DESIGNING RADIATION PROTECTION FOR PETRA IV: CONCEPTS AND CHALLENGES

E. Panofski*, W. Clement, A. Leuschner, T. T. Liang, S. Zander,
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

DESY, an international accelerator research center, builds on over six decades of experience in the design, construction, and operation of world-class user facilities. The upcoming PETRA IV project represents a major upgrade from PETRA III into a 4th generation light source, involving a complete rebuild of the accelerator and a full redesign of its radiation-protection systems. This upgrade requires advanced shielding calculations and designs for both the accelerator and new buildings, in particular the new user hall, a state-of-the-art personnel safety system, and safety processes fully aligned with current laws and standards. In addition, advanced radiation-detection systems are being developed to ensure continuous monitoring of beam operation. This contribution provides an overview of the initial concepts for PETRA IV's radiation-protection strategy, highlighting key design challenges, safety innovations, and implementation considerations for a modern, high-performance synchrotron facility.

PETRA IV UPGRADE OVERVIEW

The PETRA IV project at DESY represents the upgrade of the existing PETRA III storage ring into a fourth-generation, ultra-low-emittance synchrotron light source based on a multi-bend achromat lattice, aiming at a substantial increase in brilliance and coherence of the photon beam [1]. The upgrade involves the complete replacement of the storage ring, while large parts of the existing tunnel infrastructure and experimental areas are retained (see Fig. 1). The new machine is designed to deliver up to three orders of magnitude higher photon beam brilliance (see Fig. 2), enabling advanced applications such as high-resolution and time-resolved X-ray microscopy [2].

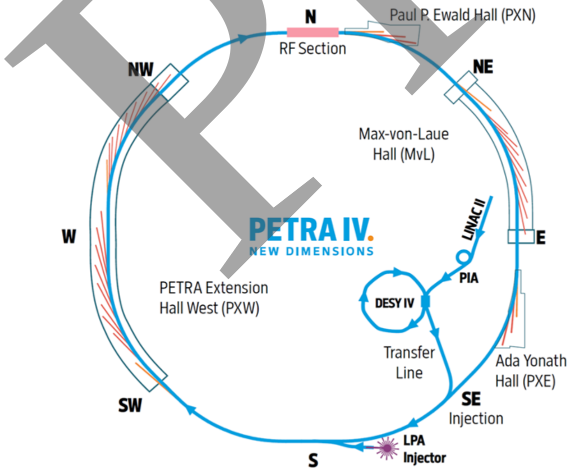

Figure 1: Layout of the future PETRA IV facility.

This performance increase is achieved, among other factors, through a significantly revised magnet lattice, including the use of several thousand permanent bending dipole magnets, allowing for a more compact and stable beam optics. As a result, the emitted X-ray radiation is substantially more focused and coherent compared to PETRA III. However, the changes in beam dynamics also result in a reduction in the beam life-time and a corresponding increase in beam losses during operation.

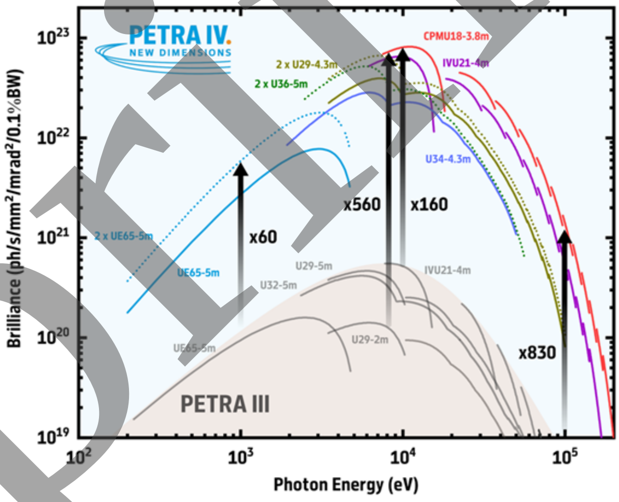

Figure 2: Spectral brightness for PETRA IV in comparison with PETRA III depending on the undulator type.

The configuration of the injector chain is currently subject to ongoing design studies. Established pre-accelerator systems, such as LINAC II and a booster synchrotron DESY IV, are considered as baseline options with largely unchanged primary operating parameters. In addition, an advanced injector concept, i.e. laser-plasma acceleration, are being evaluated as a potential future alternative.

In addition to the accelerator upgrade, a new experimental hall (PETRA West, PXW) will be constructed to host a large number of beamlines and experimental stations. The hall extends over a length of approximately 600 m and will accommodate 18 additional beamlines with roughly 40 experimental and optics hutches. It is partially located underground and extends into areas with public access above ground, imposing strict constraints on radiation shielding design.

Consequently, the radiation-protection concept for PETRA IV must combine advanced shielding methodologies, modern safety system architectures, and full compliance with current regulatory requirements.

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* eva.panofski@desy.de

RADIATION SHIELDING DESIGN AND SIMULATIONS

The shielding design for PETRA IV is driven by the need to mitigate increased beam losses in the new storage ring while reusing significant parts of the existing tunnel infrastructure. Due to the reduced beam lifetime and modified operational conditions, higher loss rates are expected during routine operation, requiring a comprehensive re-evaluation of existing shielding concepts [3].

In areas where the existing tunnel geometry is retained, shielding optimization is constrained by fixed structural conditions. Detailed Monte Carlo simulations with FLUKA, are therefore performed to assess radiation fields due to various beam loss scenarios [4,5]. For this purpose, a detailed FLUKA model of the PETRA IV accelerator has been developed from CAD-based component models, incorporating detailed magnetic field parameters of individual magnets. This allows for realistic representation of beam loss scenarios and accurate prediction of resulting radiation fields.

Experimental Hall PETRA West PXW

A key focus of the radiation shielding design is the new PETRA West experimental hall (PXW). The hall extends over a length of approximately 600 m and hosts a large number of beamlines and experimental hutches [2]. Due to its partially underground layout and publicly accessible areas above, stringent design targets well below the regulatory limit of 1 mSv/a are imposed. The shielding concept includes a combination of heavy concrete and additional soil shielding.

The shielding design is based on a conservative beam loss scenario representing the maximum expected annual losses for PETRA IV, corresponding to approximately 1.1×10^{15} electrons over 7200 hours per standard cell [3]. FLUKA simulations are used to model 6 GeV electron beam losses within the PETRA IV tunnel and to calculate the resulting annual dose distributions (see Fig. 3).

Dedicated studies were performed to evaluate the required concrete density for the PXW tunnel shielding. Results show that the use of heavy concrete is essential to effectively attenuate the photon component of the radiation field, reducing dose levels by more than one order of magnitude compared to ordinary concrete [6]. However, increasing the density within the range of heavy concrete (e.g. from 3.4 to 3.7 g/cm³) results in only a moderate additional reduction of the photon dose, on the order of a factor of two. In contrast, using heavy instead of ordinary concrete provides only a neutron dose reduction by a factor of two. In addition, the choice of heavy concrete density has negligible effect on attenuation of the neutron dose. Consequently, a density of 3.4 g/cm³ is considered sufficient for the shielding design, as higher densities provide only limited additional benefit for overall dose reduction [6].

Simulation results indicate that, under conservative beam loss assumptions, annual dose levels above the PXW hall can be limited to below 0.2 mSv/a during user operation (7200 h/a) and continuous access (8760 h/a) to publicly accessible areas.

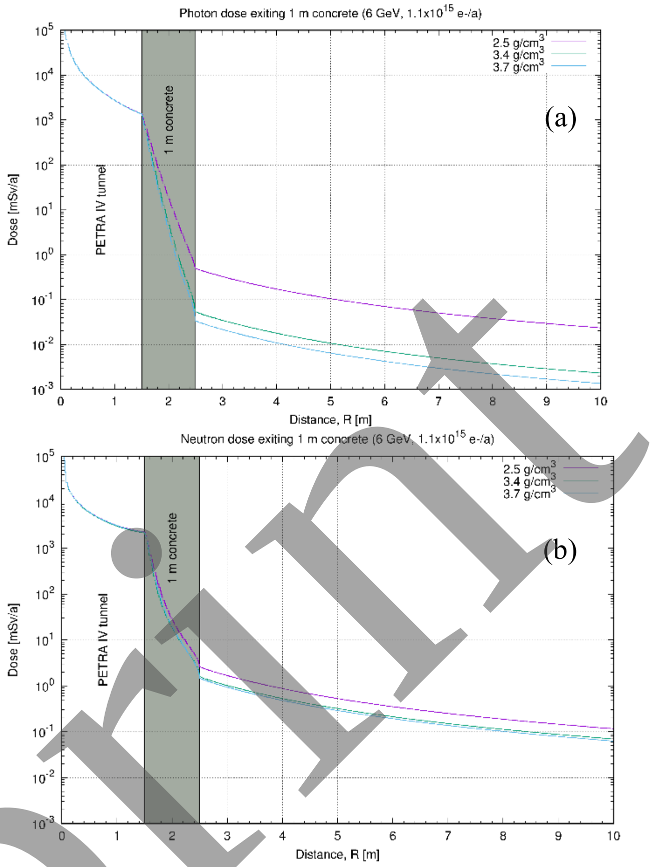

Figure 3: Photon (a) and neutron (b) dose through 1 m concrete of different densities.

These results are obtained assuming a hall height of approximately 10 m and a PETRA IV tunnel ceiling constructed from ordinary concrete. The resulting dose level is well below the 1 mSv/a limit applicable to the general public in unrestricted areas, thereby meeting the design target.

Dose levels inside the PXW experimental hall remain below 0.6 mSv/a, corresponding to a typical annual working time of 2000 h. As in the existing experimental halls PXN, PXE and Max-von-Laue at PETRA III, this area will therefore be classified as supervised area. These results demonstrate that the applied shielding strategy satisfies both the regulatory requirements and the more restrictive dose planning targets for PETRA IV.

Radiation Damage and Activation

In addition to shielding for personnel protection, radiation damage to accelerator components is assessed based on detailed FLUKA simulations.

Synchrotron radiation generated in the permanent bending dipole magnets is evaluated with respect to dose deposition in cables, electronics, and insulating materials located near the beam. The synchrotron radiation spectra from the dipole magnets in these regions have critical energies between 4 to 6 keV and maximum energies covering up to several hundred keV.

Detailed studies show that synchrotron radiation from DLQ dipole magnets with a 2 mm copper vacuum chamber results in dose rates on the order of 0.1 Gy/h at beam height. In contrast, insertion device (ID) chambers made of 5 mm aluminium can lead to significantly higher dose rates, reaching up to 1000 Gy/h at 30 cm and around 100 Gy/h at 1 m distance (see Fig. 4) [7]. These high dose levels impose critical constraints on the lifetime and placement of cables, electronics, and other radiation-sensitive components due to radiation damage.

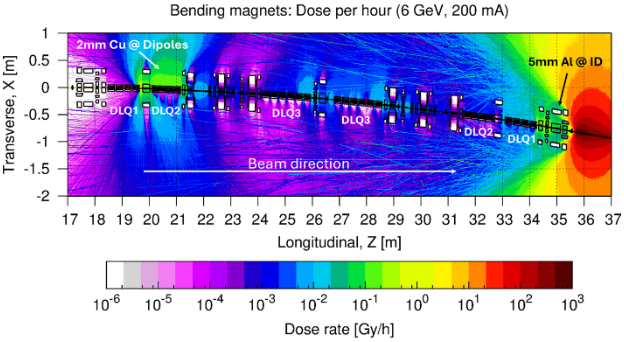

Figure 4: Dose rate in [Gy/h] to cables and electronics at beam height induced by synchrotron radiation.

Structural materials such as epoxy-based supports for magnets can also be affected by radiation damage. Epoxy materials typically exhibit radiation damage thresholds in the range of 5–10 MGy [8]. FLUKA simulations of PQD quadrupole support structures in close proximity to DLQ bending magnets yield maximum dose rates on the order of 10^{-4} Gy/h (see Fig. 5). This corresponds to an operation time of approximately 5×10^{10} h to reach the lower bound of the damage threshold, far exceeding typical operational timescales by several orders of magnitude. Synchrotron radiation from bending magnets therefore does not represent a limiting factor for these particular components.

The results support the estimation of component lifetimes and the identification of critical locations where local shielding or design modifications are required for reliable long-term operation.

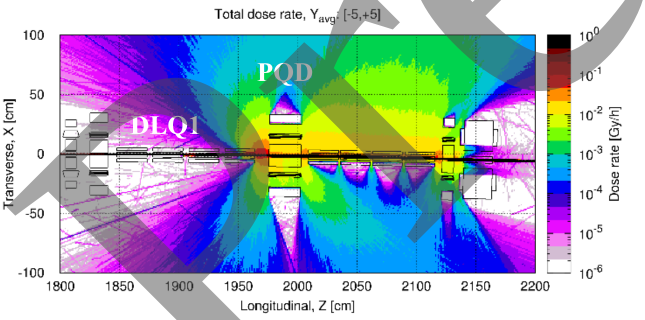

Figure 5: Dose rate in [Gy/h] to epoxy magnet supports below beam height induced by synchrotron radiation.

Activation of accelerator components due to routine electron beam losses is evaluated separately, focusing on residual radiation following beam operation. The production of activation products in cobalt-containing materials used in permanent dipoles and quadrupoles is taken into account. Typical results indicate residual dose rates of 2-3 μSv/h after one day of decay time in the vicinity of quadrupoles, depending on the assumed loss scenarios [7].

These findings form the basis for maintenance planning, controlled access to the accelerator tunnel, and the assessment of material activation and clearance procedures.

PERSONNEL SAFETY SYSTEM

In addition to shielding, the Personnel Safety System (PSS) is a fundamental pillar of radiation protection, ensuring personnel safety and controlling access to accelerator areas. The scale and complexity of PETRA IV, as well as the modified accelerator and tunnel layout, require a complete modernization of the PETRA III PSS. The existing interlock system, designed more than two decades ago, no longer reflects the current state of the art. Consequently, a new system architecture is required to ensure compliance with modern safety standards and regulatory requirements.

The PSS development follows a structured safety approach based on a dedicated safety plan, including systematic hazard identification and risk assessment process in accordance with the European Machinery Directive 2006/42/EC and relevant international standards for functional safety (IEC62061, ISO13849) [9-12]. The outcome of this process defines the required safety integrity level, resulting in an interlock design fulfilling functional safety requirements up to SIL 3 / PL$_e$. This, in turn, necessitates the use of safety programmable logic controllers (PLC) as the core technology for the interlock system.

The PETRA IV PSS integrates a wide range of sensors, including interlock doors, permission keys, emergency stops, position switches at beam shutters, or radiation monitoring devices, logic, i.e. safety PLCs, and actuators such as RF and HV power contactors. The large number of interlock areas and beamlines leads to a highly distributed system architecture with stringent requirements on reliability and maintainability.

The design, integration and validation of such a system represent a major technical and organizational challenge, particularly in the context of evolving regulatory requirements and the need for efficient operational procedures.

CONCLUSION

The upgrade of PETRA III to PETRA IV introduces significant challenges for radiation protection due to a modified accelerator layout, increased beam losses, and new experimental facilities. The shielding design is based on detailed FLUKA models, enabling realistic assessment of radiation fields.

For the new PXW experimental hall, radiation exposure was evaluated using detailed simulations, demonstrating that the design target well below 1 mSv/a for publicly accessible areas is achieved. These studies further allow the determination of an optimal shielding configuration, showing that a concrete density of 3.4 g/cm^3 provides an effective balance between shielding performance, cost, and practical implementation. Radiation damage effects on components and activation of accelerator elements are evaluated to support safe operation and maintenance. The personnel safety system is being completely redesigned following a structured safety approach and resulting in a SIL 3 compliant interlock system. Overall, the presented concepts demonstrate that the radiation-protection strategy for PETRA IV is capable of meeting the requirements of a modern, high-performance synchrotron facility.

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