PROPOSAL - (TCV-RELATED) TCA EXPERIMENTS WITH ELONGATED PLASMAS

FREDERICK B. MARCUS

ABSTRACT

By reconnecting the vertical and radial field coils in TCA, elongated plasmas with b/a up to 1.5 / 1 may be produced in the existing vessel. Experiments for assisted startup, heating and control are proposed in conjunction with TCA existing equipment and the planned gyrotron acquisition. Problems of vertical instability, required plasma-wall gap, and heating limits are investigated.

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne

PROPOSAL-(TCV-RELATED) TCA EXPERIMENTS WITH ELONGATED PLASMAS F.B. MARCUS, JUL 1988

COIL CONNECTIONS:

--WITH THE PRESENTLY AVAILABLE TCA COILS AND POWER SUPPLIES, BUT BY CONNECTING THE COILS IN A DIFFERENT ORDER:
-- NON-CIRCULAR PLASMAS SHAPES MAY BE CREATED.

--A HEXAPOLE NULL AT BREAKDOWN MAY BE FORMED, TO BE USED WITH THE GYROTRON AT 39 GHZ BEING ACQUIRED BY POCHELON.

FIELD SHAPES:

--HEXAPOLAR FIELD (EQUILIBRIUM AND ELONGATION)
PLUS RADIAL FIELD (VERTICAL POSITION STABILIZATION)
(ELONGATION OF 1.0 TO 1.5/1)

--HEXAPOLE PLUS PULSED VERTICAL FIELD GIVING A ZERO FIELD HEXAPOLE AT BREAKDOWN

PLASMAS:

--SHIFTED, ELONGATED PLASMAS WITH A HEXAPOLE FIELD, WITH ELONGATIONS OF 1.0 TO 1.5/1 DEPENDING ON CURRENT, TOROIDAL FIELD, BETA, Q, RADIAL POSITION, WITH CURRENTS UP TO 50 KAMPS (LIMITED BY COIL CURRENTS OF 2KA X 10 TURNS).

VERTICAL INSTABILITY:

--THERE IS A SERIOUS PROBLEM WITH VERTICAL INSTABILITY IN TCA.

--WITH A NORMAL PLASMA-WALL GAP OF 6 CM AND A MINOR RADIUS OF 11 CM, ELONGATED PLASMAS ARE IDEALLY UNSTABLE FOR $K > 1.3$

--WITH A 3 CM PLASMA-WALL GAP (VERY NEAR TO VESSEL ISOLATION GAP), WALL STABILIZATION BECOMES EFFECTIVE.

PRESENT TCA CONNECTIONS:
--CONTROLLABLE RADIAL, VERTICAL FIELDS
(USES SUM, DIFFERENCE OF VOLTAGE SOURCES)
--PULSED, INITIAL QUADRUPOLE FIELD
(SUPPLY TESTED OK, BUT NOT NECESSARY)

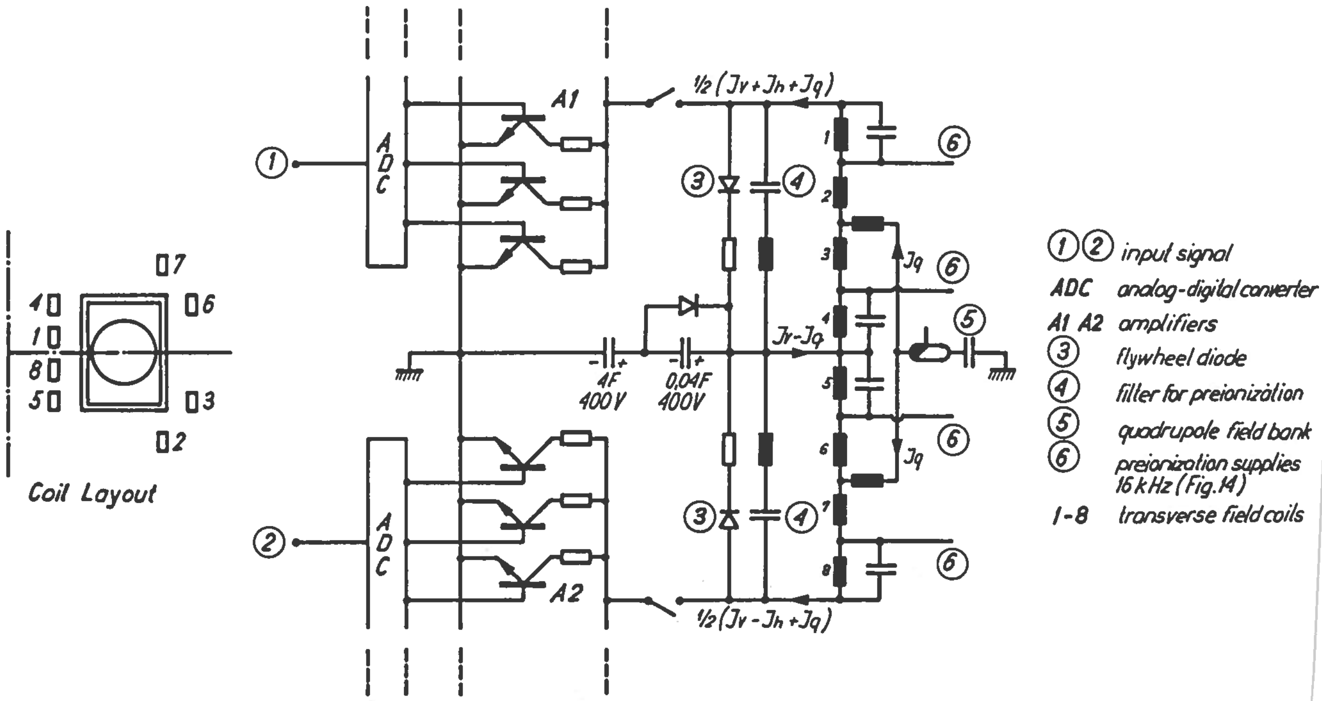
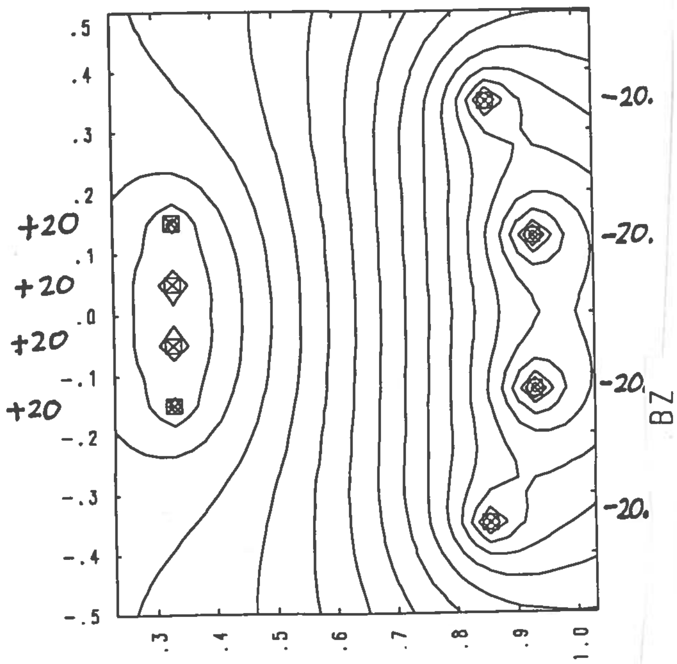
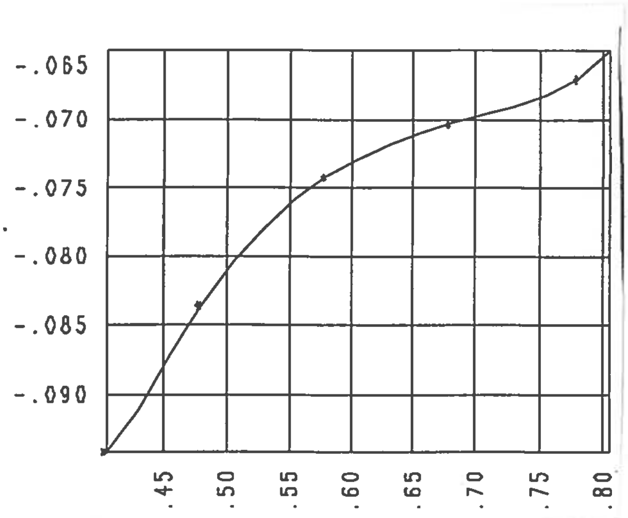


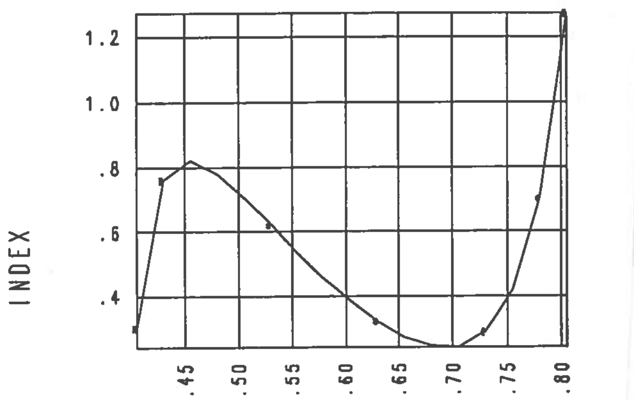
Fig 11 Transverse field power supplies

-FIELD SHAPES: DIPOLE (NORMAL IN TCA FOR CIRCULAR PLASMAS)

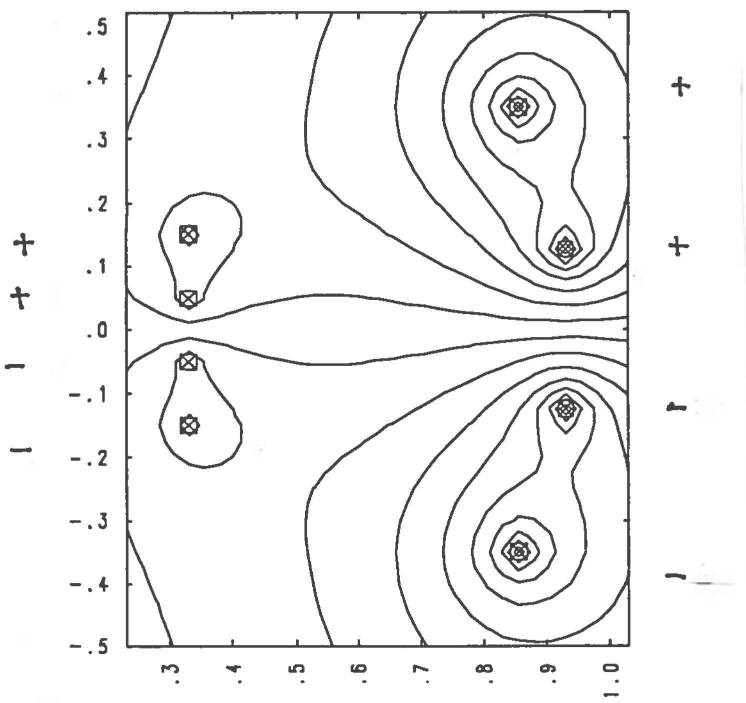


VERTICAL FIELD

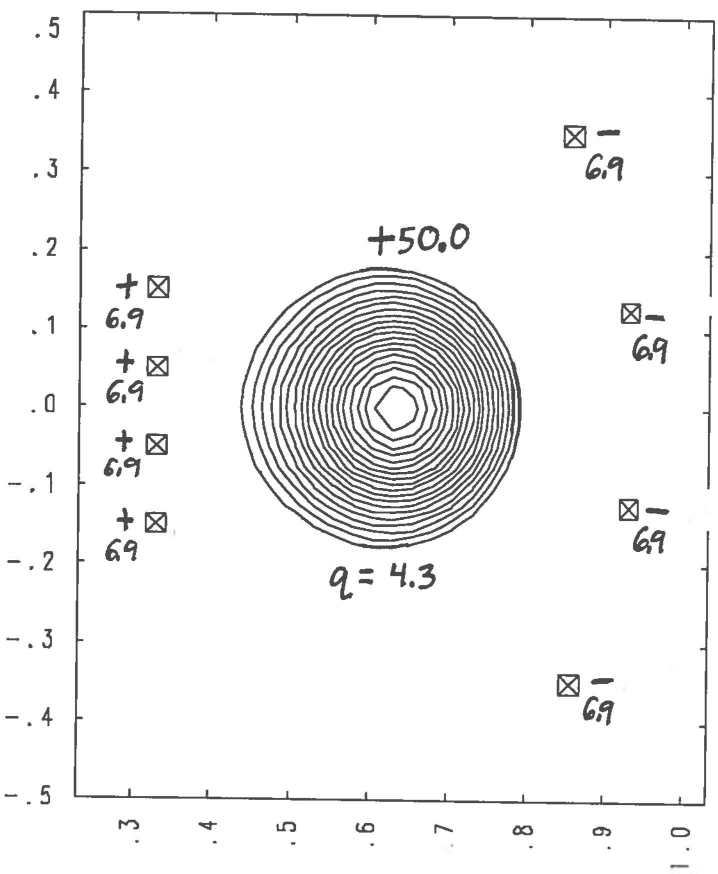




RADIAL FIELD

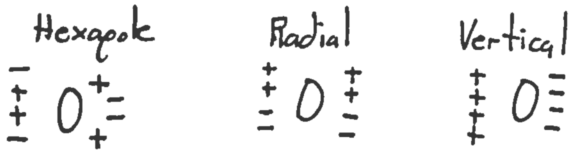


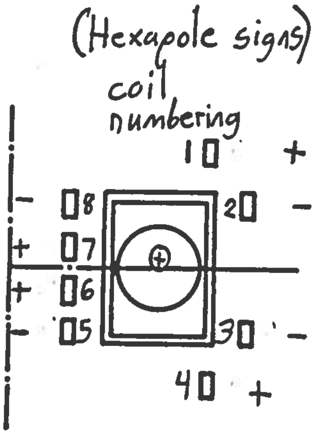
-PLASMA: CIRCULAR(NORMAL)



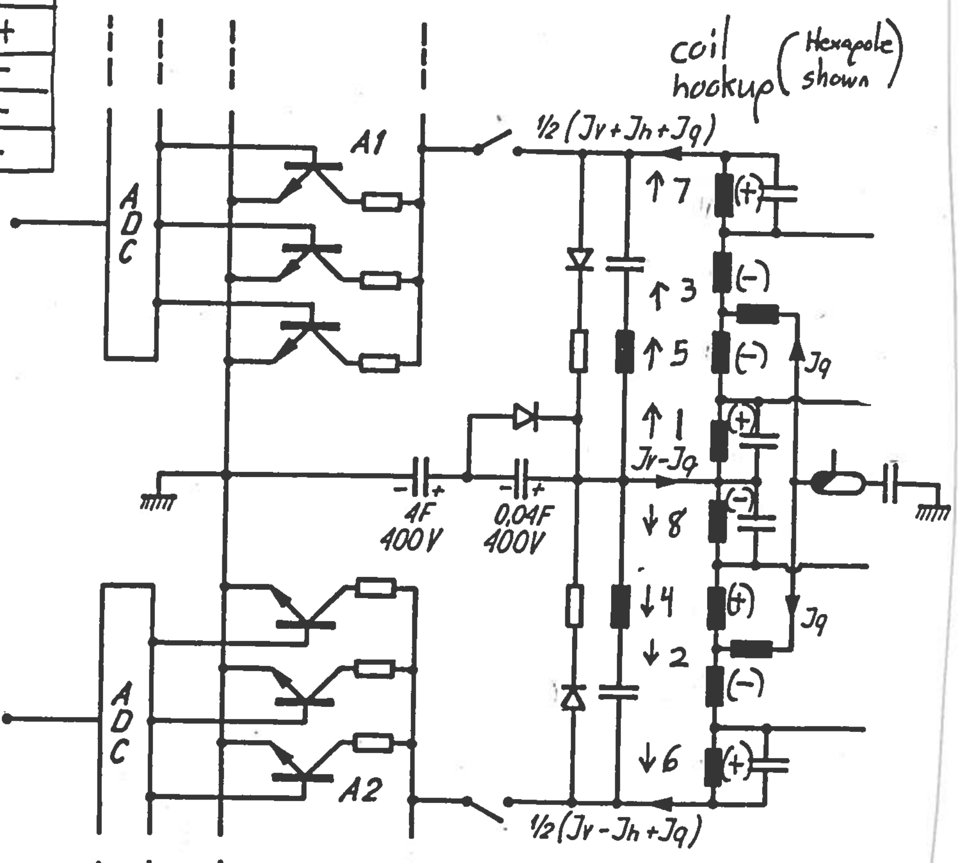
TCA CONNECTIONS TO GIVE:
--CONTROLLABLE HEXAPOLE WITHOUT NULL (EQUILIBRIUM FIELD)
--CONTROLLABLE RADIAL FIELD (VERTICAL POSITION FEEDBACK)
--PULSED, INITIAL VERTICAL FIELD (CREATES BREAKDOWN NULL IN HEXAPOLE)

coil #	Hexapole	Radial	Vertical
7	↑ +	↑ +	↑ +
3	↑ −	↑ −	↑ −
5	↑ −	↑ −	↓ +
1	↑ +	↑ +	↓ −
8	↓ −	↑ +	↑ +
4	↓ +	↑ −	↑ −
2	↓ −	↑ +	↓ −
6	↓ +	↑ −	↓ +





Coil Layout



$J_v \equiv J_{HEXAPOLE}$

$J_h \equiv J_{RADIAL\ FIELD}$

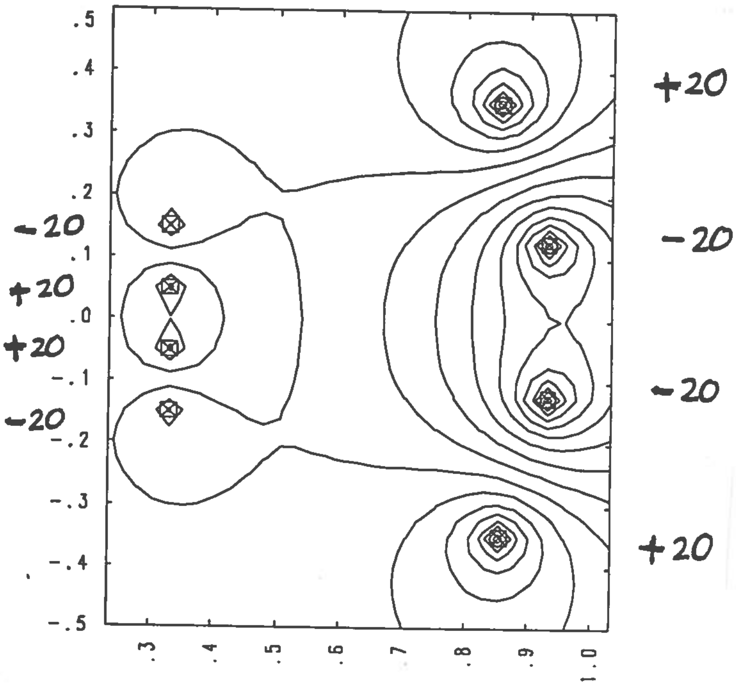
$J_q \equiv J_{VERTICAL\ FIELD}$

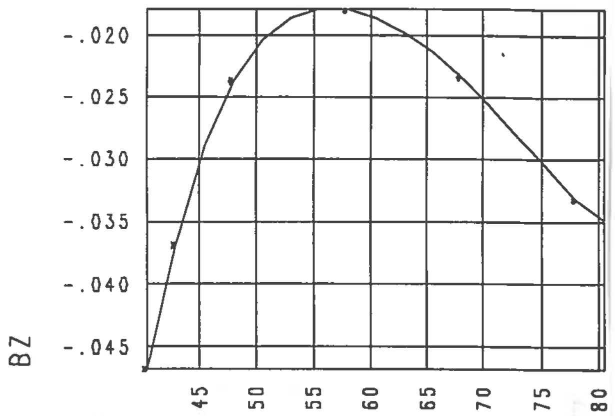
Transverse field power supplies

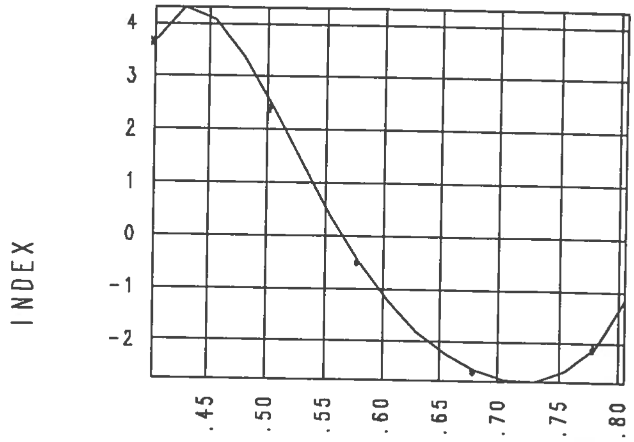
HEXAPOLE IN TCA

ONE CURRENT ONLY, SERIES CONNECTION, ZERO SUM

USING ACTUAL TCA SYSTEM, PRODUCES BOTH RADIAL AND VERTICAL FIELDS





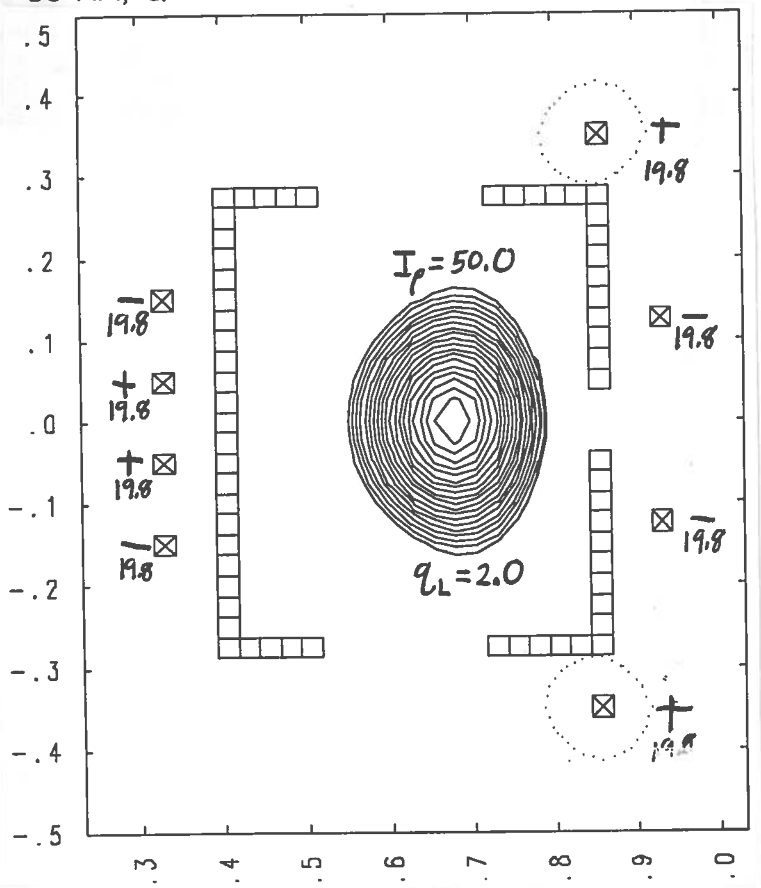


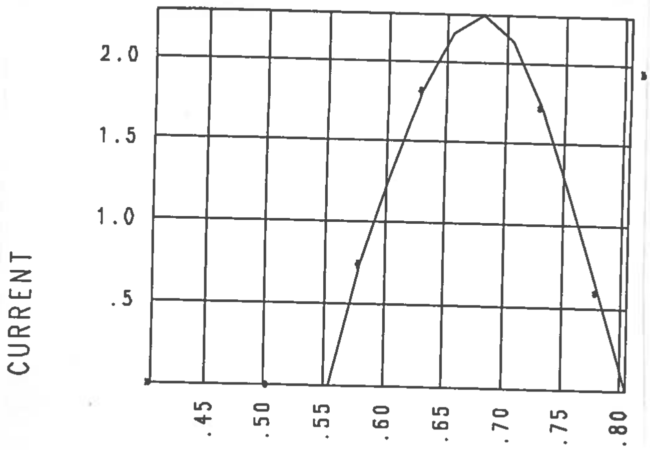
NOTE THAT THE QUADRUPOLAR VERTICAL FIELD HAS NO NULL, AND THAT THE FIELD ALWAYS HAS THE SAME SIGN

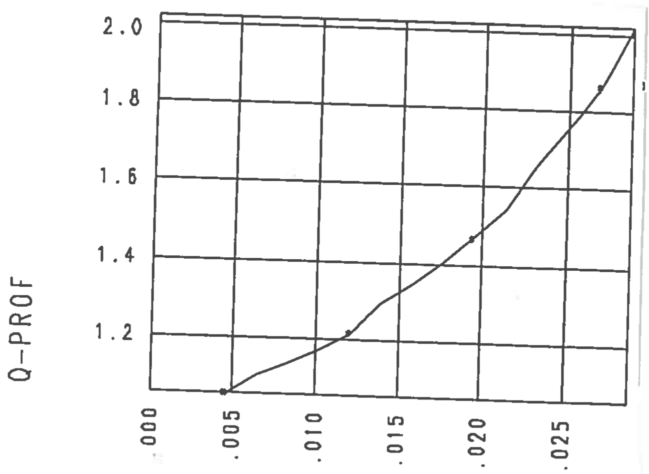
THE SHAPES OF THE RADIAL AND VERTICAL FIELD ARE THE SAME AS IN THE STANDARD TCA HOOKUP

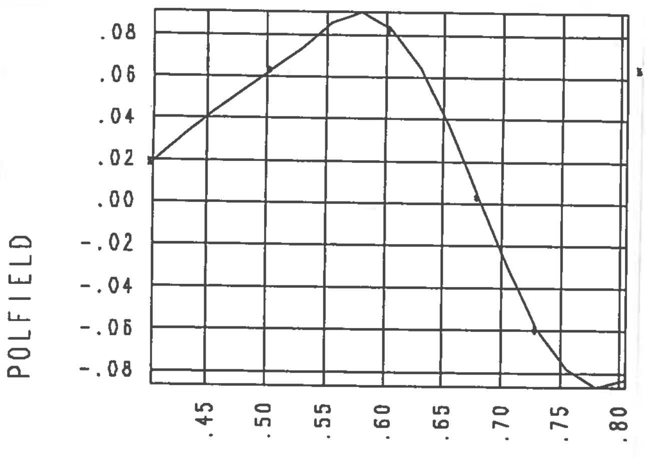
SHIFTED, ELONGATED PLASMA WITH HEXAPOLE FIELD

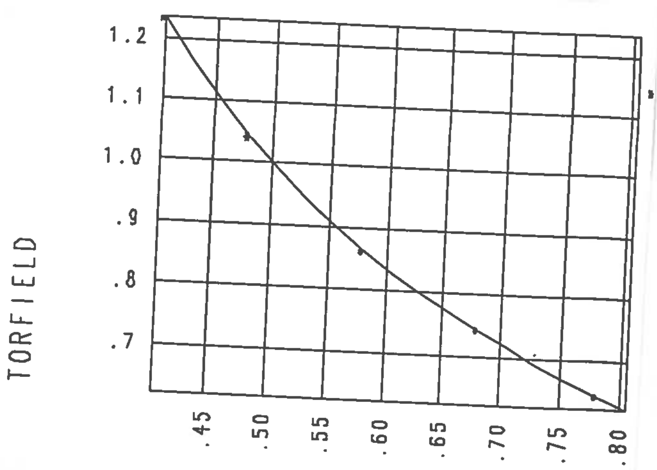
--R = 68. CM, A = 11.5 CM, **B/A = 1.34**, BTOR(68 CM) = 7.3 KG, IP = 50 KA, QLIM = 2.0 .





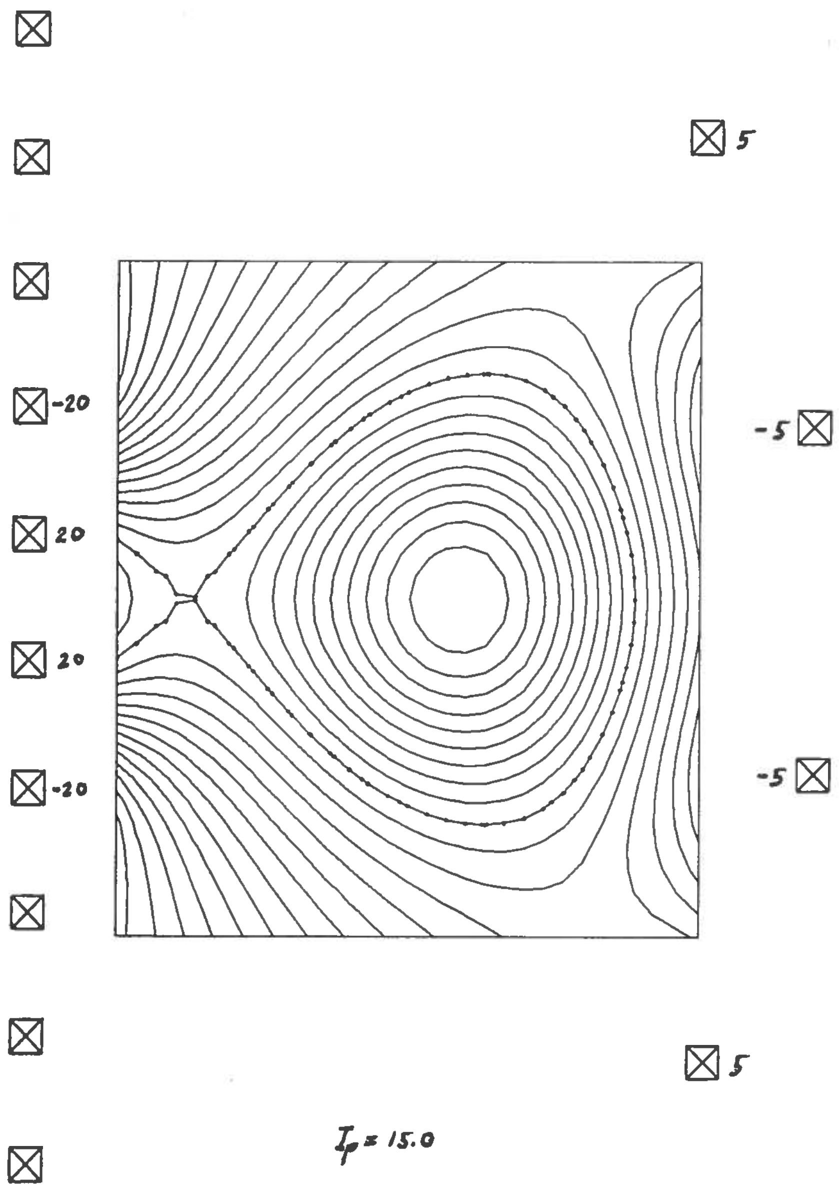






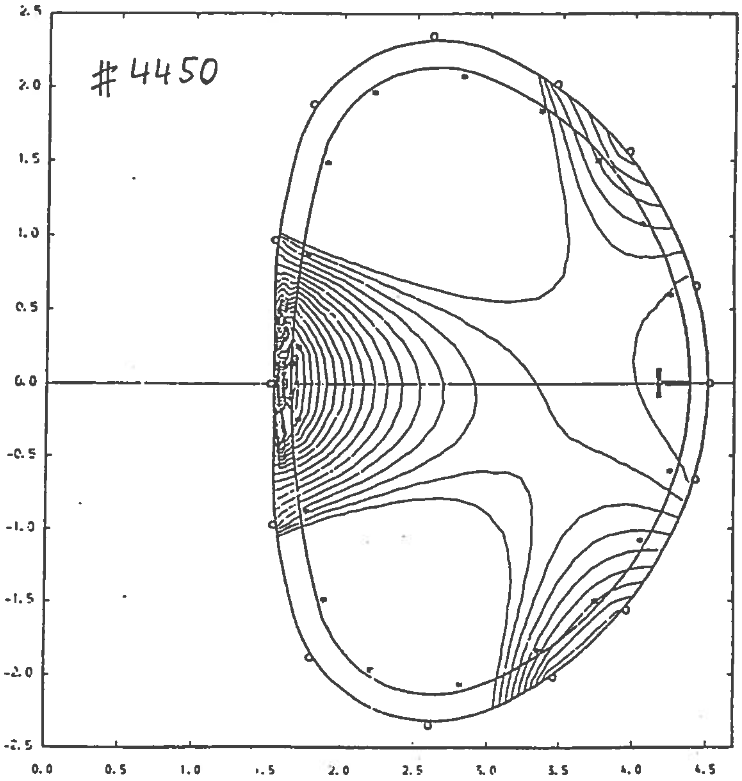
HEXAPOLE CONFIGURATIONS FOR DIVERTOR PLASMAS IN TCA HAVE BEEN PREVIOUSLY PROPOSED BY F. HOFMANN (TCA SCIENTIFIC REVIEW MEETING, 2.10.84)

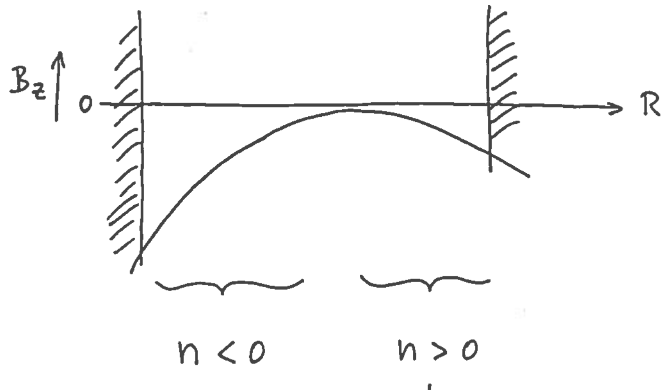
--NOTE TWO VALUES OF ZERO SUM CURRENTS USED.



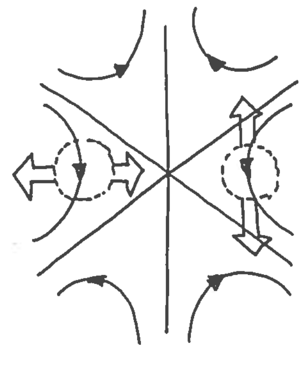
HEXAPOLE (FOR BREAKDOWN

-FIELD SHAPES: JET STARTUP

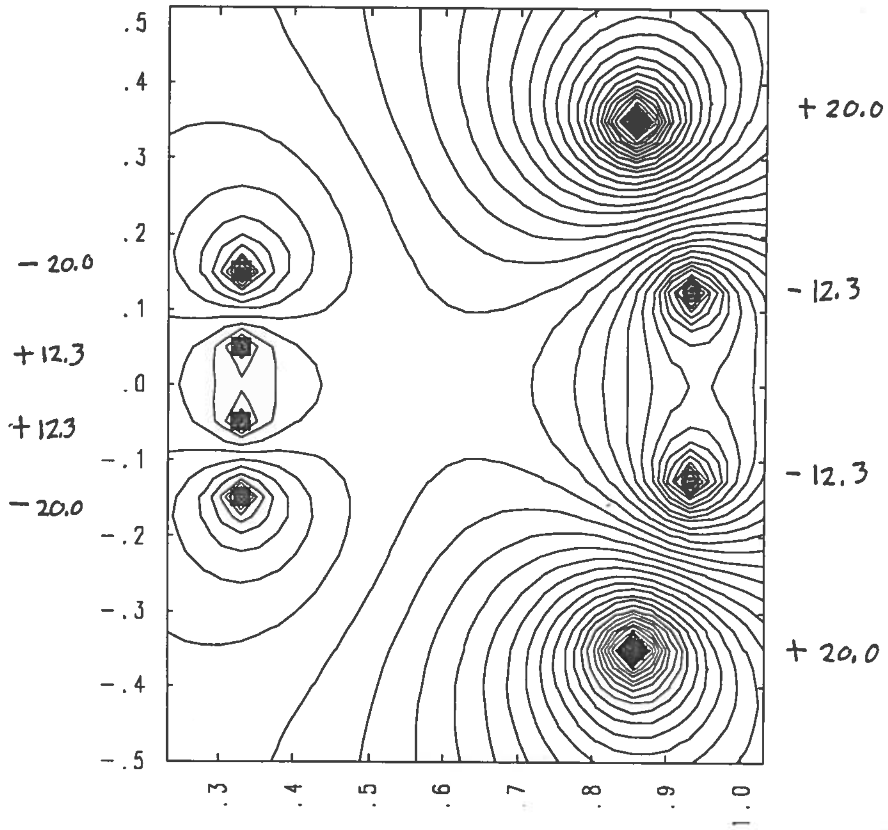


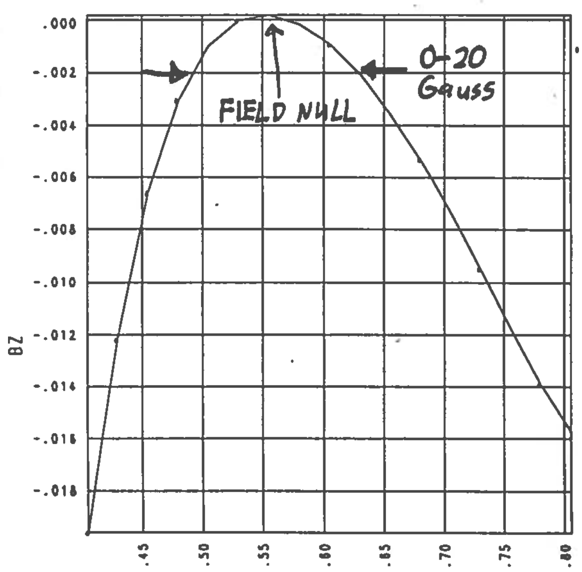


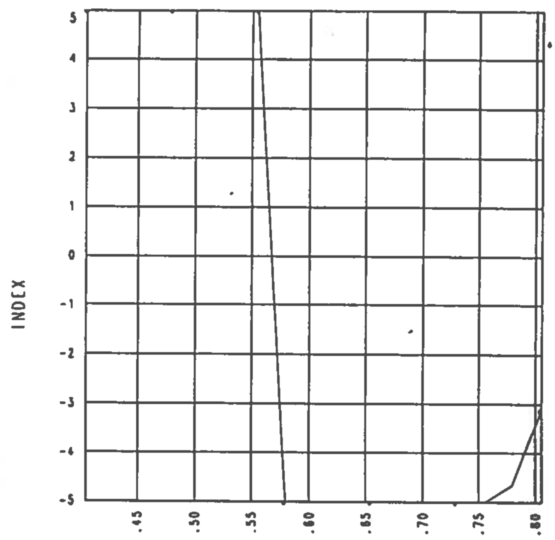
tendency for radial vertical instability



BY COMBINING THE CONTINUOUSLY CONTROLLABLE HEXAPOLE FIELD WITH A PULSED VERTICAL FIELD, A HEXAPOLE-NULL FIELD MAY BE CREATED, SIMILAR TO JET, FOR BREAKDOWN STUDIES





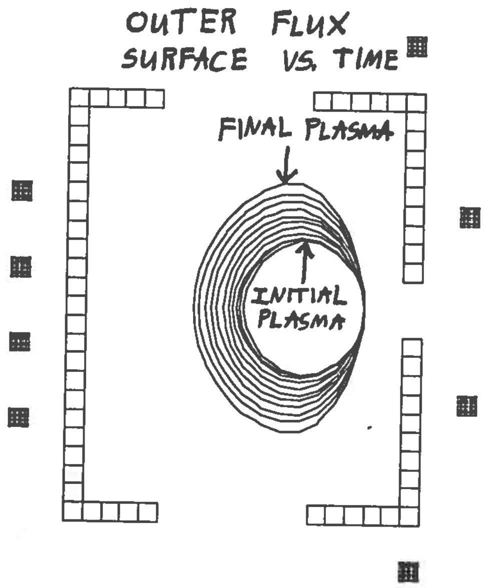


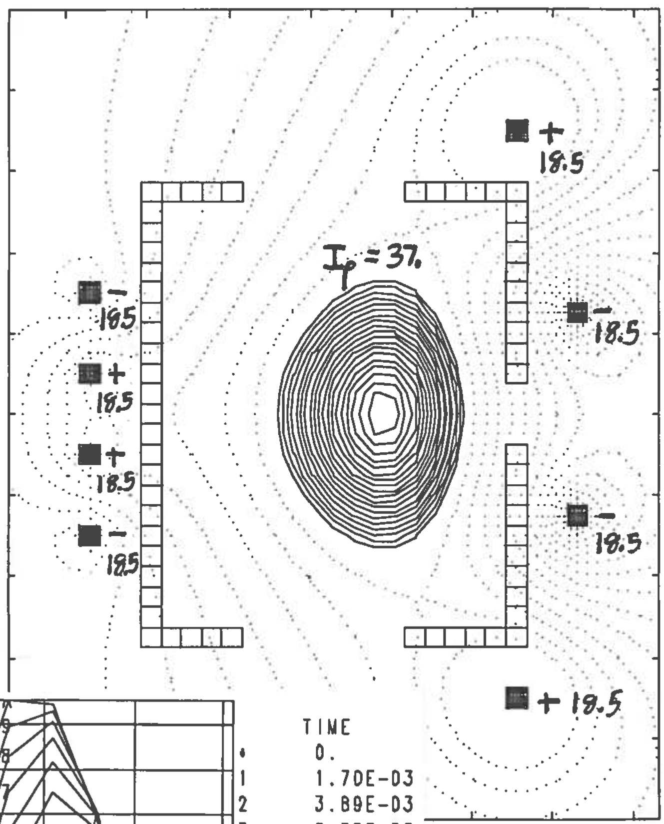
THE PULSED FIELD LASTS ONLY A FEW MSECS, THEN THE NORMAL HEXAPOLE FIELD IS USED TO CONTROL RADIAL POSITION AND HENCE SHAPE

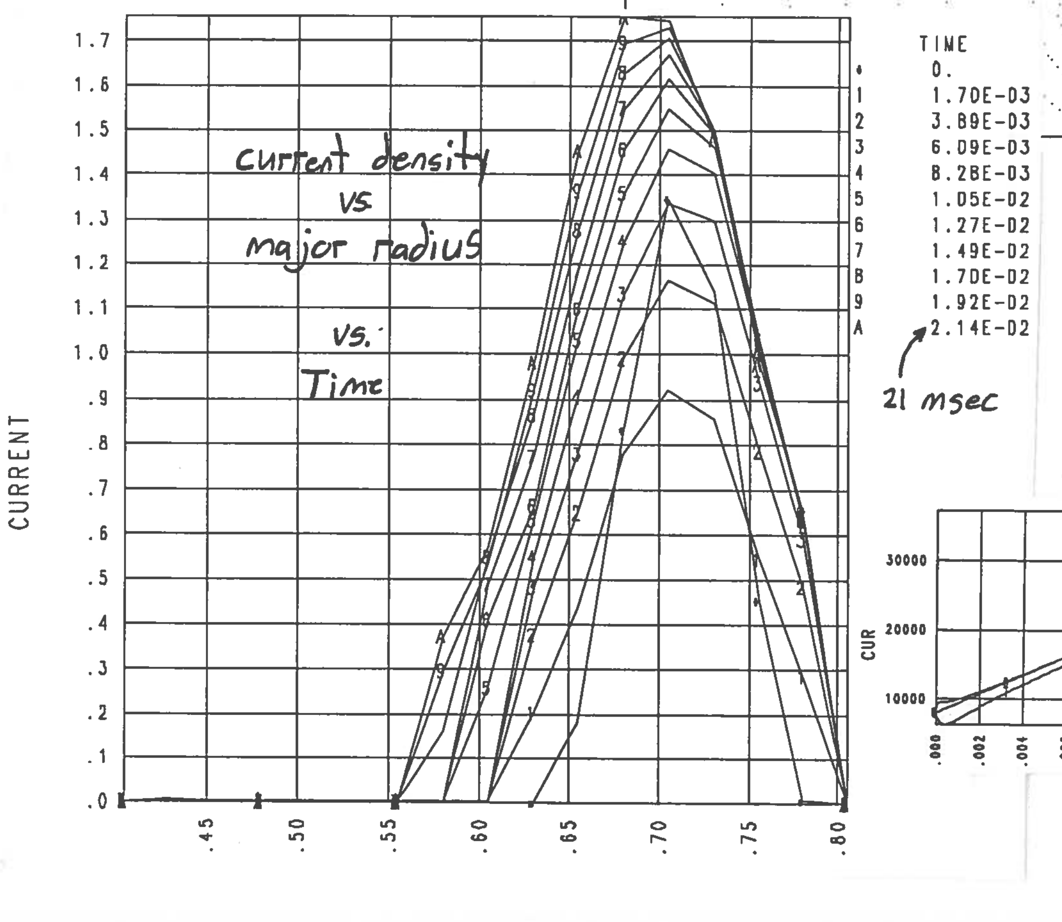
EVOLUTION IN TCA - CIRCULAR PLASMA TO ELONGATED PLASMA ON THE OUTER LIMITER

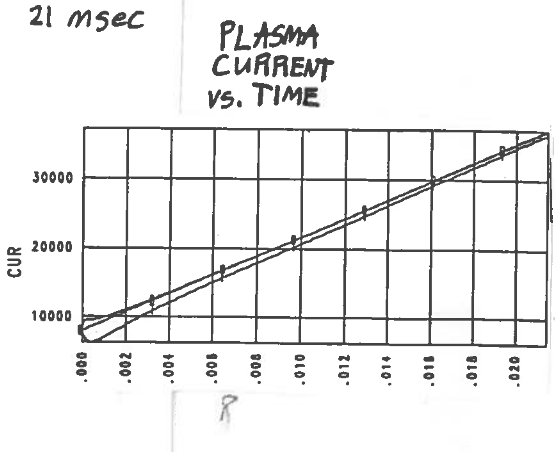
THE ELONGATION DEPENDS ON THE PLASMA RADIAL POSITION, CURRENT PROFILE, ETC.

IN THIS SIMULATION, THE CURRENT, POSITION, AND PRESSURE ARE RAMPED SIMULTANEOUSLY

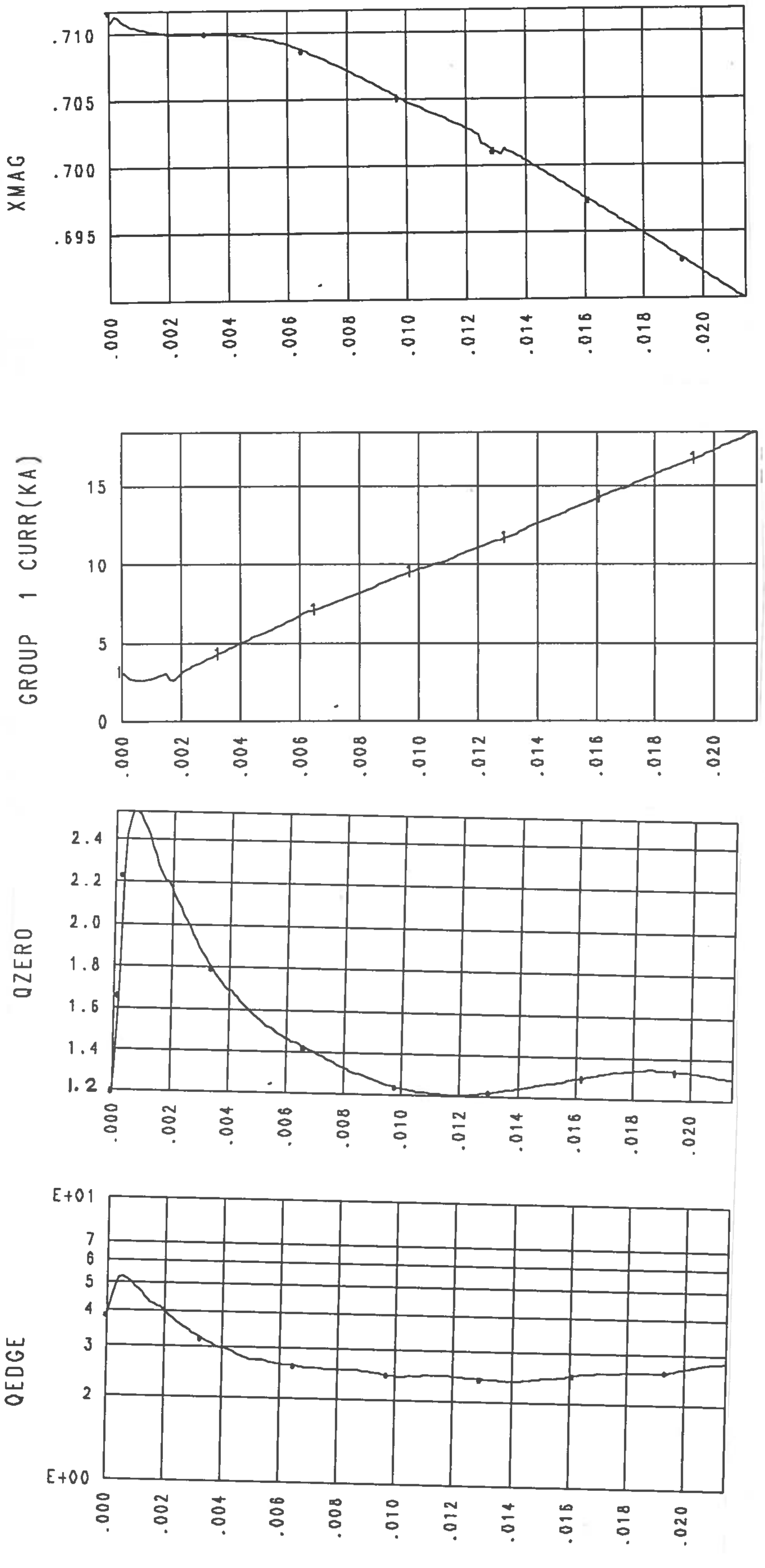








EVOLUTION IN TCA - CIRCULAR PLASMA TO ELONGATED PLASMA ON THE OUTER LIMITER AT 21 MSEC, IP=37 KAMP, B/A=1.42/1 BT=6.8T AT R-MAG=.69M



VERTICAL INSTABILITY GROWTH RATES IN TCA

--THE GROWTH RATES OF ELONGATED PLASMAS IN TCA WERE STUDIED WITH TSC BY VARYING PLASMA POSITON, ELONGATION, Q, AND FFAC FOR CONVERGENCE, TURNING OFF FEEDBACK, WITH AND WITHOUT PASSIVE STABILIZATION.

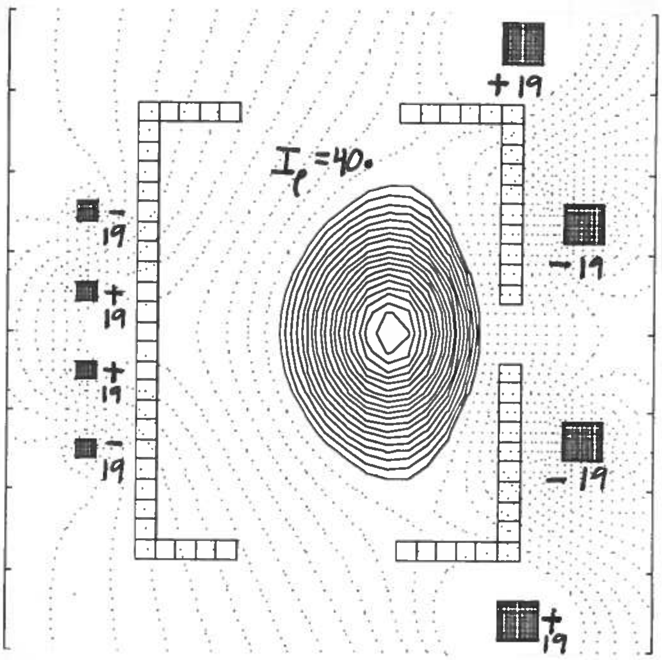
--WITH A PLASMA WALL GAP OF 6 CM, K=1.42/1, QLIM=2.6, THE PLASMA WAS VERTICALLY IDEALLY UNSTABLE (GAMMA LINEAR WITH FFAC).

--WITH A PLASMA WALL GAP OF 3 CM, THE PLASMA IS IDEALLY STABILIZED.

--RESISTIVE GROWTH RATES:
(GAP=3 CM)

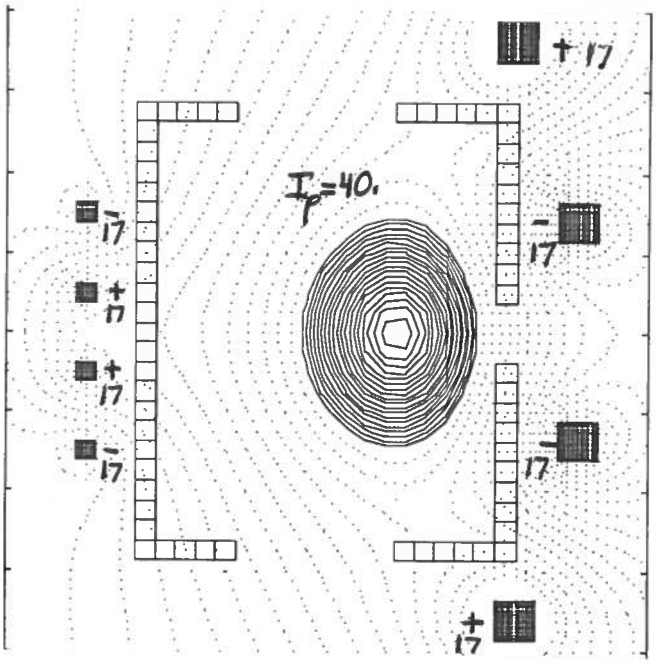
--K=1.48/1, QLIM=3.4, IP=40 KAMP,
ICOIL=1.9KA X 10 TURNS, R*BT=0.51,
RMAG-AXIS=71 CM, A=12.5 CM, B=18.5 CM,

RESULTS:
FFAC=5, WITH VESSEL: GAMMA=5000 SEC-1
FFAC=5, NO VESSEL: GAMMA=27000 SEC-1
FFAC=2.5, WITH VESSEL: GAMMA=6700 SEC-1
CONCLUSION: PLASMA IS IDEALLY STABLE, WITH ASYMPTOTIC GAMMA OF 8300 SEC-1.

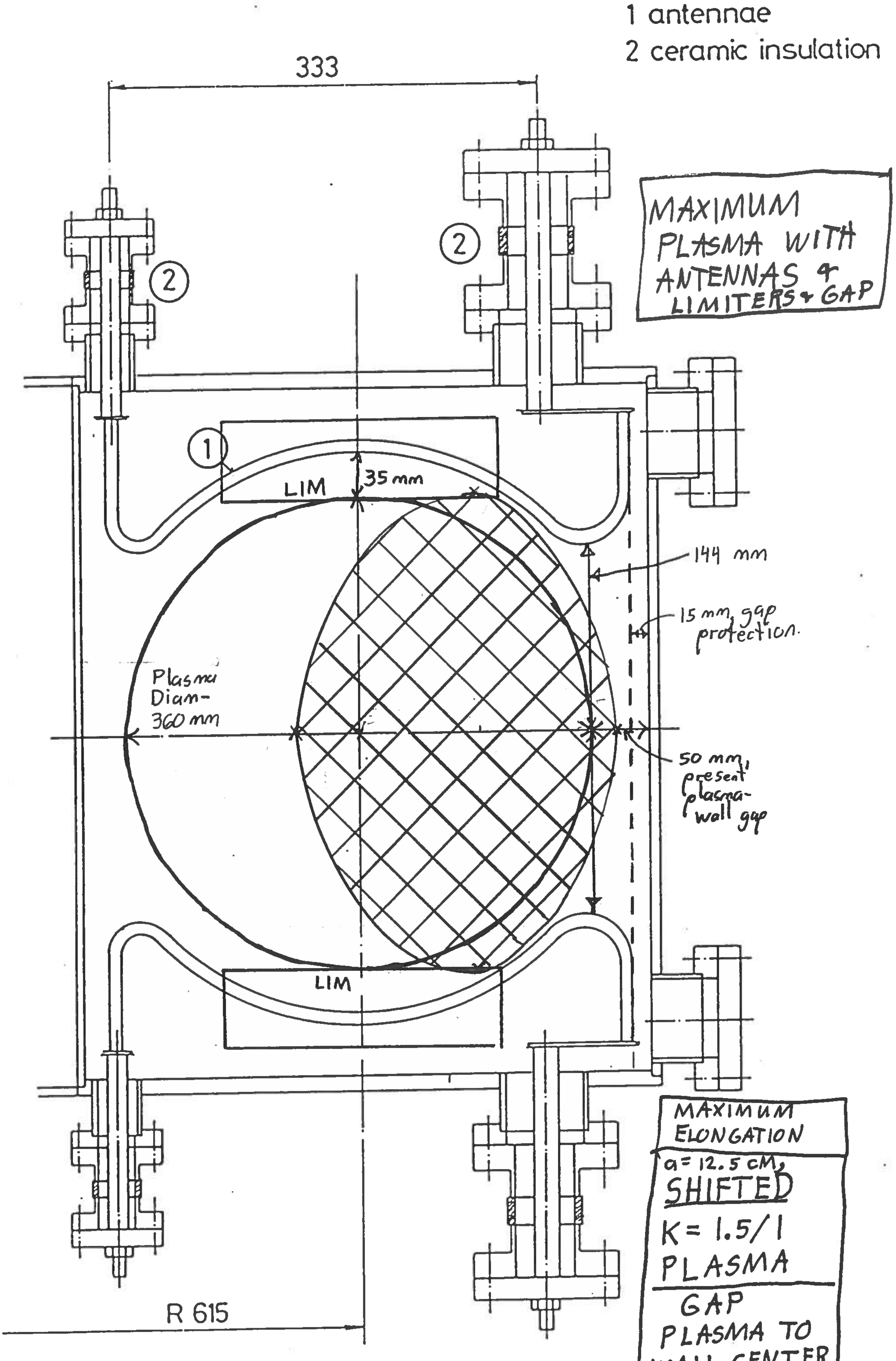


--K=1.30/1, QLIM=2.1, IP=40 KAMP,
ICOIL=1.7KA X 10 TURNS, R*BT=0.51,
RMAG-AXIS=72 CM, A=11 CM, B=14.3 CM,

RESULTS:
FFAC=5, WITH VESSEL: GAMMA=2300 SEC-1
CONCLUSION: THIS IS MUCH LOWER THAN IDEAL GROWTH RATE, AND SHOULD BE NEAR THE ASYMPTOTIC GROWTH RATE.



GENERAL COMMENT:
WITH THE HIGH FREQUENCY TRANSISTOR SUPPLIES OF TCA, GROWTH RATES OF SEVERAL TIMES THE INVERSE VESSEL TIME OF 1/(1 MSEC) SHOULD BE CONTROLLABLE, INCLUDING THE ABOVE.



TCA - poloidal section

ELONGATED TCA EQUILIBRIA WITH HIGH BETA-POLOIDAL AT LARGE ASPECT-RATIO

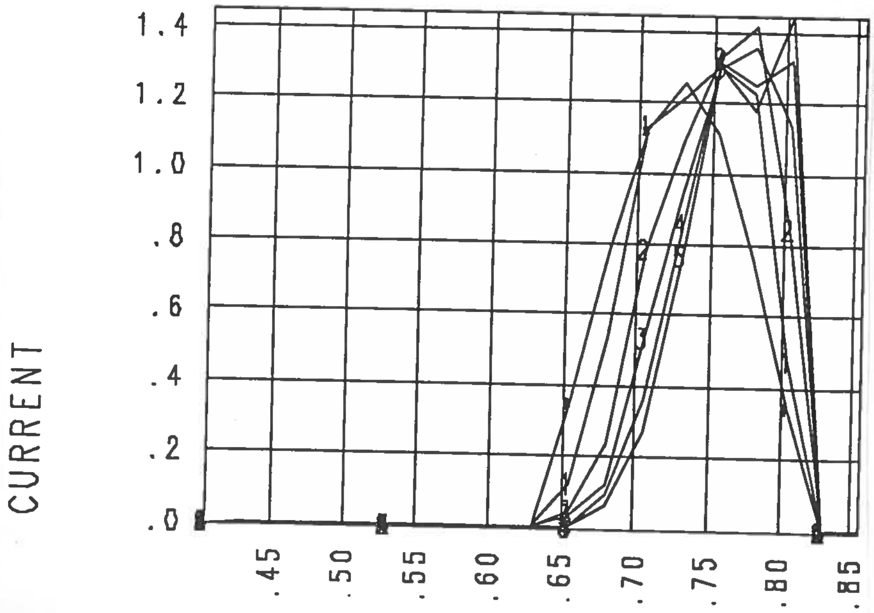
REFERENCES:

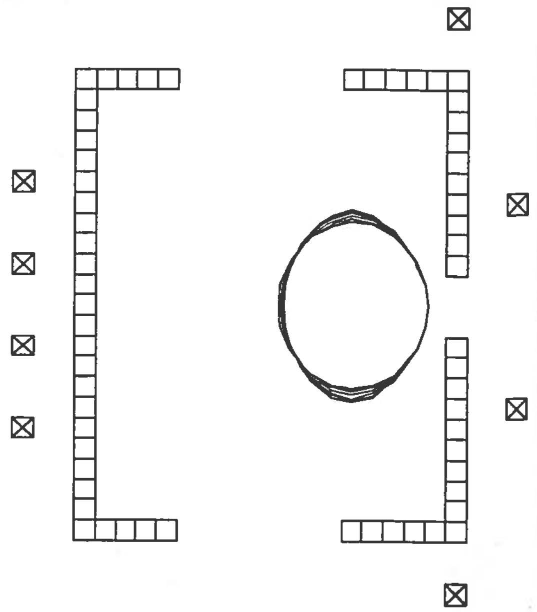
--ELECTRON CYCLOTRON HEATING EXPERIMENTS AT LARGE ASPECT RATIO HAVE BEEN DONE IN CLEO-TOKAMAK AT 3-18 KAMPS AND R/A=7, AT 2*OMEGA-CE. IN TOSCA, BETA-POL VALUES UP TO R/A WERE OBTAINED.(REF. ROBINSON ET AL., IAEA 1984)
--A PROPOSAL TO INVESTIGATE THE SECOND STABILITY REGIME BY OBTAINING HIGH BETA-POL AT HIGH R/A, 7-10, WAS PREPARED. (REF. REPORT NO. 109, DOE/ER/53222-95, COLUMBIA UNIVERSITY, 1987)

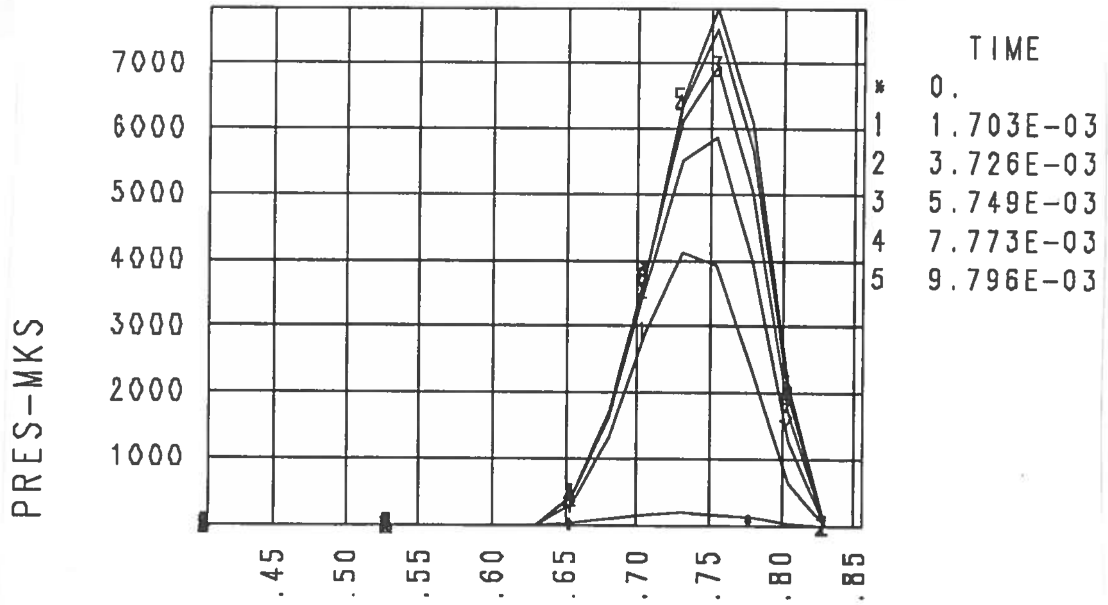
TCA EQUILIBRIA:

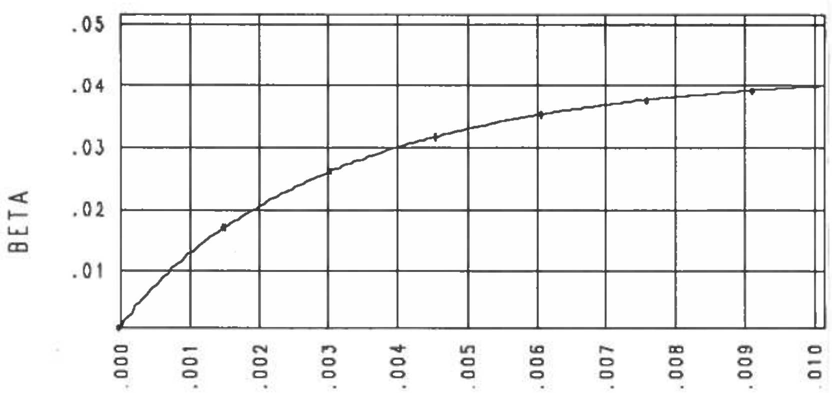
--IN TCA, EQUILIBRIA CAN BE FOUND AT HIGH BETA-POL AND HIGH ASPECT-RATIO.
--AS AN EXAMPLE, WE TAKE AN INITIAL PLASMA WITH BTOR=4.7 KG AT R=72 CM WITH IP=15 KAMPS, A=9 CM, B/A=1.14, AND PLASMA DENSITY OF 2*10**13 CM-3, THE GYROTRON CUTOFF LIMIT.
--THE TSC CODE IS USED TO CALCULATE THE PLASMA EVOLUTION IN THE PRESENCE OF 200 KW OF AUXILIARY HEATING, USING TRANSPORT COEFFICIENTS VERIFIED ON PPL TOKAMAK SIMULATION OF PBX AND TFTR.
--THE FINAL PLASMA STILL HAS 15 KAMPS, BUT B/A=1.34, THE EQUILIBRIUM WINDING CURRENT IS UP FROM 5 TO 12 KAT, QLIM HAS INCREASED FROM 2 TO 2.4, AND THE MAGNETIC AXIS HAS SHIFTED OUT BY 2.5 CM. BETA-POLOIDAL IS 7.9 AND BETA-TOROIDAL IS 4.0 % .
--THE ASPECT RATIO IS 8.5, SO THAT EPSILON*BETA-POL IS 0.93 THE NORMALIZED CURRENT IS I/(A*BT)=0.35, SO THE EXPECTED LIMITING BETA-TOR IS ABOUT 1.2 % . THE BETA-TOR IN THIS EQUILIBRIUM IS THUS UNREALISTICALLY HIGH. STABILITY CALCULATIONS SHOW THE PLASMA TO BE BOTH MERCIER AND BALLOONING UNSTABLE NEAR THE AXIS, AND BALLOONING UNSTABLE UP TO 2/3 OF THE RADIUS.
--ITS AXIS AND CURRENT ARE SHIFTED TO THE OUTSIDE, AND SHOULD BE MORE VERTICALLY STABLE, AND IT PERHAPS MAY BE MOVED FURTHER FROM THE WALL. DIVERTOR X-POINTS ARE APPROACHING THE PLASMA.
--WITH THE HEATING POWER AVAILABLE, IT SHOULD BE POSSIBLE TO EXPLORE BETA LIMITS AT LARGE ASPECT RATIO IN ELONGATED PLASMAS.
--THE ELONGATION IN TCA INCREASES WITH BETA-POL.

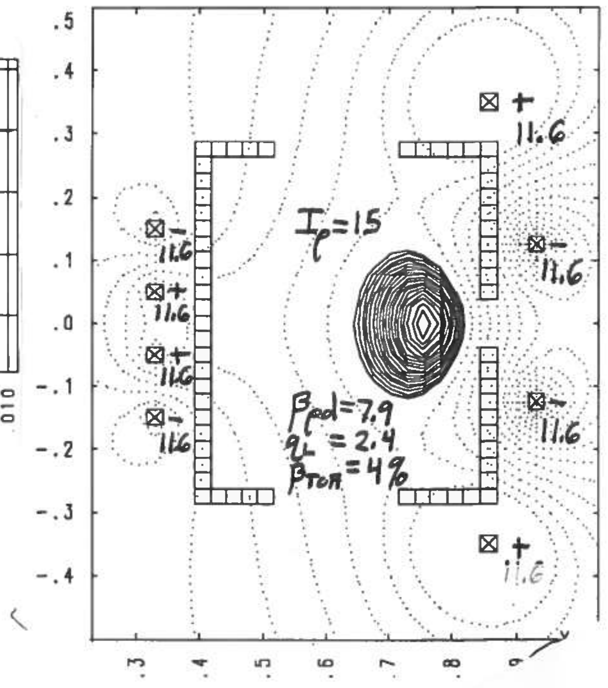
ELONGATED TCA EQUILIBRIA WITH HIGH BETA-POLOIDAL AT LARGE ASPECT-RATIO











RUNAWAY ELECTRONS, DISRUPTIONS, AND HARD X-RAYS IN TCA

--WITH GYROTRON HEATING, RUNAWAY ELECTRONS MAY EITHER BE GENERATED OR SUPPRESSED, DEPENDING ON THE MODE OF OPERATION.

--WITH ELONGATED PLASMAS IN TCA, THE POSSIBILITY OF REPEATED HARD DISRUPTIONS IS MUCH GREATER.

--BOTH FOR PHYSICS STUDIES AND FOR PERSONNEL SAFETY, A REAL-TIME HARD X-RAY MONITORING SYSTEM WILL BE REQUIRED FOR TCA, CONSISTING OF TIME-DEPENDENT HXR DETECTORS AND DOSIMETERS.

--SPECIAL CARE MUST BE TAKEN, SINCE THE SHIFTED, ELONGATED PLASMAS MAY BE ABLE TO DUMP RUNAWAYS IN UNEXPECTED PLACES, SUCH AS ALFVEN ANTENNAS, BOTH TO PROTECT THE EQUIPMENT, AND BECAUSE THE HARD X-RAYS MAY BE GENERATED IN UNEXPECTED DIRECTIONS.

--SUCH A SYSTEM IS REQUIRED TO BE DEVELOPED FOR TCV, WHICH WILL START WITH ONLY 50 CM INSTEAD OF 100 CM OF CONCRETE SHIELDING, I.E. A FACTOR OF 200 LESS IN SHIELDING EFFICIENCY.

DIVERTOR AND NON UP-DOWN SYMMETRIC PLASMAS IN TCA

--IF A NON-ZERO RADIAL FIELD IS ADDED TO TCA NON CURCULAR PLASMAS, NON UP-DOWN SYMMETRIC PLASMA MAY BE CREATED IN TCA. THIS WOULD ALLOW:

---STUDY OF COUPLING OF VERTICAL AND RADIAL OSCILLATIONS DUE TO SAWTEETH;

---CREATION OF DIVERTED PLASMAS.

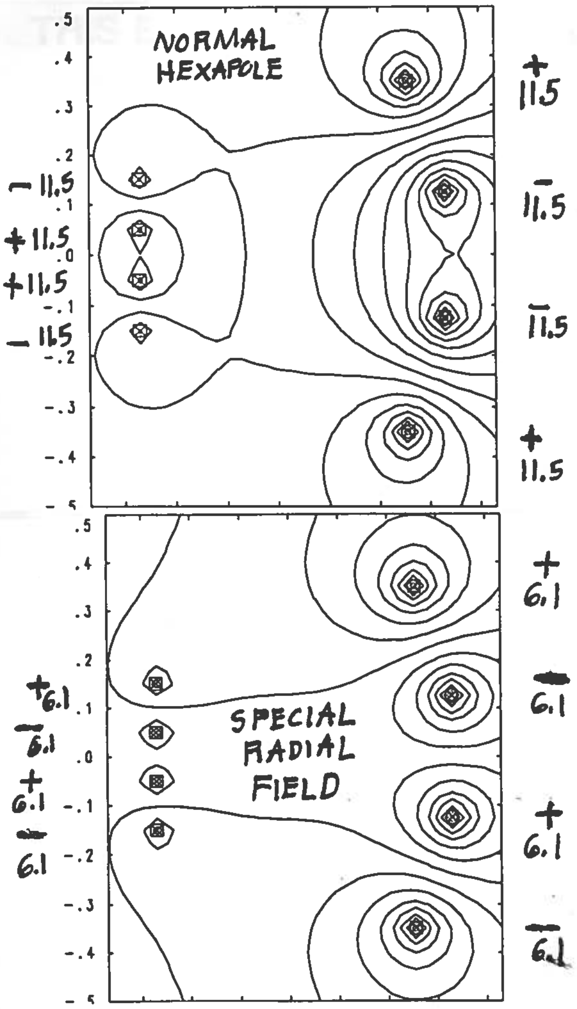
--WITH ONLY TWO CONTROLS, THE DEGREE OF FLEXIBILITY IS LIMITED. IN THE EXAMPLE OF A DIVERTOR BELOW, THE PLASMA IS SO ELONGATED THAT IT WOULD TOUCH THE ALFVEN ANTENNAS. A MORE DETAILED STUDY MAY FIND MORE DESIRABLE SHAPES.

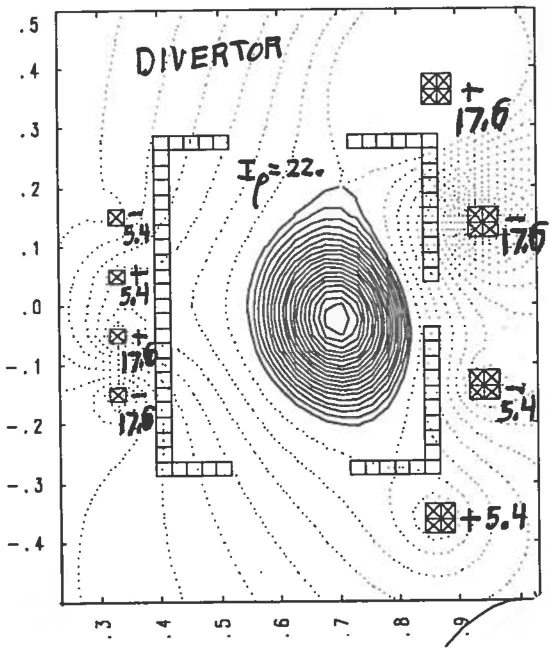
VERTICAL STABILITY

--IDEALLY STABLE

--RESISTIVE GROWTH RATE:
GAMMA=3500 SEC-1

--CONTROLLABLE





--MORE FLEXIBILITY WOULD BE POSSIBLE IF AN ADDITIONAL CONTROLLABLE POWER SUPPLY WERE PURCHASED TO REPLACE THE PULSED "QUADRUPOLE" VERTICAL POWER SUPPLY, FOR EXAMPLE THE TCV RAPID POWER SUPPLY.

CONSIDERATIONS ON TCA CONTROL SYSTEM

CIRCULAR PLASMAS

--THE PREVIOUS TCA SYSTEM WAS BASED ON SIN AND COS LOOP MEASUREMENTS OF VERTICAL AND HORIZONTAL POSITION OF CURRENT MOMENT CENTER.

--THE PRESENT SYSTEM COMPARES THE VALUES OF FLUX LOOPS ON THE VESSEL.
-----FOR UP/DOWN, FLUX LOOPS ON THE TOP AND BOTTOM ARE COMPARED DIRECTLY.
-----FOR IN/OUT CONTROL, AN INNER AND OUTER FLUX LOOP ARE COMPARED, ONE WITH A MULTIPLICATIVE CONSTANT, TO ALLOW FOR POSITIONS ON DIFFERENT SURFACES. CONTROL IS THEREFORE OF SURFACES BEYOND THE LIMITER. FOR CIRCLES IN TCA, THIS WORKS WELL.
--TO MAKE AN IMPROVED SIMULATION OF TCV BREAKDOWN IN TCA, THE VESSEL GAP MIGHT BE SHORTED (A. HOWLING)

CONTROL FOR NON-CIRCULAR PLASMAS:

FOR NON-CIRCULAR PLASMAS IN TCA, ONLY TWO CONTROL POWER SUPPLIES (PLUS OH) ARE CONTINUOUSLY AVAILABLE.

--A SIMPLE, BUT INACCURATE SYSTEM MAY BE POSSIBLE. FOR EXAMPLE, THE SAME UP/DOWN CONTROL, BUT FOR IN/OUT CONTROL, A FLUX LOOP ON TOP COULD BE COMPARED TO ONE OUTSIDE. ANOTHER POSSIBILITY IS SIMPLE FLUX PROJECTIONS OR MOMENT CALCULATIONS AS IN DOUBLET III.

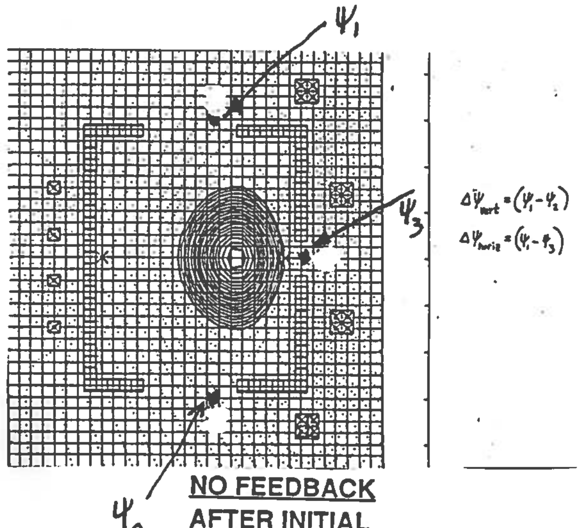
--A MUCH BETTER SYSTEM, BOTH FOR ACCURATE CONTROL AND FOR TESTING FOR TCV, WOULD BE A SIMPLIFIED PROTOTYPE OF THE TCV SYSTEM, WHERE ALL THE AVAILABLE MAGNETIC MEASUREMENTS ENTER INTO A MATRIX MULTIPLIER, TO DETERMINE THE PLASMA BOUNDARY FLUX (HOFMANN), WITH 1 (RADIAL POS), 2 (PLUS VERT), OR 3 (PLUS OH) OUTPUTS TO THE POWER SUPPLIES.

SIMPLE TCA CONTROL SYSTEM FOR NON-CIRCULAR PLASMAS

--WITH THREE FLUX LOOPS,
TOP=PSI1, BOT=PSI2, OUT=PSI3
USE DELTAVERT = PSI1 - PSI2
USE DELTAHORIZ = PSI1 - PSI3
COIL FEED IS: VOLTS (H OR V) = CONSTANT*DELTA

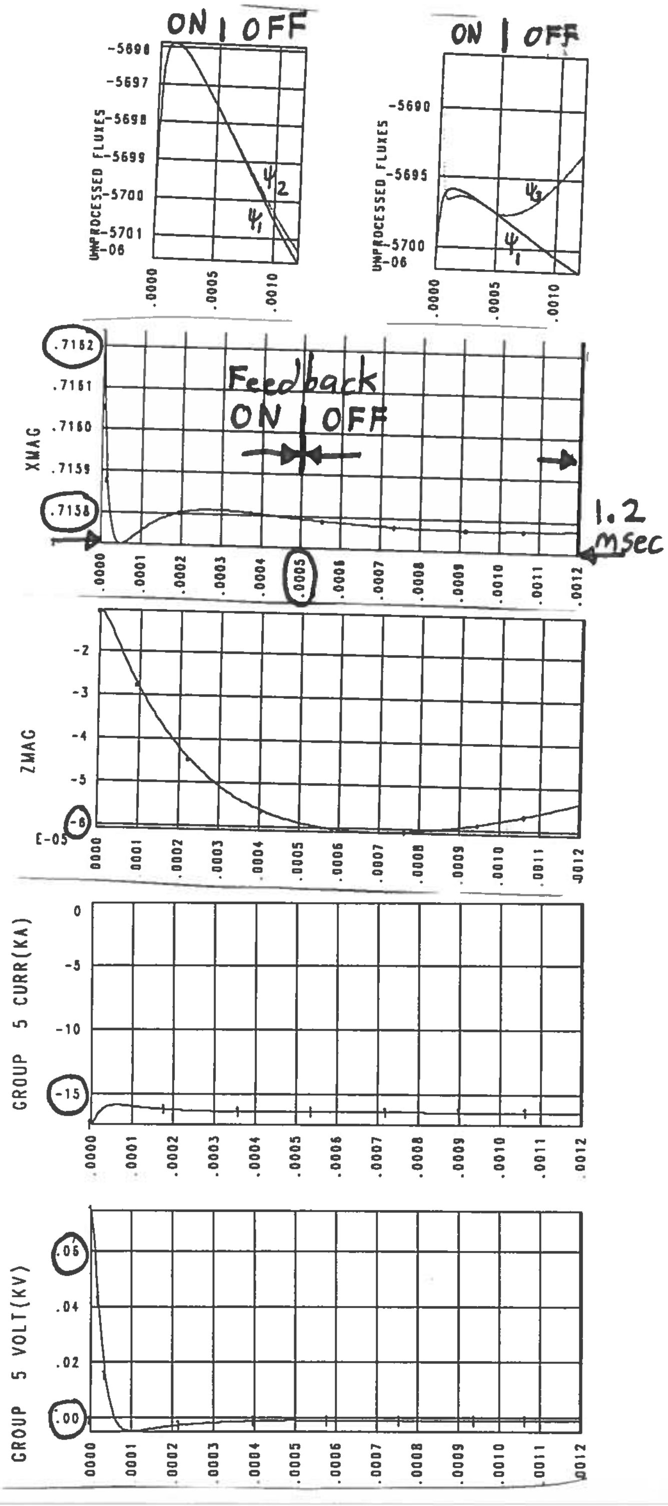
--**RESULT:**

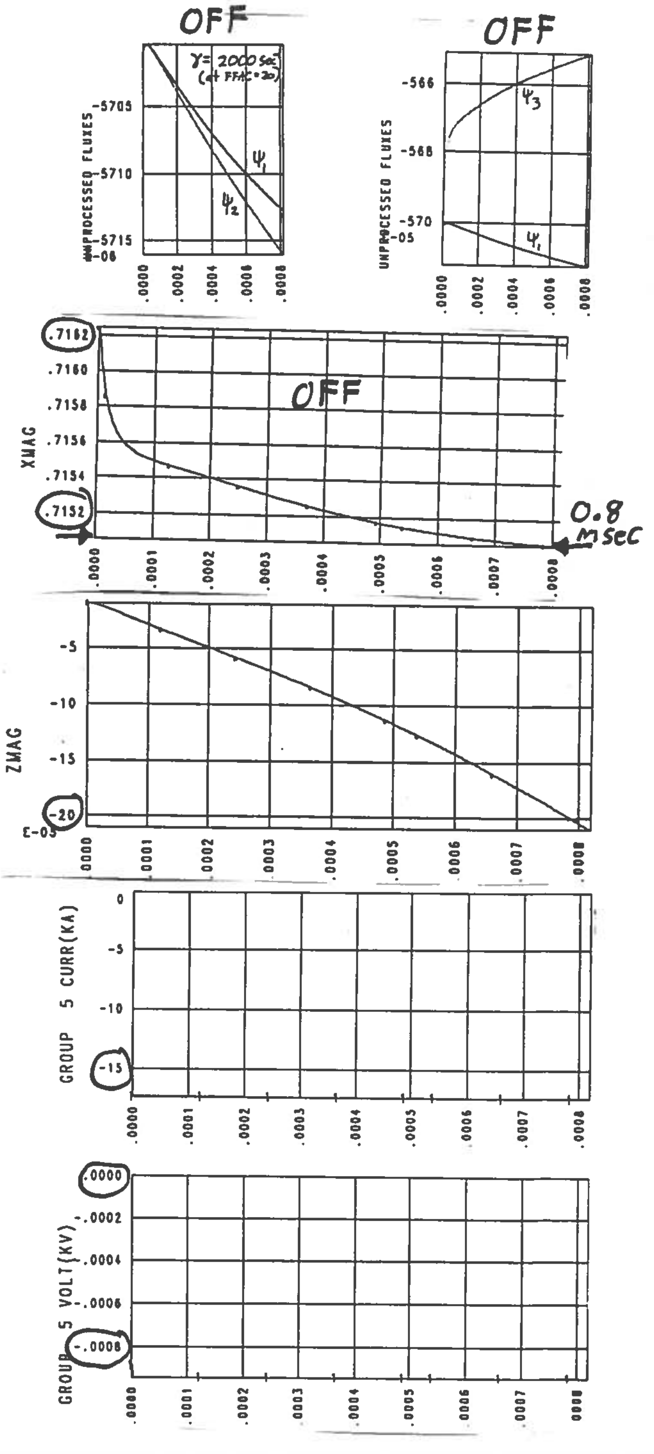
COMPARISON WITH AND WITHOUT FEEDBACK SHOWS THAT SIMPLE FEEDBACK CAN CONTROL PLASMA



FEEDBACK ON FOR FIRST 0.000500 SEC, THEN OFF

NO FEEDBACK AFTER INITIAL EQUILIBRIUM FOUND





COMMENTS ON POSSIBILITIES AND REQUIREMENTS FOR EXPERIMENTS

USE OF ALFVEN HEATING AND DIAGNOSTICS:
--IF PLASMAS NEAR THE BETA LIMIT CAN BE PRODUCED, WITH EITHER ECH OR ALFVEN, TCA DIAGNOSTICS CAN BE USED TO STUDY THE FLUCTUATION SPECTRA, IN PARTICULAR WITH THE PHASE-CONTRAST DIAGNOSTIC AT ALFVEN FREQUENCIES.
--ALFVEN HEATING IN NON-CIRCULAR PLASMAS.

MOVABLE, PUMPABLE LIMITER AND TCA VESSEL INTERIOR:
--WITH SMALL PLASMAS ON THE OUTSIDE LIMITER NEAR THE WALL, THE BEST CONFIGURATION FOR THE LIMITER NEEDS TO BE CONSIDERED.
--INTERFERENCES INSIDE TCA MAY NEED MOVING (PROBES)

MAGNETIC PROBES, FLUX LOOPS, MHD ANALYSIS:
--THE POSSIBILITY OF RECONSTRUCTING EQUILIBRIA NEEDS TO BE CONSIDERED, ESPECIALLY WITH TESTS AND DEVELOPMENT FOR TCV IN MIND, INCLUDING THE ADDITION OF EXTRA FLUX LOOPS AND PROBES AND :
--THE PURCHASE OF AN ARRAY PROCESSOR, INTEGRATED INTO THE MICROVAX SYSTEM, TO ANALYSE INVERSE EQUILIBRIUM AND FOR CORRELATION ANALYSIS ON THE FLUCTUATION DIAGNOSTICS.

REAL TIME CONTROL SYSTEM:
--FOR UP/DOWN SYMMETRIC PLASMAS WITH VERY ROUGH POSITION CONTROL, THE PRESENT CONTROL SYSTEM COULD POSSIBLY BE MODIFIED.
--FOR PRECISE CONTROL OF RADIAL POSITION OR ELONGATION AND VERTICAL STABILITY OF NON UP/DOWN SYMMETRIC PLASMAS, A PROTOTYPE OF THE TCV PLASMA CONTROL PROCESSOR COULD BE USED, FOR EXAMPLE WITH 10-20 INPUTS AND 2 OUTPUTS.

SUMMARY AND DETAILED PROPOSALS:

1. SUMMARY OF PROPOSED EXPERIMENTS:

A-GYROTRON ASSISTED STARTUP IN A HEXAPOLE NULL.
(MINIMIZE VOLT-SEC, BREAKDOWN VOLTS, TOR FIELD)
B-GYROTRON HEATING OF ELONGATED PLASMAS
C-VERTICAL INSTABILITY AND SHAPING CONTROL;
DISRUPTION, RUNAWAY (DUE TO GYROTRON) STUDIES IN ELONGATED PLASMAS.

2. TCA, TCV PRIORITIES:

A-HOW DO THESE COMPARE TO PRESENT TCA PRIORITIES?
B-IS IT USEFUL TO DO THESE SOON, BOTH FOR PHYSICS AND EXPERIENCE, OR IS IT BETTER TO WAIT FOR TCV?

3. DETAILED PROPOSAL FOR EXPERIMENTAL PREPARATION:

A-PREPARE HARDWARE, SOFTWARE - PLASMA CONTROL:
1) FLUX LOOPS AND MAGNETIC PROBES;
2) SIMPLE FLUX LOOP OR COIL CONTROL
3) TRANSFER FUNCTION CONTROL (HOFMANN, INV-EQUIL) WITH TCV PROTOTYPE.

B-PREPARE TCA VESSEL INSIDE TO REMOVE INTERFERENCE --PROBES, LIMITERS, ETC., CHECK VESSEL GAP PROTECTION
C-PREPARE MOVABLE, PUMPABLE LIMITER, FOR SMALL PLASMA, WITH SUITABLE LIMITER AND PUMPING.
D-DEVELOP ALGORITHMS IN TCA/TCV MICROVAX ENVIRONMENT FOR INVERSE EQUILIBRIUM ANALYSIS AND PLASMA FLUCTUATION ANALYSIS. DECIDE ON PURCHASE OF ARRAY PROCESSOR FOR DATA ANALYSIS.
E-CONSIDER DIAGNOSIS OF SHIFTED PLASMAS, E.G. ACCESS OF NEW PROFILE LASER, MAG PROBES, EDGE, PHASE CONTRAST DIAG, ETC.
F-ACQUIRE DOSIMETERS AND TIME-DEPENDENT HXR MONITORS FOR RUNAWAY DETECTION (NEEDED FOR TCV).
G-MAKE OLD "QUADRUPOLE" SUPPLY OPERATIONAL, CHECK ON TCA COIL REWIRING AT PATCH PANEL.