AN OVERVIEW OF THE STAR THRUST EXPERIMENT

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Abstract

The Field Reversed Configuration, FRC, is a closed field fusion confinement geometry with great potential to be used as a space propulsive device and power source. Present formation techniques are cumbersome and severely constrain the resultant FRC. An experiment is presently under construction to study the formation and sustainment of the FRC using a rotating magnetic field. If successful, this technique would vastly simplify and enable future FRC endeavors. An overview of the STX experiment is presented.

INTRODUCTION

It is recognized that nuclear fusion could be an ideal source for space power and propulsion due to the high specific energy of its fuel, and the high specific impulse which is inherent in its exhaust products. However, most fusion confinement concepts are unsuited for space power production due to their large size and complexity, and are non-ideal for propulsion due to the use of D-T fuel which releases most of its energy in the form of high energy neutrons. A notable exception to these restraints is provided by the Field Reversed Configuration (FRC) which is a simple elongated current ring confined in a modest field solenoidal magnet, as sketched in Figure 1. FRCs lack any significant toroidal field, which results in a compact high β plasma that is suitable for burning advanced aneutronic fuels. Synchrotron radiation would limit ignition of high temperature aneutronic fuels in the low β environment of most confinement geometries. The linear geometry and magnetic separatrix are a natural attribute for propulsive applications. Despite apparent experimental robustness, the stability of FRCs is uncertain due to a lack of magnetic shear, but kinetic effects have been demonstrated to stabilize FRCs up to at least modest sizes in the recently completed LSX experiments (Hoffman 1993), and recent theory points the way to maintaining stability at reactor relevant sizes (Steinhauer 1994).

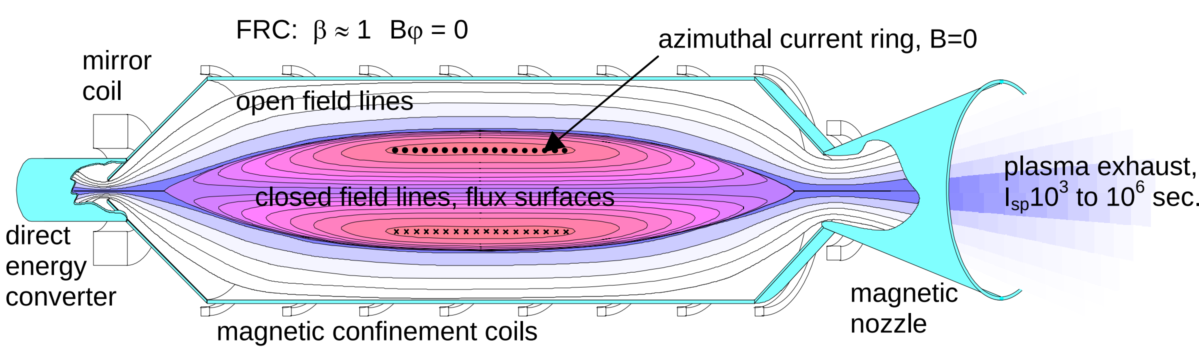

FIGURE 1. FRC as Power Source and Ion Engine for High Energy Space Missions.

The near ideal reactor attributes of the FRC has led the DOE to fund an extension of the LSX program, TCS (Translation Confinement & Sustainment), designed to reach ever larger sizes for investigating confinement and stability limits. An important aspect of that program is the application of a rotating magnetic field (RMF) to both enlarge and sustain the plasma. The RMF is a uniform rotating field that is always transverse to the axis of symmetry, as shown on Figure 2. It has been demonstrated to form and sustain small cold FRCs in Australian Rotomak experiments (Jones 1990), but has never been applied at the power levels needed to overcome initially high plasma energy loss rates. In TCS this start-up problem will be circumvented by using the standard Field Reversed Theta Pinch (FRTP) technique for making large, hot FRCs. FRTP startup technology is well developed, but is too bulky and heavy for space applications. In recognition of this, NASA is supporting a very high power, but short duration, RMF startup experiment called STX (Star Thrust Experiment). STX will study the RMF formation and sustainment of hot (100s eV) mid-sized FRCs.

RMF THEORY

The RMF drives a strong azimuthal current which reverses the direction of the external magnetic field and produces the FRC configuration (Figure 2). Unlike FRTP formation, where this current is driven by an induced azimuthal voltage caused by a rapid reversal of the external field, the RMF current is driven in an inherently steady state manner which should allow for the subsequent sustainment of the configuration. A good starting point for understanding the current drive process is the generalized Ohm's Law:

$$\mathbf{E} = \eta\mathbf{j} + \mathbf{j}\times\mathbf{B}/ne = \eta[\mathbf{j} + (\omega_{ce}/\nu_{ei})\mathbf{j}\times\mathbf{e_b}]. \quad (1)$$

If the Hall term $\mathbf{j}\times\mathbf{B}/ne$ is negligible, the electrons are unmagnetized, $E_\theta = \eta j_\theta$ is positive, and from Faraday's law, $d\phi/dt$ is negative. This means flux is leaving the FRC (less field reversal) and it is decaying. With the Hall term included, E_θ**,** for sufficiently small η or large j_zB_r, can be negative. The axial current is driven by an induced axial electric field, and the Hall term has the opposite sign of ηj_θ. When E_θ is negative, $d\phi/dt$ is positive, flux is entering the FRC, and it is growing (more field reversal). In the fluid picture, the RMF, when fully penetrated, creates an oscillatory $E_z = \omega rB_r$ which drives j_z such that $\langle j_zB_r\rangle$ reverse the ohmic ηj_θ. In the particle picture, the electrons appear to be tied to the RMF and rotate co-synchronously with it, while the ions remain at rest.

The first requirement on the RMF, as has been mentioned above, is that the electrons be magnetized while the ions are not.

$$\nu_{ei} << \omega_{ce} \qquad \omega_{ci} < \omega_{RMF} < \omega_{ce} \quad (2a,b)$$

This requirement is obvious from the extended form of Equation (1), where the Hall term is given in terms of ω_{ce}/ν_{ei}. $\omega_{ce} = eB_{RMF}/m_e$ and $\omega_{ci} = eB_{RMF}/m_I$ are the electron and ion gyro-frequencies with respect to the rotating field. Equation 2a is satisfied as one increases B_{RMF} and T_e while decreasing n ($\nu_{ei} \propto .n/T_e^{3/2}$). However, according to Equation 2b, increasing B_{RMF} forces one to select a higher ω_{RMF}. Even if the ions are not magnetized, it is also necessary that the electrons do not transfer their momentum to the ions over a long time scale. Two-fluid calculations show this is easy to achieve with even minimal fueling rates since the fuel ions are deposited with zero angular momentum, and they diffuse out much faster then they gain momentum from collisions with the electrons (Ohnishi 1996).

The second requirement on the RMF is that it penetrate the plasma. The RMF skin depth should be on the order of the FRC's radius. The solution of Ohm's law, neglecting the Hall term, is characterized by the RMF penetrating a distance $\delta = (2\eta/\omega\mu_o)^{1/2}$, which is the usual skin depth for a conductor in an RF field. The regime of interest, however, occurs for a hot low resistivity plasma, with $\nu_{ei} << \omega_{ce}$. In this regime, the Hall term dominates and the solution to Ohm's law yields $j_\theta \approx ner\omega$ and $j_z \approx E_z/(\eta\omega_{ce}^2/2\nu_{ei}^2)$, which states that the electrons are in synchronous rotation with the RMF and their axial oscillation is severely restricted. This suggests an effective resistivity of $\eta_{eff} = \eta\omega_{ce}^2/2\nu_{ei}^2$, and an effective skin depth of $\delta_{eff} = (\omega_{ce}/\nu_{ei})\delta$. The RMF has better penetration as η decreases and the plasma becomes more conductive. In the electron frame of reference, it is only collisions that knock electrons off the RMF and cause them to see an oscillatory field which they then tend to screen. As long as the electrons remain in co-synchronous rotation, they see no oscillatory field. STX, operating at B_{RMF}=.01T, T_e=100eV, n=10^{20}/m^3, and $\omega=\pi\times10^6$rad/sec, will have δ~2mm, δ_{eff}~1m, ν_{ei}~3x10^6rad/sec, and ω_{ci} ~ 5x10^5rad/sec < ω_{RMF} < ω_{ce} ~ 2x10^9rad/sec.

STX APPARATUS

The STX device is built around a 3-m long, 40-cm diameter quartz plasma tube surrounded by solenoidal coils to provide an axial confinement field. Special single turn antennas, described below, produce the rotating magnetic field.

RMF Antennas

Using the above theoretical constraints and some practical considerations regarding maximum attainable output powers for the RMF power supplies, RMF parameters of 0.5 MHz, 0.01 T amplitude, and ~ 200 μsec duration have been selected. The RMF will be generated by two mutually perpendicular coils running the length of the experiment and driven 90 degrees out of phase. (Figure 2) To satisfy field uniformity constraints, each antenna coil is separated into 2 parallel coils, where the coil separation is set by a Helmholtz minimization to be R when the wires are at radius R from the axis of the machine. The antennas are placed outside the confinement coils, at R = 0.36 m, for flexibility and ease of assembly. The large radius provides for great field uniformity inside the 0.2-m plasma tube radius, but requires a larger circulating power on the RMF antenna to create a given B_{RMF}. A cross section of STX, showing the RMF direction and amplitude as well as antenna azimuthal and radial placement, is shown in Figure 3.

Two different antennas have been constructed for use with two different RMF power supplies. About a 10 kA current is needed to produce the 0.01 T RMF. 0.6-m wide by 2-m long antennas, with inductances of 2 μH, will be driven at ±40 kV by an LC tank circuit. To reduce their inductance to 0.5 μH, the second set of antennas are divided into two 1-m long coils driven in parallel by an IGBT power supply at ±20 kV.

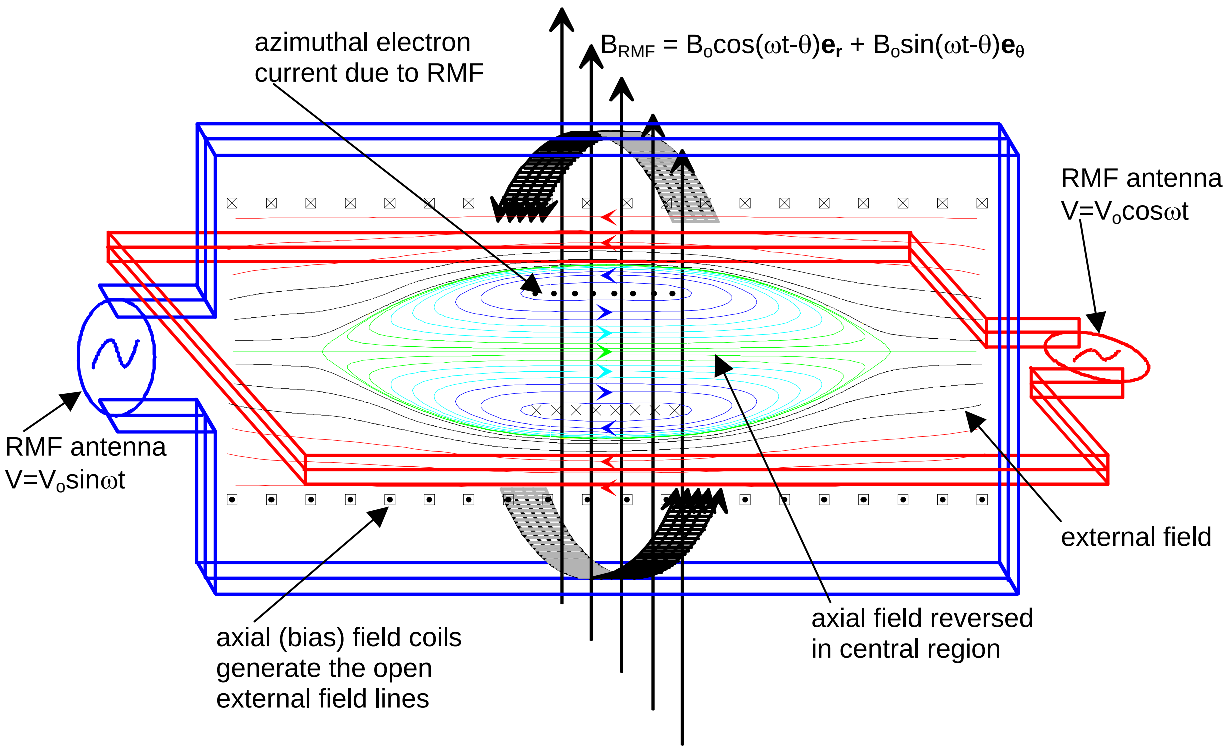

FIGURE 2. Schematic of The RMF, RMF Antenna, Axial Field Coils, and FRC Field Geometry.

RMF Power Supplies

The key components of this experiment are the power supplies used to generate the RMF. In order to drive the RMF antennas, the 2 power supplies must be capable of delivering tens of megawatts for the duration of the experiment, as well as attain peak power outputs in the hundreds of megawatts for the tens of microseconds necessary to rapidly ionize the plasma and heat it past the radiation barrier. The initial approach was to construct 2 high Q tank circuits with an initial circulating power of several GWs. A small fraction of this power would be tapped out to drive the RMF antenna. Since the power required for the RMF scales as $T_e^{-9/2}$, the LC tank exponential decay characteristics are well suited to delivering the initially high required power to a cold plasma, and then a steadily reducing power as the plasma warms. The LC tank is constrained by $\omega = (LC)^{-1/2}$, $E_{stored} = .5CV^2$, and $Q = \omega L/R$, where the Q requirement turns out to be the most restrictive. It is the value of Q that determines the duration of the RMF. Maximizing Q for a given ω and minimum realistic R leads one to select a large L. This in turn forces the use of a small C, which in turn drives one to a high voltage in order to maximize the energy available to the experiment. L, C, and Q were selected based on a maximum ±100 kV voltage. One tank has been constructed with a Q of 300, and is presently being debugged. The tank was static charged in oil, but the polypropylene insulation in the capacitor, rated at 3500 V/mil was being physically cracked as the oil surrounding the parallel copper plates broke down at 750 V/mil and allowed current to track along the insulating dielectric surface. We hope to resolve this problem by replacing the oil with propylene glycol, resistivity = $2x10^6$ ohm-cm, and thus grade the potential parallel to the dielectric surface. The extent to which the potential can be graded, i.e. the minimum usable resistivity, is set by the high Q requirement. The effective resistive short to ground must remain large when compared to the impedance of the tank.

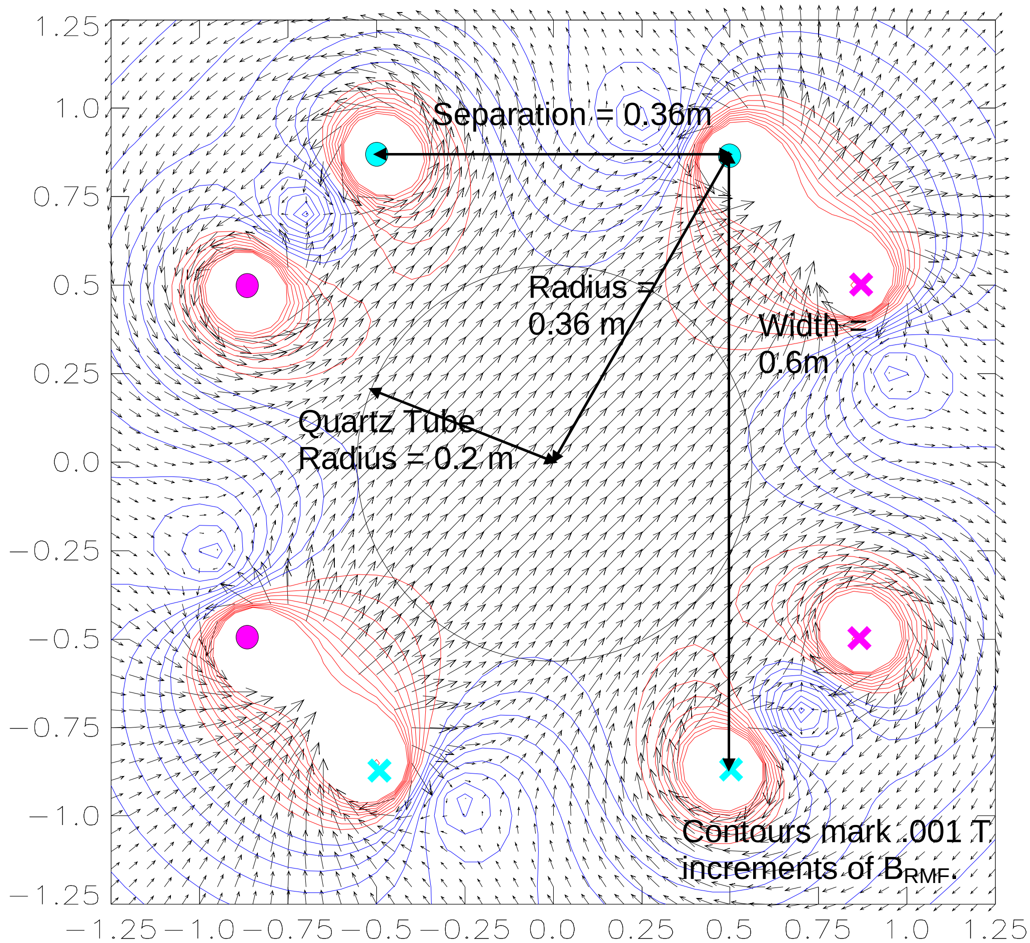

FIGURE 3. A Cross Section of the RMF and Antenna. Crosses and Dots Locate the Antenna Current.

A second very promising approach is also being pursued. Since work began on the high Q tank circuits, IGBTs (very high current on-off solid state switches) have become available that can each switch 3000 A at 1500 V at 0.5 MHz for a several hundred microsecond pulse. Two power supplies are presently under construction that will each use twelve IGBT's in parallel. Figure 4 shows the circuit schematic. The IGBT output will pass through a 20:1 air core transformer and into a parallel LC tank circuit (Q~100), where the inductor is the RMF antenna. By presenting a high impedance only to its resonant frequency, the tank circuit transforms the output waveform of the IGBT's into a clean sinusoid. Additionally, the tank circuits high Q greatly amplifies the real power delivered with circulating power, enabling the creation of a .01T RMF. With a low total inductance of ~20nH in the primary side of the circuit, as the plasma load increases, the IGBT's should be able to provide the current necessary to sustain the secondary voltage, and hence maintain a constant RMF. For tens of microseconds, the maximum current output of 3000A can be exceeded by a factor of 5 to 10. The peak output power may not be as high from the IGBTs as from the LC tank, but they have the advantage of both a longer quasi-steady duration, and an easily variable frequency for experimentation.

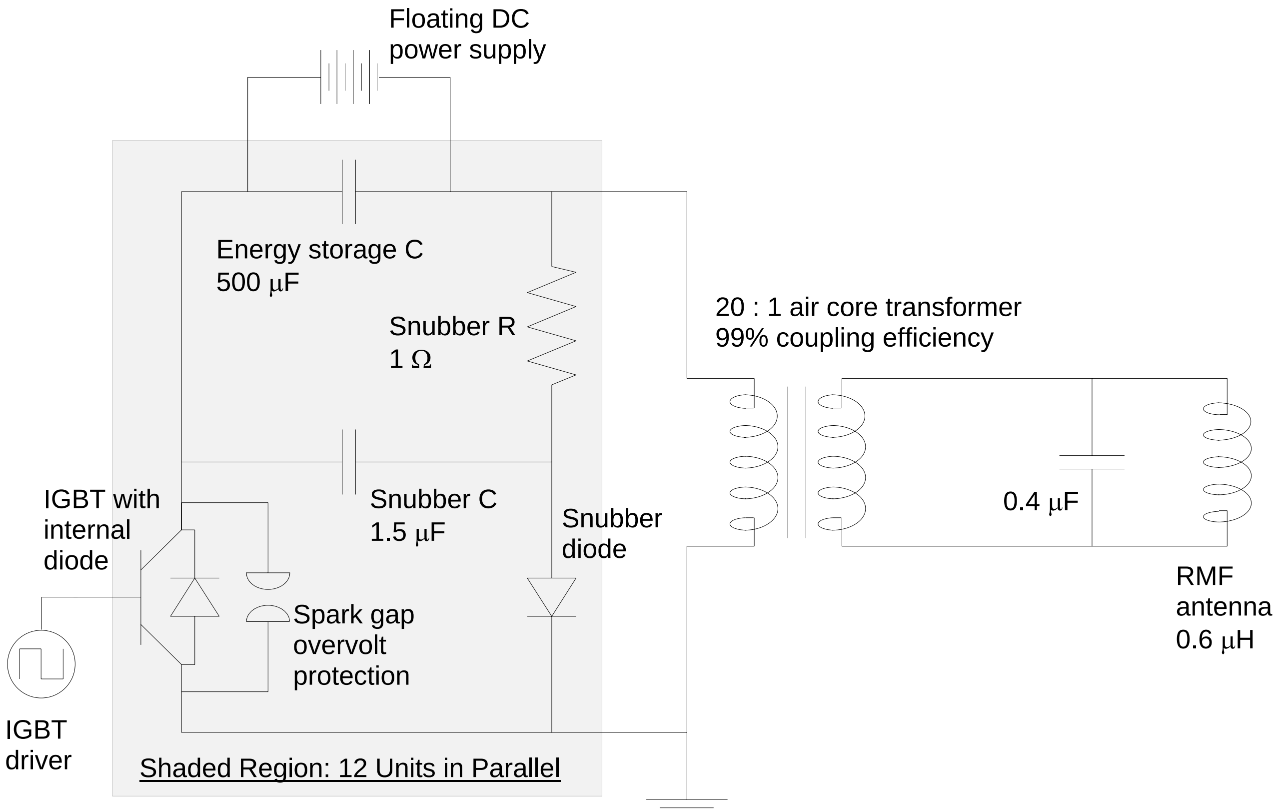

FIGURE 4. IGBT Power Supply, Transformer, and RMF Parallel Resonant Circuit.

Vacuum System

The STX vacuum chamber consists of a 40-cm diameter by 3-m long quartz tube. Attached to one end is a gas fill system with plenum and capacitive manometer, a 50 liter/sec turbo pump, a 3000 liter/sec cryo pump, and ion, cold cathode, and RGA gauges. Expected base pressures are in the mid 10^{-9} Torr range, which is important for minimizing radiation losses during startup.

Control System

High speed data acquisition will be done with multiplexed 8-channel DSP digitizers operating in Camac crates. Data will be stored in an MDS data base and analyzed using IDL. All of the low speed system control (isolation relays, power supplies, capacitor charging, vacuum system operation, etc) will be done with a Group3 ControlNet data acquisition system operating on LabView NT. This is a system explicitly designed to operate in a pulsed power environment. It utilizes fiberoptic isolation, signal conditioning and error detection and correction software.

Magnet System

Fifty-six single turn epoxy coated magnets spaced 0.05 m apart run the length of the experiment. The central 48 will be jumpered together to create 12 parallel, 4-turn magnets that will be used to produce a 0.2 T bias field. The next 4 epoxy coated magnets, two on each side, will create a mirror field to prevent the FRC from drifting axially out the end of the experiment. The final 4 magnets may be used to create a cusp field at either end of the experiment. The cusp field would be part of an axial discharge system used to rapidly ionize and heat the plasma in case the RMF either did not have enough power, or acted too slowly. It is hoped that an axial discharge is not needed since such a discharge risks contaminating the plasma with electrode and wall impurities. Single turn magnets are jumpered together in order to provide flexibility in field rise times, magnitudes, and spatial extent. The jumpers connecting the magnets are fairly easy to move.

Heating system

In addition to the axial discharge heater mentioned above, an m=0, k=0 Alfven heater is being designed. This heater will connect directly to the bias magnets and it will add a 0.5 MHz 0.1T AC component to the DC bias field. Numeric simulations indicate that this should result in rapid ion heating due to the wave being heavily damped by the 2-D radial and axial FRC oscillations. The LC tanks described above are ideally suited to this job, and pending the success of the IGBT power supplies, the initially constructed tank will be used for this application. The Alfven heater will also be used as a crowbar on the bias magnets to turn them into a partial flux conserver. As the FRC grows, the bias field around the FRC will then increase in strength and radially confine a higher pressure plasma.

CONCLUSIONS

Construction of the STX vacuum system, bias magnets, and RMF antennas is complete. The LabView/Group3 control system hardware has been assembled, and programming has begun. The high speed data acquisition system and database already exist. Preliminary testing of the IGBTs has been done, and the final circuit is being assembled. Diagnostics under construction include an interferometer, tomographic array, Langmuir probe, excluded flux array, and internal **B**-dot probes. Full scale experimentation will begin in mid 1998.

Acknowledgments

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