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Magnetic Fields on the National Ignition Facility (MagNIF)

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1. Executive Summary

A magnetized target capability on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) has been investigated. Stakeholders' needs and project feasibility analysis were considered in order to down-select from a wide variety of different potential magnetic field magnitudes and volumes. From the large range of different target platforms, laser configurations, and diagnostics configurations of interest to the stakeholders, the gas-pipe platform has been selected for the first round of magnetized target experiments. Gas pipe targets are routinely shot on the NIF and provide unique value for external collaborators. High level project goals have been established including an experimentally relevant 20Tesla magnetic field magnitude. The field will be achieved using pulsed-power driven coils. A system architecture has been proposed. The pulsed power drive system will be located in the NIF target bay. This decision provides improved maintainability and mitigates equipment safety risks associated with explosive failure of the drive capacitor. High level and first level subsystem requirements have been established. Requirements have been included for two distinct coil designs – full solenoid and quasi-Helmholtz. A Failure Modes and Effects Analysis (FMEA) has been performed and documented. Additional requirements have been derived from the mitigations included in the FMEA document. A project plan is proposed. The plan includes a first phase of electromagnetic simulations to assess whether the design will meet performance requirements, then a second phase of risk mitigation projects to address the areas of highest technical risk. The duration from project kickoff to the first magnetized target shot is approximately 29 months.

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3. Introduction and Background

Background

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory shown in Figure 3.1 is the world's largest and most energetic laser system[1,2]. The purpose of the NIF is to advance our understanding of high energy density plasma physics in support of three missions for the US Department of Energy:

- advancements in inertial confinement fusion (ICF) as a potential energy source
- science-based stewardship of our nuclear weapons stockpile
- basic science and understanding of the cosmos

Figure 3.1. The National Ignition Facility

Figure 3.2 shows the high-level architecture of the NIF system. It directs 192 high energy laser beams onto small targets to conduct high-energy physics experiments. Total beam energy is 1.8 megajoules of 351nm laser energy up to 30nsec duration with a programmable pulse shape. The 40 cm square beams are focused to sub-millimeter spot sizes on target. An array of 65 different target diagnostic systems located around the equator of the target chamber are available to collect data on various types of target experiments.

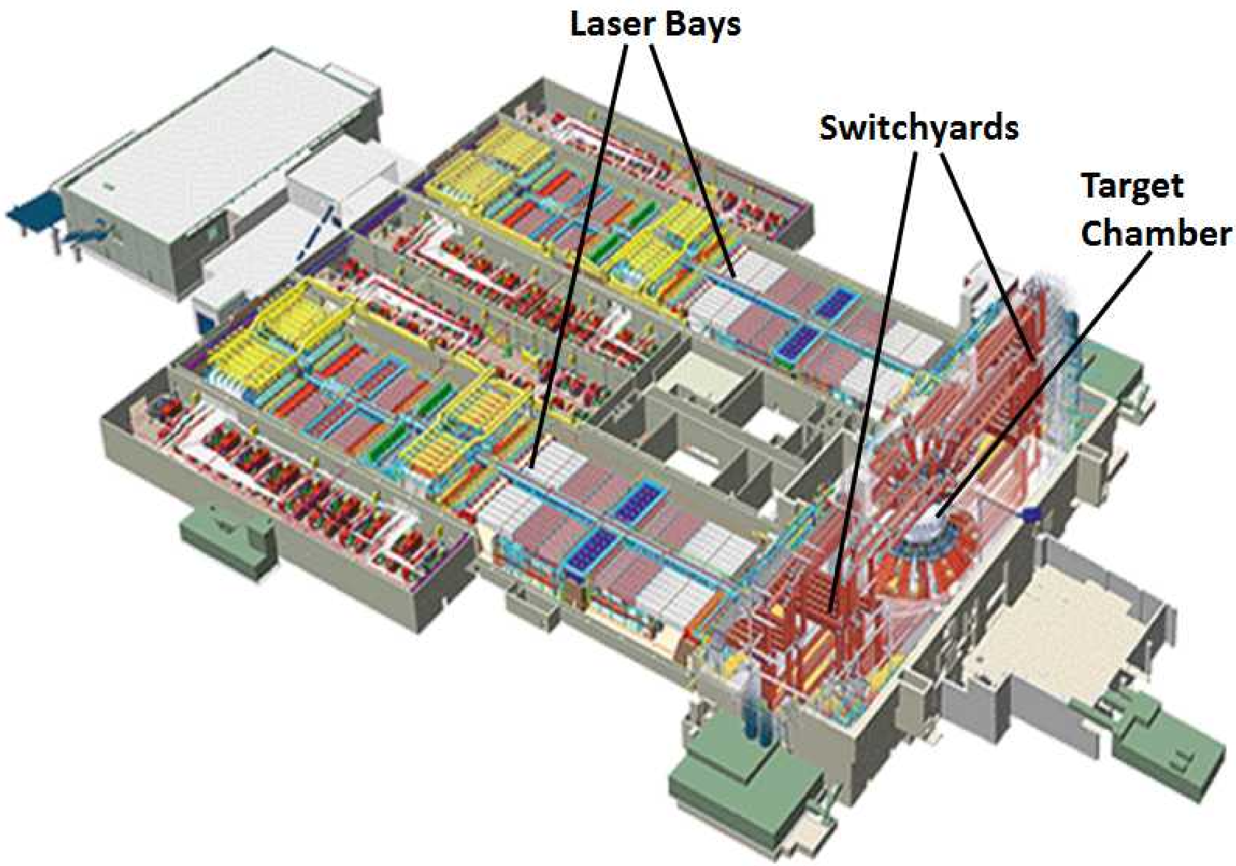


Figure 3.2. The NIF architecture. Forty centimeter beams are amplified in the two laser bays and are then directed into the target chamber where they are focused onto millimeter-scale targets.

Figure 3.3 shows a typical hohlraum target used for an ICF experiment mounted on the end of the target manipulator. The NIF ultraviolet laser beams enter the hohlraum can at the top and bottom of the target and illuminate the inside of the hohlraum where they are converted into x-rays which compress and heat a fuel capsule located inside the hohlraum. Compression to high enough pressures and temperatures causes the DT fuel to fuse into helium and release large amounts of energy. A high energy density plasma is formed during the process. In fact, nearly all NIF experiments involve the formation of a high energy density plasma.

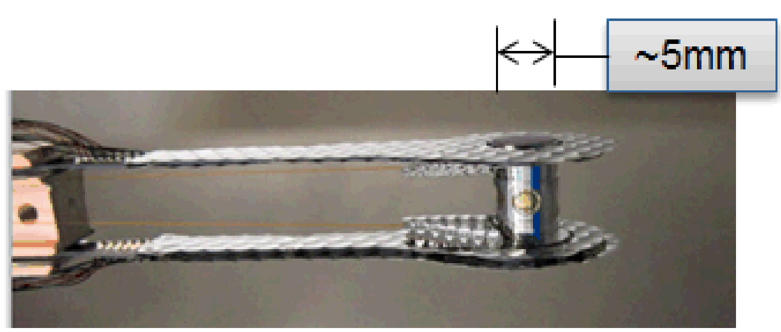


Figure 3.1. A typical target for inertial confinement fusion has the hohlraum can supported with two arms. The laser beams enter through holes in the top and bottom of the hohlraum.

The idea behind the MagNIF project is to apply a strong magnetic field around the target; the magnetic field will confine the plasma and slow its rapid outward loss of energetic particles. The particles will instead move in a spiral path and continue colliding and interacting with each other and the radiation present. As such, higher plasma electron temperatures and energies can be achieved along with increased plasma lifetime, which enables an entirely new parameter space for NIF experiments.

The MagNIF capability does not currently exist. The NIF target bay, target chamber, and target manipulators are highly complex and costly systems so that many constraints exist to add a capability such as MagNIF. An exploratory project[3] was funded to develop the MagNIF concept in which a high-voltage capacitor is discharged into a small coil to provide a momentary, but strong, magnetic field. The magnetic field needs to persist on the order of microseconds in order to carry out the NIF experiment. Figure 3.4 shows copper coils fabricated to demonstrate the large magnetic fields needed for MagNIF. On the left is a coil before overwrapping with Zylon. On the right is a finished coil mounted to a polyimide circuit board adapter, which provides mechanical support. Conductive copper sheets on the circuit board adapter are used to transmit the high-current pulse from the capacitor into the coil.

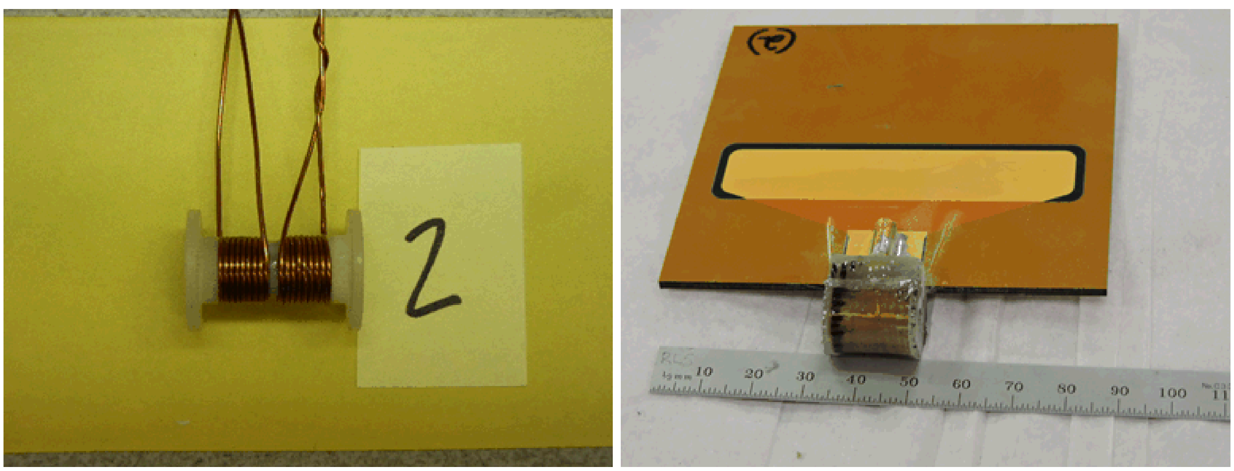


Figure 3.4. The coils used to demonstrate the large magnetic fields needed for MagNIF. On the left is a coil before overwrapping with Zylon. On the right is a coil mounted to an adapter board. (Rhodes, et. al.[3])

The prototype coils were tested with an array of four 1.6μF capacitors charged to 32kV. Figure 3.5 shows the results: a current of 39 kA generated a magnetic field of 31.4 Tesla, which is believed to be strong enough to have an impact on the plasma physics. The peak field occurred one microsecond after switch closure; NIF will be able to time the 10 nsec laser pulses to coincide with the peak magnetic field using the existing pulse timing control system.

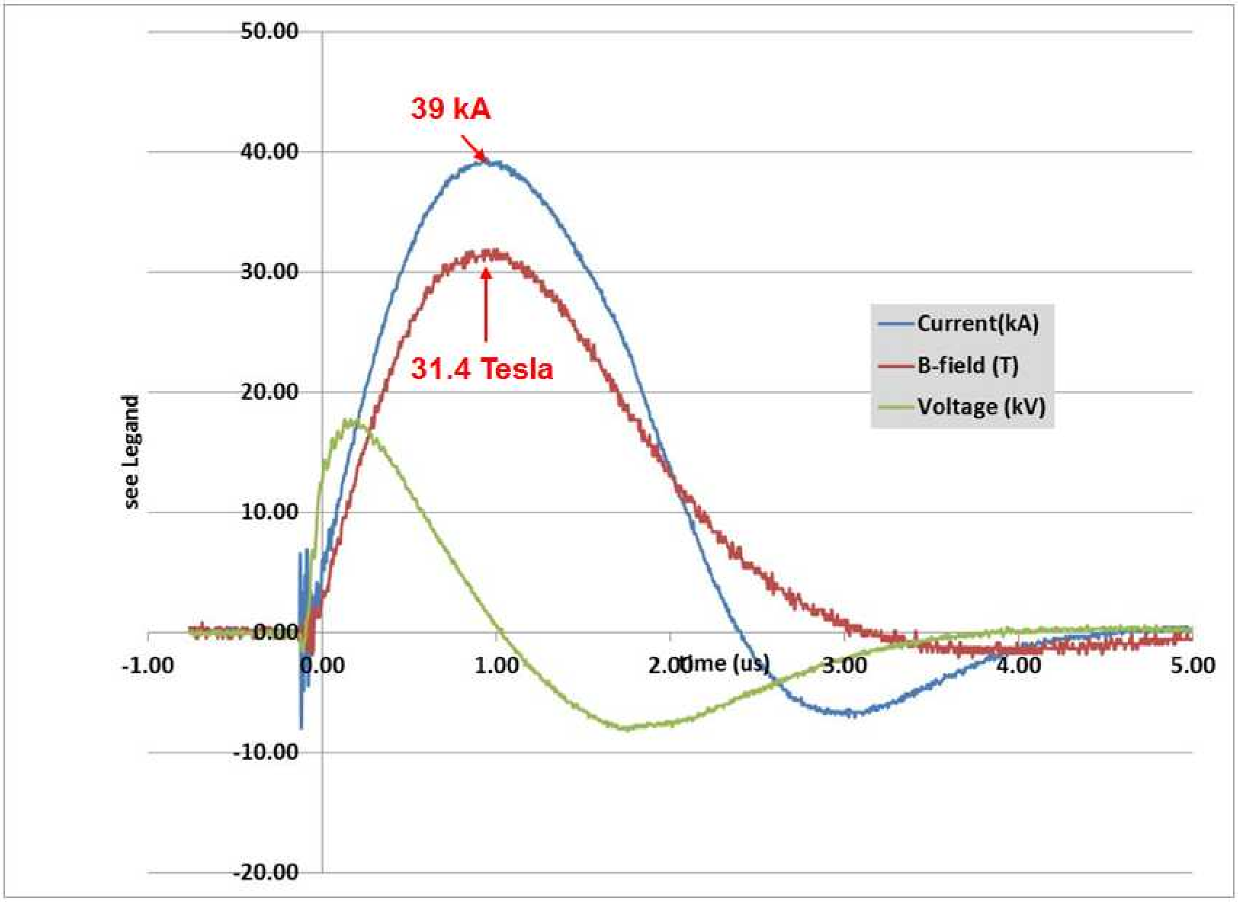


Figure 3.5. Magnetic fields above 30T were generated with the prototype coils from a capacitor charged to 32kV. (Rhodes, et. al.[3])

The decision was made to apply the MagNIF capability to a class of target experiments known as gas pipes because the requirements appear to be mutually compatible. Figure 3.6 illustrates a standard gas pipe experiment (without an applied magnetic field). A quad of four NIF beams illuminates one end of a 1cm long cylinder filled with a gas such as a neopentane/argon mixture at 1 atm pressure. A plasma is formed along the propagation direction of the beams. Optical transmission is monitored at the exit of the gas pipe while other diagnostics collect images of the plasma propagation from the side of the cylinder. The gas pipe is 100µm thick EPON-C epoxy to allow transmission of the plasma radiation; the entrance and exit windows are 0.75µm polyimide to maximize laser transmission yet hold off the 1 atm gas fill pressure in the target chamber vacuum environment.

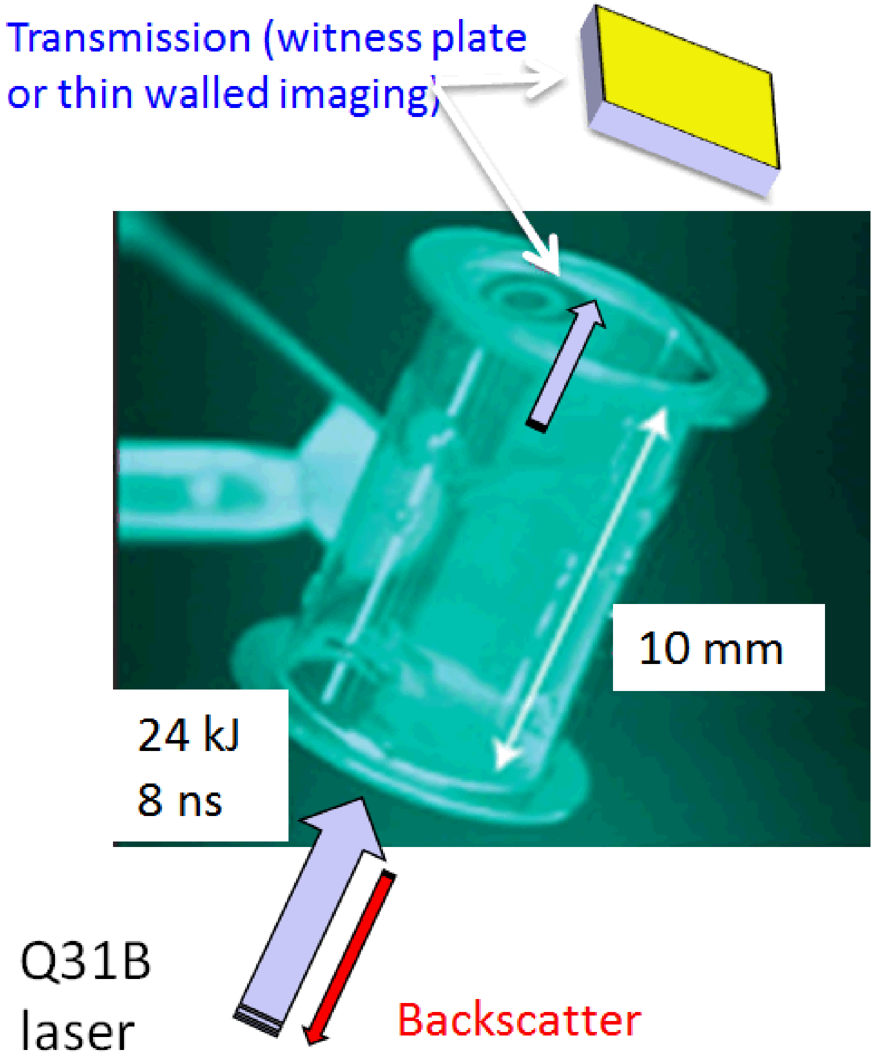


Figure 3.6. A standard gas pipe experiment. (Pollock[4])

The experimental objectives are to measure the effect of the magnetic field applied along the laser axis of gas pipe experiments on the resulting plasma temperature and lifetime. We plan to measure the difference in electron temperature (T_e) with vs. without the magnetic field. Key NIF target diagnostics to be used are the x-ray framing camera, pinhole camera, and spectrometers.

The MagNIF prototype requires several improvements for use with gas pipe experiments.

- The geometry needs to be modified to match the gas pipes.
- The thick coil wires used and their small spacing obscures the view for diagnostics to image the plasma propagation from the side of the pipe.
- The mass of copper used likely exceeds the amount allowed for NIF targets. It may generate debris and shrapnel with high enough mass and energy to damage the final optics.

- The capacitor will preferably be located remotely in the target bay, which would require 10m long transmission cables between the capacitor and the coil. Transmission losses in the cables will negatively impact generation of the magnetic field and must be well understood to properly design the system.

4. Stakeholders and needs

The MagNIF project has an interconnected set of stakeholders and needs. Table 4.1 lists the stakeholders and their needs. A key stakeholder is the US Department of Energy (DOE) which provides the funding for the project. The highest level stakeholder is the US taxpayer, who funds the DOE. The benefits to those stakeholders are twofold: one is increasing the knowledge base in the basic science of high energy density physics, the second is increased expertise in our science-based stockpile stewardship program which ensures a safe and secure US nuclear stockpile. Lawrence Livermore National Laboratory is the DOE lab at which the work is performed. Sandia National Laboratory is an external stakeholder which operates another high energy density physics experimental system called the Z pinch; the Sandia scientists are interested in applying a version of MagNIF to their Z pinch system. The international high energy density physics community is very interested in the application of external magnetic fields to NIF target experiments. Many NIF experiments generate their own large magnetic fields; it will be very interesting to explore the effect of adding an external magnetic field.

Table 4.1 MagNIF Stakeholders and Needs

	Stakeholder Group	Contacts	Needs
	US Dept. of Energy		support basic science in high energy density physics
			support science-based stockpile stewardship
	Lawrence Livermore National Laboratory		perform basic science in high energy density physics
			perform science-based stockpile stewardship
			avoid negative press
	US Taxpayers	Joan Rubin	safe and secure US nuclear stockpile
			judicious use of taxes for basic science
	NIF Director	M Herrmann / D Larson	add new experimental capability
			strengthen partnership with Sandia National Lab
	Sandia National Lab		expand knowledge base applicable to Z-pinch
	NIF operations	Bruno Van Wonterghem	successful, efficient and safe use of the NIF facility
	NIF safety	Darryl Gorman	ensure the safety of operators and hardware
	High Energy Density Physics	Warren Hsing	Ensure all HED projects meet strategic needs, and are successful
	NIF Target Diagnostics	P Datte	collect accurate and reliable data during NIF experiments
MagNIF Project Team	Experimental Physics Team	J. Moody, lead scientist	manpower and resources to build MagNIF
		Brad Pollock	
	Target fabrication	Jeremy Kroll	deliver targets to support NIF experiments
	TALIS	Nathan Masters	Protect optics and other NIF hardware from target debris and shrapnel
	NIF alignment (Target and Diagnostics)	Tom Parham	Assure targets and diagnostics are alignable and aligned
	NIF cleanliness steering committee	Bill Gourdin	Assure only acceptable materials enter the NIF
	MagNIF core project team	Phil Arnold, lead engineer	pulsed power
		Glen James	pulsed power
		Bruno Legalloudec	pulsed power
		J Javedani	magnetic field modeling
		Dan Mason	systems engineering
		Jim Folta	systems engineering

Several other stakeholders are on the NIF project team, but not necessarily on the MagNIF project team. Two examples are the NIF operations team which operates NIF to support target experiments, and the NIF safety team which ensures safe operation of the complex laser facility. The NIF target diagnostics group will utilize already-existing diagnostic systems to collect data from the MagNIF experiments.

The bottom half of table 4.1 shows stakeholders within the MagNIF project team. These consist of the experimental physics team which designs the experiments and analyzes the results. The other stakeholders within the project team are responsible for carrying out the project in support of the physics team. The core project team at the bottom has primary responsibility for design, fabrication, operations, systems engineering and project management. Since the primary technical challenges and risks for MagNIF are related to the pulsed power system used to generate the magnetic field, the NIF Director has assigned NIF's senior pulsed power electrical engineer, Phil Arnold, to lead the project team. The other teams are expert groups which apply their expertise and capabilities to support the design and experimental efforts.

Figure 4.1 shows a diagram of the MagNIF stakeholder value network (SVN) and depicts the value flows among the stakeholders. The external stakeholders, defined as external to LLNL, are denoted with the orange boxes. While we labeled the high energy density physics community as an external stakeholder, a large portion of that group also resides within LLNL.

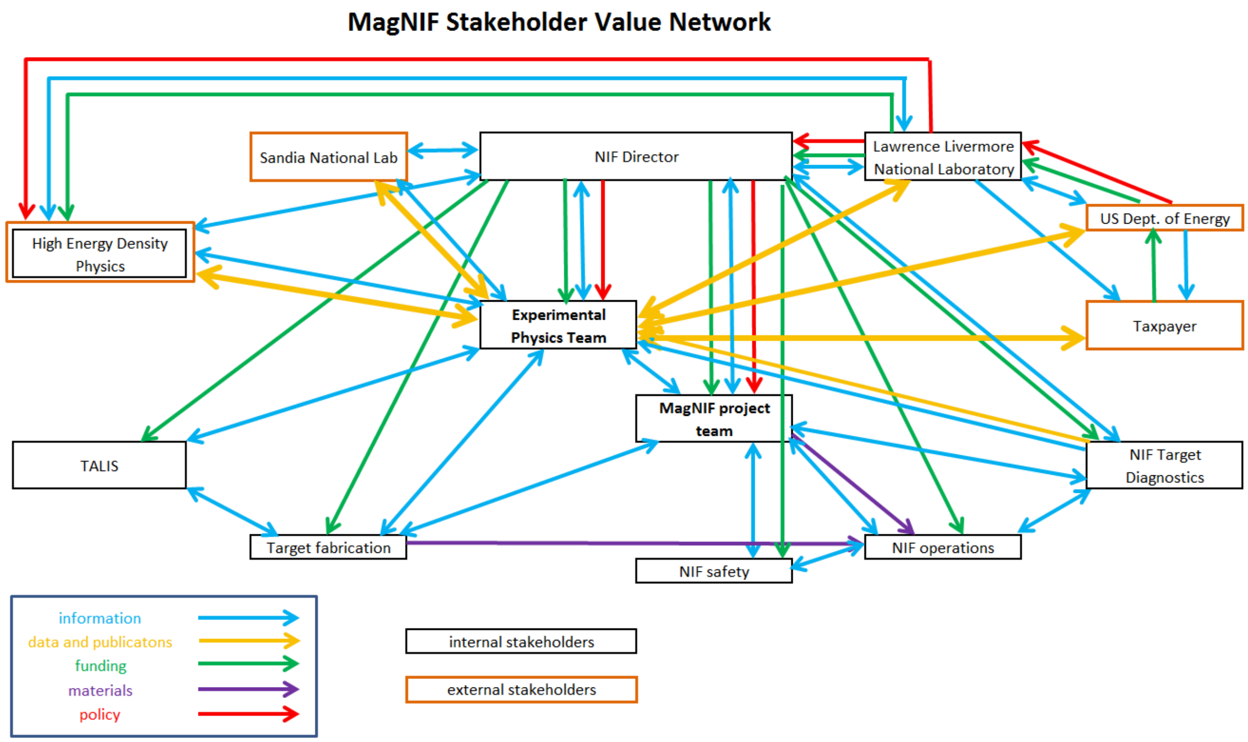


Figure 4.1. The MagNIF Stakeholder Value Network. The SVN allows visualization of value flow related to the new experimental capability. The primary value-added products generated by the project are the data and publications generated by the experimental physics team. These are noted by the emboldened yellow arrows.

Most of the value flows among the stakeholders are in the form of information. That should come as no surprise for a project at a national laboratory, since the generation of information is the laboratory's primary product. Information flows have been broken down into 2 components: the data and publications produced by the project (yellow arrows); and the rest of the information such as design details, project plans, staffing plans, budgets, and procedures (blue arrows). The primary value-added products generated by the project are the data and publications generated by the experimental physics team. These are noted by the emboldened yellow arrows. The flow of funding (green arrows) originates from the taxpayer and flows through the Department of Energy to LLNL. LLNL funds the NIF directorate which manages NIF operations and funds projects such as MagNIF. Flow of materials among the stakeholders is relatively sparse: the MagNIF project delivers and installs hardware to NIF (owned by NIF operations), and the target fabrication group provides targets. Policy originates at the Department of Energy and flows to the project via LLNL and the NIF directorate.

5. Goals

After analyzing the stakeholders and their needs, the following four goals were generated and socialized among the key stakeholders.

1) Develop the capability to apply magnetic fields to NIF targets to confine the plasma and increase plasma energy. The MagNIF capability has 3 major components:
   - The facility infrastructure and controls needed to safely power the magnetic coils
   - The facility diagnostics required to diagnose the experiments
   - The design and fabrication of targets to support the experimental program
2) Deploy a 20 Tesla pulsed-power driven magnetic field capability for a new generation of gas pipe experiments at ambient conditions by the middle of CY18.
3) Deploy an architecture that is upgradeable to support future cryogenic and hohlraum experiments in the 3-6year timeframe.
4) Ensure that operation of the high-voltage capacitor used to power the coil will meet NIF safety requirements for both personnel and machine safety.

6. System Architecture

Concept

The concept for the MagNIF project can be succinctly described as:

To confine the plasma during NIF target experiments **by** applying a magnetic field **using** high-energy capacitors discharged into conducting coils.

The concept can be illustrated with an Object Process Methodology (OPM) diagram as shown in Figure 6.1. The MagNIF system hardware generates a magnetic field around the NIF target. The field confines the plasma which results in higher temperatures of the plasma generated by the NIF laser beams. The labels to the right of the diagram describe the operand/process/instrument relationships shown in the diagram.

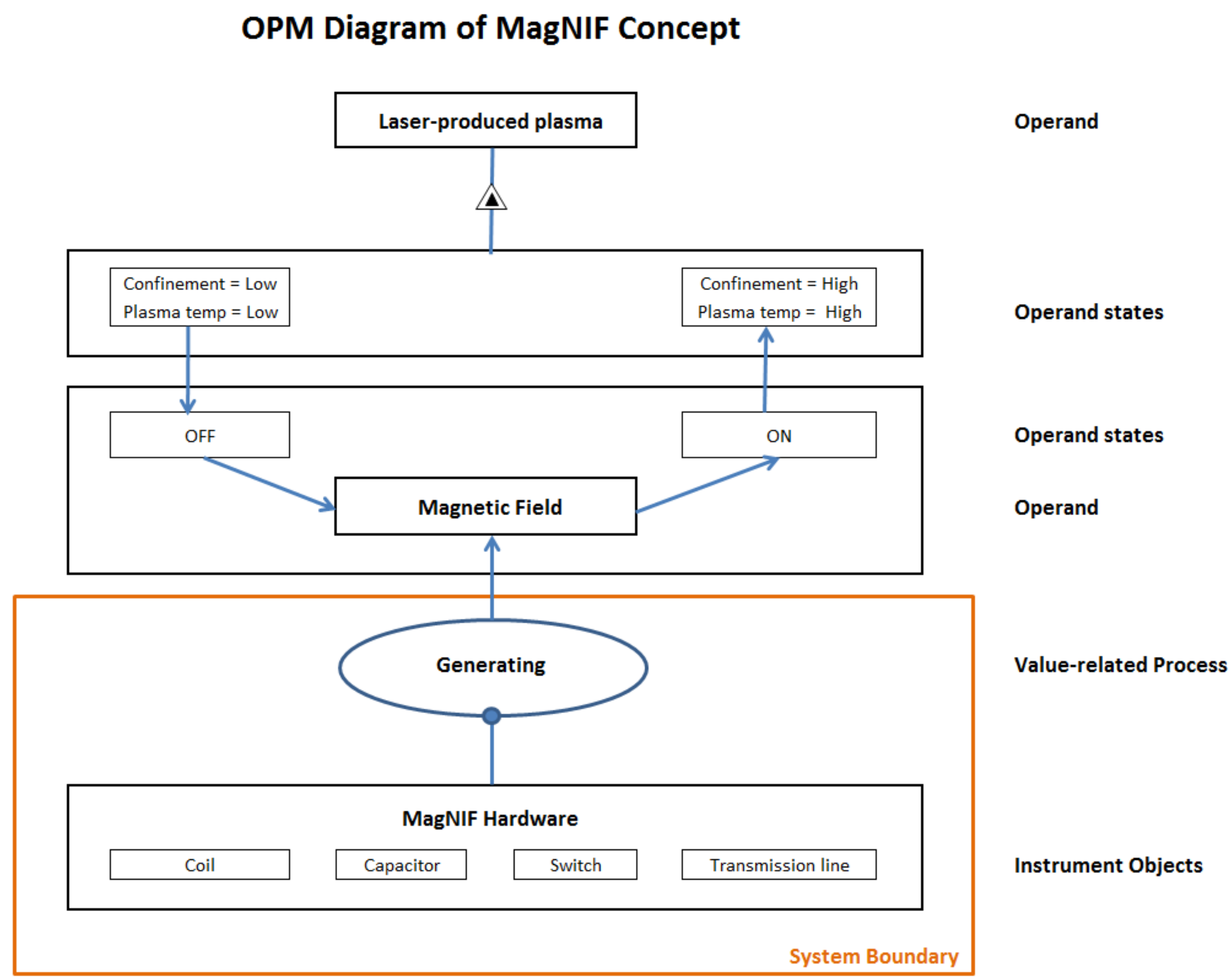


Figure 6.1. The MagNIF concept as depicted with a level 1 OPM diagram

Formal Decomposition

The formal structure of the MagNIF hardware can be further decomposed to a second level as shown in Figure 6.2. In addition to showing the components of the 6 subsystems, the OPM also shows the locations of the subsystems within the NIF facility. From a pulsed power engineering perspective, the capacitor and switching circuit would be located as close to the coil as possible to reduce losses and maintain the fidelity of the current pulse. However there is a risk of capacitor explosion which would cause major damage to the NIF target vacuum chamber. Therefore, an alternate architecture was proposed to mitigate that risk. Figure 6.2 shows the favored, baseline configuration in which the capacitor and switching circuit are remotely located within a vented explosion proof enclosure in the target bay. Long transmission lines within the diagnostic insertion module (DIM) are used to transfer the current pulse to the magnet coil mounted on the end of the DIM (at target chamber center).

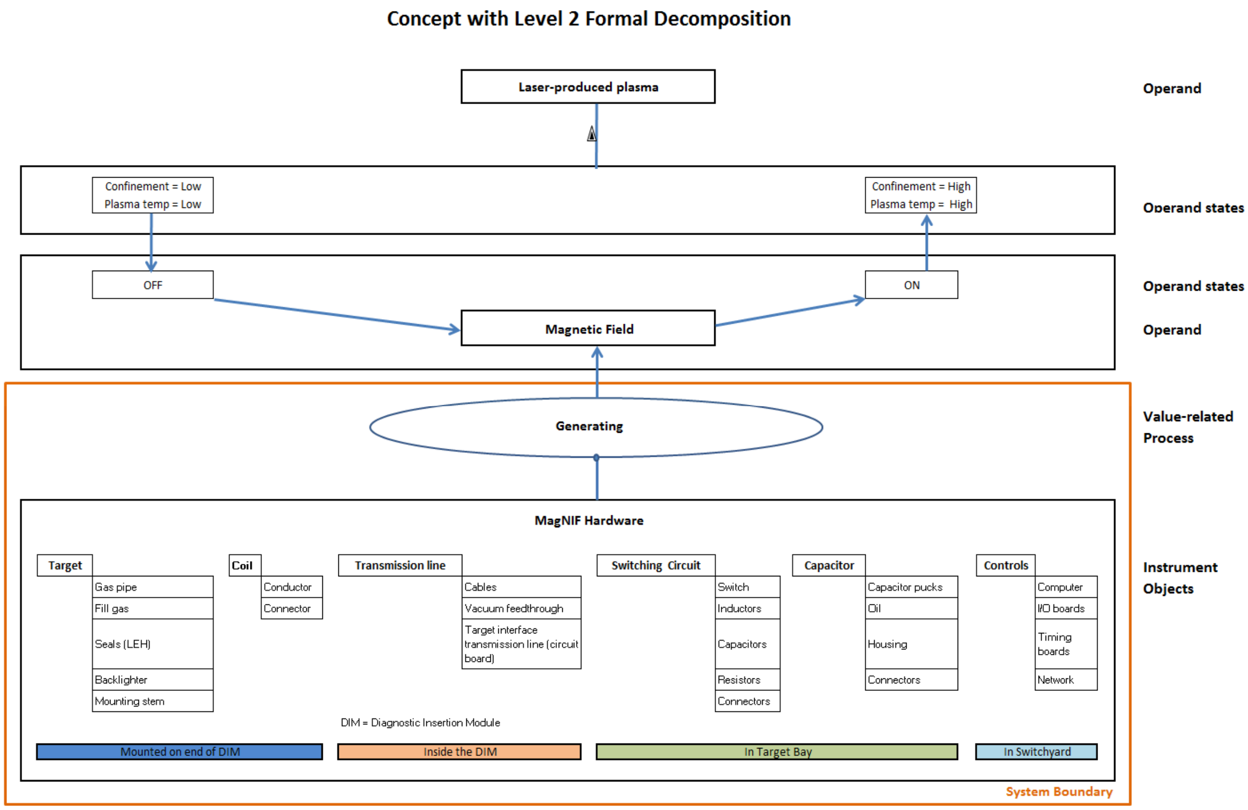


Figure 6.2. The MagNIF concept with a level 2 formal decomposition. The boxes at the bottom of the diagram indicate the locations of the subsystems within the NIF facility. Locating the capacitor in the target bay is a key architectural decision.

The impedance of the long transmission line and the associated losses in the current pulse, however, limit the ability to generate the required strong magnetic fields within the coil. The solution may be to use multiple transmission lines in parallel, but that approach is limited by space constraints within the DIM cable ways. The location of the capacitor represents a key architectural decision because of the trade-off between safety and system performance. Extensive use of electromagnetic computational models will simulate performance of the electronic circuit and the generated magnetic field before a final decision is made on the system architecture.

Functional Decomposition

The functional decomposition of Figure 6.3 presents an alternate view of how the MagNIF system generates the magnetic field. Low voltage cables are used to charge the capacitor to a high-voltage. A switching circuit is used to discharge the capacitor which produces a current pulse into low impedance, high current capacity transmission lines and into the coil. The high currents in the coil generate a strong magnetic field. The right side of Figure 6.3 shows the supporting instruments: ICCS is the NIF control system hardware and software; the target area cart contains the capacitor and switching circuitry; the DIM supports the target at target chamber center and houses the high-voltage transmission lines. The labels at the bottom of the diagram classify the operand/functional/instrument relationships of the various elements and functions. Note that nearly all of the elements and functions are considered to be within the MagNIF system boundary.

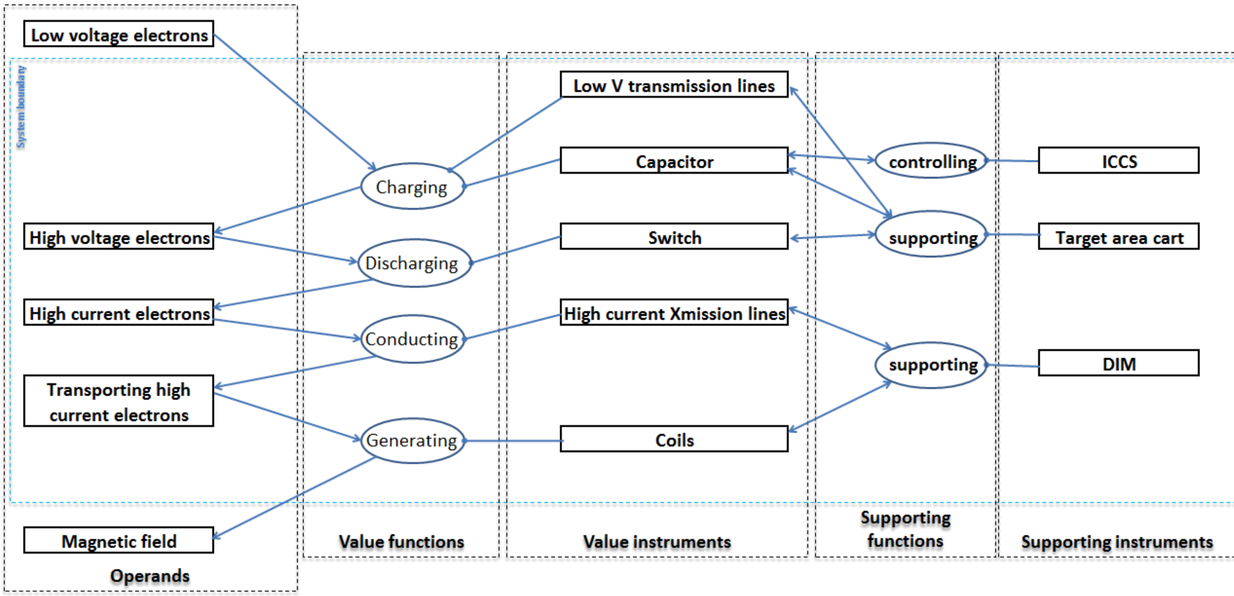


Figure 6.3. The functional decomposition of the MagNIF system describes how the magnetic field is generated and classifies the operand/functional/instrumental relationships.

Concept of Operations

The concept of operations is nearly identical to those used to perform other experiments with the NIF.

1. Design physics experimental goal
2. Design target
3. Determine target diagnostic requirements
4. Determine laser parameters
5. Schedule the experiment
6. Fabricate target
7. Install the MagNIF cart (capacitor and switch) in the target bay near the DIM
8. Install target on end of DIM
9. Confirm electrical connections
10. Configure the laser and diagnostics
11. Charge the capacitor
12. Perform the experiment (discharge the capacitor and fire the laser)
13. Remove target remnants
14. Remove the MagNIF cart
15. Generate shot report (collect the target diagnostic and laser diagnostic data)
16. Physics team analyzes and interprets the data

External Interfaces

The MagNIF hardware must interface with existing NIF infrastructure. The primary interfaces span hardware, software, safety systems and procedures. The primary interfaces are:

1. The TANDM DIM

2. ICCS controls hardware
3. ICCS controls software
4. ICS Industrial Safety Controls
5. NIF target bay hardware
6. NIF utilities
7. NIF laser
8. NIF target diagnostics
9. Target factory

The MagNIF project team has partnership interfaces with several external groups. The external interfaces are illustrated in the stakeholder value network diagram in Figure 4.1 and consist of the following 5 groups:

1. NIF Operations
2. NIF Safety
3. NIF target diagnostics
4. Target fabrication
5. TALIS (simulates the debris and shrapnel and other contamination from the exploding target which could damage the final optics or other hardware in the target chamber)

All of these interface groups participate in the design and review process. In addition, new capabilities such as MagNIF are required to undergo the Work Acceptance Process (WAP) in which all of the stakeholders are identified and must approve readiness to use the new hardware before it can be used. The WAP process has been proven to successfully enforce management of interface issues.

7. Requirements

MagNIF high level and first level subsystem flowdown requirements have been established. The requirements document is attached as a separate MS Excel file associated with this report. Functional and performance requirements are based on stakeholder needs, project goals, and use context. Constraint, interface, and environmental requirements are derived using operational requirements associated with planned installation location. Requirements for the “-ilities” of the system are driven by management guidance, established organizational policies, and quality standards. Tables 7.1 and 7.2 show the count of requirements by type and by subsystem.

Table 7.1 and 7.1 MagNIF requirements type and subsystem summary

Requirement Type	Requirement Quantity	
Functional	5	11%
Performance	10	21%
Constraint	18	38%
Interface	2	4%
Environmental	3	6%
-ilities, other	9	19%
Total	47	

Subsystem	Requirement Quantity	
System level	16	34%
Target	5	11%
Transmission lines	6	13%
Drive electronics	10	21%
Diagnostics	9	19%
Controls	1	2%
Total	47	

The MagNIF requirements focus on the new capabilities and hazards being added. In some cases the simple count of requirements is misleading. For example, the controls implementation is highly constrained since the hardware and software infrastructure is currently installed and in routine operations. This fact constrains feasible design solutions to use the existing infrastructure. Instead of a high number of detailed constraint requirements in this area, a single overarching requirement is included. In addition, some of the constraint requirements refer to detailed interface control documents. An example of this is the TANDM positioner target interface requirements. The requirements list includes a pointer to NIF document # 1000496066, which is the detailed description and requirements associated with the TANDM instrument interface. This includes fastener connection patterns, volumetric stayout zones, and mass requirements relative to the desired target installation location.

The plan going forward for the MagNIF capability includes two separate coil designs. These two coil designs represent different optimal solutions depending on the users' value weighing of diagnostics visibility against field performance. To accommodate this, parallel sets of requirements have been generated as necessary. For example, the field is specified for the quasi-Helmholtz geometry and solenoid geometry separately. Where not explicitly noted, requirements listed in the document apply to both experimental platforms.

A verification method for each requirement is included in the requirements document. Table 7.3 shows the count of requirements by verification method. The INCOSE definitions for verification methods are used. These methods are Demonstration, Analysis, Inspection, and Test[6].

Table 7.3 MagNIF requirements verification method summary

Requirement Verification Method	Requirement Quantity	
Demonstration	13	28%
Analysis	11	23%
Inspection	11	23%
Test	12	26%
Total	47	

An offline laboratory exists for pulsed power and capacitor development. This laboratory will be repurposed in order to support Demonstration and Test requirements verification activities prior to deployment of MagNIF into the NIF laser system. This is discussed in detail in the project planning section of this document.

Some safety aspects of the design, such as the explosives containment vessel, will be verified using Analysis. The engineering required to safely contain the stored energy in this system is well understood at LLNL and can be addressed with Analysis. This is appropriate given the cost and schedule impact associated with running a test program to establish a design margin on an explosives containment vessel.

The goal of the requirements document is to provide a framework to start the formal Requirements Review process. The design team will then utilize the document during the development of more detailed subsystem requirements. One of the major documents that will be generated from this set is a detailed controls requirement document, the Software Design Description (SDD). Detailed safety interlock information will be included along with logic diagrams to define permissible states and the response to faults. In addition, automation and scripting is included. In addition to controls, detailed subsystem requirements will be established. Detailed diagnostics requirements are another area of future focus. This includes timing and calibration specifications. The requirements (or deltas) are reviewed at each gate review as the project progresses.

8. FMEA

The Failure Modes and Effects Analysis (FMEA) is a process implemented in the NIF and Photon Sciences directorate (NIF&PS) as a method to assure design and procedure adequacy[3]. This tool provides a structured method for analysis of how risks are addressed by the design in question. The FMEA is a required deliverable prior to the Conceptual Design Review and is a useful tool that encourages the early incorporation of safety in designs.

The quality and completeness of the FMEA can be improved if the definition of “Failure” is widened to include the broader context of operation using System-Theoretic Process Analysis (STPA) tools as discussed in the MIT SDM curriculum[7]. Including human operators, software, management, and adjacent systems allows identification of unsafe control actions that lead to failures in addition to single component failures. This method has been applied to the MagNIF FMEA.

A MagNIF-specific definition for severity grading of equipment risk consequence has been established as outlined in table 8.1 below. For the standard NIF&PS FMEA process, the equipment risk consequence definition is a simple cost of replacement for each instance of a failure. This is based on perceived risk to future project funding in addition to certain accident reporting requirements mandated by the sponsor. Since the main stakeholder value associated with MagNIF is enhanced experimental data, a severity category has been reserved for failures resulting in lost or incorrect experimental data.

Table 8.1 Equipment Risk Consequence Definitions (cost thresholds not shown – business sensitive)

Severity	Definition
Very High	Damage to NIF hardware and/or optics >$--k
High	Damage to permanent MagNIF infrastructure and/or damage to NIF hardware <$--k
Medium	Failure resulting in lost or incorrect experimental data
Low	Minor damage <$--k

The standard NIF&PS definitions for personnel risk have been used for this analysis. They are included in table 8.2 below. These thresholds are less precise than the equipment risk category, which requires the FMEA author to consider the specific context of the project being evaluated. For the MagNIF project, only Catastrophic, Marginal, and None are used.

Table 8.2 Personnel Risk Consequence Definitions

Severity	Definition
Catastrophic	Death
Critical	Severe Injury
Marginal	Minor Injury
Minor	Less than minor injory
None	No Hazard

Twenty two failure modes were evaluated using the methodology. The FMEA document is attached as a separate MS Excel file associated with this report. Summary metrics for equipment and personnel risks associated with each failure mode are shown in table 8.3 below.

Table 8.3 FMEA Summary Metrics

Equipment Risk

BEFORE MITIGATION

Severity	Probable	Infrequent	Remote	Improbable
Very High	1	-	-	-
High	12	2	-	-
Medium	7	-	-	-
Low	-	-	-	-

AFTER MITIGATION

Severity	Probable	Infrequent	Remote	Improbable
Very High	-	-	-	-
High	-	-	8	-
Medium	-	-	8	-
Low	1	4	1	-

Personnel Risk

BEFORE MITIGATION

Severity	Probable	Infrequent	Remote	Improbable
Catastrophic	2	2	-	-
Critical	-	-	-	-
Marginal	-	-	-	-
Minor	-	-	-	-
None	18	-	-	-

AFTER MITIGATION

Severity	Probable	Infrequent	Remote	Improbable
Catastrophic	-	-	-	-
Critical	-	-	-	-
Marginal	-	-	3	-
Minor	-	-	-	-
None	1	4	14	-

Specific hardware and controls mitigations outlined in the FMEA have been incorporated into the high level MagNIF requirements. For example, switch reliability has been identified as a key driver of equipment safety. If the switch fails to actuate on demand, the result would be a loss of experimental data and excessive target shrapnel due to the laser impacting the target before the current pulse has liquefied the metal conducting coils. The response to this is to include additional reliability requirements on the switch hardware in addition to the system level reliability requirements.

The failure modes with “Catastrophic” personnel risk prior to mitigation are important to evaluate in detail. One example is the risk associated with explosive failure of a charged capacitor. This risk has been mitigated with a layered approach to provide redundancy, which is appropriate given the consequence of failure. At the hardware level, the capacitor will be used at a de-rated voltage value to increase the safety margin. In addition, the capacitor will be enclosed in a safety-rated explosive containment vessel. For controls, the charging sequence will be automated using the NIF ICCS system and performed remotely so that personnel are not required to be in the vicinity of a charged capacitor. This leverages existing organizational processes and controls infrastructure. To mitigate controls failures, there will be a hardware level safety interlock on the device (NIF SIS) run off of separate controls infrastructure with low level logic control that prevents charging unless the target bay has been swept of human occupants in preparation for a shot and the safety enclosure is closed. This will use separate dump resistor hardware that is controlled using a separate system as the main NIF automation/scripting system and is effective regardless of the commands given by the ICCS system. This 3-tier approach will assure personnel safety. (NIF has decades of experience managing the safe use of high energy capacitors. The NIF houses 4 large bays of high energy capacitors which discharge into flashlamps to energize the 3072 laser glass amplifiers for every NIF shot.)

Another classification of risks that are useful to evaluate is any item that falls in the marginal or “bad” category of severity vs. probability in either equipment or personnel risk. The only risk remaining in this category after mitigation is in the “Low” severity / “Probable” category for equipment risk. This failure mode is the failure to reach coil melt temperature prior to destroying the target with the laser.

Table 8.4 Remaining “Probable” Equipment Risk FMEA Item

FMEA ID#	18
Primary System	Target
System or Subsystem	Coils
Failure Mode	Excessive high mass & velocity target shrapnel
Cause	Insufficient total current to reach melt action temperature prior to laser-induced disassembly
Effects	Damage to final optics system requiring replacement of optics
Equipment Damage Consequence before Mitigation	High
Personnel Consequence before Mitigation	None
Probability Before Mitigation	Probable
Preventive and Mitigative Measures	Destructor beams assure complete target vaporization regardless of pulse
Equipment Damage Consequence after Mitigation	Low
Personnel Consequence after Mitigation	None
Probability after Mitigation	Probable

This remaining “Probable” risk highlights an important design tradeoff. The desire to reach coil melt temperature prior to opening up a short in the conduction path, but *after* the relevant physics is captured by the diagnostics is an extremely challenging timing and current ramping requirement. Due to the uncertainty associated with material properties and modeling of simultaneous large deformations with rapid phase change, a proposed mitigation is to use additional laser beams to assure more complete destruction of the target. This approach, however, will need to be revisited following additional testing on the coils during the early project phase risk reduction projects. Opening up additional laser beamlines, while potentially reducing risk on the beamlines participating in the physics experiment, adds to the overall quantity of beams exposed to a low level of risk.

9. Project Plan

The MagNIF project plan was developed with the following primary objectives:

- address technical risks early in the project
- minimize total cost
- minimize unplanned rework cycles

The project plan shown in Figure 9.1 was built with MS Project 2013 and includes 171 tasks. A full version of the plan in MS Project format accompanies this report.

Risk reduction during Conceptual Design

As previously discussed, the location of the capacitor and switch is a key architectural decision, with the preferred location being remotely located in the target bay. However this may limit the ability to achieve the required strong magnetic field. An extensive set of electromagnetic simulations of the capacitor/switch/transmission lines/coil circuit performance was planned to explore the design parameter space and assess the feasibility of the remote location of the capacitor. This assessment must be complete and socialized among the physics and engineering teams before the conceptual design review.

Risk reduction during Preliminary Design

Numerous additional technical risks remain to be addressed in parallel with the preliminary design. Six risk reduction projects were identified as necessary to provide a solid foundation for the design and to reduce rework cycles later in the project.

Risk reduction projects:

1. **Switch and safety system** - prototype the switch and safety system and test it in an off-line lab
2. **Transmission cables** - procure samples of the selected transmission cables. Test their ability to withstand the rated voltage. Test their ability to fit in the space available in the TANDM DIM. Test their ability to flex without binding in the U-shaped cable track.
3. **Vacuum power feedthroughs** - buy or design the vacuum feedthroughs to make the connections between the air side cables and the vacuum side cables. Test their ability to withstand the rated voltage without arcing, their outgassing characteristics, and their mechanical integrity.
4. **Target fabrication** - design and fabricate targets for the off-line testbed. Design and fabricate prototype targets for the NIF experiments. Begin engaging the TALIS group to ensure the targets will be acceptable for use on the NIF.
5. **Magnetics Testbed** - restart operation of the magnetics testbed that was built to support an LLNL research project which was the predecessor to this project. Modify the testbed as necessary to support MagNIF.
6. **Final Testbed demonstration** - perform a series of testbed demonstrations to show that the 20T magnetic field can be achieved repeatedly and reliably. Collect sufficient data to allow timing of the NIF laser pulse near the peak of the magnetic field.

The preliminary design will start in parallel with the risk reduction projects to the extent possible. However many of the risk reduction projects are predecessors to preliminary design tasks. This is reflected in the project plan. The preliminary design review is scheduled after both the risk reduction projects and preliminary design are complete.

Final Design and Production

The final design is planned to be completed shortly after the preliminary design review, after which there is a fairly lengthy hardware production cycle. In parallel with the hardware production is completion of the controls hardware and software. Twenty days were allocated for rework cycles.

Installation and operation

Because time in the NIF facility is very expensive, considerable time is allocated for training and developing the installation qualification (IQ) and operational qualification (OQ) plans and procedures.

After the hardware gets installed and qualified, MagNIF is ready to load the first target and take a laser shot!

Resources

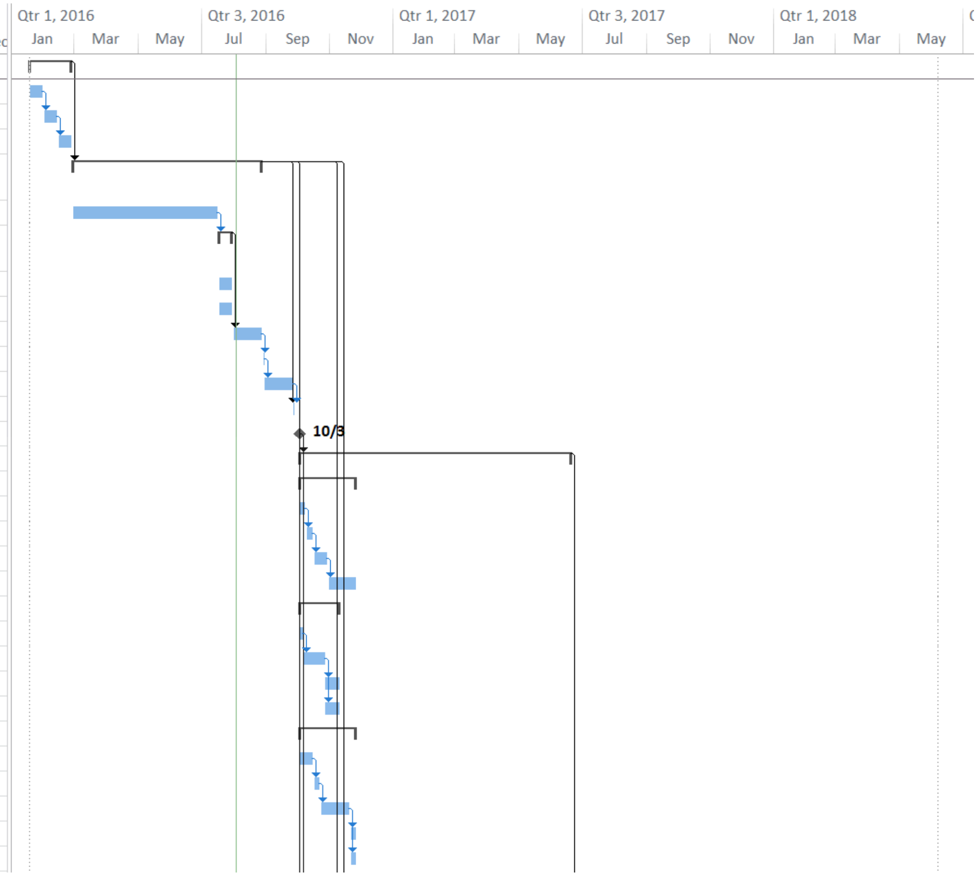
After the conceptual design review, NIF management will make the go-forward decision on funding the MagNIF project and allocate resources from the FY17 budget planning process. The plan assumes a funding start date of October 3, 2016 (the beginning of the LLNL fiscal year), after which the risk reduction projects and the preliminary design can begin.

The project plan has yet to allocate manpower resources to the tasks. The project planning process can be completed in two different ways:

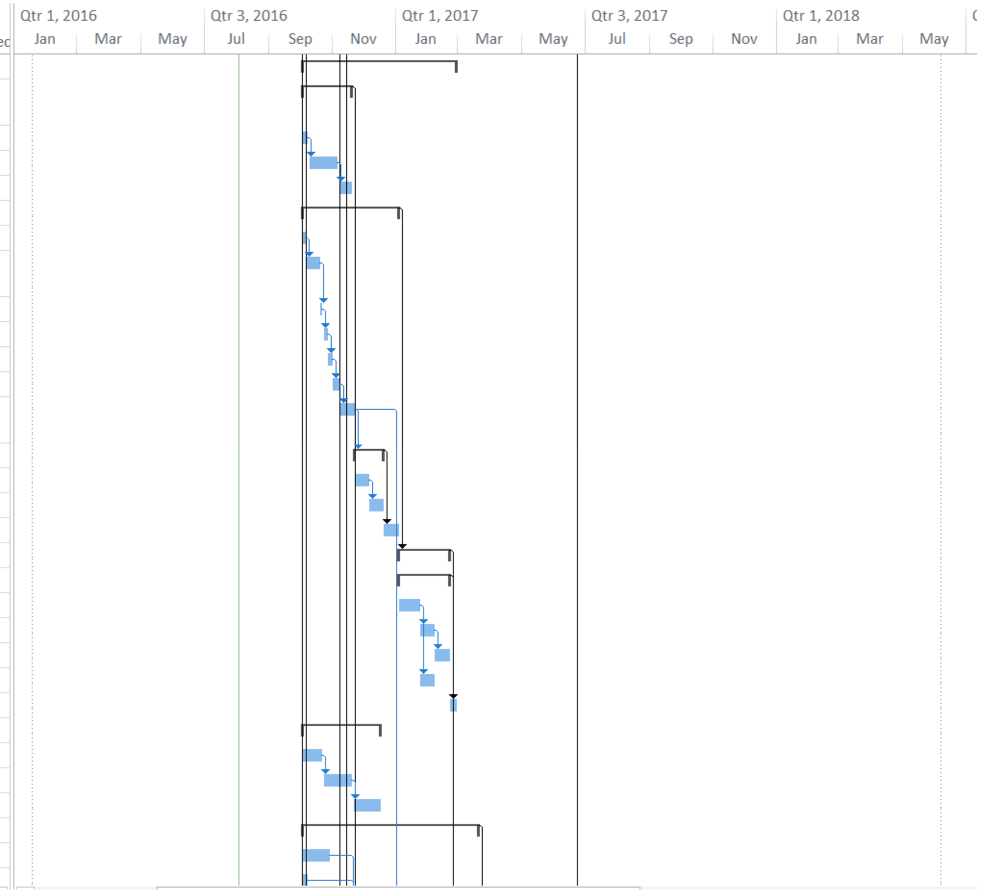
1. Provide manpower resources on a "%-time" basis for each of the main contributors (for example, "50% of Eliseo for 9 months"). The project manager then applies these resources to the tasks and projects an updated project completion date.
2. The other approach is to set a fixed, but reasonable, date on which the project must be complete. The project manager then determines what staffing levels are required to meet that completion date.

The first approach is more likely. The procurement budget for MagNIF is expected to be relatively modest compared to the manpower costs, so no procurement estimates have been performed.

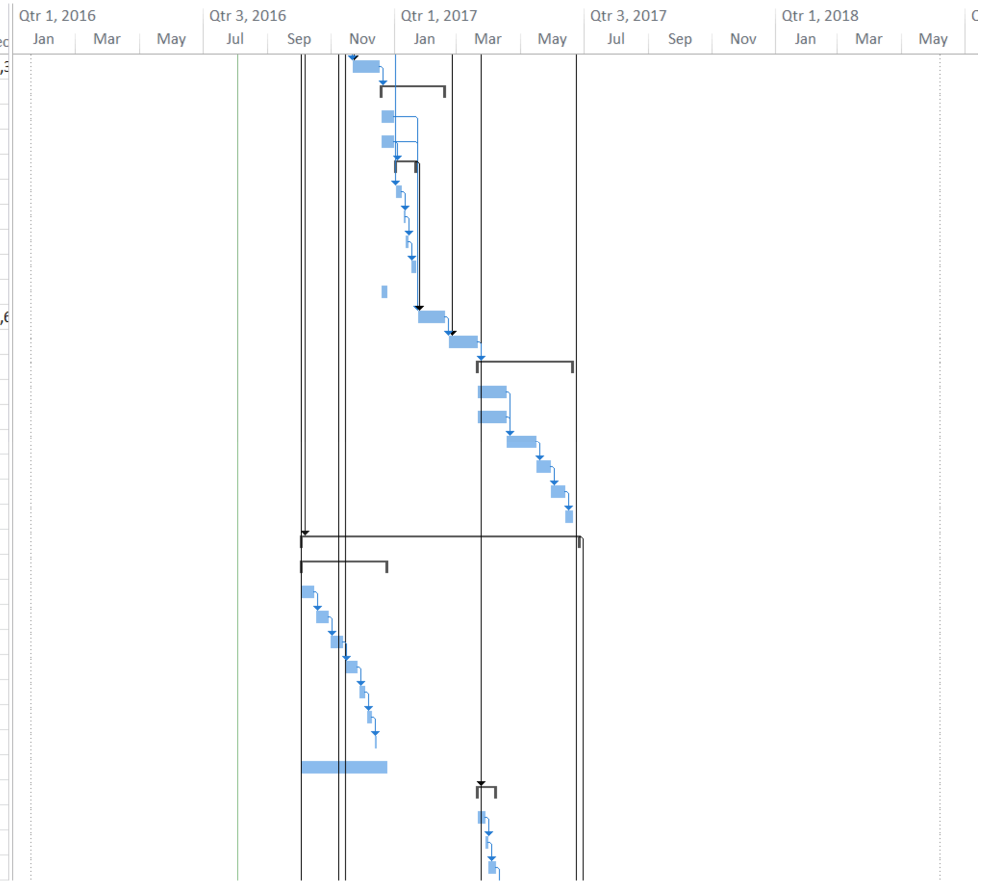
	Task Mode	Task Name	Duration	Start	Finish	Predec
1		**Determine scope and high level requirements**	**30 days**	**1/18/2016**	**2/26/2016**	
2		Define initial experimental platform	10 days	1/18/2016	1/29/2016	
3		Define baseline requirements	10 days	2/1/2016	2/12/2016	2
4		Propose conceptual design	10 days	2/15/2016	2/26/2016	3
5		**Preliminary EM simulations for feasibility of coil, drive circuit and transmission lines**	**130 days**	**2/29/2016**	**8/26/2016**	**1**
6		Electromagnetic simulations	100 days	2/29/2016	7/15/2016	
7		**Determine specific goals and requirements of MagNIF**	**10 days**	**7/18/2016**	**7/29/2016**	**6**
8		minimum B-field and uniformity	10 days	7/18/2016	7/29/2016	
9		Specify B field diagnostics	10 days	7/18/2016	7/29/2016	
10		Revise requirements and conceptual design	20 days	8/1/2016	8/26/2016	7
11		**Requirements Review**	1 day	8/29/2016	8/29/2016	10
12		Prepare CDR package	1 mon	8/30/2016	9/26/2016	11
13		**CDR**	1 day	9/27/2016	9/27/2016	5,12
14		**Funding start**	0 days	10/3/2016	10/3/2016	
15		**Risk Reduction Projects**	**186 days**	**10/3/2016**	**6/19/2017**	**14**
16		**Switch and safety system**	**40 days**	**10/3/2016**	**11/25/2016**	
17		assess existing safety system in test bed	5 days	10/3/2016	10/7/2016	
18		specify switch	5 days	10/10/2016	10/14/2016	17
19		procure switch	10 days	10/17/2016	10/28/2016	18
20		test switch and safety system	20 days	10/31/2016	11/25/2016	19
21		**Transmission cables**	**28 days**	**10/3/2016**	**11/9/2016**	
22		specify number and type of cables	3 days	10/3/2016	10/5/2016	
23		Procure cables and cable track	15 days	10/6/2016	10/26/2016	22
24		Perform material suitability tests	10 days	10/27/2016	11/9/2016	23
25		offline concept validation	10 days	10/27/2016	11/9/2016	23
26		**Vacuum power feedthroughs**	**40 days**	**10/3/2016**	**11/25/2016**	
27		research options	10 days	10/3/2016	10/14/2016	
28		make buy vs. build decision	5 days	10/17/2016	10/21/2016	27
29		fabricate or buy feedthroughs	20 days	10/24/2016	11/18/2016	28
30		Test feedthroughs	5 days	11/21/2016	11/25/2016	29
31		Perform material suitability tests	5 days	11/21/2016	11/25/2016	29



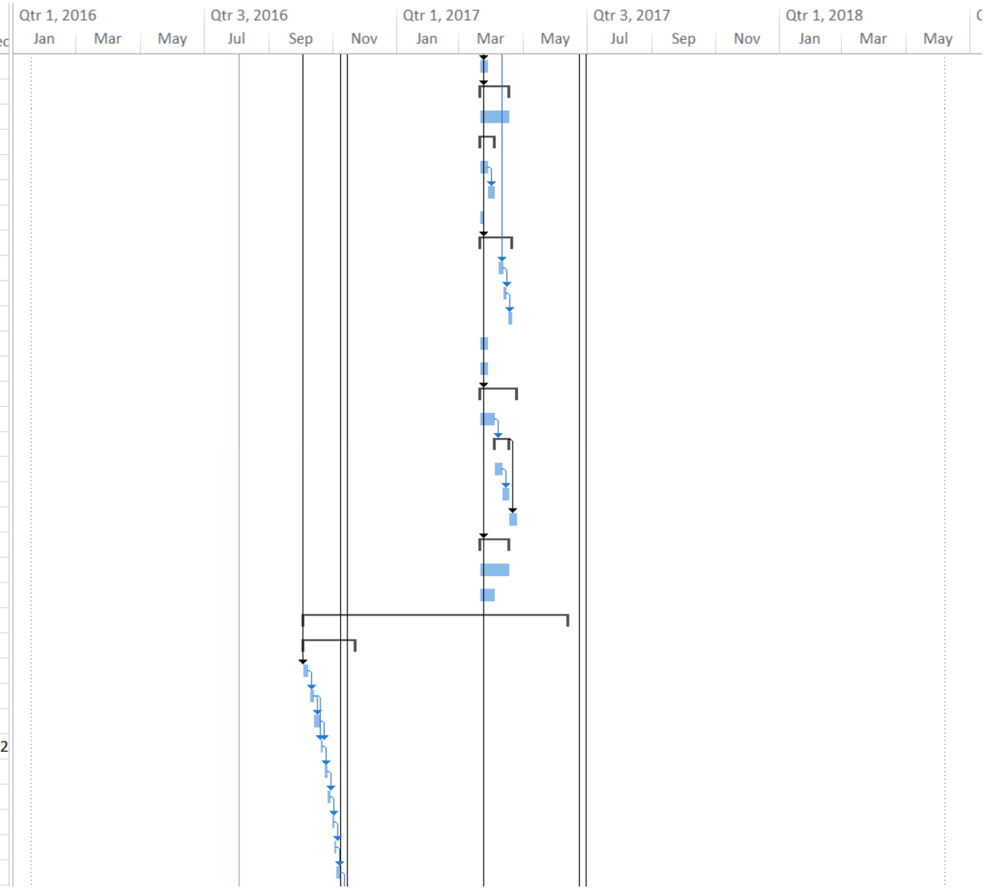
	Task Mode	Task Name	Duration	Start	Finish	Predec
32		**Target fabrication**	**106 days**	**10/3/2016**	**2/27/2017**	
33		**Fabricate prototype targets for test bed restart**	**35 days**	**10/3/2016**	**11/18/2016**	
34		Verify Rhodes design	5 days	10/3/2016	10/7/2016	
35		Procure materials	20 days	10/10/2016	11/4/2016	34
36		Fabrication	10 days	11/7/2016	11/18/2016	35
37		**Design Targets for 20T**	**66 days**	**10/3/2016**	**1/2/2017**	
38		Draft mass budget from TALIS	3 days	10/3/2016	10/5/2016	
39		Field quantities (amplitude, acceptable deviation from norm)	10 days	10/6/2016	10/19/2016	38
40		Coil material	2 days	10/20/2016	10/21/2016	39
41		Number of turns/cross section	3 days	10/24/2016	10/26/2016	40
42		Pitch/variable pitch	3 days	10/27/2016	10/31/2016	41
43		Develop support structure	5 days	11/1/2016	11/7/2016	42
44		Design drive interface, coil support	10 days	11/8/2016	11/21/2016	43
45		**TALIS analysis of target design**	**20 days**	**11/22/2016**	**12/19/2016**	**44**
46		Model debris pattern	10 days	11/22/2016	12/5/2016	
47		Make destructor beam decision	10 days	12/6/2016	12/19/2016	46
48		Complete target drawings	10 days	12/20/2016	1/2/2017	45
49		**Fabricate targets for 20T demo**	**35 days**	**1/3/2017**	**2/20/2017**	**37**
50		**Solenoid version**	**35 days**	**1/3/2017**	**2/20/2017**	
51		Procure materials	15 days	1/3/2017	1/23/2017	
52		Fabricate prototypes	10 days	1/24/2017	2/6/2017	51
53		Fabricate final version	10 days	2/7/2017	2/20/2017	52
54		Perform material suitability tests	10 days	1/24/2017	2/6/2017	51
55		Measure x-ray transmission of solenoid coil	5 days	2/21/2017	2/27/2017	50
56		**Connection between T-line to target**	**55 days**	**10/3/2016**	**12/16/2016**	
57		Design prototype	15 days	10/3/2016	10/21/2016	
58		Fabricate prototype targets for test bed res	20 days	10/24/2016	11/18/2016	57
59		Test and Iterate	20 days	11/21/2016	12/16/2016	58
60		**Magnetics Testbed**	**121 days**	**10/3/2016**	**3/20/2017**	
61		Restart existing testbed	20 days	10/3/2016	10/28/2016	
62		Draft the Concept of Operations	5 days	10/3/2016	10/7/2016	



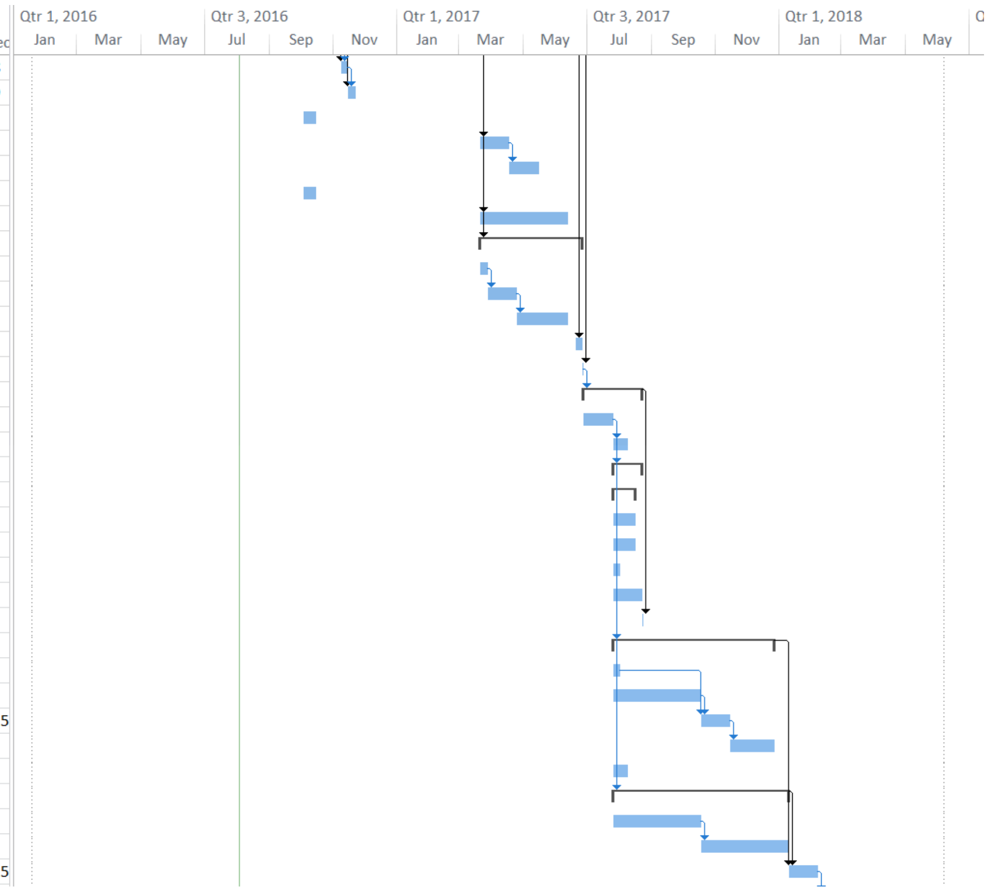
	Task Mode	Task Name	Duration	Start	Finish	Predec
63		Perform tests with prototype targets	20 days	11/21/2016	12/16/2016	61,62,3
64		**Upgrade testbed for 20T demonstration**	**45 days**	**12/19/2016**	**2/17/2017**	**63**
65		Verify existing capacitor enclosure is adequ	10 days	12/19/2016	12/30/2016	
66		Verify switch and safety system	10 days	12/19/2016	12/30/2016	
67		**Optimize circuit**	**15 days**	**1/2/2017**	**1/20/2017**	**66**
68		Determine damping "level"	5 days	1/2/2017	1/6/2017	44
69		Identify primary parameters	2 days	1/9/2017	1/10/2017	68
70		Determine strays	3 days	1/11/2017	1/13/2017	69
71		Complete modeling	5 days	1/16/2017	1/20/2017	70
72		Add high speed imaging diagnostic	5 days	12/19/2016	12/23/2016	
73		Integrate new hardware	20 days	1/23/2017	2/17/2017	65,66,6
74		Perform initial 20T demo	20 days	2/21/2017	3/20/2017	73,49
75		**Final Testbed demonstrations**	**65 days**	**3/21/2017**	**6/19/2017**	**74**
76		Improve component technologies to meet 20	20 days	3/21/2017	4/17/2017	
77		Improve diagnostics	20 days	3/21/2017	4/17/2017	
78		Perform 20T demo w/ repeated success	20 days	4/18/2017	5/15/2017	76,77
79		Address outstanding integration issues	10 days	5/16/2017	5/29/2017	78
80		Gather data to understand timing issues	10 days	5/30/2017	6/12/2017	79
81		Draft timing requirements & specifications	5 days	6/13/2017	6/19/2017	80
82		**Preliminary Design**	**191 days**	**10/3/2016**	**6/26/2017**	**14**
83		**Electrical Design**	**60 days**	**10/3/2016**	**12/23/2016**	
84		General Layout	10 days	10/3/2016	10/14/2016	
85		Block Diagram	10 days	10/17/2016	10/28/2016	84
86		One-line Diagram	10 days	10/31/2016	11/11/2016	85
87		Detailed wiring diagrams	10 days	11/14/2016	11/25/2016	86
88		Rack layout(s)	5 days	11/28/2016	12/2/2016	87
89		Cable runs	5 days	12/5/2016	12/9/2016	88
90		Power considerations	2 days	12/12/2016	12/13/2016	89
91		Draft EE safety notes	60 days	10/3/2016	12/23/2016	
92		**Design Capacitor and Enclosure**	**13 days**	**3/21/2017**	**4/6/2017**	**60**
93		Capacitor	5 days	3/21/2017	3/27/2017	
94		Capacitor support	3 days	3/28/2017	3/30/2017	93
95		Capacitor enclosure	5 days	3/31/2017	4/6/2017	94



	Task Mode	Task Name	Duration	Start	Finish	Predec
96		**Design cables**	5 days	3/21/2017	3/27/2017	60
97		**Design connectors**	**20 days**	**3/21/2017**	**4/17/2017**	**60**
98		Target to T-line interface connector	20 days	3/21/2017	4/17/2017	
99		**Design feedthrough**	**10 days**	**3/21/2017**	**4/3/2017**	
100		Feedthrough	5 days	3/21/2017	3/27/2017	
101		Vacuum interface plate	5 days	3/28/2017	4/3/2017	100
102		Design remaining connectors	3 days	3/21/2017	3/23/2017	
103		**Design switch and control electronics**	**22 days**	**3/21/2017**	**4/19/2017**	**60**
104		Damping resistor (A/R)	3 days	4/7/2017	4/11/2017	95
105		Diode (A/R)	3 days	4/12/2017	4/14/2017	104
106		Backswing resistor (A/R)	3 days	4/17/2017	4/19/2017	105
107		Shunt impedance (for load)	5 days	3/21/2017	3/27/2017	
108		Control electronics	5 days	3/21/2017	3/27/2017	
109		**Design target**	**25 days**	**3/21/2017**	**4/24/2017**	**60**
110		Modify target design	10 days	3/21/2017	4/3/2017	
111		**TALIS analysis of target design, v2**	**10 days**	**4/4/2017**	**4/17/2017**	**110**
112		Model debris pattern	5 days	4/4/2017	4/10/2017	
113		Make destructor beam decision	5 days	4/11/2017	4/17/2017	112
114		Complete target drawings	5 days	4/18/2017	4/24/2017	111
115		**Design magnetics diagnostics**	**20 days**	**3/21/2017**	**4/17/2017**	**60**
116		Proton deflection	20 days	3/21/2017	4/17/2017	
117		B-Dot, other	10 days	3/21/2017	4/3/2017	
118		**System Integration**	**181 days**	**10/3/2016**	**6/12/2017**	
119		**Identify interfaces/functionality**	**36 days**	**10/3/2016**	**11/21/2016**	
120		Timing (Charge, Trigger)	5 days	10/3/2016	10/7/2016	5
121		Gas (Pressurize/Flush switch)	3 days	10/10/2016	10/12/2016	120
122		Pressurize enclosure?	5 days	10/13/2016	10/19/2016	121
123		Pre-fire (inhibit trigs, abort charge)	2 days	10/20/2016	10/21/2016	121,12
124		Voltage setpoint	2 days	10/24/2016	10/25/2016	123
125		Raise, Lower Dumps; Emergency Abort	3 days	10/26/2016	10/28/2016	124
126		Voltage Feedback (PS)	2 days	10/31/2016	11/1/2016	125
127		Current Feedback (PS)	2 days	11/2/2016	11/3/2016	126
128		System status	2 days	11/4/2016	11/7/2016	127



	Task Mode	Task Name	Duration	Start	Finish	Predec
129		SIS	5 days	11/8/2016	11/14/2016	5,128
130		ICCS, ICS, ITS	5 days	11/15/2016	11/21/2016	5,129
131		General Layout	10 days	10/3/2016	10/14/2016	
132		Design target bay hardware cart	20 days	3/21/2017	4/17/2017	60
133		Integrate design with TANDM	20 days	4/18/2017	5/15/2017	132
134		Utilities	10 days	10/3/2016	10/14/2016	
135		Draft ME safety notes	60 days	3/21/2017	6/12/2017	60
136		**Design software and controls**	**70 days**	**3/21/2017**	**6/26/2017**	**60**
137		Refine Concept of Operations	5 days	3/21/2017	3/27/2017	
138		Design software requirements	20 days	3/28/2017	4/24/2017	137
139		Write software code	35 days	4/25/2017	6/12/2017	138
140		Refine timing requirements	5 days	6/20/2017	6/26/2017	15
141		**PDR**	1 day	6/27/2017	6/27/2017	82
142		**Final Design**	**40 days**	**6/28/2017**	**8/22/2017**	**141**
143		Incorporate changes from PDR	20 days	6/28/2017	7/25/2017	
144		Complete drawings	10 days	7/26/2017	8/8/2017	143
145		**Documentation**	**20 days**	**7/26/2017**	**8/22/2017**	**143**
146		**Safety note completion**	**15 days**	**7/26/2017**	**8/15/2017**	
147		ME	15 days	7/26/2017	8/15/2017	
148		EE	15 days	7/26/2017	8/15/2017	
149		FMEA completion	5 days	7/26/2017	8/1/2017	
150		Write procedures	20 days	7/26/2017	8/22/2017	
151		**FDR**	1 day	8/23/2017	8/23/2017	142
152		**Build production MagNIF system**	**110 days**	**7/26/2017**	**12/26/2017**	**143**
153		Order COTS hardware	5 days	7/26/2017	8/1/2017	
154		Fabricate custom HW (PCB, coils, connectors, fe	60 days	7/26/2017	10/17/2017	
155		Assemble hardware	20 days	10/18/2017	11/14/2017	153,15
156		Test "production" hardware offline	30 days	11/15/2017	12/26/2017	155
157		Develop installation plan	10 days	7/26/2017	8/8/2017	
158		**Complete controls and software**	**120 days**	**7/26/2017**	**1/9/2018**	**143**
159		Final revisions to software & GUIs	60 days	7/26/2017	10/17/2017	
160		Test software offline	60 days	10/18/2017	1/9/2018	159
161		Integrate hardware, software	20 days	1/10/2018	2/6/2018	152,15



	Task Mode	Task Name	Duration	Start	Finish	Predec
162		Rework cycles	20 days	2/7/2018	3/6/2018	161
163		Train technicians (Operators, Etechs and MechTechs)	20 days	3/7/2018	4/3/2018	162
164		**Qualify hardware/software**	**45 days**	**4/4/2018**	**6/5/2018**	**163**
165		Develop IQ	10 days	4/4/2018	4/17/2018	
166		Develop OQ	10 days	4/18/2018	5/1/2018	165
167		Install hardware	10 days	5/2/2018	5/15/2018	166
168		Complete IQ	5 days	5/16/2018	5/22/2018	167
169		Complete OQ	10 days	5/23/2018	6/5/2018	168
170		**Load target**	1 day	6/6/2018	6/6/2018	164
171		**First shot**	0 days	6/6/2018	6/6/2018	170

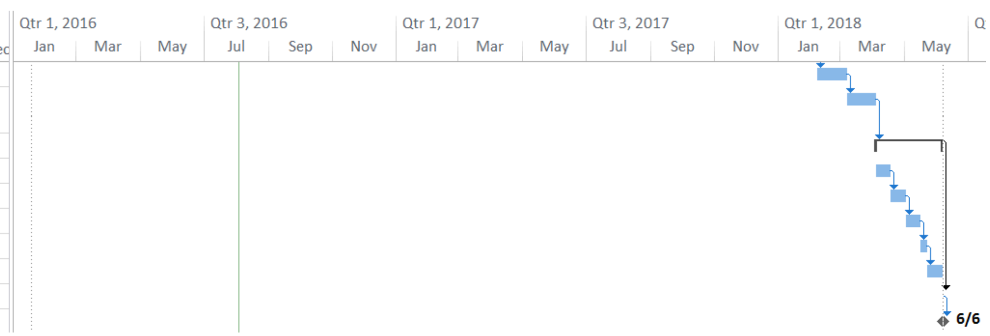


Figure 9.1. The MagNIF Project Plan. Risk reduction efforts are performed during both conceptual design and in parallel with preliminary design.

Electromagnetic analysis and Results

As part of the conceptual design, an extensive set of electromagnetic simulations of the capacitor/switch/transmission lines/coil circuit performance was performed with the ALE3D software simulation package[8]. The primary purpose was to explore the design parameter space and assess the feasibility of the remote location of the capacitor. A variety of coil geometries were studied that were driven with the LRC circuit shown in Figure 9.2. The values for R, L, and C were provided by the electrical engineering team after studying what sizes of capacitors and cables are compatible with space constraints in TANDM and the target bay, and the maximum voltage which could be used with standard hardware.

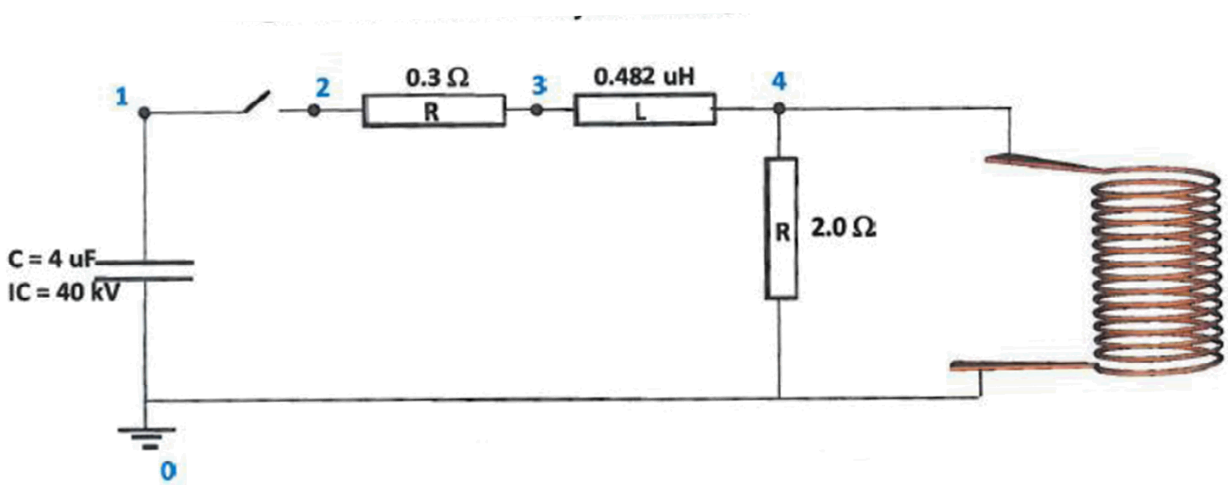


Figure 9.2. The LRC circuit used to drive the coil. (Javedani, et. al.[8])

Initial simulations were performed on a Helmholtz coil geometry, an example of which is shown in Figure 9.3. The Helmholtz geometry was favored because the magnetized volume (between the 2 coils) is largely unobscured by the wire coils. Unfortunately, the Helmholtz geometry did not seem to support generation of the required 20 T magnetic field, regardless of wire gauge and number of coil turns. Recall that TALIS considerations impose limits on the mass of copper that could be used in the target to less than 700mg, so there was a tradeoff required among the wire diameter, number of coil turns and current.

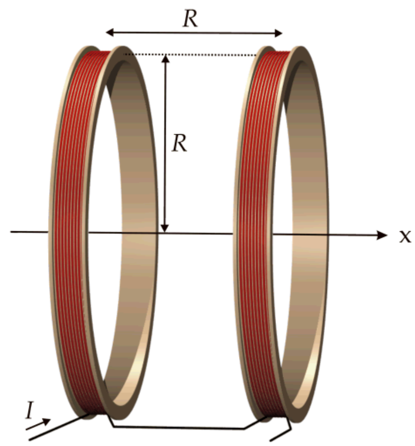


Figure 9.3. The Helmholtz coil geometry[9].

After some convincing, the physics team considered using a solenoid geometry as long as the wire diameter is small compared to the coil pitch, so that the plasma propagation within the gas pipe can still be observed with the target diagnostics. Figure 9.4 shows the proposed geometry of the solenoid coil which was selected from among those studied.

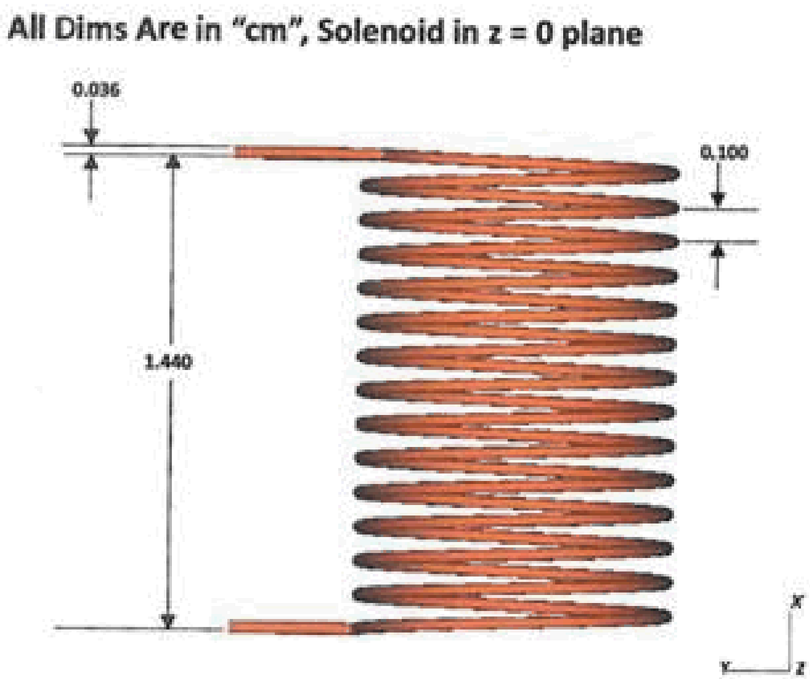


Figure 9.4. The solenoid coil geometry simulated with ALE3D, and selected as the baseline configuration. (Javedani, et. al.[8])

The ALE3D simulation predicts the current waveform to be that shown in Figure 9.5. The peak current of 30kA and, therefore, the peak magnetic field occurs about 2 µs after switch closure. The NIF laser beam pulse, which is only 20 ns in duration, would be timed to occur near the peak of the pulse. Such accurate timing is routinely available with the NIF control system. ALE3D also predicts that the coil will start to melt shortly after the peak, which is desirable from the TALIS perspective.

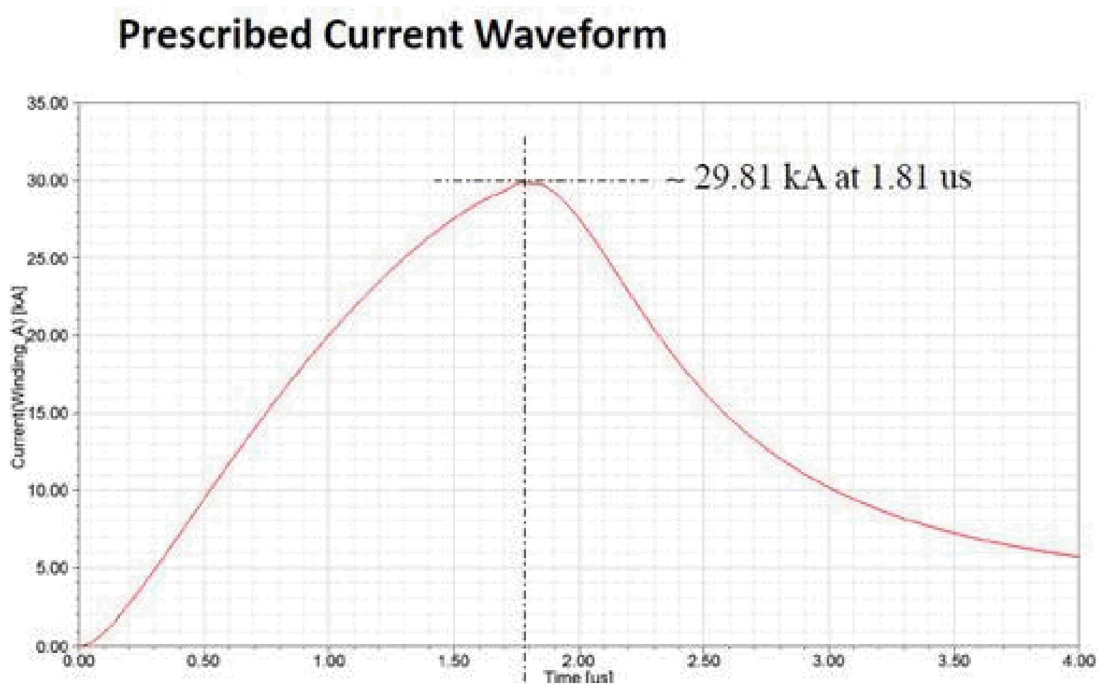


Figure 9.5. The current pulse waveform predicted with the ALE3D simulation peaks at around 2 µs. (Javedani, et. al.[8])

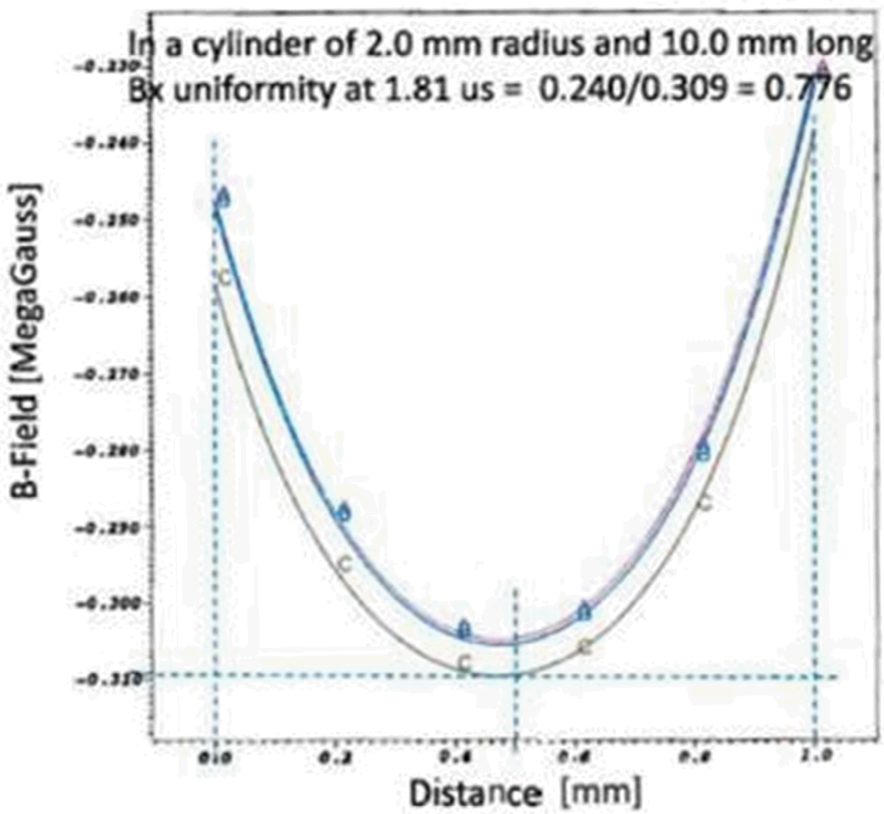


Figure 9.6. The simulated magnetic field uniformity along the length of the coil. The field meets the 20 T requirement, but is not as uniform as desired. (Javedani, et. al.[8])

Figure 9.6 shows that at the peak, the magnetic field along the length of the cylinder ranges from 24 to 31T which exceeds the requirement of 20T, although the field is not quite as uniform as desired. However the uniformity was deemed acceptable and a reasonable compromise. The decision was made to go forward with the coil geometry of Figure 9.4.

The project team is ready to prepare for the requirements and conceptual design gate reviews.

10. References

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