Design, Fabrication, and HV Testing of a HV RF Feedthrough (HVRFT) for a 1 MW CW TS-MBK

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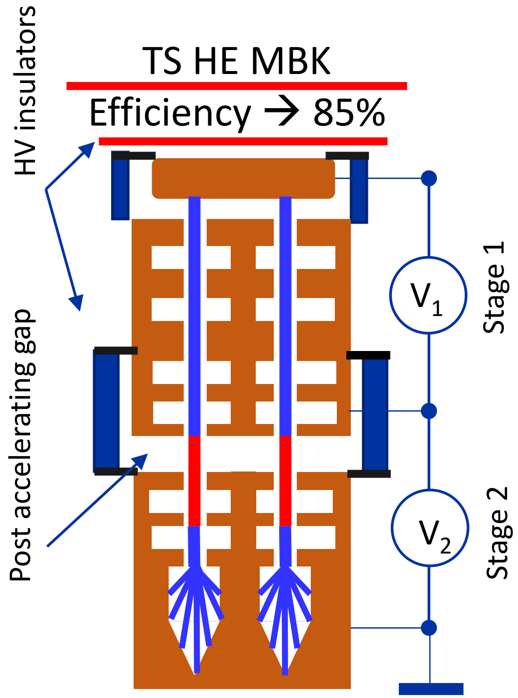
Two-Stage Multi Beam Klystron (TS-MBK) Technology in L-band

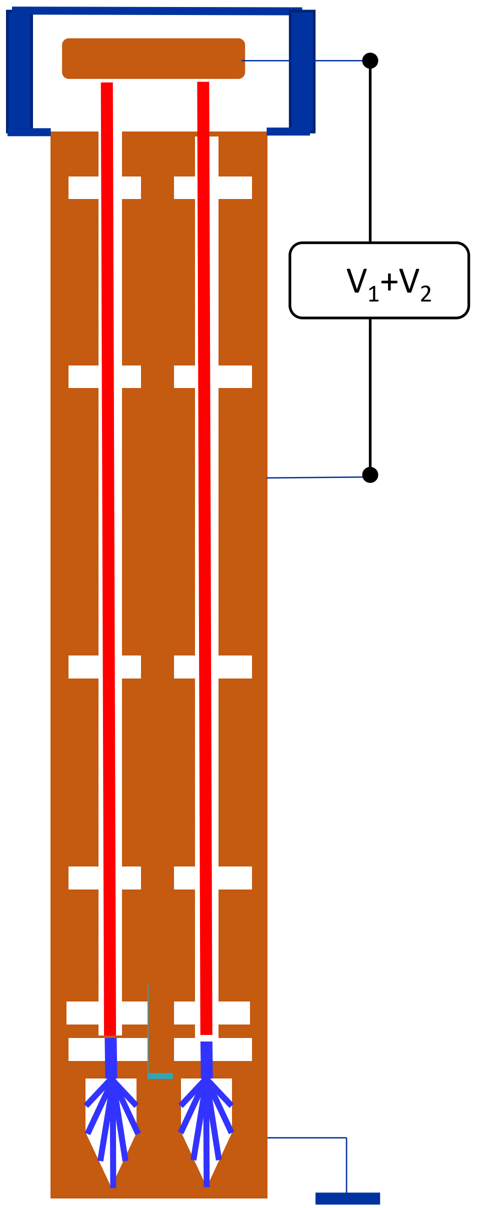
Features:

1. **Bunching at a low voltage** (high perveance). Very **compact RF bunching circuit.**
2. **Bunched beam acceleration** and cooling (reducing Δp/p) along the **short DC voltage post-accelerating gap**.
3. Final power extraction from **high-voltage (low perveance) beam → High efficiency.**

GOOD FOR:



Commercial HE MBK (η≈ 70%)

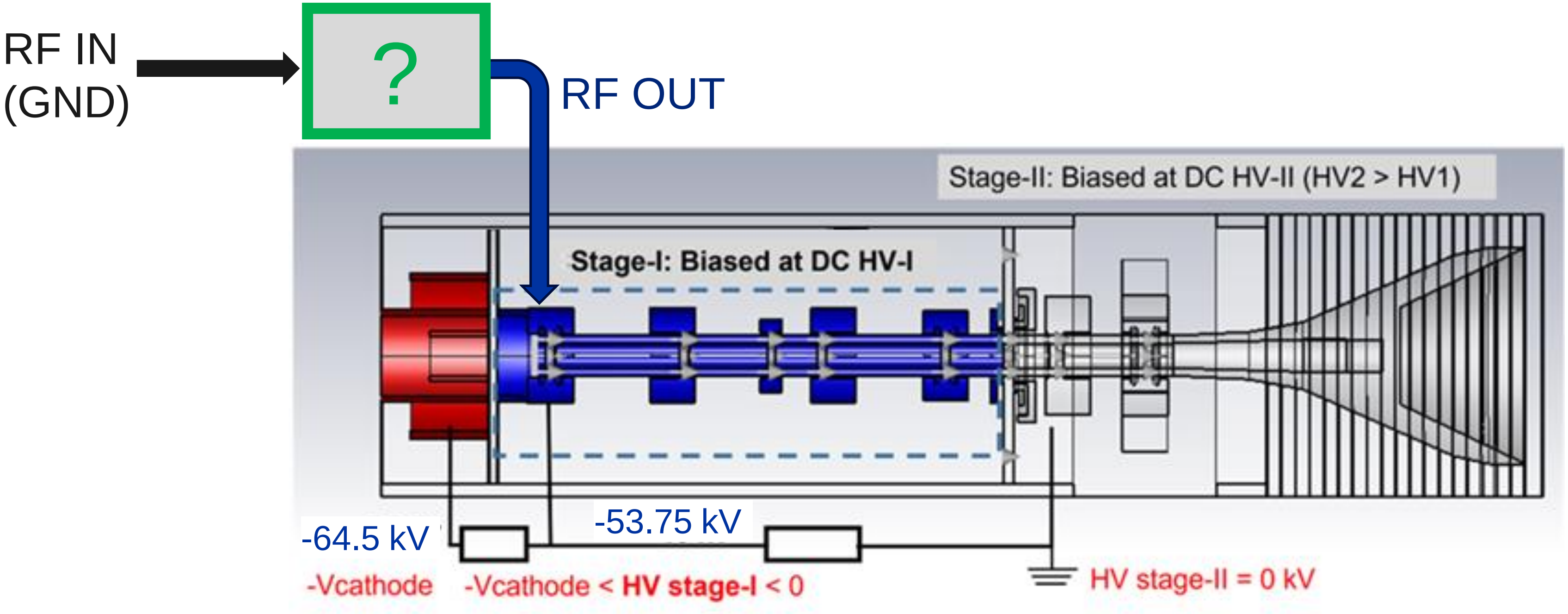


Additional advantages:

1. **For pulsed tubes, the second HV stage can be operated in DC mode. Thus, simplifying the modulator topology (cost/volume) and increasing the modulator efficiency.**
2. **Simplified feedback for the first stage pulsed voltage. Improved klystron RF phase and amplitude stability.**

Motivation:

- The input RF section of the TS-MBK is held at a potential of approximately -54 kV.
- To inject an RF while isolating the low power RF source from the HV DC side a high-voltage RF feedthrough (HVRFT) is required.



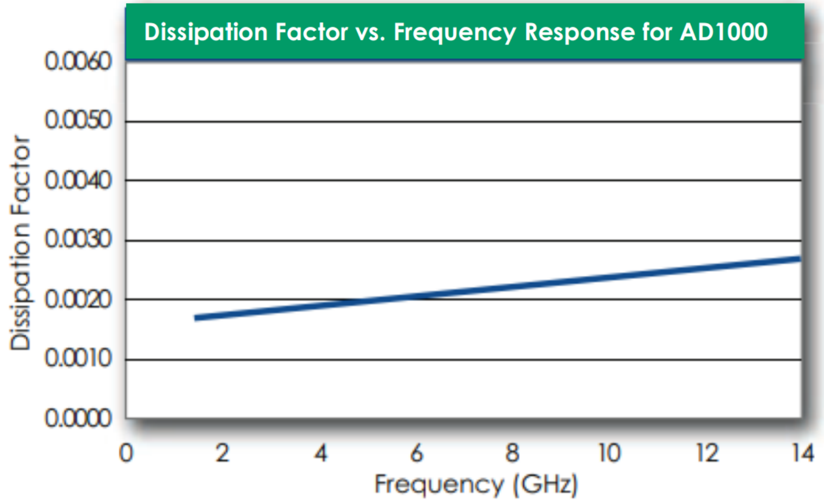
Requirements:

- To do so, a UHF band PCB microstrip filter was envisaged. A high dielectric constant, a high electrical breakdown strength, and a low dissipation factor are key requirements.

- Arlon AD1000 (woven glass reinforced PTFE/ceramic filled) meets these requirements and was selected. Rogers corporation is the sole manufacturer of this material.

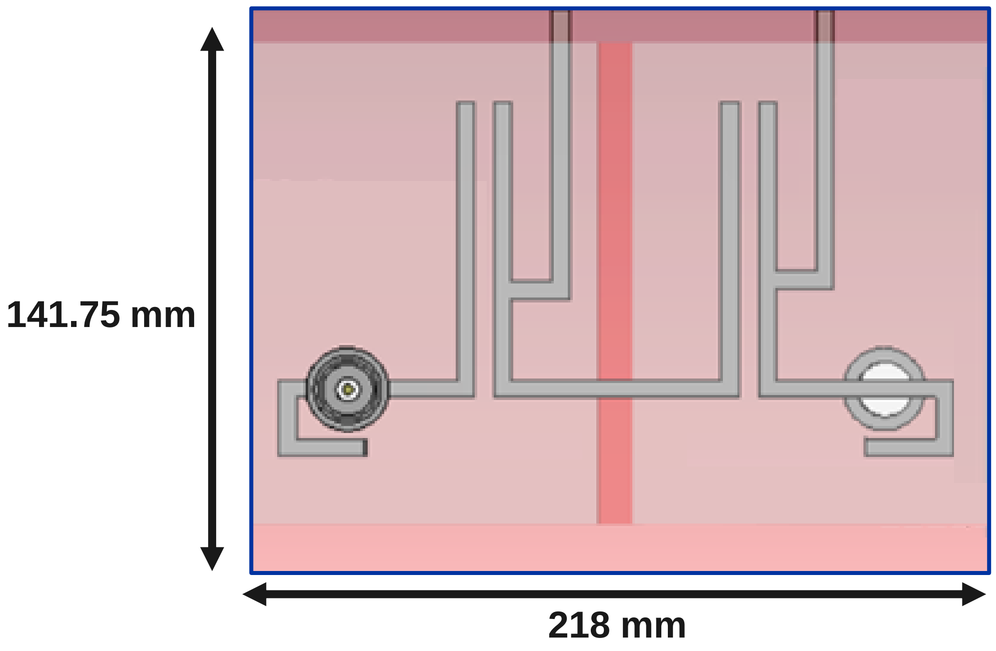
Typical Properties: **AD1000**

Property	Units	Value	Test Method
1. Electrical Properties			
Dielectric Constant (may vary by thickness)			
@1 MHz	-		IPC TM-650 2.5.5.3
@ 10 GHz	-	10.20	IPC TM-650 2.5.5.5
Dissipation Factor			
@ 1 MHz	-		IPC TM-650 2.5.5.3
@ 10 GHz	-	0.0023	IPC TM-650 2.5.5.5
Temperature Coefficient of Dielectric	-		
TCεr @ 10 GHz (-40-150°C)	ppm/°C	-380	IPC TM-650 2.5.5.5
Volume Resistivity			
C96/35/90	MΩ-cm	$1.40x10^9$	IPC TM-650 2.5.17.1
E24/125	MΩ-cm	$5.36x10^7$	IPC TM-650 2.5.17.1
Surface Resistivity			
C96/35/90	MΩ	$1.80x10^9$	IPC TM-650 2.5.17.1
E24/125	MΩ	$3.16x10^8$	IPC TM-650 2.5.17.1
Electrical Strength	Volts/mil (kV/mm)	622 (24.5)	IPC TM-650 2.5.6.2
Dielectric Breakdown	kV	>45	IPC TM-650 2.5.6
Arc Resistance	sec	>180	IPC TM-650 2.5.1

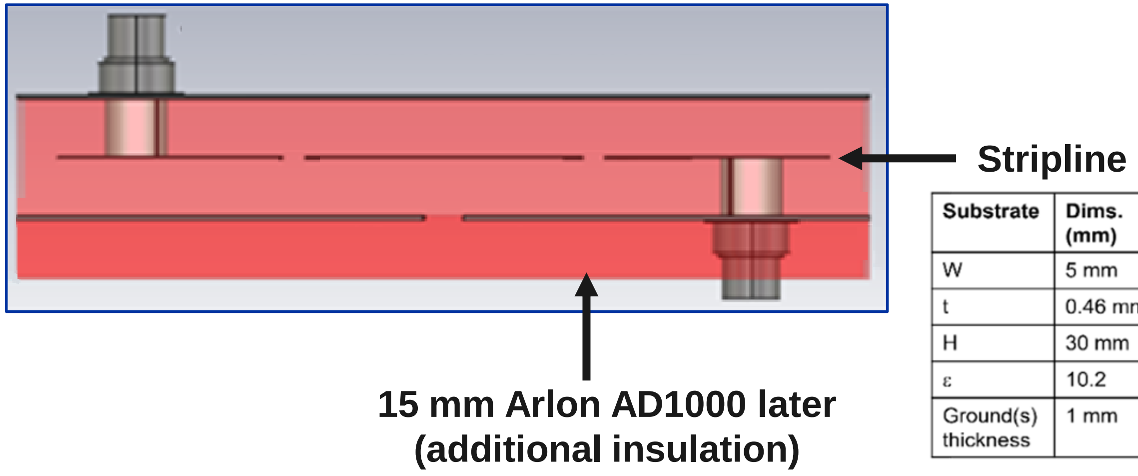


Solution: A coupled-line bandpass filter (CLBPF) PCB (AD1000) with a slotted ground plane

Stripline Layout



Arrangement of Layers



Substrate	Dims. (mm)
W	5 mm
t	0.46 mm
H	30 mm
ε	10.2
Ground(s) thickness	1 mm

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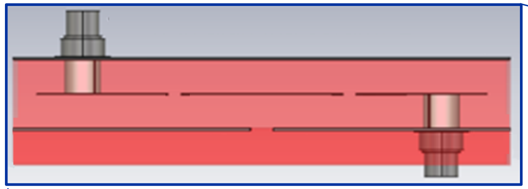
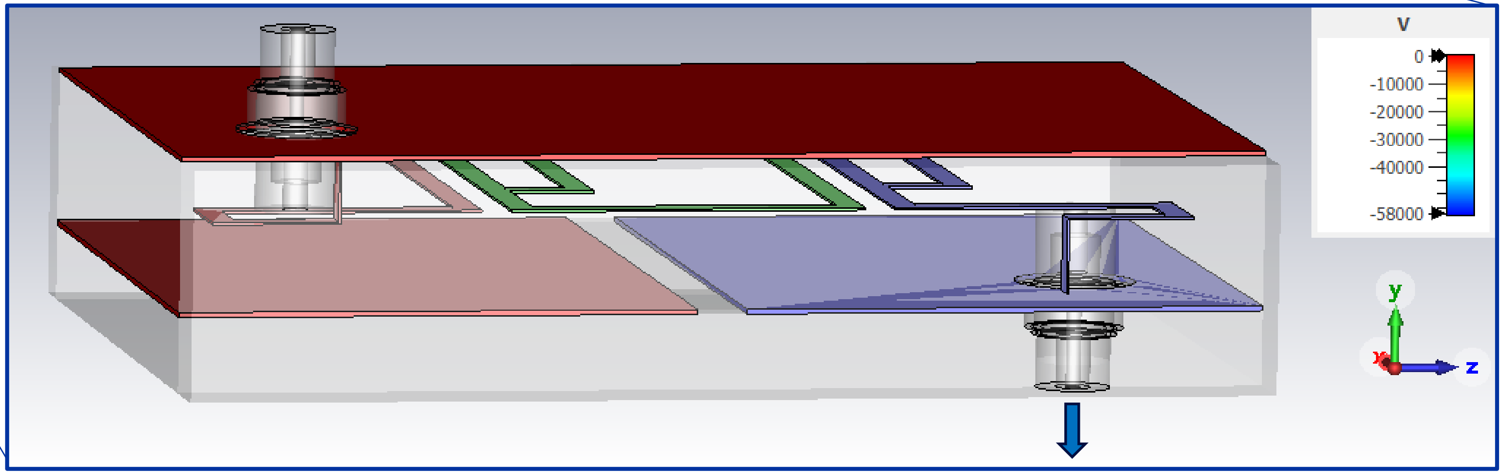


Low-power RF Input



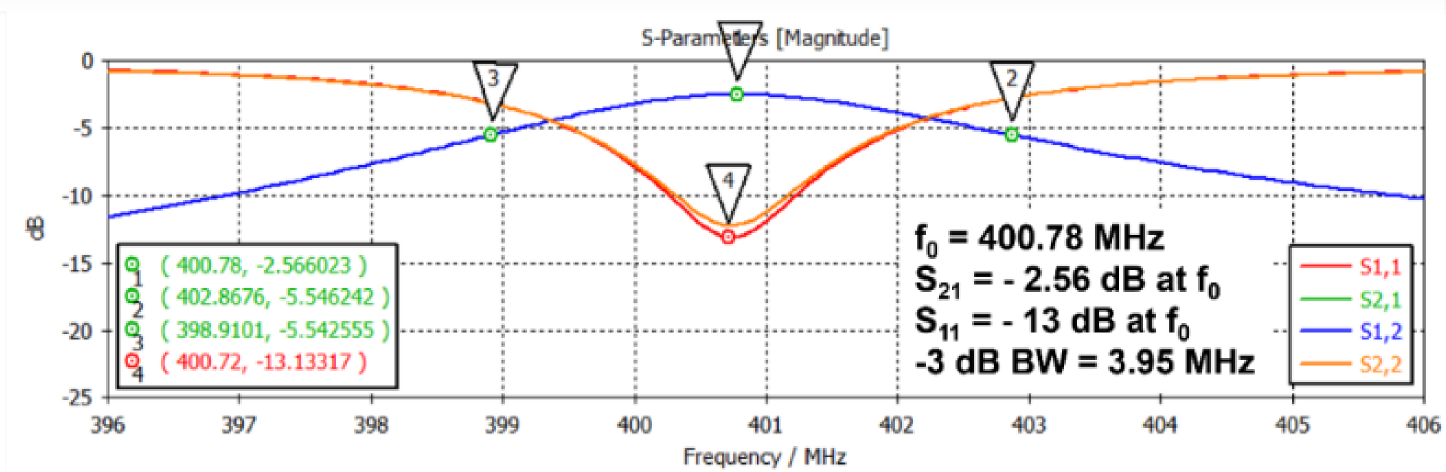
Low-power RF output
(-53.75 kV side)

Solution: A coupled-line bandpass filter (CLBPF) PCB (AD1000) with a slotted ground plane

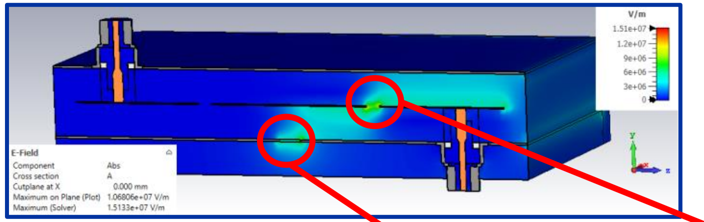
Taking Arlon AD1000 as the substrate (ε=10.2, tanδ=1.6e-3):

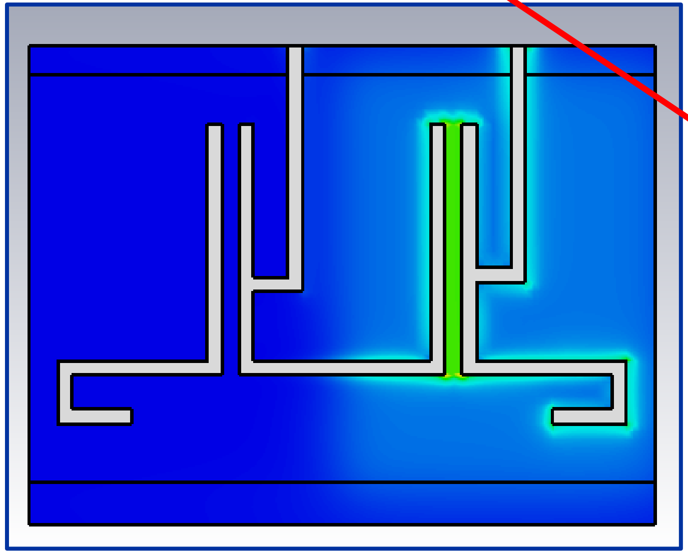
- ✓ **Freq: 400.8 MHz,**
- ✓ **S_{21}: -2.56 dB (with dielectric losses).**
- ✓ **BW: ~ 3.95 MHz**
- ✓ **Electric strength: 24.5 kV/mm**
- ✓ **DC isolation: 60 kV (tested)**
- ✓ **Compact (UHF band): 218mm x 167mm x 46mm**

Simulated S-Parameters

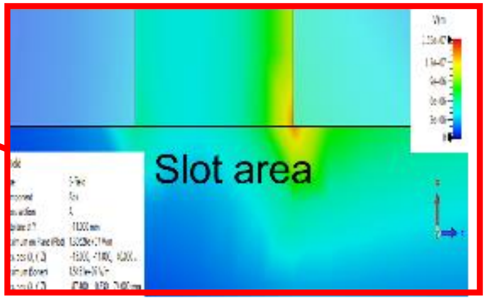


Solution: A coupled-line bandpass filter (CLBPF) PCB (AD1000) with a slotted ground plane

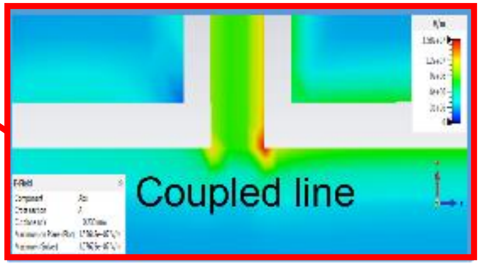




Regions of high electrostatic field:



- → Slotted ground with a width of 10mm.
- → E-field of 12.7 kV/mm.



- → Coupled line with a 6mm gap (optimized for E field, BW and S21).
- → 15.4 kV/mm.

Design was optimised to handle potentials of up to 60 kV.

Prototyping: A Two(ish)-Pronged Approach

(a) HVRFT-I → The prototype for high-voltage tests, built using a resin with similar HV properties to AD1000. The multi-layer fabrication and HV testing steps also provide valuable experience.

(b) HVRFT-II → The real deal. To be assembled in AD1000 at CERN's PCB lab. Prior to this the assembly process will also be tested with FR-4 to ensure conformity.

Overview:

Model	Material	Fabrication	Status/HV Testing
HVRFT-I (for HV test only)	SikaBiresin® RE 891-98 RESIN (similar HV specs → 27kV/mm dielectric strength vs Arlon's 24 kV/mm)	CERN's Polymer Lab (3-layer process).	**Completed in 2023.**
HVRFT-II	Rogers Arlon AD1000 (high HV and RF performances)	CERN-MPT (PCB) Lab Stack description: 4-layers thick, 166.75mm x 218mm x 56.565mm.	**Material procured and assembly in progress – to be tested in late 2024/early 2025.**

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I'll focus on how we got here first.

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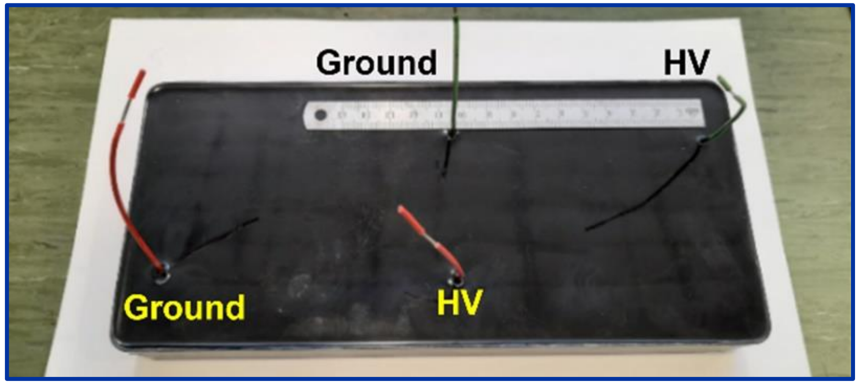
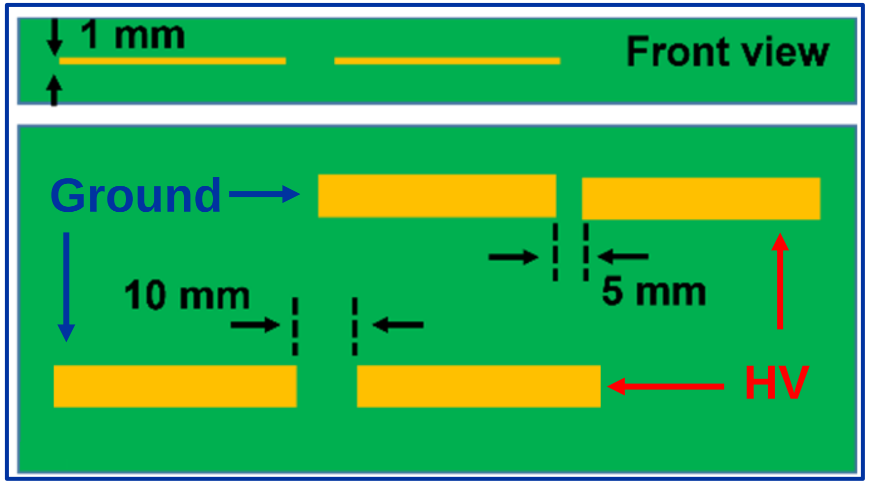
Experiment: Microstrip HV Test in SikaBiresin® RE 891-98

A preliminary high-voltage test was first conducted with the resin.

- Parallel microstrip lines were embedded, as pictured on the right.
- Gaps of 5 and 10 mm were present in the adjacent lines.





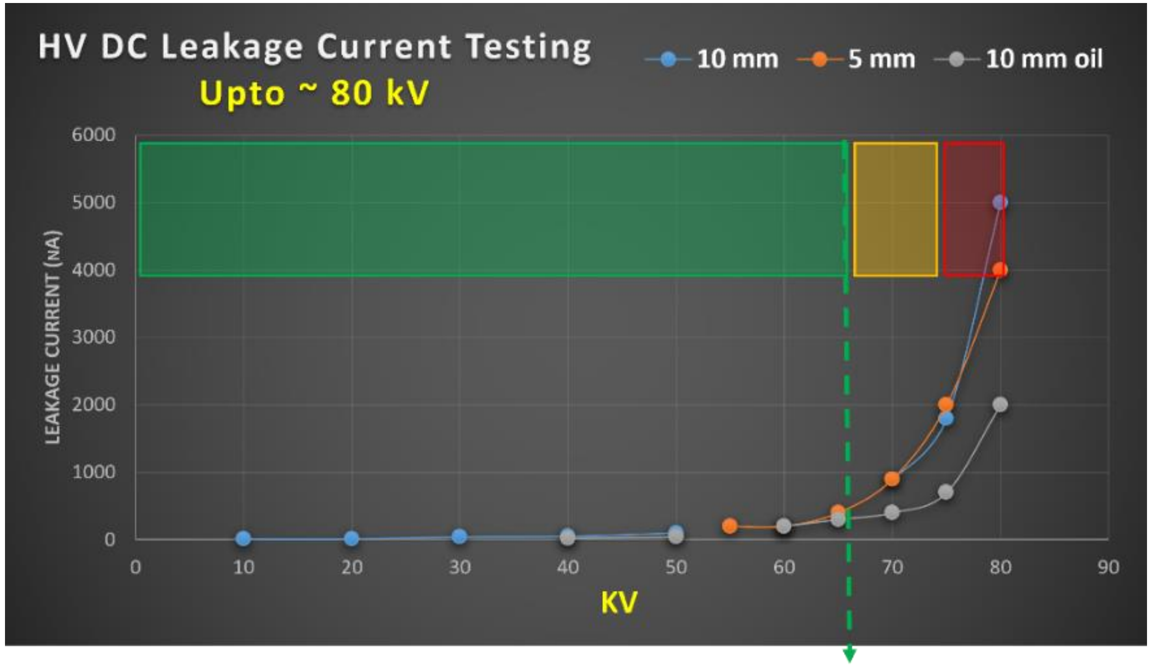
Experiment: Microstrip HV Test in SikaBiresin® RE 891-98

- No substantial leakage current below 60 kV was observed during testing, for sets of parallel strips with gaps of both 5 mm and 10 mm.

- However, for DC voltages of >60 kV, leakage current develops through combination of local discharges and surface conduction.

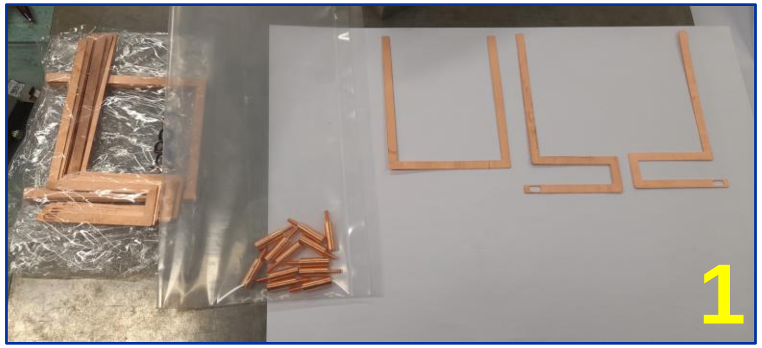
- After 70 kV, a sharp rise in leakage current was observed.

→ Onwards to assembly!

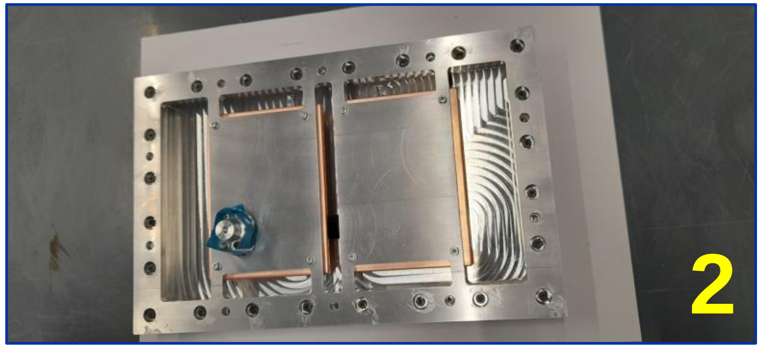


HVRFT-I (for HV test only): Assembly Process

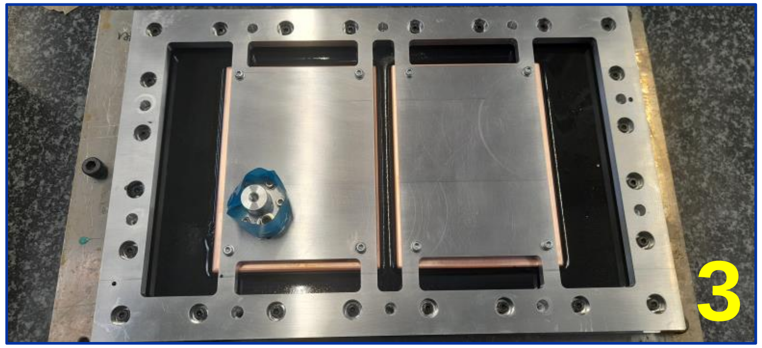
- Copper striplines prepped.



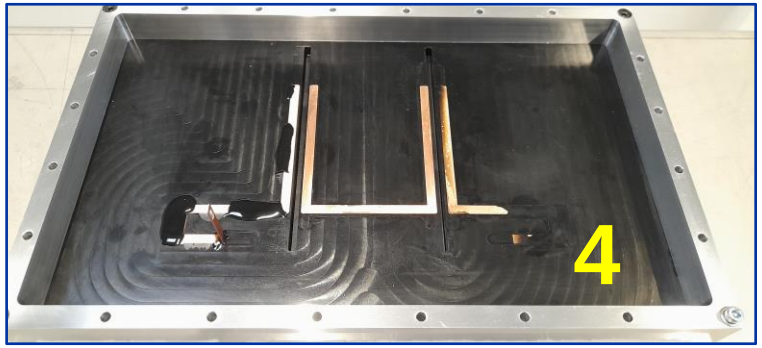
- Mould and slotted ground plane ready for 1st layer of resin.



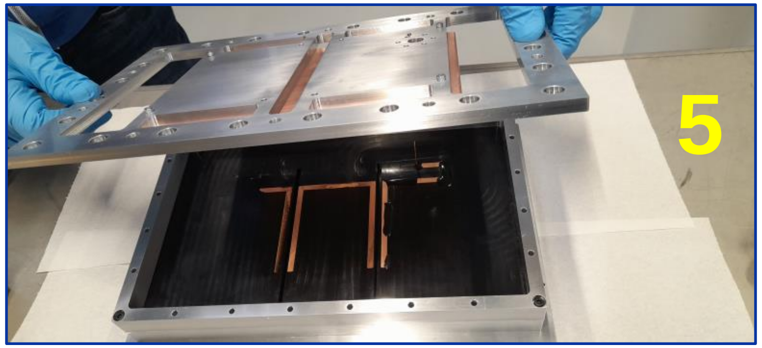
- After addition of 1st layer, resin at room temp/pressure.



- Stripline placement/alignment.



- Top plane, and addition of 2nd layer of resin.

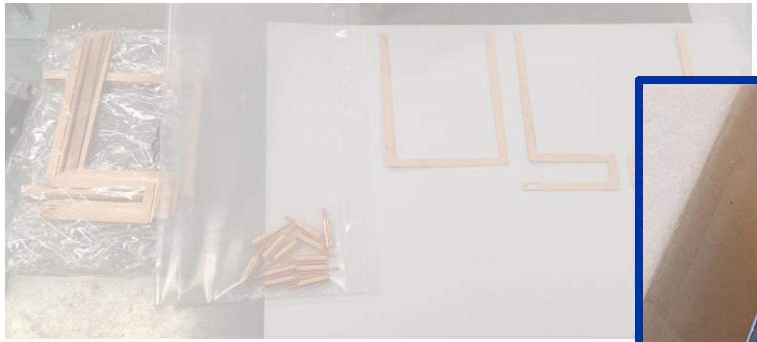


- Addition of N-type coaxial connectors.

Thanks to Gianfranco Ravida (MKS) and Sebastien Clement (CERN Polymer Lab)!

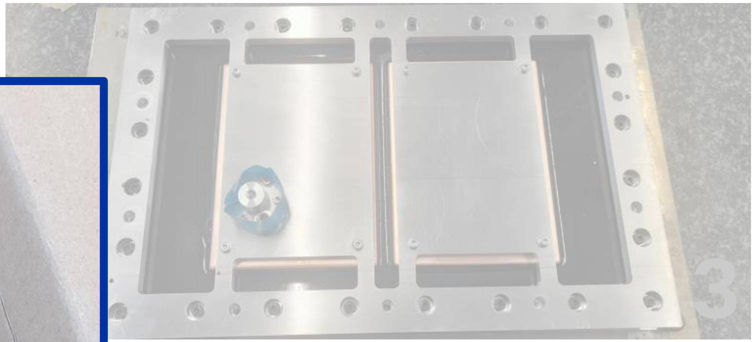
HVRFT-I (for HV test only): Assembly Process

- Copper striplines prepped.

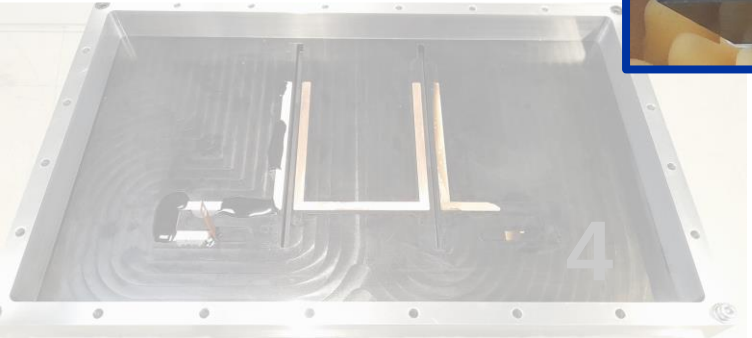


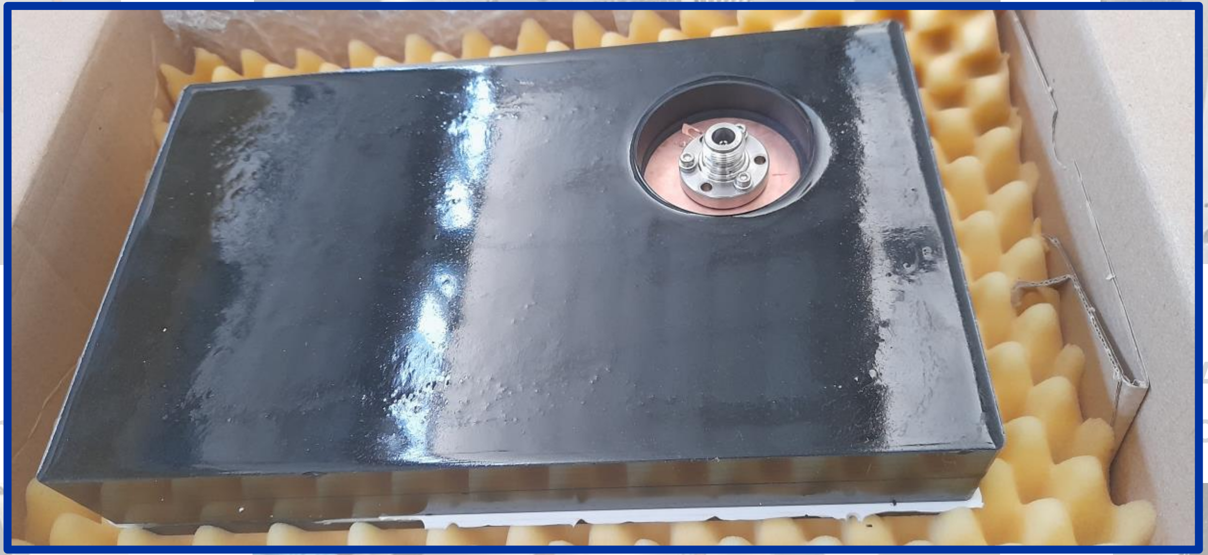
- Mould and slotted ground plane ready for 1st layer of resin.

- After addition of 1st layer, resin at room temp/pressure.



- Stripline placement/alignm





The HV Prototype.

Addition of N-type coaxial connectors.

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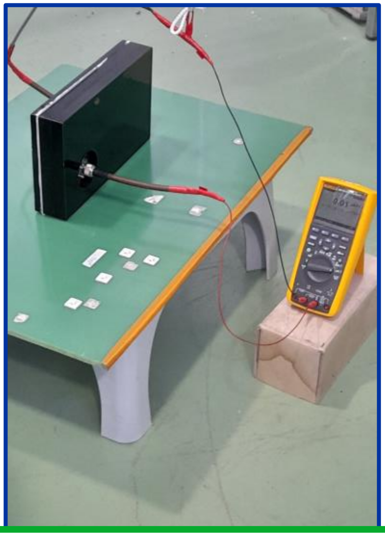
HVRFT-I: High-Voltage Test

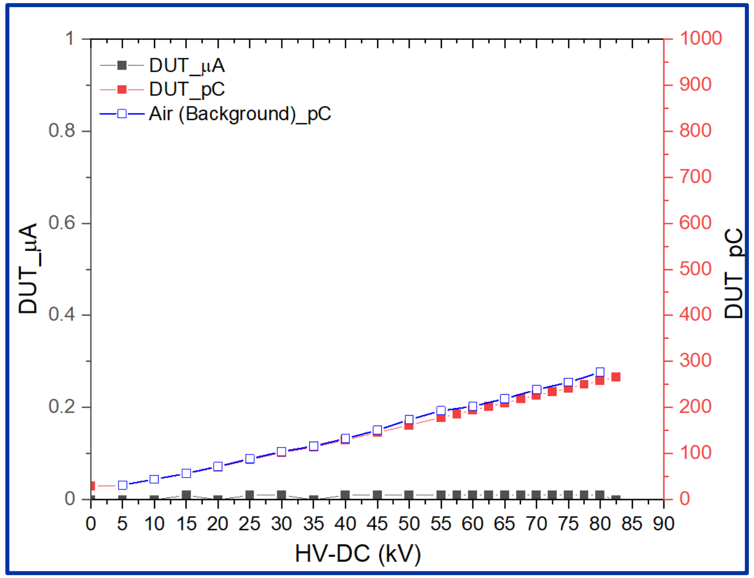
60 kV Test



Leakage current = 0.00 mA (supply)
Leakage current = 10 nA (ammeter)
Almost 100 hrs+ (endurance test !)

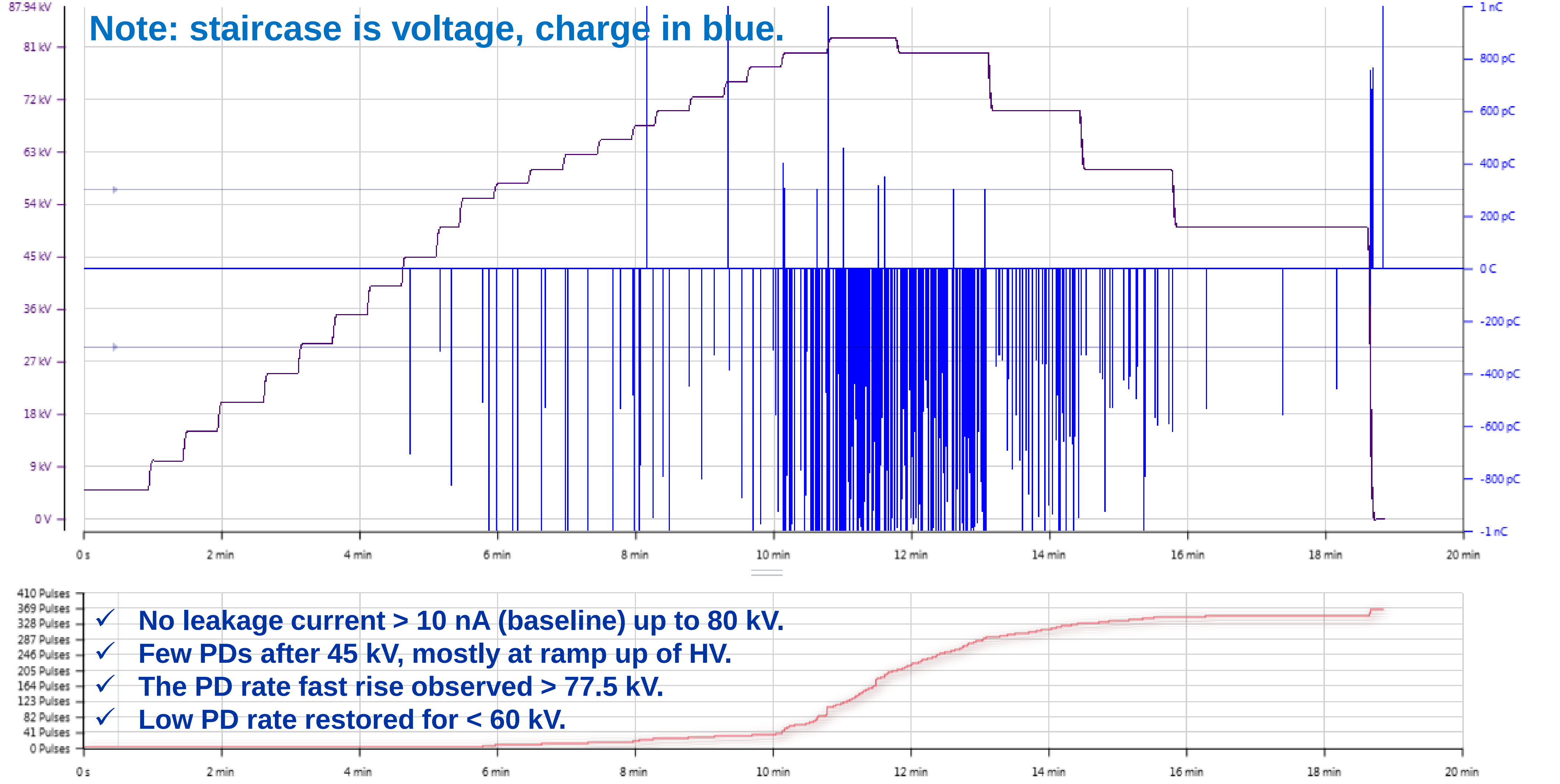
80 kV Test setup

80kV Test Results



- ✓ No leakage current observed during 60 kV tests shown on the left (sensitivities of 10 nA at ammeter and 10 µA on supply).
- ✓ 80 kV testing at Partial Discharge (PD) facility showed leakage current/charge close to background values (as in air without DUT).

HVRFT-I: Partial discharge (PD) Measurements



- ✓ **No leakage current > 10 nA (baseline) up to 80 kV.**
- ✓ **Few PDs after 45 kV, mostly at ramp up of HV.**
- ✓ **The PD rate fast rise observed > 77.5 kV.**
- ✓ **Low PD rate restored for < 60 kV.**

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And now, where we're heading next.

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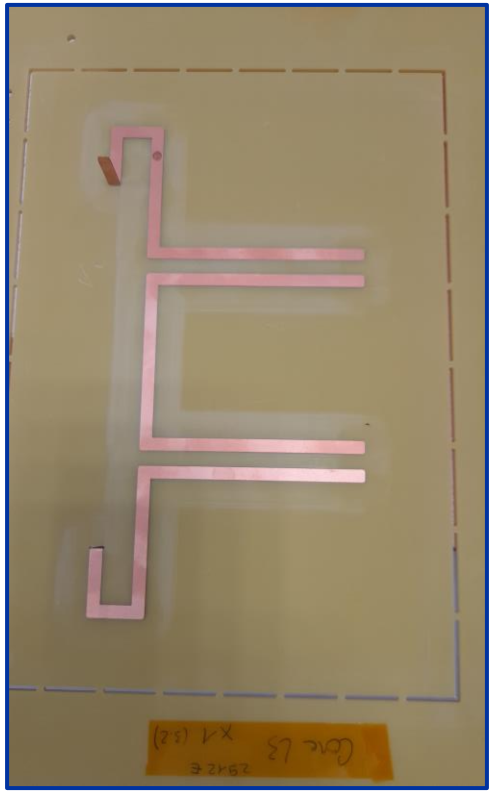
HVRFT – II (Arlon): Situation Report

- Components and material procured (AD1000 laminate/glue, stacking layout ready).
- Striplines have been prepped and connectors soldered.
- A pre-AD1000 assembly is currently being prepared prior to doing so in Arlon (“one and done” for final assembly).
- A 5x5 cm AD1000 sample is being stacked and prepared for pre-fabrication measurement of dielectric properties (done inhouse at CERN).

→ Onwards!



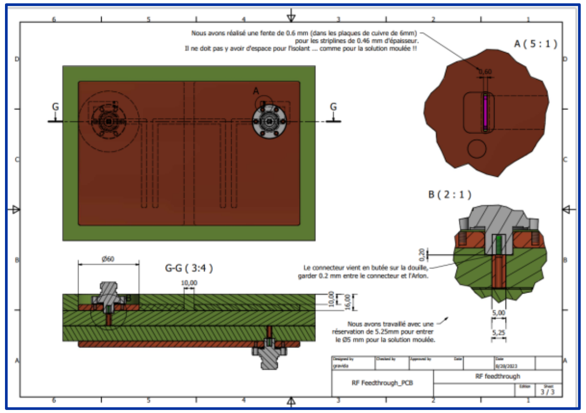
Summary:

✓ HVRFT-I prototype has been shown to withstand 60 kV for 100+ hours (completed in 2023).

➢ **HVRFT-II plan:** Production is underway at CERN Micropattern technologies workshop (PCB Lab)

July	Oct	Late 2024/Early 2025
▪ Stripline prep ▪ Pin soldering. ▪ Mock stacking	▪ Stacking at MPT workshop	▪ **Device completion, then RF and HV tests.**

(a) Coax pin bonding.



(b) Mechanical drawings prepared.

-Stack description → 4 layer Thick PCB 166.75mm x 218mm x 58.5 mm

-TOP layer: 6mm Cu embedded in FR4 (single electrode)
-Isolation 1 between TOP and inner 1 layer : 14.998mm
-Inner 1 layer : 0.46mm Cu embedded in AD1000X
-Isolation 2 between inner 1 and inner 2 layer : 15.008mm
-Inner 2 layer: 6mm Cu embedded in AD1000X (2 electrodes)
-Isolation 3 between inner 2 and BOT layer : 16.065mm
-BOTTOM layer : not existing

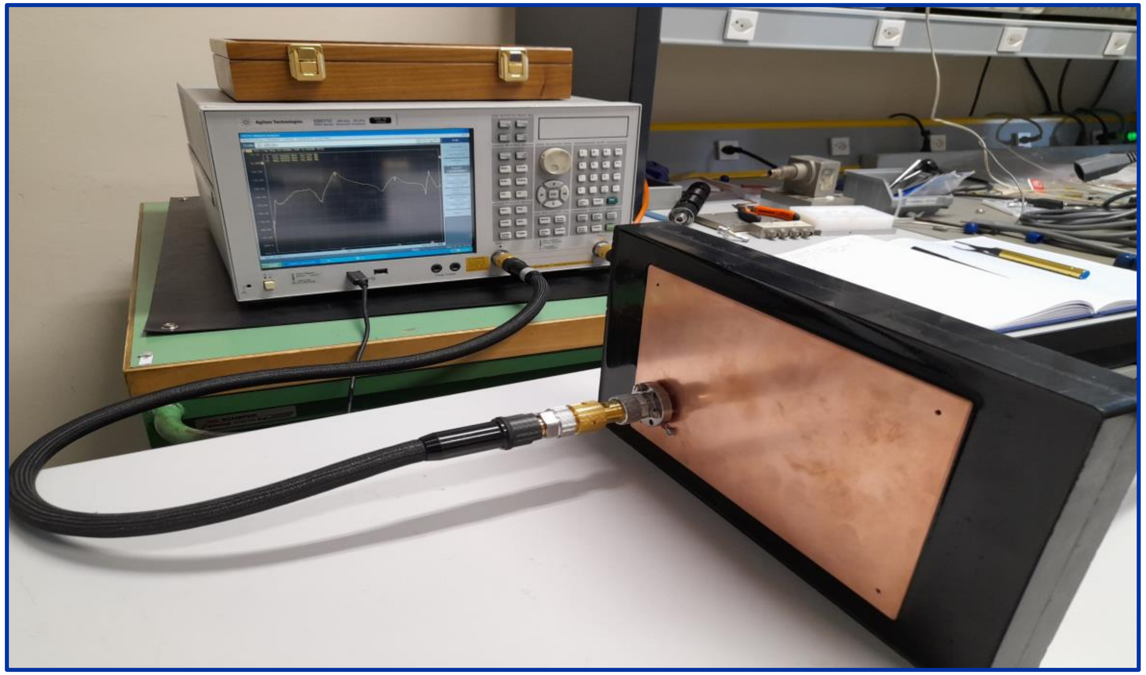
(c) AD1000 laminate/glue stacking layout prepared.

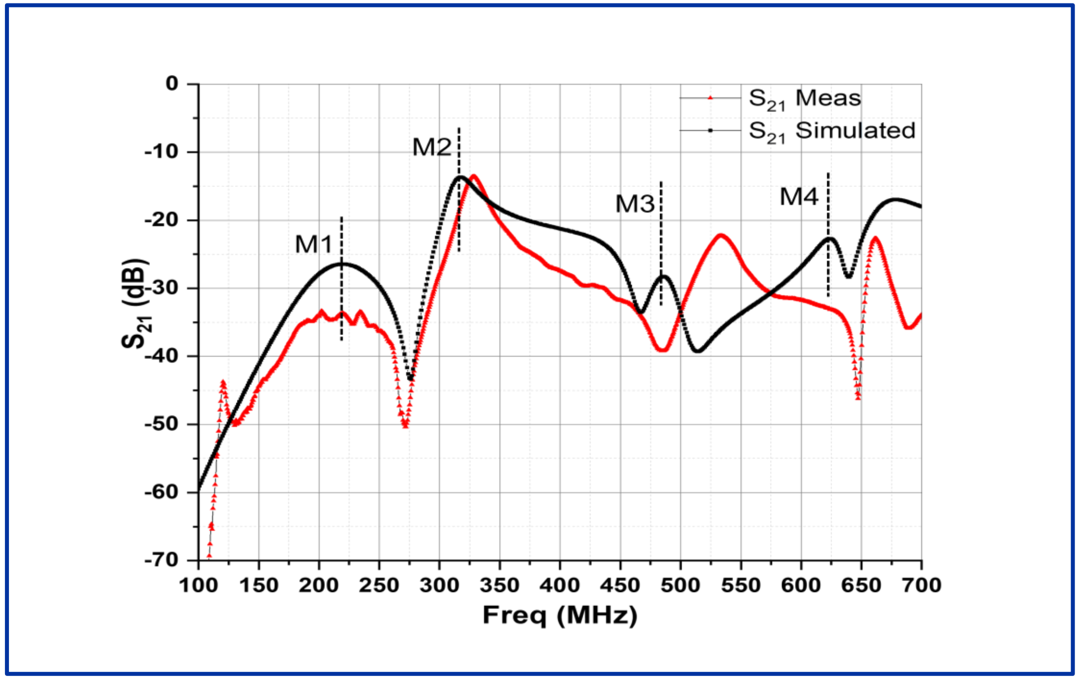
Thank you !

Bonus Slides

HVRFT-I (for HV test only): RF Measurement

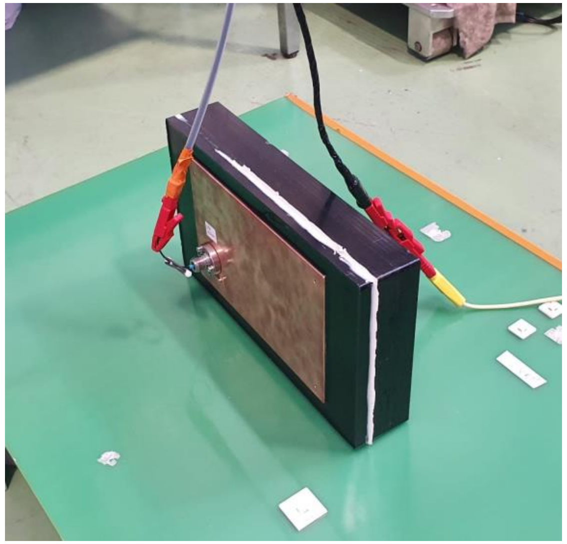
Simulation: ε = 4, tanδ = 0.04 @ 100 Hz





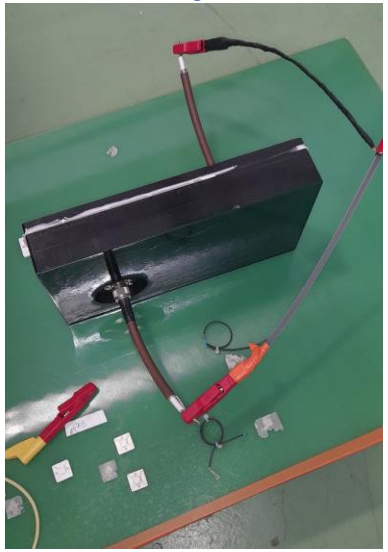
HVRFT-I: Testing Configurations

Config-A



Config-B

Config-C

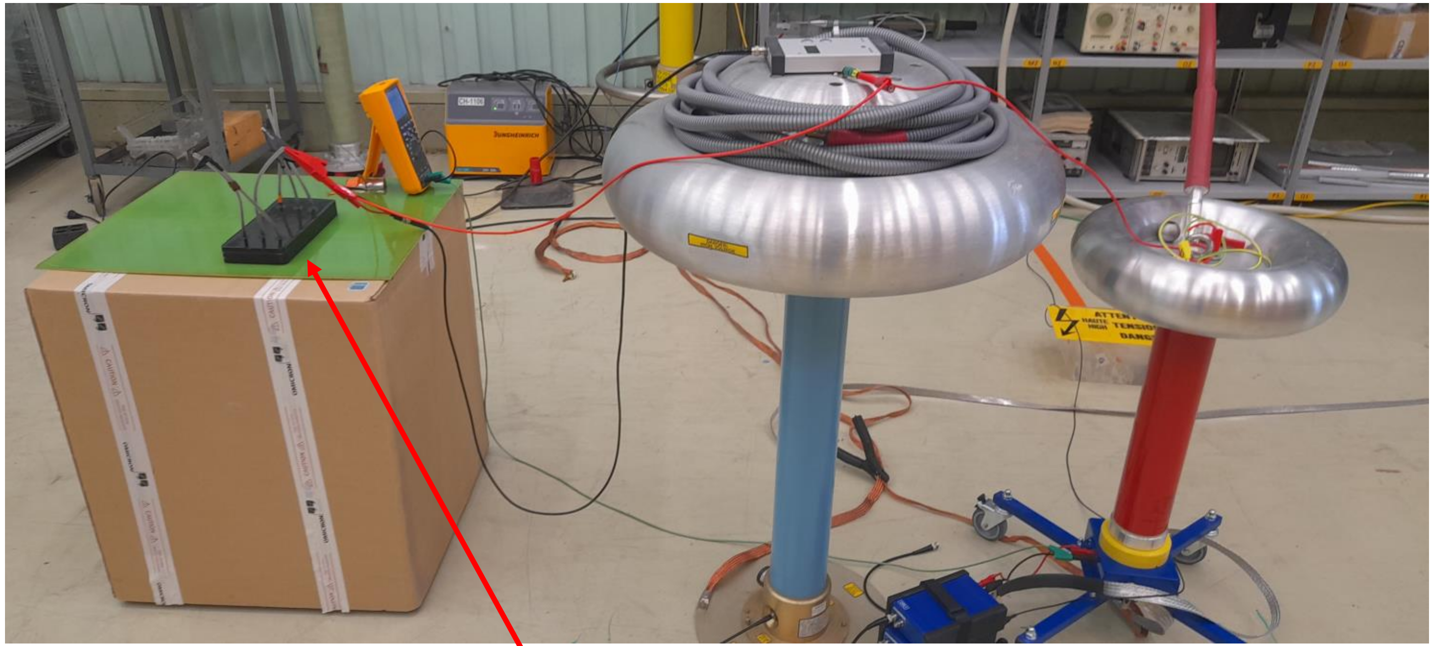


Config-D

A	centre pin-I to centre pin-II	58 kV – No leakage (res 10μA), Humming sound
B	ground conn-I to ground conn-II	> 50 kV – leakage 10μA (humming)
C	Connector's both pins @ same DC (using cable)	> 39/40 kV – leakage 10μA (humming)
D	Same as C – biased separately	Same as C

- HV Testing in different configurations showed leakage current 0.01 mA (scale in Henzinger supply) = 10 micro Amps (10,000 nA), for HV-applied > 40 kV (full connector engaged)
- **The leakage/local surface conduction we saw was merely an artifact of the measurement setup.**

PD testing instrument control



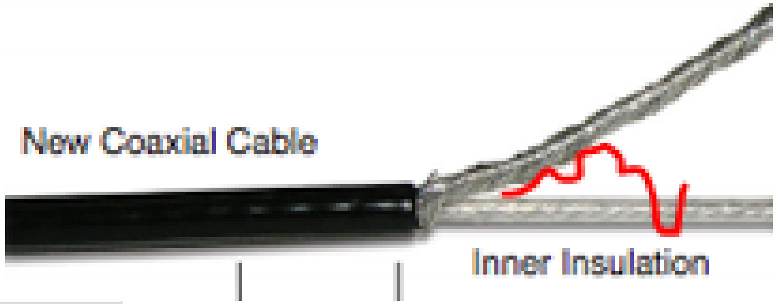
- **Striplines in epoxy under test.**
- **To compare leakage current and PD charge measurements, before actual test on HVRFT-I.**

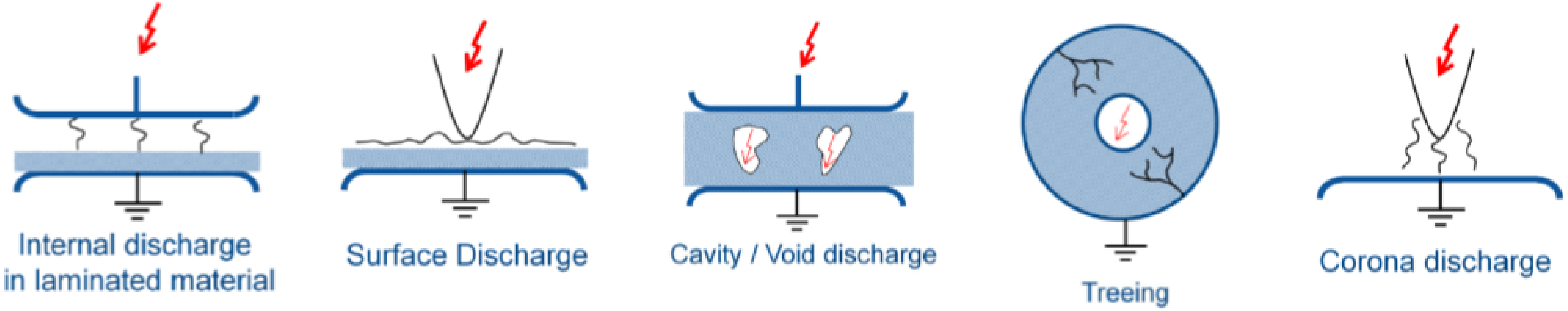
For charge calibration

Partial Discharge

What is it?

- Localized electrical discharge that only partially bridges the insulation between conductors … [IEC 60270].
- Releases energy where the constructor didn't plan.
- Decomposes the surrounding materials.
- Reduces the lifetime.
- Initiating the final breakdown.





[1]

in gaseous media e.g. around conductors

From Tobias, CERN HV team.