

Multimegawatt solid state rf driver for generating rotating magnetic fields

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A radio frequency (rf) system using solid state switching has been designed and constructed that is capable of driving a pair of loop antenna with a circulating power of 60 MW for millisecond pulses. The primary application of this system is to produce an oscillating magnetic field in the frequency range of 0.2–0.7 MHz, to generate and sustain a large plasma current. The maximum power transfer from the rf source was measured to be greater than 10 MW. The driver consisted of 12 insulated gate bipolar transistor modules driven in parallel, and was capable of switching 20 kA at 1700 V. A sinusoidal current waveform with large circulating currents was obtained on the antenna by incorporating the antenna in a high Q (60), parallel LCR resonant circuit. The low impedance switch driver was matched to the antenna load through a 20:1 step-up air core transformer with a coupling efficiency of 99%. © 2000 American Institute of Physics. [S0034-6748(00)01908-0]

In the field of experimental plasma physics, there are several occasions when one finds it necessary to produce high power rf fields. The need could be based on the desire to either heat the plasma, as in fusion plasmas,¹ or to produce and sustain a high density or large scale discharge.² Another application, one that has recently been under investigation at our laboratory, is the generation and sustainment of the magnetic configuration known as the field reversed configuration (FRC)³ with a rotating magnetic field.

The FRC has a closed-field toroidal confinement geometry where the confining poloidal magnetic field is produced solely by toroidal plasma currents. The simple and compact nature of the equilibrium imbues the FRC with great potential to be used as a space propulsive device and power source. However, since there is no transformer threading the core of the FRC, the configuration has only been produced at fusion relevant conditions by inducing the plasma current with a rapid reversal of the axial magnetic field, thus leaving no easy way to sustain the current. A method to directly drive a toroidal current that has been investigated for several years, employs a rotating magnetic field embedded in the plasma which generates a large electron current in the direction of the rotation.^{4,5} In these experiments, it was demonstrated that under the proper conditions of rotation frequency and plasma collisionality, the electrons became magnetized to the rotating field while the ions did not. Current was driven as long as the rotation frequency ω lies between the ion and electron cyclotron frequencies, i.e., $\omega_{ci} < \omega < \omega_{ce}$. This condition prescribes fields on the order of 50 G and frequencies where $\omega \sim 10^6$ for hydrogenic plasmas. The magnetic field rotation is produced by two pairs of loop antennas whose axes are at 90°, and where each pair has equal, sinusoidally oscillating currents that are separated by 90° in phase as well (see Fig. 1). For meter length antennas and plasma chamber sizes, the field magnitude requirement results in antenna circulating currents $I_c \sim 10$ kA. For frequen-

cies in the range of several hundred kilohertz, the antenna impedance is on the order of a few ohms, so that the circulating power required can be several hundred megawatts. These power levels could not be achieved in previous experiments, which led to small experiments where the plasma diameters were only a few centimeters, and the driven currents produced axial confining fields comparable to the rotating field (~ 100 G or less). Even then, the large circulating power level (≤ 10 MW) could only be achieved with pulsed power in the form of ringing capacitor discharges.⁴ Circuitry in these experiments allowed for the current to oscillate for 10–20 cycles before becoming too small to drive current.⁶ The rotating field, and hence the plasma currents, could be sustained for only a very short time. With the use of high power rf tubes, discharges could be sustained for several milliseconds, but the low antenna power produced only a cold, partially ionized plasma.⁷

A solution to this problem that did not require a large array of high power rf tubes and the associated driver cir-

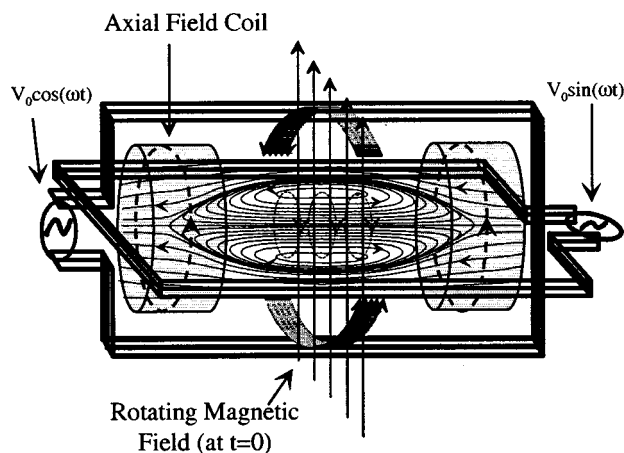


FIG. 1. Field reversed configuration where the confining toroidal plasma current is driven by a rotating magnetic field. The plasma current is driven opposite that of the current in the external axial field coils in order to produce the field reversal.

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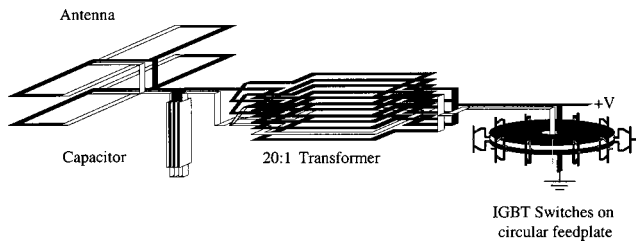


FIG. 2. Experimental layout of the rf antenna, transformer, and IGBT driver.

cuitry was found by employing fast insulated-gate bipolar transistor (IGBT) switches (Semikron SKM 400 GA 173 D) in a high Q , tuned circuit. A sketch of the physical layout for the rf driver and the coil loops that form the vertical field antenna is found in Fig. 2. The circuit schematic is shown in Fig. 3 with the circuit element values given in Table I. With a simple switch being used to drive the circuit, a very low impedance load can be driven. Since it is a large antenna current (larger B_ω) that is needed, the switch is an ideal source. To achieve an even lower antenna impedance, the antenna was subdivided into four parallel loops with a total inductance, L_A , of $0.67 \mu\text{H}$. With the nominal oscillating frequency of $2 \times 10^6 \text{ rad/s}$, the antenna impedance Z_A was 1.3Ω .

For a single IGBT in steady state, the device is capable of switching 400 \AA at 1700 V up to frequencies of 40 kHz . The rise and fall times for the device however are 120 and 50 ns , respectively, so that the device is capable of operating at much higher frequency at the cost of increased internal switch heating. For a pulse train length on the order of 1 ms , which was sufficient for the experiment, it was found that many of the continuous wave operating parameters of the IGBT could be greatly exceeded. Specifically, it was found that the switched current could be as large as 3 kA , and that the switching frequency could be as high as $4 \times 10^6 \text{ rad/s}$. These were not necessarily the limits of the IGBT for pulsed operation as there was no indication of failure under these conditions. The driver requirements for the IGBT were quite modest. The gate voltage required to switch 2 kA at 1700 V was only 20 V .

To produce the 50 G field over the 2 m length of the 40 cm diameter quartz vacuum chamber required a total circulating current, I_A , of 10 kA . Given the antenna impedance, the antenna voltage V_A of 13 kV was provided by a $20:1$

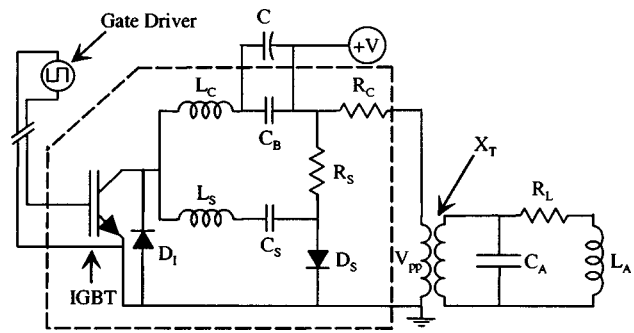


FIG. 3. Circuit diagram for the rf system depicted in Fig. 2. Elements inside the dashed area represent 12 identical units in parallel. Element values can be found in Table I.

step-up transformer between the IGBTs and the antenna. In order to produce the sinusoidally varying waveform on the antenna from a switch, a capacitance was added in parallel to the antenna and the antenna was driven as a parallel LCR circuit at resonance, where R is the sum of the antenna vacuum resistance and plasma resistance. At almost any significant Q of a LCR circuit, only for the resonant harmonic component of the switches' square wave drive is there any significant load impedance, so that the circulating current in the antenna I_A was sinusoidal (see Fig. 4). At resonance, the antenna impedance is purely real, and R_p , the resistance as seen by the IGBTs, is given by $R_p = \cdot QZ_A/N^2$, where N is the transformer turns ratio. The primary current I_p that must be switched by the IGBTs then is given by $I_p = 2I_cN/Q$, since Q is just the ratio of reactive to resistive impedance. The factor of two is due to the fact that the switch can only transfer power during the half period that it is closed. Thus, the current in the primary oscillates between 0 and I_p , which corresponds to the circulating current oscillating between $\pm I_c$.

Clearly a high Q circuit is advantageous in minimizing the primary current. If the vacuum resistance can be kept small compared to the plasma resistance then the only loading, and thus power flow, will be into the plasma. In the absence of plasma, the main losses are resistive losses in the capacitor and connections. To this end, high Q , high current capacitors were constructed inexpensively out of aluminum foil and polyethylene sheets. The sheets were rolled up and placed in PVC pipe filled with food grade mineral oil to

TABLE I. Values for the circuit elements displayed in Fig. 3. The values for elements marked with an asterisk are the net values for 12 components in parallel.

Element	Value	Element	Value
Antenna capacitance, C_A	$0.35 \mu\text{F}$	Antenna inductance, L_A	$0.67 \mu\text{H}$
Air core transformer, X_T		IGBT (12 in parallel)	
Turns ratio	20-1	Internal inductance*	1.7 nH
Primary inductance	$1.5 \mu\text{H}$	Internal resistance* (on)	$1 \text{ m}\Omega$
Stray inductance	15 nH	Duty cycle	40%
Charge supply capacitance, C^*	12 mF	Circuit stray inductance, L_C^*	6 nH
Charge supply voltage, $+V$	800 V	Primary voltage swing, V_{pp}	1300 V
Bypass capacitance, C_B^*	$36 \mu\text{F}$	Circuit resistance, R_C^*	$8 \text{ m}\Omega$
Snubber capacitance, C_S^*	$18 \mu\text{F}$	Snubber stray inductance, L_S^*	3 nH
Snubber resistance, R_S^*	0.33Ω	Load resistance, R_L	$25 \text{ m}\Omega$

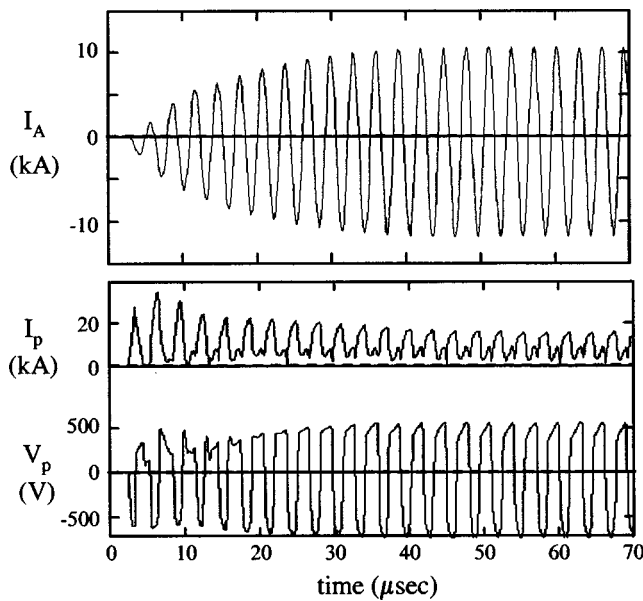


FIG. 4. Experimental traces during the initial ramp up of antenna current. From the top down, I_A is the total circulating current, I_p is the current flow in the transformer primary, and V_p is the voltage across the transformer primary. The initial supply charging voltage was 800 V.

avoid flash over at the higher voltages. From previous experiments it was found that with these materials, a Q of several hundred could be produced. Five of these capacitors, each with roughly 70 nF of capacitance, were connected in parallel to form the antenna C_A . The antenna itself was constructed of copper strip 6 cm wide and 0.25 mm thick. For the frequencies of interest, the thickness of the strip is over two skin depths. All connections were soldered to minimize contact resistance. With no structures near the antenna, a Q of 100 was measured. With the antenna placed on the experiment with magnet coils, cables, pumps, etc. nearby, the dissipative coupling dropped the Q to 60. This vacuum Q however was sufficient, since the Q with plasma loading was typically 20–30, so most of the power was delivered to the plasma.

From the previous discussion, to maintain I_A at 10 kA with a loaded Q of 20, the required primary current I_p \sim 20 kA. In order to provide this current, 12 IGBTs were driven in parallel. Paralleling the IGBTs also had the added benefit of reducing the switching resistance, as well as any stray inductance associated with the IGBT. Very low stray inductance on the primary side of the transformer was essential. At the lowest Q of 20, the load as seen looking into the primary was only 65 m Ω . At the frequency of interest, one can associate 2 m Ω of impedance of every nanohenry of inductance. By attaching the IGBTs and electrolytic capacitors to parallel circular feed plates the total stray inductance was estimated to be 6 nH. The circular arrangement of the circuit elements assured uniform current sharing among the 12 IGBTs. All connections between feedplates, transformers, and antenna components were accomplished using stripline, so that the only significant stray inductance was that associated with the transformer coupling.

To maintain the antenna voltage at lower Q , the transformer stray inductance had to be very small. At the same

time the transformer primary impedance needed to be large enough to keep the magnetization current small compared to the driven current. These two conditions can only be satisfied by a transformer with a very high coupling coefficient and the minimum primary inductance. Experimentally, these two conditions were met by constructing an air core transformer with a coupling coefficient of roughly 99%. The transformer stray inductance was determined to be only \sim 15 nH, with a primary winding inductance of 1.5 μ H (3 Ω), which limited the magnetization current to a few percent of the total primary current.

To achieve the high coupling coefficient, the transformer was constructed in the following manner. The primary winding was effectively a single turn loop. It consisted however of a stack of 21 rectangular loops made of copper strip 10 cm wide and 0.25 mm thick all connected in parallel. Interleaved between these loops were 20 identical secondary loops connected in series (see Fig. 2 where four of the windings are shown). The primary and secondary loops were separated by polyethylene sheets 1.5 mm thick. The insulating thickness was made much greater than needed for voltage hold off in order to minimize the capacitive coupling between the primary and secondary turns. By paralleling all of the primary turns the flux through all of them was held constant. By interleaving a secondary turn between two primaries, with only a narrow gap between the strips, the flux through each secondary winding was forced to be the same as well. The transformer stack height of 8 cm was much smaller than the cross-sectional dimensions (\sim 0.5 m) so that the inductance of the transformer was more like that of loop than a solenoid.

The startup phase of the rf antenna to an operating current of 10 kA is shown in Fig. 4. During startup, the largest primary current is observed as the LCR tank is initially being charged. The maximum power transfer to the load (\sim 15 MW) was observed at this time. Circuit calculations were made based on the values for the various components measured in the experiment. The circuit parameters are given in Table I, and the results of calculations for the same startup conditions as the experiment reproduced the waveforms shown in Fig. 4. In order to reduce the inductive spike that is produced when the IGBT switch is opened, a RCD snubber was employed across each IGBT module. The RCD snubber provides for current flow during switch turn off, and discharges the accumulated charge through the primary winding during switch closure. The voltage ring up of the snubber capacitor had the effect of increasing the switching voltage to almost double that of the initial charge voltage on the storage capacitors. This allowed for the energy storage bank to be operated at no more than 900 V (two sets of 450 V electrolytic capacitors in series), and still produce circuit voltages near the IGBT maximum. In order to suppress the switch turn-off spike, a resistor–diode pair was added in series with the IGBT gate, which slowed the switch turn off without effecting the turn on. The combination of the snubber and gate delay produced a switch waveform that looked somewhat more sinusoidal than square wave (see Fig. 4) and minimized the power loss into the nonresonant harmonic components. In addition, it was found that by operating the switch with a 40% duty cycle, the steady harmonic compo-

ment of the primary current could be kept small (see Fig. 4), with only a small decrease in driven resonant current.

The circuit elements given above were arrived at after optimization by operating a smaller number of IGBTs to failure. It was found that when operating these devices well beyond their rated steady operating currents, the main failure was an overvoltage of the internal bypass diode (D_1 in Fig. 3) from the large voltage spike due to the high dI/dt during IGBT turn off. No external snubbing was effective in this case since the origin of the voltage was the internal IGBT connection inductance ($V_{\text{spike}} \sim L_{\text{int}} dI/dt$). A finite external gate resistance however reduced the rate at which the current in the IGBT could be turned off, and this reduced the voltage transient. It was accomplished however, at the price of increasing the power dissipation during the switching. The slower IGBT turn-off time meant that the device spent a longer time in transition from on to off. Since the switch resistance is much higher during this transition, the dissipation was roughly doubled for an external gate resistance of 20Ω compared to no external resistance. The slower turn off allowed the IGBT device to operate at up to ten times the rated steady current (~ 3 kA). The time period over which the switch could be operated at the higher dissipation level was never determined since the drop is stored capacitor en-

ergy limited the time that such large currents could be sustained to less than 0.5 ms.

During operation with 1 mTorr deuterium fill gas, the presence of the plasma reduced the antenna inductance and increased the resonant frequency by as much as 5%. The frequency shift required to maintain resonance could be made in either of two ways. The simplest method was to change the drive frequency in time in a prescribed manner based on experiment. A more satisfying method was to detect the off-resonant phase shift between the LCR tank voltage, and the current flowing into the tank from the secondary of the transformer. The drive frequency could then be corrected by feedback of the phase shift to a voltage-controlled oscillator. This method is currently being tested.

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