LIQUID METAL MAGNETOHYDRODYNAMIC (LMMHD) TOROIDAL FACILITY UPDATE

(PART OF APEX TASK I)

PRESENTED BY
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24 MARCH 2000

ELECTRONIC APEX MEETING

PRESENTATION OUTLINE

- WHY APEX NEEDS A LMMHD TOROIDAL FACILITY
- SOME ISSUES TO INVESTIGATE EXPERIMENTALLY
- FACILITY DESIGN AND EXPERIMENTAL PARAMETERS
- APPROXIMATE SCHEDULE
- CONCLUSIONS

APEX NEEDS A LIQUID METAL MHD TOROIDAL FACILITY

•ALL MAGNETIC PLASMA CONFINEMENT SCHEMES SERIOUSLY CONSIDERED TODAY FOR FUSION HAVE TOROIDAL GEOMETRY. MOST OF THEM ALSO CLOSELY APPROACH AXISYMMETRY OF PHYSICAL SHAPES AND MAGNETIC FIELDS, E.G., TOKAMAKS.

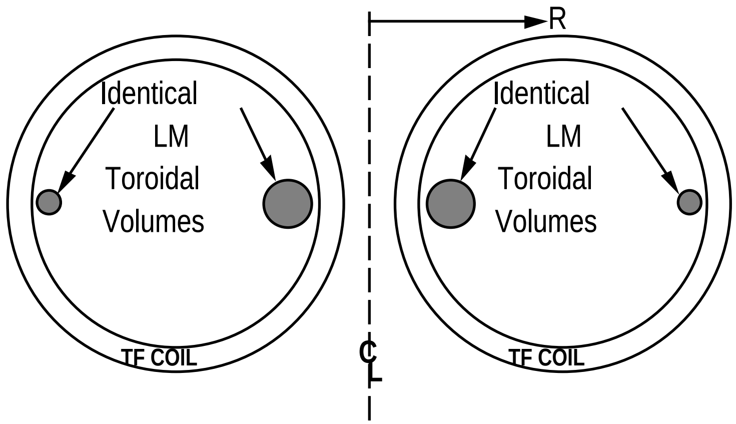
•APEX SCHEMES INVOLVE FREE-SURFACE FLOW OF A CONDUCTING LIQUID CLOSE TO THE PLASMA EDGE, WHERE PLASMA, MAGNETIC FIELDS, AND THE BACKING SURFACES NEEDING COVERAGE ARE ALL NEARLY AXISYMMETRIC, AND THUS REQUIRE AT LEAST NEAR-AXISYMMETRY OF THE LM FLOW.

• PUBLISHED EXPT. FREE-SURFACE LMMHD STUDIES IN FUSION-RELEVANT MAGNETIC FIELD AND FLOW GEOMETRIES DON'T EXIST.

•APEX NEEDS AN EXPERIMENTAL TEST-BED TO PROVIDE "REALITY CHECKS" ON COMPUTER SIMULATIONS OF FREE-SURFACE LMMHD FLOWS IN FUSION-RELEVANT GEOMETRIES.

- **THE FACILITY WOULD ALSO SUPPORT INITIAL TESTING OF APEX LIQUID METAL FLOW CONCEPTS WITHOUT THE TECHNICAL COMPLICATIONS AND CONSTRAINTS OF A PLASMA.**

TOROIDAL LMMHD DIAMAGNETIC DRAG



•IF AN AXISYMMETRIC LIQUID VOLUME MOVES RADIALLY OUTWARDS ITS CROSS-SECTIONAL AREA SHRINKS TO MAINTAIN CONSTANT VOLUME=$2\Pi^2A^2R$. TOROIDAL MAGNETIC FIELD STRENGTH VARIES AS 1/R SO INTERCEPTED FLUX VARIES AS $1/R^2$.

•RADIAL MOTION INDUCES EDDY CURRENTS COMPRESSING TOROIDAL MAGNETIC FLUX “FROZEN” INTO THE LIQUID METAL, PRODUCING MOTION-OPPOSING “DIAMAGNETIC DRAG” FORCES.

• **FREE-SURFACE LIQUID METAL FLOW IN A TOKAMAK MAY BE DOMINATED BY THIS “DIAMAGNETIC DRAG”, WHICH DOES NOT OCCUR FOR UNIFORM FLOWS IN A UNIFORM MAGNETIC FIELD.**

TF-ONLY ISSUES IN THE TOROIDAL FACILITY

•POLOIDAL CURRENT CAN BE INJECTED INTO LIQUID METAL VIA ELECTRODES AND AN EXTERNAL POWER SUPPLY. IF DONE, THE CURRENT DENSITY, J_{POL}, INTERACTS WITH THE TOROIDAL MAGNETIC FIELD, B_{TF}, TO CREATE A FORCE FIELD,

$$F = J_{POL} X B_{TF} ,$$

PUSHING THE LIQUID AGAINST THE SOLID WALL BEHIND IT.

•WHAT STEADY-STATE AXISYMMETRIC FREE-SURFACE LMMHD FLOWS ARE POSSIBLE IN A TOROIDAL MAGNETIC FIELD WITHOUT INJECTING POLOIDAL CURRENT INTO THE LIQUID ? HOW DO THE LM LAYER THICKNESS AND THE VELOCITY PROFILE VARY ?

•HOW DO FLOWS CHANGE WITH INJECTED POLOIDAL CURRENT ? TO WHAT EXTENT DOES NONUNIFORM J X B PROPEL RADIAL LM MOTION ?

TO WHAT EXTENT DOES NONUNIFORM CURL(J X B) AFFECT THE INTERNAL VELOCITY PROFILE ?

TF-ONLY ISSUES (CONTINUED)

•CAN THE “CLIFF” SCHEME AVOID INJECTING POLOIDAL CURRENT?

•WHAT MEASURABLE STABILITY PROPERTIES (E.G. TURBULENCE ONSET POSITION OR CHARACTERISTIC BREAK-UP LENGTH) ACCOMPANY EACH FLOW FIELD AND HOW DO THEY VARY?

-WHAT IS THE MINIMUM INJECTION SPEED (VS. CHAMBER CURVATURE) TO AVOID RALEIGH-TAYLOR INSTABILITIES WITH THE BACKING SURFACE CONCAVE DOWNWARDS ?

-HOW IS MINIMUM SPEED MODIFIED BY POLOIDAL CURRENT ?

-HOW DOES THE SAUSAGE INSTABILITY DEVELOP IN MOVING LIQUID METAL FLOWING AGAINST A “CENTERSTACK” WALL WHILE CARRYING POLOIDAL CURRENT.

-CAN THE RESISTIVE REDISTRIBUTION OF ELECTRICAL CURRENT BETWEEN THE FLOWING LIQUID METAL LAYER AND ITS SOLID METAL BACKING WALL PROVIDE STABILIZATION ?

TF+PF ISSUES FOR THE TOROIDAL FACILITY

•LOCAL MISMATCH OF THREE IMPORTANT POLOIDAL COMPONENT DIRECTIONS, I.E.,

(1)POLOIDAL ELECTRICAL CURRENT,

(2)POLOIDAL FLUID FLOW VELOCITY, AND

(3)POLOIDAL MAGNETIC FIELD,

CAN

(A) PRODUCE LOCAL TOROIDAL LM MOTION, AND/OR

(B) GENERATE LOCAL LM TOROIDAL CURRENT.

•THESE EFFECTS COULD ALSO OPPOSE POLOIDAL LM MOTION. THEY NEED TO BE EXPERIMENTALLY STUDIED.

•SMALL-SIGNAL DYNAMIC CHARACTERISTICS OF POLOIDAL FIELD TRANSIENT PENETRATION THROUGH FLOWING FREE-SURFACE LM LAYER IS CRUCIAL FOR TOKAMAK CONTROL AND NEEDS STUDY.

DEPARTURES FROM AXISYMMETRY ISSUES

• LM FLOW MAY BE DIVIDED INTO DISCRETE TOROIDAL SEGMENTS, EACH WITH A CONSTANT TOROIDAL ANGLE AS WIDTH. THEN FLOW IS NOT AXISYMMETRIC DUE TO HARTMANN BOUNDARY LAYERS.

-HOW LARGE IS NONAXISYMMETRIC MAGNETIC FIELD RIPPLE PRODUCED BY LMMHD EFFECTS ? HOW DOES IT COMPARE WITH LIMITS ON ACCEPTABLE TOKAMAK ERROR FIELDS ?

•HOW WELL DO NONAXISYMMETRIC FEATURES ON THE SOLID BACKING WALL SURFACE SLOW THE LM FLOW ?

•HOW QUICKLY ARE TRANSIENT NONAXISYMMETRIC PERTURBATIONS OF THE LM FLOW FIELD DAMPED ?

OTHER EXPERIMENTS COMPATIBLE WITH TOROIDAL FACILITY

(1)TEST METHOD TO CONTINUOUSLY REMOVE FREE-SURFACE LIQUID METAL FROM MAGNETIC CONFINEMENT SYSTEMS.

-A FREE-SURFACE LM "SUMP" CONTAINER IS LOCATED INSIDE THE TF TORUS NEAR ITS BOTTOM. ELECTRODES INJECT POLOIDAL CURRENT, WHICH ACTS TOGETHER WITH TOROIDAL FIELD TO PRESSURIZE LM AGAINST THE CONTAINER BOTTOM, WHERE AN EXIT TUBE DIRECTS LM TO AN EXTERNALRESERVOIR.

(2) DEVELOP LOW-PUMPING-POWER LM INJECTION AND REMOVAL.

-AS PROPOSED BY L. ZAKHAROV, LM PUMPING POWER COULD BE REDUCED IF MANY NARROW, HIGH-SPEED LM JETS, NOT IN CONTACT WITH PIPES, WERE USED TO ENTER AND EXIT A TF TORUS BETWEEN TF COILS. INSULATING VACUUM AROUND EACH JET REDUCES LOSS-

CAUSING CURRENT PATHS. NEED DEVELOP JET FORMERS AND CATCHERS OPERATING IN MAGNETIC FIELDS.

LMMHD TOROIDAL FACILITY DESIGN ISSUES

•IDEALLY, THE FACILITY SHOULD BE CAPABLE OF PRODUCING SEVERAL TESLA STEADY TOROIDAL MAGNETIC FIELD, A SMALLER POLOIDAL FIELD, USE LOW DENSITY LM WITH HIGH CONDUCTIVITY (E.G. LITHIUM), AND HAVE EXCELLENT LMMHD DIAGNOSTICS.

•ACTUALLY, THE LIMITED AVAILABLE BUDGET CONSTRAINS THE FACILITY TO WHATEVER CAN BE ASSEMBLED FROM EXISTING EQUIPMENT, WITH MINIMUM ADDITIONAL COSTS.

•NOW AVAILABLE AT UCLA:

- -24 COILS FROM THE TARA DEVICE PREVIOUSLY AT MIT.
- -1 DC POWER CONVERTER LOANED FROM PPPL.
- -EXPERIMENTAL AREA WITH ADEQUATE FLOOR SPACE, AN OVERHEAD CRANE, SUFFICIENT 480 VAC POWER TO OPERATE THE DC

POWER CONVERTER, AND SUFFICIENT DEIONIZED COOLING WATER FOR THE TARA COILS.

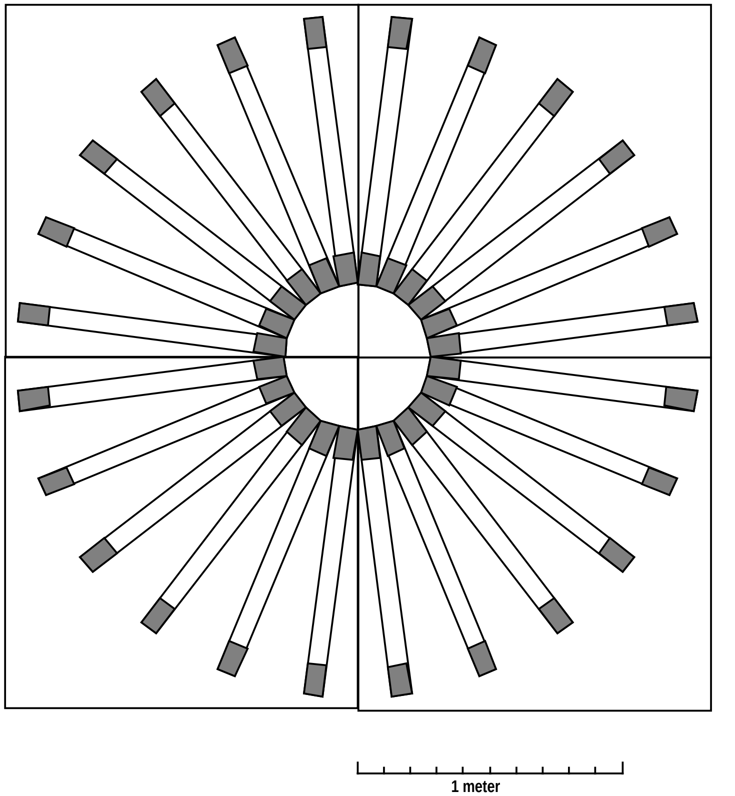
THE TARA COILS

•THE DIAGRAM SHOWS 24 TARA COILS IN PLAN VIEW, ALONG WITH A NEARBY METER SCALE. WINDINGS ARE SHOWN SHADED. TARA COILS ARE NOT WEDGED IN “NOSE” REGION.

•THE COILS FORM A TORUS, MOUNTED ON FOUR MOVEABLE SQUARE TABLES FOR ACCESS

•THE MAGNETIZED TOROIDAL VOLUME HAS A CIRCULAR CROSS-SECTION. ITS MAJOR AND MINOR RADII ARE R_0=0.78M AND A=0.39M.

•EACH TARA COIL HAS TWO 14-TURN WINDINGS RATED AT 3664 AMPERES EACH. THAT EXCEEDS AVAILABLE POWER.

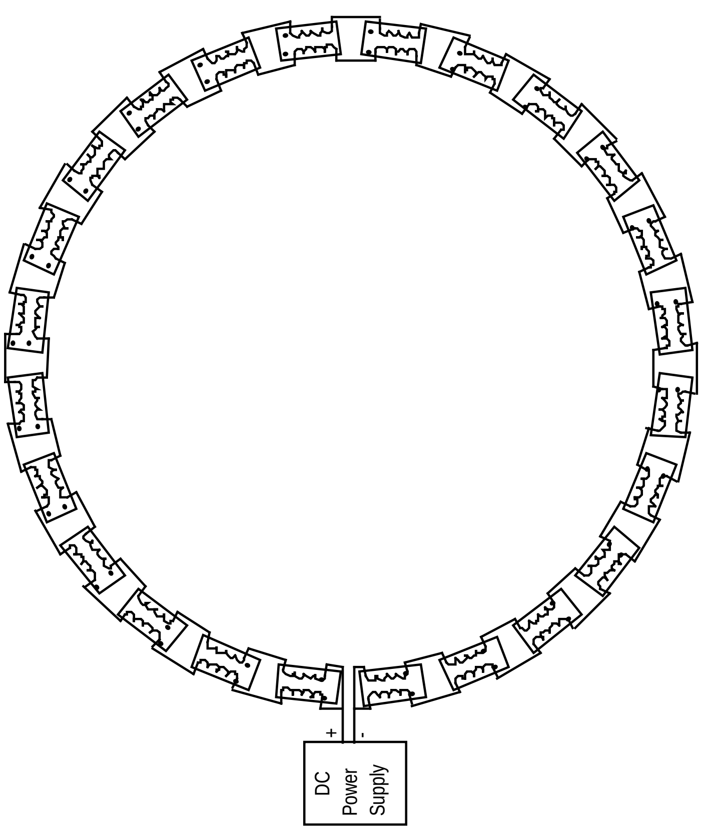


TF POWER CIRCUIT

•THE PPPL DC POWER CONVERTER IS RATED AT 3000 AMPERES, 150 VOLTS, BUT HAS BEEN OPERATED AT 3600 AMPS, 188 VOLTS.

•THE CIRCUIT SHOWN CAN DRIVE 1800 AMPERES DC STEADILY IN BOTH WINDINGS OF 24 TARA COILS. RESISTIVE VOLTAGE WITH ADEQUATE WATER COOLING AT ΔP=100PSI IS 166 VOLTS.

•THE 480 VAC LOAD WILL BE 600KW, WELL WITHIN THE 750 KVA CAPABILITY OF EITHER OF THE TWO AVAILABLE 480 VAC POWER SOURCES.


+
-
DC
Power
Supply

TOROIDAL FIELD STRENGTH & COIL FORCES

• WITH 1800 AMPERES PER WINDING, THE TF VARIES AS FOLLOWS:

MINIMUM RADIUS R=0.39M	MAJOR RADIUS R_0=0.78M	MAXIMUM RADIUS R=1.17M
B_{TF} =0.62 TESLA	B_{TF} =0.31 TESLA	B_{TF} =0.21 TESLA

• THE NET MAGNETIC FORCE ON EACH TARA COIL IS HORIZONTAL, DIRECTED TOWARDS THE SYMMETRY AXIS, WITH A LINE OF ACTION THROUGH THE COIL WINDING CENTER. WITH ONLY TARA COIL CURRENTS, THERE ARE NO OTHER NET MAGNETIC FORCES OR TORQUES. AT 1800 AMPERES, THIS FORCE IS 7263.5 NEWTONS=1630.6 POUNDS.

• A HYPOTHETICAL TOKAMAK USING TARA TF COILS COULD DEVELOP OVERTURNING MOMENTS UP TO 1900 NEWTON-METERS.

TOROIDAL FACILITY SUPPORT STRUCTURE

• TOM SKETCHLEY OF UCLA HAS DESIGNED A FLEXIBLE SUPPORT SYSTEM FOR THE 24 TARA COILS.

•THE DESIGN RELIES PRIMARILY ON UPPER AND LOWER SHELVES MADE OF 1” ALUMINUM PLATE INTO WHICH SLOTS ARE CUT. THE SLOTS HOLD THE COILS IN THEIR PROPER POSITION, ESPECIALLY WITH RESPECT TO OUT-OF-PLANE ROTATION. RESTRAINT OF THE CENTERING FORCE MAY USE AN INTERFACE TO SPREAD OUT CONTACT PRESSURE.

•THE SHELVES ARE CONFIGURED IN FOUR 6-COIL QUADRANTS, SOME OF WHICH ARE EASILY MOVEABLE.

•UPPER AND LOWER SHELVES ARE INTERCONNECTED BY STRUTS.

- **UPPER SHELF WILL CARRY BUSWORK AND COOLING WATER**

UNPLANNED PARTS

•AT PRESENT THERE IS NO PLAN FOR FULL TOROIDAL COVERAGE OF LIQUID METAL FLOW, NOT EVEN FOR A NONAXISYMMETRIC IMPLEMENTATION

•AT PRESENT, THERE IS NO PLAN FOR AN AXISYMMETRIC LM FLOW CAPABILITY.

AT PRESENT, THERE IS NO PAN FOR A COMPLETE TOROIDAL VESSEL AGAINST WHICH LM WOULD FLOW AS IN APEX CONCEPTS.

AT PRESENT, THERE IS NO PLAN FOR A SYSTEM TO INJECT SIGNIFICAN POLOIDAL CURRENTS INTO THE LIQUID METAL.

•AT PRESENT THERE IS NO PLAN FOR A PF COIL CAPABILITY.

AT PRESENT, THERE IS NO PLAN FOR NEW LMMHD DIAGNOSTICS.

APPROXIMATE SCHEDULE

•UCLA PLANS ARE TO COMPLETE REPAIR OF MINOR TARA COIL PROBLEMS AND TO COMPLETE FABRICATION OF THE TF COIL SYSTEM BY EARLY SUMMER.

•INTEGRATION AND COMMISSIONING OF THE 24 TF COILS WITH THEIR COOLING WATER AND DC POWER SUPPLY WILL FOLLOW DURING THE SUMMER.

•IN INITIAL LM FLOW CONDITION WILL BE CREATED IN THE FACILITY BEFORE THE END OF THE PRESENT FISCAL YEAR.

• ADDITIONAL WORK FOR NEXT FISCAL YEAR INCLUDES:

-EXTENDING TOROIDAL COVERAGE OF LM FLOW,
-PROVIDING A TOROIDAL VESSEL, PREFERABLY TRANSPARENT,
-PROVIDING HIGH CURRENT LOW VOLTAGE DC TO INJECT IN LM,
-PROVIDING SOME PF COIL CAPABILITY,

-EXTENDING DIAGNOSTICS,
-PERFORMING EXPERIMENTS.

CONCLUSIONS

• AN EXPERIMENTAL LMMHD TOROIDAL FACILITY WILL BE USEFUL FOR THE APEX EFFORT.

•THE EFFORT TO CONSTRUCT A LMMHD TOROIDAL FACILITY AT UCLA IS ON TRACK, WITH COMMISSIONING OF THE TOROIDAL FIELD SYSTEM EXPECTED THIS SUMMER AND FIRST LIQUID METAL OPERATIONS EXPECTED AT THE END OF THIS FISCAL YEAR.

•THE TF STRENGTH WILL BE LOW (0.31 TESLA@ R_0=0.78M), LIMITED BY COST, BUT STILL SUFFICIENTLY STRONG SO THAT IMPORTANT EFFECTS CAN BE MEASURED USING GOOD DIAGNOSTICS.

- **DURING NEXT FY IT WILL BE NECESSARY TO COMPLETE OTHER FEATURES OF THIS FACILITY, AND TO CONDUCT A USEFUL EXPERIMENTAL PROGRAM.**