Developments Toward a Rapidly Tunable RF Cavity at FAR-TECH, Inc.

Presented by Jin-Soo Kim

Work Performed By: D. Newsham, X. Chang and J. Thompson

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US Patent #8508319

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Acknowledgement

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Andy Sessler – LBNL
Dejan Trbojevic – BNL

This problem was suggested to us by Dr. A. Sessler.

Motivation

Rapid-Cycling Accelerators (synchrotron, FFAG) have varying revolution times on successive orbits, requiring different accelerating cavity frequency for each cycle.

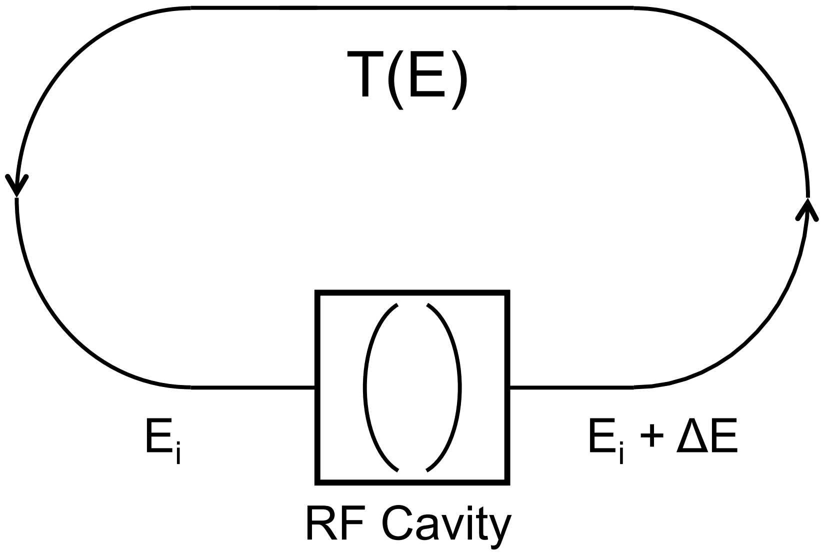
The short time required of adjusting the accelerating cavity frequency became a bottleneck for the development of such accelerators.

- **These revolution times can be as low as 100 ns**
- **Ferromagnetic (ferrite) tuning cannot adjust the frequency of the cavity rapidly enough**
- **Low Q solutions (magnetic alloy or high external Q) waste RF power**

Motivation - continued

- Ferroelectric material in accelerator applications have shown response times < 10ns
- FAR-TECH is developing a ferroelectric tuned cavity in the frequency range 375 – 400 MHz as a start.
- Potential uses include proton/C^{6+} ion cancer therapy and sub-critical reactors

The Problem in a Nutshell



Cartoon Schematic of a Generic Recirculating Accelerator

- **Want $\varphi_{rf}/2\pi$ to be an integer for on-crest acceleration**
- **For fixed frequency, this only happens if *f* is a harmonic of 1/T**
- **This makes fixed frequency acceleration difficult if T changes (which it does)**

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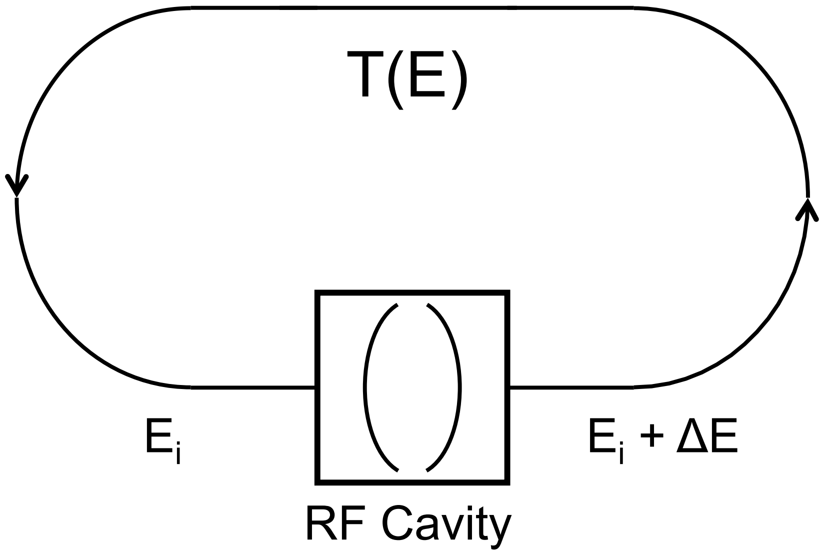


Cartoon Schematic of a Generic Recirculating Accelerator

- **Want $\varphi_{rf}/2\pi$ to be an integer for on-crest acceleration**
- **For fixed frequency, this only happens if *f* is a harmonic of 1/T**
- **This makes fixed frequency acceleration difficult if T changes (which it does)**
- **For *changing* frequency, adjust *f(t)* such that the phase change between crossings ($\varphi_{rf}/2\pi$) is an integer**
- **The time history of the frequency is just as important as the size of the change in frequency over the revolution**

$$\frac{\varphi_{rf}}{2\pi} = \int_{t_i}^{t_i+T} f(t)\, dt$$

Low Q vs. "Higher" Q RF Cavity

- **Low Q RF Cavity (Q ~ 2-500)**
  - **Wide resonance implies**
    - Stored RF energy is "dumped" between cavity crossings
    - Greater RF losses
    - Generally does not require active tuning
  - **Short fill time allows for replacement of RF power between cavity crossings**

- **"Higher" Q RF Cavity (Q > 1000)**
  - **Must be actively tuned**
  - **Narrow resonance implies lower RF losses**
  - **Stored energy is "conditioned" and remains in the cavity for many cycles**
  - **To maintain stable power levels, the RF power feed must be synchronous in both *frequency* and *phase* with the stored energy in the cavity**

Ferro*electrics* (FE) are the key

Ferroelectric materials change permittivity (ε) when exposed to a biasing electric field and can have low loss tangent

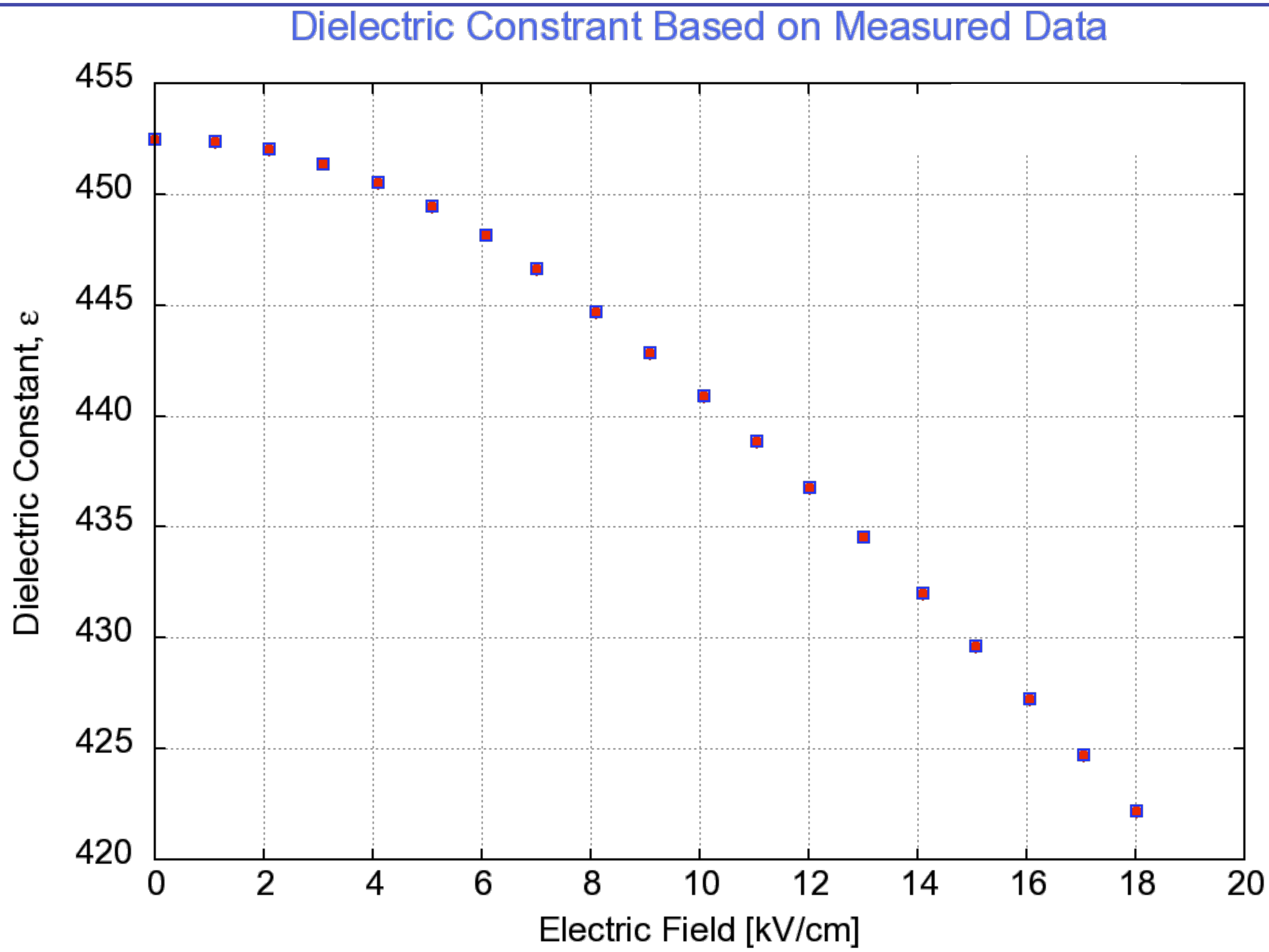
- **ε changes with changing *electric* field bias**
- **Base ε values between 75 and 800 are possible**
- **Low loss tangent does not mean low losses due to high ε**

  Loss ∝ ε tanδ
- **Material properties do not allow for high ε tuning and low loss tangent simultaneously**
- **Material response time < 10 ns (limit of manufacturer's testing)**

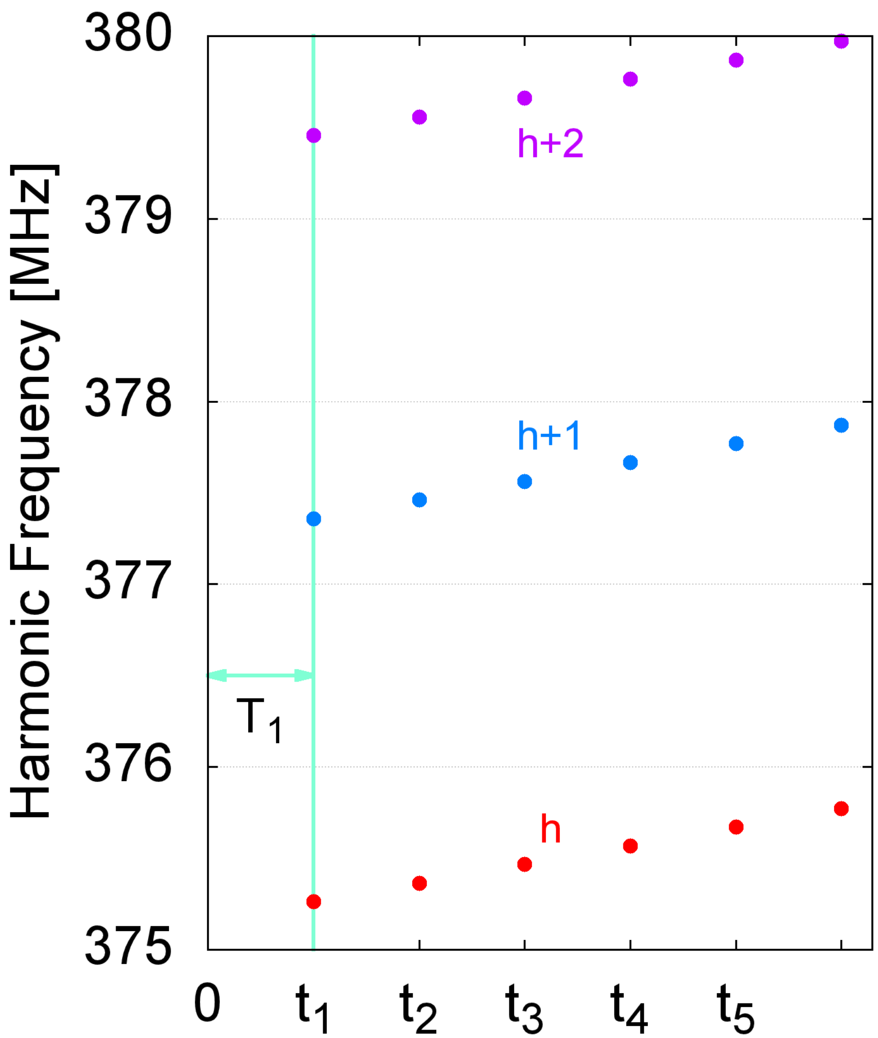
Ferro*electrics* (FE) are the key - continued

- Ferroelectric tuning is directly analogous with ferrite tuning
  - Permittivity (permeability) change results in a frequency shift
  - Strength of the effect is based on the fraction of electric (magnetic) RF field stored energy in the material.
  - Losses are associated with the stored energy in the material and the electric (magnetic) loss tangent
  - Heat mitigation is a primary concern
- The effect of a large change in the dielectric constant results in non-linear perturbation of the RF field patterns

Characteristics of Ferroelectric Material



Harmonic Number Ratcheting



Consider a case:
(h= harmonic number)

At $t=t_1$, orbit time is T_1

If h =100, $f_{100} = 100 / T_1$

If h =101, $f_{101} = 101 / T_1$

If h =102, $f_{102} = 102 / T_1$

At $t=t_2$, orbit time is T_2

If h =100, $f_{100} = 100 / T_2$

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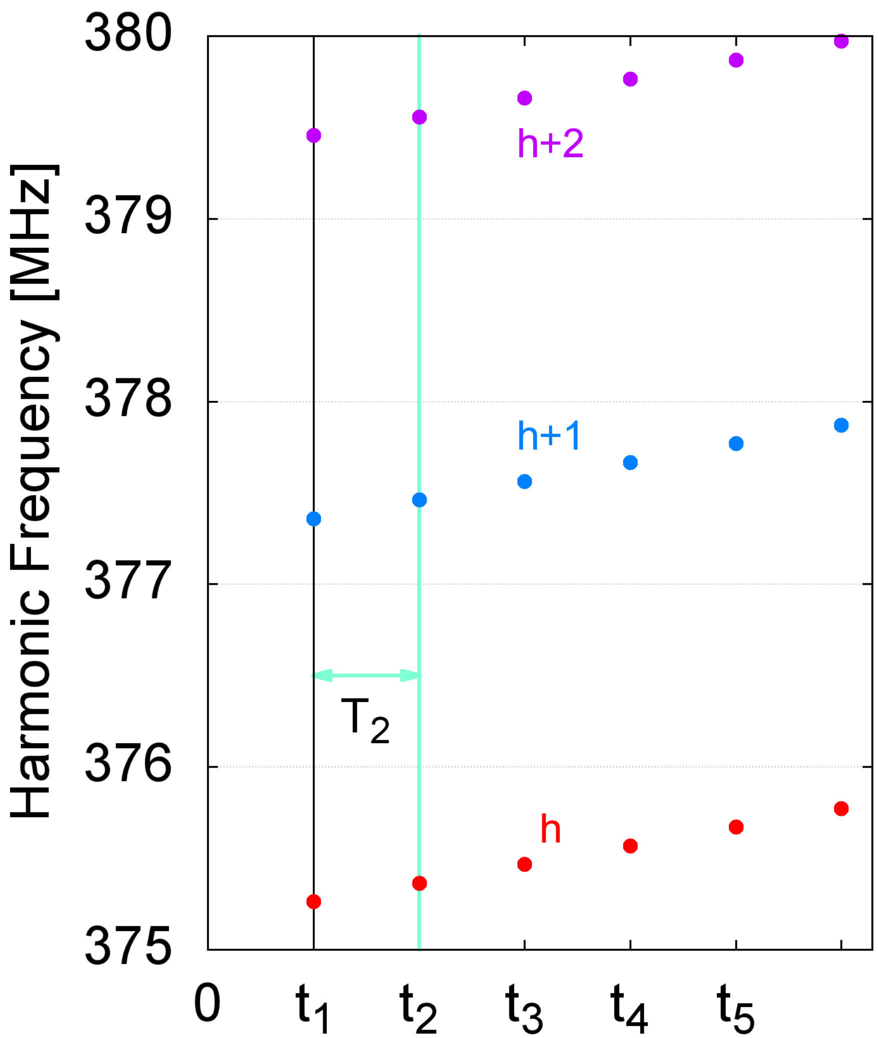

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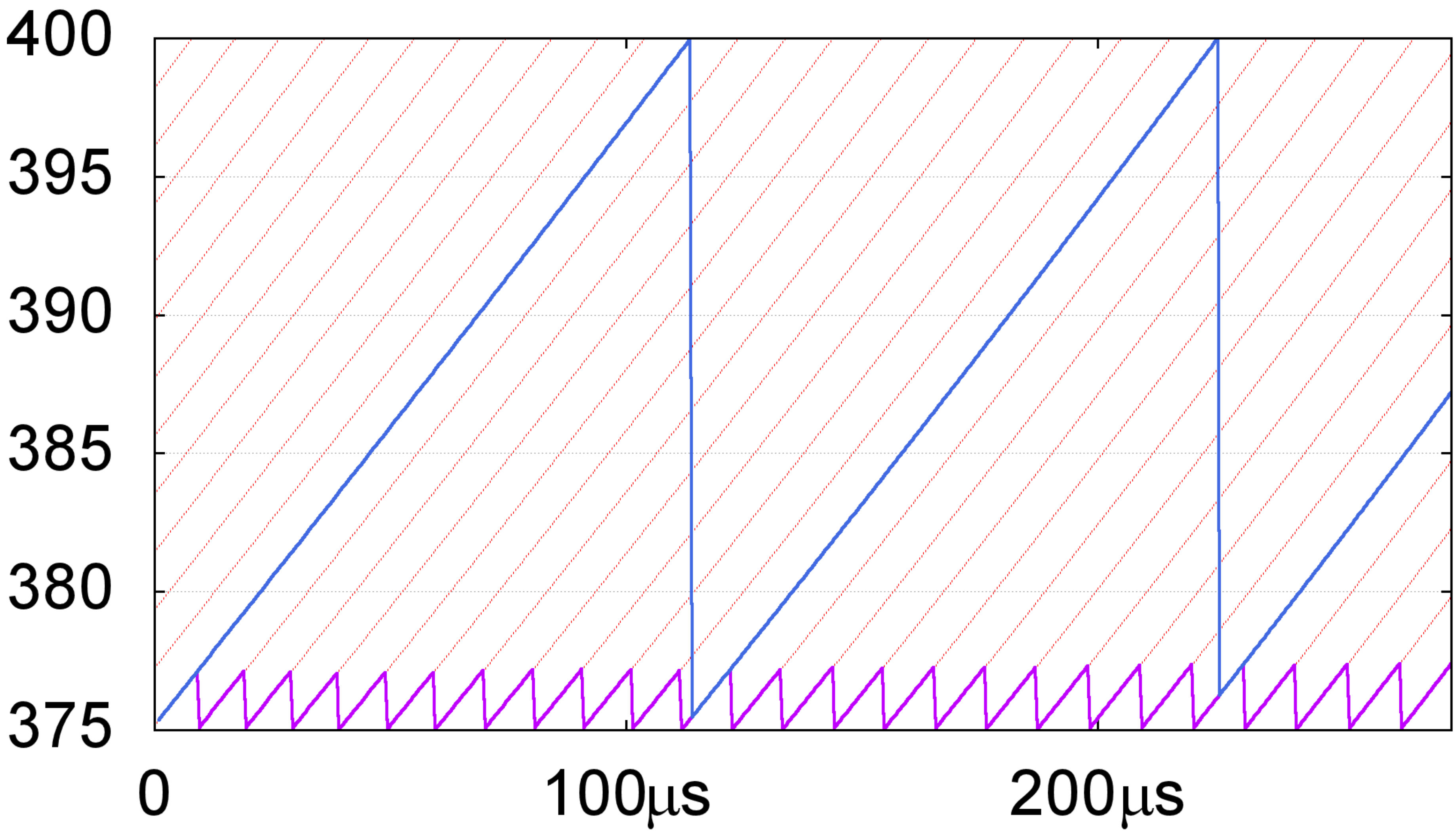
Harmonic Number Ratcheting - continued



A tunable cavity design by FAR-TECH, Inc.

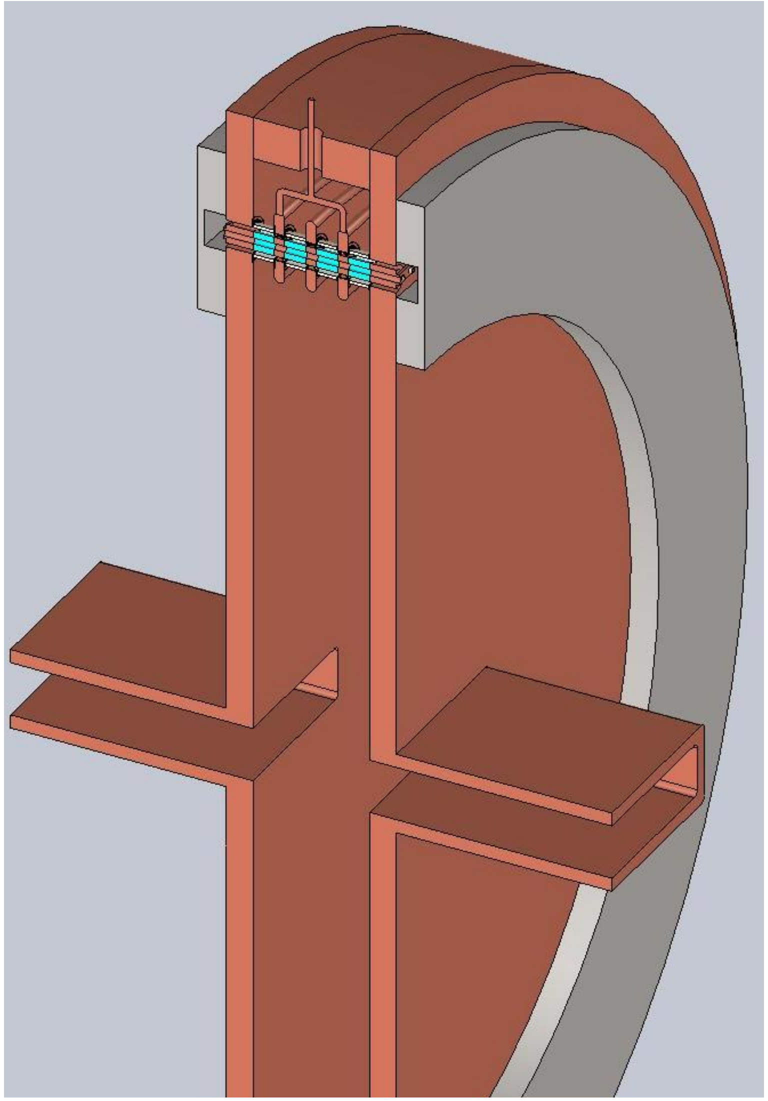
For $\Delta f_{full\ bias}$ = 25 MHz, the estimated (realistic) phase shift is **0.3π in 150 ns**

Cartridge is placed in low E_{RF} region

The biasing scheme requires careful considerations

- Bias is not DC
- Bias load is a capacitor, with stray and fixed inductance
- Without an energy conserving scheme, bias power loss could be as high as 1 MW

Cooled cartridge is separated from the cavity vacuum.



Tunable cavity design parameters

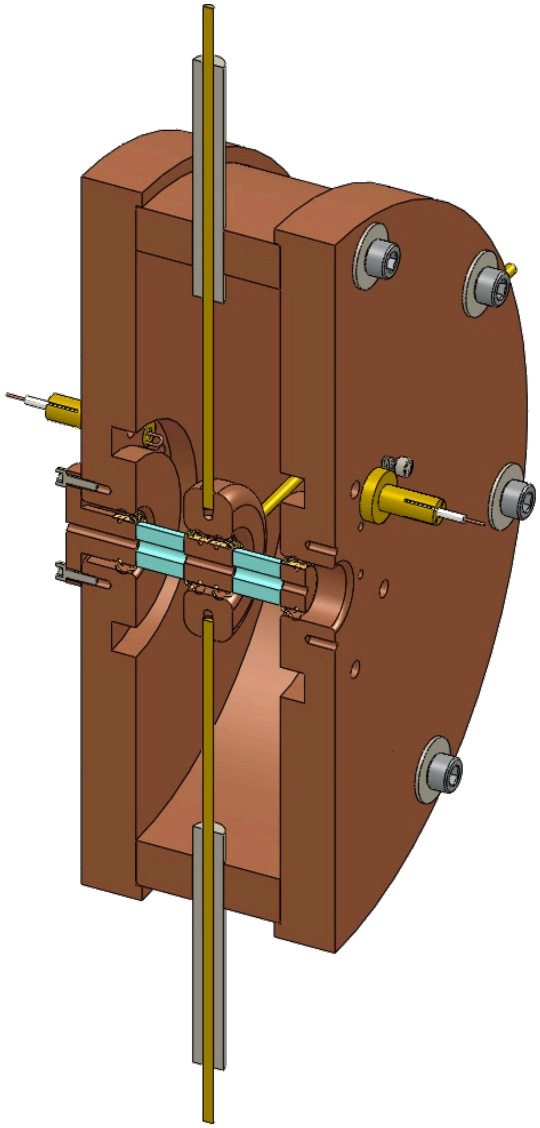
Property	Unbiased case	Biased case
Permittivity	ε = 450	ε = 322
Frequency (MHz)	376	400
Q-Factor	3970	5890
Copper Losses (W)	3640	2070
Ferroelectric Losses (W)	4200	1510
Total Losses (W)	7840	3580
Energy Gain (β = 0.4) (keV)	30	30
RF Energy Stored in Vacuum (mJ)	6.8	6.2
RF Energy Stored in Ferroelectric (mJ)	6.3	2.1
ZTT (MΩ/m)	0.57	1.26
r/Q (Ω)	29.0	42.7

For an unloaded pillbox cavity (no beam pipe) of the same radius:

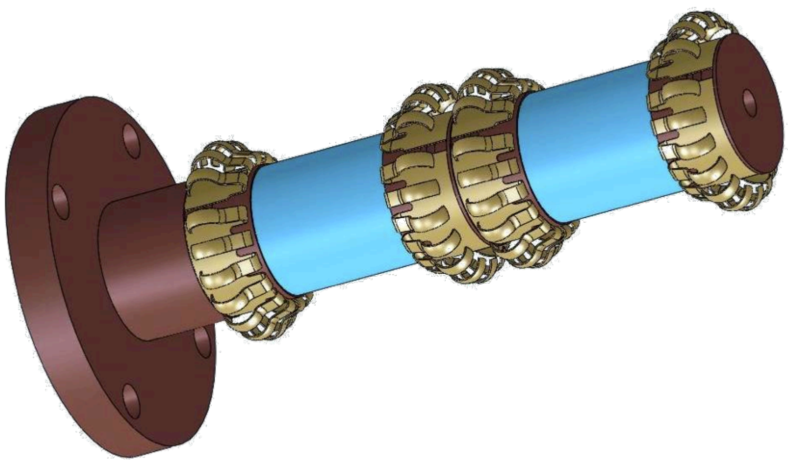
f = 428.9 MHz

Q = 22800

Cold Test Cell for Basic Verification Studies



- Placed the cartridge in center
- Test construction details
  - Contact spring
  - Solder joints
  - Test FE coating technique
- Cavity Q measurements



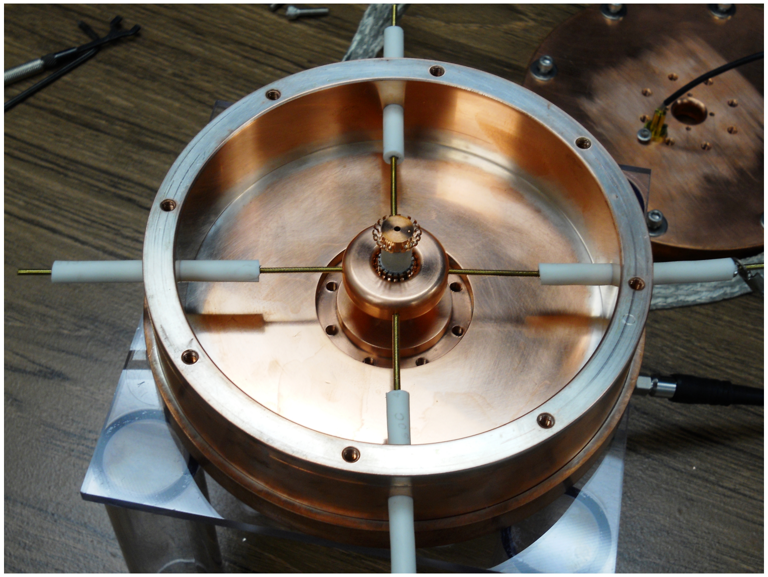
Cold Test Without Cartridge

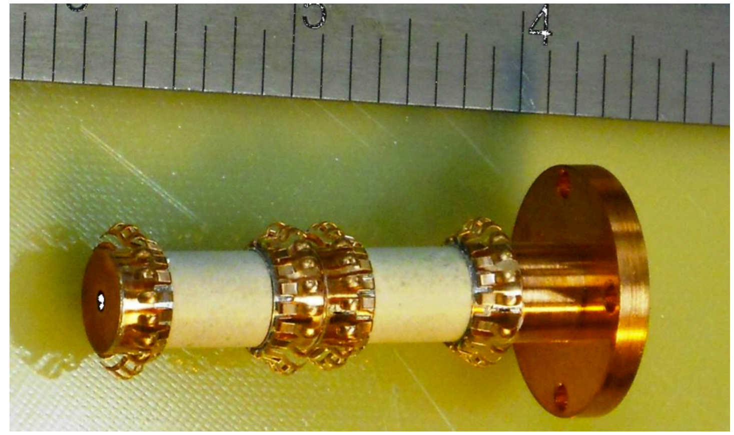
	Fundamental	Quadrupol e
f_{meas} (MHz)	1809.3	3830.1
f_{HFSS} (MHz)	1809.6	3834.6
Q_{meas}	10800	14700
Q_{HFSS}	12820	18008

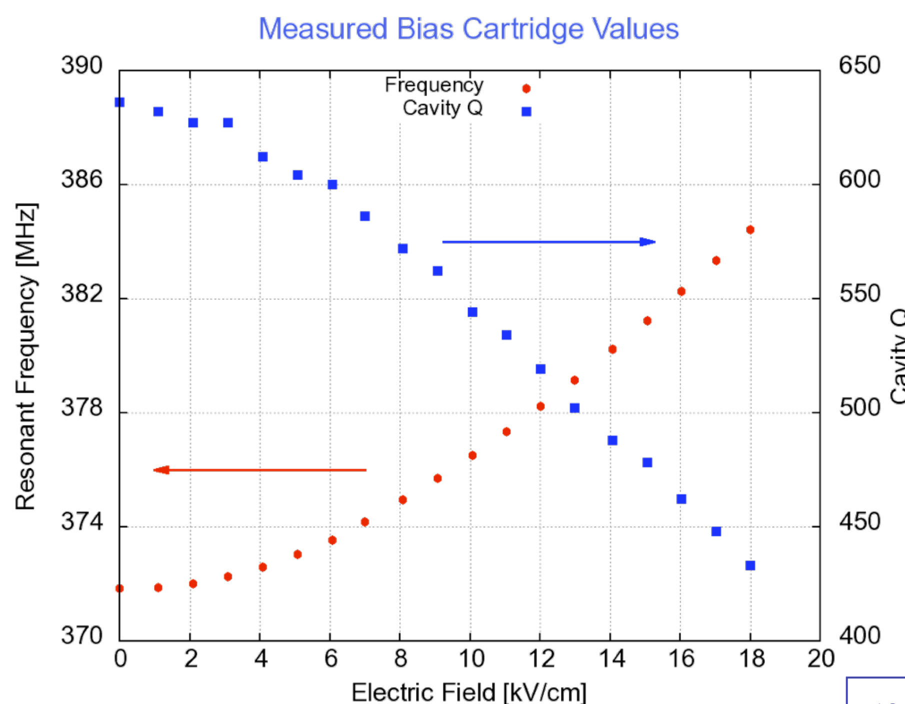
Due to joint resistance in bolted cavity

~375 MHz w cartridge

Cartridge Cold Test with Network Analyzer

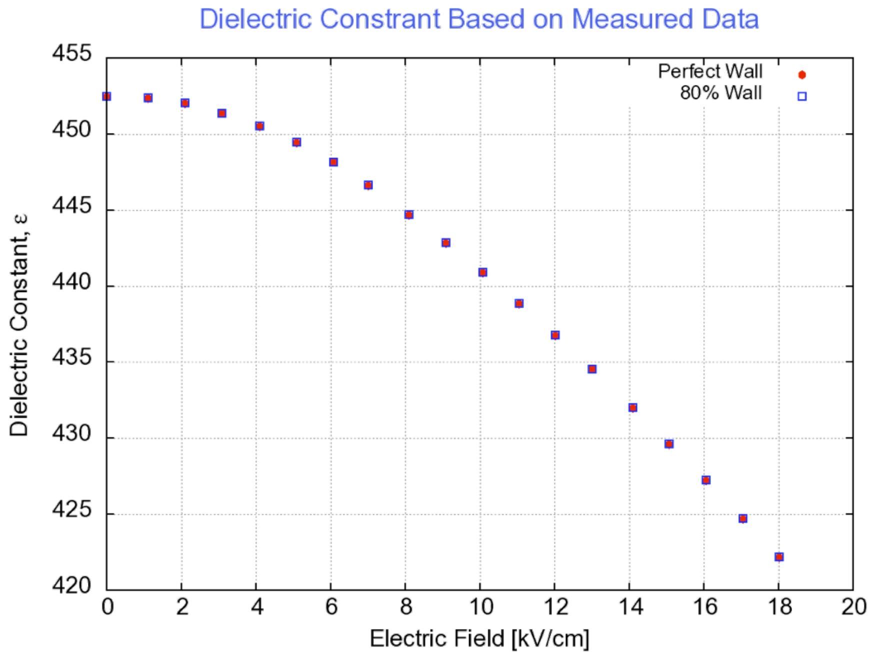


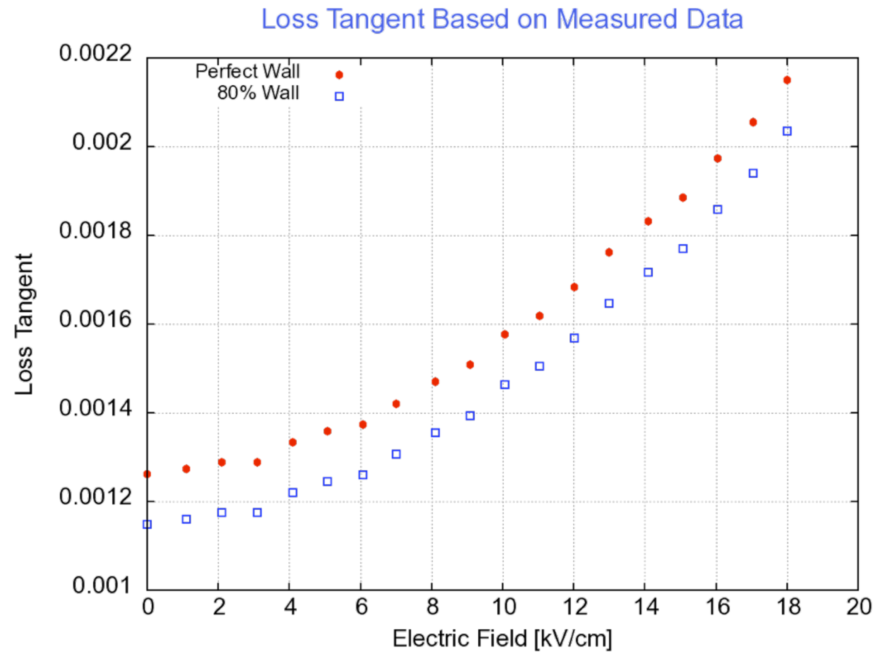




- **Transformer oil needed inside tube to reduce arcing**
- **DC electric field bias inferred from voltage and 1cm FE length**

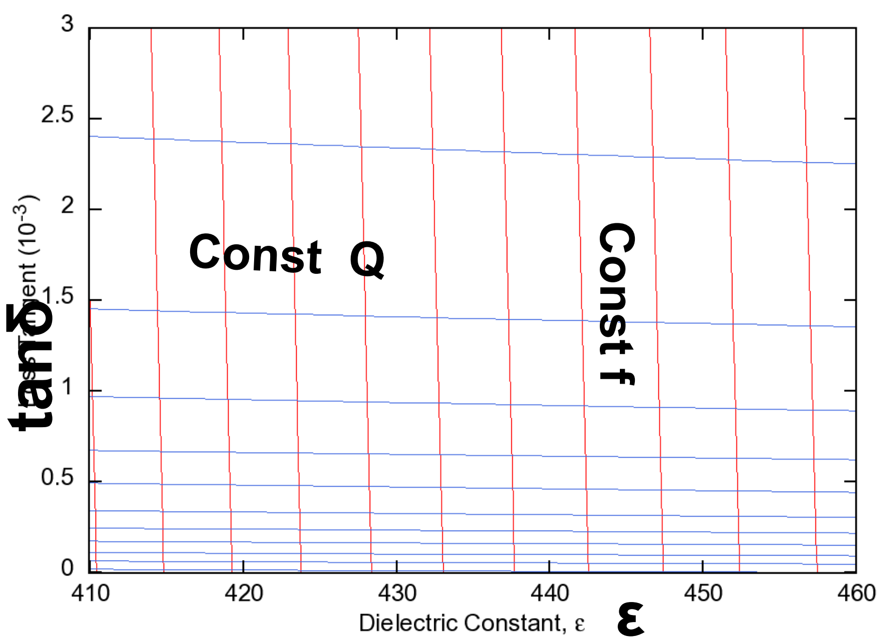
ε and tanδ from Cold Test Data

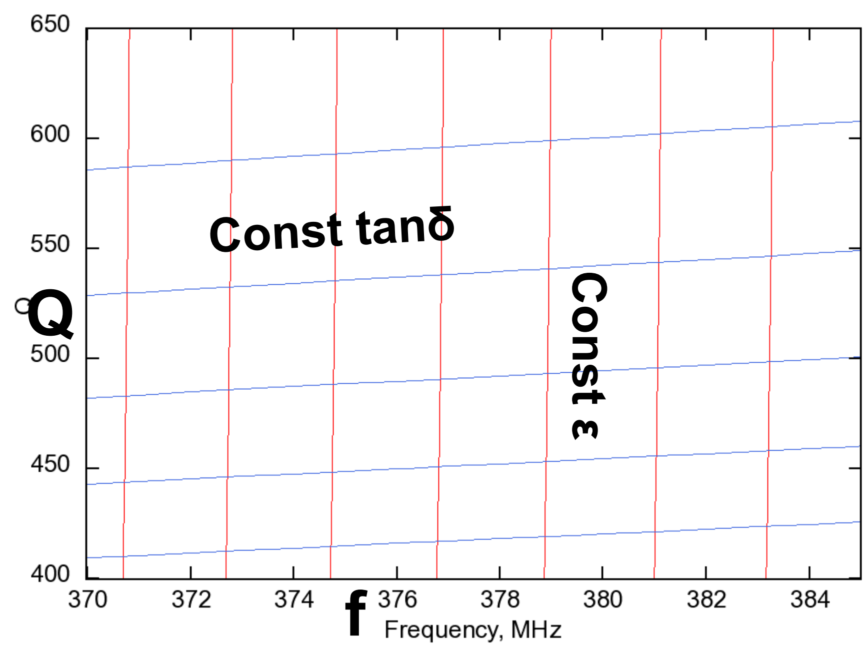




- **FE losses from tanδ only – termination effects folded into bulk losses**
- **HFSS simulations to determine (f,Q) from (ε, tanδ)**
- **$Q = Q_{wall} \,||\, Q_{FE}$**
  - **Reduction of Q_{wall} to 80% HFSS value to account for contact losses**
- **Use simulation data to determine (ε, tanδ) from measured (f,Q) – cubic spline interpolation**

ε and tanδ from Cold Test Data





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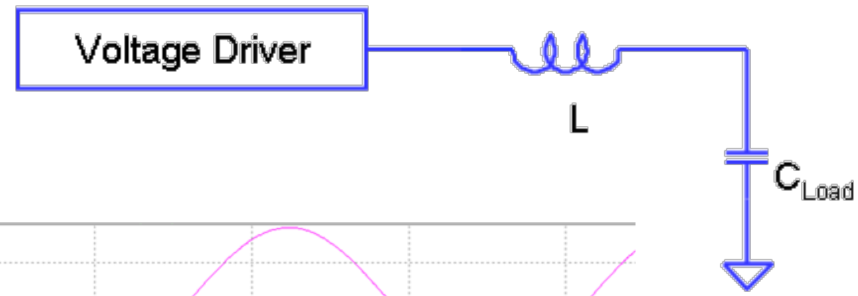
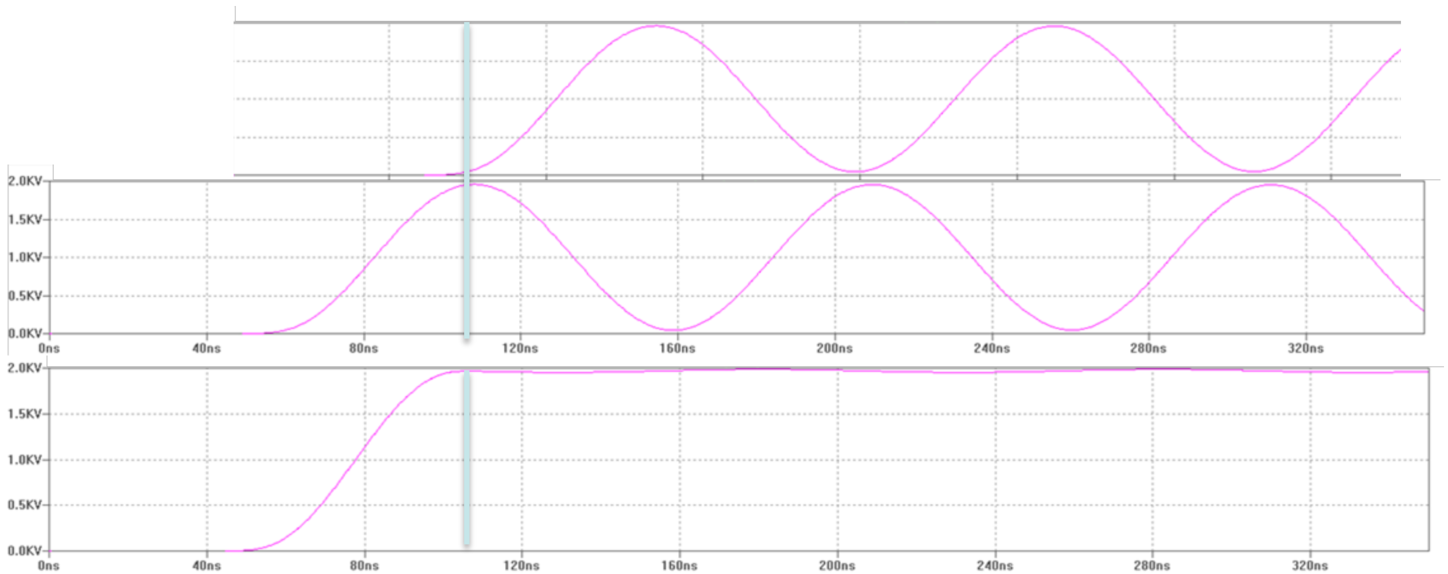
Biasing the Cartridge

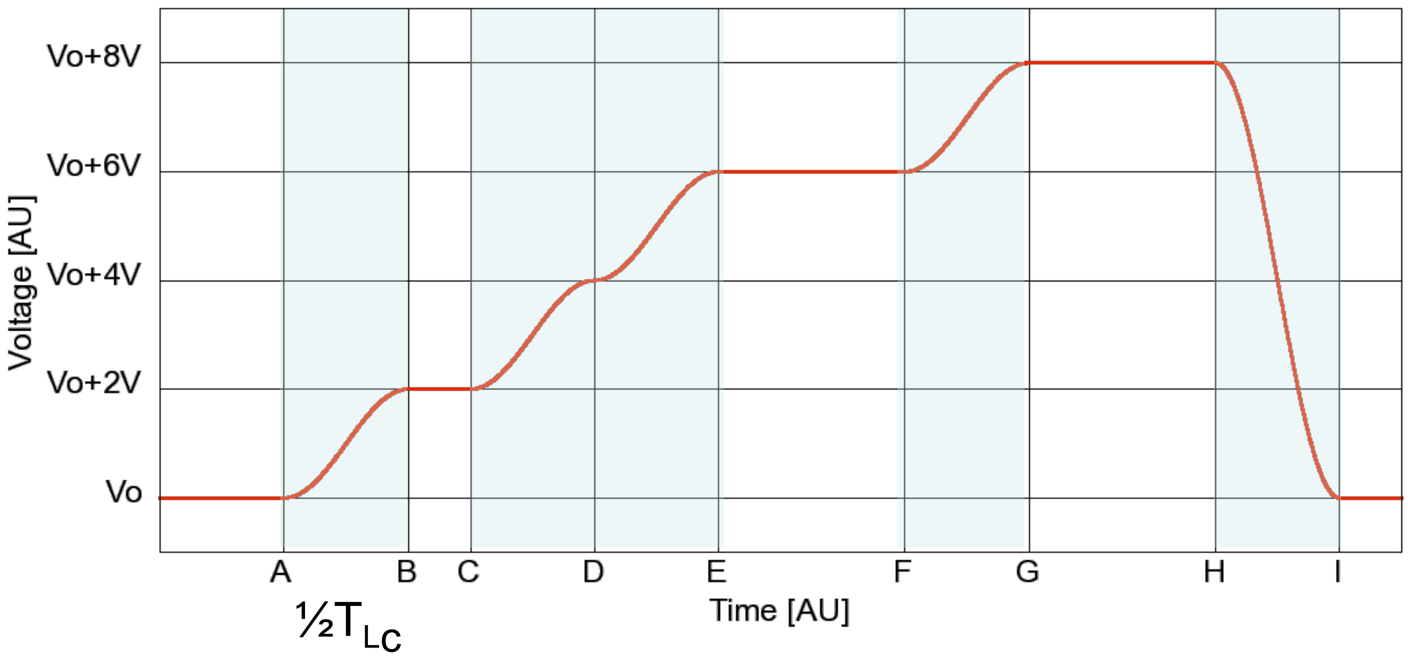
- **A scenario:**





t=0 t=½T_{LC}

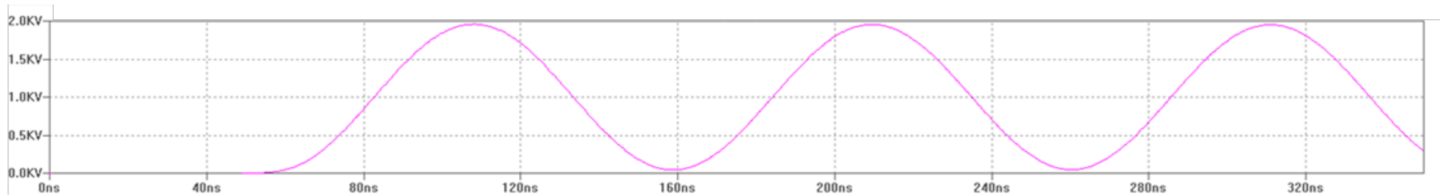
A Scenario of Voltage Ramp on C_{Load}



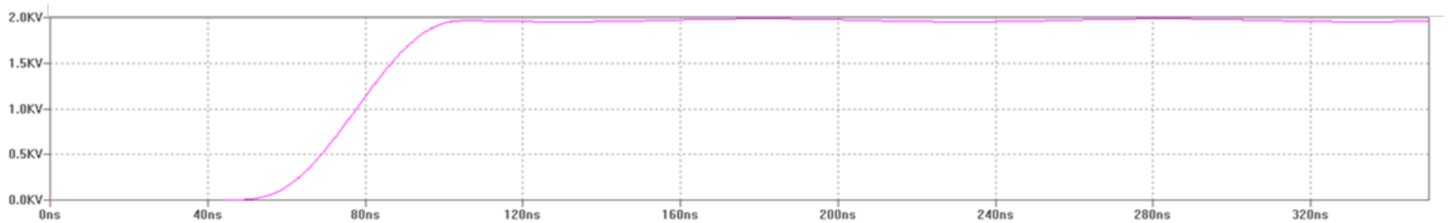
Scenario with 4-voltage sources
Delay between (dis)charge and park (shaded) is ½T_{LC}
Arbitrary delay between park and next (dis)charge

Spice Simulation – Results

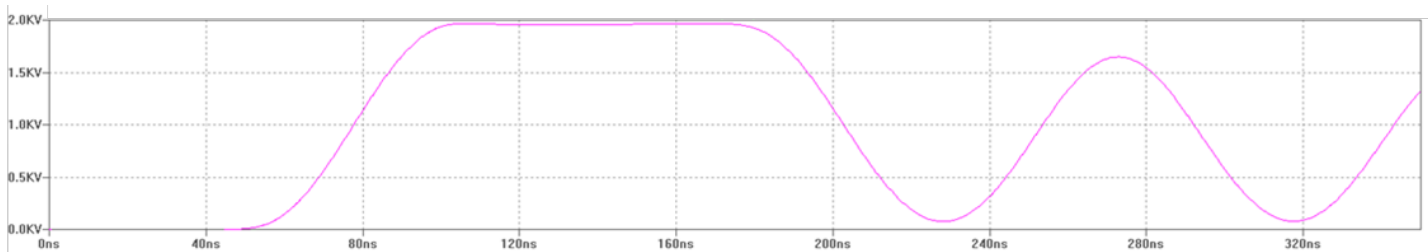
Charge
Open #1 & #3
Close #2



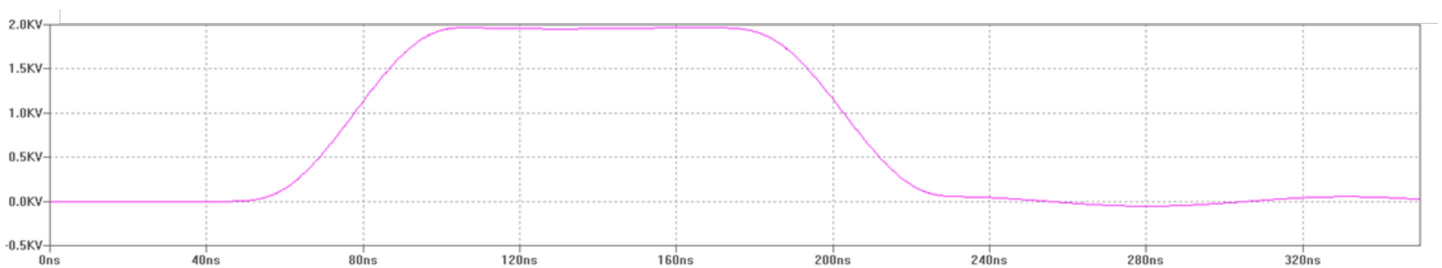
& Park
Close #4



& Discharge
Open #2 & #4
Close #3

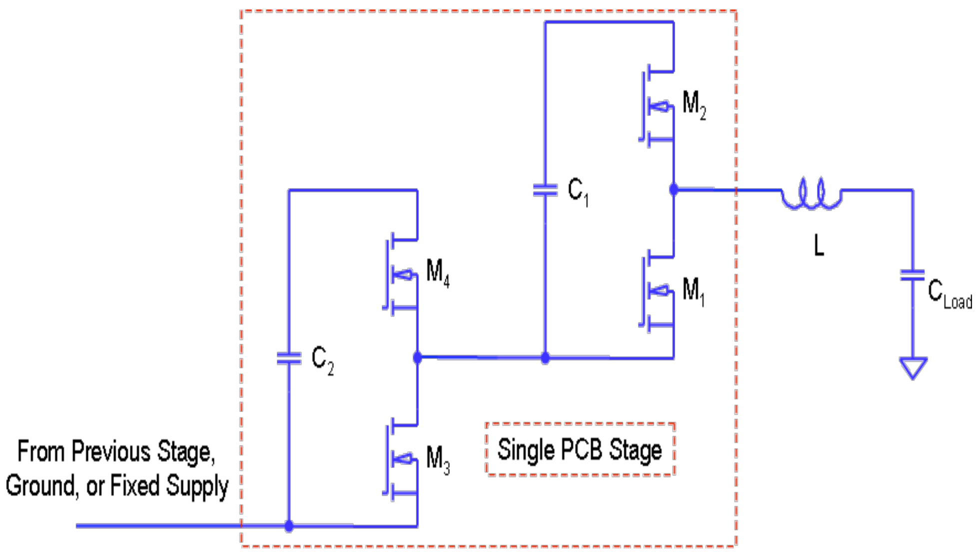


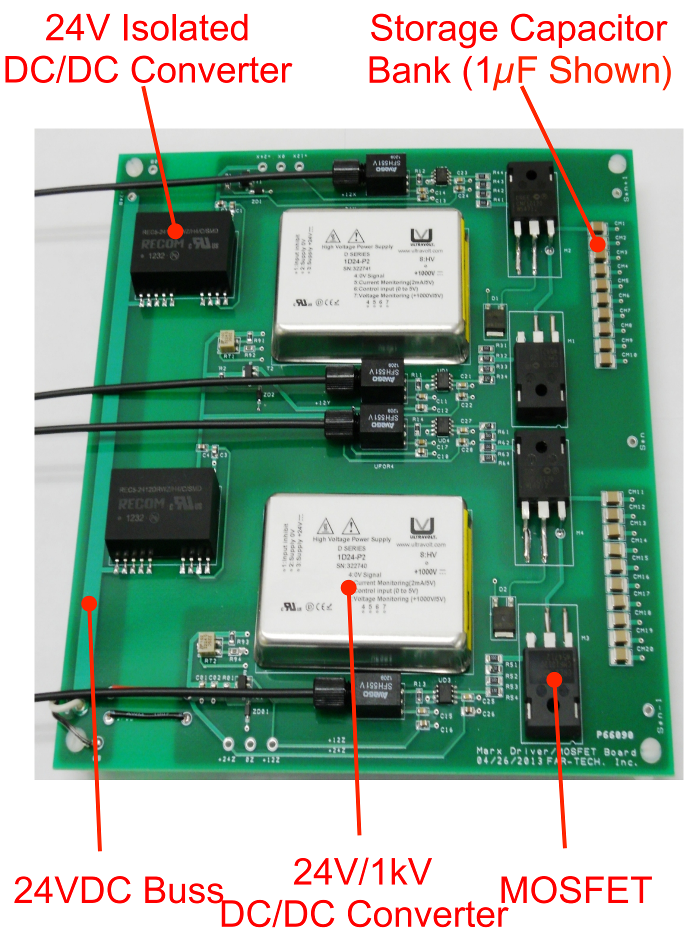
& Park
Close #1



Imperfect “flat ” parking due to switching energy loss, and resulting miss-match in voltages between stages and load

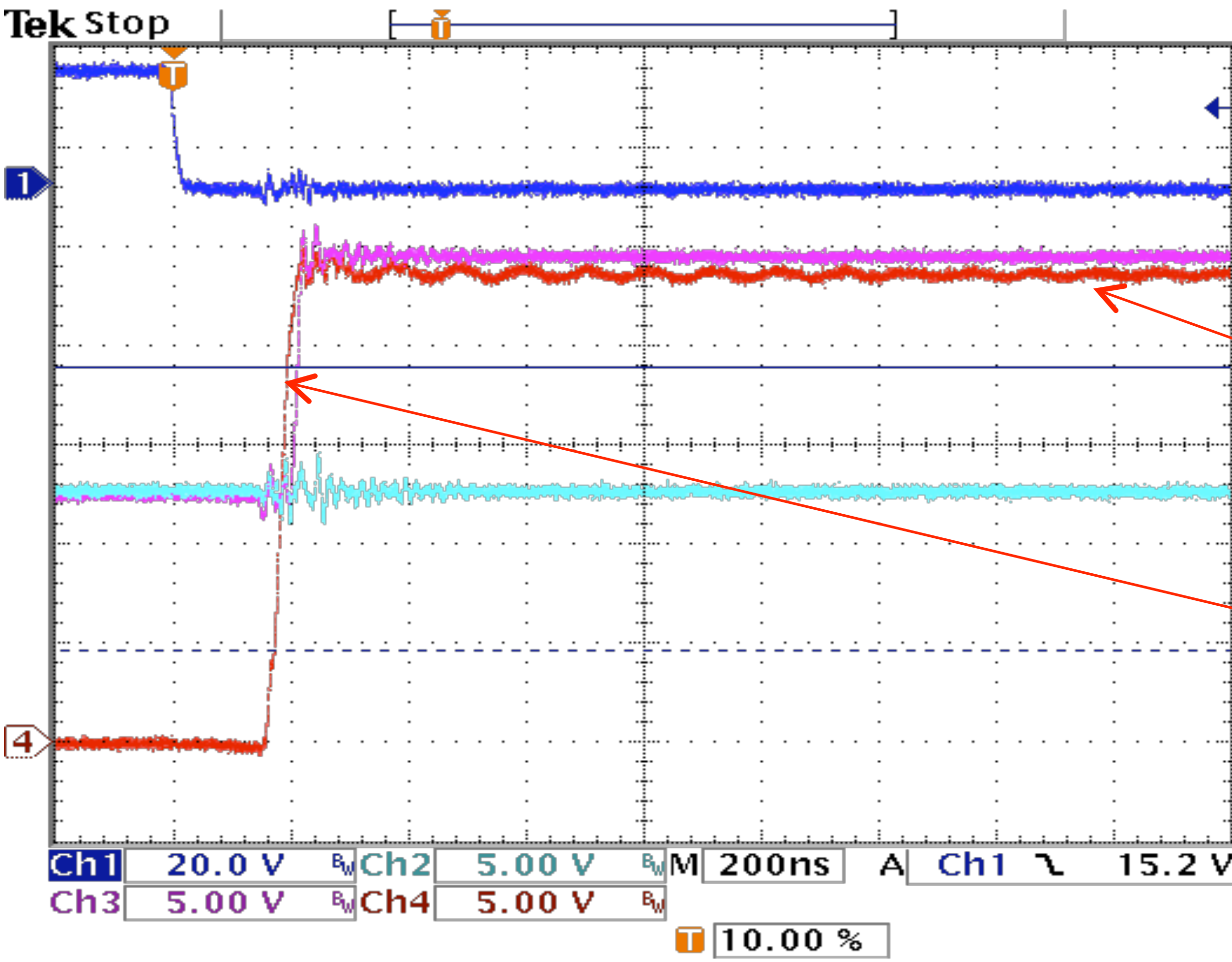
Bias Voltage Switching Circuit Board





2 kV Testing with Fixed C_{Load} -- Charge

Charge & Park

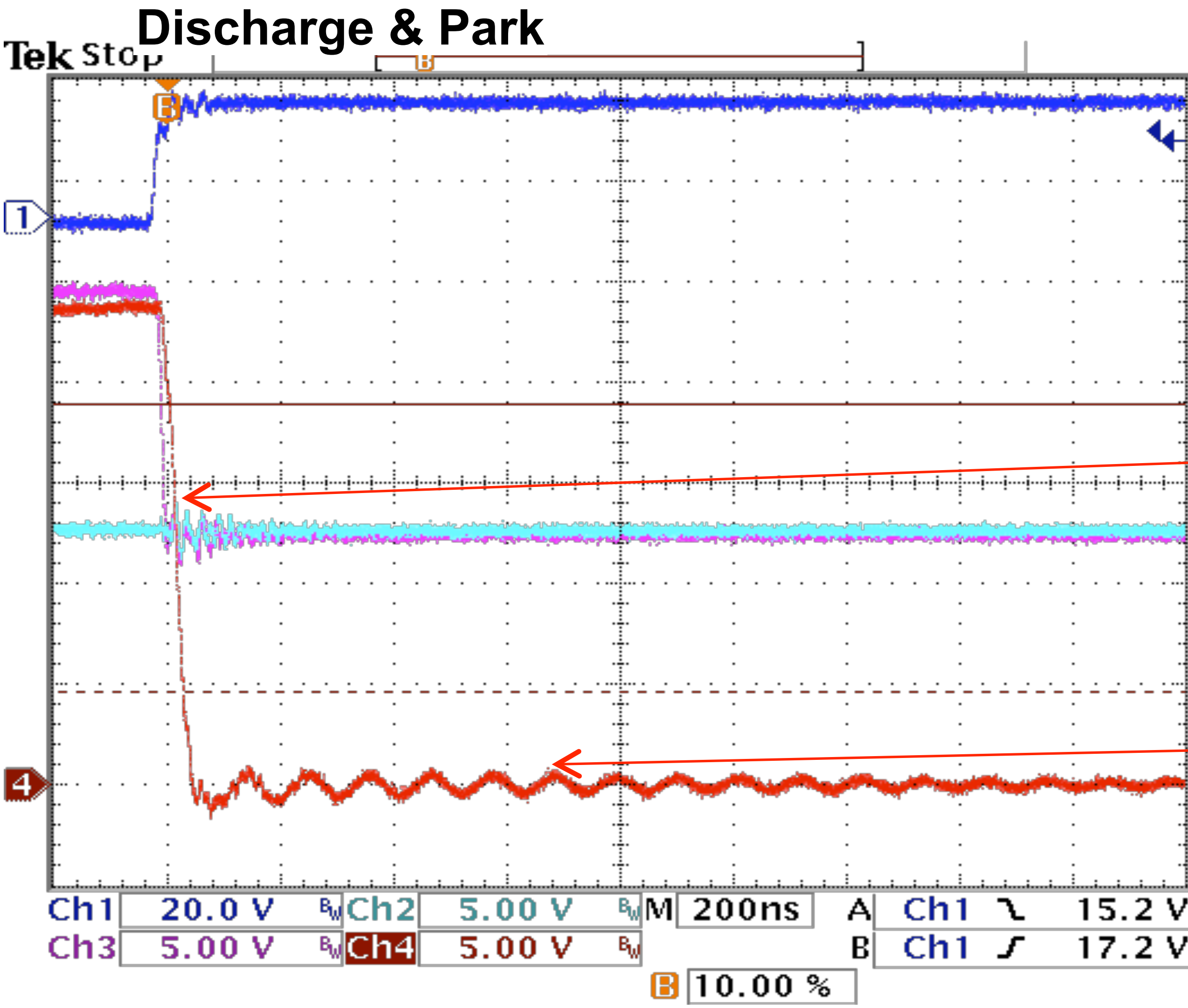


M3 Gate (trigger)
Voltage on C2
Voltage on C1
Voltage on C_{Load}

Adjust timing to minimize ring

Voltage on load increases from 0 to ~2 kV

2 kV Testing with Fixed C_{Load} – Discharge



M3 Gate (trigger)

Voltage on C2

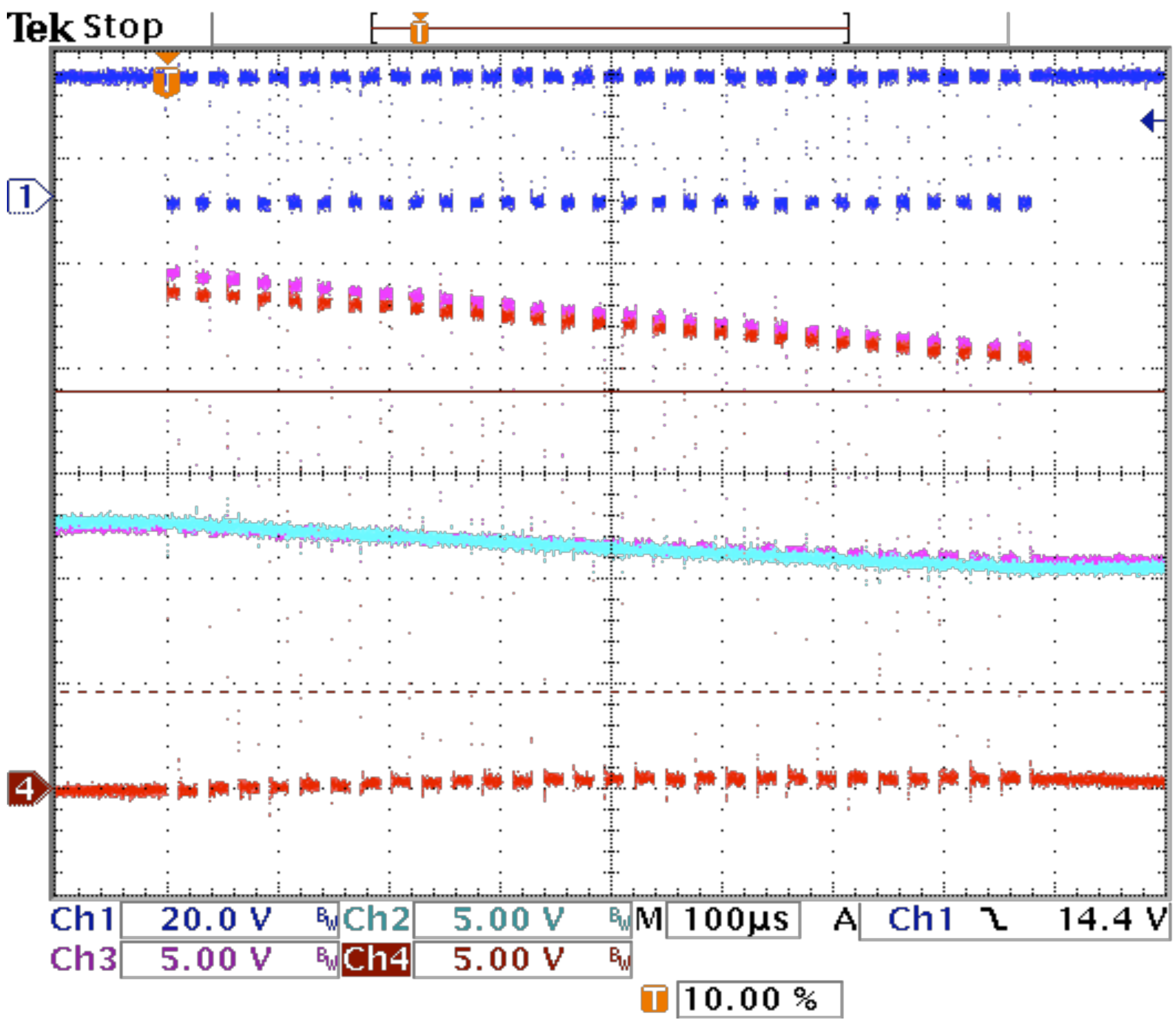
Voltage on C1

Voltage on C_{Load}

Voltage on load decreases from ~2kV to 0

Adjust timing to minimize ring

2 kV Testing with Fixed C_{Load} – Losses

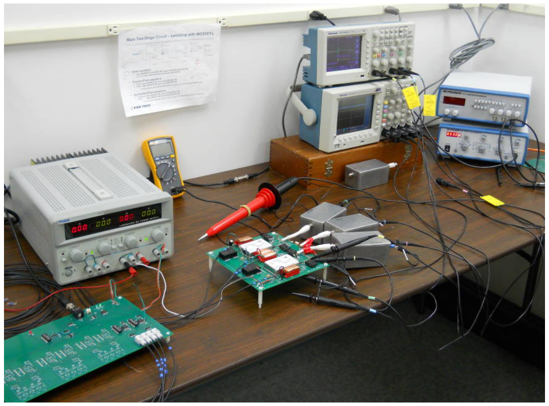


M3 Gate (trigger)

Voltage on C2

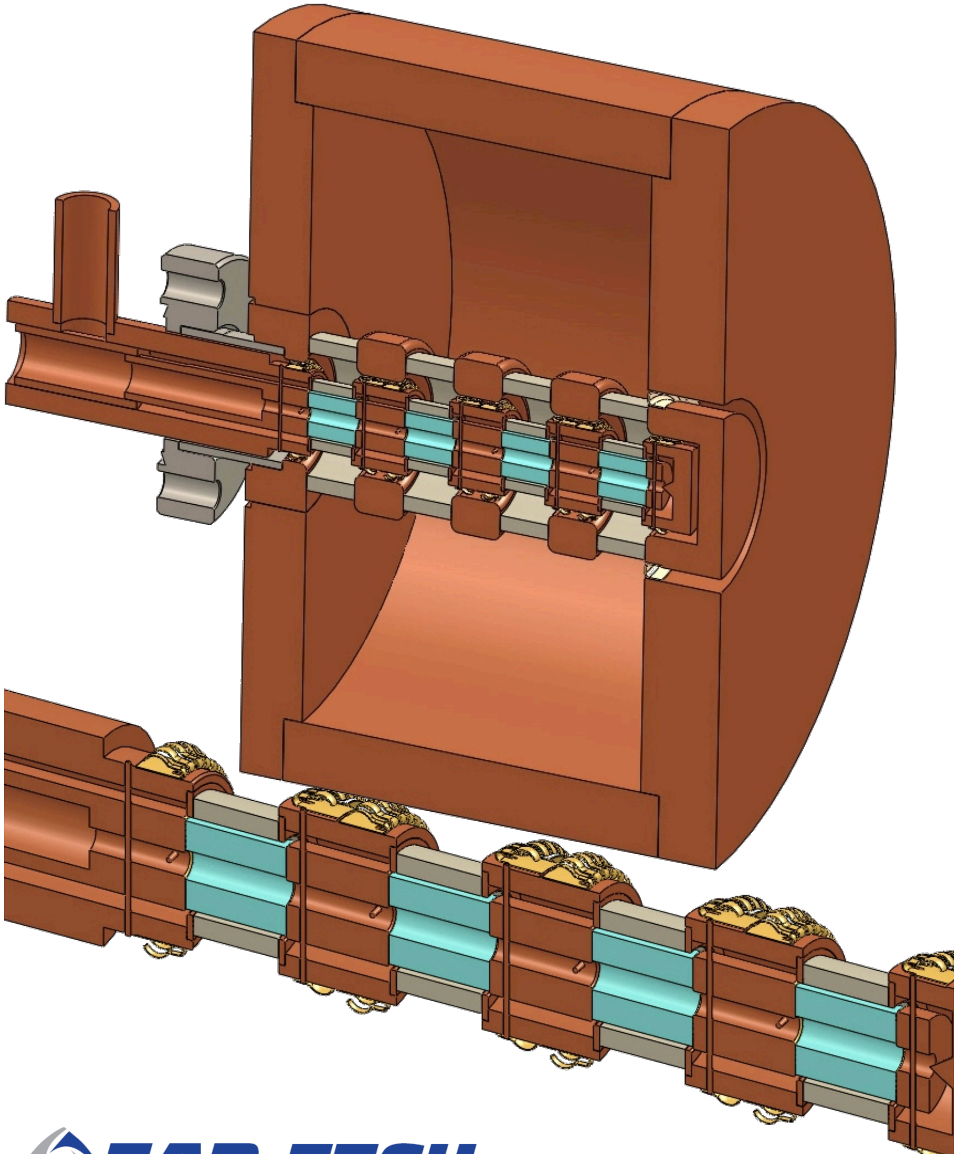
Voltage on C1

Voltage on C_{Load}



Multiple pulses with deliberately reduced storage capacitance enhances the effect of losses for measurement and determines charging requirements

High Power Equivalent Test Cell for Cartridge Development (work in progress)



- The goal is to determine maximum possible RF electric field on the FE and study hysteresis effects
- Place cartridge on axis:
  - Concentrates RF electric field
  - RF power reduced for same RF field in the FE as seen in a real accelerating cavity
- FE is cooled with dielectric fluid in a series flow
- Vacuum, and dielectric fluid coolant are separated by outer layer of Al_2O_3
- Cartridge is removable under vacuum operation – major advantage
- Complicated construction process, many issues are under investigation

Conclusion

- Ferroelectric cartridge has potential for rapidly tunable cavity.

- Rapidly tunable cavity opens up new lattice design possibilities that have not been fully explored

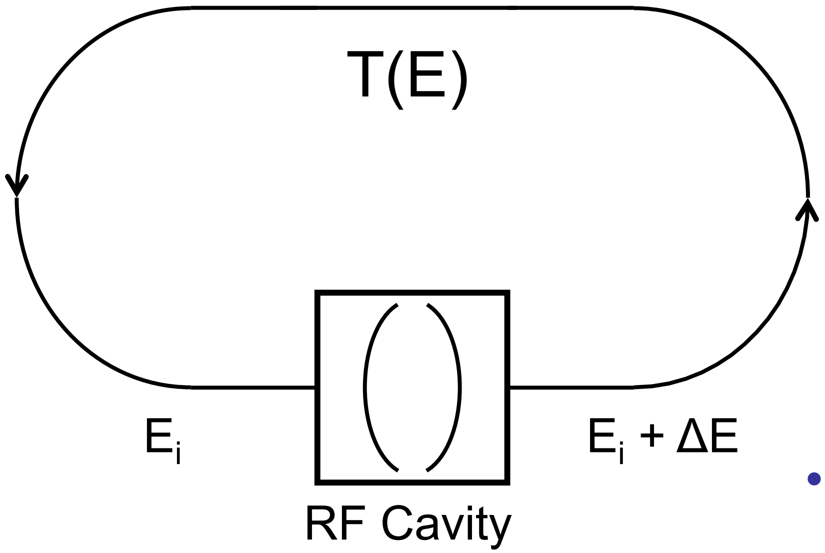
- Cold tests of the 2-cell cartridge performed.
  - Inferred ε and $\tan\delta$ from measured f and Q as function of bias V

- DC Voltage control and fast switching fabricated. Tested up to 2KV in 55 nsec.

Next step: ----

4-cell cooled cartridge in vacuum cavity
with 8 kV pulser 55 nsec (50 pC load)

A message …



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- **For *changing* frequency, adjust *f(t)* such that the phase change between crossings ($\varphi_{rf}/2\pi$) is an integer**
- **Required tunability could be less than what we thought**

FAR-TECH

Fusion and Accelerator Research and Technology, San Diego CA

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