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THE UNIVERSITY OF WISCONSIN

Physical Sciences Laboratory
MADISON, WISCONSIN

TITLE
HSX-Upgrade Engineering Recommendations

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Contents

1 – Introduction

The Helically Symmetric Experiment (HSX) is a quasi-helically symmetric stellarator (2) located in Engineering Hall at the University of Wisconsin Madison. There lies an opportunity with this proven stellarator device to investigate new design options for stellarator and other fusion machines. This report discusses a variety of potential improvements to the system in its mechanical and electrical systems and the new tools to implement them.

2 – Existing System

HSX can be separated into its electrical and mechanical systems. The primary mechanical systems of interest include the coils and vessel, held by supports and adjusters which align them (Figure 1). The electrical system of interest is the set of motor generators powering the machine.

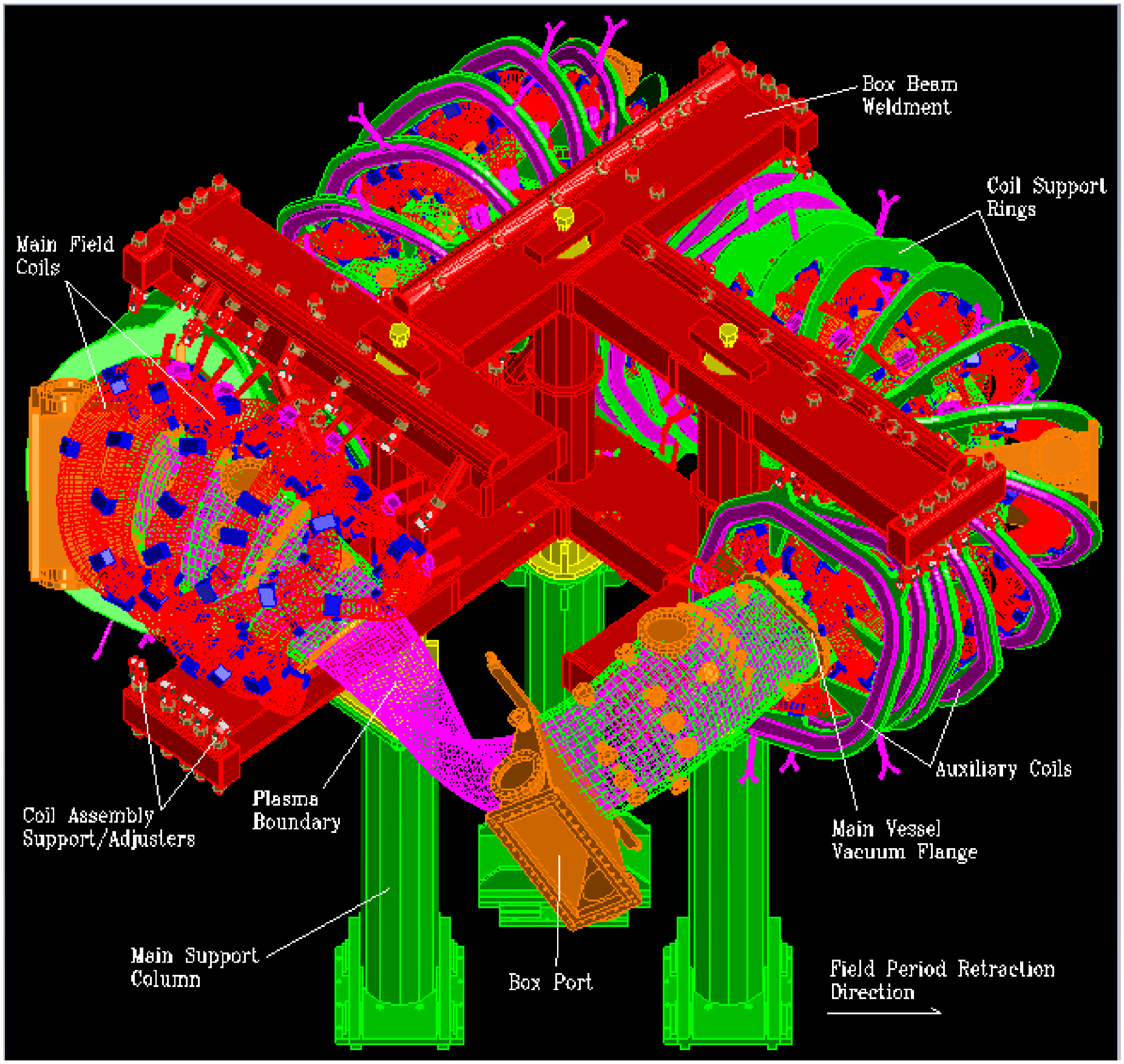

Figure 1: HSX Assembly with callouts

2.1 – Mechanical System

2.1.1 – Coils

The coil system is a series of six non-planar solenoids made with wound copper conductors (14 turns) and bound with epoxy resin impregnated glass (Figure 2). Each wind is a set of 6 bus bars in parallel, the outer 4 solid copper and the inner two including a cooling feature (Figure 3). The coils are connected in series, and the six coils repeat in a pattern around the machine (Figure 4). Each coil then has a secondary coil which has two purposes: It affixes to the box beam supports and adjusters, and it has a secondary coil which fine-tunes the magnetic field (Figure 5).

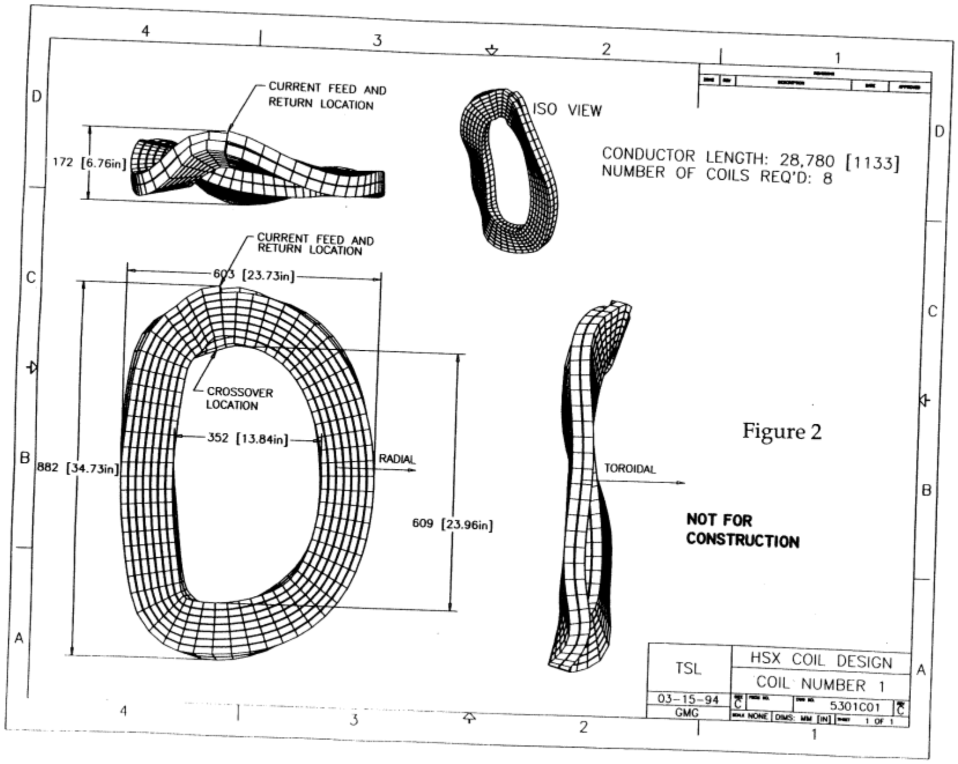

Figure 2: Coil One Detail Drawing (1)

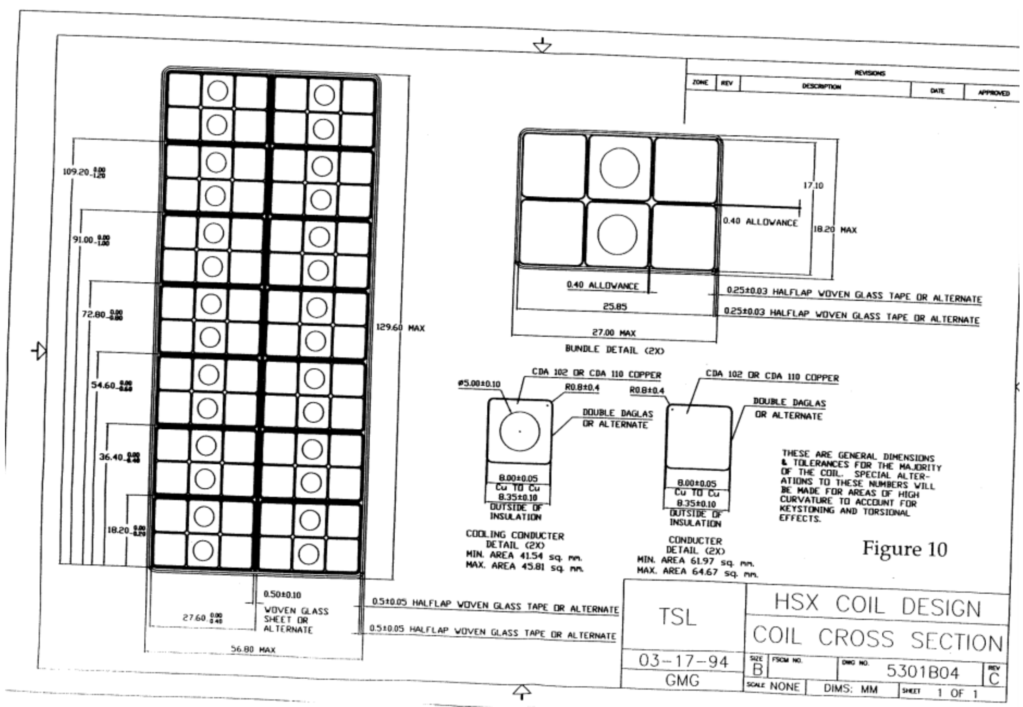

Figure 3: Coil cross section detailing (1)

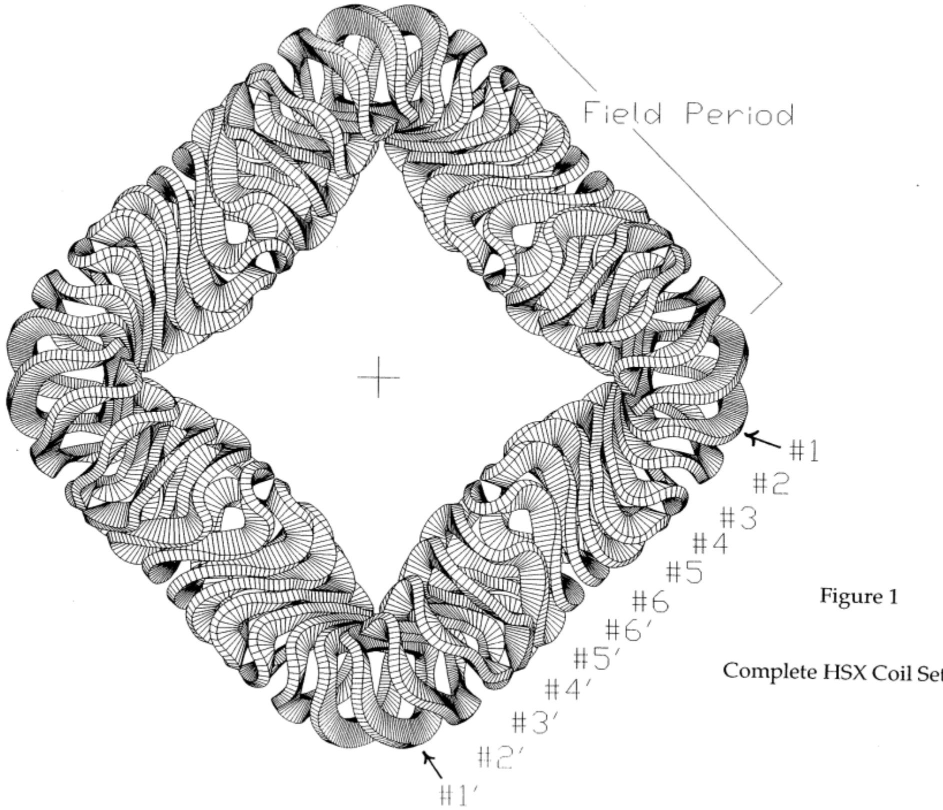

Figure 4: HSX Complete Coil Set with Pattern (1)

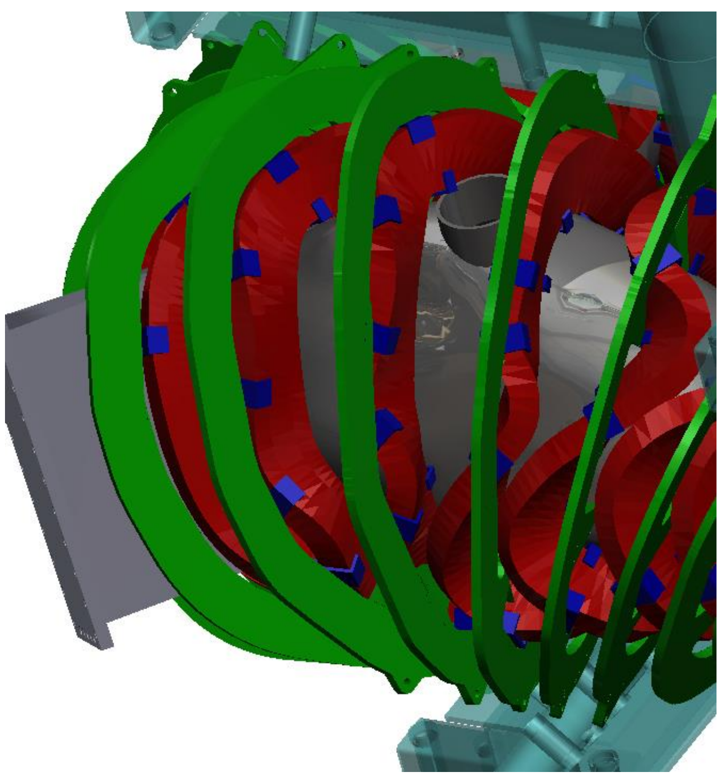

Figure 5: Coils and Support Rings

The coil system will be retained for the upgrade, with potential for some alterations to the secondary coil and support ring system to accommodate new hardware discussed below in section 4.

2.1.2 – Vessel

The vessel is a stainless-steel vacuum vessel that contains the plasma and mimics the natural contour of the plasma. The vessel has a four-fold symmetry around the torus (four field periods). The vessel is “flipped” between each field period in the toroidal angle. This is defined by the quasi-helical symmetry unique to HSX (2).

The existing vessel was divided into sections which were explosion formed by American Exchanger Services and welded to its final shape. Ports were cut to fit and welded in place after the vessel was in its final location. The vessel was divided by half field periods, or eighths of the entire machine (Figure 6). These eighths are connected by flanges along the “straight” sections (Figure 7) and by box ports on the corners.

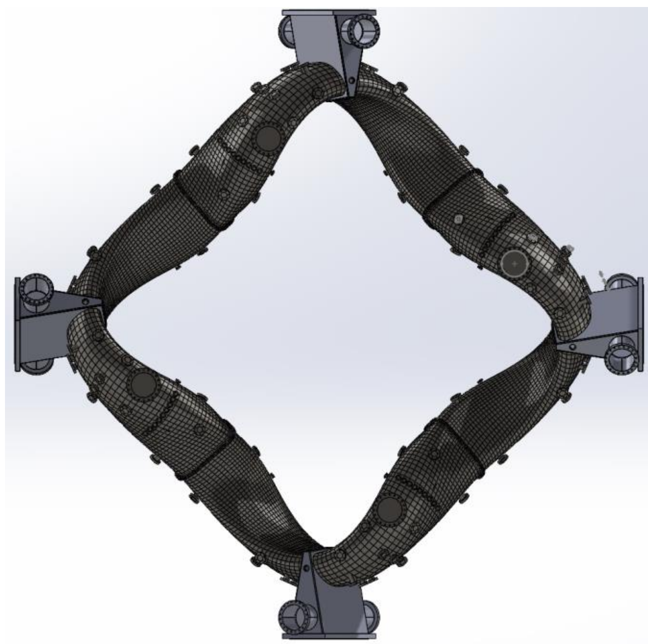

Figure 6: HSX vessel top view

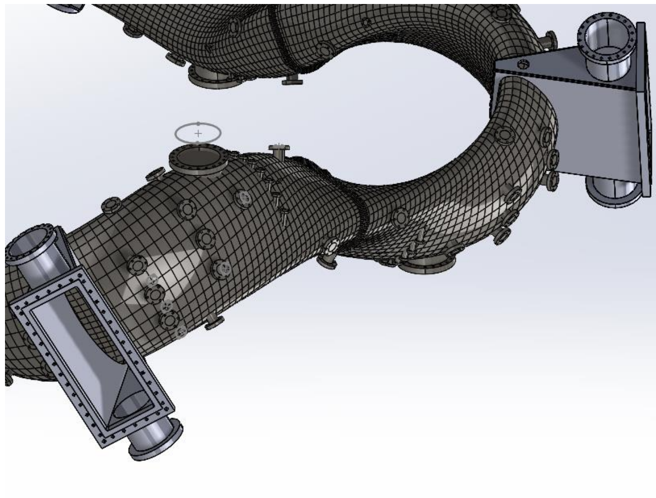

Figure 7: HSX vessel "straight" section

2.2 Electrical System

Most fusion research facilities, including the test facility at HSX, use rotating electrical machines as electromagnetic capacitors. HSX utilizes eighteen GE752 DC traction motor generators (MG), each offering 735 kW of power. When their electrical outputs, or armatures, are connected in parallel, they can generate an output exceeding 1,000 VDC and 13.75 kA, yielding a 1.5 T field at the HSX coils. Each MG serves dual purposes here: it functions both as an electric motor and then a generator. A 900 kg flywheel is linked to each MG, acting as an energy storage system. This stored energy in the form of rotational movement can then be steadily released into the HSX coil system as needed. Figure 8 shows a view of these motor/generators in the HSX Power Room (B442).

Figure 8: Four of eighteen GE-752 motor generators (MG)

3 – Mechanical System Upgrades

The major mechanical system upgrades focus on the vessel design and integration of a Neutral Beam Injector (NBI). This upgrade allows for an investigation into alternative methods for stellarator manufacturing, such as additive manufacturing.

3.1 – Vessel Design

There are incentives to design a new vessel for HSX. The larger, optimized volume can accommodate additional instrumentation and new technologies. These include options such as divertor structures and the addition of a neutral beam injector (NBI).

The foundation of a new vessel design is derived from lofting a surface starting from the last closed flux surface of the plasma out towards pre-set stops defined by the coil boundaries for an eighth of the machine. The resulting shape is then assessed for interferences and erroneous geometry using 3D CAD software. This is then iterated, feeding back complications from the CAD software to the initial loft until a satisfactory shape was found, Figure 9.

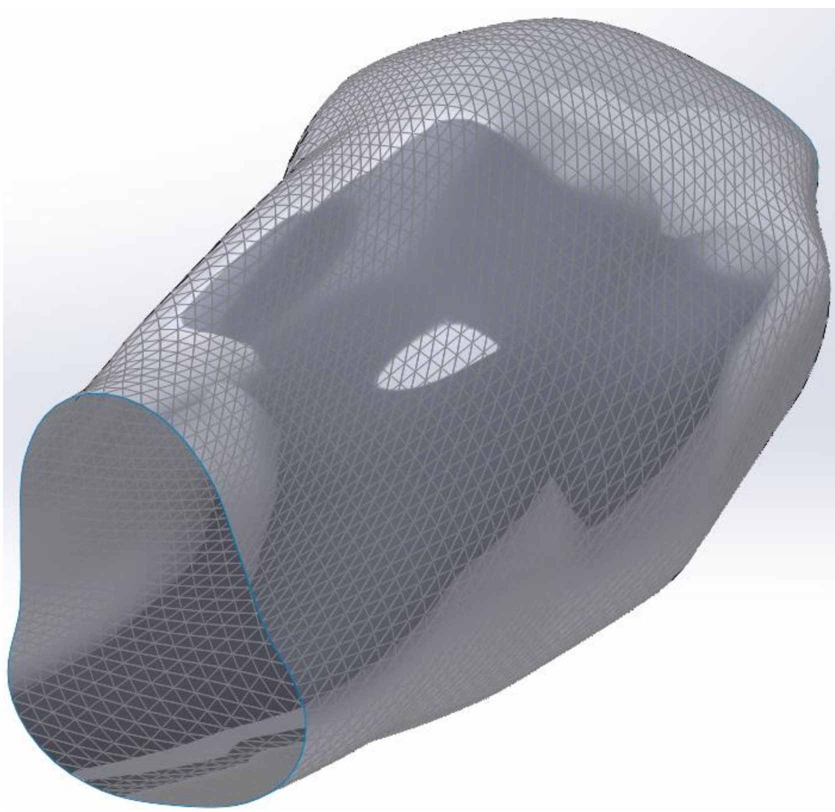

Figure 9: Vessel surface loft (mesh body)

This loft is generated by physics simulation as an .STL file format, then it is manipulated via the Autodesk tool, Fusion360 to convert the mesh body to a boundary representation body (B-rep). This allows the model to be exported as an IGES file into standard 3D modeling software, SolidWorks, in a way that makes it compatible with usual modeling tools, Figure 10.

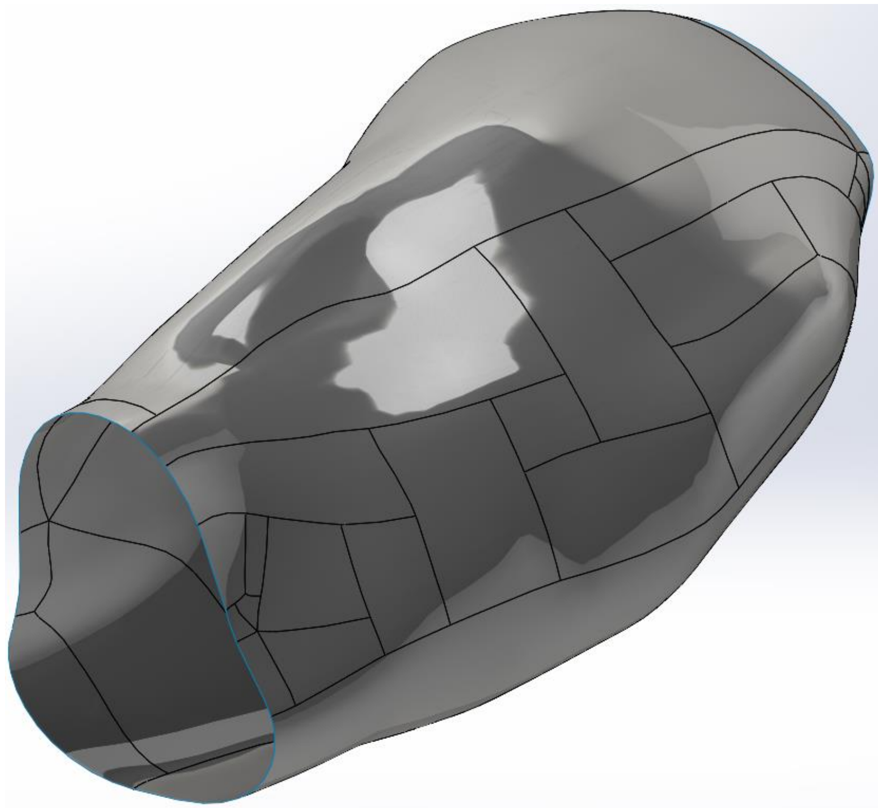

Figure 10: Vessel surface loft (b-rep)

From here the surface undergoes manipulations to turn it into a solid volume that may include ports, flanges, and other features.

3.1.1 – Ports

In the existing HSX vessel, ports were added to the vessel after it was in place with coils in position. Holes and the mating ports were cut to fit on-site and welded into place. This process is physically arduous, and one area where the original methods could be upgraded.

With additive manufacturing methods, vessels could be built with existing features which interface with ports. These mechanisms are features such as tabs which enforce concentricity and weld features (Figure 11). In this format one half of the port would be connected directly to the vessel wall, either directly during the manufacturing process or through a weld to an area already prepped.

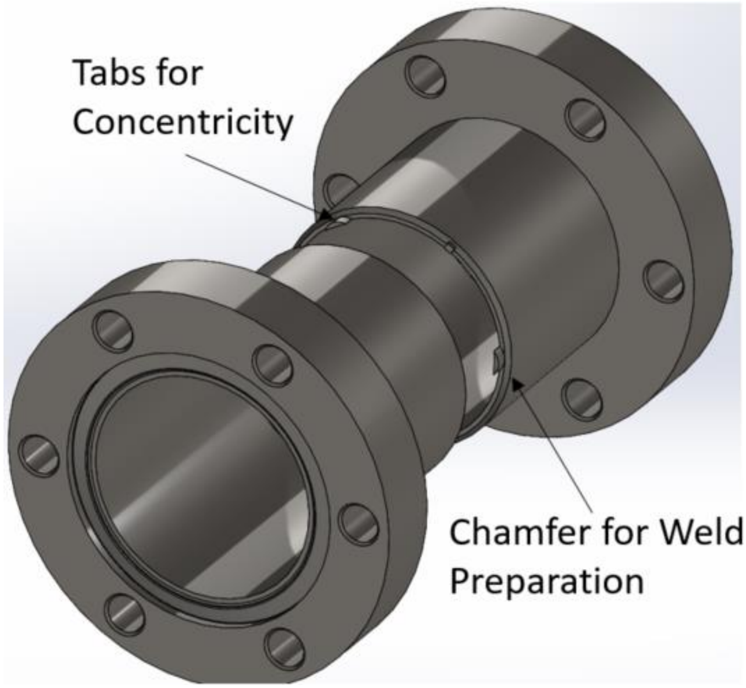

Figure 11: Test port example with callouts

A special category of port used on the HSX is labeled a Box Port and can be identified by its 6-sided box type shape. The Box Port is integral to the plasma path and vacuum vessel, whereas the round ports merely provide access to the vacuum vessel. The four box ports are also the load path between vacuum vessel and HSX structural support. The Box Ports will need to be redesigned and manufactured to mate with any new HSX vessel geometry.

A further category of port may be introduced to the HSX vessel for access and installation of Divertor assemblies. This port is notionally designed as a square flange or bulkhead panel that is co-located near the installation position of a Divertor.

3.2 – Vessel Manufacturing

The baseline manufacturing option for the vacuum vessel is explosive forming of the toroid sections to form the complex cross-section profile. The explosive forming method was proven on the original HSX vacuum vessel and can be repeated for a vacuum vessel with different geometry. This method requires subdividing a half field-period into rings which are subsequently welded together to form one eighth of the vessel. The cost of this manufacturing method is decreased when reducing the total number of unique rings, thereby reducing the tooling cost. However, the vacuum vessel form is smoothed from a computed shape into a mostly uniform, cross-section defined by a continuous spline. The simplified vessel no longer matches the ideal plasma shape and does not optimize available space in the experiment or incidentally influences the plasma formation.

The investigation of new vessel geometry allows for the consideration of alternate manufacturing methods. Traditional manufacturing methods of automated CNC cells and explosive forming have advanced in capability but there are novel new technologies such as additive manufacturing. Additive manufacturing methods are quickly evolving and have been assessed to a limited extent for use with vacuum applications. The technology is appealing because it can efficiently and reproducibly replicate the complex shape of the HSX vessel, thus reducing assembly cost. However, the HSX operating environment is more extreme than literature reported investigations into additively manufactured vacuum components.

The Additive Manufacturing field is composed of a variety of technologies and processes which optimize for certain considerations, such as cost per part, precision, part scale, material type, etc. The HSX vessel requires a metallic part capable of holding sufficient vacuum and non-magnetic qualities. Therefore, the Additive Manufacturing methods surveyed for this investigation focus on metallic substrates formed via fusion. Two methods of part formation correlate with the technologies used: Free-standing or supported components. A free-standing component tends to deposit metal directly to the previous layer and fuses via energy source (laser, electron beam, plasma arc, etc.). The free-standing component is relatively quickly produced and with moderate accuracy at larger scales. A supported component is molded in a compacted bed of powdered substrate and fused layer by layer. The powder-bed component (supported component) is a slow manufacturing process but exhibits the highest precision.

A functional test of a powder-bed AM component was completed to provide benchmark measurements for review against HSX requirements. The powder-bed component produces the greatest precision for formed features, surface finish and is the least scalable process. Therefore, if the test coupon is not functional or otherwise unsatisfactory, then it can be assumed that Additive Manufacturing is not a viable manufacturing option at the current technical maturity. The test coupon, shown in Figure 12, mimics common vacuum components of a flange mated to a pipe section. The test coupon is functionally evaluated for holding vacuum, machinability, weldability and other characteristics important to manufacturing of the full-size vessel.

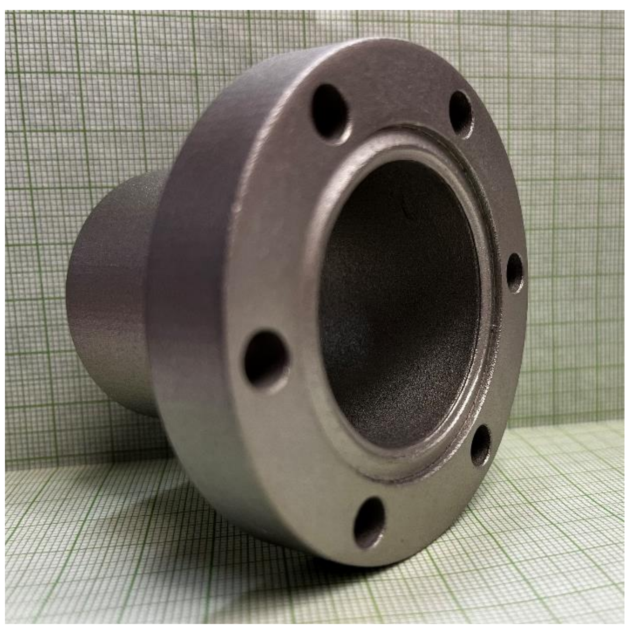

Figure 12: Additively manufactured test coupon, half of vacuum assembly

Test Coupon Results:

Manufacturing Comparison:

Table 1: Manufacturing method comparison

	Technical Acceptable	Risk	Cost	Tech Maturity
Explosive Forming	Proven	Low		Proven
CNC machining	High	Low		High
AM: Wire Additive	Medium	Medium	$20k x 8	High
AM: DMLS	High	High	$32k x 16 (= x8 x2 clamshell)[1]	Low, unavailable at sufficiently large build size
AM: EBAM (Blown Powder DED)	Medium	Medium	$150k x 8	Medium

[1] : GE Line X 2000R machine which is a large-envelope, commercially available machine but insufficiently sized for this project. The cost is representative of the operating cost for a cutting-edge machine.
[2] : The print envelope of future machines is assumed to increase and must increase to an acceptable threshold to accommodate this project.

3.3 – NBI Integration

One of the major potential upgrades for HSX is to incorporate Neutral Beam Injection (NBI) in the final design. The NBI is intended to energize the plasma by injecting a high-energy beam of particles. This requires identifying a path of best fit for the beam that optimizes absorption. The beam is generated outside the HSX experimental volume, so integration also requires minimizing interference of the incoming beam with necessary external features (magnet coils, etc.) modifying the vessel ports to adapt to the potential NBI, and how the NBI device fits in the space of HSX. Note the omission of an exit port due to an assumed high level of absorption into the plasma and use of a capture target on the exit path of the beam before exiting the experimental volume.

Vessel modifications to fit the NBI entry port take form of a port into the side of one of the four box ports on the device “corners.” The dimensions of this port are driven by the tight tolerances between neighboring coils and may define the final allowable diameter of the NBI beam itself. An iterative process was used to identify viable beam paths. The physics group identified paths through the plasma with acceptable absorption, and the engineering team checked for clear line-of-site through the HSX machine. One particular optimized beam path of 3.25in diameter is estimated to have an acceptable absorption rate. This sample condition does exhibit some interference with secondary experimental components, such as coil structural supports, which could be altered without functional impact to the HSX experiment. Interferences with vacuum vessel walls or magnetic coils are not present but are of comparatively of greater concern.

The NBI system is not yet defined or with specified hardware. However, two notional examples of NBI system were integrated into the assembly model to determine the space requirement as it scales with system power. The two NBI systems are a 40keV system in use by the Wisconsin HTS Axisymmetric Mirror (WHAM) project and a 65keV system RudiX purchased by the Wendlestein 7-X project. The analysis is limited to the space claim of the ion source and the neutralizing vacuum chamber and does not allot space for power supply and control electronics or vacuum pumps. There are infrastructure requirements necessary for integration of an NBI, however one of note is a possible need for structural modifications to the building. The NBI beam will likely enter the experiment at an inclined angle relative to horizontal centerline and may interfere with the floor or ceiling of the laboratory should the NBI be particularly large or have an extended focal length (Figure 13).

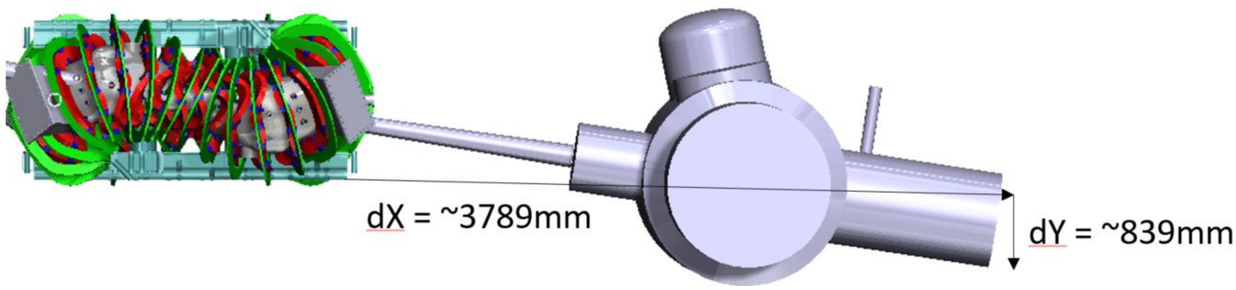

Figure 13: NBI integration and space-claim model

3.4 – Divertor Integration

The integration of divertors inside of the vacuum vessel is one of the major reasons for expanding the vessel size. Divertors are defined as a surface separated from the confining structure, or vessel, which interact with the plasma. These structures would be placed according to simulation results following the strike line analysis (Figure 14).

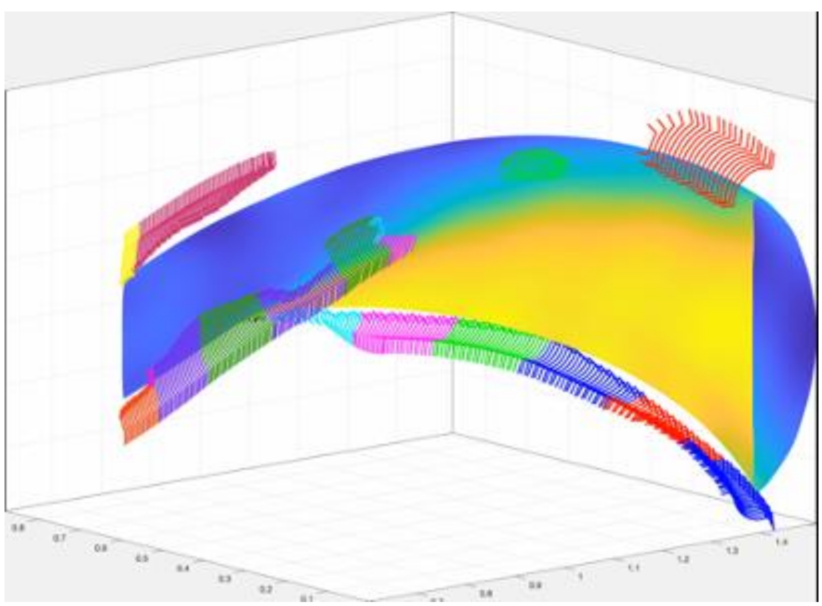

Figure 14: Divertor modeling

To implement these divertors, they would be mounted in the vessel along the vessel "edges" in small - potentially up to an eighth of the vessel long - sections. There is a benefit to having infrastructure conducive to remove and replace divertors after a predetermined lifetime. There exist mechanisms in

HSX to disconnect up to a fourth of the structure and slide out that section on rails. From this point, divertors could be disconnected, and new ones installed.

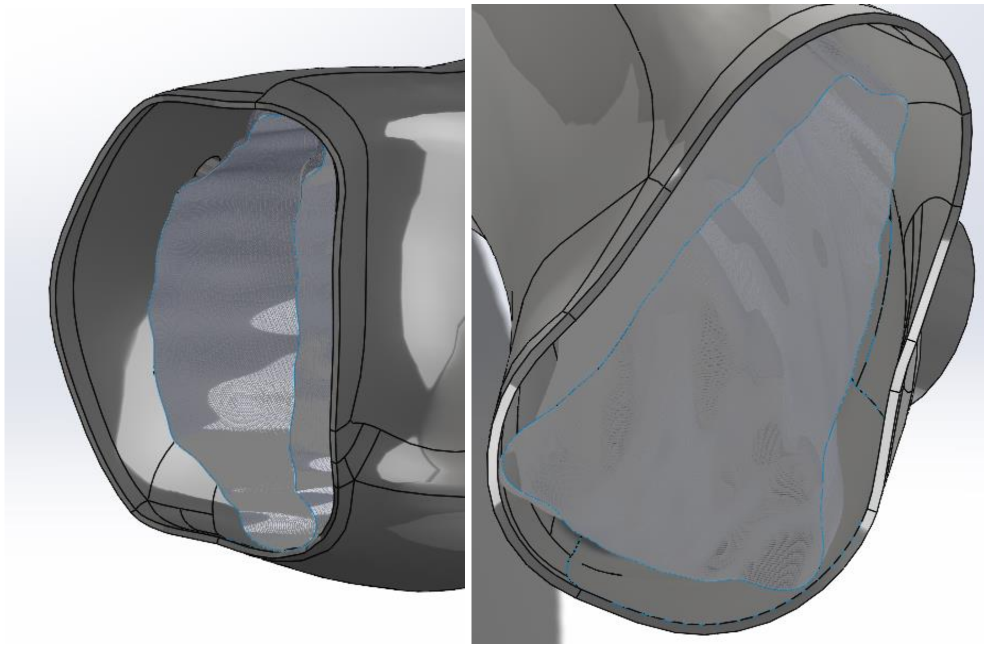

Figure 15: Divertor nested in vessel

4 – Assembly Plans

For the planned upgrades to the HSX machine, as much of the existing infrastructure and assembly methods as possible will be reused. For example, it is planned to use the existing linear rails which allow quadrants of the machine to be slid together/apart from one another. See Figure 16 for image of the HSX machine showing the linear slides circled at the bottom of the main support columns.

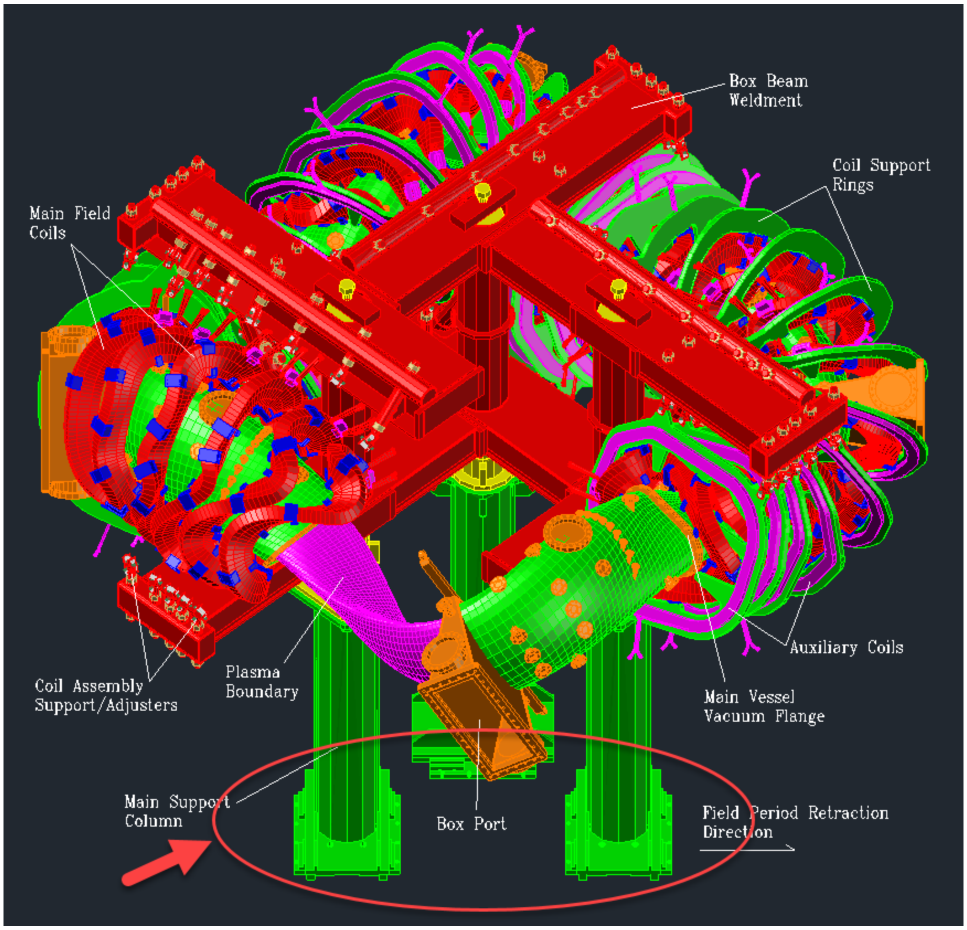

Figure 16: CAD image of HSX showing linear slides which allow for opening up the machine

While no documentation has been located which describes the original assembly sequence, some of the original engineers and technicians have been consulted. The current understanding is that after the support structure was installed (main support columns and box beams), one of the first stellarator components to be mounted was the main vessel. The vessel has structural members which protrude from the box port that connect to the box beam through adjustable linkages. Before the coils were installed, they were assembled into their support rings and auxiliary coils. Each of the six coil assemblies were then threaded onto the vessel and each coil was connected at three mounting points. The three mounting points for each coil are adjustable, and metrology was performed with a coordinate measurement arm to ensure proper placement of the coils. Once the coils were installed, the toroidal rigs, as seen in Figure 17, were installed to stiffen the coil assemblies under higher magnetic loads.

While more work remains to be done to understand the original HSX assembly sequence, the information provides a framework to build upon for the HSX upgrade.

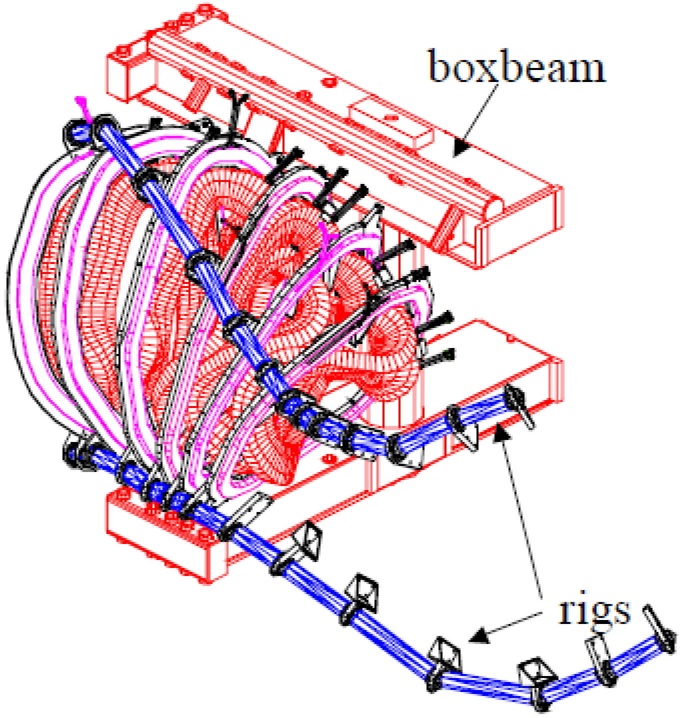

Figure 17: CAD image showing toroidal rigs and support box beams (3)

The size of the vessel is a key factor in the assembly sequence. With the most aggressive vessel concept, coils 1 and possibly 2 cannot be installed onto the vessel from the flange end of the main vacuum vessel due to an enlarged vessel cross section near coil 3. If this aggressive vessel is used, the assembly sequence may proceed as follows:

1. Mount box port to support structure.
2. Mount coils 1 and 2.
3. Install the 1/8th vacuum vessel section and weld to box port.
4. Install remaining coils (3 through 6).

If the vessel can be reduced in cross section and still meet the requirements, then the original assembly sequence may be used:

1. Mount box port and vessel to support structure.
2. Install all coils (1 through 6).

Because of the close clearance between the vessel and coils, any amount of space that can be regained is beneficial to the assembly process. Ports protrude from the vessel between the coils and compete for the space that is needed for sliding the coils over the vessel. One formal possibility is to slice the vessel into segments that fit within each of the coils. Welding the vessel segments in-situ adds extra work and complication to the installation process. One area that space can be regained is at the ports, and may allow more coils to be installed without subdividing the vessel. Two options for port installation are being investigated. One option is to weld the ports onto the vessel after the coil passes over the respective vessel section during coil installation. The other option is to make low profile ports. Both options aim to minimize the vessel profile at installation and enable more/all coils to be installed over the vessel and avoid having to break the vessel into sections smaller than an eighth of the machine.

5 – Electrical System Upgrades

5.1 – Motor Generator Upgrades

The Motor-Generator (MG) system is a reliable source of high current pulses for the HSX coils. Our aim is to extend the current pulse duration from 50 msec to 1 second, ensuring the current remains stable within 1% of its value. The system needs to deliver six pulses per hour, totaling up to 60 per day.

Despite restrictions such as limited upgrade capacity due to the power storage limit of individual MGs and restricted floor space for additional units, our strategy is to efficiently utilize all available rotational energy in the MG/flywheel system. Calculations show that the system has enough energy for a 1-second pulse of 13,750 A, with the rotating mass reducing from 2,000 RPM to 1,250 RPM during the pulse. This indicates there is adequate kinetic energy to support a longer pulse. While the energy calculations show there is sufficient kinetic energy for a 1-second pulse, there are physical limits on the MGs that will reduce that time.

A Direct Current (DC) generator, which converts mechanical to electrical energy, operates on electromagnetic induction. The field current flowing through the generator's windings determines the strength of its magnetic field, influencing the induced voltage according to Faraday's law of electromagnetic induction, see Figure 18. A change in field current impacts the armature current—increasing field current increases the armature current and vice versa, given a constant load resistance.

To maximize energy extraction from the MG system, we propose a control system to modulate the MG's field current. As the flywheel's rotational speed decreases, we will increase the field current, leading to faster deceleration while maintaining output current—a technique known as "field strengthening." However, the MG's torque limits and the field coils' 1,000 VDC rating limit the extent of field strengthening, and hence the pulse width.

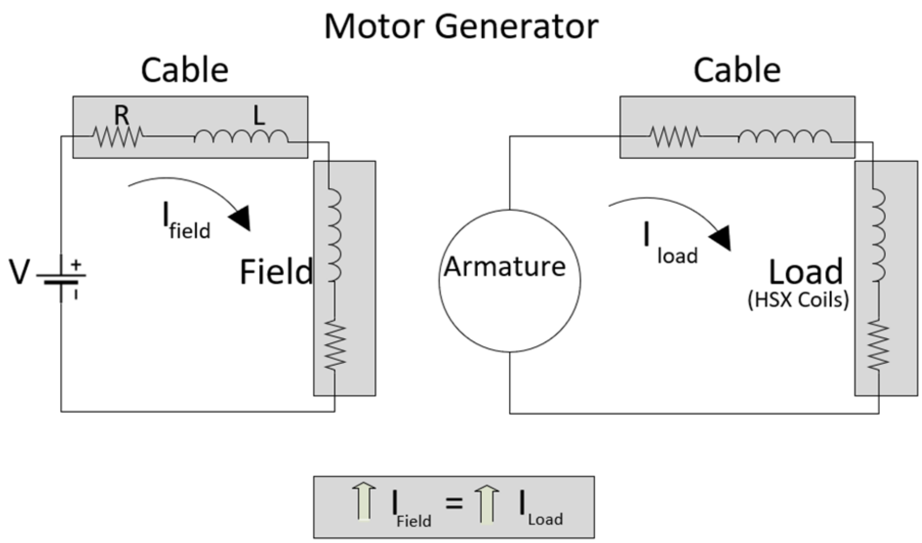

Figure 18: MG simplified schematic

MATLAB/Simulink was chosen as the modeling tool to examine the performance of the MG system, see Figure 19. A first order model was developed, which contains the eighteen (18) motor generators; field coils connected in series, armature outputs in parallel, all driving the coils integrated into HSX. The system can deliver greater than a 1,000V, 13,750A pulse for fractions of a second.

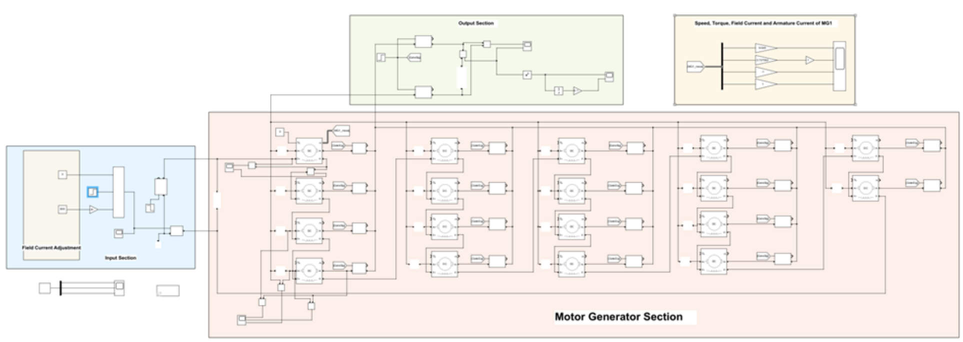

Figure 19: 18 MG Simulink Model

The model was validated to an HSX data set from a shot dated 04/25/2017, taken across the main shunt Figure 20. The model performs well, closely matching real pulse data. This gives us confidence to start exploring options for expanding the duration of the pulse. The difference at the tail of the curve is due to a difference in the "dump" circuit, where the field current is dumped to a resistive network at the end of test. This circuit does not impact the shot current delivered to the HSX coils, and no further effort was devoted to resolving this difference.

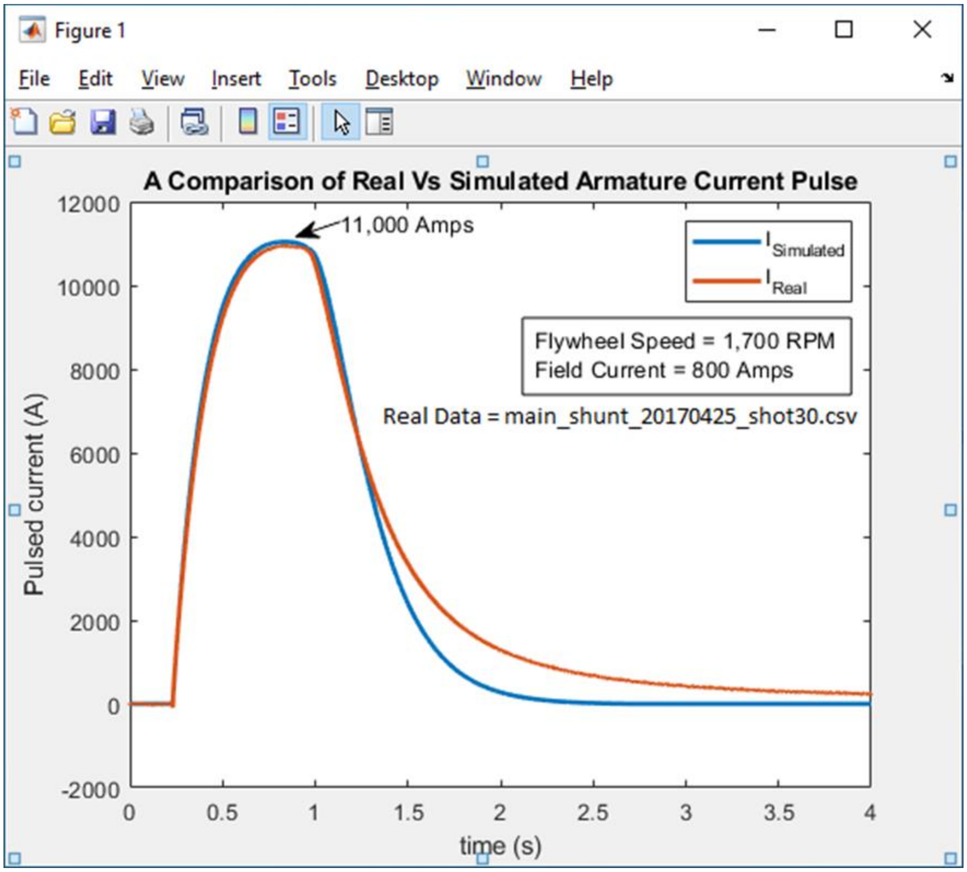

Figure 20: Overlay of real and Simulink model data

In examining the real data provided, we see a current pulse with a maximum value of 10,955 Amps. This pulse has a 1% peak time of 225 msec. Of this 225 msec, HSX typically uses about 50 msec of this pulse, see Figure 21. Without any modification to the MG system, save a more exact triggering system, this 225 msec current pulse is presently available to HSX.

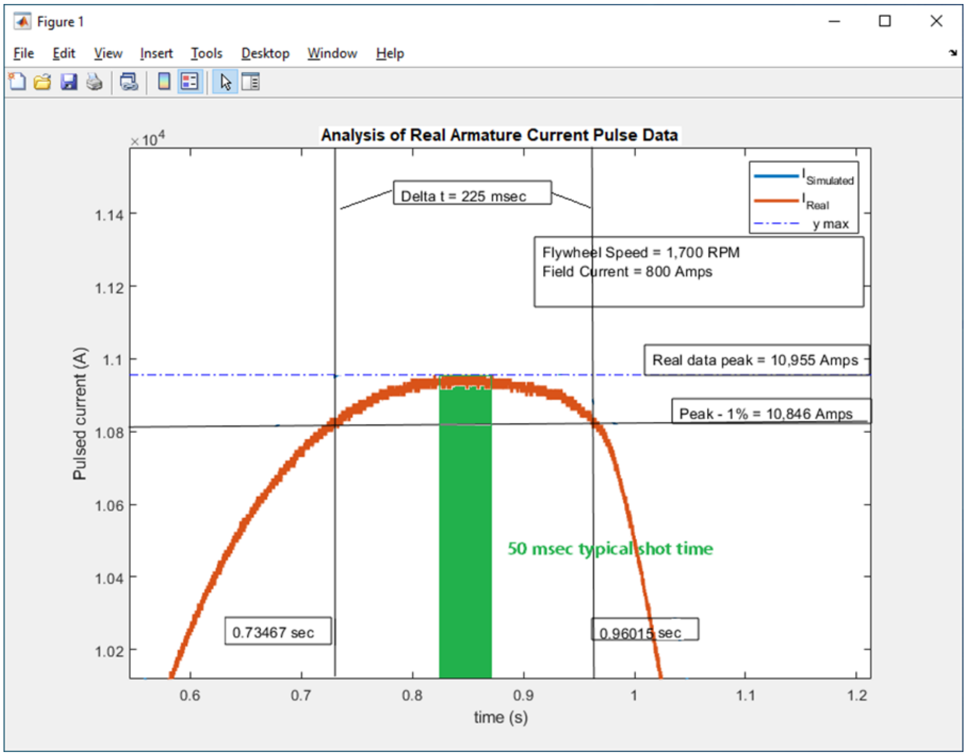

Figure 21: Examination of real MG pulse data

To further the pulse time, we began by developing an open-loop approximation of the field strengthening control system. Instead of a feedback circuit, we used a feedforward model for initial analysis, which provided insights into the system response.

A Simulink feedforward model was created based on a 2,000 RPM flywheel speed and an initial field current of 825A, with field strengthening, see Figure 22. Field strengthening was implemented to maintain the armature output current at 13,750 Amps. During the process, the MG flywheel speed decreased from 2,000 RPM to 1,468 RPM (see Figure 23), keeping the torque under the limit of 5,650 ft-lb (see Figure 24).

Utilizing field strengthening, we achieved a pulse of 13,750A for 716 msec, see Figure 25, with the limiting factor being the maximum field voltage to avoid damaging the commutator due to arc risks.

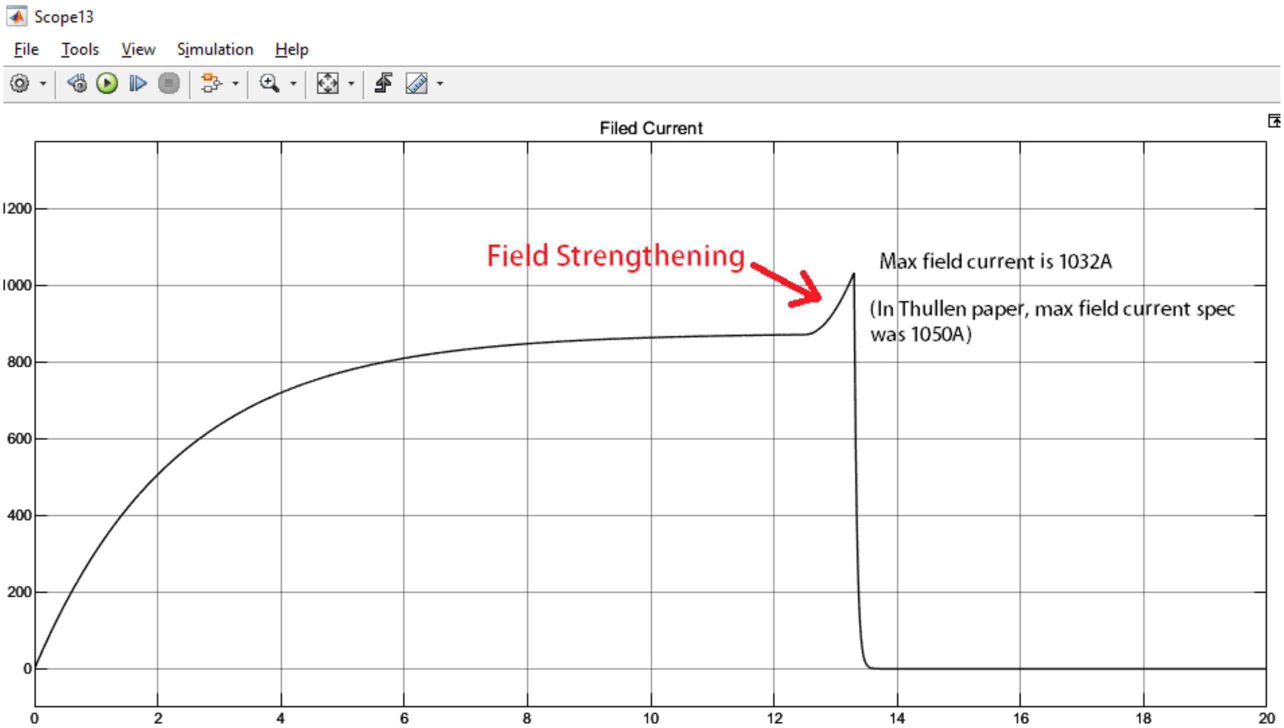

Figure 22: Field current during field strengthening (per MG)

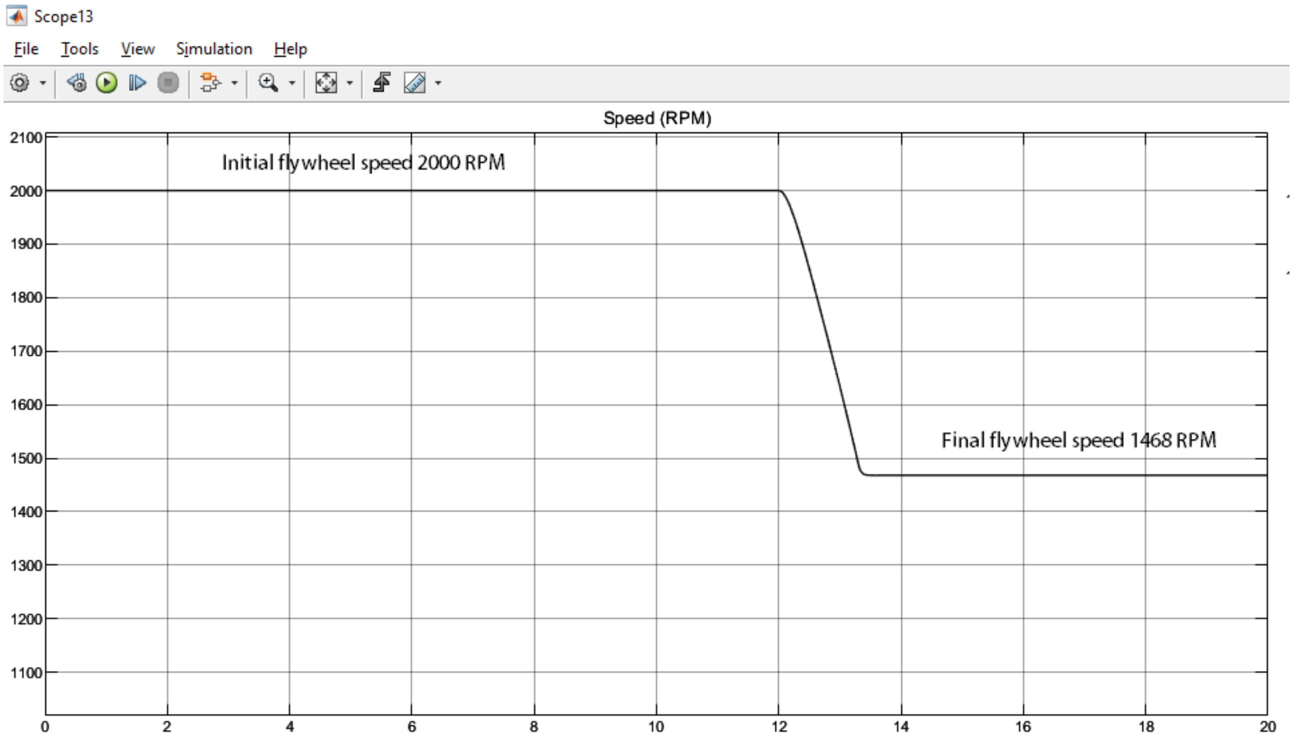

Figure 23:Flywheel speed profile during field strengthening (per MG)

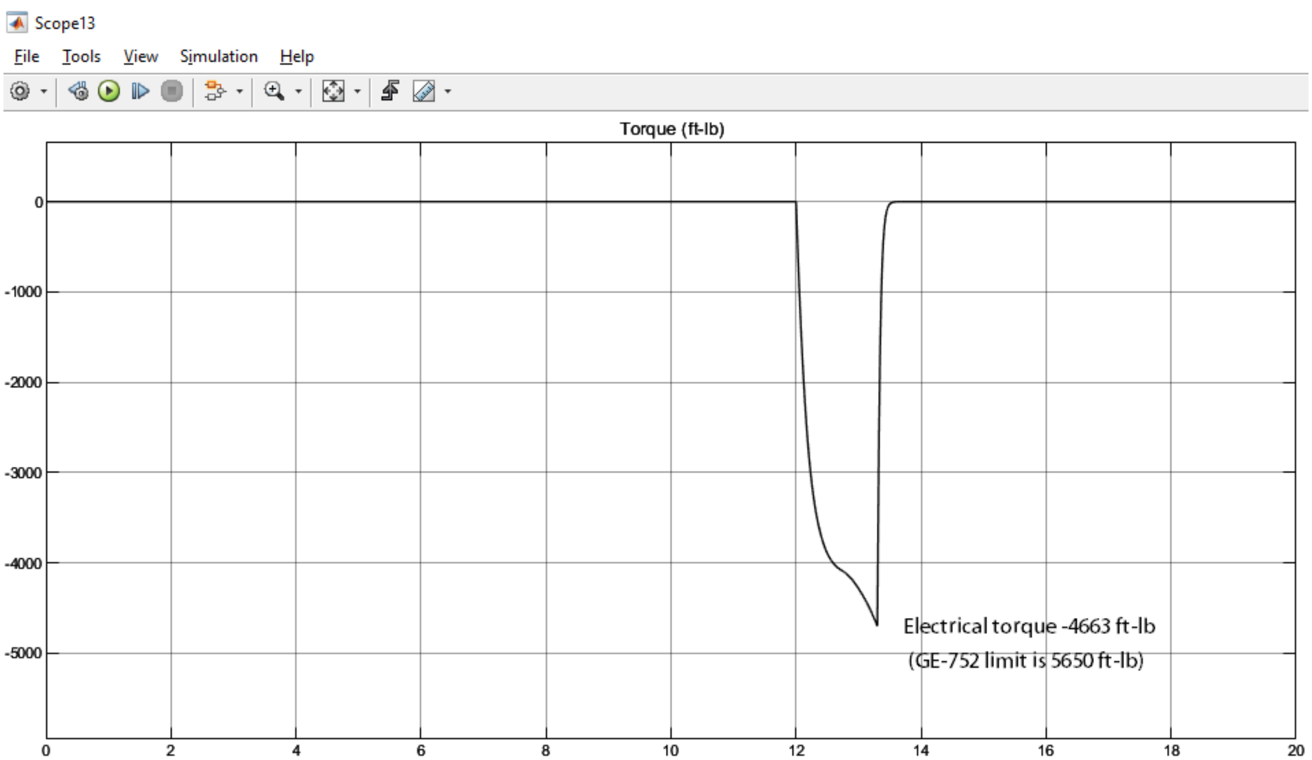

Figure 24: Torque profile during field strengthening (per MG)

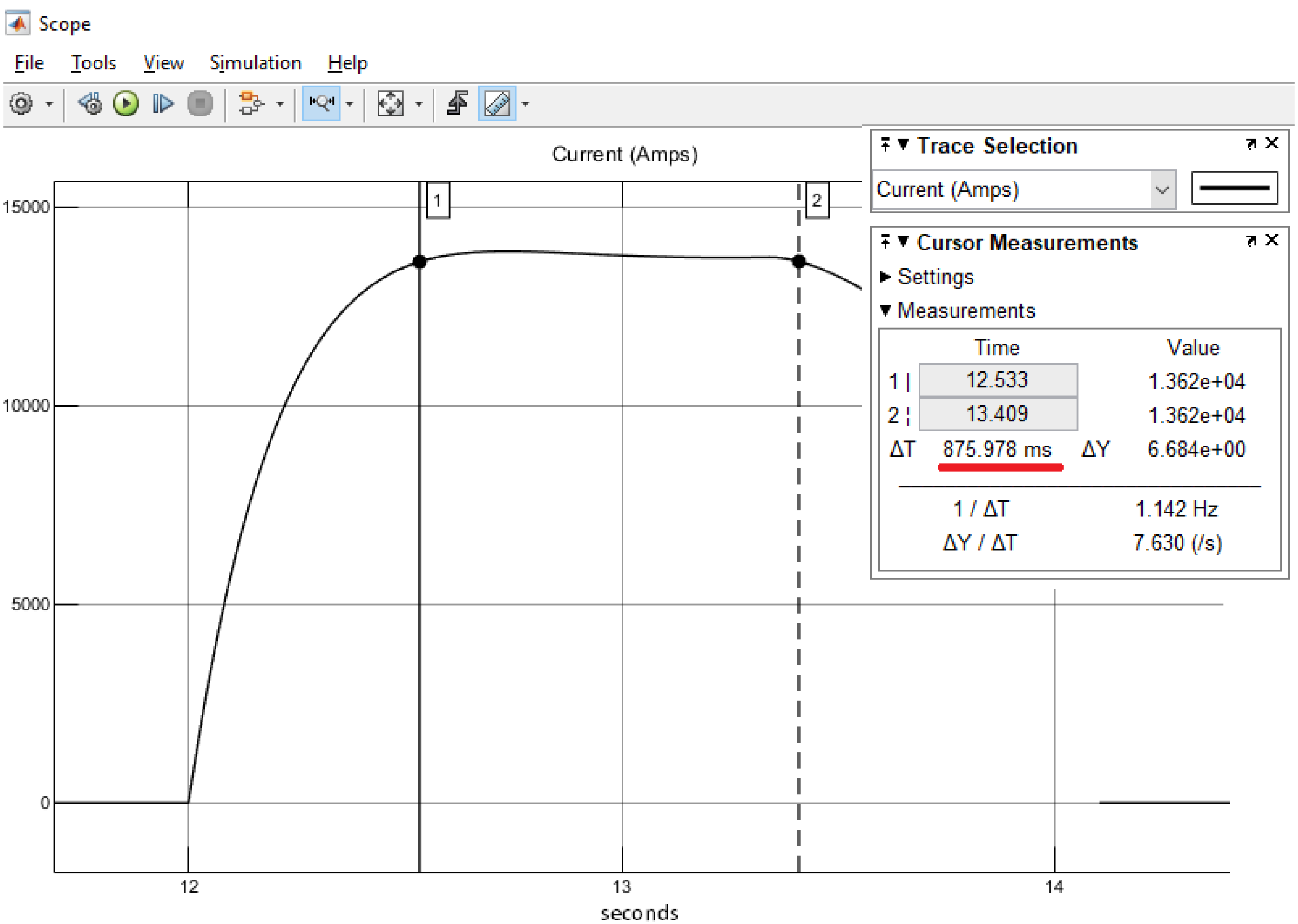

Figure 25: MG field strengthening (all eighteen MG armature outputs)

The field strengthening control system will require the design and fabrication of a system to modulate the field current. We propose a system similar to that used in industrial motor drives, a pulse-width-modulated controller, whereby the duty cycle of the current pulse is varied to change output current, see Figure 26.

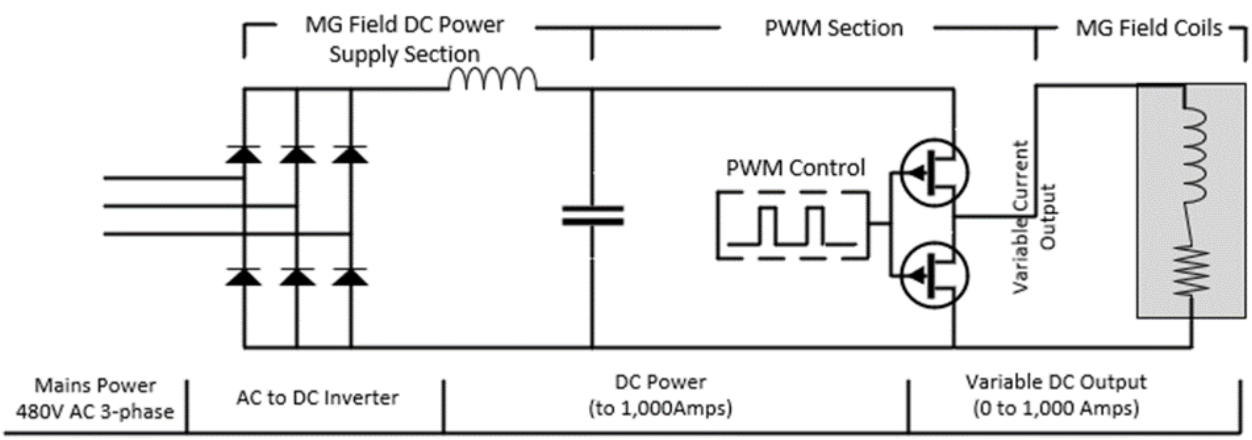

Figure 26 : Pulse Width Modulated (PWM) Controllable DC Power Supply

Using PWM we control the full output of the MG field DC power supply, from 0 to 1,000 Amps, simply by changing the duty cycle of the control circuit, see Figure 27. This is a proven technique for control of electric motors, and the equipment is readily available.

There are two concerns with this approach. First, the ability of the MG DC power supplies to provide the current needed. If they prove to be insufficient, they will need to be upgraded. Again, this type of power supply is well understood, and components are readily available. The second deals with the harmonics of the PWM field current impacting the flatness of the resulting armature current supplying the HSX coils. The inductance of the field windings, and the HSX coils themselves will help to attenuate these harmonics. The frequency of the PWM switching will need to be chosen to minimize the impact of the harmonics on the armature current.

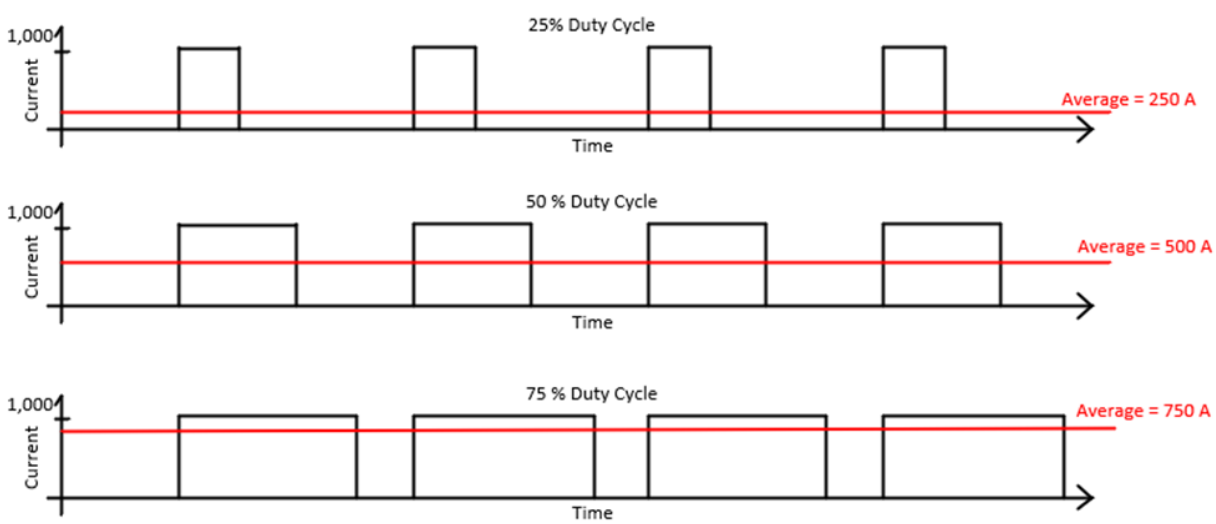

Figure 27: PWM control of output current to MG field coils

Our goal is to enhance the pulse duration of the existing MG system for the HSX coils, by maximizing the use of the available rotational energy. Our model indicates that a 875 millisecond pulse delivering 13,750A is achievable. To boost the HSX pulse width, we plan to employ a pulse-width-modulated controller on the MG's field foils. However, we still need to explore the MG DC power supplies' capacity and the potential effects of harmonics on the MG armature current.

To extend the 13,750 amp pulse beyond 875 milliseconds, we will need extra hardware, either additional MGs or a battery system. While space for more MGs is limited, adding just two more MGs will allow a pulse width of 1,025 milliseconds. Adding additional MG will increase the pulse width, see Table 2.

Table 2: Number of MG's versus pulse width:

Number of MGs		Maximum Pulse Width (m-sec)
18		875
20		1,025
22		1,122
24		1,253

Another option to extend the pulse beyond our 1-second goal is to use a battery system. This would involve connecting banks of batteries to the HSX coils using a PWM controller. The limitations of this system would be the capacity of the battery bank and the HSX coils. To achieve a 1-second pulse, we would need an additional 125 milliseconds of power from the battery system. This would require 1,944 12-volt batteries, set up in 27 parallel groups, each containing a string of 72 batteries, to generate a 1,000 VDC, 13,750 amp pulse. These specifications call for 70 amp-hour batteries, which is well within the capabilities of cost-effective lead acid batteries.

6 – Conclusion

Upgrading HSX is an opportunity to test a variety of new approaches to stellarator design and manufacturing practices. There is a wide scope of improvements available while still maintaining much of the original machine. By upgrading the machine, we can extend its lifespan of productivity and provide meaningful information for the next generation of stellarator devices.

7 – References

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