euclid TECHLABS

Ferroelectric Fast Reactive Tuners for SRF Cavities: High-Speed Dynamic Frequency Control at High Power

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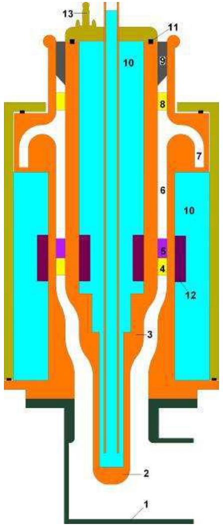
on behalf of Euclid's team

February 5, 2026

Supported by the DOE NP SBIR DE-SC0007630

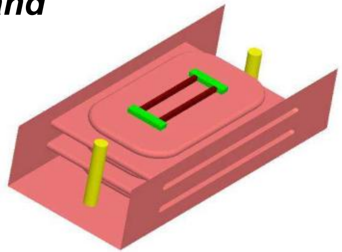
History of the Fast Ferroelectric Tuner Development



Ferroelectric phase and amplitude control was proposed during the 1990's[1], and for the RF switching by changing the frequency of an NC cavity by **V. Yakovlev in 2003[2]**.
In 2006 Ilan Ben-Zvi initiated FE-FRT research at BNL whereby the frequency of a SRF cavity would be controlled by an external ferroelectric tuner.

Initial project to develop an ultra-fast (~1us) phase shifter/tuner using ferroelectric was carried out in collaboration with Omega-P/Yale University (V. Yakovlev, S. Kazakov) and BNL (I. Ben-Zvi) in 2004-2010[3]. The phase shifter/tuner was intended to control of coupling of accelerating structures (phase/amplitude), and to tune resonance frequency of the cavity. With this project, Euclid developed a ferroelectric material with dielectric constant ε~ 500, tanδ~2×10^{-3} at 1.3GHz but low tuning range $\partial\varepsilon/\partial E_{\mathrm{bias}}$ ~2/ kV/cm[3,4].

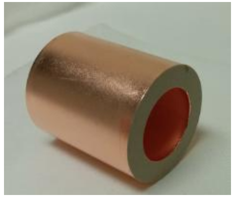
In 2013, I. Ben-Zvi (BNL) proposed a new topic for the DOE SBIR/STTR program on the ferroelectric fast reactive tuner (F-FRT) development for microphonics compensation. It allowed Euclid to develop a new improved ***ferroelectric ceramic with ε~ 150, tanδ<1×10^{-3} at 1.3GHz and the tuning range up to Δε/ε~10% at 15 kV/cm[5]***.

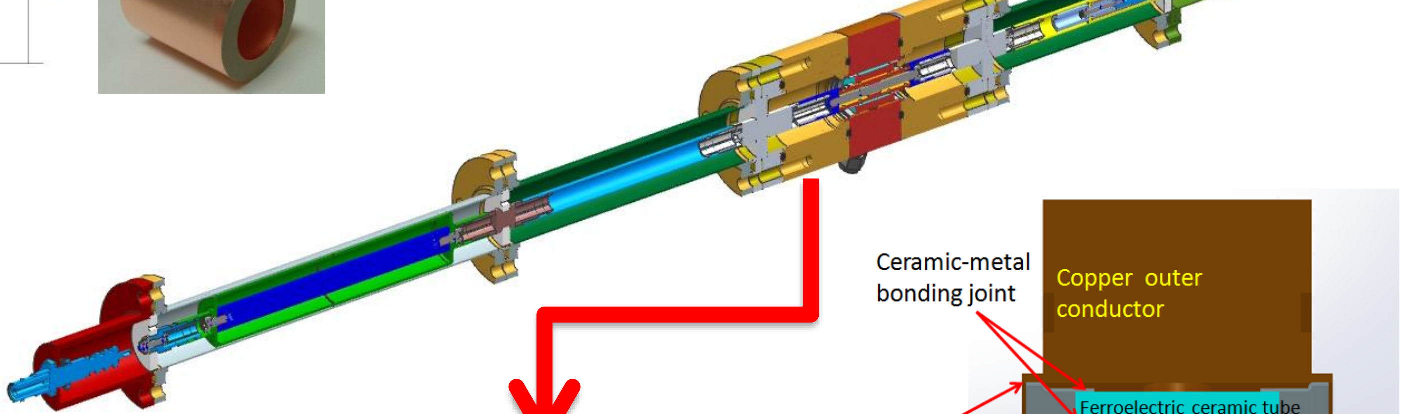


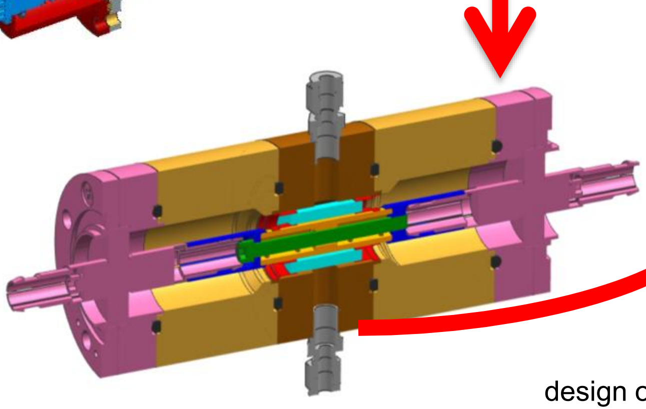
A new, simple coaxial tuner design (S. Kazakov) for the F-FRT became feasible[5], and the 400 MHz tuner prototype was fabricated by Euclid and tested at CERN in 2019 with the 400 MHz SRF cavity[6].

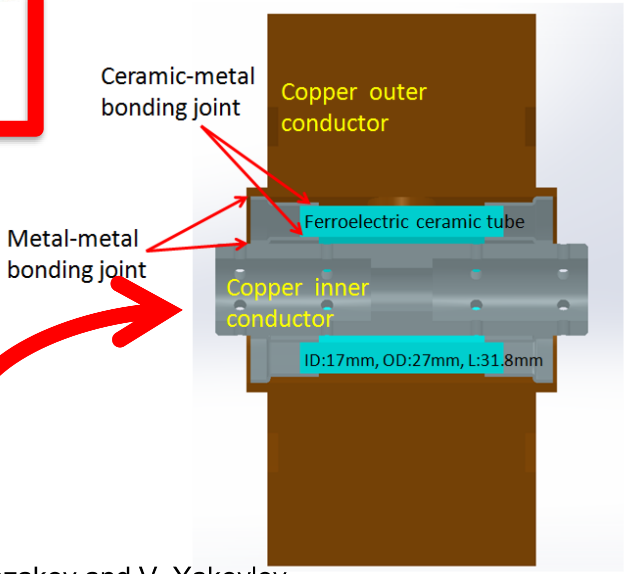
[1]R. Babbitt et al., 1994. "US Patent, US5334958A, 1993.
[2]V. Yakovlev et al. AIP Conf.Proc. 691,187, 2003.
[3]S. Kazakov et al. PRAB 13, 113501, 2010
[4]A. Kanareykin et al. Proc. EPAC 2006, 3251, 2006.
[5]A. Kanareykin et al. Proc. IPAC2013, 2486, 2014.
[6]N.Shipman et al. Proc. SRF2019, Dresden,WETEB7, 2019.

BST Based Tuner Design (assembly)



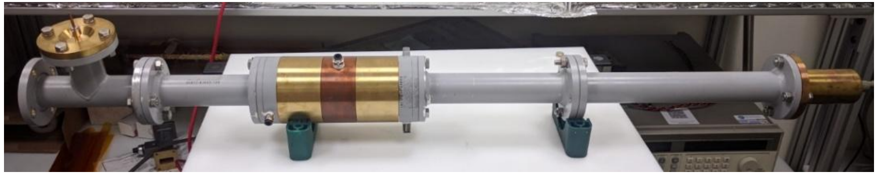






design of S. Kazakov and V. Yakovlev

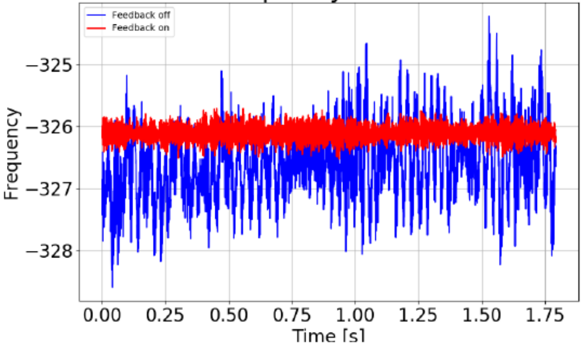
Microphonic Suppression at CERN



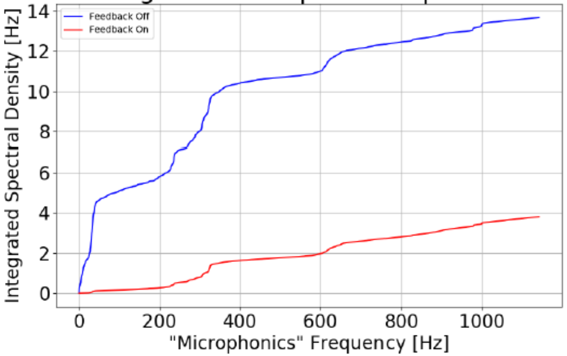
N. Shipman, et al., IPAC'21,

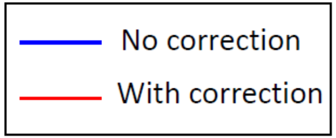
Vibration Generator Off

Frequency vs time

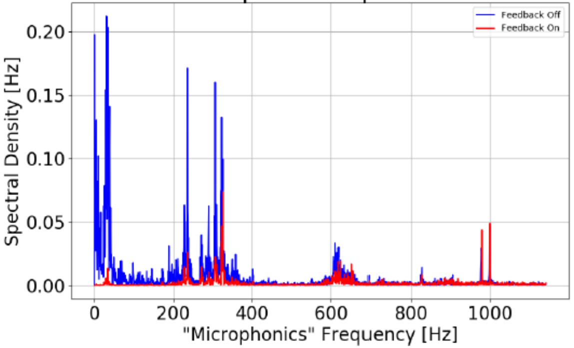


Integrated Microphonics Spectrum

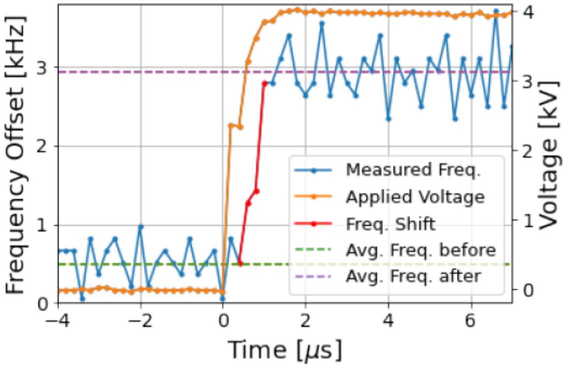




Microphonics Spectrum



- Stiff cavity => Very low levels of microphonic
- Integrated microphonics spectral density up to 1kHz reduced by factor ~4
- More reduction at lower frequencies
- Peak deviation with correction $< \pm 0.5\mathrm{Hz}$



Measured at CERN frequency response at 600 ns of a cavity to a 4 kV high voltage pulse

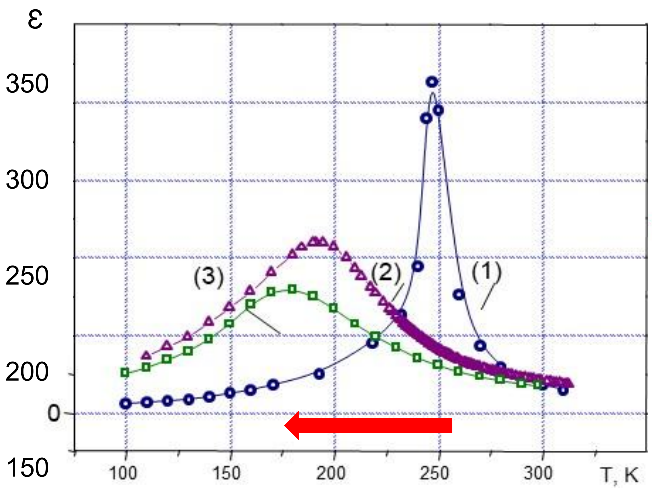
- First ever Ferroelectric Fast Reactive Tuner (FE-FRT) test with a superconducting cavity

Fast Tuning Ferroelectric Material

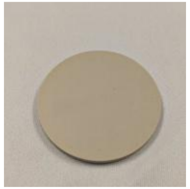
- **Dielectric constant** has to be low (~ 100-150)
- **Loss factor** has to be low ~ 1×10^{-3} a 1 GHz and ~1×10^{-4} at 100 MHz
- **Tuning range** has to be high ~ 6-8% at 15kV/cm
- Can be done with **(Ba, Sr)TiO_4+Mg oxides**

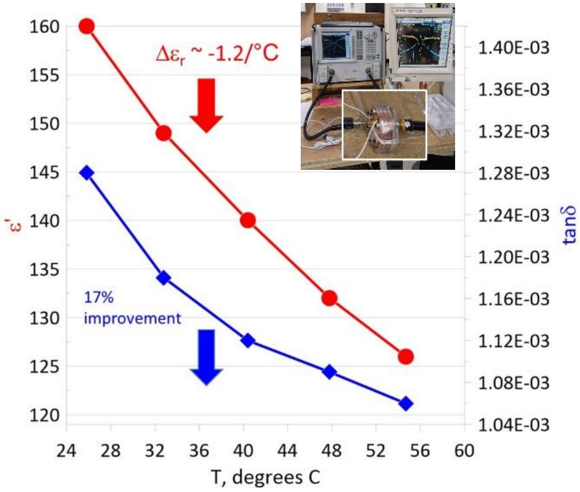
Dielectric constant of pure BST > 1000, and it's lossy. To reduce both eps and tanδ, one has to develop a mixture (solid solution) of BST ferroelectric and low loss linear ceramic

A.Macpherson, CERN, https://events.hifis.net/event/2275/contributions/20221/attachments/4893/10290/Workshop_141125_ALM.pdf



Curie temperature dependence on Mg-oxide content. Curie temperature shift with Mg based oxide from ~300K down to ~ 180K-200K region.





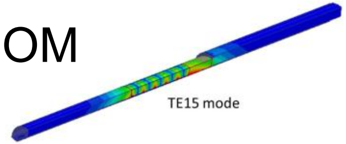
Dielectric constant and tanδ measurements in the temperature range T=20^0C-60^0C at 400 MHz for the BST(M) ferroelectric material: tanδ=1.3×10^{-3} T=22^0C and ~ 17% improvement at T=55^0C.

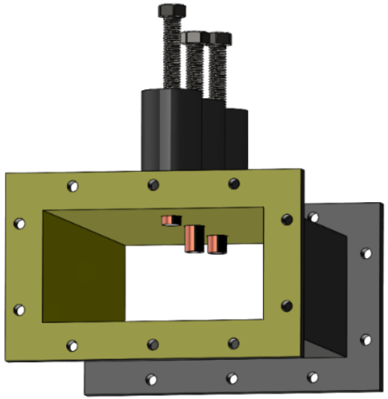
Tree-stub tuner for variable loads, CEBAF

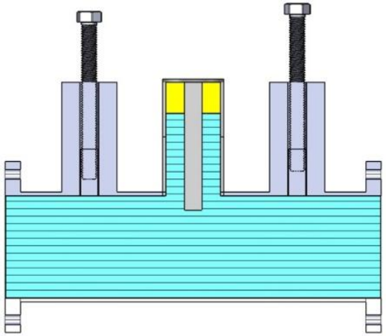
A. Hutton, A.Costilla, SBIR, JLab

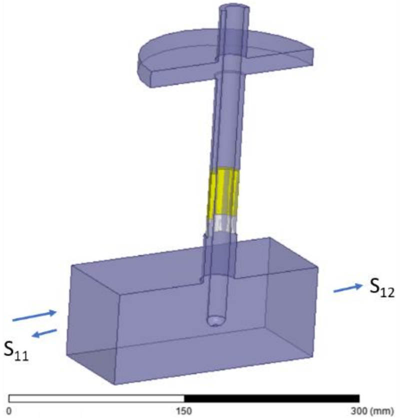
S.Kuzikov, Jlab, LDRD

HOM

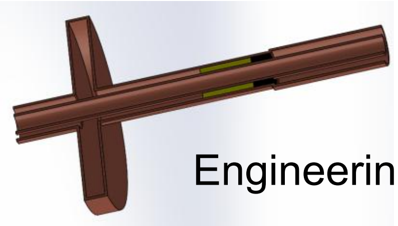


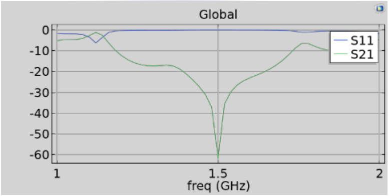




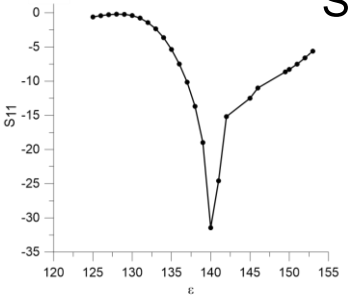


Engineering



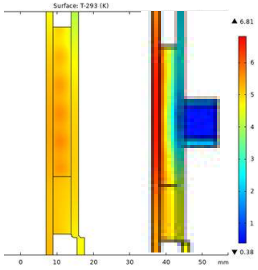


Using a three-stub tuner to minimize the reflected power only works if the load has a constant impedance, which is often, but not always, true. If the load is varying in time, the best that can be done is to match the stub tuner to the average value.



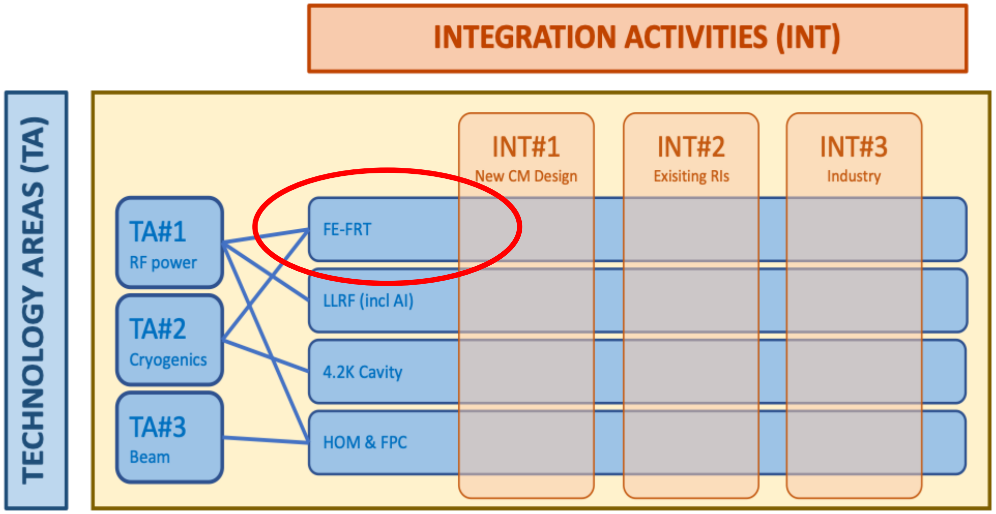
S11 vs. eps

Thermal



iSAS Program

Innovate for Sustainable Accelerating Systems (iSAS)



The Horizon Europe iSAS project focuses on improving accelerator efficiency and includes the integration of a ferroelectric fast reactive tuner (FE-FRT) to enhance energy conservation. Applications under this initiative include an

- FE-FRT for 400 MHz transient beam loading compensation in the LHC (CERN),
- FE-FRT systems for microphonics compensation in 1.3 GHz SRF cavities (HZB),
- FE-FRTs for energy recovery linac (ERL) applications (HZB),
- retrofitting FE-FRTs into existing HL-LHC cryomodules (CERN)

A New Era in SRF Frequency Control

First Workshop on Ferro-Electric Fast Reactive Tuners (FE-FRTs) Dec 2025, Berlin Germany.
https://events.hifis.net/event/2275/

- FRTs provide **ultra-fast frequency adjustment** without mechanical motion,
- Enable electronic, **room-temperature control** of cavity detuning,
- Offer response times capable of **active microphonics compensation**, thereby significantly reducing RF amplifier power requirements.

FE-FRTs are drawing strong interest from CERN and other major accelerator centers for **transient detuning** correction, **beam loading compensation**, and **fast variable attenuation** in high-power RF distribution systems. Additional applications **include fast control of phase-locked magnetrons**.

Euclid Techlabs collaborates with many ongoing FE-FRT development programs at **CERN, HZB, Daresbury/Lancaster University and Mainz University** in Europe, as well as **Jefferson Lab** in the United States.

https://indico.ijclab.in2p3.fr/event/10302/contributions/33165/attachments/23296/33595/iSAS-kickoff_WP1_ANeumann_150424.pdf