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DEVELOPMENT OF A PLASMA STREAMING SYSTEM FOR THE MIRROR FUSION TEST FACILITY*

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Summary

The Plasma Streaming System (PSS) is an essential portion of the Mirror Fusion Test Facility (MFTF), scheduled for completion in October, 1981. The PSS will develop a plasma density of at least 2 x 10^{12} particles/cm^3 at the MFTF magnet centerline by injecting particles along the field lines. The plasma will have a midplane plasma radius as large as 40 cm with variable plasma particle energy and beam geometry. Minimum amounts of impurities will be injected, with emphasis on minimizing high Z materials. Each of the 60 PSS units will consist of a gun magnet assembly (GMA) and a power supply. Each GMA consists of a plasma streaming gun, a pulse magnet that provides variable beam shaping, and a fast reaction pulse gas valve.

The gun power supply consists of a pulse forming network at 900 V (capable of delivery up to 4000 A for 10 ms), a small capacitor bank, a 6-kV ionization pulse circuit, an SCR switching system, and a charging supply. The magnet power supply consists of a capacitor bank at 2400 V (capable of delivering up to 1750 A for 30 ms), an SCR switching system, and a charging supply. Cabling will be installed to all 100 ports on the MFTF vacuum vessel from a patch panel that will allow any 60 of the ports to be connected. All units will be operated either from a common computerized control system for routine operation or a local control and monitoring system for test and maintenance. System design and testing have resulted in an integrated GMA and power supply design, easily variable plasma output, high degree of operational flexibility, and an advanced test program.

The variable plasma output is achieved by altering particle energy by adjusting gun to magnet position and by changing power supply voltages, pulse widths, and relative timing between units. Operational flexibility is achieved through algorithm-derived control settings, closed loop control system, reporting by exception, and waveform analysis for preventive maintenance. The test program includes parametric sensitivity analysis, life testing for reliability and failure analysis, materials, geometry, and triggering system stability testing.

Role of the PSS

The role of the PSS on MFTF is to provide a sufficient target plasma to facilitate startup neutral beams interaction, which serves as the target for the sustaining neutral beams. Since the MFTF and the neutral beam systems are described in detail in other papers, we confine this paper to a system description of the PSS.

An array of 60 guns and supporting auxiliary subsystems are mounted on the end domes of the vacuum vessel (shown in Fig. 1) with a maximum of 50 guns on either end dome. Depending upon the selection of PSS operating mode and the ports of the gun mounts, a target plasma of varying density, temperature, and geometry can be generated at the MFTF midplane by plasma injection along the field lines in the plasma fans regions. An average plasma density of 1 x 10^{12} to 5 x 10^{13}/cm^3 can be provided; however, a strong correlation exists between gun lifetime and the high gun electron currents necessary to generate higher values of plasma density. For a particular operating array of guns, the average density is easily controlled by varying the gun voltage and/or the flow rate of gas through the gun. In addition, the granularity or spot size can be adjusted by varying the strength of a localized auxiliary magnetic field at the gun. The geometry of the target can be operationally varied by adjusting the plasma output of each gun between shots or by changing the gun mount ports during maintenance periods.

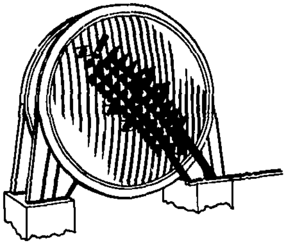

Fig. 1 End Dome Layout

System Description

The PSS (see Fig. 2) consists of 100 vacuum valves mounted on the vacuum vessel 6-in. end dome ports, 60 gun magnet assemblies mounted on the vacuum valves, 60 power supplies located in the high voltage areas, a control and monitor system in the low voltage area (LCIS and LCMS), a computerized operator and data analysis system (SCDS), and various cables, plumbing, etc.

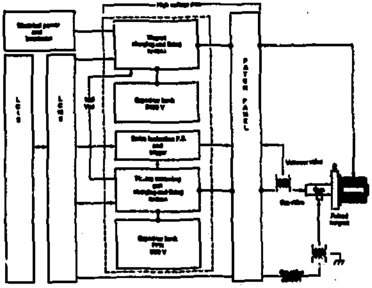

Fig. 2 Plasma Streaming System Block Diagram

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The PSS is designed and tested as an integral system design in that power supplies are designed for optimum GMA cost/benefit and vice versa. The GMA development test has been both extensive and performed with power supplies whose characteristics closely match final designs.

The entire system is self-protecting in that power supplies are incapable of damaging the GMA's unless there is a failure of a hardwire interlock specifically designed to prevent either failure or significantly accelerated wear. Two examples serve to illustrate unusual and nonobvious applications of this philosophy. By monitoring the value of magnet peak current (purely resistive), magnet voltage at peak current, and comparing the two values, a measure of inferred magnet resistance is obtained that correlates to magnet temperature. If the value of inferred resistance exceeds a fixed value, the magnet is too hot and the power supply for that GMA is hardwire-interlocked off. The operator is notified through the exceptions system; i.e., only exceptions to anticipated operational conditions are reported.

A second example of self-protection does not use an interlock system. The dynamic impedance of the gun varies over a wide range depending upon the operating mode; i.e., magnetic field values, gas flow rates and pressure, and gun current levels. The anticipated operational range of gun dynamic impedance is 40 to 200 mΩ. The current correlation to plasma density is a set of curves depending on the independent operational parameter being varied. A profile of desired current flow as a function of impedance is generated that, in turn, governs the ability of the power supply to deliver power. Consequently, neither hardware or software failures or operator errors can damage the gun.

System requirements specify that at least 50 units will be available at all times, but that all operational units will be used. The existence of the patch panel makes this requirement realizable without demanding unnecessarily high unit reliability. If a power supply feeding a GMA at a critical location fails, a power supply feeding a less critical GMA may be quickly substituted by the maintenance crew within minutes. The act of reconnecting the power supply automatically results in a change in the operator's list of power supply to GMA connections in a manner that precludes error.

Gun Magnet Assembly

Each of the 60 GMA's are capable of independent operation and may be easily mounted and any of the 100 precabled and preplumbed port locations. The GMA (see Fig. 3) consists of an array of subassemblies; each performs a specific task.

Fig. 3 Gun Magnet Assembly

The actual plasma is generated in the plasma gun stack subassembly (see Fig. 4). Either deuterium, hydrogen, or neon gas is inserted into an evacuated cavity defined by the inside diameters of the conductive and insulative washers, the anode ring, and the cathode.

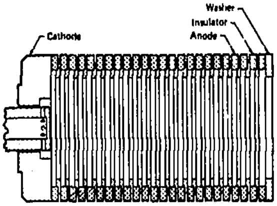


Fig. 4 Gun Stack Subassembly

When the gas reaches an appropriate geometry and density, a 6-kV, 2-μs-wide ionization potential is applied between the cathode and the anode. An arc progressively forms along the conductive washers such that the gas is ionized. As the ionizing arc forms, the dynamic impedance of the gun drops from near infinite to less than an ohm. The current through the gun is power supply-limited to less than 100 A to insure continued ionization without significant gun wear and minimal power supply cost. Current contribution from the energy storage unit rapidly grows to the operationally preselected value. The minimum sufficient values for ionization potential and current varies with the magnetic field strength, gas flow, and the degree of wear in the stack subassembly.

Extensive tests were conducted on the stack subassembly to evaluate wear vs operational conditions, material, and geometry. At a standard operating condition of 2500 A and 125 V for 10 ms applied to the stack, wear does progressively accumulate in a noncatastrophic manner over a thousand shot period. The molybdenum cathode looses material at an insignificant rate to be concerned about cathode integrety; however, the material deposits on the ceramic insulator washers in decreasing amounts the further the washers are from the cathode. A casual relationship exists between the degree of molybdenum deposition on the ceramic and the amount of molybdenum washer wear only on that washer surface that faces the cathode. However, GMA performance is surprisingly insensitive to stack wear to the extent that stack life is a meaningless term without a definition of performance.

Earlier tests centered around the use of copper instead of molybdenum. The copper wear was about an order of magnitude more severe than molybdenum; however, no catastrophic failures occurred and plasma was still generated with nearly half the copper washers erroded away.

Use of copper was terminated due to inferior life and excessive generation of contaminants into the plasma. Wear patterns are highly dependent upon operating conditions; consequently, an attempt to establish dominant wear mechanisms by deliberate over test met with failure. At higher stack current levels wear becomes dominate in the molybdenum washers nearest the anode instead of the cathode.

The magnet, gas injection system and vacuum barrier subassemblies are shown with respect to the stack subassembly in Fig. 5. The magnet is required to provide an adjustable 3 to 1/2 T field for 10 ms with a uniformity variation of less than 10 percent.

This field is necessary to ensure that excessive plasma beam impingement does not occur inside of the GMA and to shape beam geometry for optimum mapping into the MFTF guide field.

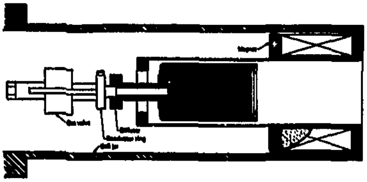


Fig. 5 Magnet, Gas Injection and Vacuum Barrier Subassemblies

The magnet and magnet power supply are examples of integrated system design where optimization factors included bank size, bank voltage, peak current, magnet winding, magnet cooling, transmission line, field waveshape, and switching system. The actual magnet consists of 352 turns of 11 AWG solid copper magnet wire. The resistance is 0.5Ω and the inductance 7.25 mH; a current of 1750 A results in a centerline field of 3 T mounted in the GMA. Slotting the conductive washers in the stack has a surprisingly minor effect on magnetic field strength when measured at the magnet centerline. Significant heating occurs on each pulse with an anticipated temperature rise of 20°C per pulse. This energy is removed by forced air transmission around the magnet.

The gas injection system provides a fast rise and fall time, less than 15-ms pulse of gas upon command. A piezoelectric gas valve is currently being evaluated for operation outside of its specification with modifications designed to improve both the rate of gas flow and its radiation resistance. The valve is mounted close to the cathode to improve gas pulse rise and fall times so that minimal amounts of gas are inserted into the vessel. A gas diffuser serves as a transition tube between the valve and the cathode. In addition, the electrical connection to the cathode is achieved by a conductor ring clamped on the valve outlet tube.

The vacuum barrier is provided by a stainless steel bell jar assembly. This assembly provides rugged vacuum integrety and minimizes both the number of subassemblies inside the vacuum chamber where they are exposed to the plasma and the number of feedthrough. In addition, the relative gun-to-magnet position can be adjusted without the requirement for either bellows or sliding seals. The outer surface of the bell jar is machined to a No. 16 finish, since it must maintain vacuum integrety during gun insertion through the vacuum valve.

Ceramic insulators provide both voltage isolation and serve as a vacuum barrier (see Fig. 6). The insulator around the washers is deliberately made slightly longer than the stack to insure the stack does not have to withstand the vacuum pressure. Thus, a Belville washer can be inserted into the stack to mitigate against the effects of thermal shock, and the ceramic washers can be made thinner than otherwise possible. The insulator is made in two pieces to allow for ease of GMA assembly and disassembly. The cathode screws onto the diffuser to provide appropriate assembly tightness, allowing insertion of each insulator portion from opposite ends.

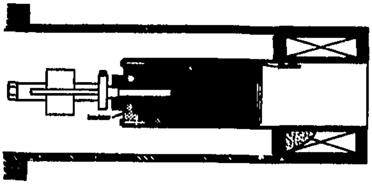


Fig. 6 Insulator Subassembly

Gun Power Supply

The gun power supply consists of four subsystems: an ionization system; a sustaining current source; a 25.6 KJ conventional pulse forming network; and charging and switching units that combine to deliver energy as shown in Fig. 7. The ionization subsystem consists of a small energy storage capacitor, charger, and switch located in the high voltage area; a coaxial cable; and a transformer, resistor, and capacitor isolation system located in the GMA. This subsystem is operated at high ionization potential; consequently, energy requirements minimize the need for cost effectiveness, and isolation is provided to minimize the need for high voltage capability in the remainder of the power supply.

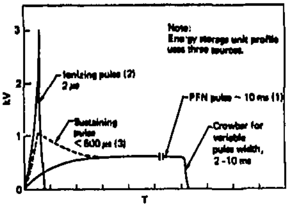
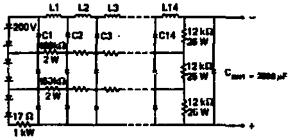


Fig. 7 Energy Waveshape

The sustaining current source is a simple and relatively small capacitor bank attached to the output of the pulse forming network, charged to the same potential, and switched at the same time. Thus, ionization transformer saturation is more quickly achieved and traditional multisection tapering or compensation elements are not required in the pulse forming network. The pulse forming network is a standard 13-section system. Actual design is shown in Fig. 8.



Note:

C1 - C8	are	2900 UF		L1 - L8	are	80 µH
C9 - C10	are	2800 UF		L9 - L10	are	73 µH
C11	is	1900 UF		L11	is	53 µH
C12 - C13	are	1000 UF		L12 - L13	are	38 µH
C14	is	600 UF		L14	is	18 µH

Fig. 8 Pulse Forming and Sustaining Network

The charging and switching subsystem nearly is identical for the gun and magnet power supplies with only transformer connection and a switch vs a diode substitution necessary to convert from one configuration to the other. The charge module is shown in the gun power supply configuration in Figs. 9, 10, and 11 and is reactor-limited. The secondary is soft-grounded with the only hard ground occurring at the patch panel or the GMA. The switch unit module is shown in Fig. 10. A hard crowbar is provided for safety and adjusting the pulse width; a soft crowbar is provided for adjusting the stored potential downward and for system shutdown.

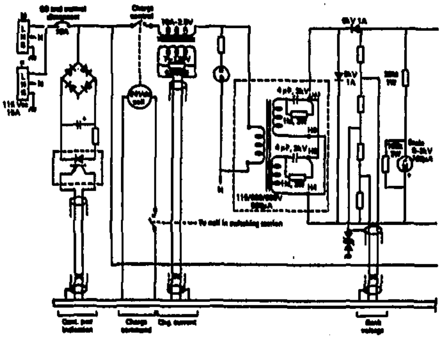


Fig. 9 Charge Module

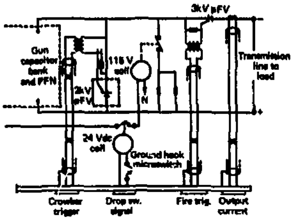


Fig. 10 Switch Module

Magnet Power Supply

The magnet power supply consists of a 48 KJ capacitor bank charged to 2400 V and a charging and switching subsystem. Figure 11 illustrates the tradeoffs between possible bank configurations for the selected magnet design. A free-wheeling diode is used in place of the hard crowbar in the switching modules to ensure that the capacitors are not reverse-charged by transient energy stored in the magnet.

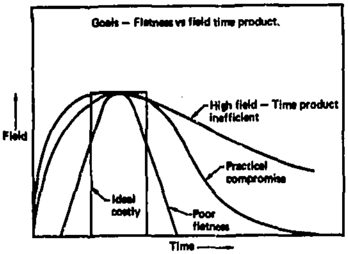


Fig. 11 Magnet Waveform

Local Control and Monitor System

The LCMS provides a capability to control and monitor the PSS independent of the MFTF control system during test and maintenance periods. Although control and monitor functions are less automated in LCMS, they are more complete, particularly in providing diagnostics data for troubleshooting purposes. The LCMS also provides the necessary hardware to implement commands sent by the MFTF control system and provides data to the MFTF monitor system. The LCMS consists of a local panel, common equipment (common to all 60 PSS units), 60 PSS unit controllers, 60 auxiliary unit controllers, and a simulator module.

The local panel (see Fig. 12) provides a capability to set a series of commands in time sequence to individual PSS unit controllers (one controller at a time) and to monitor the performance of that PSS unit. The four-trace waveform system has not been defined at this time pending evaluation of magnetic field effects. Once a set of commands has been read into an individual controller, that controller remembers and executes the commands; this allows any number of units to be fired in any independent sequence. The common equipment consists of a LCMS clock for time sequencing in the absence of MFTF control, common interlock system, gas pressure control and monitoring, coolant air flow, and other miscellaneous equipment. Each of the 60 PSS unit controllers consists of interface isolation couplers, digital command modules, and analog and digital monitor modules (see Fig. 13). As in all subsystems of the PSS, care is taken to isolate units from each other to ensure independent operation is not compromized by cross-coupled noise. The 60 auxiliary controllers provide shaped energy pulses to control and monitor gas injection, vacuum valve position, and gun insertion position. Position command is generated locally but accomplished pneumatically through the use of multitube flexible plumbing to the end dome ports, thus eliminating the need for electrical solenoids in the high magnetic fields present at the end domes. The simulator model mocks the operation of the PSS controllers and power supplies such that the MFTF control and monitor system can be tested without the entire system being in place. This allows the simultaneous test or repair of either half of the system independent from the other half.

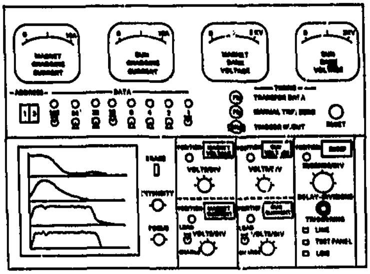


Fig. 12 Load Panel

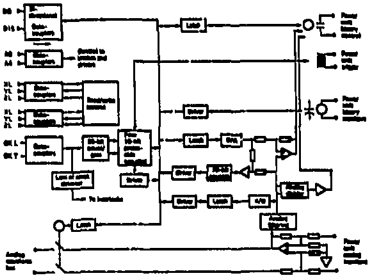


Fig. 13 PSS Unit Controller

Local Control and Instrumentation System

The LCIS serves as an interface between the LCMS and the MFTF control and monitor system. It consists of an LSI-11 computer, a fiber optics communication system, and the local interface system. The LCIS is described in detail in another paper.

Supervisory Control and Diagnostics System

The MFTF control and monitor system is described in detail in other papers, and the PSS interaction falls within that description.

Operations

During each MFTF operations cycle, the following sequence of events occurs:

1. The gun and magnet power supplies automatically start charging to a value written in the SCDS or LCIS software. Each power supply can be set for a different value. Time to maximum charge is less than 3.5 min.
2. Until PSS fire countdown starts, the operator can command a new charge value for any of the 120 power supplies. If the new value has not been reached, the charge unit remains on until it is reached and continues cycling on whenever the monitored value decays by greater than one-half of 1 percent. If the new value is less than the currently reached value, the soft crowbar activates to reduce the charge to the desired value.
3. All power supply charge values are monitored periodically. Variations from command result in an exception report to the SCDS operator; or, if greater than deemed suitable for equipment safety, a hardwire interlock disables that PSS unit and sends an exception report.
4. Until PSS fire countdown starts, the SCDS operator can insert command fire times for power supplies, crowbars, ionization pulses, and gas insertion start and stop.
5. MFTF zero time is defined by the SCDS operator and fire countdown starts.
6. Countdown abort can be introduced at any time by the SCDS operator.

At the operator's option, gun and magnet voltage and current waveforms can be monitored from any one PSS unit. If no specific request is made, each unit is monitored in turn. For each shot all monitors are recorded and available for later data analysis. As operating experience is acquired, algorithms will be generated for computer prediction of wear patterns in GMA stacks and degraded performance of subsystems potentially requiring diagnostics and repair effort.

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