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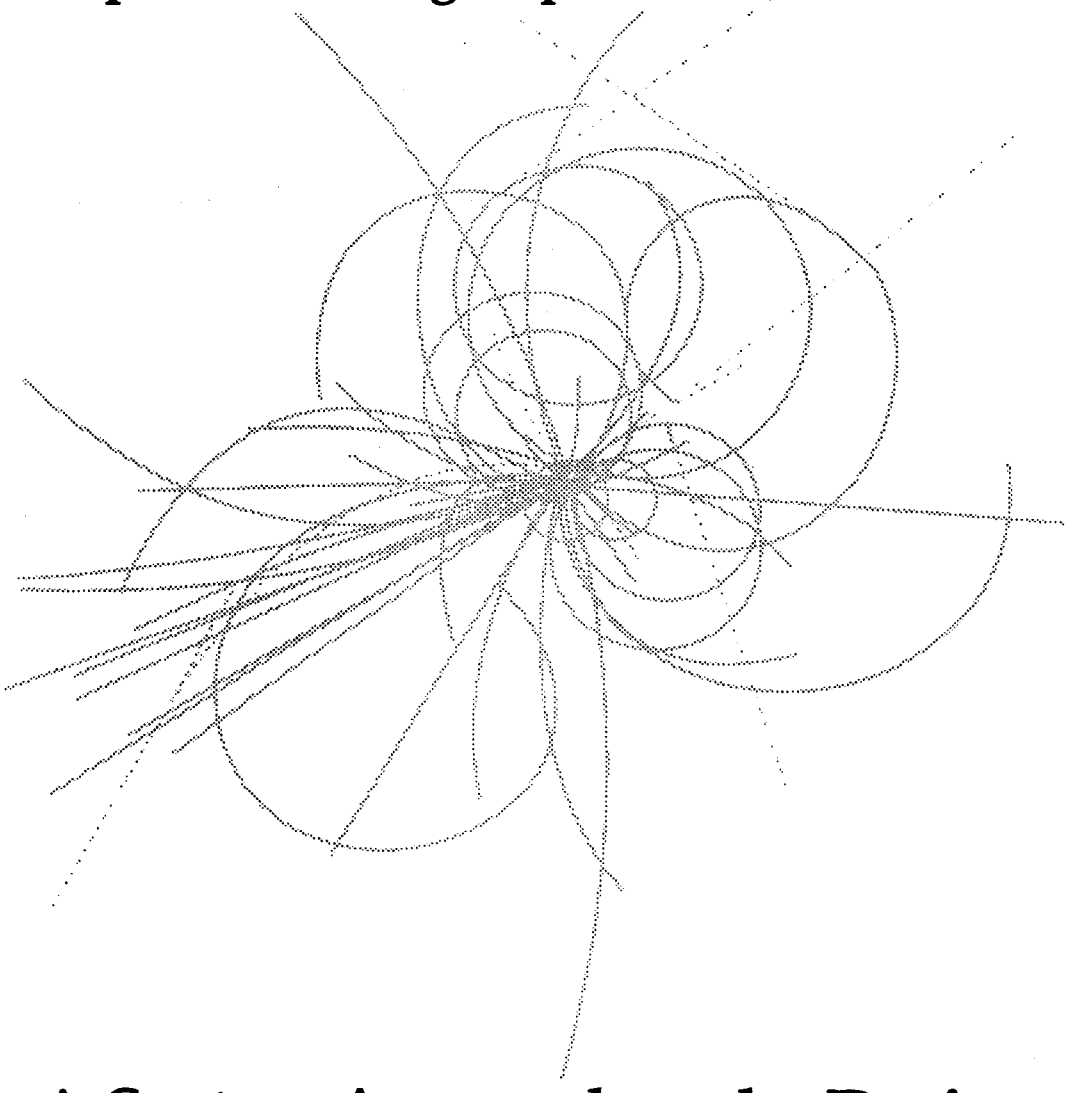
Superconducting Super Collider Laboratory



A System Approach to the Design of Superconducting Magnets

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A SYSTEM APPROACH TO THE DESIGN OF SUPERCONDUCTING MAGNETS

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INTRODUCTION

The design of superconducting magnets poses numerous technical, engineering and physics challenges to ensure that the magnets, when installed in the operational environment, will satisfy performance requirements of the accelerator. The discussion presented here will address the systematic, methodical process, as applied by the magnet system design engineer, that defines magnet performance requirements, the allocation of requirements to magnet components, and the development of design solutions which will satisfy the requirements. The approach presented will show how the system engineer parses top-level performance requirements as established by the system specification ("shall" statements), develops design solutions, performs design trades to ensure selection of the best solution in terms of life-cycle cost and performance, verifies the design through analysis and computer modelling, and then validates the design by build-and-test. The process shows the methods for achieving traceability of design and correlation of design solutions to performance parameters.

Since the early 1950s, the development of large and sophisticated systems has provided the impetus for the application of a systems engineering approach to the development and implementation of design solutions. The difficulties experienced in evolving new systems have led to the development of specific tools and techniques within the systems engineering discipline which permit better control and insight into the development process, and to better documentation to show traceability to optimized design solutions.

Systems engineering is the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration established through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, integrity, human, and other such factors into total engineering effort to meet cost, schedule, and technical performance objectives.

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The systems engineering process is a systematic analytical and management methodology which provides both a technical and a management process leading to the successful completion of system development. The systems engineering process begins with the identification of needs, constraints, and capability requirements to satisfy mission objectives through the application of technology.

RESPONSIBLE AUTHORITY

Responsibility for the systems engineering effort leading to the design of superconducting magnets for application in the Superconducting Super Collider (SSC) lies with the associate director and division head of the Magnet Systems Division of the SSC Laboratory. A Task Responsibility Matrix, developed by the magnet product manager and, negotiated with the responsible functional area group leaders, identifies the responsibility of the assigned personnel for detailed system development disciplines. A close correlation with SSCL program management planning is maintained to keep SSC program and technical functions synchronized. The system design major milestones and product development charts form a common basis for both management functions to ensure proper tracking of activities.

TECHNICAL PLANNING AND CONTROL

In defining the elements of this process, a standard system of technical planning and control is applied. The first technical planning task is to analyze the SSC baseline documentation to establish a tailored research and development series of activities and a detailed program schedule based on a standard PERT technique. The results of these activities by the engineering group, in consonance with the product manager and systems engineering, forms the basis for planning and conducting of the engineering efforts and monitoring of magnet development progress. In the case of the SSC, the baseline was established by the initial Collider Design Group (CDG) and was published in the Conceptual Design Report (CDR) in October 1989. This report was subsequently updated to the Site-Specific Conceptual Design Report (SCDR), released in June 1990, to reflect the move to the 50-mm collider dipole magnet configuration. In parallel with the release of the SCDR, the Magnet Systems Division developed and released a Research and Development Plan in June 1990, with a reissue in December 1990. The SSC design baseline, as revised to the 50-mm configuration essential to satisfying field quality requirements, will be analyzed as the technical design baseline for the collider dipole magnet (CDM). The CDM serves as the basis for the development of all other superconducting magnets for the SSC.

Any credible systems engineering approach must, prior to implementation, establish a means to ensure traceability of design and measurement of progress in reaching the desired solution. This is accomplished through the implementation of specific technical program assurance methods. These methods include:

- Technical Performance Measurement (TPM). TPM is exercised throughout the system design process following the System Design Review (SDR). Key technical performance requirements and acceptable tolerances are identified and monitored during the follow-on system design. These performance requirements will be measures of effectiveness (MOE) type parameters such as system availability, quench performance, cool-down and warm-up times, and mean-time-to-replace. A Performance Compliance and Verification Matrix is used to document the results and status of all TPM activities. Design deficiencies identified through TPM will be investigated, and appropriate corrective actions will be recommended to the engineering group leader.

- Quality Assurance. Early in the program, i.e., during the "Requirements Definition and Operations Analysis" process, system test concepts will be developed and documented in a Master Integration and Test Plan (MITP). This plan defines the detailed quality assurance activities necessary to ensure that all system level requirements comply with developed acceptance criteria. System test plans and procedures based on this system test concept will be developed during the system engineering process. A Verification Cross Reference Index will be developed to identify test levels and methods for each system requirement.

- A Risk Management and Control Process. This process is based on a Risk Management Plan and is initiated during the "System Analysis and Design" phase of the system engineering process. The prime efforts of this process are to identify and analyze the dominant risk areas, develop an overall program risk profile, and recommend the most advantageous approaches to minimizing overall program risk.

MAJOR PHASES OF THE SSC LIFE CYCLE

The life cycle for the SSC development and acquisition is depicted by Figure 1. The life cycle is initiated by the determination of a need for a collider system that can provide a controlled acceleration of proton masses to the 20 TeV level and cause a collision of two such masses to occur, resulting in the combined energy of 40 TeV and the measurement of the event. The initial exploration of alternative approaches to satisfying the desired SSC system objectives results in preliminary design concepts developed by the SSCL, collaborating national laboratories, and selected subcontractors. These concepts are documented in conceptual design reports and form the basis for the issuance of requests for proposal to industry.

During Phase I of the industrialization program, technology transfer to industry provides a definition of the initial baseline design for demonstration and validation through analysis and test.

Phase II proceeds with full-scale engineering development by the selected subcontractor(s) and with preliminary design, including the design and build-and-test of prototype magnets to prove both the magnet design and design-specific tooling. Following successful completion of a prototype test and a design iteration to incorporate enhancements identified during test evaluation, a critical design review is conducted prior to the authorization to build production units.

Finally, Phase III carries the process to production, installation, and checkout in the tunnel, and then to commissioning for operation.

This systematic and analytic flow process is depicted in more detail in Figure 2.

PLANS AND SCHEDULES FOR DESIGN AND PROGRAM REVIEW

As shown by Figure 2, the systems engineering process documents all program reviews from start to finish and maintains design baseline control. Specifications and interface design documents are established during the design process to ensure that the evolving design will be based on the appropriate set of system requirements as established for the SSC by the Accelerator System Division (ASD) of the SSCL. The scheduling of program reviews and the establishment of design baselines are based on both the program management plans and the technical planning and control (TPC) plans and milestones.

MILESTONE		I	II	III
MISSION NEED DETERMINATION	CONCEPT EXPLORATION PHASE	DEMONSTRATION & VALIDATION PHASE	FULL SCALE DEVELOPMENT PHASE	PRODUCTION INSTALLATION PHASE
DOE	SSC LABORATORY STUDIES	PARALLEL EFFORT BY SSCL, NAT. LABS & SUBCONTRACTOR(S)	ONE (OR MORE) SUBCONTRACTORS	CONVENTIONAL CONSTRUCTION SUBCONTRACTOR
		RFP	RFP	RFP
• SSC MISSION ANALYSIS	• ALTERNATIVE STUDIES	• SUBCONTRACTOR SELECTION	• PDR DETAILED DESIGN	• INITIAL PRODUCTION
• STATEMENT OF NEED	• PRELIMINARY SYSTEM SPECIFICATION	• SYSTEM REQUIREMENTS REVIEW	• CDR	• PHYSICAL CONFIGURATION AUDIT
• OPERATIONS CONCEPT	• SOWs/RFPs	• TRADE STUDIES	• TEST & EVALUATION	• PRODUCTION
	• PREPARE CONCEPT DESIGN REPORT	• SYSTEM DEFINITION	• PRODUCT BASELINE	
		• ALLOCATE BASELINE		
		• SYSTEM DESIGN REVIEW		

Figure 1. Major Phases of the SSC Life Cycle.

Requirements Definition Methodology and Control

System requirements are classified and allocated to magnet system functions. Functions, in turn, are allocated to configuration items (CIs), and these CIs are allocated to prime items (hardware or software components). This process provides a consistent allocation of requirements over several design stages leading to the final magnet product. In addition, all requirements can be traced back from any design entity to the top-level requirement specified by the ASD. The specific magnet Prime Item Development Specification prepared and controlled by the MSD Engineering Group establishes and controls all magnet system requirements.

Subcontractor Control

The physical size of the SSC (approximately 87 km in circumference) and the magnitude of the total project have generated a need for superconducting magnets in quantities never before envisioned. Approximately 13,000 magnets of 27 differing configurations will be designed, manufactured, tested, and delivered by industry. Because of the large number of differing magnet configurations and the quantities in demand, several subcontracts will be let to multiple vendors. Full-scale engineering development procurements of superconducting magnets of this complexity and magnitude have imposed the need to establish practices for supplier evaluation, qualification, risk analysis, and source selection.

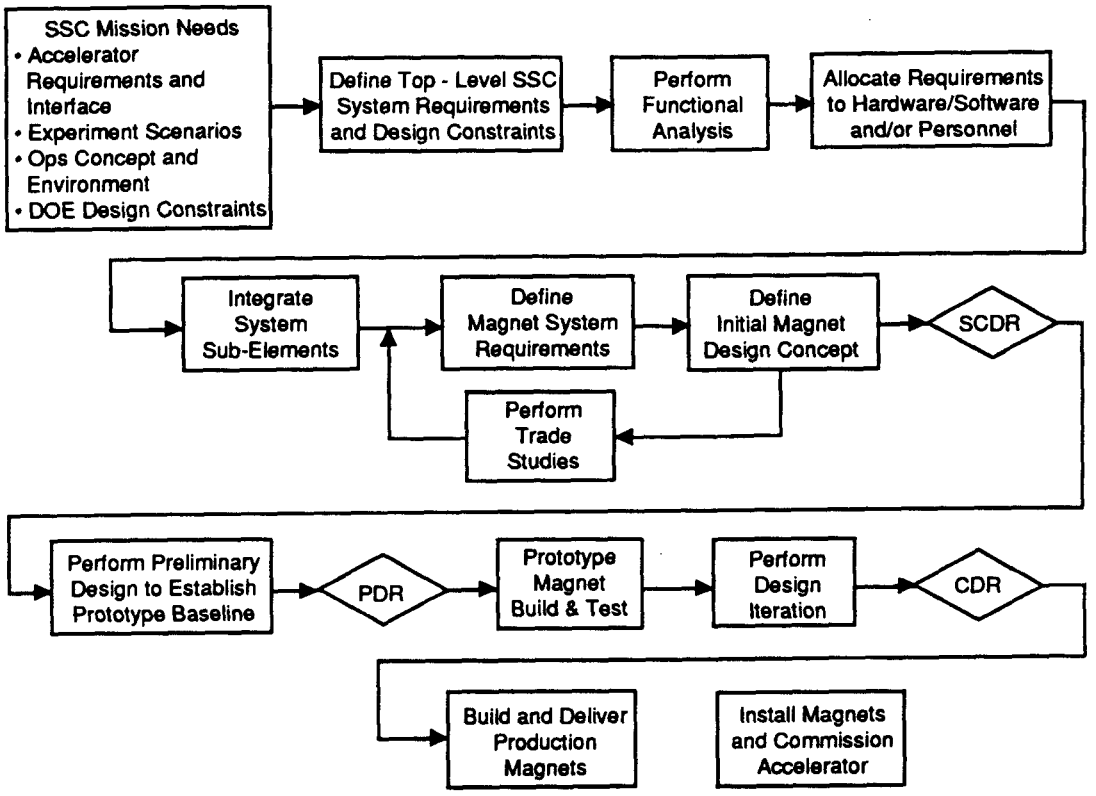
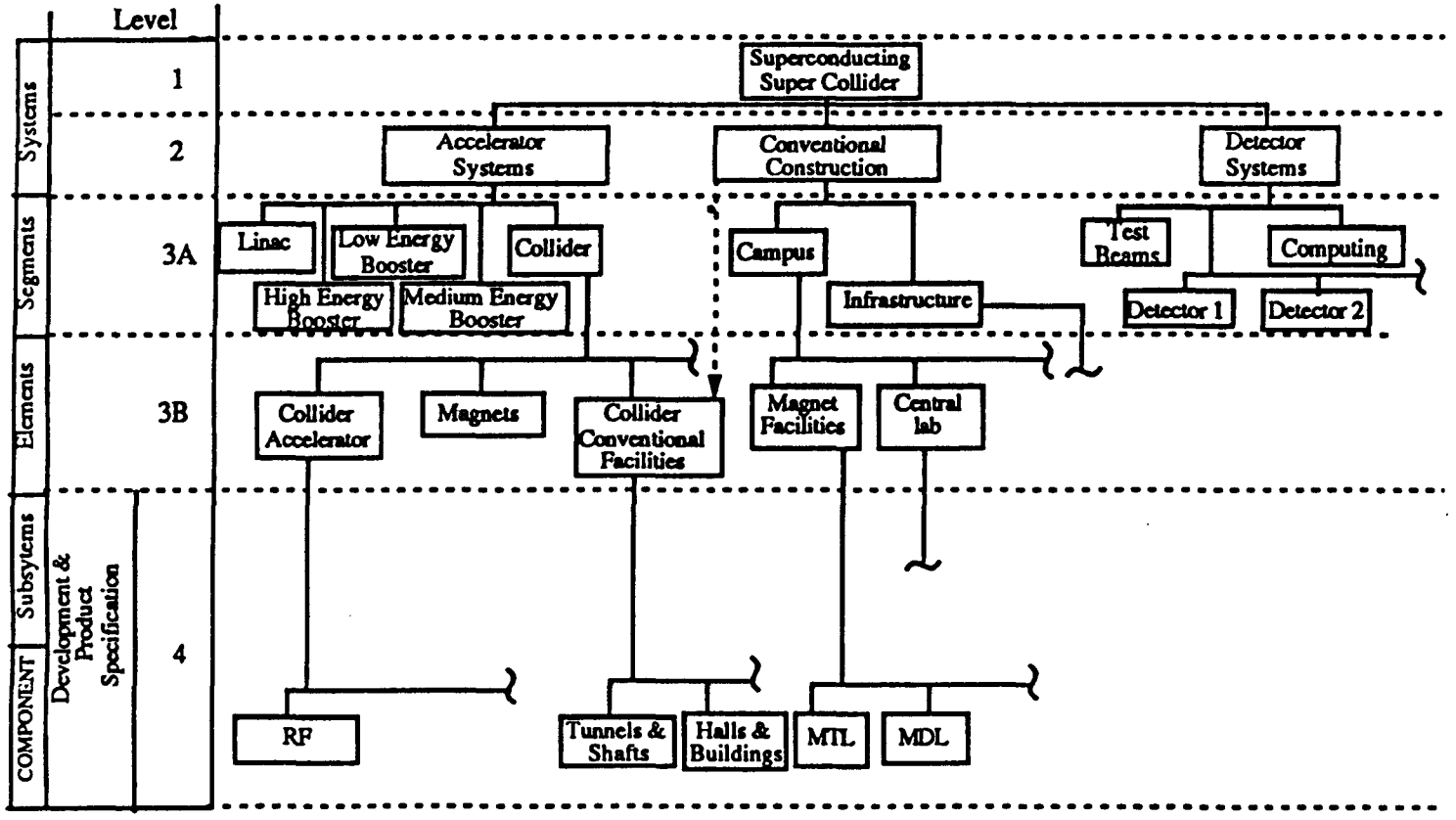


Figure 2. System Engineering Process.

Subsequent to subcontract award, subcontractor progress requires monitoring through regularly scheduled in-process reviews and test witnessing. Where necessary, corrective actions are initiated through a Corrective Action Request process using a Subcontractor Product Assurance Rating system.

Documentation Control

Design baselines have been or are in the process of being established for the three major families of superconducting magnets: the Collider Dipole (CDM), Collider Quadrupole (CQM), and the High Energy Booster (HEB) magnets. Documentation defining these design configurations including Prime Item Development Specifications (PIDS), drawings, and supporting analyses are provided to the magnet subcontractors as elements of the technology transfer program sponsored by the SSCL. Beginning with the first in-process review, the subcontractors system design review (SDR), the PIDS (B1 Specification) and configuration drawings are placed under internal subcontractor configuration control. Changes to this baseline documentation are tracked to ensure traceability of design through the development process. The PIDS is revised to a hardware product specification (C-Level) at the subcontractors' preliminary design review (PDR) and is placed under internal configuration control board (CCB) management. The subcontractor must notify the SSCL of any subsequent changes to the PDR baseline design. Subsequent changes to the baseline may be implemented only through formal (internal subcontractor) engineering change proposals (ECPs). The next milestone in the control process occurs at the subcontractors' formal critical design review (CDR) at which time the baseline is "frozen" and any subsequent changes require formal ECP submittal and review and approval by the SSCL prior to implementation. The SSC specification hierarchy is depicted in the Superconducting Super Collider Specification Tree (Figure 3).



* Construction guidance will be used from the level 2 specification but technical guidance will be from the technical system supported.

Figure 3. Superconducting Super Collider Specification Tree.

THE SYSTEMS ENGINEERING PROCESS

The systems engineering process is really quite simple and is defined as the methodical, analytical approach to defining top-level (the SSC) system performance and functional requirements, and decomposing these into lower-level (magnet and other system segments) performance and functional requirements. Once the magnet system performance and functional requirements have been adequately defined, these requirements can be allocated to each of the magnet families, i.e., CDM, CQM, HEB, and other specialty magnet designs. A further decomposition of magnet system functions will then lead to the identification of a complete set of magnet functions required to support SSC system-level performance within the operational environment. These functions are then analyzed to define magnet interfaces and the optimum allocation to magnet hardware and/or software, operational and support equipment, and personnel consistent with the operations concept for the SSC. The process flow shown by Figure 2, Systems Engineering Process, consists of the following distinct tasks.

Definition of Top-Level System Performance Requirements and Design Constraints

The first step in evaluating SSC concepts is to determine all factors which must be considered in satisfying SSC mission objectives. This mission analysis results in the translation of the accelerator functional requirements into design requirements. Needs expressed by the high-energy physics community—the ultimate users of the SSC—are formulated as a set of operational objectives and are quantified in broad terms and basic functions which satisfy operational SSC needs. In addition to these operational functional and performance requirements, certain design constraints are imposed by the Department of Energy and other government regulatory agencies. Mission analysis then proceeds to identify and express requirements in measurable parameters which state the needs in terms that the magnet technologists can use to develop magnet design concepts. The following inputs are typically considered in the establishment of the accelerator and accelerator components in arriving at performance requirements and design solutions.

- SSC Mission Needs
- Accelerator Requirements and Interfaces
- Experiment Scenarios
- Operations Concept
- Operational Environment (Site-Specific)
- DOE Design Constraints

Functional Analysis

Functional analysis is the method for analyzing performance requirements and decomposing them into discrete tasks or activities. This process involves the decomposition or parsing of the SSC functions into subfunctions at ever increasing levels of detail; it supports the mission analysis in defining functional areas, sequences, and interfaces. Functional analysis also provides an understanding and permits the development of the SSC accelerator configuration and its operational capability. Functional analysis is used by the engineering and physics specialties and support organizations to develop requirements for equipment, software, personnel, and operational procedures to complete implementation and commissioning of the SSC.

Flowdown and Allocation of Requirements

Completion of the functional analysis will result in a hierarchical tree structure which progressively divides and allocates requirements to the lowest level (component or subroutine) that fulfills a definable requirement. This approach permits hierarchical modularity where independent modules are arranged in downward levels of increasingly specialized functions to promote management efficiency. Advantages in design, design verification through modelling, simulation, testing, and design iteration for enhancement of performance are realized.

The decomposition of system functional areas or segments, each of which satisfies an allocated portion of the basic system functions, permits the clear definition of interfaces and documents the interface requirements. Ideally, decomposition is a totally logical process, carried to completion without need for definition of a physical design concept or solution. Adherence to this process prevents the premature definition of design solutions with improper constraints and limitations imposed.

System Integration

Tradeoff Analysis

Trade studies are performed throughout development of the magnet configuration to ensure that the best solution is selected to satisfy accelerator requirements, including SSC performance objectives, cost, schedule, reliability/availability, and maintainability. During the concept design phase, trade studies are performed to establish the optimum magnet configuration. Once a subcontractor has been selected, trades studies serve as the tool for analysis of the detailed design for each magnet configuration. Trade studies are applied to the production phase for evaluation of production alternatives to ensure repeatability and producibility. Trade studies are developed and implemented as the design process progresses toward the definition of the magnet system requirements.

Magnet System Requirements Definition

Definition of the magnet system requirements typically focuses on the following specific critical issues of magnet design:

- Field Strength
- Field Quality
- Luminosity
- Quench Performance
- Availability
- Endurability
- Transportability
- Operational Safety
- Others as identified during development.

Design Concept Definition

Through the process of performing and documenting the engineering analyses described to this point in the systems engineering approach to the design of magnets, a design concept evolves.

Establish Baseline Design

Baseline designs are established at three distinct levels to define and document the magnet configuration for management and control:

Functional. The initial, approved design configuration documentation describing a specific magnet's functional characteristics and the method by which each characteristic is verified—by test, analysis, or inspection—to demonstrate the achievement of the specified characteristic or set of characteristics.

Allocated. The initially approved documentation describing a magnet's functional characteristics allocated from the set of accelerator requirements, interface requirements with other associated items, additional design constraints, and the method by which each characteristic is verified—by test, analysis, or inspection—to demonstrate the achievement of the specified characteristic or set of characteristics.

Product. The initially approved documentation describing all of the necessary functional and physical characteristics of the magnet configuration (including a comprehensive summary of the other interfacing configuration items, systems or equipment), and the selected functional and physical characteristics designated for production acceptance testing and tests necessary for support of the magnet.

Magnet System Build-and-Test

Magnet system build-and-test is normally performed at a minimum of two levels of design completion. The first level of testing is performed on a model magnet to prove the functional feasibility of the design to satisfy performance requirements. The second level is a full-size prototype of the preliminary design which is tested to verify that all magnet performance requirements are satisfied. Prototype testing also verifies production tooling and the ability to produce the magnet in production quantities. Prototype units are also tested under accelerated life conditions to verify the ability of the final design to satisfy system integrity requirements under operational environments.

Iterative Design Process

Results of the test activities are analyzed and are provided as inputs to the design engineer to permit the correction of design deficiencies or enhancements to the design which were identified as a result of magnet performance under test.

Finalize Design

Upon documentation of any design changes made as a result of the design iteration process, the design is finalized through the conduct of a critical or final design review (CDR). Additional model magnets may be built to incorporate the design iterations evolving from the test program. Successful completion of the CDR results in the authorization to proceed with magnet production.

The following phases leading to the completion of the SSC system design and implementation are the final steps in arriving at an operational Superconducting Super Collider.

- Build and Deliver Production Magnets
- Install Magnets
- Commission Accelerator
- Operate Accelerator.