DESIGN AND INITIAL OPERATION OF THE MADISON SYMMETRIC TORUS

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Design and Initial Operation of the Madison Symmetric Torus*

T.W. Lovell, R.N. Dexter, F. Feyzi, D. Kortbawi, S.C. Prager, and J.C. Sprott, University of Wisconsin-Madison--The Madison Symmetric Torus (MST) is a new, versatile reversed field pinch that began operation in June of 1988. MST was designed to operate anywhere in the region from tokamak to reversed field pinch. Initial operation has been as an RFP and has more than met design expectations. The device has consistently produced 500kA, 34ms discharges.

MST is a toroid 1.5 meters in major radius and has a circular cross section 0.52 meters in minor radius. The device is aluminum (primarily 6061-T6) and has a 0.05 meter wall thickness. Tank fabrication was accomplished by pressing 6061-T4 aluminum plate into toroidal sectors, age hardening the sectors to T6 temper, welding the sectors together, and finish machining. Primary fabrication was contracted to DePretto-Escher Wyss in Schio, Italy, and final fabrication and design assistance was provided by the U.W. Physical Sciences Laboratory (UWPSL).

The aluminum tank functions as the vacuum vessel, "single turn coil" for toroidal field application; and conducting shell (for RFP operation), maintenance and modification are both simple and economical. The lack of field coils encircling the tank also provides excellent diagnostic access (the MST has >175 separate diagnostic access positions). The "single turn coil" concept reduces toroidal field ripple. Considerable attention was given in design to producing a device with minimal field errors. The designed poloidal field system uses an innovative multiprimary method to reduce radial field errors at the poloidal field gap and to reduce error fields due to core magnetizing currents. Operation to-date has been with the winding intended for DC core biasing. Installation of the designed pulsed poloidal field winding will be completed this summer. UWPSL has provided design assistance and is fabricating the coil parts from drawings drafted by Los Alamos National Laboratory.

The tank is split at one toroidal azimuth and fitted with gap insulators, flanges, and continuity windings to allow the coupling of the plasma with an external, 2.0 volt-second iron core. Toroidal field is introduced by directly driving the tank walls with a poloidal current at a toroidal insulated gap. Long flanges on the toroidal field drive help assure field uniformity (errors <0.2%). To accommodate tokamak operation, the tank and toroidal field system has been made strong enough for up to 0.6 Tesla average fields. An additional toroidal gap, bolted and electrically shorted, allows the tank to be easily split along its midplane for modifications or repairs within the vessel. Such modifications might include liners, carbon tiles, and limiters.

Vacuum sealing at the poloidal and toroidal gaps is provided by viton sheet gaskets, allowing the vacuum seal also to function as an electrical insulator. The insulated gaps are protected from the plasma by a system of ceramic tiles. Tank pumping is provided by an array of 193 - 0.038 meter diameter holes in the tank wall connected by a large duct. This system results in a theoretical nitrogen pumping speed of ~25,000 l/s without significant field errors due to large pumping ports. Presently the machine is pumped by three turbomolecular pumps and a cryopump resulting in ultimate base pressures in the 10^{-8} Torr range. Titanium gettering in the pumping duct is planned. Both glow and pulse discharge cleaning systems are in use.

*Work supported by U.S.D.O.E.

Engineering Design Goals:

- ❍ ease of fabrication

  Simple design as well as innovative and careful fabrication by DPEW and UWPSL resulted in a machine without any overwhelming difficulties being encountered during construction.

- ❍ good plasma parameters

  The MST has met our expectations for initial operations. This is especially pleasing since we have been operating by driving the Bias Winding since the Poloidal Field Winding has yet to be completed.

- ❍ minimize field errors

  The single turn toroidal field, flanged gaps, and the pumping duct concept have significantly reduced field errors. The Poloidal Field Winding presently being installed is expected to further reduce poloidal gap errors.

- ❍ simplicity of maintenance and modification

  The absence of field windings encircling the tank and the use of the vacuum vessel as the conductive shell has considerably eased the repair, installation, and modification of internal structures (diagnostics, limiters, etc.)

- excellent diagnostic access

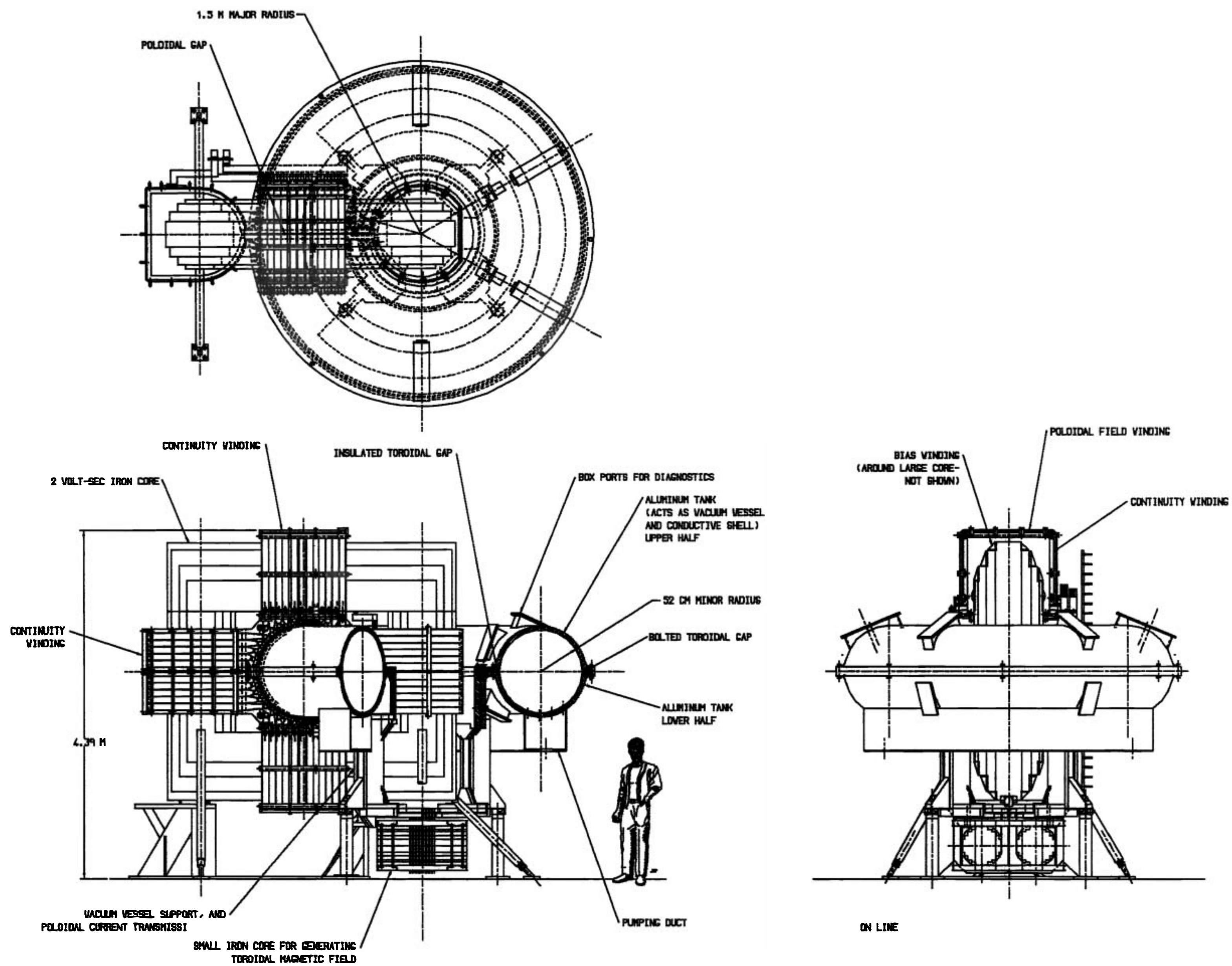
  More than 175 separate diagnostic access positions exist. The lack of interference caused by field windings simplifies the optimum placement of diagnostics and associated apparatus.

- high pumping speed

  The pumping duct concept provides ~25,000 l/s of theoretical pumping speed through an array of 193 0.038 meter diameter holes without seriously compromising our field error goals. Presently the MST is pumped by 3 - 1150 l/s and 1 - 600 l/s turbomolecular pumps and a cro-panel. Getter pumping using Titanium sublimation within the pumping duct is also under consideration.

- reliable operation

  Since initial operation in June of 1988, the MST has logged more than 33,000 shots. The machine is operated and maintained by a small technical staff, graduate students, and part-time undergraduate hourly employees.



MADISON SYMMETRIC TORUS ASSEMBLY

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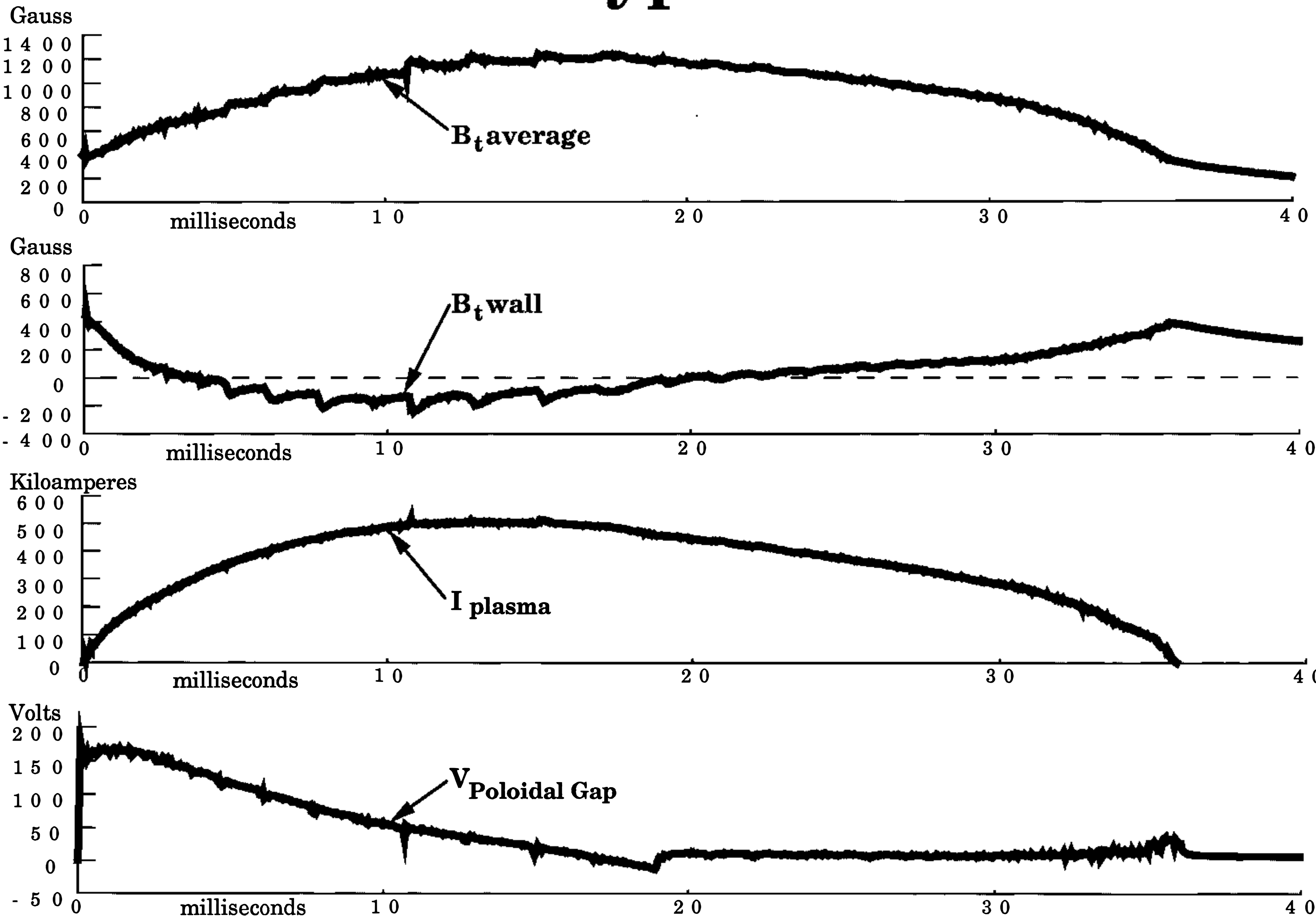
MST Typical Parameters:

Plasma Current	**500 KA**
Loop Voltage	**30 V**
Ohmic Power	**15 MW**
Average Toroidal Field	**1.2 KG**
Edge Toroidal Field	**-150 G**
Flux Swing	**1.4 V-S**
τ_E	$\leq$ **1 ms**
Plasma Duration	**36 ms**
T_e	**300 eV**

MST Typical Shot

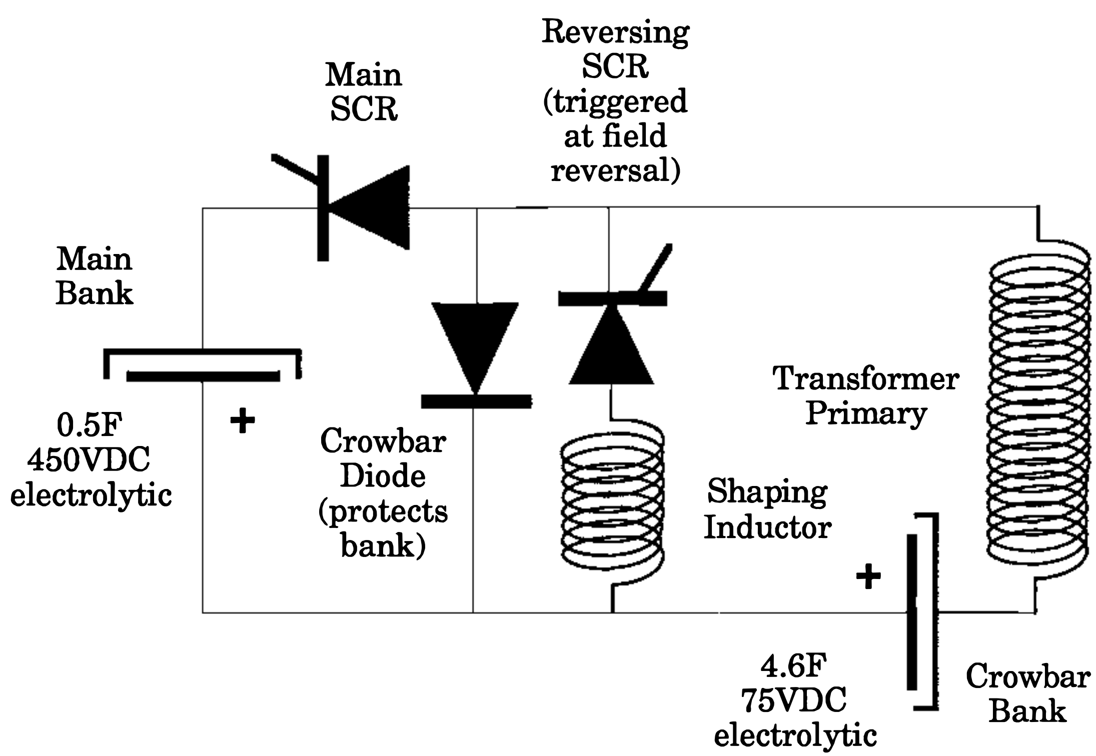


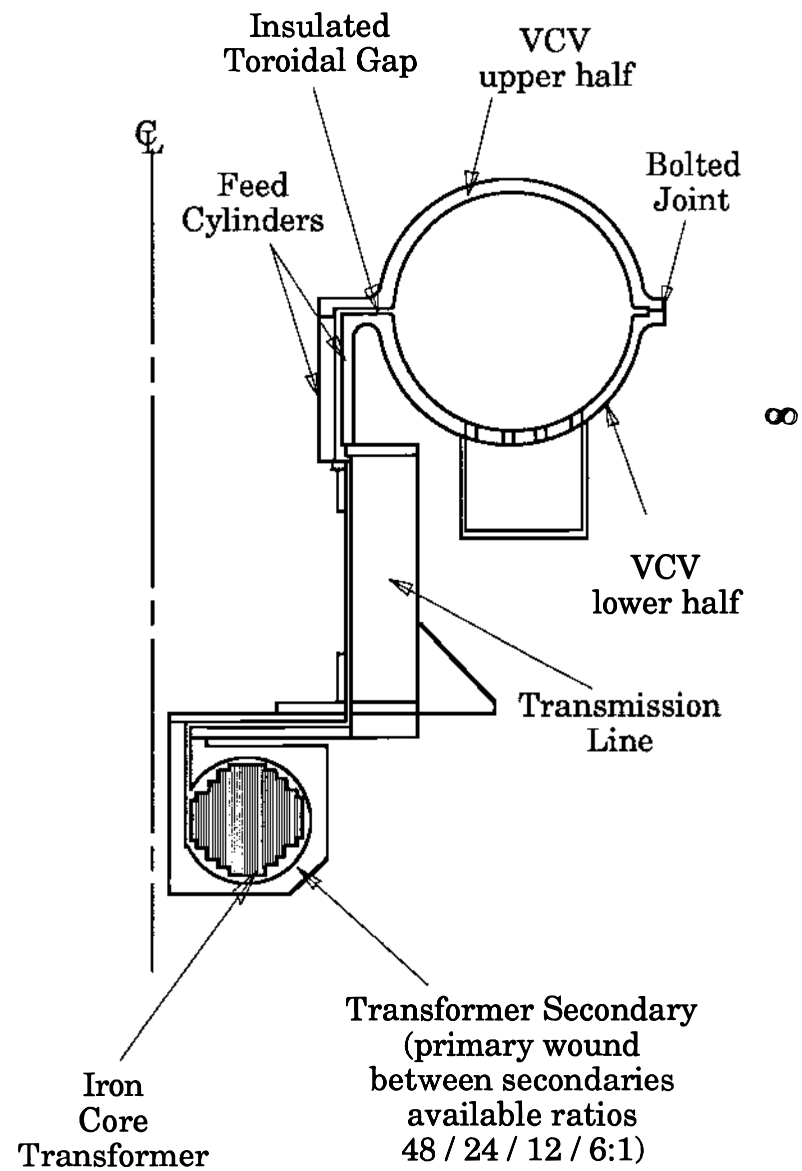
Single Turn Toroidal Field:

One of the unusual features of the MST is the use of a single turn toroidal field winding. Toroidal field is induced by directly driving a poloidal current in the tank wall. Current from a capacitor bank flows through a multiturn primary on an iron core transformer below the MST. Single turn secondaries on that transformer are connected to 4 transmission lines (which also serve as the tank support structure).

These transmission lines connect to coaxial cylinders (the Feed Cylinders) and a radial flange to smooth out the ripple before reaching the tank. Bolted conductive joints are provided to allow the easy removal of the upper half of the tank for modification or repair of internal structures. The transmission line, Feed Cylinders, and tank assembly has been designed to allow upgrading the toroidal field to 0.6 Tesla for operation of the MST in the region from tokamak to reversed field pinch.

MST Toroidal Field System



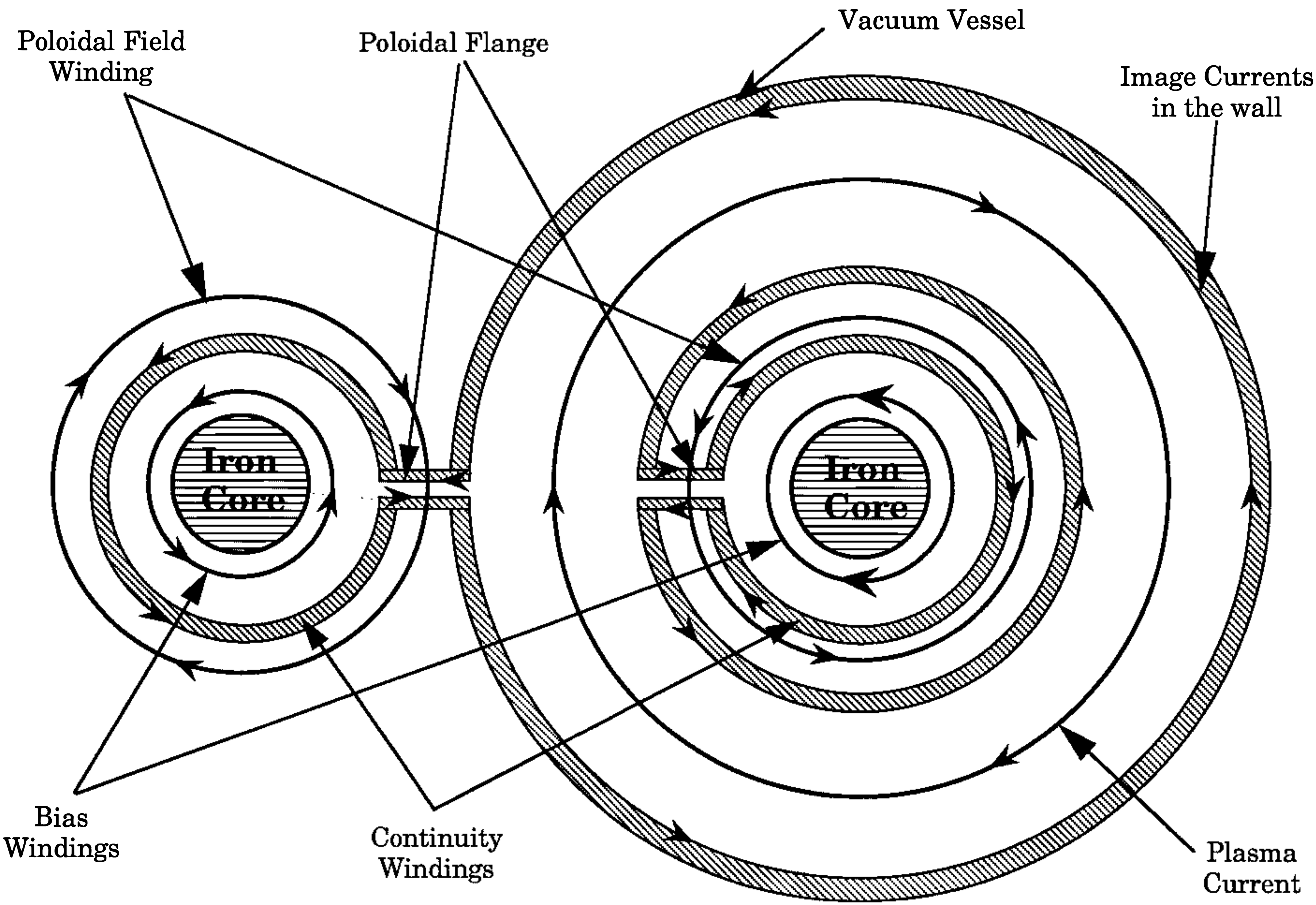


Poloidal Field System:

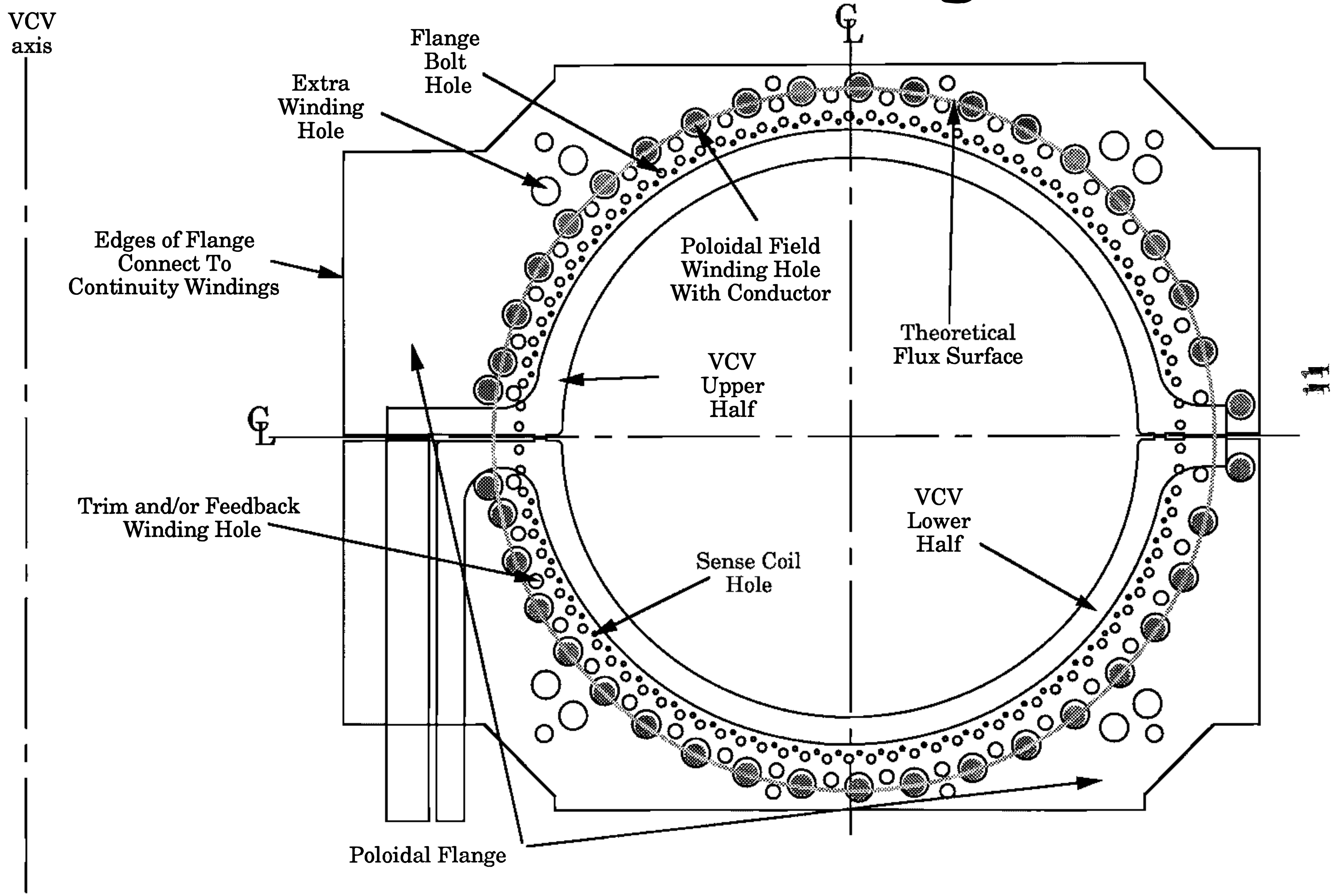
The MST has several unique features in it's Poloidal Field System.

- ❋ *First the field is shaped entirely by the thick (0.05 meter) conductive vacuum vessel. The vessel also provides the vertical field (although design provision has been made for an external DC vertical field for plasma centering if the experiments require it). Plasma current is induced by a primary winding on a large iron core that threads the toroid.*
- ❋ *The second unique feature are the Continuity Windings which place the core topologically inside the conductive vessel.*
- ❋ *The third unique feature is the primary winding system. In order to take full advantage of the flux capacity of our core a Bias Winding has been placed on the core and a DC current is supplied to saturate the core in the direction opposite to the flux swing caused by the plasma current. The Bias Winding has been carefully placed to create minimum external field since that field would soak through the conductive vacuum vessel and cause a field error. In pulsed operation, however, the image currents flowing across the poloidal gap would be distorted in matching the boundary condition set by the Bias Winding and create radial error field . Consequently, a second primary, the Poloidal Field Winding, has been designed to pierce the poloidal gap flange in the position and with the current density necessary to match the image currents at the gap. This winding is presently being installed and will be completed by the end of this summer. Provision has been made for trimming any residual errors at the gap through additional coils threading through the poloidal flange.*

MST Poloidal Field System

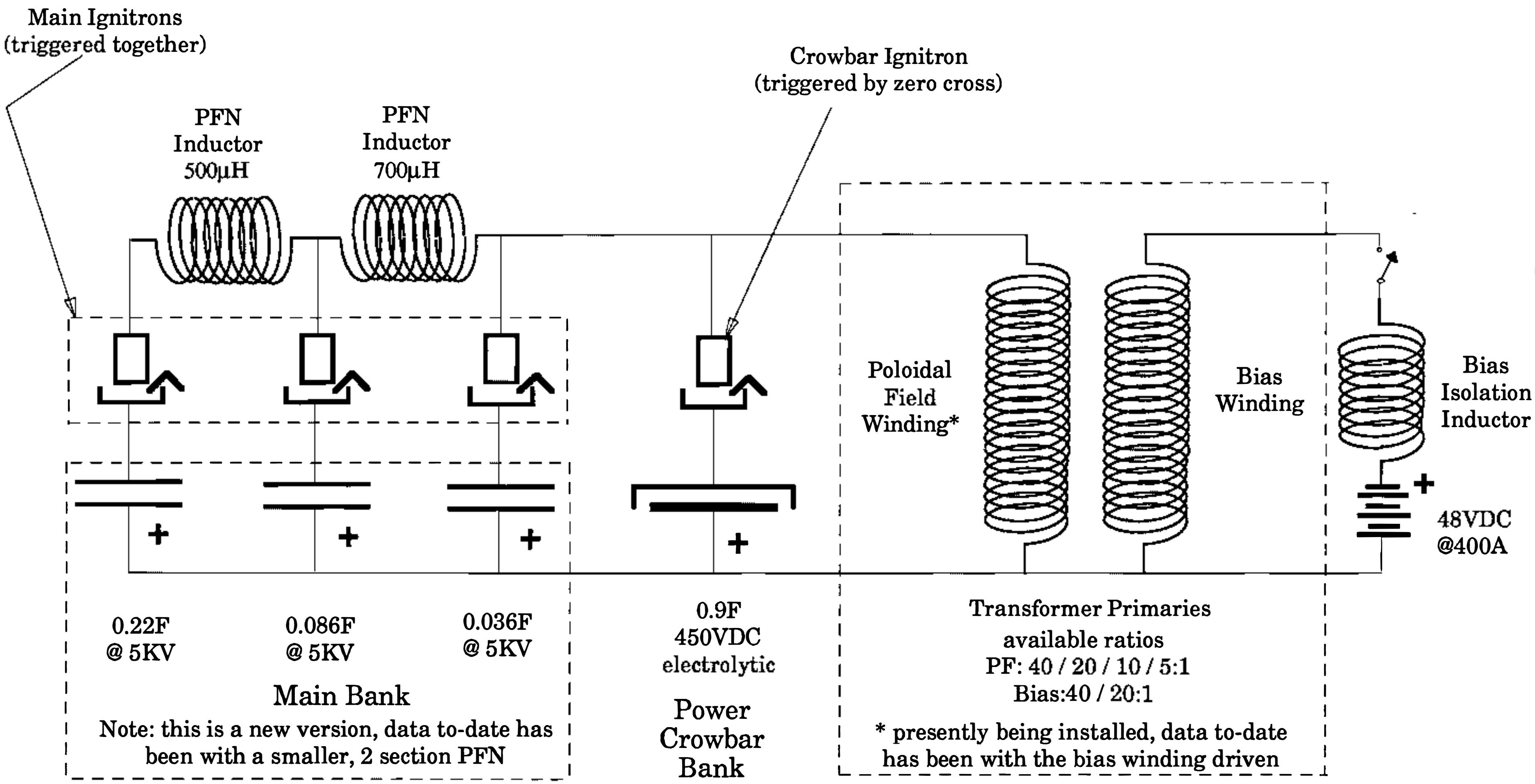


MST Poloidal Flange



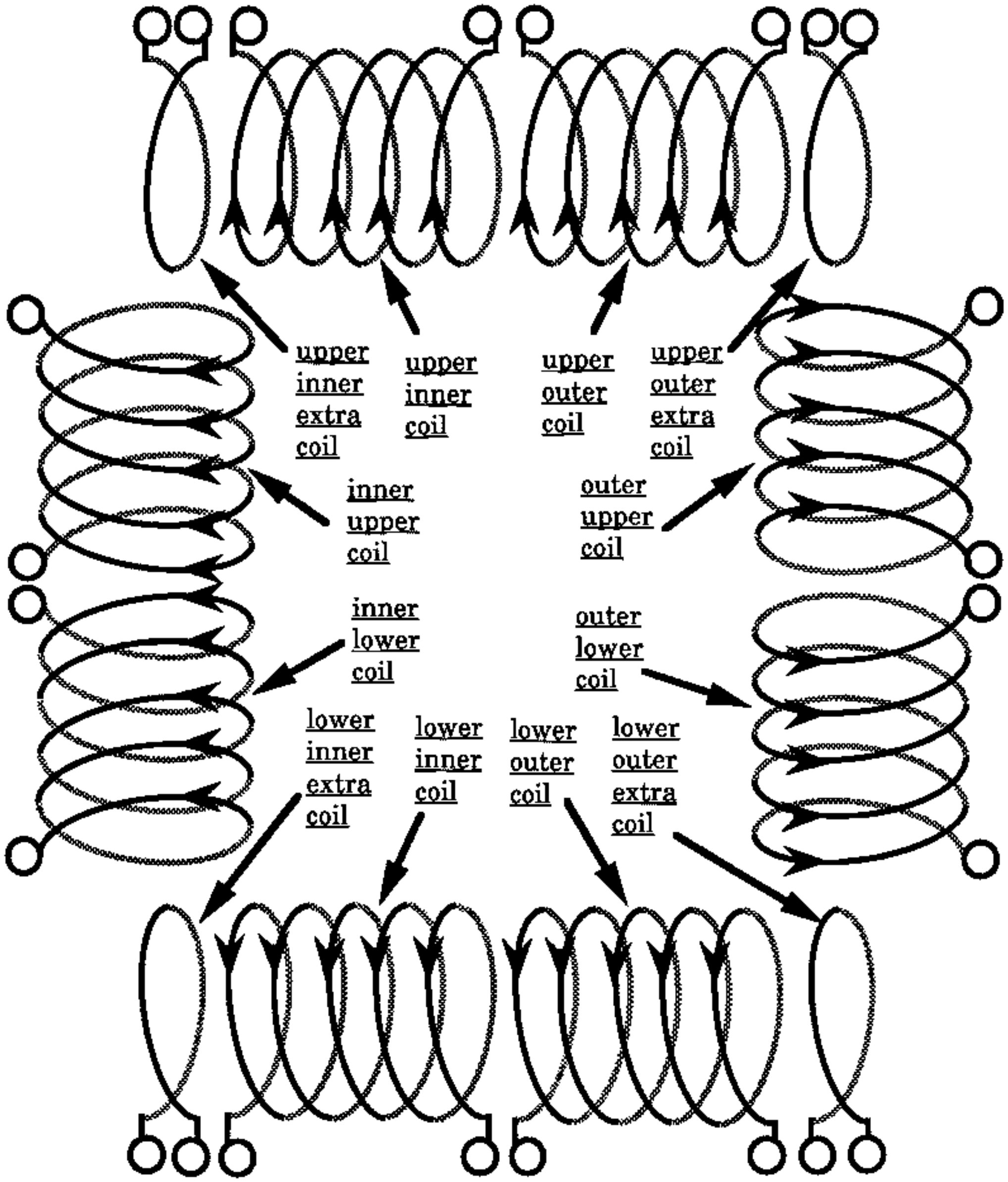
MST Poloidal Field System

Schematic



MST Poloidal Field Windings

Schematic



Flexible Design Allows:

* *multiple turns ratios for different plasma conditions and/or drive impedances*

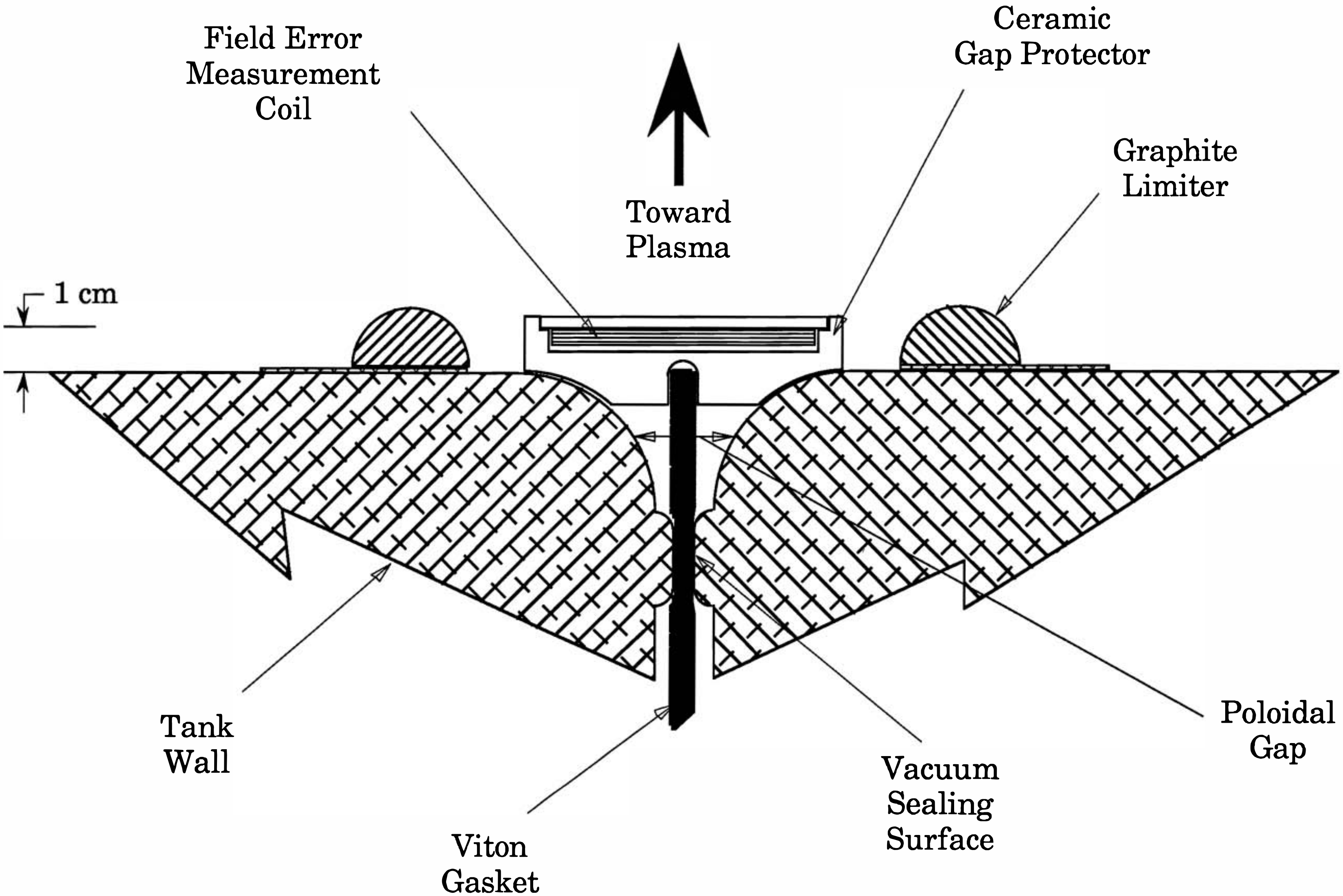
* *first order correction for plasma position through the use of "extra" coils*

Note: *We are indebted to LANL for their invaluable assistance in drafting the production drawings for the PF project*

Gap Protection:

The design of the MST requires both poloidal and toroidal voltage gaps. Past experience, both in our laboratory and elsewhere, led to concern over plasma induced arcing at these gaps. The poloidal gap was expected to be especially troublesome if large loop voltages were necessary to start the RFP discharge. Fortunately, loop voltage requirements have been moderate. Our gap protection design utilizes a viton sheet as both the vacuum sealing gasket as well as the gap insulator. The viton sheet and the interior of the gap are protected from the plasma by a ceramic (lava) tile. This simple system has worked well for both the poloidal and toroidal gaps. In our present upgrade we are adding graphite limiters to protect the tiles from the bulk of the plasma since we have observed some small damage to the tiles and expect to achieve even more energetic plasmas. We also are modifying the tiles to contain coils to both assess the magnitude of any gap field error and for possible use as the feedback element in any active trimming scheme.

MST Poloidal Gap Protection



Conclusions:

The MST is a successful engineering design. It has met it's initial goals without great difficulty and should continue to prove to be both a reliable and flexible research device. The unique features in its design have proved to be of practical value. The Poloidal Field Winding, when installation is complete, will provide a significant test of our approach.