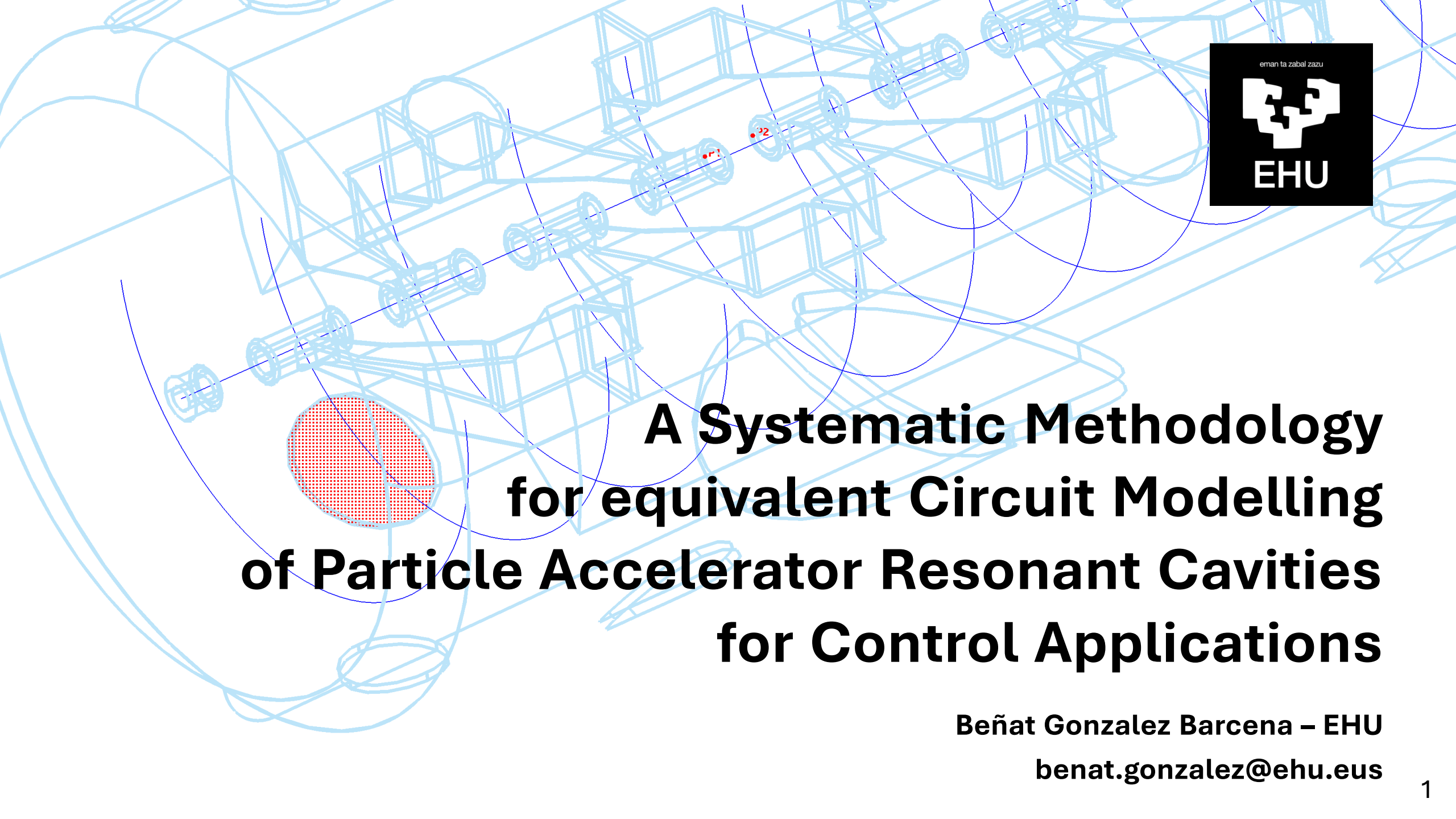




A Systematic Methodology for equivalent Circuit Modelling of Particle Accelerator Resonant Cavities for Control Applications

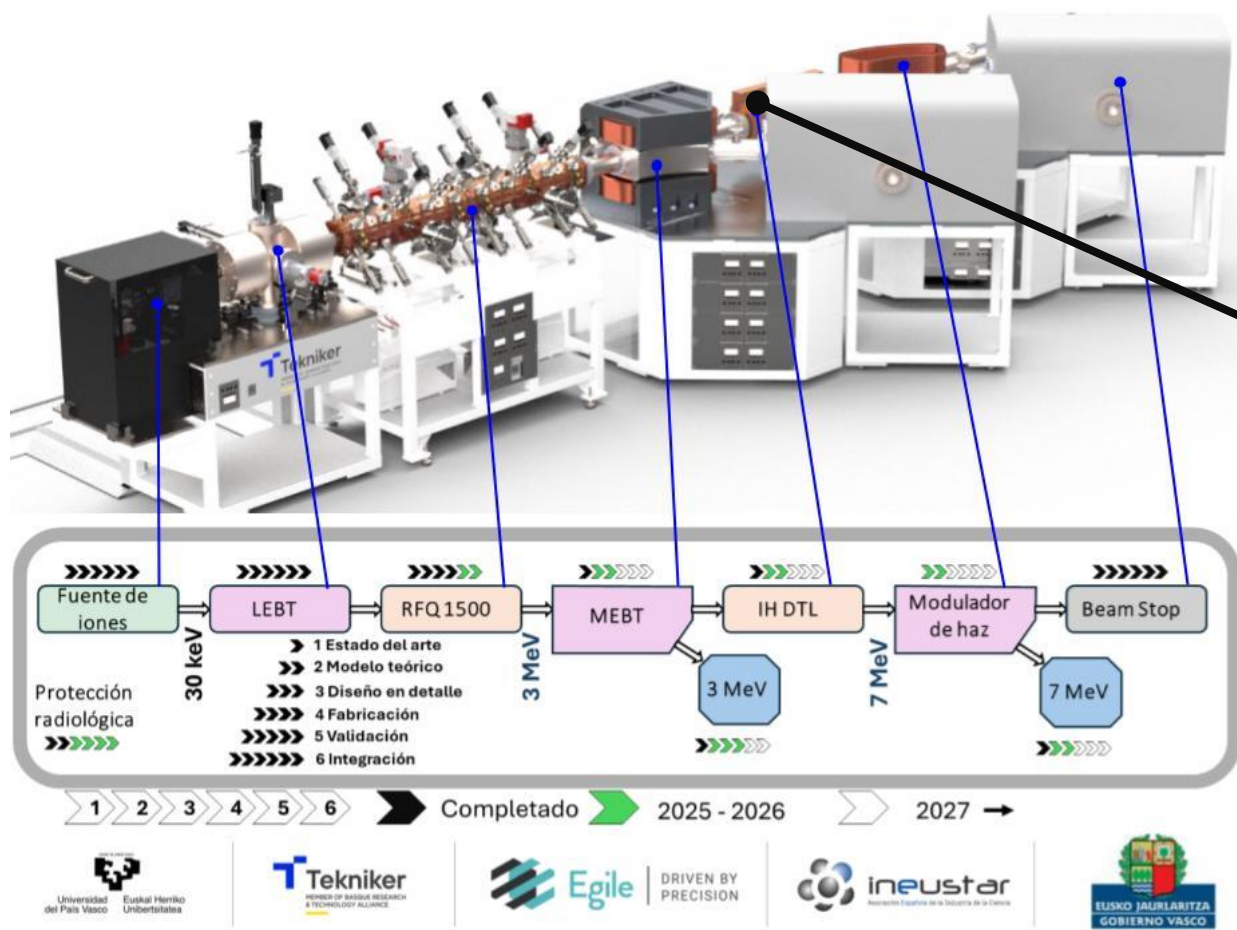
Beñat Gonzalez Barcena – EHU
benat.gonzalez@ehu.eus

Outline of the presentation

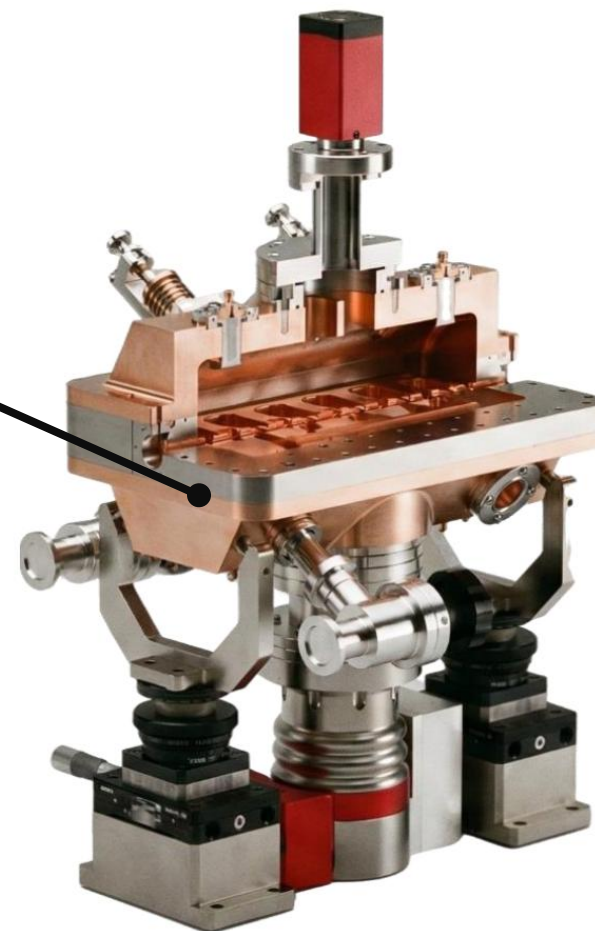
- Context
- Problem
- Methodology for parameter extraction
- Application to IH-DTL cavity
 - Control perspective
- Conclusions
- Future Work



Context



LINAC-7 Project Visualization

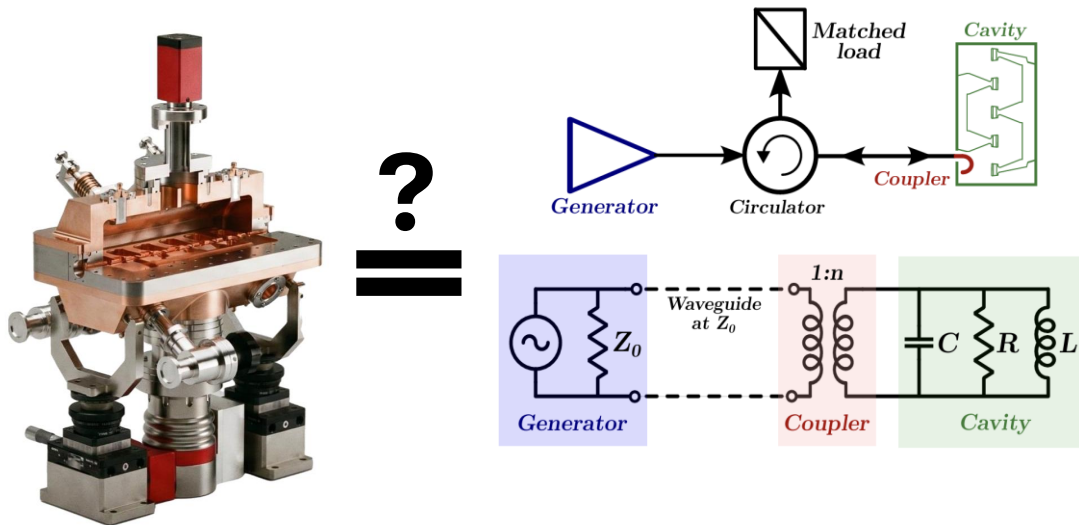


IH-DTL Cold Model

Problems

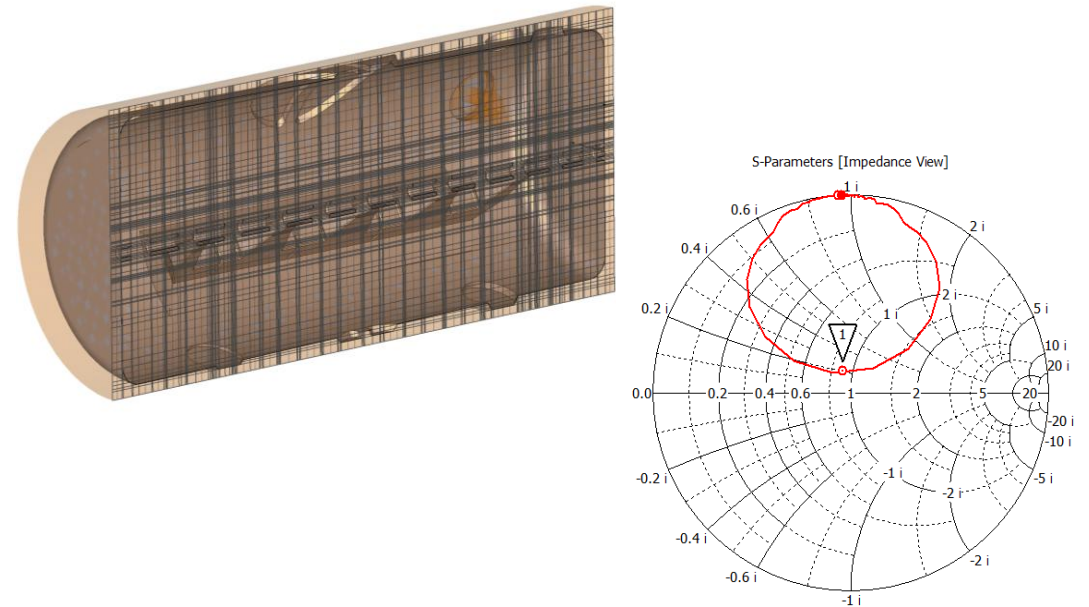
Going over simple RLC model

1. Catching more phenomena
2. Help on parameter optimization
3. Understanding better the structure



Control oriented model

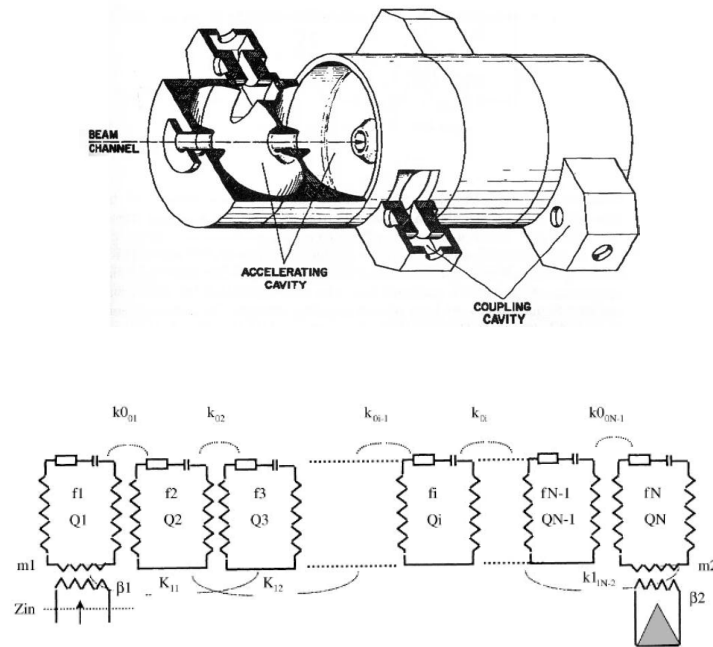
1. Fast simulations
2. Implement control loops
3. Remove dependency on mesh



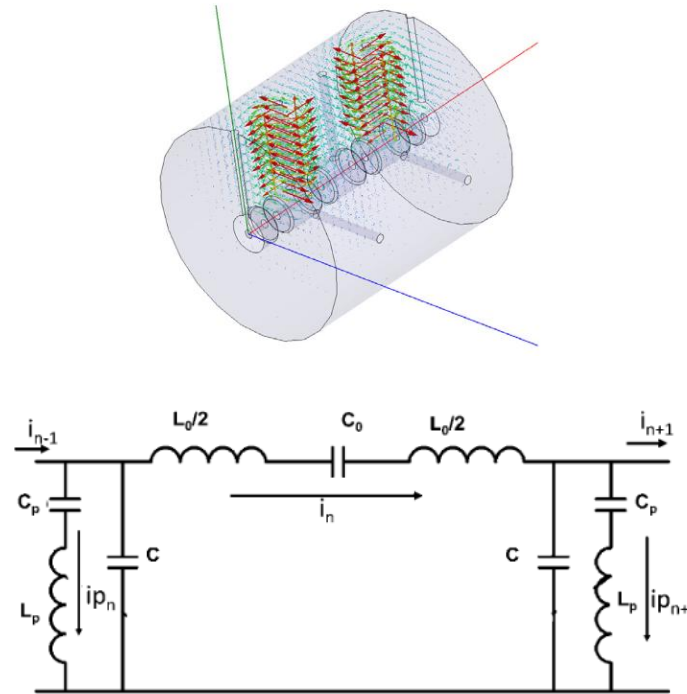
Methodology for parameter extraction

Extraction from electromagnetic simulators

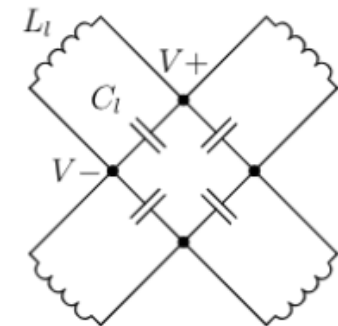
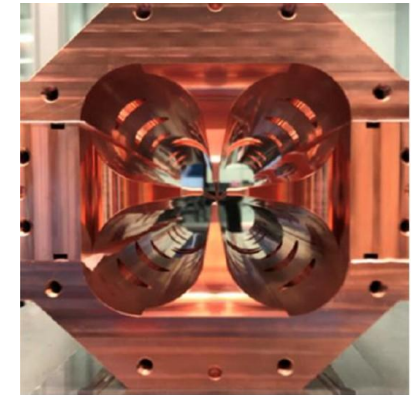
Different cavities – same model?



Coupled cavity model¹



DTL with postcouplers
transmission line model²



RFQ transverse fields model³

1. N. Yi et al. / *Nuclear Instruments and Methods in Physics Research A* 462 (2001) 356–363
2. F. Grespan, "Equivalent circuit for postcoupler stabilization in a drift tube linac," *Phys. Rev. ST Accel. Beams*, vol. 15, no. 1, p. 010101, Jan. 2012
3. T.P. Wangler. *RF Linear accelerators*. Michigan State University: Wiley-VCH, 2008.

Parameter extraction from fields

$$L = \frac{2W_m}{|I|^2} \quad C = \frac{2W_e}{|V|^2}$$

- Capacitors 
 - Define voltage integration path
 - Energy density in the volume
- Inductors 
 - Divide volume
 - Currents: define path, Ampère's law...
- Resistances 
 - Change resistors to match the quality factor of the cavity – charge/discharge dynamics.

Eigenmodes/
Freq. domain
simulations

+

E/H field
monitors

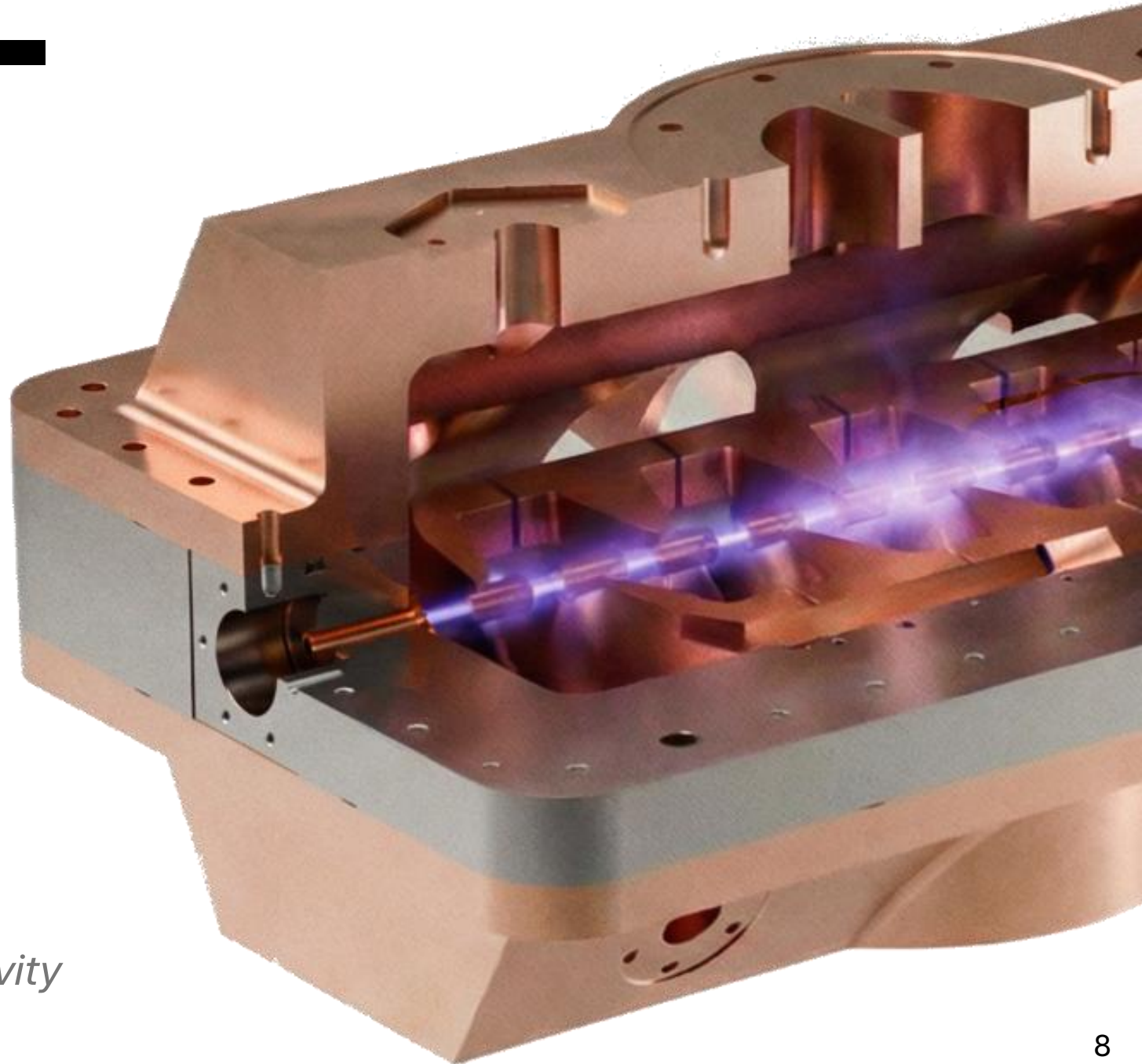
EM energy
density
monitors

Power losses
in materials

S parameters

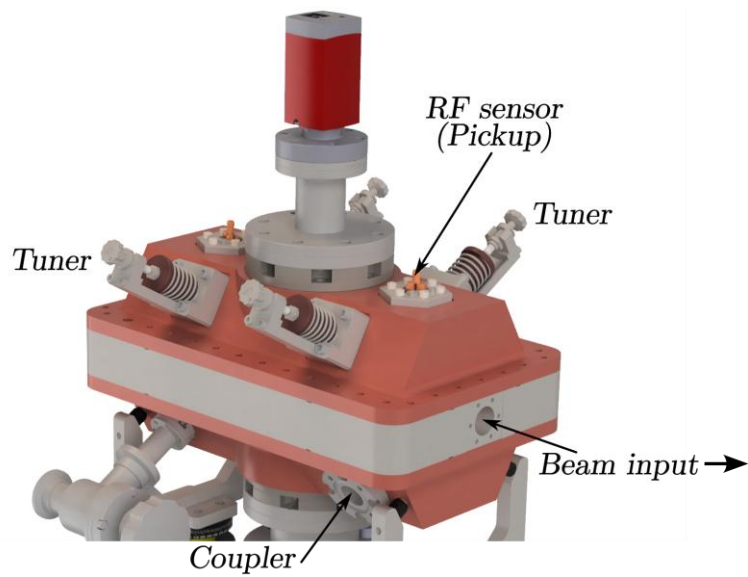
Time domain
simulations

Application to IH-DTL cavity

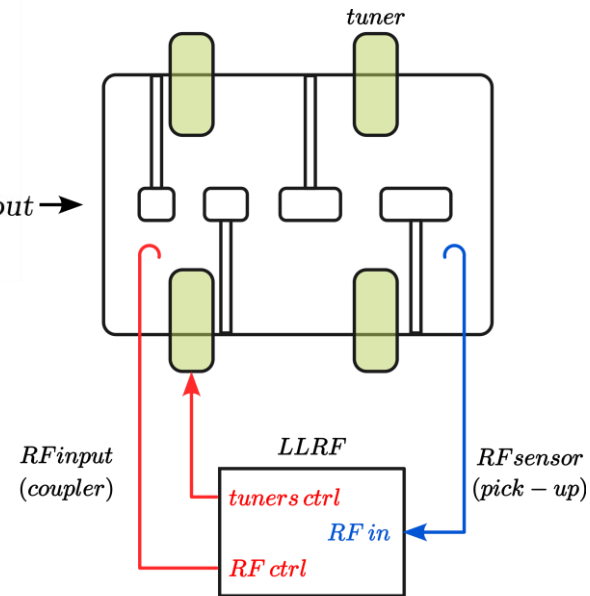


Lumped-parameters modelling of a cavity

IH-DTL Cavity

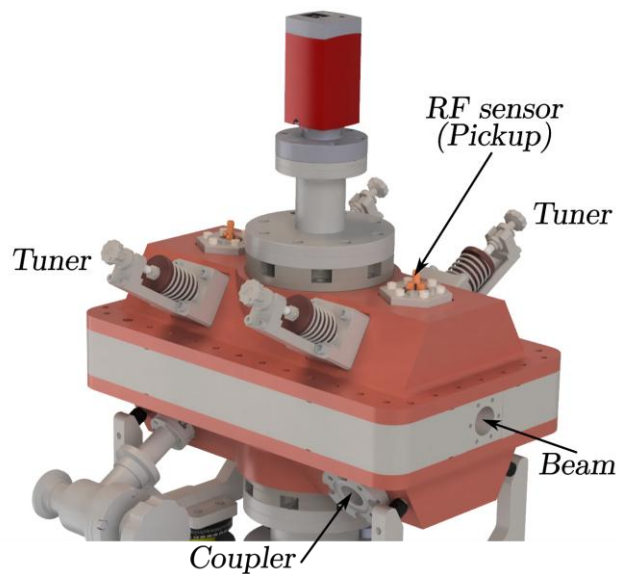


IH-DTL Cold Model

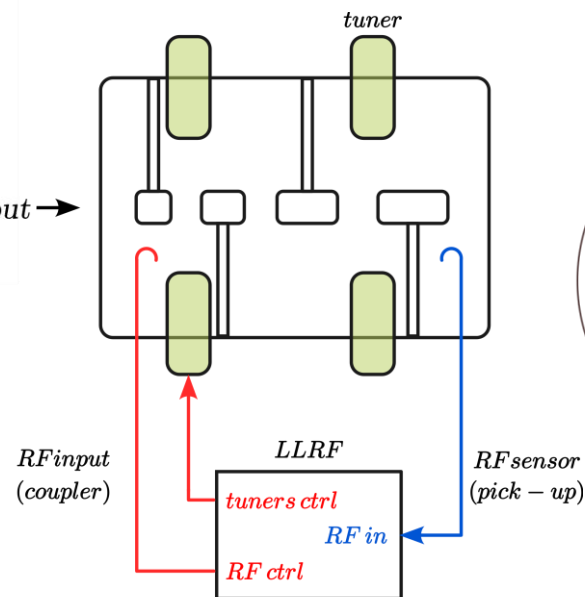


Control Scheme

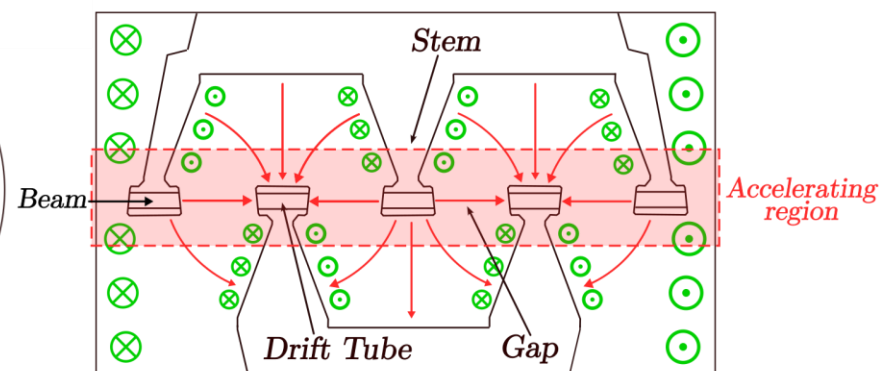
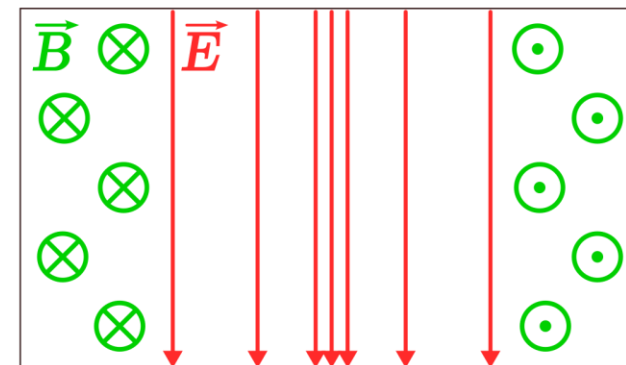
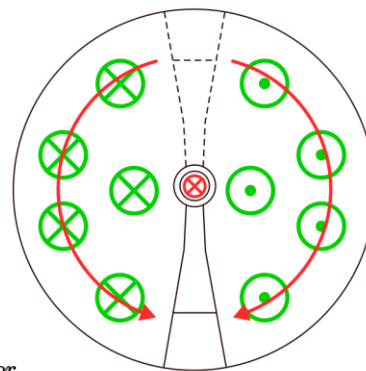
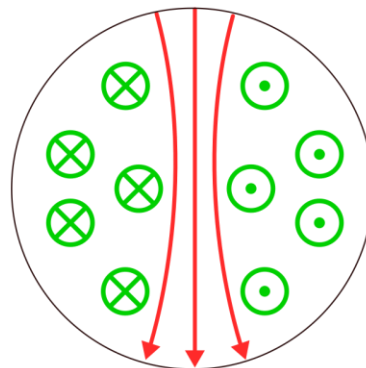
IH-DTL Cavity



IH-DTL Cold Model

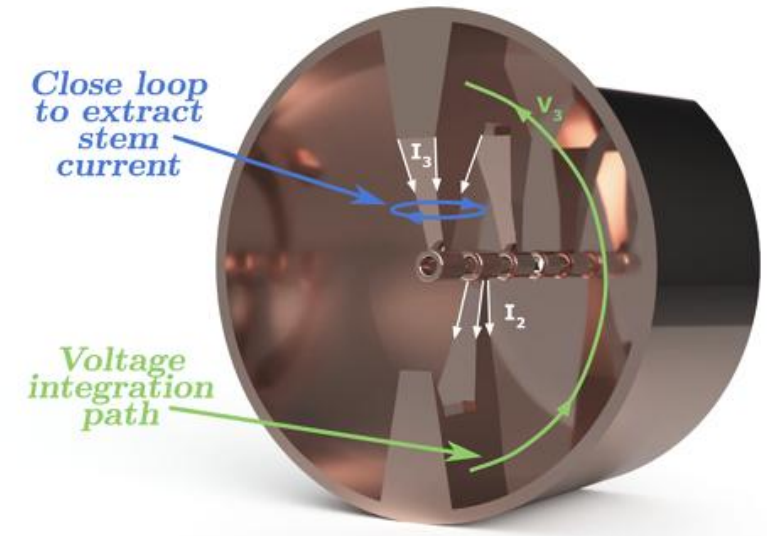
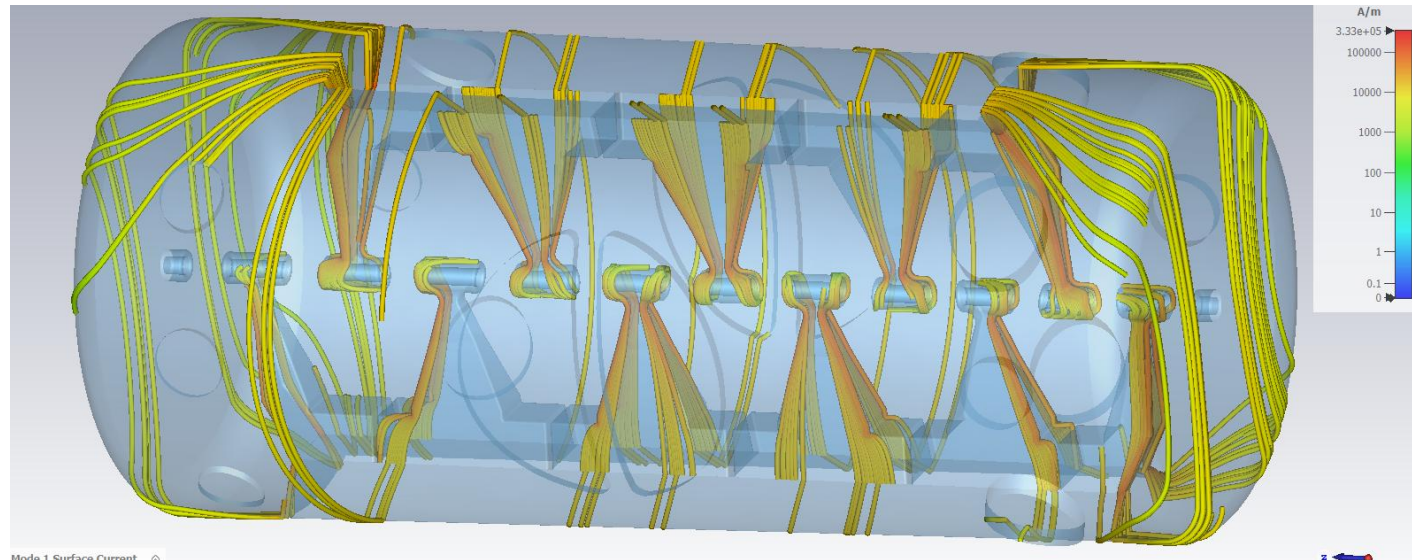
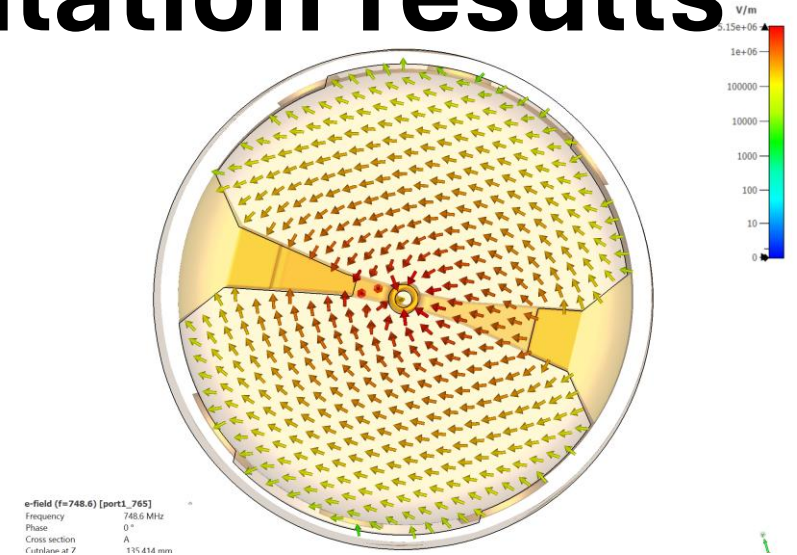
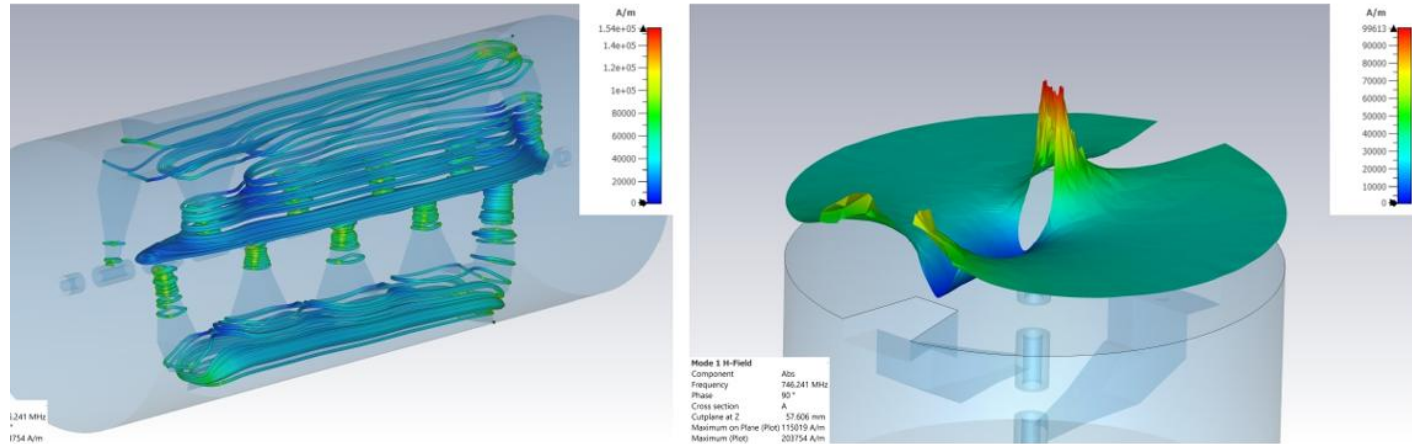


Control Scheme

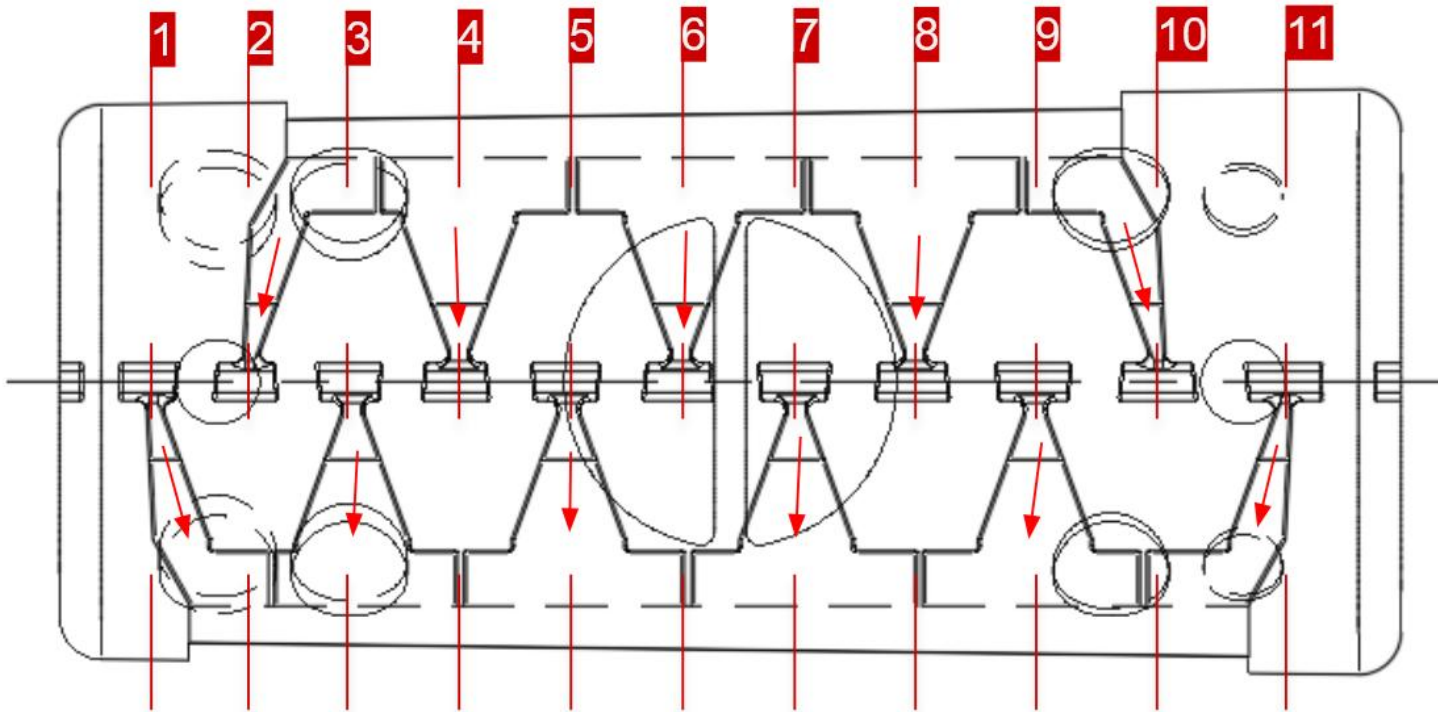


Working principle and field shape

Parameter extraction – Simulation results



Discretization of the system



IH-DTL Cold model:
11 stems and tubes

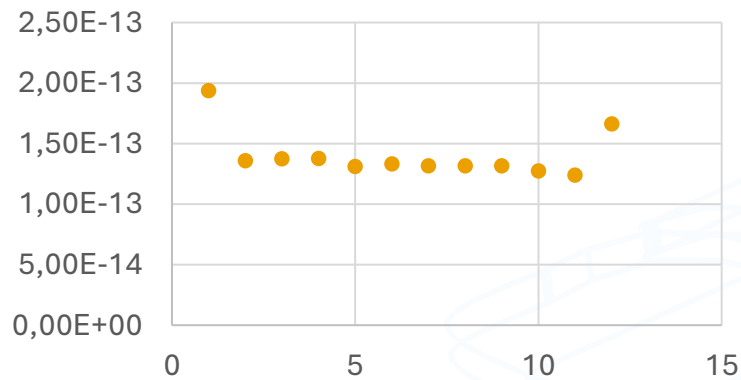


11 slices
12 gaps

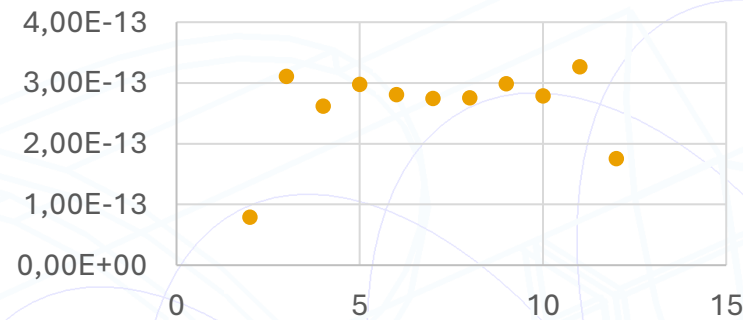
11 Stem Currents
11 Resonator Voltages
12 Gap Voltages

Parameter extraction – Obtained values

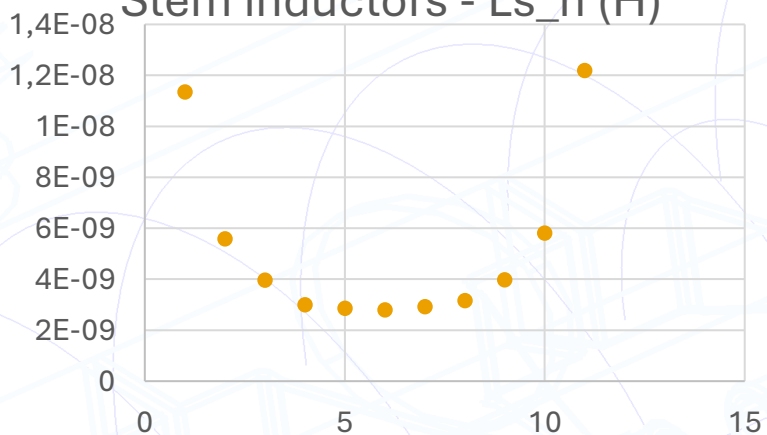
Axis capacitors - C_d (F)



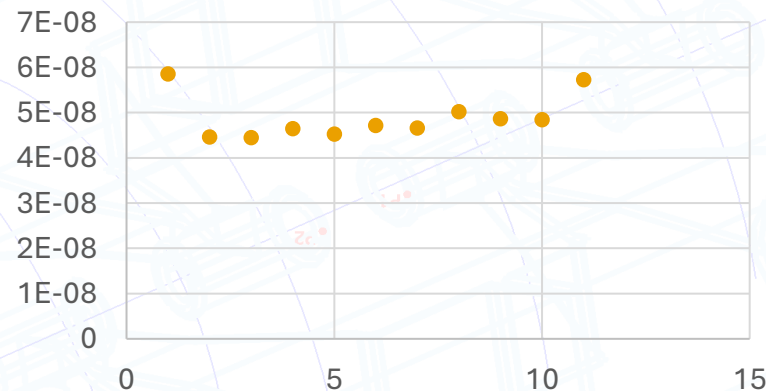
Resonator capacitors - $2 \cdot C_{p_n}$ ($r=40$)



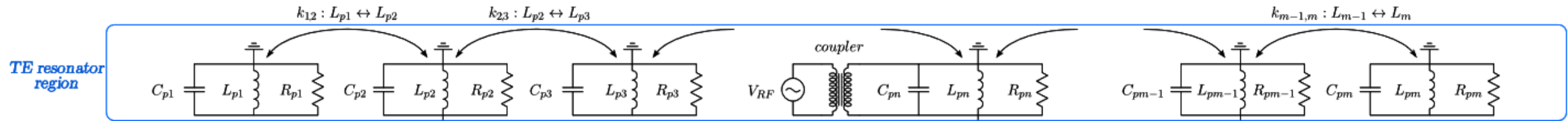
Stem inductors - L_{s_n} (H)



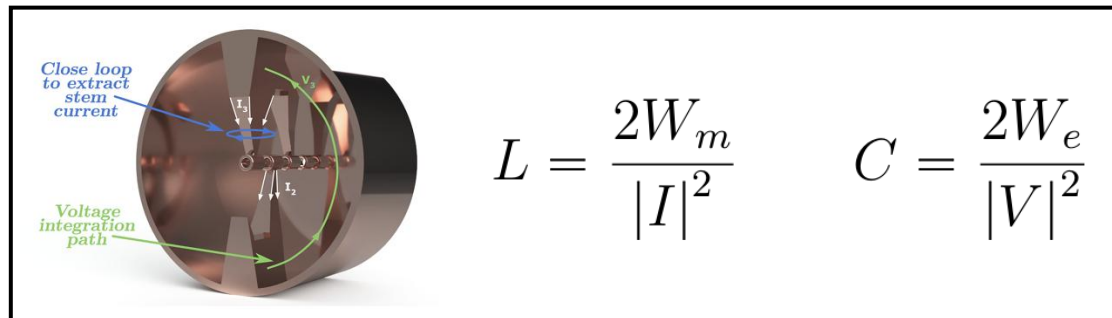
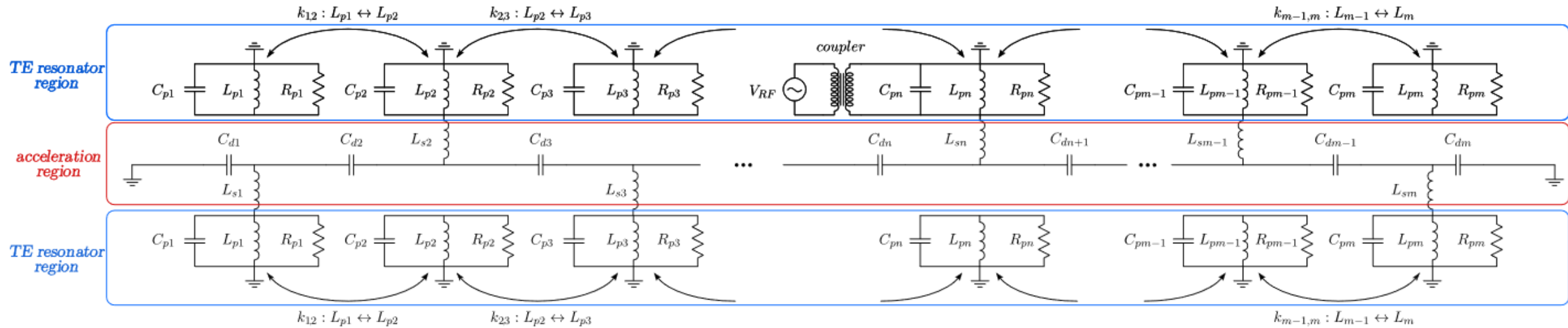
Resonant inductors - L'_n (H)



Model proposal



Model proposal



- ✓ Resonant frequency
- ✓ Mode shape
- ✓ Voltage distribution
- ✓ Frequency shifts

Model proposal

- ✓ Resonant frequency
- ✓ Mode shape
- ✓ Voltage distribution
- ✓ Frequency shifts

Only resonant structure

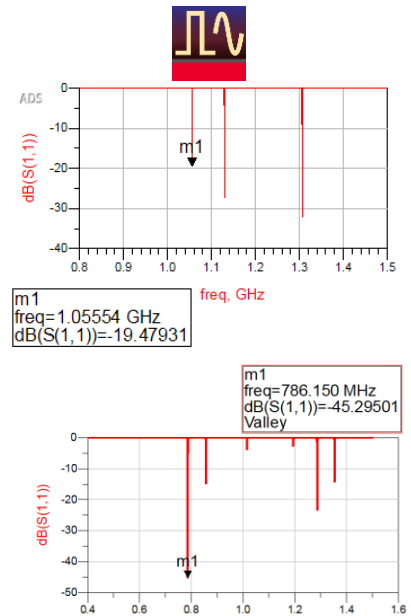
Full Structure

Mode 1 E-Field

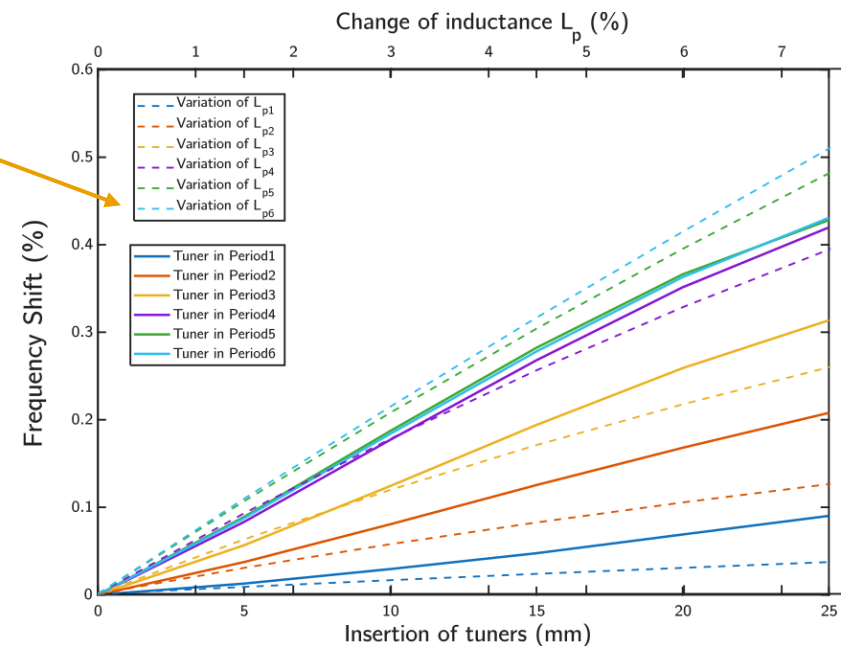
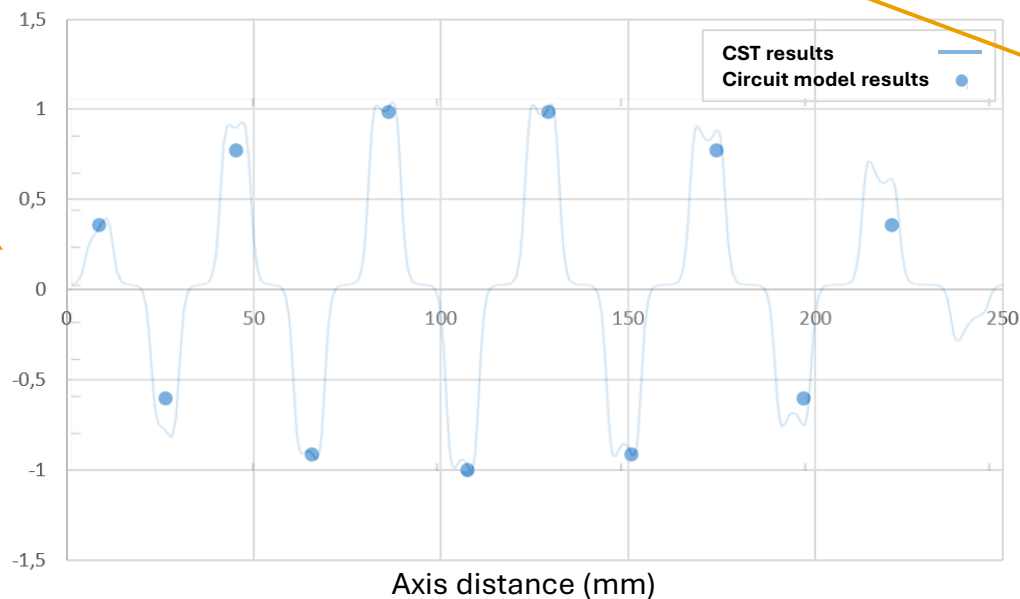
Type E-Field
Frequency 1062.77 MHz

Mode 1 E-Field

Type E-Field
Frequency 748.405 MHz

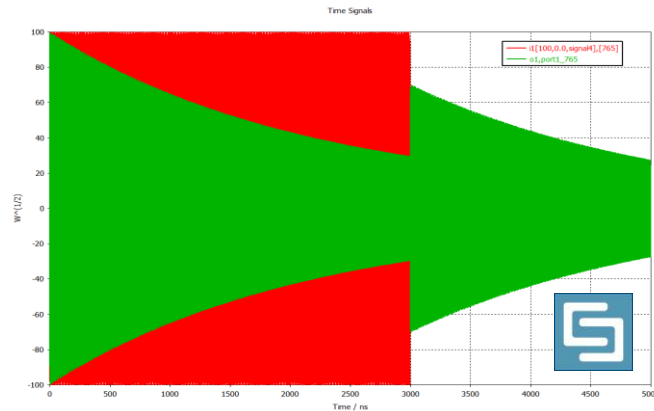


Normalized voltage on the axis



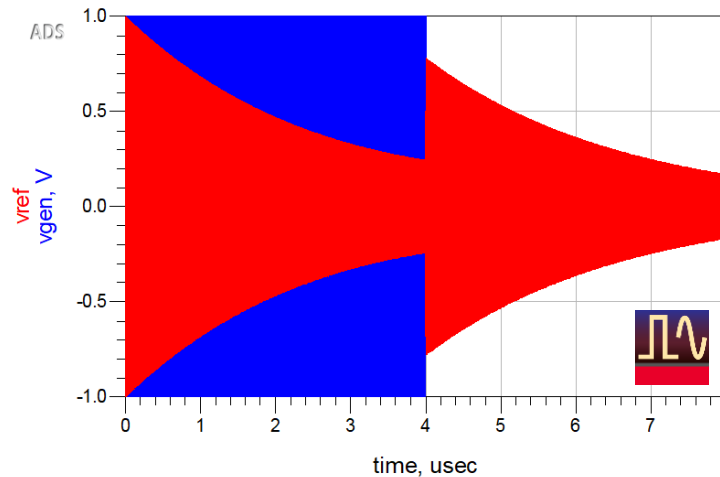
CST vs ADS vs Simulink

Full EM 3D simulation

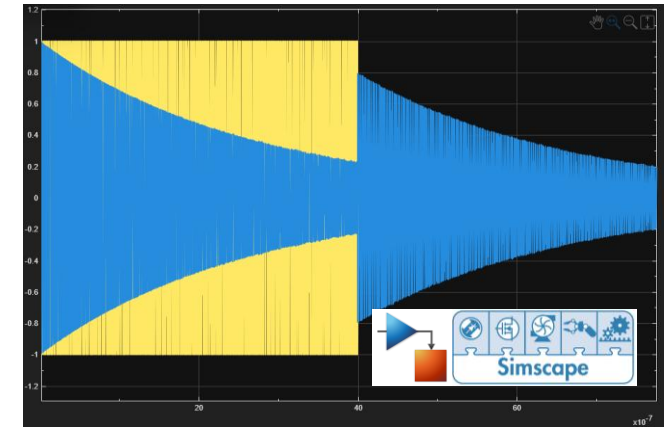


- ✓ Full characteristics of the cavity.
- × Long simulation time (hours).
- × Very dependent on mesh.

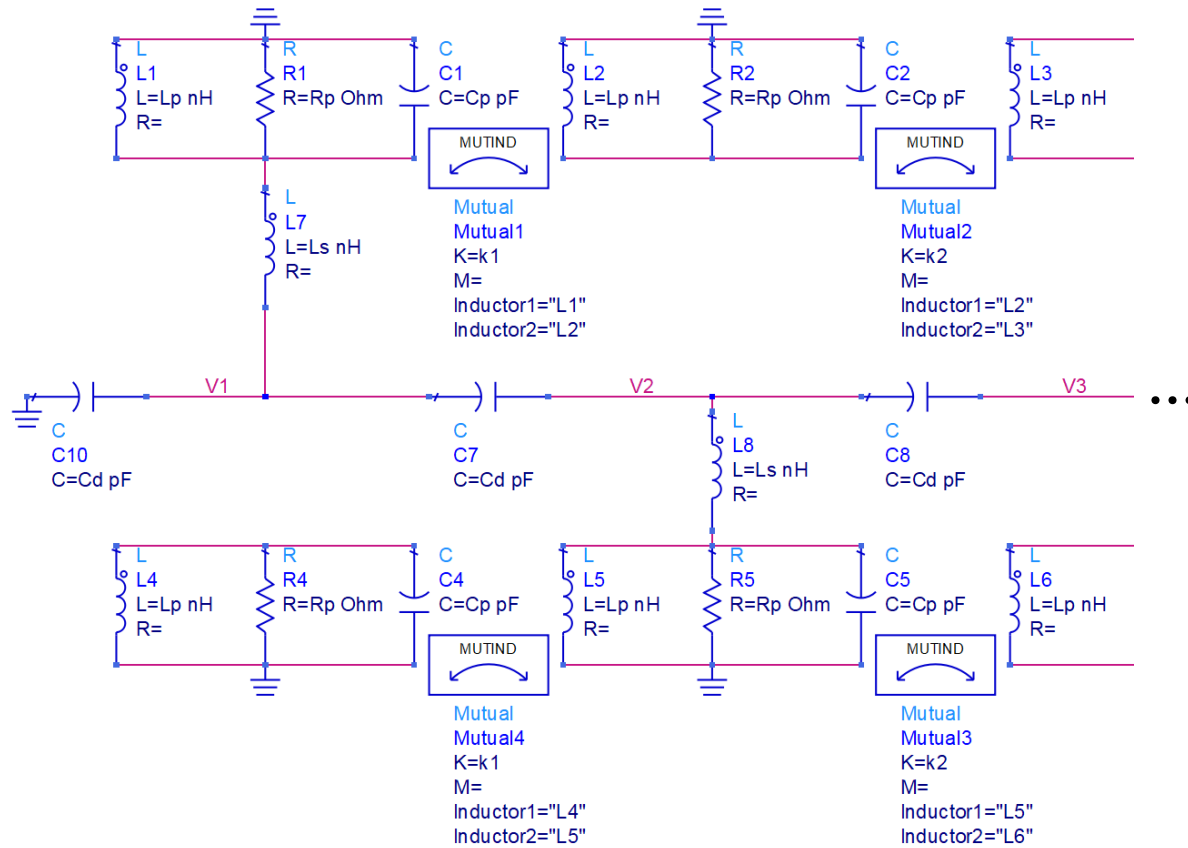
Circuit simulation



- ✓ Fast simulation time (minutes).
- ✓ Easy tuning and optimization.
- ✓ Suitable for control.
- × Shows only specific phenomena.
- × Needs validation with physical structure.

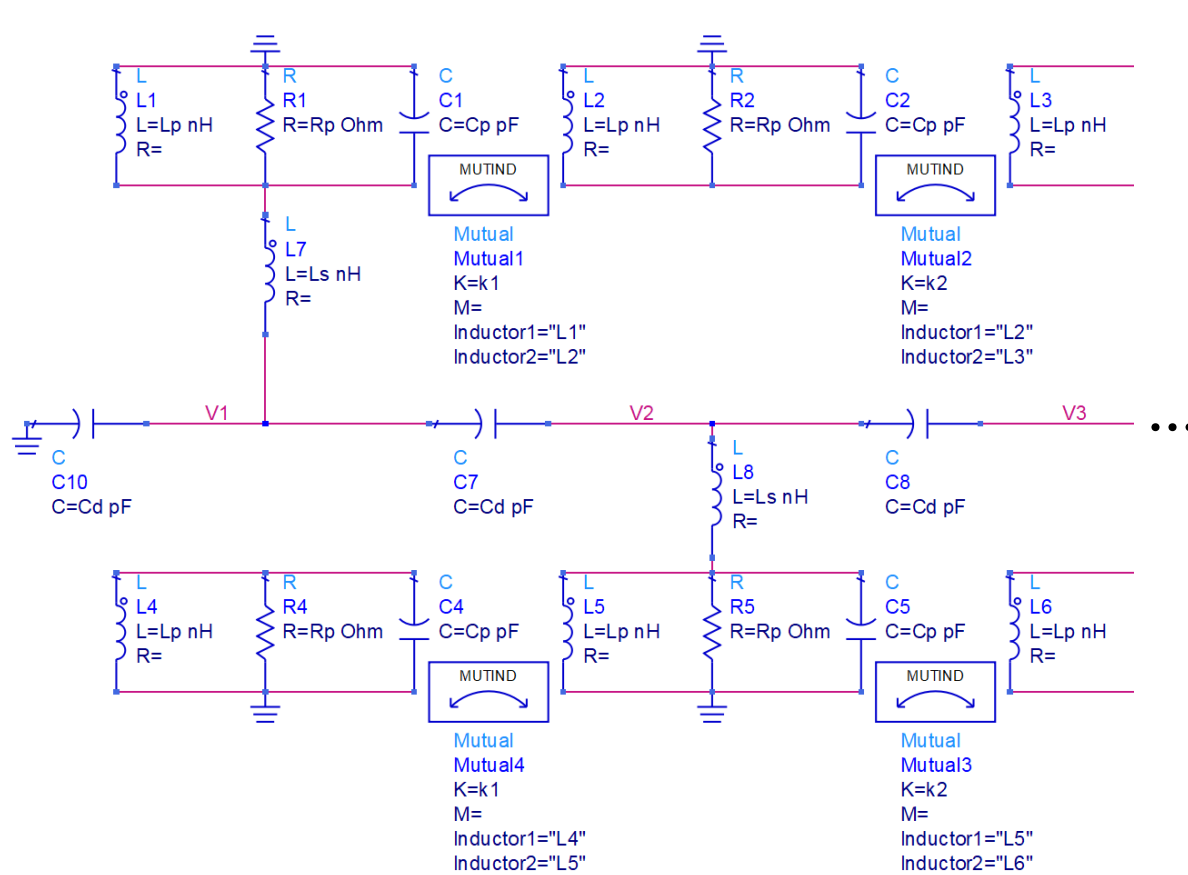


Variations of the general model

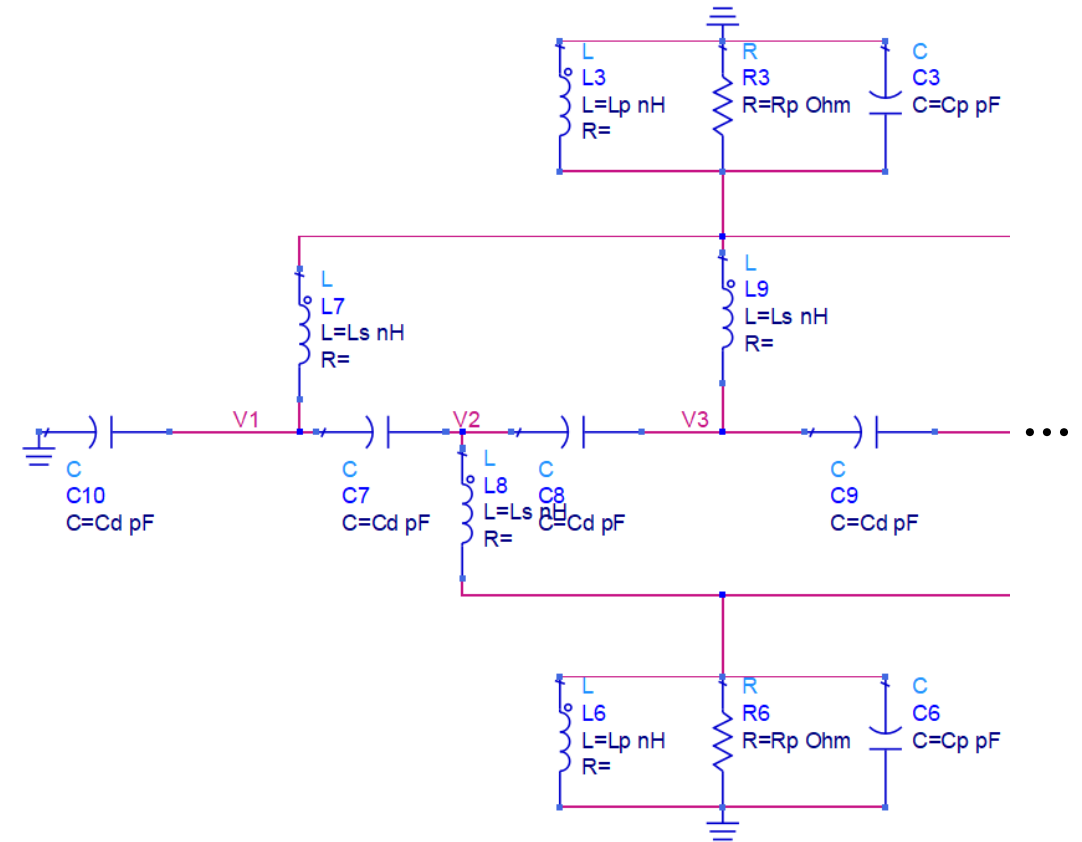


Symmetric case, same value for each parameter

Variations of the general model

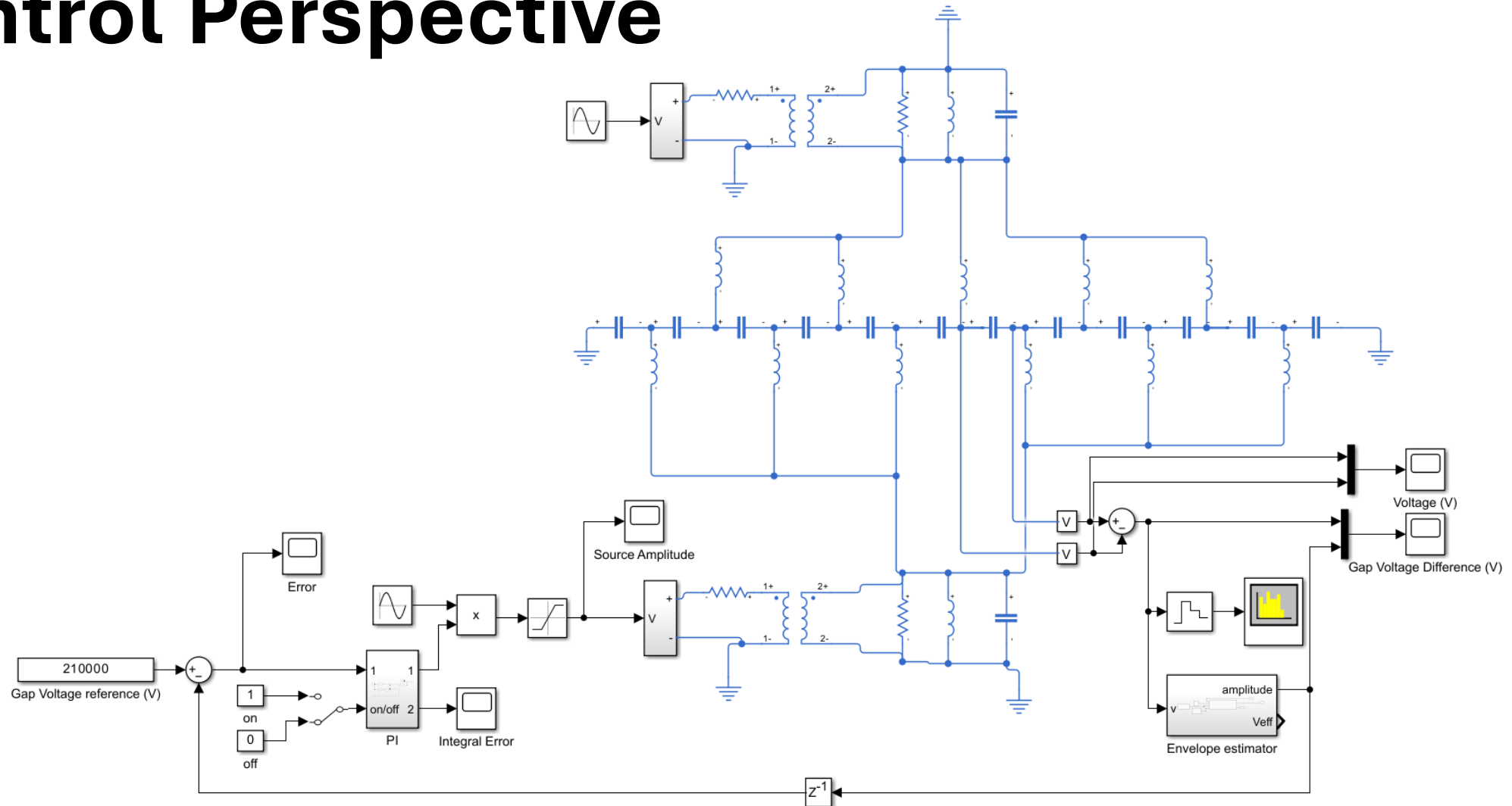


Symmetric case, same value for each parameter



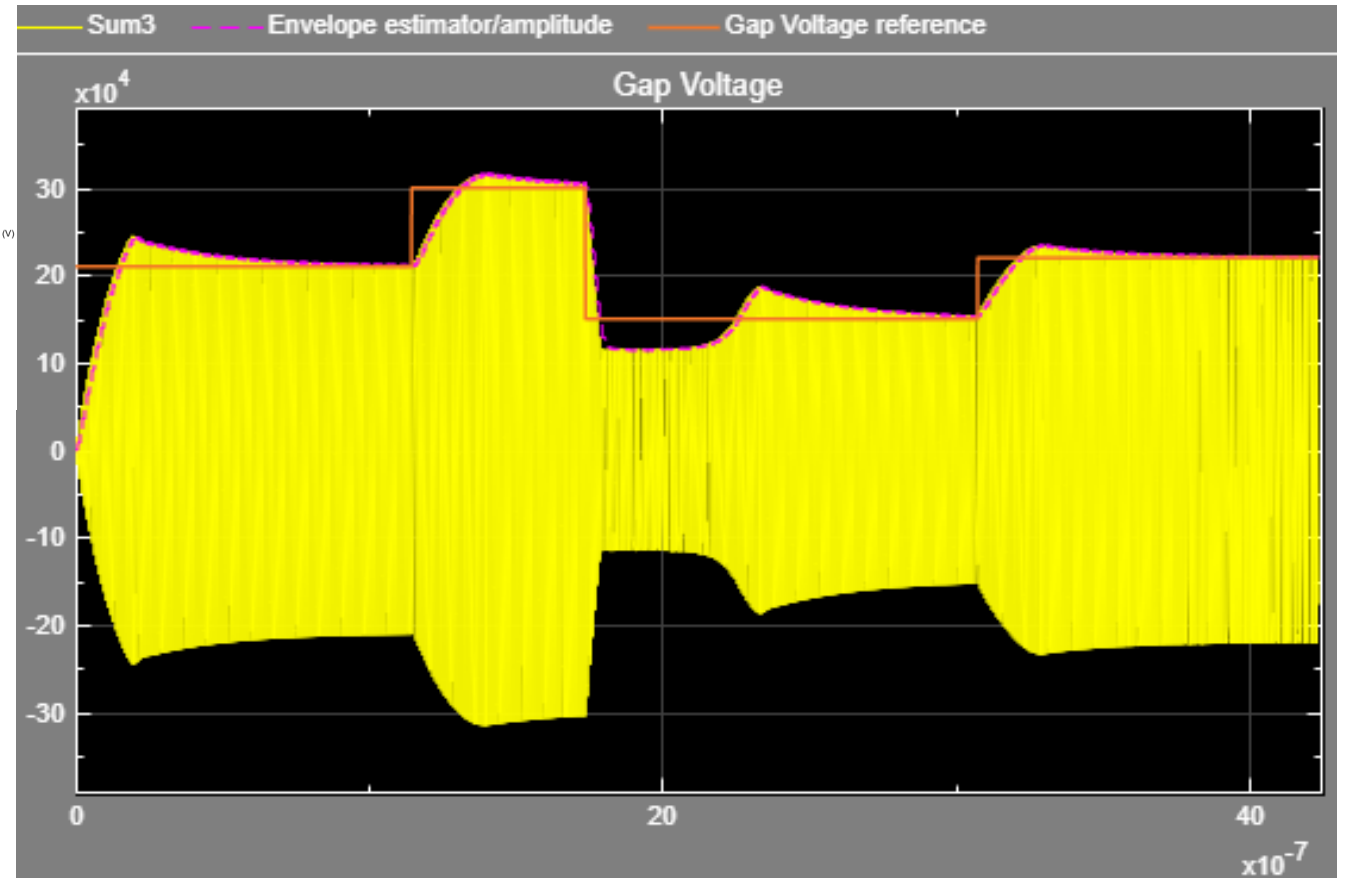
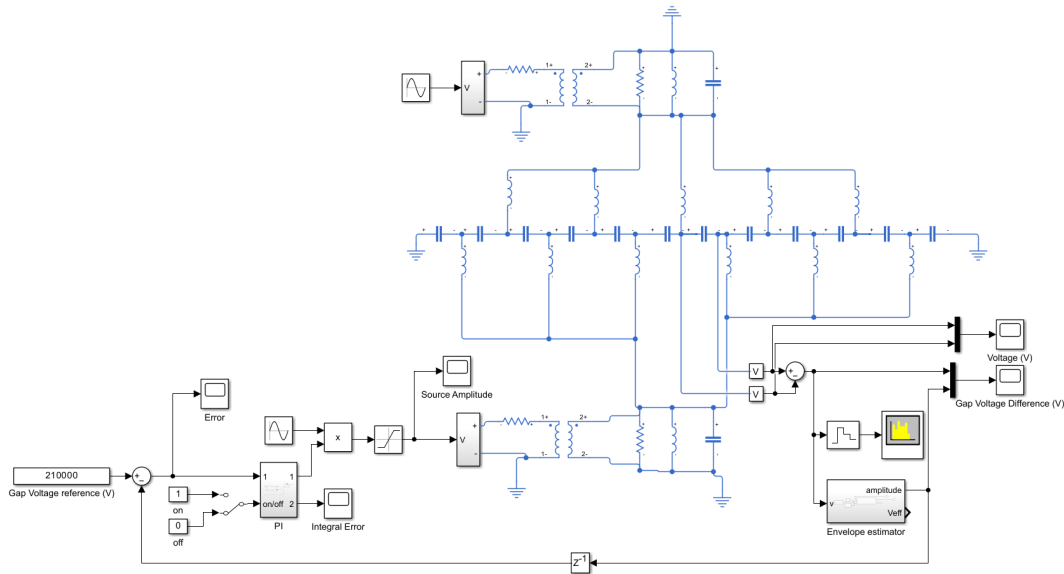
TE resonant regions as RLCs

Control Perspective



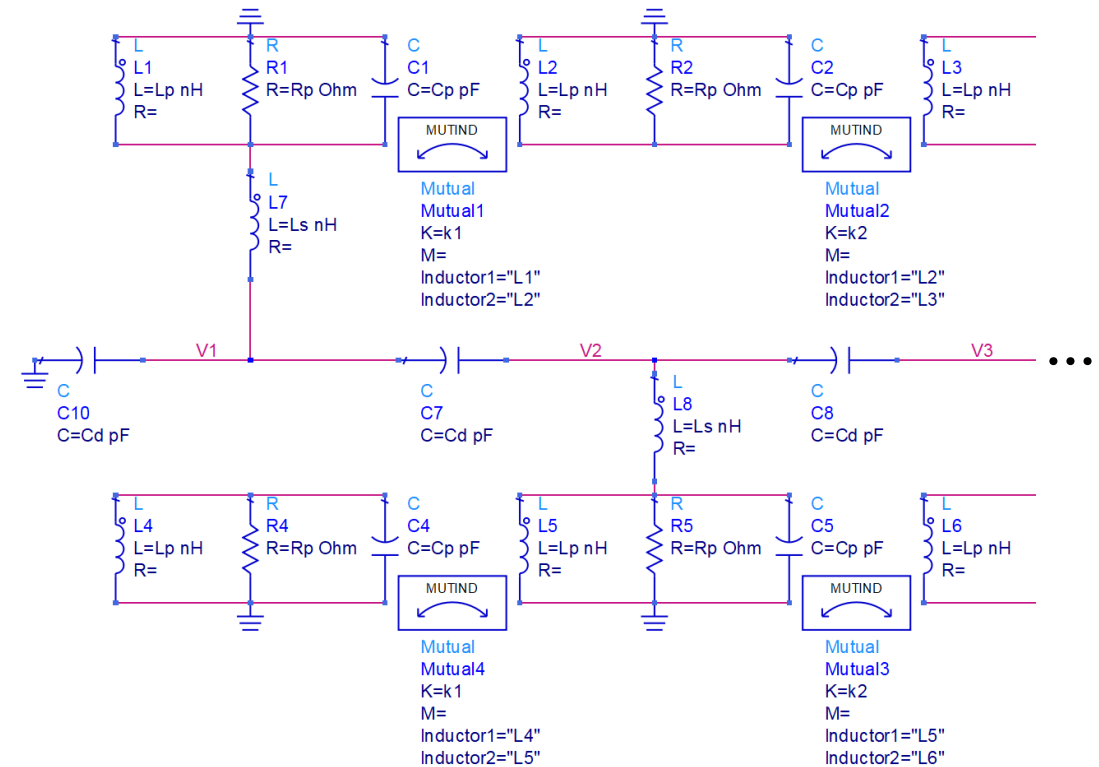
Simulink project with **simplified model**

Control Perspective – First results



Conclusions

- It is possible to **extract lumped elements** from electromagnetic simulations knowing the field and energy distribution in the system.
- The parallel RLC circuit is the most used model for RF cavities. However, **some phenomena cannot be described** with this simple description.
- **Multiple circuitual models** can be employed to describe the same system. Some are better at representing some effects than others.
- A **new lumped parameter circuit** for the IH-DTL cavity has been proposed allowing to directly reflect the gap voltages, positional effects and possibility for multiple couplers.
- **Simulation time decreases drastically** compared with full electromagnetic simulation. Importance of the solver used.



Circuit implementation in *Keysight ADS*.

Future work

- Optimize the proposed circuits to each observed phenomena. Study if **other structures** can give better results.
- Identify the detuning mechanisms and **implement control loops** to solve them.
- Study mechanisms to **accelerate the simulations**: different solvers, Julia...
- Extract the final parameters from the real cold model and **validate the proposed circuital models** vs real actuation.

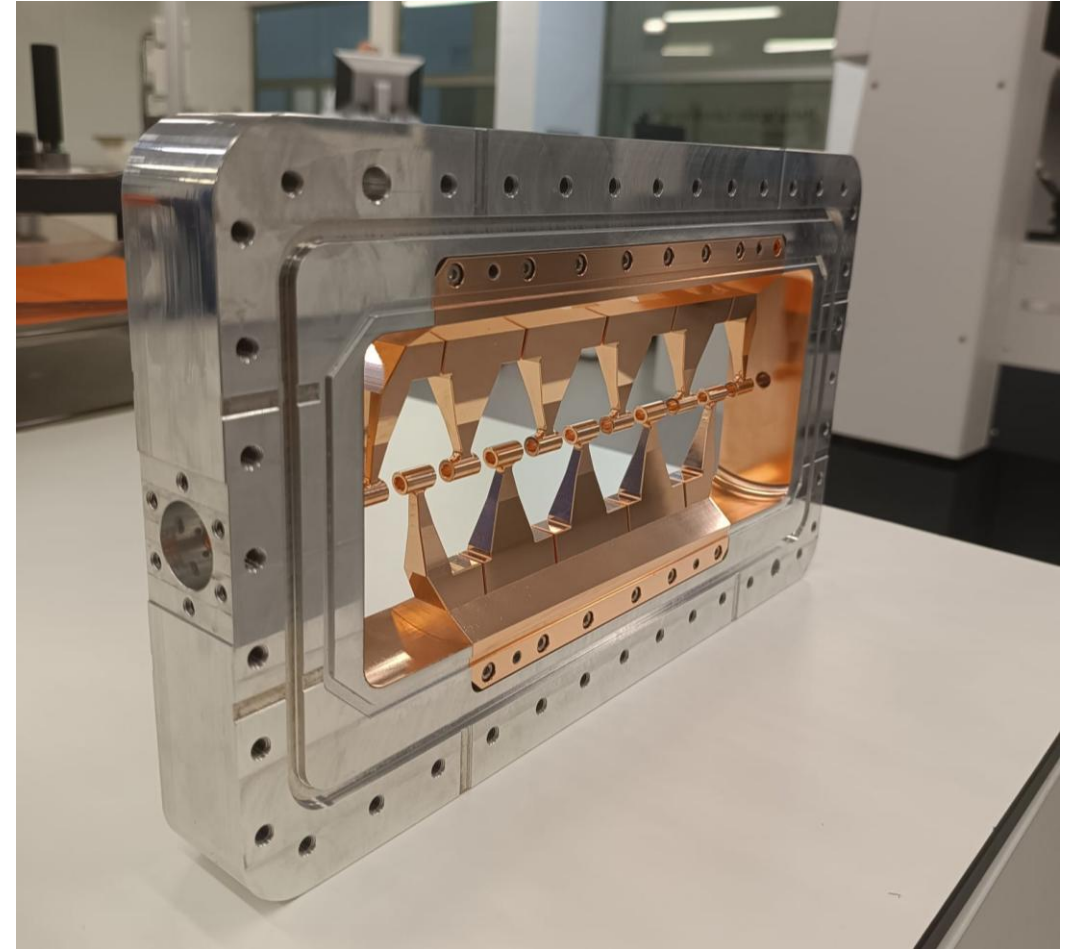


Photo of the **Cold Model** of the IH-DTL

Acknowledgments

Directors:

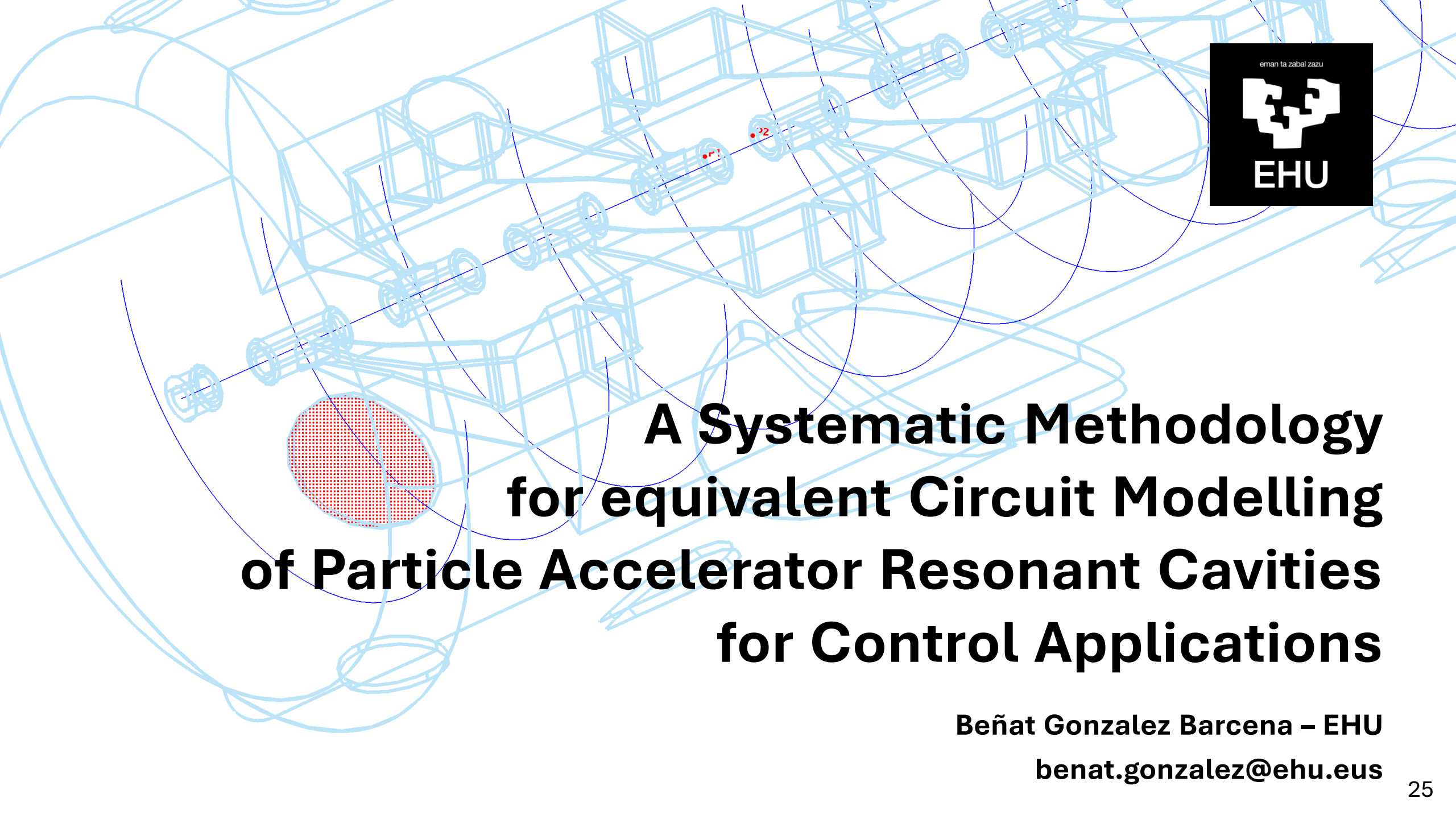
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Joaquín Portilla

Contributors:

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Jon Vivas
Andoni Egurrola
Jorge Feutchwanger
Markel Larrea

With funding from the PID2023-148792OB-I00 project





A Systematic Methodology for equivalent Circuit Modelling of Particle Accelerator Resonant Cavities for Control Applications

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