The New PEGASUS-III Experiment

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Abstract—Developing attractive means of initiating current without using magnetic induction from a central solenoid is a critical scientific and technical challenge facing the spherical tokamak (ST). The PEGASUS program has focused on developing the physics basis and predictive models for nonsolenoidal tokamak startup using local helicity injection (LHI) and has demonstrated startup to ∼0.2 MA in a low-field, near-unity aspect ratio (A) ST. The PEGASUS facility is being upgraded into a solenoid-free ST called PEGASUS-III. Major features include: increased toroidal field (TF) to 0.6 T for up to 100 ms, improved shape control, and retaining the low-aspect ratio geometry of A ∼ 1.2. This TF directly supports the new mission to expand the breadth of solenoid-free research on the facility with multiple reactor-relevant techniques. The implemented TF upgrade is comprised of a new center rod, outer TF coil system, torque plate assemblies, and TF interconnects between the center rod and outer conductors. The center rod is comprised of 24 water-cooled, insulated wedge conductors inside a new inner vacuum wall. There is no ohmic solenoid, which allows additional TF conductor for the 48-kA/turn TF current. The outer TF conductors are 12 pairs of air-cooled, reinforced Al plate conductors. Pairwise crossed conductor links connect the outer C-plates to the central rod conductor to eliminate the need for a toroidal compensation wind-back coil. Torque plate assemblies on top and bottom mechanically secure both the outer C-conductor and the interconnecting links, counteract torsional magnetic loads during a pulse, and provide compliance for vertical displacement. The assembly accommodates magnetic and thermal forces, limiting the axial excursion of the central assembly to < 1 mm.

Index Terms—Electromagnets, magnetic confinement, toroidal magnetic fields.

I. PEGASUS-III UPGRADE AND MISSION

PEGASUS-III is an upgrade to the PEGASUS facility [1] that will be dedicated to solenoid-free startup development. The mission of PEGASUS-III is to solve the spherical tokamak (ST) startup plasma challenge by comparing, contrasting, and investigating synergistic effects of nonsolenoidal current drive techniques using reactor relevant technology. Nonsolenoidal plasma startup is critical to the success of ST-based reactor designs [2] and would also benefit advanced tokamak designs [3].

The PEGASUS program developed the physics basis for local helicity injection (LHI) startup and identified the important parameters that define the limits of this technique [4]. PEGASUS-III will focus on evaluating multiple solenoid-free startup techniques on a single platform including: LHI, coaxial helicity injection (CHI) [5], and RF—electron Bernstein wave (EBW)/electron cyclotron (EC)—startup techniques [6]. The PEGASUS-III facility has no ohmic solenoid, so the only inductive drive possible is through the poloidal field coil set, which is designed mainly for plasma position and shaping control. A CAD drawing of the upgraded PEGASUS-III facility is shown in Fig. 1, illustrating possible locations for helicity injection and RF startup hardware.

Increased toroidal field (TF) will allow improved nonsolenoidal startup for all of these techniques. Both
LHI and CHI rely on the Taylor limit to determine the upper limit on the poloidal flux that can be generated [7] through helicity injection. The Taylor limit indicates that the maximum achievable plasma current is proportional to the square root of the TF rod current, so increased TF raises the Taylor limit and the maximum achievable plasma current through either LHI or CHI.

Increased TF also has the benefit of reducing thermal transport, allowing hotter plasmas for a given input power. The maximum achievable current from helicity injection is reached when the rate of helicity injection matches the rate of helicity dissipation through resistivity. Hotter plasmas will have reduced resistivity and therefore reduced helicity dissipation. This benefits all startup and sustainment techniques. Additionally, EC RF systems experience a density cutoff that is proportional to the field, so increased TF raises the density cutoff. There are also a wide variety of sources in the necessary frequency range at higher field.

Due to these benefits, increased TF capability is a primary upgrade needed for PEGASUS-III. A comparison of the operational parameters affected by the upgrade of PEGASUS to PEGASUS-III is shown in Table I.

PEGASUS LHI experiments to date have been performed at an on-axis TF of 0.15 T maximum. The PEGASUS-III facility will have capability of operating at an on-axis TF of up to 0.6 T or a factor of 4 increase. The engineering analysis required to upgrade the TF capability is the focus of this article.

Increased upgrades to the power supplies to accommodate the higher TF operation as well as increased total power and pulselength of the helicity injection drive systems are also being performed as discussed in a separate paper [8]. Upgrades to install a CHI system are also discussed separately [9]. The remainder of this article is structured as follows. Section II will discuss the forces of concern for the TF design, Section III will describe the design of the upgraded TF system, Section IV presents the stress analysis, and Section V gives a summary and the present status of the upgrade.

### II. Forces of Concern for PEGASUS-III

Two major changes to the facility during the upgrade to PEGASUS-III will greatly affect the electromechanical forces on the experiment. Removal of the ohmic solenoid will eliminate all of the forces due to the fringing fields at the ends of the solenoid interacting with the other electromagnets. However, the increase by a factor of 4 in the TF will greatly increase all of the thermal and electromechanical forces associated with this system. This section will describe the major forces on the system that must be accounted for during the design process.

The forces on the overall system that will be described include the magnetic expansion forces, magnetic overturning forces, and thermal expansion forces. The forces on the center column will also be described. For all cases presented, worst case loads at maximum field and current for the relevant coil sets were assumed.

#### A. Magnetic Expansion and Overturning Forces

The magnetic forces of concern are described in [10]. The magnetic expansion force results from the cross product of the coil current and the self-field of that current (in this case the TF rod current) and creates an outward expansion force on the TF magnets and is given by

$$dF = I_{TF} \times B_{TF} dl \propto \frac{\mu_0 N I_{TF}^2 R}{4\pi}$$

(1)

where $dF$ is the resulting differential force, $I_{TF}$ is the TF rod current, $B_{TF}$ is the TF, $dl$ is the appropriate differential length element, $N$ is the number of TF coil turns, and $R$ is the major radius, with the largest force in the $Z$-direction on the central column.

The portion of the TF conductor outside of the center column that experiences the greatest stress from the self-expansion force is the radial connections to the center column, which is exacerbated by the small radius of the center rod. These forces will cause unsupported copper or aluminum conductors to fail at the highest field, and therefore, the conductors require significant reinforcement.

The largest self-expansion force is on the center column portion of the TF magnet. The net result of this force is a central compressive load, which can lead to an axial expansion of the column. Estimates of this load indicate that the effect is similar to a 3 °C temperature rise, which is a small fraction of the expected temperature excursion during a pulse. Since this is a minor effect, it is ignored throughout the remainder of this analysis.

The magnetic overturning force results from the interaction of the TF current and the vertical and radial magnetic fields. This force is given by

$$d\bar{F} = I_{TF} \times B_{r} d(Z, R).$$

(2)

These forces act orthogonally to the TF magnet structure or in the toroidal direction. The overturning force changes sign at the vertical midplane, due to both $I_{TF}$ traveling in opposite directions along the top and bottom horizontal returns and $B_{r}$ changing sign at the midplane. This sign change results in a net torsional force on the TF cage as shown for a single TF conductor in Fig. 2(a). The differential force magnitude is over 10 kN/m in some locations on the inner return legs and the fingers, as shown in Fig. 2(b), the contact joint and Fig. 2(c) for the horizontal portion of the outer conductor. This force is acting on the weak axis of bending for the magnet structure and must be counteracted to prevent damage to the TF coil structures.
B. Thermal Forces

Thermal expansion of the center column due to the energy resistively dissipated during the pulse is the main thermal force of concern. The 48 kA/turn of the TF required to achieve the 0.6-T on-axis operating field results in a current density of 160 MA/m$^2$ in the TF center conductor segments. The resistive power dissipation from the current causes a temperature rise ($\Delta T$) for pulselength $t_{\text{pulse}}$ in the central column given by

$$
\Delta T = \frac{I_{\text{TF}}^2 R_{\text{cond}}}{c_p \rho A_{\text{cond}} l_{\text{cond}} t_{\text{pulse}}} \tag{3}
$$

which results in a thermal expansion force approximated by

$$
F_{\text{thermal}} = \alpha E A_{\text{cond}} \Delta T \tag{4}
$$

where $R_{\text{cond}}$ is the resistance of a single TF center rod conductor, $c_p$ is the conductor heat capacity, $\rho$ is the density of the conductor, $A_{\text{cond}}$ is the cross-sectional area of the conductor, $l_{\text{cond}}$ is the length of the conductor, $\alpha$ is the thermal expansion coefficient, and $E$ is the conductor modulus of elasticity. For a pulselength of 100 ms, the temperature rise will be approximately 11 $^\circ$C, giving a thermal force of 6.5 kN. For design purposes, a 20 $^\circ$C temperature rise is assumed, giving $F_{\text{thermal}} \approx 12$ kN.

The high cross-sectional area of the aluminum outer leg return conductors leads to a small temperature rise (<1 $^\circ$C) and thus negligible thermal forces on the return conductor. The finger joint interconnect has varying cross-sectional area but is made of copper and is estimated to have a temperature rise of ~1 $^\circ$C and also expected to experience negligible thermal forces.

III. PEGASUS-III TF Design

PEGASUS-III features an entirely new center column to facilitate the increase in the maximum TF from 0.15 to 0.6 T. The central solenoid was integral to the vacuum wall of PEGASUS, so this entire structure has been removed and replaced with a new central vacuum wall of similar diameter, allowing access to the same low-A physics regime of PEGASUS. The removal of the solenoid frees space for an increased volume of TF conductor, which is necessary to minimize heating at the higher currents required for increased field. In addition to this new center column, the upgraded TF coil set is comprised of outer return legs, interconnects between the center rod and outer legs, and a torque assembly to counter forces on the system. This new coil set has an inductance of 1.04 mH and is powered by an insulated-gate bipolar transistor (IGBT) driven power supply with 900-V capacitor banks for stored energy and is capable of ramping to full current in 50 ms with a 100-ms flat top [8].

An exploded view of the vacuum vessel and the major components of the upgraded TF coil set is shown in Fig. 3. The vacuum vessel is a thin-walled (1/4 $\frac{\text{in}}{\text{in}}$) 304 stainless steel chamber that consists of a 1-m-tall, 2-m-diameter cylinder capped by elliptical domes. The vessel was designed to withstand atmospheric loads as well as the electromechanical loads at the original PEGASUS operational parameters. The thickness of the wall was minimized under these constraints to minimize the magnitudes of the induced currents in the vacuum vessel. Reinforcing ribs are welded to the domes to increase the mechanical strength. As part of the upgrade to PEGASUS-III, additional plates are welded across the horizontal portions of the ribs along with vertical reinforcements to make a box structure for further increased mechanical strength to counter the overturning forces. The four major assemblies of the TF upgrade will be discussed in the following sections.

A. TF Center Bundle

The central column, or TF bundle, consists of 24 individual wedge-shaped conductors made from copper extruded with a central cooling channel in the conductor. They are wrapped with Kapton and glass for electrical insulation, centered on a stainless-steel tube, and assembled into a single round bundle, as shown in Fig. 4. The central cooling channels allow for direct cooling of the conductor. Moderate flow rates (<1 m/s)
of room-temperature cooling water will be able to return the conductor to ambient temperature within 5–7 min for the most aggressive TF current pulses with 100 ms duration, so thermal ratcheting and stresses will not be an issue with a relatively short shot cycle.

Thermal expansion during the shot cycle could potentially induce buckling of the center column. A commercial analysis was performed by GSC Engineering Services (gsc-3d.com) to determine the critical buckling load for the center column. The bundling of the individual wedge conductors into the larger, glass-wrapped structure with a stainless tube in the center provides sufficient reinforcement, such that the contact joint material will fail by yielding before the column will buckle.

B. TF Outer Return Leg Assembly

There are 12 individual return leg assemblies, each consisting of two aluminum conductors secured to either side of steel I-beams, as shown in Fig. 5. The magnetic expansion forces for the upgraded TF current are sufficient to cause the original TF outer leg conductors from PEGASUS to experience yield failure. The aluminum conductors for this design would also suffer intolerable displacement without the steel I-beams for additional mechanical support.

The I-beams have a gap at the device midplane, and the aluminum conductors have an intentional narrowing to create a flexible joint region. This joint allows the ends of the assembly to move in the vertical direction when the center column expands to relieve the stress on the joint assembly between the return legs and the center column. The flexion of the outer leg set in response to thermal expansion and contraction is shown in Fig. 6. At ambient temperature, the I-beams are unflexed, while chilling or heating the center bundle results in flexion.

As the center column expands and the aluminum joint is allowed to flex, the vertical portions of the outer return I-beams near the midplane split move radially inward. During the pulse, the magnetic expansion force counteracts this inward radial motion, thereby reducing the vertical expansion of the center column. The maximum displacement from combined forces is expected to remain less than 0.5 mm.

C. Joint Assembly and Contact Interface

The interconnect between the return legs and the center bundle must provide good electrical contact and be able to survive the thermal and electromechanical stresses where the field is highest. A drawing of the joint concept developed for PEGASUS-III is shown in Fig. 7. The crossover portion of the design allows for an integrated wind-back scheme to prevent a net toroidal current. The two conductors on each leg are effectively part of two independent coil sets, with the toroidal connections for the two sets proceeding in opposite directions to give net zero toroidal current, as shown in Fig. 8. Fig. 8 shows a top-down view of the TF conductors with the two independent coil sets highlighted in red and blue to illustrate the countercurrent path through the crossover joints.

The joint connects to the outer TF return legs using bolts; however, the connection to the center bundle is through
Fig. 7. One interconnect between outer TF return legs and TF center bundle. Notch in the crossover region allows paired interconnect from other side of TF return leg to pass through, eliminating any need for a TF windback to prevent a net toroidal current and associated vertical field.

Fig. 8. Top down view of crossover joint connections. The two different conductors on each return leg are colored red and blue to highlight the countertraveling current paths.

Fig. 9. CAD drawing showing cutaway of interconnects assembled onto a torque plate along with the wedge and belt compression clamp.

Fig. 10. CAD drawing of vacuum vessel with torque block mounted and two outer legs connected to the torque plates and other torque block.

PEGASUS TF bundle compression schemes. The clamp is designed to apply 30 kN of compressive force on each contact, which is equivalent to 30 MPa of pressure. A silver mesh composed of 0.01″-thick wires in a 40 wire per inch square grid, giving a 0.02″ mesh thickness, is placed between the contact surfaces to ensure reliable, multipoint, low-resistance electrical contact across the contact area. Compression testing of the mesh shows 0.014″ of compression of the mesh at 30 kN, which indicates that both layers of the mesh are fully in contact.

The thermal expansion of the center bundle will result in a vertical force transverse to the radial compression on the inner joint. The greatest magnitude force for the most aggressive pulses will be 5 kN or a factor of 6 from slipping assuming a unity friction coefficient for the interface. Most operation is expected to be far below this level of force.

D. Torque Assembly

To counteract the torsional forces described in Section II-A, a torque assembly is used to transfer the forces from the TF return legs to the vacuum vessel. This torque assembly consists of steel plates that attach to the I-beam portion of the TF return legs and a set of blocks and pins that attach to the vessel and the torque plates, as shown in Fig. 10. The pins allow unconstrained vertical motion of the plates to accommodate thermal expansion of the center bundle, while transferring any torque in the toroidal direction to the vessel. A box structure has been added between the ribs to strengthen the vessel structure against the overturning moment and provide a mount point for the torque blocks.

IV. Stress Analysis

To ensure a robust design, finite element analysis (FEA) has been performed for the TF magnets, vessel, and reinforcing structures using Solidworks Simulation. Several different force combinations, corresponding to different phases of operation...
throughout a typical run day, were simulated to get the von Mises stresses for different situations. Early in the run day, the system is under the magnetic stress alone during a pulse. Then after a pulse, the thermal forces are at their maximum while there is no magnetic load. Scenarios were also modeled with a $20^\circ C$ prechilled core and with a core that has been allowed to thermally ratchet to $20^\circ C$ above ambient to simulate the combined thermal and magnetic loads.

The magnetic expansion forces are greatest along the center column. The joint between the inner bundle and outer legs experiences the highest stresses at the surface compression joint. The magnetic overturning forces cause the highest stresses at the interface between the torque plates and the I-beams. All components have a safety factor $>3$ everywhere for the individual magnetic forces, but the combined magnetic force reduces the safety factor to 2.5 at the interface between the I-beams and the torque plates.

Thermal stresses alone were calculated for a $\Delta T$ of $\pm20^\circ C$. The greatest stress is concentrated at the top corner of the friction joint contact area. This stress concentration results in a safety factor of $\sim2.5$, while the rest of the joint contact area has a safety factor $>5$. The stresses for the combined magnetic and thermal forces are shown in Fig. 11. The stress is again greatest at the contact between the I-beams and the torque plates and at the top of the friction joint contact area. The joint contact stress is reduced slightly from the thermal forces only case to give a minimum safety factor of 2.8.

V. Summary and Current Status

PEGASUS-III is a major upgrade to the PEGASUS facility with the mission to test multiple solenoid-free startup techniques on a single platform. As part of this upgrade, the ohmic solenoid is being removed and the TF is being increased from 0.15 to 0.6 T, requiring the construction of new TF magnets capable of withstanding more than an order of magnitude increase in electromechanical forces as compared to PEGASUS. The primary forces are the magnetic expansion and overturning forces and the thermal expansion force on the center column.

The new TF magnet set consists of four major subassemblies: the center bundle, the outer return legs, the joint interconnects between the inner bundle and the outer legs, and the torque assembly. FEA has been performed for these systems under combined magnetic and thermal stresses. All systems are found to have a safety factor $>2.5$ for the most extreme operational scenarios.

All major components of this system are in-house, TF outer return legs have been assembled and aligned to submillimeter tolerance, reinforcing box structures have been welded to the vacuum vessel, and the torque blocks have been installed. A test assembly of the torque assembly and all 12 outer TF return legs on the vacuum vessel has been performed with all pieces showing good alignment. The TF center bundle is under preparation for final installation. The joint interconnects have been designed and are in procurement.

The new TF system built for PEGASUS-III is a robust electromagnet that addresses challenging mechanical engineering aspects of the ST. Commissioning experiments of PEGASUS-III will verify the operation of the novel flex joint with strain measurements and comparison to the model as the field is increased, justifying subsequent operation at the full 0.6 T capability.

ACKNOWLEDGMENT

Data from this publication are publicly available in openly documented, machine-readable formats [11]. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy.

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