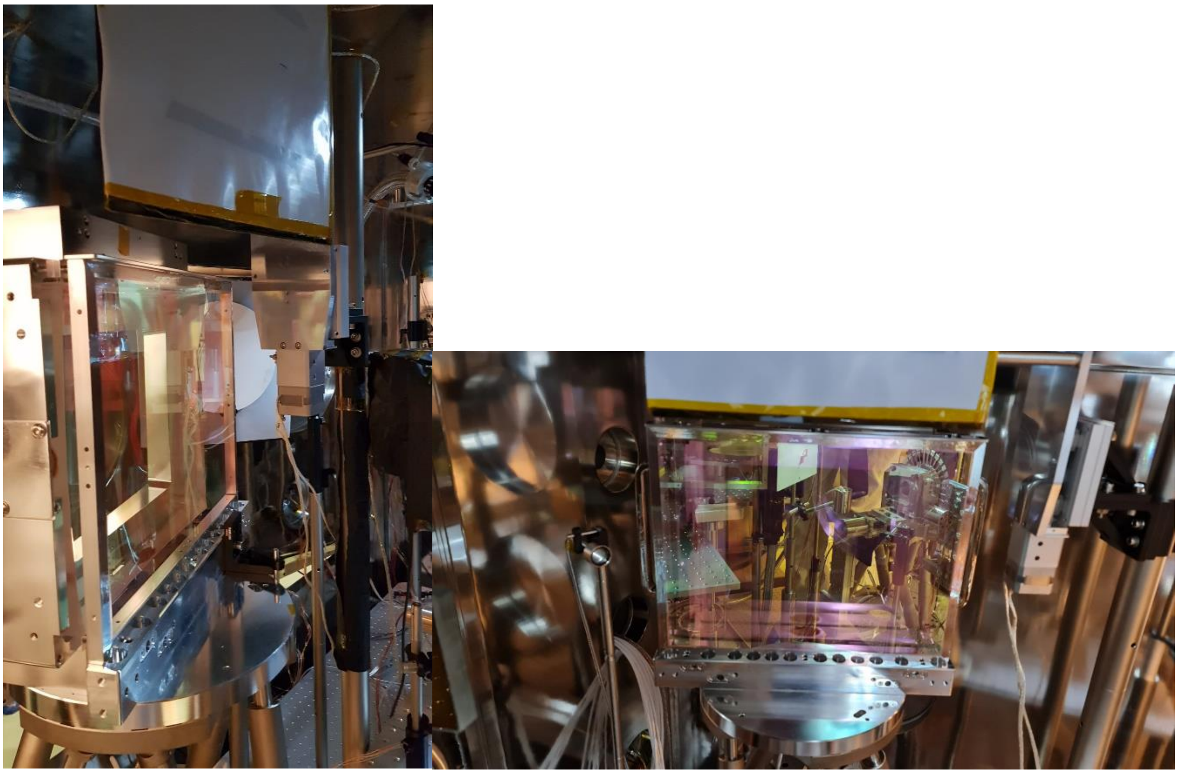

Figure 27 Protective pellicle placed in front of the OAP in solid target experiments

Another way to limit the side-effect of the interaction is using an AR coating single plasma mirror in between the OAP and target. This has the dual purpose of blocking the direct sight between target and parabolic mirror, then greatly reducing the debris impinging the parabolic mirror; and also improving the laser temporal contrast.

- Laser induced debris

To protect different critical components of the setup from laser ablation, generated by the specular reflection of the laser from the target or from stray light, PTFE screens were also used inside the vacuum chamber.

Gaseous target experiments:
In this configuration, debris is typically generated by the scattered/transmitted laser beam through the plasma and the interaction with the laser beam dump. Protection of the optical and other components inside the vacuum chamber from the debris is typically done with baffles and shielding. PTFE screens are also used to protect from reflections of stray light.

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6.4 Debris Mitigation at ELI-Beamlines

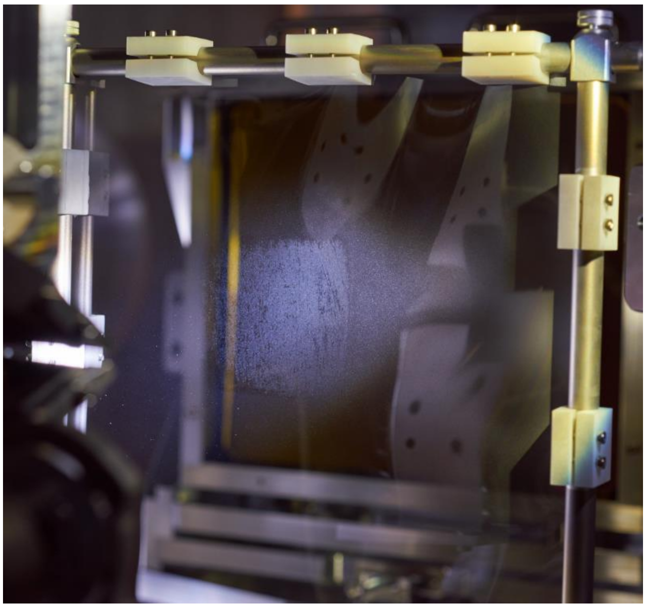

Figure 28 Debris shield appearance after high power single shots and bursts at the end of December 17th, 2021. The L3-HAPLS beam imprint is visible. Furthermore, the shield's left side is clean, while the right side is significantly more coated with debris.

Debris shields

Schott slide (30 µm thick glass) was used during high power shots and placed between the OAP and the interaction point according to the experimental setup in Figure 2. In addition, other debris shields from General Atomic (GA) (different types of 2 µm thick plastics) were also tested but in low power shots. The main reason was the risk of beam clipping due to the not adapted GA shields sizes to HAPLS beam size and experimental setup. However, a GA shield was permanently placed inside the P3 chamber to monitor its mechanical robustness during multiple pumping and venting cycles. As a result, the shield stayed intact for all ten pumping cycles during the experimental campaign.

The Schott slide survived hundreds of 10 J shots and prevented the OAP from being damaged by the debris, as discussed above and shown in Figure 28, after 908 shots. Without the debris shield and considering the repetition rate of the laser, the OAP would be most likely, severely damaged by solid targets debris in a single day during future user operations.

It can be partially seen in Figure 28 that part of the slide was coated by target debris. Furthermore, the HAPLS beam imprint is clearly visible. This imprint is not due to target debris but rather by a high fluence of the partially focused beam, which we estimate to reach a level of about 300 mJ/cm^2.

Unfortunately, the thin slides did not survive the standard default P3 vacuum chamber venting cycle using the central CS default procedure. Venting is too fast, causing the slides to break instantly. Instead, the P3 had to be vented manually while constantly inspecting the status of the slides and adjusting the venting speed accordingly.

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7. Summary and outlook

In this report we addressed the topics of EMP and debris generation in high power laser experiments and presented a wide range of measurement tools, mitigation solutions, theoretical and simulation techniques.

The report presents in Section 4 an extensive survey done for the targets needed by the ELI facilities and their different characteristics. A large category is represented by the solid targets that in particular are the source of generating the EMP when hit by the high power laser as described in Section 5. Details are provided in Sections 5.1 and 5.2 on the measurement tools used to characterize the electromagnetic pulses and the results obtained for the two typical target types – solid and gaseous with a strong focus on the first type. In Section 5.3 we addressed the relevant topic of EMP theoretical modelling and simulations. Among other relevant data, several preliminary numeric simulations are summarized that predict EMP mitigation via different target geometry or enclosing concepts, where applicable.

Section 5.4 is reserved to EMP shielding techniques where a broad range of solutions is presented from equipment shielding, detectors positioning to target insulation. Finally, Section 6 addresses the topic of debris generation and describes different solutions used to overcome the contamination of optics and targets damage.

A wide and evolving range of target types are required by the scientific users of the ELI experimental systems, therefore the mitigation effort will be a constant endeavor building on the experience obtained within the ELI user community.

Advanced solutions to shield optics in high rep rate experiments have to be developed as well as recoating capabilities for the final focusing elements. ELIAS coating capability is expected to be a great asset allowing quick recoating of parabolas or debris shields. Simple debris shield or window recoating procedures like i.e. sol-gel process should be ideally tested as well.

Cleaning mitigation procedures should be investigated together with task 4.1 in order to allow high rep rate operation in contaminated high vacuum environments.

Efficiency of debris/blast shields shall be continuously assessed during the high energy ELI experiments to enable optimized operation of the target setups.

EMP mitigation and metrology solutions will have to be adapted to the 10 PW class experiments expected in the near future. Additionally, the simulation of the EMP generation and different attenuation methods could be numerically investigated and tested for multi-PW experiments.
Evaluating the vulnerability of plasmas diagnostics and of various optical components is a key challenge due to the harsh environment created by the interaction of laser beam in the 1PW to 10PW range operated at high intensity. The workshop organized in the context of the impulse task 4.3 has been reviewing a large set of existing data and simulations on electromagnetic pulse and debris shielding and is offering preliminaries strategies to mitigate

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risks. For robust diagnostics operating on a long term with users, studies will have to be continued on specific ELI facilities using various experimental geometries. The present work is a very useful guide for the design of experiments and associated diagnostics in order to achieved noise control and optimization of the component life time. Lessons learned about vulnerability from experimental programs actually initiated at ELI will be important to extend the present work including the effects of high level of radiation (hard X-rays and gamma rays) and energetic particles.

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