2 MHz 65 kV Isolation Transformer for SNS Ion Source

Proto-type Performance Report

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SNS RF

Monday September 28, 2009

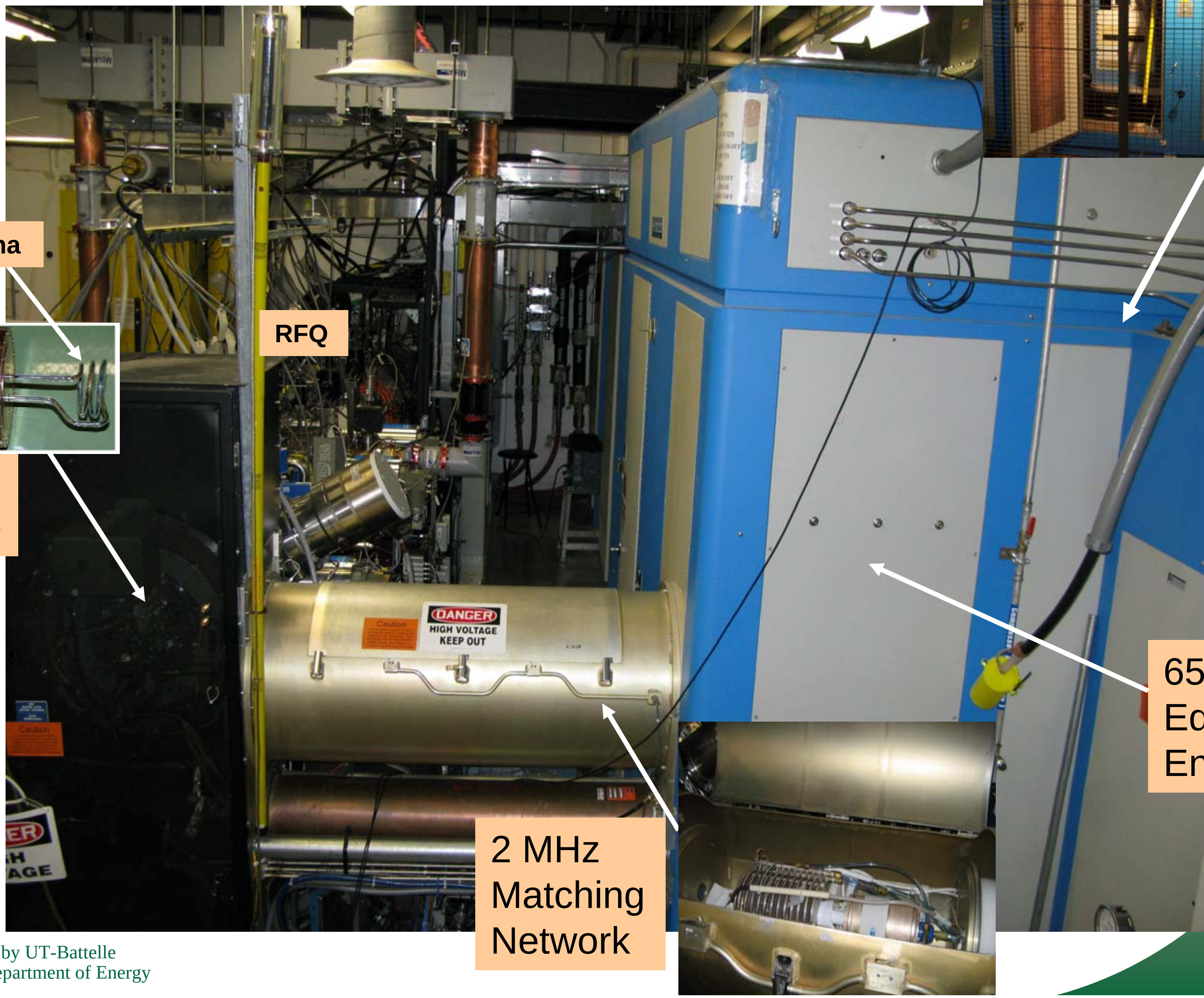
Managed by UT-Battelle
for the Department of Energy

Oak Ridge National Laboratory

Why an Isolation Transformer (XFMR)?

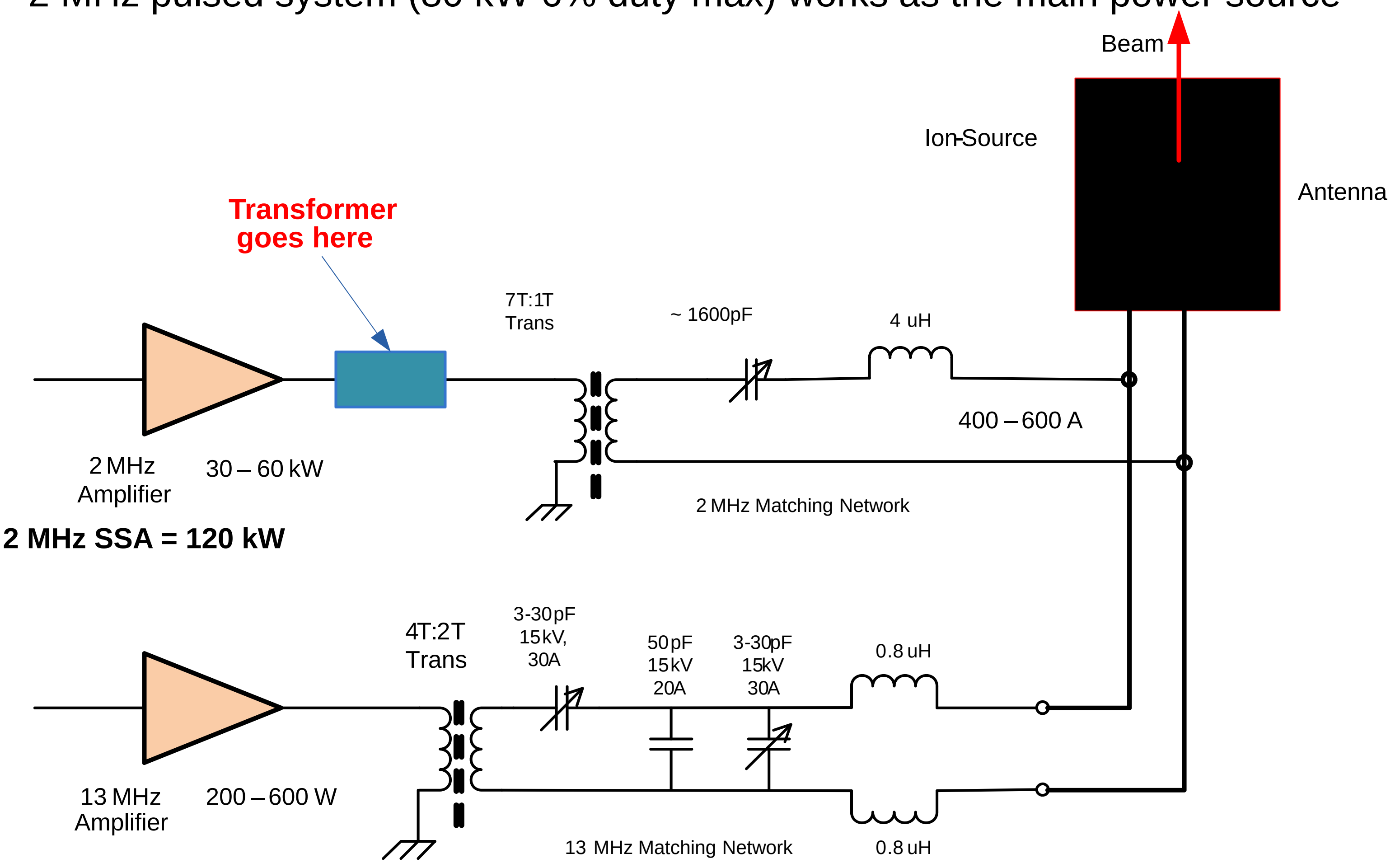
- **65 kV arcs presently trip the Ion Source (I.S.) 2MHz amplifier requiring physical access to the HV enclosure with corresponding delays.**
- **An isolation XFMR would allow 2 MHz I.S. amplifier to be located outside the 65kV enclosure.**
- **It would allow better monitoring and control of the 2 MHz Amplifier.**
- **It would allow much quicker diagnosis, repair and facilitate routine servicing.**
- **It might prevent the amplifier from tripping off line.**

Ion Source Equipment Arrangement



Ion-Source Antenna Matching Networks

- Presently, two RF amplifiers (at 2 MHz and 13.56 MHz) are combined through matching networks to deliver the RF power to the Ion-source
  - 13 MHz CW system (~1200 W max) works as a igniter and sustainer
  - 2 MHz pulsed system (80 kW 6% duty max) works as the main power source



Original courtesy of Y. Kang

1:1 Isolation XFMR Requirements:

- **Stand off 65 kV DC secondary to primary**
  - **Electrostatic grounded shield between xfmr secondary and primary**
- **Must couple 2 MHz 120 kW pulsed RF with 6% duty cycle:**
  - **2450 Vrms @ 50 A (~ 7000 Vpp, 141 App)**
- **Efficiency > 89% (-0.5 dB loss); goal ≥ 95% (-0.22 dB loss)**
- **Bandwidth > 400 kHz (FWHM) centered at 2 MHz**
- **RF leakage (<0.2 mW/cm2) outside XFMR enclosure**
- **65 kV arc pulses from ion source are attenuated to <14 kVpp (comparable to full power rf reflected from a short.)**
- **All components operate lower than 100C (60C goal)**
- **Must be robust and low maintenance.**
- **Must be Safe (lockable with key kept inside 65kV enclosure, PPS certifiable)**

Design Overview

Note HV is exposed here not here

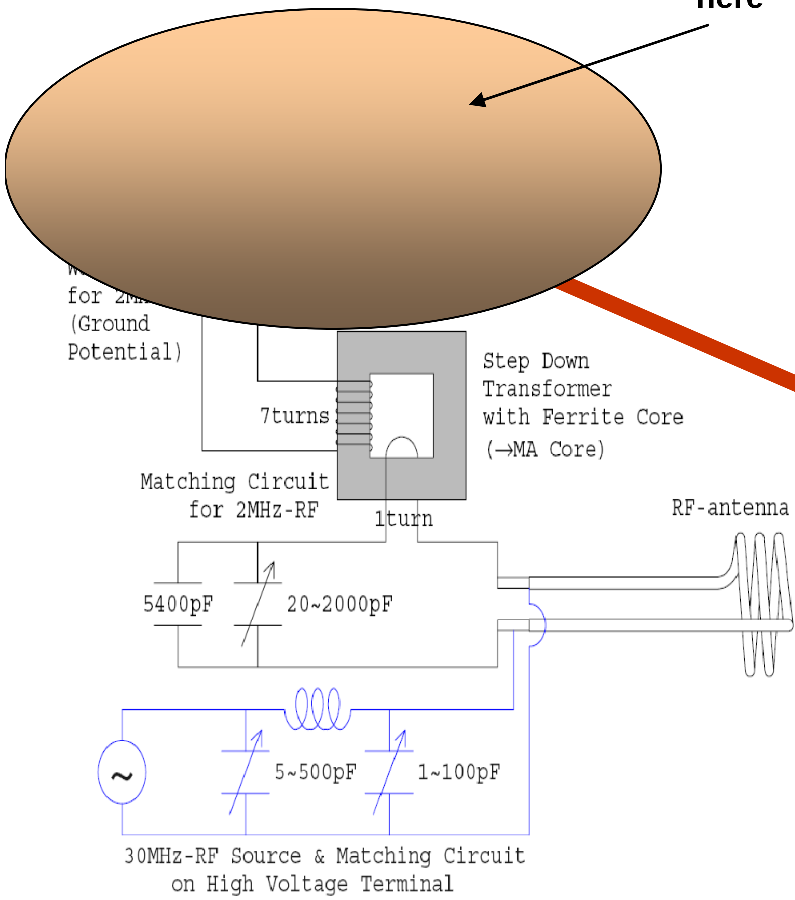
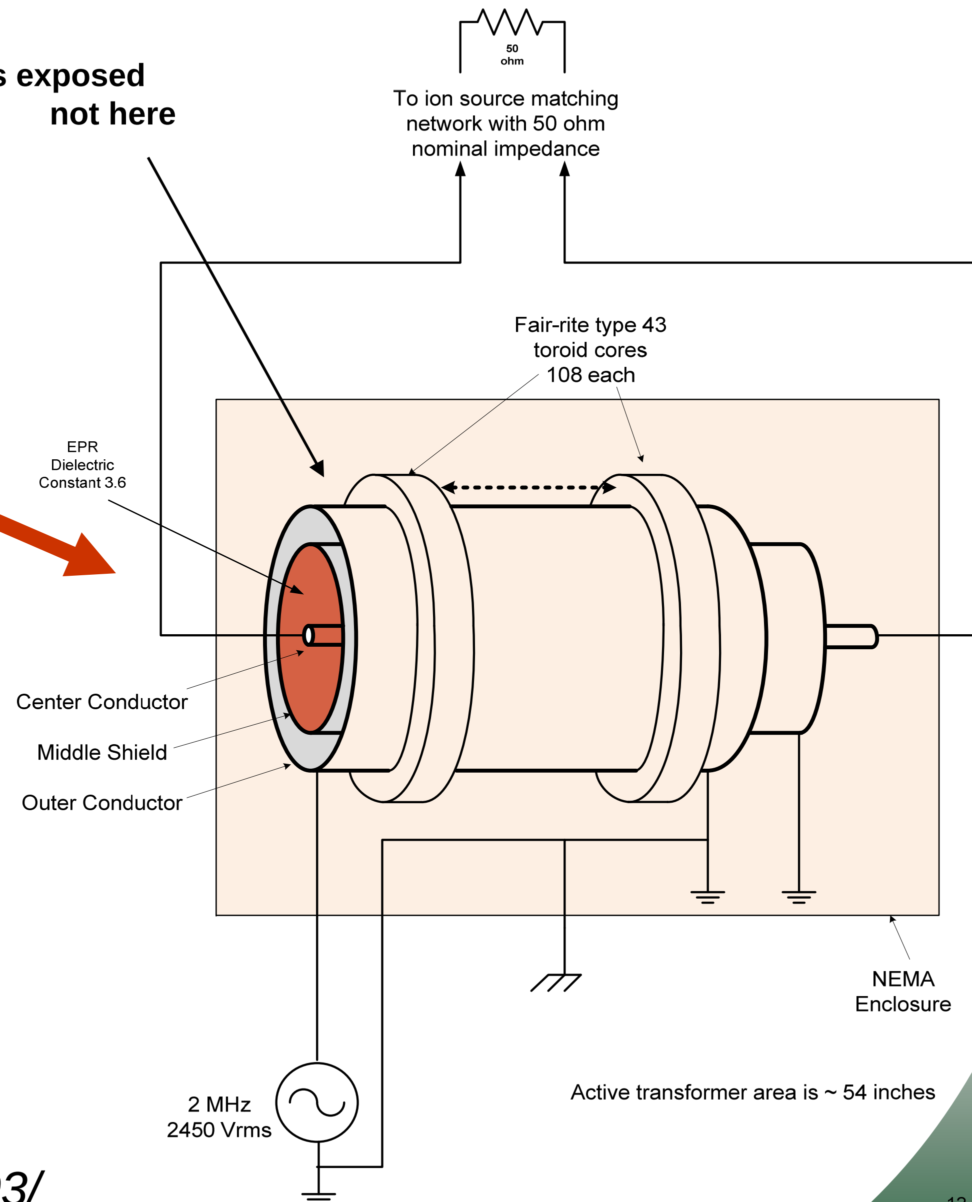


FIG 3.1.1.6 Block diagram of matching circuits for 60kW-2MHz-RF (pulse operation) and 100W-30MHz-RF (CW operation to maintain low temperature plasma).



hadron.kek.jp/~accelerator/TDA/tdr2003/

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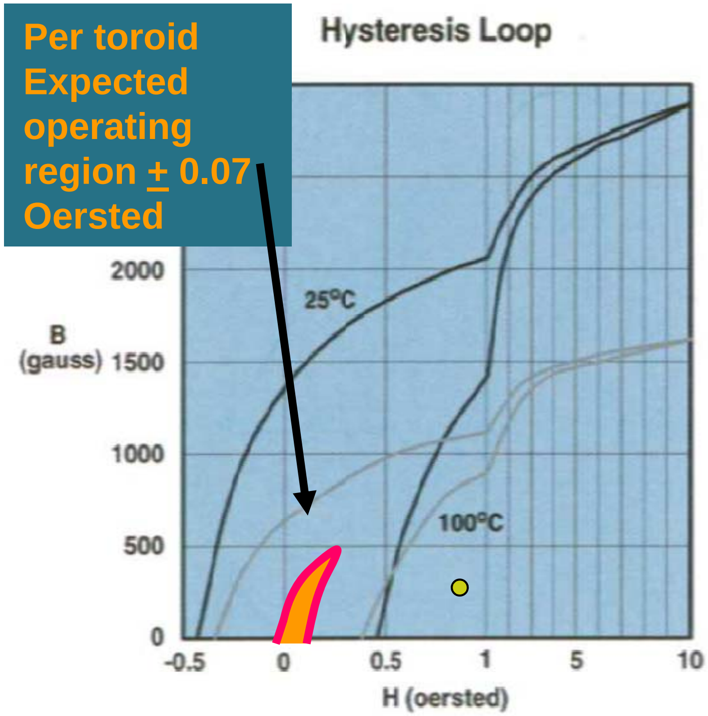
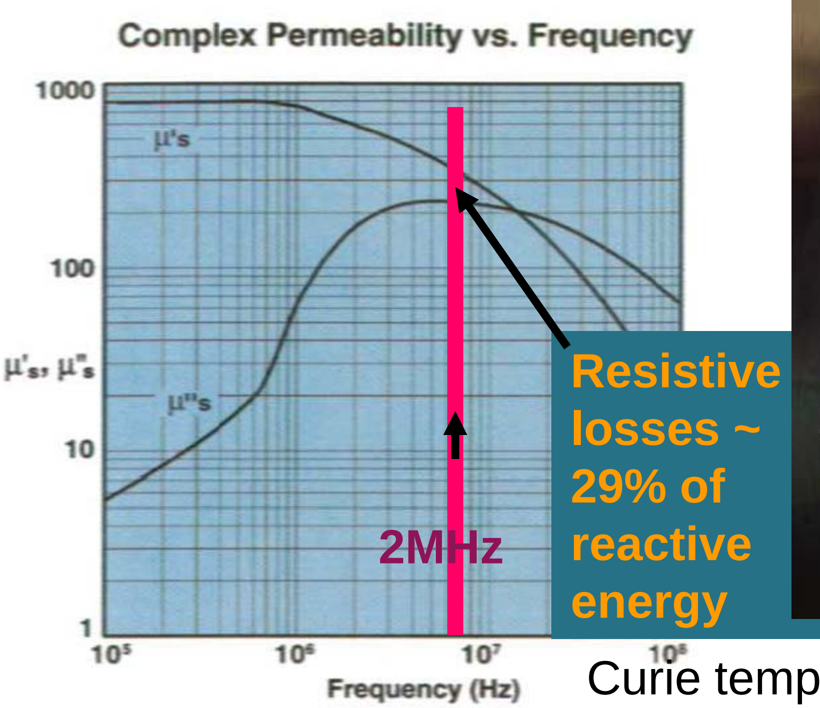
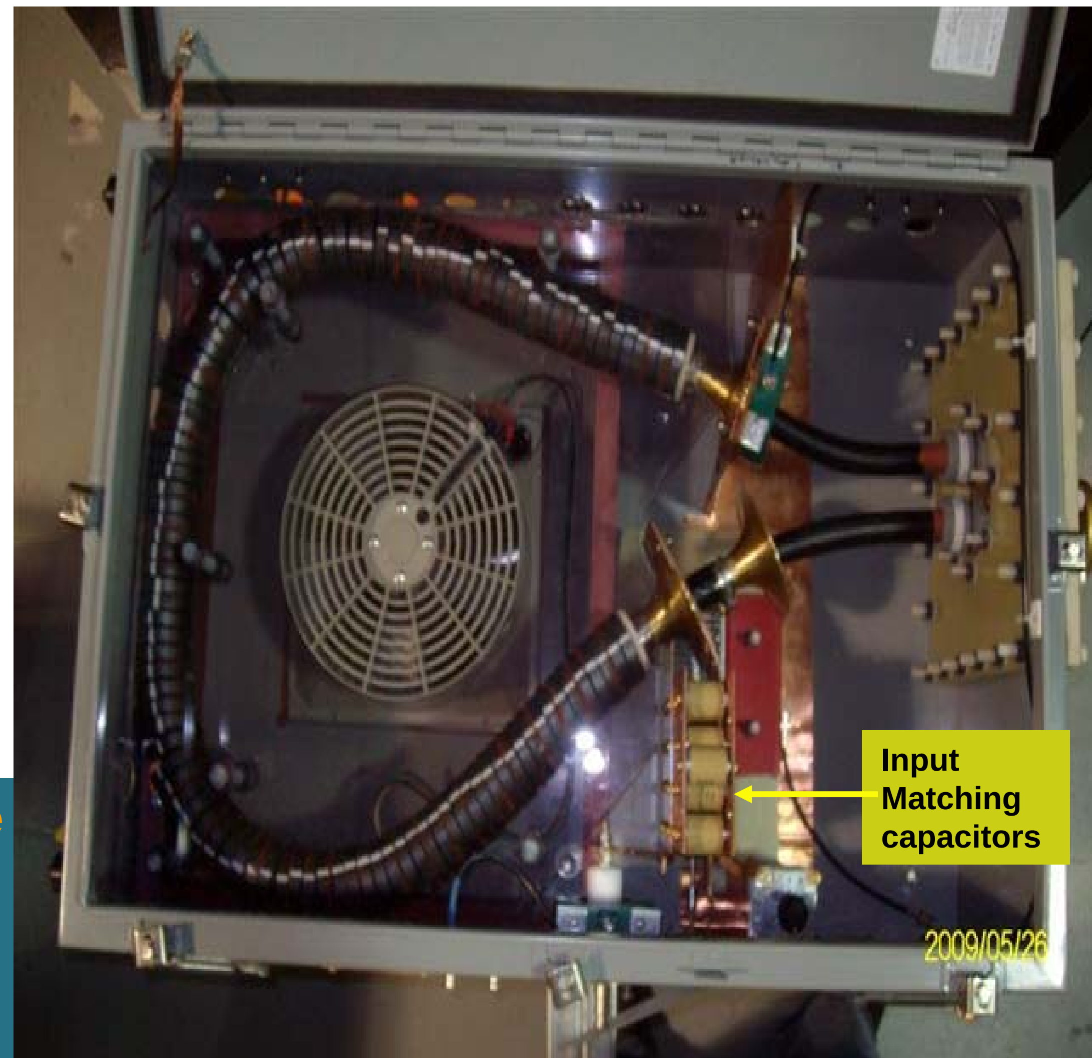
Type 43 ferrite core from Fair-rite Co.



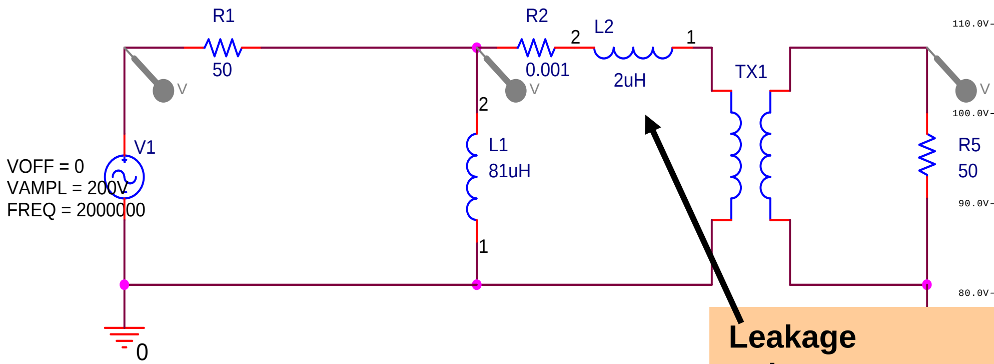


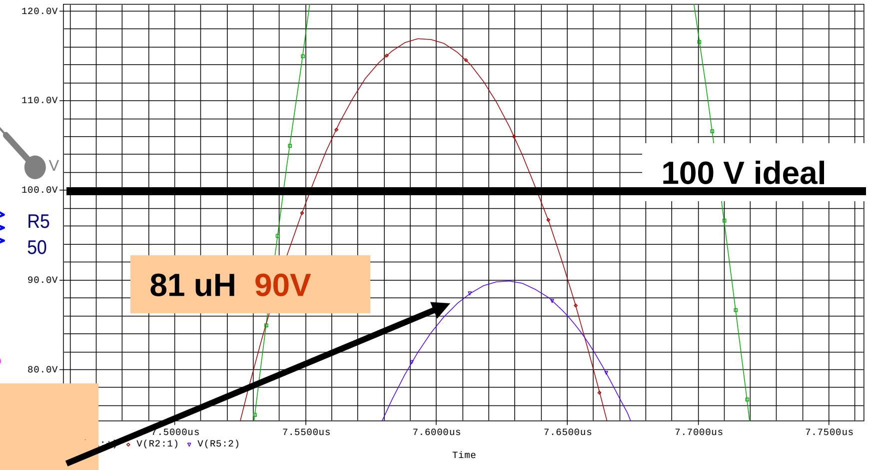


Curie temperature > 130C

Input Matching
(for real transformer)

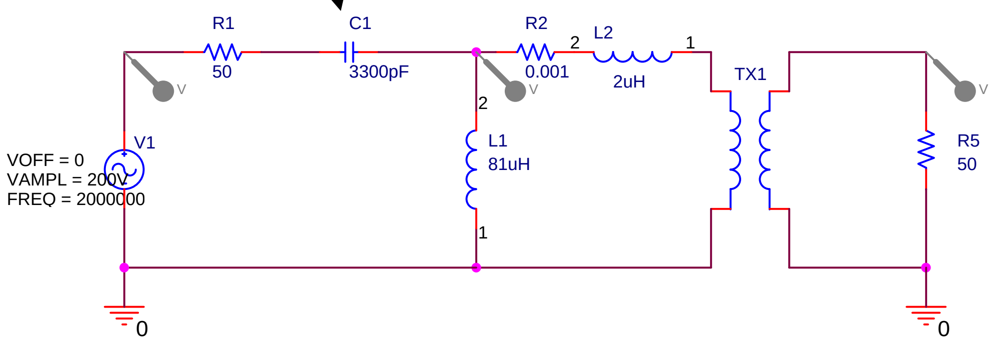
Note: leakage inductance value of 2 uH is based on Network analyzer measurements.

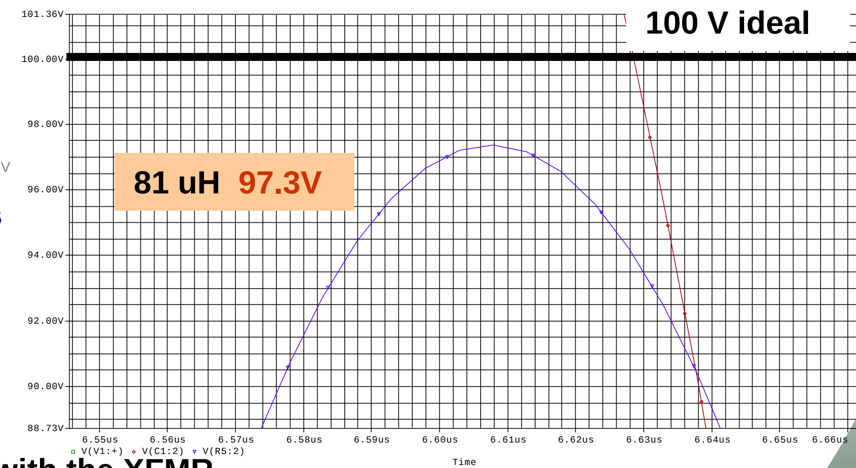




Leakage Inductance reduces voltage across primary

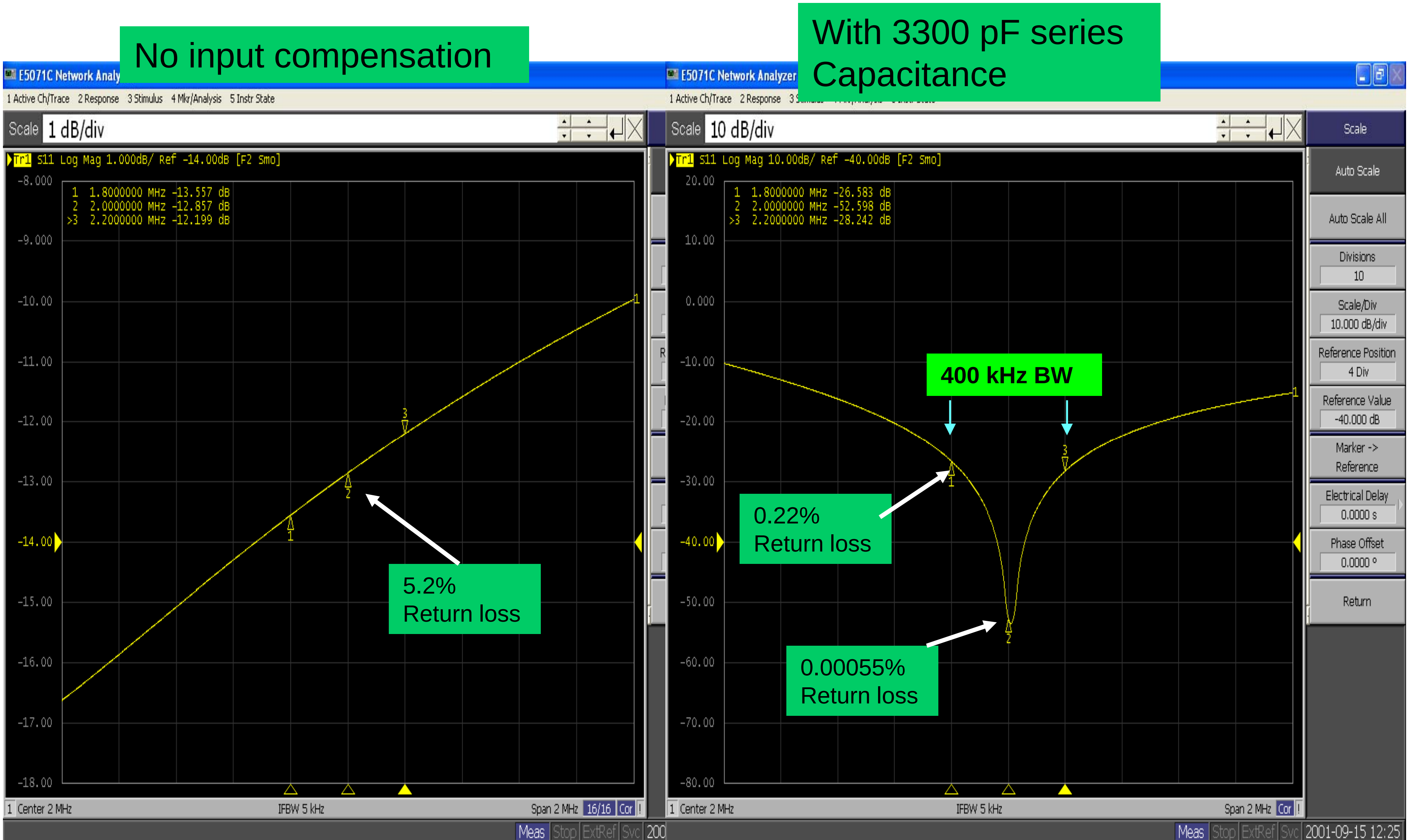
Series Input Capacitance resonates out the leakage inductance.



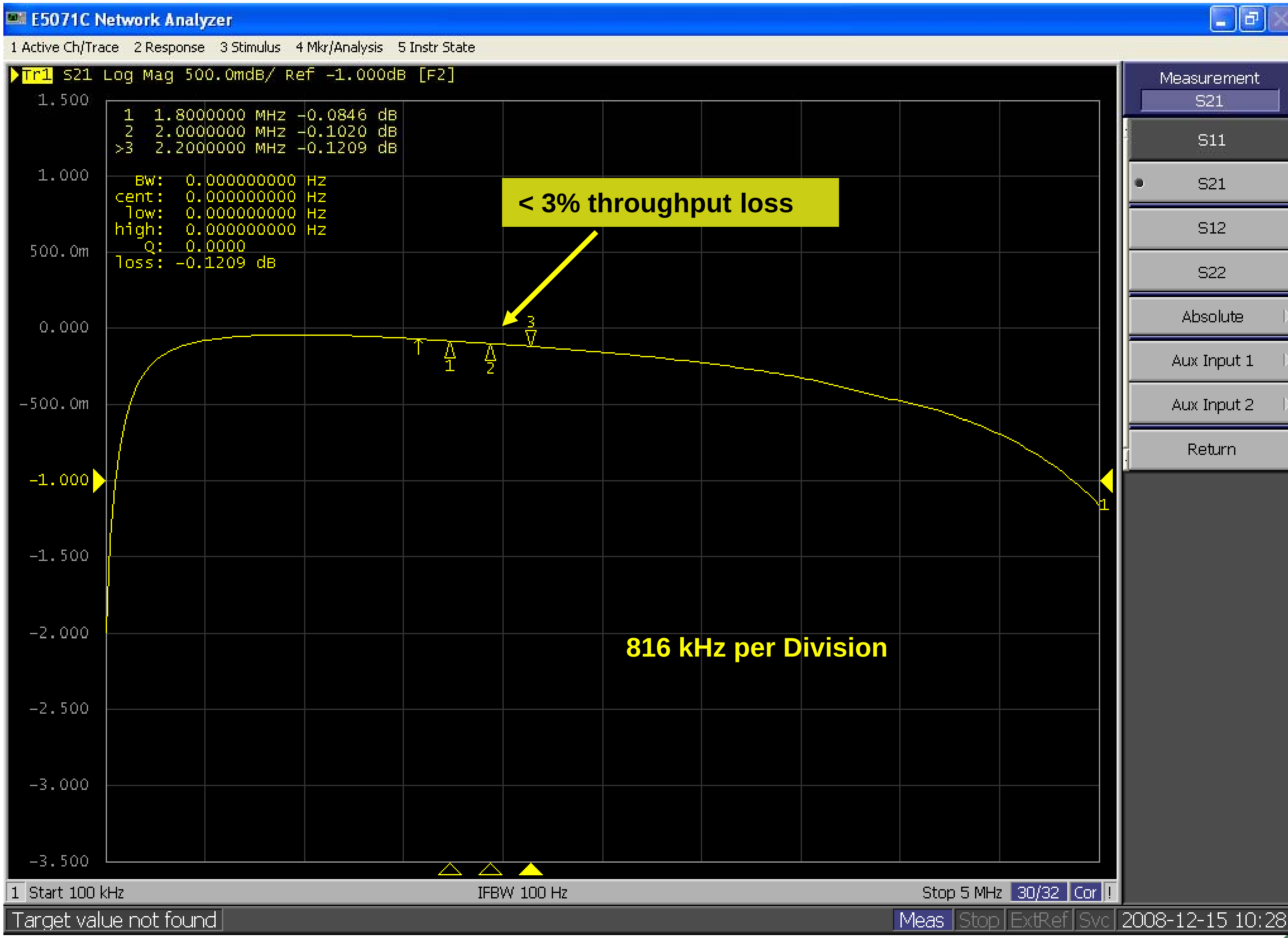


An ~ 3300 pF capacitance will be placed in series with the XFMR input. This also acts as an additional DC break between the amplifier and XFMR primary.

Better Match with Input Compensation

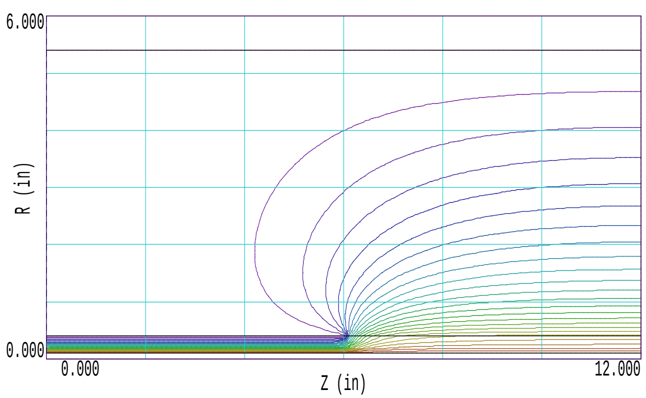


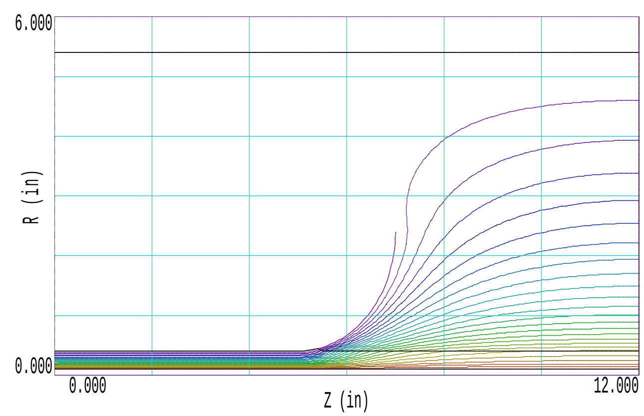
T43—60_S21_625 PF.BMP 12-15-08



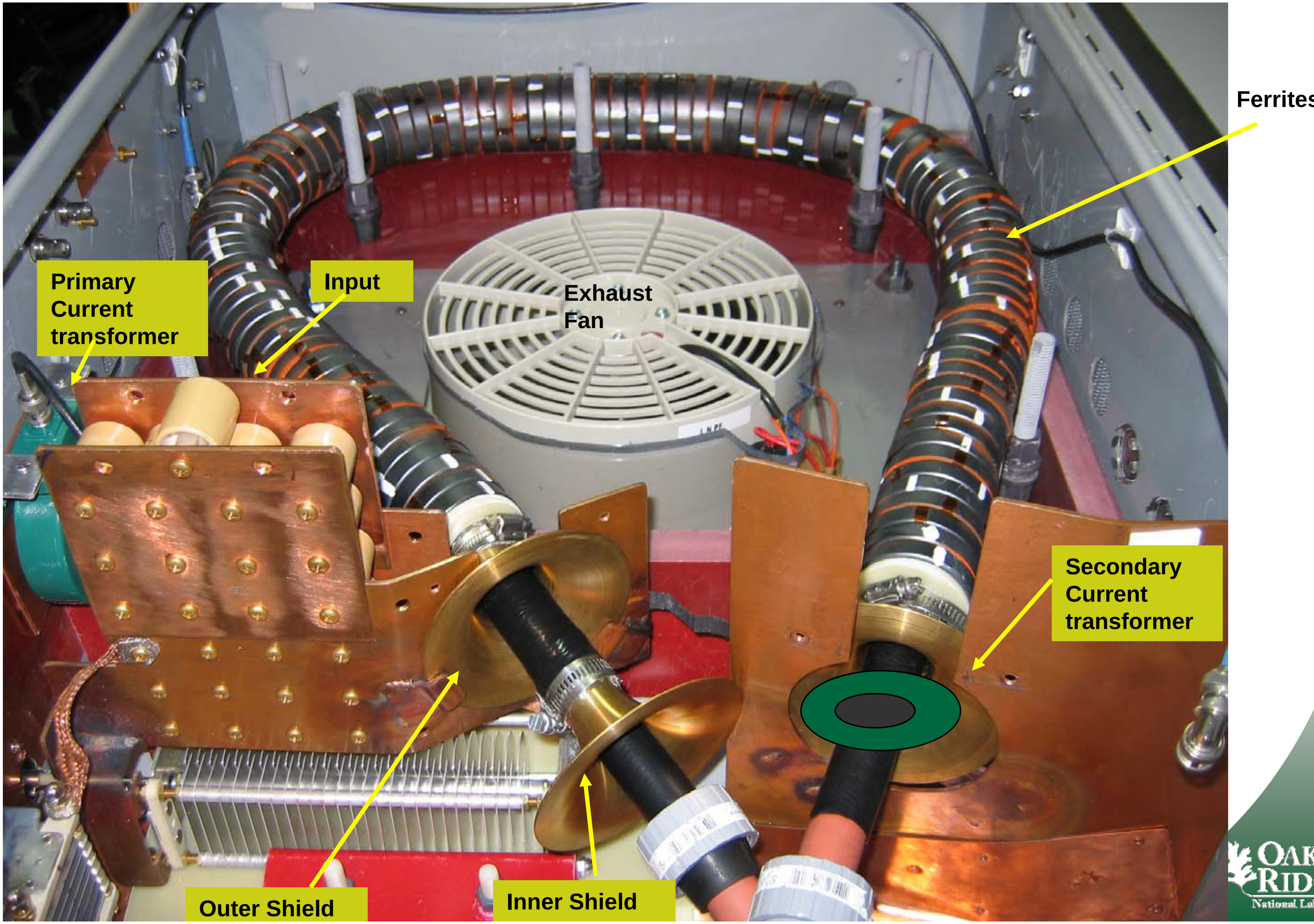
Corona Horns Mitigate Steep Gradients

The corona horns provide a gentle transition between the intense 65 kV field at the center conductor and free space.   The left plot is the HV coax cable with the outer shielding ending abruptly. The right plot has the same field gradually changing with the horn. Note that the plot is of field gradient not field lines.

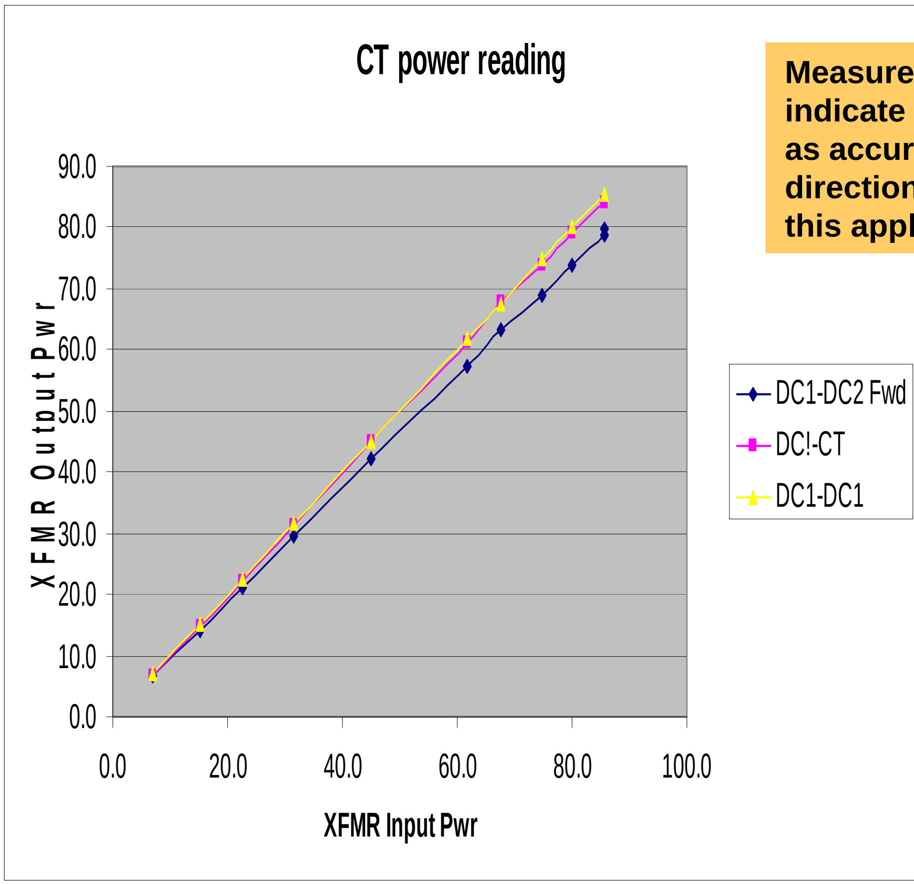




Amplifier Physical Layout



High Power Measurements with CT

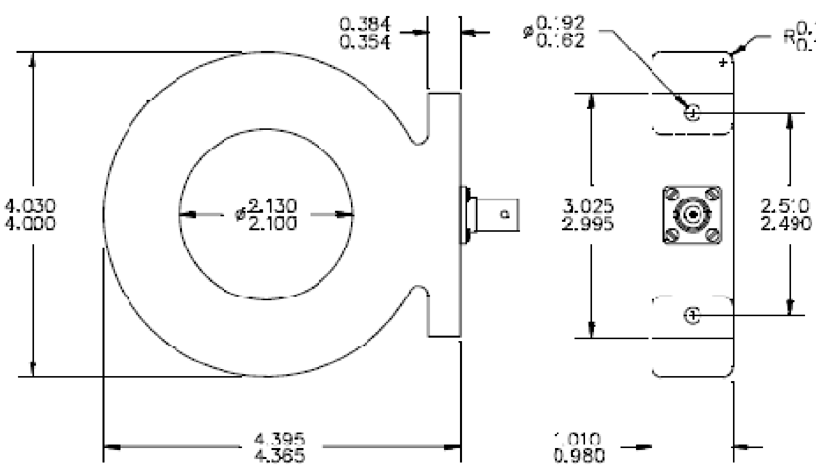


Measurements indicate that this CT is as accurate as a directional coupler for this application

PEARSON™ CURRENT MONITOR MODEL 110

Sensitivity	0.1 Volt/Ampere +1/-0%
Output resistance	50 Ohms
Maximum peak current	5000 Amperes
Maximum rms current	65 Amperes
Droop rate	0.8 %/millisecond
Useable rise time	20 nanoseconds
Current time product	0.5 Ampere-second max.*
Low frequency 3dB cut-off	1 Hz (approximate)
High frequency 3dB cut-off	20 MHz (approximate)
I/f figure	1.5 peak Amperes/Hz
Output connector	BNC (UG-290A/U)
Operating temperature	0 to 65 °C
Weight	22 ounces

* Maximum current-time product can be obtained by using core-reset bias as described in the *Application Notes*. 0.2 Ampere-second is typical without bias.



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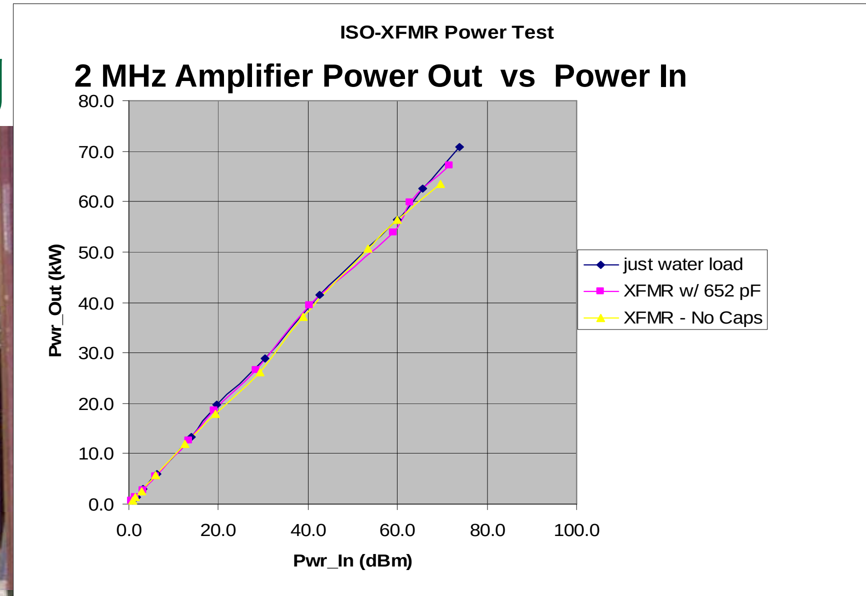
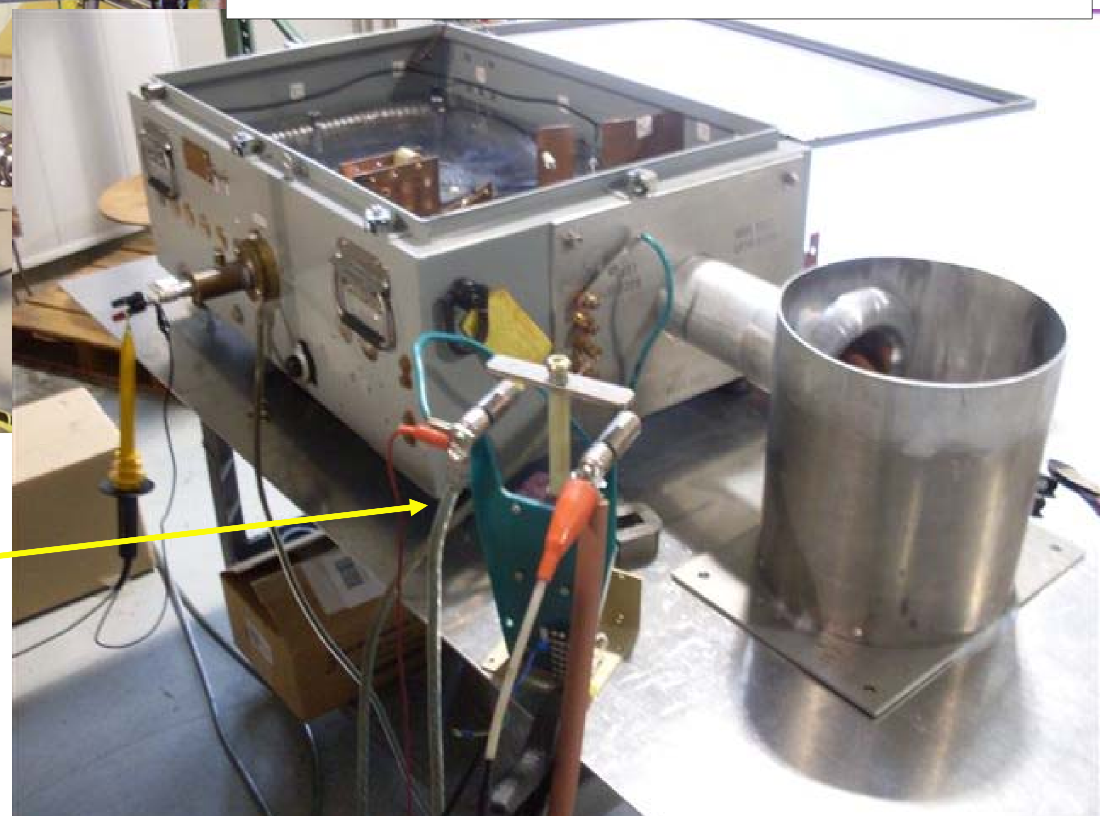
High Power RF Testing

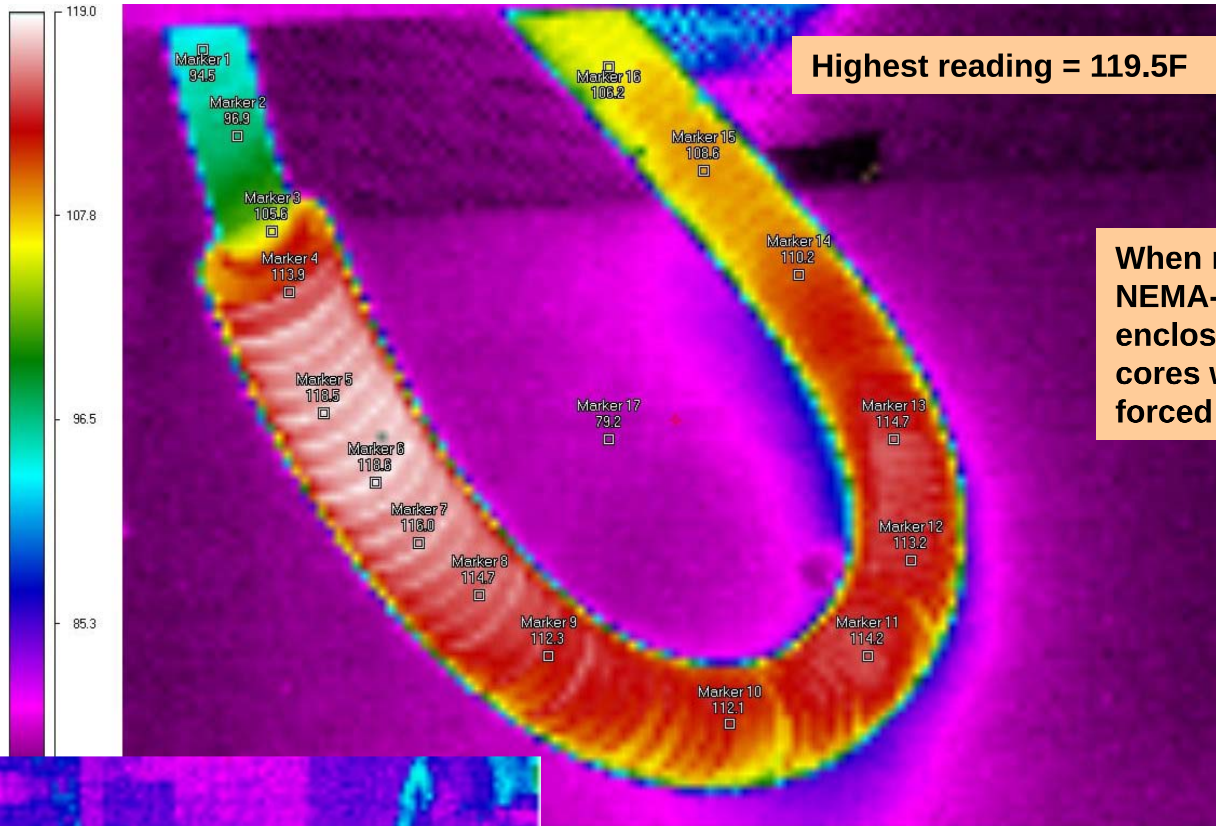




Water Load

Ross Relay used to simulate antenna arcs.

Thermal Images of XFMR Cores at 100 kW 6% duty cycle

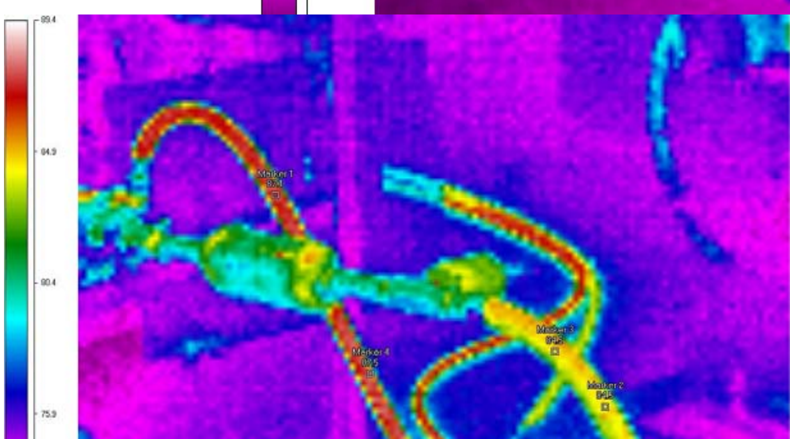


Highest reading = 119.5F

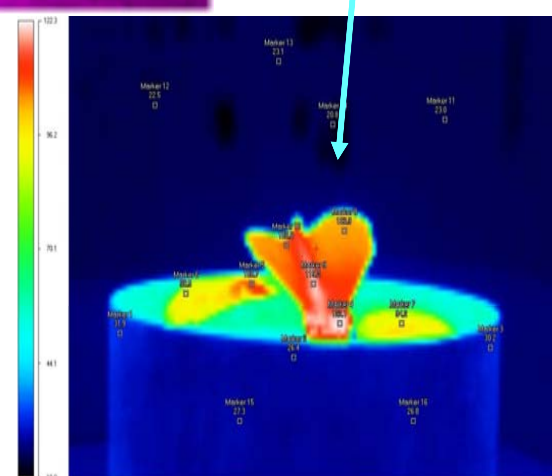
When mounted in NEMA-4 enclosure the cores will have forced air cooling.

Air Flow Indicator on Amplifier Chimney

T =122.5F

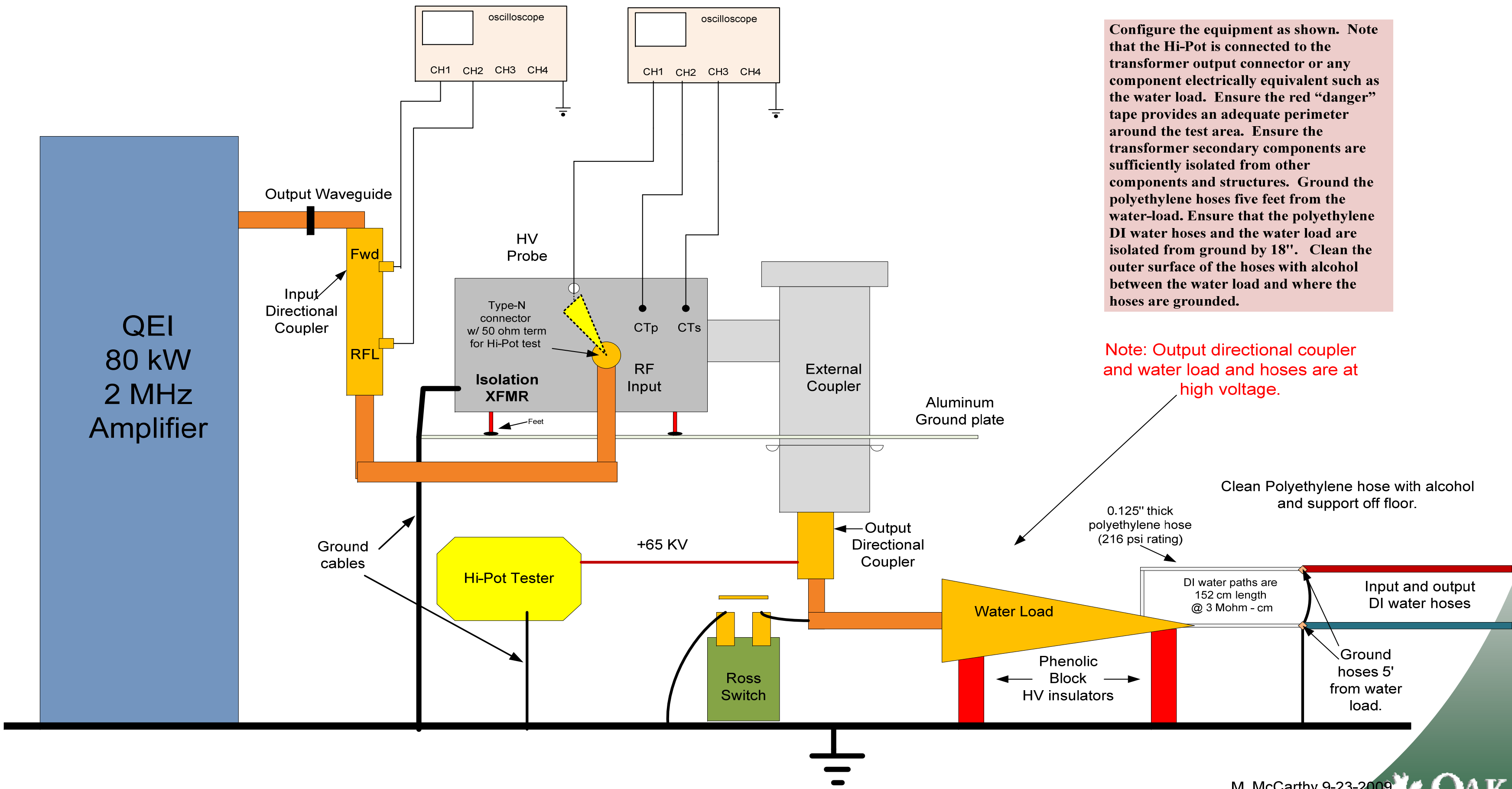


Water Load Hoses: 84.5F In, 87.5F Out,
Flow = 15 gpm Pdiss ~ 6.6 kW



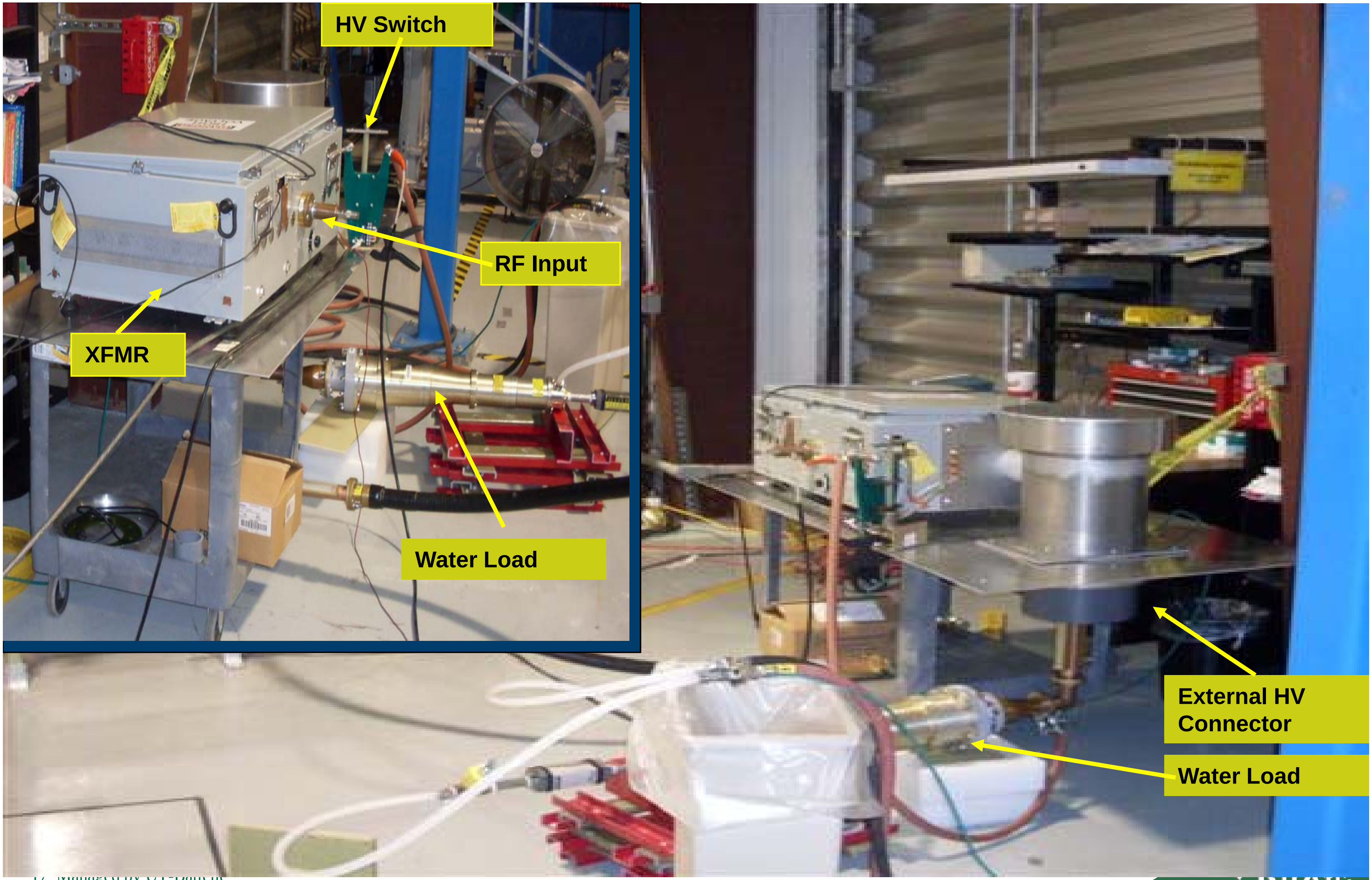
Antenna Arc to Amplifier Pulse Tests

Isolation Transformer HV Test Set-Up

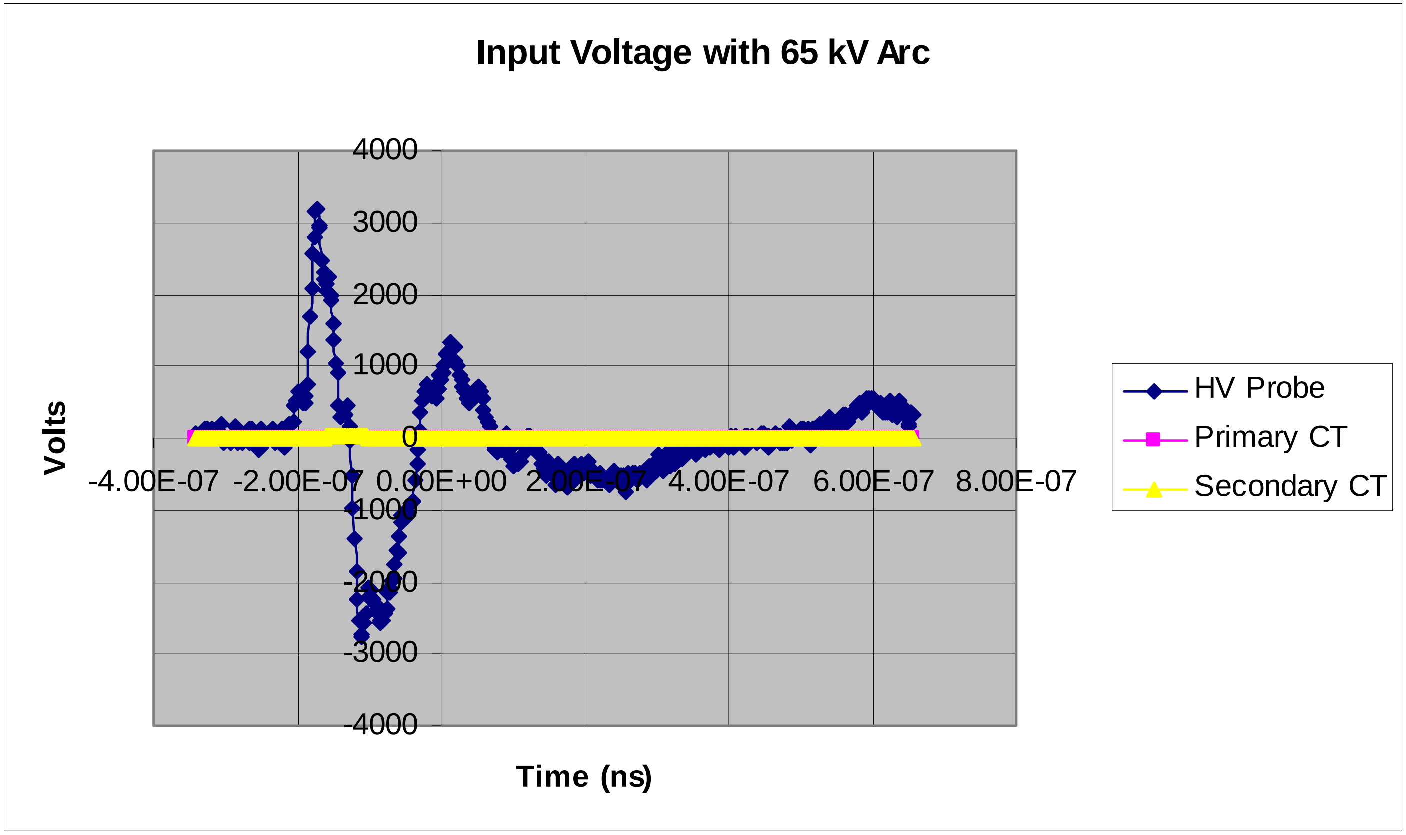


Configure the equipment as shown. Note that the Hi-Pot is connected to the transformer output connector or any component electrically equivalent such as the water load. Ensure the red "danger" tape provides an adequate perimeter around the test area. Ensure the transformer secondary components are sufficiently isolated from other components and structures. Ground the polyethylene hoses five feet from the water-load. Ensure that the polyethylene DI water hoses and the water load are isolated from ground by 18". Clean the outer surface of the hoses with alcohol between the water load and where the hoses are grounded.

Antenna Arc to Amplifier Pulse Tests



Arc test results



Transformer was tested at 85kV for 1 hour with no arcs.

Leakage current ~ 2.6 uA

Conclusion

- **All specs were met or exceeded**
- **Measured loss <3%**
- **S11 bandwidth ~400 kHz with > 26 dB return loss**
- **S21 bandwidth > 1 MHz with < 5% loss**
- **Highest measured component temperature < 120 F**
- **HV isolation > 85 kV**
- **Measured RF leakage is well within ORNL limits.**

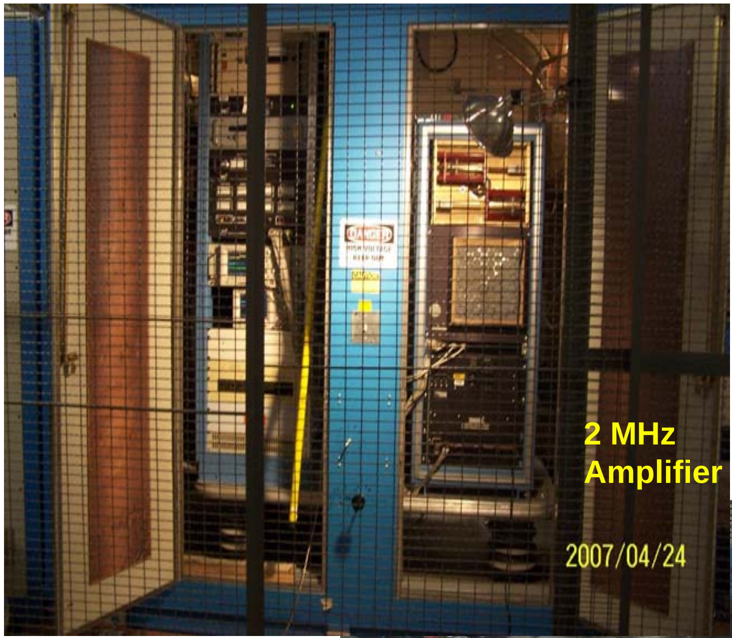
- **Tested for 1 week on I.S. test stand at nominal operating power with no issues.**

TBD

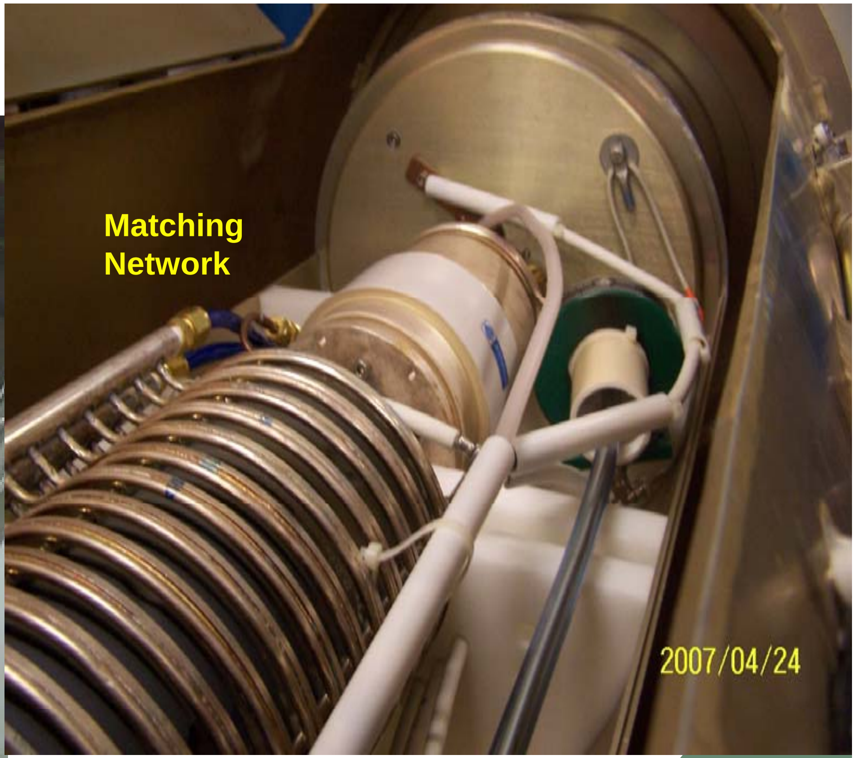
- **Final testing of transformer with amplifier at full power whilst instigating 65 kV arcs from secondary to ground.**
- **Cut 30 cm hole in 65 kV enclosure ceiling needed for xfmr output connector installation (expands existing fan hole).**
- **Lay 8” wide ground plane between xfmr and 2 MHz amplifier.**
- **Install 3.125” Coax for RF power between amplifier and XFMR.**
- **XFMR cover requires interlock to shut off RF Power.**
- **Conduit to carry CT primary and secondary signals and interlock status back to amplifier controller.**

Fin

High Power Test on Ion Source Test Stand



Transformer was placed between the 2 MHz amplifier and the antenna matching network. There was no high voltage. It ran continuously for eight days at 50 – 60 kW with no issues.



HV Cable Specs

ESSEX-X-RAY - 2200 SERIES TRIAXIAL CABLE - DATA SHEET

VOLTAGE		PART	CONDUCTOR SIZE				SEMICON	DIELECTRIC		INNER SHIELD				INTERSHIELD	RATED
DC	AC	NUMBER	AWG	STRANDS	MM2	DIA (M/M)	DIA (M/M)	MATERIAL	DIA (M/M)	CONSTRUCTION	AWG	Coverage	SEMICON	INSULATION	VOLTAGE
(kV)	(kV)										(equiv)	(%)			(DC)
22.5		2122	4	30 BC Briads	21.00	23.40	31.10	EPR	41.90	28 TC Braid	4	85	TAPE	MYLAR	5
40		2186	16	19/29 SPC	1.31	1.50	2.50	SILICONE	7.50	34 TC Braid	16	86	ink & tape	SILICONE	40
50	17	2032TNJ	16	19/29 SPC	1.31	1.50	2.50	SILICONE	7.50	34 BC Braid	16	86	ink & tape	POLYOLEFIN	1
60	20	2024TVJ	12	19/25 SPC	3.31	2.30	3.40	SILICONE	9.10	34 BC Braid	15	81	ink & tape	polyethylene	1
75	25	2241	14	19/27 SPC	1.94	1.80	2.80	EPR	7.80	2 x 30 TC Braid	10	90	EXTRUDED	EPR	75
100	30	2212TVJ	10	76x	4.92	1.30	4.80	EPR	15.70	34 TC Braid	14	80	EXTRUDED	PVC & Mylar	2
125	40	2243TPJ	8	49x	8.37	4.20	5.60	EPR	15.70	30 TC Braid	8	90	TAPE	TPR	5
160	50	2042TVJ	11	76x	4.17	1.30	6.10	EPR	24.90	34 TC Braid	15	80	EXTRUDED	PVC & Mylar	2
350		2068-R2	2	7x	33.62	7.40	7.60	Paper/Oil	23.60	35 x 0.08 Cu	4	100	TAPE	PAPER/OIL	350

Test Setup for ISO-XFMR and 65 kV Enclosure

Calculated Values

Hi-Pot test of 65 kV Isolation transformer to simulate shorted secondary

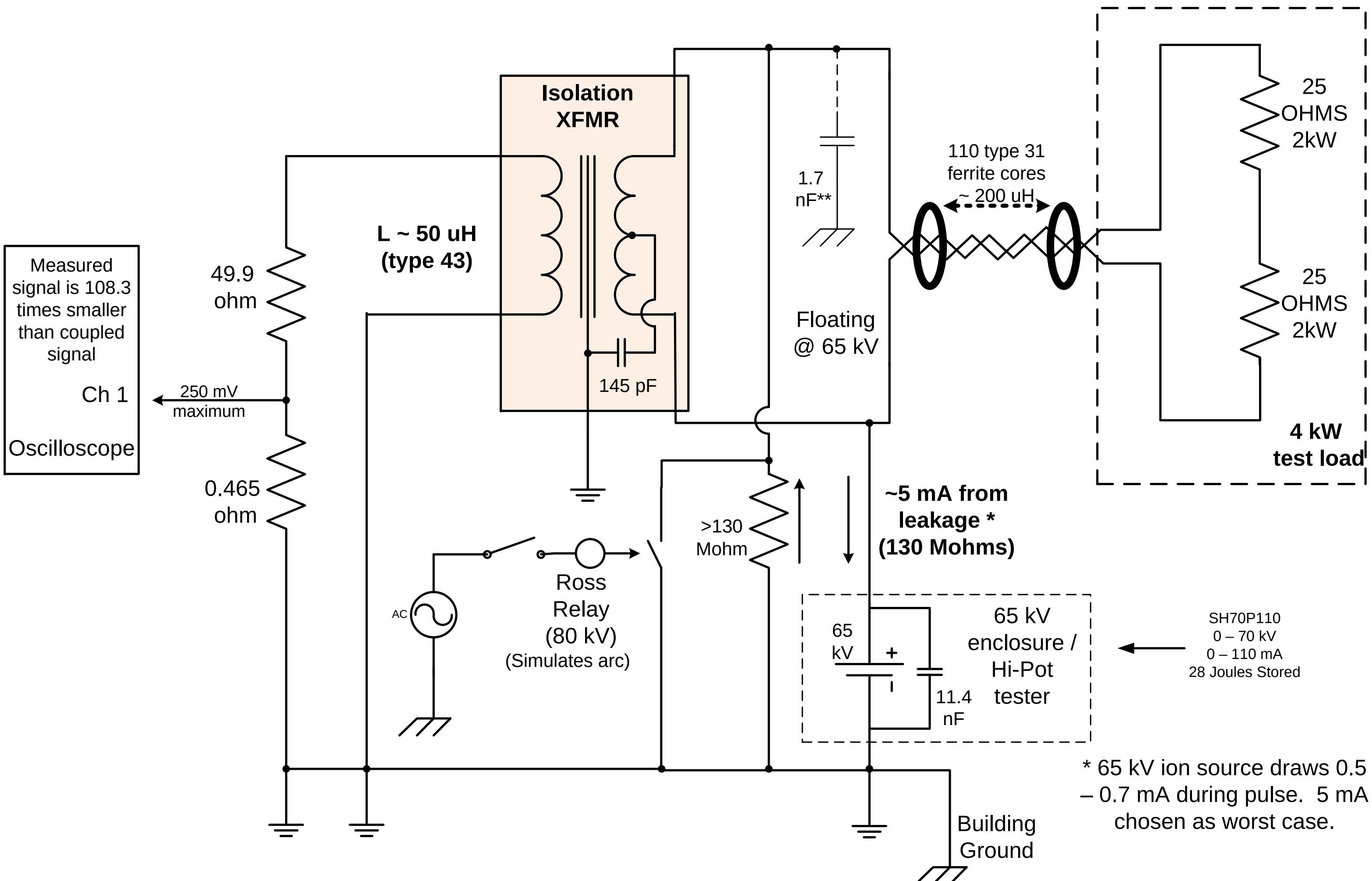
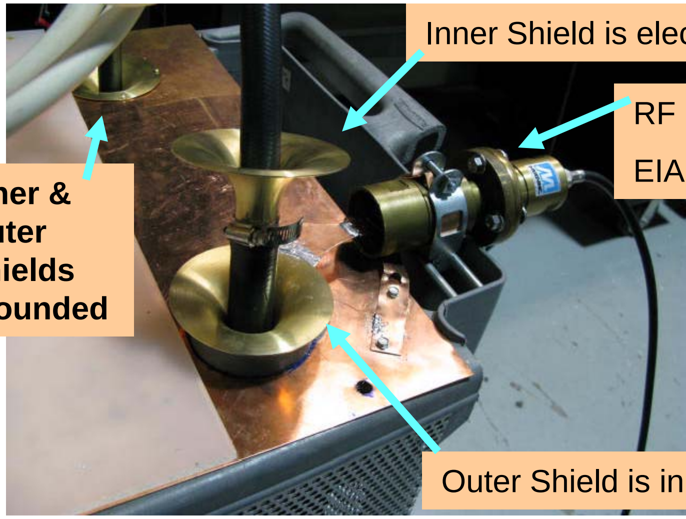


Figure 1
Test Layout

** 1.7 nF is estimated distributed capacitance of 65 kV enclosure from M. Stockli (not included in test circuit)

M. McCarthy
12-2-2008

Transformer Structure



Inner Shield is electrostatic shield between 65 kV and input

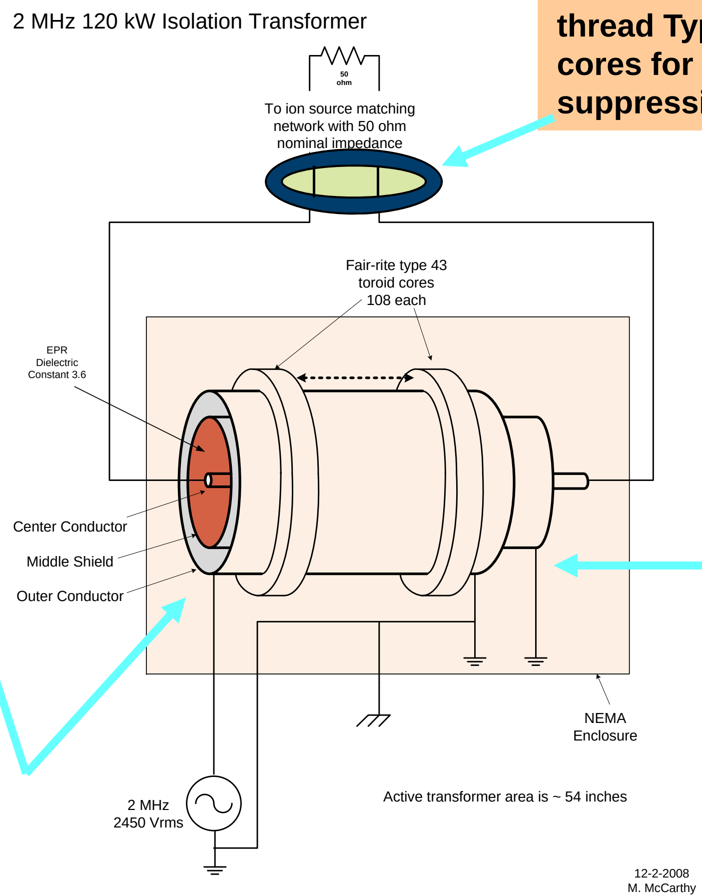
RF input

EIA 1-5/8”

Inner & Outer Shields grounded

Outer Shield is input

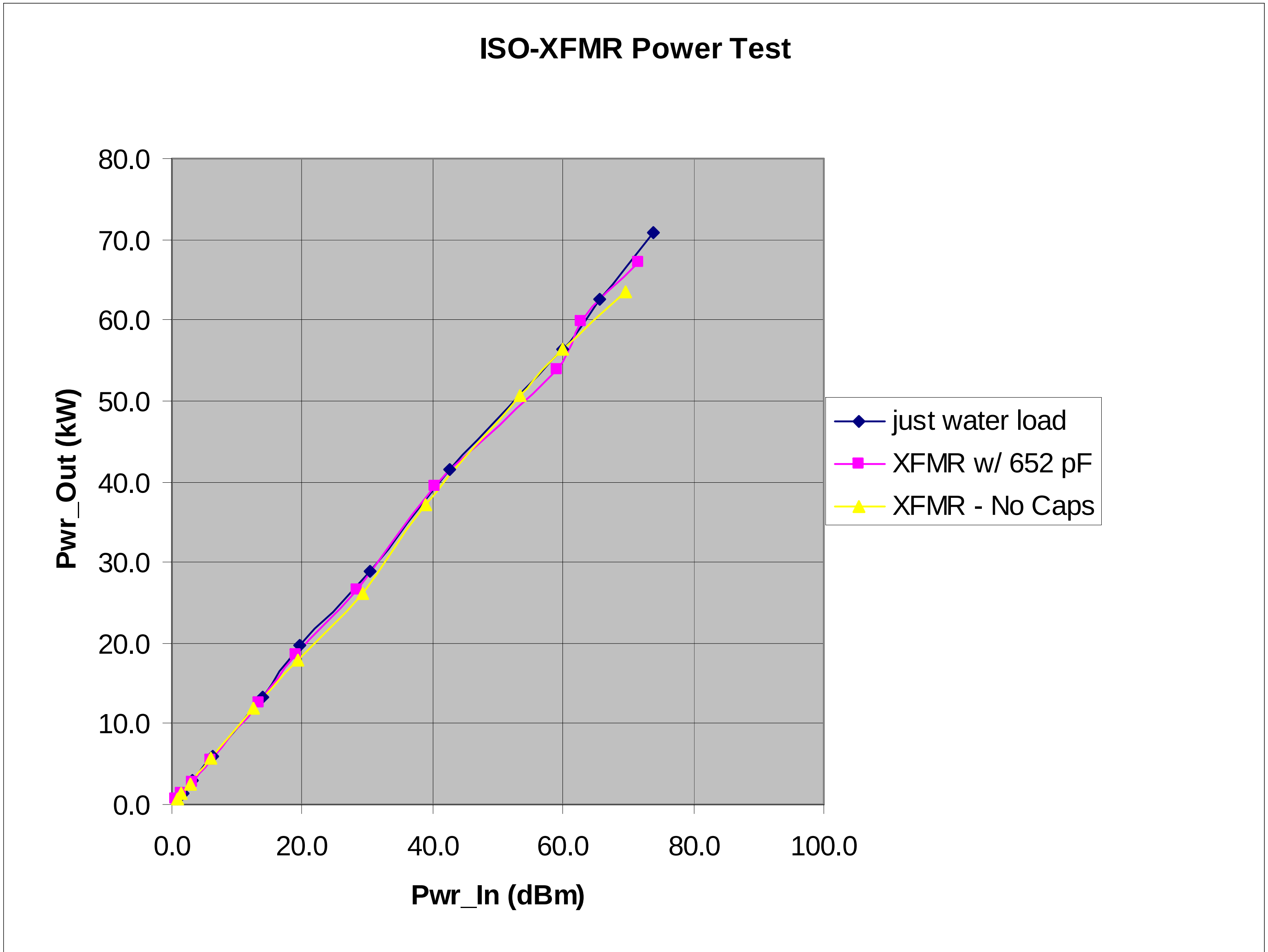
Cores under test



XFMR output will thread Type-31 cores for arc suppression

Inner & Outer Shields grounded

Power In vs Power Out



Cable Specs

CABLE TYPE	CABLE PART NO.	NUMBER OF CORES	VOLTAGE WITHSTAND KV DC	VOLTAGE WITHSTAND KV AC	VOLTAGE BETWEEN CORES	CORES C/S AREA mm^2	CORE RESISTANCE mΩ/M	CAPACITANCE ρF/M	SHIELD COVERAGE %	SEMICON LAYER	JACKET MATERIAL	OUTSIDE DIAMETER mm	MIN-BEND RADIUS mm	WEIGHT KG/M
S	C2212	3	100	65	2 KV DC 600 V AC	1.64 1.64 1.62	11.5 11.5 11.7	130±10%	80	YES	GREY PVC	20±0.4	80	0.5
L	C2236	3	250	90	5 KV DC 2 KV AC	2.07 2.07 3.24	8.9 8.9 5.6	101±10%	80	YES	BLACK PVC	38±0.6	153	1.7
P	C2214	3	75	55	2 KV DC 600 V AC	1.64 1.64 1.62	11.5 11.5 11.7	154±10%	95	YES	GREY PVC	16.5±0.4	66	0.5
S4	C2213	4	100	65	5 KV DC 2 KV AC	1.64 1.64 0.52 2.49	11.5 11.5 79.1 7.8	160±10% (GRID 230)	80	YES	GREY PVC	21.5±0.4	86	0.6
Q	C2231	3	75	55	2 KV DC 600 V AC	1.64 1.64 1.62	11.5 11.5 11.7	154±10%	80	YES	GREY PVC	16.5±0.4	66	0.4
A	C2226	4	75	55	5 KV DC 2 KV AC	1.64 1.64 1.31 2.49	11.5 11.5 13.7 7.8	197±10%	95	YES	GREY PVC	16.8±0.4	66	0.5

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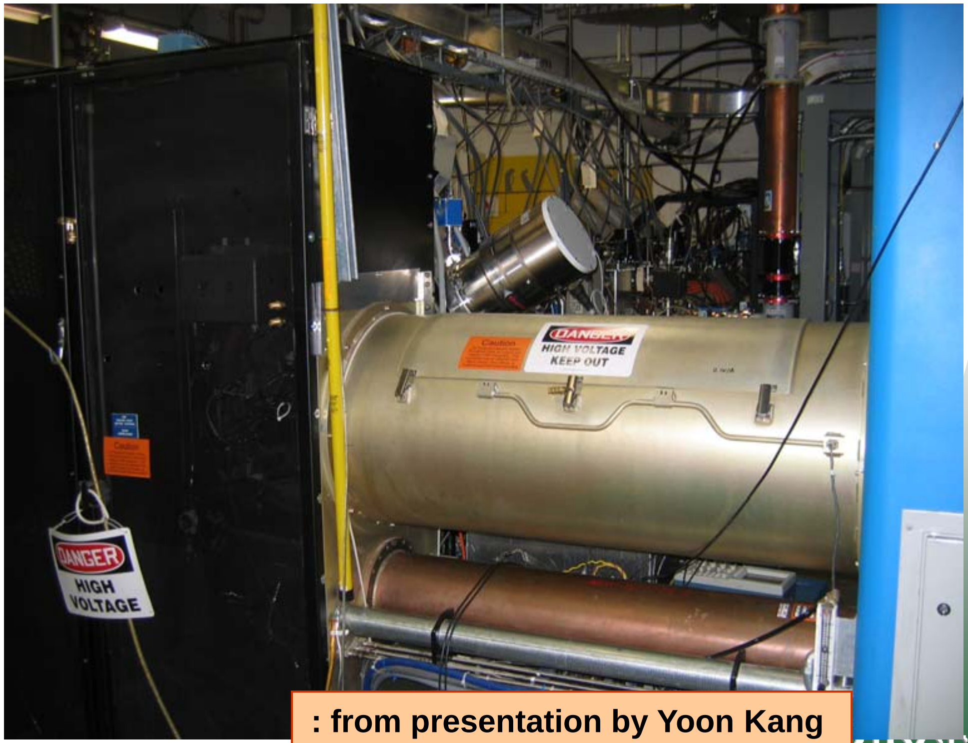
TITLE: CABLE DATA SHEET

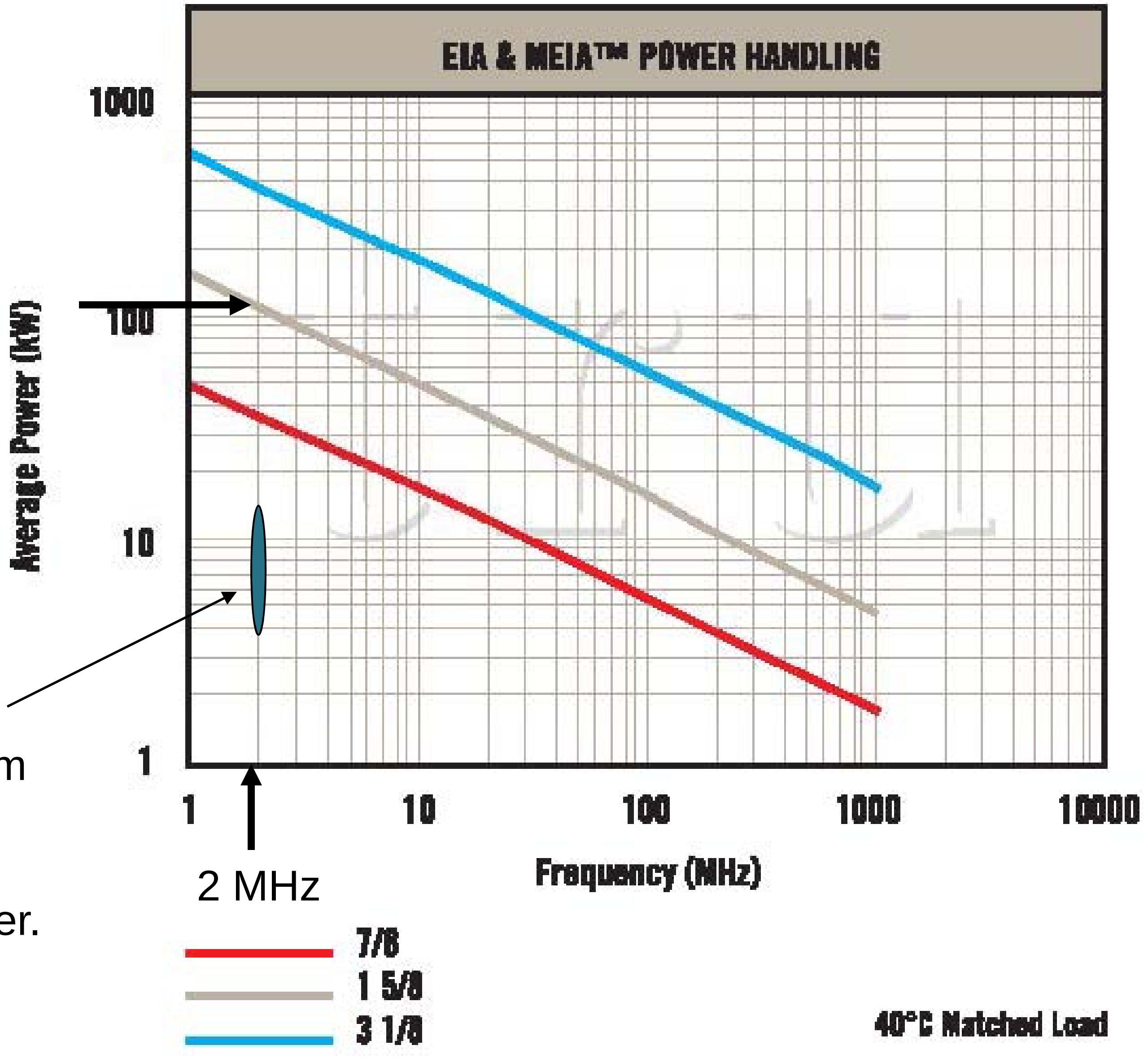
DRAWING No. DS1001

Ion-Source Antenna Matching Networks

- Provide impedance matching between the amplifiers and the antenna
  - The Ion-source antenna has a very low impedance (Re{Za}<1 Ω)
  - 2 MHz amplifier has a standard 50 Ω output impedance
- capacitor is not ideal for good impedance matching
  - Impedance matching requires 2 or more adjustable reactive elements to achieve perfect matching
  - For 2 MHz system, a 2 capacitor type matching network is being developed

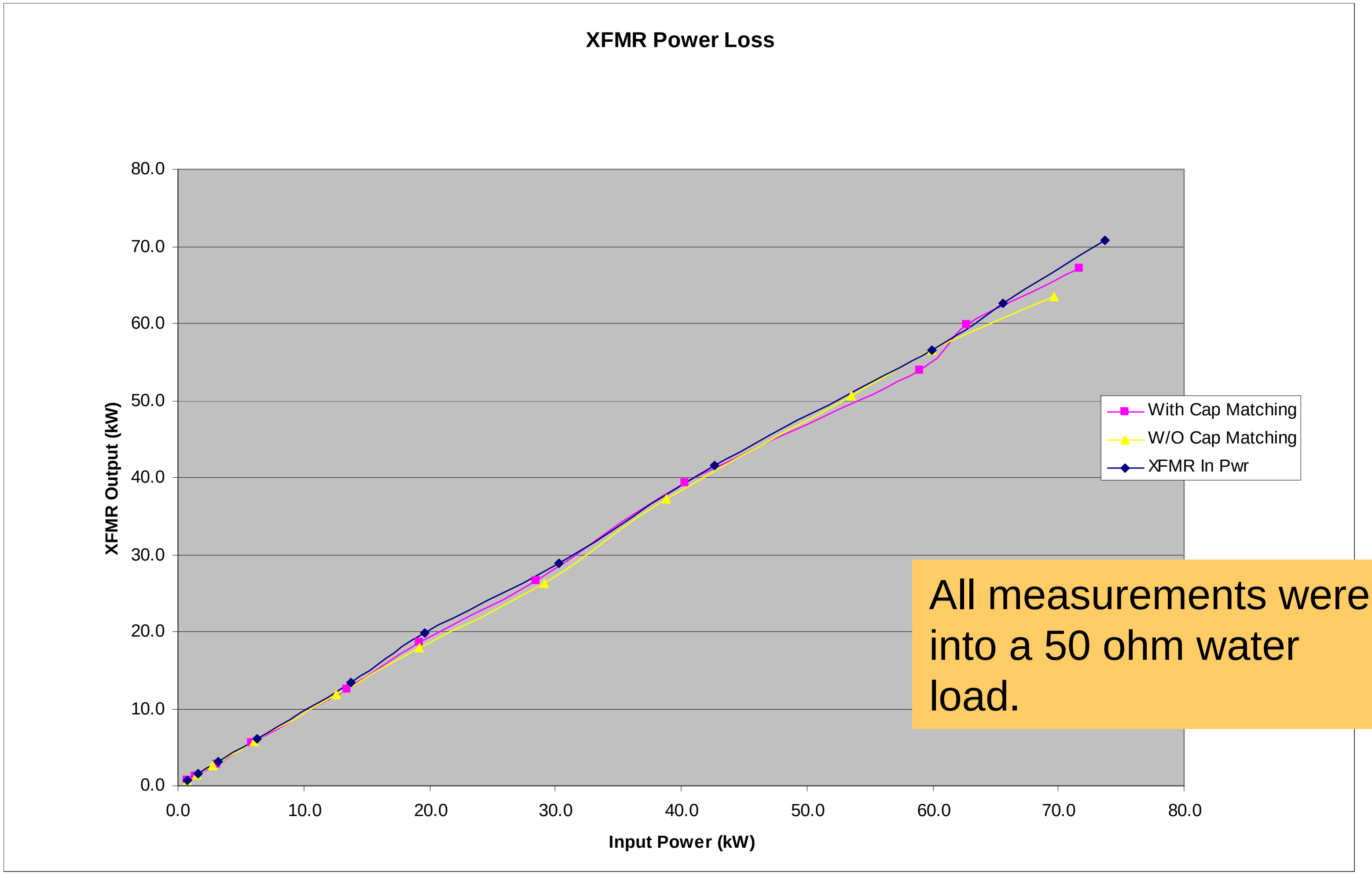


: from presentation by Yoon Kang



Operating region from 30 kW to 120 kW peak power.


DELL
CAUTION
WARNING
WARNING



All measurements were into a 50 ohm water load.

Choosing Ferrites (from Fair-rite Co. – selection of 17 types):

Ferrite Selection

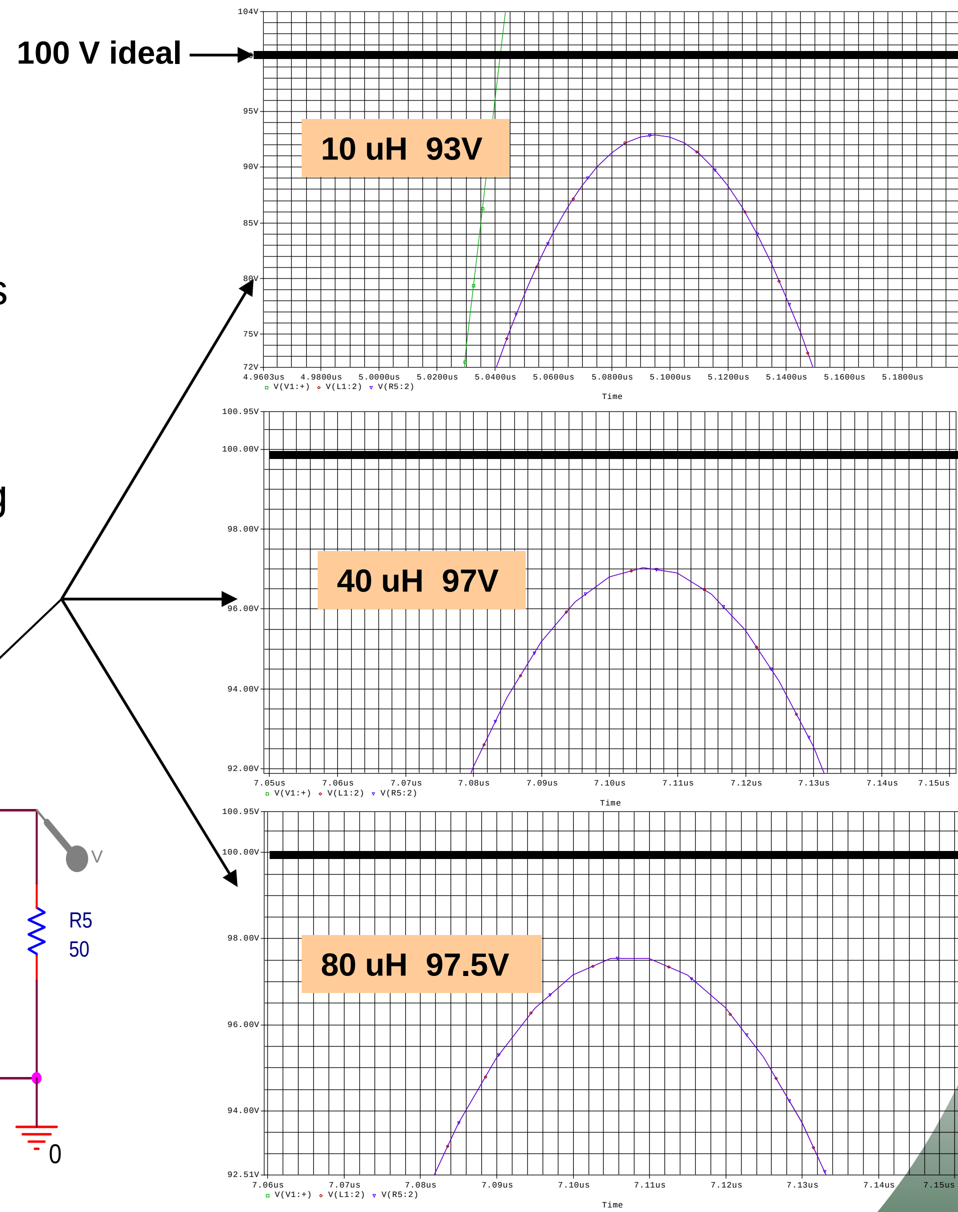
Ferrite type	Upper Freq (MHz)	Permeability 2 MHz	XL per Core ohms	# Cores per 1000 ohms	Available 1.4 " I.D.	Loss Factor (2 MHz)	% Heat
68	400	20	0.33	3042			
67	300	40	0.66	1521			
61	100	125	2.05	487	Y	0.01	0.0%
52	20	275	4.52	221	N		
51							
44							
46							
33	3	700	11.51	87	N		
85							
43	10	580	9.53	105	Y	80	13.7%
79							
31							
77	3	1000	16.44	61	Y	1400	81.4%
78	2.5	1650	27.12	37	Y	1700	71.8%
73							
75	0.75						
76	0.5						

Note: Type 31 is good for suppression of RF from 1 - 300 MHz
It will be used between the XFMR and the I.S. matching network.

Type 43 ferrite cores were chosen. They are available in a size to fit the HVCM cable with the outer insulator removed (1.4" I.D.). They have a reasonable loss factor indicating ~13% of the energy required to develop the flux in the core is dissipated as heat. They have good permeability at 2 MHz resulting in a reasonable number of cores.

Number of Cores

The inductive reactance (XL) of the cores act in parallel with the ideal transformer and the 50 ohm load. With higher XL less magnetizing current is used and more power goes into the load. However, longer cable = higher resistive losses. We compromised with 108 cores resulting in a calculated 81 uH inductance.



XL = 9.44 ohms per core.