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Optimization of HOM Couplers using Time Domain Schemes

Workshop on HOM Damping in Superconducting RF Cavities

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Overview

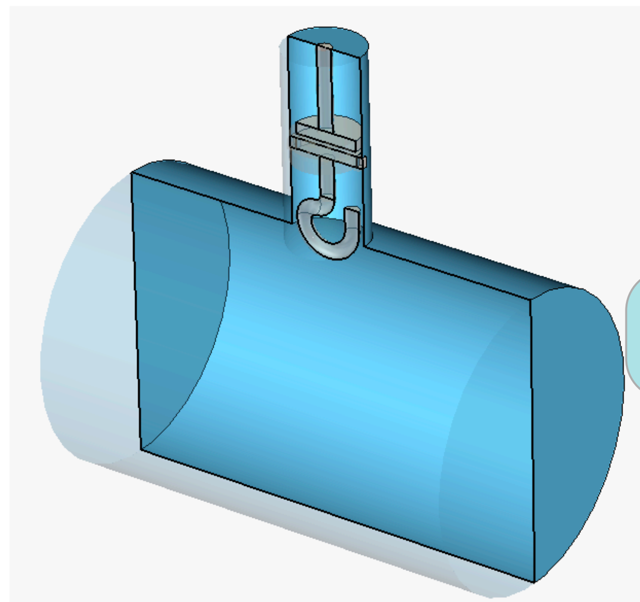
- Introduction
- Comparison of selected numerical time domain schemes
- Application Example: Optimization of the filter characteristics of a preliminary HOM coupler design with SPL dimensions.
- Conclusions

Introduction - Numerical Optimization

Design

Geometrical parameters

Model



Simulation

Results

- scattering properties
- thermal load
- ...

assessment

new set

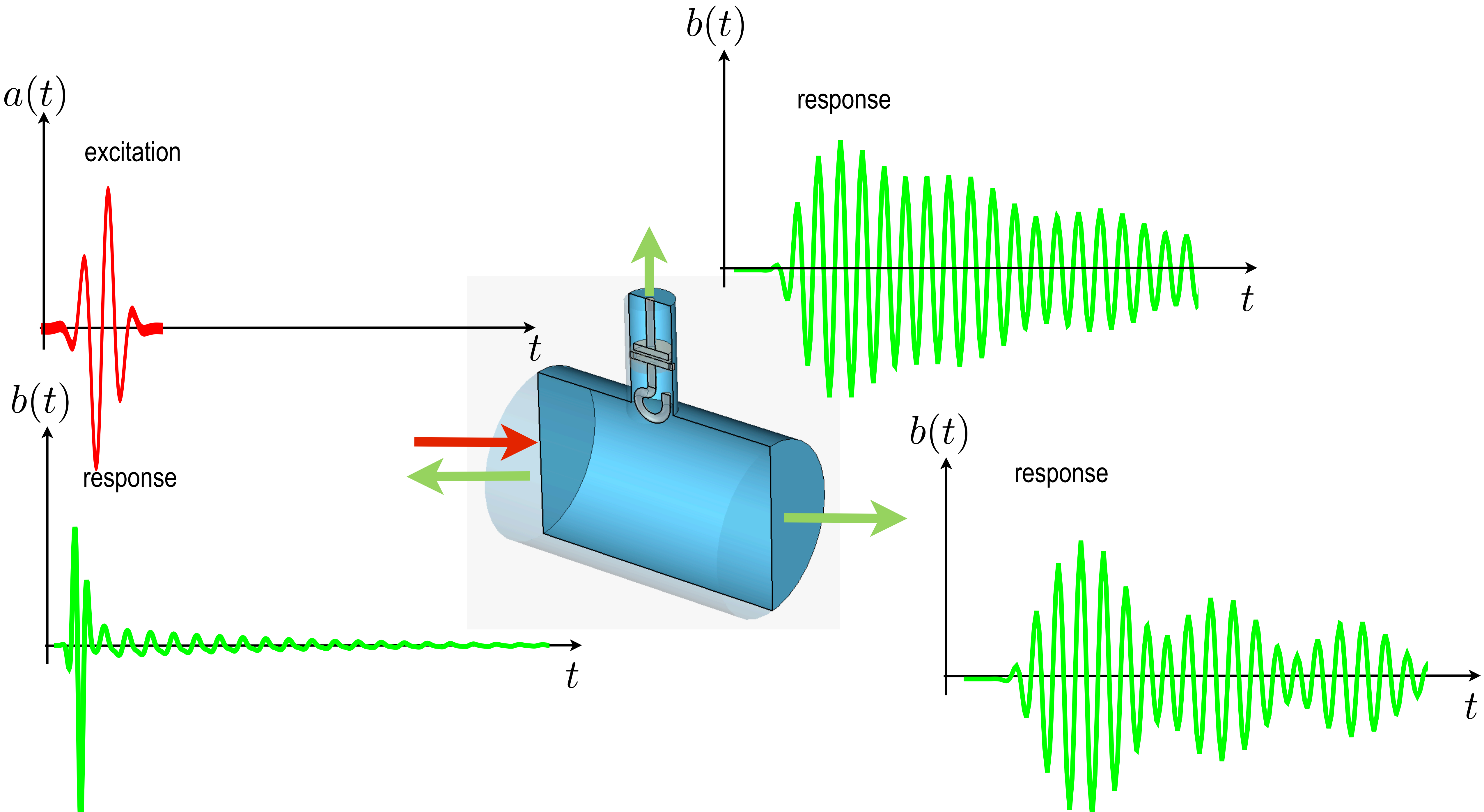
optimization algorithm

Criterions met?

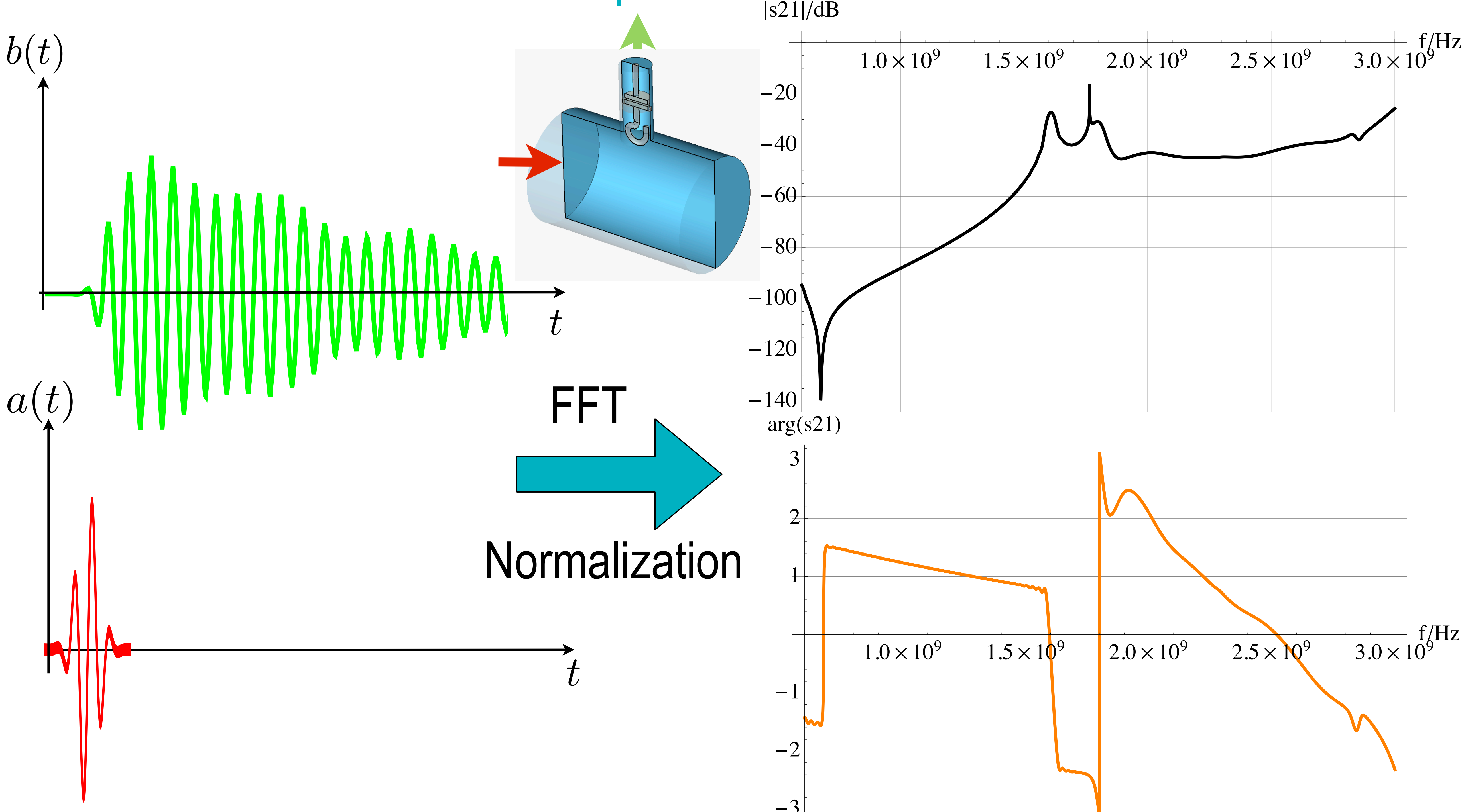
Optimized Design

- Simulation is (in general) the most time consuming part
- Use as few simulations as possible and a suited numerical scheme!

Time Domain Computation of S-Parameters #1



Time Domain Computation of S-Parameters #2



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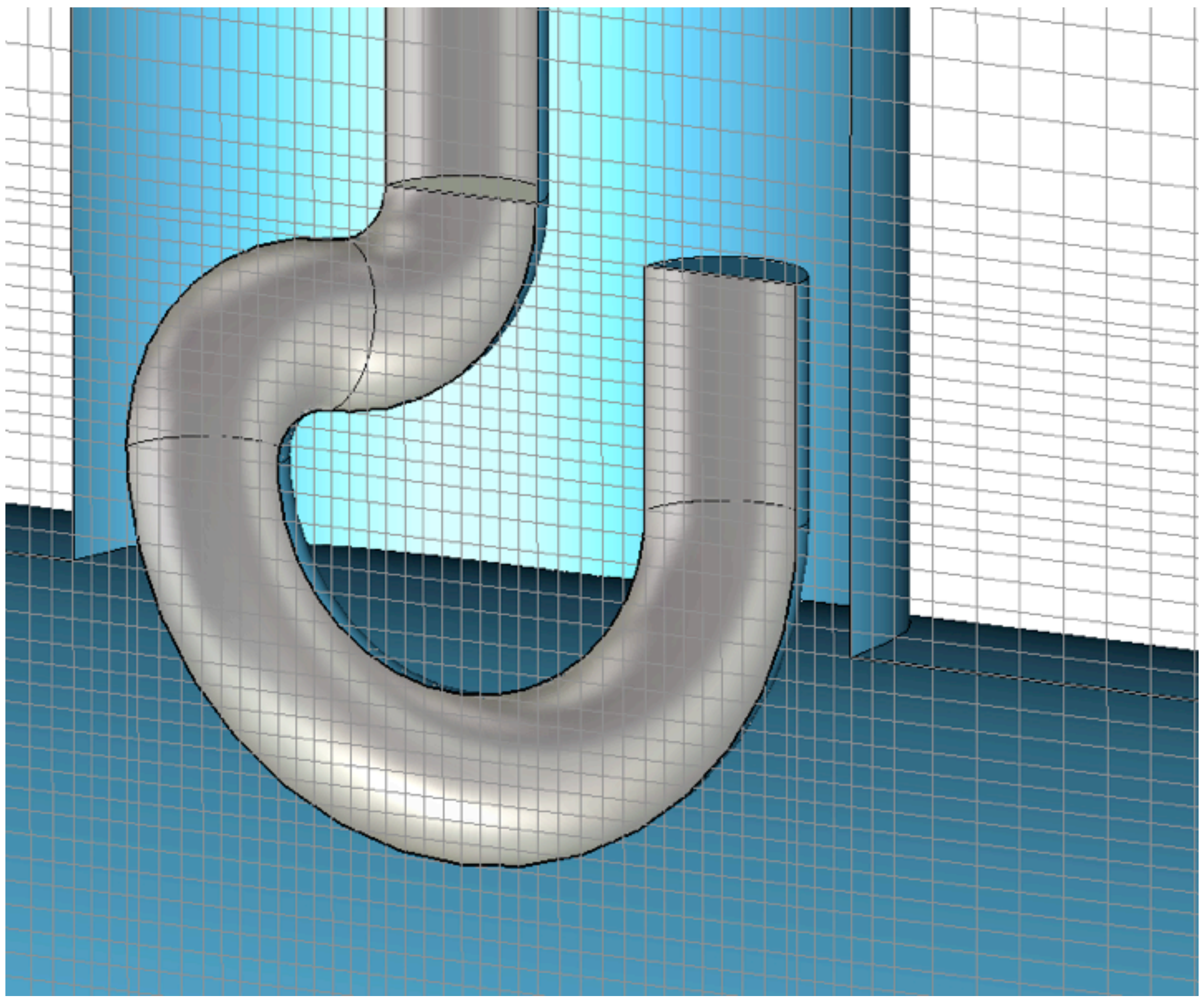
Numerical Schemes - „Stencil“ Approach



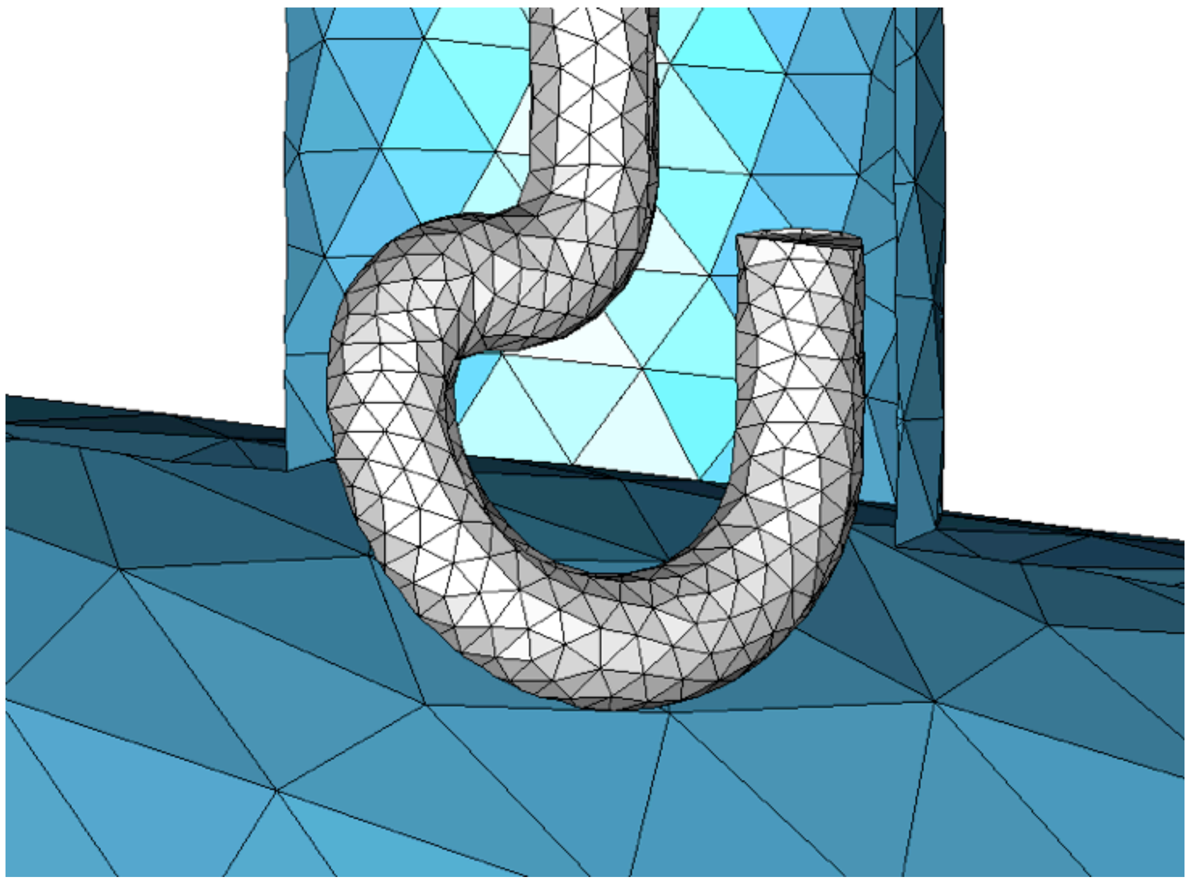
HOM section and cartesian grid

- FDTD/FIT
- Commonly used on regular grids (orthogonality!)
- Compute fields/fluxes at a location by surrounding fields/fluxes (linear operators L1,L2)
- Explicit update equation for discrete field vectors ($\underline{e}$,$\underline{h}$):

$$\frac{d}{dt}\begin{pmatrix}\underline{e}\\ \underline{h}\end{pmatrix} = \begin{pmatrix}L_1(\underline{e},\underline{h})\\ L_2(\underline{e},\underline{h})\end{pmatrix}$$

Explicit but limited geometric flexibility.

FEM Approach



HOM section discretized unstructured tetrahedral grid (coarse)

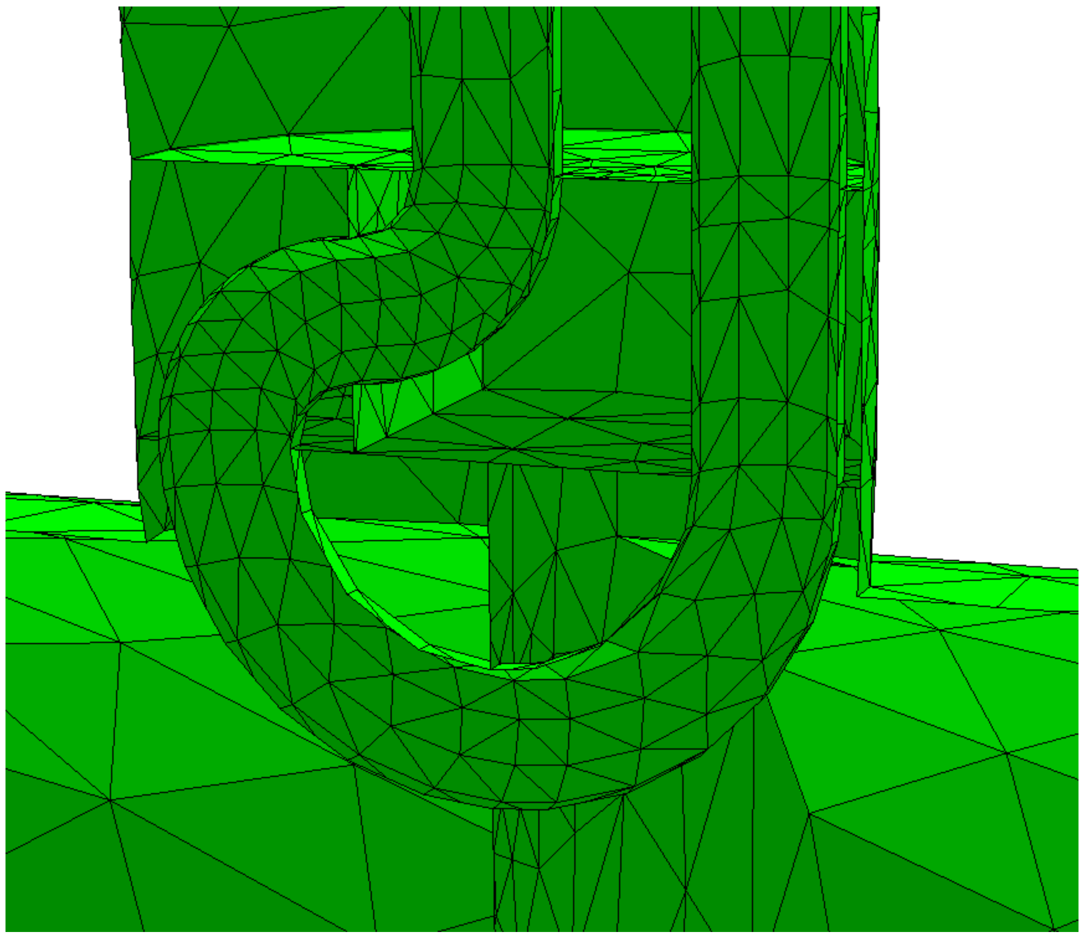
- Allows for unstructured grids => suited for complex curved structures and a reasonable number of elements/dofs
- Project fields on a finite function space, compute inner product with test functions (commonly used approach: Galerkin)
- Problem: Leads to implicit semi-discrete formulation (unless problem is sufficiently small and mass matrices can be inverted)

$$\frac{d}{dt}\begin{pmatrix} \underline{\underline{M}}_1 \underline{e} \\ \underline{\underline{M}}_2 \underline{h} \end{pmatrix} = \underline{\underline{S}} \begin{pmatrix} \underline{h} \\ \underline{e} \end{pmatrix}$$

Global matrices

Geometrical flexibility but implicit.

Discontinous Galerkin (DG) - FEM Approach #1



HOM section discretized (12k elements, second order)

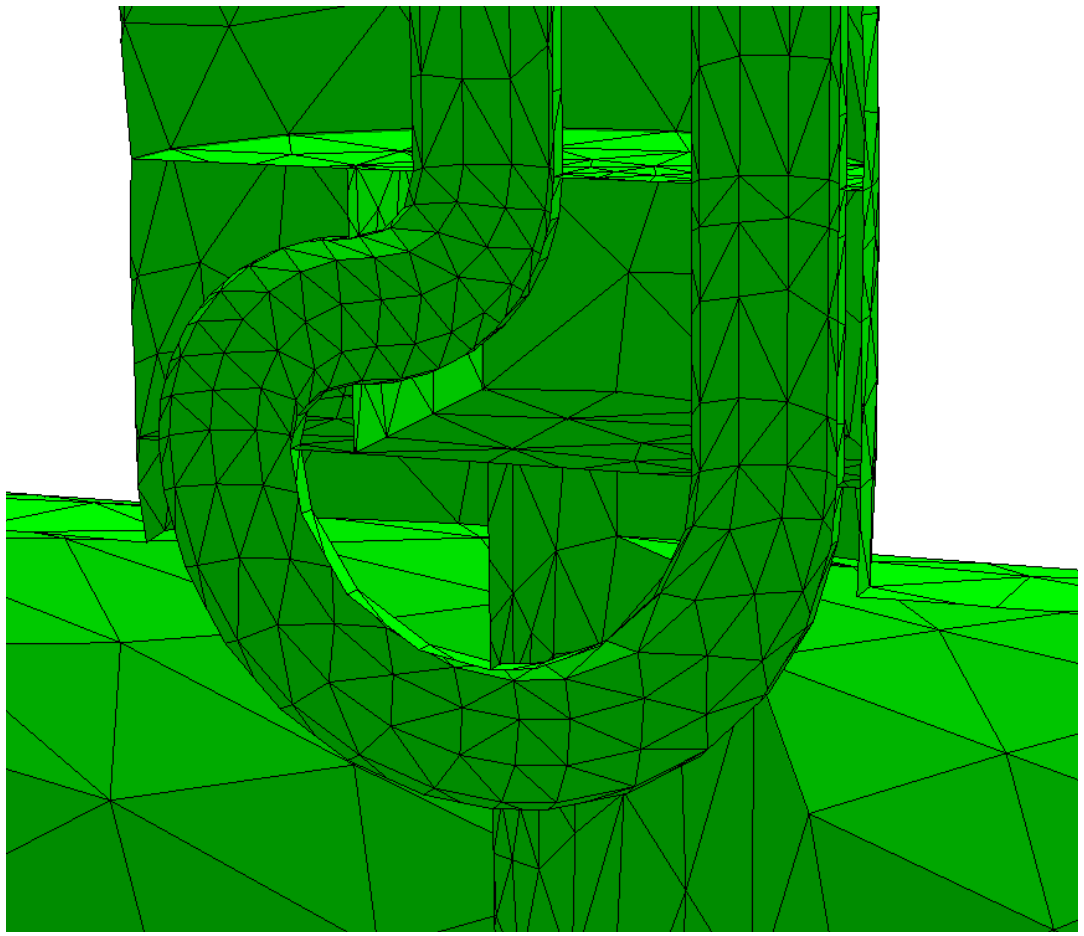
- Allows for unstructured grids => suited for complex curved structures
- Support of basis and test functions is limited to the individual corresponding elements
- Adjacent elements connected by boundary fluxes
- All matrices defined element wise => small
- Matrix inversion is feasible => explicit
- „Parallel by design“

$$\frac{d}{dt}\begin{pmatrix}\underline{e}\\ \underline{h}\end{pmatrix} = \underline{\underline{M}}^{-1}\,\underline{\underline{S}}\begin{pmatrix}\varepsilon^{-1}\underline{h}\\ -\mu^{-1}\underline{e}\end{pmatrix} + \underline{\underline{M}}^{-1}\,\underline{\underline{F}}\begin{pmatrix}\varepsilon^{-1}\hat{n}\times f_H\\ \mu^{-1}\hat{n}\times f_E\end{pmatrix}$$

element wise matrices — coupling of adjacent elements

Geometrical flexibility and explicit.

Discontinous Galerkin (DG) - FEM Approach #2



HOM section discretized (12k elements, second order)

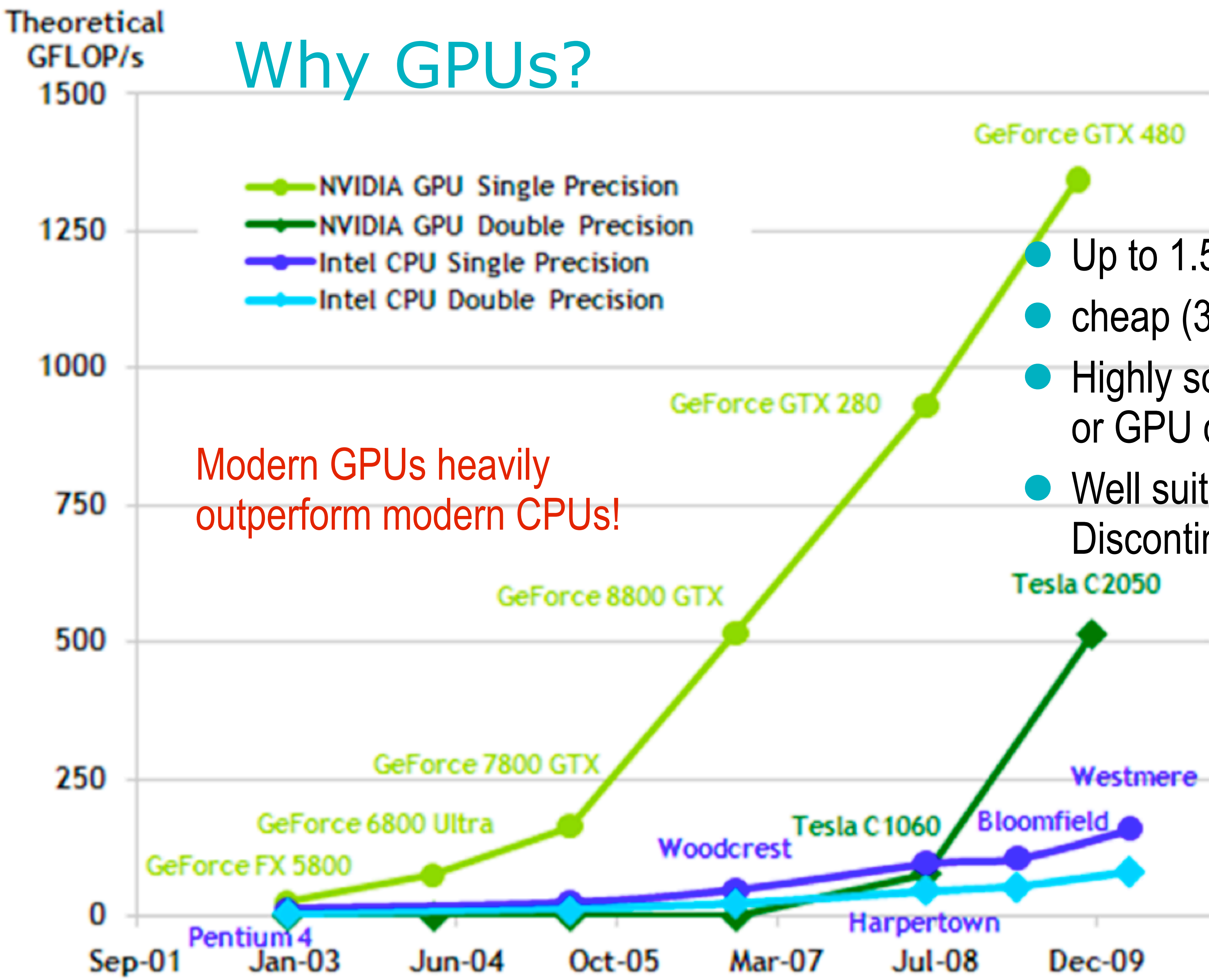
- Our S-Parameter code is based on NUDG* framework
- NUDG* framework (open source) implements basic operators, time integrator,...
- We added: boundary conditions (broadband waveguide excitation and absorption), improved PML, modal analysis, ..., pre- and post processing

=> on graphic card (GPU - NVIDIA CUDA based)

Why graphic cards?

* www.nudg.org

Why GPUs?



Modern GPUs heavily outperform modern CPUs!

Comparison theoretical GFLOP/s GPU vs. CPU (source: NVIDIA)

- Up to 1.5 TFlops / GPU (single precision)
- cheap (350 € /Unit)
- Highly scalable => multiple GPU/Workstation or GPU clusters
- Well suited for highly parallel algorithms like Discontinuous Galerkin FEM

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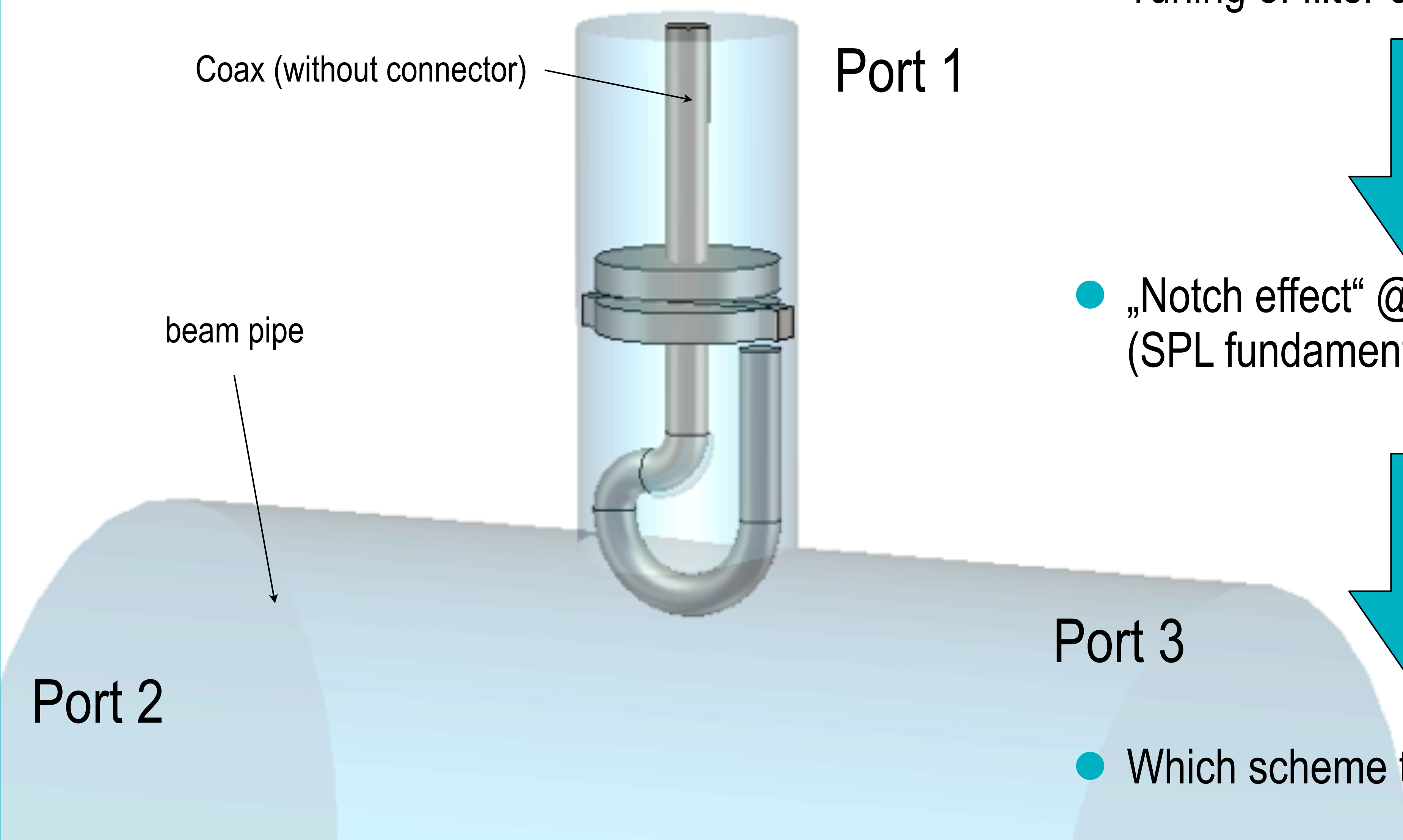
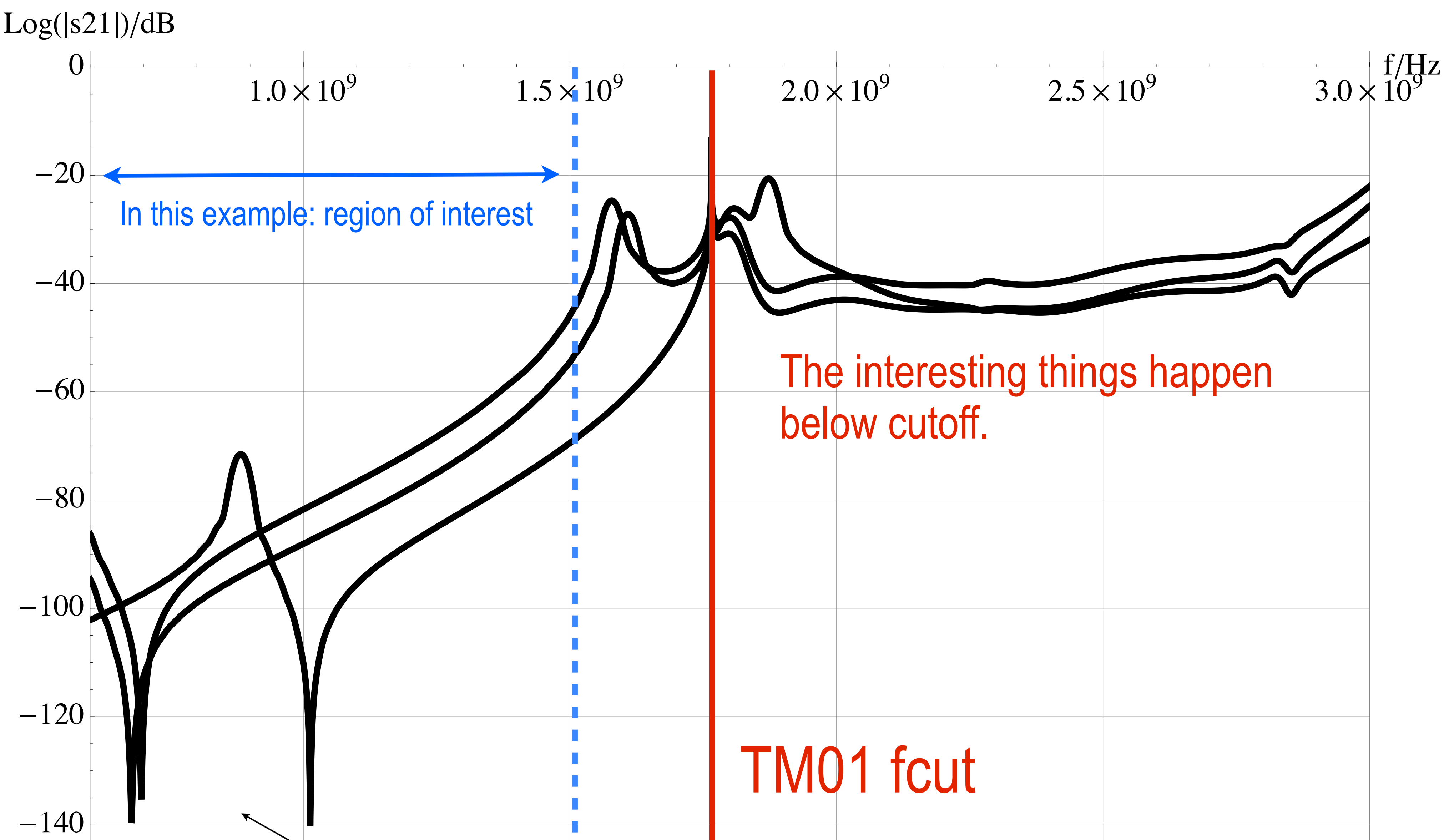
Application Example: HOM coupler with SPL geometric properties



- Tuning of filter characteristics
- „Notch effect“ @ 704.4 MHz (SPL fundamental mode)
- Which scheme to use for optimization?

(Preliminary) Model of a HOM coupler/beam pipe section with SPL specs.

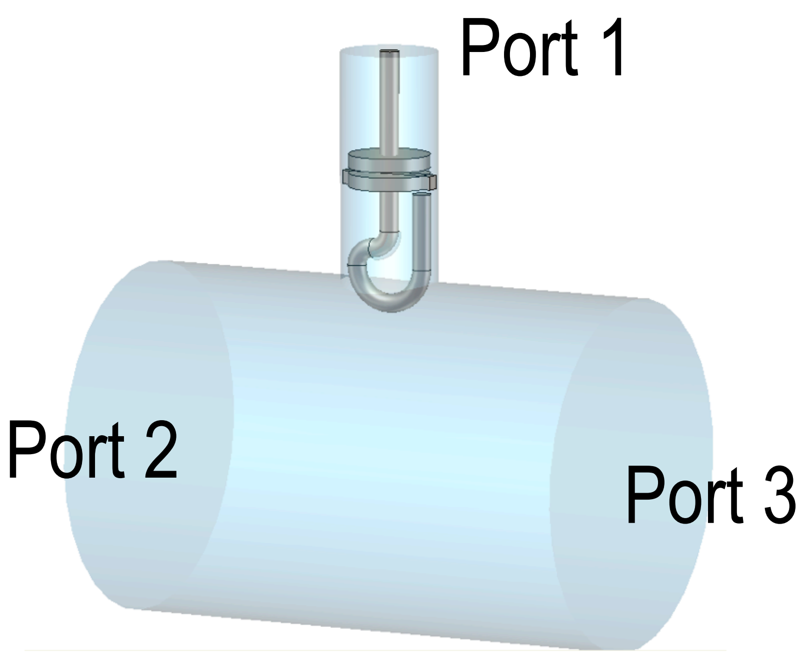
Filter Characteristics

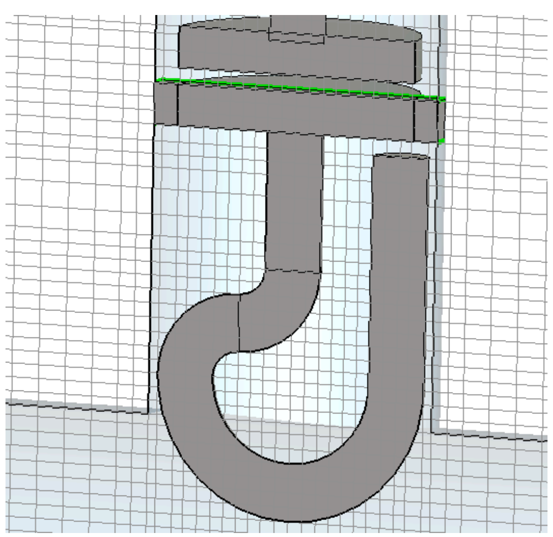


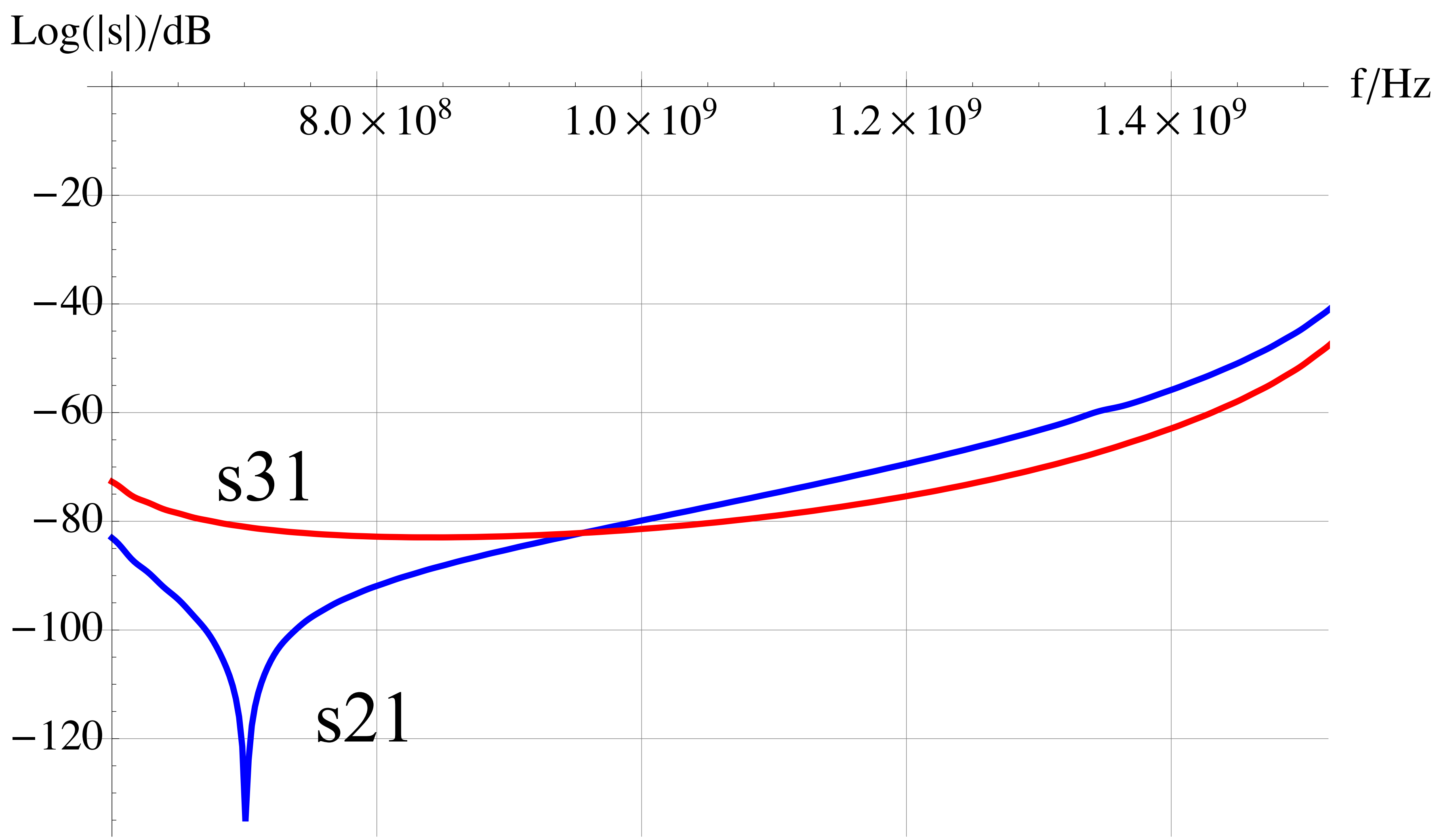
Filter effect for different geometric parameter combinations

Selected transmissions from TM01 to TEM (computed with DG-FEM) with different geometric parameters

First Simulation - CST MW Studio



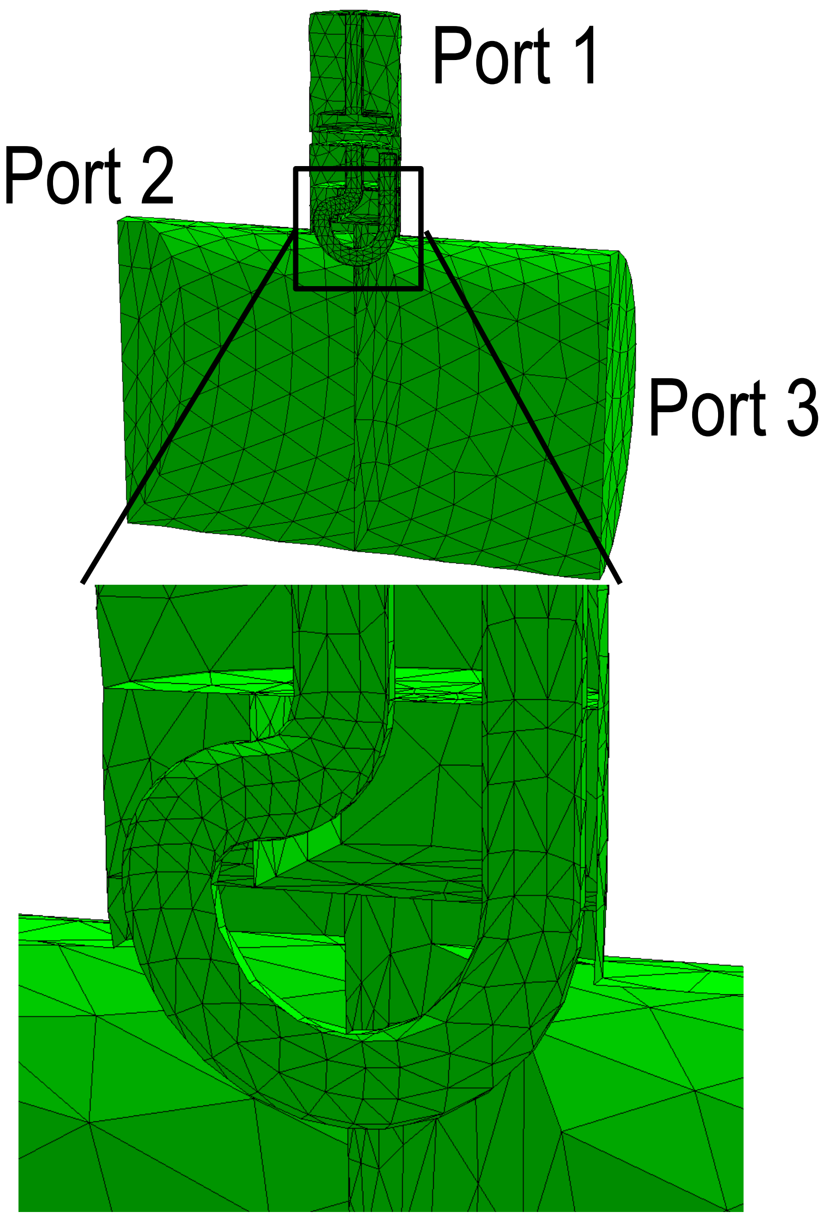


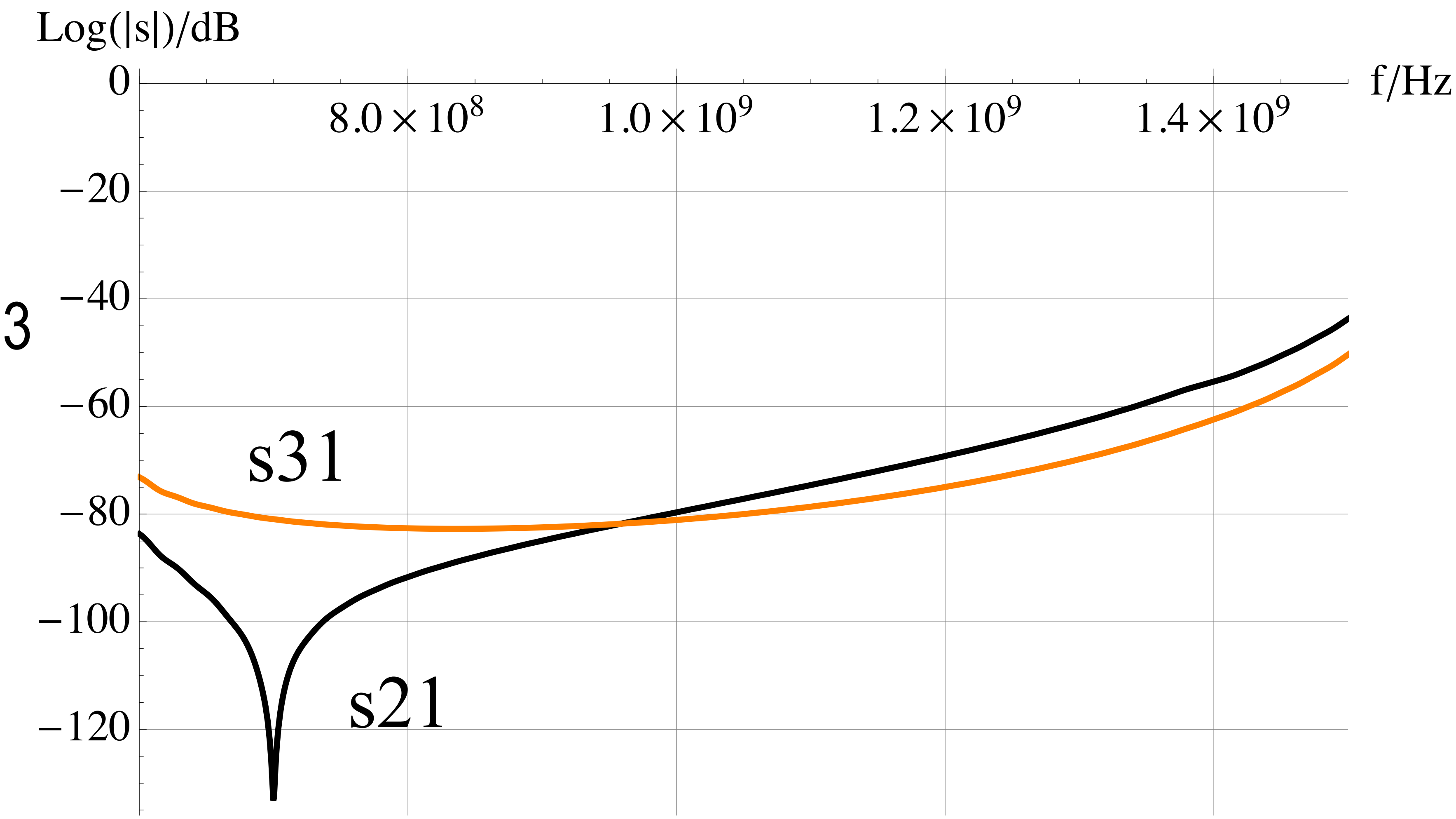


Transmission of TM01 to TEM, Computational Time ~1700s on 4 Cores @ 3.2 GHz

HOM section discretized (528k meshcells total, first order)

Then - GPU Accelerated DG-FEM (NUDG*)



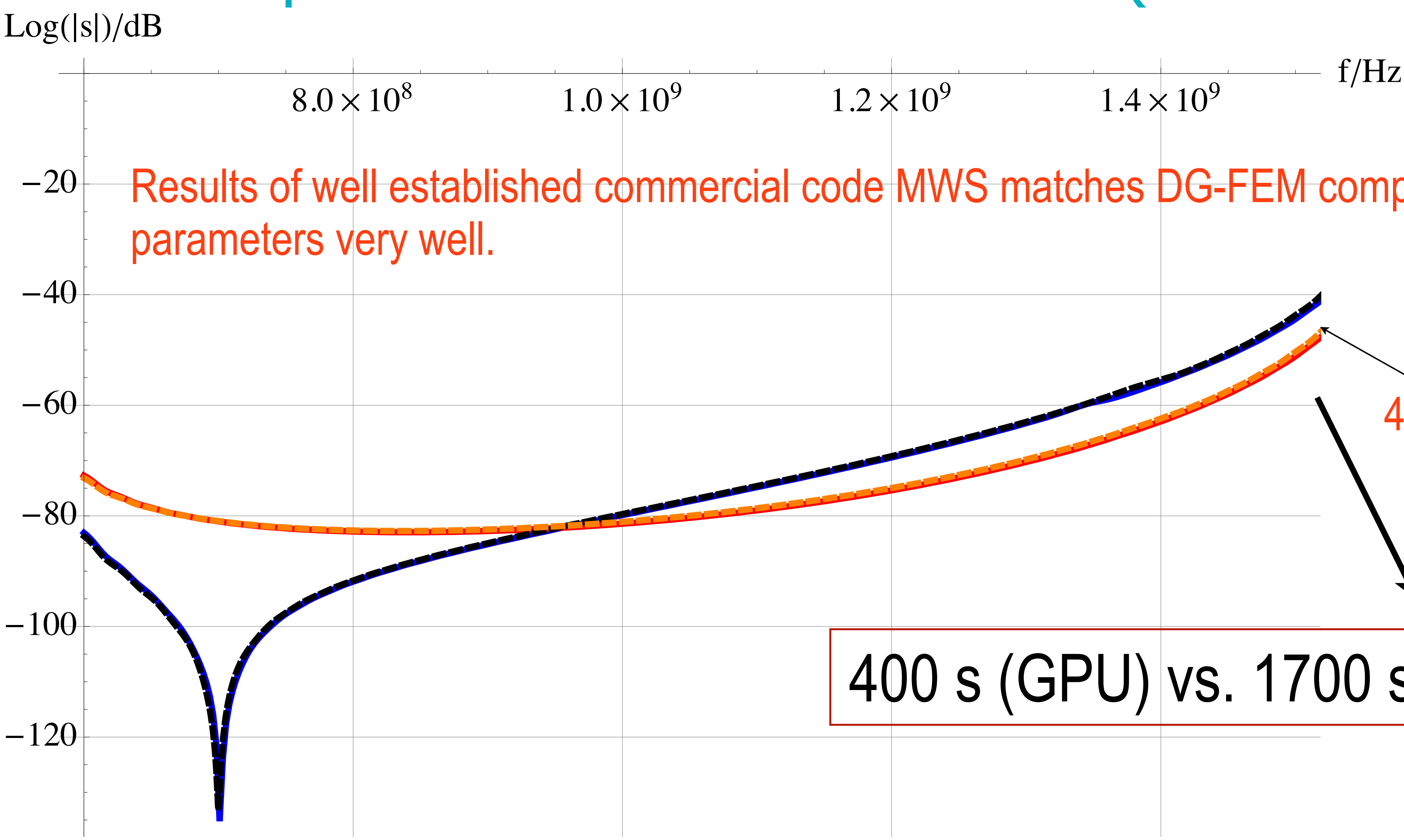


Transmission of TM01 to TEM, Computational Time ~400s on GPU GTX 470

HOM section discretized (12k elements)

*www.nudg.org

Comparison of both schemes (accuracy vs. time)



Results of well established commercial code MWS matches DG-FEM computed S-parameters very well.

4 graphs! Match very well.

400 s (GPU) vs. 1700 s (4 CPU Cores)

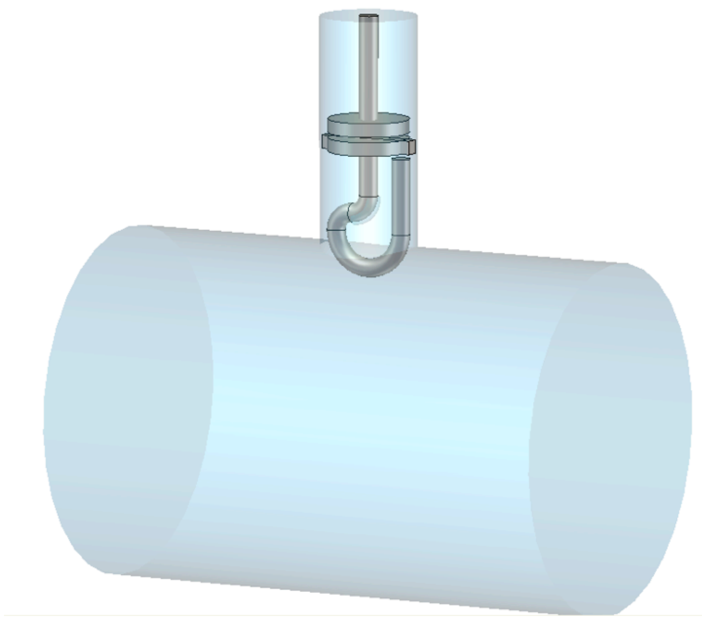
Transmission of TM01 to TEM, Comparison of computed transmissions

Speedup by a factor of ~ 4

=> use DG-FEM for further optimization!

Interlude - Further Speedup?

- MWS: Use more Cores?



1700 s (4 CPU Cores) => 1610 s (8 CPU Cores)
(Performance is limited by memory bandwidth, not arithmetic operations count!)

- DG - FEM:

- Local timestepping => Implementation in development (Expected gain ~ 2...3)
- Multiple GPUs => coming soon: GPU Cluster

} Reduces optimization time by at least one magnitude

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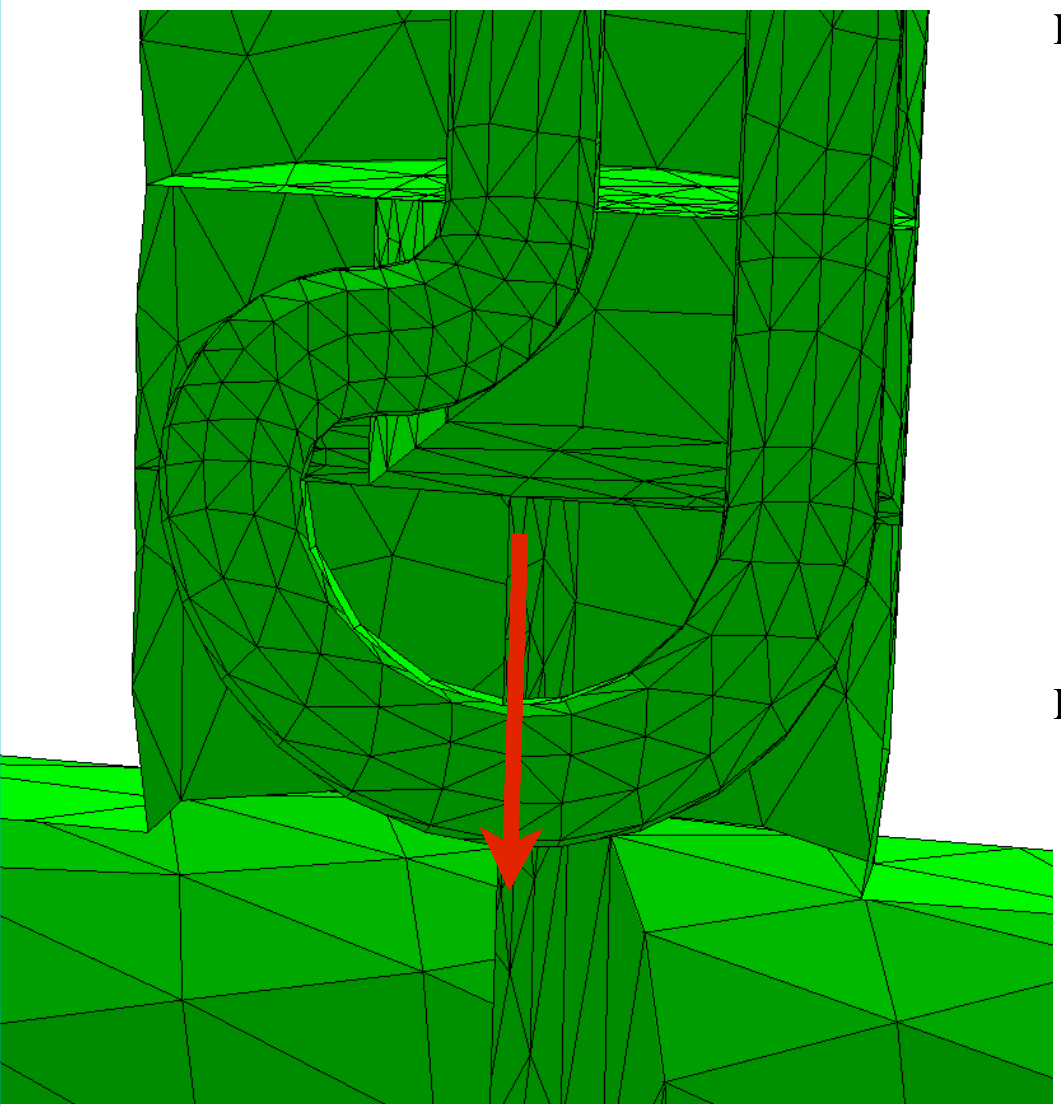
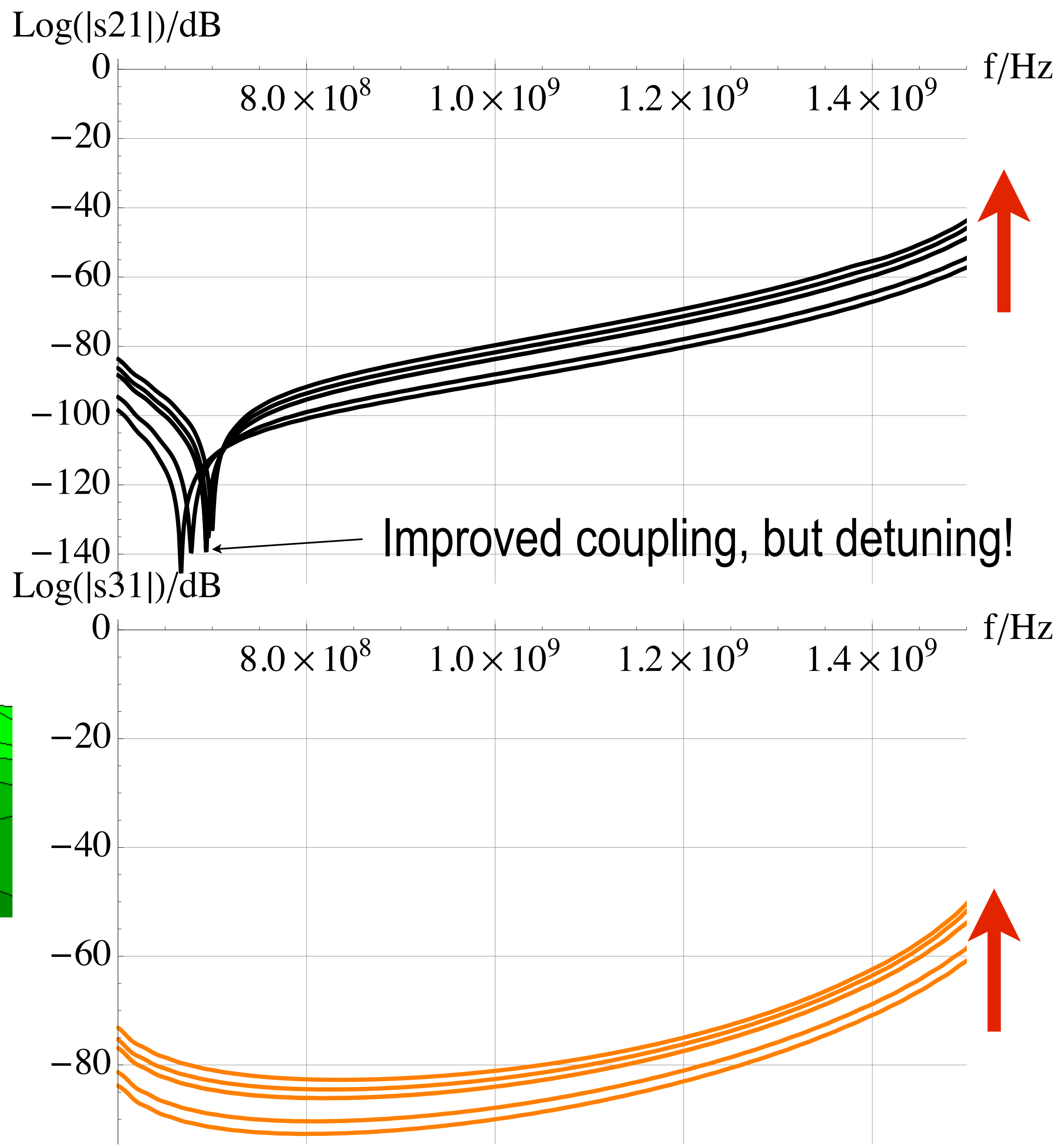
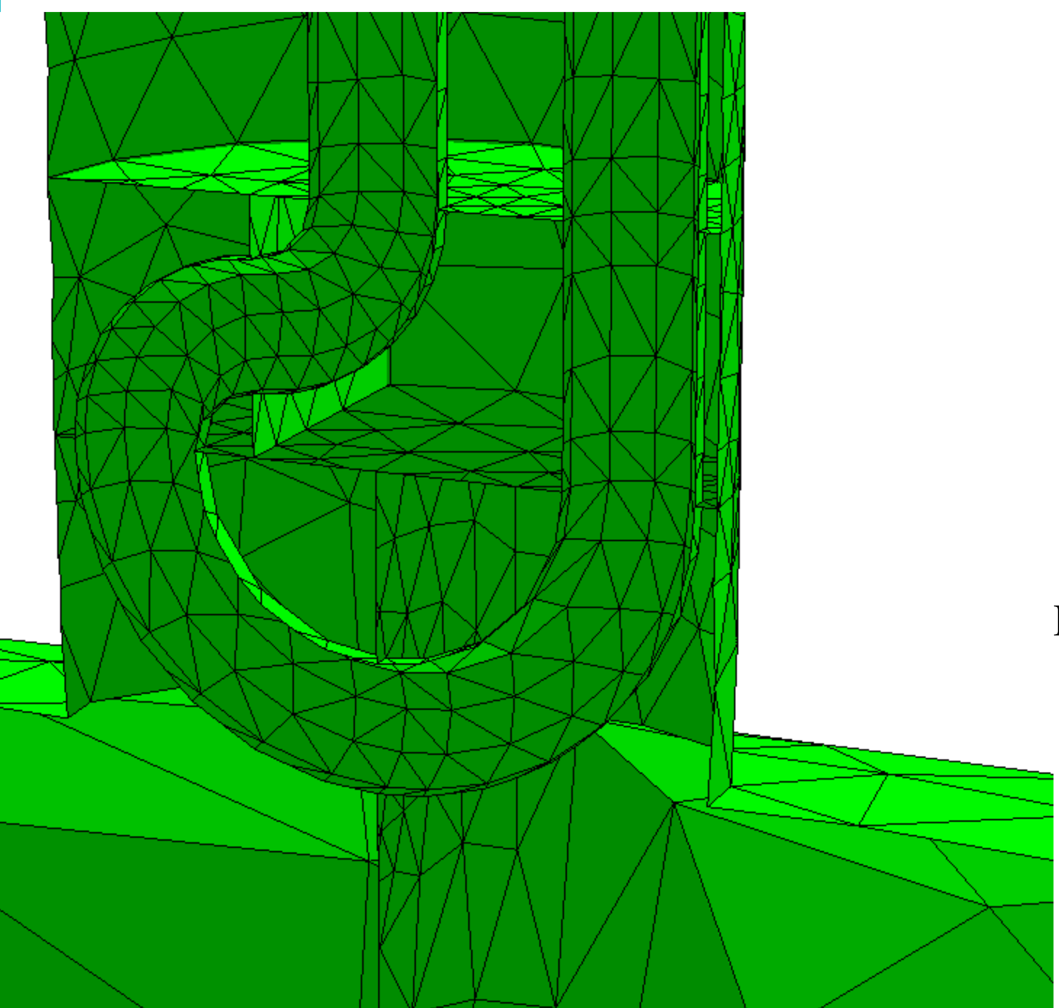
Text example #1



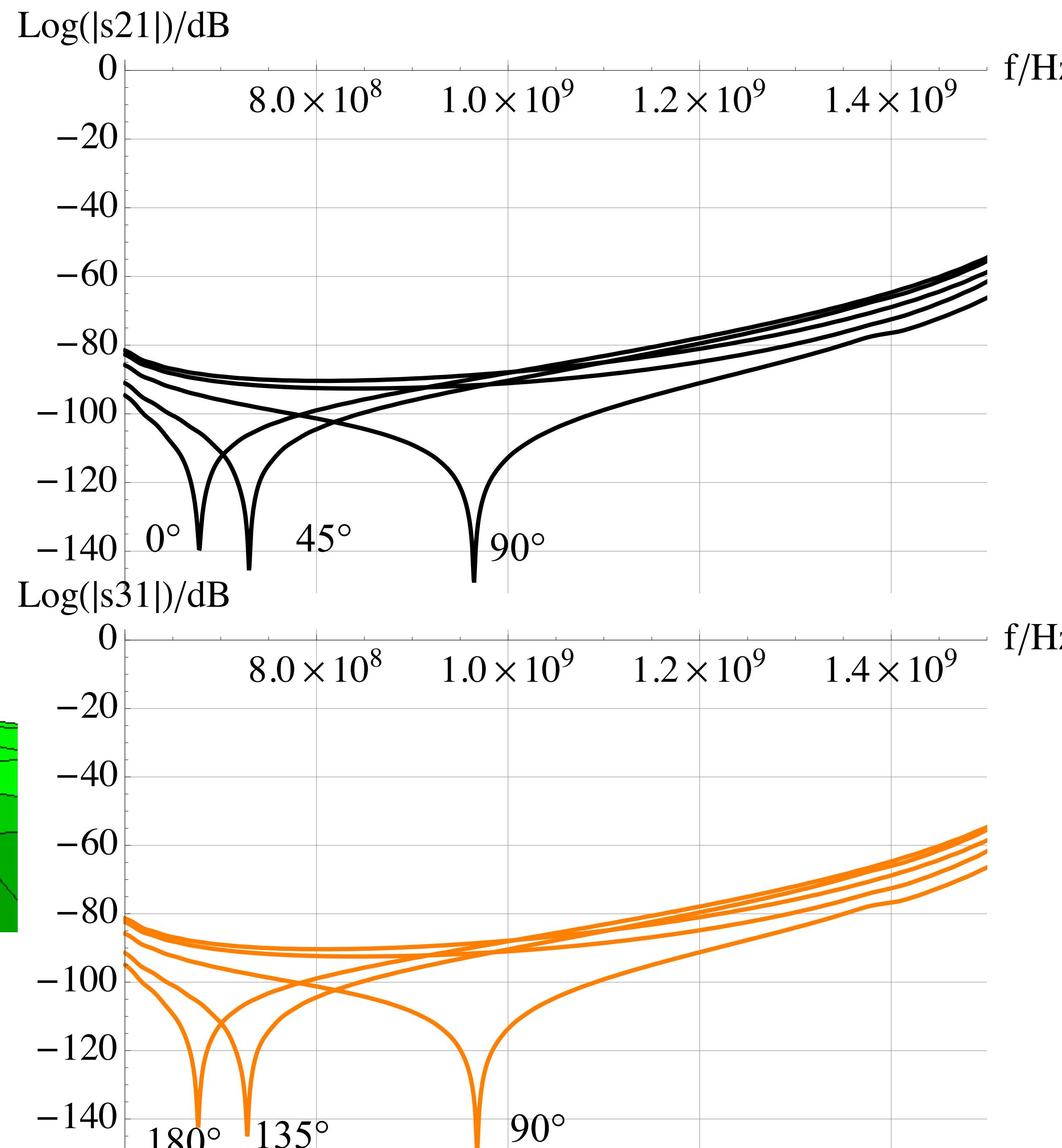
Lowering the „hook" in the beam pipe



Text example #2



Rotation around axis



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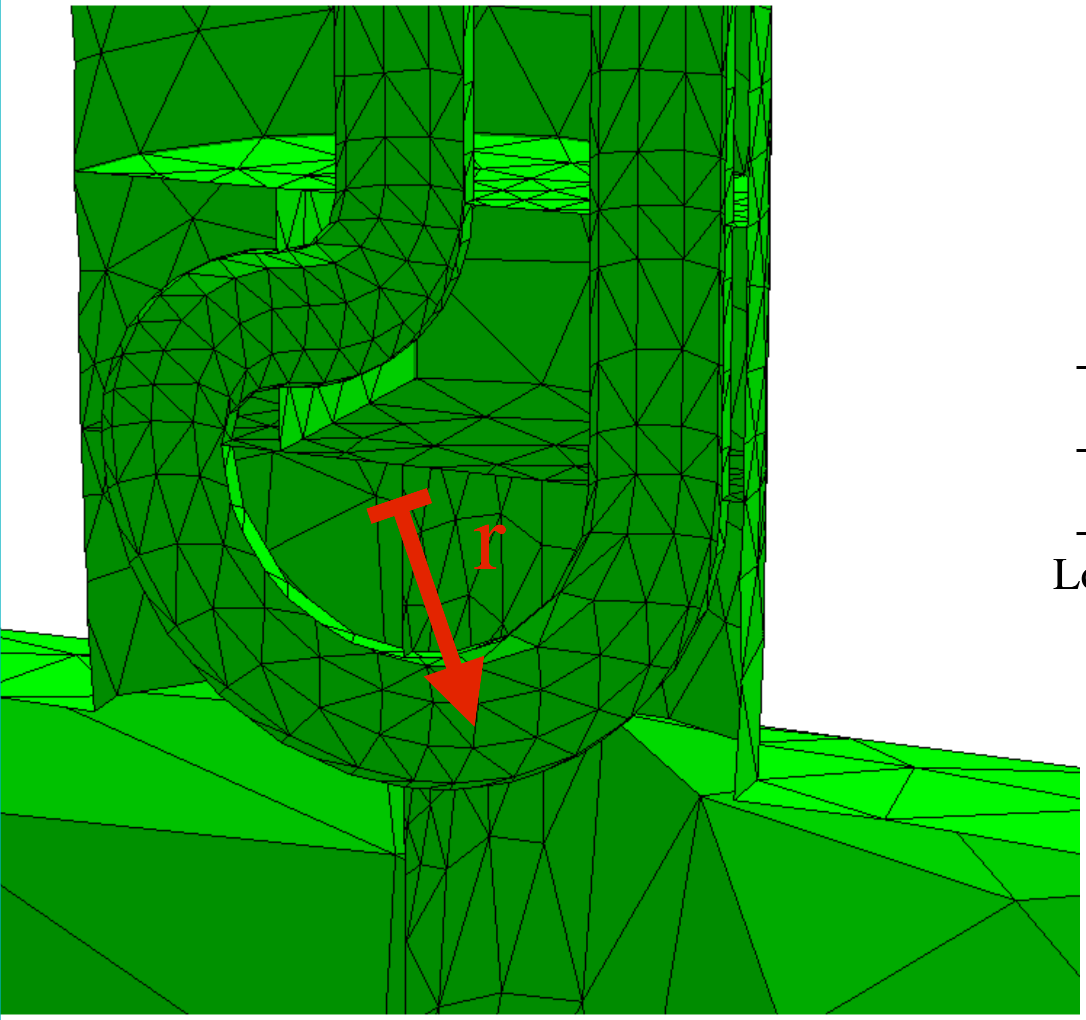
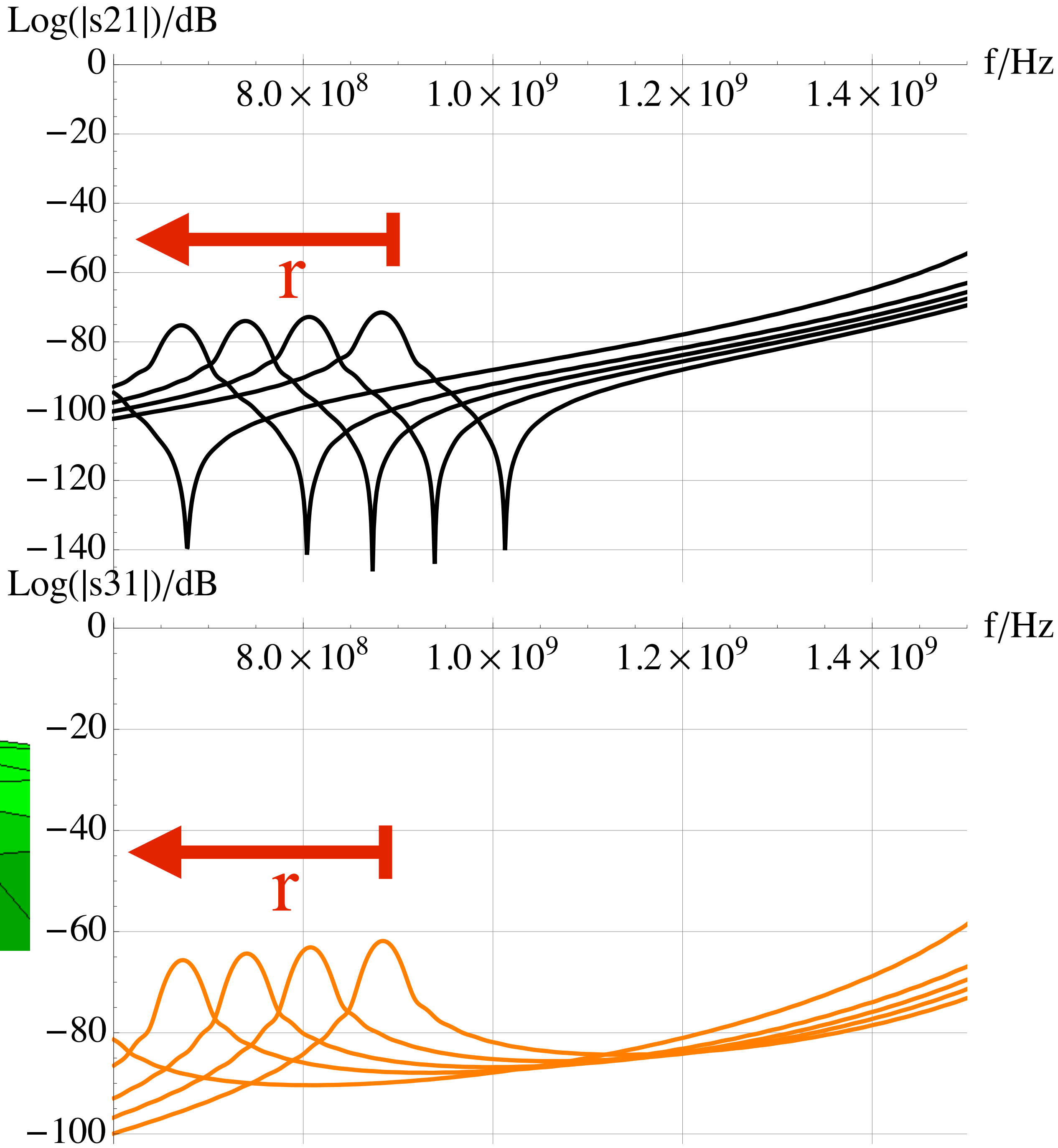
Text example #3



Scaling of the „hook's" radius



Conclusion

- Systematic optimization (= extensive parameter sweeps) is required for HOM coupler design
- Therefore, a suited numerical scheme is essential
- Based on an (preliminary) application geometry:
  - S-Parameters computed with DG-FEM are in very good agreement with well established code (MWS)
  - Computation time (and thus optimization time) can be reduced significantly by GPU accelerated DG-FEM