

Capacitor Charging Power Supply

10 + KJ RESEARCH

CCPS

By Vaughn P. McDowell

10KJ/HVPS\ Initial Design

Background: ==>> the 10KJ/s CCPS initial design is based upon the following references:

/__ “Development of a Capacitor-Charging Power Supply for a Smart Modulator”, J.S. Oh, S.D. Jang, Y.G. Son, M.H. Cho, W. Namkung

/__ “Development and Application of an Inverter Charging Supply to a Pulse Modulator”, J.S. Oh, S.D. Jang, Y.G. Son, M.H. Cho, W. Namkung

Both describe some design information which is useful toward the 10KJ/s initial design

Purpose: ==> to use much of their design approach for the 10KJ/s initial design; present the design calculations

DESIGN:

> Full H Bridge series resonance type CCPS; assume:

/__ resonant frequency	50kHz
/__ DC bank voltage (V)	300 to 350
/__ target charging rate	10kJ/s

Calculate Resonant Capacitor:

> joules per switching cycle ==>> $1E4/5E4 = 0.2$ joules

/__ want 10kJ/s for $V_{min} = 300VDC$ ==>> $E_o = 0.5C_R (2V)^2$

/__ $C_R = E_o / [0.5 (2V)^2] = 0.2 / [0.5 (600)^2] = 1.1\mu f$

$P = f_o E_o = 5E4 \times 0.2 = 10000$ Watts

Calculate Resonant Inductor: $f = [2\pi(LC)^{1/2}]^{-1} \implies L = [C(2\pi f)^2]^{-1} = 9.22E-6$ F

Comment ==> don't want the transformer primary stray inductance greater than this value

/__ $I_{AV} = 2/\pi * I_p$, $I_p = V_{DC}/Z$, $E_R = 0.5C_R (2V_{DC})^2$

/__ $Z = (L/C)^{1/2} = (9.2E-6/1.1E-6)^{1/2} = 2.9$ OHMS

/__ $I_p = 300/2.9 = 103$ AMPS peak

/__ $I_{AV} = 2/\pi * 103 = 65.6$ AMPS avg

/__ $P_o = 0.5 V_{DC} * I_{AV} = 1/\pi (V_{DC}^2/Z) = f_R E_R$

/__ $P_o = 0.5 V_{DC} * I_{AV} = 0.5 * 300 * 65.6 = 9835.7$ W

/__ $P_o = 1/\pi (300^2/2.9) = 9878.6$ W

/__ $P_o = 5E4 * 0.2 = 10000$ W

Comment: cross check calculations ^^

Core Selection:

Magnetics PN OP49925UC WaAc = 168 cm⁴

$$P_o = \frac{W_a A_c B f}{K' 10^8} = [168 * 1600 * 5E4] / [5.3E-3 * 10^8] = 25.3kJ/s$$

Comment: Provides a comfortable safety margin : ie staircase problems, etc

Primary Turns: ==> series resonant drive at primary ==> assume sinusoidal for full H drive +/- 300V peak

/__ Magnetics ==> "Section 4. Power Deign E = 4.44 BAc Nf x 10⁻⁸ (sine wave) B => gauss, Ac => cm²
300VDC IN

$$N = 300 / [4.44 * 1.6E3 * 6.45 * 5E4 * 1E-8] = 13 T$$

$$\text{for square wave} ==> 300 / [4 * 1.6E3 * 6.45 * 5E4 * 1E-8] = 14.5 T$$

350 VDC IN => 15 turns sine wave 17 sq wave

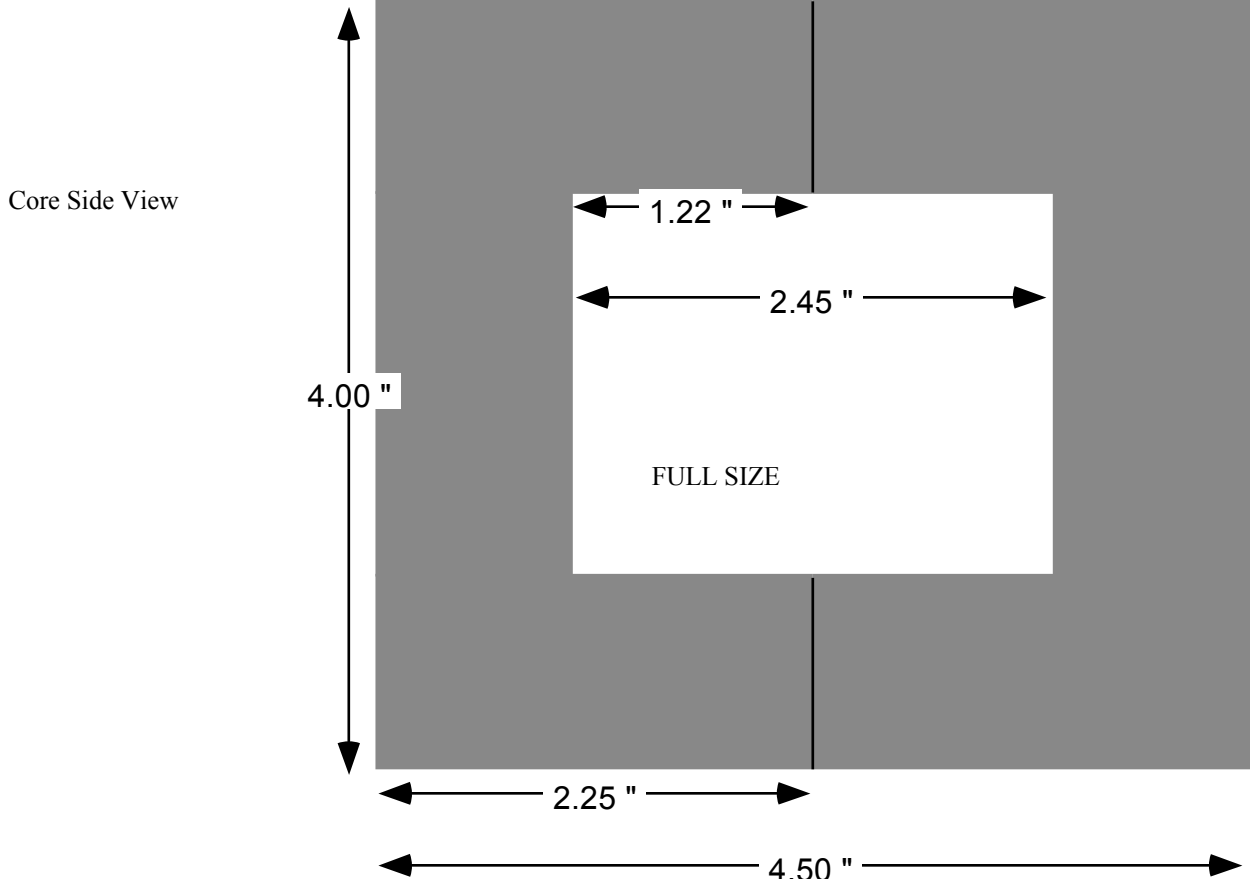
Assume 15 turns PRI turns

Secondary Turns: @ 300 VDC IN assume 50 kVmax ==> 166:1 turns ratio ==> 15 * 166.7 = 2500 turns sec

@ 350 VDC IN ==> 58.3kV max

if have 5 secondary pie windings ==>> 2500/5 = 500 turns each

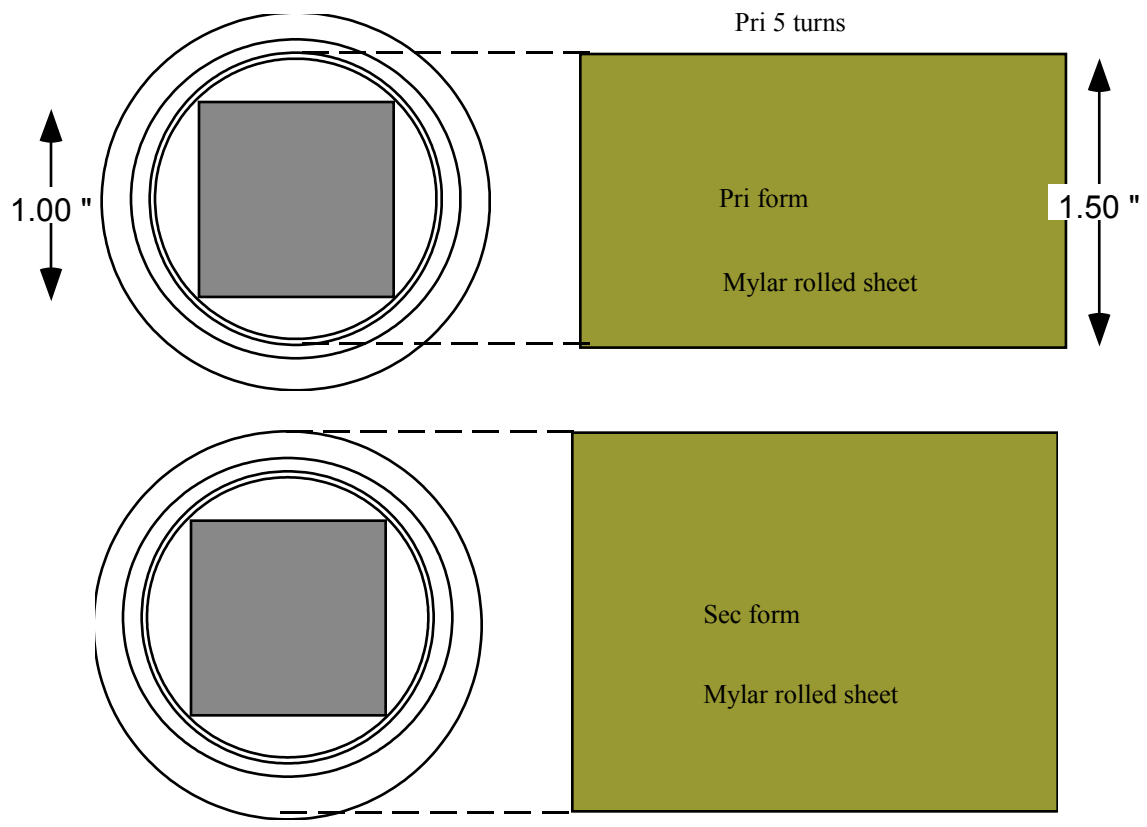
Initial Transformer Physical Layout:

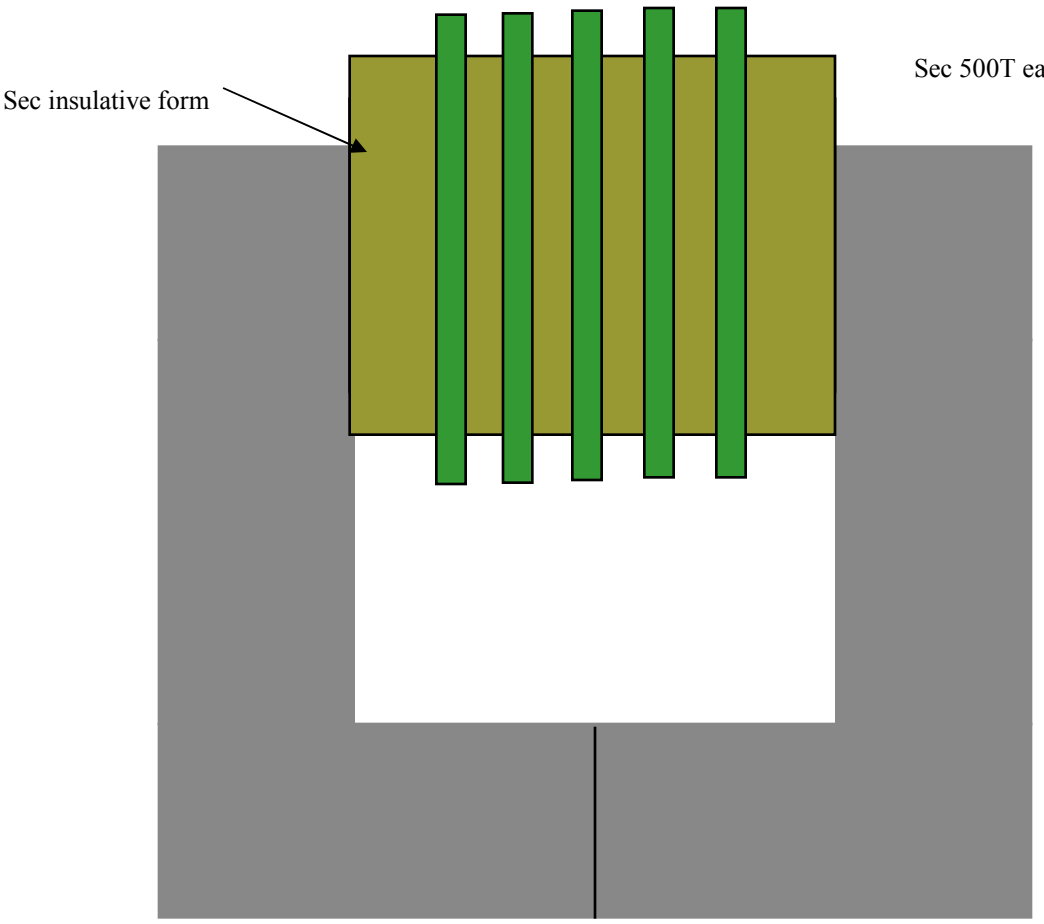
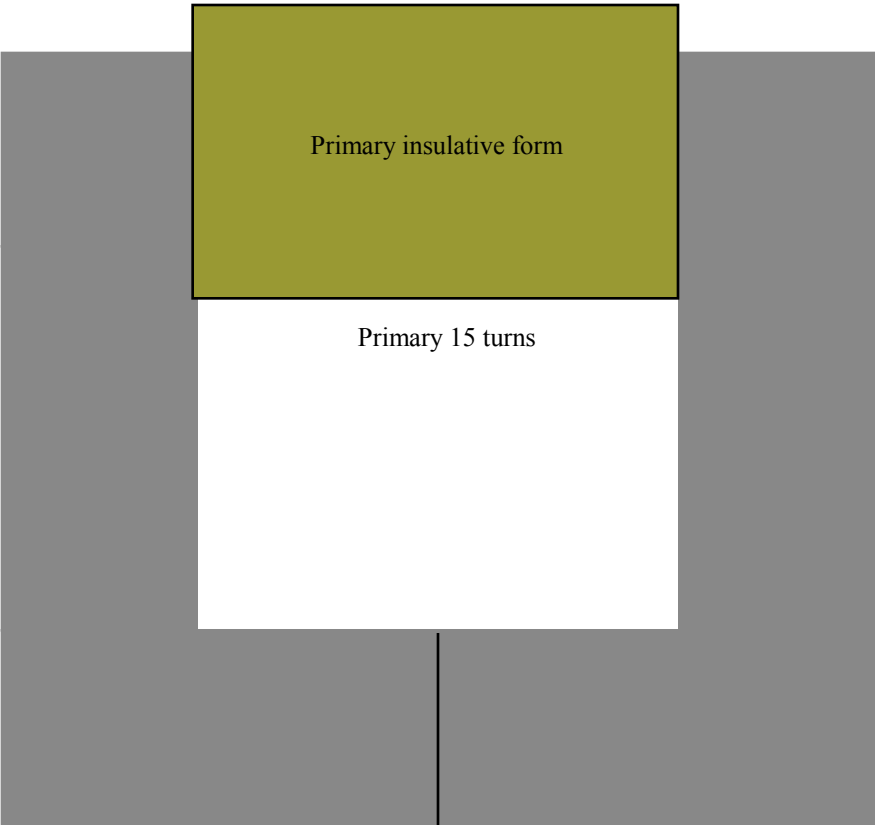


FULL SIZE

Core & Coil Form End View

Coil Form Side View



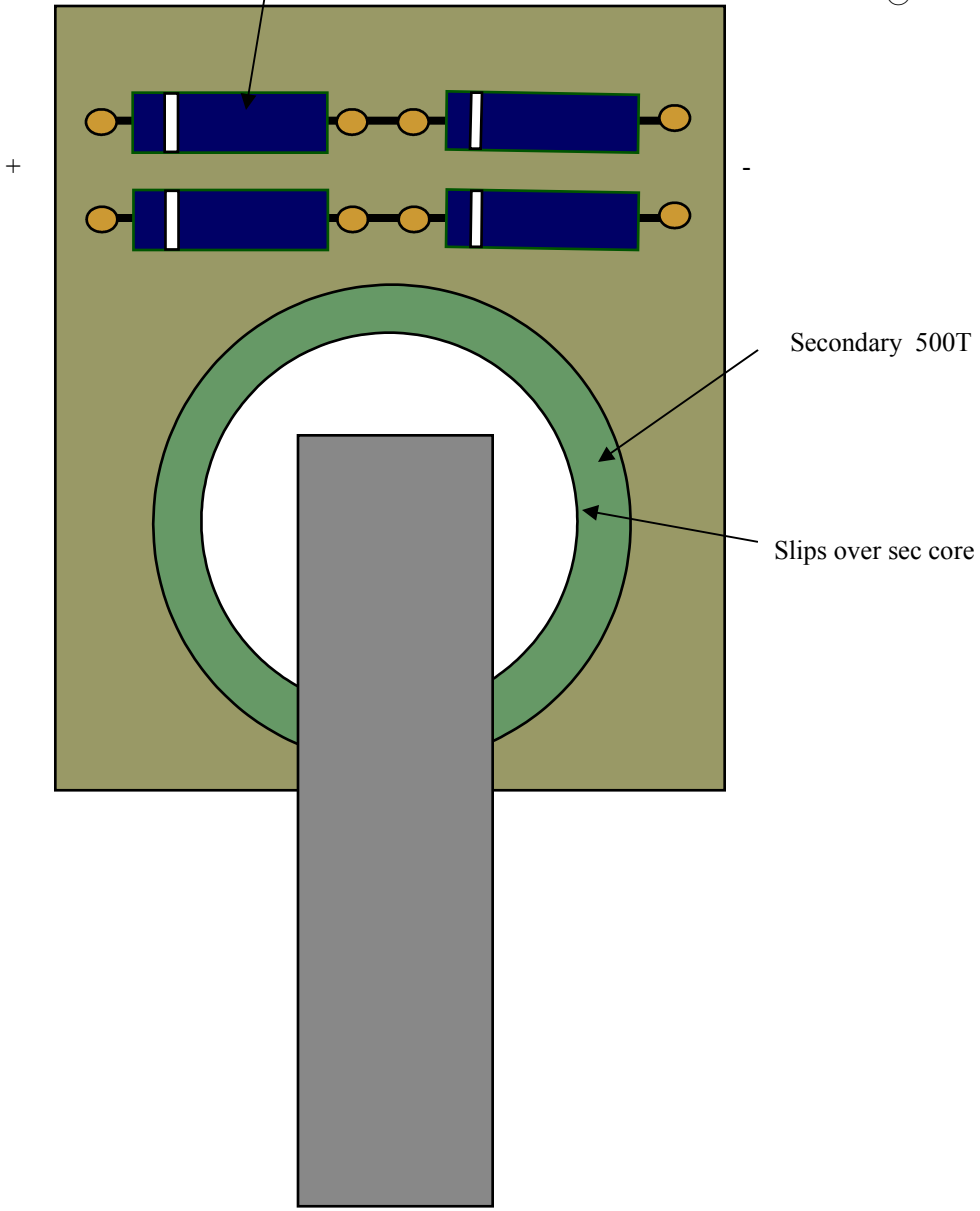


FULL SIZE

Bridge rectifier

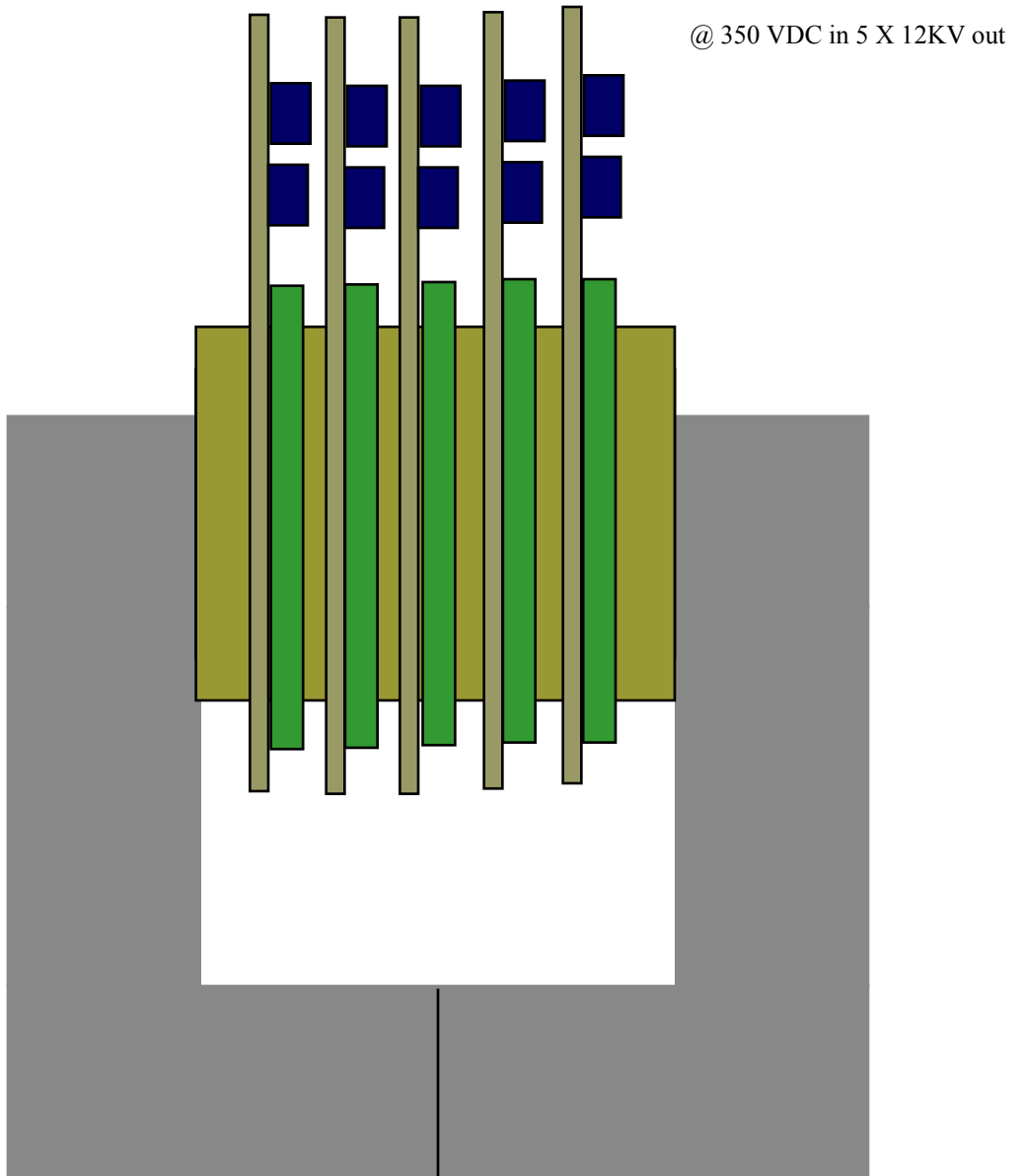
UF1007s (20 ea 70nsec 1A, 20KV)

12KV each @ 350VDC in



ACTUAL SIZE

Transformer with bridge rectifier \Front



Notes: Mathcad Series Resonant / 10KJ 50kv Full H Bridge HVPS Design \ 1st MathCad run

3 June 05a

Purpose: ==> do 1st MathCad 10KJ templet run

Notes: 10KJ\ 50Khz CCPS\Calculations

Design: > full H Bridge series resonance CCPS

/___ resonant frequency

$$f_R := 50\text{KHz}$$

/___ DC bank voltage
(300 to 350) use minimum

$$V_{DC} := 300\text{V}$$

$$T_p := \frac{1}{f_R}$$

/___ target charging rate (J/s)

$$P := 10000\text{W}$$

$$T_p = 2 \times 10^{-5} \text{ s}$$

Calculating Resonant Capacitor:

> joules per switching cycle

$$E_C := \frac{P}{f_R}$$

$$E_C = 0.2 \text{ J}$$

> determine CAP for V min $E = 1/2 CV^2$

$$C_R := \frac{E_C}{0.5 \left[(2V_{DC})^2 \right]}$$

$$C_R = 1.111 \times 10^{-6} \text{ F}$$

Calculating Resonant Inductor:

$$L_R := \frac{1}{C_R \cdot (2 \cdot \pi \cdot f_R)^2}$$

$$L_R = 9.119 \times 10^{-6} \text{ H}$$

Calculate LC impedance

$$Z := \sqrt{\frac{L_R}{C_R}}$$

$$Z = 2.865 \Omega$$

Peak Current

$$I_p := \frac{V_{DC}}{Z}$$

$$I_p = 104.72 \text{ A}$$

Avg Current

$$I_{av} := \left(\frac{2}{\pi} \right) \cdot I_p$$

$$I_{av} = 66.667 \text{ A}$$

PWR Po using avg current

$$P_{o1} := 0.5 V_{DC} \cdot I_{av}$$

$$P_{o1} = 1 \times 10^4 \text{ W}$$

PWR Po using Z

$$P_{o2} := \left(\frac{1}{\pi} \right) \cdot \left(\frac{V_{DC}^2}{Z} \right)$$

$$P_{o2} = 1 \times 10^4 \text{ W}$$

PWR Po using res freq and energy stored in C / cycle

$$P_{o3} := E_C \cdot f_R$$

$$P_{o3} = 1 \times 10^4 \text{ W}$$

MAGNETICS CALCULATIONS

Core PWR Rating (open air cooled)

Ferrite Window Area * Core Area Product WaAc (cm⁴)

$$WaAc := 168$$

switching frequency (Hz)

$$f_s := 50 \cdot 10^3$$

Max +/- flux at 50Khz Bmax (gauss)

$$B_{max} := 1600$$

Ku = constant for UU core

$$K_u := 0.0053$$

PWR rate Pferr (watts)

$$P_{ferr} := \frac{WaAc \cdot B_{max} \cdot f_s}{K_u \cdot 10^8}$$

$$P_{ferr} = 2.536 \times 10^4$$

$$V_{DC} = 300 \text{ V}$$

Number of Turns Primary:

Have LC series resonant CCPS; use sine wave Faraday Eq
/ __ want avg of VDC in => Vrms max to primary

$$V_{rms} := V_{DC} \cdot 0.707$$

$$V_{rms} = 212.1 \text{ V}$$

core area (cm²)

$$A_c := 6.45$$

turns primary

$$N_p := \frac{V_{rms} \cdot 10^8 \cdot \frac{1}{V}}{4.44 \cdot B_{max} \cdot A_c \cdot f_s}$$

$$N_p = 9.258$$

desired peak voltage out for 300VDC in

$$V_{out} := 50000 \cdot V$$

turns ratio

$$N_r := \frac{V_{out}}{V_{DC}}$$

$$N_r = 166.667$$

total secondary turns

$$N_s := N_p \cdot N_r$$

$$N_s = 1.543 \times 10^3$$

CORE:



MYLAR SLEVES:

deviated from initial layout\ use square form instead of the cylindrical concept

made two

/__ for primary form

/__ alignment for other U leg



SLEVE ON CORE:



Wind 9 turns close to calculation

PRIMARY:



SECONDARY PIE MOUNT:

Deviation from initial layout

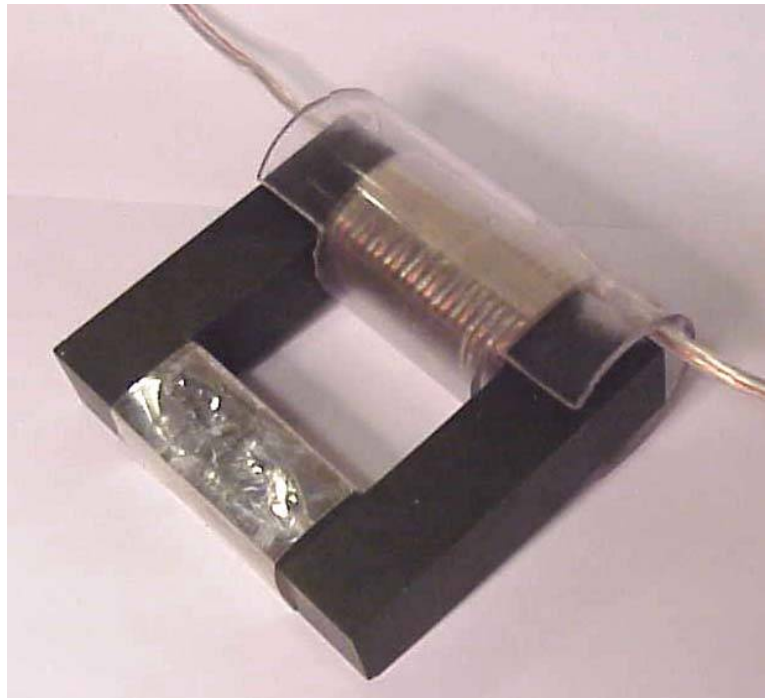
/__ used plastic tube instead of rolled mylar

- OD = 2.0"

- ID = 1.75"



- length matches U-U core width



Deviated from the initial physical layout

/__ used 4 secondary pies instead of five

/__ diode bridge elements are mounted on two planes instead of one as in the initial layout

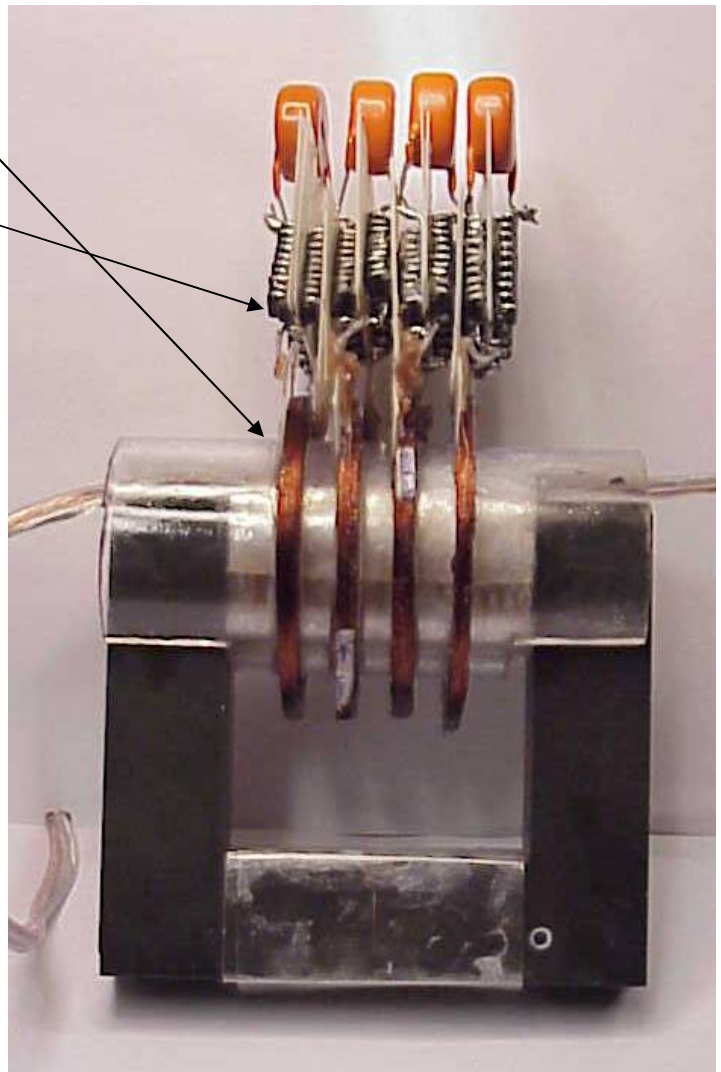
secondary pies:

- avg. height = 0.45"

- width = approx => 0.16"

- 400 turns each instead of the calculated 386

- spacing about 0.3"



Note:

- calculated 167:1 => actual 178:1

for $V_{in \text{ min}} = 300\text{VDC} \Rightarrow 53.4\text{KV}$

$V_{in \text{ max}} \Rightarrow 350 \text{ VDC} \Rightarrow 62.3\text{KV}$

Measurements:

note that the U-U core was not tightly clamped during these measurements; during measurements the core sections were manually pressed making significant changes. The purpose was to get some idea of the inductance for the primary and secondary coils; the main interest was to get the primary stray inductance to see if it was less than the series resonance inductance calculated ($9.1\mu\text{H}$)

primary (secondary open) $\Rightarrow 3.35\mu\text{H}$

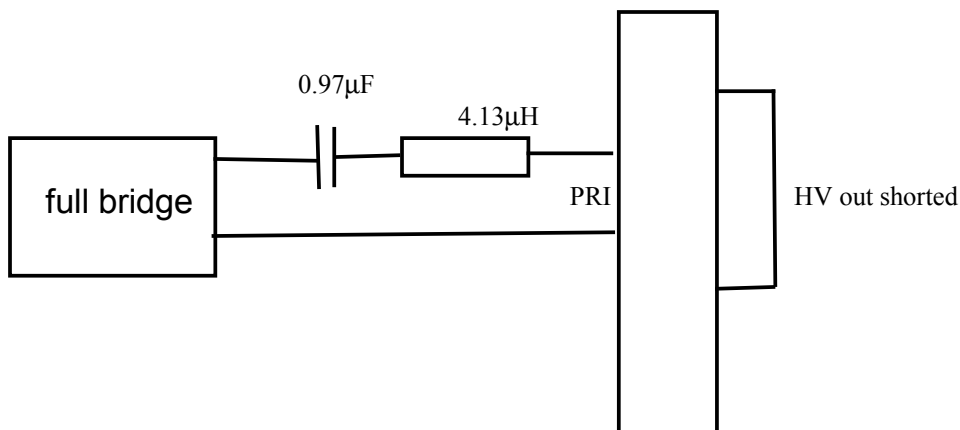
secondary (primary open) \Rightarrow each pie about 260 mH

primary stray inductance (all secondary pies shorted) = $4.4\mu\text{H}$

comment: - well within limits

wound an external series resonance inductor $4.13\mu\text{H}$ to be added to the stray $4.4 = 8.53 \mu\text{H}$ total

The experimental setup full bridge is powered by a 0 -30VDC PS ; the gate drive is powered by a function generator



The resonant frequency was determined by sweeping the function generator frequency while monitoring the PS analog AMP meter for a maximum value

- measured resonance $\Rightarrow 58\text{KHz} ::$ calculated LC $\Rightarrow 8.3\mu\text{H} \text{ C} = .097\mu\text{F} \Rightarrow 55.36\text{KHz}$

remove L external \Rightarrow have only primary L stray

- measured about 78KHz :: calculate LC $= 4.4\mu\text{H} \ \& \ \text{C} = 0.97 \ \Rightarrow 77\text{KHz}$

REMOVE output short \Rightarrow at 20VDC in get powerful HV arc; get 3/4" spark; did not try much higher

/__ wait until it can be immersed in oil