Rapidly Tunable RF Cavity Development

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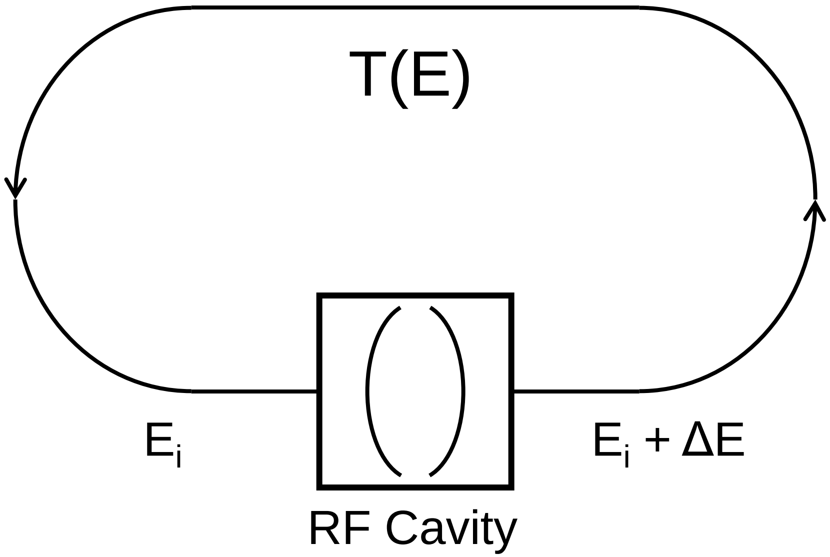
FAR-TECH, Inc.

- Located in San Diego, CA
- Founded in 1994, formerly known as Fusion and Accelerator Research (FAR), to pursue fusion and accelerator related research, technology and development.
- Core staff of over 10 PhDs Physics/Engineering
- Facility:
  - Linux cluster (88 processors) with 96GB of memory via Infiniband connection; 15 TB redundant storage
  - RF, UHV, laboratory and assembly

Motivation

- Rapid-Cycling Accelerators (synchrotron, FFAG) have varying revolution times on successive orbits, requiring a different accelerating cavity frequency for each cycle.
- Ferromagnetic (ferrite) tuning cannot adjust the frequency of the cavity rapidly enough
- Low Q solutions (magnetic alloy or high external Q) waste RF power by dumping the energy after every revolution
- Ferroelectric (FE) material in accelerator applications have shown response times < 10ns
- FAR-TECH is developing a ferroelectric tuned cavity in the frequency range 325 – 350 MHz as a start

The Problem in a Nutshell



Cartoon Schematic of a Generic Recirculating Accelerator (from a cavity perspective)

- **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)**

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

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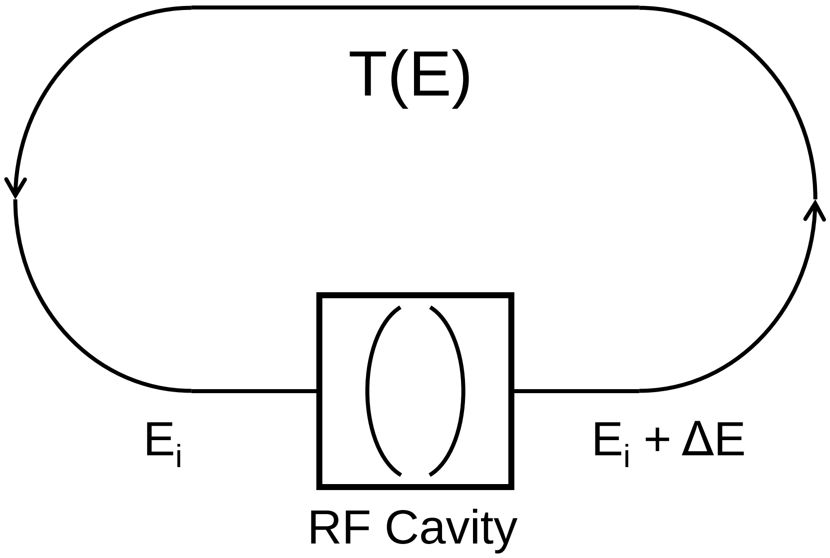

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- For fixed frequency, this only happens if *f* is a harmonic of 1/T
- This makes fixed frequency acceleration difficult if T changes (which it does)
- **For *changing* frequency, adjust *f(t)* such that the phase change between crossings ($\varphi_{rf}/2\pi$) 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 ~ 2-300)**
  - 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 at the appropriate phase 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

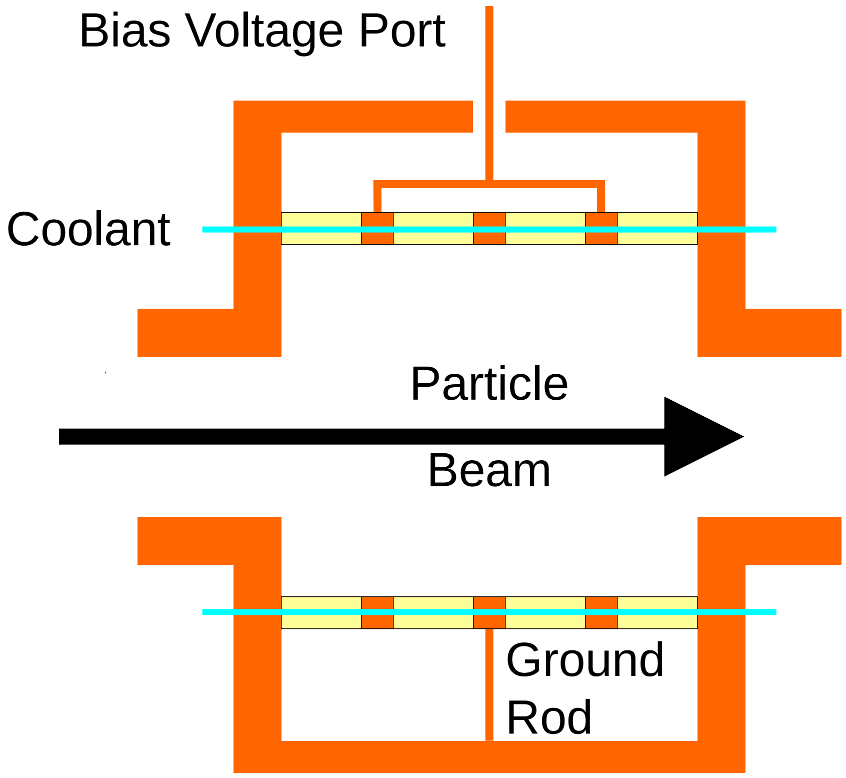
Ferro*electrics* are the key

- **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**
  - **Low loss tangent does not mean low losses due to high ε**

    $\text{Loss} \propto \varepsilon \tan\delta$
  - **Material response time < 10 ns (limit of manufacturer's testing)**
- **Ferroelectric tuning is directly analogous with ferrite tuning**
  - **Permittivity change results in a frequency shift**
  - **Tuning strength is based on the fraction of electric RF field stored energy**
  - **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**

Ferroelectric material from Euclid Techlabs

What Might a Cavity Look Like?

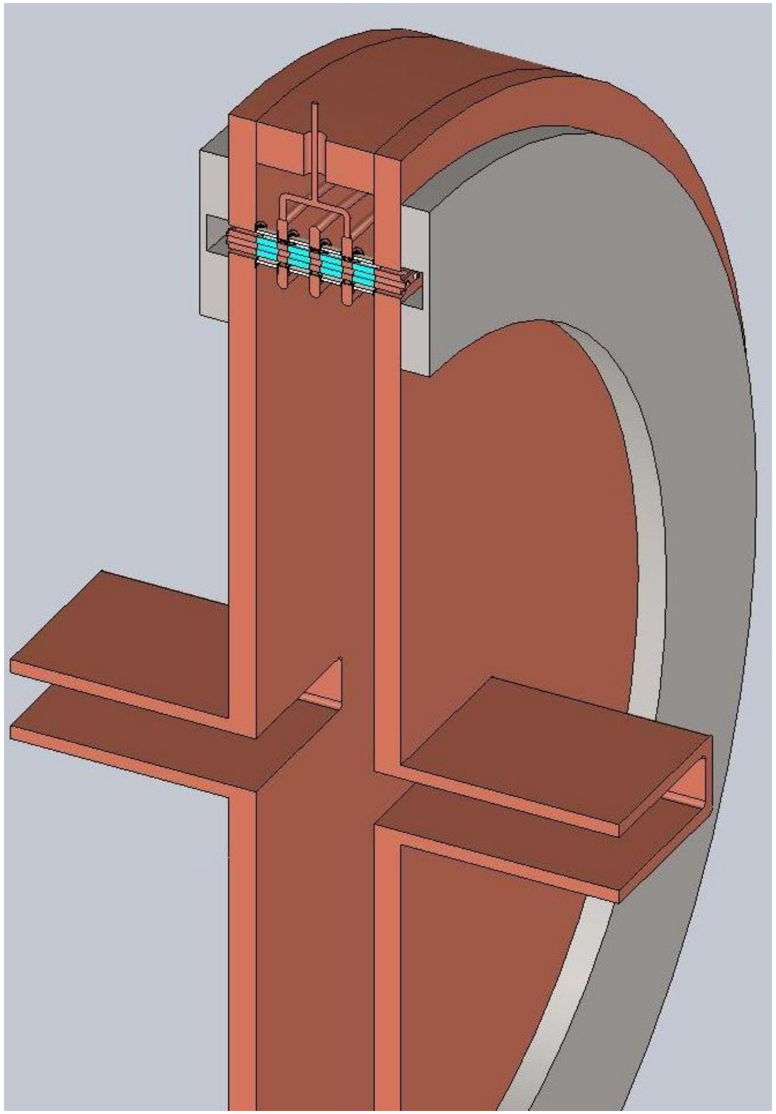


- Off-axis ferroelectric tubes separated by electrodes
- Reduces tuning effect compared to on-axis
- Reduces heat dissipation in ferroelectric
  - Dielectric constant is temperature dependent
- Tubes separate cavity vacuum from central portion of tube
  - Allows the use of dielectric coolant
  - Real design has ability to remove ferroelectric cartridge from cavity without vacuum break

A Semi-Conceptual Tunable Cavity Design

- **For $\Delta f_{full\ bias}$ = 25 MHz, the estimated (realistic) phase shift is 2π in 1 μs (0.3π in 150 ns)**

Property	Unbiased	Biased
Permittivity, ε	450	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 in Vacuum (mJ)	6.8	6.2
RF Energy in Ferroelectric (mJ)	6.3	2.1
ZTT (MΩ/m)	0.57	1.26
r/Q (Ω)	29.0	42.7

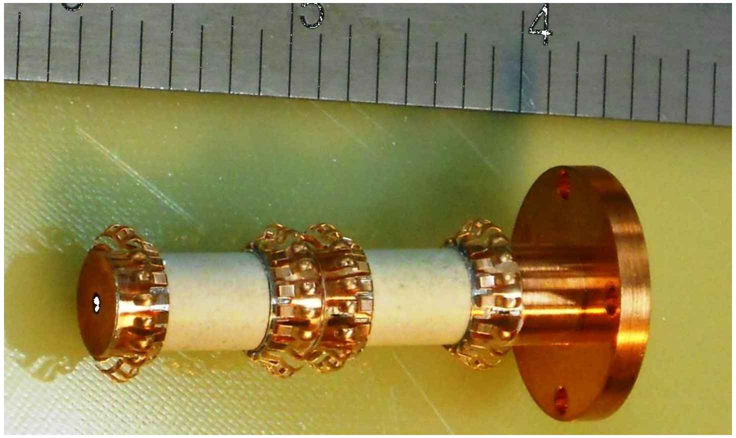


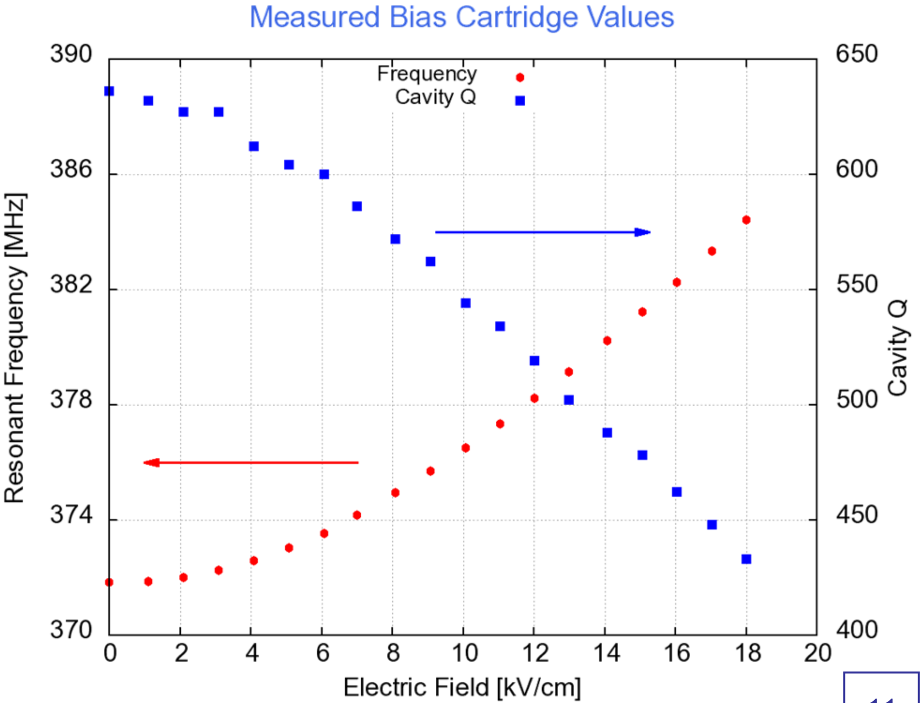
For an unloaded pillbox cavity (no beam pipe) of the same radius:

f = 428.9 MHz

Q = 22800

Cartridge Cold Test

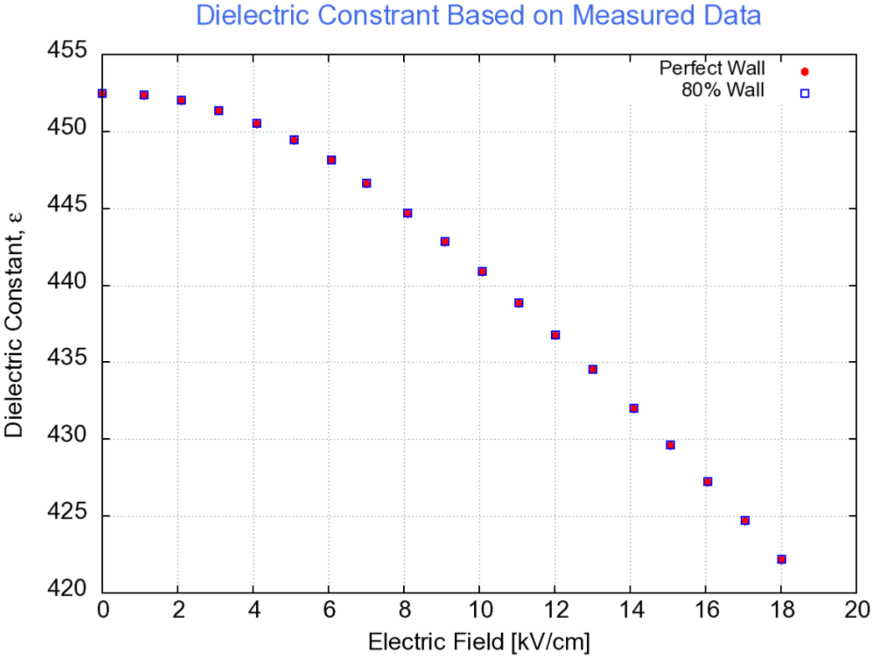


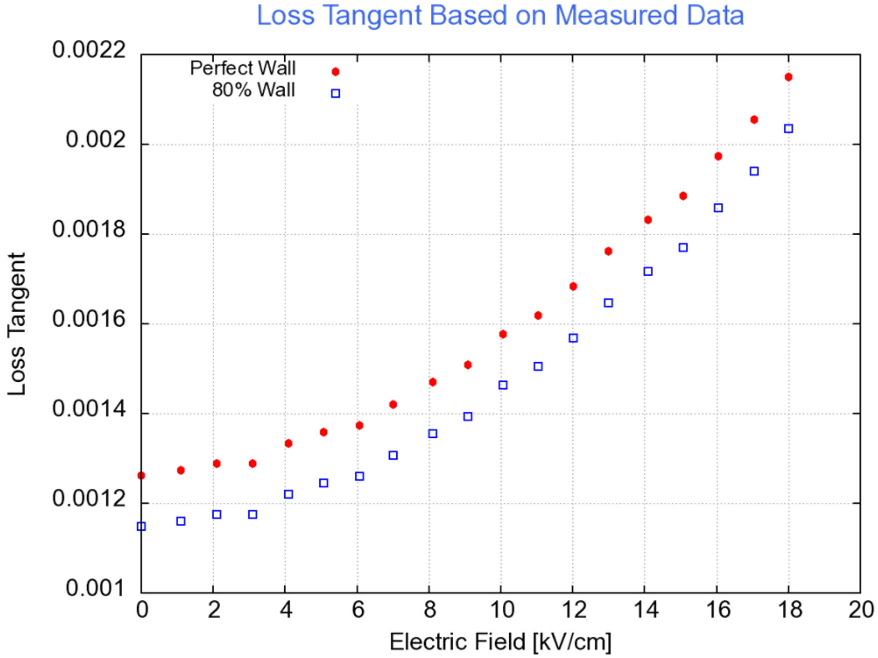


- **Cartridge on cavity axis to increase RF electric field**
- **Initially used to test construction details**
- **Used to prepare for High Power Equivalent (HPE) test cell experiments**

Ferroelectric material from Euclid Techlabs

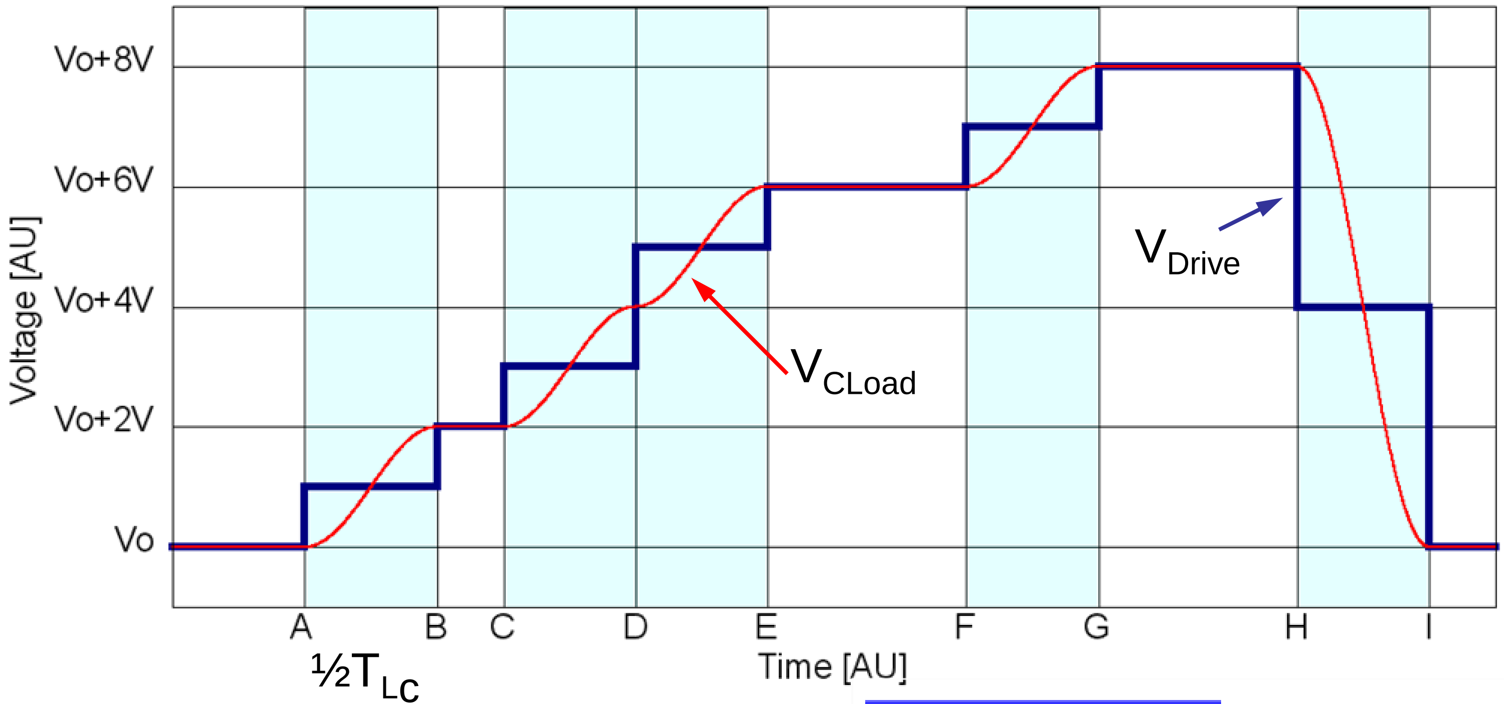
ε and tanδ from Cold Test Data

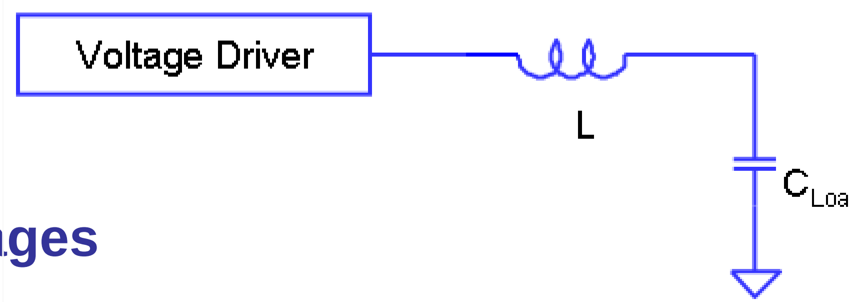




- **FE losses from tanδ only – termination effects folded into bulk losses**
- **HFSS simulations to determine (f,Q) from (ε, tanδ)**
- **$Q = Q_{wall} \,||\, Q_{FE}$**
  - **Reduction of Q_{wall} to 80% HFSS value to account for contact losses**
- **Use simulation data to determine (ε, tanδ) from measured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

A Scenario of Voltage Ramp on C_{Load}





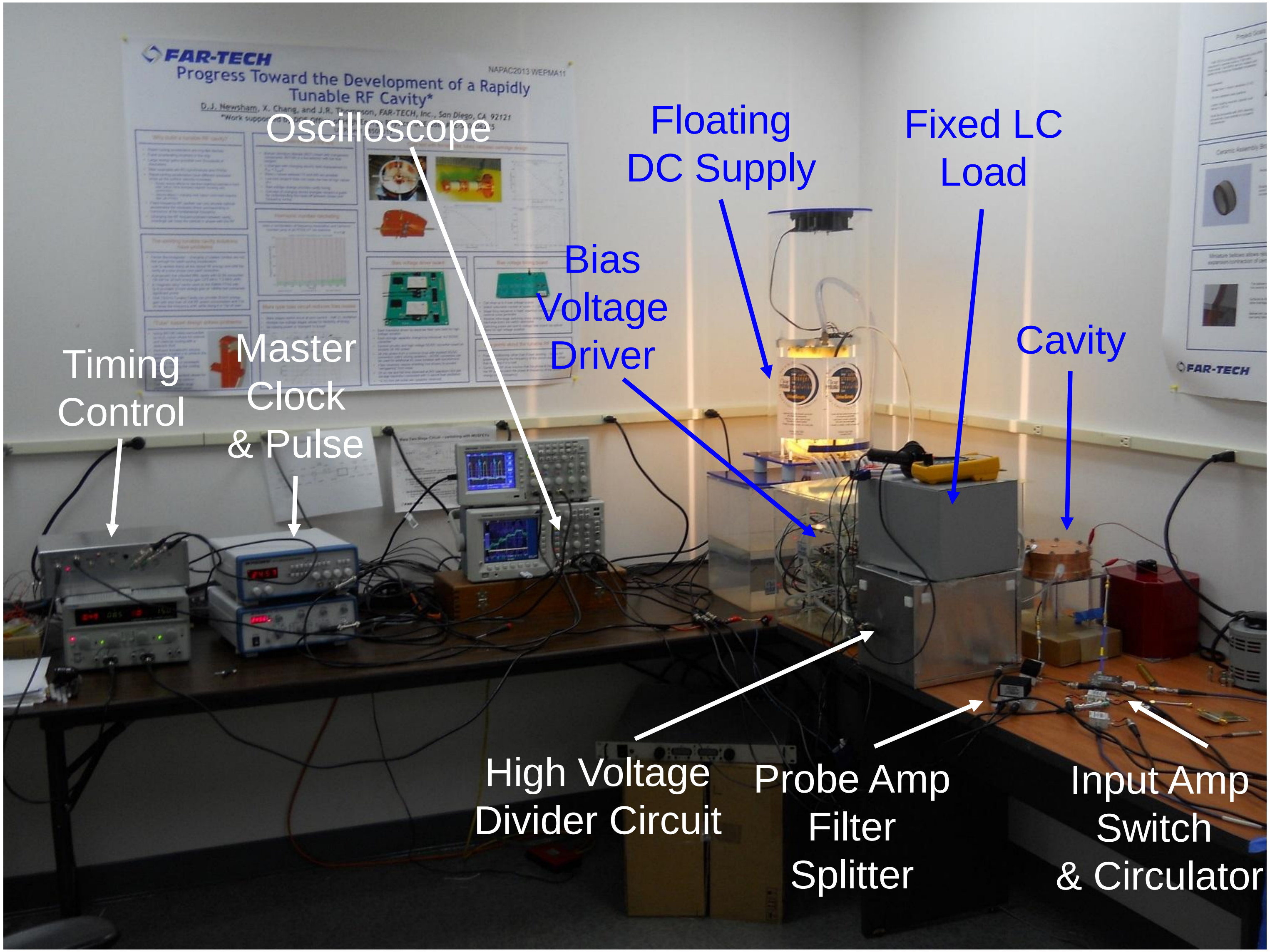
Ferroelectric cartridge is C_{Load}

Scenario with 4 bias voltage driver stages

Delay between (dis)charge and park (shaded) is ½T_{LC}

Arbitrary delay between park and next (dis)charge

Voltage Driver Test on Cold Cavity

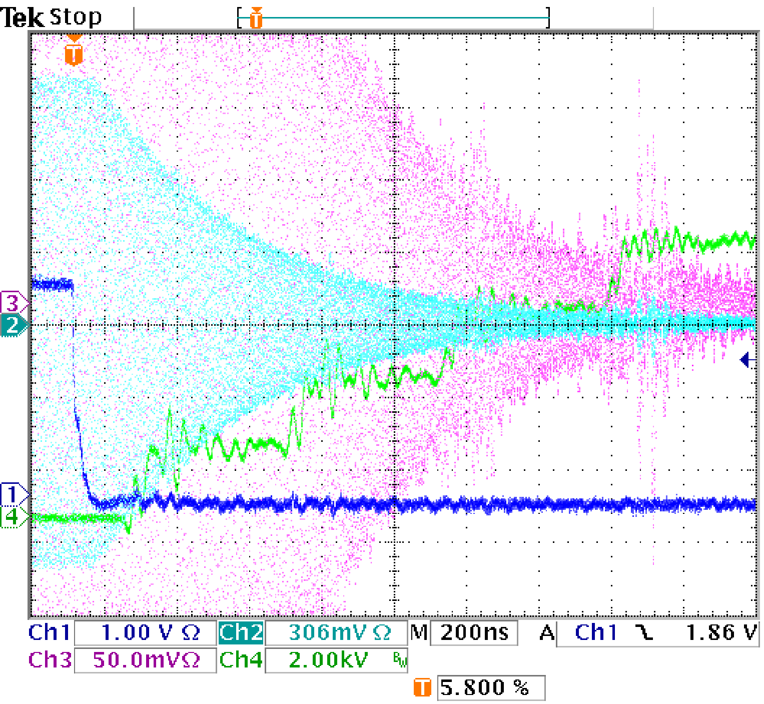


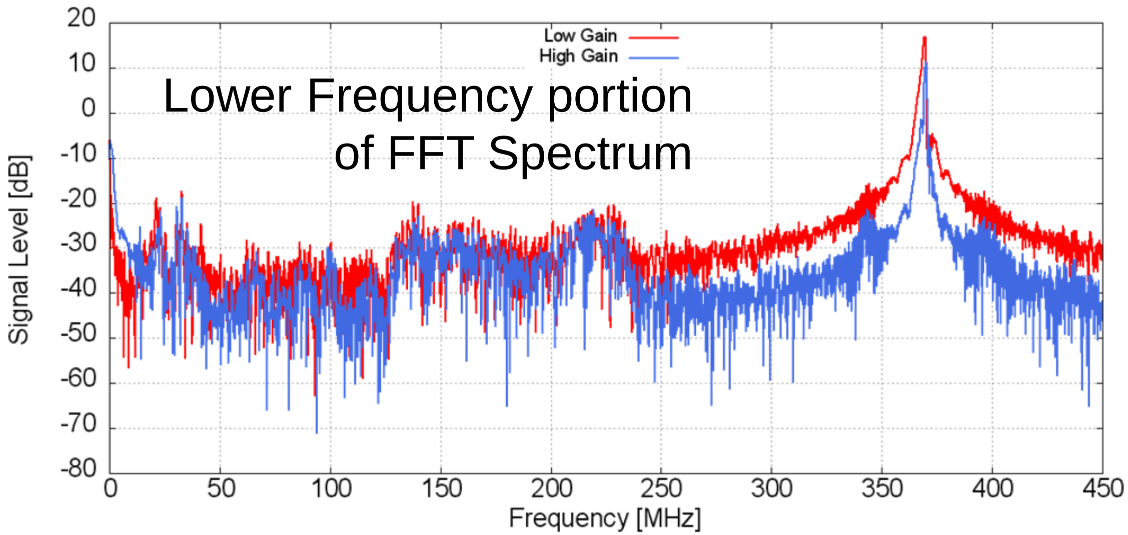
Frequency Shift Analysis – Initial Study

- Measure cavity field probe voltage with oscilloscope
  - Tektronix TDS 3054C 500MHz oscilloscope
  - 5 GS/sec – greater than 5x Nyquist
  - 10,000 sample record – allows 2 μs window at full resolution
- Numerical IQ Demodulation – Data Analysis Method
  - Create numerical cosine and sine signal to serve as local oscillator for I and Q
  - Multiply each with measured data
  - Strong low pass filter to isolate difference frequency and remove noise
  - Determine phase, φ = ArcTan(cosine,sine)
    - Gives instantaneous phase of the RF signal relative to the local oscillator (with $-\pi$ to π wrapping)
  - Derivative of phase/2π gives linear frequency shift

8kV Bias Test

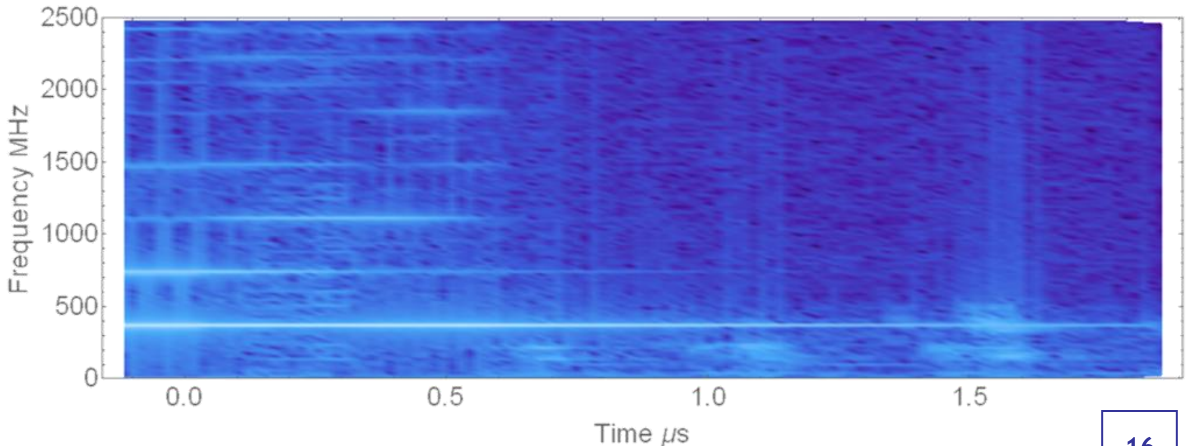
HV pulse rate ~2.24 MHz
HV rise/fall ~ 85 ns



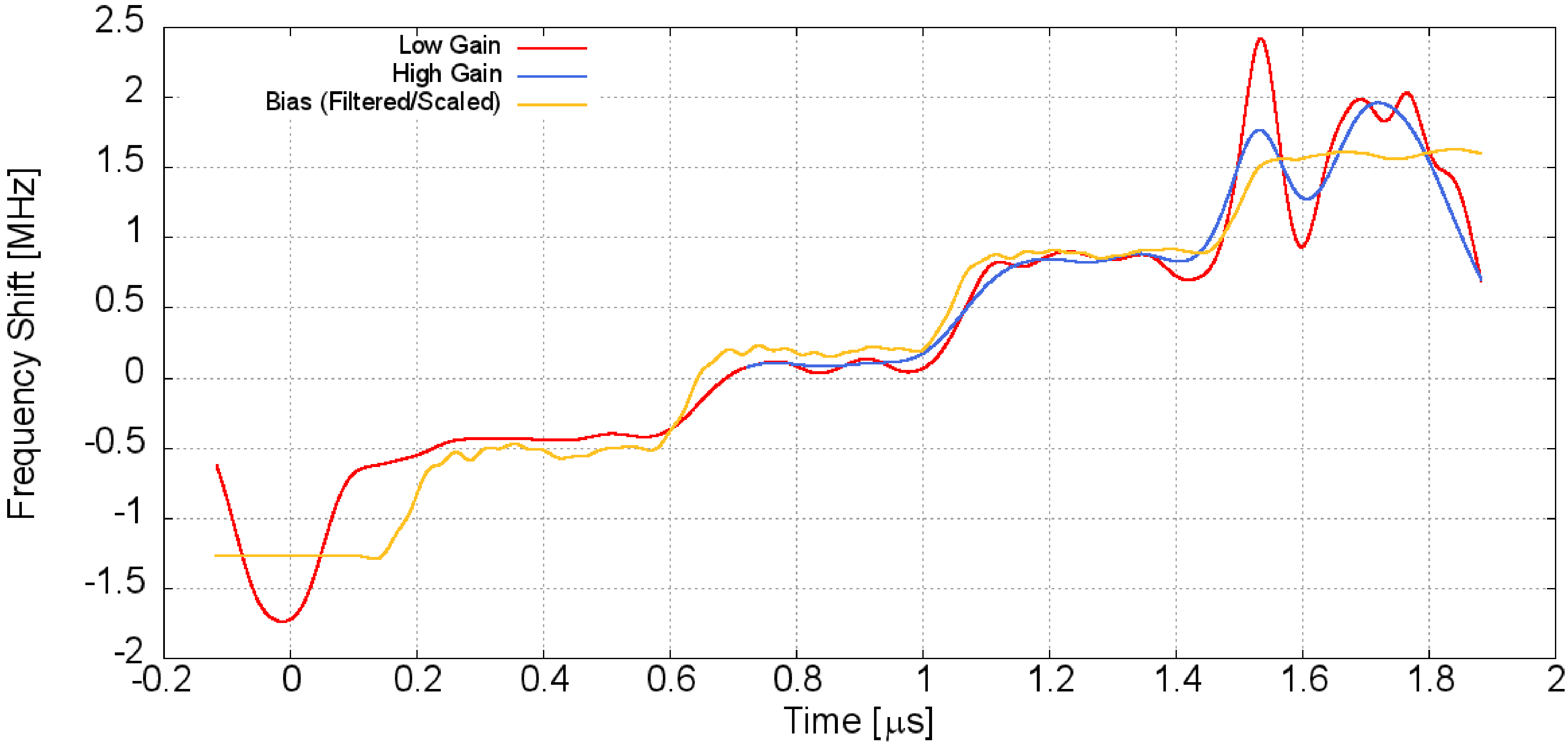


RF Switch (trigger)
Low Gain
High Gain
Voltage on C_{Load}

High Gain Spectrogram



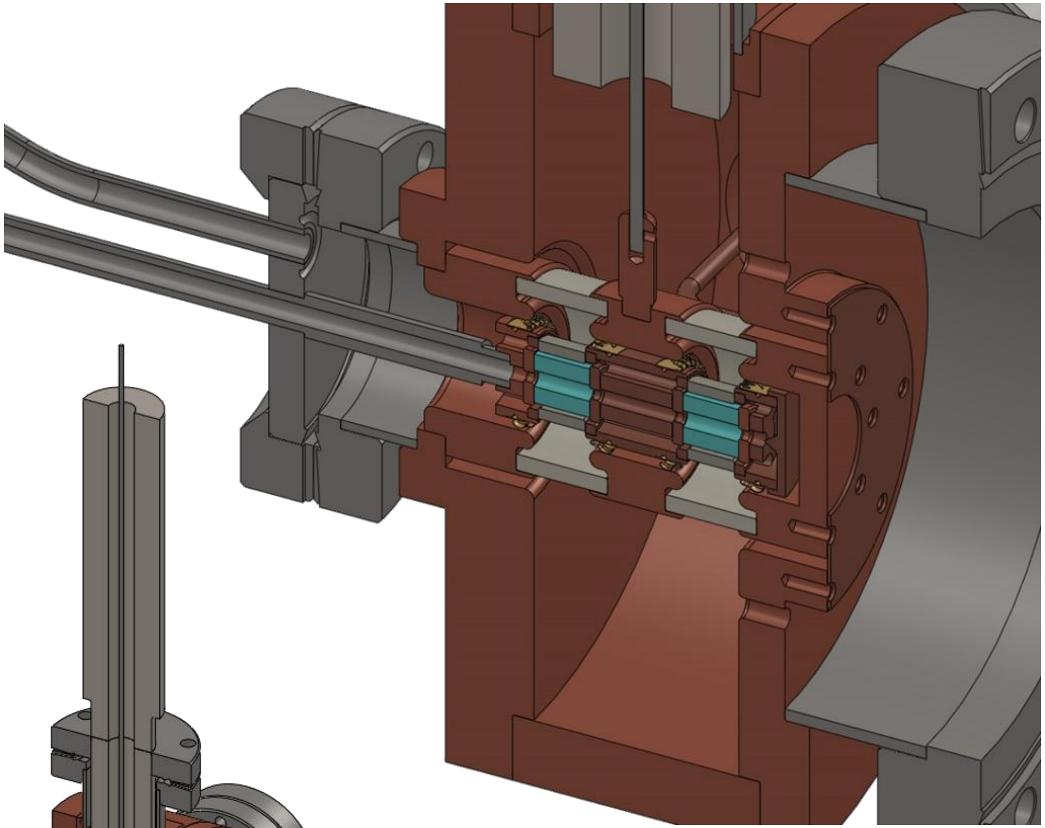
Frequency Shift – 8kV Bias Test

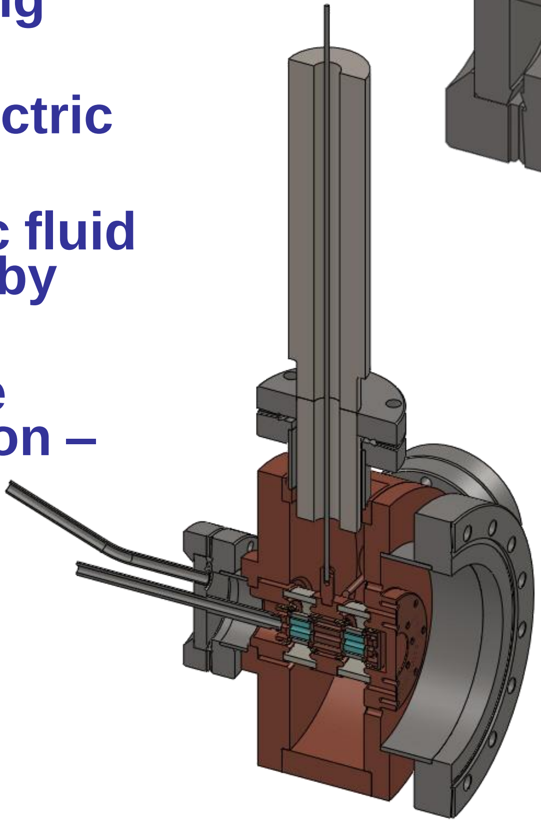


F_{LO} = 370.0 MHz

High Power Equivalent Test Cell & Cartridge (under construction)

- The goal is to determine maximum possible RF electric field on the FE
- Purposefully concentrate RF electric field on FE to reduce RF power requirements by placing cartridge on axis
- FE is cooled with dielectric fluid in a series flow
- Vacuum, and dielectric fluid coolant are separated by outer layer of Al2O3
- Cartridge is removable under vacuum operation – major advantage





8kV Pulse Results Summary

- ~ 2.25 MHz frequency shift in 1.4 µs presented with 8kV bias (2.25 MHz in 750 ns observed)
- The frequency shift of a real cavity would be smaller because the test cell is purposefully enhanced (factor of 2-3)
- The switching noise contaminates all signals
  - Master clock
  - Timing control board
  - Bias voltage measurement
  - Oscilloscope itself
  - Input and output amplifier supply voltages
- Faraday cage impractical to implement given time and budget
- Analog high-pass filters for RF signals before digitizing creates some artifacts
- Continue tests on cold cavity to improve technique while high power cell is being constructed

END

Tunable Cavity Development

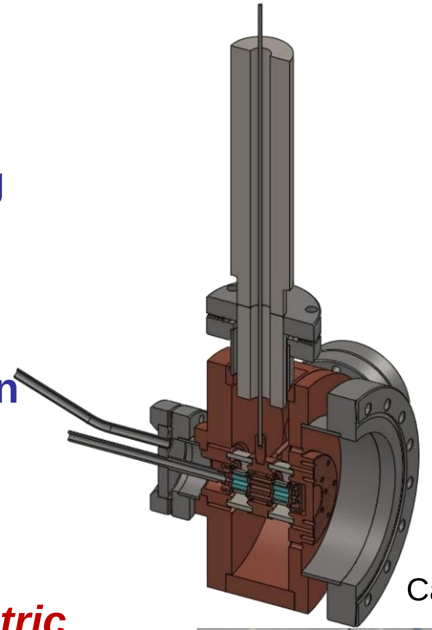
Motivation

- **Rapid-Cycling Accelerators (synchrotron, FFAG) require fast frequency tuning of the accelerating cavity**
- **Ferrite cavities are too slow, low Q cavities waste power**
- **Potential uses include proton/C^{6+} ion cancer therapy accelerators and possibly sub-critical reactors**

Development

- **FAR-TECH is developing a ferro*electric* tuned cavity in the frequency range 325 – 350 MHz as a start**
- **An actively cooled ferroelectric cartridge and high voltage bias generator are the top priorities**
- **~ 2.5 MHz frequency shift at 8kV pulse bias with 2π phase shift in 750 ns was observed in cold testing**

Ferroelectric material from Euclid Techlabs



Cartridge test cavity

“Warm” Test Cavity for cartridge testing

UHV for voltage standoff

Active cooling with dielectric fluid

Cartridge can be removed under vacuum