PROPOSED EXPERIMENTS IN THE LIQUID METAL MAGNETOHYDRODYNAMIC (LMMHD) TOROIDAL FACILITY

(PART OF APEX TASK I)

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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

DIAMAGNETIC DRAG EXPERIMENTS- TF+ POL.VEL.

- INVESTIGATE HOW FREE SURFACE LM FLOW IS AFFECTED BY THE AXISYMMETRIC TOROIDAL MAGNETIC FIELD, WHOSE NONUNIFORM STRENGTH VARIES CHARACTERISTICALLY IN PROPORTION TO 1/R.

- THE AXISYMMETRIC VERSION OF AN INCLINED PLANE (I.E., A CONE) SERVES AS THE LM BACKING SURFACE. LM IS INJECTED AT A CONTROLLED VELOCITY VIA A NOZZLE.

- THE FREE SURFACE FLOW'S DEPTH VS. DISTANCE PROFILE IS MEASURED ALONG WITH LM VELOCITY AT SELECTED LOCATIONS.

- MEASUREMENTS FOR VARIOUS LM NOZZLE VELOCITIES, TF STRENGTHS, AND BACKING SURFACE INCLINATIONS ARE COMPARED WITH COMPUTER SIMULATION PREDICTIONS.

CLIFF CONCEPT MOCKUP TESTS -TF + POL.VEL.

• LM BACKING SURFACES, CURVED IN EACH POLOIDAL PLANE AND CONCAVE TOWARDS THE “PLASMA” REGION, ARE INSTALLED ON THE INBOARD AND OUTBOARD SIDES, RESPECTIVELY.

•LM IS INJECTED AT THE TOP OF A BACKING SURFACE AT A CONTROLLED VELOCITY VIA NOZZLE.

•THE LM LAYER THICKNESS AND VELOCITY PROFILE ARE MEASURED.

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

FLOW PHYSICS- TF + POL. V & CUR

- FOR EACH BACKING SURFACE SHAPE, POLOIDAL ELECTRICAL CURRENT IS INJECTED INTO THE LM VIA ELECTRODES WITH THE CURRENT DIRECTION CHOSEN SO THAT $J_{POL} X B_{TF}$ PUSHES AGAINST THE BACKING SURFACE.

- MEASURE HOW FLOWS CHANGE WITH INJECTED CURRENT. TO WHAT EXTENT DOES THE CONFIGURATION PROPEL NET LM MOTION OR PRODUCE INTERNAL LM CIRCULATION ?

- OBSERVE SAUSAGE AND RT INSTABILITIES. CAN THE RESISTIVE REDISTRIBUTION OF ELECTRICAL CURRENT BETWEEN THE FLOWING LIQUID METAL LAYER AND ITS SOLID METAL BACKING WALL PROVIDE STABLIZATION ? CAN CURVATURE OR MINIMUM STABLE VELOCITY BE REDUCED WITH INJECTED CURRENT PRESENT ?

ELECTROMAGNETIC PUMPING-TF+ POL. V & CUR

(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 EXTERNAL RESERVOIR.

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

-AS PROPOSED BY L. ZAKHAROV, LM PUMPING POWER MIGHT 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.

TF+PF ISSUES LEADING TO EXPERIMENTS

•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 IN A SET OF EXPERIMENTS

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

DEPARTURES FROM AXISYMMETRY EXPERIMENTS

• 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 ? MEASURE AND COMPARE WITH SIMULATIONS.

•HOW WELL DO NONAXISYMMETRIC FEATURES ON THE SOLID BACKING WALL SURFACE SLOW THE LM FLOW? MEASURE AND COMPARE WITH SIMULATIONS.

•HOW QUICKLY ARE TRANSIENT NONAXISYMMETRIC PERTURBATIONS OF THE LM FLOW FIELD DAMPED ? MEASURE AND COMPARE WITH SIMULATIONS.

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 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.

LMMHD TOROIDAL FACILITY COST-DRIVEN PHASING

PHASE 1: TOROIDAL FIELD, POLOIDAL CURRENT AND MOTION

- INITIALLY WILL HAVE TOROIDAL FIELD BUT NO PF (SINCE NO PF COILS NOR PF COIL POWER SUPPLY). LM FLOW ONLY IN A TOROIDAL SECTOR (DUE TO LIMITED PRESENT LM INVENTORY AND LM PUMPING CAPACITY). MEASUREMENTS WILL AVOID HARTMANN LAYERS.
- INITIALLY CAN HAVE POLOIDAL ELECTRICAL CURRENT INJECTED INTO LM USING EXISTING LOW VOLTAGE DC POWER SUPPLY.
- NEED DIAGNOSTICS FOR LM FREE SURFACE SHAPE, VELOCITY.

PHASE 2: POLOIDAL + TOROIDAL FIELD, CURRENT AND MOTION

- LATER EXPERIMENTS INCLUDING POLOIDAL MAGNETIC FIELD WILL REQUIRE PF COILS INSTALLED, POWERED, COMMISSIONED.
- FULL 360° AXISYMMETRIC LM FLOW IS NEEDED ALONG WITH THE POLOIDAL FIELD, SINCE THE PF MAY DRIVE TOROIDAL LM MOTION OR TOROIDAL ELECTRICAL CURRENT IN THE LM.

Facility Philosophy –LMMHD Flow Physics Focus

•EXPERIMENTAL LM IS ORDER OF MAGNITUDE DENSER THAN LITHIUM.
•EXPERIMENTAL LM HAS LOWER ELECT. CONDUCTIVITY THAN LITHIUM.
•FACILITY MAGNETIC FIELD IS WEAKER THAN TYPICAL FUSION DEVICE.
•FACILITY SIZE IS SMALLER THAN TYPICAL FUSION DEVICE.

•THUS, THE RATIO OF LMMHD INDUCED FIELD TO APPLIED FIELD AND THE RATIO OF LMMHD FORCE TO LM WEIGHT ARE EACH SMALLER THAN IN A TYPICAL FUSION DEVICE.

•LITHIUM SYSTEMS MOCKED UP IN THIS FACILITY MAY BEHAVE DIFFERENTLY THAN IN A FUSION DEVICE BECAUSE OF THESE SCALING ISSUES; MOCKUP TESTS REQUIRE SPECIAL INTERPRETATION.

•IT'S NECESSARY TO USE PRECISION MEASUREMENTS TO 'BENCHMARK' CHECK LMMHD COMPUTER SIMULATION CODES.

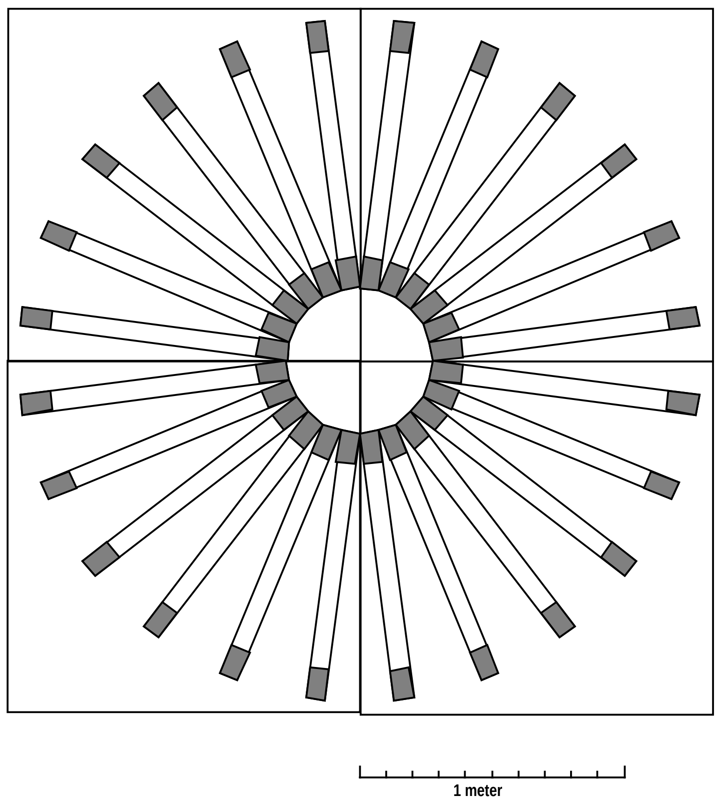
THE TARA COILS

•THE DIAGRAM SHOWS 24 TARA COILS IN PLAN VIEW. 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.

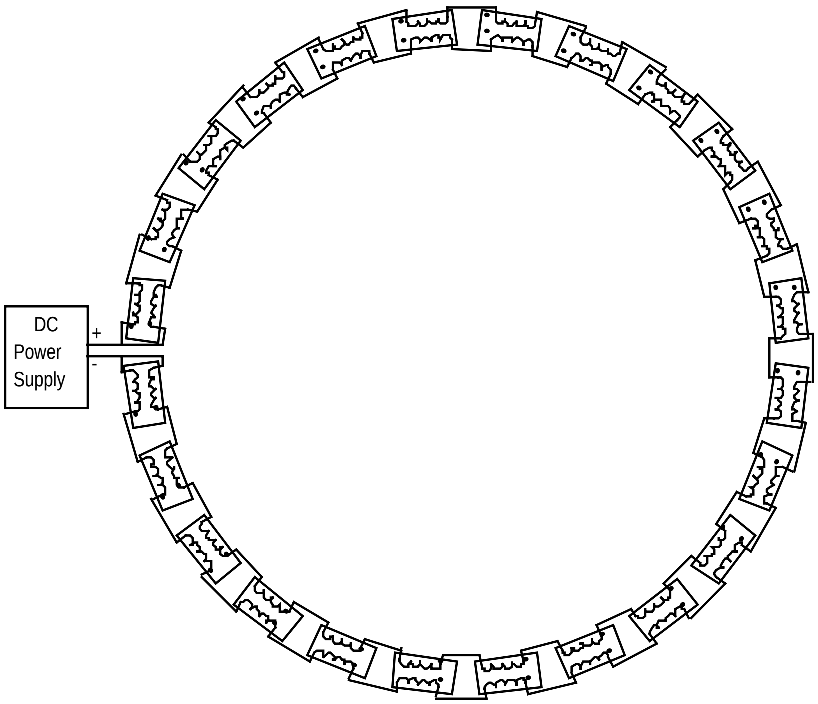


TF POWER CIRCUIT

- 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 (HALF OF RATING) 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.



24 TARA COILS IN TOROIDAL FACILITY

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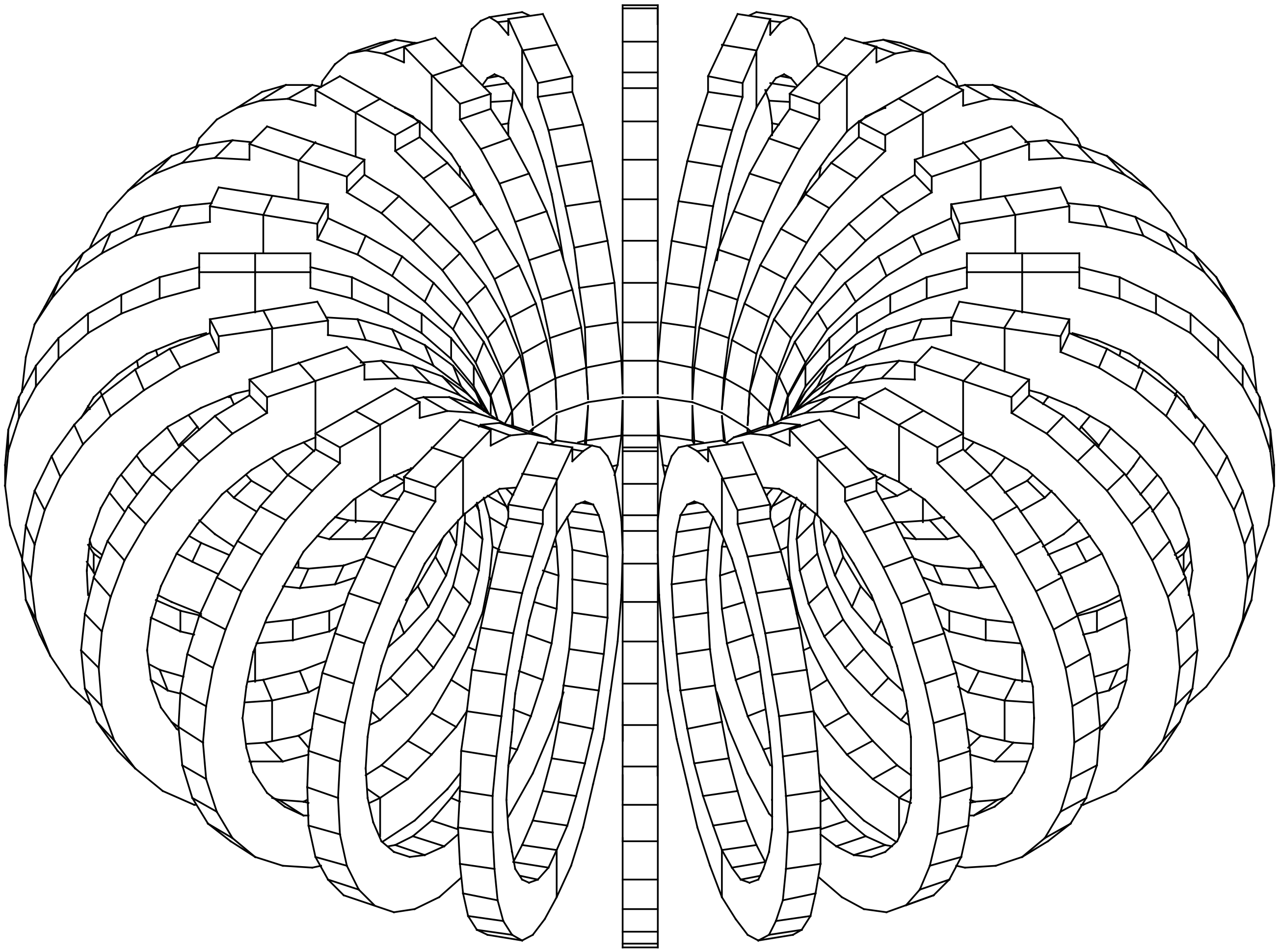


TOROIDAL FIELD STRENGTH & COIL FORCES

•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, 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.

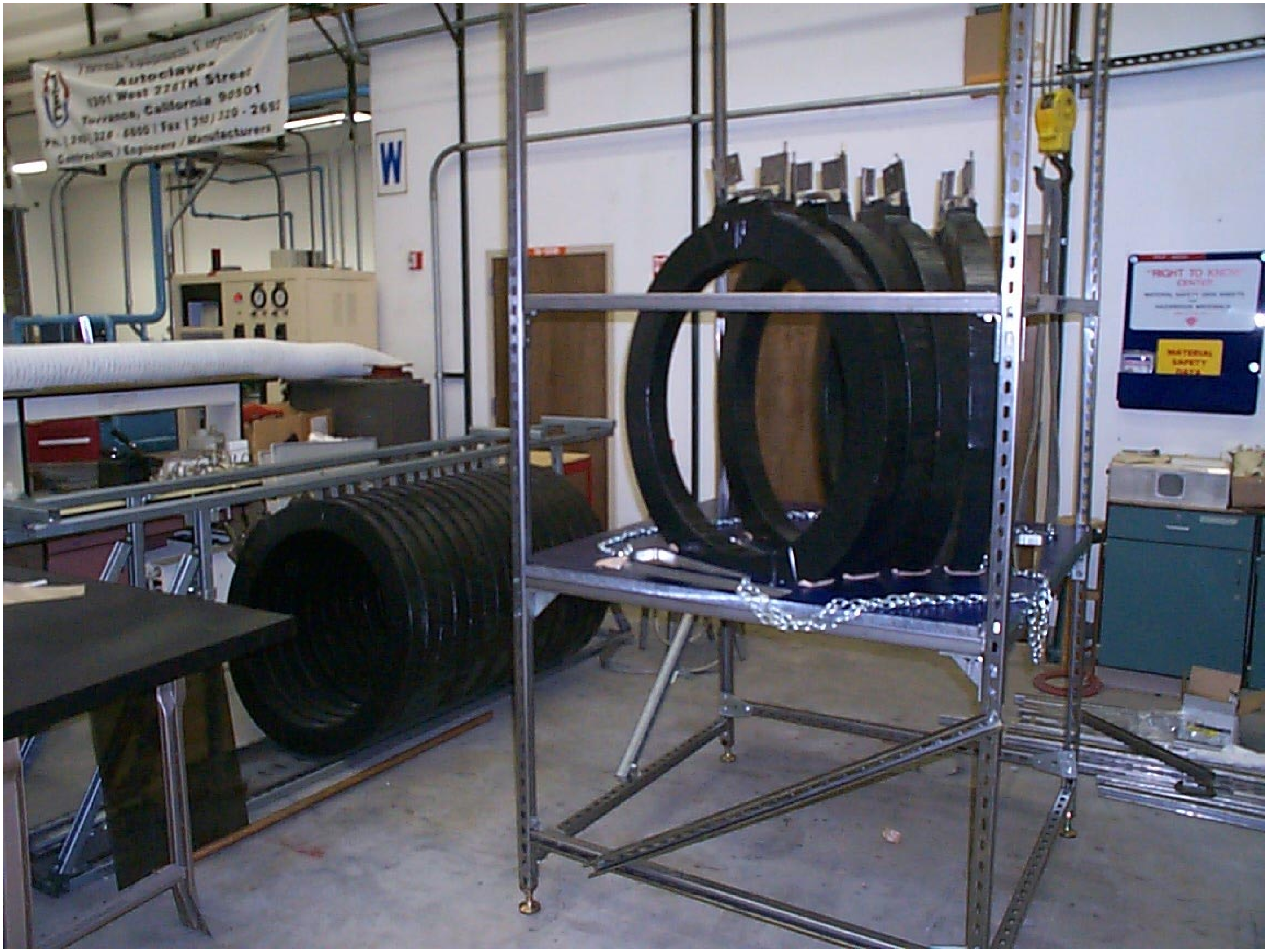
TOROIDAL FACILITY SUPPORT STRUCTURE

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

- THE DESIGN RELIES 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 EASILY MOVEABLE.

- UPPER AND LOWER SHELVES ARE INTERCONNECTED BY STRUTS.
- UPPER SHELF WILL CARRY BUSWORK AND COOLING WATER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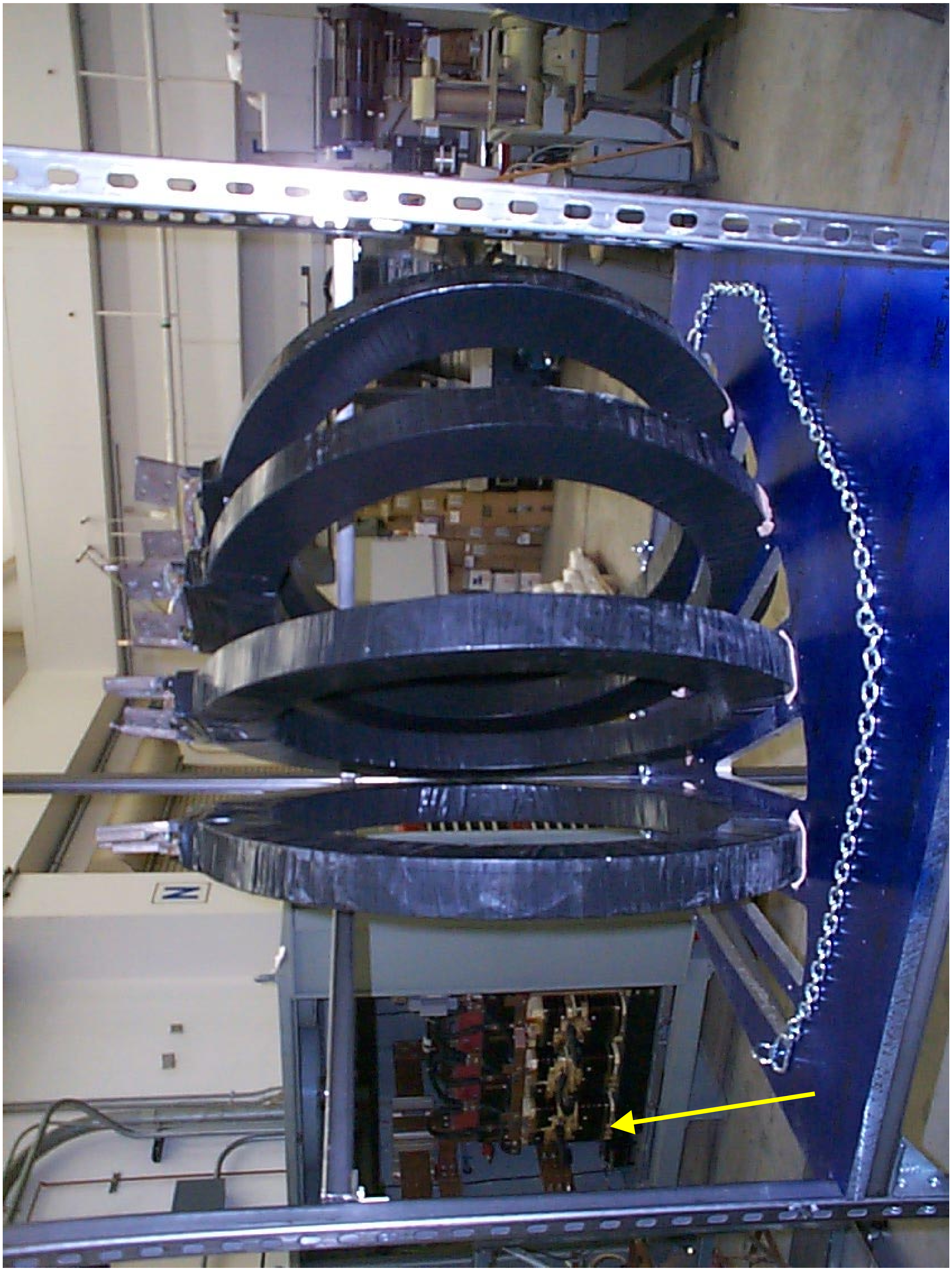

RELEVANT SCHEDULES—CDX-U & NSTX

•FLOWING LIQUID LITHIUM IN NSTX MAY BE AN APEX OPPORTUNITY, AND IT SETS THE SCHEDULE FOR EXPERIMENTAL LMMHD FACILITY RESULTS. FLOWING LI WOULD PROVIDE NSTX LONG-PULSE COOLING SUPERIOR TO CARBON TILES, BUT MAY NOT BENEFIT NSTX MISSION.

•BENEFIT TO NSTX MISSION OF PLASMA OPERATION WITH LOW HYDROGEN RECYCLING MAY EXIST. IF SO, IT SHOULD BE OBSERVED EXPERIMENTALLY IN CDX-U. THE CDX-U PLANNED LITHIUM EXPERIMENTAL PROGRAMME EXTENDS THROUGH SEPTEMBER 2002, INCLUDING POLOIDAL DIVERTOR OPERATIONS.

•NSTX INSTALLATION OF SYSTEMS PROVIDING LIQUID LITHIUM WOULD PROBABLY COINCIDE WITH INSTALLATION OF A NEW NSTX CENTERSTACK, NOW ANTICIPATED LATE IN FY2003. HOWEVER, THE DETAILED ENGINEERING DESIGN OF NSTX LITHIUM SYSTEMS WOULD NEED TO START IN FY2001 (ALONG WITH THE NEW CENTERSTACK ENGINEERING DESIGN WHICH NSTX PLANS FOR FY2001).

OVERVIEW LMMHD TOROIDAL FACILITY SCHEDULE

PHASE 1: TOROIDAL FIELD, POLOIDAL CURRENT, POLOIDAL MOTION

FY2000 DESIGN, CONSTRUCTION, COMMISSIONING & INITIAL EXPERIMENTS OF TF SYSTEM, LM SUPPLY,DRAIN, FLOW GUIDES, PUMPING, LM CURRENT INJECTION, SURFACE SHAPE DIAGNOSTICS, VELOCITY PROFILE DIAGNOSTICS.

FY2001 TF ONLY EXPERIMENTS

PHASE 2: TOROIDAL + POLOIDAL FIELD, CURRENT, MOTION

FY2002 INSTALL, COMMISSION PF COILS AND FULL 360° LM FLOW SYSTEMS.

FY2003: ALL COMPONENT (TOROIDAL+POLOIDAL) EXPERIMENTS

FACILITY VISION –EXPERIMENTERS & PROTOCOLS

•UCLA WILL MANAGE AND CONTROL THE LMMHD TOROIDAL FACILITY.

•EXPERIMENTERS WILL INCLUDE UCLA STAFF AND STUDENTS, APEX COLLABORATORS FROM OTHER INSTITUTIONS, AND PERHAPS OTHERS. (PROGRESS MAY BE LIMITED BY PERSONNEL AVAILABILITY.)

• EACH EXPERIMENT PLAN TO BE WRITTEN/REVIEWED IN ADVANCE.

•MEASUREMENTS AND FINDINGS SHOULD BE DOCUMENTED AND AVAILABLE TO ALL ASAP AFTER DATA ARE OBTAINED. IMMEDIATE APEX WEB POSTINGS OF PRELIMINARY RESULTS WOULD SUFFICE.

•EVENTUAL PUBLICATION OF EXPERIMENTAL RESULTS IS DESIRED.