Physically-Based Distributed Models for Multi-Layer Ceramic Capacitors

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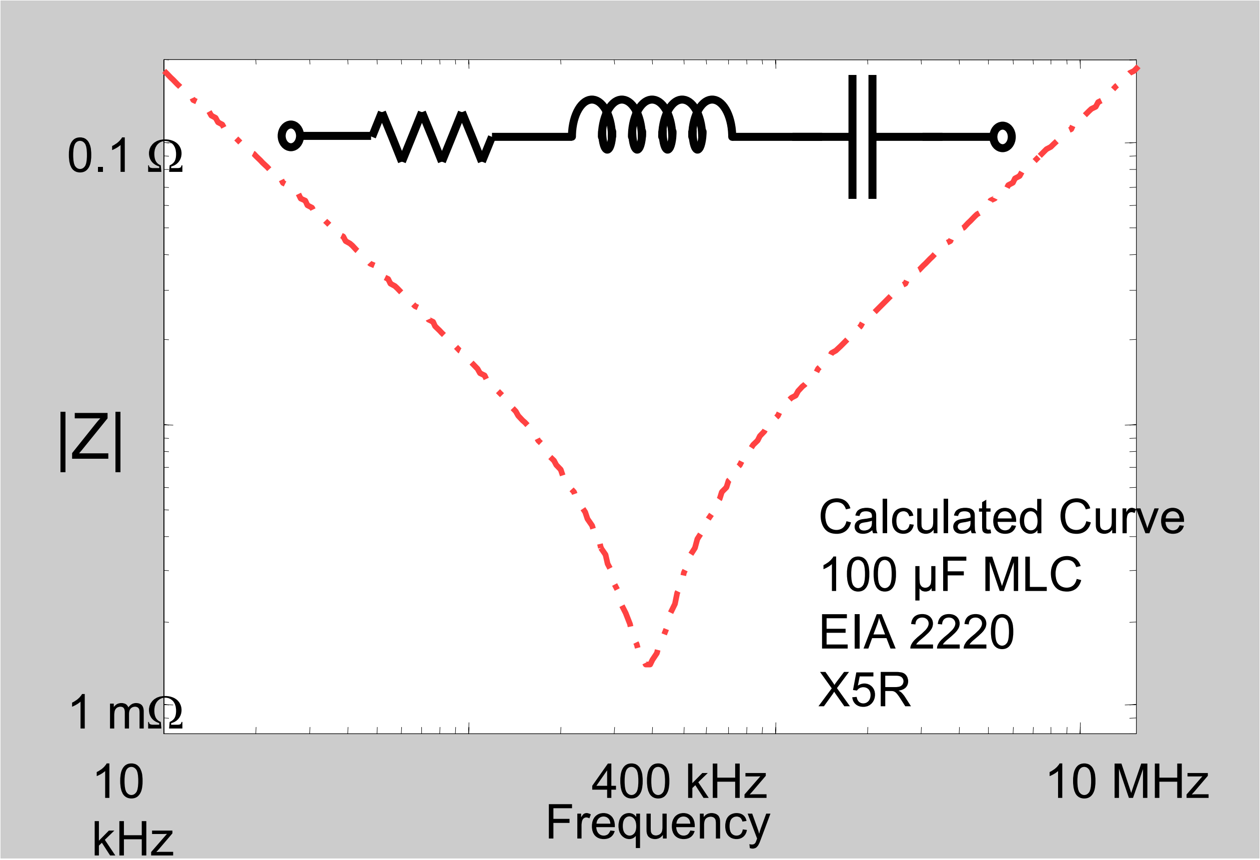
Introduction

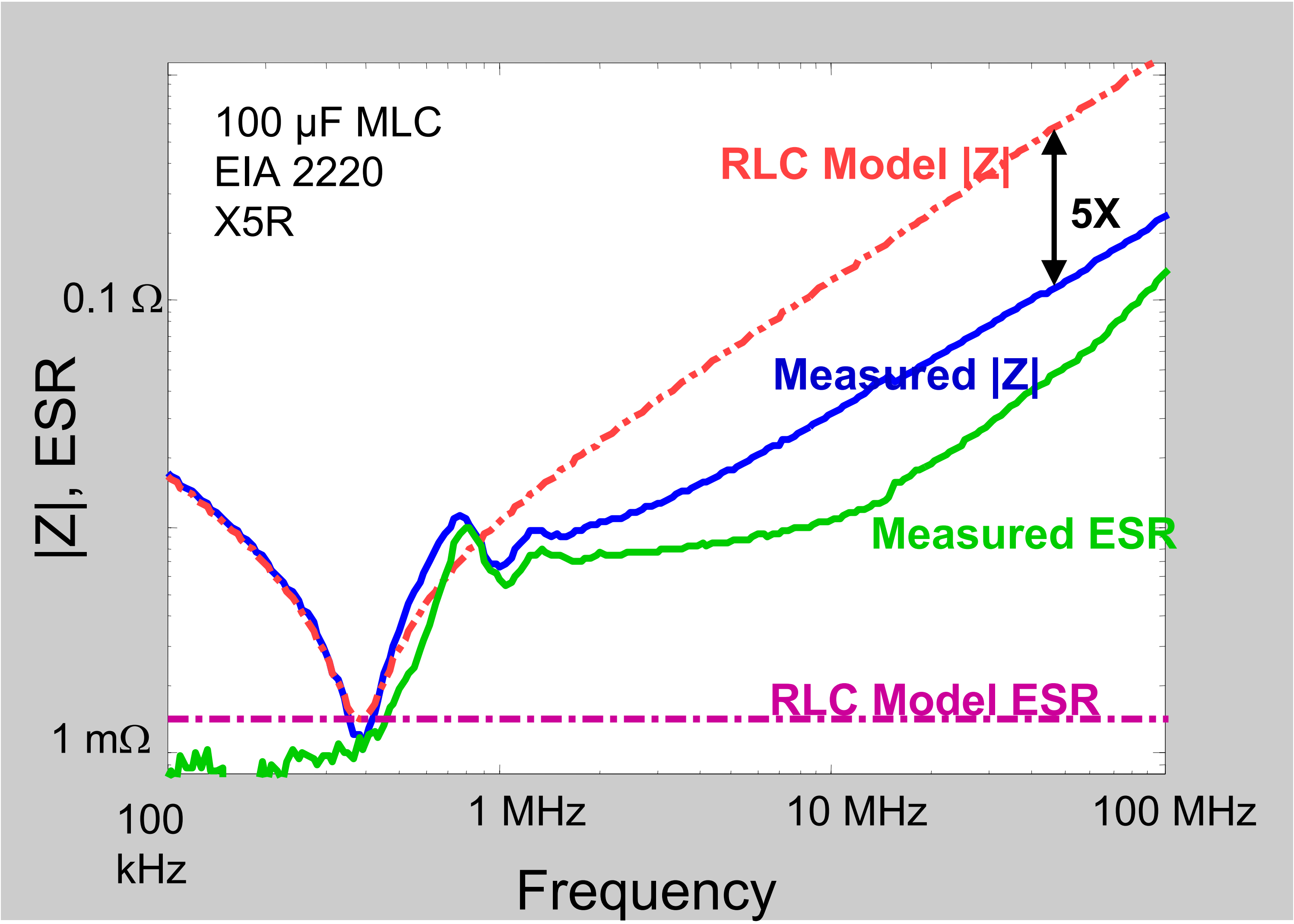
Why an RLC model won’t do.

Standard RLC Model for a Cap

- Simple but not accurate
  (as much as 5X impedance error).

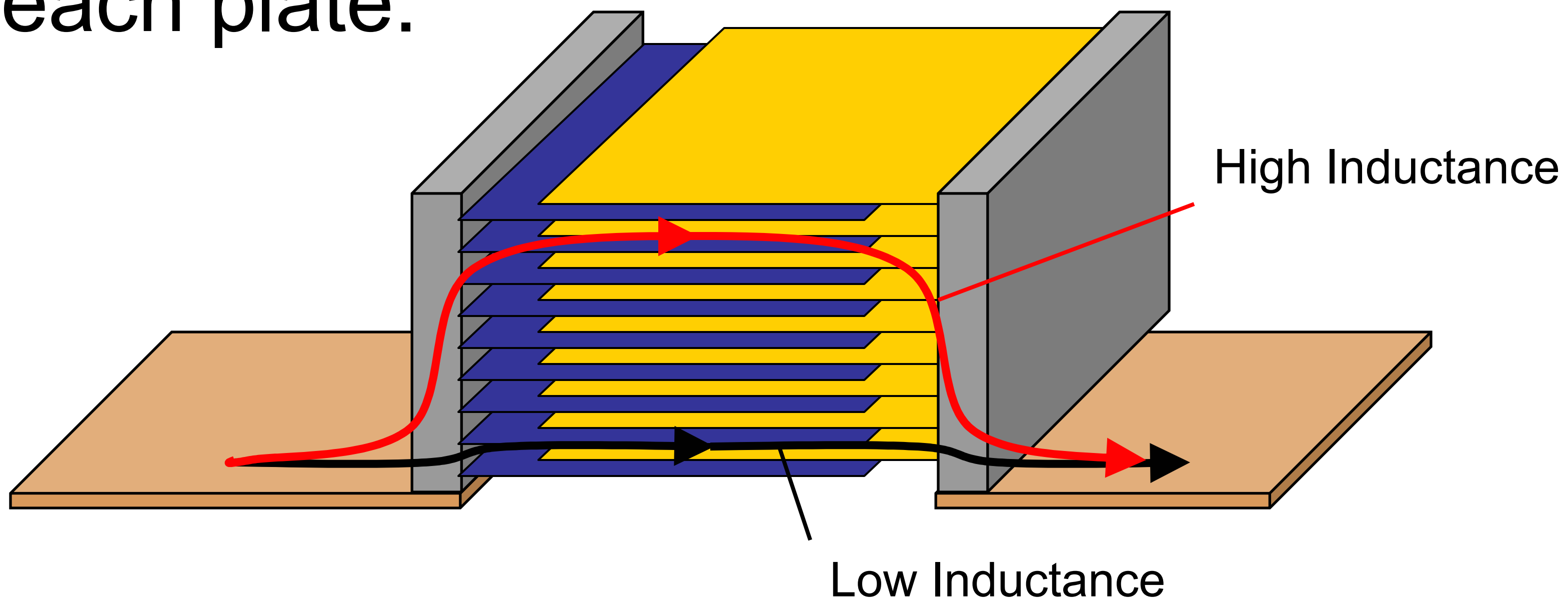


Measurements vs. RLC Model



What's Going On?

- Inductance is distributed effect; different for each plate.

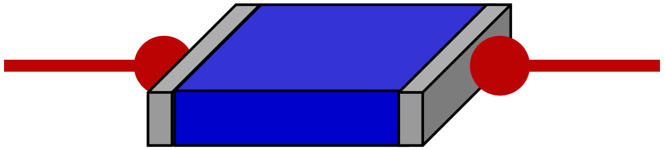


- Behavior is like a transmission line.

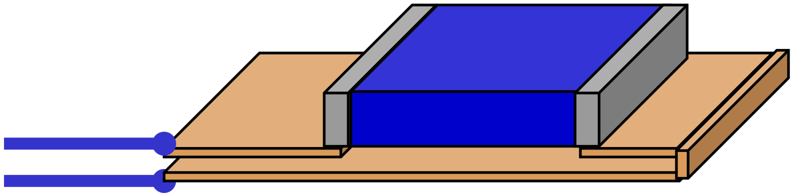
Measurements

What to Measure

- Need to be sure measurement technique captures real in-circuit behavior.
- Inductance is only defined for a closed loop.



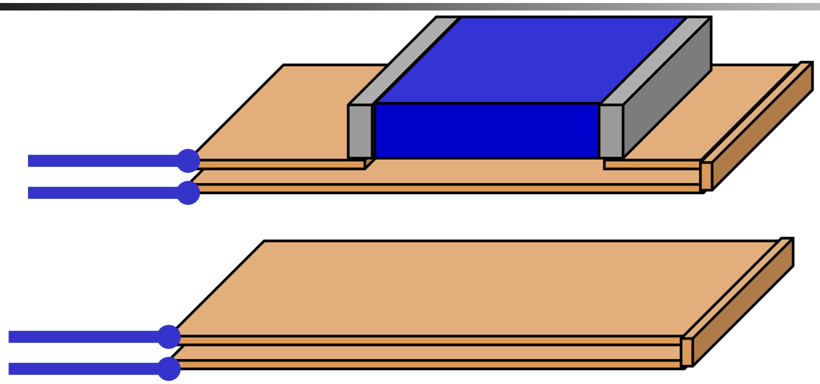
Z undefined



Z defined…..

But includes some *Z* interconnect!

Defining Impedance



Z_{total}

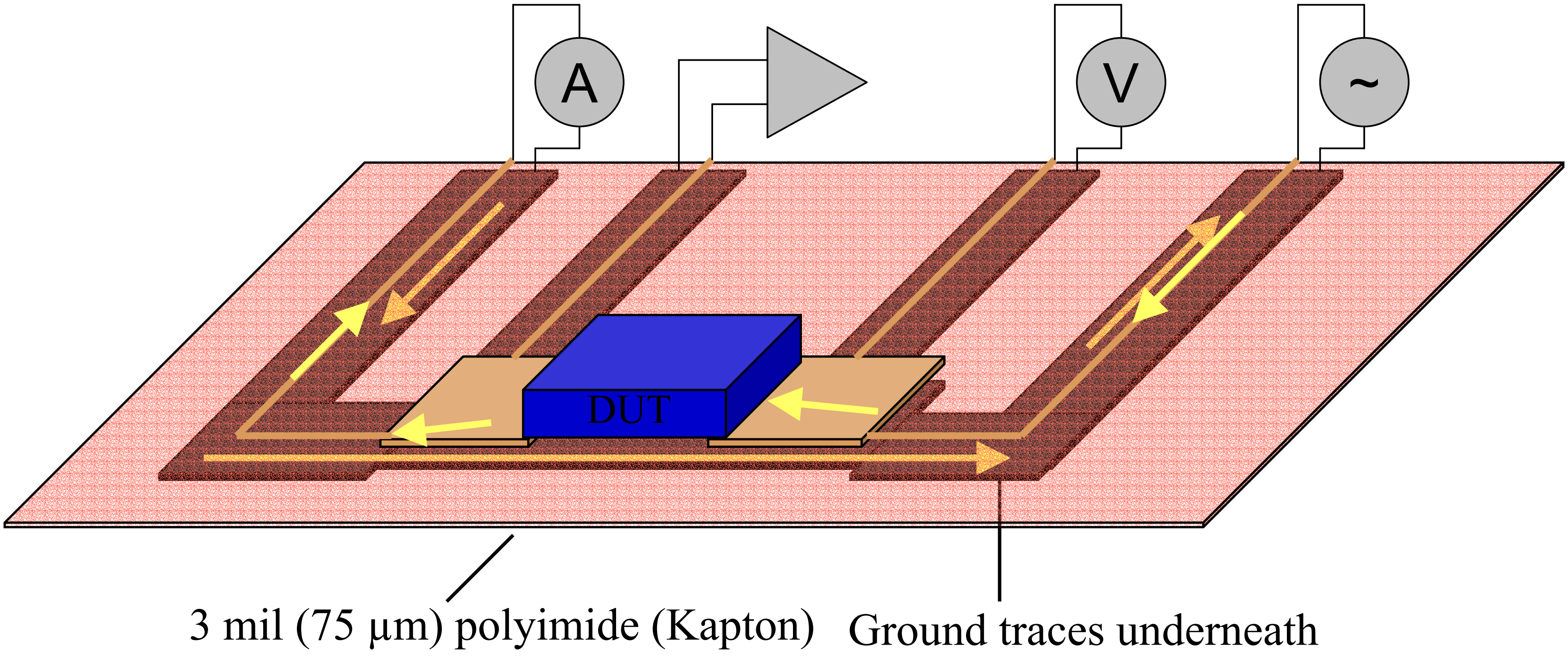
Z_{board}

$$Z_{cap} = Z_{total} - Z_{board}$$

- The relevant impedance for application with adjacent ground plane.
- Same inductance as Z_{total} with zero board thickness.
- Can correct for resistance.
- How to measure: pH accuracy test fixture:
Session 35, paper 2—here this afternoon.

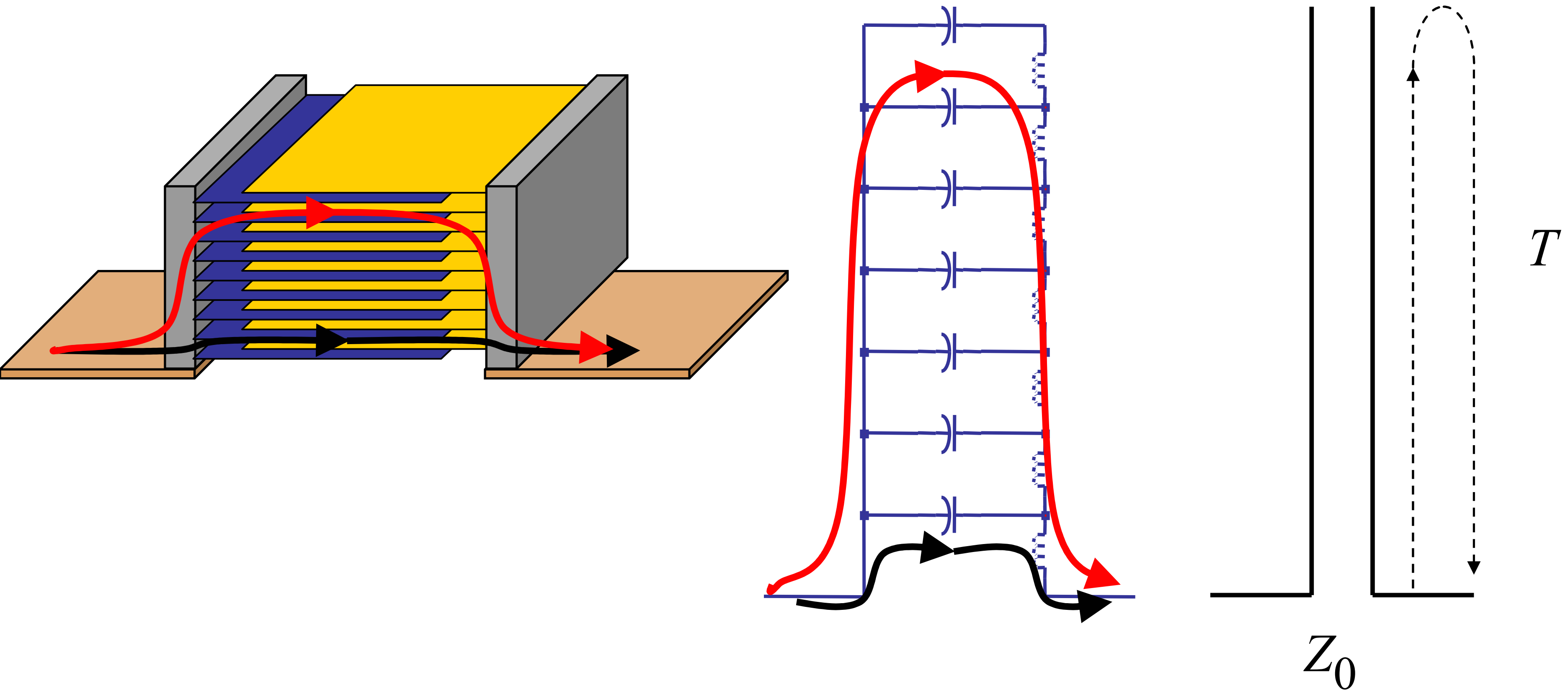
New Low-Impedance Test Fixture

- Based on Agilent 4TP (four terminal pair) configuration.
- Less than 100 pH stray inductance, ~3 pH repeatability



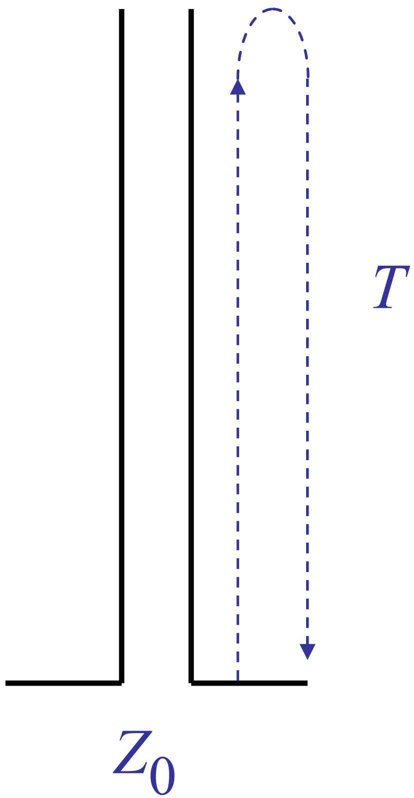
A Better Model

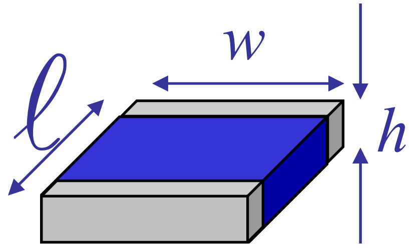
I. Simple Transmission Line Model



- Actual system: hundreds of plates.
- Model as continuous distributed transmission line.

Two Parameters Describe the Transmission Line Model





- Parameters linked to geometry.

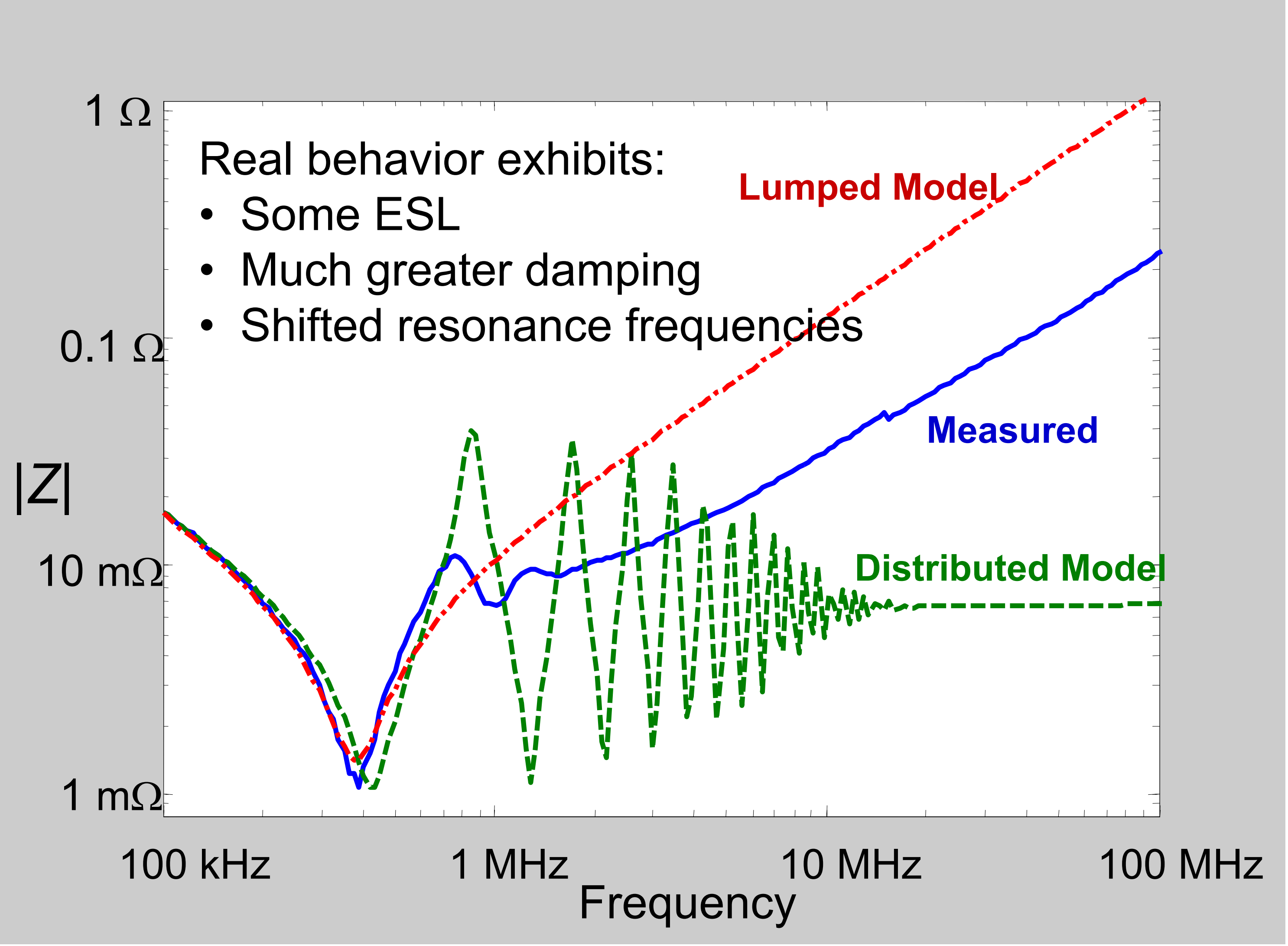
$$Z_0 = \frac{1}{w}\sqrt{\frac{\mu_0}{C_v}}$$

$$T = 2h\ell\sqrt{\mu_0 C_v}$$

where C_v is capacitance per unit volume.

Ideal Transmission-Line Behavior

Calculated from geometry and ESR



II. Improving the Model

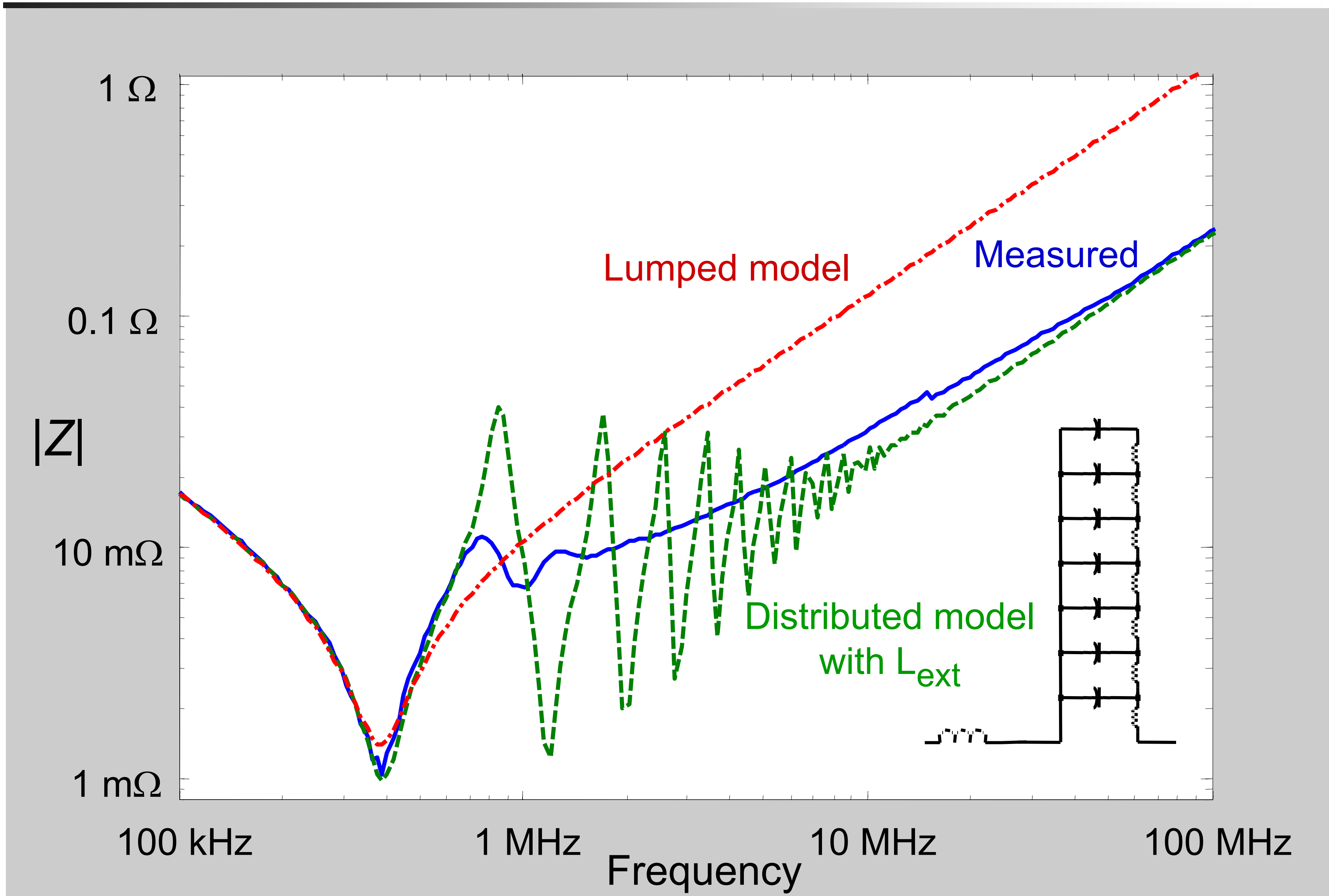
- External L: Models **Coating Effect**
- Damping:

  Real damping effects include:

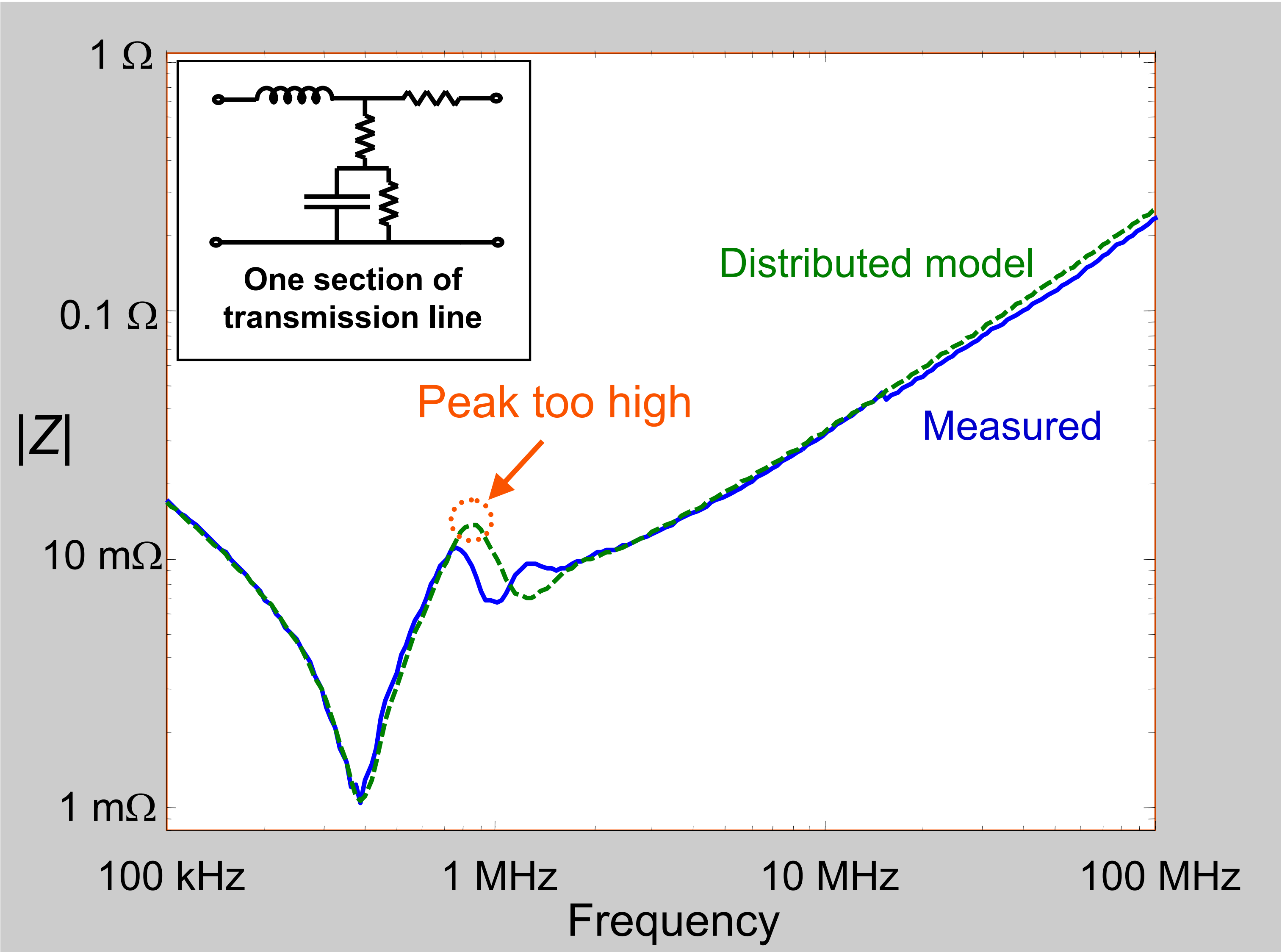
  - Series R of plates.
  - Eddy-current losses in plates.

  Must model both effects

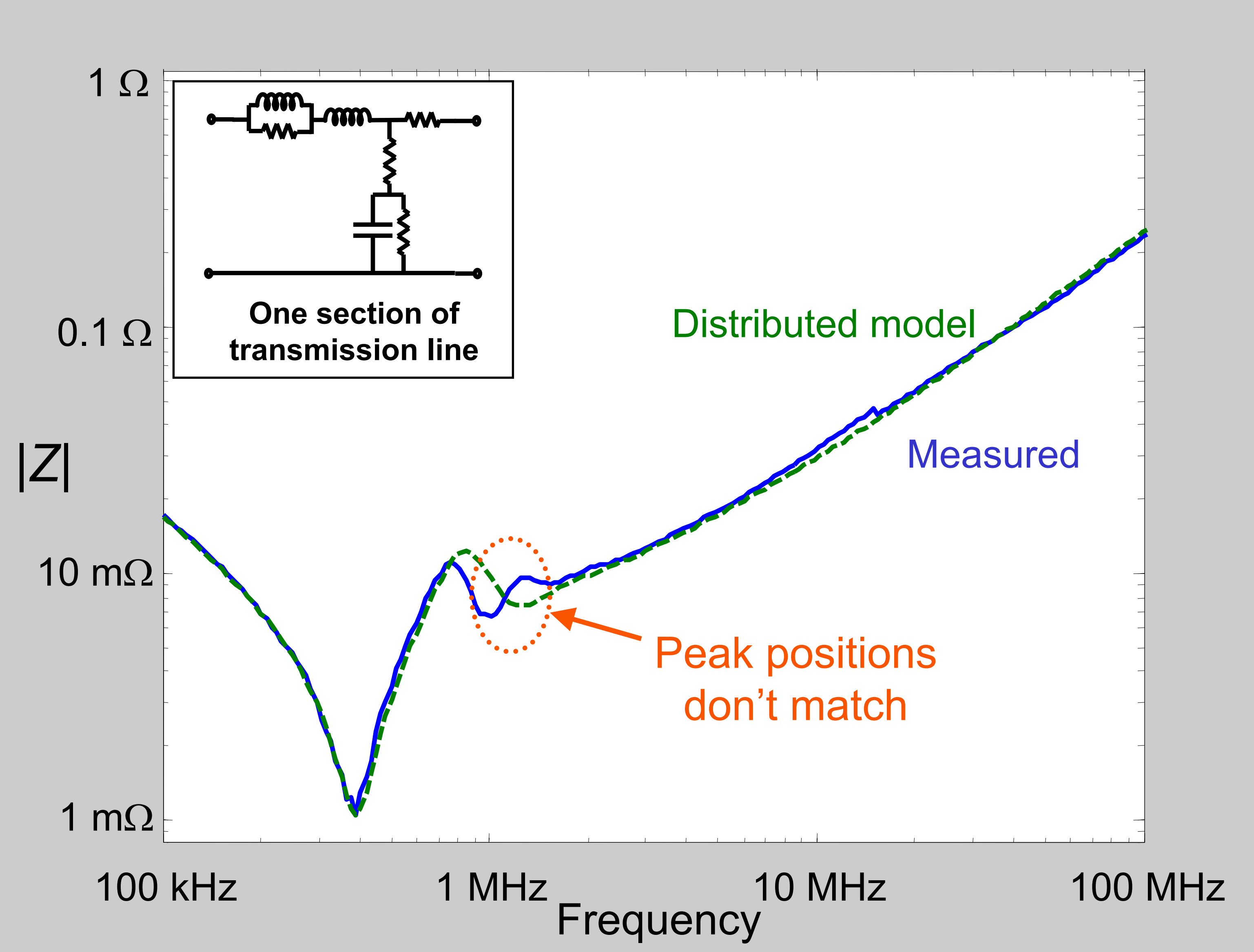
Distributed Model with Added External L



Model with Damping from Series R of Plates

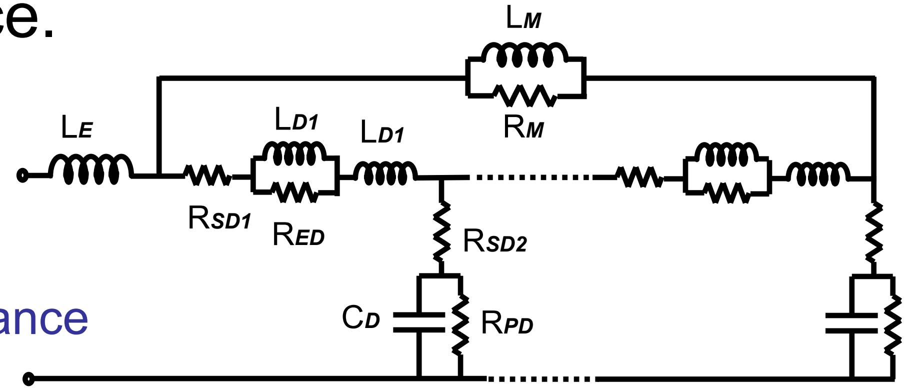


Add Effect of Eddy Currents in Plates



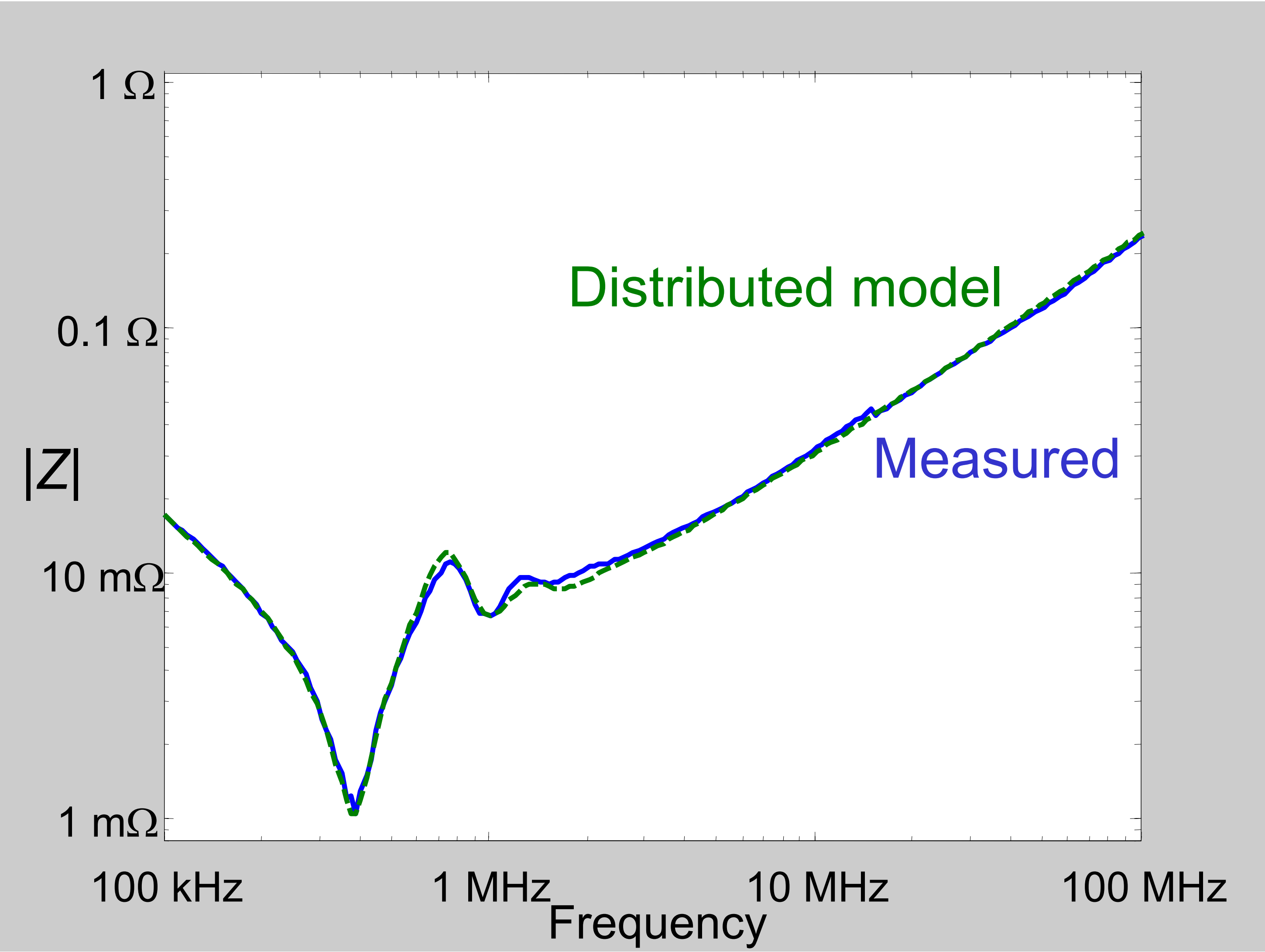
III. Final Model Improvements

- Damping model works OK by including
  - Series R of plates.
  - Eddy-current losses in plates.
- Last remaining discrepancy: non-uniform spacing of resonant peaks.
  - Two possible causes:
    - Non-uniform distributed inductance.
    - Mutual Inductance.



Model including mutual inductance

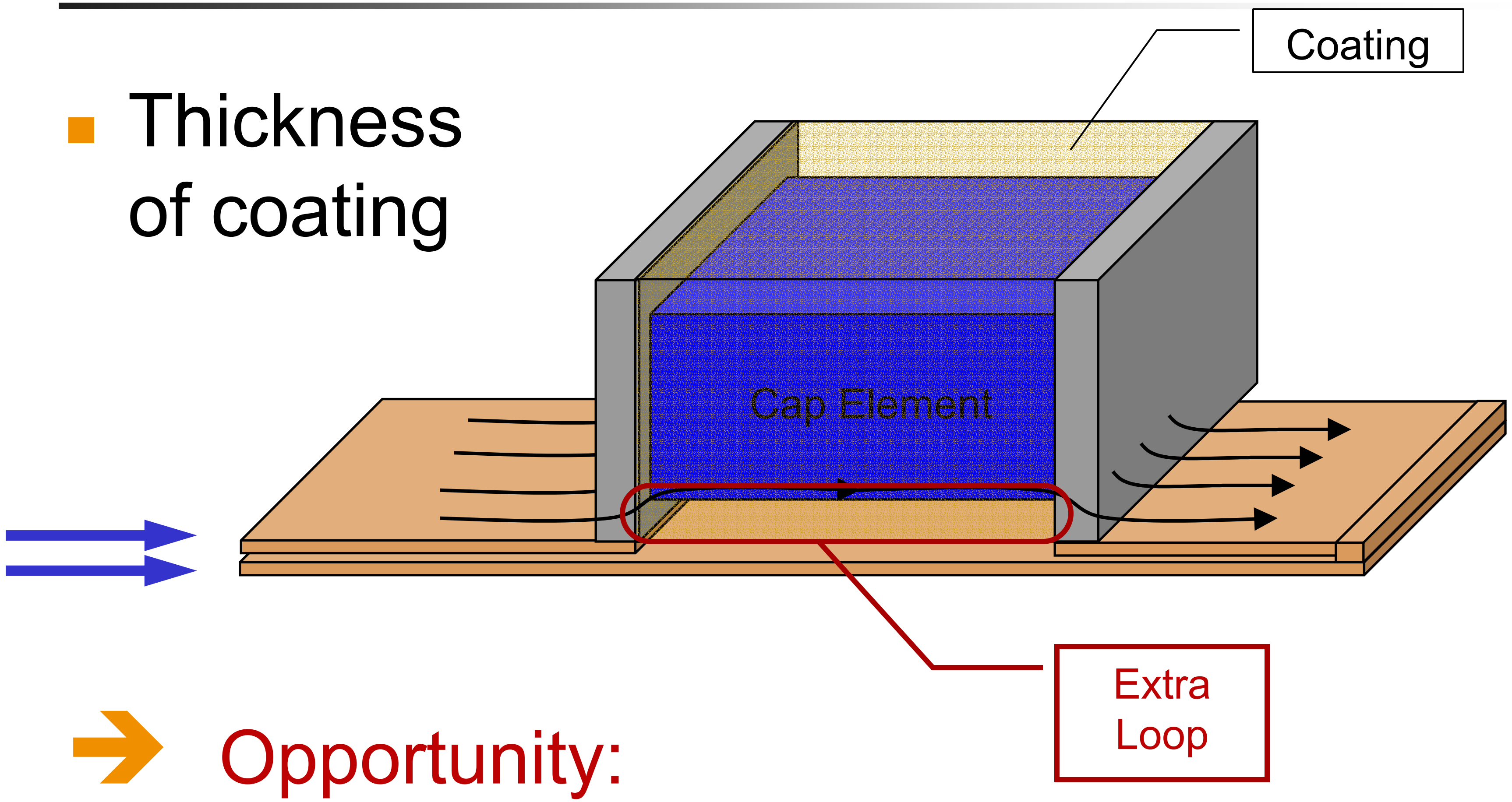
Model with Both Damping Effects and Non-Uniform Inductance



Coating Effect

Why Does Cap Have Extra Series L?

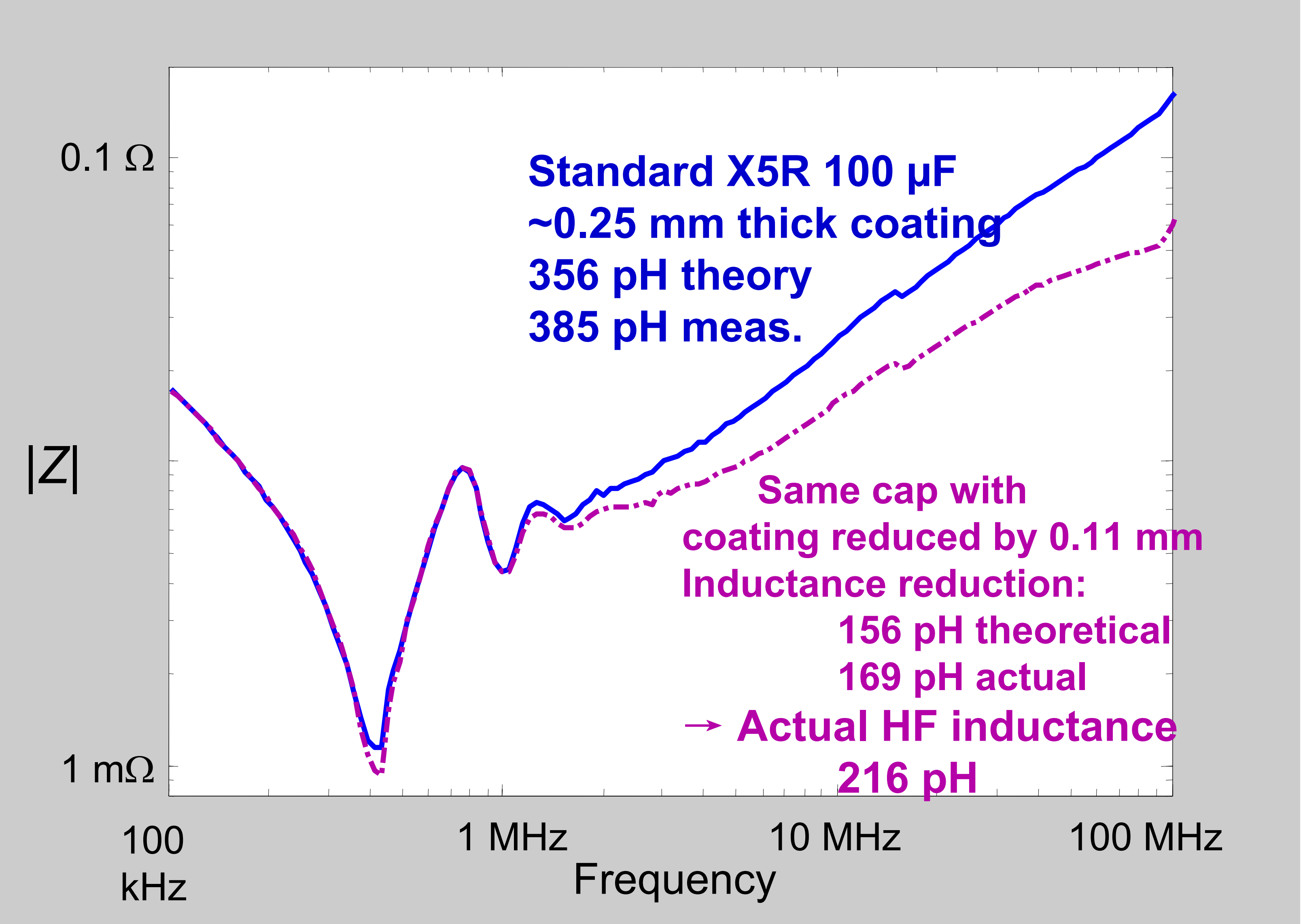
- Thickness of coating



➔ Opportunity:

Reduce coating thickness to reduce external L and HF |Z|

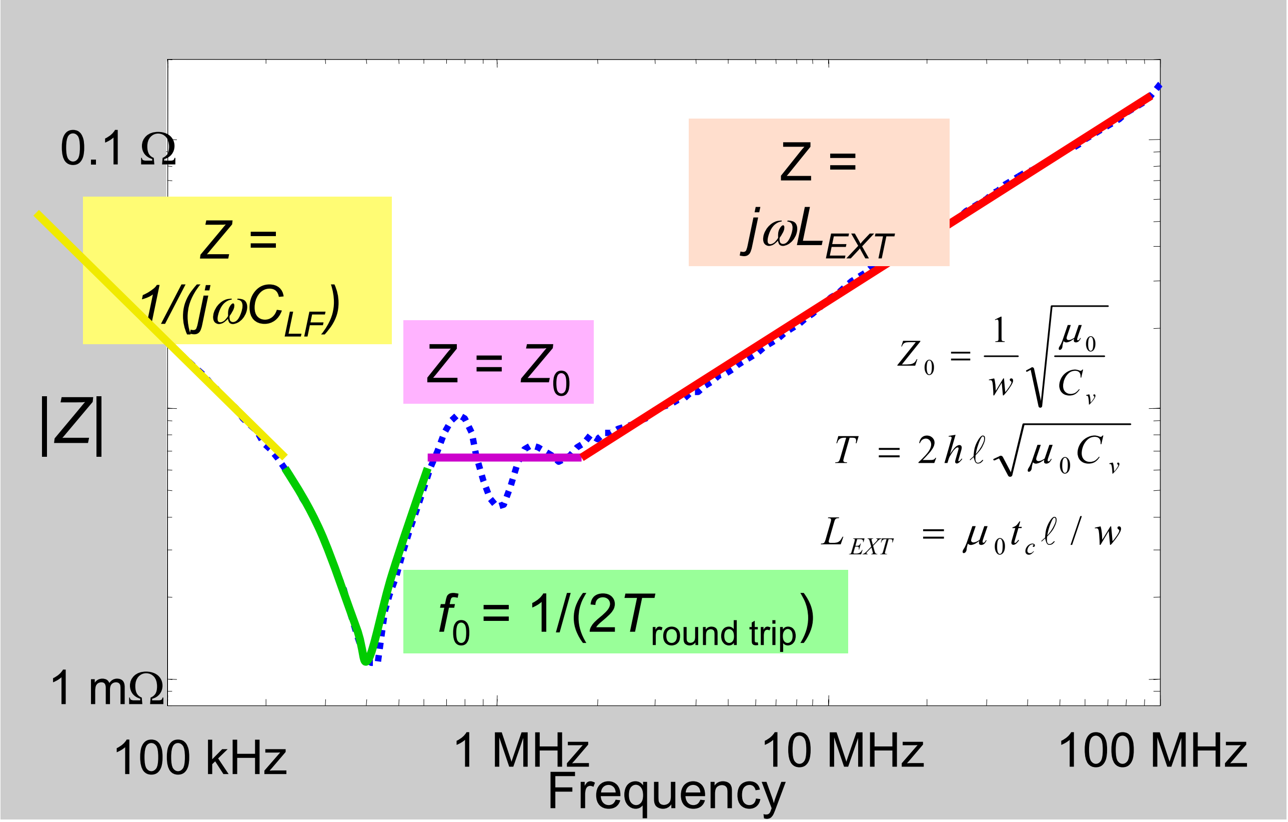
Measured Effect of Coating Thickness



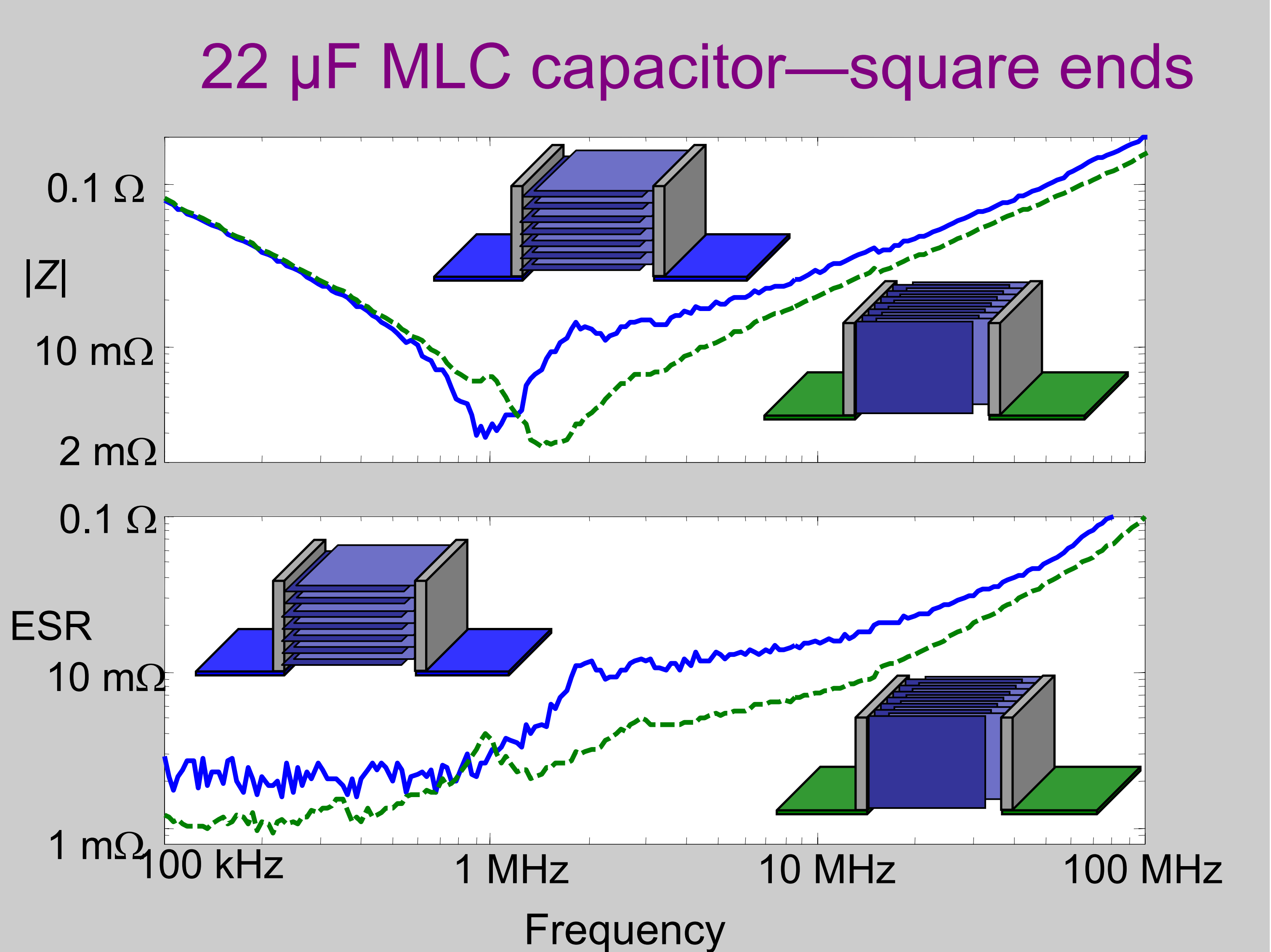
Observations

Simple Frequency Domain Model

- All parameters needed to sketch impedance can be simply calculated



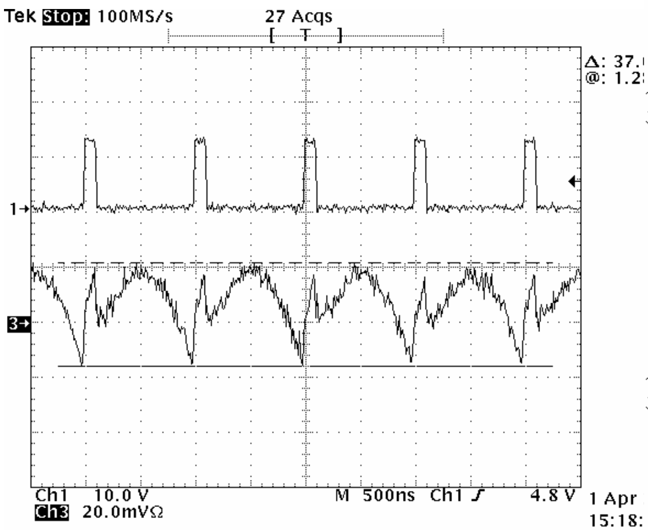
Effect of Plate Orientation



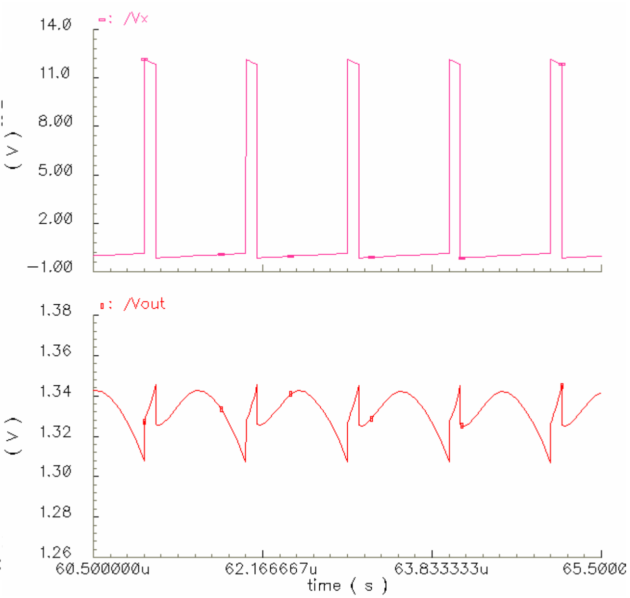
Application

DC-to-DC Converter Output Filter

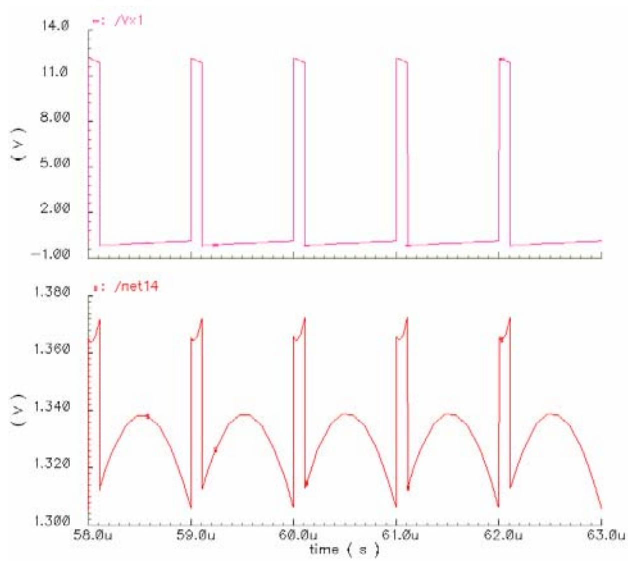
- PWM waveform and output voltage waveform.



Measured
ΔV=37.6mV



New model
ΔV=37.7mV



Lumped RLC model
ΔV=66.4mV

- 12 V to 1.2 V, 1 MHz buck converter with 2 x 22 µF caps
- Distributed model is much better than RLC model.

Conclusions

- MLC capacitors exhibit distributed behavior.
  - LRC model can have factor-of-five error.
  - Improved distributed model can
    - Fit measurements precisely.
    - Match observed in-circuit behavior.
  - Simple model is also useful conceptually.
    - Parameters are easily obtained from geometry.

- High-frequency impedance:
  - Dominated by L_{EXT}, due to coating thickness.
  - Reducing coating thickness can greatly reduce high-frequency impedance.