MARCH 1989 INT 158/89

DYNAMIC PLASMA EVOLUTION IN TCV

FRED MARCUS

ABSTRACT

The tokamak simulation code (TSC) is used to study dynamic evolution of plasmas to high elongation in the TCV tokamak. Previous work with TSC has concentrated on evolution with limiter q in the range $2<q<3$. Separate studies on kink stability indicate that q should be >3 at high elongation. At high q, axisymmetric stability growth rates increase, and dynamic shape control becomes more difficult. The following memo contains the seminar presented at the CRPP on 21 Feb. 1989, with the following conclusions discussed:

- shaping control during dynamic evolution becomes difficult at elongations of about 2/1
- optimum preprogrammed shaping coil currents can increase elongation
- a rapid current ramp can broaden the current profile and increase elongation
- vertical stability is adversely affected by a decrease in plasma width as the elongation of diverted plasmas is increased
- plasma transport restricts the range of current profiles available, although the results are affected by high or low electron temperature
- volt-second consumption depends on plasma shape, discharge time and electron temperature as well as plasma current change
- operation at $q>3$ restricts the TCV operating range in elongation and β, when considering only axisymmetric instability

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

OUTLINE

- -INTRODUCTION
- -TCV AND TSC DESCRIPTION
- -TSC PHYSICS AND EQUATIONS
- -EXAMPLE OF TSC INITIAL PROFILES
- -GROWTH RATES AND CONVERGENCE
- -EVOLUTION FROM TOP OF VESSEL WITH $q = 2$
- -EVOLUTION OF A CENTERED DEE PLASMA WITH $q = 2$
- -EVOLUTION OF $q > 3$ CENTERED PLASMAS
- -EVOLUTION $q > 3$ WITH IMPROVED CURRENT PREPROGRAMMING
- -GROWTH RATES OF $q > 3$ CENTERED PLASMAS
- -EVOLUTION $q > 3$ WITH HIGH CURRENT RAMP RATE
- -EVOLUTION WITH FLUX SURFACE AVERAGED ENERGY TRANSPORT
- -CONCLUSIONS

INTRODUCTION

-IN THE PREVIOUS PRESENTATION, F. HOFMANN HAS SHOWN:
---SEQUENCES OF STATIC EQUILIBRIA GOING FROM CIRCULAR TO 3/1 ELONGATION IN TCV (TOKAMAK à CONFIGURATION VARIABLE)
---AXISYMMETRIC STABILITY IS FAVORED BY LOW q AT THE LIMITER.
---NON-AXISYMMETRIC STABILITY IS FAVORED BY HIGH q.

-IN THIS PRESENTATION, EVOLUTION SCENARIOS OF PLASMA EQUILIBRIA ARE STUDIED WITH TSC (TOKAMAK SIMULATION CODE), AN AXISYMMETRIC, RESISTIVE, 2D MHD CODE, DEVELOPED BY STEVE JARDIN AT PRINCETON.

-A DYNAMIC STUDY WITH TSC ALLOWS THE FOLLOWING TOPICS TO BE STUDIED:

---EFFECTS OF LIMITER q AND POSITION IN THE VACUUM VESSEL ON GROWTH RATES AND COMPLETE EVOLUTION SCENARIOS.

---REQUIRED POWER SUPPLY VOLTAGES, RESPONSE TIME, AND FEEDBACK METHOD AS A FUNCTION OF:
------RATE OF CURRENT RISE AND PROGRAMMED MOTION
------PLASMA GROWTH RATE
------PERTURBATIONS: SAWTEETH, INTERNAL DISRUPTION

---EVOLUTION OF PROFILES WITH TIME, ALLOWING FOR RESISTIVE CURRENT EVOLUTION WITHIN THE DEFORMABLE PLASMA.

---ACCURACY OF POSITION AND SHAPE CONTROL

TCV DESCRIPTION

-THE TCV PHYSICAL CHARACTERISTICS AND POWER SUPPLIES AFFECT THE PLASMA EVOLUTION .

-TCV PARAMETERS: R = 0.87 M, A = 0.24 M, B = 1.43 T, PULSE LENGTH = 1.0 SEC, MAX HALF-HEIGHT = 0.72 M, MAX ELONG = 3/1, MAX PLASMA DESIGN CURRENT = 1.2 MA

-TCV SHAPING COILS: 16 INDEPENDENT COILS, EACH WITH 4 QUAD THYRISTOR SUPPLY, 96-120 HZ, 15V/TURN AT SMALL RMAJ, 30V/TURN AT LARGE RMAJ, 260 KILOAMP-TURN MAX/COIL.

-TCV OHMIC COILS 10V/TURN MAX.

-RAPID RESPONSE COILS INSIDE THE VACUUM VESSEL FOR VERTICAL STABILITY ON FAST RESISTIVE TIME SCALE

-TCV VACUUM VESSEL: CONTINUOUS, 15 MM THICK, TAU (M=1) = 6.7 MSEC

- -

TSC DESCRIPTION

-THE TSC CODE IS USED TO MODEL THE ABOVE TCV CONFIGURATION, INCLUDING A COMPLETE DESCRIPTION OF FLUX MEASUREMENT AND FEEDBACK TO THE POWER SUPPLIES.

-THE PLASMA IS MODELLED AS A 2D MHD AXISYMMETRIC RESISTIVE FLUID, WITH THE ALFVEN TIME INCREASED BY A FACTOR <u>FFAC</u> TO REDUCE COMPUTER CALCULATION TIME. THIS FACTOR IS VARIED IN CONVERGENCE STUDIES OF THE RESISTIVE GROWTH RATE.

TSC PHYSICS AND EQUATIONS

Consider a subset of the resistive MHD equations with a modified inertial term equivalent to enhancing the plasma mass, giving

$$\frac{\partial \vec{m}}{\partial t} + \vec{F}_V(\vec{m}) = \vec{J} \times \vec{B} - \nabla p$$ where:

$\vec{m}$ is the plasma momentum density, and
$\vec{F}_V(m)$ is the plasma viscosity operator.

Scalar forms of the equation are obtained, where static solutions for Ψ, p, g are consistent with the Grad-Shafranov equation.

$$\Delta^* \Psi + \mu_0 X^2 \frac{\partial}{\partial \Psi} p(\Psi) + \frac{1}{2} \frac{\partial}{\partial \Psi} g^2(\Psi) = 0$$

Transient solutions are always within $\varepsilon \equiv S_M^{-2}$ of satisfying Grad-Shafranov, where $S \equiv \frac{a_0 B_0}{\eta} \sqrt{\frac{\mu_0}{n M_i}} \gg 1$ is the Magnetic Reynolds number.

The enhancement factor FFAC increases $\sqrt{M_i}$ so that the time scale difference between Alfven & resistive phenomenae is reduced, and total computer time is reduced.

A complete set of equations is then derived and solved using Faradays law, Ohm's law, flux-surface averaging, and plasma particle and heat flux terms.

The equations may be solved with either fixed or flux-surface averaged transport solutions of pressure and temperature profiles

CURRENT AND PRESSURE PROFILES USED IN TSC

Pressure: $p = p_0 (\tilde{\Psi})^{\alpha_p}$ where $\tilde{\Psi} \equiv (\Psi_{lim} - \Psi)/(\Psi_{lim} - \Psi_{min})$

Toroidal Field $(R B_{TOR})^2 = g_0^2 - 2\left[g_1 (\tilde{\Psi})^{\alpha_g} + 4 g_2 (\tilde{\Psi})^{\alpha_g} (1 - \tilde{\Psi})\right]$

For Grad-Shafranov equation:

$$p' \equiv \frac{d}{d\Psi}(p) \;, \quad ff' \equiv \frac{1}{2} \frac{d}{d\Psi}\left[(R B_{TOR})^2\right]$$

Toroidal Current Density (Initial Value):

$$J_{TOR} = -R p' - \frac{1}{\mu_0 R}(ff')$$

Pressure Profile assumes $p_e = p_i = p/2$

Density profile $n(\Psi, t) = n_0(t)\left[1 - \tilde{\Psi}^{\beta_R}\right]^{\alpha_R}$

Temperature Profile = Pressure / Density

In $(R B_{TOR})^2$, the TSC code chooses g_1 and g_2 such that $q = q_0$ on axis and total current is I_p, <u>initially</u>

During evolution, current profile evolves resistively, with the total current controlled by ohmic voltage feedback.

If q on axis falls below q_{saw} the resistivity is locally increased

---

Example of TSC Initial Profiles.

Pressure, $\alpha_p = 1.2$, $p_0 = 65000$ **Density**: $\beta_R = 1.0$

$\alpha_R = 0.6$

$n_0 = 2.1 \times 10^{14}\,\mathrm{cm}^{-3}$

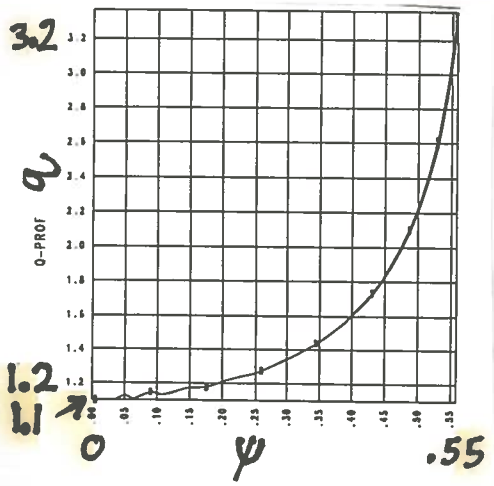
Toroidal Field, $g_0 = 1.24 = (1.43\,T \times .87\,m)$

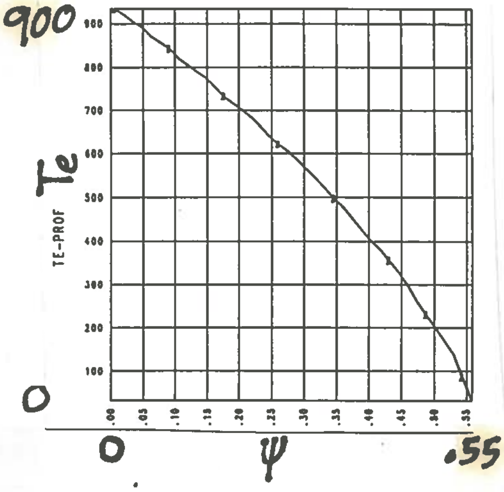
$q_0 = 0.70$ [Circ eq] → 1.0 Elong

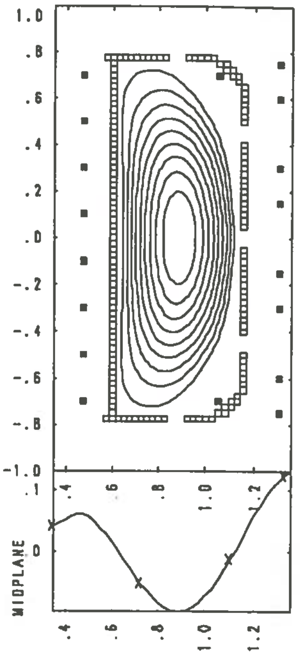
$I_p = 1200$ KA

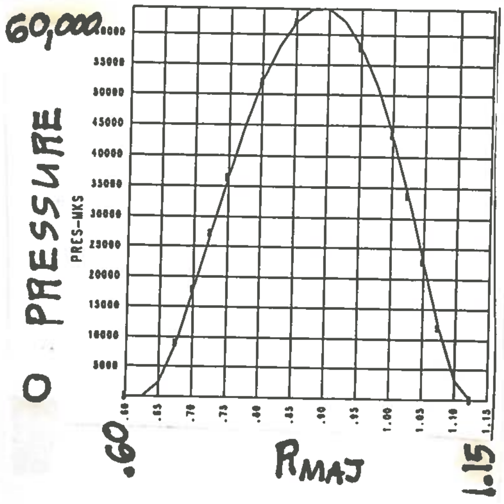
$\alpha_g = 1.24$

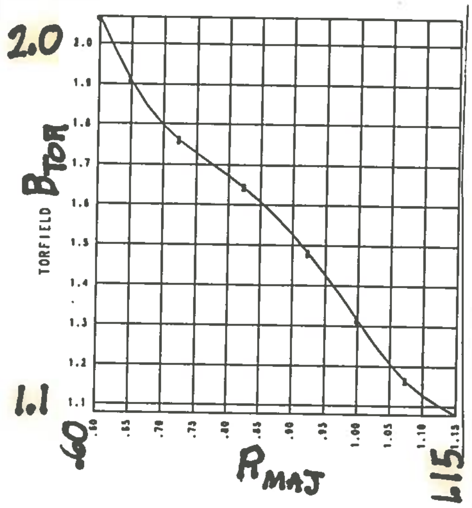
$q_{saw} = 1.0$

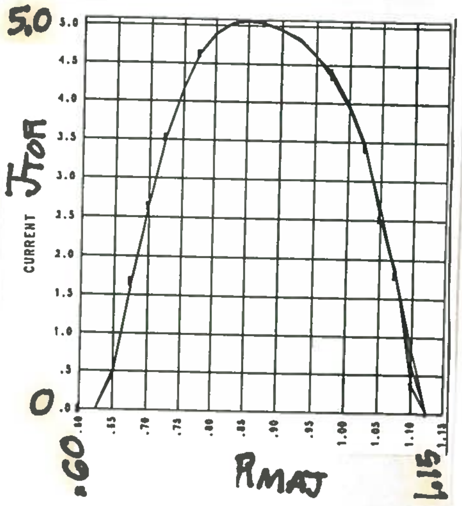












Resulting Parameters: $I_p = 1200$ kAmps,
$q_{axis} = 1.1$, $q_{LIM} = 3.36$, $\beta_{pol} = .185$, $\ell_i = .48$, Vol = 3.0,
$\beta_{TOR} = 2.7\%$, $R_{ax} = .889$ m, elong = 2.91/1

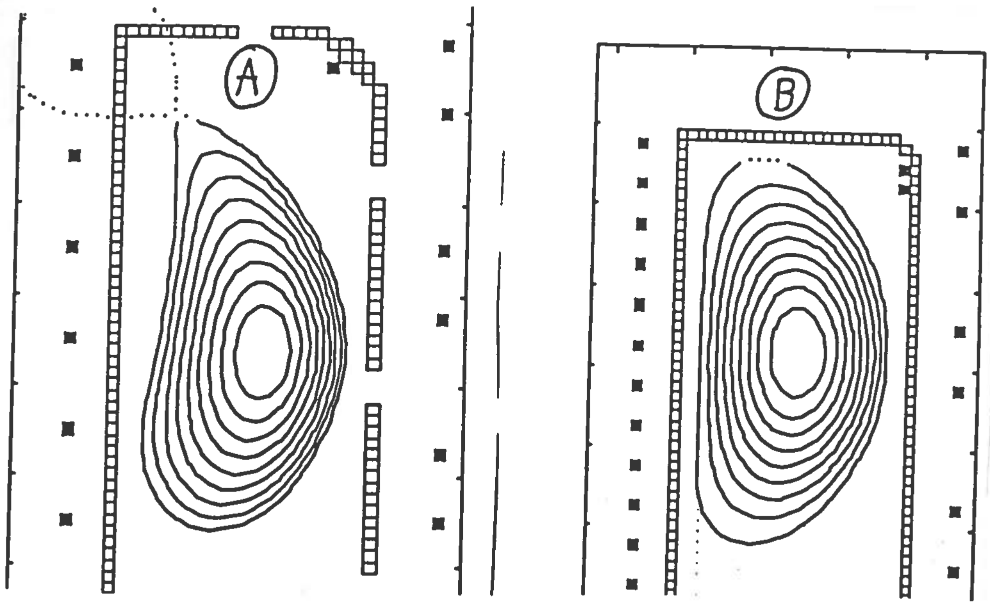
GROWTH RATES AND CONVERGENCE

- TO FIND THE AXISYMMETRIC RESISTIVE GROWTH RATE γ :
---AN EQUILIBRIUM IS FOUND WITH THE TSC CODE
---THE FEEDBACK IS TURNED OFF, AND GAMMA MEASURED
---THE MASS AND ALFVEN ENHANCEMENT FACTOR <u>FFAC</u> IS VARIED TO GET CONVERGENCE, USING $1/\gamma$ prop. TO FFAC.

-EXAMPLE: 3/1 DEE JUST SHOWN, WITH 5 CM WALL GAP:
-AT FFAC=40,20,10, OBTAIN γ = 3300,4600,5000 /SEC, WHICH EXTRAPOLATES TO γ = 6000 /SEC AT FFAC=1, THE TRUE ALFVEN TIME. (COMPUTER TIME prop. to 1/FFAC)

-FOR COMPARISON, FROM CALCULATIONS BY HOFMANN, A 3/1 DEE, 1.2 MA, 4 CM WALL GAP PLASMA WITH A COMPARABLE (NOT IDENTICAL) CURRENT PROFILE, HAS τ_s/τ_p=20, GIVING γ = 3000 /SEC.

EXAMPLES WITH q=3.5 AND γ=1200 (+-100) /SEC:



COMMENTS ON FFAC

-TO RUN COMPLETE EVOLUTIONS LASTING 100'S OF MSEC, FFAC MUST BE INCREASED TO SEVERAL 100'S, SINCE COMPUTER TIME prop. to 1/FFAC.

-IF THE PLASMA IS IDEALLY UNSTABLE, THE GROWTH RATE γ IS SEVERAL 10 000'S /SEC, AND γ IS prop. to 1/FFAC.

-IF THE PLASMA IS IDEALLY STABLE, THE GROWTH RATE CHANGES SLOWLY WITH FFAC, AND CONVERGES

-FOR COMPLETE EVOLUTION SCENARIOS, CARE MUST BE TAKEN TO VARY FFAC AND TO VERIFY THE GROWTH RATE OF SELECTED INTERMEDIATE EQUILIBRIA WITH CONVERGENCE TESTS.

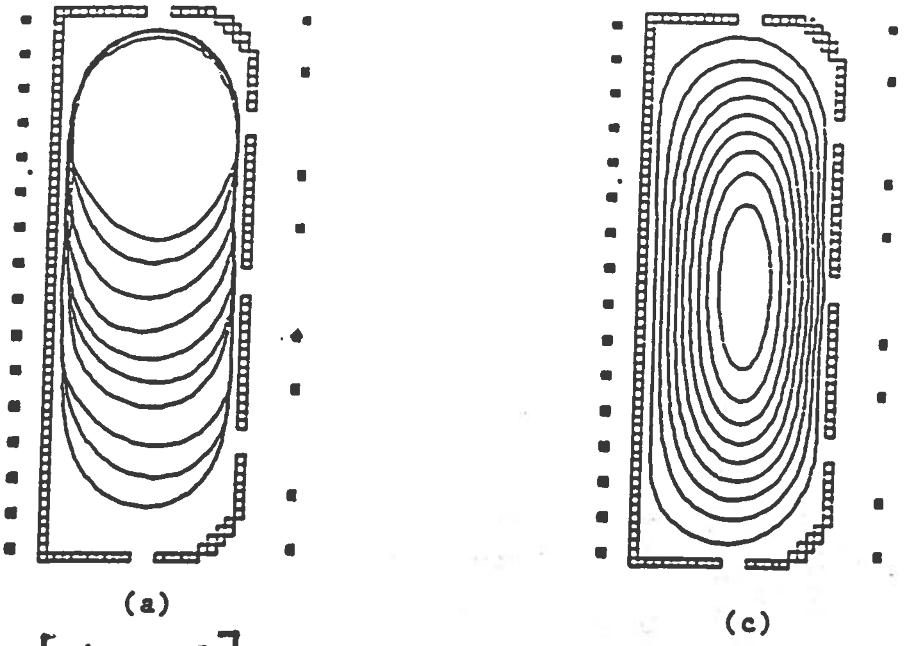
COMPLETE EVOLUTION SCENARIOS

-TO RUN A COMPLETE SCENARIO, COIL CURRENT PRE-PROGRAMMING AND FEEDBACK ARE USED, WITH TIME VARIABLE SHAPES OF FEEDBACK MOMENTS
REF: MARCUS, JARDIN, HOFMANN, PHYS. REV. LETT. 55 (1985) 2289

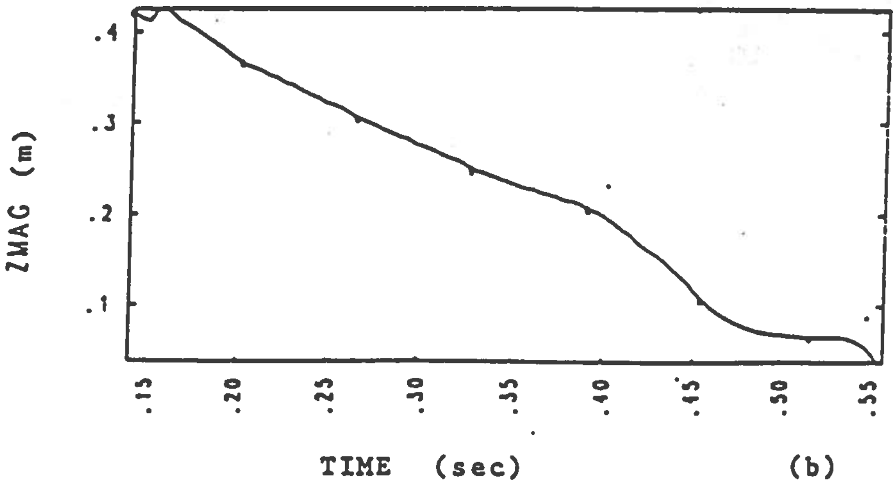
-IF THE PLASMA BECOMES IDEALLY UNSTABLE, THE PLASMA VERTICAL MOTION CANNOT BE CONTROLLED.

-COMPLETE EVOLUTIONS VERIFY THE POWER SUPPLY LIMITS AND SHOW CURRENT PROFILE EVOLUTION.

COMPLETE EVOLUTION FROM TOP OF VESSEL.
LOW $Q_L/Q_0 = 2.$ SCENARIO



[#463]



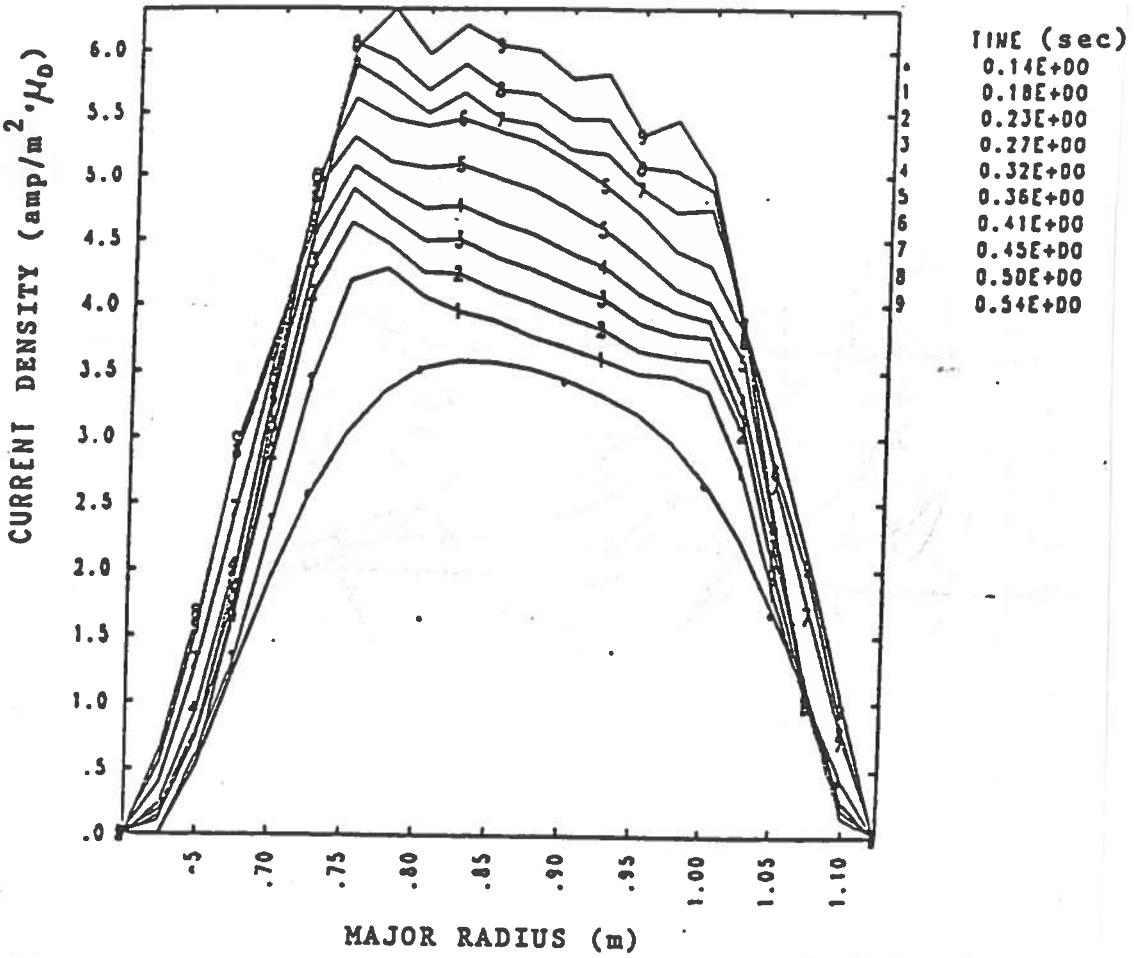
Evolution of plasma from K=1.25 to K=30 with $q_L/q_0=2$ and vessel 1.88cm thick stainless

(a) Envelopes of MHD equilibria at selected times

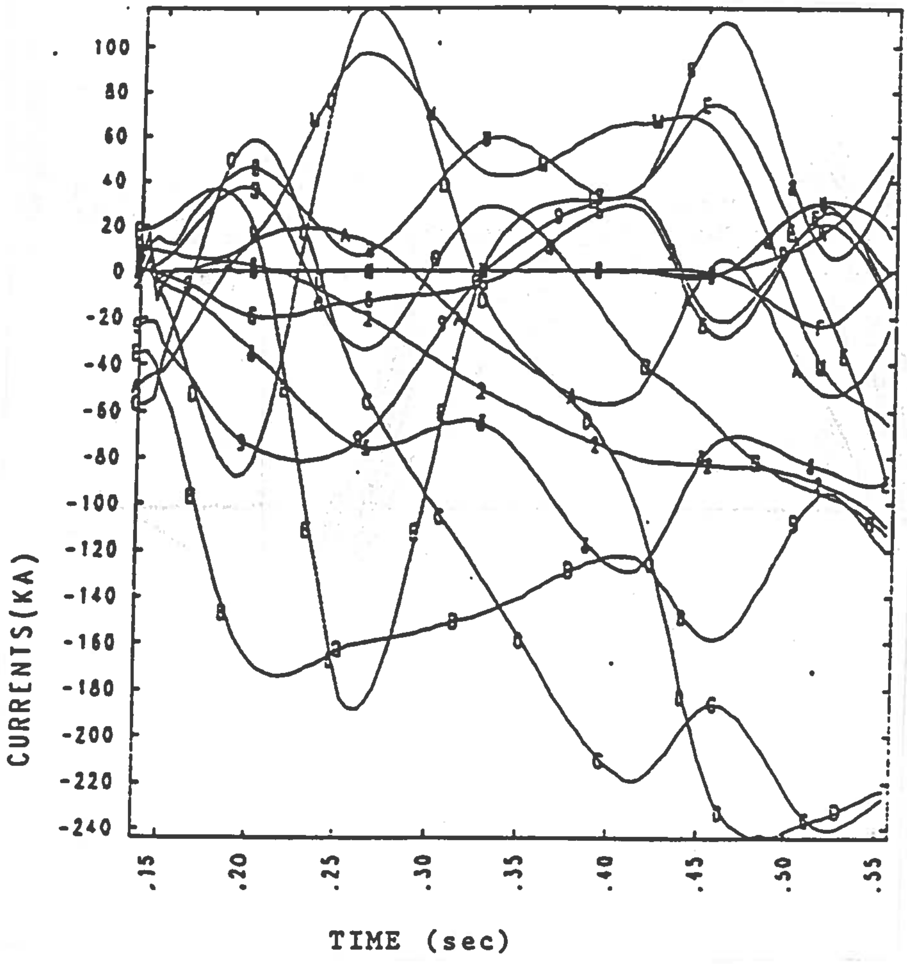
(b) Temporal evolution from 0.14 to 0.55 sec. of vertical height of magnetic axis above machine midplane

(c) Final 3/1 elongated equilibrium

EVOLUTION OF PLASMA CURRENT PROFILE + COIL CURRENTS



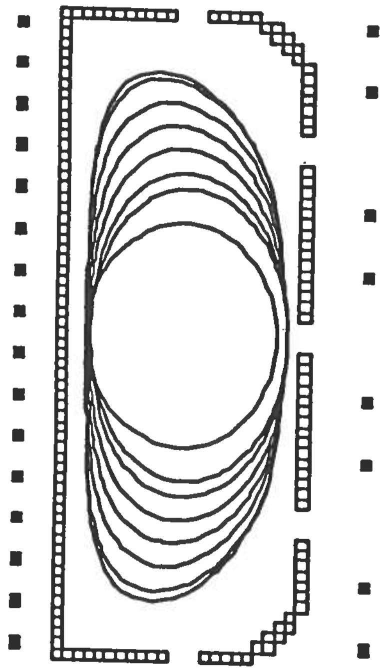
SMALL OR
NO SKIN
CURRENT
DURING
0.5 SEC
RAMP



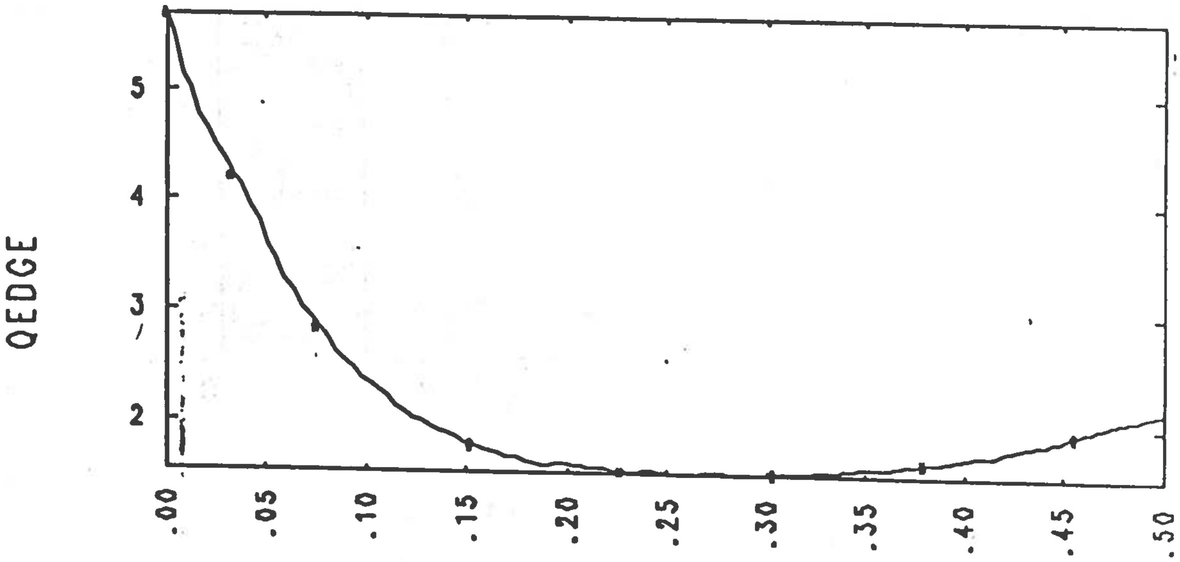
– STARTING ON
TOP REQUIRED
4- QUADRANT
OPERATION

COMPLETE EVOLUTION - CENTERED

- HIGH ELONGATION IS OBTAINED, BUT ONLY AT Q~2.



[#708]



EVOLUTION OF $\boxed{q/q_0>3}$ CENTERED PLASMAS

ADVANTAGES:

-KINK STABILITY IMPROVED
-COMPATIBLE WITH MIDPLANE DIAGNOSTICS
-LIMITER NEEDED ONLY AT MIDPLANE
-REDUCTION OF POWER SUPPLY VOLTAGES
-COIL CURRENTS ARE MOSTLY MONO-DIRECTIONAL

PROBLEMS:

-AXISYMMETRIC STABILITY IS WORSE
-PLASMA IS MORE DIFFICULT TO ELONGATE

COMPLETE EVOLUTION EXAMPLE:

-IN THE FOLLOWING FIGS. 2A-E, AN EVOLUTION STARTING FROM A NEAR-CIRCULAR PLASMA IS SHOWN, WHERE q IS KEPT >3 DURING THE ENTIRE EVOLUTION

-THE MAXIMUM ELONGATION OBTAINED WAS ONLY 2/1, EVEN WITH ADDITIONAL PULLING FIELDS.

[#1062]

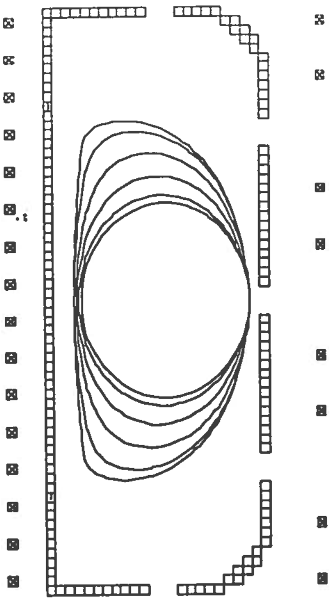


FIG. 2 A EVOLUTION OF NEAR-CIRCULAR PLASMA UP TO 2/1 ELONGATION

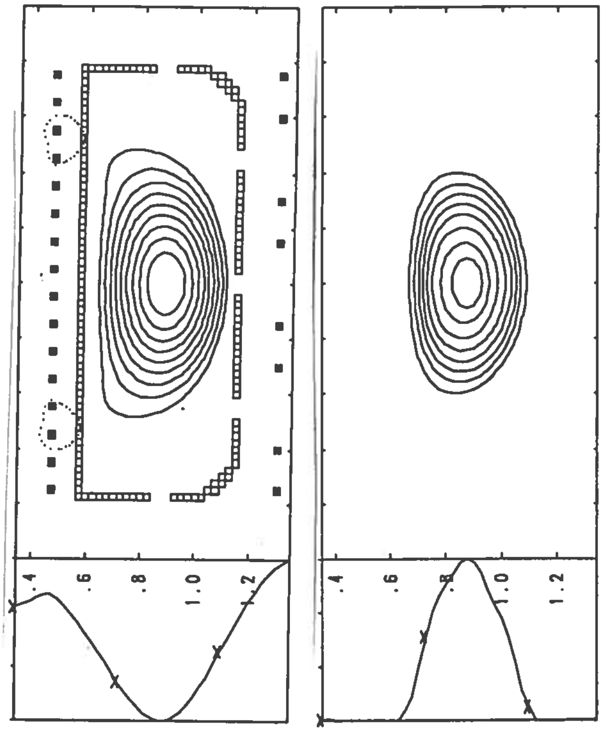


FIG. 2 B FLUX AND CURRENT PROFILE CONTOURS OF 2/1 EQUILIBRIUM

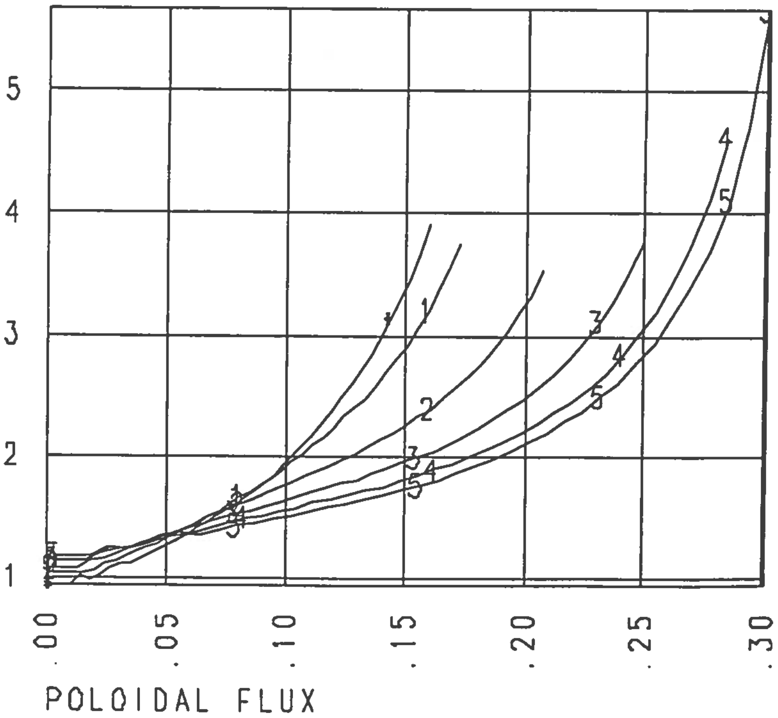


FIG. 2 C Q-PROFILE AS A FUNCTION OF TIME DURING EVOLUTION

FIG. 2D PLASMA CURRENT AS A FUNCTION OF TIME

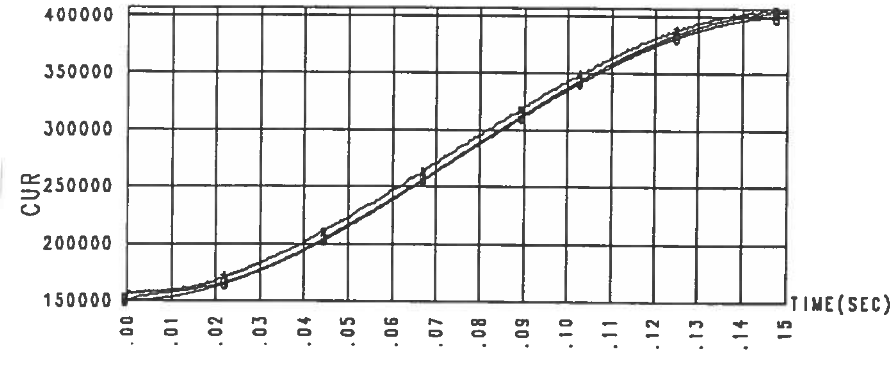
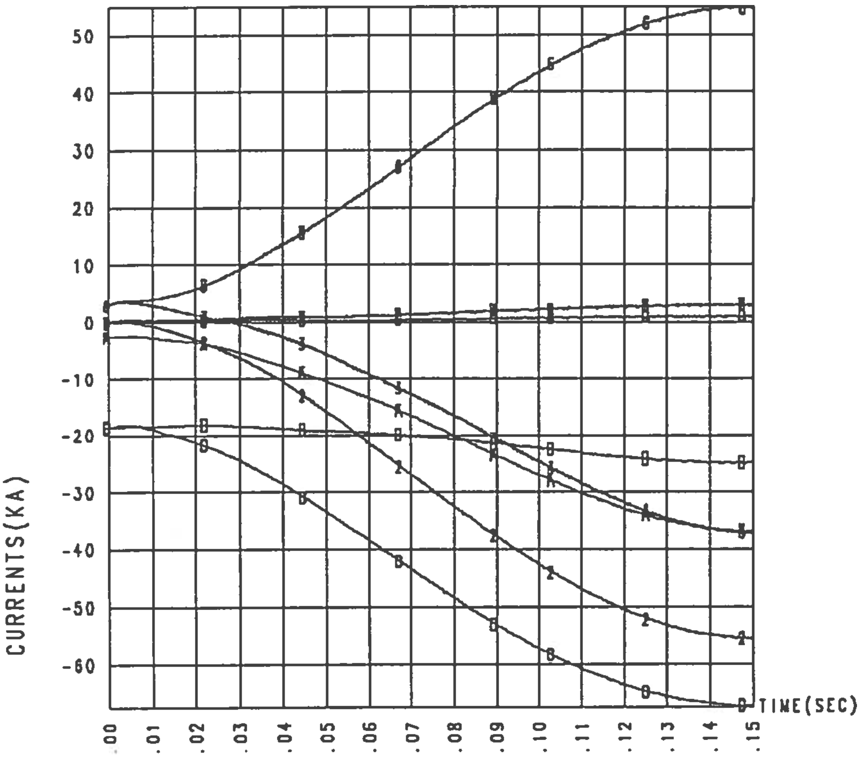


FIG. 2E SHAPING COIL CURRENTS DURING THE EVOLUTION WITH THYRISTOR CONTROLLED POWER SUPPLIES



COMPLETE EVOLUTION, $q>3$, WITH IMPROVED PRE - PROGRAMMING

-ATTEMPTS WERE MADE TO REACH HIGHER ELONGATION.

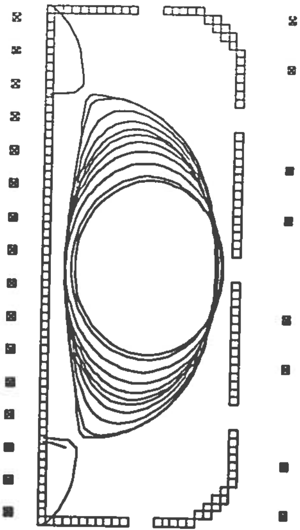
-THE PRE-PROGRAMMING OF COIL CURRENTS WAS BASED ON STATIC EQUILIBRIA FROM F. HOFMANN, BUT WITH LOWERED COIL AND PLASMA CURRENTS TO INCREASE q. AGAIN, ELONGATION OF ONLY 2/1 WAS REACHED

-INCREASED PULLING CURRENTS IN COILS NEAR THE INNER CORNERS OF THE DEE PLASMA ALLOWED ELONGATIONS UP TO 2.2/1.

-THIS RESULT IS SHOWN IN FIGS. 3A-E.

-HIGH ELONGATION WITH $3<q<4$ SEEMS DIFFICULT, BUT MORE CAREFUL PRE-PROGRAMMING MAY HELP.

FIG. 3 A EVOLUTION OF NEAR-CIRCULAR PLASMA UP TO 2.2/1 ELONGATION



[#1067]

FIG. 3 B FLUX AND CURRENT PROFILE CONTOURS OF 2.2/1 EQUILIBRIUM

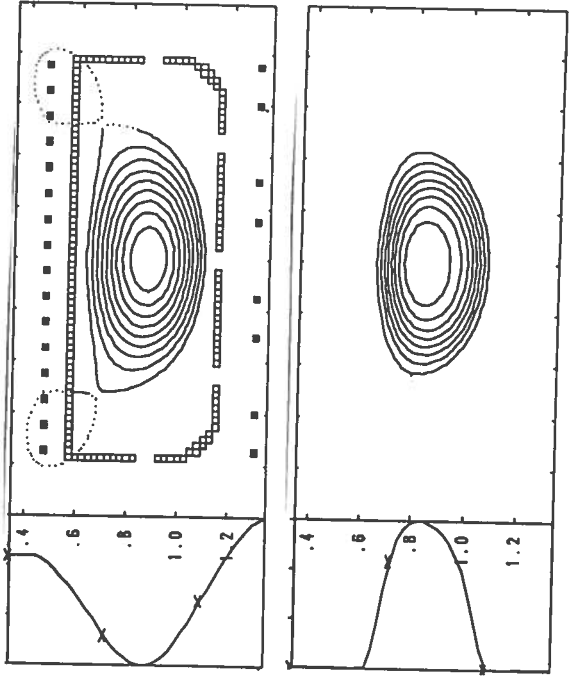


FIG. 3 C Q-PROFILE AS A FUNCTION OF TIME DURING EVOLUTION

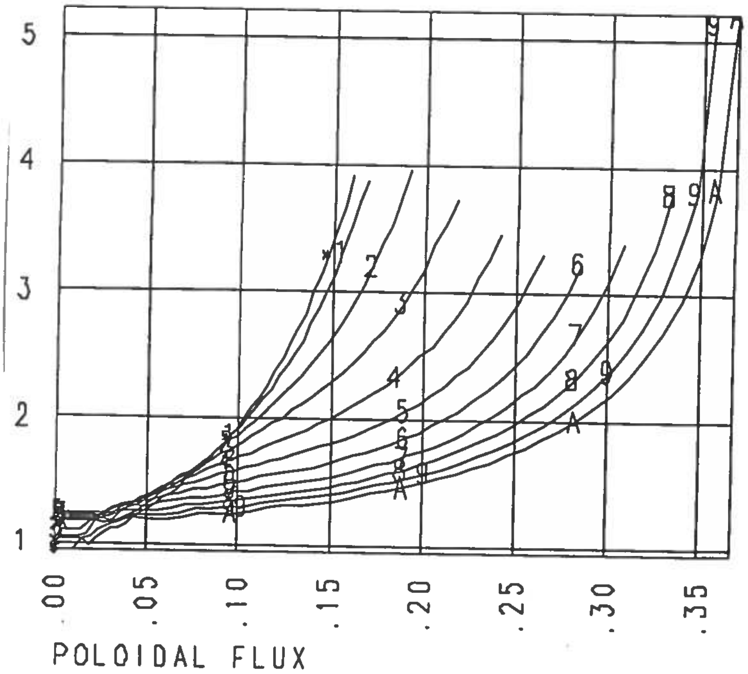


FIG. 3D PLASMA CURRENT AS A FUNCTION OF TIME UP TO 2.2/1 ELONGATION

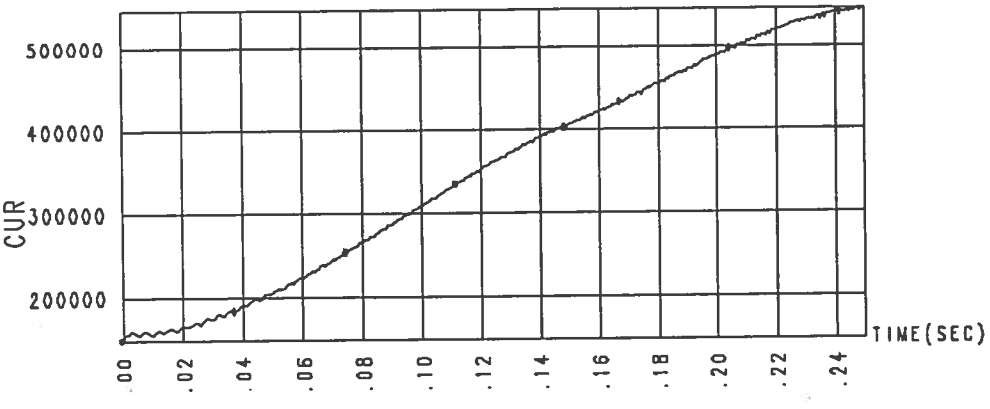
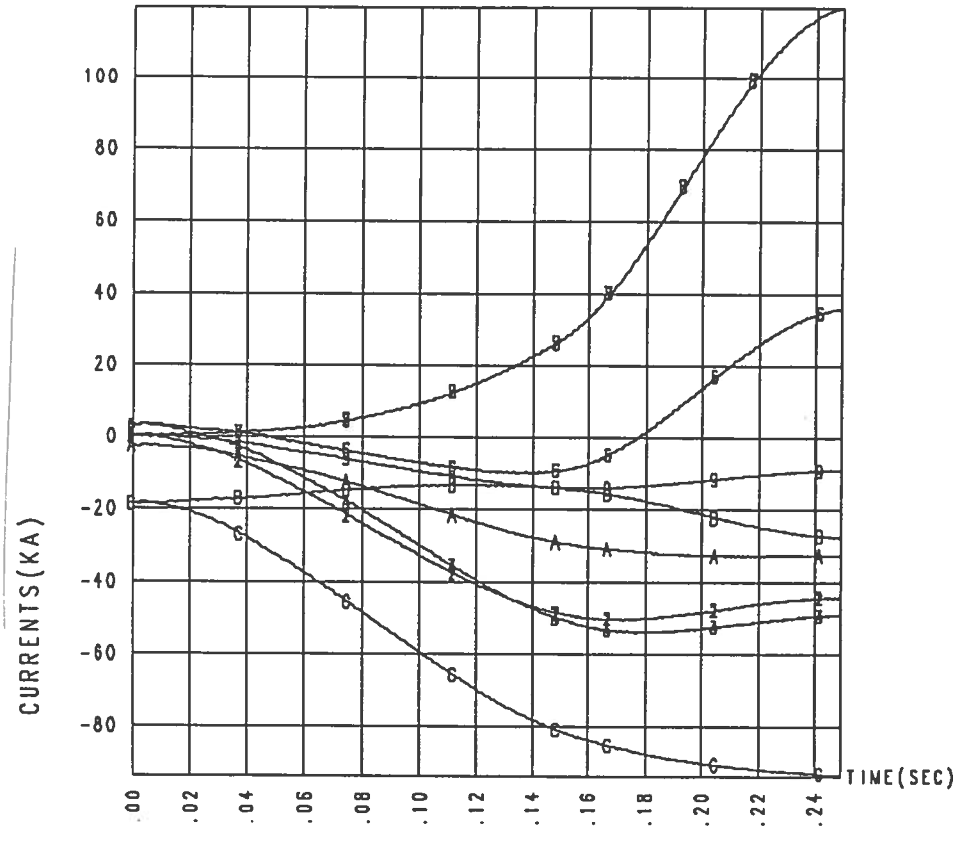
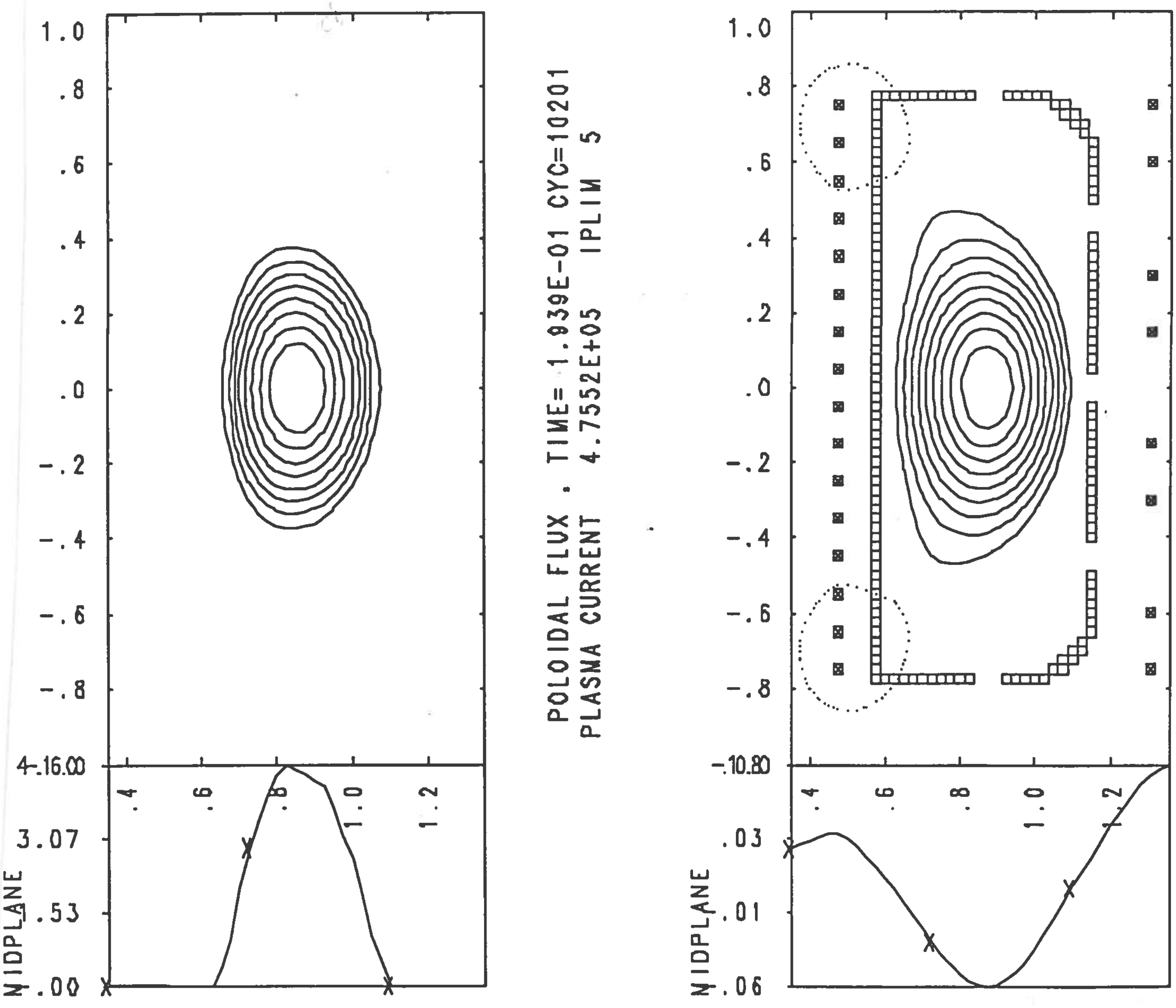


FIG. 3E SHAPING COIL CURRENTS DURING THE EVOLUTION WITH THYRISTOR CONTROLLED POWER SUPPLIES



GROWTH RATES OF ELONGATED PLASMAS WITH HIGH Q AND CENTERED

MHD EQUILIBRIUM FLUX SURFACES (RIGHT) AND CURRENT DENSITY PROFILE CONTOURS (LEFT) WITH ELONGATION 2/1, PLASMA CURRENT 476 KILOAMPS, INSIDE PLASMA-WALL GAP 5. CM, OUTSIDE PLASMA-WALL GAP 5. CM, ASYMPTOTIC AXISYMMETRIC RESISTIVE GROWTH RATE OF 10000 /SEC



COMMENTS - CENTERED, HIGH q/q_0 EVOLUTION

-EVOLUTION TO HIGH q, WITH q ALWAYS >3, IS DIFFICULT

-IT IS DIFFICULT TO MAINTAIN WALL GAPS AT HIGH $q>3$, SINCE THE PLASMA HAS A TENDENCY TO NARROW.

-AN INCREASED WALL GAP WORSENS AXISYMMETRIC STABILITY.

-SKIN CURRENTS WERE NOT OBSERVED. SKIN CURRENTS COULD IMPROVE STABILITY BY BROADENING THE CURRENT PROFILE, AS SHOWN BY HOFMANN.

IMPROVEMENTS MAY BE POSSIBLE IF THE FOLLOWING ARE OPTIMIZED:

--PLASMA-WALL GAP

--CURRENT RAMP RATE, PLASMA T_e , IMPROVING PROFILE

--PLASMA PRESSURE AND BETA

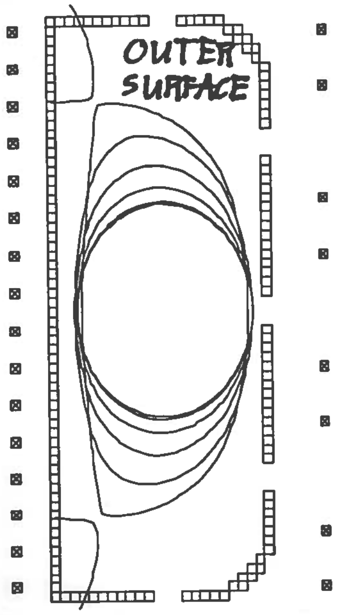
--EXTERNAL FLUX SURFACE SHAPE

--PRE-PROGRAMMED SHAPING CURRENTS

EVOLUTION TO 2.44/1 DIVERTED EQUILIBRIUM WITH CURRENT RAMP RATE OF 5 MAMP/SEC

-WITH A VERY HIGH CURRENT RAMP RATE AND HIGHER PRESSURE, BETAPOL=1, A MODERATE SKIN CURRENT FORMS, ALLOWING HIGHER ELONGATION.

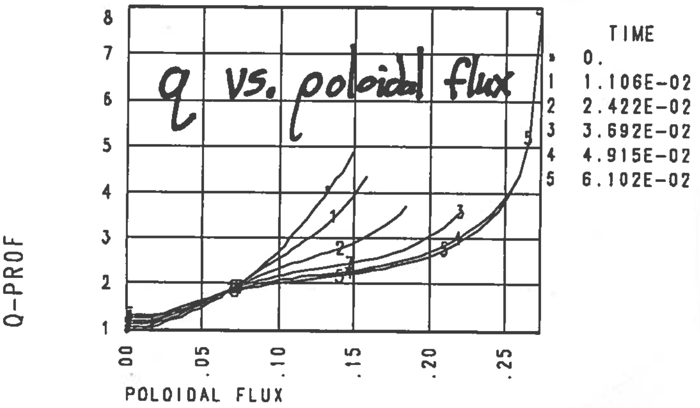
-AT THE TRANSITION TO A DIVERTOR, THE PLASMA NARROWS, THE GAP TO THE WALL INCREASES, THE ELONGATION INCREASES, AND THE PLASMA BECOMES UNSTABLE.

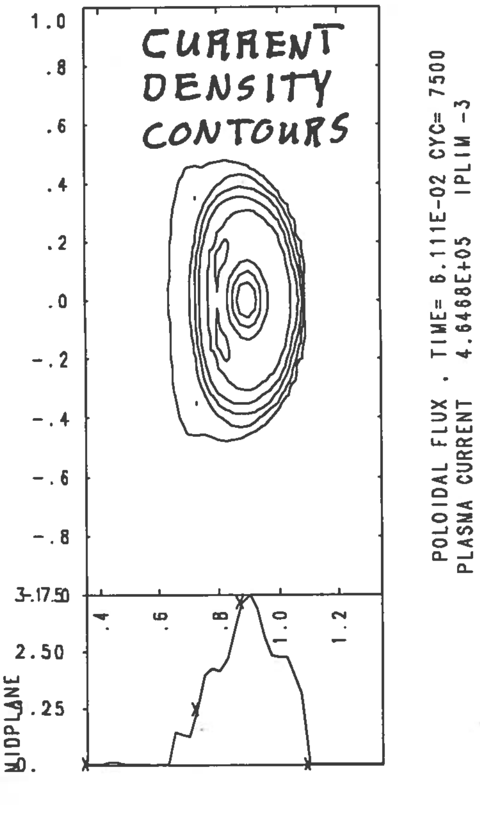


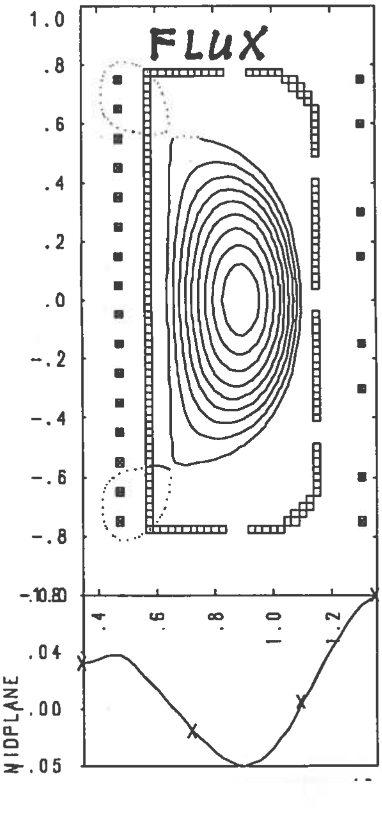
NOTE: REDUCED DIVERTOR WIDTH

$q_L > 3.5$ DURING ENTIRE EVOLUTION

[#1089]







I_{plasma} = 464 KA

AT T= 61 MSEC

DIVERTED

$\kappa = 2.44/1$

$\beta_{pol} = 0.95$

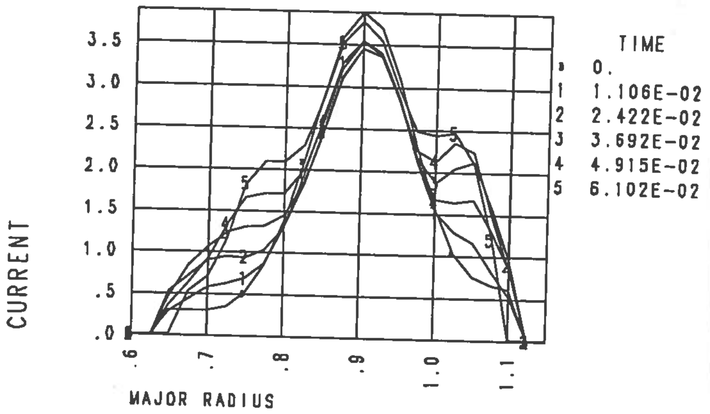
$\beta_{TOR} = 2.4\%$

$q(0) = 1.3$

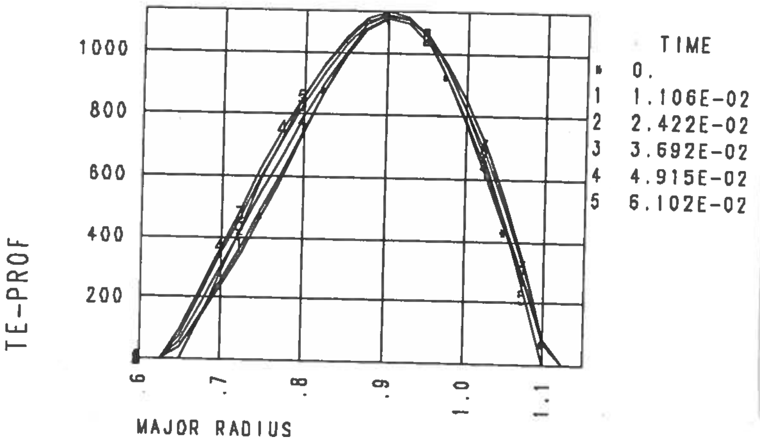
$l_i = 0.64$

EVOLUTION TO 2.44/1 DIVERTED EQUILIBRIUM WITH CURRENT RAMP RATE OF 5 MAMP/SEC

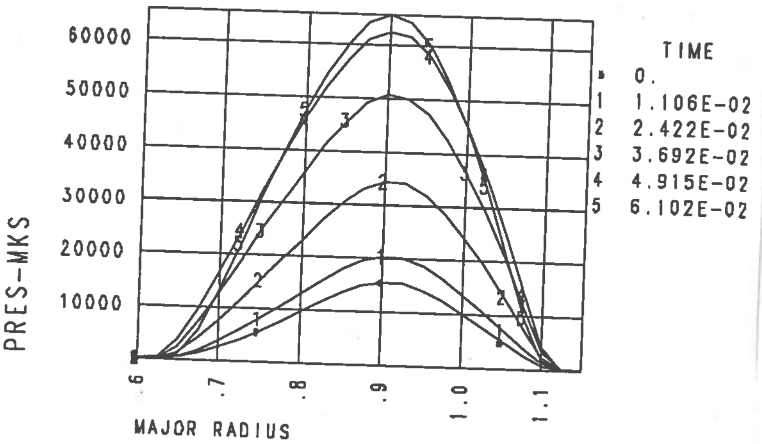
- A SKIN CURRENT DEVELOPS IN THE PLASMA
- J(0) CHANGES LITTLE



- THE ELECTRON TEMPERATURE PROFILE IS HELD FIXED $T_e(0) = 1100\ eV$



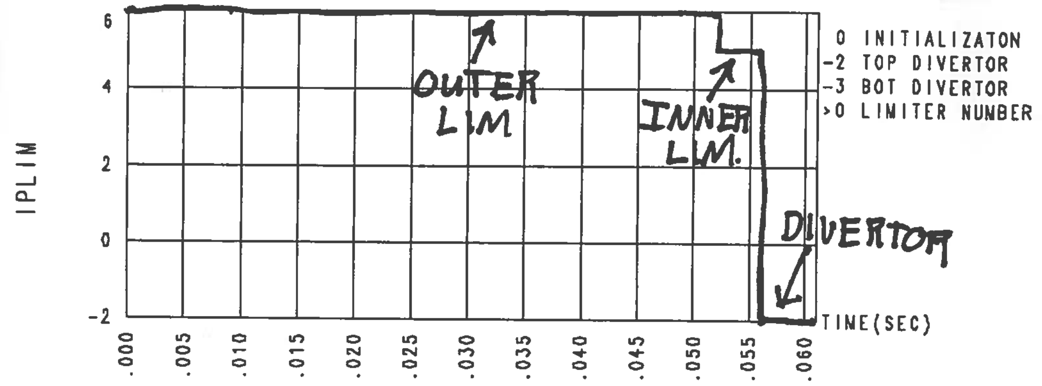
- THE PLASMA PRESSURE IS RAMPED UP
- β_{pol} INITIAL AND FINAL VALUE IS ~0.95.



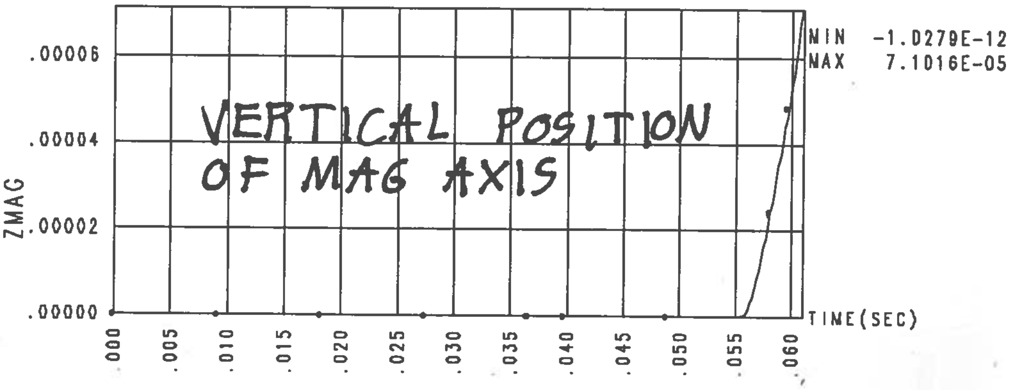
MAJOR RADIUS
[0.63 → 1.11 M]

EVOLUTION TO 2.44/1 DIVERTED EQUILIBRIUM WITH CURRENT RAMP RATE OF 5 MAMP/SEC

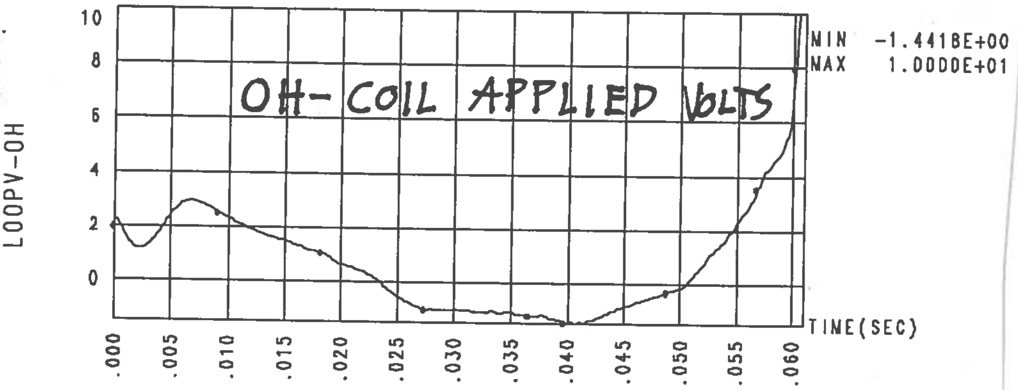
-THE PLASMA IS ON THE OUTER LIMITER, THEN INNER, THEN DIVERTED

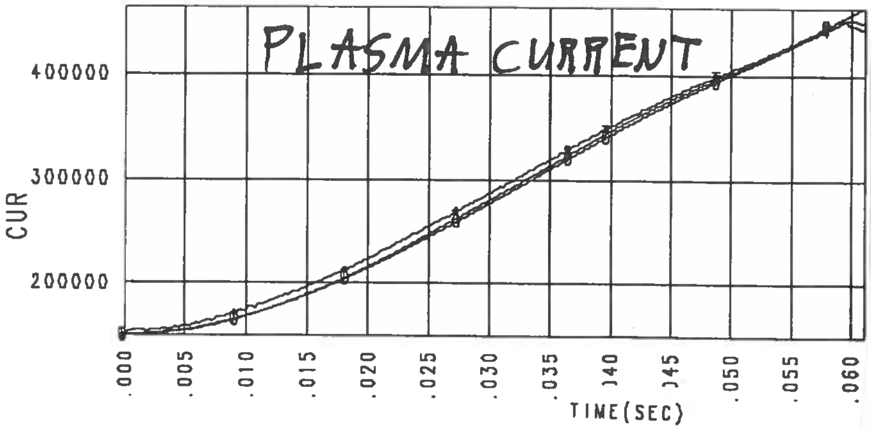


- WHEN THE PLASMA BECOMES DIVERTED, AND NARROW, IT GOES VERTICALLY UNSTABLE



-THE OH COIL CAN PROVIDE THE 5 MA/SEC RAMP RATE OF THE PLASMA CURRENT

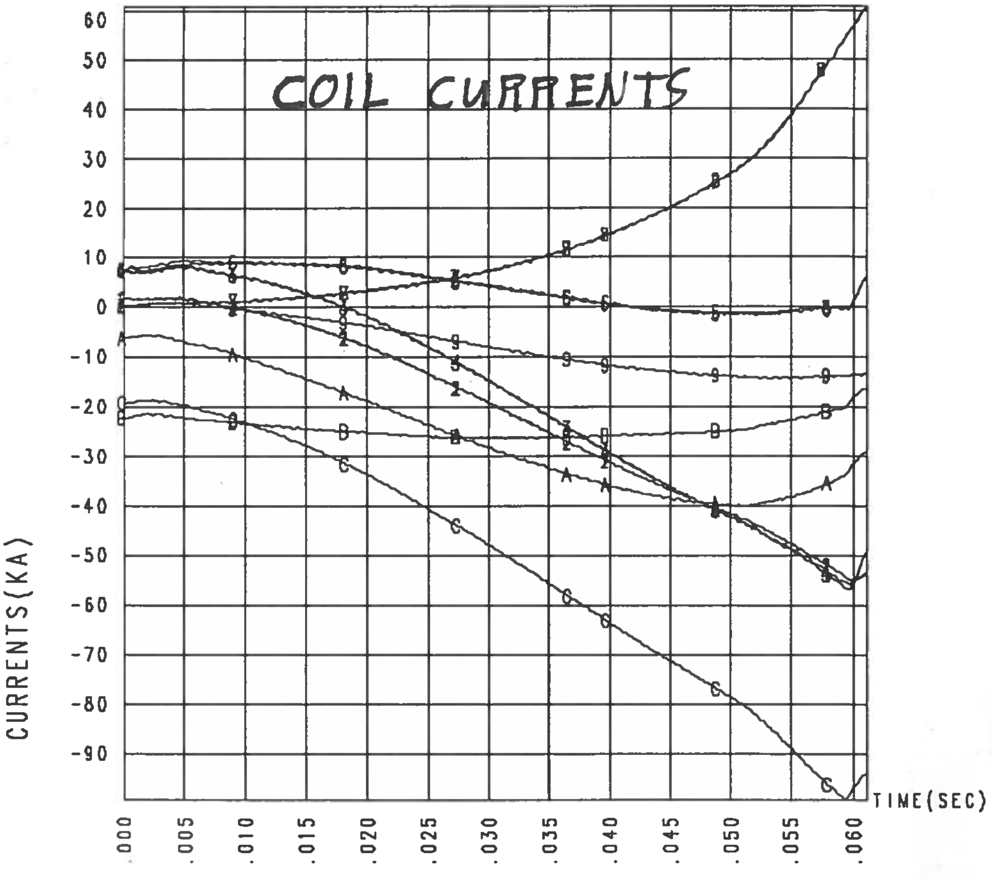




TIME [0 - 60 MSEC]

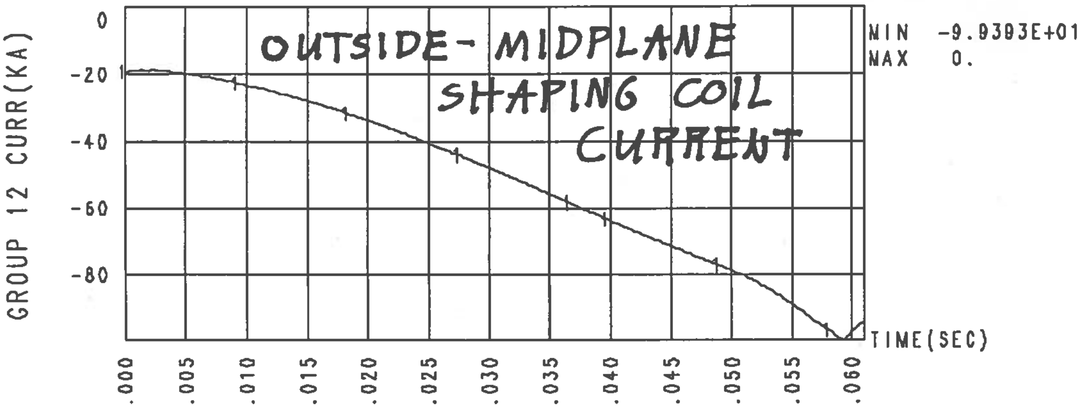
EVOLUTION TO 2.44/1 DIVERTED EQUILIBRIUM WITH CURRENT RAMP RATE OF 5 MAMP/SEC

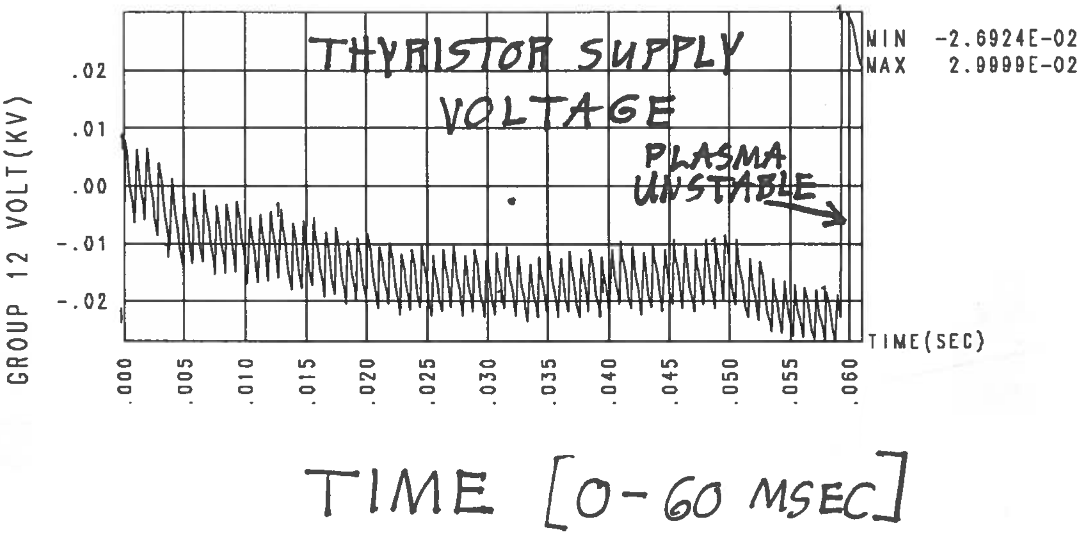
- SHAPING CURRENTS ARE WITHIN DESIGN RANGE



- SHAPING COIL VOLTAGES WITHIN DESIGN RANGE, EVEN FOR 5 MA/SEC.

NOTE: PID CURRENT/VOLTAGE FEEDBACK ON A FEW MOMENTS





TIME [0-60 MSEC]

EVOLUTION IN THE PRESENCE OF FLUX SURFACE AVERAGED ENERGY TRANSPORT

-IN PREVIOUS EXAMPLES, THE PRESSURE P AND ELECTRON TEMPERATURE T_e PROFILES WERE FIXED AS A FUNCTION OF FLUX.

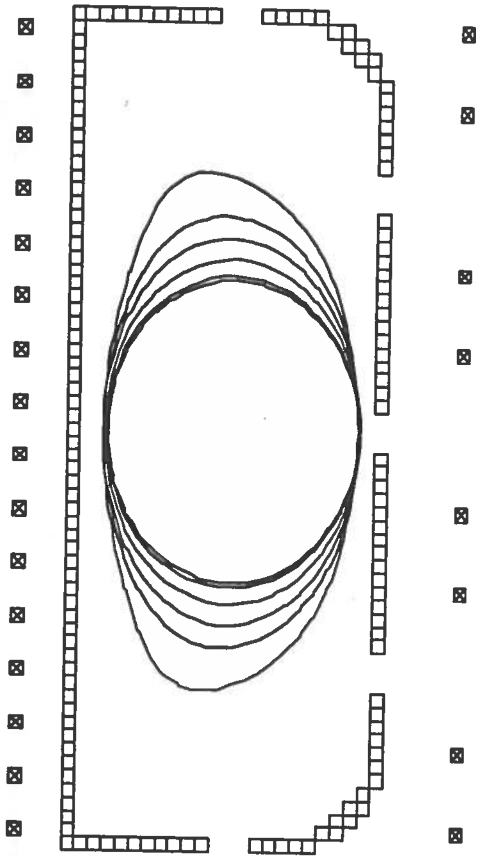
-IN WHAT FOLLOWS, P, T_e , AND J ARE COMPUTED USING TANG-COPPI TRANSPORT (PPPL - 2311), WHICH CONSIDERS THERMAL TRANSPORT BASED ON MICRO-INSTABILITY AND PROFILE CONSISTENCY.

-WHEN THE PREVIOUS EXAMPLE IS RE-RUN, USING THIS TRANSPORT, VERY DIFFERENT CURRENT PROFILE AND SHAPE EVOLUTION ARE OBSERVED:
---THE PROFILE OF CURRENT BROADENS, AND PEAK TEMPERATURE IS REDUCED
---A SKIN CURRENT IS NO LONGER EVIDENT
---THE MAXIMUM ELONGATION IS ONLY 2/1, AND THE SHAPE IS MORE ELLIPTICAL
---THE MAXIMUM TOROIDAL BETA FROM OHMIC HEATING IS ONLY 0.69 %.

-WE OBSERVE THAT PLASMA TRANSPORT IN THE PRESENCE OF OHMIC HEATING RESTRICTS THE RANGE OF PLASMA CURRENT AND PRESSURE PROFILES THAT ARE AVAILABLE.

-RE-OPTIMIZED COIL CURRENT PREPROGRAMMING AND FEEDBACK CONTROL ARE REQUIRED FOR THIS NEW CURRENT PROFILE.

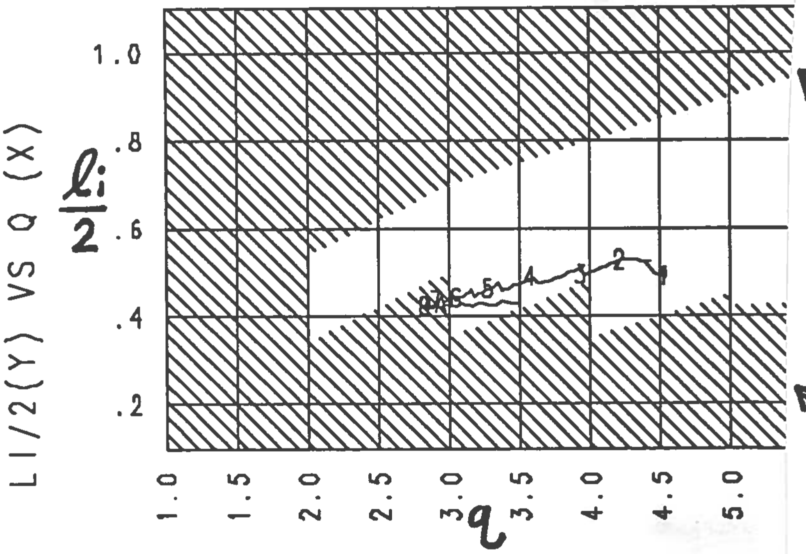
EVOLUTION WITH FLUX-SURFACE AVERAGED TRANSPORT



NOTE REDUCED
ELONGATION
AND TRIANGULARITY

[#1090]

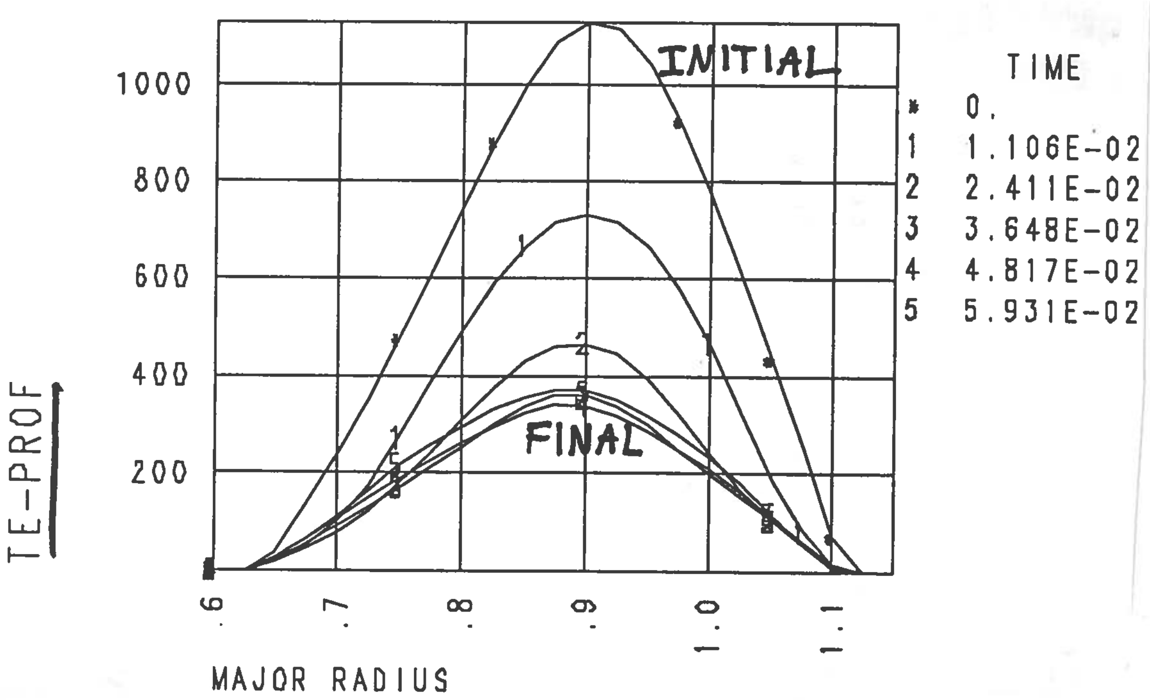
"JET - PLOT"
HATCHED REGION
FOR <u>CIRCULAR</u> PLASMA.

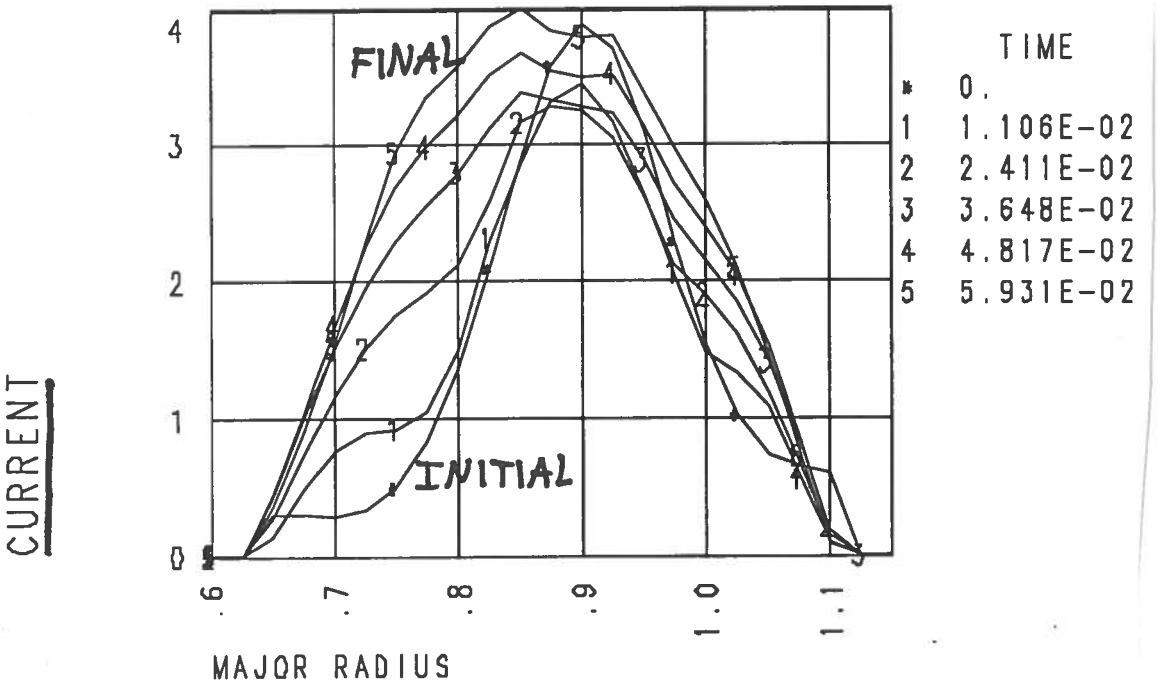


RESISTIVE MODES

IDEAL KINKS

EVOLUTION WITH FLUX-SURFACE AVERAGED TRANSPORT





- T_e and $\bar{J}$ profiles are strongly modified and constrained by transport.

EVOLUTION WITH FLUX SURFACE AVERAGED TRANSPORT AT FIXED, LOW DENSITY

-THE PREVIOUS EXAMPLE WAS RERUN WITH THE DENSITY FIXED AT THE INITIAL LOW VALUE OF 3.5 X 10^{13} CM^{-3}. (CASE NO. 1096)

-THE CENTRAL ELECTRON TEMPERATURE NOW DROPS MUCH LESS TO 700 eV INITIALLY AND THEN INCREASES TO 900 eV AT THE HIGHEST CURRENT.

-THE ELONGATION IS NO LONGER LIMITED TO 2/1, BUT INCREASES UP TO THE HIGHER ELONGATION DIVERTED CONFIGURATION WITH REDUCED WIDTH.

-THIS HIGH ELONGATION, NARROW WIDTH CONFIGURATION IS STILL VERTICALLY UNSTABLE.

-EVEN AT THESE HIGHER ELECTRON TEMPERATURES, WINGS ARE NOT OBSERVED TO FORM ON THE CURRENT DENSITY PROFILE. THIS IS NOT SURPRISING SINCE PROFILE-CONSISTENT TRANSPORT IS BEING USED.

-THE VOLT-SECOND CONSUMPTION IS SMALL DUE TO THE SHORT RISE TIME AND CONTRIBUTIONS FROM THE OUTER SHAPING COILS. FOR A 0.4 MA CHANGE, ONLY 0.17 VOLT-SECS ARE PROVIDED FROM THE OH TRANSFORMER COIL, GIVING 0.43 VOLT-SEC/MA.

-IN A SEPARATE TEST, WHEN THE CURRENT IS RAMPED UNTIL THE ELONGATION IS 2/1, AND THEN HELD CONSTANT, THE PLASMA CURRENT DENSITY PROFILE CHANGES LITTLE DURING THE FLATTOP.

-WE CONCLUDE THAT VARIATIONS OF DENSITY AND CURRENT RAMP CAN AFFECT THE CURRENT PROFILE, BUT ONLY WITHIN LIMITS, DEPENDING ON THE ACTUAL TRANSPORT MECHANISM.

VOLT-SECOND CONSUMPTION

-FOR THE EVOLUTIONS SHOWN (WITH CASE NUMBER) IN THIS MEMO, THE VOLT-SECOND CONSUMPTION IS LISTED IN THE FOLLOWING TABLE, DEFINED AS THE INTEGRAL OF THE VOLTAGE PROVIDED BY A PERFECT OHMIC COIL:

-THE TABLE INCLUDES DESCRIPTION; CASE NUMBER; DELTA VALUES OF TIME, PLASMA CURRENT, OHMIC COIL VOLT-SECONDS; AND THE RATIO OF VOLT-SECOND CHANGE TO PLASMA CURRENT CHANGE.

-NOTE THAT THE RATIO IS INFLUENCED BY SHAPE (SHAPING COIL CONTRIBUTION), DISCHARGE TIME AND ELECTRON TEMPERATURE (RESISTIVE VOLT-SECONDS), AND TOTAL CURRENT SWING.

DESCRIPTION	CASE (NO.)	ΔT (SEC)	ΔI_P (MA)	ΔV-SEC (VS)	$\Delta VS/\Delta I_P$ (VS/MA)
RACETRACK EVOLUTION FROM TOP OF VESSEL	0463	0.56	1.2	0.95	0.79
LOW-Q CENTERED DEE EVOLUTION	0708	0.50	1.3	1.33	1.02
CENTERED EVOLUTION TO 2/1 DEE	1062	0.15	0.25	0.13	0.52
CENTERED EVOLUTION TO 2.22/1 DEE	1067	0.25	0.40	0.41	1.03
CENTERED DEE WITH RAMP RATE 5 MA/SEC, FIXED HIGH T_E	1089	0.061	0.28	0.046	0.16
CENTERED DEE WITH RAMP RATE 5 MA/SEC, FLUX SURF AV TRANSP, HIGH N_E, LOW T_E	1090	0.060	0.30	0.12	0.40
CENTERED DEE WITH RAMP RATE 5 MA/SEC, FLUX SURF AV TRANSP, LOW N_E, HIGH T_E	1096	0.073	0.38	0.17	0.45

CONCLUSIONS

-OPTIMUM PREPROGRAMMING OF SHAPING COIL CURRENTS CAN INCREASE THE POSSIBLE ELONGATION AT $q > 3$.

-A RAPID CURRENT RAMP CAN INCREASE THE POSSIBLE ELONGATION AT $q > 3$ BY THE FORMATION OF A SKIN CURRENT, THEREBY BROADENING THE CURRENT PROFILE.

-THE PLASMA VERTICALLY STABILITY IS CRITICALLY DEPENDENT ON WALL GAP AT HIGH $q > 3$, BUT THE PLASMA WIDTH HAS A TENDENCY TO SHRINK AT HIGH ELONGATION, LEADING TO INSTABILITY.

-PLASMA ENERGY TRANSPORT RESTRICTS THE RANGE OF CURRENT PROFILES AVAILABLE, AND THEREFORE RESTRICTS THE RANGE OF PLASMA OPERATION.

-ALTHOUGH POSSIBLE, EVOLUTION SCENARIOS WITH $q > 3$ ARE MORE DIFFICULT THAN WITH $2 < q < 3$.

-AN ELONGATION OF K=2 SEEMS TO BE THE REGION WHERE CONTROL BECOMES DIFFICULT WITH $q > 3$. AN OPTIMUM SCENARIO MIGHT BE TO KEEP q LESS THAN 3 AS LONG AS POSSIBLE, THEN INCREASE q WITH ELONGATION TO MAINTAIN KINK STABILITY.