UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

itee PhD
information technology
electrical engineering

Leonardo Sito

Metamaterials for beam-coupling Impedance mitigation

Tutor: Prof. Giovanni Breglio

co-Tutor: Prof. Francesco Fienga (DIETI)
Dr. Carlo Zannini (CERN)
Dr. Benoit Salvant (CERN)

Cycle: XXXVIII

Year: Third

itee PhD
information technology
electrical engineering

My background

- **MSc degree:** Electronics Engineering @ UNINA
- **Research group/laboratory:**
  - **DIETI, OptoPowerLab**
  - CERN Beam, Accelerator and Beam Physics, Coherent Effects and Impedance (**BE-ABP-CEI**) section
  - CERN Experimental Physics, CMS TOTEM (**EP-CMT**)
- **PhD start date:** 01/01/2023 – **end date:** 31/12/2025
- **Scholarship type:** CERN Doctoral Student Program
- **Partner company/Period abroad:** European Organization for Nuclear Research (CERN)

Summary of study activities (I)

- **Ad hoc PhD courses:**
  - "**Statistical data analysis for science and engineering research**"
    - Lecturer: Prof. Roberto Pietrantuono, DIETI
  - "**Academic Entrepreneurship**"
    - Lecturer: Prof. Pierluigi Rippa, Silvia Cosimato, Nadia di Paola, DIE
  - **"Artificial Intelligence and Natural Language Processing"**
    - Lecturer: Prof. Francesco Cutugno, dr. Dr. Maria Di Maro, prof. Antonio Orilia, prof. Vincenzo Norman Vitale
  - "**Numerical Methods for Thermal Analysis, Modeling, And Simulation: Application to Electronic Devices And systems**"
    - Lecturer: Dr. Antonio Pio Catalano, DIETI
  - **"Fiber optic sensing and optoelectronic circuits: design and application"**
    - Lecturer: Dr. Vincenzo Romano Marrazzo, DIETI

- **PhD schools:**
  - "**Wakefields and Collective Beam Instabilities**", USPAS, Houston, Texas, USA.
    - Lecturers: Gennady Stupakov (SLAC), Ryan Lindberg (Argonne National Lab) Boris Podobedov (Brookhaven National Lab).
  - "**Surface Electromagnetics for Wireless Communications and Sensing**", Uni Trento.
    - Lecturers: Prof. Giacomo Oliveri, Dr. Salas-Sanchez Aaron A., Prof Marco Salucci
  - "**Spring School on Transferable Skills**"
    - Lecturers: Prof. Pasquale Maffia and Prof. Valeria Costantino, University of Naples Federico II
  - "**Metalenses for Antenna Applications**", European School of Antennas and Propagation (ESoA), Sevilla, Spain.
    - Lecturers: Prof. Oscar Quevedo-Teruel (KTH), Prof. Francisco Mesa (Universidad de Sevilla), Dr. Astrid Algaba-Brazalez (Ericsson).
  - "**Advanced Accelerator Physics** ", CERN Accelerator School (CAS), Spa, Belgium.
    - Lecturers: Dr. Frank Tecker (CERN)

- **6 International Conferences/Workshops attended:**
  - Joint Accelerator Performance Workshop 2023 (**JAP23**), Montreaux, Switzerland.
  - Proton Precision Spectrometer 2nd Upgrade Workshop 2023 (**PPS2**), Geneva, Switzerland.
  - High Brightness Hadron Beams Workshop 2023 (**HB2023**), Geneva, Switzerland.
  - Proton Precision Spectrometer Upgrade Workshop 2023 (**PPS@LHC**), Geneva, Switzerland.
  - Beam-Beam Wire Compensation Review Meeting 2024 (**BBWC24** Review), CERN, Geneva, Switzerland.
  - 16th International Particle Accelerator Conference (**IPAC'25**), Taipei, Taiwan.

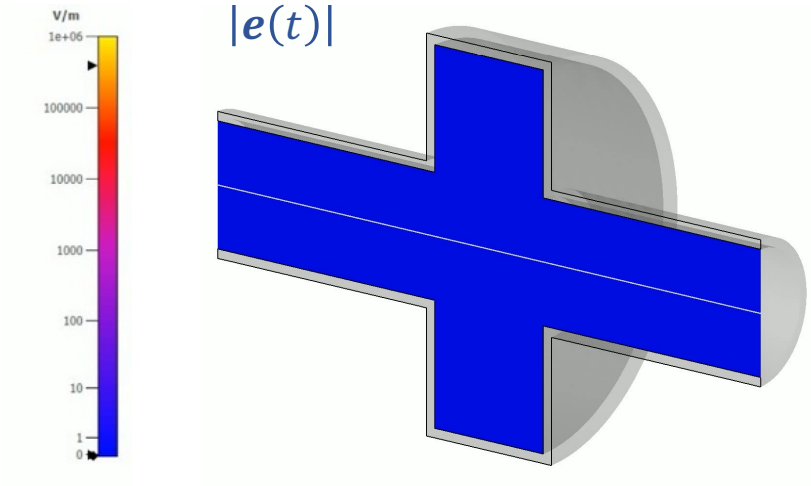
Summary of study activities (II)

- **Seminars:**
  - **5G Academy:** "*Open Digital Framework*"; "*Il cloud e gli Hyperscalers / High Performance Computing*"; "*Sustainable Strategy*".
  - **BBWC Review:** "*The beam dynamics case of the Beam-Beam Wire Compensators in HL era*".
  - **CERN:** "*Nonlinear surface impedance of superconductors in high magnetic fields*"; "*Optimization of the High-Brightness Beam Performance of the CERN PSB with H-Injection*"; "*The design of the ENUBET beamline*"; "*Diffusive models and chaos indicators for non-linear betatron Motion*"; "*Studies on the interplay between beam- beam and impedance at the FCC-ee*"; "*Collective effects for muons during ionisation cooling*"; "*LHC DA studies with e-cloud in the triplets*"; "*wakis: 3D Electromagnetic Time-Domain Wake and Impedance Solver*"; "*Characterization of low-beta impedances*".
  - **CERN ABP Forum:** "*High Power Targetry R&D Program with the RaDIATE*", "*Beam-Beam Bremsstrahlung Beam-Size Effects and FCC-ee Beam Lifetime*".
  - **CERN ATS:** "*The Laser-hybrid Accelerator for Radiobiological Applications*".
  - **CERN CEI Meeting:** "*Xwakes in Xsuite*"; "*Non-relativistic wakes and resonator*"; "*Impedance model for FCC-ee*".
  - **DIETI:** "*Learning gene association networks using single-cell RNA-seq data: a graphical model approach*"; "*Accurate and Efficient Numerical Modeling Methods for Superconducting Circuit Quantum Information Processing Devices*"; "*The power of nanoscience to explore the frontiers of neuroscience*"; "*Symbiotic Control of Wearable Soft Suits for human motion assistance and augmentation*"; "*Ensuring Electronic Reliability Against CERN's Radiation Environment*".
  - **HB:** "*Collective Effects in Lepton Circular Colliders and Synchrotron Light Sources*"; "*Predominantly electric "E&m" storage ring with nuclear spin control capability*".
  - **QST Seminars:** "*Enhancing qubit readout with Bayesian Learning*".
  - **RF Seminars:** "*Large signal characterization of High-Power Amplifier*"; "*Examples and procedures for High Power Amplifiers measurements*".
  - **SSM:** "*Multi-Robot Control of Heterogeneous Herds*".
  - **Tektronix:** "*Fundamentals of Oscilloscopes and Probes*"; "*Fundamentals of Jitter Analysis* "; "*Multichannel Radio Frequency Signal Analysis*".
  - **Teledyne LeCroy:** "*TDR for Instant Highly Accurate Impedance Measurements*".
  - **UNINA:** "*From ACE Technologies to Sustainable, Accessible and Equitable Urban Mobility: An Optimization Journey*"; "*Superconducting Radio Frequency Cavities for Quantum Computing and Communication*".

Research Area

Electromagnetism applied to High-Energy Particle Accelerator Physics:

Bunches of charged particles → Subsequently injected and accelerated in metallic **vacuum chambers**



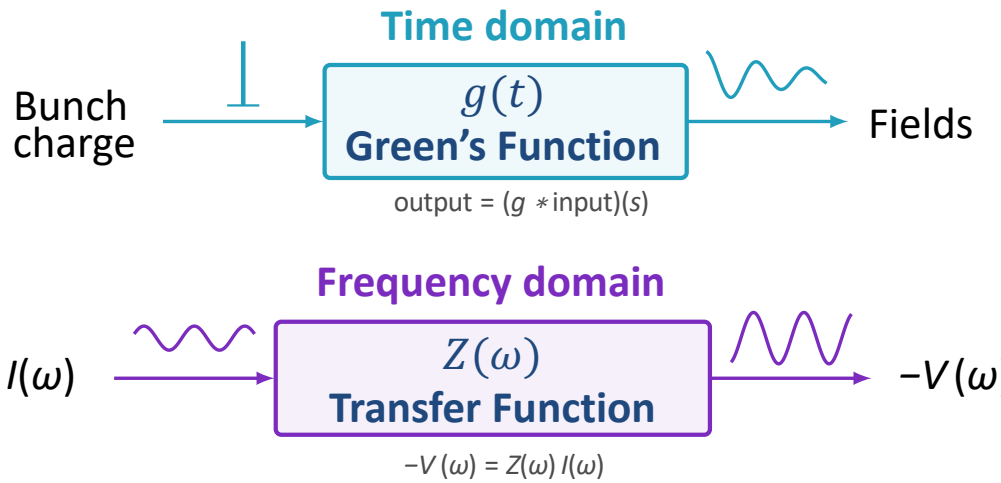
EM modes excited in **"parasitical" cavities**.

The **following bunches** will **"feel"** this field and may **contribute** to it!

- **Instabilities** in the particle motion
- **Dissipated power** on the device

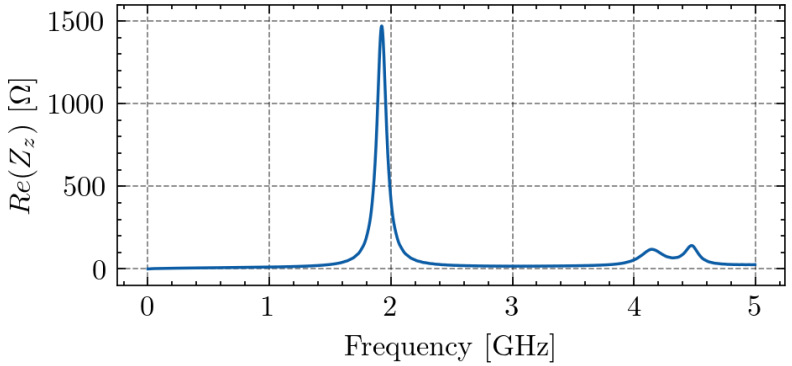
Research Area

Formalism **beam/structure** interaction:



Beam-Coupling Impedance
(complex frequency dependent <u>vector</u> function)

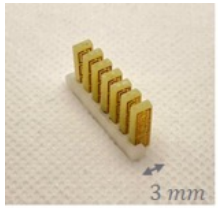
Longitudinal ($\hat{z}$) impedance



Similar approach for **Transverse ($\hat{x}$, $\hat{y}$) impedance**, which acts on the transverse plane!

Research Problems and Results

1. Evaluation of Beam-coupling Impedance:
   - A. Electromagnetic **Simulations** (CST) [P2, P7, P10 to P12]
   - B. VNA **measurements** [P3]
2. Evaluation of power dissipated on the vacuum chamber: → BIHC Python **code**: https://github.com/ImpedanCEI/BIHC [P14 to P16, P19]
3. Monitoring: → Optical fibre temperature sensing. [P5, P6]
4. Techniques for mitigating the beam-coupling impedance:
   - A. Ferrites, Couplers [P11, P15]
   - B. **Metamaterials** [P8, P13]



"Artificially structured materials that allow to engineer the interaction of fields with matter with properties (ε and μ) that depend on constituent materials and geometry"

Research products (I)

Awards

[P1]	**Best Student Poster Prize** For the work titled *Metamaterial absorbers for beam-coupling impedance mitigation,* 16th International Particle Accelerator Conference (IPAC'25) Taipei, Taiwan, Jun. 2025

Scientific Publications

[P2]	C. Antuono, et al., *Impact of High-Intensity LHC Beam Operation on Warm Vacuum Modules*, **Physical Review Accelerators and Beams,** vol. 28(4), p. 041001, 2025, DOI: 10.1103/PhysRevAccelBeams.28.041001.
[P3]	C. Antuono, et al., *A Novel Method for Transverse Beam-Coupling Impedance Measurements in Particle Accelerator Devices Using the Bead-Pull Method*, **IEEE Transactions on Instrumentation and Measurement**, vol. 73, pp. 1-9, Art. no. 8005209, 2024, DOI: 10.1109/TIM.2024.3458042.
[P4]	G. Acampora, et al., *SND@LHC: The Scattering and Neutrino Detector at the LHC*, **Journal of Instrumentation**, vol. 19(05), p. P05067, 2024, DOI: 10.1088/1748-0221/19/05/P05067.
[P5]	V. R. Marrazzo, et al., *Experimental Tests of a Full Analog Fiber Optic Monitoring System Suitable for Safety Application at CERN*, **IEEE Transactions on Instrumentation and Measurement**, vol. 72, pp. 1–8, Art. no. 7002408, 2023, DOI: 10.1109/TIM.2023.3250283.
[P6]	F. Fienga, et al., *Direct Measurement of Beam-Induced Heating on Accelerator Pipes with Fiber Optic Sensors: Numerical Analysis Validation*, **IEEE Transactions on Instrumentation and Measurement**, vol. 72, pp. 1-9, Art. no. 9508709, 2023, DOI: 10.1109/TIM.2023.3279420.

Research products (II)

[P7]	C. Zannini et al., *Simulations of beam-coupling impedance to guide model-based mitigations in Hadron Rings,* **71st Advanced Beam Dynamics Workshop on High-Intensity High-Brightness Hadron Beam (HB'25),** Huizhou, China, Oct. 2025, pp. 161-165. DOI:10.18429/JACoW-HB2025-WECDB02
[P8]	L. Sito et al., *Metamaterial absorbers for beam-coupling impedance mitigation*, **16th International Particle Accelerator Conference (IPAC'25)**, Taipei, Taiwan, Jun. 2025, pp. 2172-2175. DOI:10.18429/JACoW-IPAC2025-WEPM085
[P9]	R. Tomas et al., *Towards a High Luminosity LHC with even higher performance*, **16th International Particle Accelerator Conference (IPAC'25)**, Taipei, Taiwan, Jun. 2025, pp. 278-281. doi:10.18429/JACoW-IPAC2025-MOPM008
[P10]	C. Antuono et al., *Beam impedance investigation of the elliptical interconnecting vacuum modules of the LHC and prospect for HL-LHC*, **16th International Particle Accelerator Conference (IPAC'25)**, Taipei, Taiwan, Jun. 2025, pp. 2141-2144. doi:10.18429/JACoW-IPAC2025-WEPM075
[P11]	L. Sito et al., *LHC beam-beam wire compensator impedance contribution*, **16th International Particle Accelerator Conference (IPAC'25)**, Taipei, Taiwan, Jun. 2025, pp. 2176-2179. doi:10.18429/JACoW-IPAC2025-WEPM086
[P12]	P. Krkotić, et al., *Understanding of the LHC Warm Vacuum Module Heating*, **15th International Particle Accelerator Conference (IPAC'24)**, Nashville, TN, USA, May 2024, pp. 947–950, DOI: 10.18429/JACoW-IPAC2024-TUAN3.
[P13]	C. Zannini, L. Sito, *Metamaterials for Impedance Optimisation and Sustainability,* **15th International Particle Accelerator Conference (IPAC'24)**, Nashville, TN, USA, May 2024, pp. 925–930, DOI: 10.18429/JACoW-IPAC2024-TUXN1.

Research products (III)

[P14]	R. Veness, L. Sito, et al. *Overview of Beam Intensity Issues and Mitigations in the CERN-SPS Fast Wire Scanners*, **15th International Particle Accelerator Conference (IPAC'24)**, Nashville, TN, USA, May 2024, pp. 2248–2251, DOI: 10.18429/JACoW-IPAC2024-WEPG26.
[P15]	L. Sito, et al., *Impedance and Thermal Studies of the CERN SPS Wire Scanners and Mitigation of Wire Heating*, **15th International Particle Accelerator Conference (IPAC'24)**, Nashville, TN, USA, May 2024, pp. 2260–2263, DOI: 10.18429/JACoW-IPAC2024-WEPG29.
[P16]	L. Sito, et al., *A Python Package to Compute Beam-Induced Heating in Particle Accelerators and Applications*, **68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'23)**, Geneva, Switzerland, Oct. 2023, pp. 611–614, DOI: 10.18429/JACoW-HB2023-THBP52.
[P17]	G. Rumolo, et al., *Beam Performance with the LHC Injectors Upgrade*, **68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'23)**, Geneva, Switzerland, Oct. 2023, pp. 1–8, DOI: 10.18429/JACoW-HB2023-MOA1I1.
[P18]	L. Sito, et al., *Beam-Beam Long Range Compensator Mechanical Demonstrator*, **14th International Particle Accelerator Conference (IPAC'23)**, Venice, Italy, May 2023, pp. 4916–4918, DOI: 10.18429/JACoW-IPAC2023-THPM015.

Tools

[P19]	**Python package for beam-induced heating computations:** *bihc*. Available at https://github.com/ImpedanCEI/BIHC

PhD thesis overview (I)

Problem statement:

New "trends" in accelerator physics:

1. ***Higher number*** *of charged particles*
2. ***Shorter*** *particle bunches (broader frequency range)*

} Electromagnetic interactions (**Beam-coupling impedance**) are the **bottleneck**

Investigate alternative strategies for beam-coupling impedance reduction to tackle limitations in current methods:

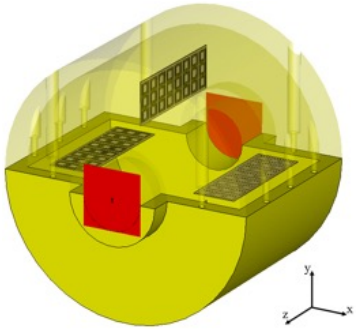
1. **Material constraints:**
   - Vacuum compatibility
   - EM absorption at high frequency
2. Design **constraints**
3. **Budget & Time**

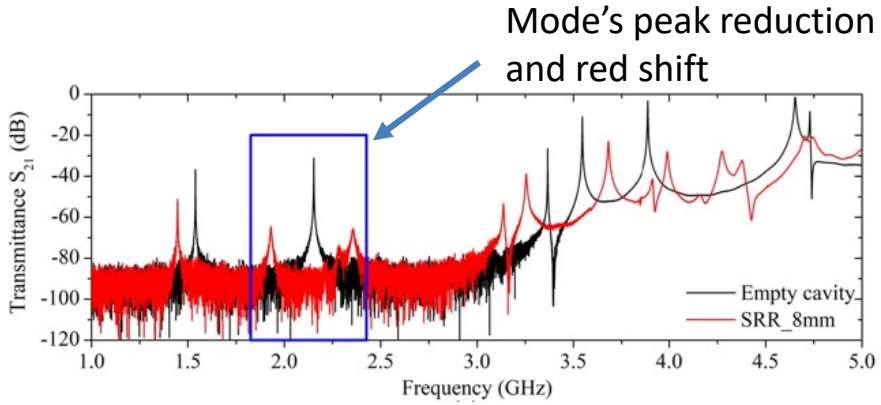
PhD thesis overview (II)

Objective:

*Explore the possibility of using **EM metamaterials** to mitigate the beam-coupling impedance.*

Extend the work: M.R. Masullo et al., "*Metamaterial-Based Absorber for the reduction of Accelerator Beam-Coupling Impedance*"





Metamaterials are damping EM modes in resonant cavities

However:

- No quantification on **impedance** reduction
- No **transverse** mode analysis
- No **power** dissipation analysis

PhD thesis overview (III)

Methodology:

Background studies:

- Validation of existing **simulation** tools
- Validation of existing **measurement** methodologies

} + extensions (when needed)

Design, produce and validate:

1. Impedance Test Structure

(Well defined resonant mode frequencies)

2. Metamaterials insertions

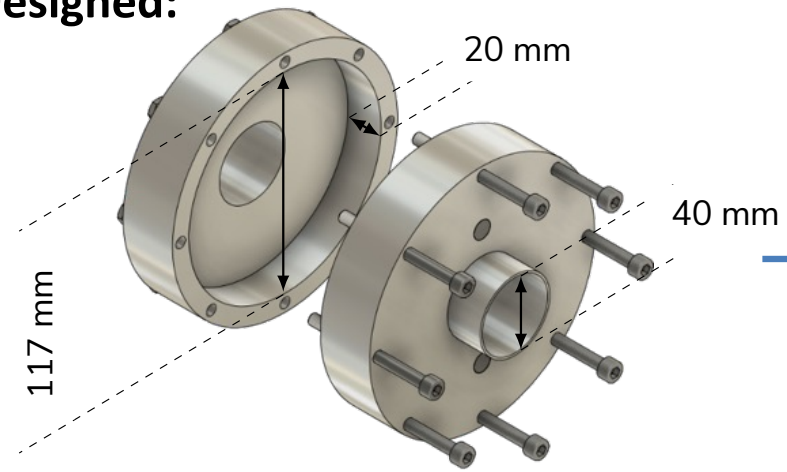
(With proper absorption peaks)

Insertion of metamaterials in the test structure

Simulation and measurements:
Impact on the beam-coupling impedance

1. Impedance Test Structure

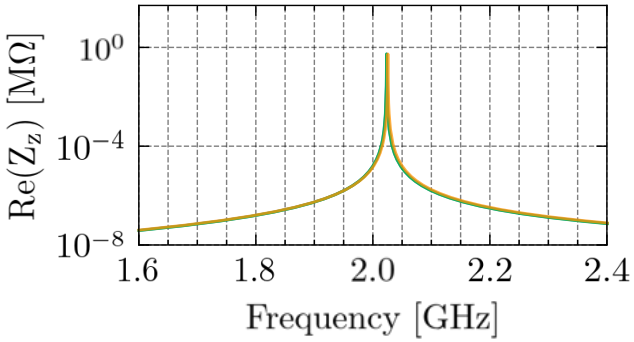
Designed:



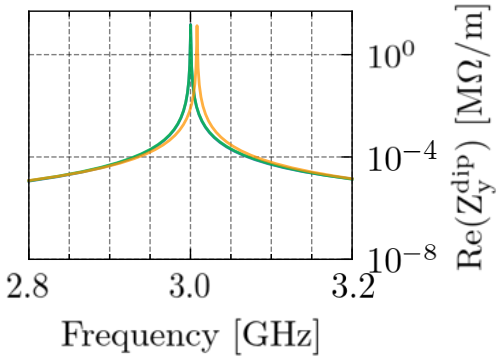
Fabricated: with CNC milling

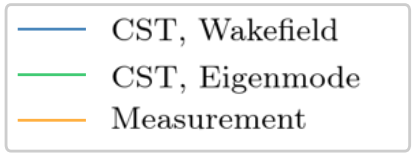
Characterized:

Longitudinal Mode TM010 ~ 2 GHz



Transverse Mode TM110 ~ 3 GHz





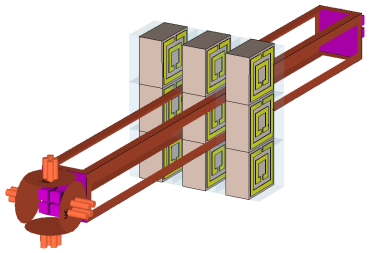
2. Metamaterials

Controlled engineering of metamaterials

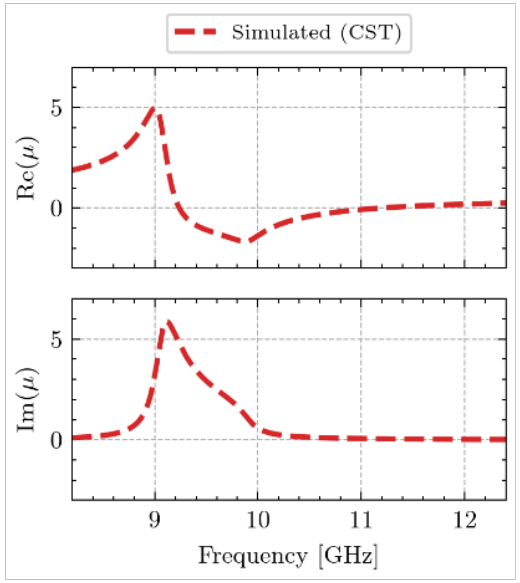
1. **Design**
2. **Production**
3. **Characterization**

Effective **parameter retrieval methods** → **Nicholson-Ross-Wier**

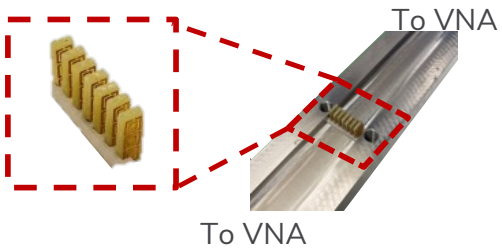
Full wave **simulation** with frequency domain solver (CST)



Ideal TM plane wave Excitation
+
Infinite Periodic Structure



Production and **measurement** in WR90 waveguide



In waveguide
+
Finite Periodic Structure

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Controlled engineering of metamaterials

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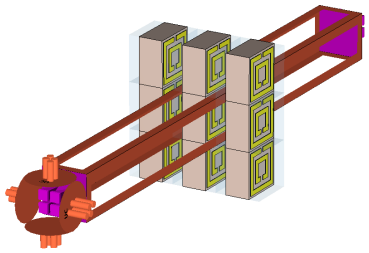

Ideal TM plane wave Excitation
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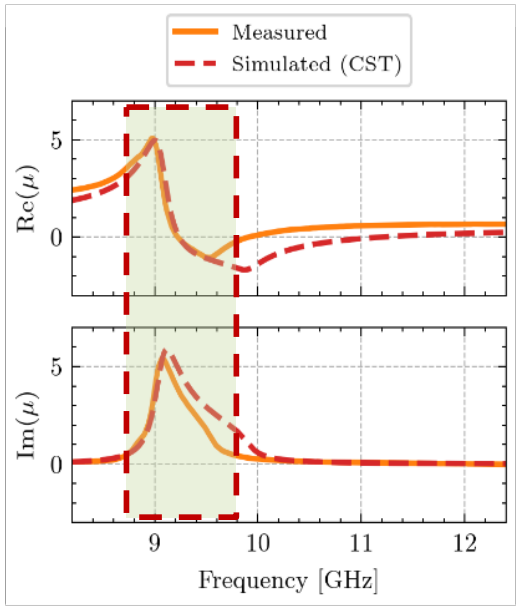

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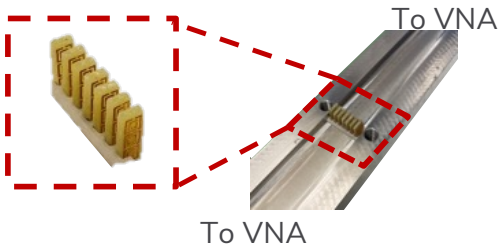
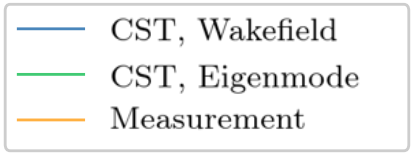


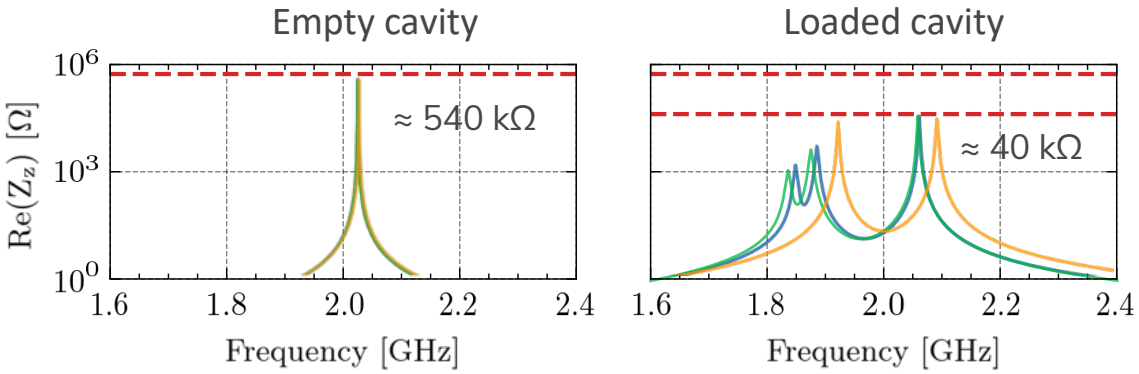
In waveguide
+
Finite Periodic Structure

- **Resonant behaviour**
- **Frequency region** with **high losses**

Metamaterial Insertions (I)

2 Metamaterial slabs
Resonating @ 2 GHz



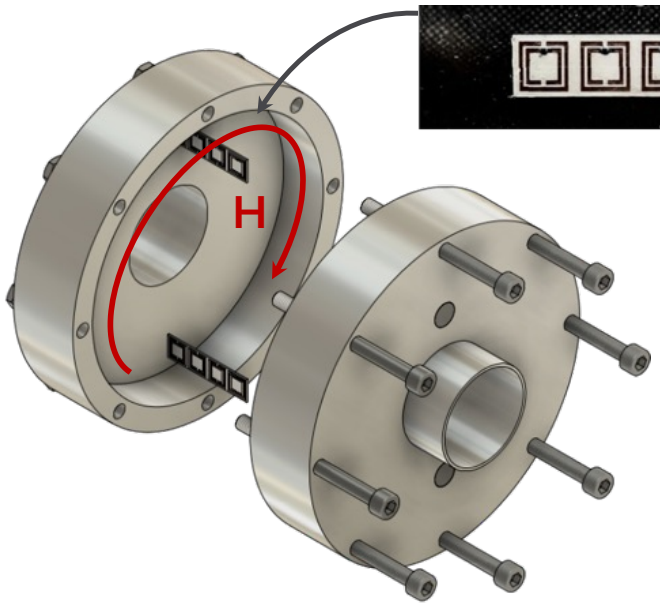


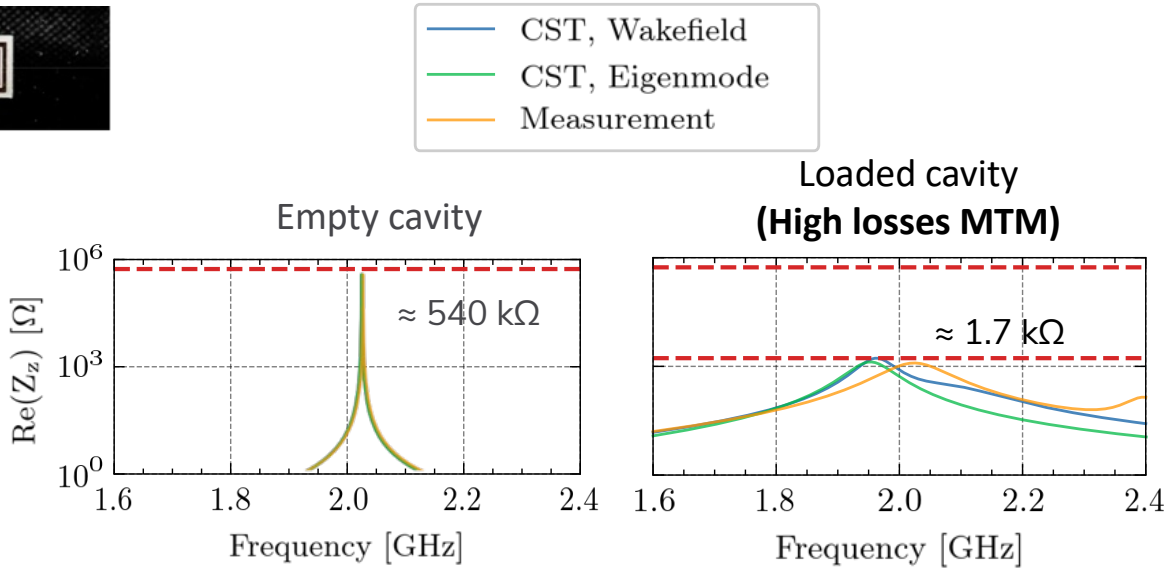
- **One order of magnitude impedance reduction**
- **Mode splitting**

Metamaterial Insertions (II)

Higher losses!

100 Ohm resistor mounted





- ~~One~~ Three order of magnitude reduction
- ~~Mode splitting~~

With the same methodology:

- **Transverse** impedance **selective** damping (3 GHz)
- **Bulk** metamaterial design
- **Beam-Induced Heating** of metamaterial slabs study (CST+ANSYS)
- Study for **application** in a real accelerator device

Conclusions

Explored alternatives for beam-coupling impedance mitigation (Metamaterials)

1. Proved **damping of longitudinal** beam coupling **impedance**
2. Proved selective **dipolar transverse impedance damping**
3. Tested different designs (increased losses and bulk design)
4. **Power handling** studies

For the future:

1. **Power handling** capabilities in an **experimental** scenario
2. Vacuum compliance
3. **Implementation** in an operating device

Thank you!