High Magnetic Field Generation Using Single-Turn Coils

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Abstract. **The advent of the homopolar generator has recently permitted the demonstration of a 20 T on-axis, single turn toroidal magnet. Homopolar generators are inherently high current, low-voltage machines which ideally match the requirements of single-turn coils. Magnetic field levels previously limited by the insulation's thermal and voltage breakdown capability have been surpassed. The entire coil volume is essentially occupied by high strength, high conductivity conductor. A current density of 840 MA/m^2 has been achieved in a 9 cm major radius, toroidal coil with a 9.14 MA, 56 V open-current discharge (sinusoidal pulse, 150 ms). Experimental test results are presented, as well as discussion of the potential for applying this technology to solenoid-type coils. This research is funded by the Texas Atomic Energy Research Foundation.**

Introduction

Since Faraday proposed the principle of the homopolar generator (HPG) in 1831, various machines have been built and operated [1]. The performance limitations with the early machines were primarily due to collector current density and low output voltage. In the early 1970s, HPG technology was advanced through research in areas of magnetic fusion, pulsed welding and electromagnetic launch. Today, state-of-the-art HPGs routinely produce megamp-level currents, and although voltages are limited to several hundred volts, HPGs are ideally suited for loads such as single-turn magnets. The HPG output is inherently very smooth because the current is collected by slip rings, rather than a commutator. Furthermore, HPGs are compact energy sources that connect directly to low-impedance loads and do not require large numbers of rectifiers for power conversion. Because of their virtually rippleless operation, actively-cooled dc machines have also been pursued [2].

Single-turn coils (solenoid or toroidal), like HPGs, are mechanically simple and robust due to their monolithic nature. The most obvious advantage of the single-turn coils is the elimination of high voltage insulation. This results in better utilization of the available area for mechanical and thermal management. Maximum temperatures and stresses are not limited by the physical properties of turn-to-turn insulation, and differential thermal problems between insulation and conductors are minimal. High voltage has been responsible for destroying many multiturn coils and producing electrical noise due to capacitive accumulations within the insulation. On the other hand, single-turn coils and the associated high-current busbars require more mechanical clamping and are physically larger than those of a multiturn coil.

The high-current technology required for a single-turn magnet exists and has been demonstrated on numerous high-current experiments including a 20 T toroidal magnet. A 9 cm major radius, toroidal magnet was designed, built and tested as a technology demonstration for a fusion ignition experiment known as IGNITEX [3]. IGNITEX was proposed as a simple, low cost path to achieve thermonuclear fusion ignition and do so in a reasonable time frame. The concept proposes to use ohmic heating alone to achieve ignition temperatures by using a single turn toroidal field (TF) coil capable of operation at 20 T. In addition, the poloidal field (PF) coils are located in the plasma bore to provide maximum coupling with the plasma, thereby reducing the flux necessary to induce the very high plasma currents required. To minimize difficulty with joints in the PF coils, they are also of single-turn design. Use of proven technologies and simplicity in design and operation form the basis of the IGNITEX device and its power supplies. An IGNITEX-type experiment is a means to study an ignited plasma, verify scaling laws and learn how to achieve ignition in a more efficient manner, and should not be compared to experiments simulating reactor operation. The design intentions of the TF magnet demonstration were to reproduce temperatures and stresses that would occur in a 1.5 m coil (the original IGNITEX major radius) with a 5 s flat-top current profile. The magnet has a TF aspect ratio of 3.0 and a major radius of 9 cm. A high strength, high-stiffness design was achieved by stacking 36, wedge shaped, beryllium copper (Brush Wellman Alloy #3HT) plates (without insulation) to form the torus. High flatness tolerances and intermediate machining steps minimize assembly tolerance stack-ups. The lack of electrical insulation in the toroidal plate stack-up gives the coil a high percentage of conductor material in the critical inner leg region. The result is stress and thermal limitations dictated by the conductor material only. The coil design utilizes wedging as the predominate stress management technique but does require a "bucking post" at high fields. The radial gap between the coil and the bucking post is sized to allow inward magnetic radial forces to close toroidal gaps without contacting the bucking cylinder. To achieve 20 T on-axis, the inner leg of the magnet must

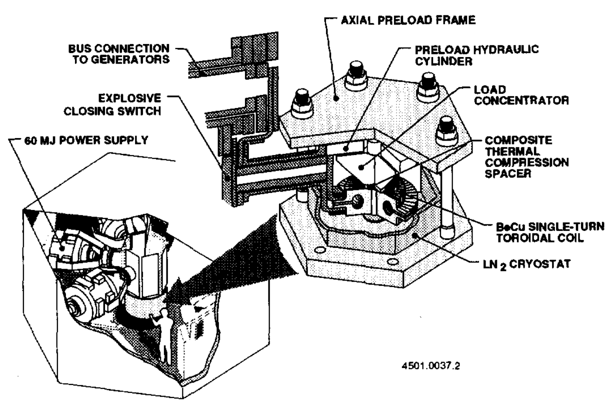

Figure 1. TF magnet/60 MJ homopolar generator pit layout

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be preloaded, and it must be precooled to liquid-nitrogen temperature. High busbar forces are managed by common techniques of clamping and preloading and sensible use of materials and geometry to manage the electromagnetic loads [4].

An existing 60 MJ, 9 MA, HPG power supply located in the CEM-UT laboratory fulfills the low voltage, high current, power supply requirements. The 60 MJ HPG system consists of six, 10 MJ generators each rated at 1.5 MA, 100 V open current (fig. 1). The TF magnet (consisting of six, 60° sectors) is connected to the six HPGs in a parallel configuration. To accommodate the fast current rise time of the HPG/TF magnet circuit, each HPG and 60° sector is in series with an explosive closing switch. Typically, the HPG brush gear is used as the making switch when discharging into inductive loads. A coaxial explosive closing switch was designed based on an existing, highly reliable switch used on other pulsed power experiments [5]. Due to the high demand on the 60 MJ HPG system from other experimental programs and the need to minimize circuit impedance, the TF magnet experiment was located below ground level in the center of the generator pit. An axial magnet preloading system and a liquid-nitrogen supply and exhaust system were incorporated into the magnet/generator pit design. The diagnostic system for the TF magnet prototype is designed to determine strain, temperatures and magnetic fields at several locations in the TF magnet [6]. These values are used to verify numerical predictions by electromechanical and thermomechanical analyses [7].

Prototype Toroidal Magnet Testing

Testing of the single-turn toroidal magnet has been performed intermittently since 1990 due to limited funding and/or power supply availability. Tests performed in 1992 culminated in a successful test that produced a magnetic field density of 20.3 T on-axis. The test program of the TF magnet consisted of three phases: low current, room temperature testing ($B \leq 11.0$ T); intermediate current with LN_2 cooling testing, ($B \leq 15.0$ T); and high current with LN_2 cooling and axial preloading testing ($B \leq 20.0$ T). A summary of magnet tests performed in 1992 is given in table 1. Only the tests of significance are described in detail.

Test #29—20.3 T

Test #29 was a successful discharge resulting in an on-axis field density of 20.3 T. The magnet was precooled to liquid nitrogen temperature (-196°C) and preloaded axially with the hydraulic press to provide 310 MPa (45 ksi) on the inner leg of the magnet. The HPGs were motored to 3,400 rpm and produced an open-circuit voltage of 56.7 V. The current data shown in figure 2 is approximately 6% lower than actual due to an integrator clipping phenomenon [10]. The current-data error, discussed in the next section, was not discovered until after test #32. The actual average generator current was 1.524 MA, giving an on-axis magnetic field density of 20.3 T. Figure 3 shows the voltages of the six HPGs for test #29. Three of the six closing switches experienced small amounts of contact melting which is believed to be an indication of uneven current distribution. Also, minor arcing occurred in the #1 switch stackup as a result of insufficient tightening.

The typical variation in HPG speeds was less than 0.4% and the variation in HPG voltages was within 0.5%. Discharge currents measured using Rogowski coils and active integrators varied between 2 and 5% depending primarily on the closing switch performance for a given test. Minor differences in circuit resistance could also exist due to bolt torque variations or thermal gradients in the busbars produced by busbar heaters and/or cooling asymmetries due to the location of the liquid nitrogen coolant lines. Assuming one had a high confidence in his current measurements, the individual HPG/TF magnet circuits could easily be 'fine-tuned' to produce current levels equal within 1%.

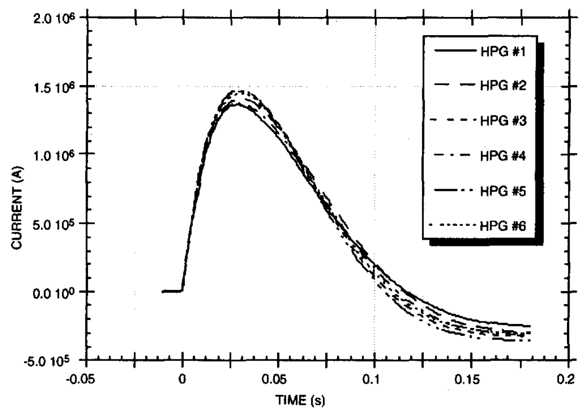

Figure 2. TF magnet test #29—20.3 T HPG discharge currents

Table 1. Summary of 1992 TF magnet testing

Parameter/Test #	Test #22	Test #23	Test #24	Test #25	Test #26	Test #27	Test #28	Test #29	Test #30	Test #31	*Test #32*
Date of Test	2/28/92	3/3/92	3/5/92	3/24/92	3/25/92	3/27/92	3/29/92	3/31/92	4/27/92	4/28/92	*4/30/92*
HPG Speed (rpm)	1125	1800	1712	1800	2300	2675	3100	3400	1800	2350	*4000*
Average OC Voltage (V)	19.0	30.6	29.1	30.3	38.9	44.8	52.0	56.7	30.3	38.7	*65.5*
Average Gen. Current (kA)	497	824	849	824	1125	1284	1455	1521	818	1128	*1702***
Total Current (MA)	2.98	4.94	5.09	4.94	6.69	7.50	8.27	8.64	4.94	6.71	*8.66*
TF Magnet Field (T)*	6.6	11.0	11.3	11.0	15.0	17.0	19.4	20.3	10.9	15.0	*22.7***
Magnet Initial Temperature (° C)	23.0	23.0	-196.0	23.0	-196.0	-196.0	-196.0	-196.0	23.0	-196.0	*-196.0*
Maximum Measured Temperature (° C)	65	140	-86	137	-9	50	135	160	122	-62	-
Hydraulic Preload, Inner Leg of Magnet (ksi)	0	0	0	45	45	45	45	45	0	45	*45*

* On axis magnetic field density based on average generator current

** Based on the four sectors that did not experience a closing switch failure

Thermocouples mounted on the inner leg of the TF magnet indicated a peak temperature of 160°C which is consistent with predictions. Figure 4 shows the thermocouple #6 data for four LN_2 precooled tests. AC excitation of the strain gages (Micro Measurements WK-09-062AP-3050) was used successfully at low fields without liquid nitrogen precooling. Figure 5 shows the vertical strain data for test #30; a room temperature with no axial preload, 11.0 T magnet test. The peak strains indicated are approximately 75% of predictions. This discrepancy may be explained since the predicted peak strain reflects the strain at the point of maximum stress and not the average over a specific gage length.

The Hall generators (FW Bell BHT-921) which measure the magnetic field density at the axis of the torus have indicated higher fields than those extracted from the current data. The Hall generators (calibrated at the MIT National Magnet Lab) for test #29 indicated an on-axis field of 21.4 T (figs. 6 and 7).

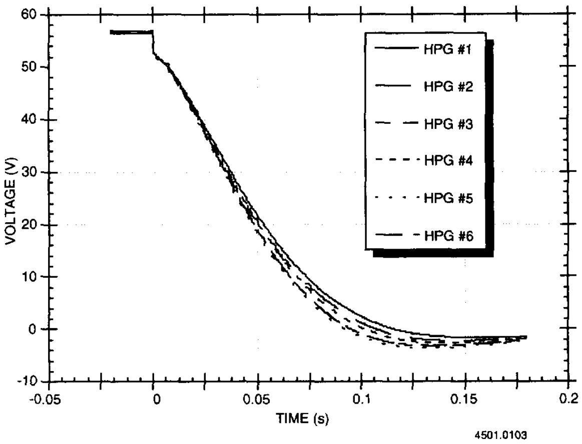

Figure 3. TF magnet test #29 -- 20.3 T HPG voltages

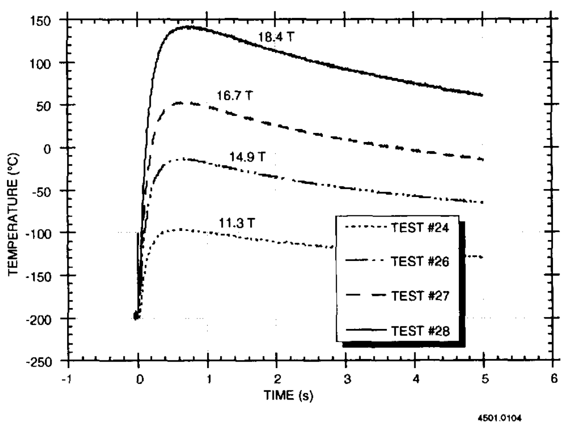

Figure 4. TF magnet test #24, 26, 27, and 28 - thermocouple #6

Test #32—Closing Switch Failure

Test #32 was thought to be an attempt at achieving an on-axis field density of 20 T, but because of the integrator error discovered later, was actually an attempt at 22 T. The six HPGs were motored to 4,000 rpm with full-field excitation, producing an open circuit voltage of 65.5 V. All six explosive closing switches actuated properly. However, at approximately 15 ms into the discharge, switch #1 errantly opened, followed 3 ms later by the opening of switch #3. The inductive energy stored in the #1 and 3 circuits induced excessive current levels in the adjacent sectors and initiated a chain reaction busbar joint failure around the magnet. The outside busbar leads of sectors 2, 4, 5 and 6 (which connect the aluminum coax to the individual magnet plates) failed at the connecting joints. The magnet sustained no damage to the toroidal or inner leg region; however, it did experience bending and arc damage to the joint region around the perimeter. The beryllium copper busbar leads remained essentially intact.

The damage occurred because of unbalanced loads and overcurrents in four of the six magnet sectors. This failure was initiated by two of the explosive closing switches errantly opening prior to peak current. Post-mortem analysis indicated that the buswork should not have failed even though the generator current data indicated levels in excess of 1.6 MA. The Balcones HPG current-measuring system utilizes six Rogowski coils mounted in each of the six generator busbar coaxes and active integration circuits to process the signals. Integration constants are derived by short-circuit discharges through precision current-viewing resistors. Close examination of the high energy TF magnet current data revealed a negative current offset after the discharge. The negative current offset and the lack of sufficient currents to cause the bus failure of test #32 led CEM-UT engineers to believe that the Rogowski signals were being clipped because of a voltage limitation within the integrator circuits. An extensive calibration check was performed on the integrators, revealing that indicated peak current levels for the high energy tests were as much as 13% lower than the actual current [8]. The results are supported by the magnetic field density instrumentation which consistently predicted higher fields than the current data. Consequently, test #29 produced an on-axis field density of 20.3 T. The connecting buswork failure which occurred during test #32 produced sector current levels equivalent to 24 T test prior to the bus failure.

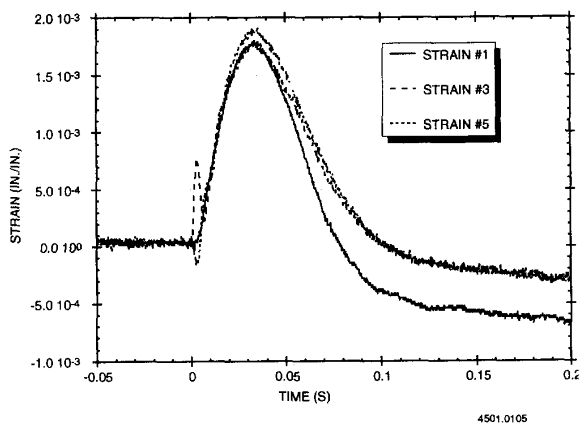

Figure 5. TF magnet test #30, vertical strain data from middle of inner leg -- 11 T

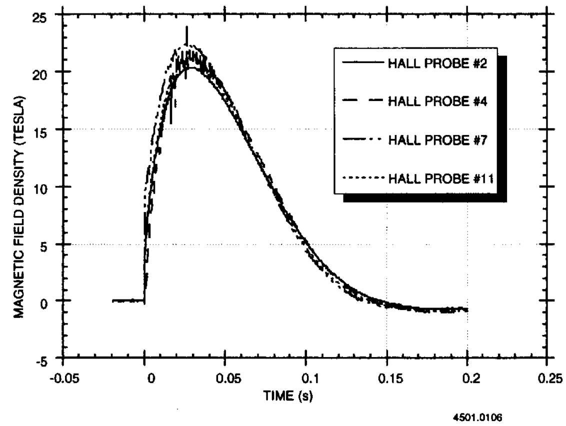

Figure 6. TF magnet test #29, on-axis Hall generator data

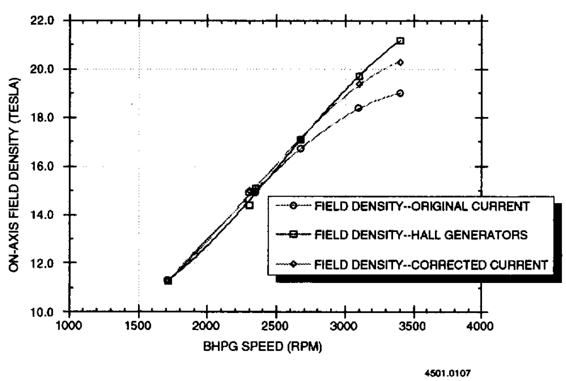

Figure 7. 1992 TF magnet tests on-axis magnetic field density vs. HPG speed based on Hall generators and HPG current

Generator #6 reached a peak current of 1.84 MA before its busbar joints failed. The magnet plate/busbar lead closest to the sectors with the failed switches made electrical contact and coupled inductively, and therefore saw as much as 6% higher current than the average in that particular sector. It is estimated that the magnet plate/busbar lead in sector #6 adjacent to the failed switch sector #1 exceeded its rated current and forces by 23% and 50% respectively. Once this failure occurs, the remaining magnet plates/busbar leads share the additional current, and consequently the magnet busbars fail in a chain reaction around the magnet.

Solenoid Magnet Applicability

Although design and testing efforts presented in this paper focus on a toroidal magnet configuration, a single-turn solenoid magnet powered by HPGs is equally attractive. Given the design parameters of the most ambitious pulsed solenoid coils (60 T flat top pulse for 100 ms and 44 mm bore), several possible single-turn coil/HPG configurations are available. As with the toroidal magnet, a single-turn solenoid offers mechanical simplicity and strength, but unlike the toroidal geometry, a distributed current feed may not be desirable for a solenoid because of the need for radial preload. A design with a "few turns," however, would allow current feeds at the ends of the coil and still allow a radial preload structure to occupy the periphery. Using multiple HPG circuits, a hybrid coil design could also be incorporated to assist current diffusion in distributing current. Several HPGs could be connected in series to provide the necessary voltage/current requirements.

Conclusion

The single-turn, toroidal magnet prototype powered by multiple homopolar generators has successfully demonstrated on-axis magnetic field densities up to 20.3 T. A voltage clipping phenomenon with the integrator circuits has been fully investigated and characterized. Unawareness of the integrator circuit limitations resulted in an attempt to produce 22 T, which ultimately exceeded the design parameters of the experiment. The open-circuit fault experienced during test #32 produced sector loadings equivalent to a 24 T test with no damage to the critical inner leg region of the toroidal magnet. Although closing switches are not necessary for a full-scale toroidal magnet system, the switch opening phenomenon should be thoroughly investigated and understood. Future magnet tests need to resolve the closing switch issue in addition to considering current and action-limiting elements in the circuit. The single-turn technology demonstrated with the HPG powered, 20 T toroidal magnet experiment shows promise for high field solenoid applications and warrants further study.

Acknowledgments

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