Development of a Novel Wide-Bandwidth Pickup for Intra-Bunch Measurements

The Semi-Coaxial Pickup: Design, Simulation & Prototype

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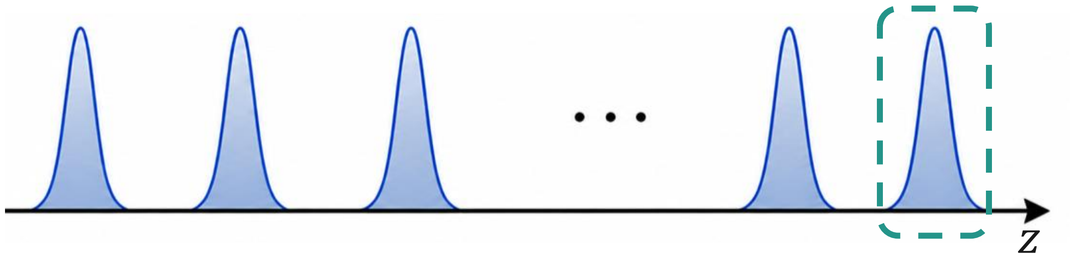
Outline

- **Motivation and Requirements**
- **Semi-Coaxial Pickup Concept**
- **Electromagnetic Design and CST Simulations**
- **Prototype and Laboratory Validation**
- **Conclusions and Next Steps**

What is an Intra-Bunch Measurement?

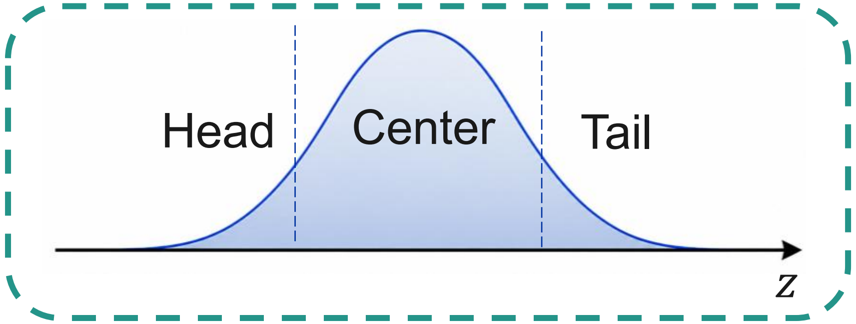
- **Conventional beam position monitor**

  → one transverse position per bunch.

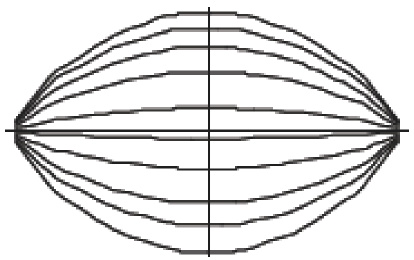


- **Intra-bunch diagnostics**

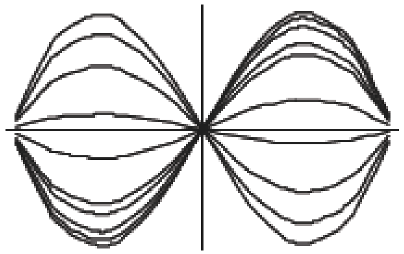
  → transverse motion within a single bunch.



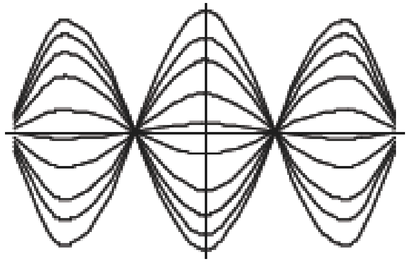
Mode 0:
rigid transverse motion



Mode ±1:
head and tail out of phase



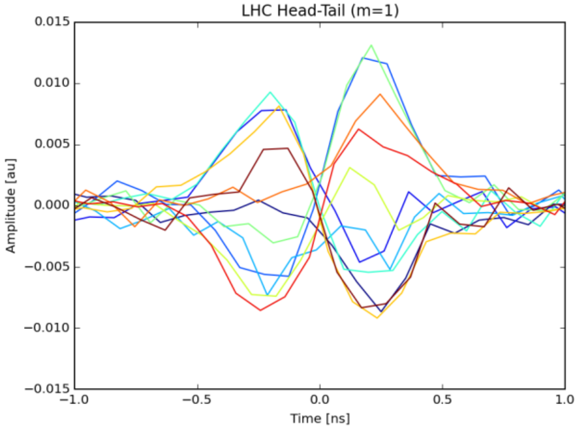
Mode ±2:
head and tail in phase,
center in opposition

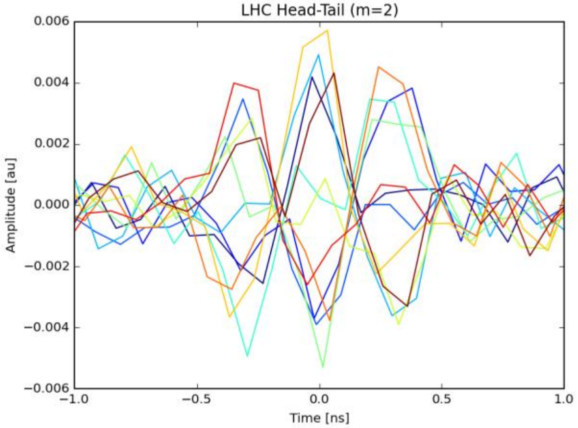


Resolving higher-order ($m \geq 1$) intra-bunch dynamics requires diagnostics with **high temporal resolution.**

The Need for Intra-Bunch Diagnostics in the LHC

1 LHC: Head-Tail Instability Monitoring

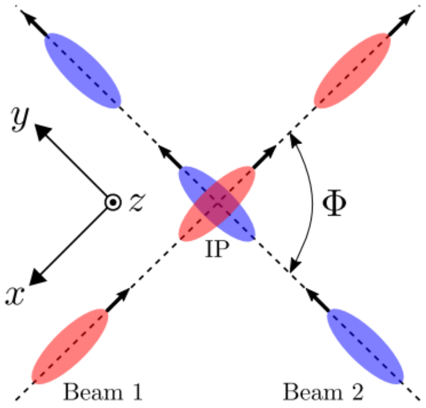


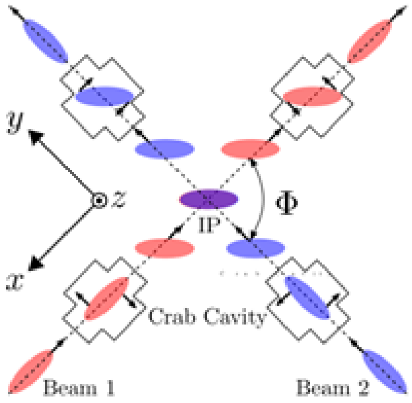


- Transverse beam instabilities can produce different motion along the bunch.
- Intra-bunch diagnostics enables the identification and characterization of transverse head-tail modes.

→ **Main role of the current LHC Head-Tail Monitor.**

2 HL-LHC: Crab Cavity Tuning



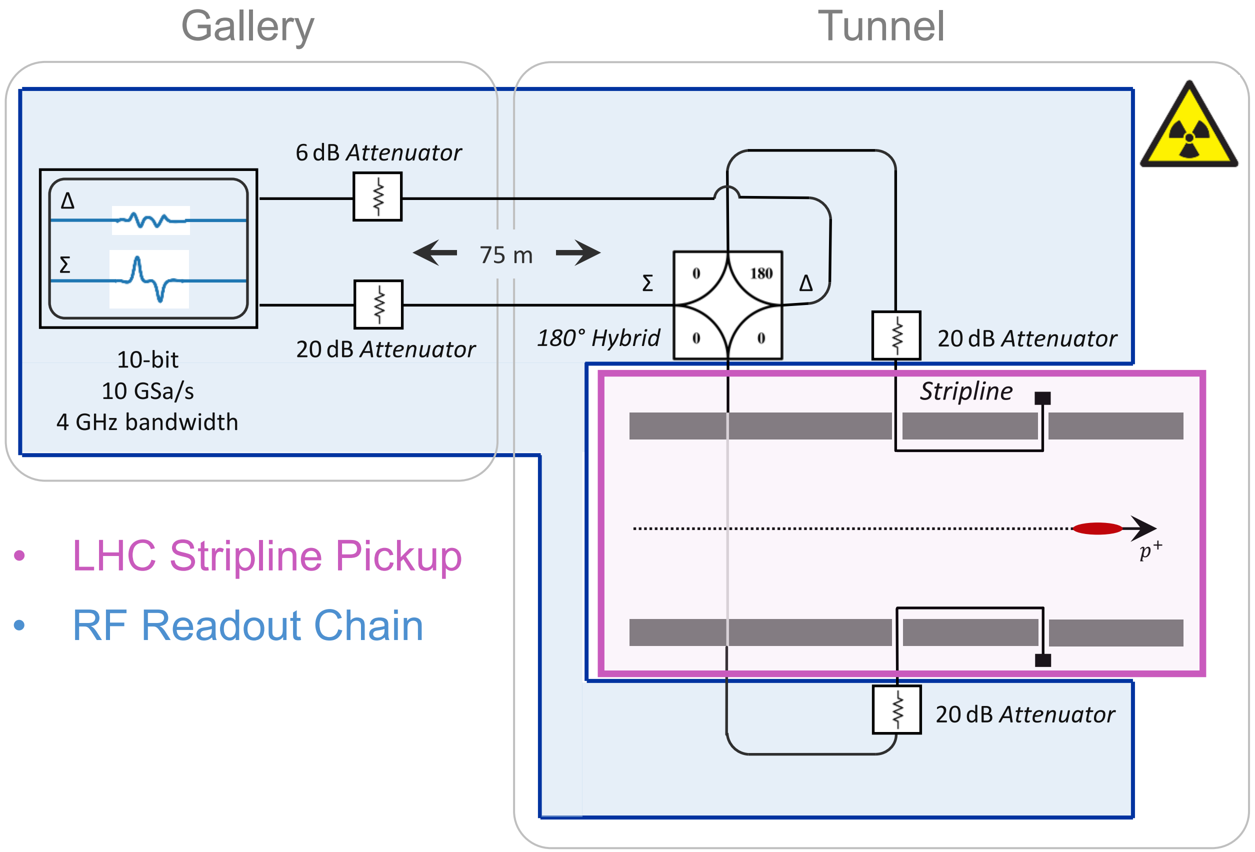


- Crab cavities introduce a controlled transverse tilt along the bunch.
- Accurate measurement of the bunch rotation requires higher temporal resolution.

→ **More demanding intra-bunch diagnostic requirement for HL-LHC.**

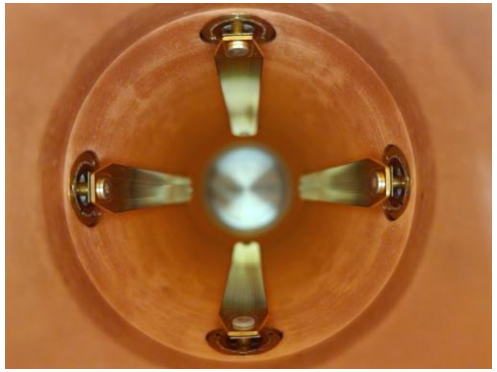
Limitation of the Stripline Pickup in the Current LHC HT Monitor

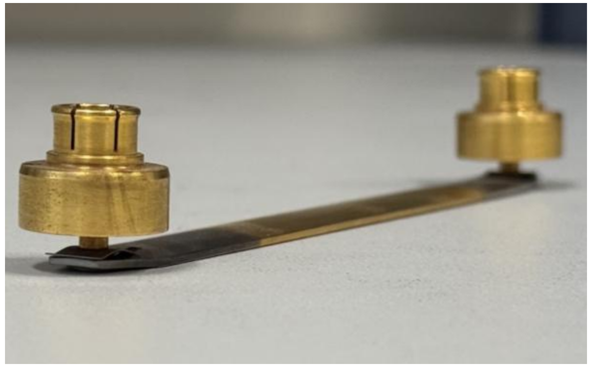
- **Current LHC Head-Tail Monitor**: long stripline pickup and RF readout chain for transverse intra-bunch diagnostics.



- LHC Stripline Pickup
- RF Readout Chain

400mm Stripline Pickup Limitations





1. **Limited RF transmission bandwidth** of the stripline electrode (~2GHz).
2. **Abrupt electrode-to-feedthrough transition:**
   - Impedance discontinuities
   - High-frequency response degradation.
3. **Large output voltage signal →** strong attenuation required in the readout chain.

A Novel Pickup Concept for Future Intra-Bunch Measurements

Stripline Pickup Limitations

→

New Pickup Requirements

- Wider RF bandwidth
- Well controlled 50 Ω signal path
- Tailored beam coupling

→

Proposed Solution

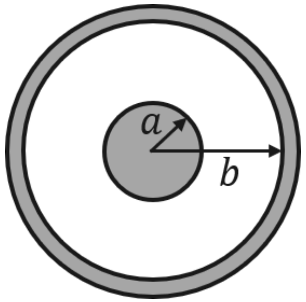
Semi-coaxial Pickup

A novel concept for CERN accelerator diagnostics

Semi-Coaxial Concept

- **Why "semi-coaxial"?**

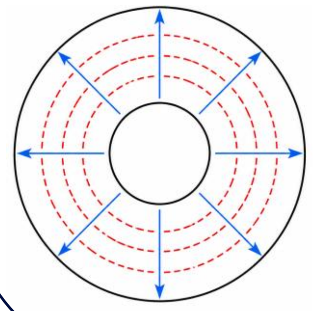
Coaxial Transmission Line



Two concentric conductors:

$\boldsymbol{b} = Outer\ Conductor\ Radius$

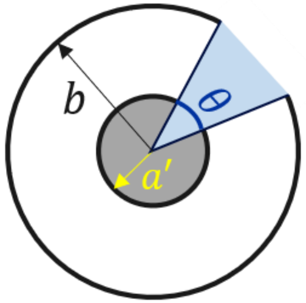
$\boldsymbol{a} = Inner\ Conductor\ Radius$



Transverse Electromagnetic (TEM) mode

$$Z_0 \simeq \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{b}{a}\right)$$

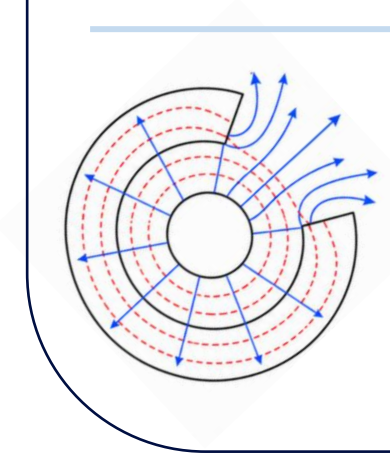
Semi-Coaxial Transmission Line



Two concentric conductors:

$\boldsymbol{b} = Outer\ \boldsymbol{Open}\ Conductor\ Radius$

$\boldsymbol{a'} = Inner\ Conductor\ Radius$



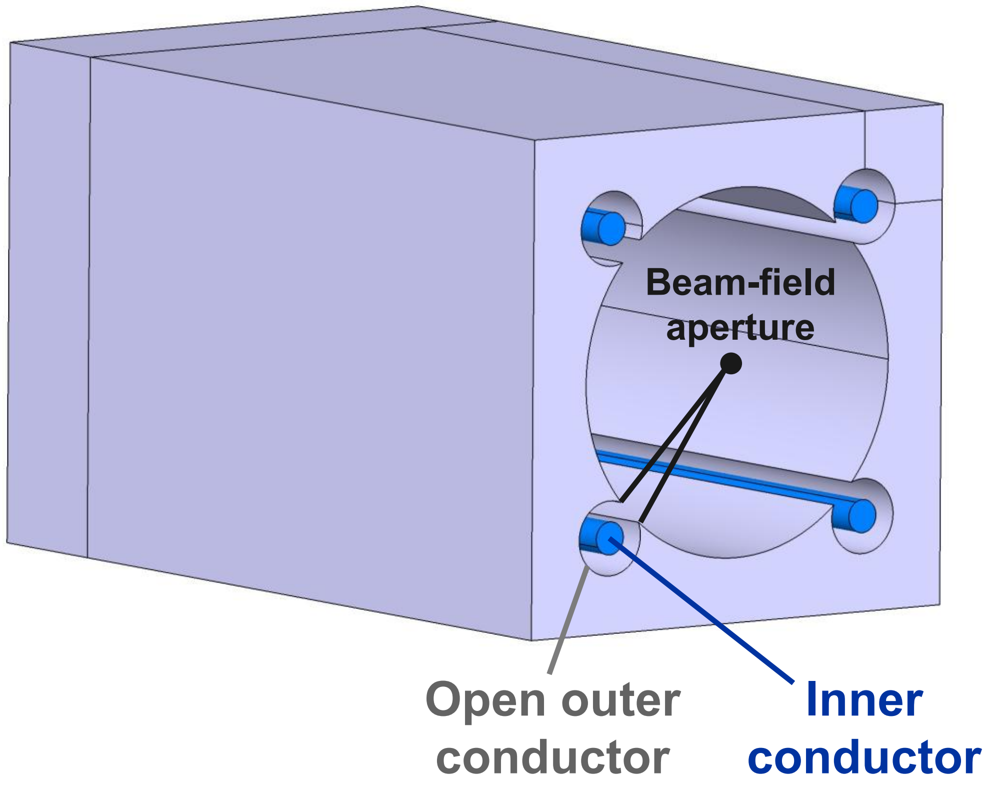
quasi-TEM mode

$$Z'_0(\theta) \approx \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{b}{a'(\theta)}\right)\left(\frac{360°}{360° - \theta}\right)$$

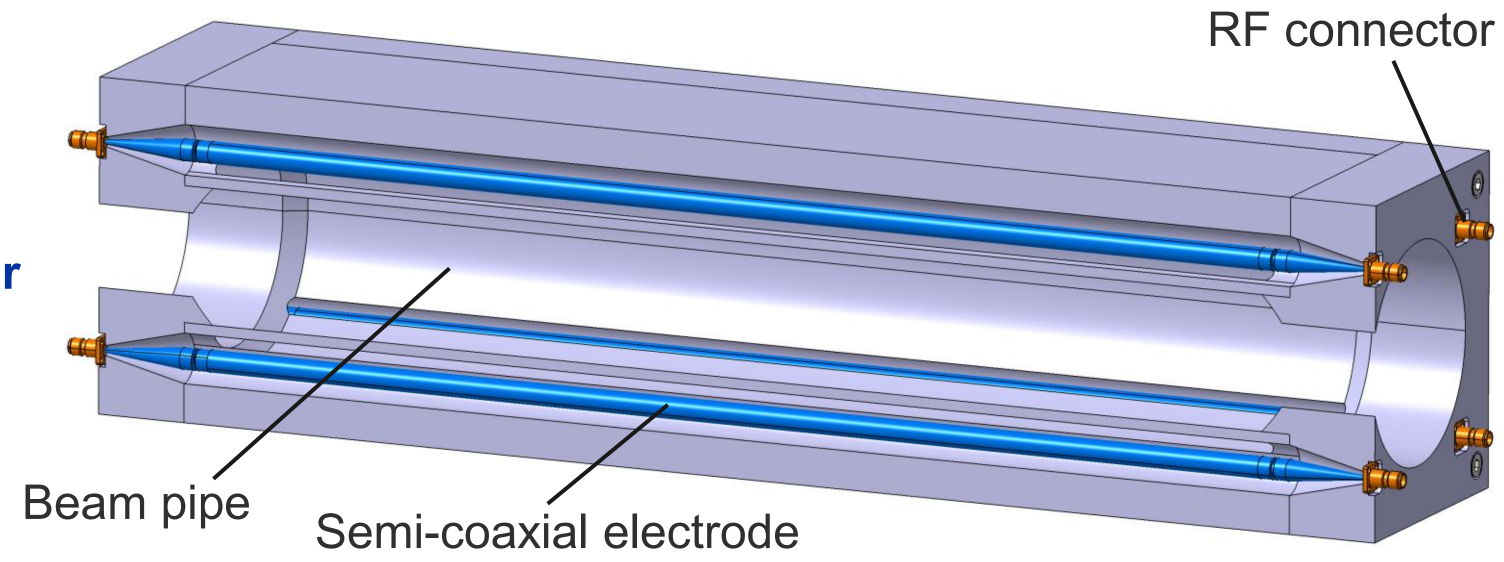
$$Z'_0(\theta) = 50\ \Omega \ \Rightarrow \ \boxed{\boldsymbol{a'(\theta) \simeq a\left(\frac{a}{b}\right)^{\frac{\theta}{360°}}}}$$

Semi-Coaxial Pickup

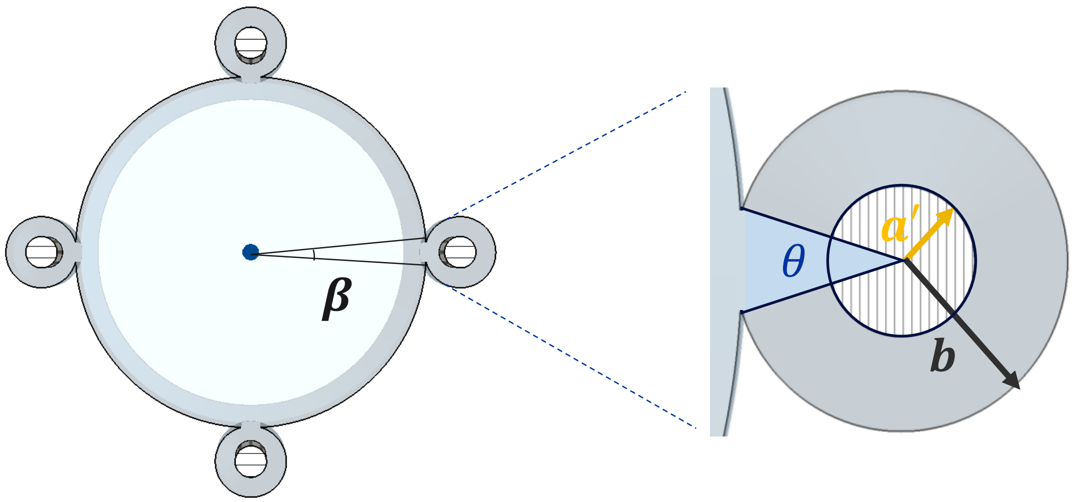
Cross-section view of the semi-coaxial pickup



- Electrode = Inner conductor
- Outer conductor (part of the beam pipe) is partially opened towards the beam.
- Beam-field aperture = opening of the outer conductor from the beam axis that allows the coupling.



Semi-Coaxial Pickup: Beam Coupling Control



Beam field aperture β

- Controls beam **coupling** and pickup output voltage

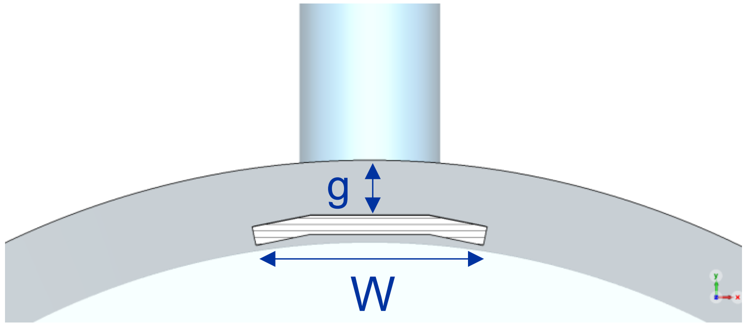
$$\downarrow \beta \quad \Rightarrow \quad \downarrow \text{beam coupling} \quad \Rightarrow \quad \downarrow V_{out}$$

Conductor ratio $\frac{b}{a'}$

- Controls **characteristic impedance:** $Z_0 \to \dfrac{b}{a'}$

Once β is set, the $50\,\Omega$ condition is recovered by re-optimizing b/a' **within the semi-coaxial geometry**.

- **Coupling Control: comparison with a conventional stripline pickup**

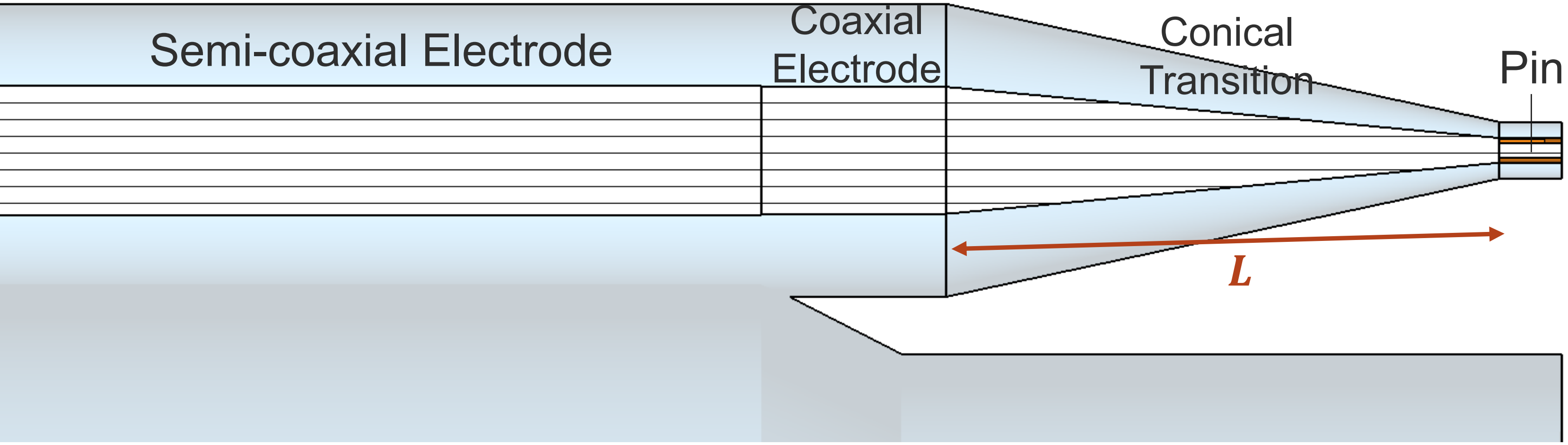


- $\downarrow$ Electrode Width (W) $\Rightarrow$ $\downarrow$ beam coupling, $\uparrow Z_0$
- $\boxed{\downarrow \text{Electrode-to-pipe gap (g)}}$ $\Rightarrow$ to recover $Z_0 = 50\Omega$

Smaller gap can increase the sensitivity of Z_0 to electrode positioning and geometrical tolerances.

Semi-Coaxial Pickup: Smooth Transition to the RF Connector

- The semi-coaxial geometry enables a gradual and impedance-controlled transition from the electrode to the RF connector.



Transition length L:
RF / mechanical trade-off

Shorter L → more compact, but steeper transition and potentially larger reflections.

Longer L → smoother RF transition, but larger longitudinal footprint.

Semi-coaxial Electrode → Coaxial Electrode →

The beam-field aperture is progressively closed, transforming the semi-coaxial electrode into a conventional coaxial line.

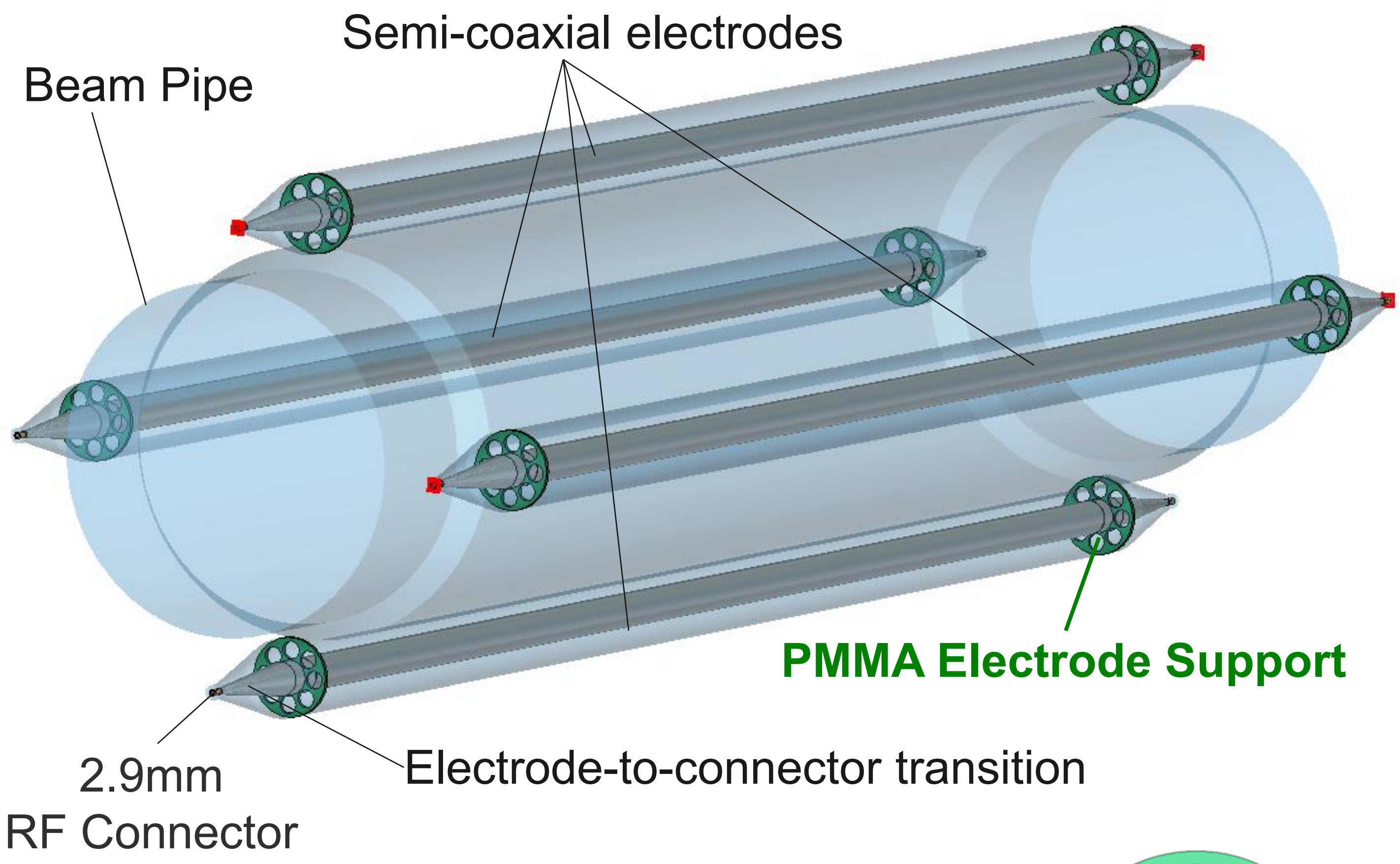
$$\frac{b}{a'} \rightarrow \frac{b}{a} \qquad a < a'$$

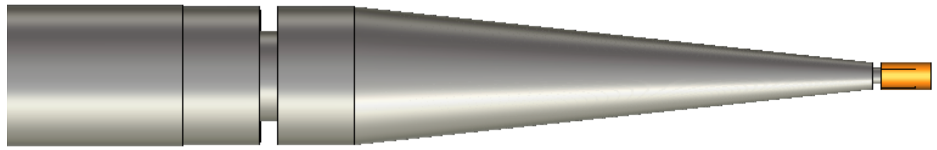
Conical Transition → RF Connector

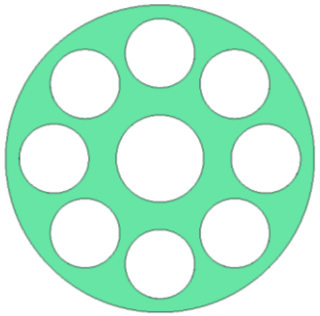
The inner and outer conductor radii are simultaneously tapered towards the connector dimensions.

$$\frac{\boldsymbol{b(z)}}{\boldsymbol{a(z)}} \simeq \mathbf{const} \quad \Rightarrow \quad Z_0\,(z) \simeq \mathbf{50\Omega}$$

CST Model of the Semi-Coaxial Pickup







Included in the CST model

- Beam pipe and four semi-coaxial electrodes.
- Smooth electrode-to-connector transition.
- 2.9mm RF connectors and PMMA supports.

PMMA support

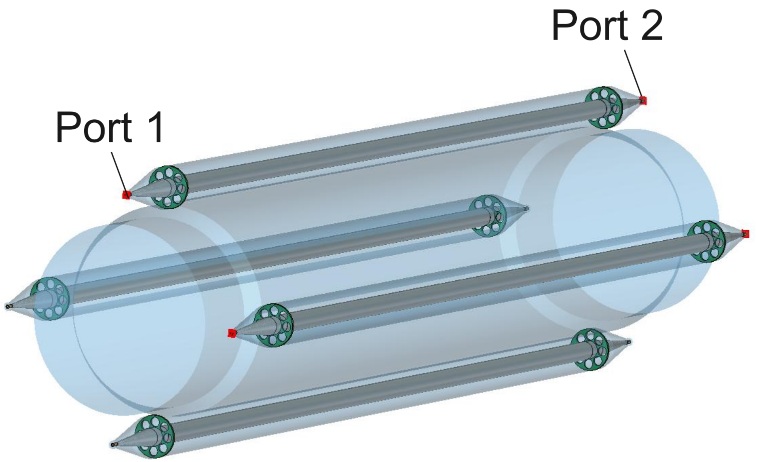
- Ensures electrode positioning and mechanical stability.
- Geometry designed to minimize RF perturbation.

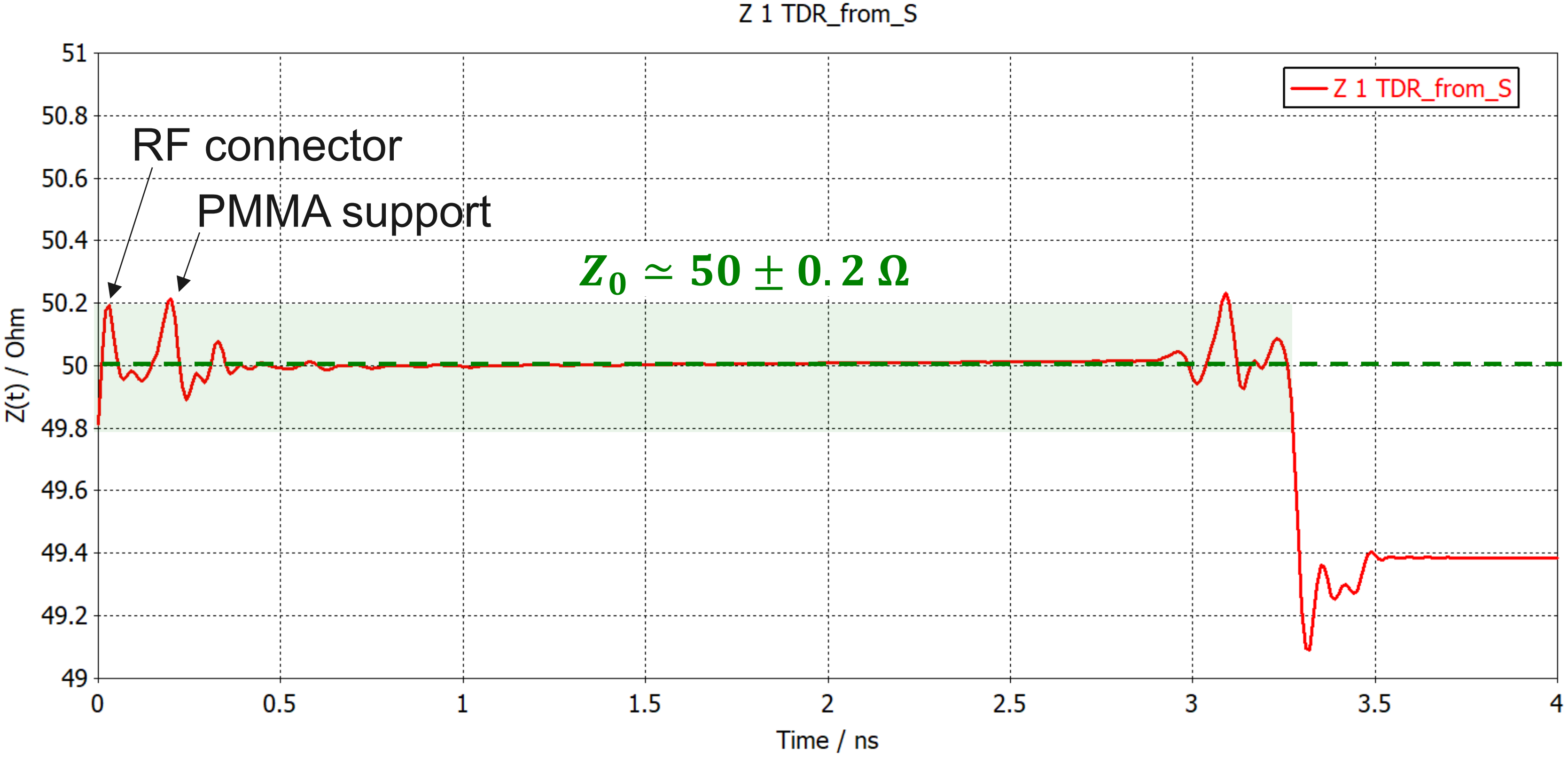
Optimized local electrode shape

- Local reduction of the electrode to accommodate the PMMA support.
- Shape refined to minimize local impedance variation.

CST TDR: Impedance Profile Along the Semi-Coaxial Electrode

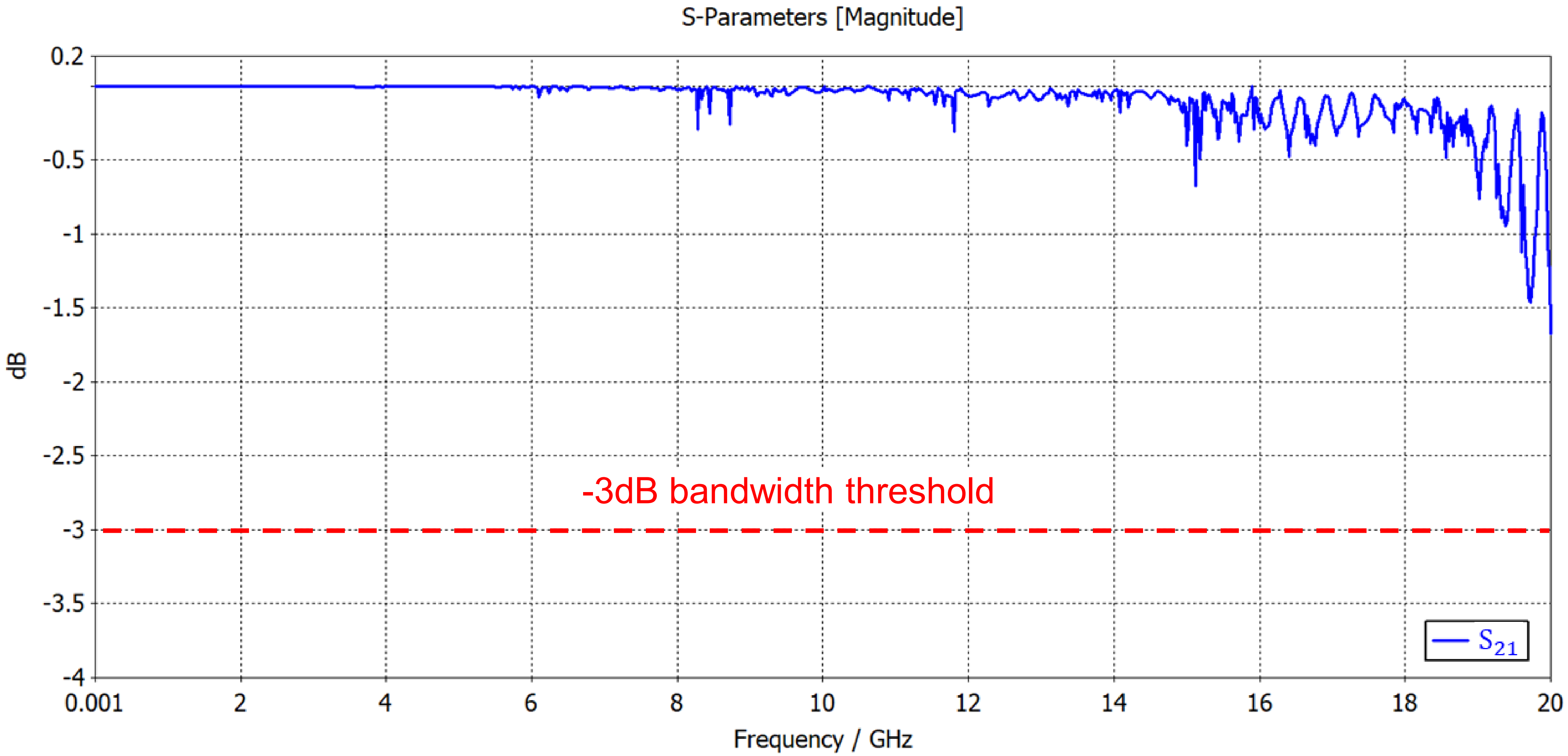
- **Time Domain Reflectometry (TDR)** provides the characteristic impedance profile along the entire electrode, from Port 1 to Port 2.





Well-controlled 50Ω signal path: small impedance variations ($\Delta Z_0 \simeq 0.2\ \Omega,\ \sim 0.4\%$) are localized mainly around the RF connector interfaces and the PMMA supports.

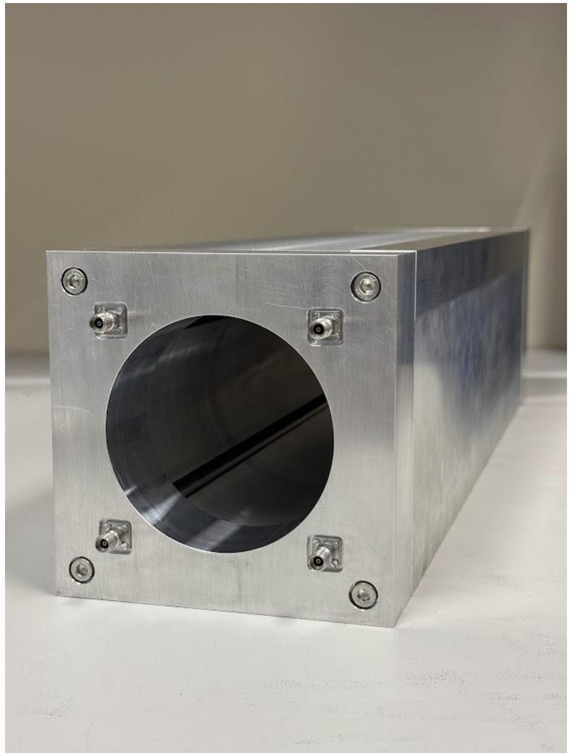
CST S_{21}: RF Transmission Bandwidth of a Semi-Coaxial Electrode



Electrode RF transmission bandwidth $>$ 20 GHz

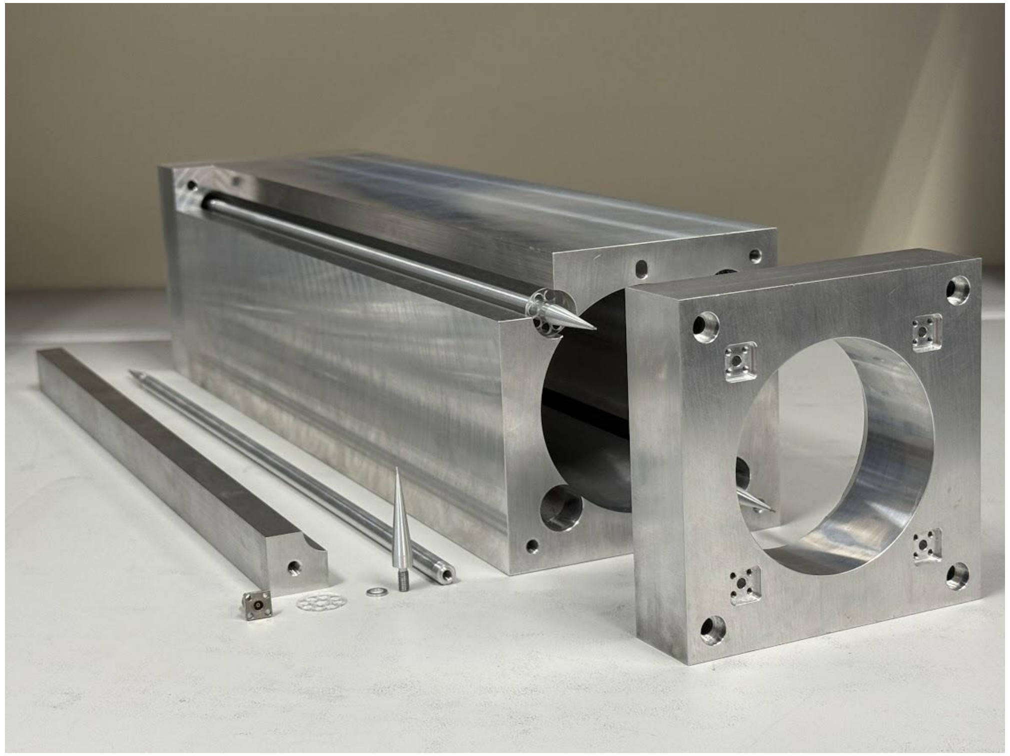
Semi-Coaxial Pickup Prototype

- Aluminium prototype manufactured to validate the RF design.
- Modular construction allows individual component to be removed, re-machined or replaced.
- RF characterization up to 20 GHz using a Vector Network Analyzer (VNA): TDR and S-parameters.



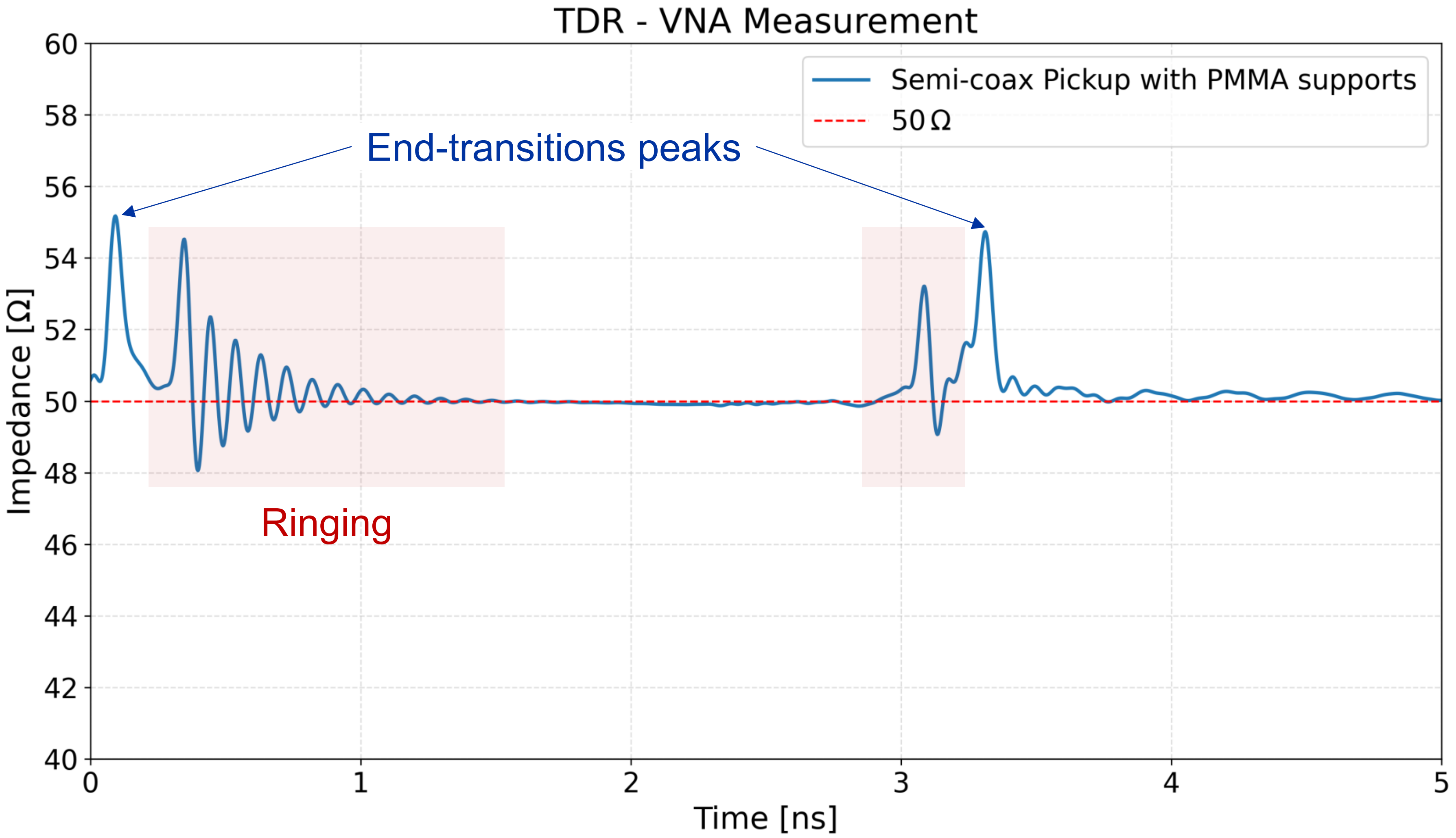
Assembled prototype

Four semi-coaxial electrodes



Modular assembly and removable components

TDR Measurement of the Fully Assembled Pickup



Measurement vs CST Result:

- Same discontinuity locations.
- Stronger ringing and end-transitions peaks.

TDR Measurement – PMMA Supports Removed

Test:

- Remove the PMMA supports.
- Keep the electrode concentricity through the connector mounting.

Ringing disappears

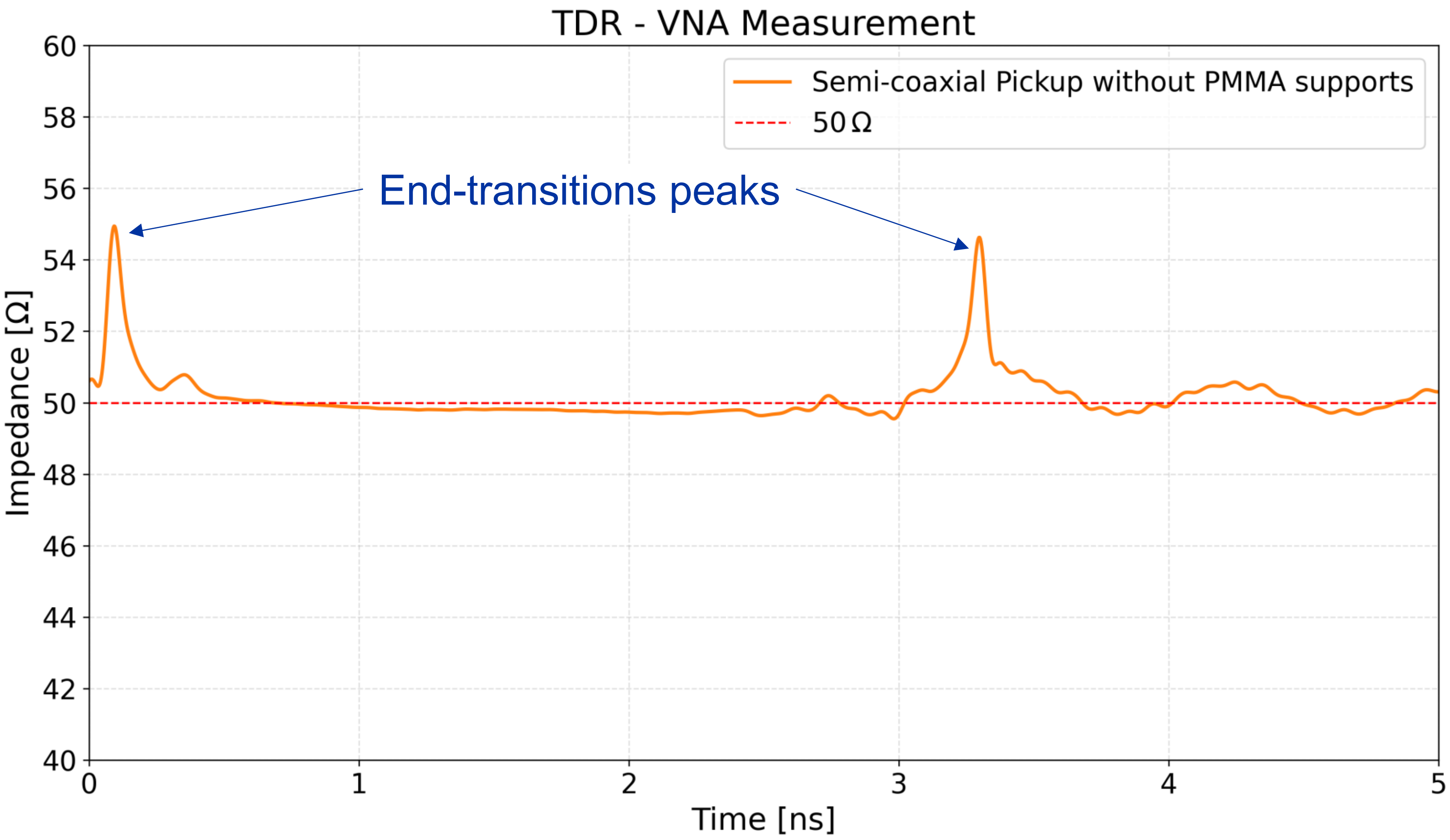
↓

PMMA supports identified as the main source

End-transition peaks remain

↓

Separate mechanical origins



End-transition Diagnosis and Correction

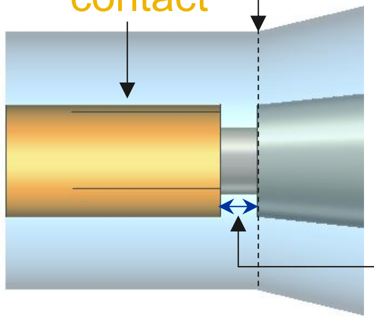
- Mechanical origins of the end-transition peaks:

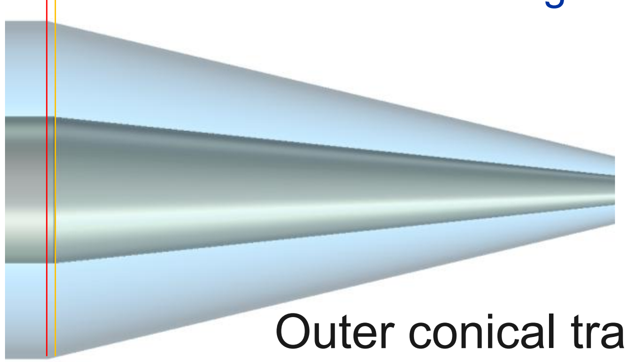
1. RF Connector gap

- Female centre contact recessed by ~0.5 mm.
- Leaves a short section of the pin exposed before the electrode transition.

2. Cones misalignment

- Outer conical transition manufactured ~0.4 mm longer.
- Local radius ratio is not preserved along the conical transition → impedance perturbation.

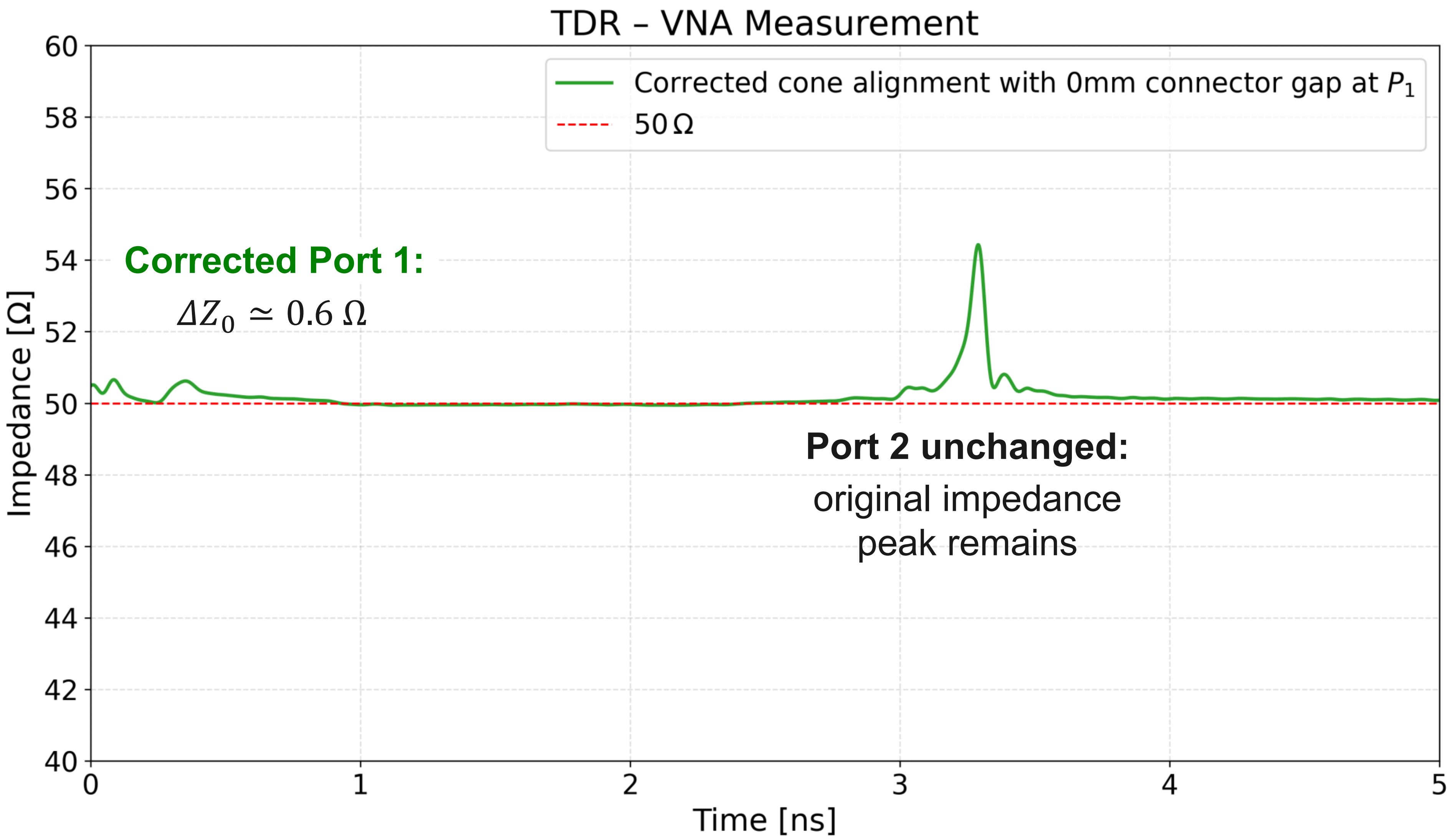




- **Temporary corrections applied at Port 1:**

1. **Connector gap removed** → Mounting face filed by ~0.5 mm.
2. **Inner-outer taper alignment restored** → New longer electrode cone manufactured.

TDR Measurement – Validation of the Port 1 Correction



Corrected Port 1:

$\Delta Z_0 \simeq 0.6\ \Omega$

Port 2 unchanged:

original impedance peak remains

TDR Comparison: Stripline State of the Art vs Semi-Coaxial Pickup

- **Current LHC stripline pickup**

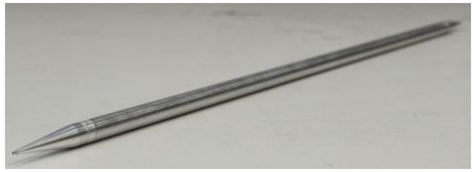
  Large impedance offset and end discontinuities.

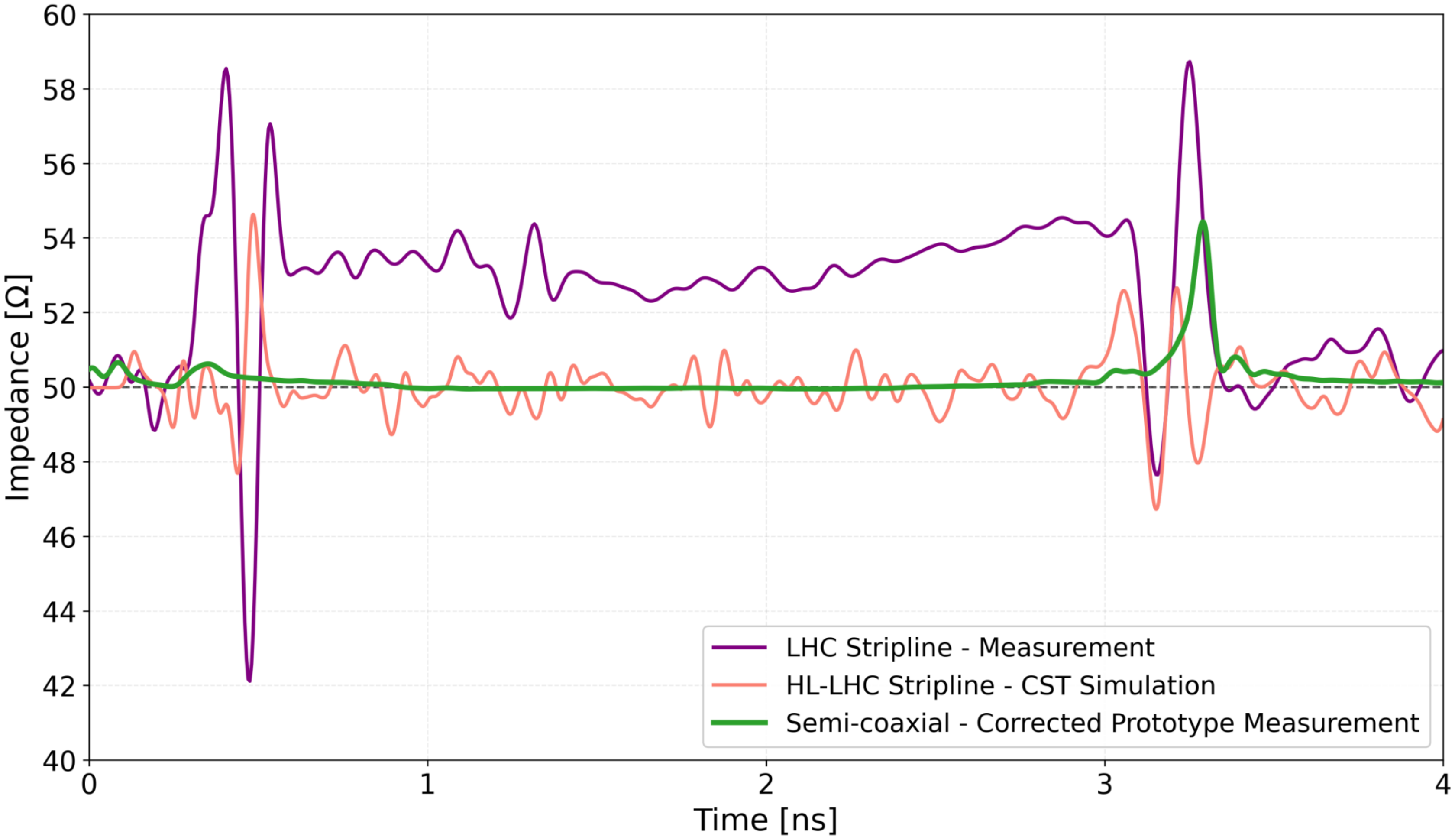
- **HL-LHC BPW stripline pickup**

  Improved transition and better impedance control.

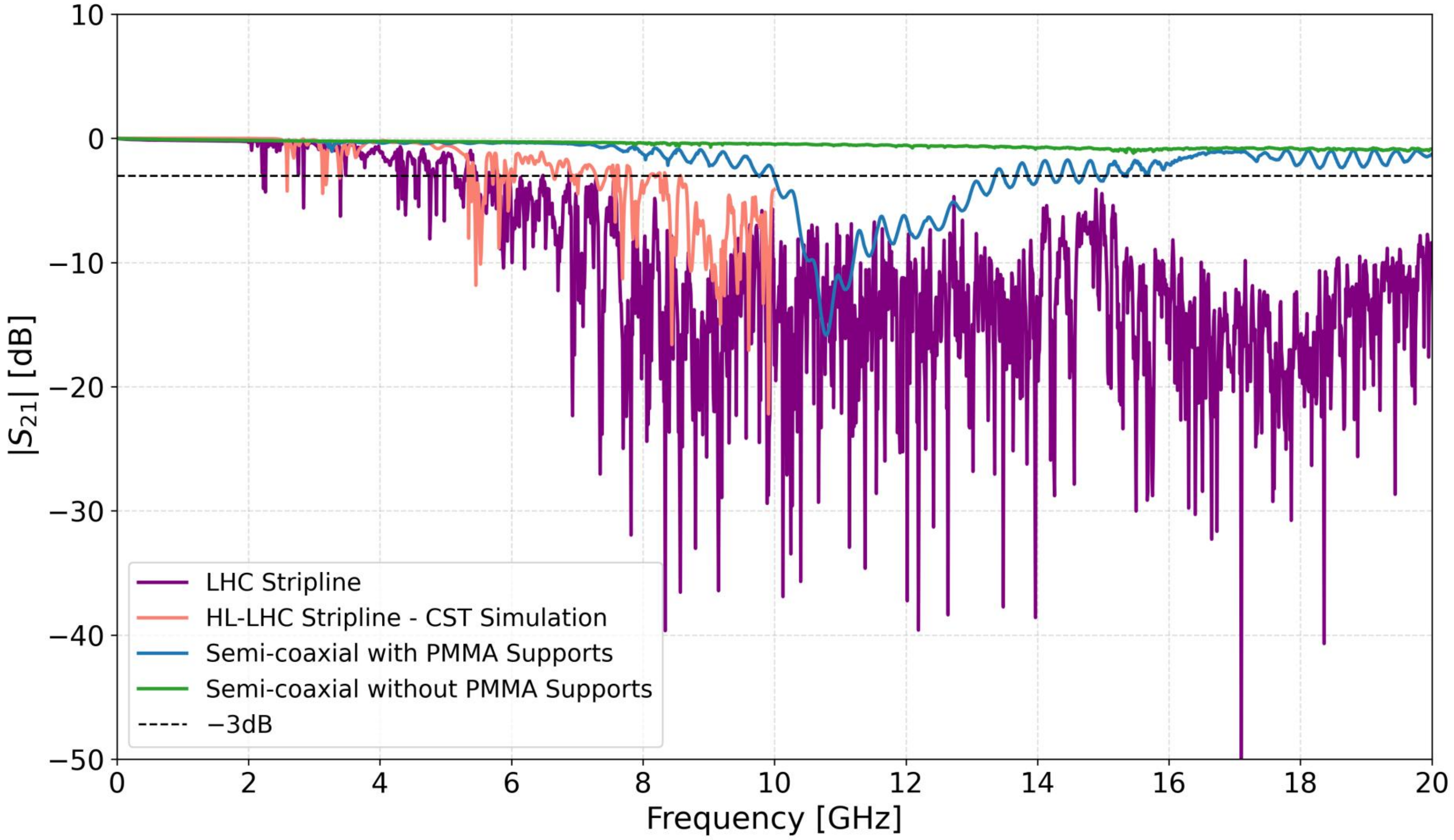
- **Semi-coaxial pickup**

  Well-controlled 50Ω signal path.





S_{21} Comparison: Stripline State of the Art vs Semi-Coaxial Pickup



-3dB RF transmission bw:

LHC Stripline Pickup

$f_{BW} \simeq 2$ GHz

HL-LHC Stripline Pickup

CST Simulation

$f_{BW} \simeq 2.5$ GHz

Semi-Coaxial Pickup with PMMA supports

$f_{BW} \simeq 10$ GHz

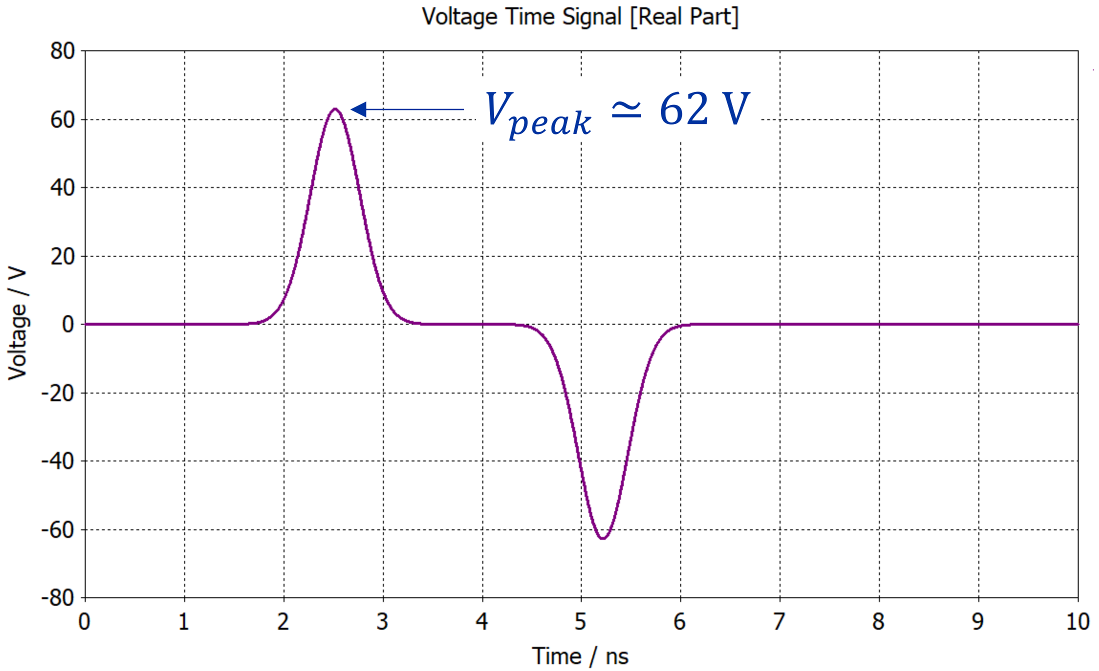
Semi-Coaxial Pickup without PMMA supports

$f_{BW} > 20$ GHz

Beam-Induced Voltage Amplitude: Stripline vs Semi-Coaxial

- Same beam excitation

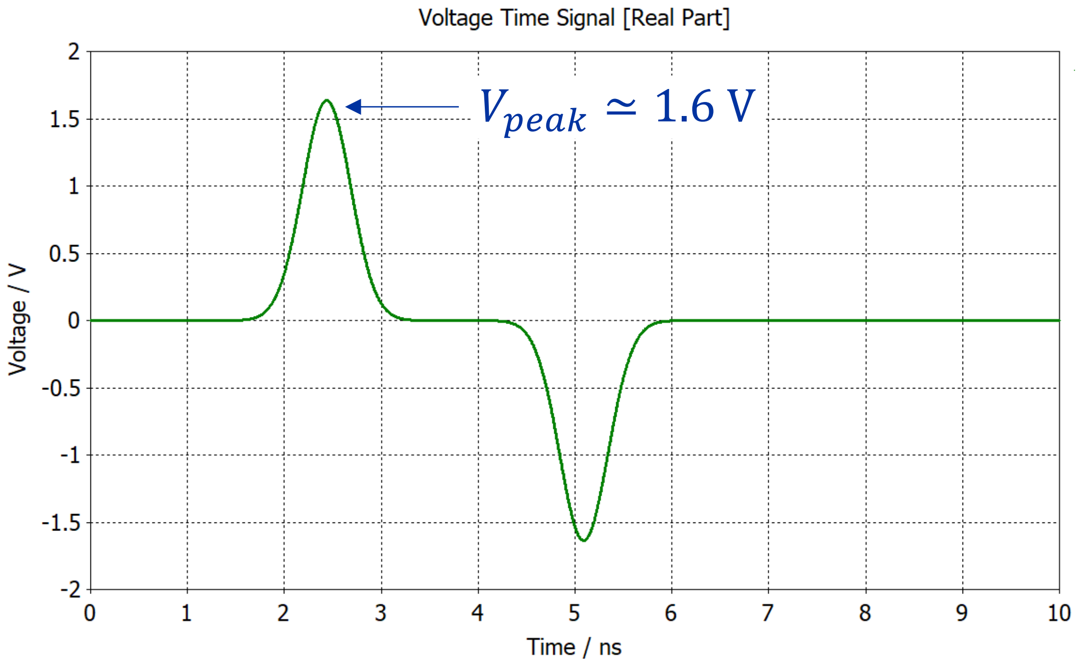
Stripline Pickup



Strong beam coupling → more signal that needed

Attenuation required before the readout

Semi-coax Pickup



Controlled beam coupling ($\beta \simeq 9°$)

Readout-compatible signal level

Conclusions

- **Semi-coaxial pickup shows promising performance for future intra-bunch diagnostics**

  Well-controlled 50 Ω RF path.

  RF transmission bandwidth > 20 GHz without PMMA supports.

  Beam-induced voltage adaptable to the downstream Electro-Optical (EO) readout.

- **Prototype measurements identified the main mechanical integration issues**

  PMMA supports and connector-cone interfaces are the main areas for further optimization.

Next Steps

- **Electrodeconnector interface and taper alignment**
  - Develop a robust connector-interface solution without modifying the commercial connector.
  - Restore the correct inner/outer taper alignment at all electrode ends and validate the fully assembled pickup.
- **Mechanical supports**
  - Investigate alternative supports materials and geometries to reduce dielectric loading and RF resonances.
- **Beam validation at CLEAR**
  - Perform beam tests with the improved prototype directly connected to the EO readout, validating its wide-bandwidth response under beam conditions.
- **Further development towards UHV compatibility**
  - Develop vacuum-compatible RF feedthroughs – potentially in collaboration with industry.
  - Adapt the pickup design for future UHV-compatible implementation.

Thank you for your attention!