Dielectric sample testing for high-pressured RF cavity

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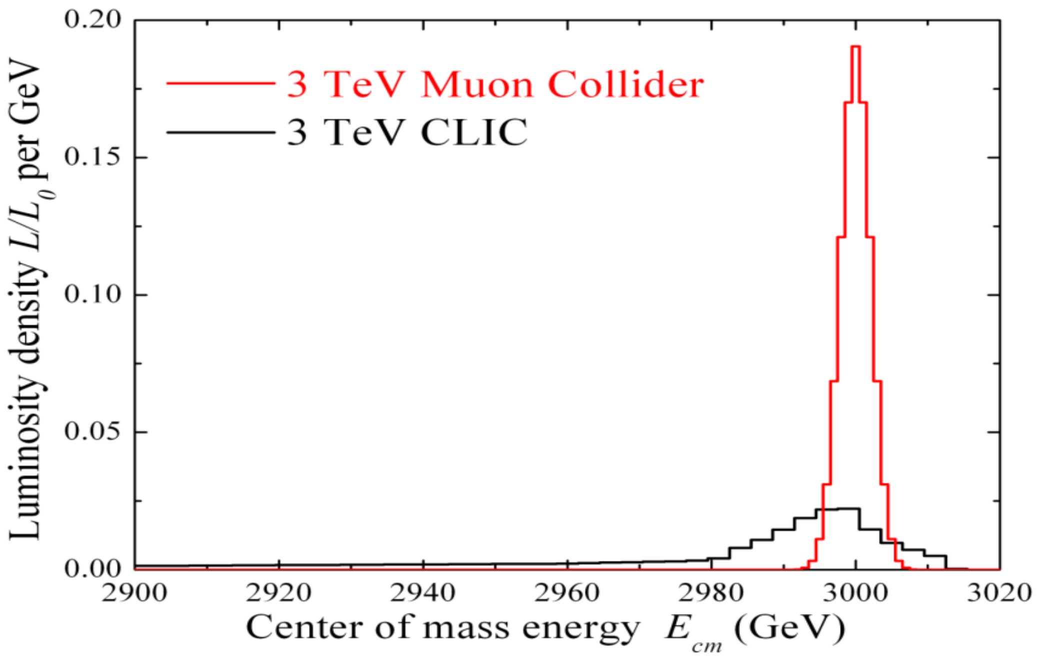
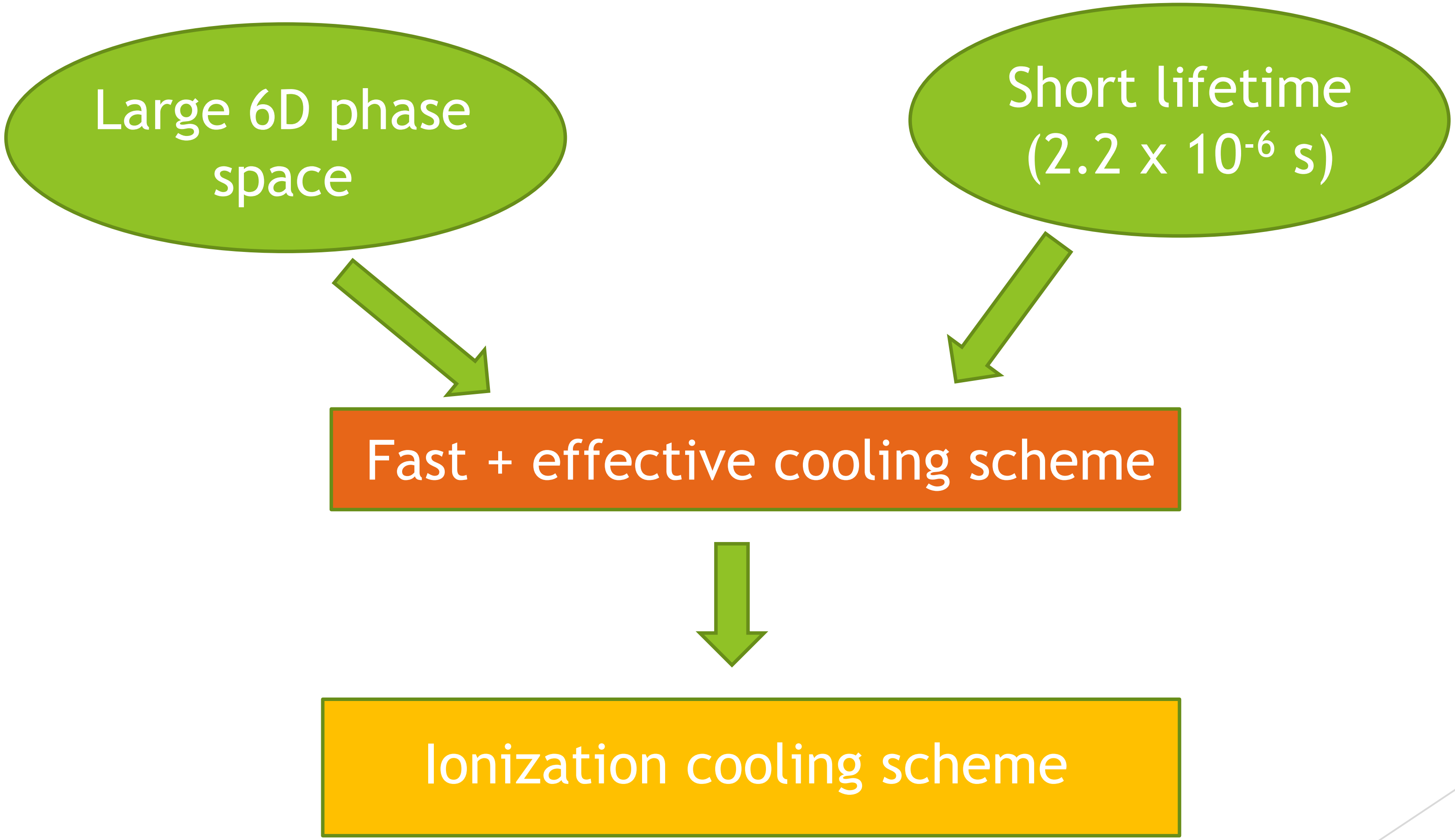
Muon collider

▶ Why?

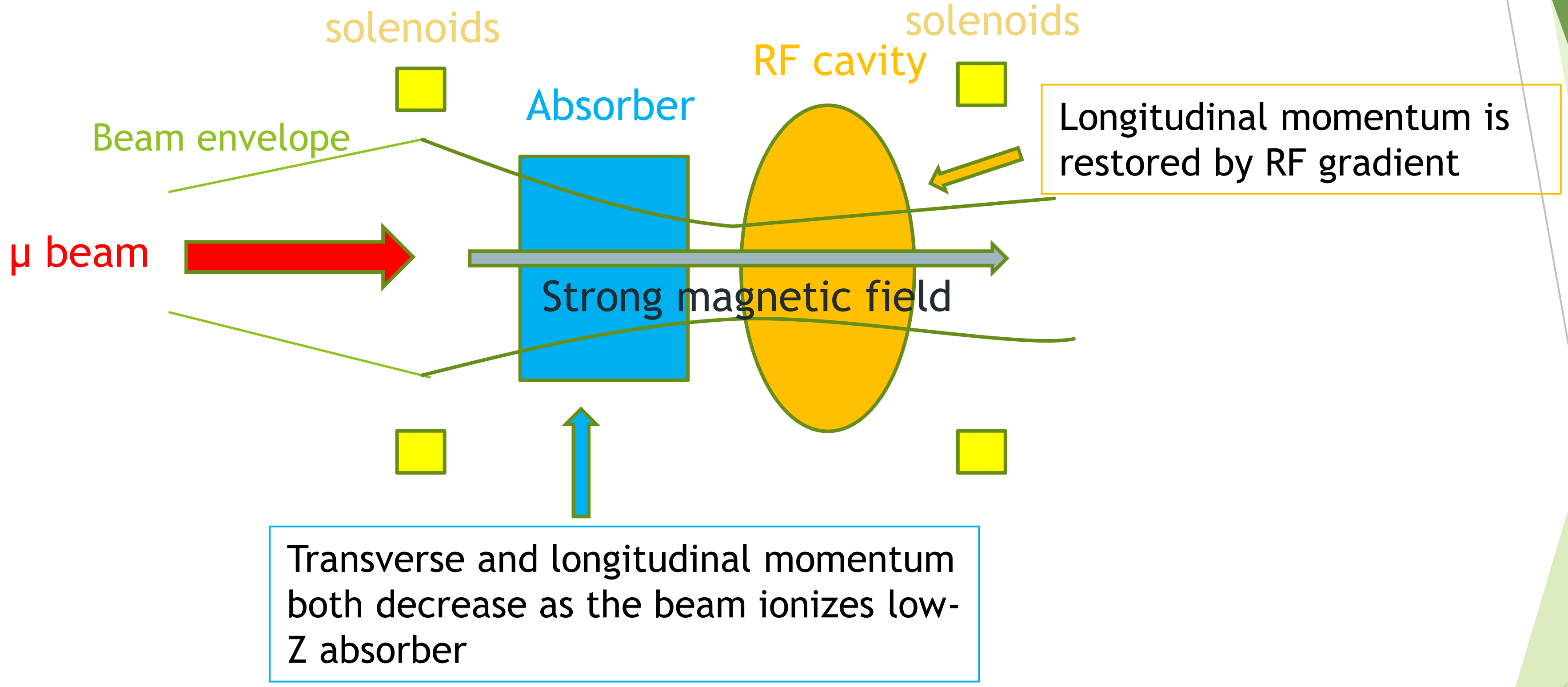


- Cleaner collision
- Much less synchrotron radiation
- Small energy spread at interaction region
- Potential Higgs Factory

Challenges

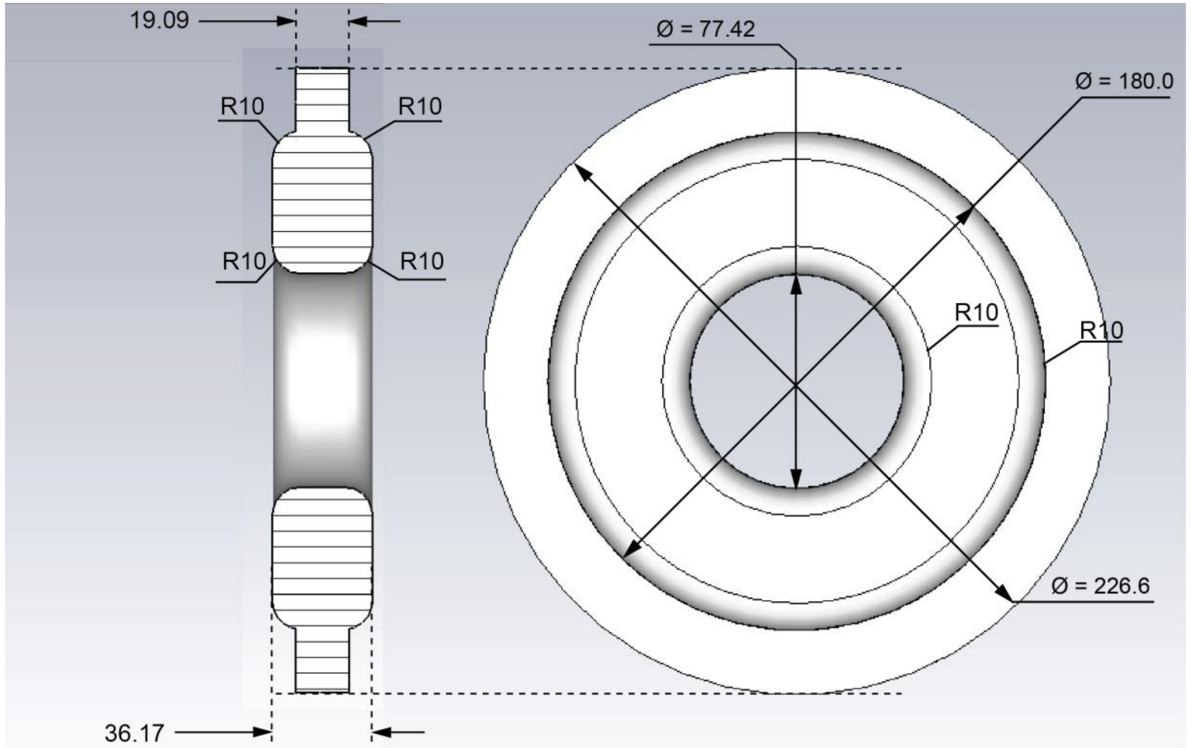

Large 6D phase space
Short lifetime (2.2 x 10^{-6} s)
Fast + effective cooling scheme
Ionization cooling scheme

Ionization cooling channel



Necessity in reducing RF cavity's radial size to fit inside solenoids

Dielectric insert ring



$$f \propto \frac{1}{R\sqrt{\mu\varepsilon}}$$

f: resonant frequency(Hz)
R: radius of cavity (m)
ε: relative dielectric constant
μ: permeability ($H.m^{-1}$)

By loading the cavity with dielectric structure, smaller radius is enough to attain same resonant frequency

Important parameters of dielectrics

- Dielectric constant (permittivity): material properties that determines how electric field affects, or is affected by some medium.

$$\varepsilon = \varepsilon' - j\varepsilon''$$

- Loss tangent: ratio between the lossy reaction to electric field and lossless reaction to electric field

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

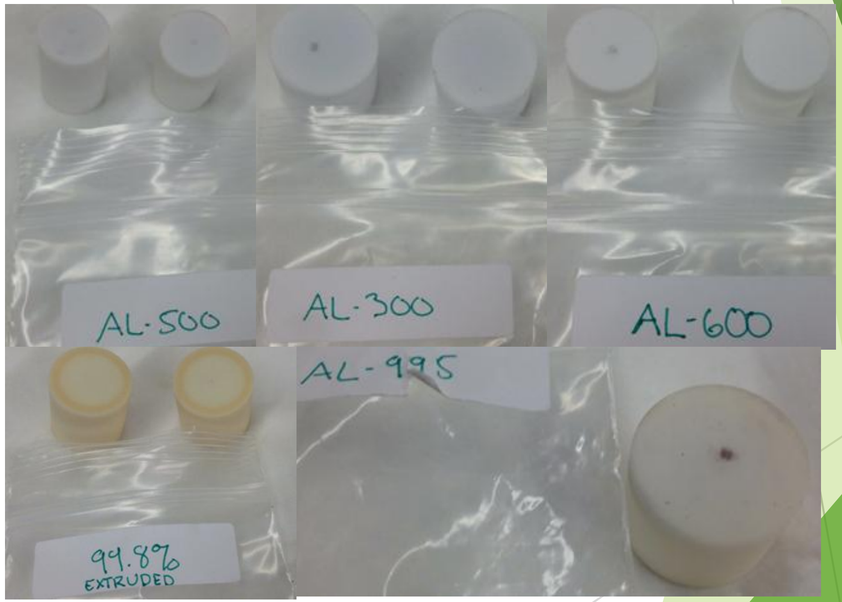
- Loss tangent quantifies how much electric field energy will be dissipated into heating the dielectric

- Dielectric material reduces quality factor of cavity => choose material that gives small loss but can still achieve desired cavity radius

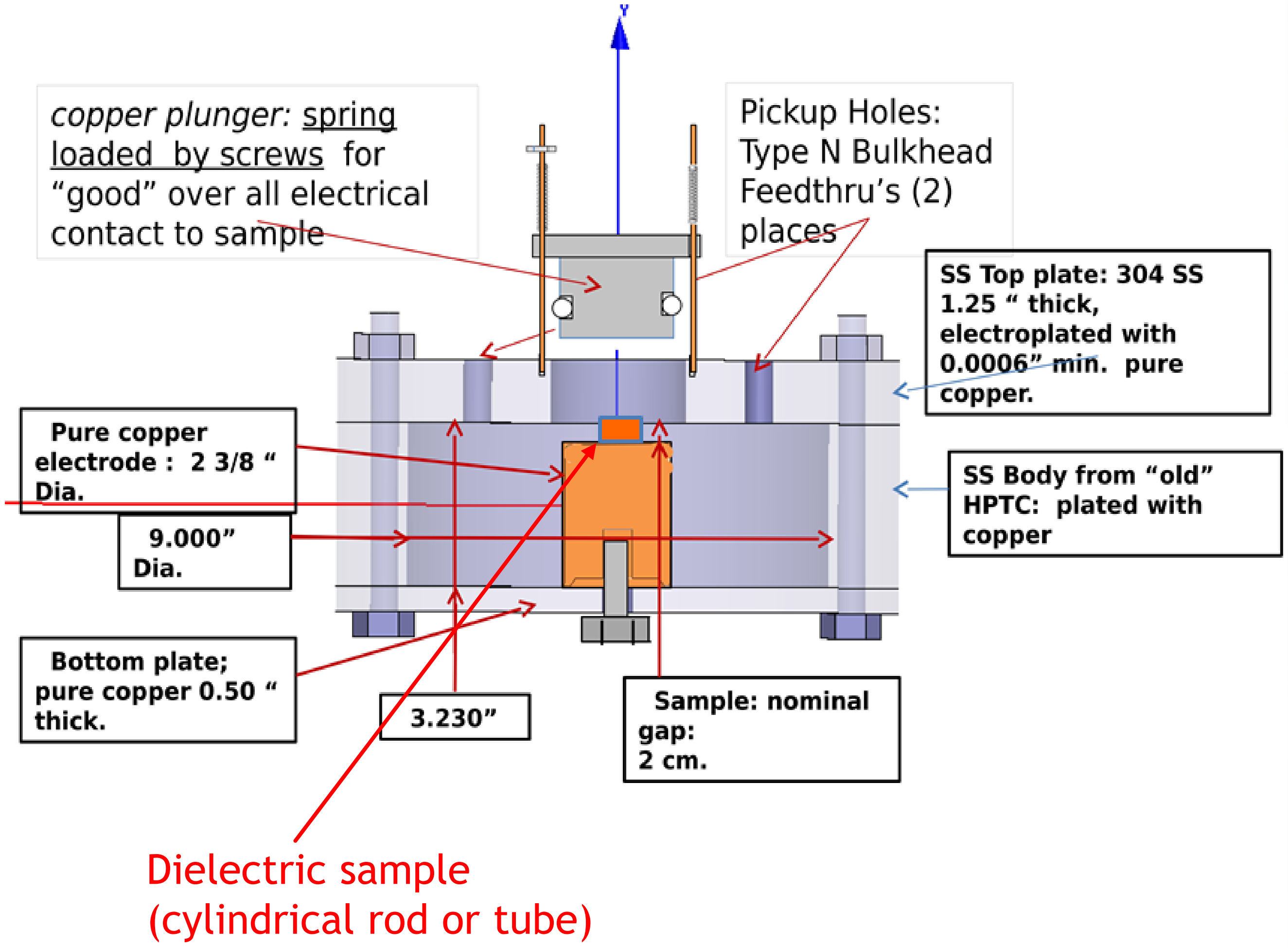
Dielectric sample test

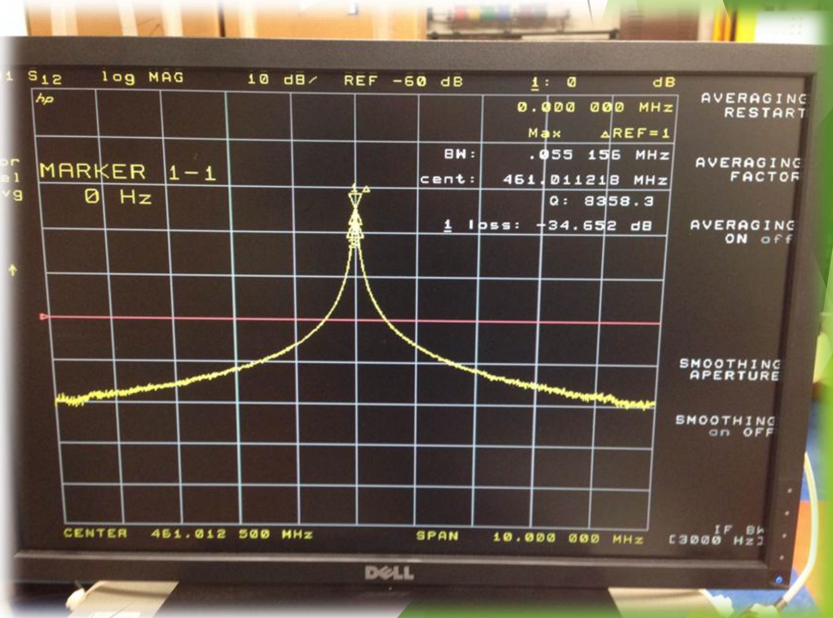
- Goal:
  - Determine dielectric constant and loss tangent of various materials
  - Analyze experimental results to find optimal material for the insert ring

- Sample tested:
  - Alumina (Al_2O_3) with various purity
  - Magnesium Calcium Titanate (MCT)
  - Corderite ($(Mg,Fe)_2Al_4Si_5O_{18}$)
  - Aluminum Nitride (AlN)

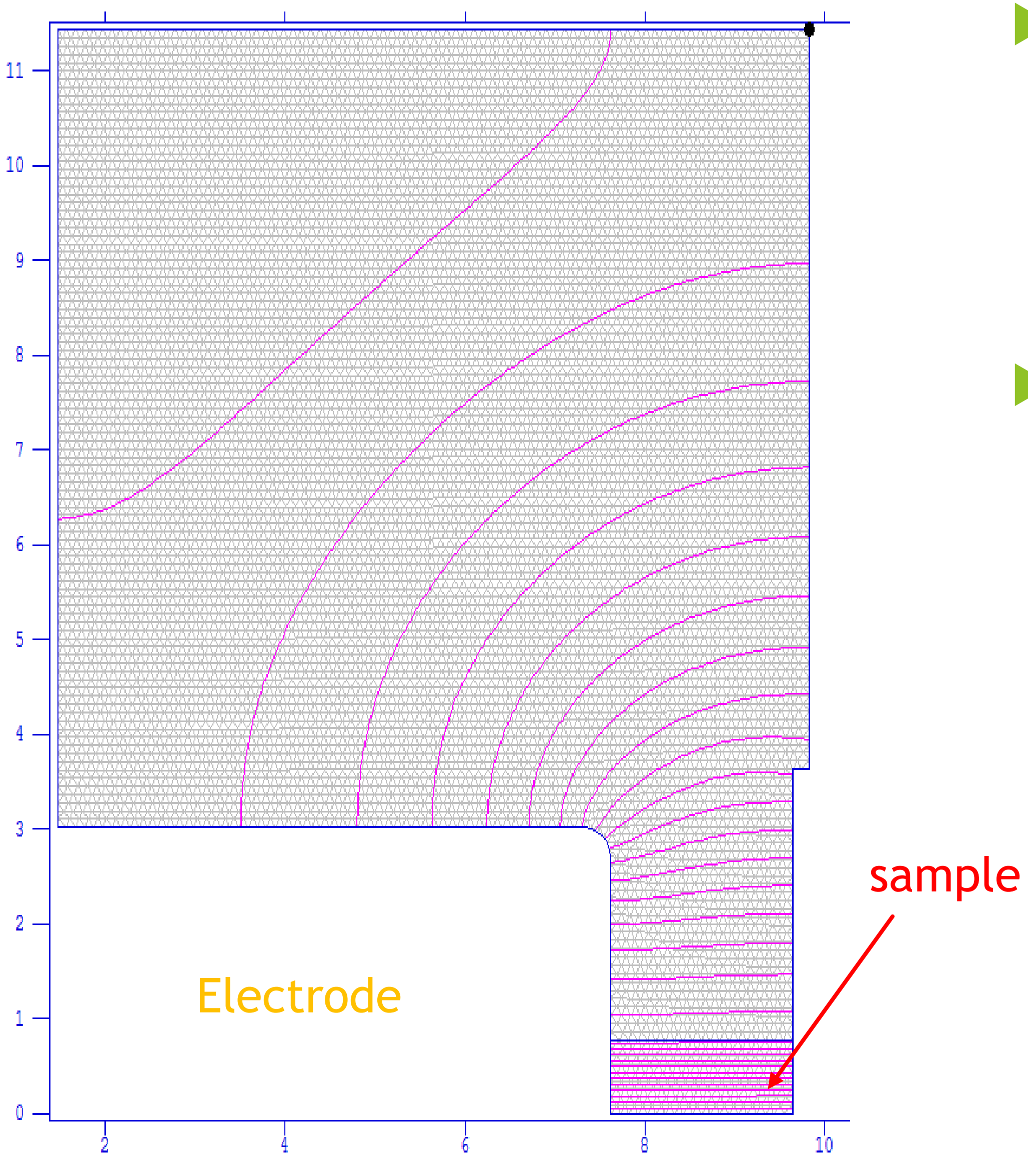


Experimental setup





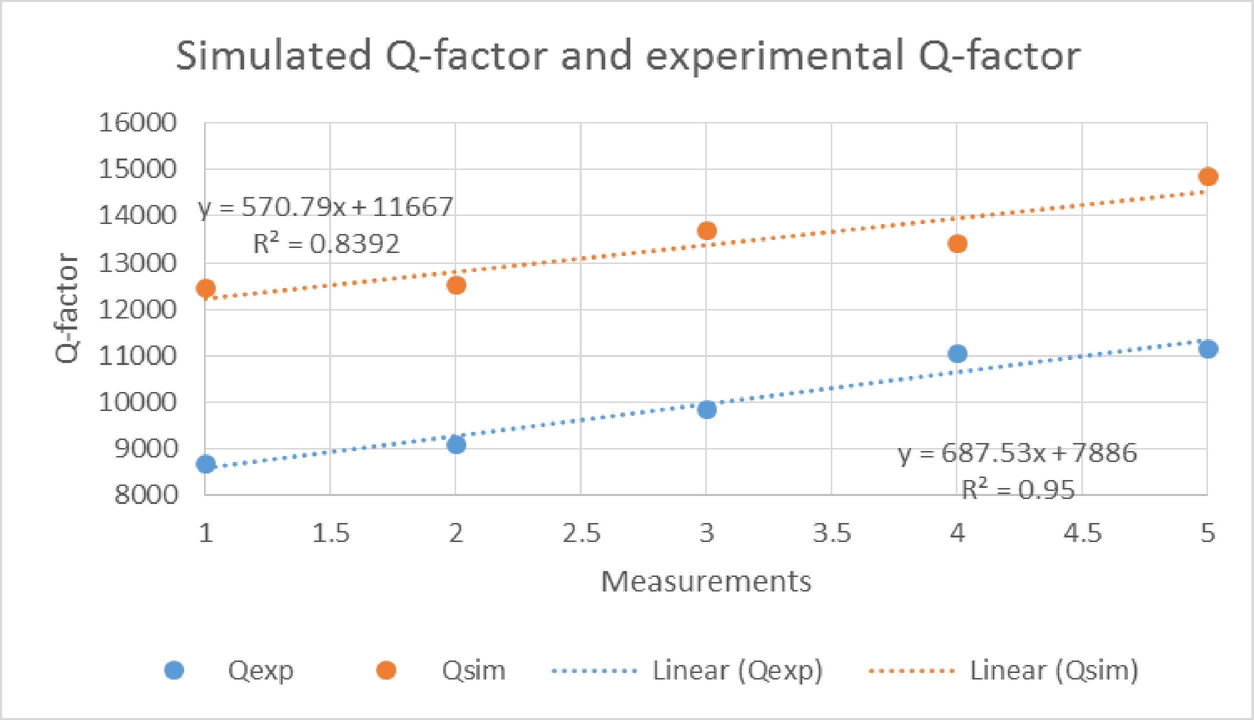
Method



- Measure quality factor and resonant frequency of cavity with dielectric sample inside
- Compare with quality factor vs loss tangent plot and resonant frequency vs dielectric constant plot obtained from POISSON/SUPERFISH simulation to determine sample's properties

Calibration

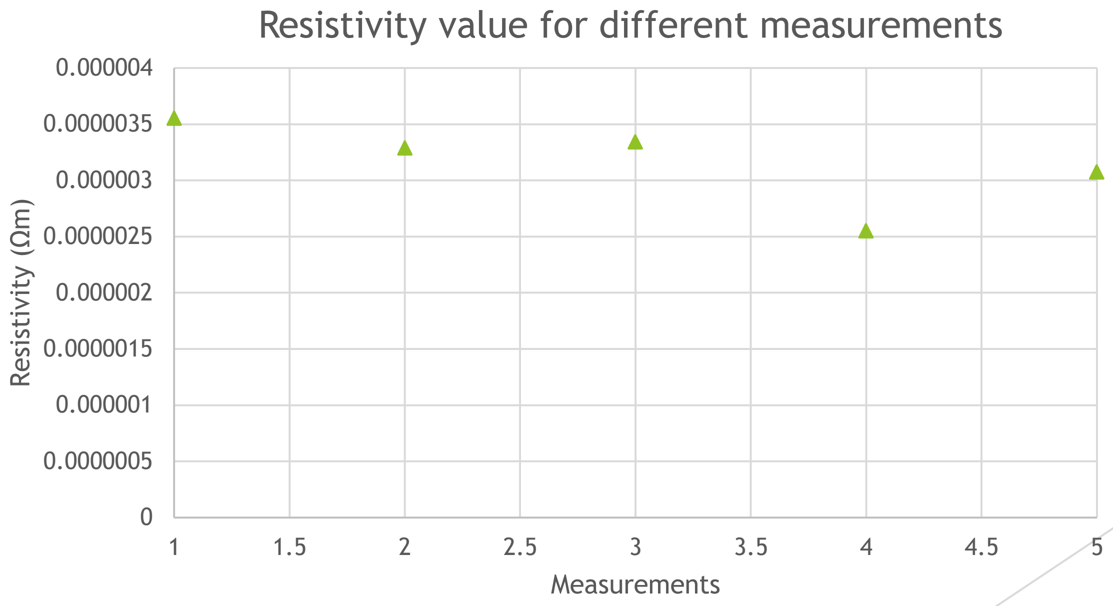
- SUPERFISH assumes ideal resistivity for copper wall => need to find actual wall resistivity
- Simulate empty cavity and compare with actual empty cavity with no sample



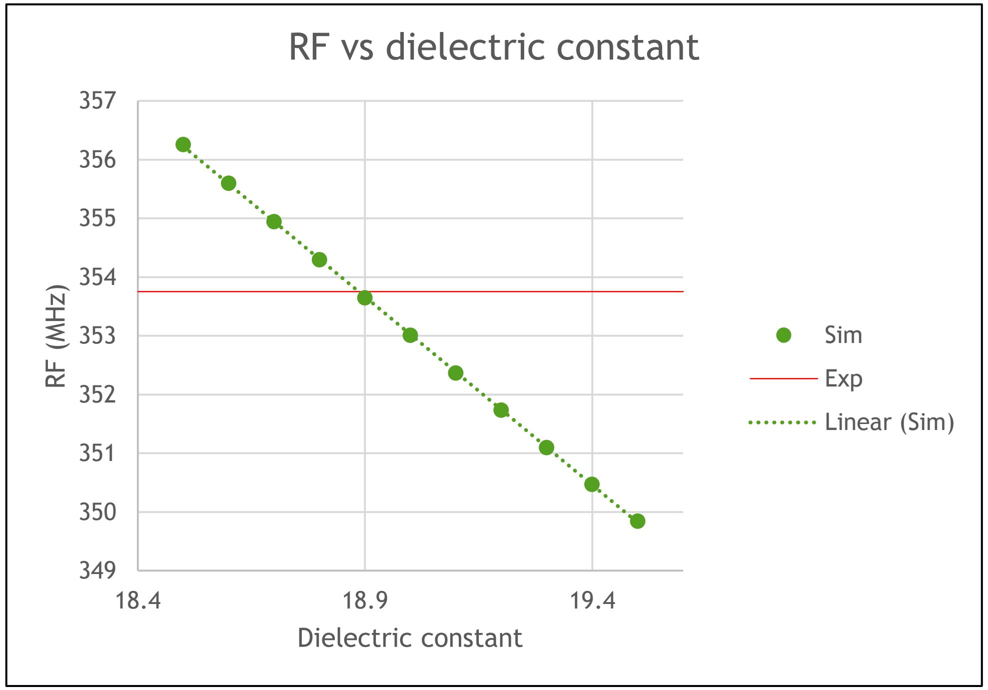
- Relationship between wall resistivity and quality factor:

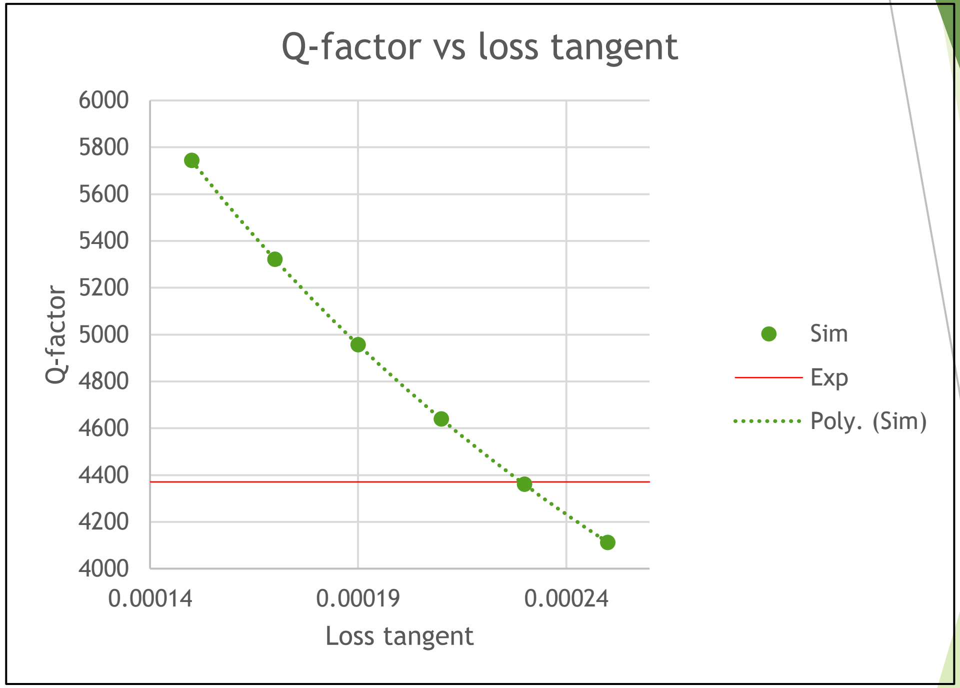
$$\rho_{wall} = \left(\frac{Q_{simulation}}{Q_{experimental}} \right)^2 \rho_{ideal}$$

- $\rho_{wall}=3.16x10^{-6}(\Omega.m)$



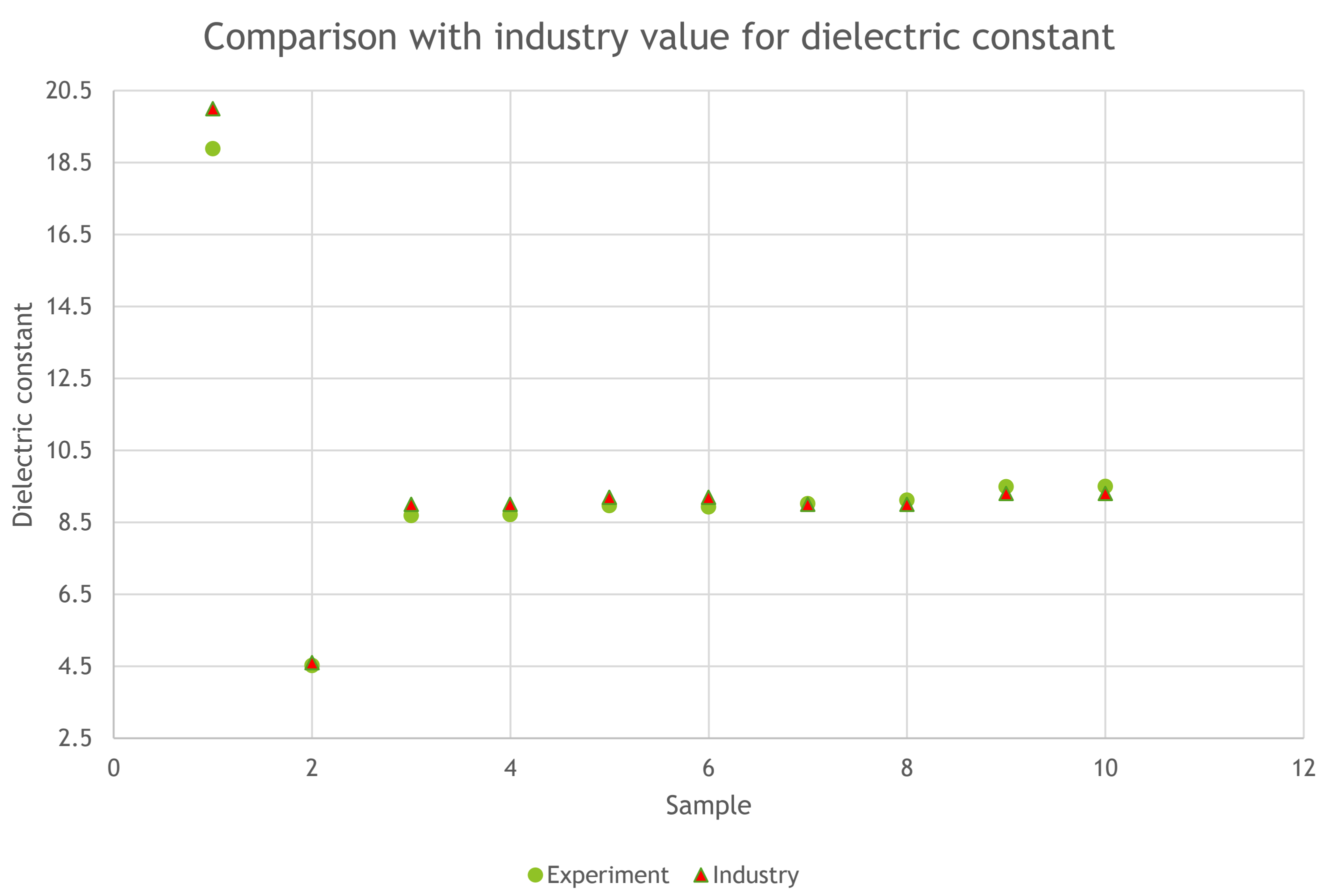
Results





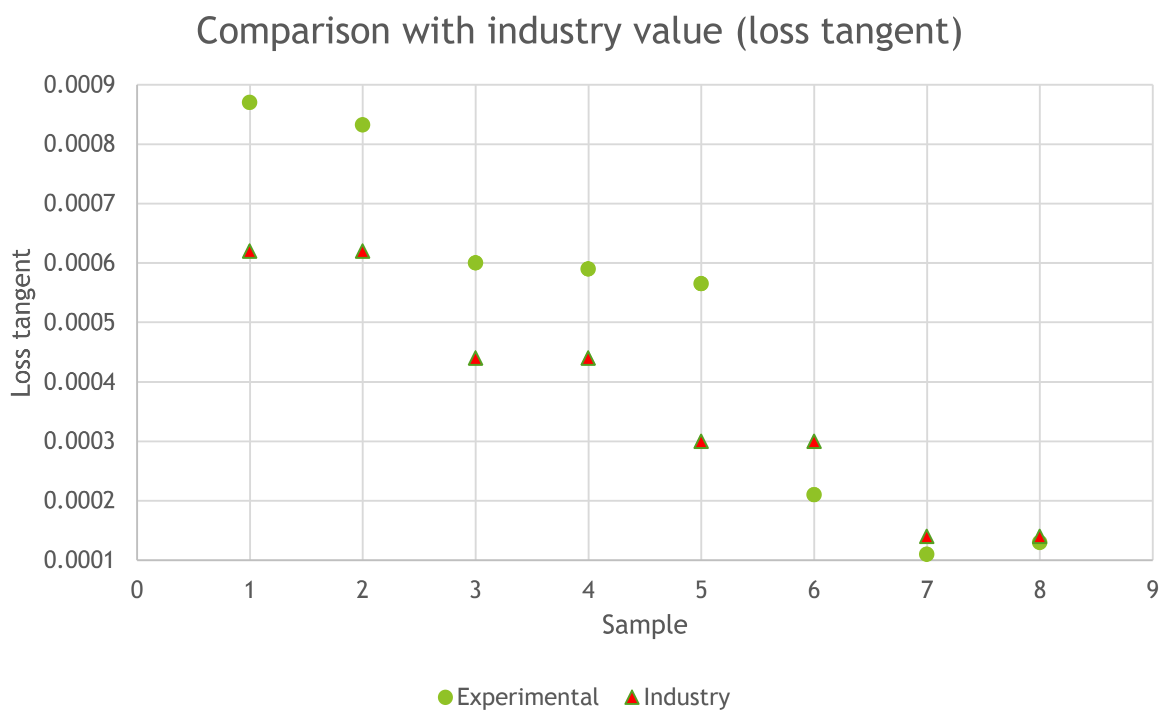
Sample data of MCT

Dielectric constant and loss tangent => intersection between simulated relationship and measured values



1/ MCT
2/ Corderite
3/ Alumina 94%
4/ Alumina 94%
5/ Alumina 96%
6/ Alumina 96%
7/ Alumina 97.6%
8/ Alumina 97.6%
9/ Alumina 99.5%
10/ Alumina 99.5%

- Dielectric constant error all falls within 6%
- Closely match industry-given value for dielectric constant



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7/ Alumina 99.5%
8/ Alumina 99.5

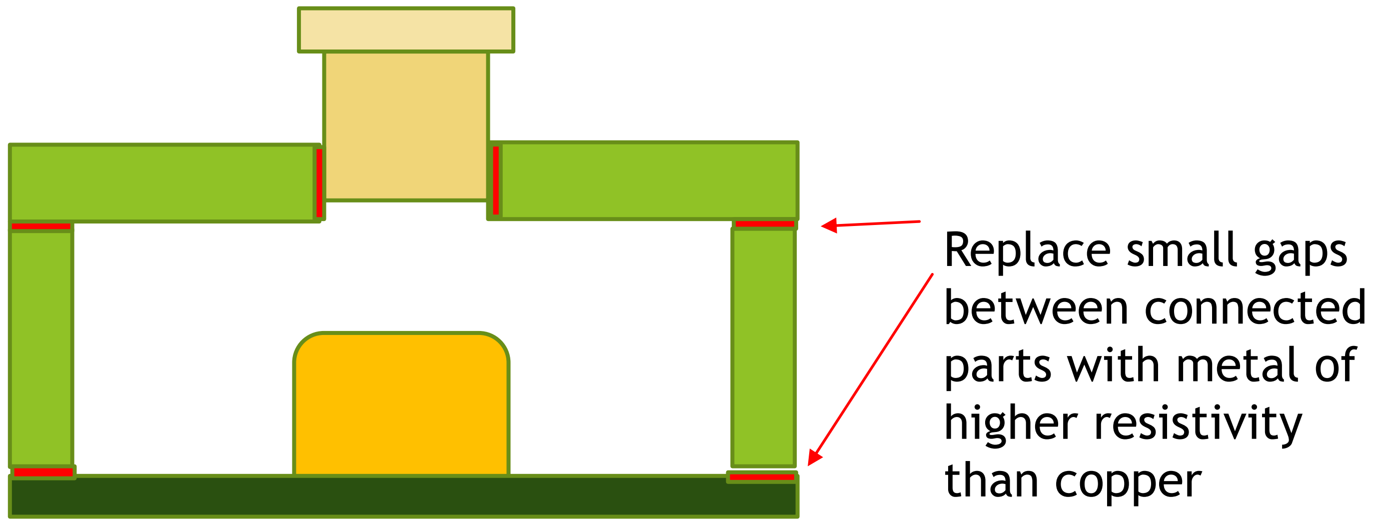
- Comparison used only alumina samples since there is no given loss tangent for others.
- Calculated loss tangent experiences increasing discrepancy with decreasing alumina purity.
- Either the vendors calculate it wrong or there is systematic error in the simulation
- Possible source of systematic error: resistivity at connected joint between cavity's components

Conclusion

- Calculated dielectric constants follow consistently with vendor-provided values
- Discrepancy between calculated loss tangent and vendor-provided values might be because of connection’s resistivity.
- Overall, alumina 99.5% gives the most desirable values for dielectric constant (~9.5) and loss tangent (0.00013)

Future step

- Proposed new model to describe better wall resistivity of test cavity:



- Apply same test for the actual ring in high-powered beam test.

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