RF absorber development at IJCLab

CNRS/IN2P3/IJCLab

Akira Miyazaki and Axel Perez Ruiz

Outline

- Introduction
- Theory
- Preliminary warm experiments at CERN
- Cryogenic experimental setup at IJCLab
- Conclusion

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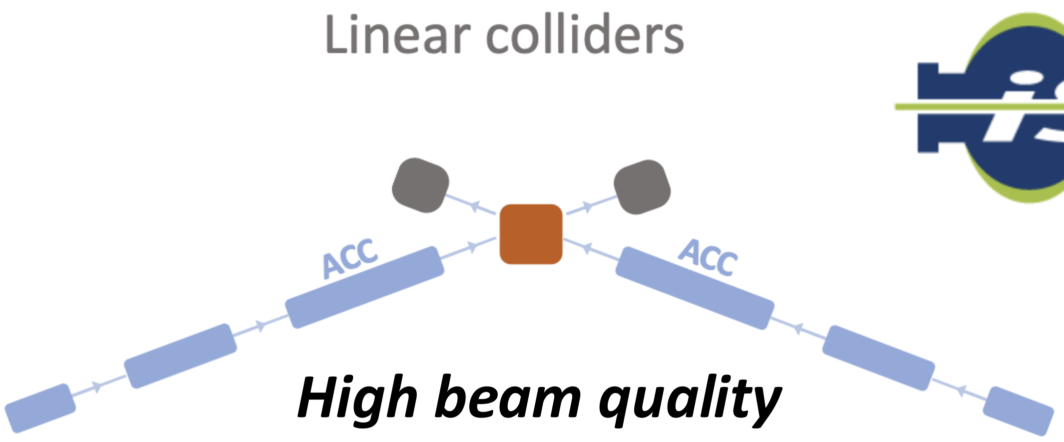
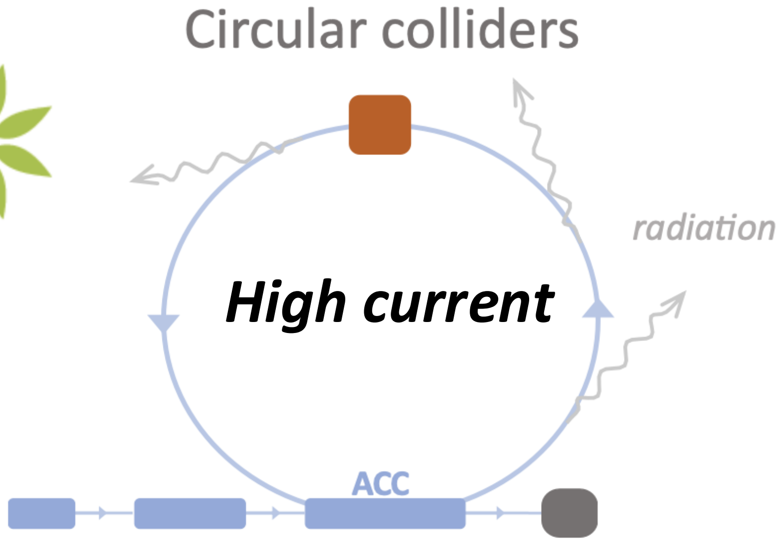
Toward more sustainable accelerators

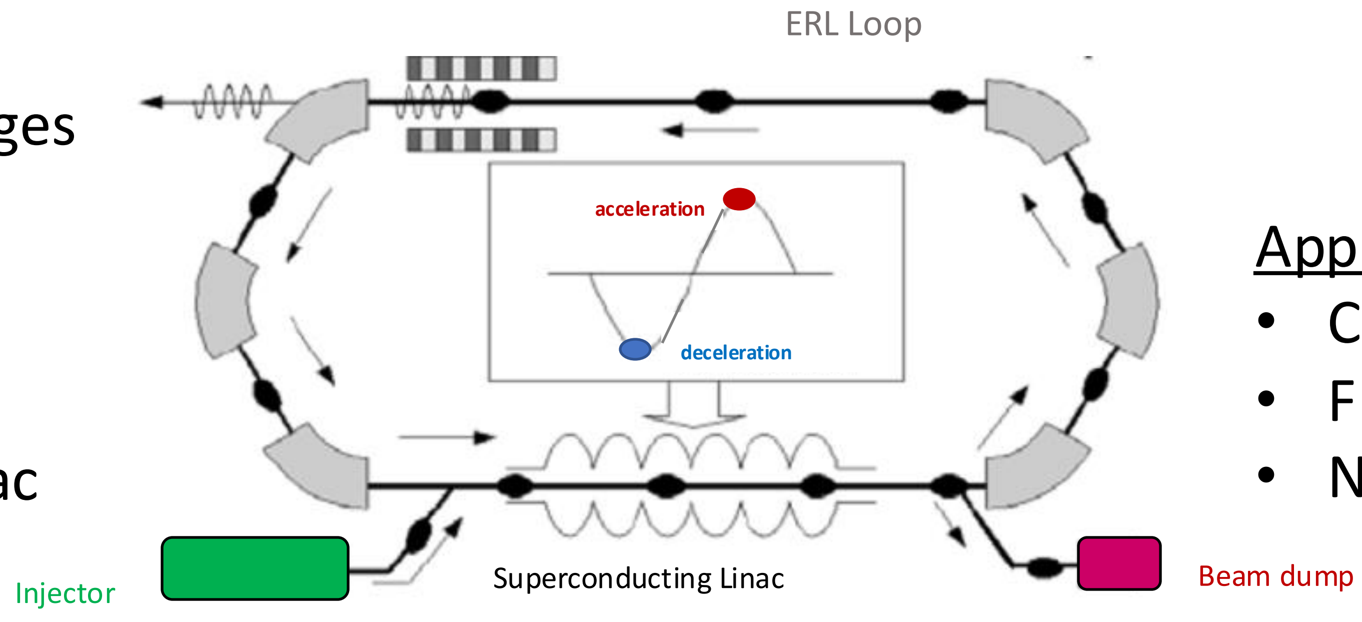




Combine the advantages of linear and circular accelerators

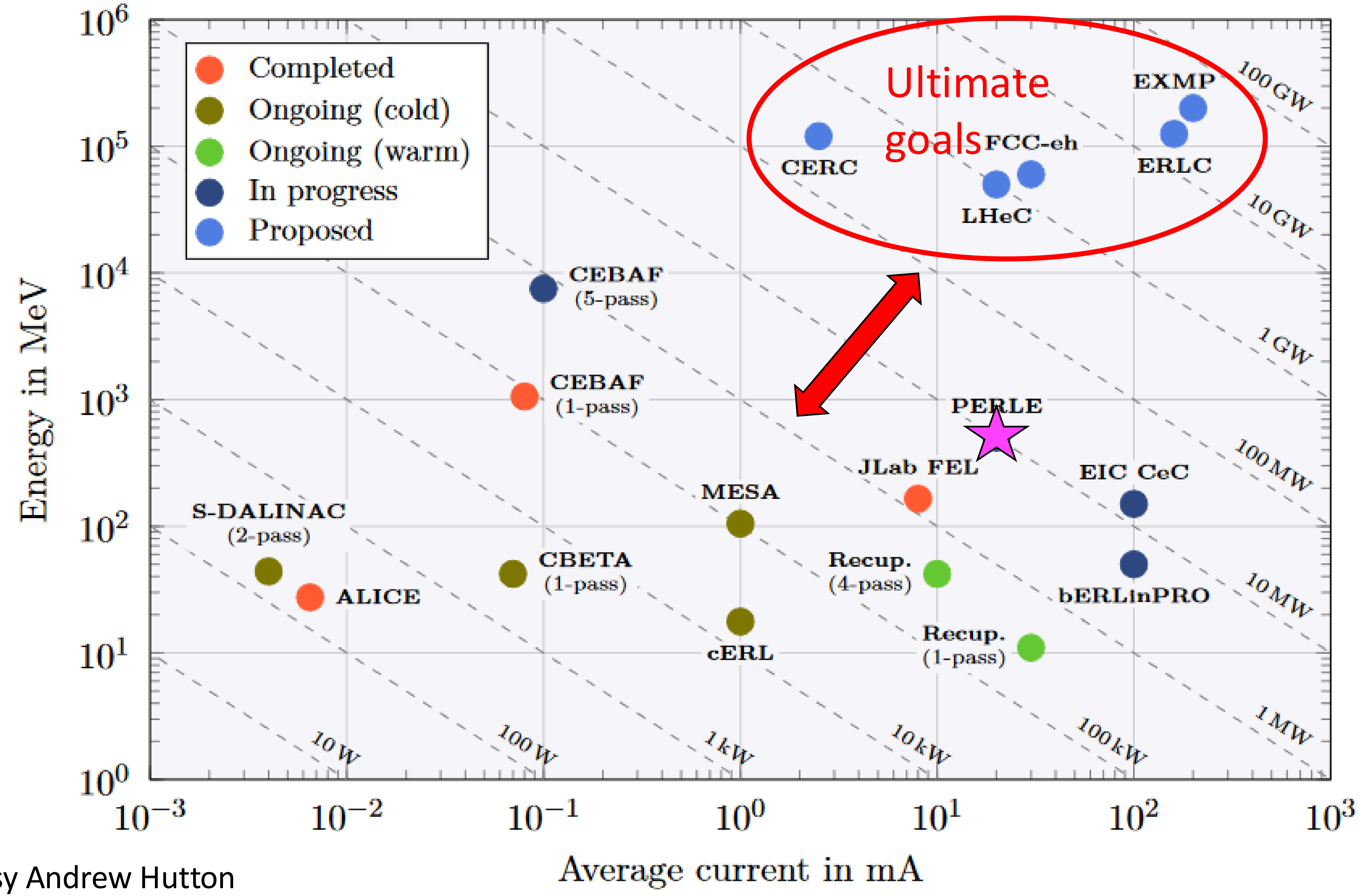
→

Energy Recovery Linac



<u>Applications</u>

- Colliders
- FEL
- Nuclear physics



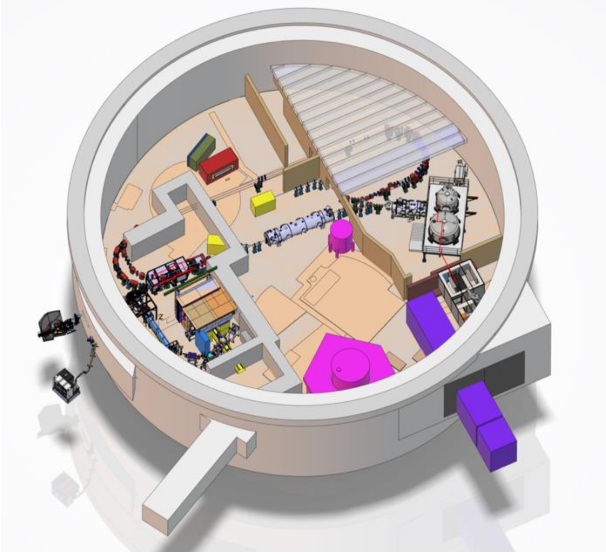
Courtesy Andrew Hutton

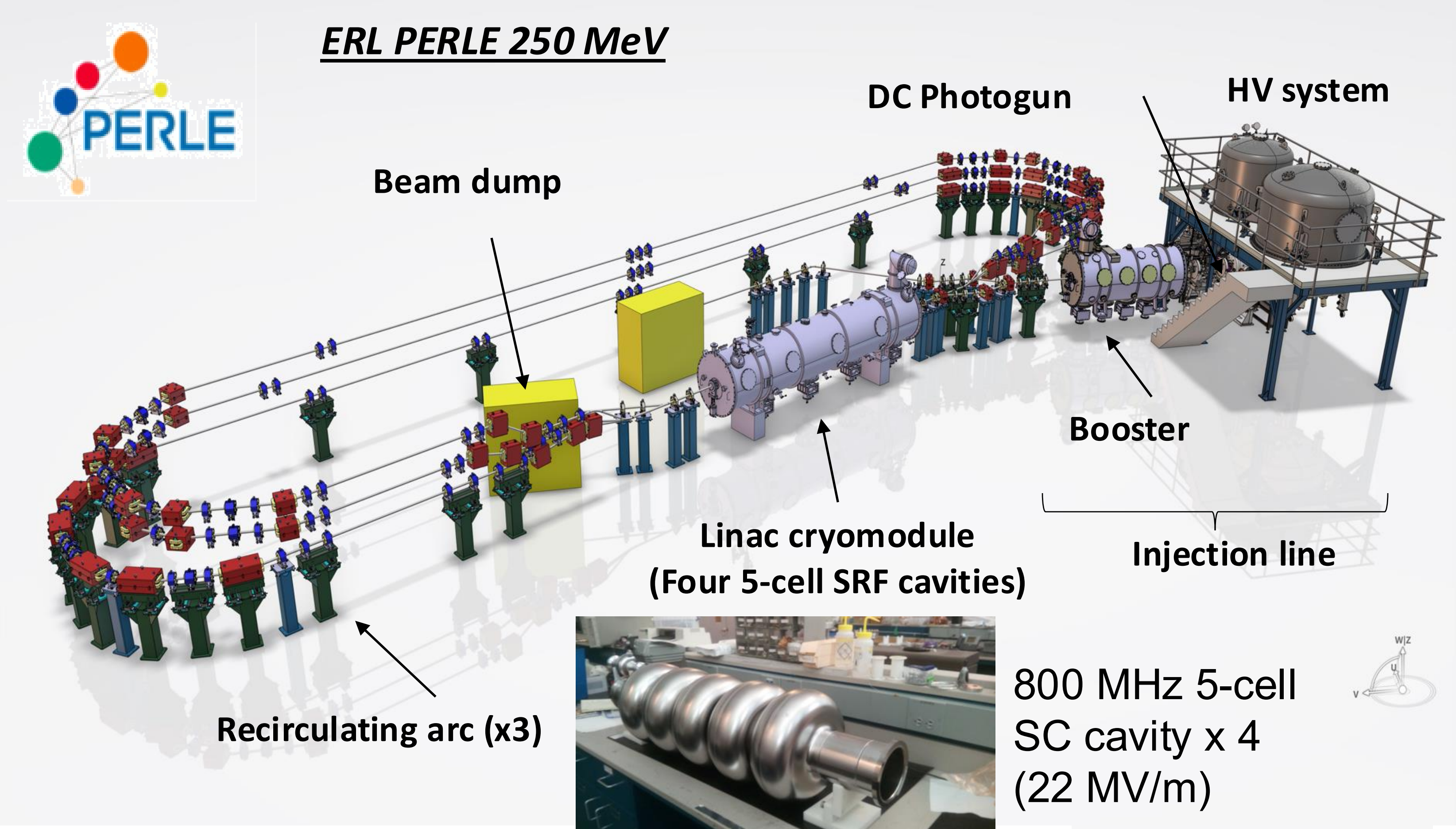
PERLE project at IN2P3/IJCLab

Ultimate goal of PERLE: first multi-turn ERL designed to operate at 10 MW (20 mA, 87→250 MeV)

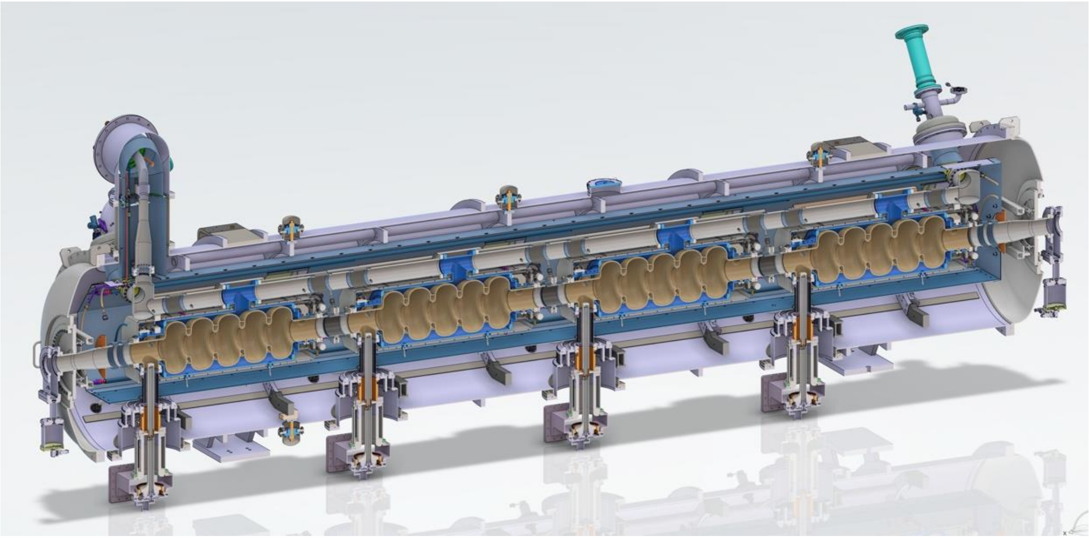
→ A hub to explore a broad range of accelerator phenomena and to validate technical choices improving accelerators for future energy and intensity frontier machines

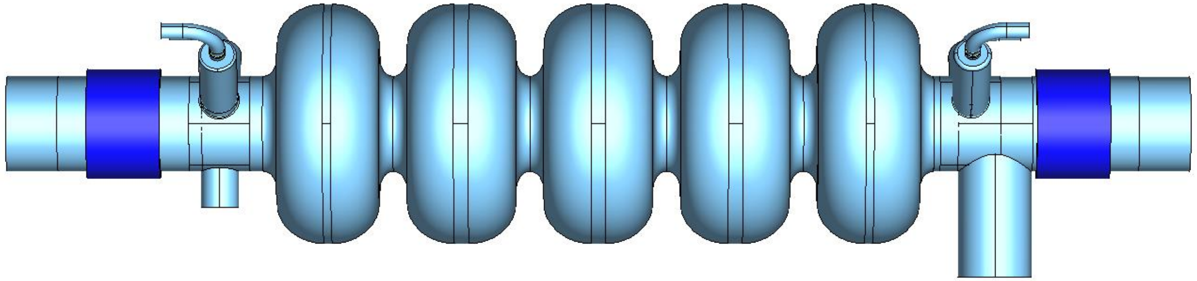
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	250
Average beam current	mA	20
Bunch charge	pC	500
Duty factor		CW

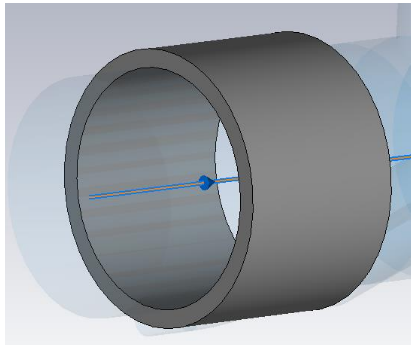


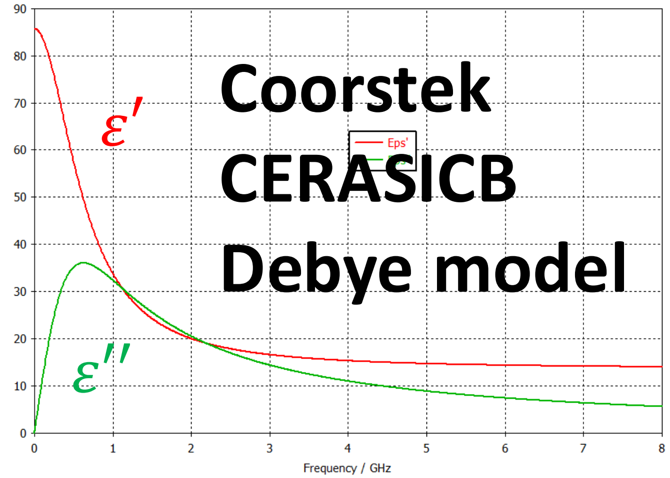


800 MHz 5-cell SC cavity x 4 (22 MV/m)









(HOM couplers → Patricia Duchesne's talk)

Preliminary study by Carmelo Barbagallo

- Between two cavities could be feasible
- He-cooling and thermal intercept (**40K**)
- Power absorbed: ~**120 W**
- Power flux limit (simulation): 3.09e-03 W/mm2

- CERASICB is known to be **lossless** at 40K
- Coorstek products are out of market (?)
- Realistic ($\epsilon_r, \tan\delta$) in CST/COMSOL?
- Measurement?

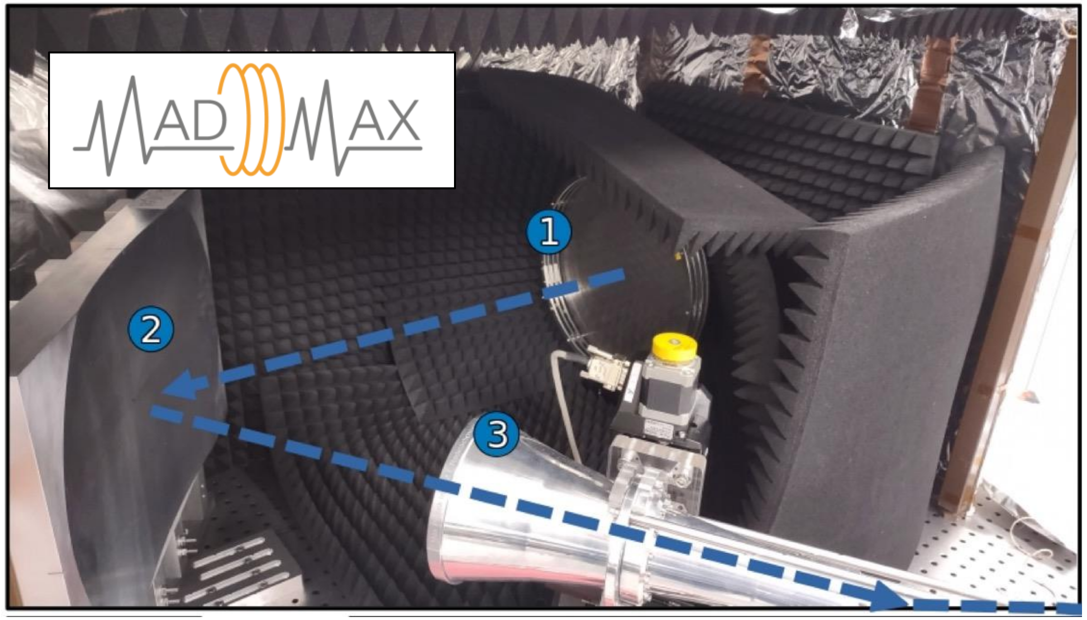
→ Basic studies of BLA and its materials are proposed locally at IJCLab

Technical synergy with other science fields

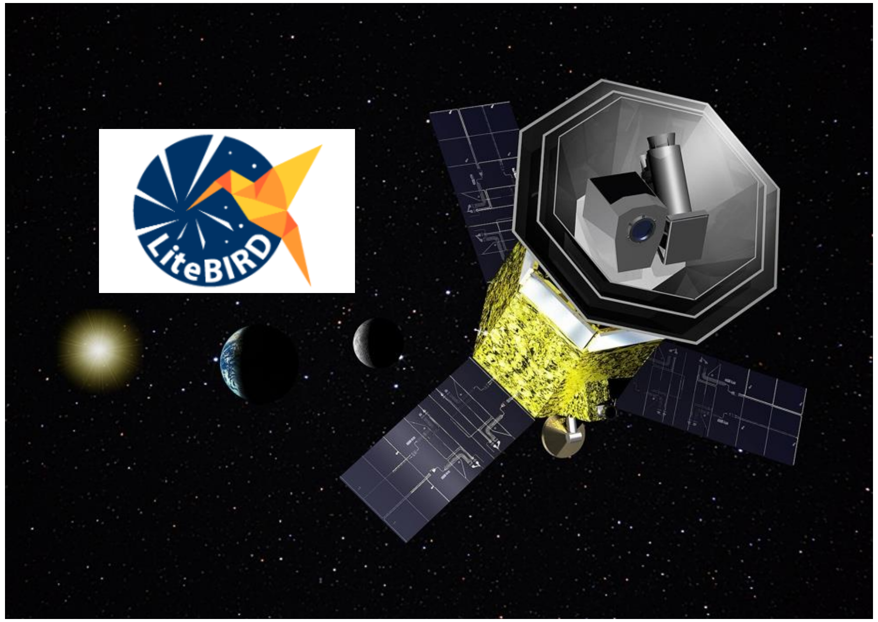
"Give us budget for **ONLY** BLA material studies…" may sound too technical for funding agencies.

<u>The need of dielectric RF absorbers is not limited to the accelerators</u>

Axion dark matter search (20 GHz)



Cosmic Microwave Background (>40 GHz)



"Fundamental studies of RF absorbers in fundamental science" convinced university

- Preparation of **test-stand** for PERLE/MADMAX/LiteBird: 20 kEUR (GS transverse 2025)
- Procurement of dielectric material: 20 kEUR (AAP P2I project 2025) → **more funding** (?)

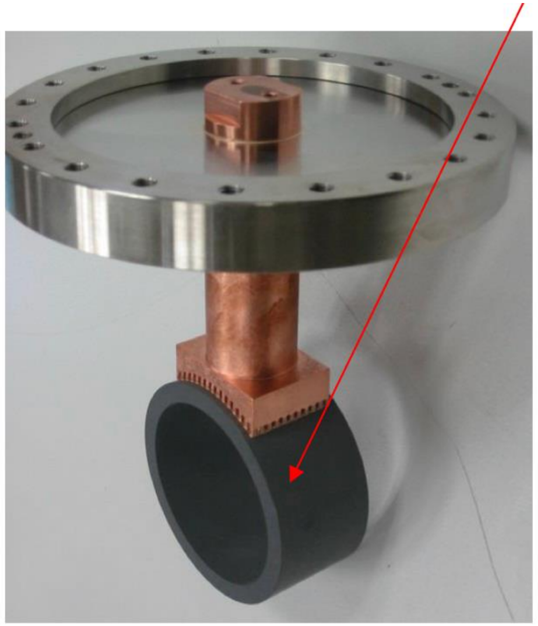
HOM absorbers for accelerators in the literature

Type	Company	Product	T [K]	projects	tanδ	σ [S/m]	P [W]
SiC	Coorstek	CERASIC-B → Hexoloy	300	KEKB, KEK-PF, SKEKB	0.4		
SiC	Coorstek	SC-30/SC-35	80-300	APS, CBETA	-	-	-
SiC	Kyocera	SC1000	300	EIC	-	1e-10	200
SiC	ECM	Cesic	50	ARIEL	-	1.5e4	30
AlN	Ceradyne	Ceralloy 137CD1	70	LCLS-II, EuXFEL	-	-	-
AlN	Sienna	STL-150D14	40	LCLS-II, CEBAF	0.4	-	120
AlN	Sienna	STL 100HTC	300	BESSY, BERLinPro	0.2	-	120

- Previously ferrite (dusty) → either SiC or AlN recently
  - Most of candidates absorbs RF via **dielectric loss**
  - Cesic exceptionally eliminates RF via **Ohmic loss**
- Limited market (Coorstek SC-30/35 & Ceradyne no longer available)
- Some materials **lose tanδ at cold** (→ problem for PERLE)
- Some materials are promising but **very expensive** (x10 than others)

Courtesy:
JALB, HZB,
KEK. TRIUMF

AlN STL-150D: LCLS-II standard



inner diameter ϕ90mm
Thickness 10 mm
length 50mm
40 K operation

- 2-12 GHz loss tangent data at 2 K
- 13.8 W HOM power OK in LCLS-II
- RMS bunch length 25 μm → 1 THz HOM
- Capable of 100 W absorption

https://siennatech.com/wp-content/uploads/2021/10/STL-150D-1.pdf

https://indico.fnal.gov/event/10102/contributions/813/attachments/436/508/Solyak_HOM_Absorber.pdf

	STL-100	STL-150D
Composition	AlN - SiC (Composite)	AlN (Doped)
Density, g/cm^3	3.25	3.28
Outgassing	No	No
Thermal Conductivity, W/m•K	90±10	120±10
Thermal Expansion Coefficient, X10^{-6}/°C	5.5	4.0
Dielectric Constant		
2 GHz	42	35
4 GHz	38	29
6 GHz	36	26
8 GHz	33	24
10 GHz	32	22
12 GHz	31	21
Loss Tangent		
2 GHz	0.20	0.41
4 GHz	0.24	0.44
6 GHz	0.29	0.46
8 GHz	0.31	0.48
10 GHz	0.32	0.50
12 GHz	0.32	0.44
Flexural Strength, MPa	500	300
Elastic Modulus, GPa	350	325
Hardness, GPa	12	12
Application	Lossy Dielectric replacement for BeO-SiC composites, HOM Absorbers, Severes, Terminations, Wedges	Lossy Dielectric replacement for BeO-SiC composites, HOM Absorbers, Severes, Terminations, Wedges
Additional Attributes	• Properties can be tailored by changing composition.	• Properties can be tailored by changing composition. • Maintains loss characteristics at cryogenic temperatures to 2 K.

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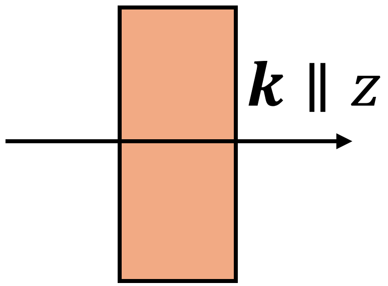
Propagation of microwaves into a material



$$\nabla \times \boldsymbol{H} = \boldsymbol{j} + \frac{\partial \boldsymbol{D}}{\partial t} \qquad \begin{matrix} \boldsymbol{D} = \varepsilon \boldsymbol{E} \\ \boldsymbol{j} = \sigma \boldsymbol{E} \end{matrix} \qquad \varepsilon = \varepsilon' - i\varepsilon'' \qquad \boldsymbol{E} = \boldsymbol{E}_0 \exp(i\omega t - ikz)$$

$$\rightarrow \nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + (\varepsilon' - i\varepsilon'') \times i\omega \boldsymbol{E} = (\omega\varepsilon'' + \sigma)\boldsymbol{E} + i\omega\epsilon' \boldsymbol{E}$$

$$= i\omega\varepsilon'[1 - i \tan\delta]\, \boldsymbol{E} \qquad \tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \boldsymbol{B} = \mu \boldsymbol{H} \qquad \mu = \mu' - i\mu'' = \mu'[1 - i \tan\delta_m] \qquad \tan\delta_m \equiv \frac{\mu''}{\mu'}$$

$$\rightarrow \nabla \times (\nabla \times \boldsymbol{E}) = -\mu \frac{\partial}{\partial t}(\nabla \times \boldsymbol{H}) = -\mu'(1 - i\tan\delta_m)i\omega\varepsilon'(1 - i\tan\delta)\frac{\partial \boldsymbol{E}}{\partial t}$$

$$= -\mu'(1 - i\tan\delta_m)i\omega\varepsilon'(1 - i\tan\delta)i\omega \boldsymbol{E}$$

$$\nabla \times (\nabla \times \boldsymbol{E}) = \nabla(\nabla \cdot \boldsymbol{E}) - \nabla^2 \boldsymbol{E}$$

$$\nabla \cdot \boldsymbol{E} = \rho$$

$$= +\omega^2\mu'\epsilon'(1 - i\tan\delta_m)(1 - i\tan\delta)\boldsymbol{E}$$

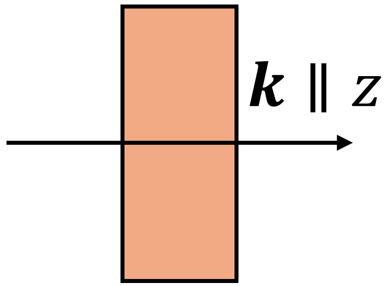
$$\rightarrow \rho - (-ik)^2 \boldsymbol{E} = +\omega^2\mu'\epsilon'(1 - i\tan\delta_m)(1 - i\tan\delta)\boldsymbol{E}$$

If $\rho = 0$

$$k^2 \boldsymbol{E} = +\omega^2\mu'\epsilon'(1 - i\tan\delta_m)(1 - i\tan\delta)\boldsymbol{E}$$

Generalized skin depth δ_{gen}

$$\begin{cases} k' = \dfrac{\omega\sqrt{\mu'\varepsilon'}}{\sqrt{2}}\sqrt{-\tan\delta_m \tan\delta + 1 \pm \sqrt{(1-\tan\delta_m\tan\delta)^2 + (\tan\delta_m + \tan\delta)^2}} \\ k'' = \dfrac{\omega\sqrt{\mu'\varepsilon'}}{\sqrt{2}}\sqrt{\tan\delta_m \tan\delta - 1 \pm \sqrt{(1-\tan\delta_m\tan\delta)^2 + (\tan\delta_m + \tan\delta)^2}} \end{cases}$$



$$\boldsymbol{E}(t,z) = \boldsymbol{E}_0 \exp(i\omega t)\exp[-ik'z - k''z]$$

Thanks to the correction by Justine Gabrael!

$$\delta_{gen} \equiv \frac{1}{k''} = \sqrt{\frac{2}{\mu'\sigma\omega}}\sqrt{\frac{\sigma}{\omega\epsilon'}}\sqrt{\frac{1}{\tan\delta_m\tan\delta - 1 \pm \sqrt{(1-\tan\delta_m\tan\delta)^2 + (\tan\delta_m + \tan\delta)^2}}}$$

$\equiv \delta_{skin}$

Conventional skin depth of normal conductor

$\equiv \alpha$

Correction factor due to dielectric and magnetic loss

$$I(z) \equiv |\boldsymbol{E}(t,z)|^2 = I_0 \exp[-2k''z] = I_0 \exp\left[-\frac{z}{\delta_{gen}/2}\right]$$

$$\tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \qquad \tan\delta_m \equiv \frac{\mu''}{\mu'}$$

Check 1: normal metal $\mu'' = 0, \varepsilon'' = 0$

$$\tan\delta_m \equiv \frac{\mu''}{\mu'} \to 0$$

If the frequency is below the plasma frequency, the effective real permittivity of metal is $\varepsilon' = \varepsilon_0$

$$\tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \to \frac{\sigma}{\omega\varepsilon_0} = \frac{5.8\times10^{7}\times(\sigma/\sigma_{Cu})}{8.85\times10^{-12}\times1\times10^{9}\times(2\pi f/1\ \mathrm{GHz})} = 6.6\times10^{9}\frac{(\sigma/\sigma_{Cu})}{(2\pi f/1\ \mathrm{GHz})} \gg 1$$

$$\alpha = \sqrt{\frac{\sigma}{\omega\epsilon'}}\sqrt{\frac{1}{\tan\delta_m\tan\delta - 1 \pm \sqrt{(1-\tan\delta_m\tan\delta)^2 + (\tan\delta_m + \tan\delta)^2}}}$$

$$\to \alpha \sim \sqrt{\frac{\tan\delta}{1 \pm \sqrt{1+(\tan\delta)^2}}} \sim \sqrt{\frac{\tan\delta}{1 \pm \tan\delta}} \to 1$$

(+ is taken from $\pm$)

$$\therefore \delta_{gen} \equiv \delta_{skin}\alpha \to \delta_{skin}$$

Check 2: purely dielectric material $\mu'' = 0, \sigma = 0$

$$\tan\delta_m \equiv \frac{\mu''}{\mu'} \to 0$$

$$\tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \to \frac{\varepsilon''}{\varepsilon'} \equiv \tan\delta_e < 1$$

$$\mu' = \mu_0$$

$$I(z) \equiv I_0 \exp\left[-\frac{z}{\delta_{gen}/2}\right]$$

$$\delta_{gen} \equiv \frac{1}{k''} = \sqrt{\frac{2}{\mu'\sigma\omega}} \quad \sqrt{\frac{\sigma}{\omega\epsilon'}} \sqrt{\frac{1}{\tan\delta_m \tan\delta - 1 \pm \sqrt{(1-\tan\delta_m\tan\delta)^2 + (\tan\delta_m + \tan\delta)^2}}}$$

$$= \frac{1}{\omega}\sqrt{\frac{2}{\mu'\varepsilon'}}\sqrt{\frac{1}{-1 \pm \sqrt{1+\tan^2\delta}}} \sim \frac{1}{\omega}\sqrt{\frac{1}{\mu'\varepsilon'}}\sqrt{\frac{2}{-1 \pm \sqrt{1+\tan^2\delta}}}$$

Consistent ☺

$$I(z) = I_0 \exp\left[-\frac{z}{z_0}\right]$$

$$n'' = \frac{\sqrt{\varepsilon'}}{\sqrt{\varepsilon_0}}\sqrt{\frac{-1+\sqrt{1+\tan^2\delta}}{2}}$$

$$z_0 = \frac{c}{2n''\omega} = \frac{1/\sqrt{\varepsilon_0\mu_0}}{2\omega}\frac{\sqrt{\varepsilon_0}}{\sqrt{\varepsilon'}}\sqrt{\frac{2}{-1 \pm \sqrt{1+\tan^2\delta}}} = \frac{1}{2\omega}\sqrt{\frac{1}{\varepsilon'\mu_0}}\sqrt{\frac{2}{-1 \pm \sqrt{1+\tan^2\delta}}}$$

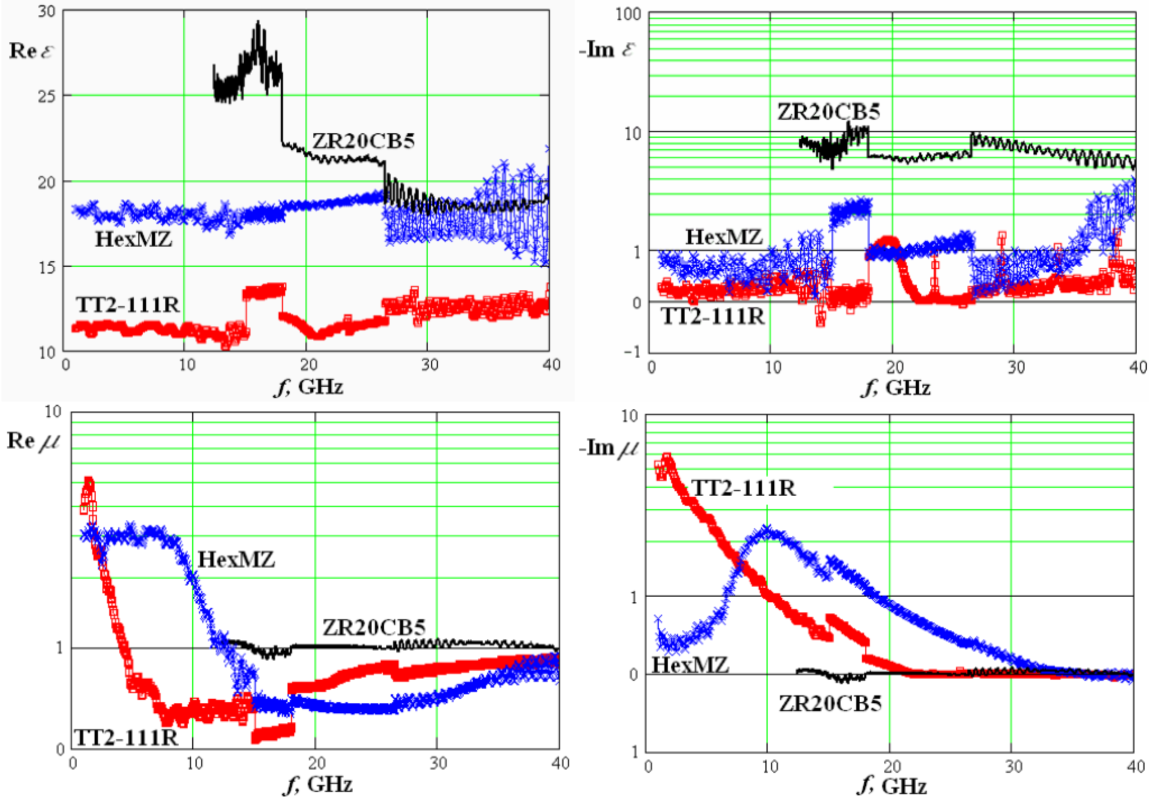
We need to take + from ±

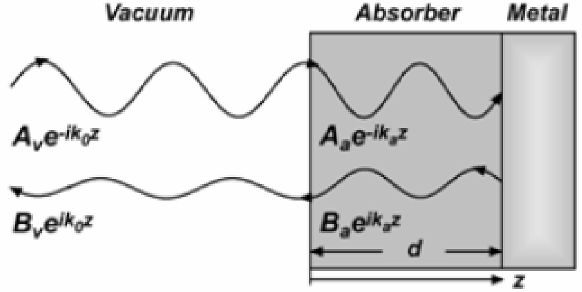
Check 3: ferrite "magnetic loss" $\sigma = 0$

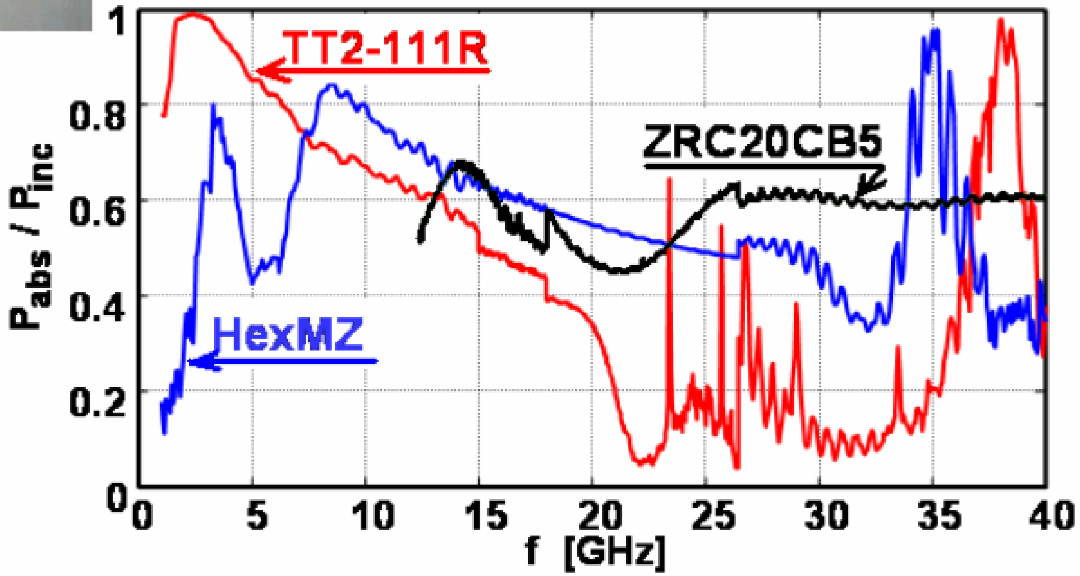
$$\tan\delta_m \equiv \frac{\mu''}{\mu'}$$

$$\tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \to \frac{\varepsilon''}{\varepsilon'} \equiv \tan\delta_e$$

$$\begin{cases} k' = \dfrac{\omega\sqrt{\mu'\varepsilon'}}{\sqrt{2}}\sqrt{-\tan\delta_m\tan\delta_e + 1 \pm \sqrt{(1-\tan\delta_m\tan\delta_e)^2 + (\tan\delta_m + \tan\delta_e)^2}} \\ k'' = \dfrac{\omega\sqrt{\mu'\varepsilon'}}{\sqrt{2}}\sqrt{\tan\delta_m\tan\delta_e - 1 \pm \sqrt{(1-\tan\delta_m\tan\delta_e)^2 + (\tan\delta_m + \tan\delta_e)^2}} \end{cases}$$







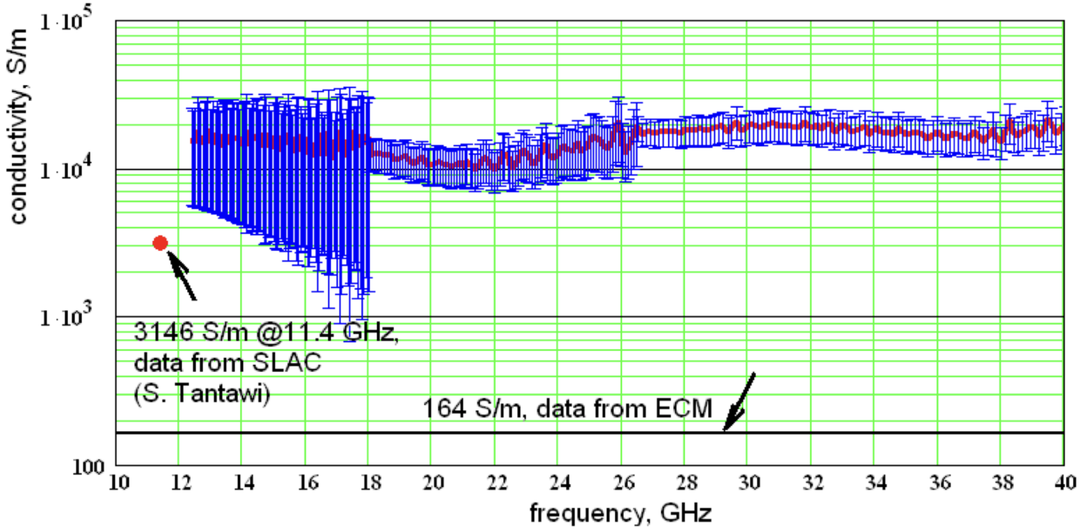
Cesic: **conductive** dielectric ceramic

$$\tan\delta_m \equiv \frac{\mu''}{\mu'} \to 0$$

$$\tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

$$\mu' = \mu_0$$

$$\begin{cases} k' = \dfrac{\omega\sqrt{\mu_0\varepsilon'}}{\sqrt{2}}\sqrt{1 \pm \sqrt{1^2 + \tan^2\delta}} \\ k'' = \dfrac{\omega\sqrt{\mu_0\varepsilon'}}{\sqrt{2}}\sqrt{-1 \pm \sqrt{1 + \tan^2\delta}} \end{cases}$$

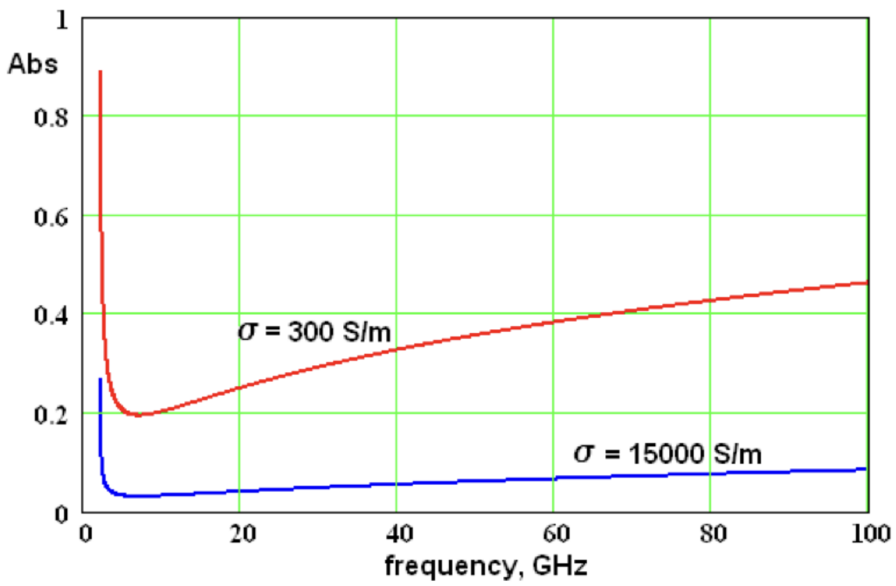


We need to know three parameters $(\sigma, \varepsilon', \varepsilon'')$

$$\to \tan\delta \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} = \frac{\omega\varepsilon''}{\omega\varepsilon'}\left(1 + \frac{\sigma}{\omega\varepsilon''}\right) = \tan\delta_e(1 + \beta)$$

A parameter representing deviation from pure dielectric ceramic

$$\beta \equiv \frac{\sigma}{\omega\varepsilon''}$$



Cesic: $\sigma = 1.5 \times 10^4$ S/m at 300K from Cornell's study

→ high thermal & low electric conductivity (≠ metal)

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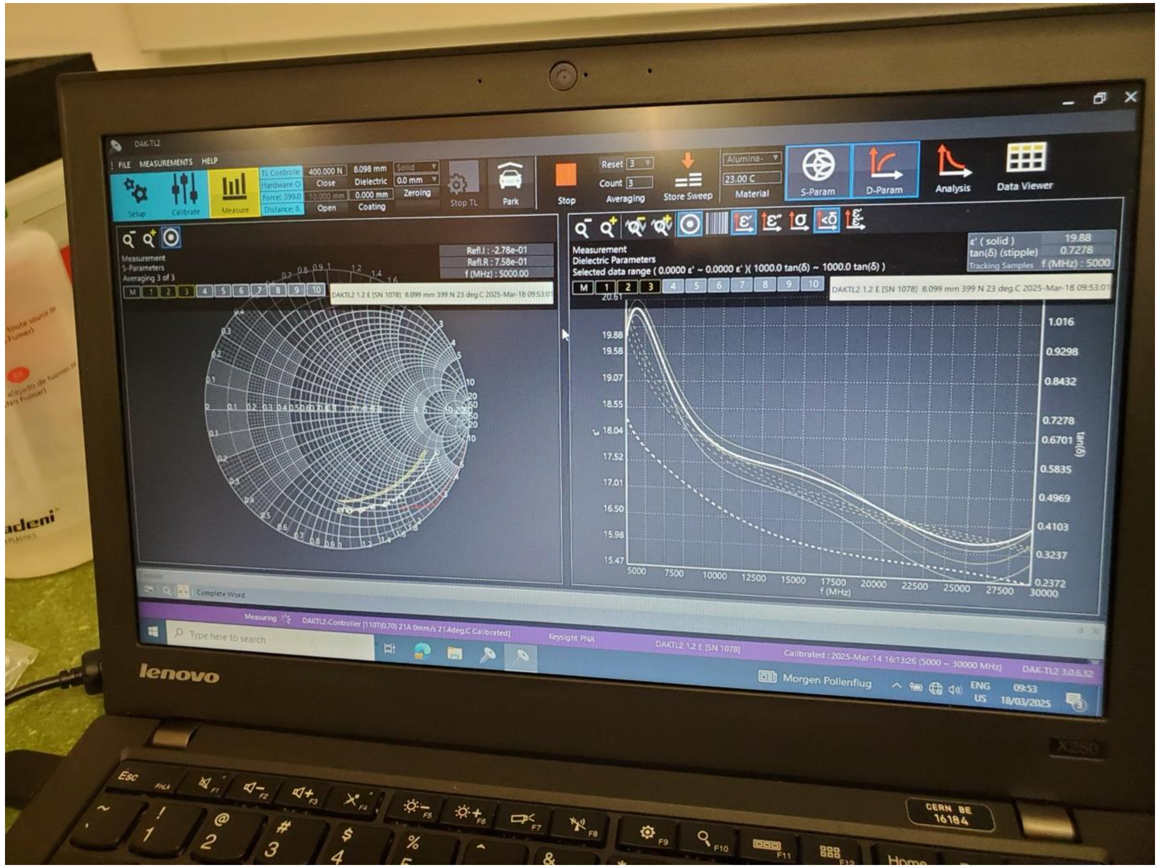
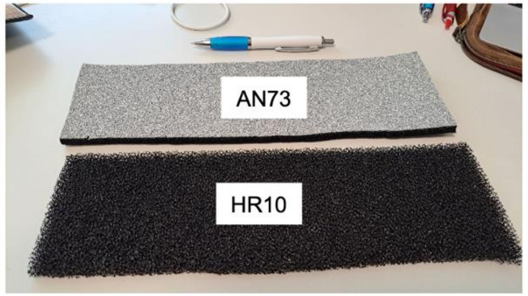
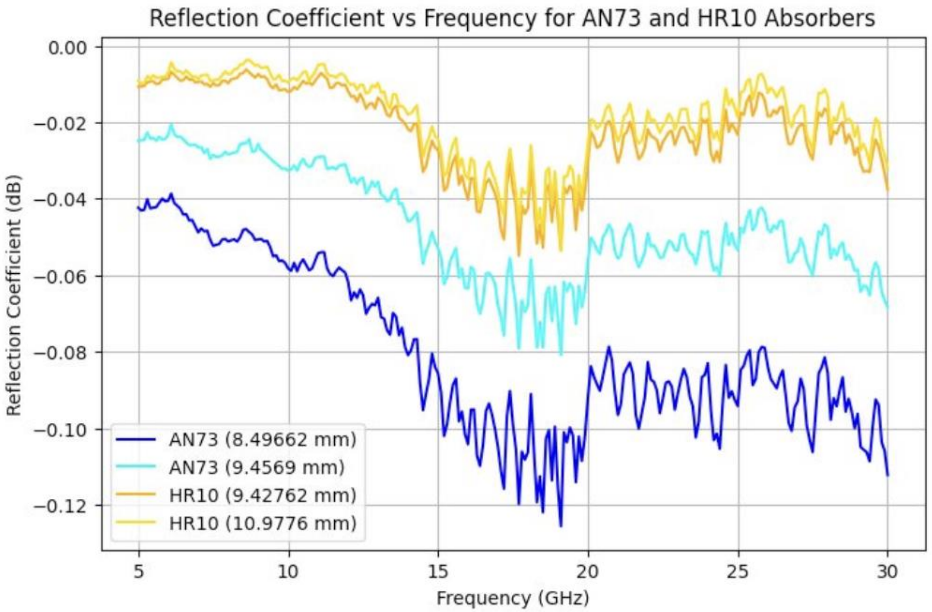
Test stand at CERN CLIC RF measurement bench



- Commercial device for dielectric measurement (ϵ', ϵ'') DAK-TL2 (5-67 GHz) with VNA E8364B
- **Warm & low power** measurement → CLIC X-band
- Sample size: 5 cm x 5 cm x 1 cm
- Calibration (5-30 GHz) with the dedicated probe seems like the key → cryogenic application is non-trivial

Tests with ECOSORBS for dark matter experiments



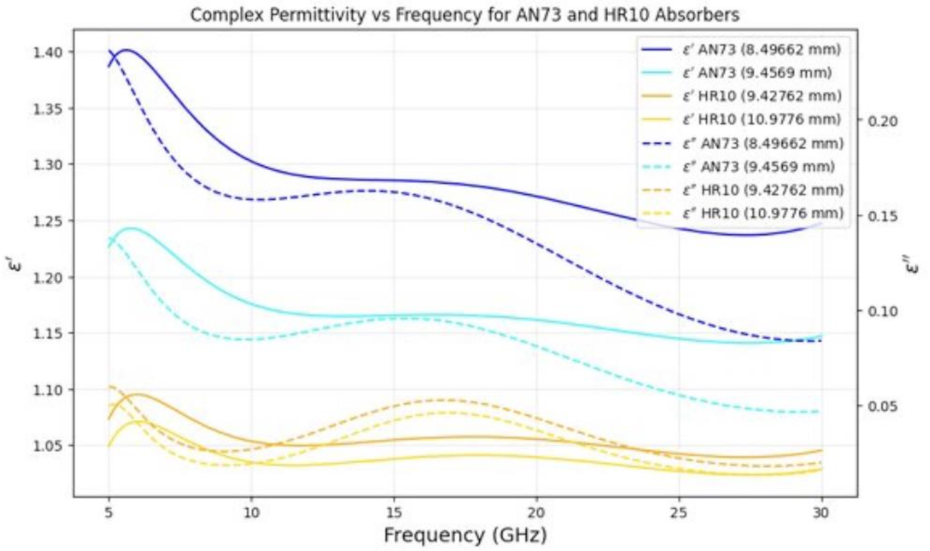


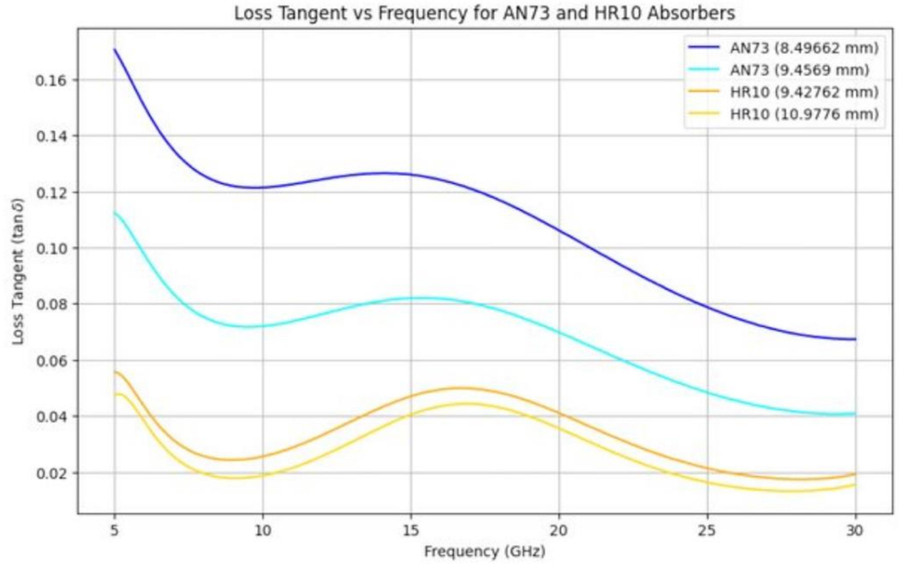
$$\Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad \Gamma = \Gamma_r + j\Gamma_i = |\Gamma| e^{j\theta}$$

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

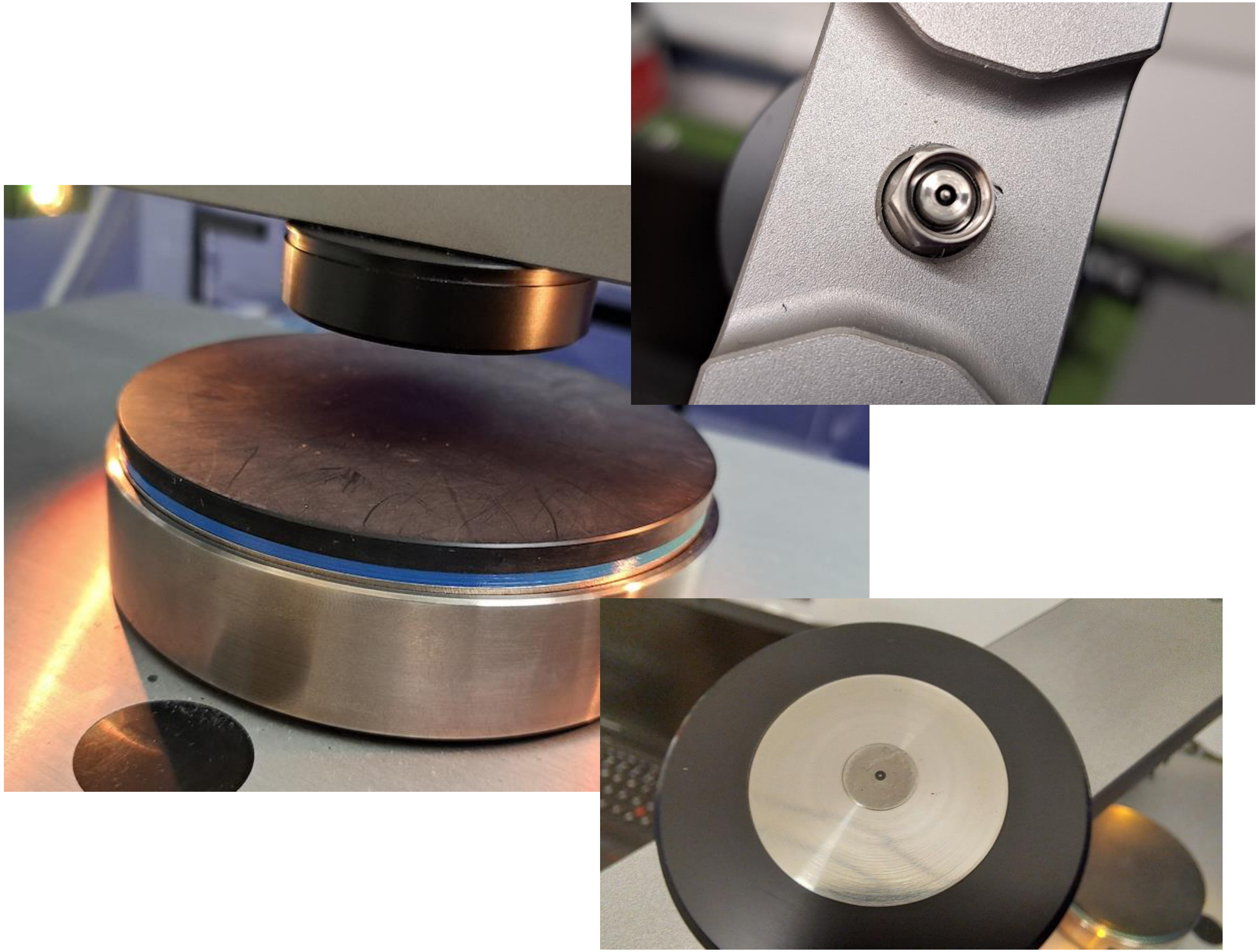
Black box

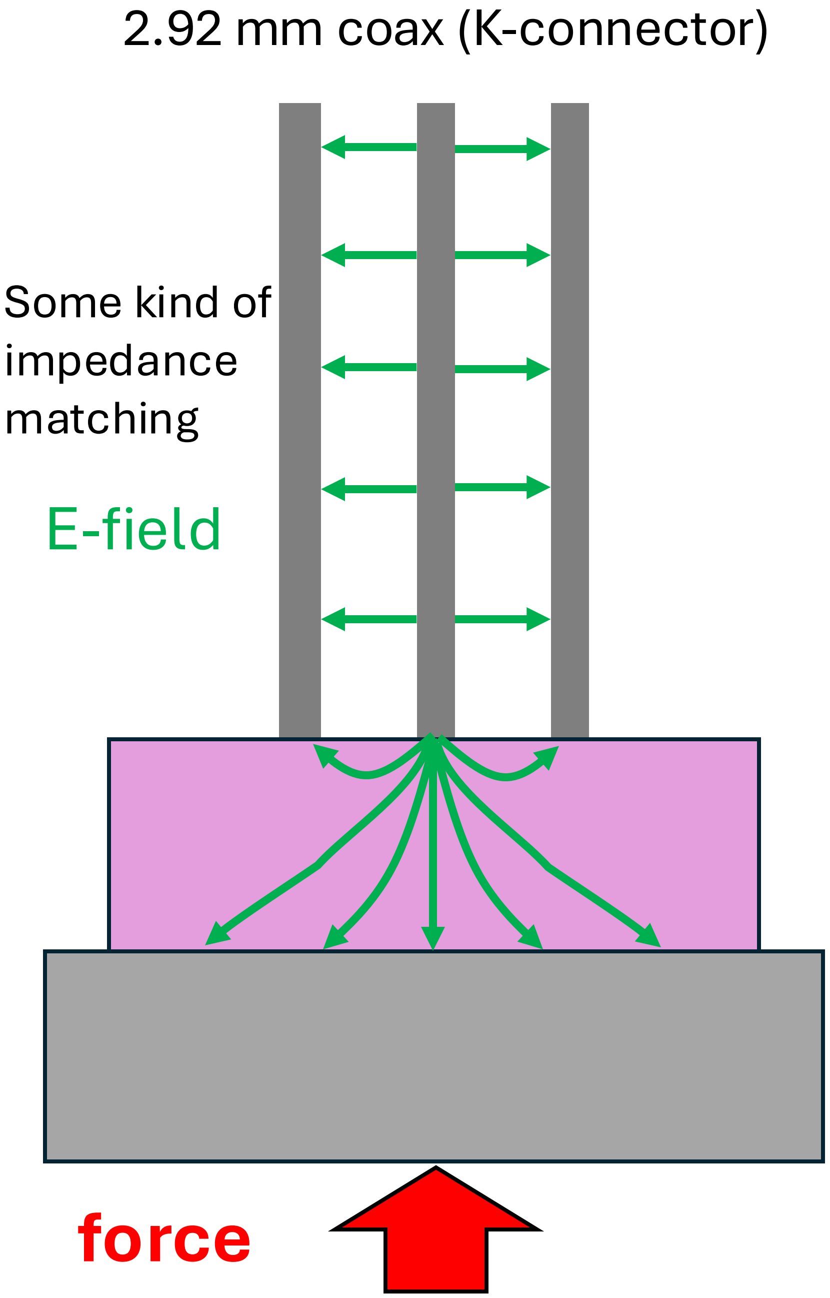
$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$



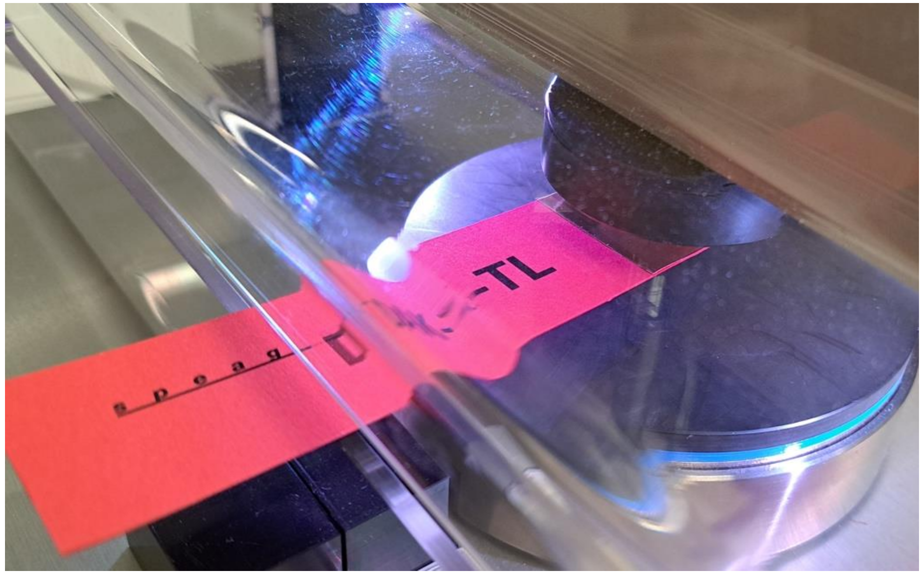


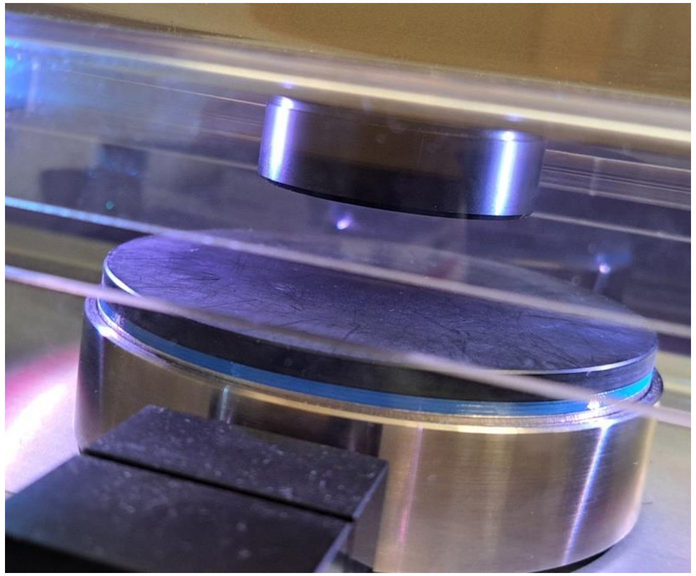
Probe = coax + metal plate

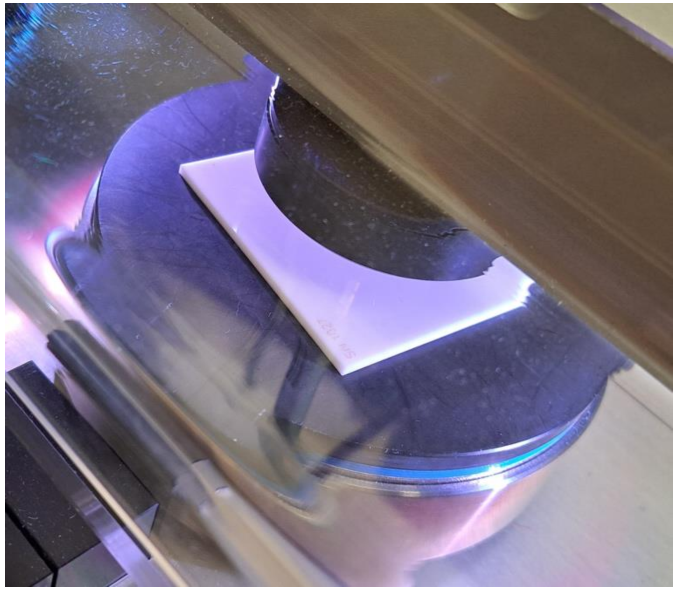




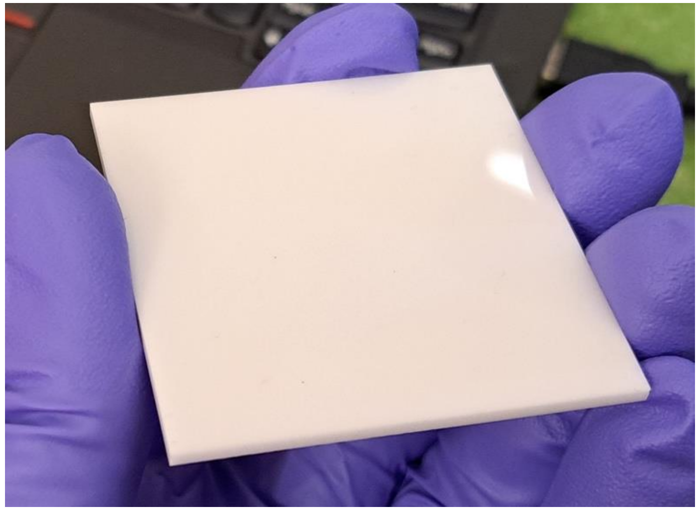
Short/Open/Load calibration







- Very similar to the normal VNA calibration
- Load may be with known $(\varepsilon', \varepsilon'')$?



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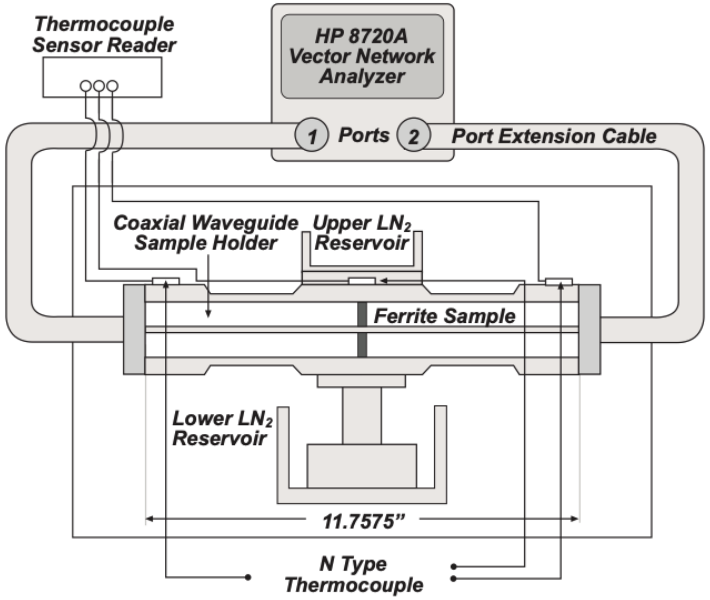
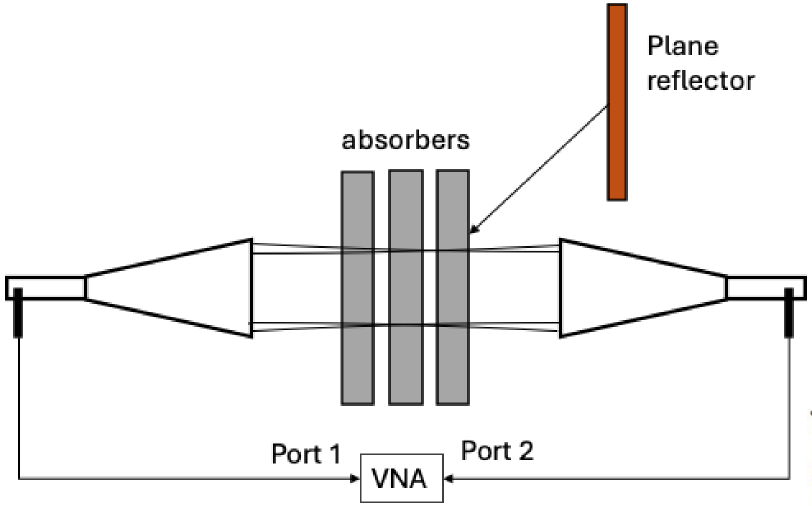
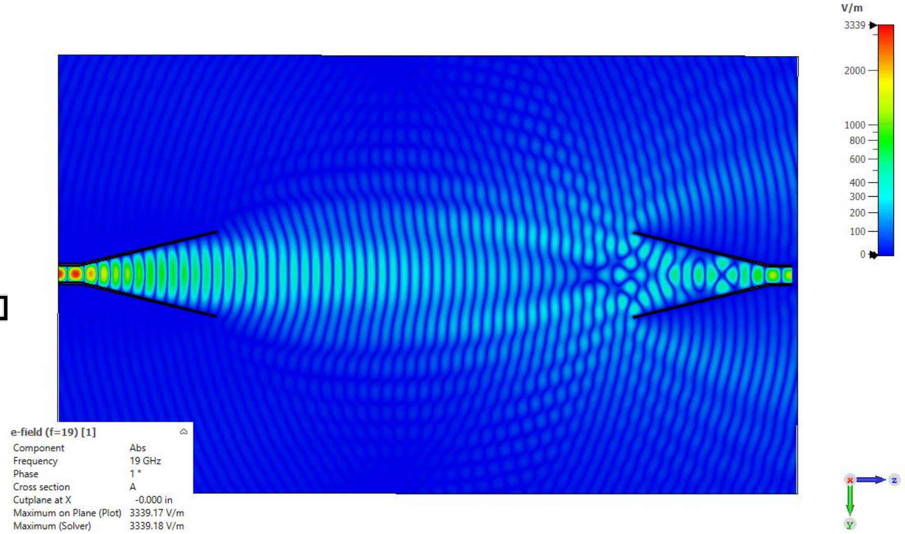
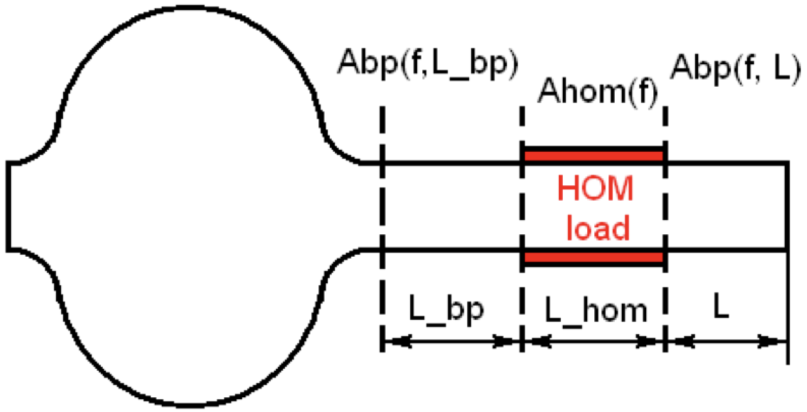
Brainstorming: cryogenic testing setup (?) at IJCLab

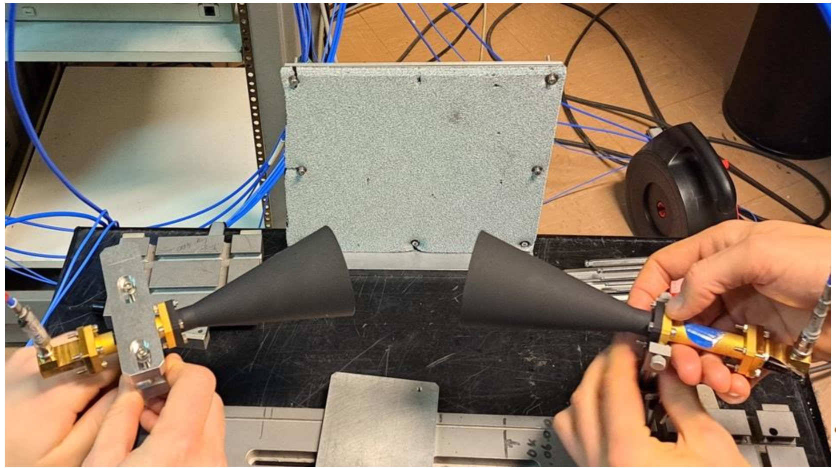


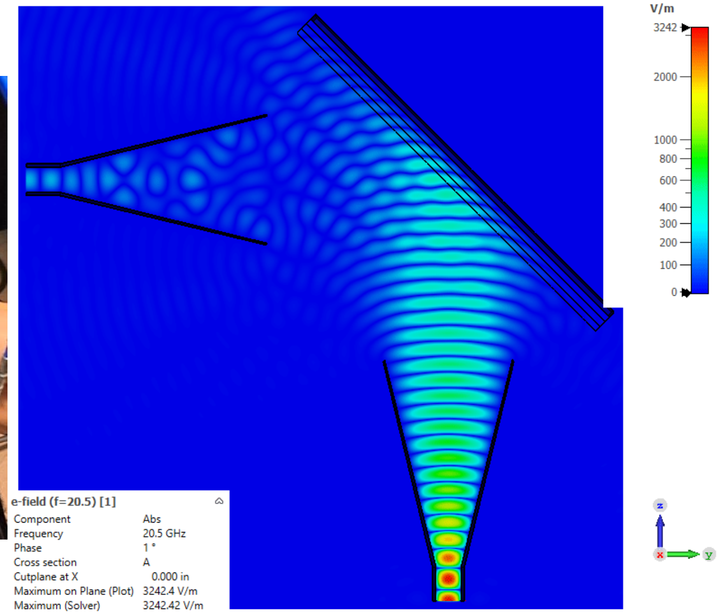




https://accelconf.web.cern.ch/p03/PAPERS/TPAB053.PDF

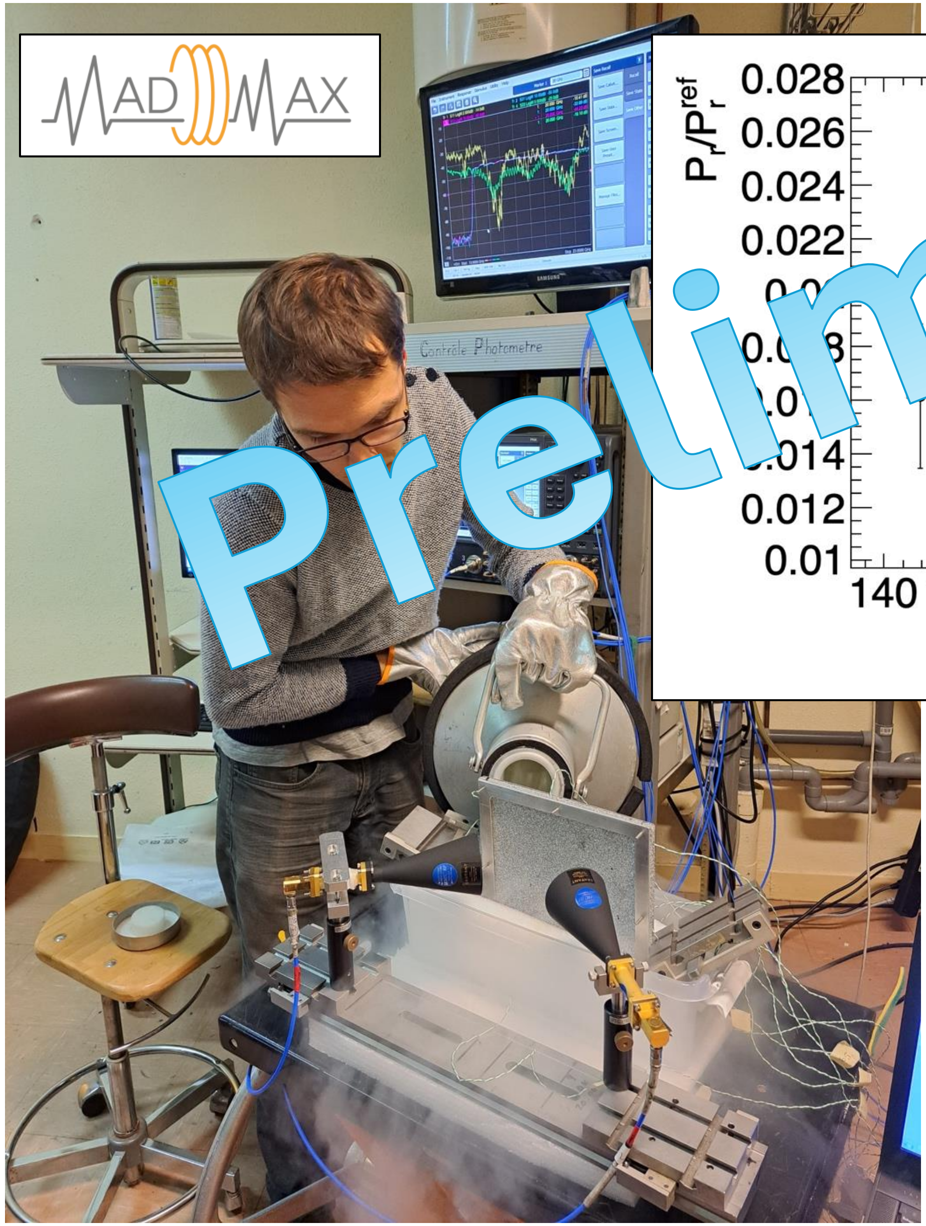


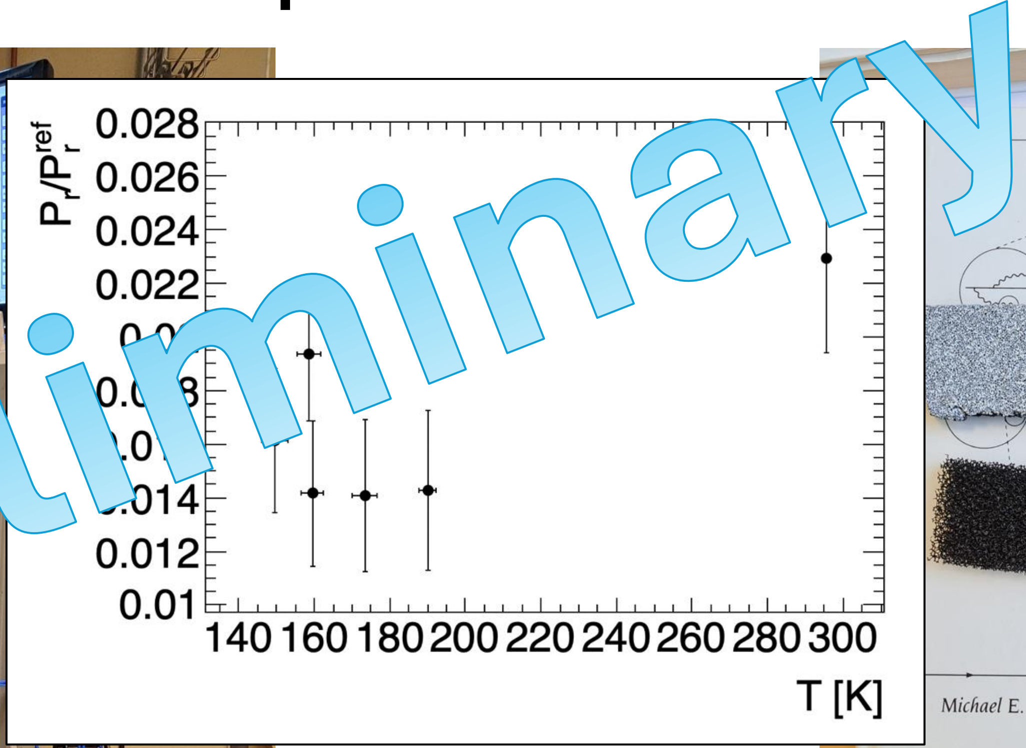


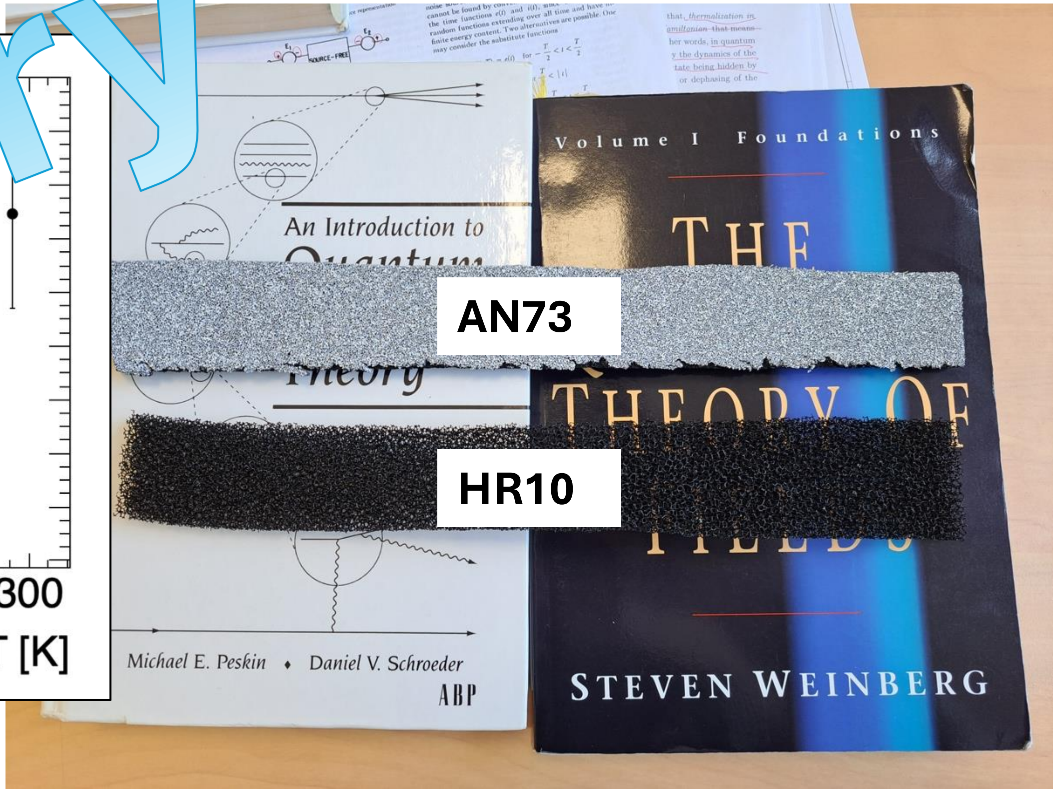


P. Kolb et al , Cold tests of HOM absorber material for the ARIEL eLINAC at TRIUMF, NIMA A 734 (2014) 60–64

Test stand development at Université Paris Saclay

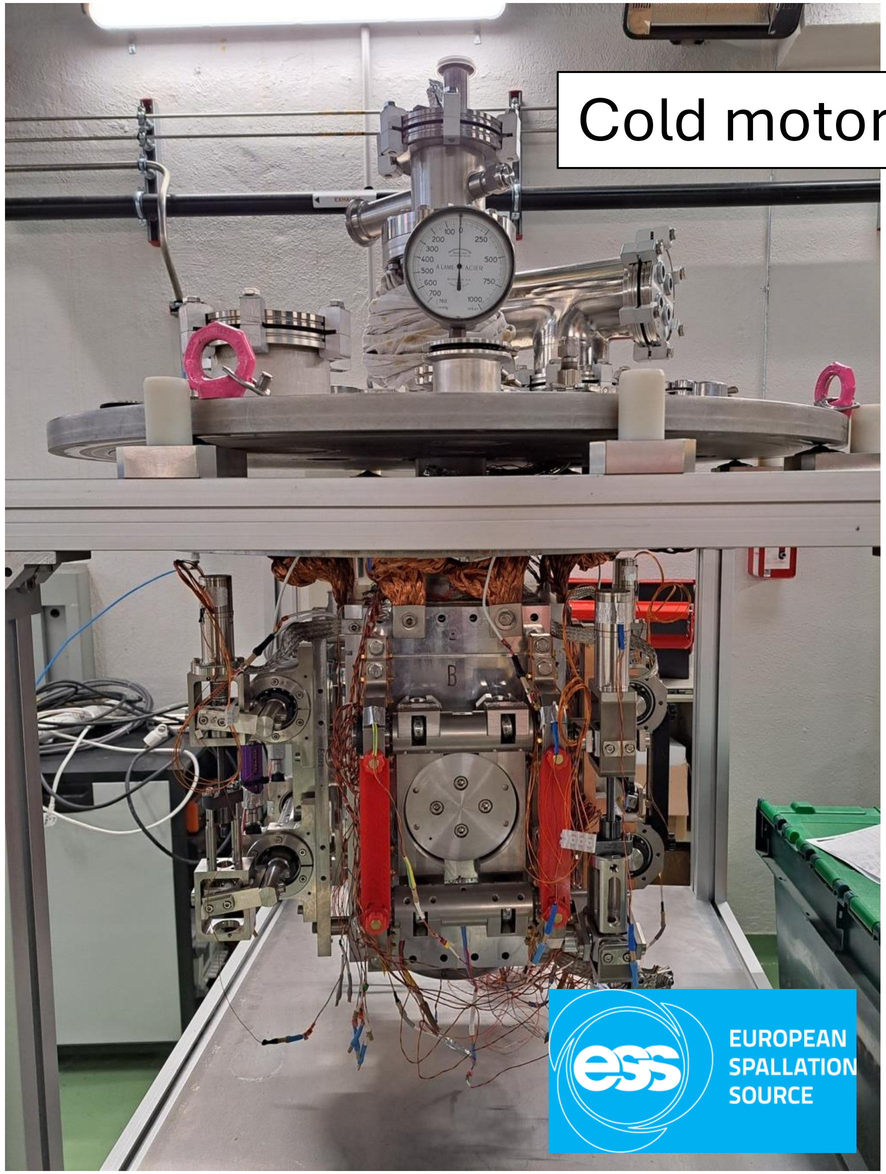






- Collaboration with particle physics (dark matter axion) and astrophysics (CMB)
  - Cryogenic compatibility of ECOSORB is studied
  - ECOSORB is NOT for particle free applications
- Implementation to the MADMAX project is on-going

Cryostat for the RF experiment at cold (?)



- We have a LN2 cryostat originally developed for the tuner tests
- 2^{nd} cryostat arrived at IJCLab → 1^{st} one is not in use
- Enough space for quasi-optics setup (?)
- Otherwise, waveguide setup may be more realistic by preparing different WR_{nm} to cover the whole frequency band

Outline

- Introduction
- Theory
- Preliminary warm experiments at CERN
- Cryogenic experimental setup at IJCLab
- Conclusion

Conclusion

- PERLE@IJCLab needs efficient cryogenic Beam Line Absorbers
  - 100W, 40K, <40 GHz
- Collaboration with other science fields to justify funding
  - 20 GHz dark matter axions
  - > 40 GHz CMB
- Literature search → dedicated R&D on dielectric absorbers seem mandatory
  - Material parameters to be included into the simulation are missing in general!
  - The most promising option is simply too expensive
  - A private company MARUWA will collaborate us to prepare new AlN samples
- Theory has developed
  - Dielectric, magnetic, conductive RF absorbers
  - High-power / mechanical properties are not included → multi-physics simulation
- Warm tests with a commercial solution at CERN CLIC
  - CERN has measured a lot of dielectrics at low power
  - Reverse engineering to understand the relation between S-parameters and material parameters as well as calibration scheme
- Cryogenic testbench will be developed at IJCLab
  - A new PhD student has just started on Oct 1 2025

backup

DAK manual says $\sigma = \varepsilon'' \omega \varepsilon_0$

The relative permittivity is further separated into its real and imaginary parts: $\epsilon_r = \epsilon' - j\epsilon''$. The real part of the permittivity is related to the energy stored in the material under test, whereas the imaginary part represents losses. The conductivity σ or the loss tangent $tan(\delta)$ may be considered instead of ϵ''. The three quantities are directly related to each other: $\sigma = \epsilon'' \omega \epsilon_0$ and $tan(\delta) = \epsilon''/\epsilon'$.

<u>In my theoretical analysis</u>

$$\nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + (\varepsilon' - i\varepsilon'') \times i\omega \boldsymbol{E} = (\omega\varepsilon'' + \sigma)\boldsymbol{E} + i\omega\epsilon' \boldsymbol{E} \qquad \tan\delta_e \equiv \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

σ and $\varepsilon'' \omega \varepsilon_0$ are rather ***indistinguishable*** from reflectometry

→ $\sigma = \varepsilon'' \omega \varepsilon_0$ sounds strange

This understanding would be critical for conductive SiC Cesic that TRIUMF installed in ARIEL electron linac