DESCRIPTION OF PULSED-POWER HOMOPOLAR TECHNOLOGIES FOR A FUSION IGNITION EXPERIMENT

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ABSTRACT

The concept for a single-turn tokamak experiment IGNITEX [1] makes possible the realization of a controlled, self-sustained fusion reaction in the near term with relative simplicity and low cost. The IGNITEX tokamak utilizes low-impedance toroidal field (TF) and poloidal field (PF) magnet systems which induce the high-level fields and currents required for fusion ignition. These magnet systems require power supplies that can meet strict operational conditions. Homopolar generators (HPGs) are well suited for operation of a single-turn tokamak because they are inherently high current, low-voltage machines which can kinetically store all the energy required for a pulsed discharge. The energy storage is accomplished in a compact manner by using high speed composite flywheel technology and provides the added advantage of keeping electrical grid power requirements very low. Finally, since HPGs are simple dc machines, their cost is low and rectifier systems are not necessary.

In this paper, the HPG technologies to be utilized in a fusion ignition experiment are described. The various components, materials, and design considerations for the HPG current-collection systems are reviewed, including rotor slip ring, brushes, and actuators. Design, fabrication, and assembly techniques for the lightweight, composite, energy-storage flywheel are given. The status of these HPG technologies relative to IGNITEX power supply requirements are reviewed. The modes of operation of the TF and PF magnet systems are analyzed. Questions of reliability of operation, maintenance, and cost evaluation are also addressed. Finally, the construction and testing of a full-scale prototype IGNITEX HPG power supply module is proposed.

INTRODUCTION

Achieving controlled thermonuclear fusion in a tokamak device depends upon the ability to heat a plasma of sufficient density to temperatures where fusion reactions will occur while maintaining adequate particle confinement and purity. Ohmic heating has been proven as the most well behaved, well-understood method of raising the plasma temperature. Unfortunately, plasma resistance decreases as its temperature increases, so ohmic heating becomes less efficient as ignition temperatures are approached. As ohmic current in the plasma is raised, a greater confinement field is needed to maintain plasma stability. Conventional tokamak technology, which uses multiturn TF coils, may not permit generation of confinement fields high enough to allow ohmic heating to ignition temperatures.

The IGNITEX concept proposes to use ohmic heating alone to achieve ignition temperatures by using a single-turn TF coil capable of operation at 20 T.[2] In addition, the PF coils are located in the TF bore to provide maximum coupling with the plasma and thereby reduce flux necessary to induce the very high plasma currents required. PF coils are also of single-turn design to minimize difficulty with joints. Use of proven technologies and simplicity in design and operation form the basis of the IGNITEX device and its power supplies.[3]

Pulsed HPG development was pursued in the early 1970's as a potential power supply for the Texas Experimental Tokamak (TEXT) at The University of Texas at Austin. Although HPGs were determined to be suitable pulsed-power supplies, a more conventional power supply arrangement was selected. Since that time, HPG development has been an ongoing effort by industry for materials processing and pulsed resistance welding applications, and by the military for use as power supplies for electromagnetic launchers. This development effort has established significant advances in the technologies of high speed, high current sliding electrical contacts (brushes), high energy density flywheels for energy storage, sophisticated control systems for modular HPG power supplies, and real-time HPG output pulse shaping. These advances, in addition to the inherent HPG characteristics of low voltage and high current, make them very attractive for driving single-turn magnets in a pulsed mode.

For the baseline 1.5 m major radius IGNITEX device, the single turn, alloy copper TF coil requires 150 MA at approximately 10 V to achieve 20 T on-axis. In setting the power supply energy requirements, a pulse length of at least 10 times the anticipated energy confinement time was considered necessary. This results in a 5 s flat top operational requirement on the TF coil. Including a 3 s ramp up and a 2 s shutdown period, the total pulse length is 10-s long. About 18 GJ of initial stored energy is required to power the TF magnet and overcome circuit resistive losses. A set of 12 HPGs, each storing 1.5 GJ and supplying 12.5 MA, will drive the magnet in parallel. A single TF coil power supply module is shown in cross-section in Figure 1. The machine utilizes a conventional iron-core magnetic circuit, solid current collecting brushes, and a fiber reinforced epoxy composite flywheel for bulk energy storage. Interesting features of the device are provided in Table 1.

Table 1. TF coil HPG module characteristics

Parameter	Value	Unit
Energy stored	1,500	MJ
Diameter	4.0	m
Length	2.65	m
Mass	47,760	kg
Rotor speed	2,040	rpm
Flywheel tip speed	430	m/s
Average flux density	1.6	T
Maximum generated voltage	60	V
Peak current	12.5	MA
Peak discharge torque	2×10^6	Nm

The PF coils use HPGs as power supplies; however, they operate in a slightly different mode than the TF-coil generators. The PF-coil circuits are purposely underdamped to allow a positive-to-negative oscillation in the output current to minimize peak current while maintaining the ability to induce adequate plasma current. Pulse shapes for the TF coil and the combined current in the PF coils are shown in Figure 2.

CRITICAL HPG TECHNOLOGIES

Current Collection

The iron-core portion of the HPG module consists of a steel rotor which has a copper alloy rotor conductor installed onto it; a set of field coils

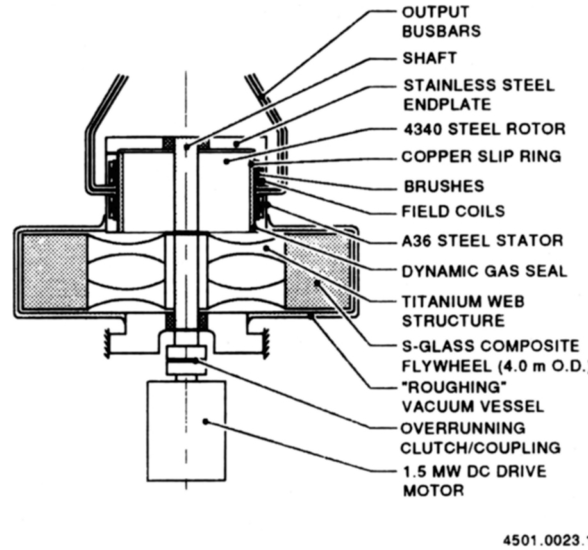

Figure 1. Conceptual design of an IGNITEX TF coil HPLG module

and steel backiron; and a pair of current collecting brush mechanisms. Transfer of the 12.5 MA, 10 s long pulse from the rotor slip ring to the output bus represents the most demanding task of any component in the machine. Each of the two brush mechanisms is designed to have 4,600 individual brushes, which will carry roughly 3-kA apiece at peak generator current. Design of the brush mechanisms for the IGNITEX power supplies is based on those used in several generations of prototype and production pulsed HPGs. The basis for the design, shown in Figure 3, is a sintered copper-graphite brush pad attached on a trailing arm strap which serves as the current path to a collector ring. Actuation of the brushes onto the rotor surface is accomplished with pneumatic bladder-type devices which deflect the brush strap and its brush down to the rotor surface, and then provide a predetermined normal force on the sliding contact. Upon completion of the pulsed discharge, the brushes are lifted by the residual spring force of the brush straps. Operating parameters for the brushes in the IGNITEX generators are included in Table 2, which also shows demonstrated pulsed HPG brush performance for comparison.

Table 2. IGNITEX HPG operating brush parame ter compared with present pulsed HPG brush technology

Parameter	TF Coil HPG Requirement	Demonstrated Performance
Brush Slip Speed (m/s)	200	240
Brush Current Density (kA/cm ^{2})	1.25	2.5
Current per Brush (A)	2,750	5,000
Pulse Width (s)	10	30

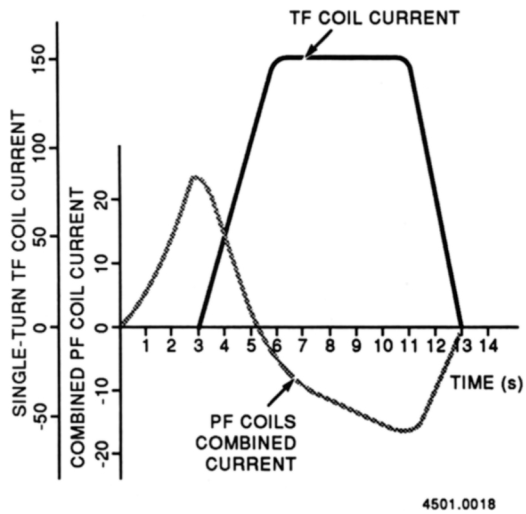

Figure 2. Current pulse requirements for the IGNITEX magnet systems

As mentioned before, the PF coil power supply circuits are designed to be underdamped and to "ring" during operation. This will require the rotor to reverse direction. While design of the PF HPG brush mechanisms may include special provisions to accommodate rotor reversal, the mechanism described above has successfully operated in an underdamped HPG-cryogenic inductor circuit wherein the rotor reversed to approximately 50% of its initial forward speed.[4]

Design of the rotor slip ring is heavily influenced by the 12.5 MA current rating of the machine and the relatively long 10 s pulse length. The slip ring is 6.35 cm thick and a high strength, high conductivity zirconium copper alloy is specified. An interference fit onto the steel rotor with sufficient initial pressure will be required to prevent it from loosening during spin up or after it is resistively heated. Active water cooling of the slip ring is provided by internal passages fed from the rotor shaft during the discharge pulse. Table 3 provides a breakdown of TF coil/HPG circuit losses for each of the TF coil modules.

Table 3. IGNITEX TF coil circuit resistive energy distribution

Circuit Element	Loss Mechanism	Estimated Loss (MJ)
1) Rotor slip ring	Resistive	45.2
2) Brushes	Friction	8.5
	Voltage drop	375
	Resistive	1.6
3) HPG internal Bus	Resistive	111
4) TF Coil Bus (LN cooled)	Resistive	180
5) TF Coil	Resistive/Inductive	710
Total Energy Required		1.5 GJ

Composite Flywheel Energy Storage

Even though the steel rotor of the iron-core portion of the IGNITEX HPG module represents a relatively large inertia spinning at a peripheral velocity of 160 m/s, it only stores about 100 MJ of kinetic energy. Providing the required 1.5 GJ energy storage would therefore require an unrealistically large steel rotor. Fiber reinforced, epoxy-composite rotors, however, can operate at higher tip speeds and much higher specific energies.[5] The 4 m diameter S-Glass epoxy flywheel designed for the machine stores 1.4 GJ and weighs only 50% more than the steel rotor.

The flywheel will consist of a set of nested cylinders, each one fabricated by winding wet filament S-glass fiber onto a steel mandrel. Assembly of the rings is accomplished with interference fits to induce initial radial prestressing of the flywheel. This is important to insure that spin induced radial

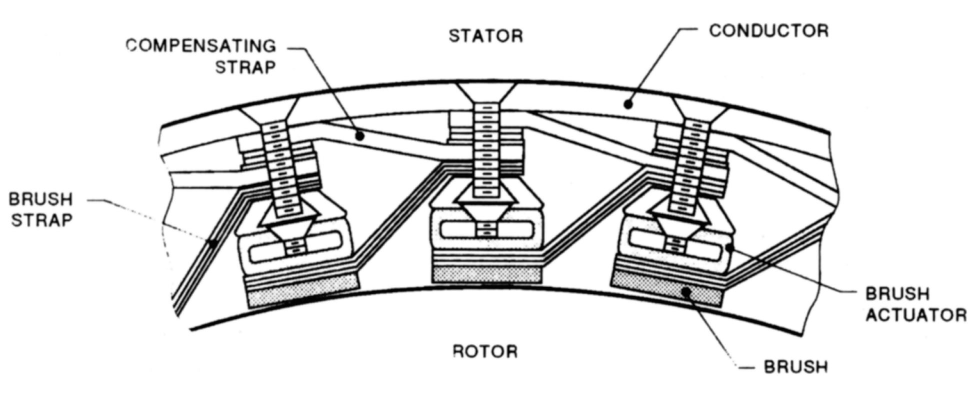

Figure 3. HPG brush mechanism design

stresses do not result in delamination of the composite material. The flywheel is mounted onto a stainless steel shaft with two titanium support ribs. Design of the ribs allows the flywheel to grow radially in a uniform fashion as it is spun up without creating high radial interface stresses.

As the discharge proceeds and energy is extracted from the rotor, it decelerates quickly. Discharge current flow in the rotor slip ring interacts with the excitation field and produces a torque which retards rotor forward motion. The iron rotor beneath the slip ring is decelerated by friction between it and the slip ring, but torque-to-composite flywheel must be transferred across the interfaces between the iron rotor and the flywheel shaft. The present design uses a face spline coupling to effect this torque transfer, which will be as high as 3.87 MN-m at peak current.

TF Coil Power Supply Control and Switching

Each of the 12 TF coil power supply modules will have a dedicated controller to handle sequencing and monitoring during operation. Overall power supply control will be accomplished by a master controller to which each of the individual controllers report and receive instructions. This control strategy has worked very well at CEM-UT for the six machine Balcones HPG power supply.[6]

Initially, the HPG rotors are motored to the desired speed (energy). Speed matching between the 12 HPG rotors is required by the controller prior to proceeding. Once the rotor speeds of the individual modules are properly synchronized, the HPG excitation fields are energized. Discharge of the machines is begun by actuating the brushes onto the rotor and closing the switches in the the TF coil sector circuits simultaneously. The HPG excitation is initially maximum to provide sufficient voltage to drive the circuit current to the flat top value of 12.5 MA per module. At that time, the excitation is sharply lowered to drop HPG voltage to the sum of circuit resistive drops. As the rotor energy is extracted and the circuit components become more resistive due to Joule heating, the HPG excitation is raised to compensate and maintain the desired flat top pulse shape. Finally, the excitation is reduced to ramp the TF coil current to zero as the experiment is shut down. Current in each TF coil circuit is continuously monitored during the entire experiment to insure it follows a predetermined pulse shape. This type of HPG output current control has been experimentally demonstrated previously at CEM-UT using a 10-MJ machine.[7] The use of six generators in parallel to drive a single turn TF coil has been demonstrated at 1/16th scale and is reported in a companion paper at this meeting.[8]

Explosively driven closing switches were used in the 1/16 scale TF coil demonstration due to the short rise time of the current (90 ms). These switches provide very fast closing times and jitters on the order of 10 μs. For the full scale IGNITEX system, where rise to full current occurs in 3 s, mechanical closing switches seem to be more appropriate. Jitter times of a few milliseconcd are common for these switches, which have been used extensively with pulsed HPGs for the last 15 years.[9,10]

PF Power Supply Operation

Poloidal field power supplies are controlled with HPG excitation in the same manner as the TF generators. However, each PF coil circuit is purposely underdamped to allow the currents to swing from a positive to negative peak during the experiment. Good coupling of the PF coils with the plasma and the use of underdamped HPG power circuits provides a very efficient plasma current induction system.

Shown in Figure 4, operation of these machines begins by discharging the full HPG rotor energy into the PF coils over 3 s. Plasma breakdown is then produced and the TF coil current is ramped up. Plasma current is induced as the magnetic energy stored in the PF coils is transferred back into the HPG rotors, causing them to accelerate in the opposite direction. This inductive-capacitive "ringing" is allowed to complete one full period before the circuit is opened as the current passes through zero at t = 13 s. Again, the HPG excitation is used to control the pulse shape by altering the circuit time constant as needed.

HPG AUXILIARY SYSTEMS

One of the advantages of the pulsed HPG power supply proposed for IGNITEX is that all the energy for a discharge is stored in the rotating flywheels prior to the experiment. This means that grid power requirements for IGNITEX are extremely low compared with conventional tokamak power supply designs. Assuming a rotor spin-up time of 30 minutes, the average power required for the TF power supplies is 18 MW. Similarly, the PF power supplies (which store 3.5 GJ) will require 4 MW grid power for motoring.

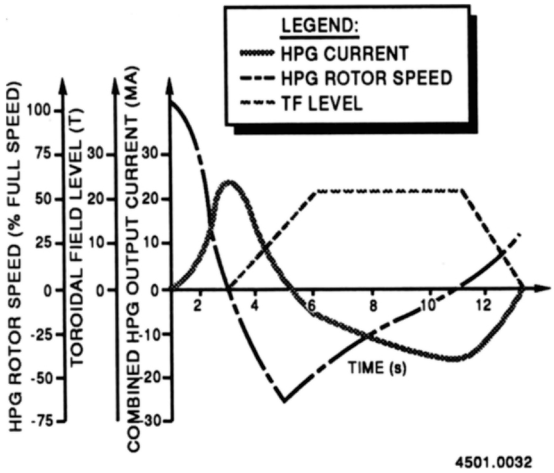

Figure 4. Operating cycle of rthe PF coil HPG circuits

Other auxiliary functions required to operate the HPG power supplies include bearing hydraulics, flywheel cavity vacuum, field coil power and cooling, brush slip ring cooling, and brush actuation systems. These systems will be very similar to the auxiliary systems designed and built for the Balcones HPG power supply at CEM-UT.[11] Grid power for these auxiliary functions is estimated to be 18 MW, so total power required will be only 40 MW.

HPG MAINTENANCE AND RELIABILITY

The reliability of pulsed HPG power supplies has been demonstrated and well documented [12] over the past 10 to 15 years. They can be characterized as robust machines requiring limited maintenance and good operational flexibility. Potential reliability problems with HPG power supplies are generally associated with auxiliary systems. Loss of bearing oil pressure, for example, can cause significant damage to the machine. Critical auxiliary functions are therefore monitored continuously and redundant systems are provided in the event a problem is sensed. Prior to and during spin up, any problem sensed with any of the generators will generally result in a system-wide shutdown. Once a discharge has begun, the options available for shutdown are more limited. In these situations, current flow in the HPG/magnet circuits must be brought to zero. This can be accomplished by reducing HPG field current to zero, or by switching a high impedance load into the magnet circuit. These operational procedures will be defined as control guidelines are established.

Maintenance of pulsed HPGs primarily involves replacement of the sliding contacts as they wear. Based on wear rates for sintered copper-graphite brushes in pulsed HPGs[12], a set of brushes should require replacement after approximately 500 full-energy discharges. Given the proposed operating schedule for the IGNITEX experiment, the generators would be re-brushed once or twice per year. Research into reduced wear brushes[13] is currently ongoing and can be incorporated as made available to extend the period between brush replacements. Bearing seal replacement and routine inspections would also be performed coincidentally with brush replacements.

POWER SUPPLY COST

Cost estimates for the IGNITEX power supply have been made and are based on final costs of the 9 MA Balcones supply, composite flywheel development at ORNL and CEM-UT, and general experience obtained at CEM-UT in building and operating pulsed HPG facilities over the last 17 years. A prototype machine is planned and the costs involved with designing, fabricating, and testing it are not included in the cost estimate for the power supply. The technology demonstration generator project is described briefly below and would provide a completed design and most of the fabrication tooling necessary to build the required IGNITEX power supplies. All auxiliary and control systems are included, as is prime power for bringing the HPG rotors to speed prior to each discharge. Closing switches and HPG excitation field power supplies are likewise included in the cost estimate. A three-year period is allowed for fabrication and testing of the generators and the estimate provided in Table 4 is based on beginning work in fiscal year 1992.

IGNITEX HPG TECHNOLOGY DEMONSTRATION

The IGNITEX Technology Demonstration (ITD) Program has been established to verify the operation of the critical components. In order to

Table 4. Cost estimate for the IGNITEX HPG power supplies

Item	Units	Cost Each (* Million)	Total (* Million)
1) TF Coil HPGs	12	$2.7	$32.4
2) TF HPG controller	1	1	1.0
3) TF switches	12	0.07	0.84
4) PF coil HPGs	4	1.8	7.1
5) Elong. coil HPG	1	0.43	0.43
6) PF switches	5	0.07	0.35
7) Transporation	NA	NA	0.24
8) Contingency	NA	NA	15%
TOTAL COST			$48.75 M

demonstrate the HPG power supply technology necessary for IGNITEX, the design and fabrication of one TF coil module has been proposed. An 18 month effort at a cost of about $6M USD is anticipated for building and testing the device.[2] If begun in 1991, the machine could be built and tested in time to begin production of the power supply modules for IGNITEX in FY 1992. Once completed, the HPG demonstration will provide further technical support to the feasibility of a simple and low cost ignition experiment and provide the power supply design, fabrication tooling, and operating experience needed to carry out that experiment.

CONCLUSIONS

Study of controlled, ignited thermonuclear plasmas is essential to making fusion power a viable energy source in the future. Tokamak confinement and ohmic heating are the most advanced technologies in this area and are therefore a logical choice for demonstrating the ability to produce (and allow the study of) ignited plasmas. Single-turn magnets and HPG power supplies provide the opportunity to use the experience base in tokamak confinement and scaling to achieve ohmic ignition in a compact, low cost experiment.

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