FE-FRT Research at HZB

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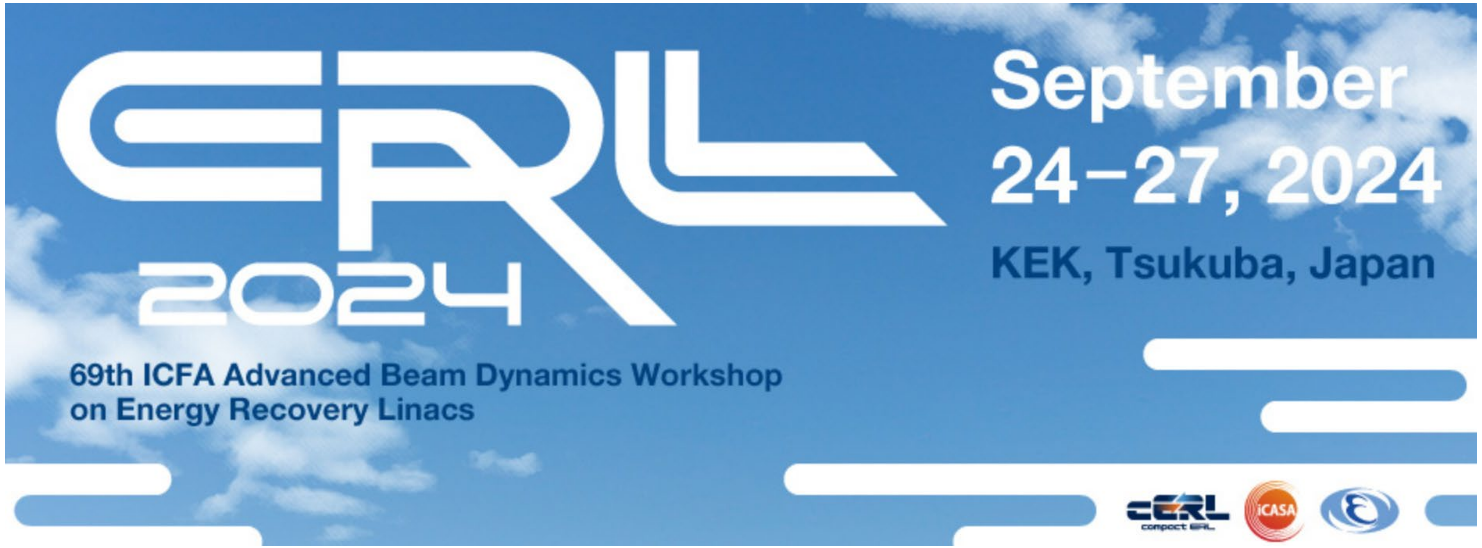
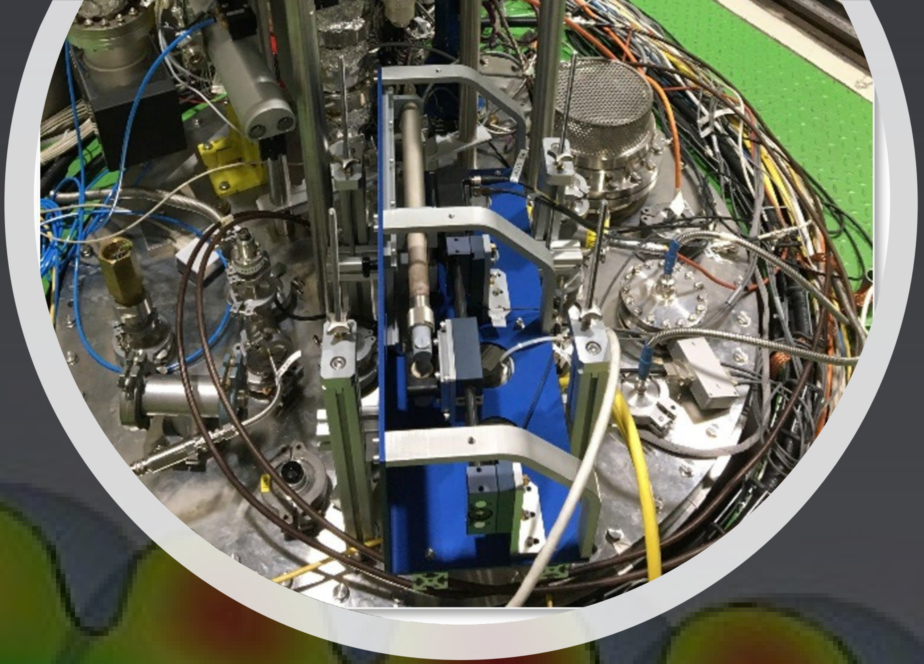
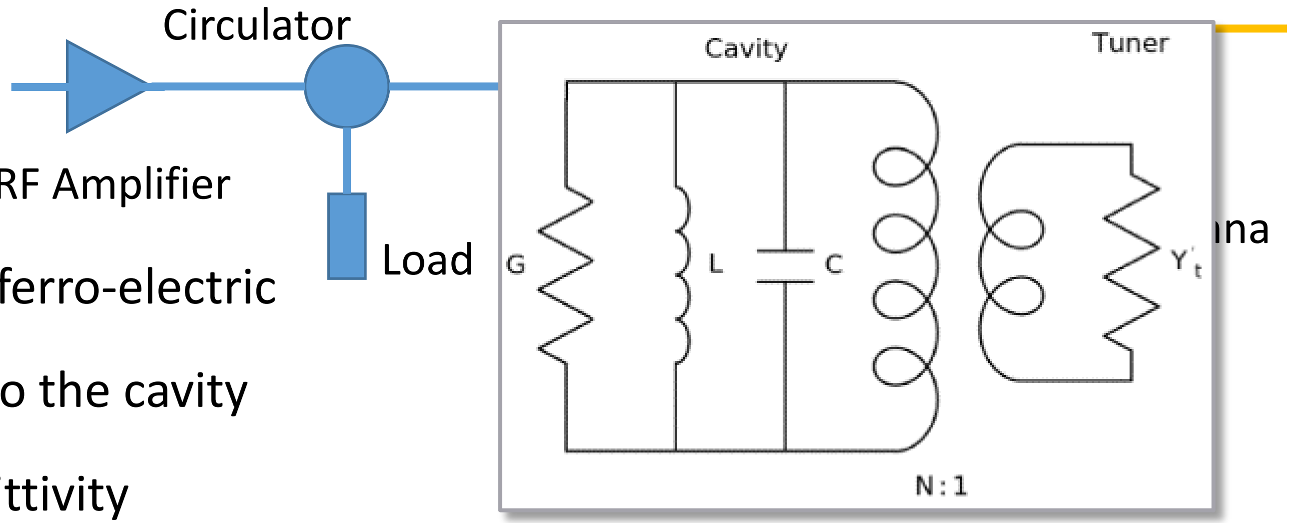
Acknowledgements: Euclid Techlabs



Introduction to FRTs



FE-FRT Concept



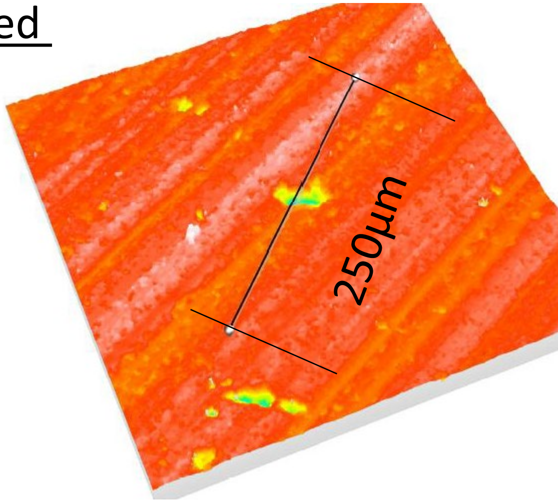
- An FE-FRT is a shorted co-axial structure containing a ferro-electric
- RF power flows into the FE-FRT and is reflected back to the cavity
- Voltage applied to the ferro-electric changes its permittivity
- Permittivity change → Phase change of the reflected power → Cavity frequency change
- Usually, the FE-FRT would require its own port, although other arrangements have been proposed
- Operates outside cryomodule at room temperature
- Tunes cavity without mechanical deformation
- Tuning speed measured at less than 600ns, limited by HV circuit

$$\boxed{\mathrm{FoM} = \frac{\Delta\omega_{12} U_{cav}}{\sqrt{P_1^{diss} P_2^{diss}}}}$$

Ferro-electric material

Parameter	Value
Relative Permittivity	160
Tunability	1.4
Breakdown Strength	20 Vμm^{-1}
Thermal Conductivity	7.02 Wm^{-1}K^{-1}
Speculated Max. Safe Temperature	50 K

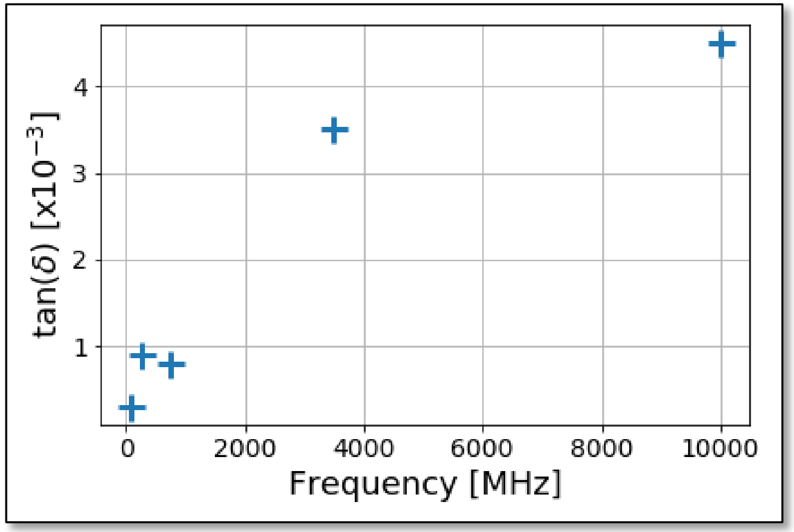
<ins>Optical Microscopy/Profilometry as received</ins>
(courtesy A. Prudnikava)



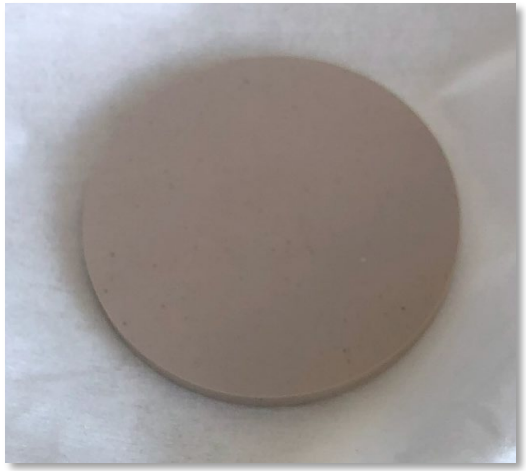
- Machining marks ±5µm and pores diameter 40-100µm depth up to 40µm visible with laser profilometry.

- Discoloration ca. 300um viewed with optical microscope. Also visible by eye.

Loss tangent measurements

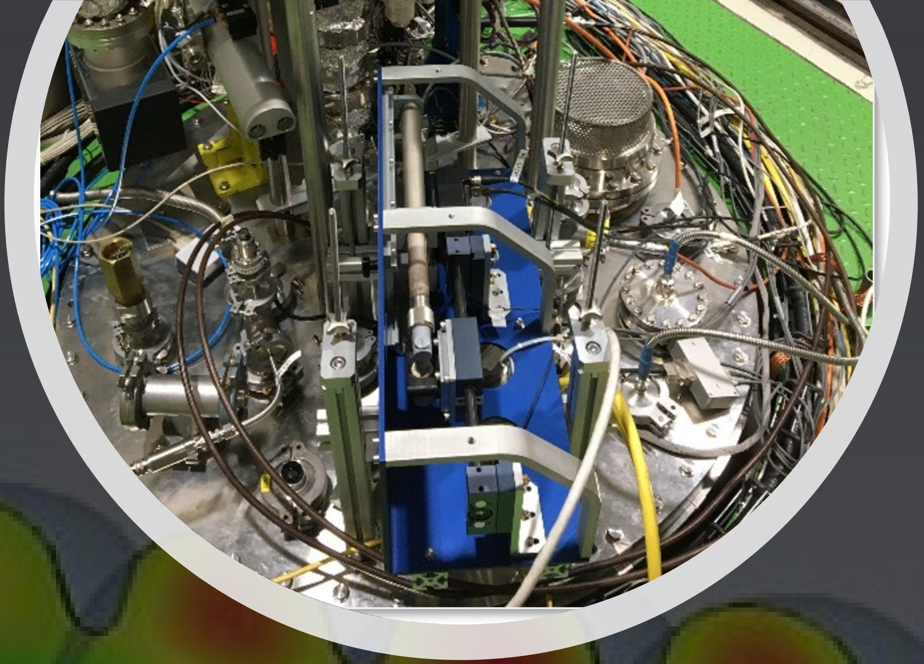


- BST(M) material
  - $BaTiO_3$-$SrTiO_3$ with Mg based additives
- High Tunability
- Low loss tangent
  - $\propto f$ between 10MHz – 10GHz
  - very roughly
- “Low” relative permittivity



A BST(M) Ferroelectric Sample

40mm diam
2.5mm thicl

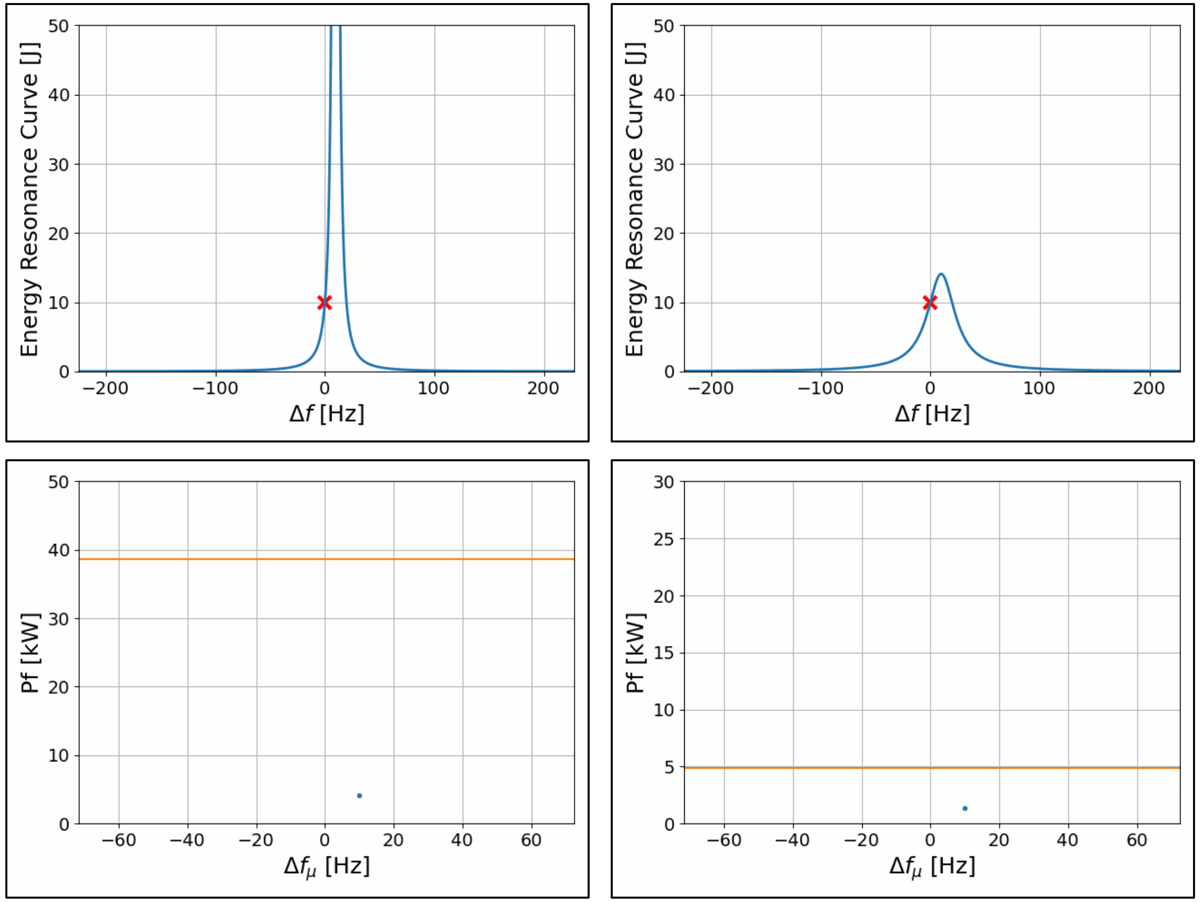


Microphonics Suppression

Microphonics Suppression

$$P_{RF} = \frac{V_c^2}{4 \,{}^{R}\!/_{Q}\, Q_L}\,\frac{\beta+1}{\beta}\left[1+\left(2Q_L\frac{\Delta\omega_\mu}{\omega_0}\right)\right]$$

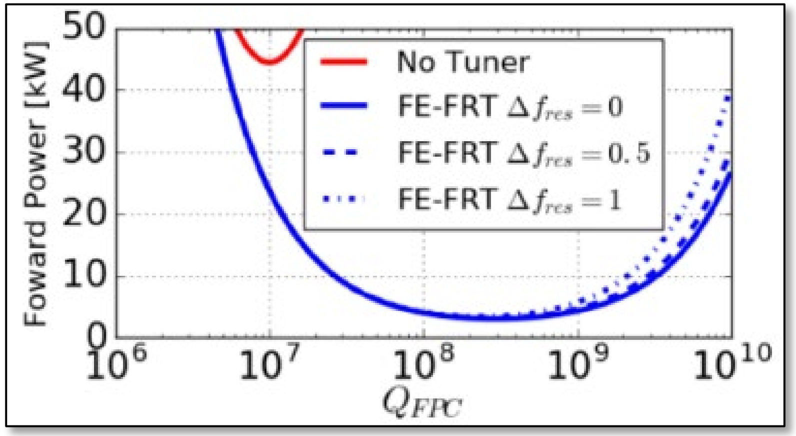
- For low beam loading machines RF power is dominated by microphonics
- The effect of microphonics can be reduced passively or actively
  - Stiffening of cavity
  - Isolation of noise sources
  - Active feedback e.g. piezo tuners
- Residual microphonics require over-coupled FPC
- Typically, RF power required is still many times larger than for critical coupling case



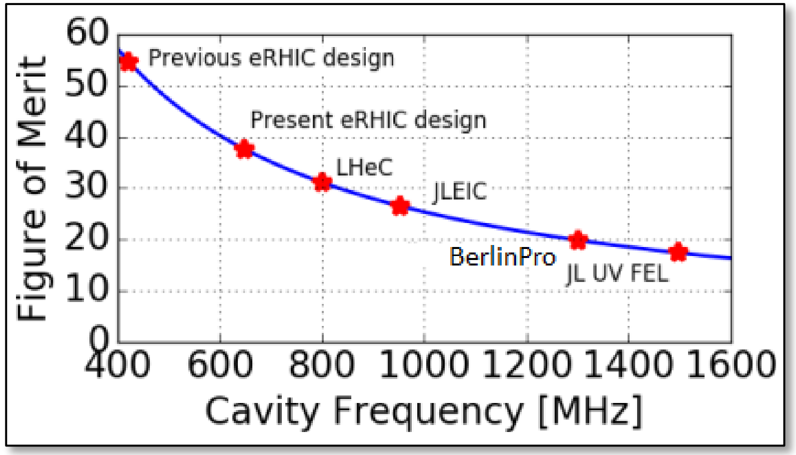
Decreasing Q_L

Microphonics Suppression

- FRTs are an excellent tool for microphonics suppression
  - High Tuning speed
    - ~600ns measured limited by external HV circuit
  - No excitation of mechanical modes
  - Simple transfer function/negligible phase delay at frequencies of interest
- Peak and average RF power reduced by $\frac{FoM}{2}$ and $\frac{FoM}{4}$ respectively
- Increased dielectric and conductor losses at higher RF frequencies reduce effectiveness
- FRTs can be combined with other suppression technologies
  - E.g. piezo tuners
- Estimate FRTs could still beneficial up to ~2-3 GHz
  - Not experimentally verified



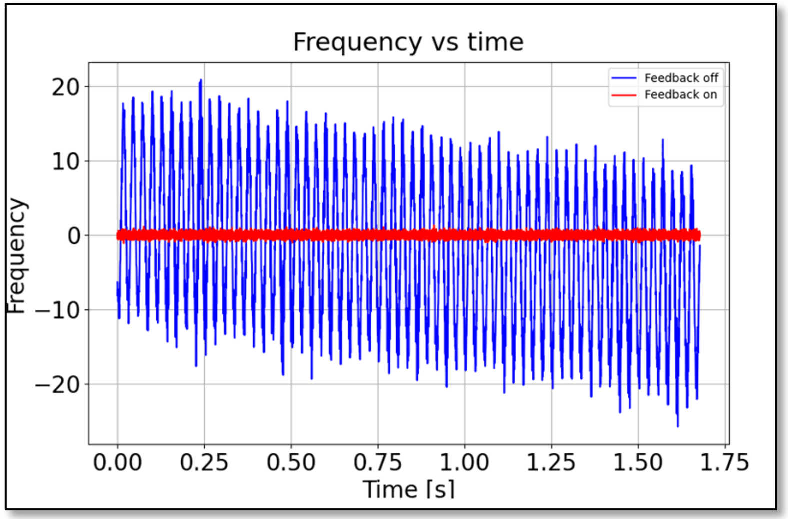
Case study: RF power for PERLE vs Qe with and without FRT

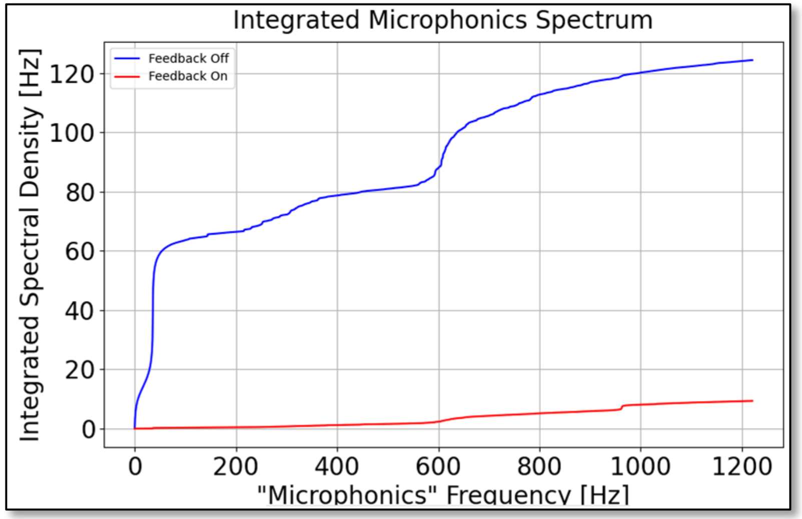


Estimated FRT FoM vs RF frequency

Microphonics Suppression Results (CERN)

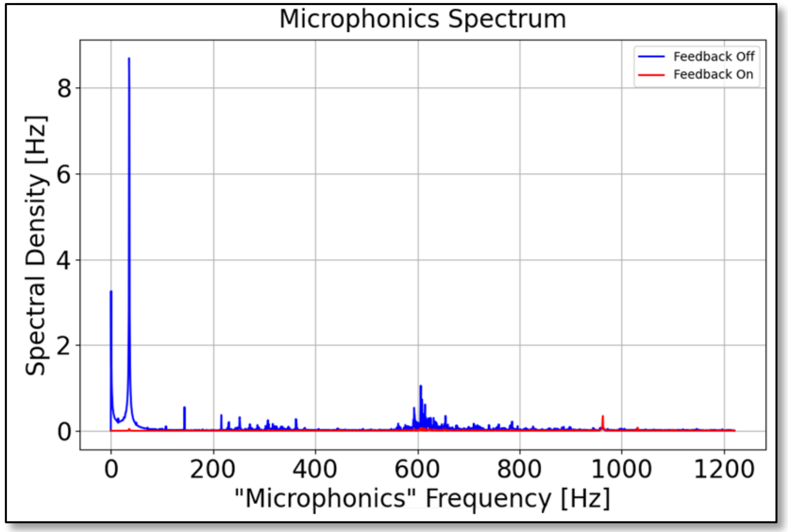
(with vibration generator @ 37Hz)





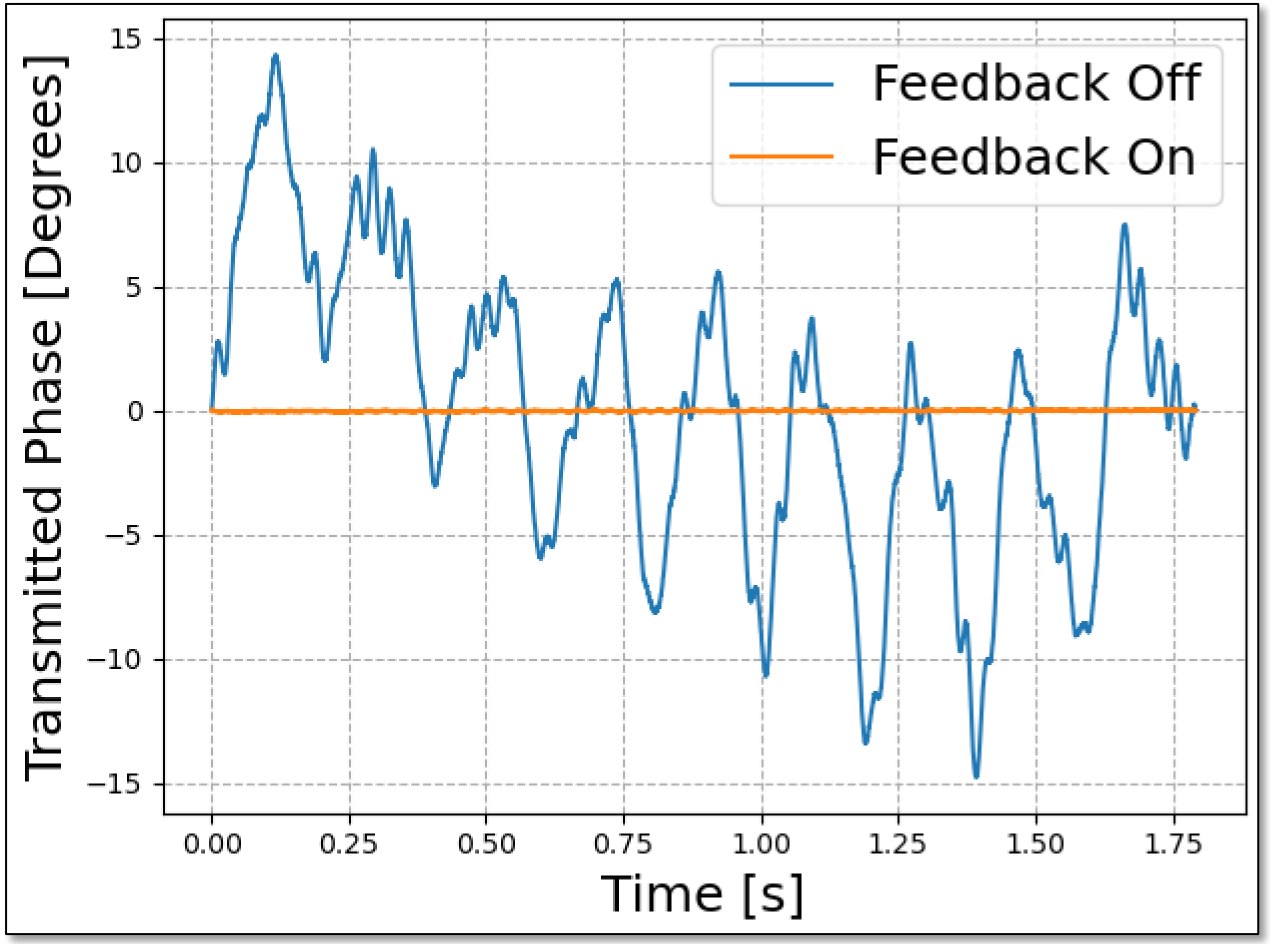
🟦 No correction

🟥 With correction

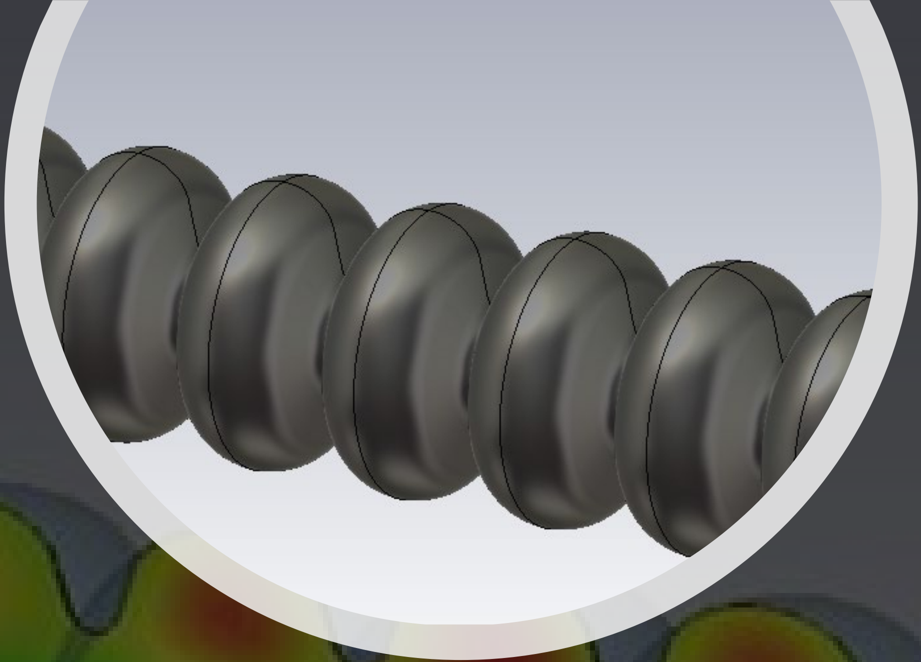


- Vibration generator set to 37Hz
- Integrated microphonics spectral density up to 1kHz reduced by factor ~14
- Greater reduction with more microphonics.
- Peak deviation with correction $< \pm 1.2\text{Hz}$

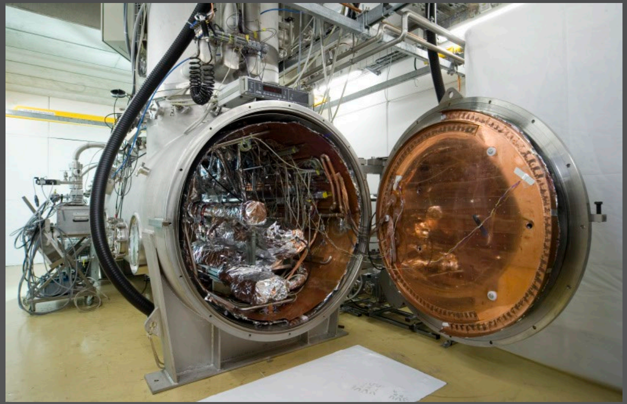
Microphonics Suppression Results: Phase Stability (CERN)



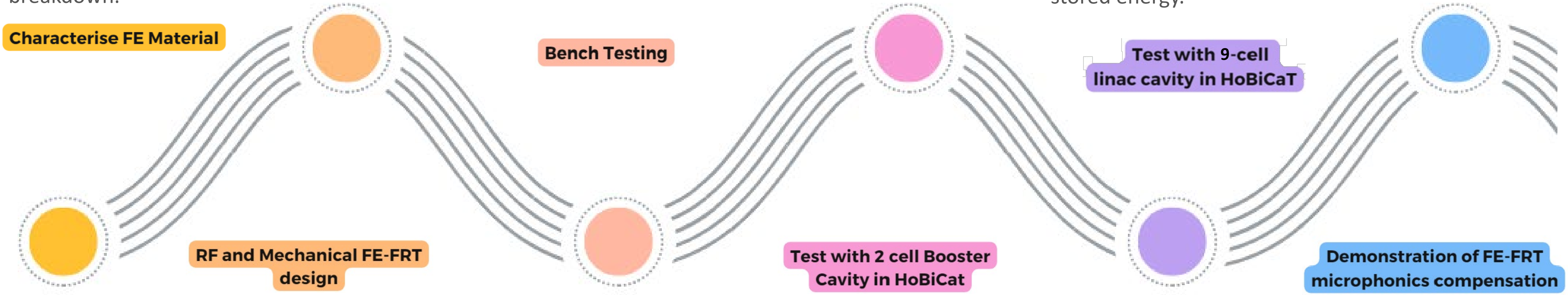
- Measured phase with FE-FRT feedback off vs on
- Phase relative to average frequency over meas. period
- Sampled at ~2.3kS/s
- Standard deviation with feedback on < 0.019 degrees
  - Without RF feedback!
  - With vibration generator on!
  - Without beam



FE-FRT for BerLinPro



WP1 Task 1.3 timeline



Characterise FE Material

Loss tangent and permittivity vs electric field and temperature at 1.3GHz. Compression and breakdown.

RF and Mechanical FE-FRT design

Principle challenges:

- Obtain high FoM at 1.3GHz
- Don’t significantly impact heat load
- High electric bias field without breakdown
- Machining/compression of FE
- Integration into HoBiCaT
- Keep design simple/feasible

Bench Testing

Check RF performance as built vs simulation. Re-machine critical components to tune as necessary.

Test with 2 cell Booster Cavity in HoBiCat

Test FE-FRT with jacketed 2 cell booster cavity in HoBiCaT. Low cavity stored energy. Mechanical tuner, microphonics control and full LLRF optional.

Test with 9-cell linac cavity in HoBiCaT

Test FE-FRT with 9-cell tesla cavity in HoBiCaT. Demonstrate full tuning range with full cavity stored energy.

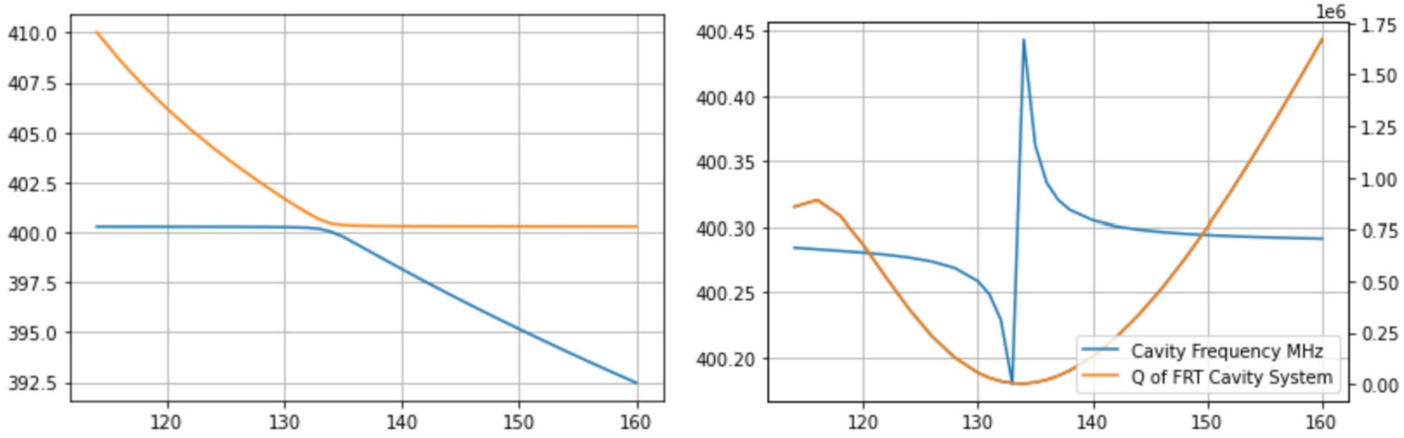
Demonstration of FE-FRT microphonics compensation

Test FE-FRT with 9-cell tesla cavity in HoBiCaT. With full LLRF control and microphonics control including piezo tuner. Demonstrate significant RF power reduction.

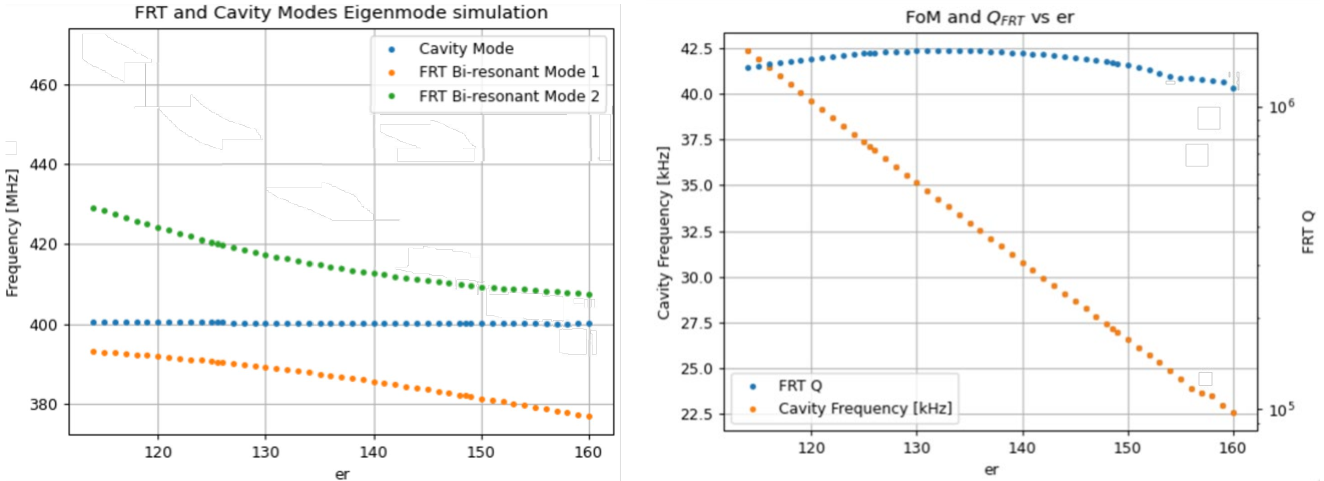
Resonant FRT design

- FE-FRTs with tunable resonance near cavity frequency allow larger tuning ranges with smaller couplers
- Changing permittivity moves FE-FRT mode above or below cavity resonance
- Cavity ‘drives’ FE-FRT either side of FRT resonance
  - => large change in reflected phase
  - => large cavity tuning range
- FRT and cavity fundamental form coupled mode system
- **Resonant Setup**
  - Cavity freq. not continuous
  - Large losses towards center of tuning range
- Solution:
  - Increase line length between cavity and FRT by $\lambda/4$
- **Bi-resonant Setup**
  - Continuous freq. change
  - Lower losses in center of tuning range

Resonant setup

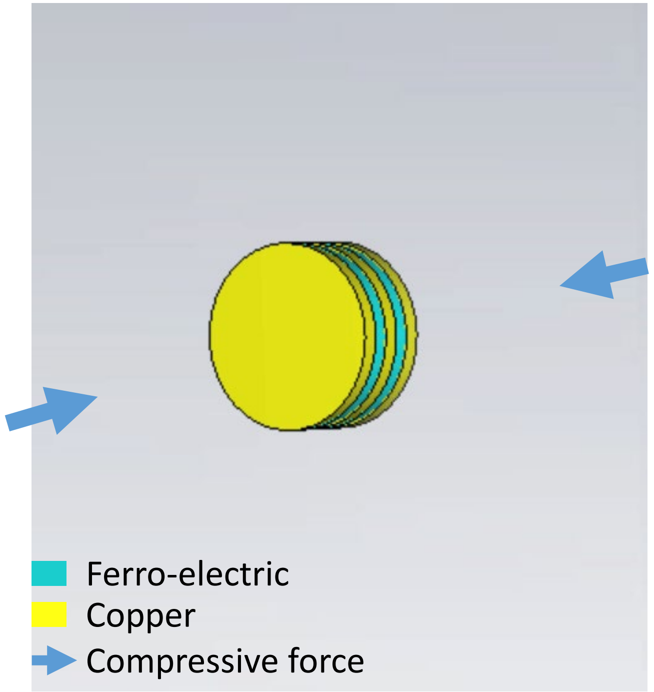


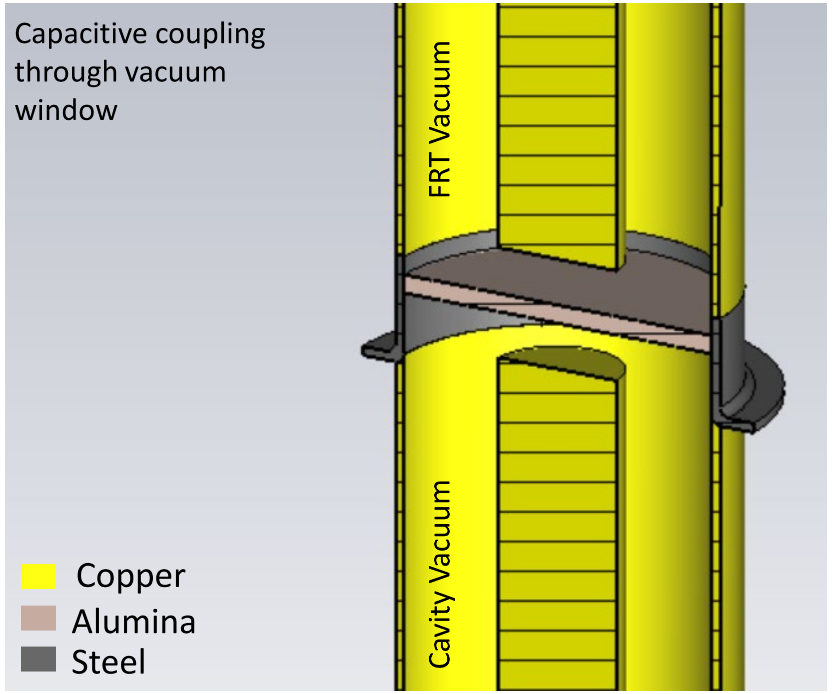
Bi-resonant setup



BE-FRT features

- Bi-Resonant
  - FRT is resonant near cavity frequency
  - Large phase change -> larger tuning range with smaller antenna
  - Add $^{\lambda}/_{4}$ transmission line -> bi-resonance avoids losses in center of tuning range
- Only two FE wafers
  - Simplifies HV biasing issues
  - Increases power dissipated per wafer
- High aspect ratio annulus FE wafers
  - Minimises losses/maximises FoM
- Simple as possible
  - Few parts requiring tight mechanical tolerances
  - Capacitive coupling through off the shelf vacuum window
  - No other ceramic or FE brazing





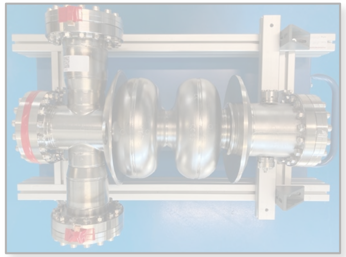
BE-FRT – Power and Temperature Estimates

- Tuning Range = 20Hz
- FoM = 25 (simulated value of current un-optimised design)
- $\mathrm{FoM}_{\mathrm{mat}}$ ~ 125
- FE thickness t = 1.25mm
- Electrode contact area $A \approx 2.2 \times 10^{-4}$
- Number of wafers = 2

		Booster	LINAC
Power dissipated in FRT:	$P_{diss}^{FRT} \approx \frac{\lvert\Delta\omega_{12}\rvert U_c}{FoM}$	12.6 W	180 W
Power dissipated in FE:	$P_{diss}^{FE} \approx \frac{\lvert\Delta\omega_{12}\rvert U_c}{FoM_{mat}}$	2.5 W	36 W
Power dissipated in cavity:	$\boldsymbol{P_{diss}^{cav} \approx \frac{\omega_0 U_c}{Q_0}}$	1 W	**15 W**
Avg. RF power w/o FRT:	$\boldsymbol{P_{avg}^{RF} = \frac{\Delta\omega_{\mu}^{peak} U_c}{2}}$	200 W	**3.4 kW**
Peak RF power w/o FRT:	$\boldsymbol{P_{avg}^{RF} = \Delta\omega_{\mu}^{peak} U_c}$	400 W	**6.8 kW**
RF power with FRT:		13.6 W	**195 W**
Temperature rise in FE:	$\Delta T = \frac{P_{diss}^{FE} t}{6kA}$	2.1K	8.5K

Booster Cavity

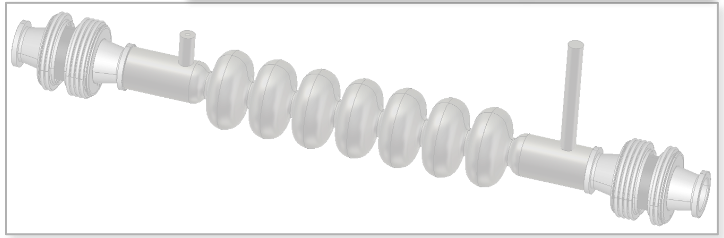
Parameter	Value
f0	1.3 GHz
Q0	2 10^10
R/Q	219
Stored Energy	2.5 J
Voltage	2.1 MV



N.B. idea is to use piezo tuner to reduce peak microphonics from 30 to 20Hz

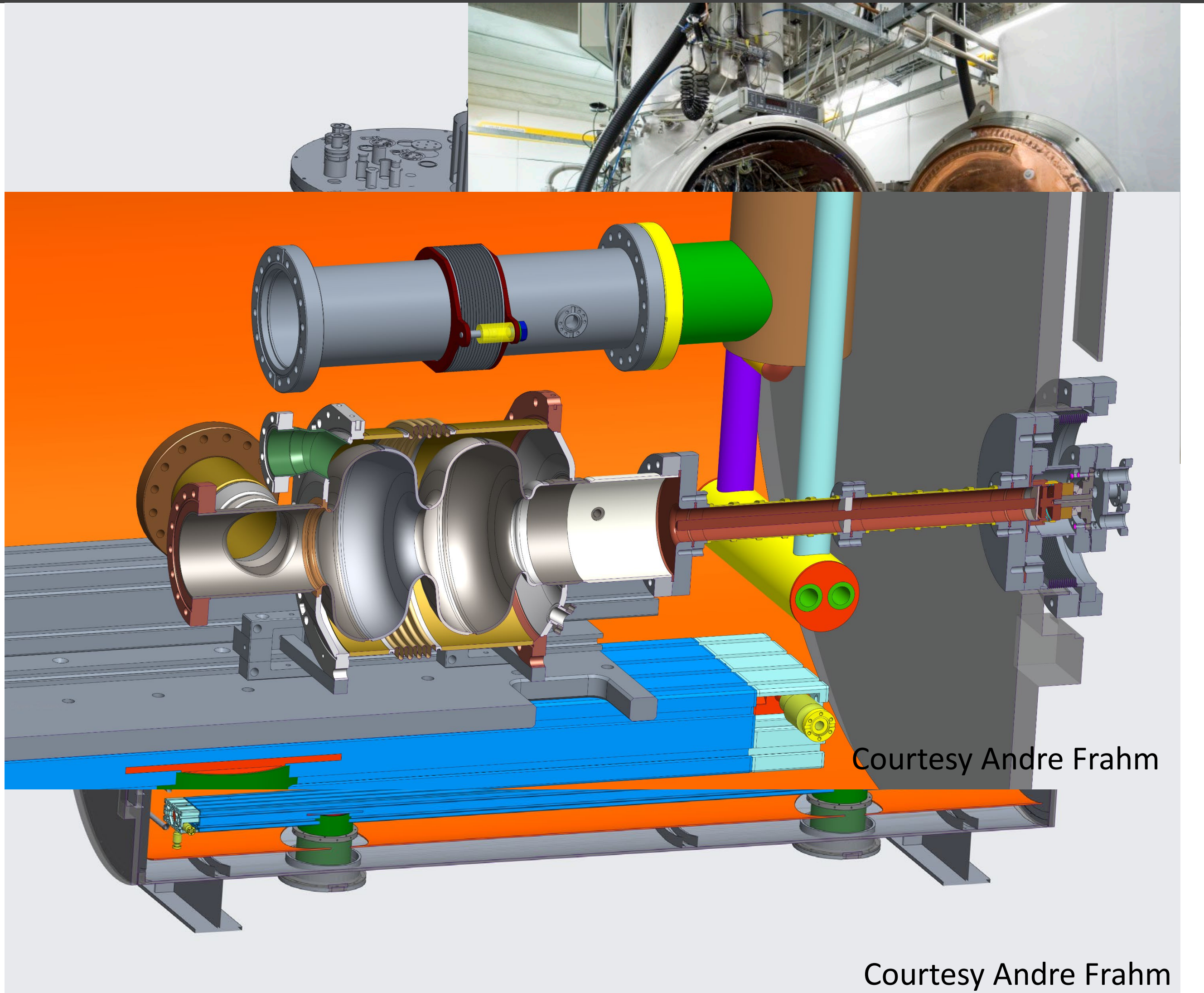
7 cell bERLinPro LINAC Cavity

Parameter	Value
f0	1.3 GHz
Q0	2 10^10
R/Q	788
Stored Energy	36 J
Voltage	15 MV
Peak µphopnics Detuning	30 Hz
Peak LF Detuning	520 Hz



Mechanical Design and HoBiCaT Integration

- HoBiCaT – Horizontal Bi-Cavity Testing
- Designed for tests of fully dressed cavities in CW mode
- Cavities can be equipped with all components needed for SRF module e.g. tuners, high power input coupler etc.
- Both 2-cell booster and 9-cell cavity FRT tests will use HoBiCaT
- Mechanical design and integration at advanced stage
- Port in HoBiCaT door used to allow FRT to be placed at room temperature outside of HoBiCaT
    - Avoids need for anti-cryostat
- 80K and 4K intercept to reduce heat load to cavity
- Assembly procedure:
    - Cavity, Tline and window assembled in clean room
    - Slid onto table, HoBiCaT door closed
    - FRT and vacuum chamber assembled



Courtesy Andre Frahm

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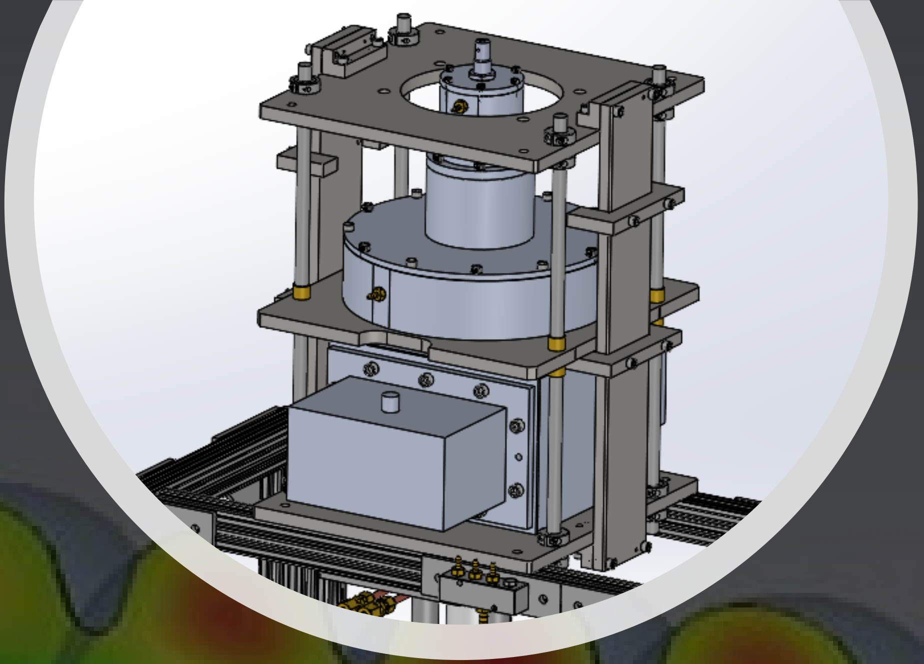
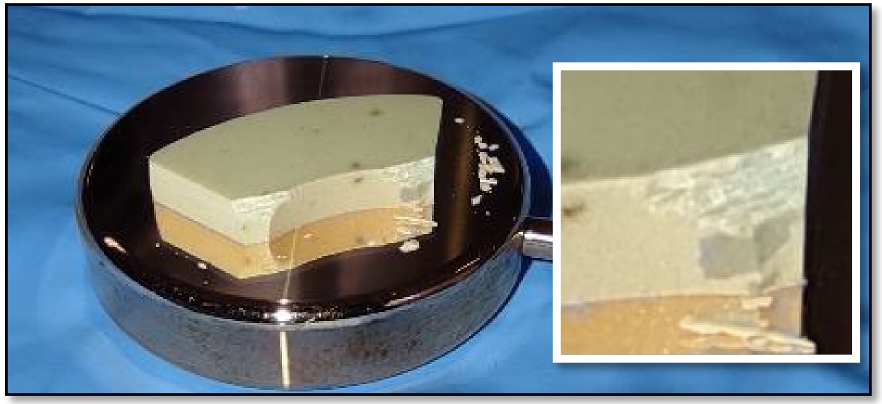


Ferro-electric Sample Characterisation

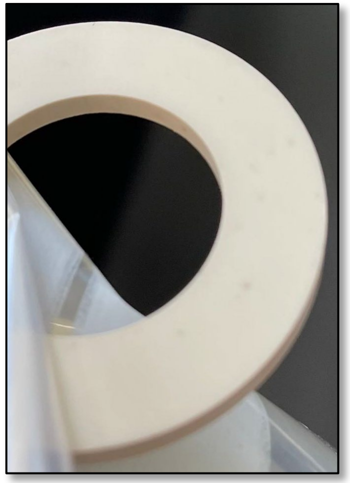
What don’t we already know?

A (very) small selection!

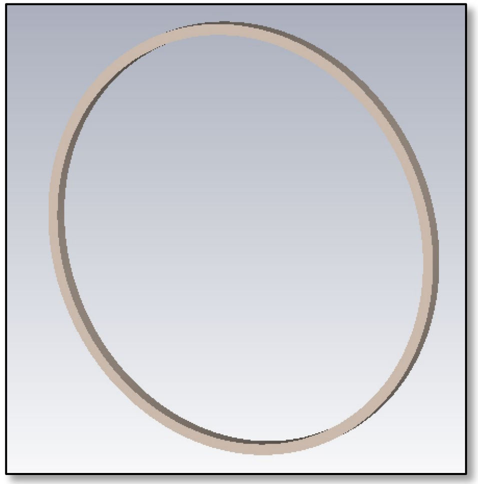
- What is the permittivity and loss tangent?
  - As a function of applied field?
  - As a function of temperature?
  - Variation between samples/batches?
- What is the maximum electric field that can be applied
  - More field => larger permittivity change => higher FoM
- How can be the samples be machined?
  - 1.25mm thick, 2mm wide, 40mm diam. annulus?
  - Does water jet cutting effect losses via absorption?
  - What surface finish is possible?
- Can heat treatments be used to lower water content and reduce losses?
  - Maximum safe temperature?
- UHV compatibility? Outgassing?
- What is the greatest compressive force that can be applied?
  - Why? Small FE-electrode gap drops a lot of voltage
  - We don’t want to braze.



Too much compression/ sub-optimal FE geometry!



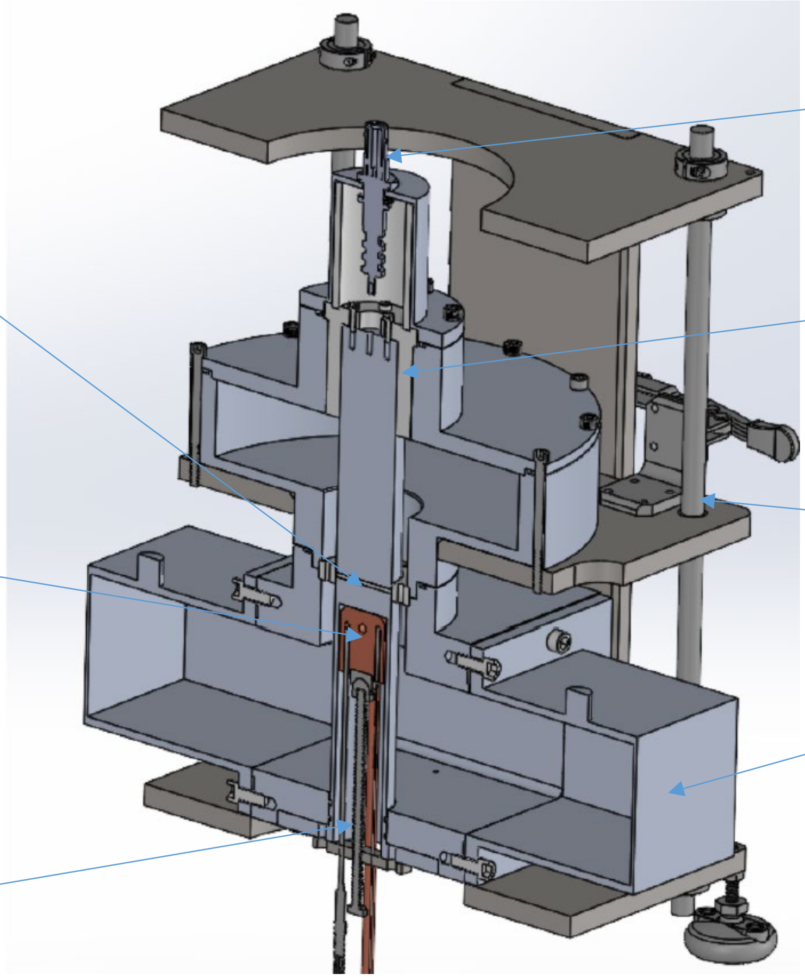
CERN TDD1 FE sample.



Nominal FE geometry for BE-FRT design.

FERMAT Design

Designed and built by: euclid TECHLABS



Ferro-electric sample

Dual use heating block
- Heater
- Thermocouple
- Coolant

Compression system
- ball and socket joint

High Voltage feedthrough

High Voltage insulation

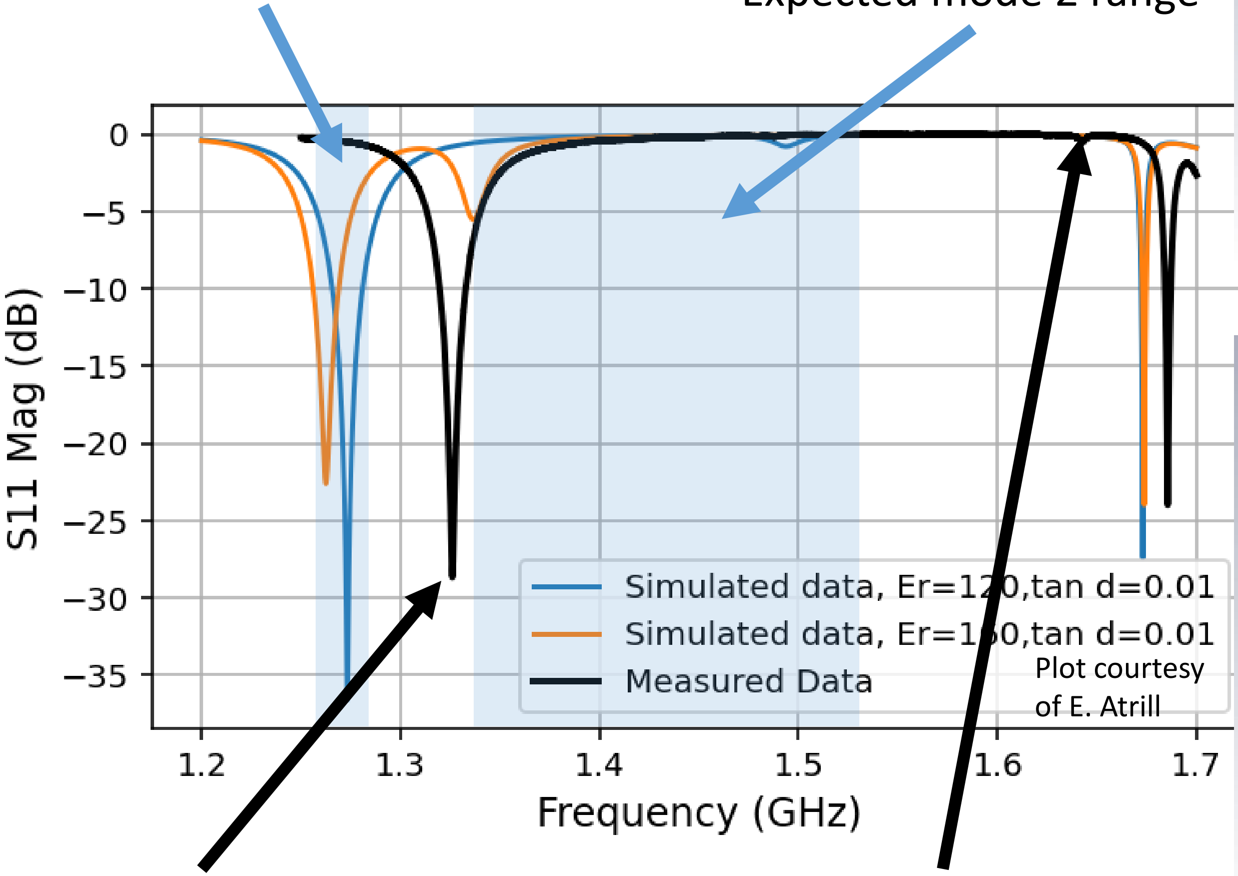
Lifting system

Co-axial-waveguide adapter

Gas tight to allow pressurised N_2 atmosphere

FERMAT Preliminary Results

- Commissioning ongoing:
  - S-params not yet close enough to simulation to allow accurate measurements of tanδ and ε_r
- Results so far:
  - ε_r decreases with T
  - ε_r decreases with E
- $\Delta\varepsilon_r$ higher with less compression
  - Opposite to expected
- 17kN compressive force applied
  - ~nominal pressure
  - No damage to sample
  - Compression system damaged
- Euclid providing full support
  - Shipping back this week
  - Minor repair
  - Investigate of S-param mismatch
  - Measurement campaign



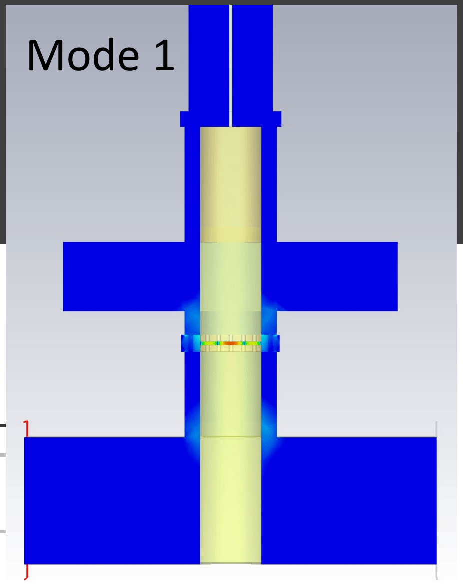
Expected mode 1 range

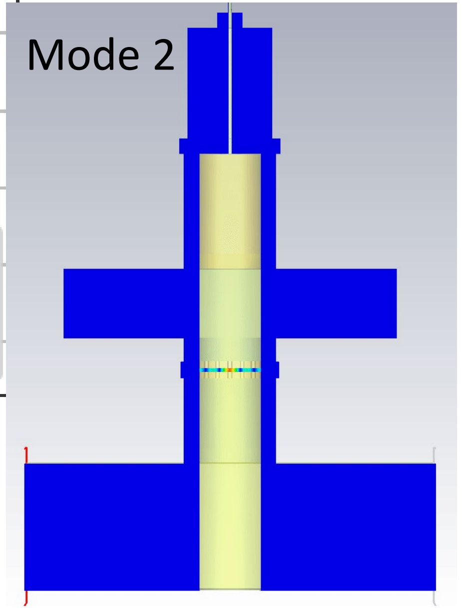
Expected mode 2 range

Plot courtesy of E. Atrill

Example of measured mode 1

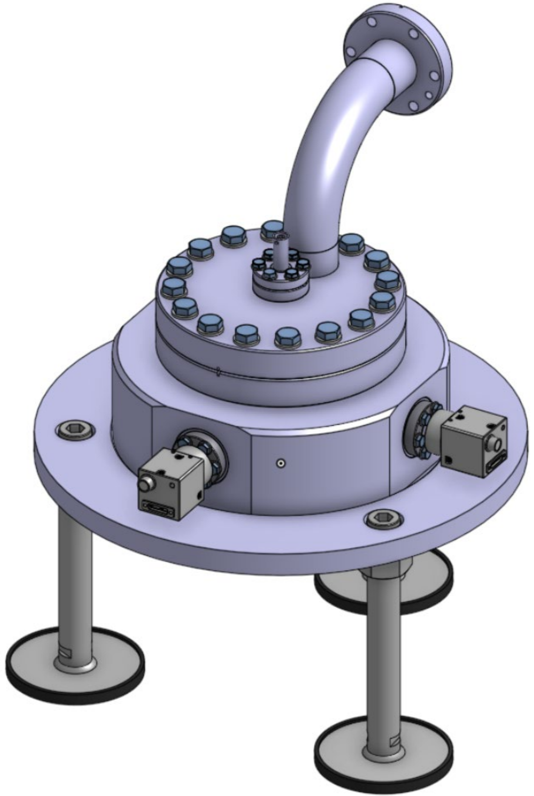
Example of measured mode 2

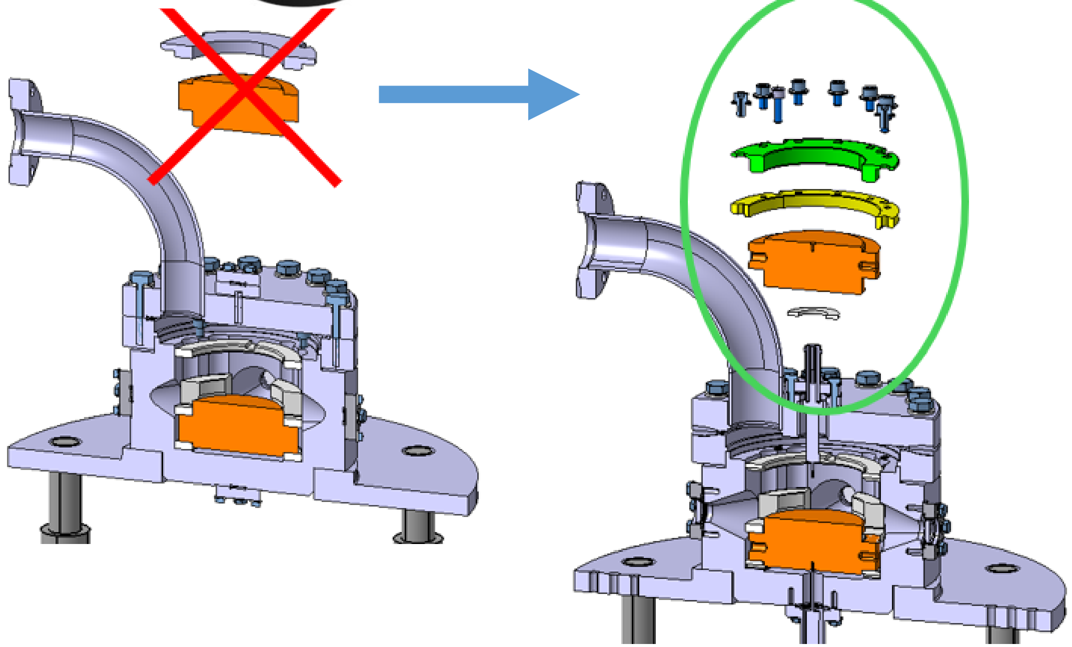


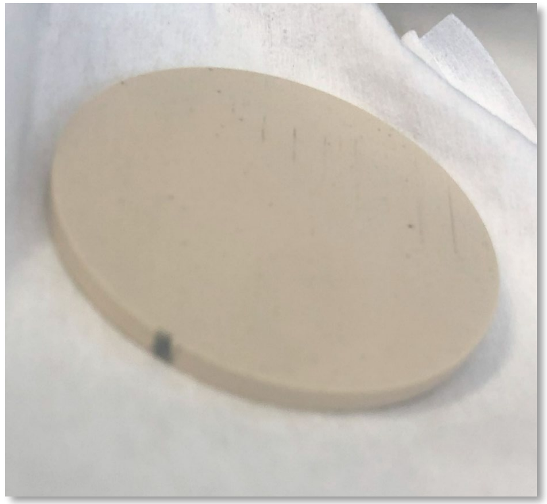


Breakdown/flashover limit

- Key to achieving desired performance
- Are DC bias fields of 8V/µm possible?
  - In ultra-high vacuum?
  - With envisioned FE geometry?
- FERMAT not UHV compatible.
- => Test in CERN LES:
  - Designed to UHV DC breakdown between two electrodes.
  - Replace vacuum gap with FE ceramic
- If not possibility to also test different FE edge geometries.
- Parts currently being machined in CERN main workshop.





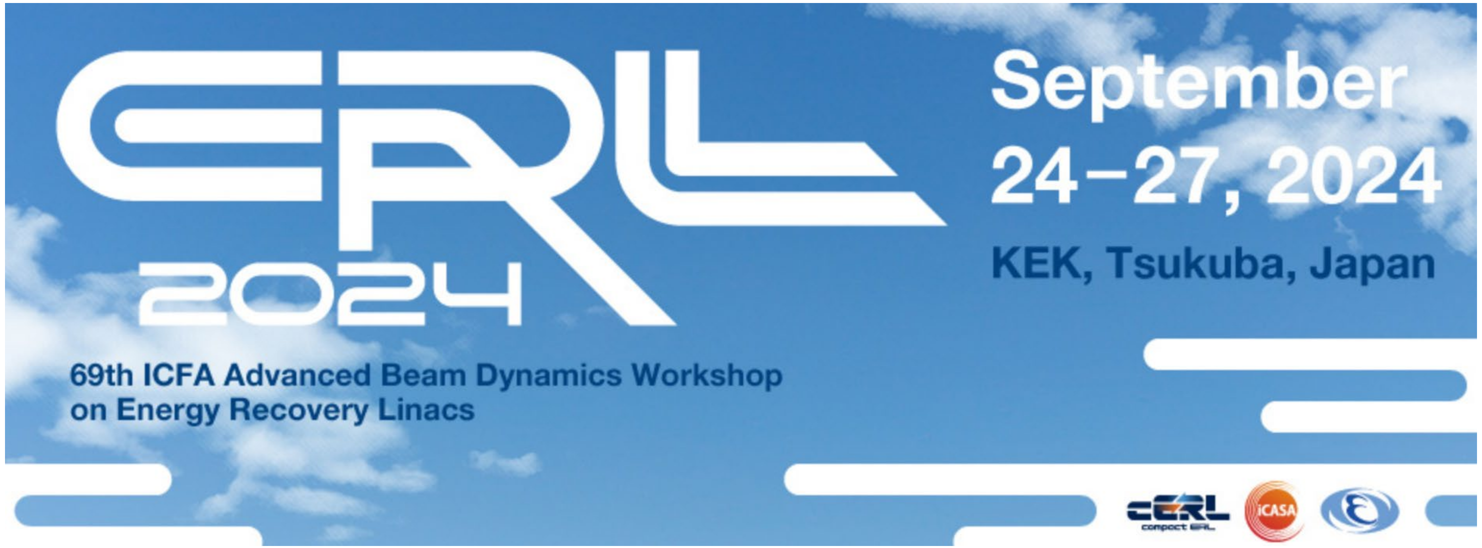


Damage from breakdown in FERMAT at 9kV (3.6V/µm) in 2.3bar N_2 atmosphere.

Conclusion and Outlook

- 4 year ISAS funded project
  - Principle collaborators: CERN, Lancaster, IJCLab
- Key milestones and deliverables:
  - Material characterization
  - 2-cell cavity test
  - 9-cell cavity test
- BE-FRT
  - Concept and preliminary FRT design complete
    - 2 wafer (bi-)resonant design
  - Mechanical design and HoBiCaT integration well advanced
  - RF design optimisation: waiting for quantitative FerMaT results
- **Fer**ro-electric **Ma**terial **T**eststand
  - Designed, built and preliminary measurements made
  - Commissioning ongoing
- Other studies
  - Demonstrated FE ceramic ability to withstand target compression pressure (~10MPa)
  - Vacuum breakdown tests in CERN LES planned
  - FE ceramic machining tests still to be performed
  - Low temperature baking investigations will be considered once quantitative loss tangent measurements in FerMaT are possible

Thank you for your attention
Any questions?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