Progress toward a 10-kA Superconducting Power Supply for Levitated Dipole Reactors

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***Abstract*—OpenStar Technologies is a private fusion company in New Zealand, developing a fusion reactor based on the levitated dipole. The levitated dipole has a stable magnetic configuration, which provides the basis for the design of a fusion concept. Levitated dipole-based fusion reactors will require large-scale high-field high temperature superconductor (HTS) magnets operating with consistent "quasi-persistent" current while levitating. Quasi-persistent currents in levitating magnets can only be supplied by on-board power supplies that continuously replenish the energy lost from magnet operation. OpenStar has designed, built, and validated an HTS rectifier which to date has charged a 0.53 H non-insulated HTS magnet to 824 A. The initial charging of this magnet to 180 kJ over 60 hours demonstrates the first integration of a large scale HTS magnet with an embedded HTS rectifier. In October 2024, this enabled OpenStar to reach the milestone of first plasma.**

***Index Terms*—Fusion, Levitated Dipole Reactor, HTS Power Supplies, HTS Transformer Rectifiers, Flux Pumps, HTS Magnets, NI Magnets.**

I. Introduction

The confinement of fusion plasmas by a dipole magnetic field was first suggested by Hasegawa [1] after observations of peaked plasma profiles around planetary magnetospheres. The Levitated Dipole Experiment (LDX) [2] and Ring Trap-1 (RT-1) [3] have both since experimentally demonstrated that levitated superconducting magnets can generate the magnetic field conditions required for creating plasma conditions at a laboratory scale.

In order to scale to fusion-scale power plants, a fusion-relevant levitated dipole magnet needs to operate at higher fields and higher currents. This requires higher current and field densities than can be achieved by the superconducting conductors used by LDX and RT-1 experiments, which were Nb_3Sn and BSCCO respectively. Newer HTS ReBCO conductors can provide the necessary increase in current capacity; however, this introduces the problem of current persistence. Making joints between long lengths of HTS conductor requires resistive jointing techniques, meaning any currents circulating in the circuit of an HTS based magnet will gradually decay as energy is lost to joule heating at the joints. Operation of HTS magnets with consistent current and field requires a power supply to continuously replenish the energy lost and achieve quasi-persistence. "Flux Pumps" are a type of superconducting power supply that was originally developed for LTS magnets to avoid penalties associated with heat leakage of large current leads into a vacuum-insulated cryogenic environment and current maintenance for larger magnet systems with a review of this area in [4, 5] and a more recent review of both LTS and HTS superconducting power supplies in [6]. Superconducting power supplies have been demonstrated in the laboratory environment with both HTS and LTS on small-scale magnets up to 12.5 kJ [7].

OpenStar Technologies has designed and built the Junior Experiment [8] to replicate and extend the work achieved at LDX and RT-1 as a path to commercial fusion power generation. The Junior Core Magnet (CM) is a 14 coil no-insulation magnet wound from HTS conductor rated to operate at 1.44 kA at 50 K. Using this magnet, OpenStar Technologies will replicate the plasma results achieved at LDX utilizing HTS technologies similar to RT-1, and demonstrate the integration of a novel HTS rectifier technology with large-scale non-insulated HTS magnets. This work is critical in demonstrating that fusion energy generation is feasible through levitated dipole reactors.

II. HTS Transformer Rectifiers

HTS transformer rectifiers are a type of HTS power supply that has been developed over the past two decades [6, 9]. They can inject large DC currents into superconducting inductive loads efficiently [10, 11]; however, they do so at low power.

A key feature of these power supplies is their use of a step-down transformer so that only small amplitude AC currents need to penetrate the vacuum and cryogenic environments in which superconducting magnets operate. This greatly reduces the penalties associated with large cross section current leads required for kiloampere-scale currents [12]. Alternating currents introduced to the superconducting circuit by the transformer are rectified over many cycles with superconducting switching elements in the same manner as traditional semi-conducting transformer rectifiers. There are a range of

different switching mechanisms that these rectifiers use, such as; semiconducting [13], thermal [13], flux flow [14], dynamic resistance [14], screening currents [15], and J_c(B) suppression [16].

OpenStar's HTS rectifier technology utilizes J_c(B) switches, a type of mechanism where a type-II superconductor has its states manipulated by an external applied magnetic field [17]. By applying a perpendicular external magnet field, the superconductor can be forced into its mixed or normal states and prevent current flow compared to its original state [16]. The idealized waveforms used to control the center tapped rectifiers utilizing these switches are shown in Fig. 1, but a more detailed description of the switching logic for an HTS center tapped rectifier can be found in [18] and optimization strategies for the performance of HTS switches in [19].

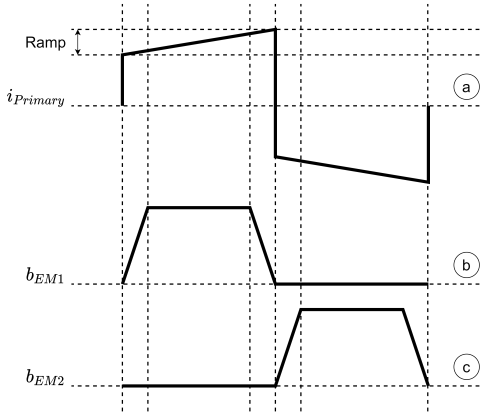


Fig. 1: The idealized waveform timings for the control of an HTS center-tapped transformer rectifier. The primary input current (a) is a symmetric square wave but with the addition of a ramped top to aid in flux transfer. The two waveforms (b) and (c) are magnetic field waveforms applied to HTS switch elements to achieve the switching action.

III. Rectifier System Design

The rectifier topology used to charge the Junior CM is a center-tapped J_c(B)-switch transformer rectifier [18]. It consists of a step down transformer (copper primary and superconducting secondary), two J_c(B)-switches and their associated electromagnets, and the HTS conductor to complete the circuit between these components and the Junior CM appropriately. A schematic of the system is shown in Fig. 2. Both the transformer and the electromagnets utilize Permendur 2V for their magnet yokes because of its high magnetic saturation. SuNAM SCN12700 was the HTS conductor used for the superconducting elements; primarily for it's critical current suppression in external applied magnetic fields [17], as this property enhances the effectiveness of the HTS switches. It is important to note that the components within the rectifier and the elements that connect it to the Junior CM are superconducting, as it allows any DC currents in the Junior CM to circulate without continuous operation of the HTS rectifier, less the joule heating due to joint resistances. The complete parameter list and performance of each rectifier component is listed in table I.

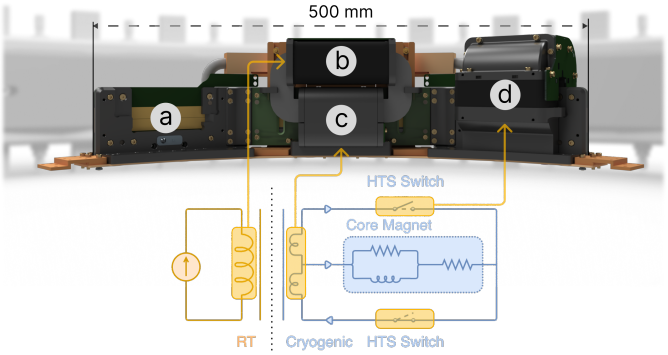


Fig. 2: The circuit diagram of the rectifier along side an illustration of physical implementation of center-tapped transformer rectifier with elements: a) HTS switching element, b) copper primary, c) HTS secondary, and d) electromagnet.

The electrical and thermal modeling of the rectifier was completed in Simulink [20] with the superconducting elements utilizing a parallel resistivity model as demonstrated in [21]. For the HTS in the transformer secondary and the HTS conductor connecting the rectifier to the Junior CM, the focus was primarily to establish a maximum temperature that could support the operation of the Junior CM at 1.44 kA, which for a design with two tapes in parallel meant operating at $\leq$65 K. The HTS switches used the same parallel resistivity model, but with the addition of the calculation of the minimum length required to generate the necessary voltage to charge the Junior CM using the total series resistance of the Junior CM (table II), its operating current, applied field, and the nominal material composition and physical properties of the chosen superconductor; SuNAM SCN12700. Mechanically, each HTS switch is arranged in a bifilar configuration within the air gap of the electromagnet to mitigate the self-field critical current due to the negative interaction between the HTS conductor and the magnetic yokes [22].

TABLE I: Key parameters for OpenStar's HTS centre-tapped transformer rectifier designed to power the Junior CM.

Rectifier Parameters	Value	Unit
Copper Primary Turns	904	arb
Primary Operating Temperature	$<$150	K
HTS Secondary Turns	4	arb
Turns Ratio	904:2:2	arb
Transformer Coupling	$\geq$ 95	arb
HTS Secondary Temperature	$<$65	K
HTS Secondary Ic	$>$2000	A
HTS Switch Tape	SuNAM 12SCN700	N/A
HTS Switch Temperature	65	K
HTS Switch Ic(B=0)	$>$2000	A
HTS Switch Ic(B=1.5T)	400-600	A
HTS Switch Width	2x12	mm
HTS Switch Length	150	mm

IV. Operational Environment

A. Junior Experiment Description

OpenStar's Junior Experiment is the facility that conducts dipole plasma experiments. The components most relevant to the operation of the HTS rectifier are the Junior CM, the cryogenic helium circulation loop, and the vacuum systems. The Junior CM is a non-insulated HTS magnet consisting of 14 separate coils with a summary of its parameters in table II. The coil arrangement is shown in Fig. 3 with further details found in [23]. During levitated dipole plasma experiments, physical connections to the Junior CM are detrimental to the quality of the plasma and the experiment results. As a result, the rectifier and its auxiliary flight electronics must be enclosed within the Junior CM and shielded from its internal magnetic fields. The coil arrangement shown in Fig. 3 produces a "zero-field region" (ZFR) inside the Junior CM where the magnetic field is by design below 10 mT, this is aided by the addition of a thin mild steel shell that surrounds the ZFR. This is critical for operation of the HTS rectifier as it prevents the magnetic yokes in the transformer and electromagnets from saturating.

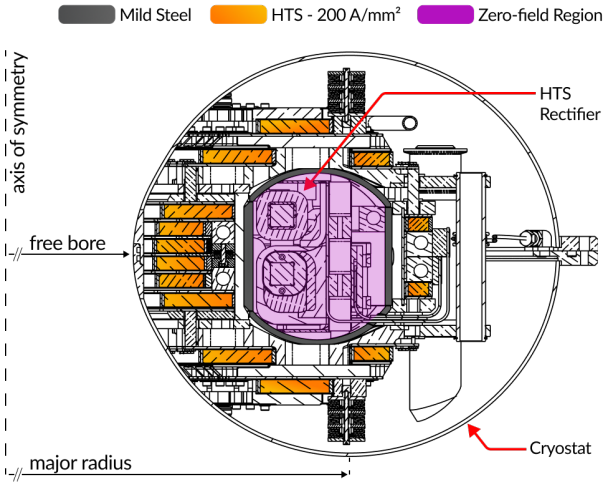


Fig. 3: Cross section of the 14 coils (orange) comprising the Junior CM and the Mild Steel shell (grey) providing additional magnetic shielding to the ZFR (purple). The rectifier and flight electronics (not shown) are mounted inside the ZFR.

TABLE II: The Junior CM design parameters.

Parameter	Design Value	Unit
$B_z(0,0)$	2.88	T
B_z Max at Windings	5.63	T
B_R Max at Windings	2.98	T
Inductance	0.53	H
Max Current	1.44	kA
Ampere-Turns	1.5	MA-T
Stored Energy	0.55	MJ
Series Resistance (30 K)	8.6	$\mu\Omega$
Series Resistance (50 K)	12.5	$\mu\Omega$
Free Bore Radius	210	mm
Major Radius	325	mm
Tape Length	6.3	km
Magnet Mass	550	kg

B. Flight Electronics Description

The key parameters for the flight electronics are shown in Table III. Currently, the key systems on-board for the operation of the HTS rectifier are the constant current (CC) drives for the transformer and electromagnets, instrumentation (voltage, current, temperature, field), heaters, batteries, and battery management systems. The HTS switch heaters are an important part of the system and enable control of the temperature of the HTS switches to within an acceptable range for operation.

TABLE III: Parameters for the flight electronics needed to remotely operate the on-board HTS rectifier.

Parameters	Value	Unit
CC Drive Voltage Rating	36	V
CC Drive Current Rating	10	A
Switch Heater Drive Power	22.5	W
Data Acquisition Rate	1-100	Hz

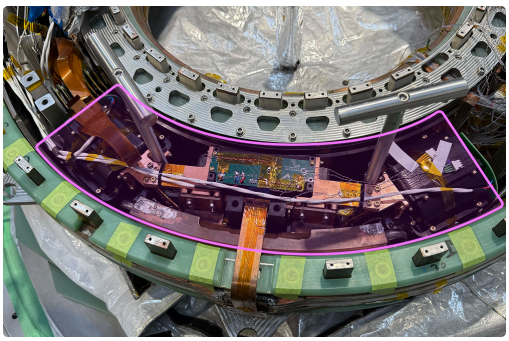


Fig. 4: The HTS transformer rectifier (outlined in purple) soldered to Junior CM, prior to installation of the upper part of the magnet.

C. Experimental Setup

Once the HTS rectifier is installed within the Junior CM, as shown in Fig. 4, the magnet assembly is completed, placed in a close-fitting cryostat shell, lifted into the main 5.2 m Junior experiment chamber, and connections are made to external electrical and cryogenic docking systems [8]. The 5.2 m chamber, with which the Junior CM cryostat shares its vacuum space, is pumped down to $\sim 10^{-7}$ mBar to provide vacuum insulation for cryogenic cooling and a suitable environment for plasma generation. Retractable bayonets within the docking system supply supercritical helium to both the Junior CM and the HTS rectifier through a closed loop heat exchanger. Heat is removed from the HTS rectifier through thermal conduction to the heat exchanger and to the magnet, which took 24 hours to get from room temperature to a base temperature of 30 K. Once at this base temperature, the HTS switches of the rectifier need to be raised to their operating temperatures. This is achieved by applying heat with Nichrome heaters that are epoxied to the substrate side of the HTS switches, which are controlled with a simple PID loop based on temperature sensors placed around the HTS switch itself. Depending on the target temperature, this took 3-4 W of the maximum 22.5 W of available heating.

V. Experimental Program and Results

Table IV summarizes the first three milestones of the OpenStar Junior experimental program. The first of these is to demonstrate plasma generation with a large scale solder impregnated HTS coil [24], or no-insulation (NI) [25], charged and maintained with an HTS rectifier. The second and third milestones will demonstrate levitation of the Junior CM at a minimum viable current before again at the full-field current. Each milestone requires the Junior CM to operate at a higher current, which must be supplied by the HTS rectifier.

TABLE IV: Operating currents necessary for experimental milestones.

Parameters	Experiment	Value	Unit
Half-field Current	First Plasma	591	A
2/3-field Current	First Levitated Plasma	854	A
Full-field Current	Full-field Levitated Plasma	1275	A

A. Charging Campaign and First Plasma

OpenStar achieved first plasma in October 2024 with a measured peak Junior CM field on conductor of 2.35 T. This corresponds to an azimuthal current in the Junior CM of 591 A, which was supplied by the HTS rectifier over 60 hours of continuous operation. The charging curve of the Junior CM throughout the plasma experiment campaign is shown in Fig. 5. The waveforms used to control the HTS rectifier during this experiment are shown in Fig. 1, with the applied field strengths for both electromagnets at 1.5 T and the amplitude of the primary current periodically increased up to 2.5 A over the duration of the experiment. The power supply was run in an open loop with no feedback between the input primary current and its output voltage or the magnet current. On average, the HTS rectifier maintained an output voltage of 4.5 mV to maintain a current suitable for plasma experiments.

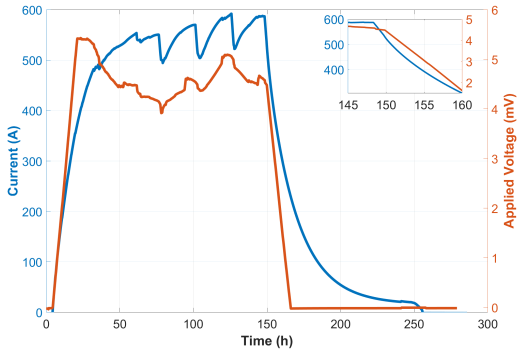


Fig. 5: The charging curve (blue) and average applied voltage (orange) on Junior CM in lead up to and throughout first plasma campaign and final discharge at the end of the campaign. The Junior CM was recharged to 590 ± 1 A (inset) and held at this current for 3 hours before final discharge. Note that the change in discharge behaviour nearing the end is due to intentional warming of the Junior CM.

There are a series of current drops from 60 hours; the first is an experiment to characterize the electrical and thermal properties of the Junior CM as a fully integrated system. The events at 80, 105 and 130 hours are plasma experiment runs in which all external systems were disconnected and the rectifier disabled, which allows currents in the superconducting circuit to continue to circulate while plasma experiments take place. Once the HTS rectifier was turned off, the Junior CM was disconnected and positioned in the vertical center of the 5.2 m chamber for plasma experiments. A successful plasma shot is shown in Fig. 7.

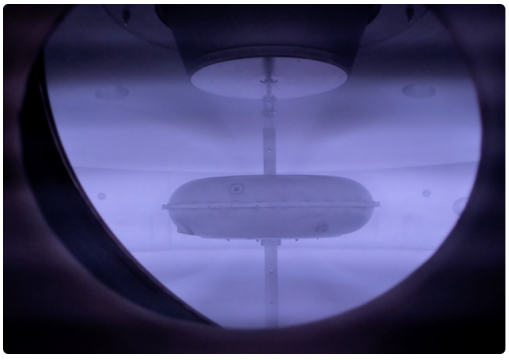


Fig. 6: Photo of a plasma shot during first plasma campaign.

During the charging campaign, the open loop current sensors were affected by the transient magnetic environment inside the Junior CM making their measurements drift over time and unreliable. However, data from ex-situ testing of the rectifier at equivalent output voltages and similar operating conditions are shown in Fig. 7. While operating the rectifier at an output voltage of 4.5 mV, each HTS switch dissipated 4 W, while the HTS secondary dissipated 2 W.

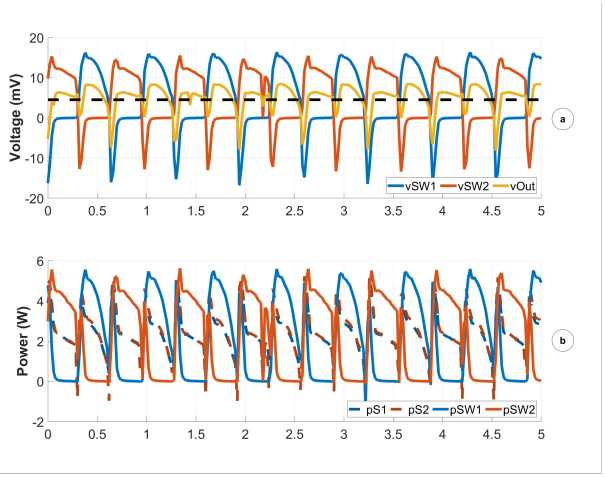


Fig. 7: Results from an iteration of the HTS rectifier ex-situ to the Junior CM run in a no load configuration. In (a) are the voltages of the two HTS switches (vSW) and the output voltage (vOut) of the rectifier with a dashed line indicating 4.5 mV average. The power dissipation in the secondary windings (pS) and HTS switches (pSW) are shown in (b).

Note that the self-dissipated power in the HTS switches replaces the power introduced by the heaters initially used to bring them up to their steady state operating temperature. In addition to the power dissipated by the HTS switches, the copper electromagnets used to activate them also dissipate energy into the system. This power is not monitored in-situ but in component testing they had a power draw of 20 W. These can be upgraded to HTS to mitigate most of the DC portion of their heat load.

The voltage normalized discharge curves for the Junior CM driven with an HTS rectifier and an external semi-conducting power supply are shown in Fig. 8. These curves are not one to one comparisons as in the case of the external power supply a sudden discharge forces the current to flow through the resistive radial paths of the Junior CM, whereas the HTS rectifier allows the DC currents to continue to flow within a mostly superconducting path. This results in a slower decay in the current with the HTS rectifier, which still retains 80% of the current by the time the configuration with the external power supply is fully discharged.

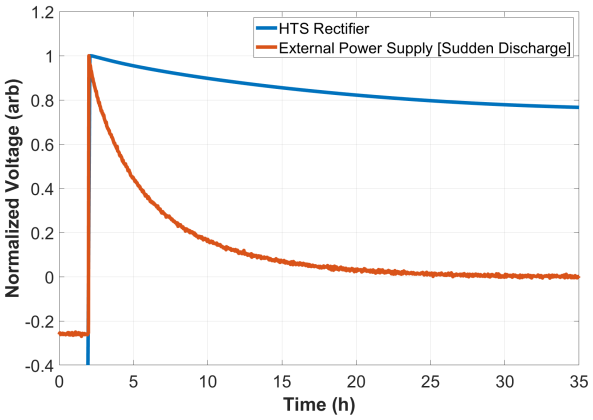


Fig. 8: A comparison of the normalized discharge voltages of the Junior CM powered by an HTS rectifier (blue) and external power supply (orange). The blue curve extracted from the discharge in Fig. 5 whereas the orange is from a sudden discharge from 20 A using a TDK Lambda GSP10-1500 power supply during the commissioning of the Junior CM. The Junior CM was operating at 30 K for both experiments during this discharging window.

B. Future Works

Further development of the HTS rectifier has focused on increasing the power output to minimize charging time and increasing the magnet operating current to reach a level necessary for our first levitated plasma experiments. Primarily, this focused on maintaining more uniform temperature gradients across the superconducting switch to ensure that the heat generated does not induce quench in the superconductor. An upgraded iteration of the HTS rectifier was tested; producing an average output voltage of 8 mV and achieved a current of 824 A in 50 hours as shown in Fig. 9.

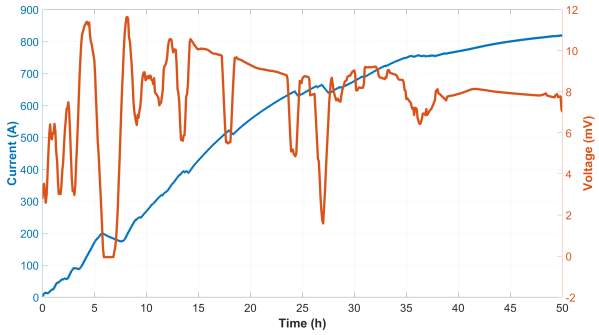


Fig. 9: Charging curve of Junior CM up to 824 A in preparation for first levitated plasma campaign.

Mechanically, this was achieved by better compliance in the soldering jigs and the pneumatic control of the applied pressure used to make these joints. This campaign had far more interruptions in charging as the HTS rectifier was pushed more aggressively than in the first campaign to establish the as-built operational limits of this power supply as this is not something that can be tested ex-situ. The drops in voltage are thermal quenches due to unstable combinations of Junior CM current, HTS switch temperature, and output powers. By comparison, in this campaign the Junior CM was charged to 591 A in one third of the time required to reach the same charge level during the previous campaign. In terms of peak power, this upgrade resulted in a 400% increase in the output power of the HTS rectifier. Work is currently underway to prepare the Junior experiment for first levitated plasma.

VI. Summary

OpenStar Technologies has designed, constructed, and experimentally verified an HTS rectifier for charging a large-scale NI HTS magnet. Using this HTS rectifier, OpenStar Technologies achieved first plasma. The HTS rectifier has produced an average output voltage of 8 mV, resulting in a final current of 824 A and a stored energy of 180 kJ after 50 hours of charging. This is more than the maximum previously demonstrated for LTS transformer rectifiers of 12 kJ. This work demonstrates that HTS power supplies are a viable solution to charging and maintaining currents in DC operated fusion magnets specifically, but also large-scale DC HTS magnets in general. This result demonstrates that the key components of a levitated dipole reactor can be integrated. The flexibility and modularity of the dipole will allow for constant iteration of the internal components to improve system level performance.

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