High Voltage RF Transformer for RFQ Booster Cavity

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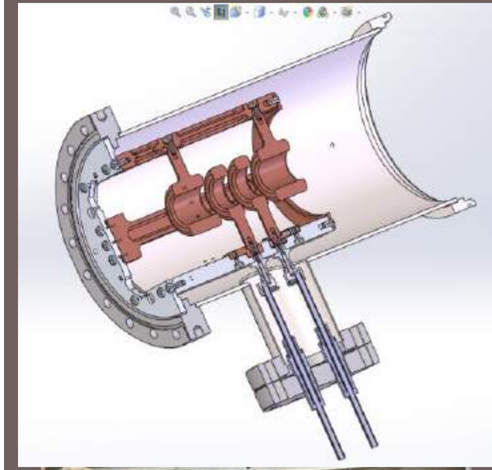
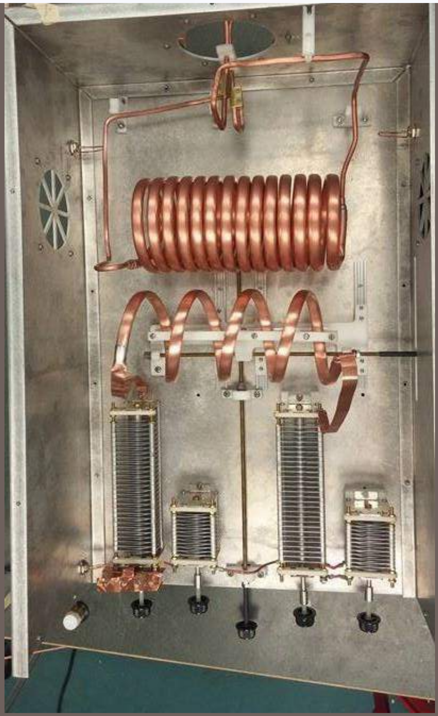




Project Background

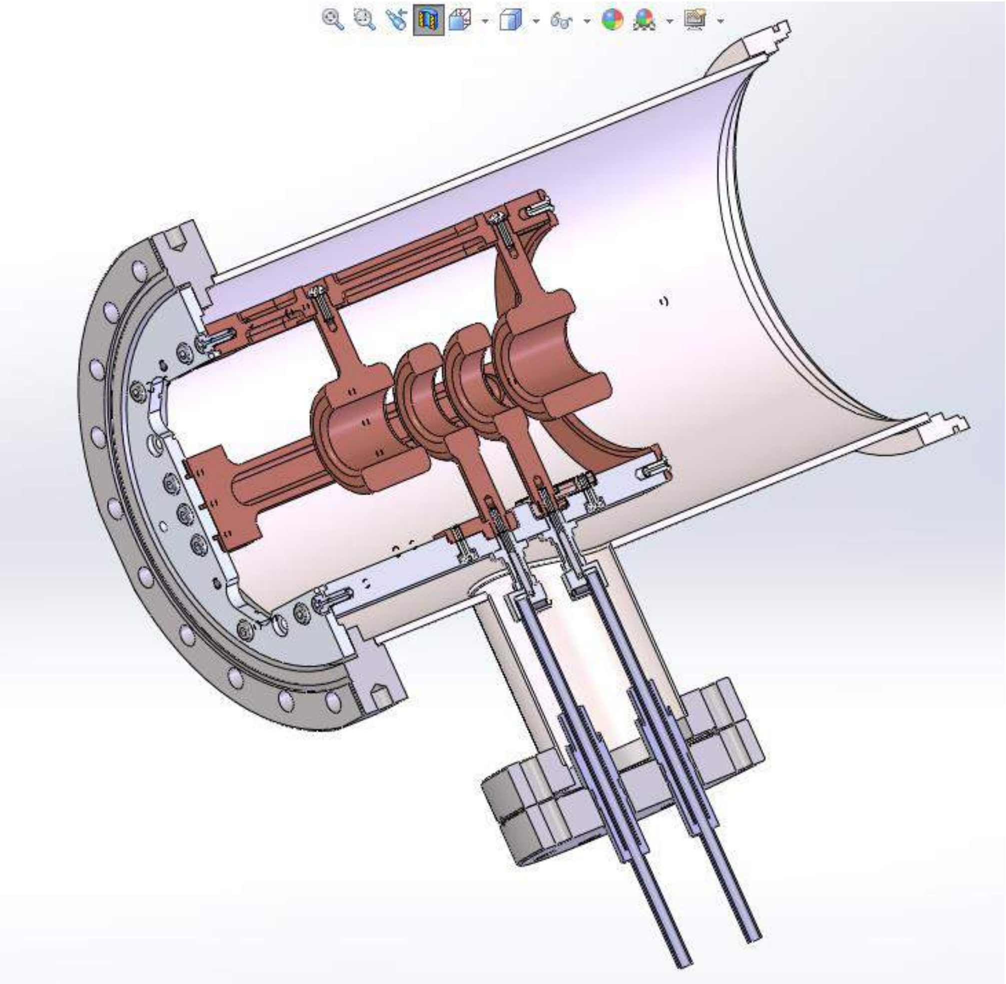
TRIUMF is a Cyclotron in Vancouver, BC, which operates a 500 MeV proton beamline.

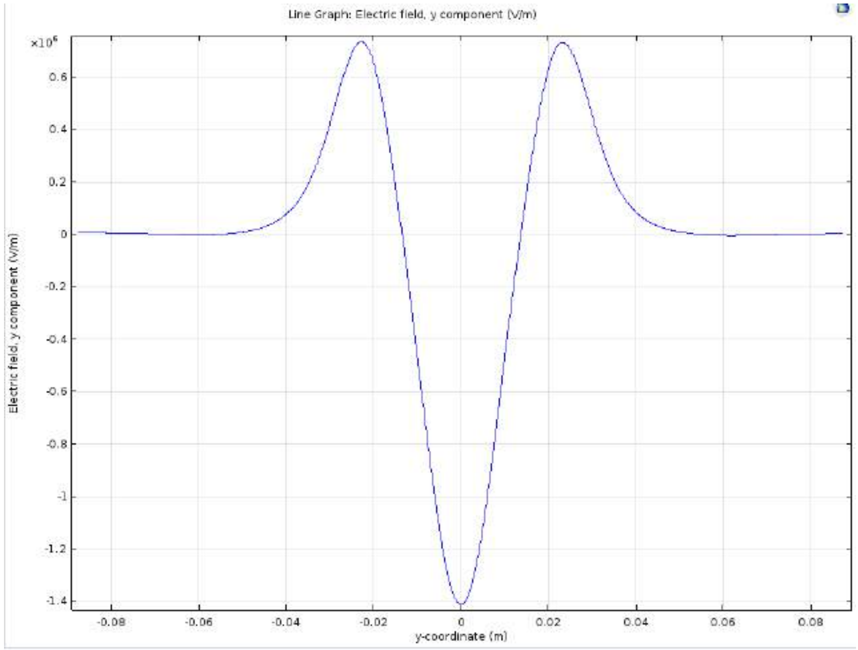
Beamline hits ‘targets’, which produce radioactive isotopes, feeds these to a number of experiments.

Accelerating Isotopes

RF Booster cavity

To accelerate in ISAC-I TRIUMF linac heavy ions with mass-charge ratio A/q>25 we need to provide boost of energy of ~16kV for the beam. 3-gap 11.78MHz structure has been developed for this purpose

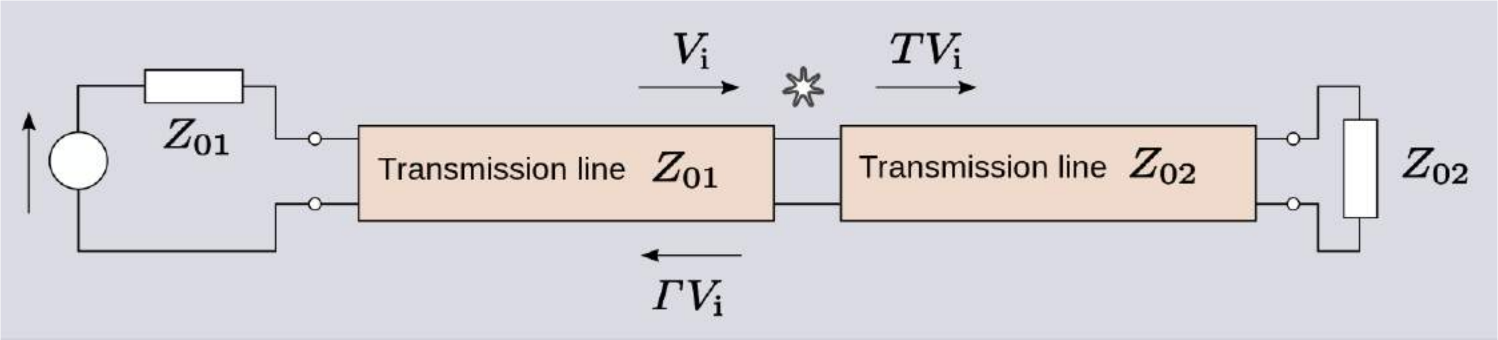




It requires 2-phase RF voltage of +/-9kV; 180deg between phases

How to Transmit Power

Impedance mismatching causes reflected power = bad news for our particles



$$\Gamma = \frac{V_r}{V_f}.$$

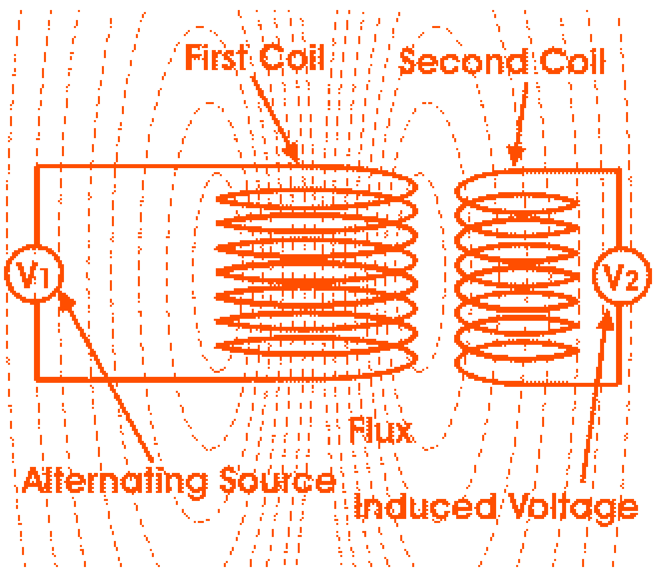
$$\mathrm{VSWR} = \frac{|V_{\max}|}{|V_{\min}|} = \frac{1+|\Gamma|}{1-|\Gamma|}.$$

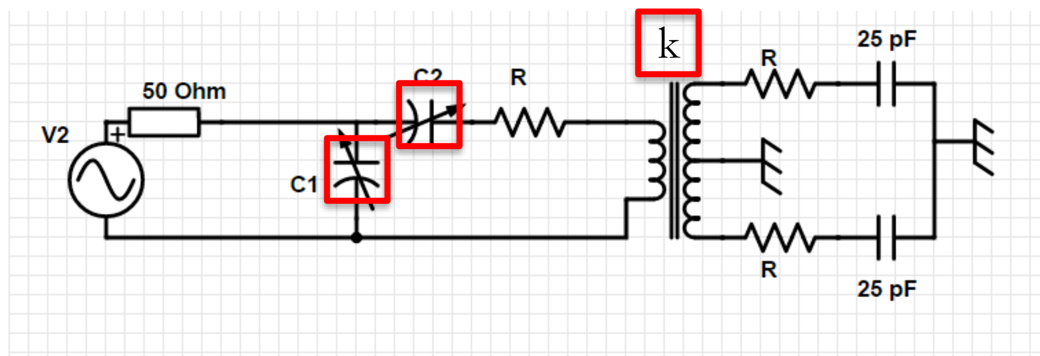
TRIUMF

RF Transformer

Functions:

- Match impedance between power supply and accelerator cavity
- Provide step up of voltage
- Resonate at operating frequency ~11.8 MHz

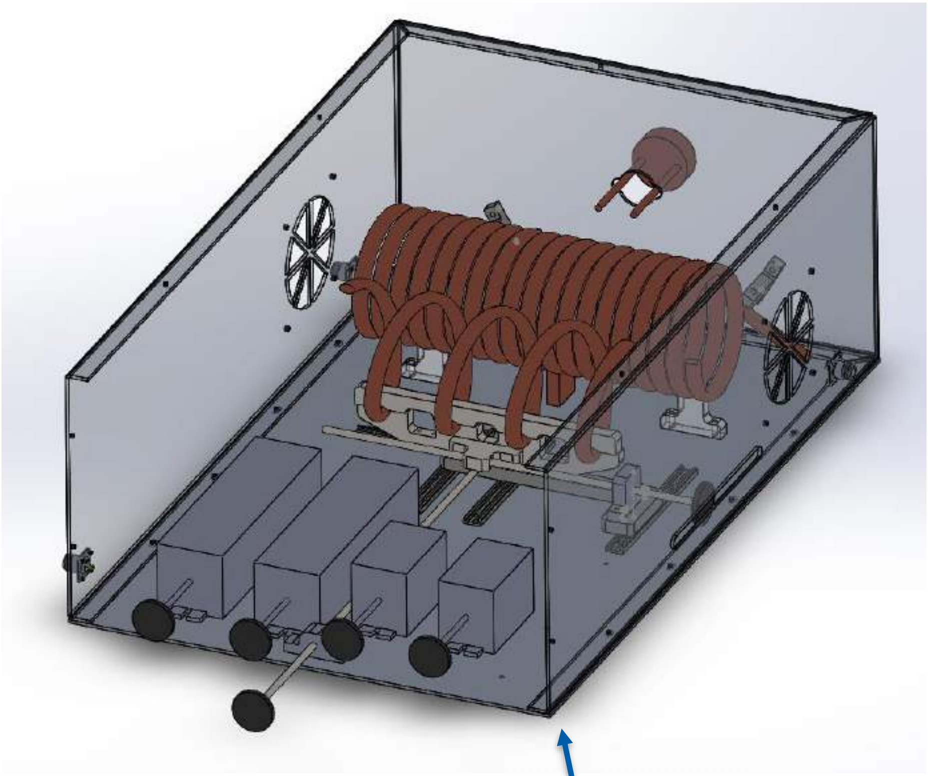




$$w \frac{L_1'^{\frac{3}{2}}}{\sqrt{C_1 R''}} = \frac{\left(L1 - \frac{1}{w^2 \boxed{C_2}}\right)}{\boxed{C_1}\left(R + \frac{\left(w \boxed{k} \sqrt{L_1 L_2}\right)}{2R}\right)}$$

Tunable elements

Design

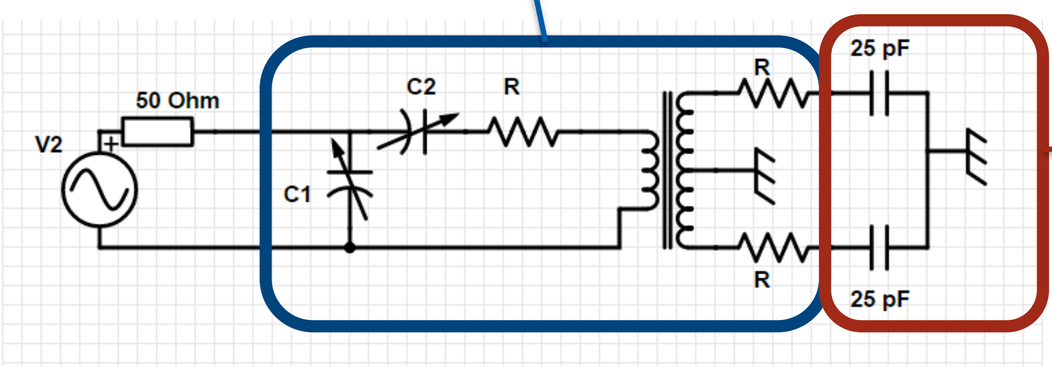


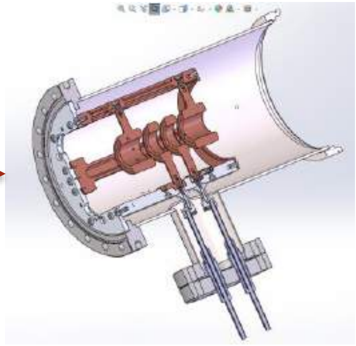
Adjustable tuning capacitors

Adjustable coupling between inductors

Cooling fans

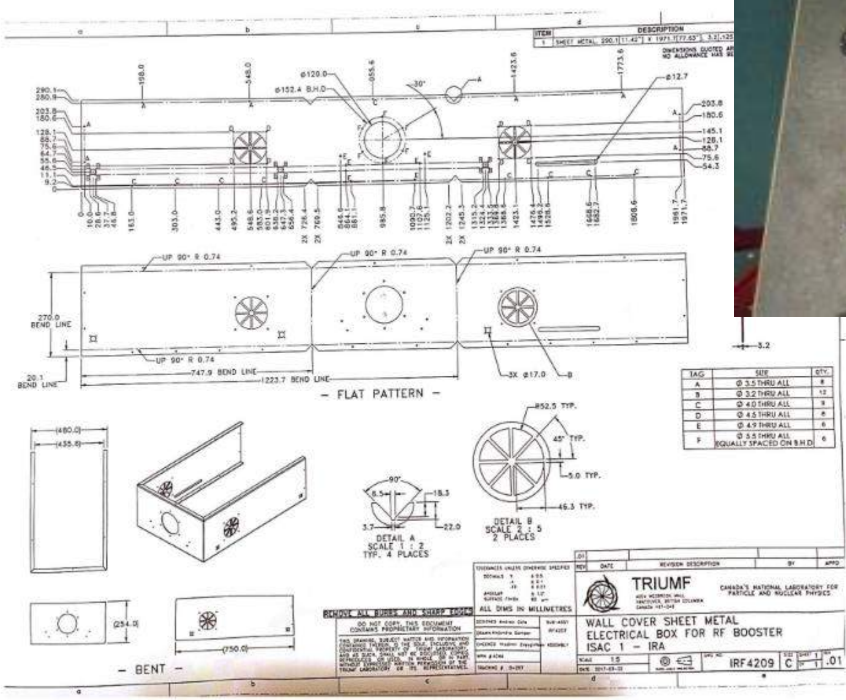
Signal outputs for control system

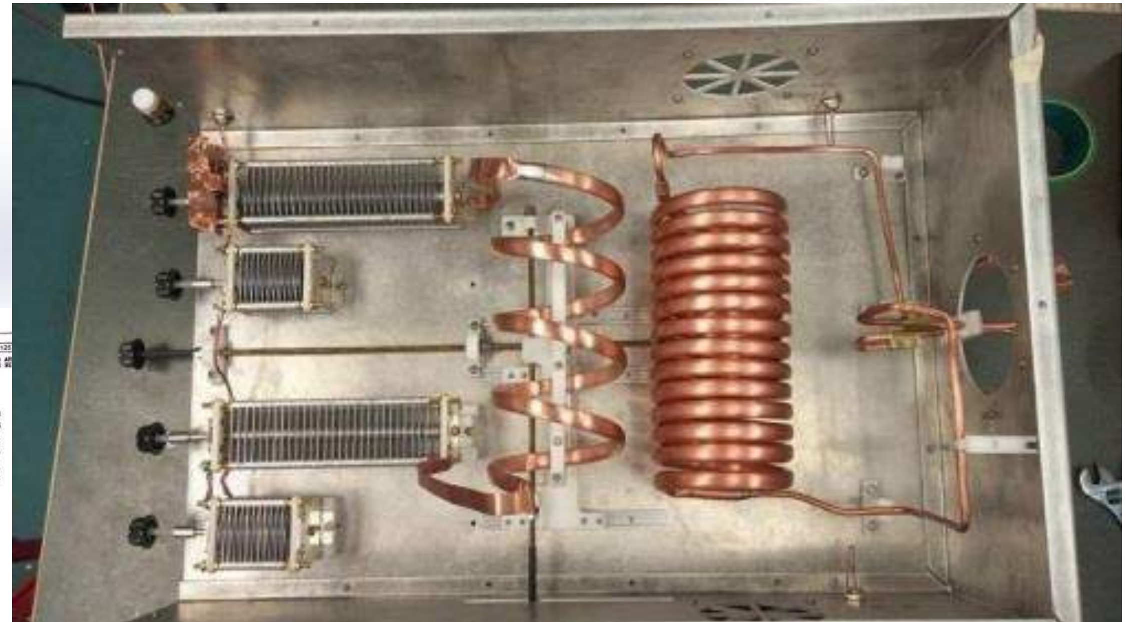




Fabrication and Design

Final Design
- Extensive SolidWorks Design
- Machineshop fabrication, CNC cutting

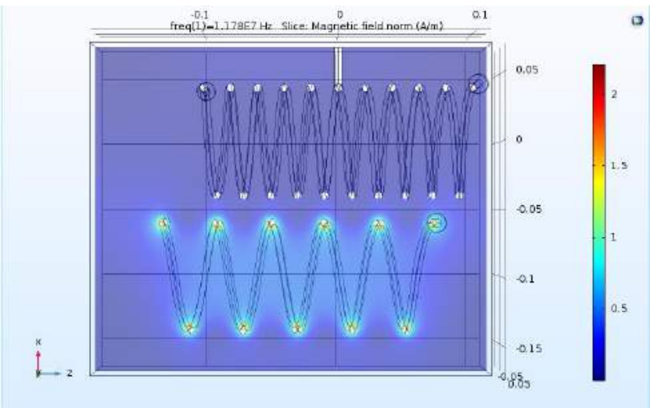


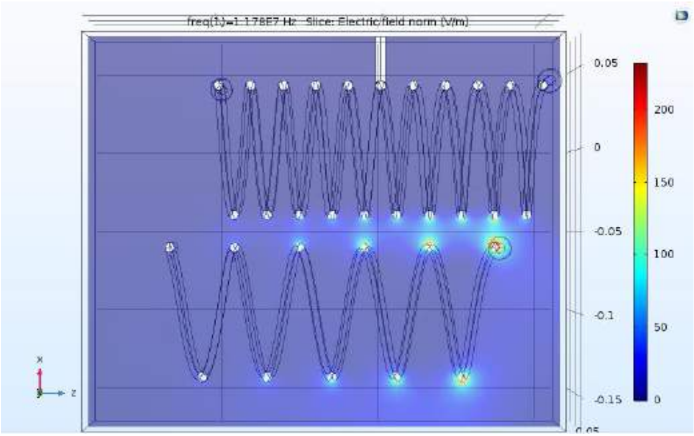


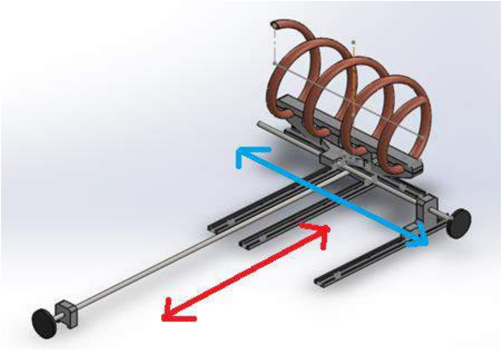
Tuning knobs for trimming capacitors

Re-Design

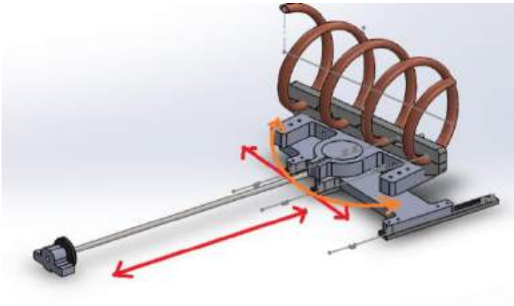
- 10% difference between voltage outputs
- COMSOL revealed capacitive effect between coils
- Slight redesign of Primary coil mount to give rotational freedom







First Version



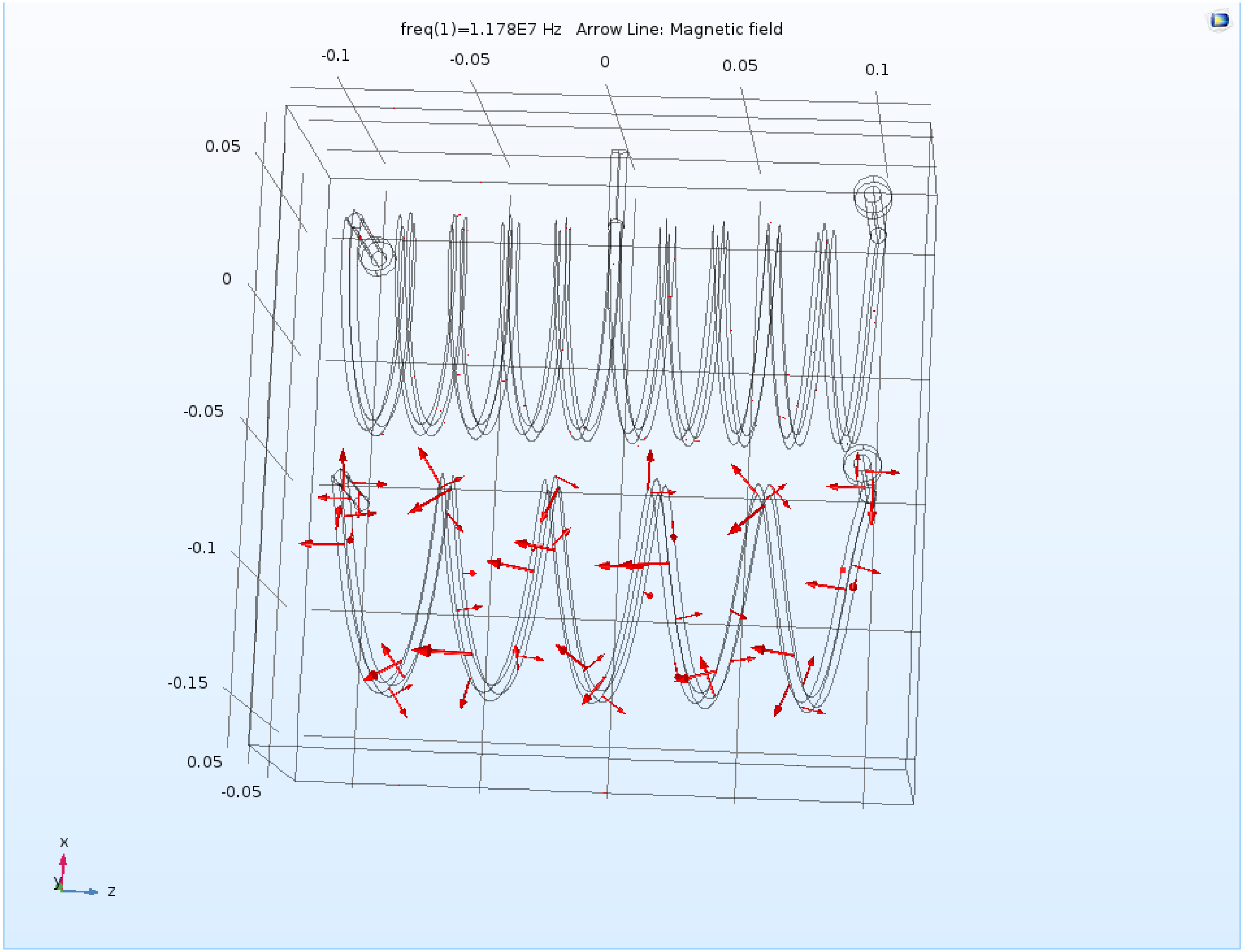
Current Version

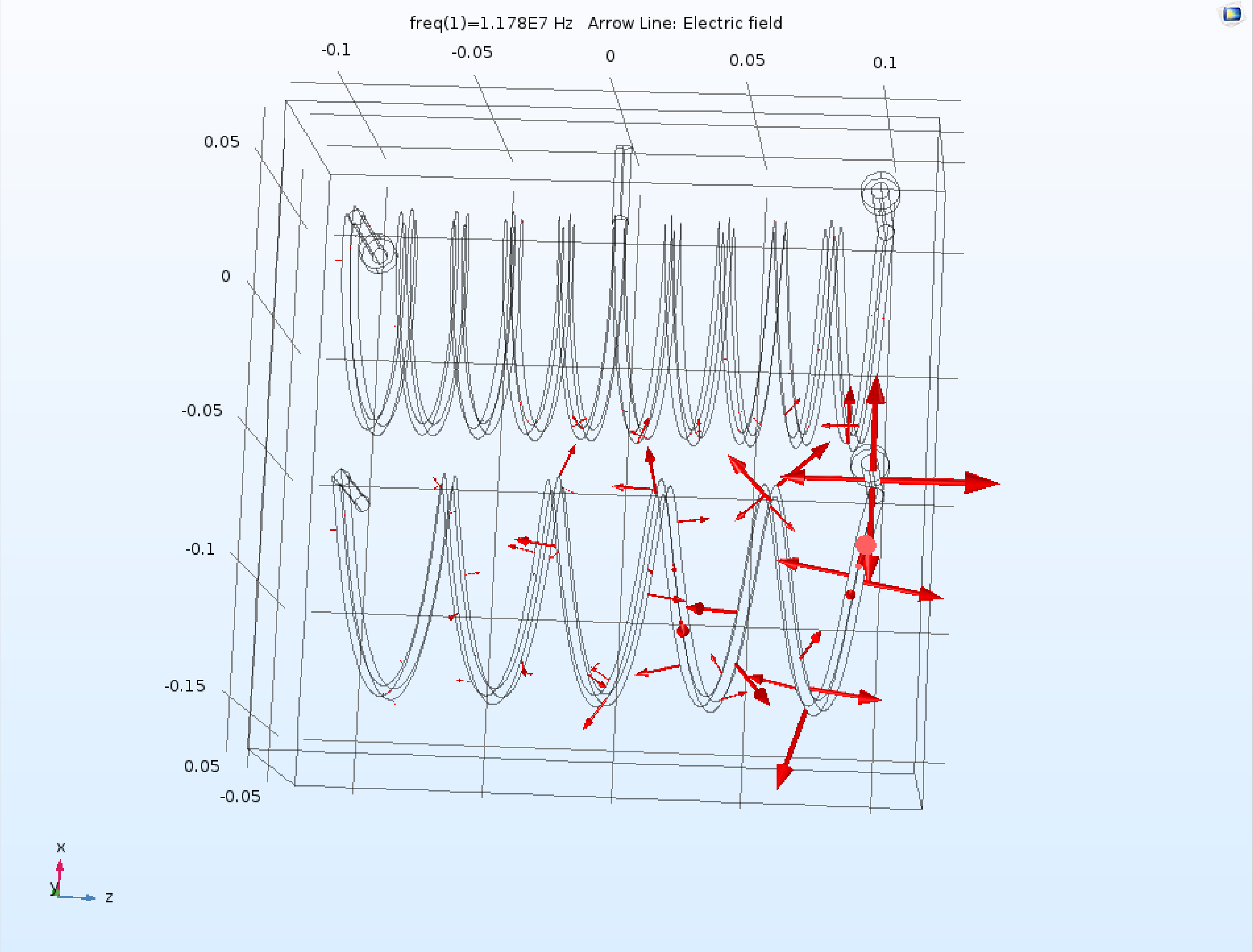
Conclusion

Results Summary

- F0 = 11.78 MHz, bandwidth 200kHz
- VSWR of 1.3, “perfect enough”
- Endurance testing of RF Box at 9kV, 115 W input power
  - intake/outtake fans provide plenty of cooling, no heating concerns
- Installed on Beamline in April 2017 – currently operational providing 16kV effective acceleration voltage for isotopes entering the RFQ.

Thanks!


freq(1)=1.178E7 Hz Arrow Line: Magnetic field
-0.1
-0.05
0
0.05
0.1
0.05
0
-0.05
-0.1
-0.15
0.05
-0.05
x
y
z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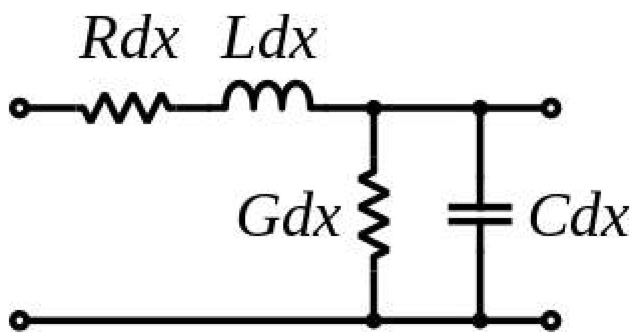
-0.1
-0.05
0
0.05
0.1
0.05
0
-0.05
-0.1
-0.15
0.05
-0.05
x
y
z

Transmission Line Theory

Transmission Line has a characteristic impedance



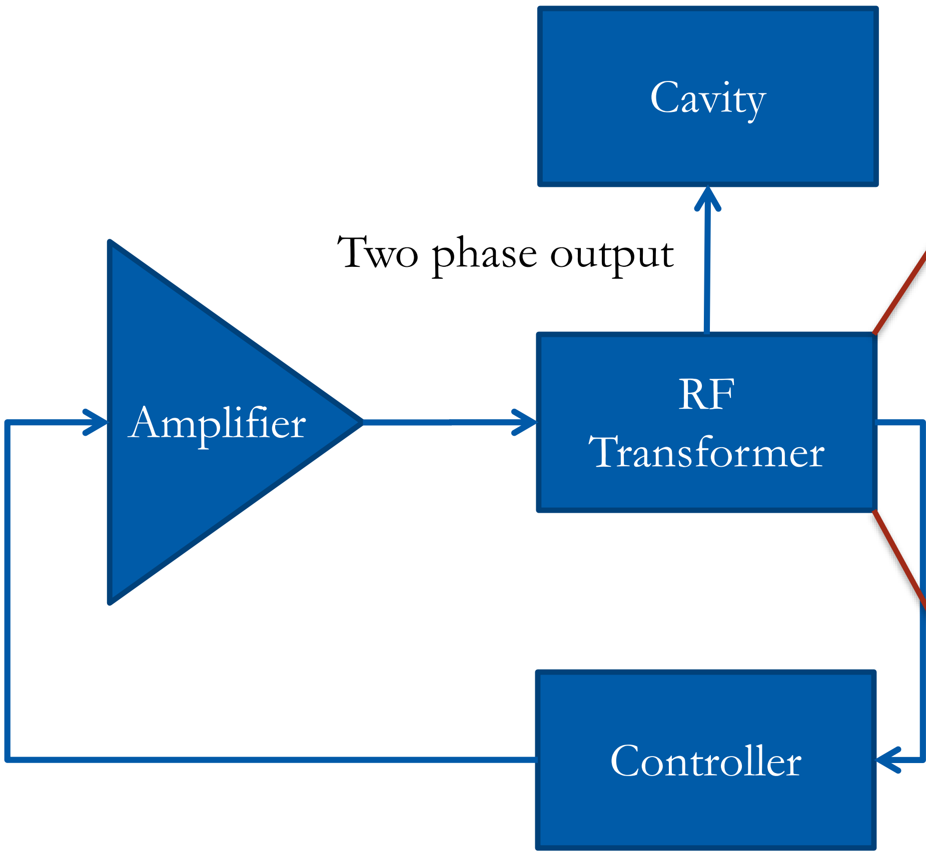
Ignore resistance

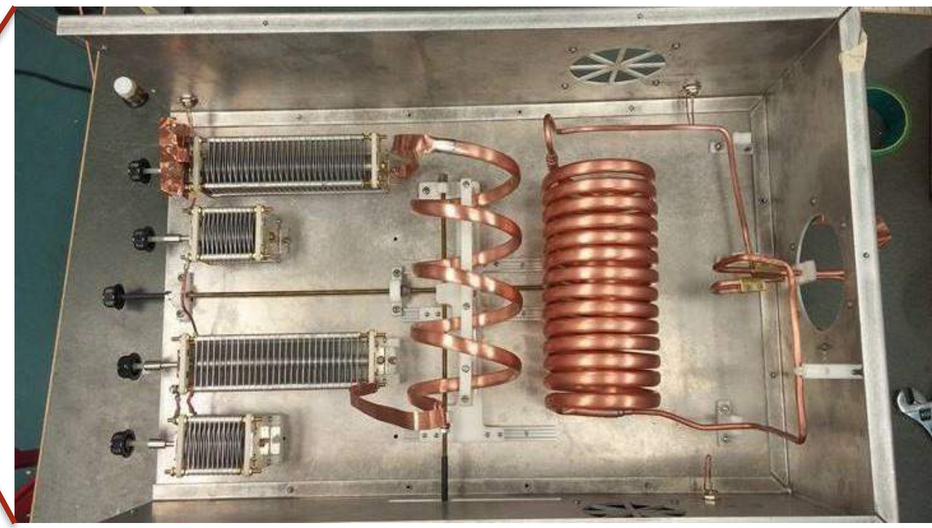
$$\frac{\partial V}{\partial x} = -L\frac{\partial I}{\partial t} \qquad \frac{\partial^2 V}{\partial t^2} - u^2\frac{\partial^2 V}{\partial x^2} = 0 \qquad u = \frac{1}{\sqrt{LC}}$$

$$\frac{\partial I}{\partial x} = -C\frac{\partial V}{\partial t} \qquad \frac{\partial^2 I}{\partial t^2} - u^2\frac{\partial^2 I}{\partial x^2} = 0$$

$$V(x) = V_1 e^{-jkx} + V_2 e^{+jkx} \qquad I(x) = \frac{V_1}{Z_0}e^{-jkx} - \frac{V_2}{Z_0}e^{+jkx}$$

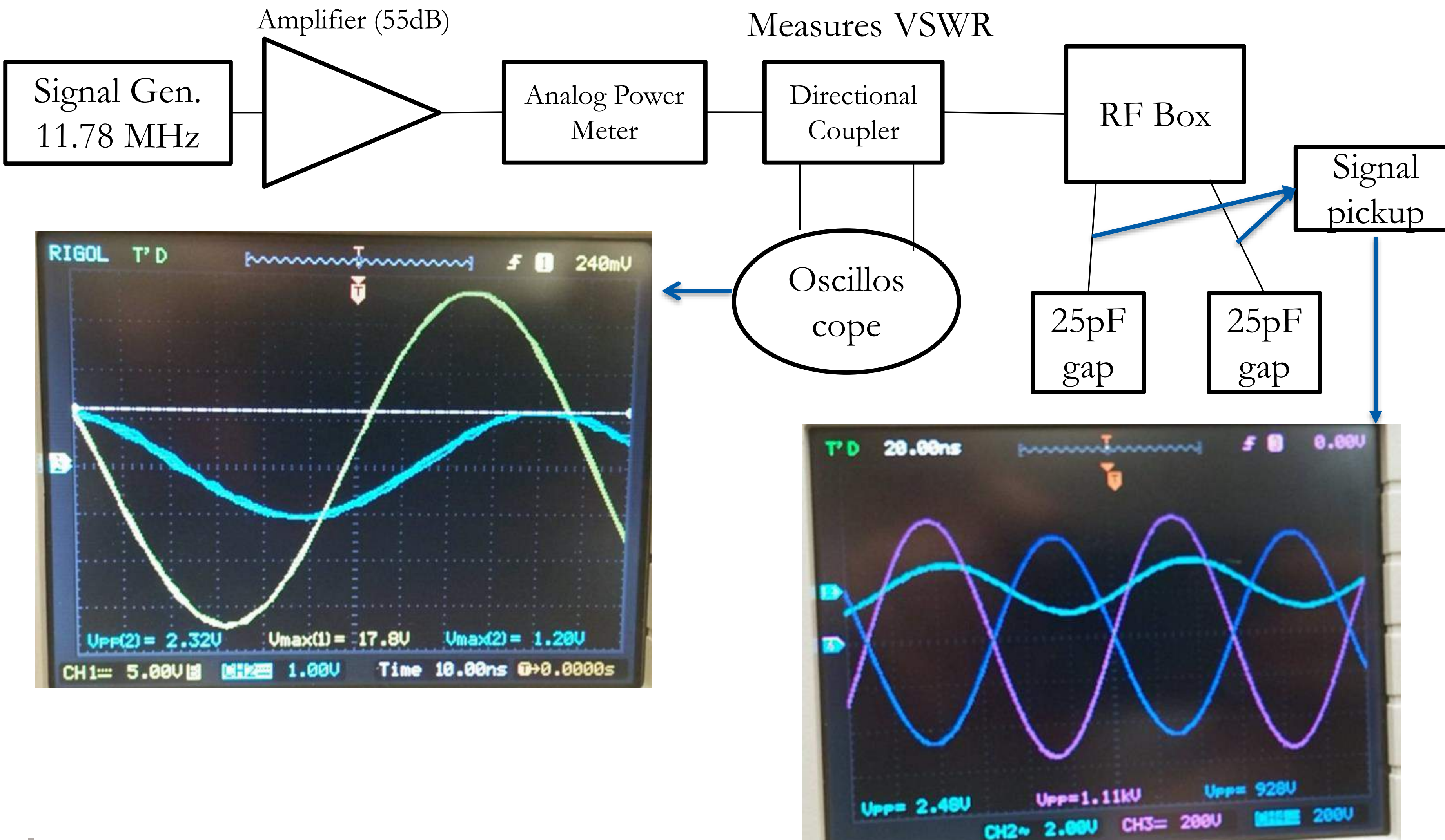
RF System and RF Box





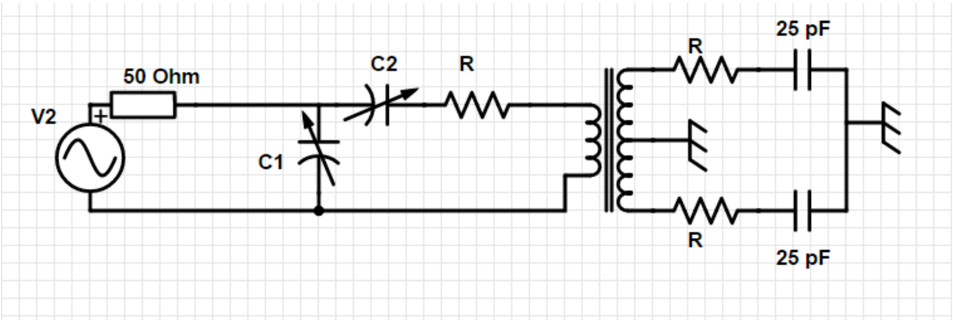
RF Transformer:
- Increases the input voltage to 9kV
- Feeds signal into Amplifier-Controller feedback loop

Testing

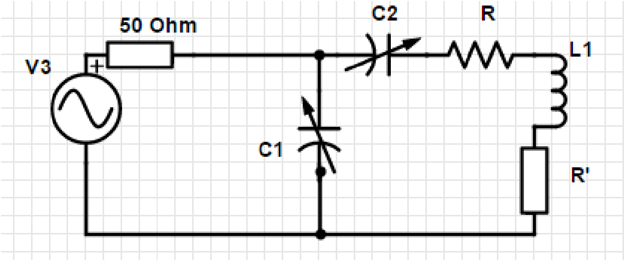

Amplifier (55dB)
Measures VSWR
Signal Gen. 11.78 MHz
Analog Power Meter
Directional Coupler
RF Box
Signal pickup
Oscilloscope
25pF gap
25pF gap
RIGOL T'D
240mV
Vpp(2)= 2.32V
Vmax(1)= 17.8V
Vmax(2)= 1.20V
CH1= 5.00V
CH2= 1.00V
Time 10.00ns
0.0000s
T'D 20.00ns
0.00V
Vpp= 2.48V
Vpp=1.11kV
Vpp= 928V
CH2~ 2.00V
CH3= 200V
200V

RF Transformer Fundamentals

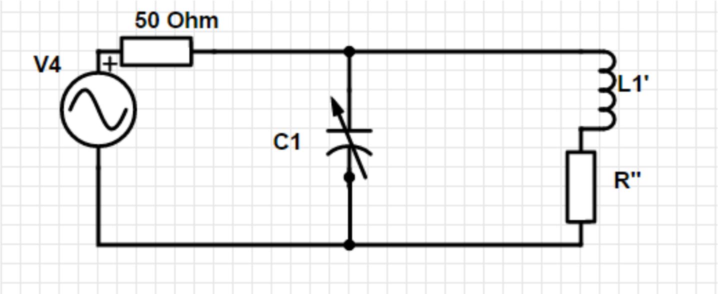
Analysis of RF Transformer



Both sides are in resonance, simplify circuit in three steps.



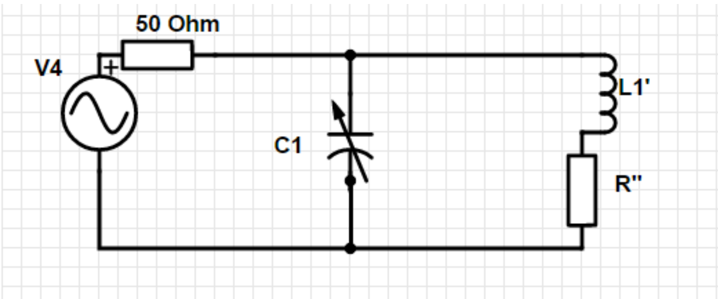
$$R' = \frac{(wM)^2}{2 \cdot R} \qquad M = k\sqrt{L_1 L_2}$$



$$L_1' = L_1 - \frac{1}{w^2 C_2} \qquad R'' = R' + R$$

RF Transformer Fundamentals

Analysis of RF Transformer



Quality Factor

$$Q = \frac{wL_1{}'}{R''}$$

Resonant Frequency

$$w_0 = \frac{1}{\sqrt{C_1 L_1{}'}} = \frac{1}{\sqrt{C_{cavity} L_2}}$$

Characteristic Impedance

$$\rho = \sqrt{\frac{L_1{}'}{C_1}}$$

Balanced condition for 50 Ohm impedance matching: $50\ Ohm = \rho Q = w\frac{L_1{}'^{\frac{3}{2}}}{\sqrt{C_1 R''}}$

$$w\frac{L_1{}'^{\frac{3}{2}}}{\sqrt{C_1 R''}} = \frac{\left(L1 - \frac{1}{w^2 \boxed{C_2}}\right)}{\boxed{C_1}\left(R + \frac{\left(w \boxed{k} \sqrt{L_1 L_2}\right)}{2R}\right)}$$

Tunable elements