THE DESIGN OF THE MST REVERSED FIELD PINCH

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Y. Ho
R.N. Dexter
D.W. Kerst
T.W. Lovell
S.C. Prager
J.C. Sprott

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The Design of the MST Reversed Field Pinch.* Y. HO, R.N. DEXTER, D.W. KERST, T.W.LOVELL, S.C. PRAGER, and J.C. SPROTT, University of Wisconsin-Madison--The MST (Madison Symmetric Torus) experiment at Wisconsin will soon begin construction. The device (R=1.5 meters, vacuum vessel minor radius=52 cm) is designed to facilitate the exchange of internal shells (a~32 cm) for boundary condition studies. Detailed calculations have been performed on key design issues involving field errors, circuit modeling, and gaps/liner protection. Field error levels are calculated to be extremely small since we use the thick conducting vacuum vessel as the toroidal and poloidal field windings, employ large current-feed flanges in both systems, employ a double-shell system and limit all portholes in the shell to no greater than 1-1/4" diameter. Extrapolation from present devices indicates that we should be able to achieve 400 KA plasma currents for ~40 msec with the 32 cm shell. Electrical testing of our gap protection scheme in the presence of plasma is underway. The current goal is to run without a continous liner, although we are planning for that contingency. More details of our final design will be presented.

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INTRODUCTION

Scientific goals:

1) Boundary condition studies:
   Determine shell effects on R.F.P. stability, fluctuations, sustainment, confinement, and transport.
2) q - scaling studies:
   comparative studies of stability and confinement as plasma configuration varies from R.F.P. to non-reversed pinch to Tokamak.

Requirements placed on MST:

- Minimal field error so plasma boundary effect can be compared
  adopted criteria: all field-error-produced bump on magnetic surface < 1 cm

  total radial distance covered by islands produced by sum over all predictable field-error $< 1/10$ minor rad. (3cm)
- Easy diagnostic access to facilitate measurement of fluctuations and other relevant quantities.
- Expeditious exchange of internal shells.

APPROX. SCHEDUAL

Technical Review

present

Begin construction of VCV

1986

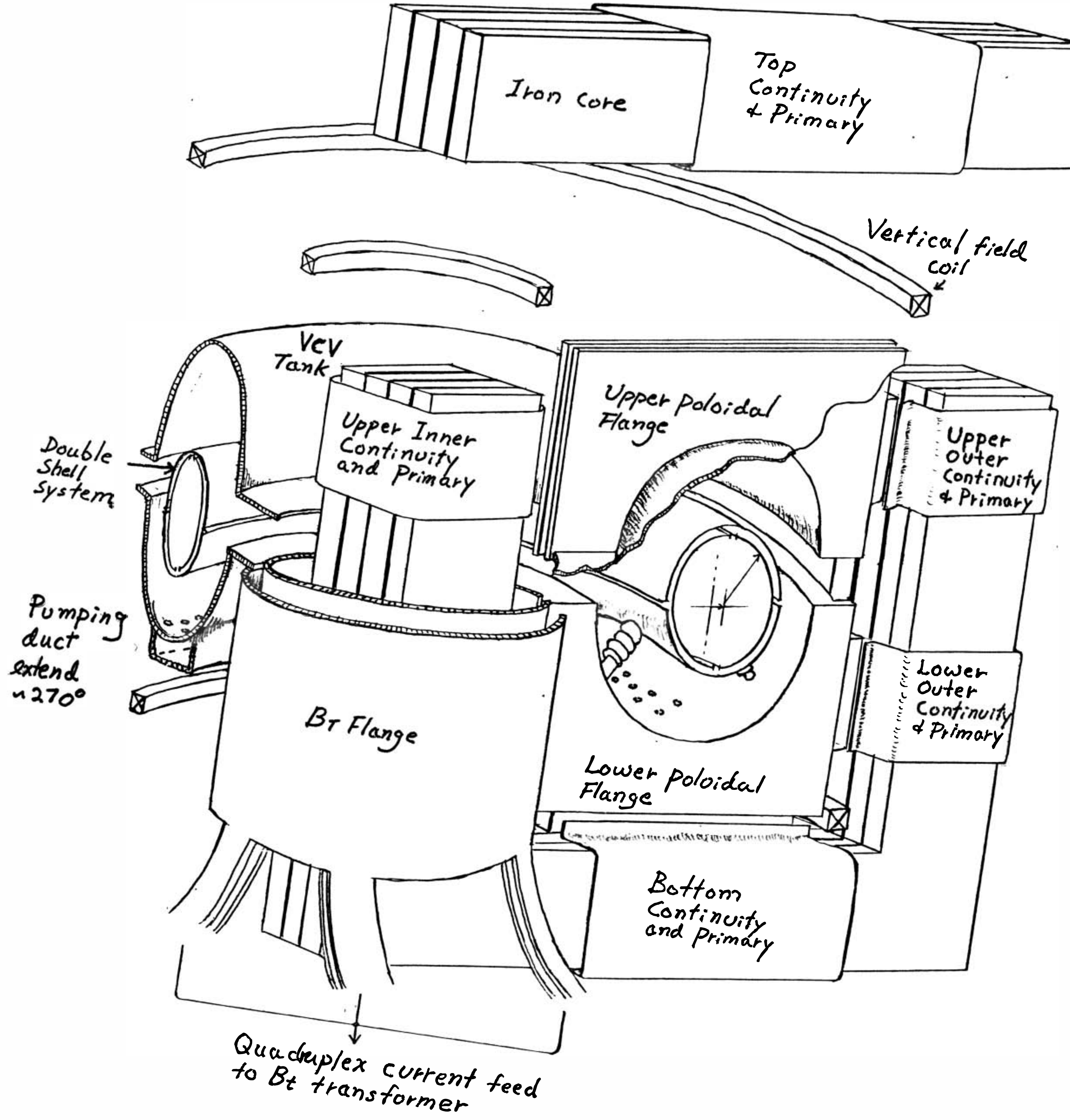
Thick shell design and drafting

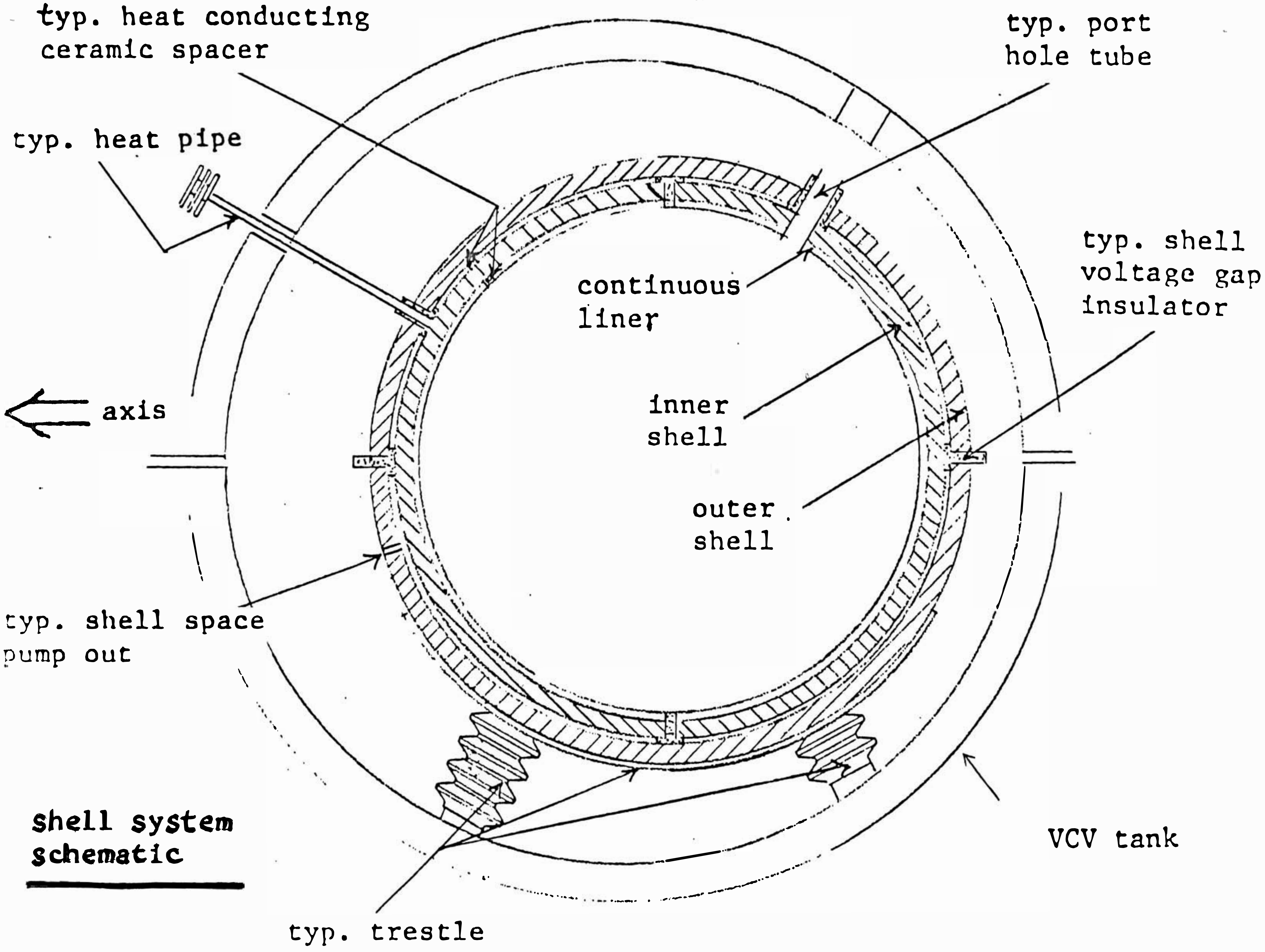
Install VCV

1987

R. F. P. operation (no shell experiment)
Install thick shell
Thick shell experiment

M.S.T. LAYOUT


Iron core
Top Continuity & Primary
Vertical field coil
VCV Tank
Double Shell System
Upper Inner Continuity and Primary
Upper Poloidal Flange
Upper Outer Continuity & Primary
Pumping duct extend ~270°
Bт Flange
Lower Outer Continuity & Primary
Lower Poloidal Flange
Bottom Continuity and Primary
Quadruplex current feed to Bt transformer



shell system schematic

Features :

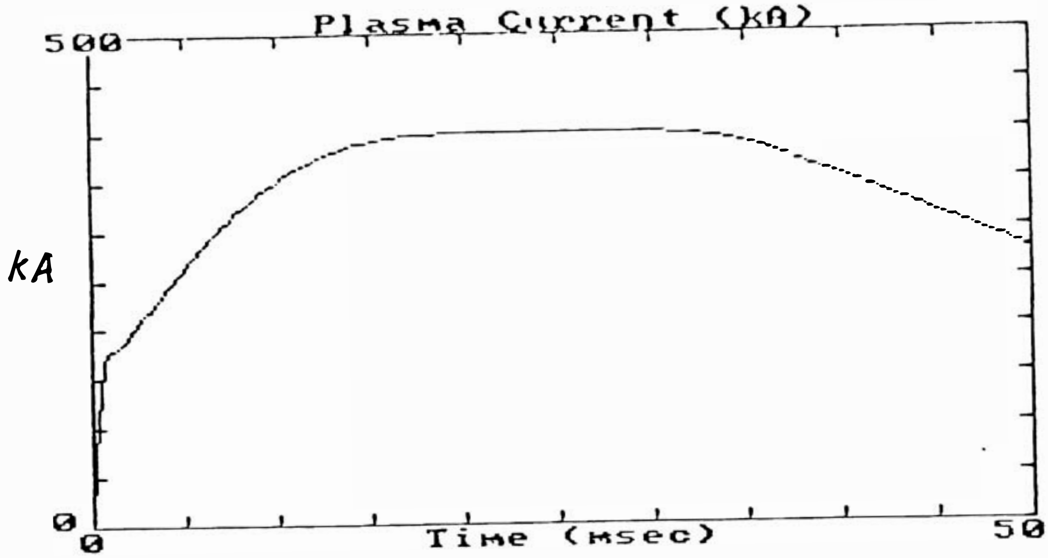
- Take-apart vacuum vessel (VCV).
- Thick conducting VCV (5cm Al).
- Internal double shell centered on tank flux surfaces.
- First wall need not hold off vacuum.
- Conducting VCV functions as B_T field winding.
- Flanged B_T and B_P gaps.
- Continuity windings
- Small holes for pumping and diagnostic

ESTIMATE OF RFP PLASMA PARAMETERS

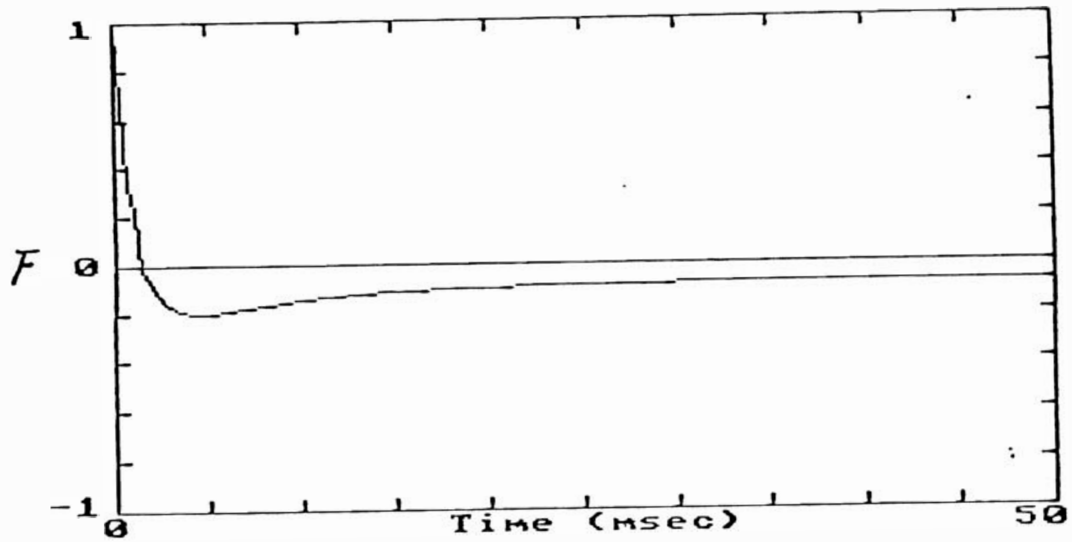
Major radius:	R_o = 1.56 meters
Minor radius:	a = 0.32 meters
Toroidal plasma current:	I_p = 400 kA
Electron temperature:	T_{eo} = 400 eV
Electron density:	$n = 3 \times 10^{19}\ m^{-3}$
Confinement time:	τ_E = 2 msec
Plasma inductance:	L_p = 2.7 μH
Poloidal flux:	Φ = 1.1 volt-sec
Toroidal loop voltage:	V_ℓ = 20 volts
Nominal pulse length:	T = 40 msec
Average toroidal field:	$\langle B_\phi \rangle$ = 0.19 tesla
Toroidal field at wall:	$B_{\phi W}$ = −0.016 tesla

Electrical Circuit Simulation based on Modified Bessel function model of the plasma is used for circuit design.

Plasma current during typical discharge



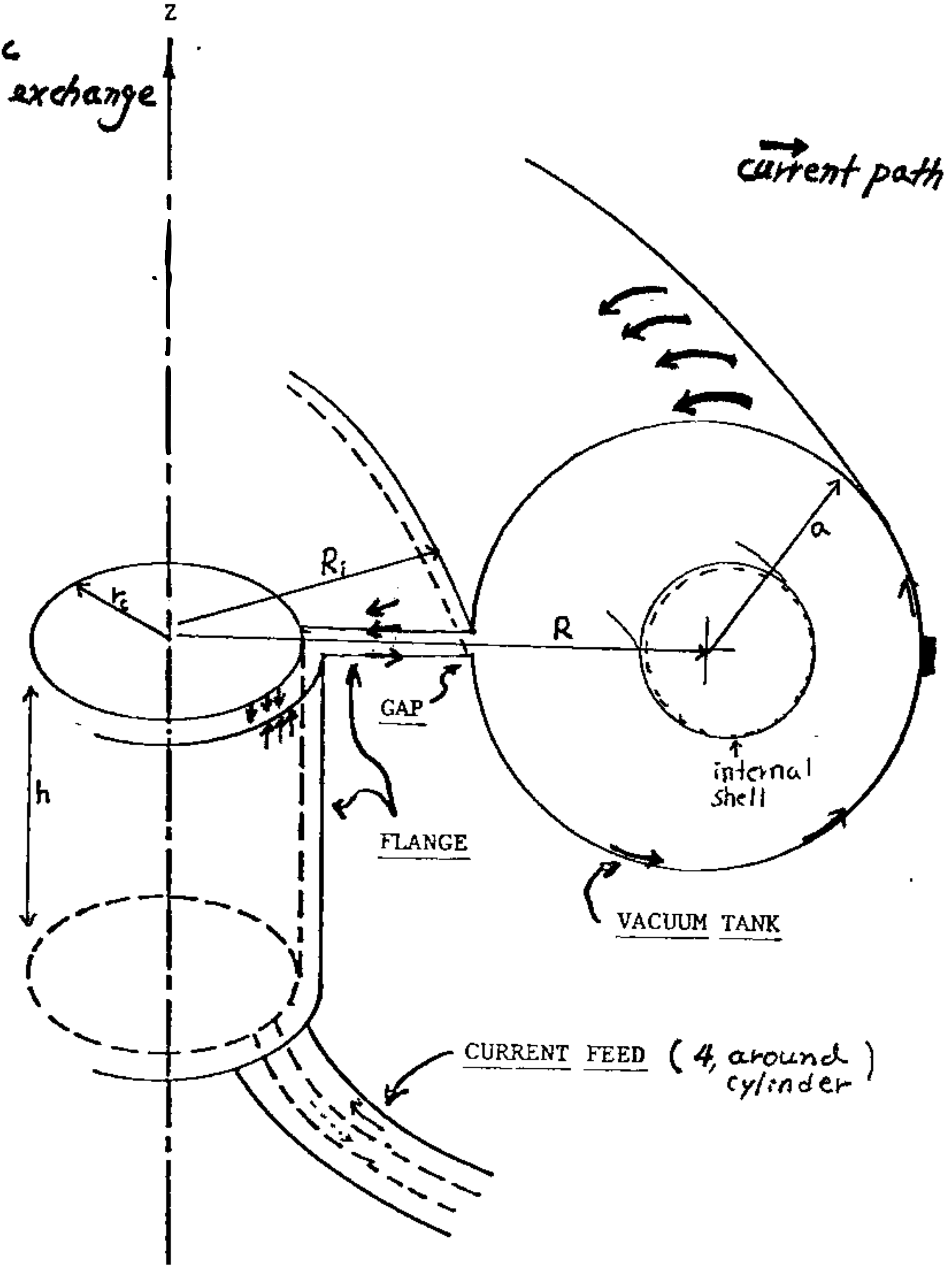
Typical waveform for F (reversal parameter)



B_T System

- Field error at reversal surface $\frac{B_{r,\,m=0}^{\,n=4}}{B_p} \sim 0.005\%$.
  Other n harmonics negligible

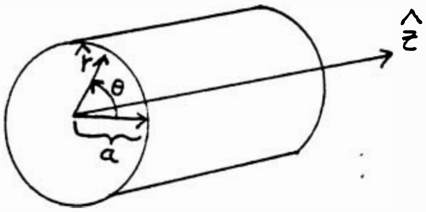
- Easy diagnostic access & shell exchange



Conductive VCV and B_T flanges reduce discrete current feed effects at the gap by a factor of 70.

Inductive limit calculation:

- Solve 2-D $B = \nabla\phi$, $\nabla^2\phi = 0$ in space between flanges.
- Solve 3-D $B = \nabla\phi$ in VCV



periodic boundary condition in $\hat{z}$

- Match solution across boundary
- Match solution to current feed distribution

Solution:

$$\underbrace{\frac{b_{r,n}}{b_{z_0}}}_{\substack{n^{th}\text{ toroidal harmonic of}\\ \text{radial } \underline{B} \text{ normalized}\\ \text{to axisymmetric field}}} = \frac{16}{7}\underbrace{\frac{a_n}{a_0}}_{\substack{\text{amplitude at base due}\\ \text{to discrete current feed}}}\underbrace{\left(\frac{r_c}{R_i}\right)^n}_{\substack{\text{decrement}\\ \text{due to disc}\\ \text{flange}}}\underbrace{e^{-nh/r_c}}_{\substack{\text{decrement}\\ \text{due to}\\ \text{cylinder flange}}}$$

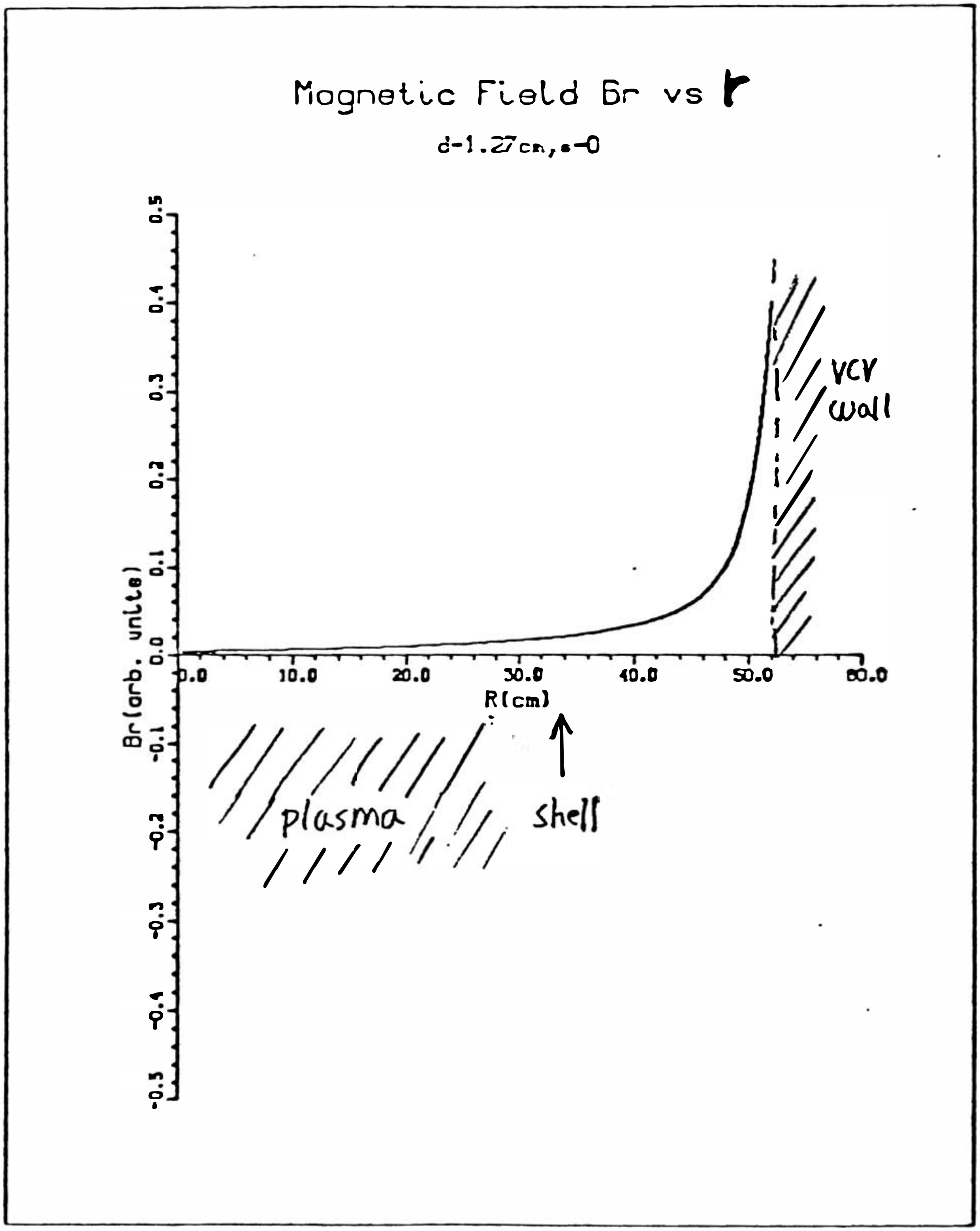
For MST, $n = 4, 8, 12, \cdots$

$$\frac{b_{r,4}}{b_{z_0}} = 3\%$$

higher harmonics negligible

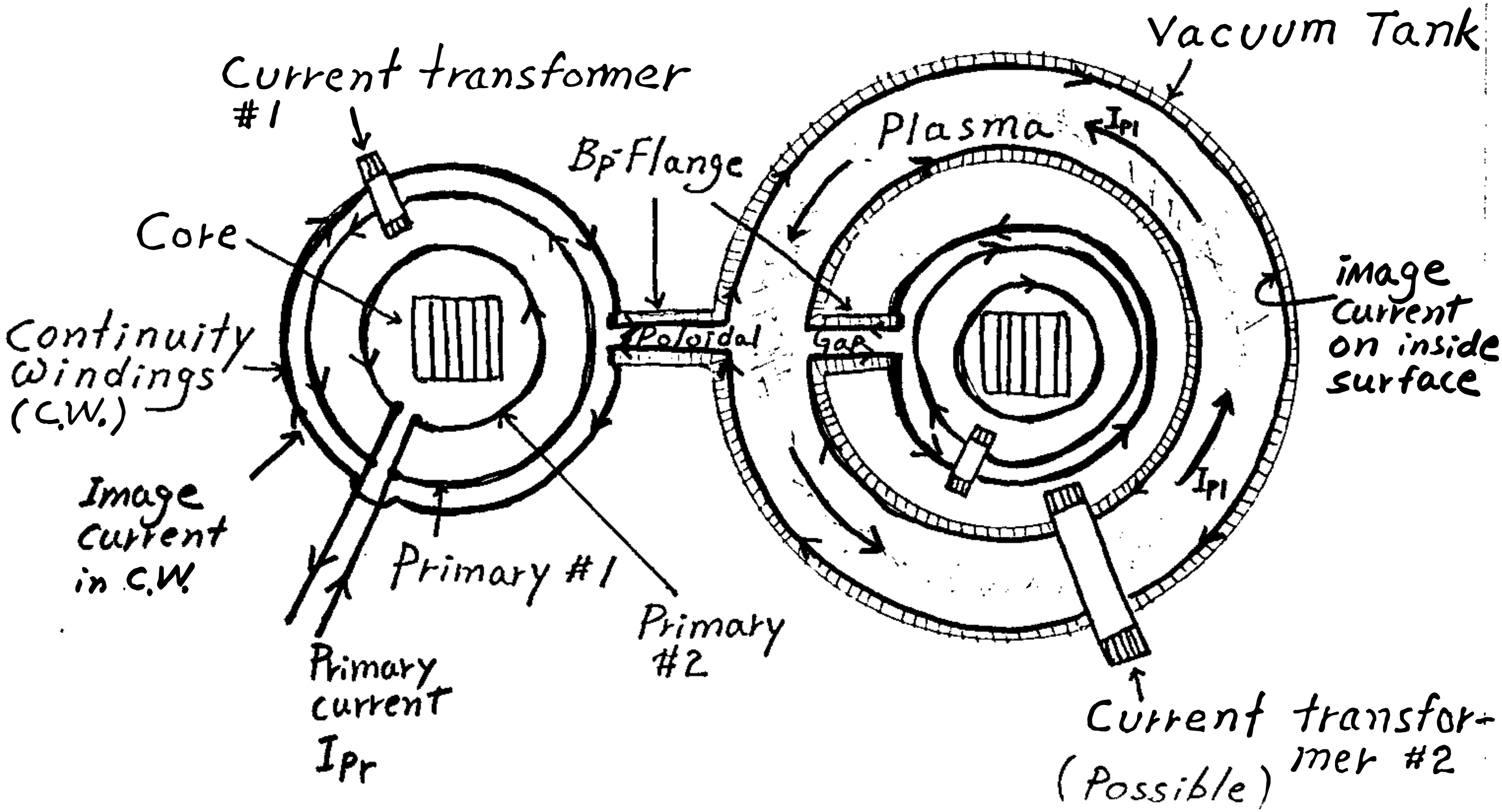
Radial field-error further reduced by the distance between shell and wall

$B_{r,\,\substack{n=4\\ m=0}}$ component ploted vs. minor radius



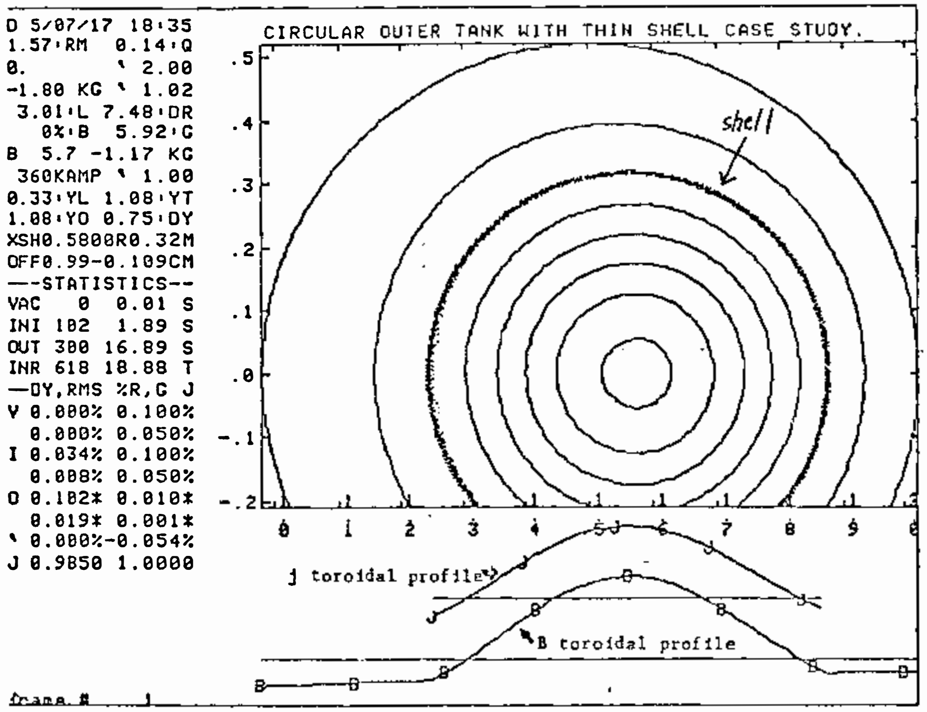
Bp System

- Negligible predictable field-error at equilibrium
- Easy diagnostic access
- Energy efficient (iron core closely coupled to primary)



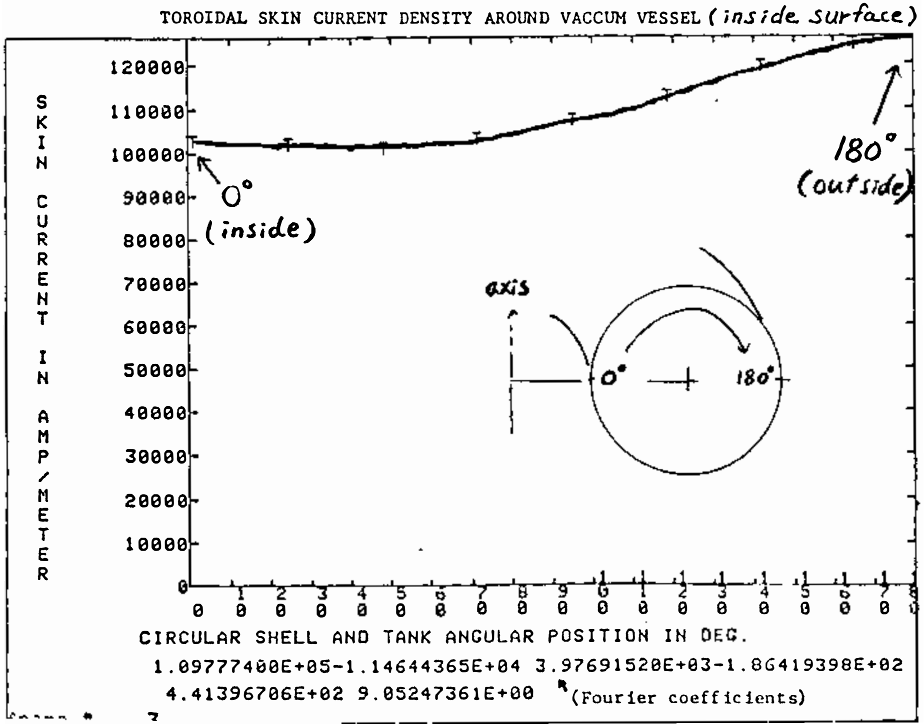
Solution of Grad-Shafranov equation provide equilibrium flux plot, plasma inductance, image current distribution (B_p at wall) and other parameters.

Flux plot of equilibrium (360 kA, const. λ)



```
D 5/07/17 18:35
1.57:RM  0.14:Q
0.          ` 2.00
-1.80 KG ` 1.02
 3.01:L 7.48:DR
   0%:B  5.92:G
B  5.7 -1.17 KG
 360KAMP ` 1.00
0.33:YL 1.08:YT
1.08:YO 0.75:DY
XSH0.5800R0.32M
OFF0.99-0.109CM
---STATISTICS--
VAC   0  0.01 S
INI 102  1.89 S
OUT 300 16.89 S
INR 618 18.88 T
—DY,RMS %R,G J
V 0.000% 0.100%
  0.000% 0.050%
I 0.034% 0.100%
  0.008% 0.050%
D 0.102* 0.010*
  0.019* 0.001*
` 0.000%-0.054%
J 0.9850 1.0000
```

Typical image current distribution rises towards outside

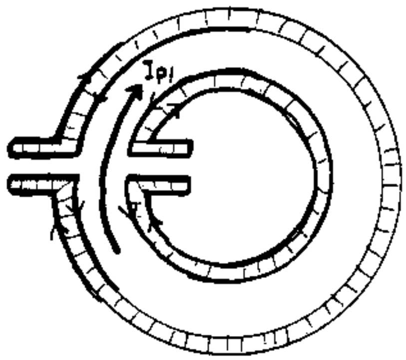


TOROIDAL SKIN CURRENT DENSITY AROUND VACCUM VESSEL (inside surface)

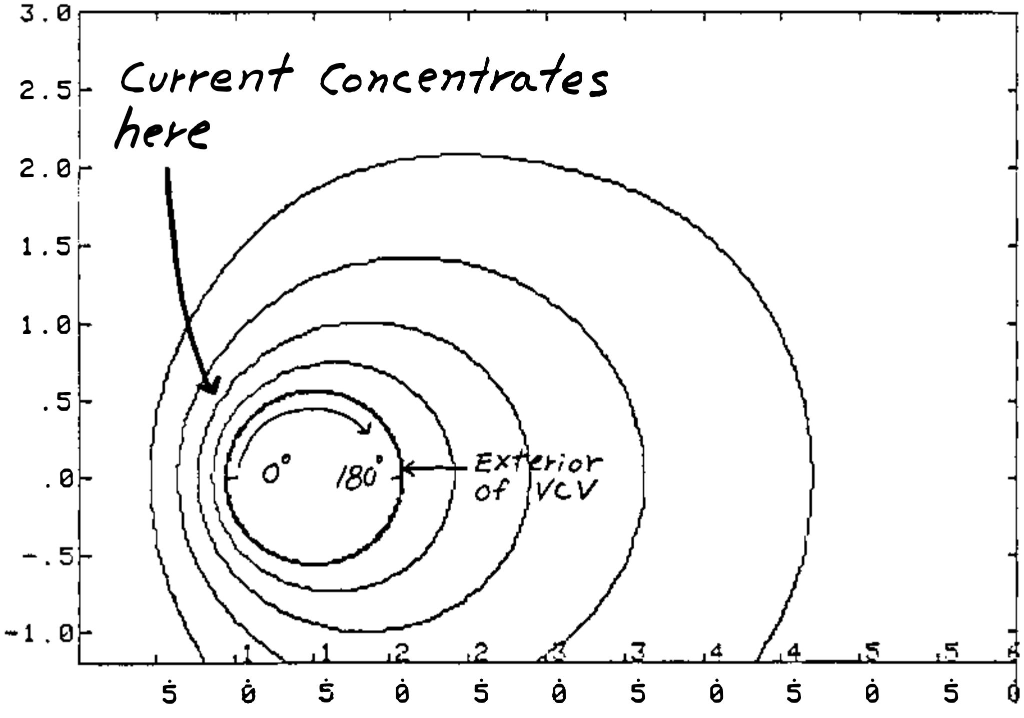
```
1.09777400E+05-1.14644365E+04 3.97691520E+03-1.86419398E+02
  4.41396706E+02 9.05247361E+00
```

(Fourier coefficients)

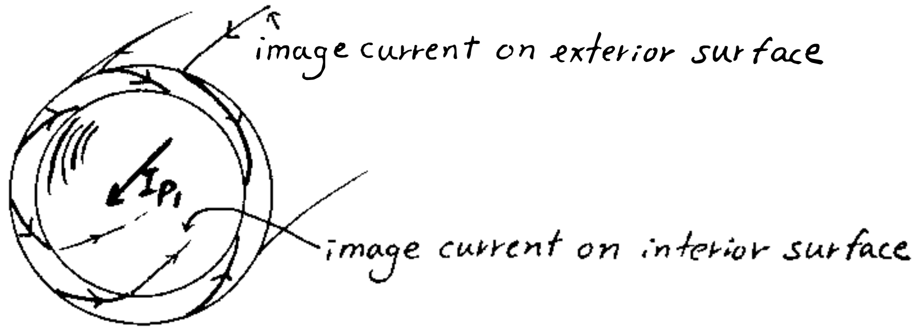
Without continuity windings, image current will flow on exterior surface of VCV



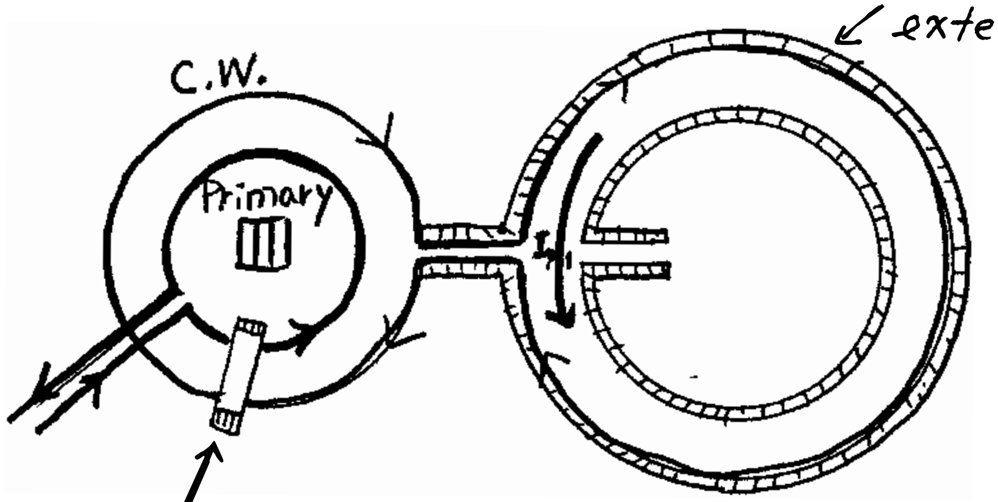
Flux plot exterior of VCV show $\frac{J_{at\ 0°}}{J_{at\ 180°}} \gtrsim 7$



Large m=1 error result from image current flowing across gap



Continuity winding (C.W.) provide path for image current to go around the core.



No current on exterior surface

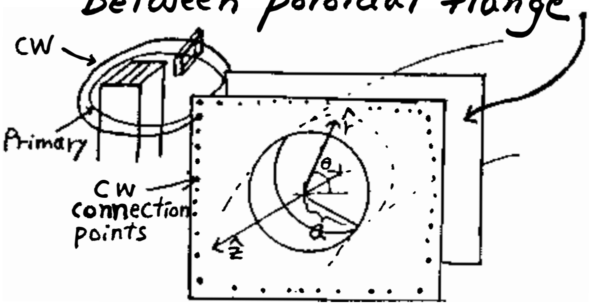
Current transformer inductively couple primary and CW.

Proper amount of current forced through each C.W.

Proper placement of the C.W. system minimizes field-error.

Approach:

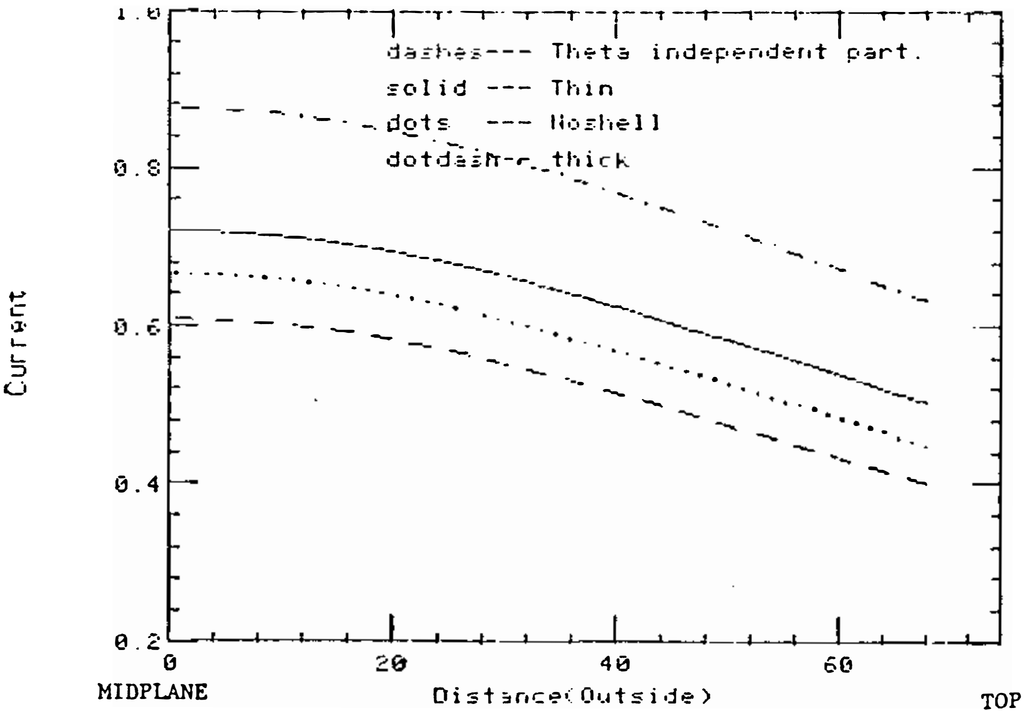
- Solve 3-D problem for $\underline{B}=\nabla\Phi$, $\nabla^2\Phi=0$ between poloidal flange.



- Apply desired boundary condition at $r=a$
    - no z dependence $\Rightarrow$ 2D problem
    - $B_r=0$
    - B_p = Grad-Shafranov solution

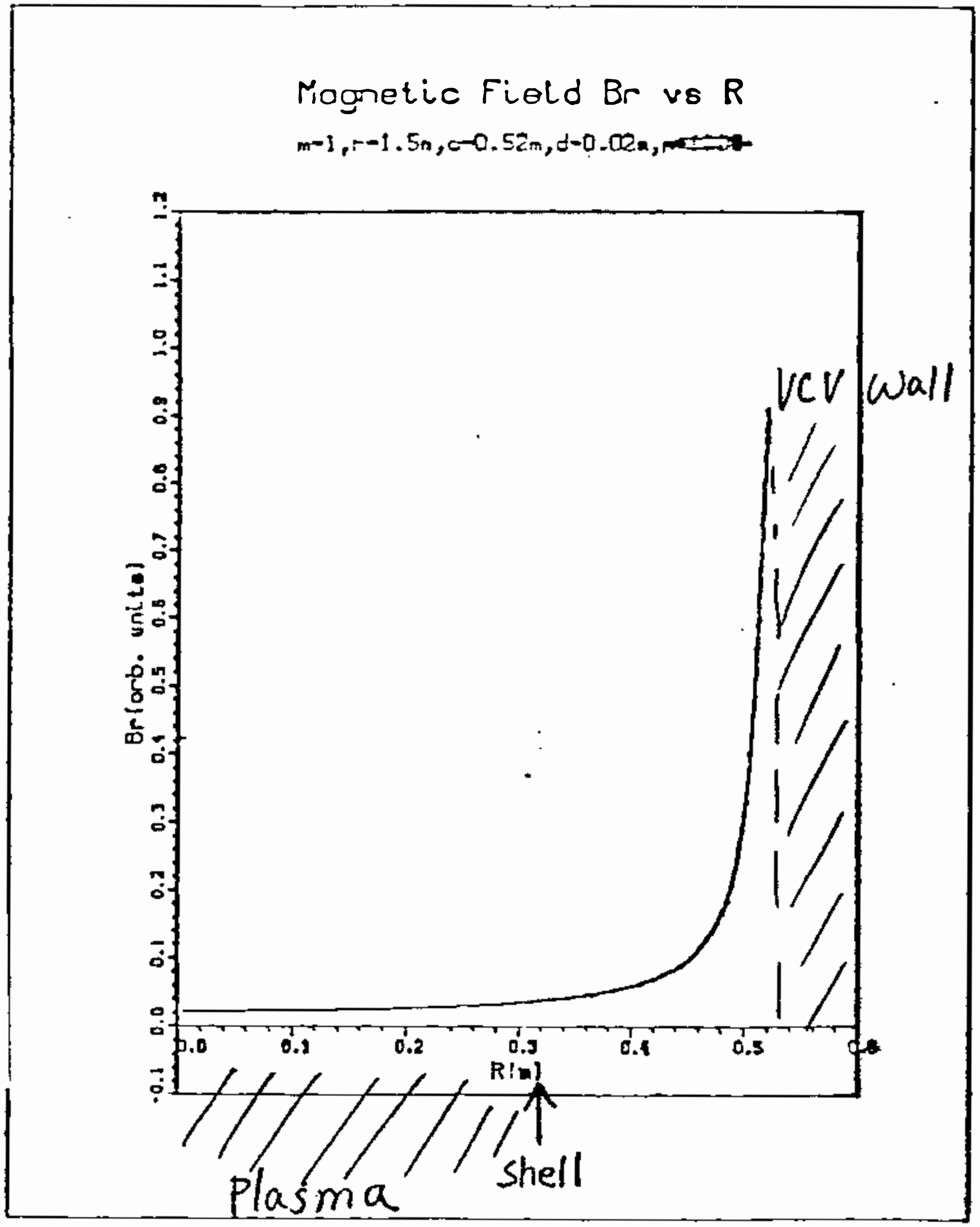
- Solution determined everywhere in the flange.

- Match primary and C.W. to $\underline{B}$ solution at flange boundary.



Field-error produced by missplaced primary/cw falls rapidly with distance from B_p gap

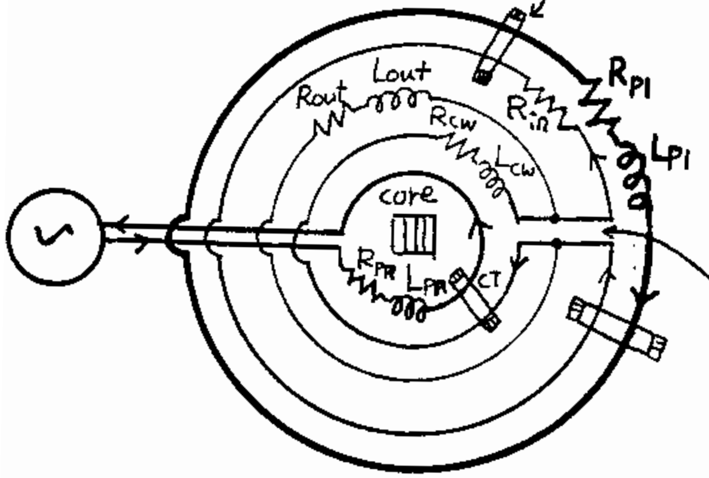
$m=1$ components of B_r vs. minor radius



Magnetization current can produce field-error.

Equivalent circuit:

Thick tank wall act as ideal CT (inductive limit)



CT - Current transformer

L - leakage inductance not linked by core

Pl - Plasma

cw - continuity winding

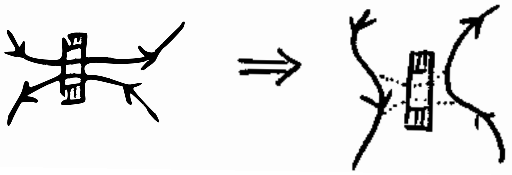
in - inside surface

poloidal gap

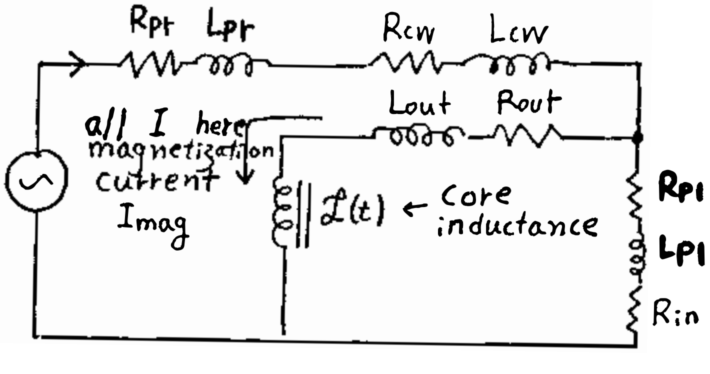
PR - Primary

out - exterior surface of VCV

if CT ideal



Circuit is simplified:

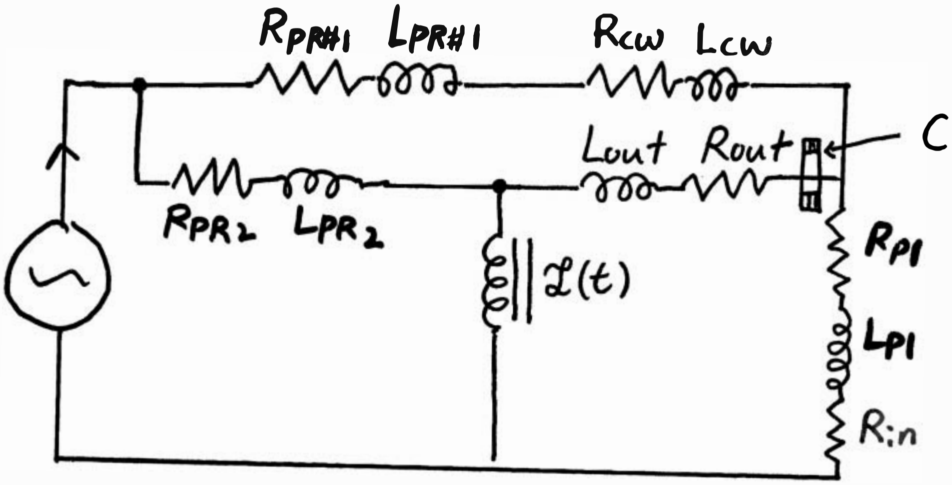


If core saturates, $\mathcal{L}(t)$ falls, Imag rises

⇒ Field-error rises from Imag flowing through cw to exterior surface of VCV

Solution to magnetization current problem.

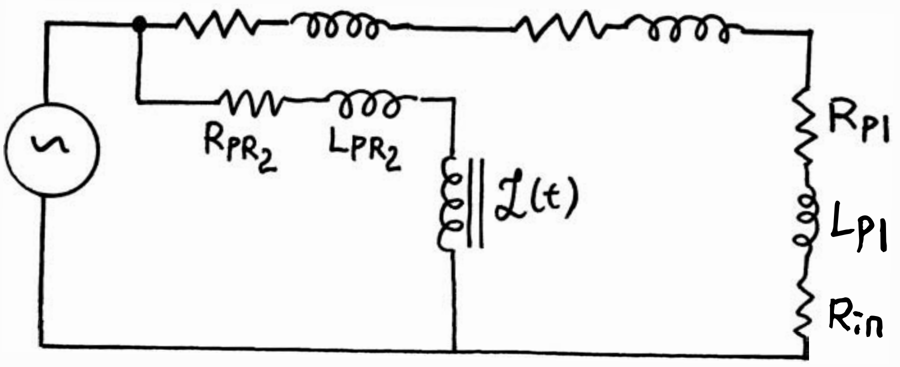
- Add second primary & CT



CT#2 keep currents from this link

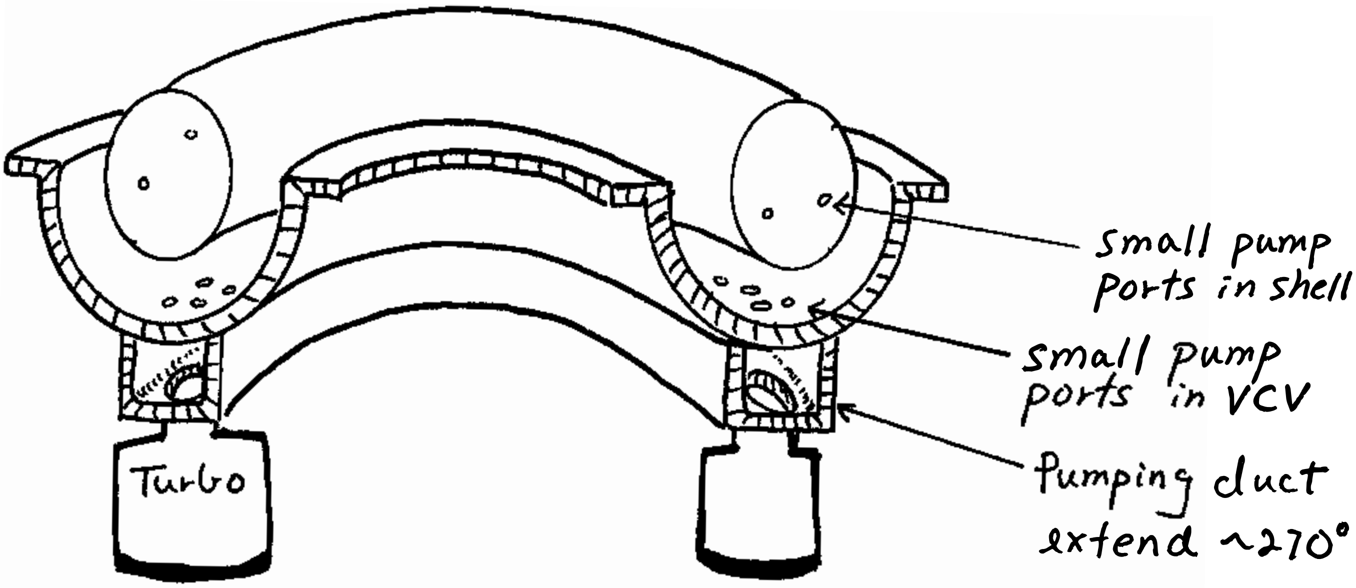
- Properly choosen L_{PR_2} and R_{PR_2} minimize the Volt-Sec needed for CT_2

- Second primary carry all magnetization current in final circuit



- Match primary #2 to core characteristics (air gaps .... etc) to produce no external $\underline{B}$

Low Field-error pumping system



- No large pump port seen by plasma
- Holes in shell $< 1\frac{1}{4}$"
- Holes in VCV $\simeq 1\frac{1}{2}$"

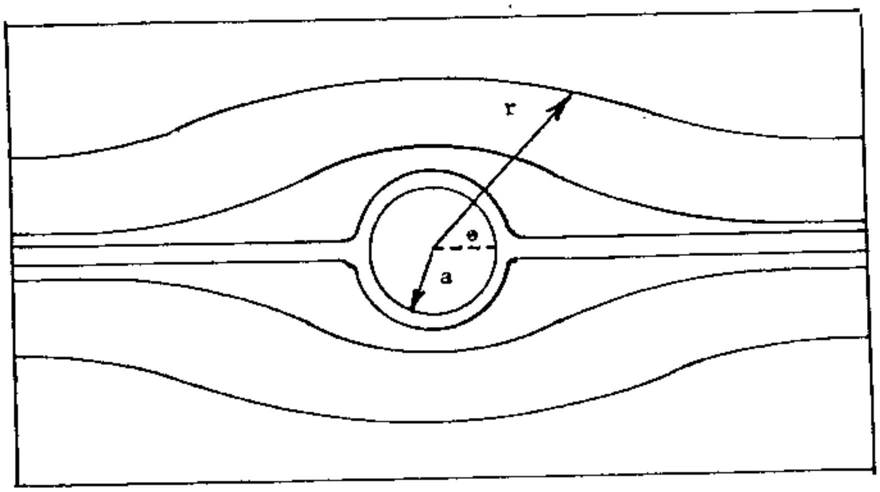
Thin conducting wall produces larger field error then thick conducting wall.

Thin wall solution of current flow around a hole:

$$J_r = (1 - a^2/r^2)\, J_0 \cos\theta$$

$$J_\theta = -(1 + \underbrace{a^2/r^2}_{\text{Deviation}})\, J_0 \sin\theta$$

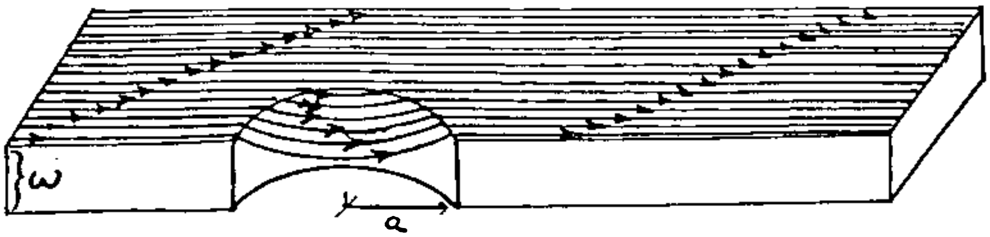
Flow pattern:



Approx. thick wall solution with thickness w.

$$j_r = (1 - a^2/r^2\; e^{-2w/a})\, j_0 \cos\theta$$

$$j_\theta = -(1 + a^2/r^2\, \underbrace{e^{-2w/a}}_{\text{Deviation smaller by exponential factor}})\, j_0 \sin\theta$$

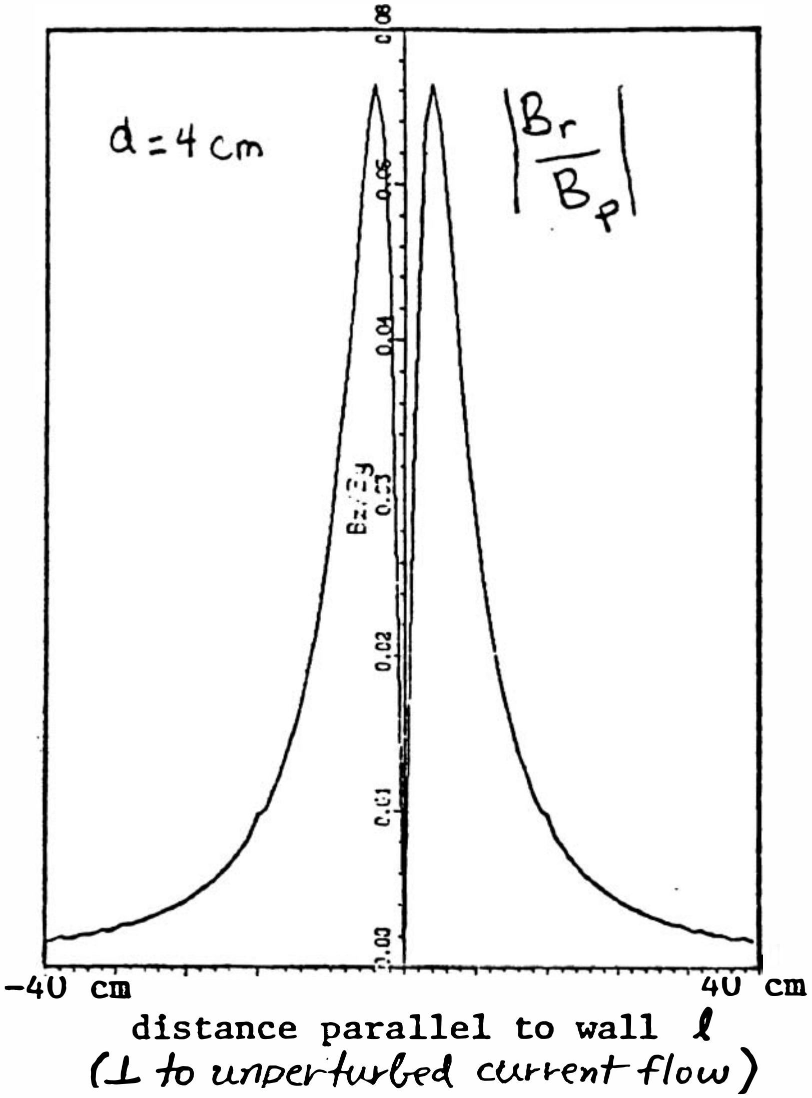


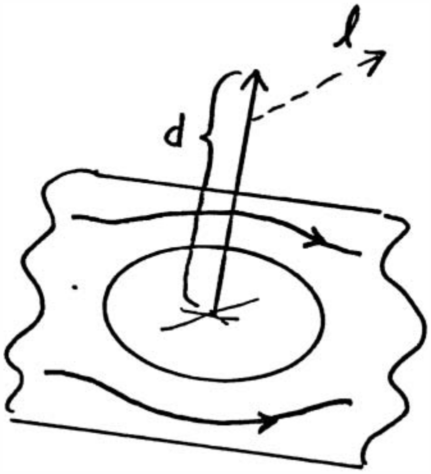
Criteria for hole size.

$$a \lesssim w$$

Calculate worst case field-error away from port hole (Resistive limit ≃ thin wall case).

- Example of field-error due to one hole





- Superpose error due to all holes in shell & VCV, Fourier analyze to calculate effect on islands

- Design pump port size & distribution to minimize field errors.

Outstanding remaining issues :

- 3D treatment of portholes
- None - wedged-gap effect (soak in ..... etc)
- Effect of soak in on equilibrium and field errors which results.
- Passive and active error trimming scheme .

Field-error summary.

Field-error minimized by :

- Using conducting VCV as B_T windings.
- Large B_T & B_p gap flanges.
- Continuity windings -
- Separate primary system for magnetization currents.
- Small port holes properly placed.
- Double shell system with overlaping gaps.
- Distance between plasma and VCV (experiments with shells)