RADIATION PROTECTION FOR LASER–PLASMA ACCELERATOR FACILITIES AT DESY

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Abstract

DESY draws on more than six decades of experience in the development, operation, and radiation protection of large-scale user facilities such as PETRA III, FLASH, and the European XFEL. In parallel, the investigation of novel accelerator technologies for future applications has become a key focus. Laser-plasma acceleration (LPA) offers the potential for highly compact, high-gradient sources, as demonstrated by the FLARE, LUX, KALDERA, and VERA facilities at DESY. However, LPA systems introduce new challenges for radiation protection due to broadband emission spectra and the interplay of high-power lasers with plasma-generated secondary radiation fields. This contribution presents the radiation-protection concept for LPA facilities at DESY, covering shielding simulations and designs with a focus on the differences compared to conventional electron accelerators. Finally, operational experience from commissioning the KALDERA LPA and further development stages is discussed, illustrating practical implementation.

INTRODUCTION

Laser-plasma accelerators (LPA) [1], are rapidly evolving from proof-of-principle experiments toward application-oriented user facilities. Their capability to sustain acceleration gradients orders of magnitude higher than conventional radio-frequency (RF) accelerators enables compact machine designs with significant potential for future accelerator technology. At DESY, this development is exemplified by facilities such as FLARE, LUX, KALDERA and VERA.

However, the transition toward higher repetition rates and increased average beam powers of plasma accelerators introduces new challenges for radiation protection. In contrast to conventional accelerators, LPAs generate electron beams with broad energy spectra, significant shot-to-shot fluctuations, and large angular divergence. These characteristics lead to complex radiation fields due to distributed beam losses, in contrast to the point-like source assumptions of conventional shielding, and therefore require adapted radiation protection strategies.

This paper presents radiation protection challenges and mitigation strategies for LPA facilities, with a focus on experimental and simulation studies performed at KALDERA. Particular emphasis is placed on radiation generation close to the laser-plasma source and the contribution of large-angle, low-energy electrons.

RADIATION GENERATION AT ELECTRON ACCELERATORS

Secondary radiation in conventional electron accelerators is primarily generated through the initial process of bremsstrahlung generation when electrons slow down and interact within matter. The resulting bremsstrahlung photon spectrum extends up to the kinetic energy of the electrons. Tertiary processes such as Compton scattering, pair production, and photonuclear interactions contribute additional components, including neutrons, to the mixed radiation field.

As emphasized in established radiation protection literature [2, 3], the relative contributions of the various radiation components depend heavily on the electron energy, the accelerator's beam power, the beam loss geometry, and the surrounding materials.

Even at comparatively low electron energies of a few MeV, significant dose rates can occur. In particular, sideways-emitted bremsstrahlung (90°) reaches a maximum around 10 MeV (Fig.1), and the dose rate scales predominantly with beam power rather than with beam energy. As a result, lower-energy electron accelerators with substantial beam power can be just as relevant for radiation protection as even GeV-range accelerators.

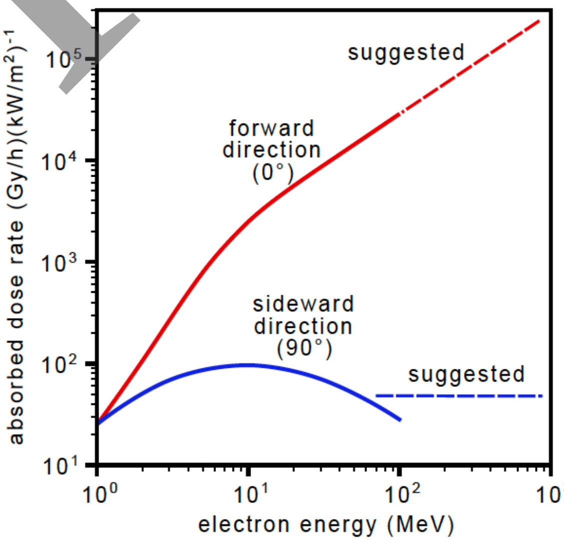

Figure 1: Absorbed dose-equivalent from thick-target bremsstrahlung as a function of electron energy for different emission geometries [2, 4].

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In LPAs, radiation generation is strongly influenced by unique beam characteristics, including percent-level energy spectra and large angular spread, often resulting in distributed beam losses. Furthermore, potential low-energy electrons, which are often not properly transported to diagnostics still contribute significantly to lateral radiation fields and must be included in safety assessments.

RADIATION PROTECTION CONCEPT AT KALDERA

The laser plasma accelerator KALDERA is an experimental facility at DESY designed to investigate laser-driven plasma acceleration at high average power. The facility is divided into a laser laboratory and an accelerator tunnel, separated by a beam shutter and personnel interlock system. Ionizing radiation is generated exclusively in the accelerator tunnel, which is classified as a restricted area during operation (Fig. 2).

The accelerator tunnel is surrounded by approximately 1-m-thick concrete walls and ceiling. The beam dump design combines layers of iron, concrete, and lead to effectively attenuate both photons and neutrons.

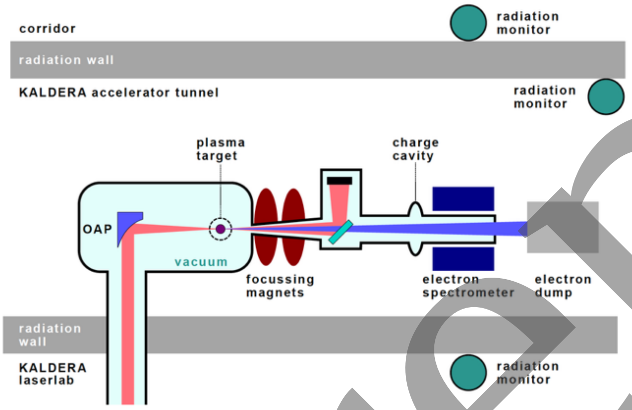

Figure 2: Schematic overview of the KALDERA tunnel setup and position of the radiation monitors [5].

Table 1: KALDERA Beam Parameters [5]

beam energy [MeV]	bunch charge [pC]	rep rate [Hz]
100	100	100
400	10	100

The shielding concept was evaluated using Monte Carlo simulations using the code FLUKA [6, 7] prior to first experiments. Simulations based on maximum beam parameters (Table 1), including electron energies up to 400 MeV and beam powers up to 1 W, demonstrate effective shielding of the facility, ensuring compliance with dose limits even under maximum conditions.

To verify the shielding performance during operation, active dose monitoring is implemented using LB6419 detectors installed outside the shielding. In addition, one detector is placed inside the tunnel to support radiation field characterization and generation studies.

SIMULATION AND MEASUREMENT STUDIES

The initial Monte Carlo simulations assumed ideal electron beam transport from the laser-plasma source into a dedicated beam dump. Under this assumption, the beam losses were localized at the dump, and the subsequent radiation fields expand outwards similar to a point beam loss (Fig. 3).

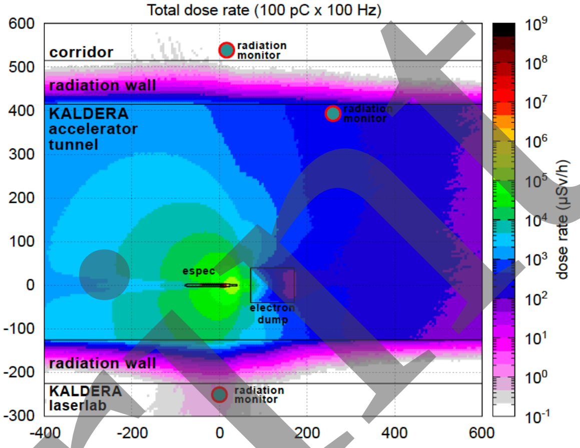

Figure 3: FLUKA simulation with idealized source term [1].

However, radiation measurements during commissioning revealed significantly higher dose rates inside the accelerator tunnel, with values exceeding 1000 µSv/h for the electromagnetic component of the dose. This is significantly above the 60 µSv/h predicted by the initial simulations, even though the measured beam power was lower than assumed. Furthermore, time-resolved detector signals exhibited a characteristic double-peak structure, indicating multiple beam-loss radiation sources.

To investigate these discrepancies, particle-in-cell (PIC) simulations of the laser-plasma acceleration process were performed (Fig. 4). Details of the simulation can be found in [4]. The simulations revealed substantial emission of electrons from the laser-plasma at large angles up to approximately 70°, with a significant fraction of low-energy electrons in the few-MeV range. The total emitted charge was orders of magnitude larger than what is transported to the dump.

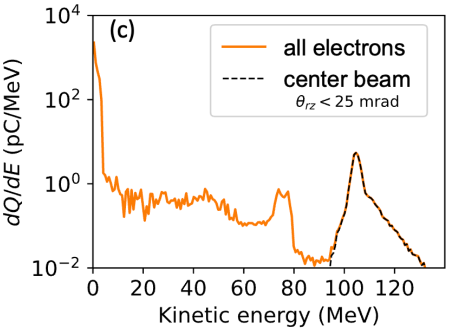

Figure 4: Electron spectrum obtained from PIC-Simulations [4].

Thus, updated FLUKA simulations incorporating the full PIC-derived phase-space distribution show a dramatic shift of the shape of the radiation field inside the accelerator tunnel, which leads to higher dose rates at the radiation monitor in the tunnel and reproduces the experimental measurements more consistently (Fig. 5). The simulation results also explain the measured double-peak structure, which indicates different beam-loss sources, in this case electrons lost close to the laser-plasma target and electrons lost at the beam dump. In particular, secondary radiation generated close to the laser-plasma target dominates the overall radiation field due to far less shielding by few-mm-thick vacuum chamber walls.

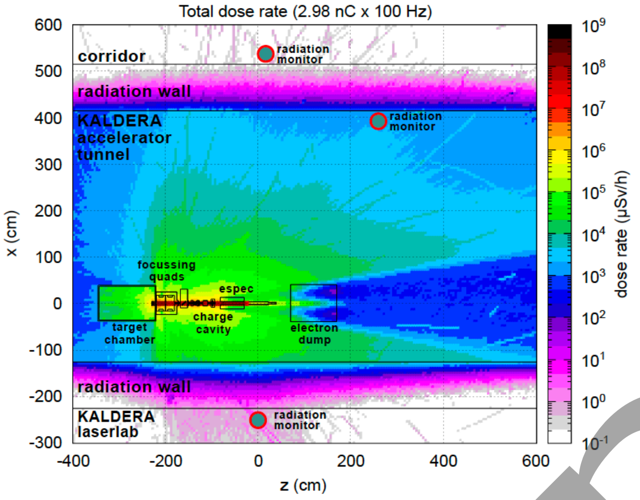

Figure 5: FLUKA simulation with full PIC distribution [4].

IMPLICATIONS FOR RADIATION PROTECTION

The results demonstrate that secondary radiation at LPAs is not limited to localized beam dump losses but is significantly influenced by distributed electron beam-loss sources near the laser-plasma target. Low-energy electrons emitted at large angles dominate dose levels in lateral directions and must be considered in the shielding design.

Conventional radiation protection models based on well-collimated beams are therefore insufficient for laser-plasma accelerators. A comprehensive description of the full electron phase space is required to accurately predict radiation fields.

In addition to personnel safety, radiation effects on components such as electronics and magnets must be considered. Total ionizing dose and single-event effects can lead to degradation or failure of electronic systems, while permanent magnets may experience radiation-induced demagnetization, especially in the vicinity of the laser-plasma target. Consequently, sensitive equipment must be adequately shielded to prevent damage from the high-energy mixed radiation fields generated at laser-plasma accelerators.

OUTLOOK

As plasma accelerators advance toward higher repetition rates and average beam powers, radiation protection will become an increasingly critical aspect of facility design. Future work should focus on improved modeling of electron emission processes, development of source models, and optimization of the shielding design with an emphasis not only on beam-dump concepts but also on the plasma chamber as a significant source of ionizing radiation in the lower-MeV range.

CONCLUSION

Radiation protection at laser-plasma accelerators requires new approaches that account for the unique beam properties and distributed radiation sources. Experimental and simulation studies at KALDERA demonstrate that low-energy, large-angle electrons can play a dominant role in secondary radiation generation. Accurate modeling of these contributions is essential for ensuring safe and reliable operation of future laser-plasma accelerator facilities.

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