SYSTEMATIC REDUCTION OF LATTICE COMPLEXITY THROUGH VARIANT MINIMIZATION

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Abstract

The design of an accelerator system requires translating the lattice into an engineering design model from which the machine can be built, fulfilling the requirements of beam dynamics and from mechanical engineering. To achieve this in an efficient manner, a systematic and manageable iterative design process has been established, which ensures consistency between the lattice and the mechanical model and enables a fast translation of the calculated lattice into a CAD model with correctly placed components within one day through the use of newly developed automation tools.

An analysis process of the lattice, a highly modular CAD structure focused on maximal reuse, and strategic variant management together minimize the number of variants necessary. As a result, design, manufacturing and logistics efforts are significantly reduced.

This approach establishes a fundamental toolkit. It ensures the traceable integration of physics and engineering requirements throughout the system design process of PETRA IV, the planned next-generation synchrotron light source at DESY.

INTRODUCTION

The lattice is the central specification of an accelerator. It results from beam optics calculations and defines the required physical properties and performance. The lattice describes all beam-influencing components and specifies their exact positions along the beamline. To allow the physical design of the accelerator, a main focus is the transfer of the lattice specification into a geometrical model. This transfer has two contributions. The first is validity, achieved through automated integration of the lattice into a consistent 3D geometry model. The second is optimization, enabled by the structuring and analysis of variant diversity. This forms the basis for iterative design improvements, in which a alignment of requirements between physical and engineering design is enabled.

In the PETRA IV project at DESY, this methodology allows the transfer of more than 4,000 beamline components into a 3D CAD environment. These are positioned precisely along the 2.3 km storage ring. The resulting geometrical representation provides the foundation for the design of dependent technical systems like support structures, alignment systems, vacuum chambers, and diagnostics.

The layout of a storage ring is highly repetitive and consists of arcs and straight sections, which are composed of cells and girders. Variants occur through local differences like variations in insertion devices or sections for injection or extraction.

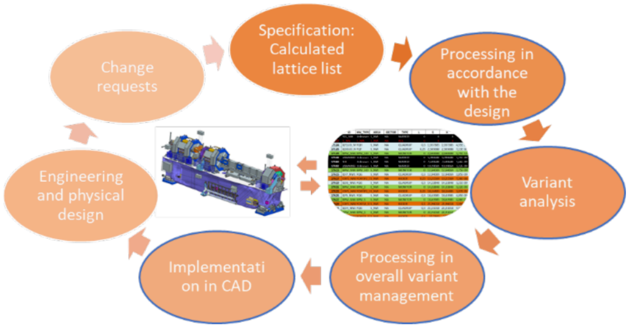

Figure 1: Iterative process for implementing a lattice specification into CAD. After the lattice list is provided by beam physics, it is adjusted for CAD implementation. The lattice is then analysed for variants and changes compared to the previous version. Variant changes are managed in the variant management system, which also tracks variants of all associated technical systems. All changes are transferred into CAD (as in section 'Automation and Black-White-Box principle'). Engineering design drives the further development of technical systems, generating requirements that are incorporated into a new lattice version. Contributions from CAD integration are highlighted in blue.

OBJECTIVES

A main objective is to provide a geometrically precise representation of the accelerator lattice as the foundation for the physical design.

A workflow is established that ensures efficiency, reliability, and traceability in the transfer of the lattice into the engineering model. The same process maintains alignment between physics and engineering through controlled feedback and iteration (Fig. 1).

A structured variant management is introduced to reduce complexity and improve quality. This approach enhances the overall overview, reduces design effort and supports manufacturing and logistical planning from the earliest design stages.

METHODS

Multiple methods are applied:

- Structured data organization is implemented. A hierarchy organizes the information and forms the basis for analysis.
- Modularity is introduced to encapsulate technical details. Modules are logical design elements and serve as the foundation for variant management.
- A girder assembly is established as the physical assembly unit.

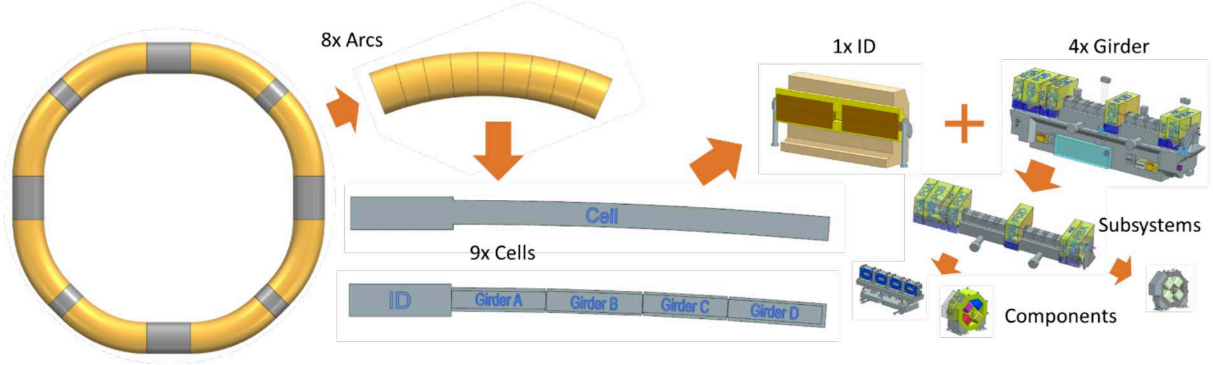

Figure 2: The CAD Structure and Modularity. The hierarchy encapsulates information. Each level can be further subdivided. Modules appear in multiple variants. Modules at each level are composed of modules from the lower level, so that variants at one consist of variants from the level below.

- A process manages the implementation of the lattice into CAD and ensures iterative coordination between engineering and physics.
- An abstraction concept based on the black-white-box principle is applied, combined with a high degree of automation using specially developed tools.

Structure, Modules, Girder-Assembly

To manage the complexity of the accelerator system in CAD, a hierarchical modular structure with defined variants has been introduced. The integrated CAD model of the storage ring machine is organized consistently across all structural levels into modules and their respective variants.

At the top level, the ring is divided into straight sections and arcs, which represent the highest-level modules. Each arc is further subdivided into nine cells. This repetitive unit from beam dynamics exist in several variants. The specific arrangement of these cell variants defines the overall configuration of each arc. Each cell is composed of four girder assemblies and one insertion device, such as an undulator. Both girder assemblies and insertion devices and exist in multiple variants. A specific combination of these components forms a particular cell variant (Fig. 2).

At the lowest structural level, the girder assemblies serve as fundamental modules to be installed in the accelerator tunnel. They are about 5 meters long and contain several subsystems, including the support structure (girder bar), beamline components (from the lattice), vacuum system elements, frontend systems, and others (Fig. 3). Each of these subsystems also exists in different variants. Their specific combination determines the girder variant.

This modular approach enables efficient reuse of design elements and minimizes the total number of necessary variants.

Variant Management

The basis for identifying and defining these variants originates from the lattice list. As the lattice defines all beamline components and their repetition patterns along the storage ring, a scripted analysis process has been developed to automatically extract and categorize these patterns. This beamline component assemblies are represented by a local section from the lattice list for the length of a girder (or insertion device). This analysis identifies where each variant is located in the ring, visualizes the layout, and highlights any differences compared to previous lattice versions.

Once this modular variant structure has been established in CAD, the engineering phase begins. In this phase, further technical differentiation between otherwise identical modules is introduced. For example, the engineering progress requires additional space for a vacuum component or differentiation between media routes. These engineering-driven variations are managed centrally and are implemented consistently in the integrated CAD model. The CAD structure is designed to accommodate this by allowing subsystem-specific variants to be integrated into each girder variant. This structure also forms the basis for manufacturing and logistics processes, which are aligned with the corresponding engineering bill of materials.

Process

These methods are integrated into a process that controls the implementation of the lattice in CAD and provides the foundation for variant management. This approach represents a living design process, characterized by an iterative feedback loop between engineering and accelerator physics (Fig. 1). Engineering requirements, such as the need to break lattice symmetry to accommodate subsystem requirements, are evaluated, documented, and systematically incorporated into lattice iterations. The CAD model is updated accordingly while maintaining previous configurations, ensuring transparency and traceability throughout the design lifecycle. A central principle in this process is that changes are applied only to the assemblies directly affected by a given modification. All other parts of the storage ring remain unchanged. This localized update strategy avoids unnecessary model revisions and significantly simplifies change tracking. After each iteration, a defined and stable configuration is established, serving as a reliable reference point for the engineering design until the next update cycle is initiated.

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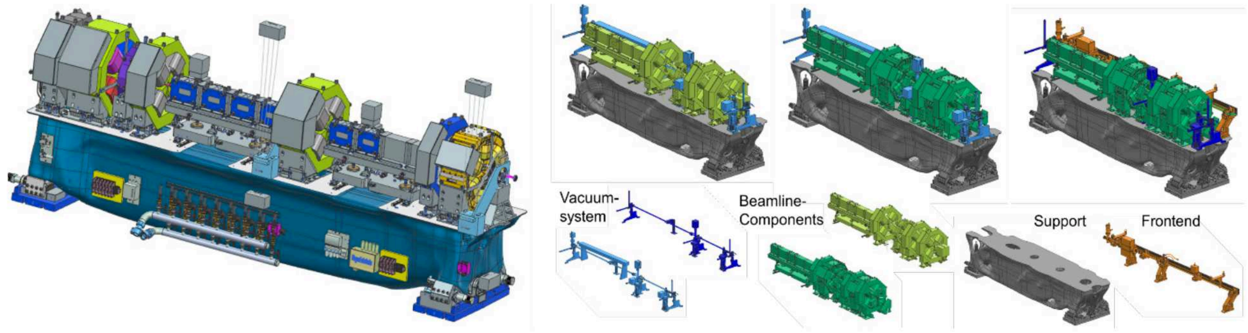

Figure 3: The modular Girder Assembly.

Automation and Black-Box/White-Box Method

A highly automated and rule-based positioning methodology ensures consistent placement of all components across the machine. At every level, modules are positioned using a Base Orphan List (BOL). A BOL part is a CAD part containing only coordinate systems (called base orphan reference nodes BORN) without geometry (Fig. 4). These coordinate systems are generated by a Python script implemented in NX, directly reading data in a central Excel document managed in the PLM system (Siemens Teamcenter). Each coordinate system is named and positioned according to the parameters in this list. Component and module positions are defined by these coordinate systems, which serve as the skeleton of the CAD assembly. The generation of the BOL and the automated placement of beamline components are handled by custom tools, ensuring robust, error-reduced implementation and consistency across all variants.

To support interdisciplinary collaboration and parallel design efforts, a black-box/white-box approach is followed. This methodology provides different representations of the same module depending on the design phase and level of detail required. The white box reveals the full internal structure of the module and is used for detailed engineering work. The black box is a simplified placeholder geometry, representing the outer shape of the model, mounting and service placeholder, as well as all interfaces. Interfaces can be media connections like power supply or cooling water as well as physical interfaces like screw connections. This abstraction enables planning support structures, services, media routing and other disciplines even while the internal design of a component is still under development [1].

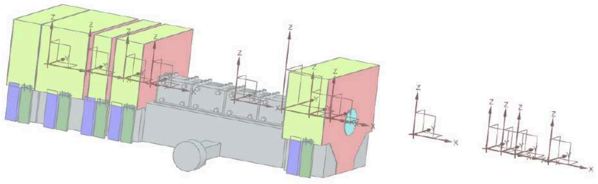

Figure 4: Beamline-Components placed with BOL.

RESULTS AND BENEFITS

A methodology is introduced to integrate accelerator lattice specifications into a CAD-based engineering environment. The approach combines automation, modular design principles, and variant management to enable efficient, consistent, and collaborative system development.

Efficiency: the iterative process with structured variant management provides transparency and saves time. Variants are clearly organized, and updates of the lattice can be implemented within a single day. The process establishes a communication basis between physics and engineering, which improves coordination and strengthens the overall control of the design workflow.

Quality: automation ensures that the current lattice is completely and consistently implemented in CAD. The process is error-reduced and guarantees traceability of every update. Variant management lowers design complexity drastically, from 288 individual girders, only 22 variants exist currently. This simplification also benefits manufacturing and logistics, while each update establishes a fixed baseline for the next design iteration.

Collaboration: abstraction concepts such as the Black-White-Box principle enable clear communication between disciplines. This improves coordination and supports simultaneous design activities, which increase efficiency in the overall development process.

Minimized downtime: preassembled girder modules with integrated subsystems are introduced. They can be installed quickly in the tunnel. This reduces on-site work and ensures minimal dark time, which is essential for the successful execution of the PETRA IV upgrade.

REFERENCES

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