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CIT EQUILIBRIUM MODELING

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Fusion Engineering Design Center

PF System Workshop
Princeton Plasma Physics Laboratory
September 15, 1988

Topics

- HEQ improvements
- Divertor coil current distributions
- Expanded radius plasma
- Limiter coil currents
- Shape control studies

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HEQ Improvements

1. Corrections in PSISRF - improved accuracy in contour integrals.

2. New profile options - more flexibility in q_o.

IPP = 5: $dP/dx = P_o[\exp(-Ax)-\exp(-A)]/[\exp(-A)-1][1-C(1-x)]$

IFF = 7: $dF^2/dx = 8\pi\,(1/BETAJ - 1)R_o{}^2P_o$
$\times\,[\exp(-Bx)-\exp(-B)]/[\exp(-B)-1][1+C(1-x)]$

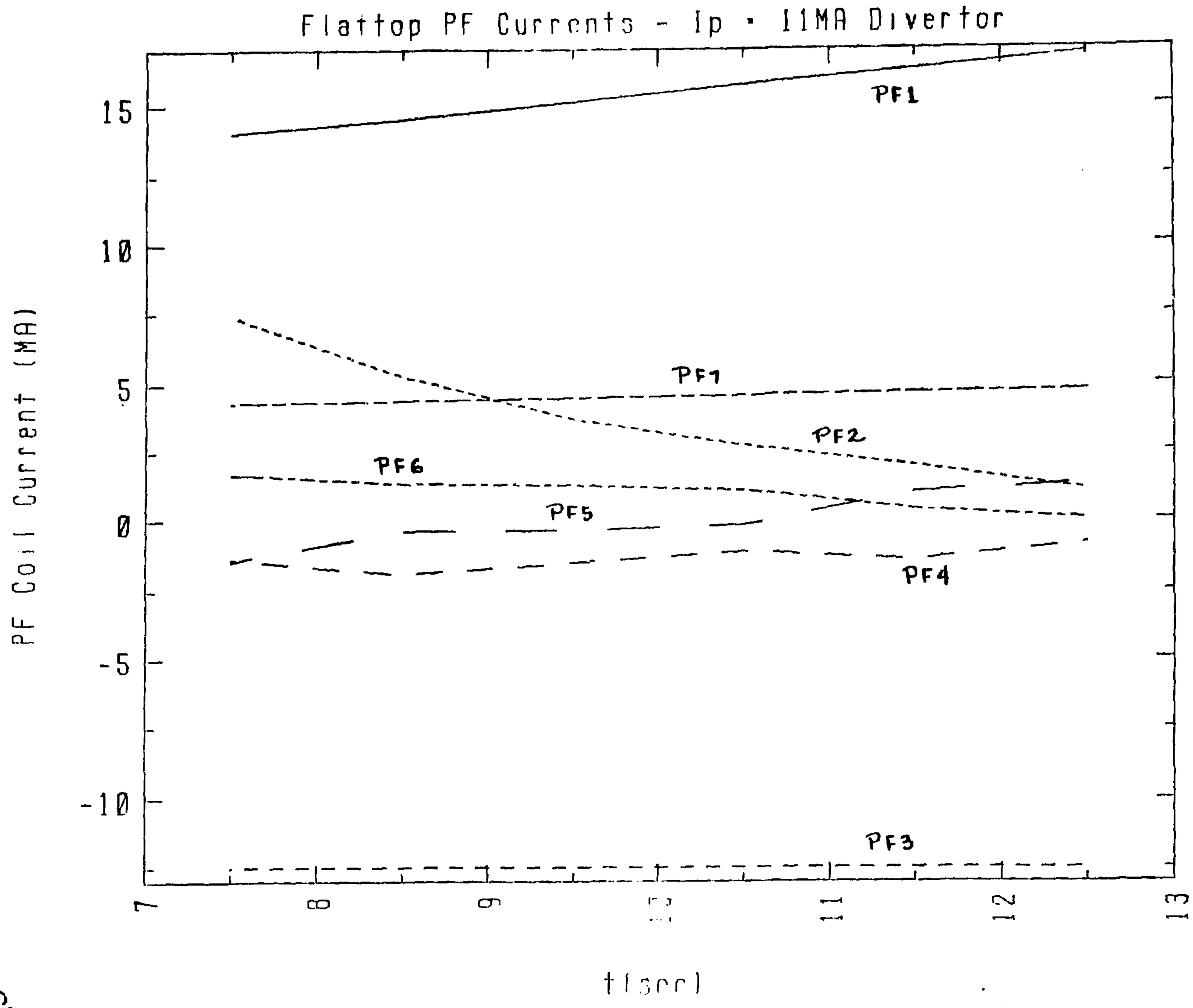
3. Option to vary A,B and BETAJ to fix $l_i/2$, poloidal beta- need good initial guess.

4. Option to store coil Green's Function - up to 50% faster, but 3X larger.

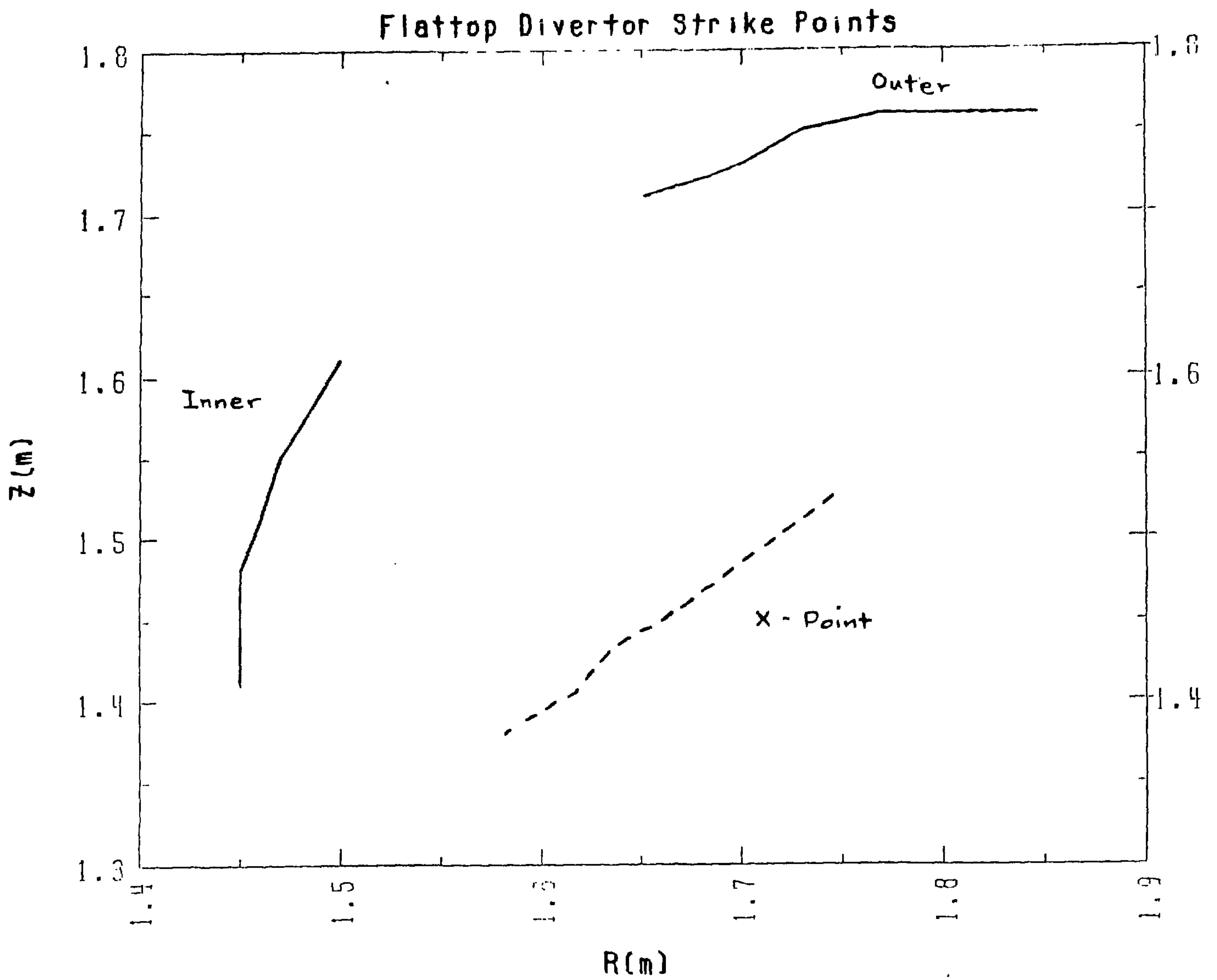
.Set NGD = NMD in PARAMETER statement & recompile.
.Set PARAM(47) = 1 in PARAMS file.

CIT - DIV11D equilibrium sequence

t	5	7.5	8.5	9.5	10.5	11.5	12.5
R_o	m	2.10	2.10	2.10	2.10	2.10	2.10
a	m	0.65	0.65	0.65	0.65	0.65	0.65
κ	(95%)	2.06	2.00	1.97	1.94	1.92	1.90
δ	(95%)	0.28	0.33	0.35	0.36	0.38	0.40
R_x	m	1.753	1.693	1.668	1.633	1.618	1.581
Zx	m	1.530	1.478	1.456	1.431	1.406	1.380
R_I	m	1.50	1.47	1.46	1.45	1.45	1.45
Z_I	m	1.61	1.55	1.51	1.48	1.44	1.41
R_o	m	1.85	1.81	1.77	1.73	1.70	1.65
Z_o	m	1.76	1.76	1.76	1.75	1.73	1.71
$\ell_i/2$		0.370	0.380	0.391	0.400	0.401	0.400
β_p		0.250	0.350	0.390	0.400	0.405	0.410
Φ	V-s	28.70	29.10	29.51	29.90	30.30	30.70
I_p	MA	-11.00	-11.00	-11.00	-11.00	-11.00	-11.00
B_t	T	10.00	10.00	10.00	10.00	10.00	10.00
I_1	MA	14.069	14.536	15.166	15.737	16.273	16.839
I_2	MA	7.404	5.291	3.693	2.708	1.939	1.052
I_3	MA	-12.500	-12.500	-12.500	-12.500	-12.500	-12.500
I_4	MA	-1.385	-1.916	-1.513	-1.130	-1.412	-0.835
I_5	MA	-1.442	-0.404	-0.369	-0.199	0.981	1.287
I_6	MA	1.696	1.321	1.254	1.050	0.365	0.018
I_7	MA	4.300	4.386	4.474	4.558	4.644	4.730
W_{PF}	GJ	1.017	0.997	1.006	1.011	1.022	1.035
Run #		0906A	0906B	0906C	0907A	0907B	0907C



Flattop PF Currents - Ip • 11MA Divertor
PF1
PF7
PF2
PF6
PF5
PF4
PF3
15
10
5
0
-5
-10
PF Coil Current (MA)
7
8
9
10
11
12
13
t(sec)


Flattop Divertor Strike Points
Outer
Inner
X - Point
Z(m)
R(m)
1.8
1.7
1.6
1.5
1.4
1.3
1.9

Increased Elongation at EOB

Elongation	(95%)	1.90	2.03	2.01
Triangularity	(95%)	0.40	0.37	0.36
R_x	m	1.581	1.580	1.610
Z_x	m	1.380	1.470	1.470
R_I	m	1.450	1.454	1.454
Z_I	m	1.410	1.492	1.494
R_O	m	1.650	1.607	1.655
Z_O	m	1.710	1.682	1.717
I_1	MA	16.839	16.474	16.273
I_2	MA	1.052	2.767	3.201
I_3	MA	-12.500	-12.500	-12.500
I_4	MA	-0.835	2.061	1.093
I_5	MA	1.287	-2.537	-1.809
I_6	MA	0.018	1.559	1.329
I_7	MA	4.730	4.730	4.730
W_{PF}	GJ	1.035	1.130	1.083
Run No.		0907C	0913A	0909B

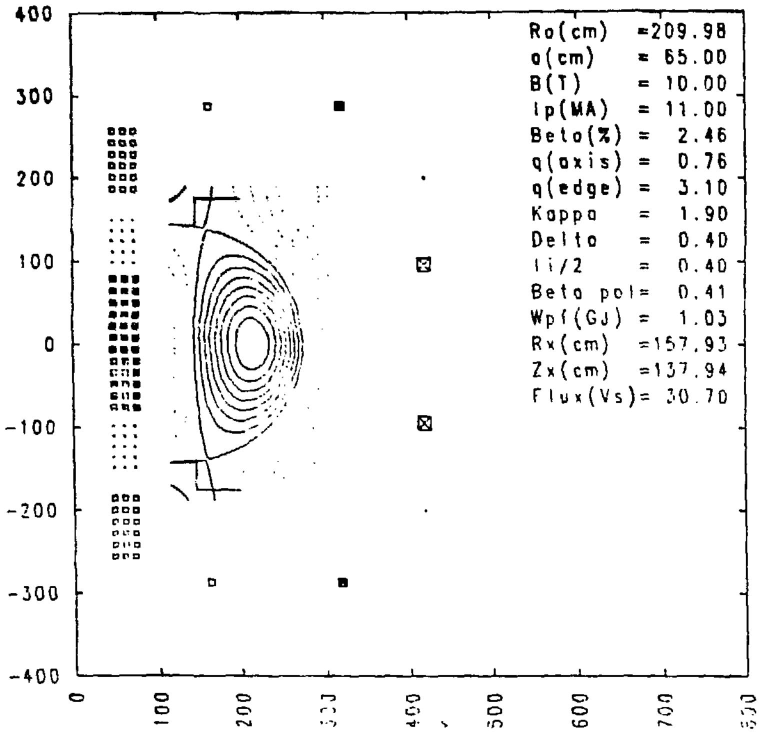
o Effect is to decrease inboard sweep distance.

EXPANDED VACUUM VESSEL -- EOB EQUILIBRIA

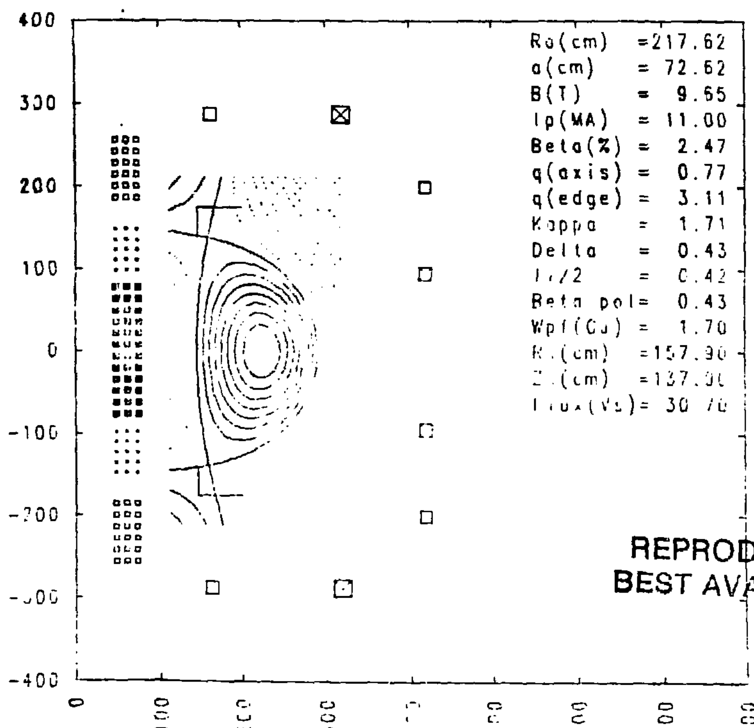
		Standard Plasma	Expanded Radius	Minimum Coil Energy
R_o	m	2.10	2.176	2.176
a	m	0.65	0.726	0.726
κ	(95%)	1.90	1.71	1.71
δ	(95%)	0.40	0.43	0.43
R_x	m	1.58	1.58	1.58
Z_x	m	1.38	1.38	1.38
$\ell_i/2$		0.40	0.42	0.42
β_p		0.41	0.43	0.43
Φ	V-s	30.70	30.70	30.70
I_p	MA	-11.00	-11.00	-11.00
B_t	T	10.00	9.65	9.65
I_1	MA	16.88	15.46	15.41
I_2	MA	0.87	2.03	2.38
I_3	MA	-12.00	-12.00	-14.47
I_4	MA	-1.06	-4.44	-1.66
I_5	MA	1.47	8.00	2.56
I_6	MA	-0.06	-3.68	2.08
I_7	MA	4.73	4.73	2.61
W_{PF}	GJ	1.03	1.70	1.00
Run #		0907D	0908A	0908C

Expanded Vacuum Vessel - EOB Equilibria

'Standard' Plasma Size

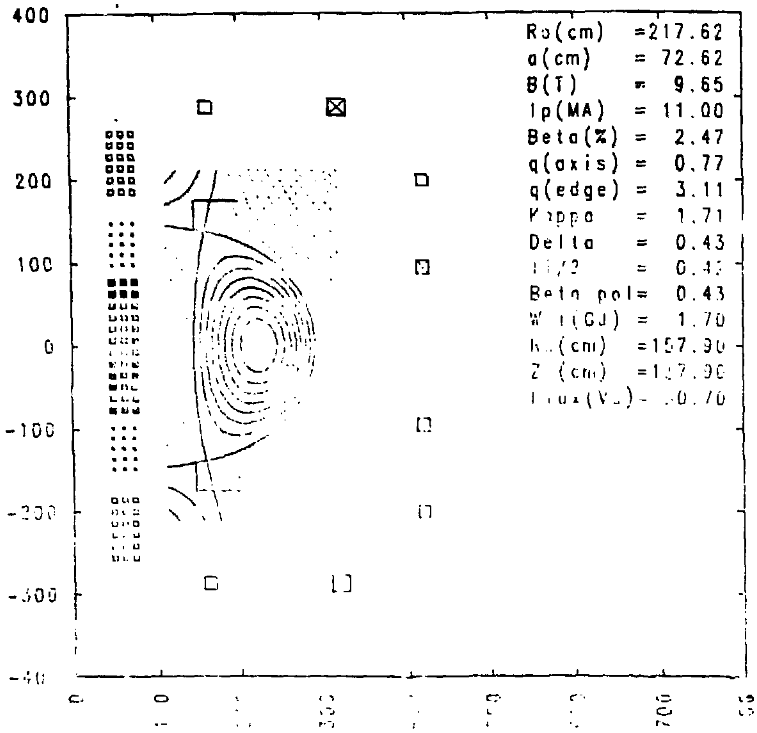


'Expanded' Plasma Size
(I3 , I7 fixed)

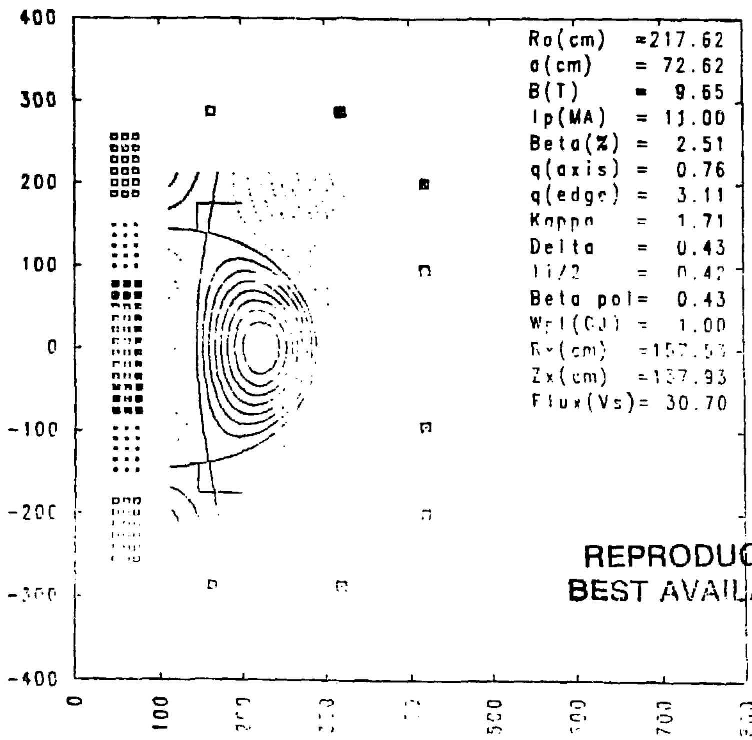


Expanded Vacuum Vessel - EOB Equilibria

'Expanded' Plasma Size (I3, I7 fixed)



'Expanded' Plasma Size (Minimum coil energy solution)



Action:t 26

*** Message 26 ***

From 004054 pomphrey n@b (p11) on 09/06/88 at 19:26:07
Subject : limiter (11MA)
Dennis; To complete our 11MA limiter studies we would like a number of time points analysed using your code. The Table (A) below gives the parameters of interest for what we will call the fiducial. In addition, we have an interest in determining how the coil currents will vary when we explore plasma shapes around the fiducial. Therefore we would like you to calculate BOFT (t=7.5 s) and EOB (t=12.5 s) coil currents for the range of elongations and triangularities listed in Table (B). Note, shape parameters are given at the plasma vacuum interface for the limiter config.

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Table (A)

Notation: t=time, phi=flux linkage at R=2.10 m (vsecs), R0=major radius, a=minor radius, Kappa=elongation, delta=triangularity, li/2=obvious, btheta=poloidal beta, PF8=coil current in what you call PF7 in kA.

t	phi	R0	a	kappa	delta	li/2	btheta	pf8
7.5	28.8	2.07	0.65	2.0	0.5	0.37	0.25	-2924.0
8.5	29.2	2.07	0.65	2.0	0.5	0.38	0.35	-3000.0
9.5	29.6	2.07	0.65	2.0	0.5	0.39	0.39	-3100.0
10.5	29.9	2.07	0.65	2.0	0.5	0.40	0.39	-3167.0
11.5	30.3	2.07	0.65	2.0	0.5	0.40	0.39	-3213.0
12.5	30.7	2.07	0.65	2.0	0.5	0.40	0.39	-3250.0

For the runs in Table A, constrain abs(PF1) < 17500. kA, PF3 < 2500. kA

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Table (B)...Variations around Fiducial

Choose phi, R0, a, li/2, btheta, PF8 from Table A at BOFT (t=7.5) and EOB(t=12.5) but run with the following Kappa, delta values:

Kappa	delta
1.4	0.5
1.6	0.5
1.8	0.5
2.0	0.3
2.0	0.4
1.8	0.3

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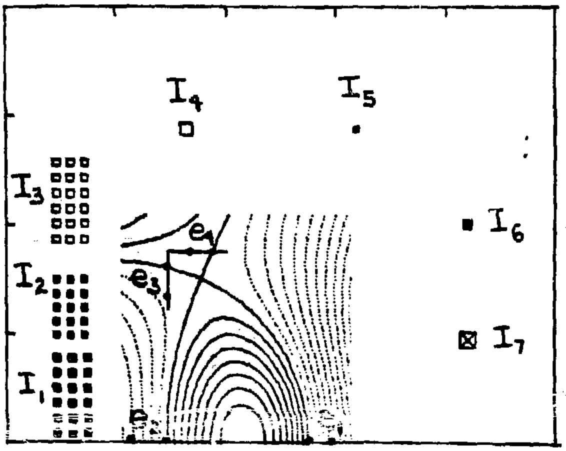
Thanks Dennis.............Neil

[Receipt Acknowledged to Sender]



PLASMA SHAPE CONTROL STUDIES

Let

$$\mathbf{e} = \begin{bmatrix} e_1 \\ \cdot \\ \cdot \\ \cdot \\ e_4 \end{bmatrix}, \quad \mathbf{dI} = \begin{bmatrix} dI_1 \\ \cdot \\ \cdot \\ \cdot \\ dI_7 \end{bmatrix}$$

- Assume $\mathbf{e} = \mathbf{F}(\mathbf{dI})$, through a free boundary equilibrium.
- 'Invert' $\mathbf{F}$ to find a linear relationship $\mathbf{dI} = \mathbf{Ae}$.

Procedure:

- Based on a reference equilibrium, compute a set of equilibria (dI^j, e^j), $j=1,\ldots,M$, varying the coil current distribution between calculations.
- Obtain the control matrix $\mathbf{A}$ by minimizing the norm of the residual vector $\mathbf{r}$ (of length 7M), where

$$\mathbf{r} = \begin{bmatrix} dI^1 - Ae^1 \\ \cdot \\ \cdot \\ \cdot \\ dI^M - Ae^M \end{bmatrix} = \begin{bmatrix} dI^1 - E^1 a \\ \cdot \\ \cdot \\ \cdot \\ dI^M - E^M a \end{bmatrix}$$

Note that $Ae^j = E^j a$, where E^j is 7 X 28, and

$$E^1 = \begin{bmatrix} e_1^1 & e_2^1 & e_3^1 & e_4^1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots \\ 0 & 0 & 0 & 0 & e_1^1 & e_2^1 & e_3^1 & e_4^1 & 0 & 0 & 0 & 0 & 0 & \ldots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_1^1 & e_2^1 & e_3^1 & e_4^1 & 0 & \ldots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & e_1^1 & \ldots \\ & & & & & \cdot & & & & & & & & \\ & & & & & \cdot & & & & & & & & \\ & & & & & \cdot & & & & & & & & \end{bmatrix},$$

and $\mathbf{a}^t = [a_{11}, a_{12}, a_{13}, a_{14}, a_{21}, \ldots, a_{71}, a_{72}, a_{73}, a_{74}]$.

Plasma Shape Control Studies - Example

S (m):

.5100e-02	1.8700e-02	2.0000e-04	1.3400e-02	e^1
.5100e-02	-1.9800e-02	-2.0000e-04	-1.3400e-02	e^2
.5000e-03	-5.6000e-03	4.3000e-03	-5.0000e-03	e^3
.5000e-03	5.3000e-03	-4.2000e-03	5.2000e-03	⋮
.0300e-02	1.0100e-02	9.6000e-03	1.9800e-02	
.0200e-02	-1.0500e-02	-9.7000e-03	-1.9500e-02	
.8500e-02	-2.8100e-02	-3.8100e-02	-2.8500e-02	
.8600e-02	2.8800e-02	4.0300e-02	3.1100e-02	
.3400e-02	-3.8400e-02	-4.9900e-02	-1.7700e-02	
.8700e-02	4.0100e-02	5.2800e-02	1.9400e-02	

LI (MA):

.8400e-01	0.	0.	0.	0.	dI^1
.8400e-01	0.	0.	0.	0.	dI^2
.	6.7500e-01	0.	0.	0.	dI^3
.	-6.7500e-01	0.	0.	0.	⋮
.	0.	-2.4000e-01	0.	0.	
.	0.	2.4000e-01	0.	0.	
.	0.	0.	3.0000e-01	0.	
.	0.	0.	-3.0000e-01	0.	
.	0.	0.	0.	2.1500e-01	
.	0.	0.	0.	-2.1500e-01	

VEC (m)

5.0000e-03	5.0000e-03	5.0000e-03	5.0000e-03	test error vector e

MAT

2.6933e+01	6.8955e+01	-4.7043e+00	-2.3003e+01	
3.1296e+01	3.2129e+01	3.0147e+01	-2.4906e+01	
2.0586e+01	3.3972e+01	1.3387e+01	-2.4149e+01	A - control matrix
2.2590e+01	-2.4471e+01	-1.7884e+01	8.2990e+00	
.6183e+00	8.3909e+00	4.0582e+00	-1.0408e+00	

VEC (MA):

(PF1) = 7.1574e-02
(PF2) = 3.0373e-02
(PF3) = 1.3121e-02 — solution vector dI
(PF4) = -5.7329e-02
(PF5) = 8.9500e-03