Methods and Simulation Tools for Cavity Design

SRF 2019 Tutorials

29.6.2019

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*A **good** and a bad news*

*You almost **made** it:*

Tutorial Lecture Schedule for SRF2019

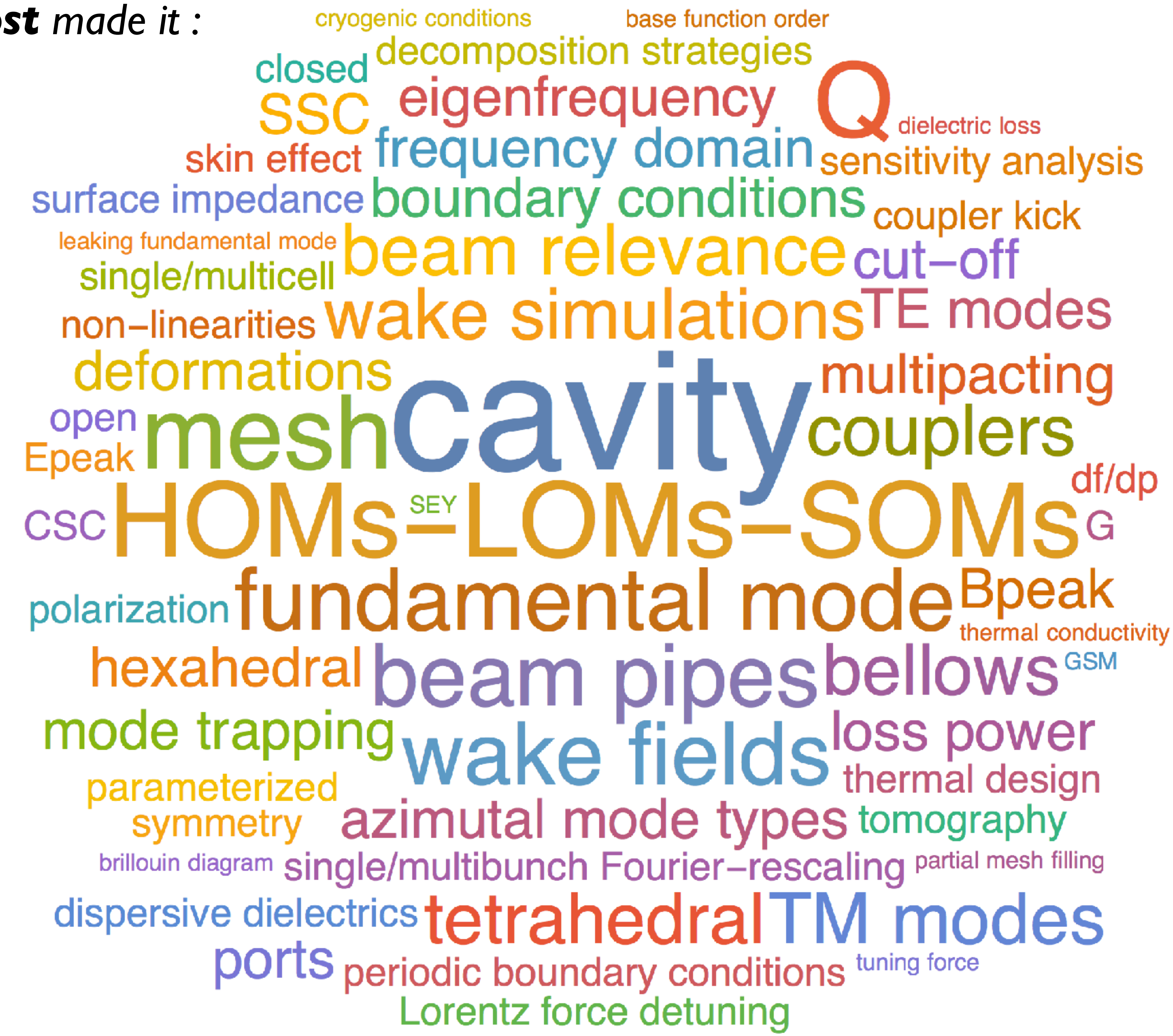
	Jun 27th, Th.	Jun 28th, Fr.	Jun 29th, Sa.
Registration and Welcome	8:30-9:00 P. Michel (HZDR)	-	-
Session 1	9:00-10:30 Basic Principles of RF Superconductivity G. Ciovati (JLab)	9:00-10:30 Superconducting Cavities of Interesting Shapes (Non-elliptical Cavities) S. De Silva (ODU)	9:00-10:30 Beam-cavity Interaction and Operational Aspects of SRF Systems With Beam S. Belomestnykh (FNAL)
Coffee Break	10:30 -11:00	10:30 -11:00	10:30 -11:00
Session 2	11:00-12:30 RF Basic and TM Cavities E. Jensen (CERN)	11:00-12:30 Cavity Processing and Cleanroom Techniques L. Popielarski (FRIB/MSU)	11:00-12:30 LLRF Controls and RF Operation J. Branlard (DESY)
Lunch	12:30-13:30	12:30-13:30	12:30-13:30
Session 3	13:30-15:00 Cavity Vertical and Horizontal Test and Operation T. Powers (JLab)	13:30-15:00 Pushing Bulk Nb Limits (High Q, High Gradient, Reliable SRF Accelerators) A. Grassellino (FNAL)	13:30-15:00 Fundamentals of Cryomodule Design and Cryogenics B. Petersen (DESY)
Coffee Break	15:00-15:30	15:00-15:30	15:00-15:30
Session 4	15:30-17:00 High Power Couplers and HOM Couplers E. Kako (KEK)	15:30-17:00 Materials Beyond Bulk Nb C. Antoine (Saclay)	15:30-17:00 Methods and Simulation Tools for Cavity Design H.-W. Glock (HZB)

*A good and a **bad** news*

*You **almost** made it.*

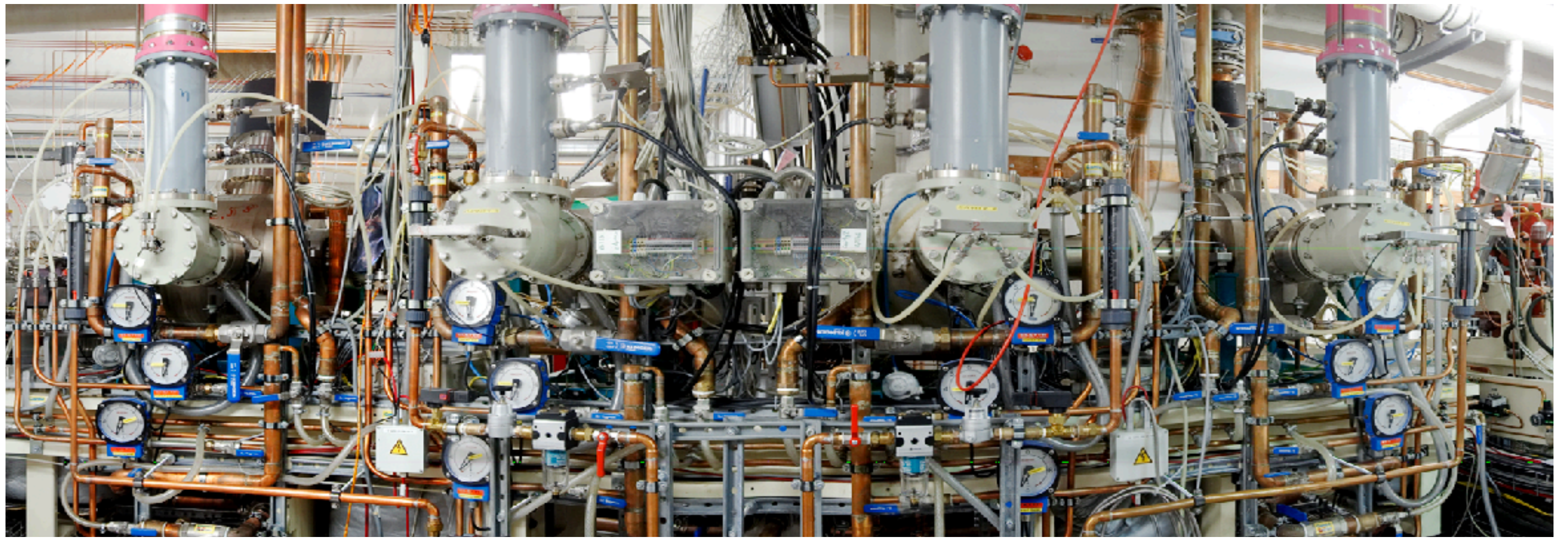
*A good and a **bad** news*

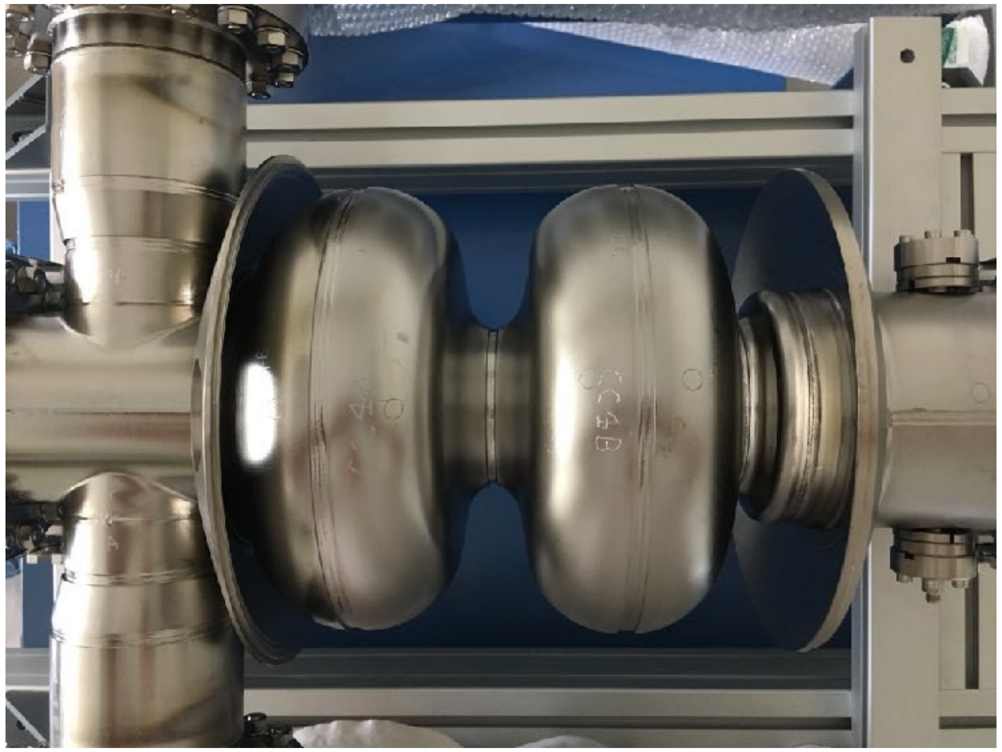
*You **almost** made it :*



What is a cavity *???*

BESSY II's four main 500 MHz cavities



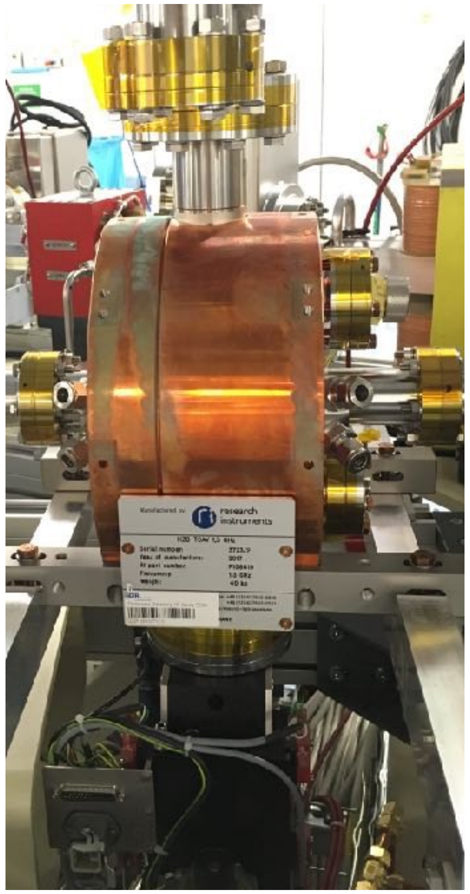


Cornell-style bERLinPro booster 1.3 GHz-2-cell without tank

cavity

by intention (found somewhere @HZB)

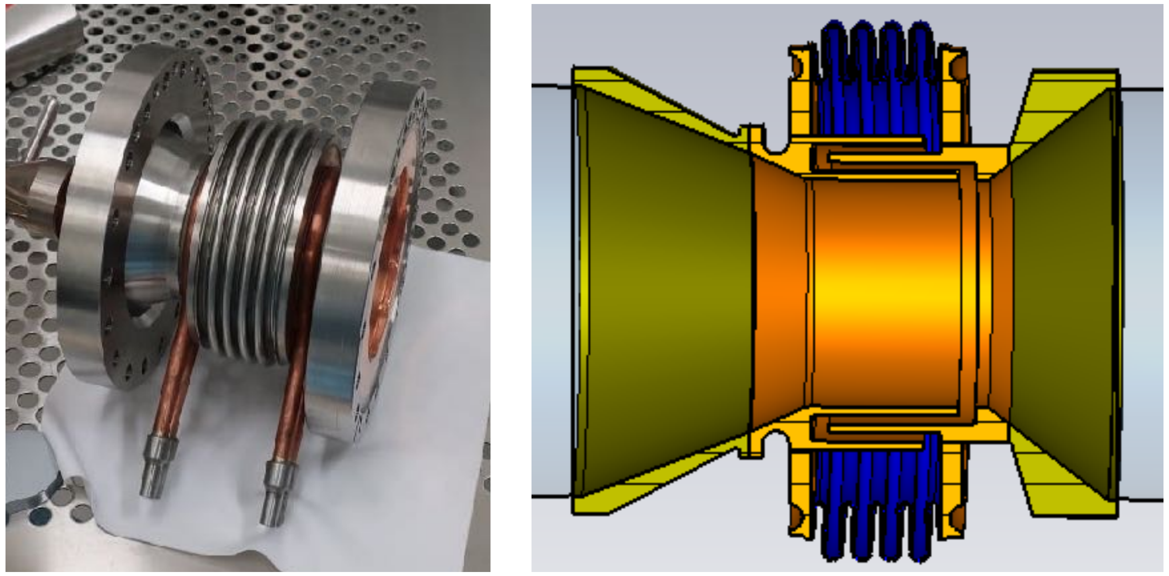
Gun1.1–cavity prepared for vertical testing



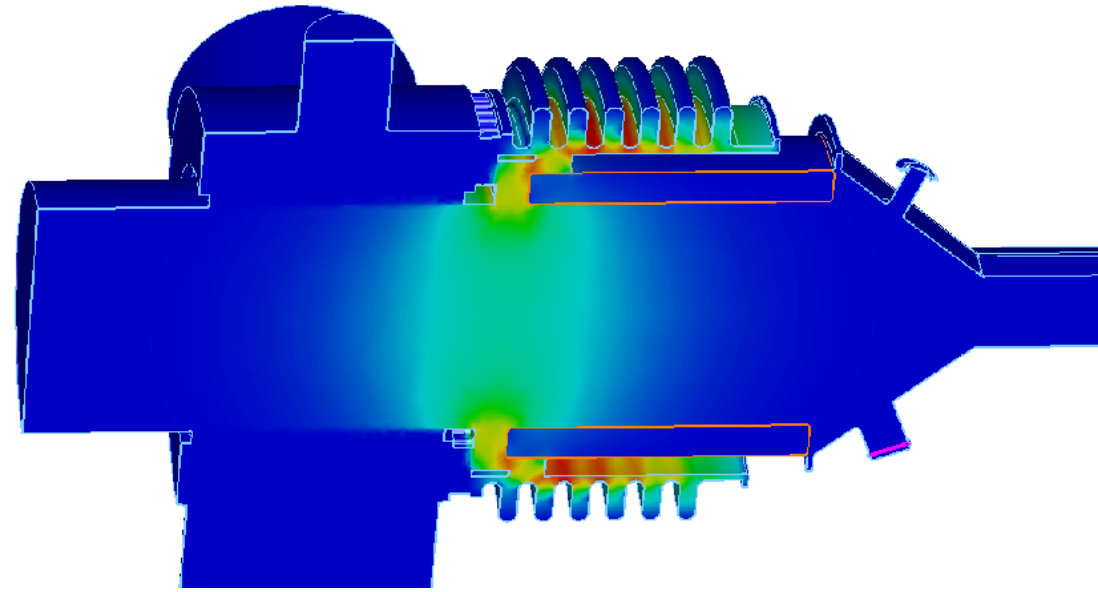
Transverse-Deflecting cavity (TCAV) in bERLinPro's diagnostic beam line

TESLA-9-cell cavity (for display purposes)

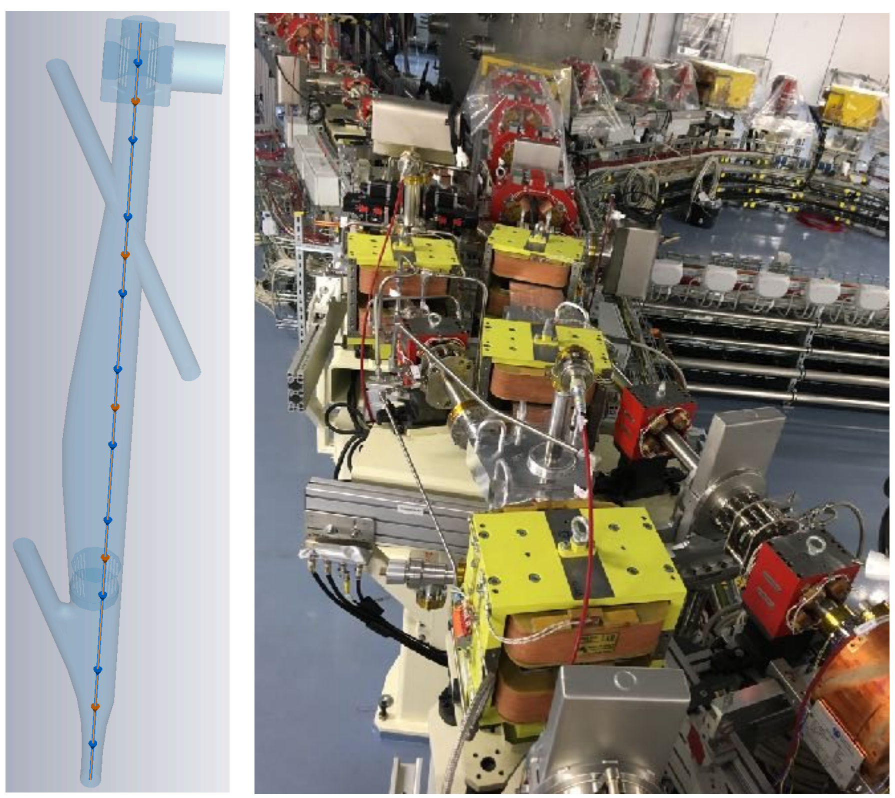
unwanted cavity (found somewhere @HZB)



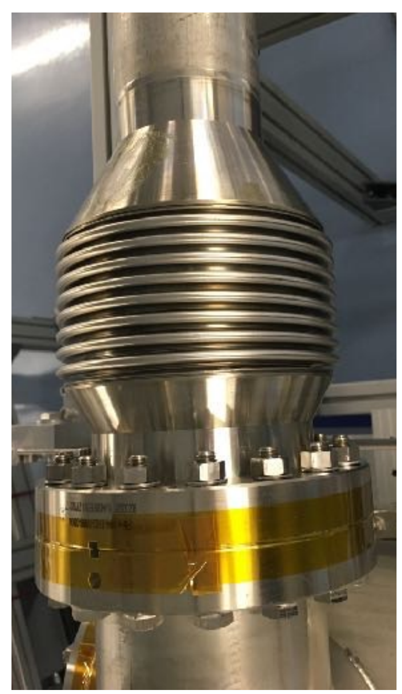
Collimating Shielded Bellow for BESSY-VSR-Upgrade



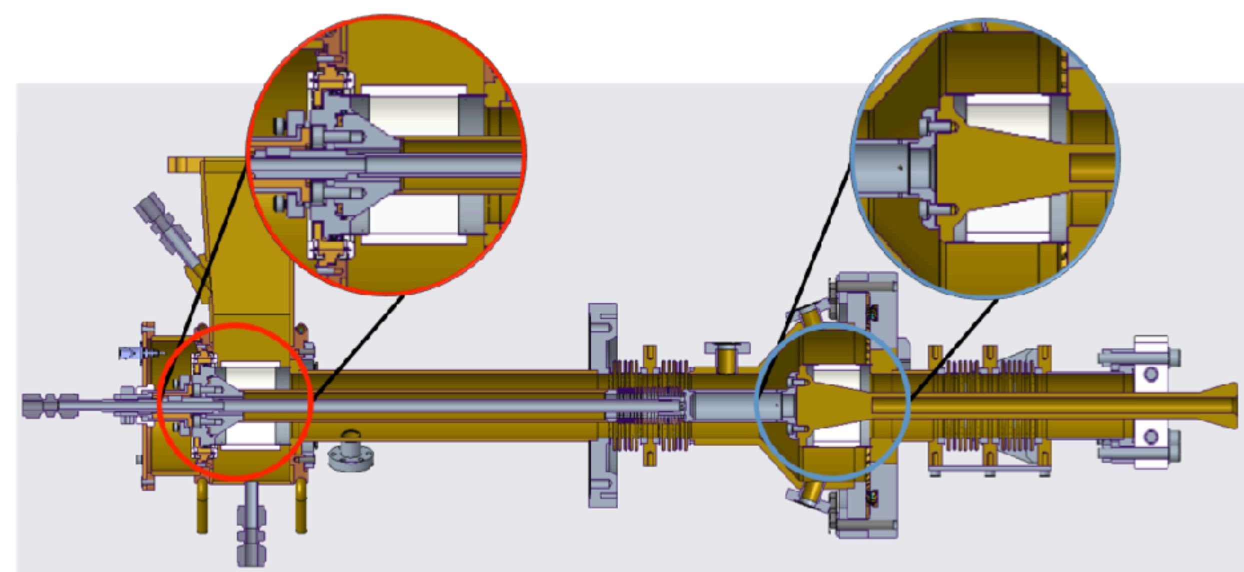
Draft of BESSY-VSR end group



bERLinPro merger section



below in bERLinPro's temporary replacement beamline



Dielectric windows in the BESSY-VSR upgrade fundamental power coupler construction (courtesy Emmy Sharples)

The tool box: You should have ...

a ***frequency domain solver*** to compute the reaction of a cavity or an open structure on externally given driving excitations

a ***wakefield solver*** to observe the time-domain reaction of a beam line element on a driving bunch

an ***eigenmode solver*** to determine the natural resonances of a closed cavity

The tool box: … and you also may find useful

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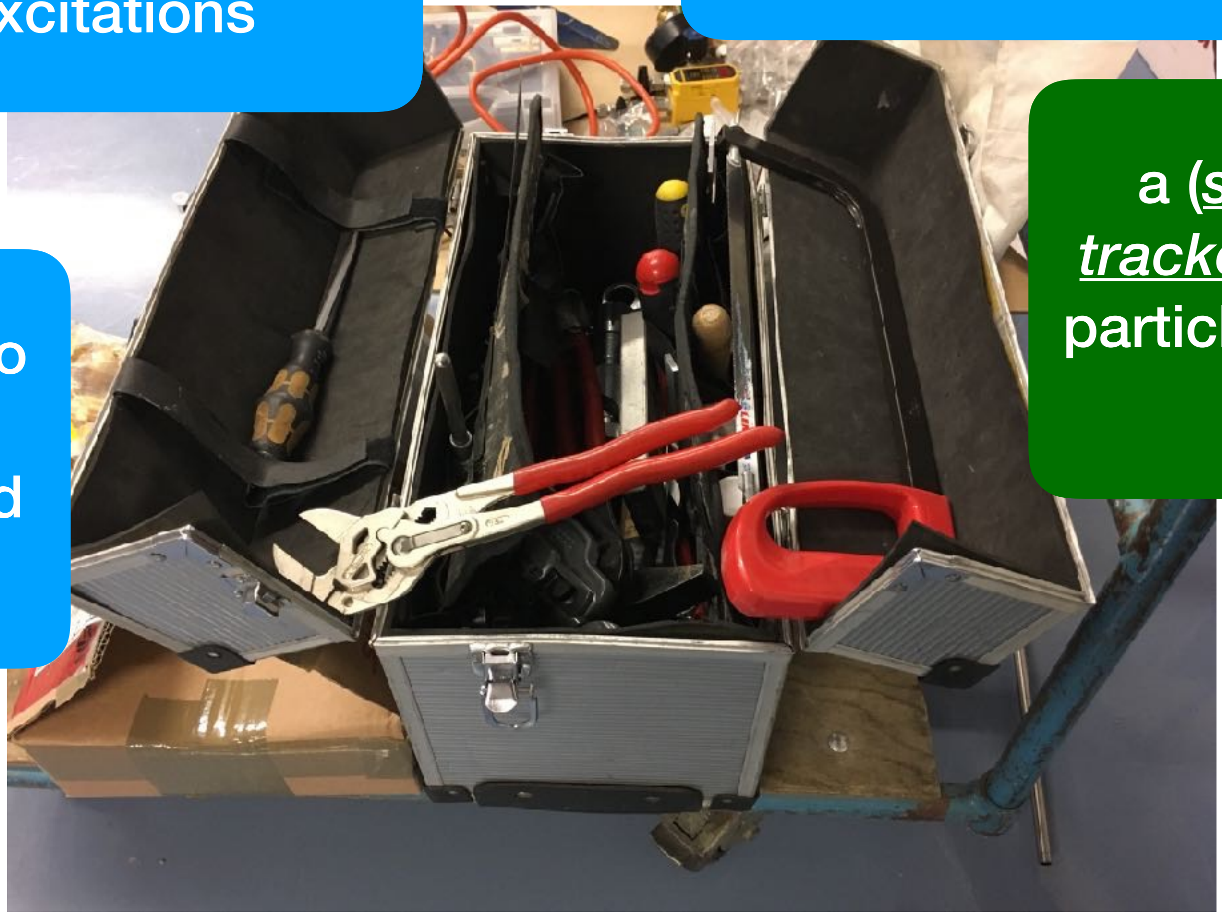
a *(self-consistent) particle tracker* to perform (expensive) particle(/field co-)simulations in time domain



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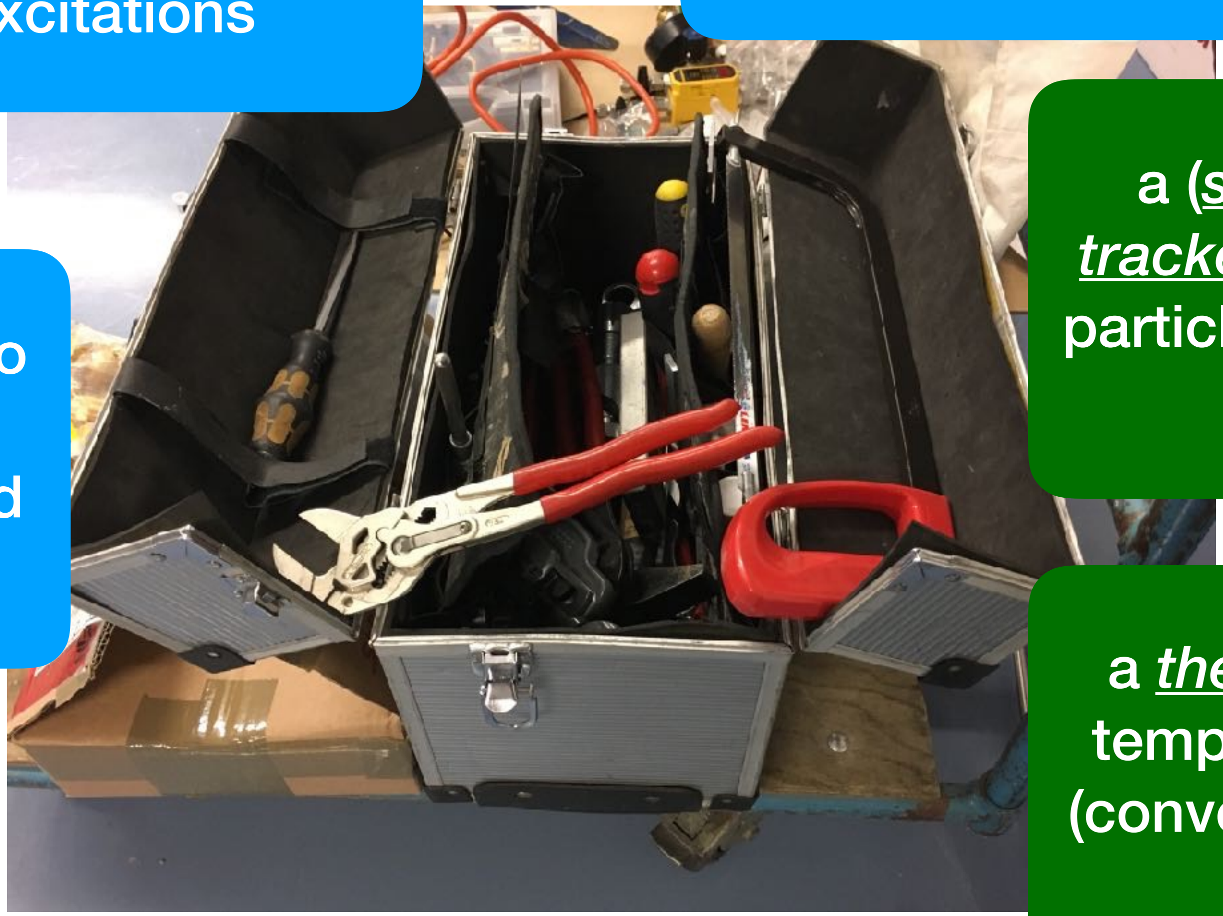

an *eigenmode solver* to determine the natural resonances of a closed cavity

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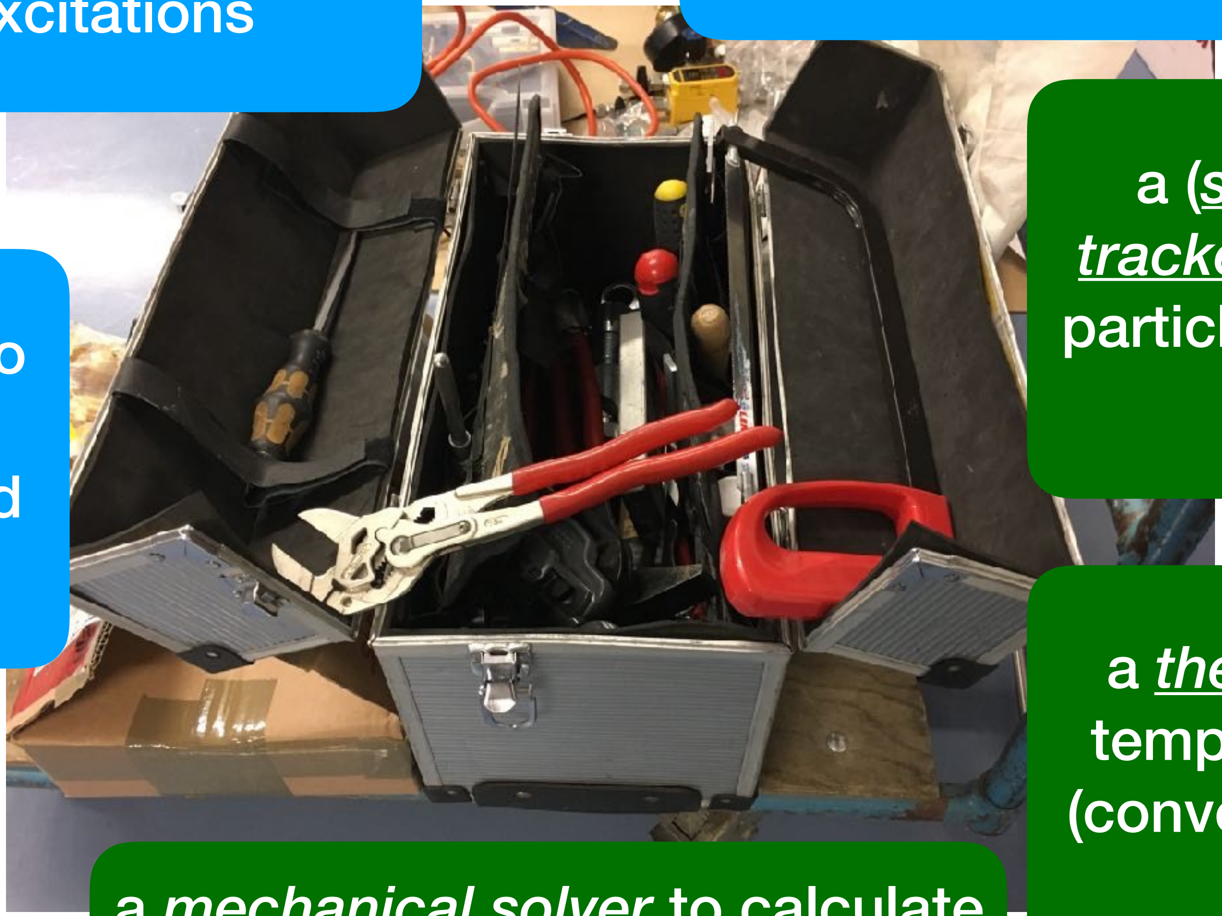

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a ***mechanical solver*** to calculate elastic(/plastic) cavity deformations based on Lorentz-/pressure/tuning forces + mechanical eigenmodes

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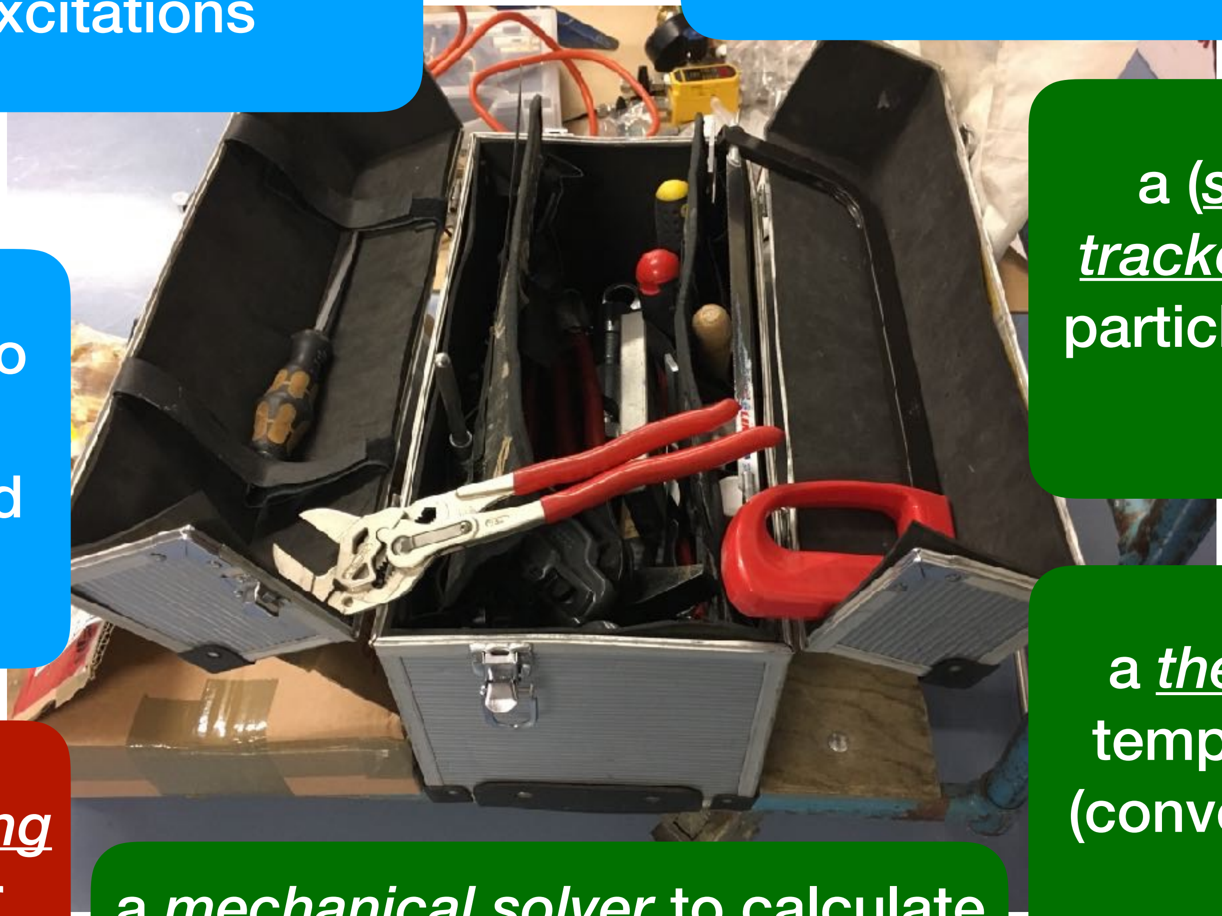

a (*self-consistent) particle tracker* to perform (expensive) particle(/field co-)simulations in time domain

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an *external programming environment* for other evaluations of exported field data

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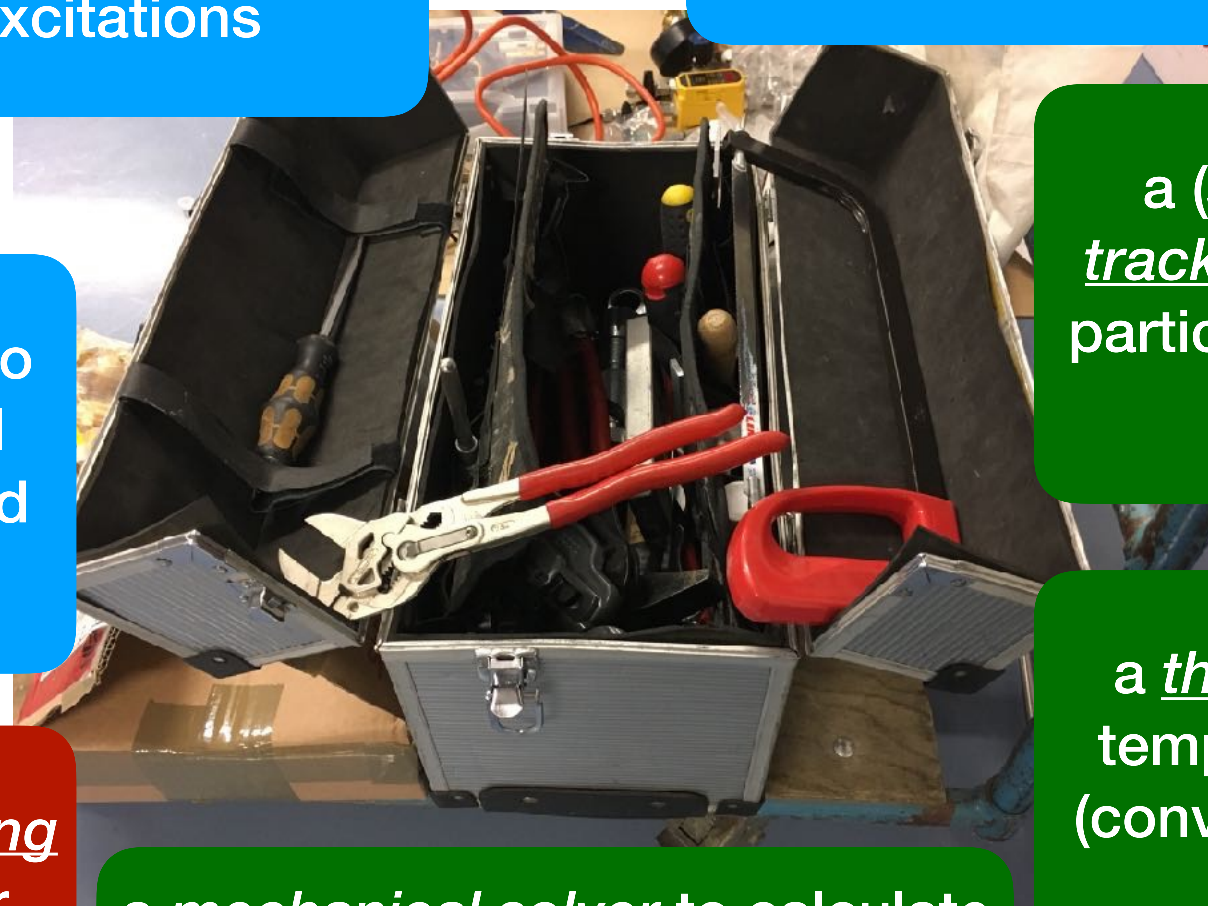

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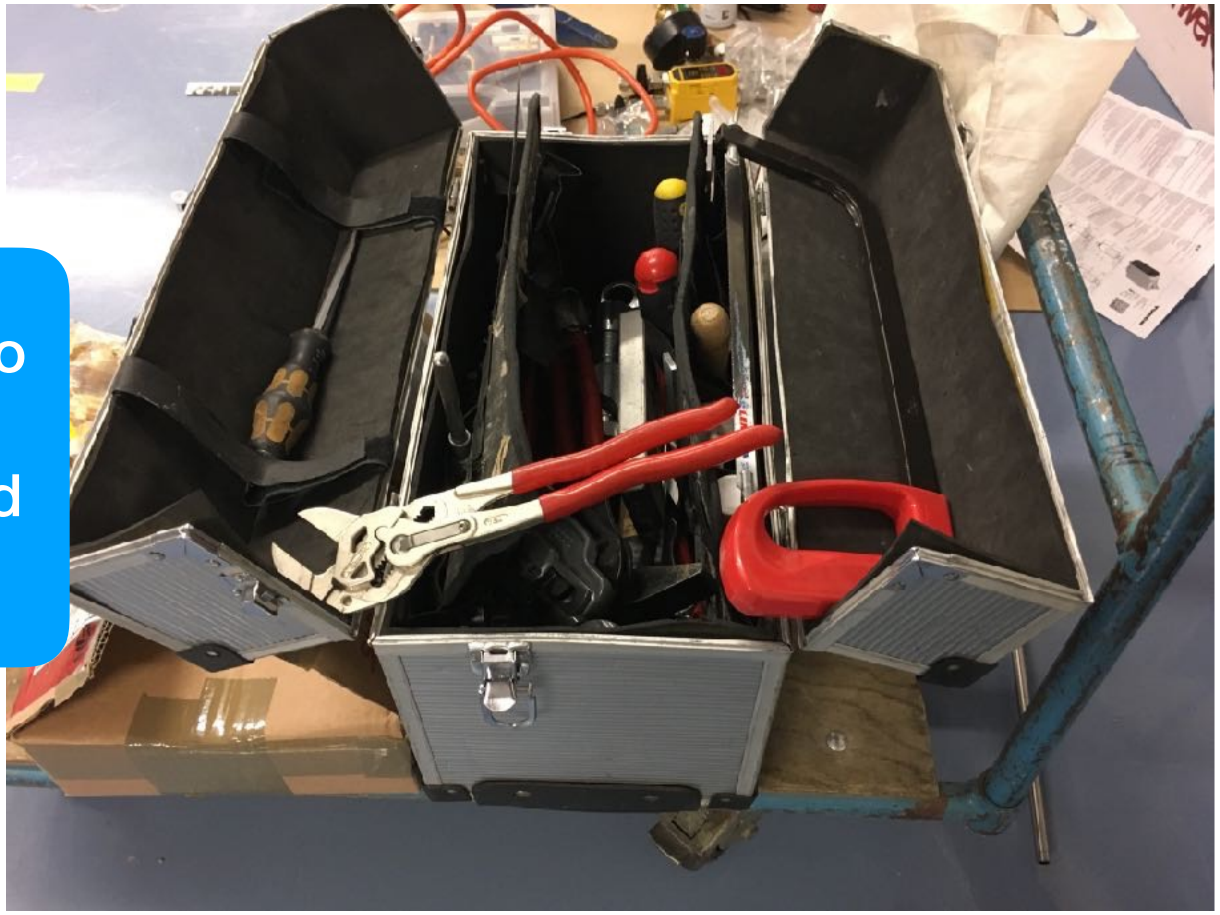
For those purposes I recommend the following software brands:

… page intentionally left free, because …

The tool box: You should have …

an *eigenmode solver* to determine the natural resonances of a closed cavity



What is an „eigenmode“ of a cavity? — rather a strange thing:

1. *It exists inside an entirely closed cavity, made of some Perfect Electric Conductor (PEC, which is a fiction).*

2. *It exists with non-vanishing amplitude without any energy source (which sounds profitable).*

3. *It oscillates infinitely long with a pure single „eigen“-frequency (which is said twice).*

4. *It has an infinite number of companions (most of them fortunately of less interest).*

What is an „eigenmode" of a cavity? — rather a strange thing:

complex **lossy** **stranger**

1. *It exists inside an entirely closed cavity, made of some Perfect Electric Conductor*

   finite **or containing lossy material**

2. *It exists with non-vanishing amplitude without any energy source (which sounds profitable).*

3. *It oscillates infinitely long with a pure single „eigen"-frequency (which is said twice).*

   but constantly decaying **complex**

4. *It has an infinite number of companions (most of them fortunately of less interest).*

… so, let us compute some eigenmodes …

… so, let us compute some eigenmodes of a:

– *7-cell elliptical cavity*

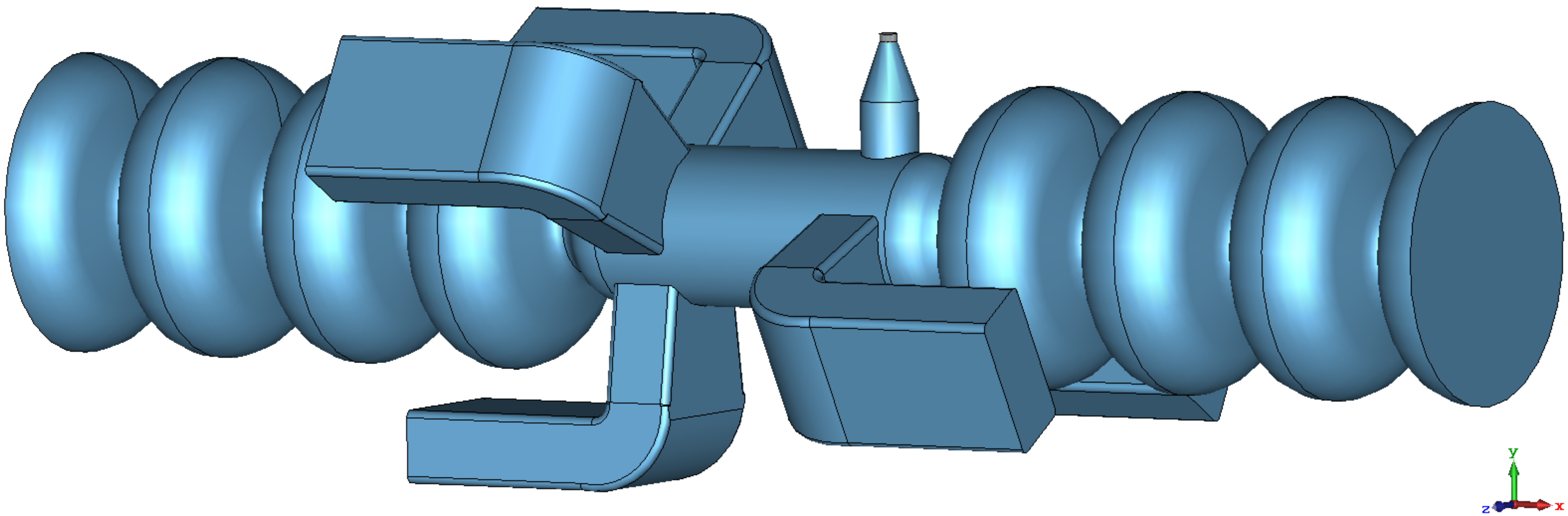
– *strongly HOM-damped with 5 waveguides*

– *a fundamental power coupler*

– *and a beam pipe*

… so, let us compute some eigenmodes of a:

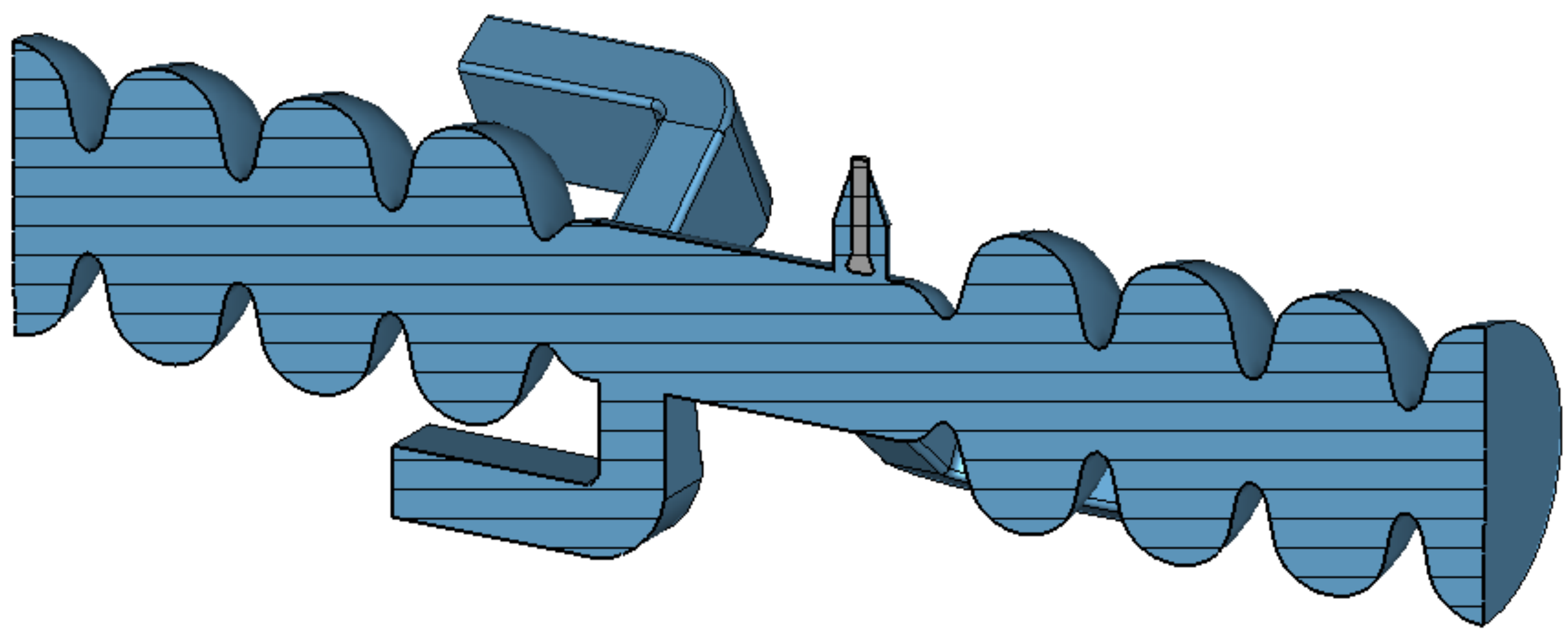
- *7-cell elliptical cavity*
- *strongly HOM-damped with 5 waveguides*
- *a fundamental power coupler*
- *and a beam pipe*



– *which is going to be placed in a chain of identical neighbors, so we would like to study the beam-pipe-coupling as well*

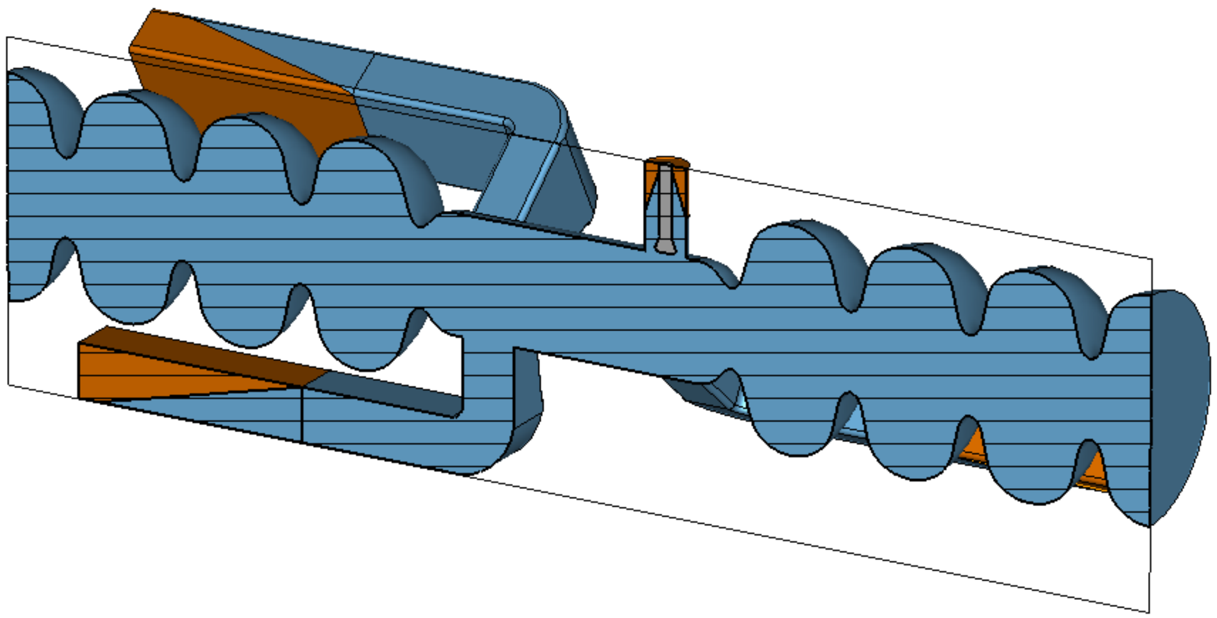
We need:

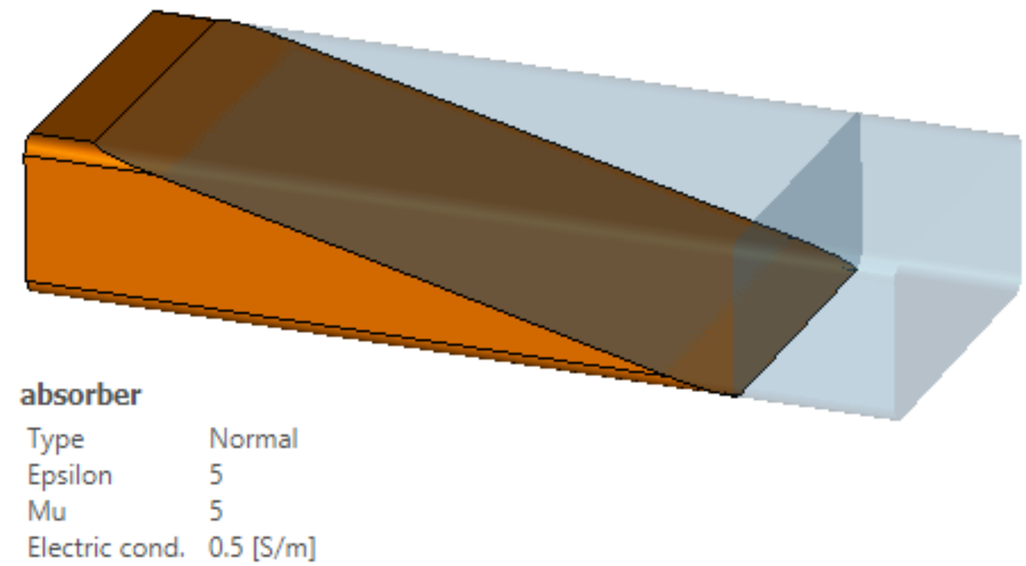
1.) the cavity (+ waveguides + coupler) shape, either CAD-constructed externally or composed using the geometrical primitives of the field solver



We need:

2.) some virtual absorber simulating well matched waveguide(/coax) terminations



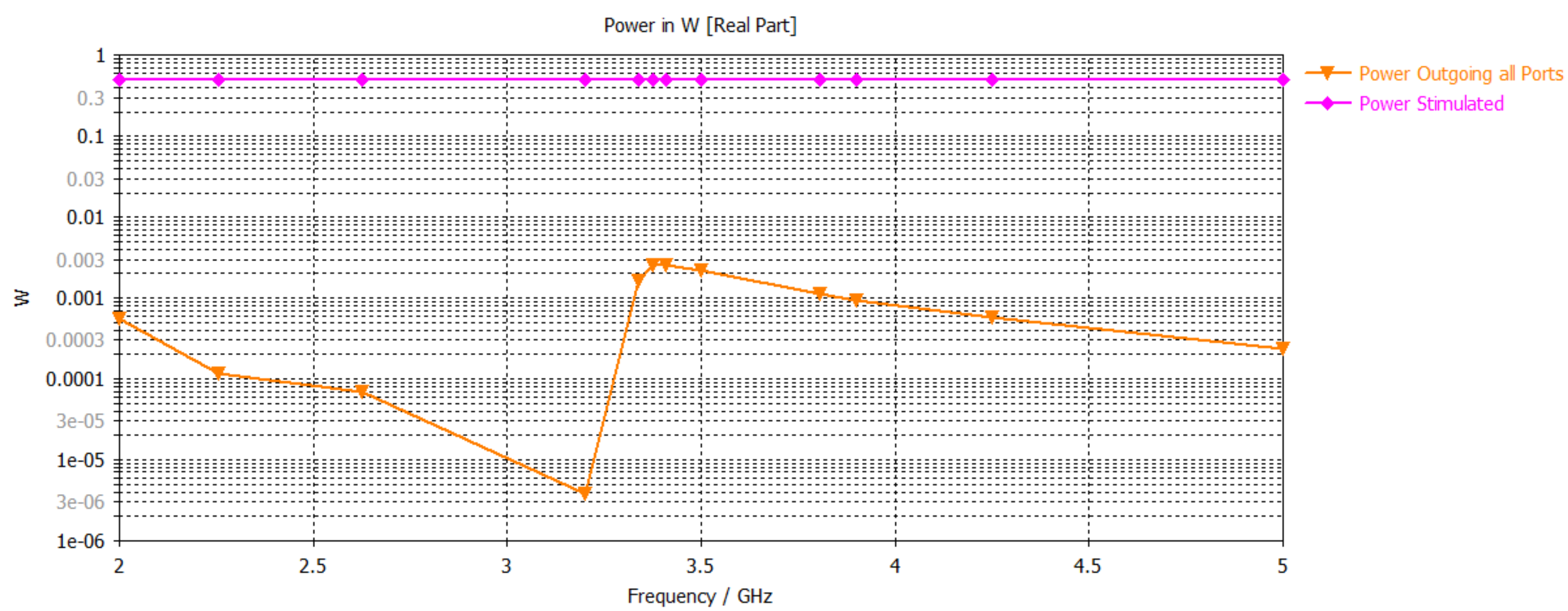


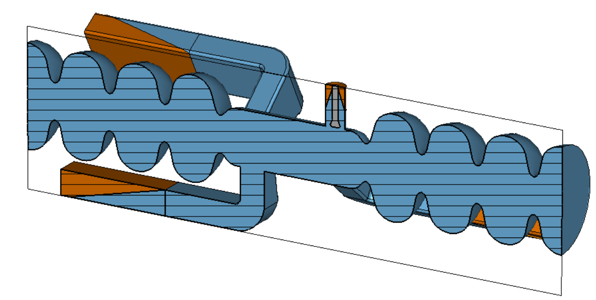
… using a virtual material of $\varepsilon'_r = \mu_r = 1$, thus keeping vacuum wave impedance to avoid reflections, with a conductivity $\sigma = 0.5\ 1/(\Omega\ m)$ to dissipate the power

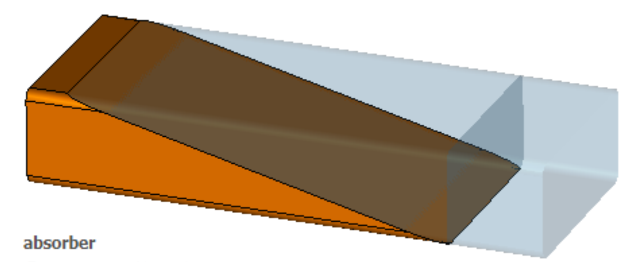
We need:

2.) *some virtual absorber simulating well (better -25 dB)*

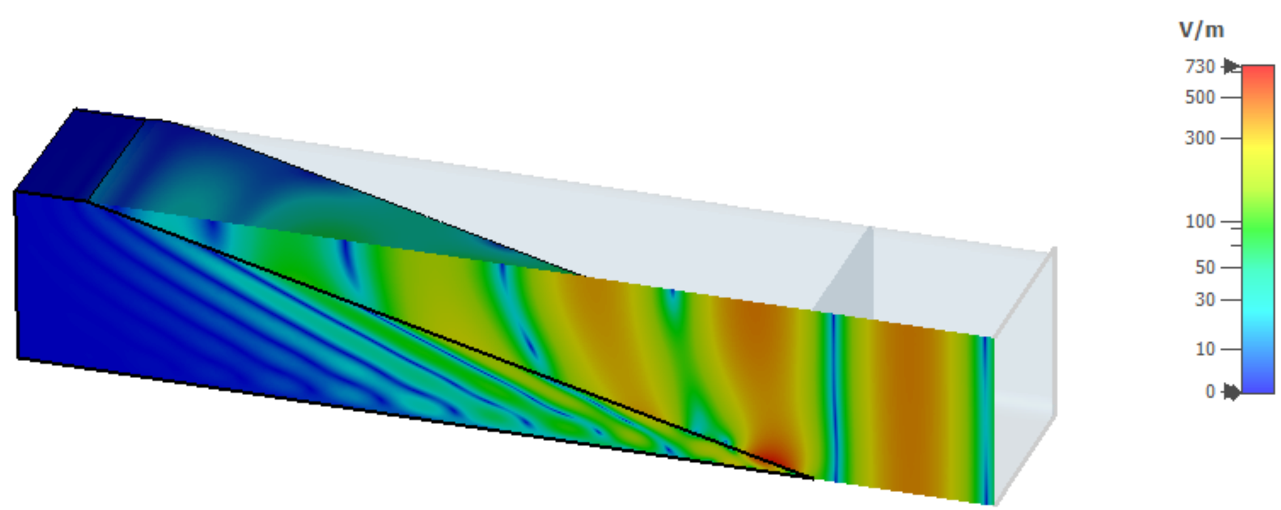
matched waveguide(/coax) terminations







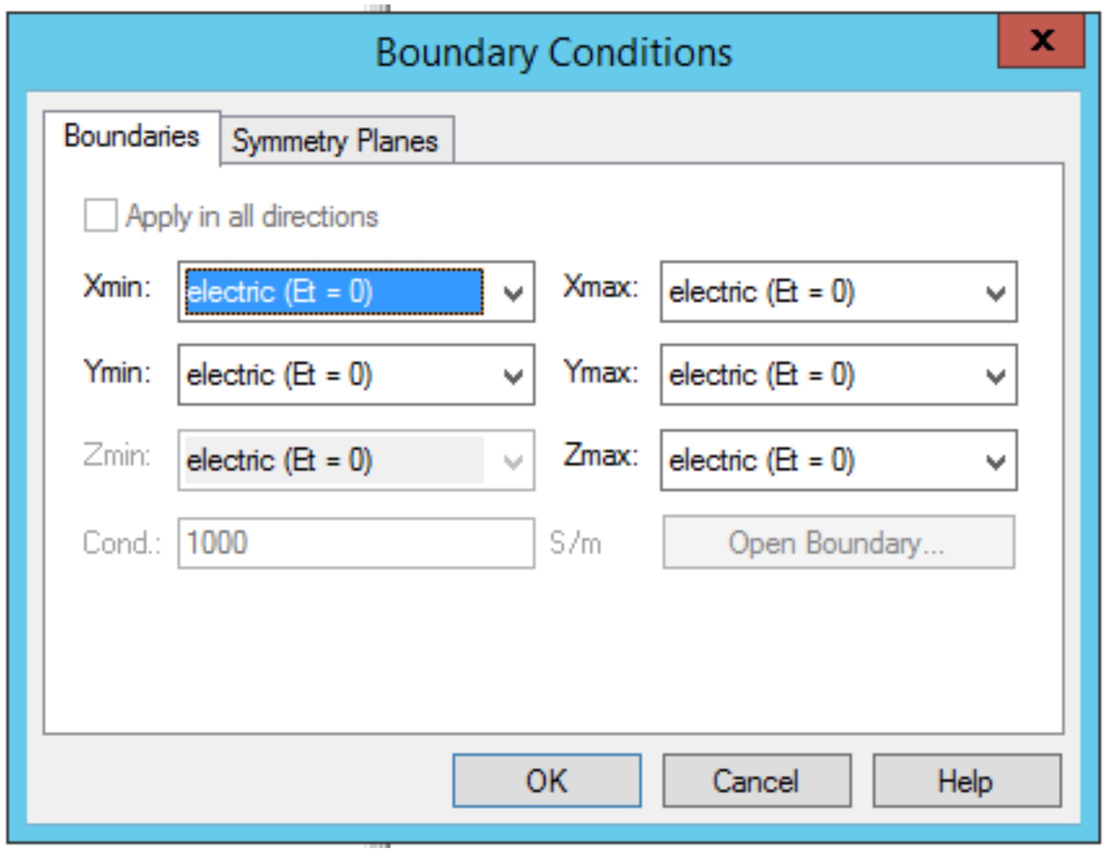
absorber	
Type	Normal
Epsilon	5
Mu	5
Electric cond.	0.5 [S/m]

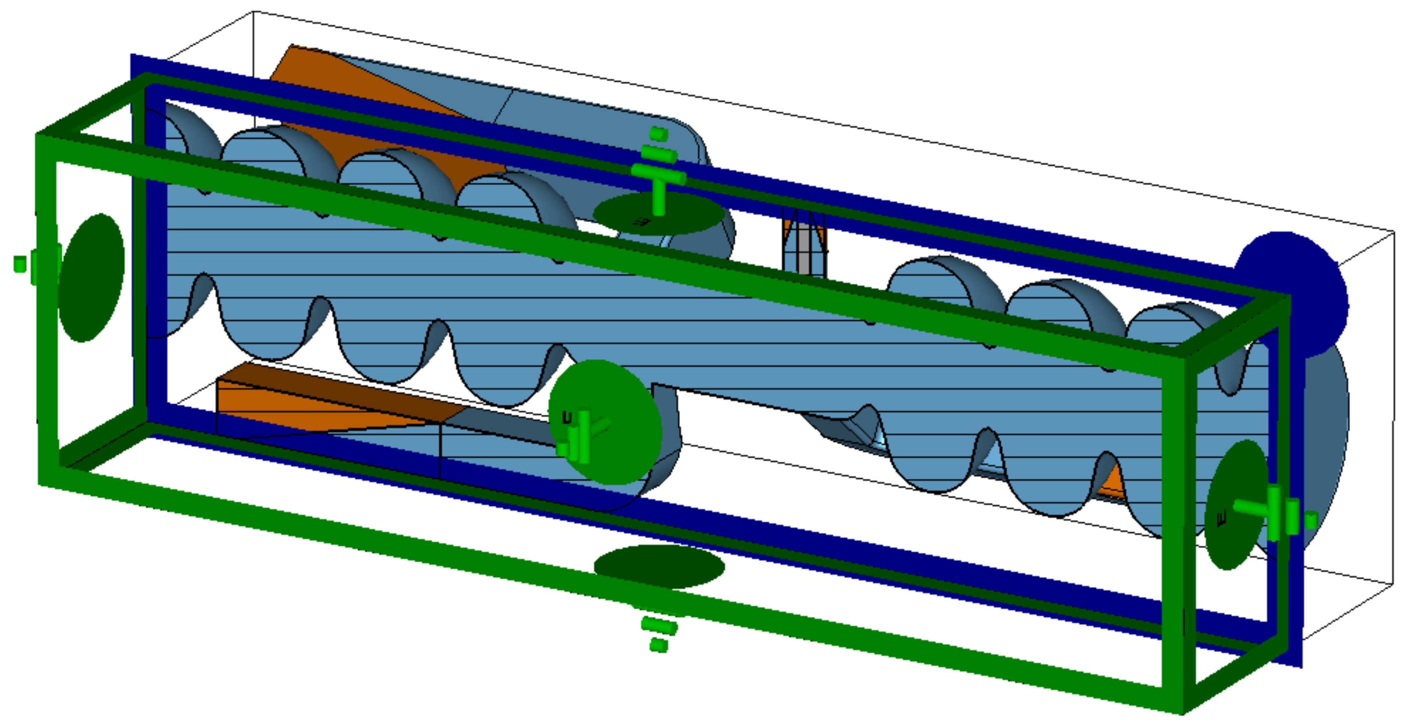


… by the way: Which kind of computation results in S-parameters ?

We need:

3.) boundary conditions, which define field behavior where the structure touches the borders of the computation domain, here: everywhere Perfect Electric Conductor (PEC) like the background material, short-cutting every tangential electric field (like a good conductor)

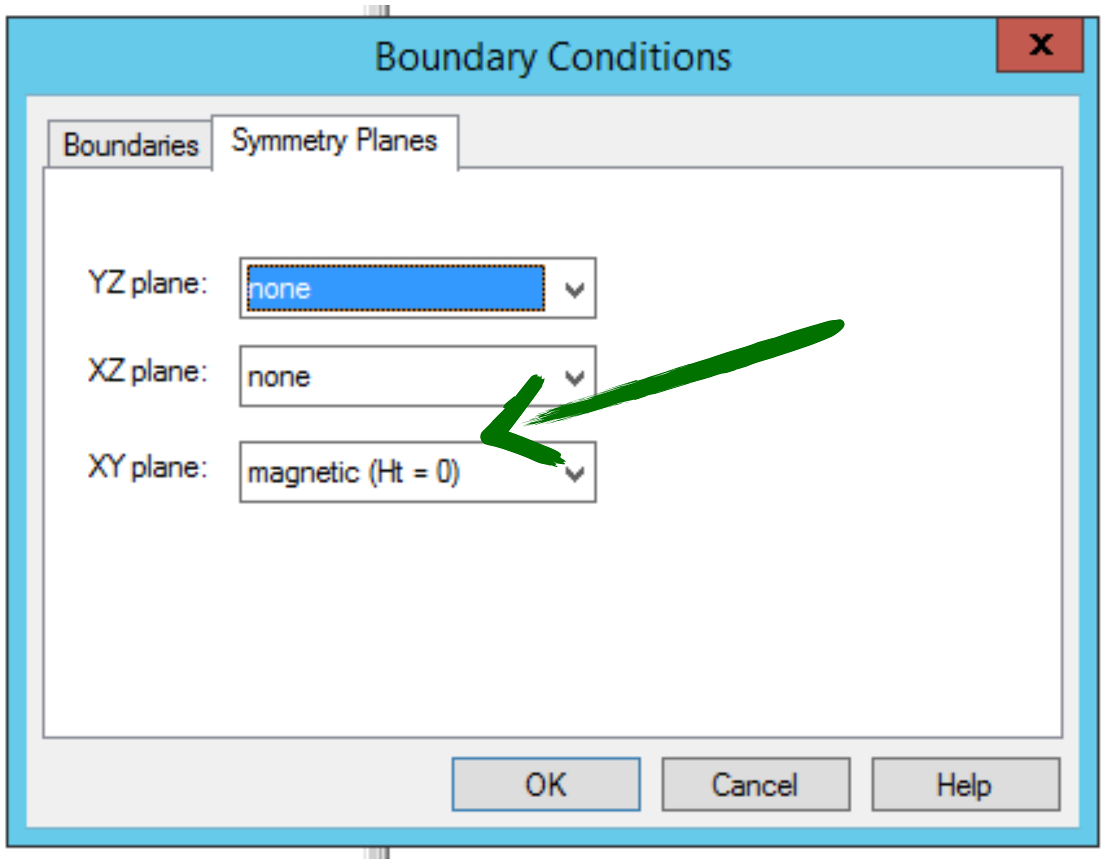


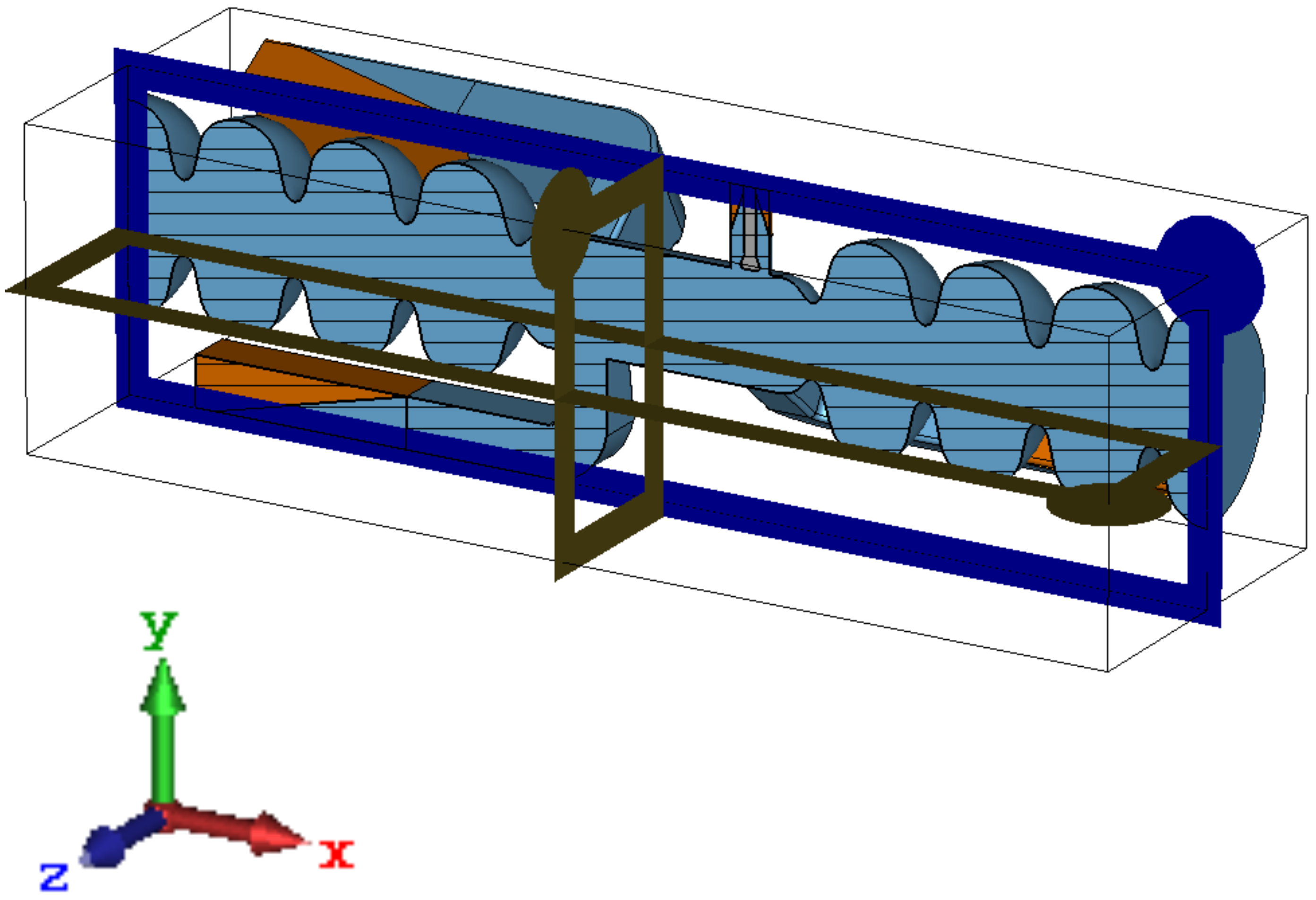


… by the way: What would you think is a PMC ?

We can (in this case) take profit of:

3.) a structure's symmetry plane, by defining one of the two different kind of fields only possible under those conditions.

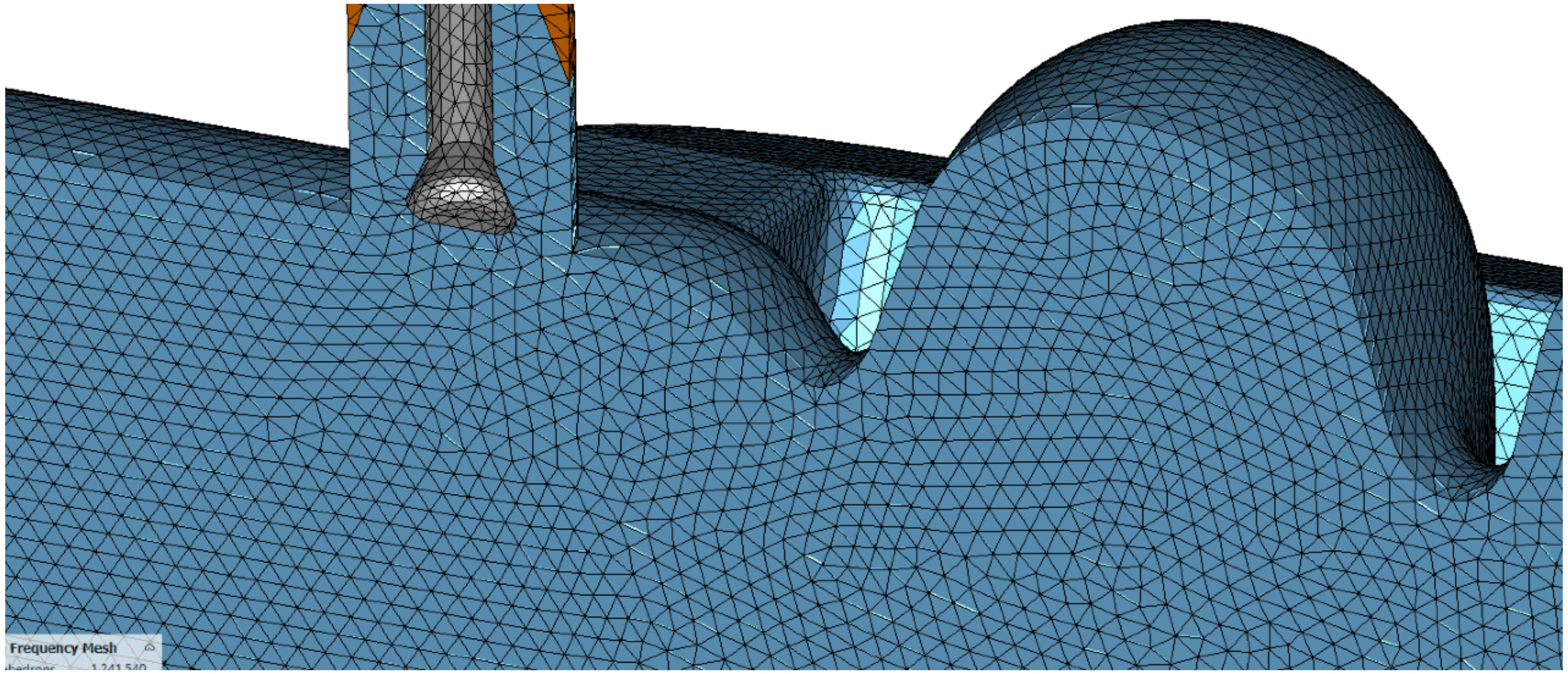


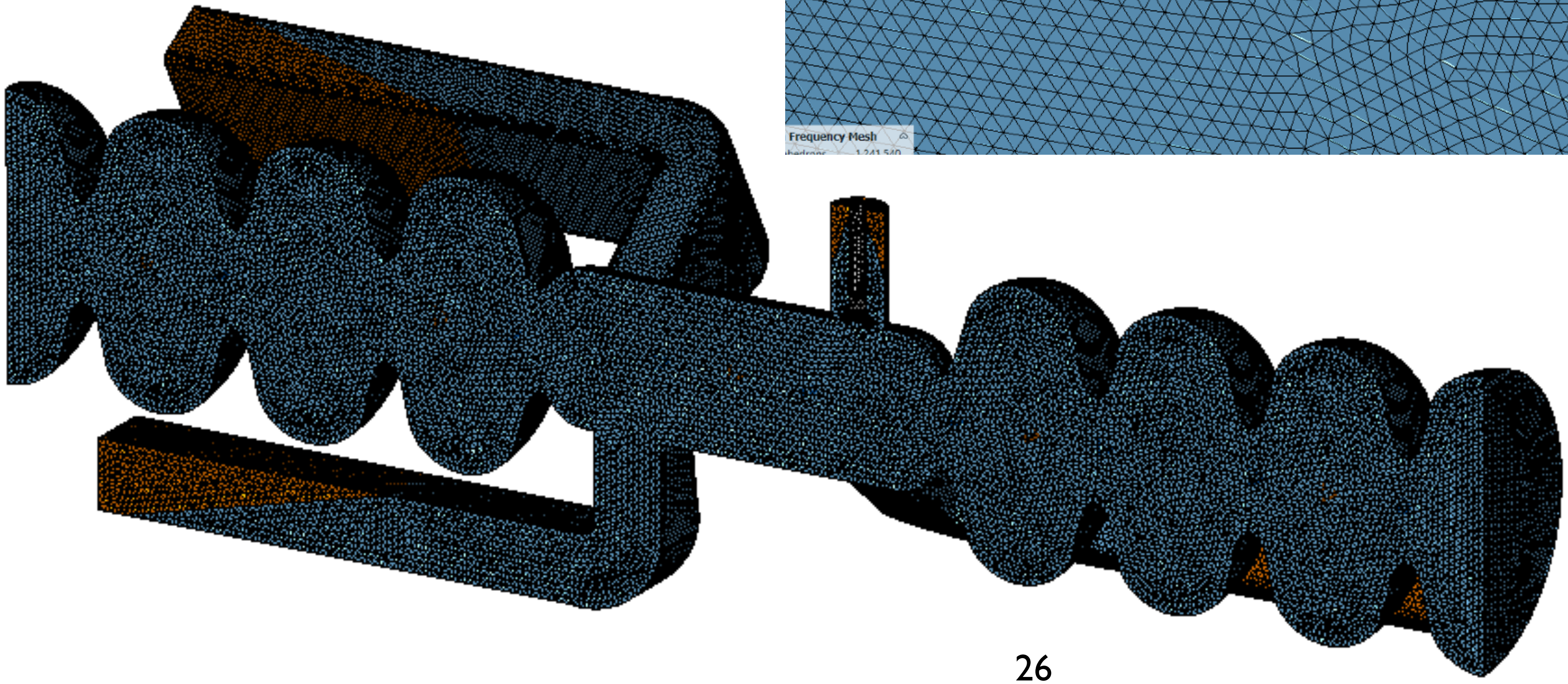


… by the way: What kind of fields do you expect if $E_{tangential} = 0$ in the symmetry plane?

We need:

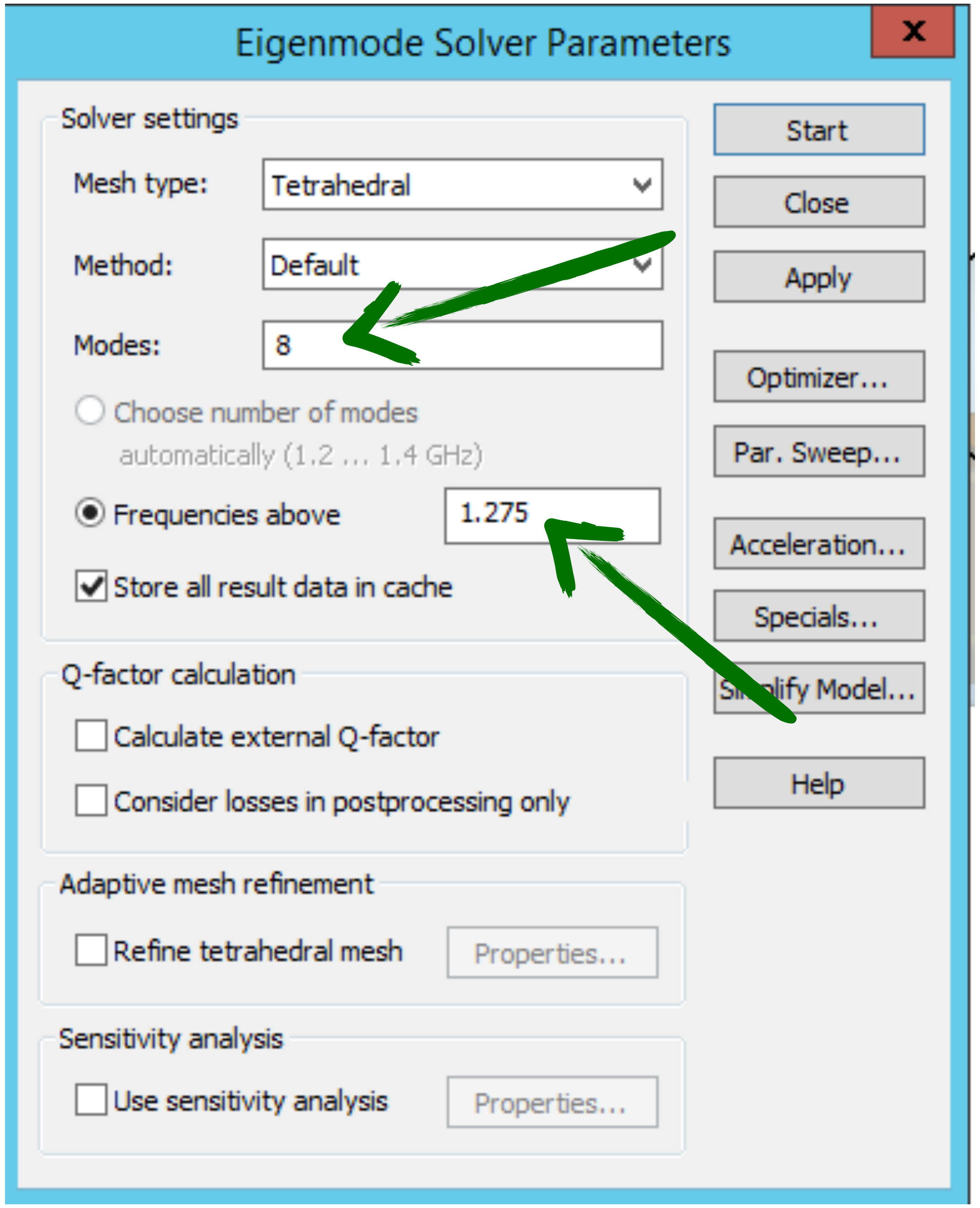
4.) a mesh to reduce the problem to a finite number of unknowns. Most common is a volume discretization in irregular tetrahedrons





We need:

5.) some parameters to control the solver, especially how many modes we are looking for starting at which frequency:



... by the way: How many modes can exist in a cavity ?

We get (after 760 s @ 12core Xeon© E5-2643v2, 3.50 GHz, allocating ~14 GB RAM) :

1.) a list of mode frequencies (here together with Q-values, cave: volume losses only)

Eigenmode solver results:

Mode	Frequency	Accuracy	Q (volume losses)
1	1.274571 GHz	1.266e-07	infinity
2	1.274573 GHz	1.15e-07	infinity
3 ^	1.283637 GHz	5.505e-08	3.638e+07
4	1.283671 GHz	4.526e-08	infinity
5 ^	1.295234 GHz	1.678e-07	1.542e+07
6	1.29524 GHz	2.28e-07	infinity
7	1.300506 GHz	6.906e-08	infinity
8 ^	1.30052 GHz	1.166e-07	2.413e+07

^ = The material properties at the evaluation frequency differ from those at the eigenfrequency.

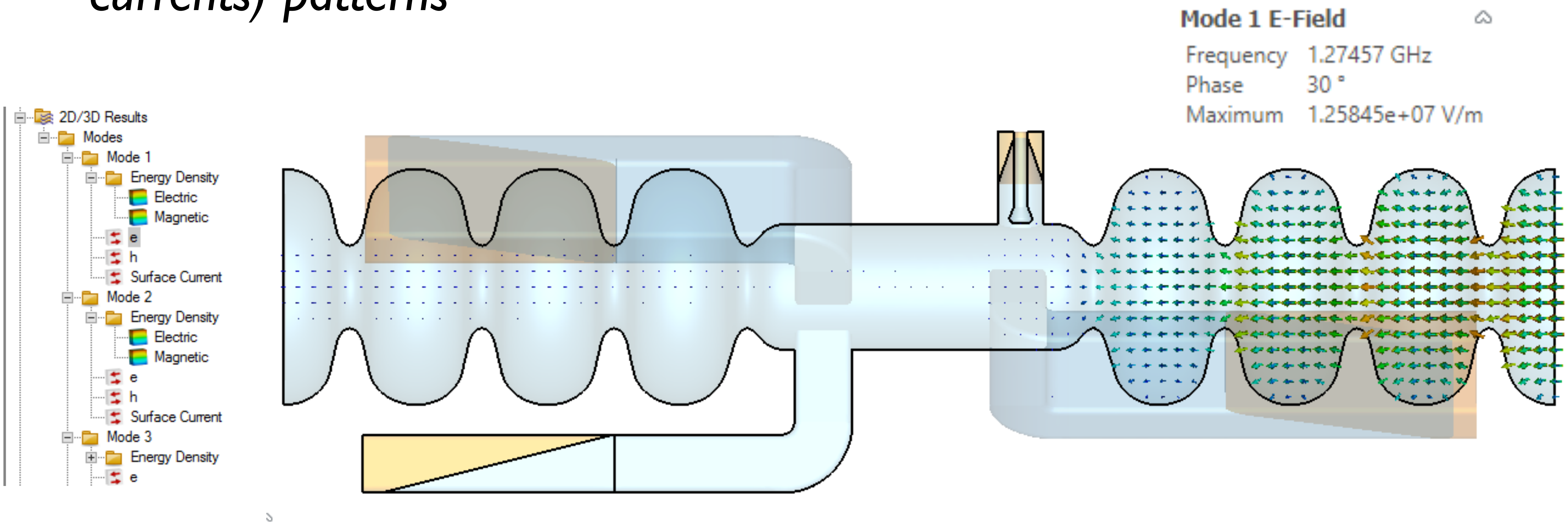
Eigenmode solver successful

Messages Progress

… by the way: Which order of Q-value do you expect for a good copper cavity ?

We get :

2.) a list of according eigenmode field (E-, H-, energy density, surface currents) patterns

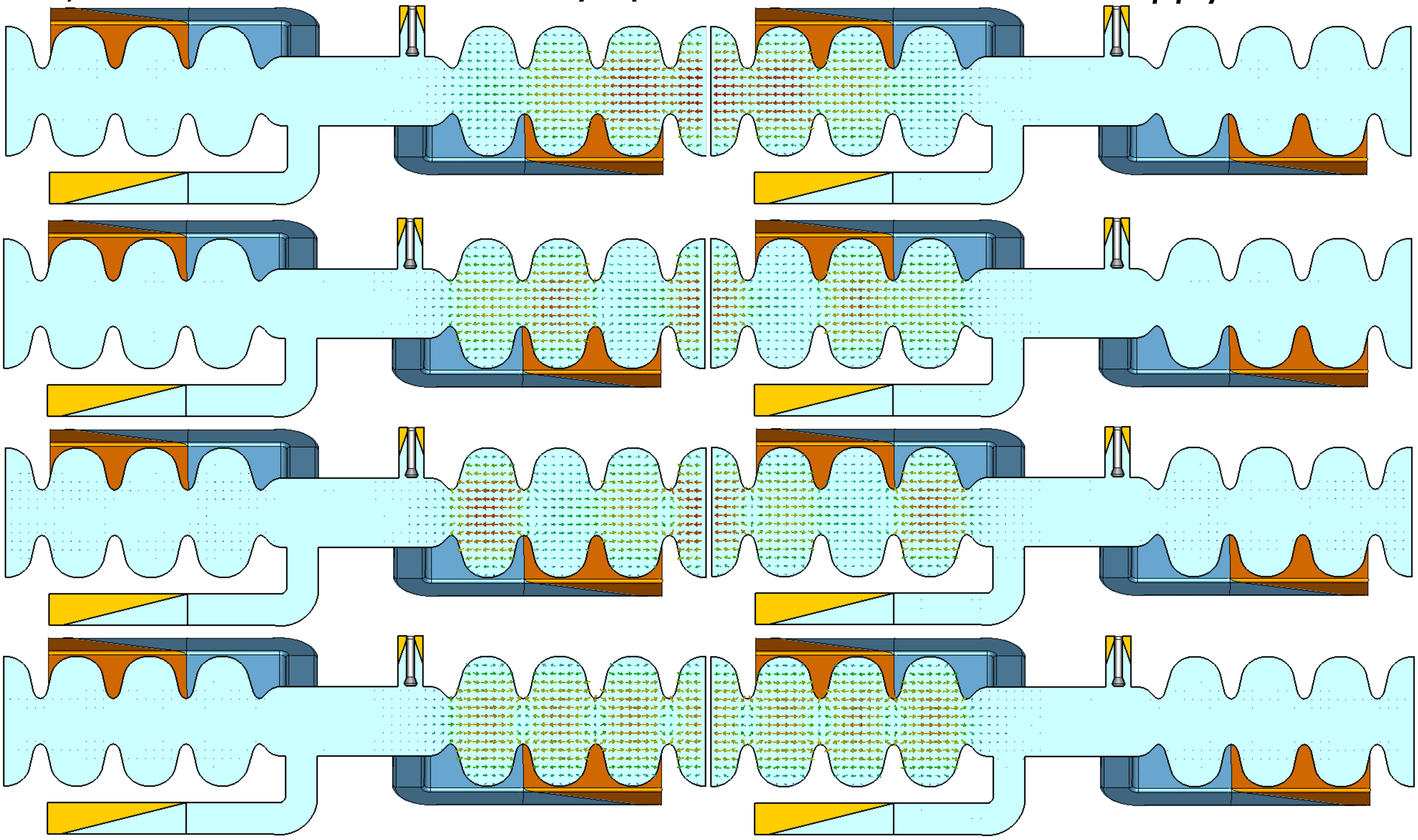


Attention: Complex-valued fields have real and imaginary part, i.e. a phase. Phase 0° not necessarily means highest field values.

… by the way: How are the currents in the cavity (inner) surface correlated with the H-field directly above ?

We get :

3.) an idea how well the theory of identical resonator chains apply

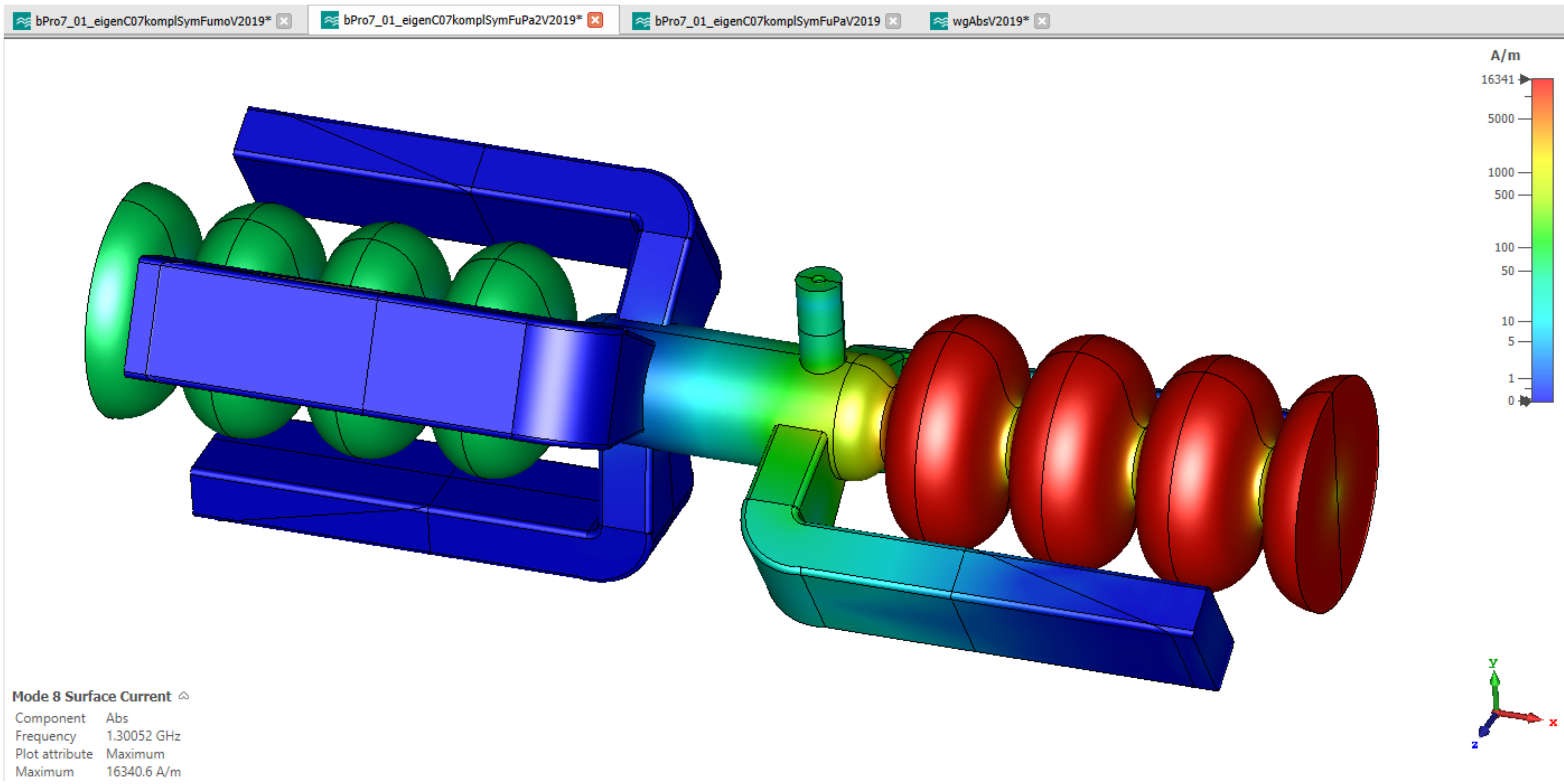


… by the way: How can we compute the missing modes of the passband ?

We get :

4.) a lot of further fancy post-processing information

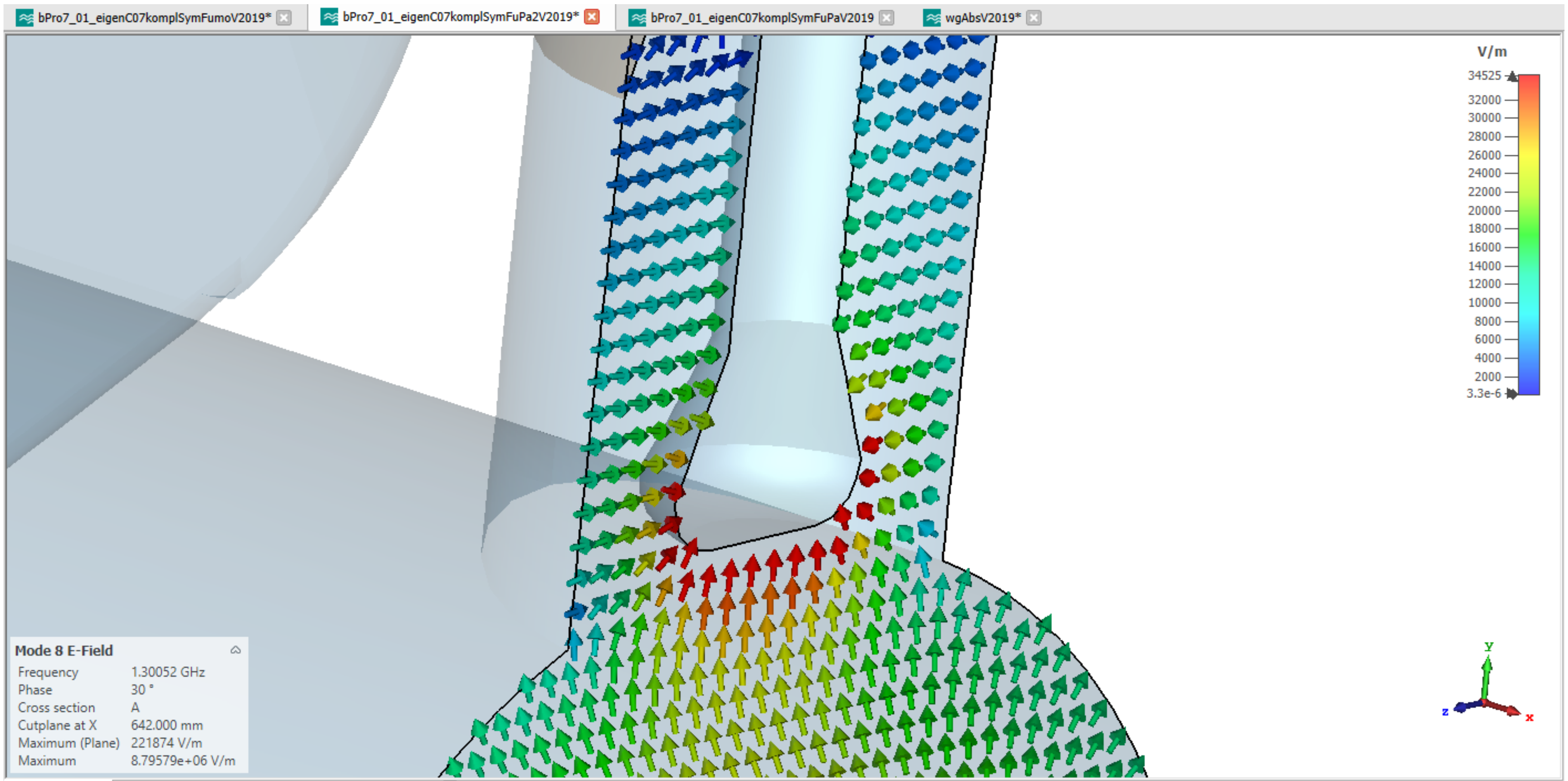
e.g. logarithmic-scaled surface current density



We get :

4.) a lot of further fancy post-processing information

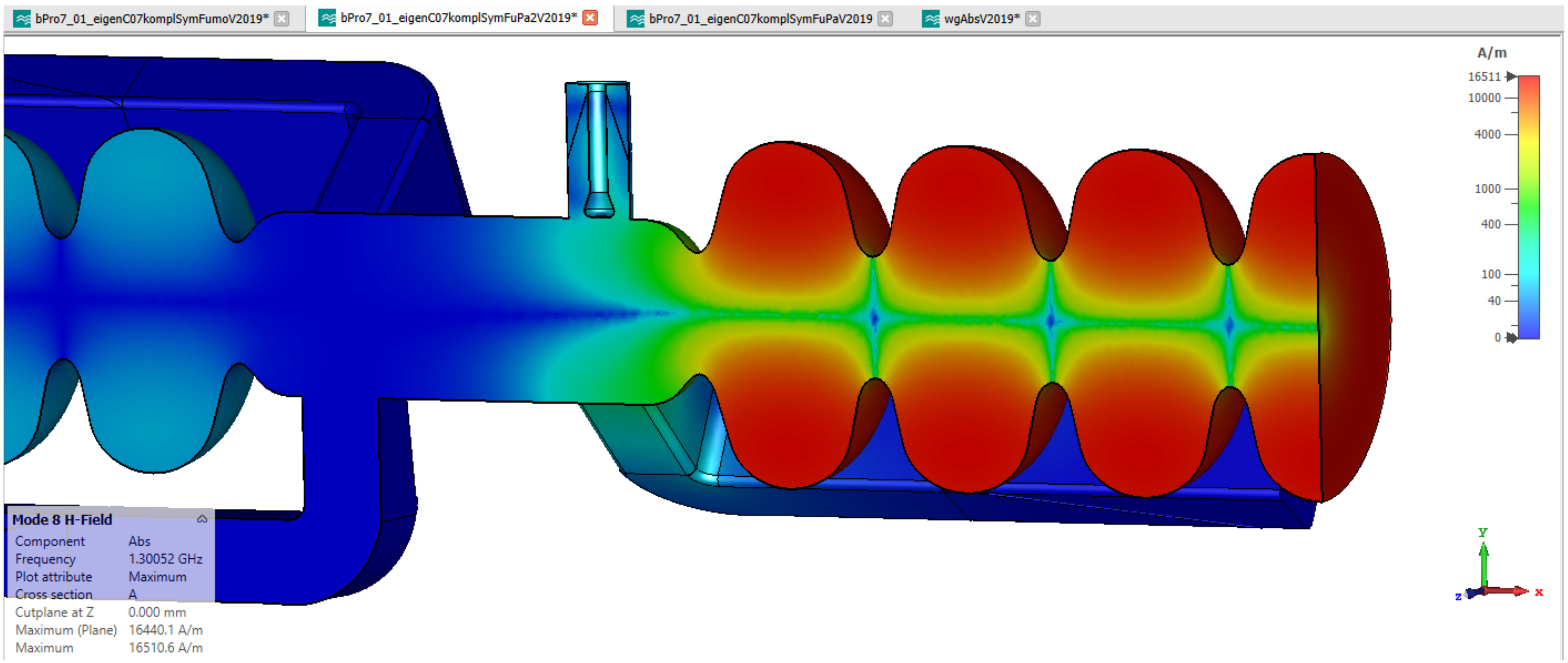
the electric field distribution close to the coupler tip



We get :

4.) a lot of further fancy post-processing information

leaking of the fundamental mode's H-field into the beam pipe



We get :

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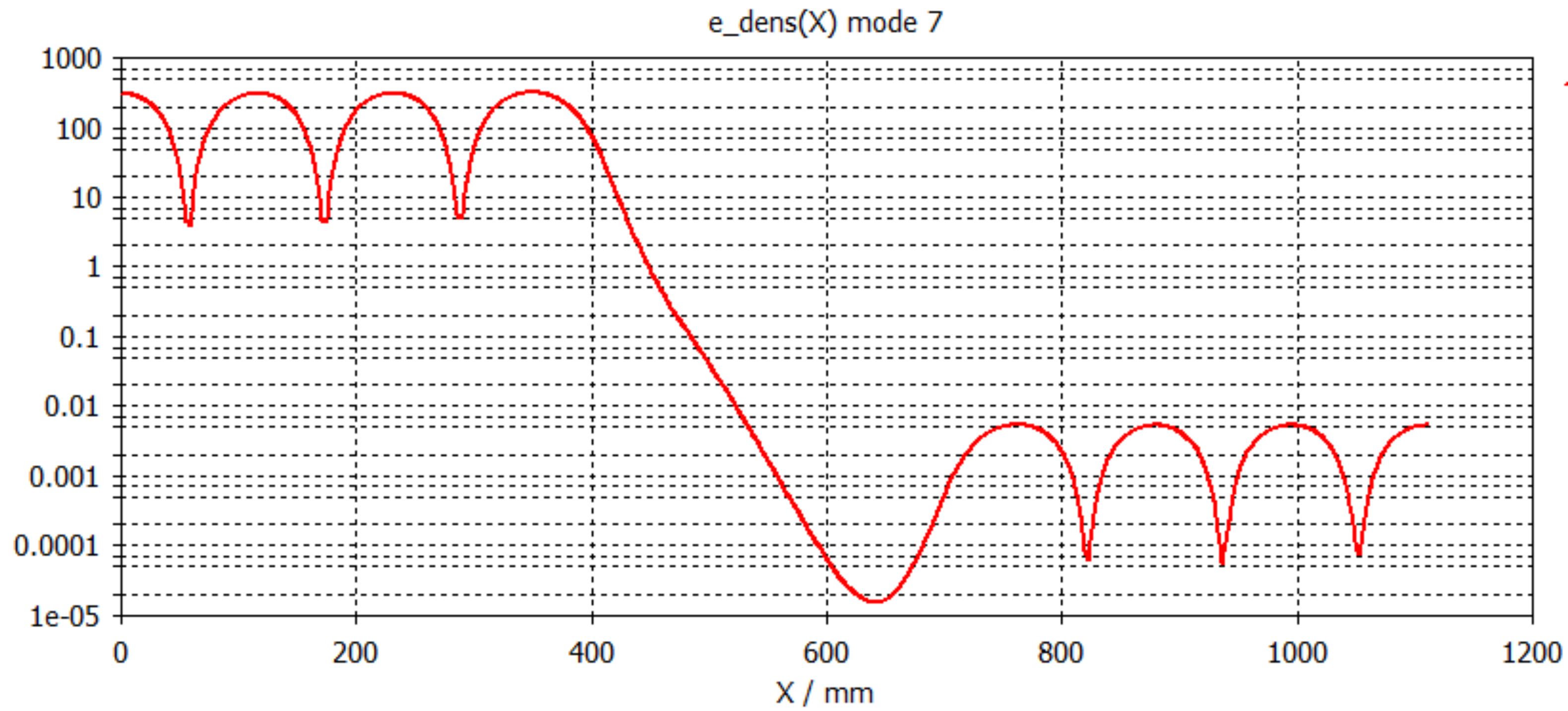
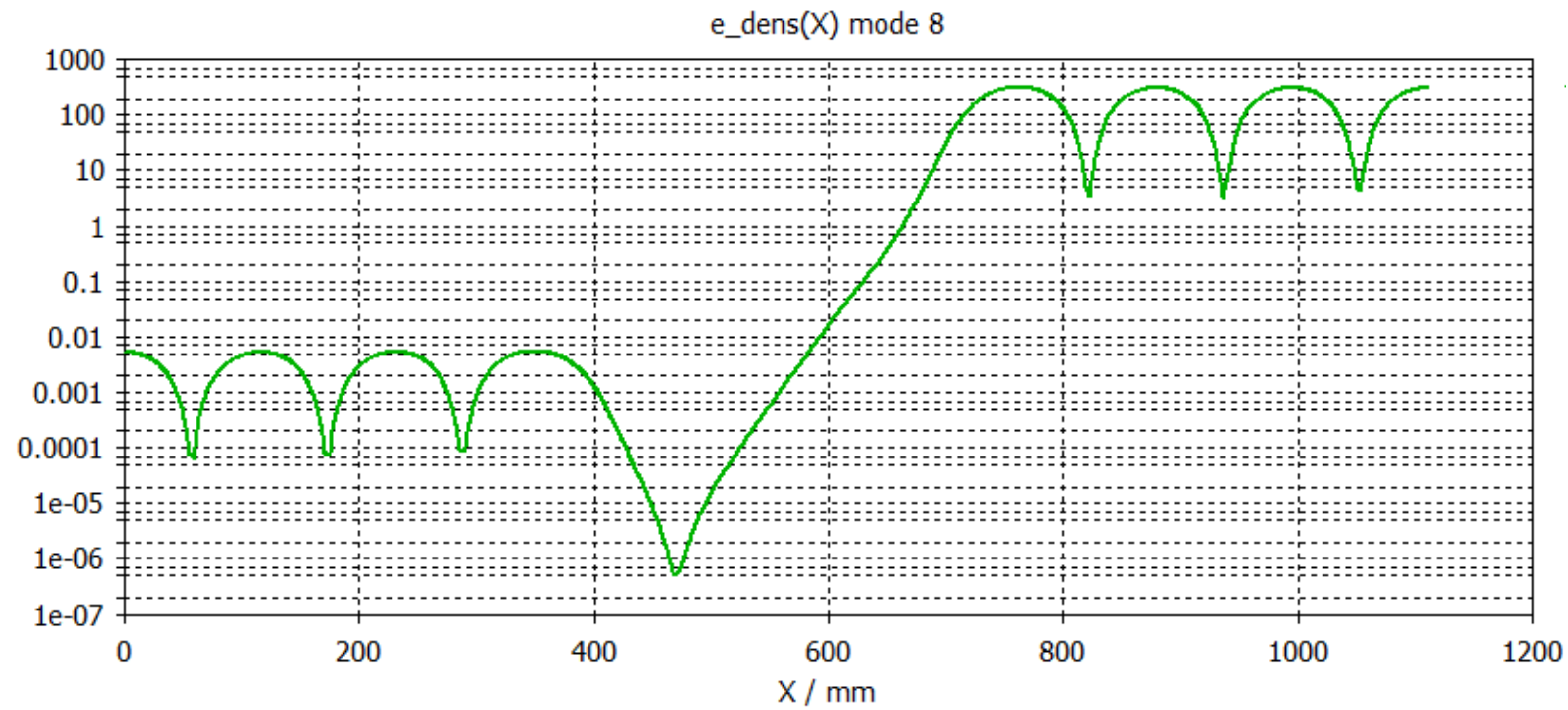
cavity-cavity coupling of the fundamental mode





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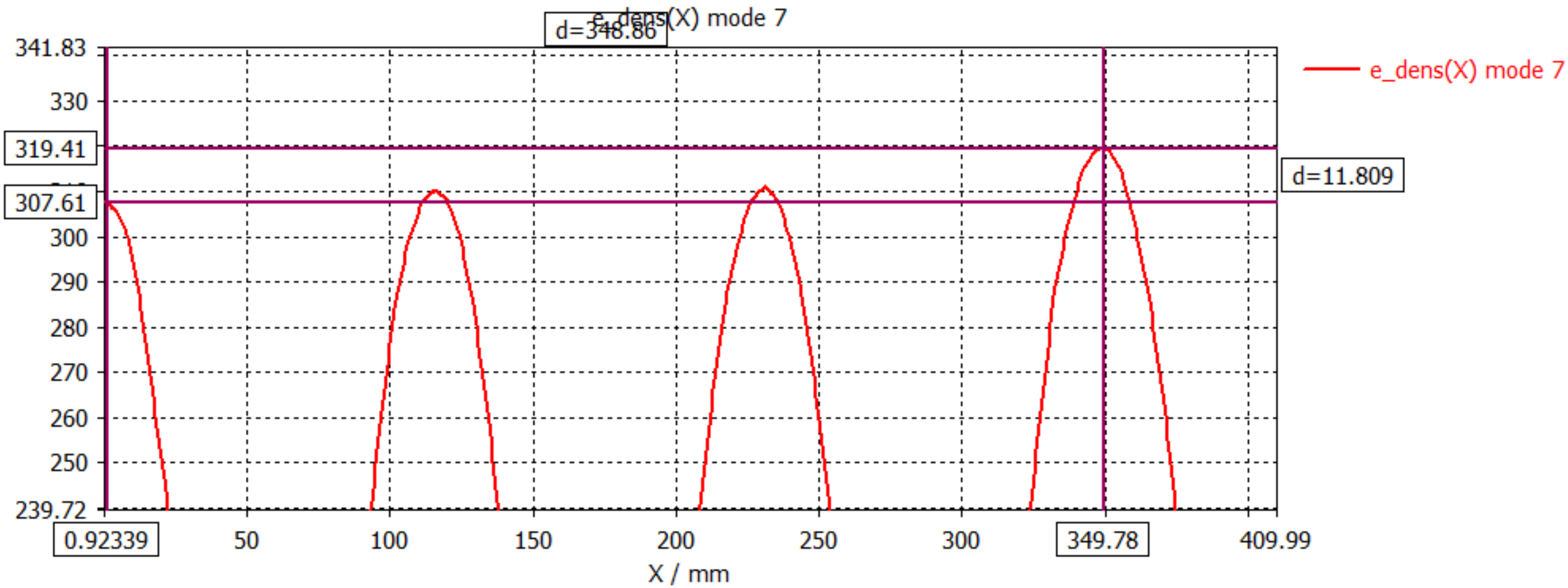
We get :

4.) a lot of further fancy post-processing information

(numerical) field flatness

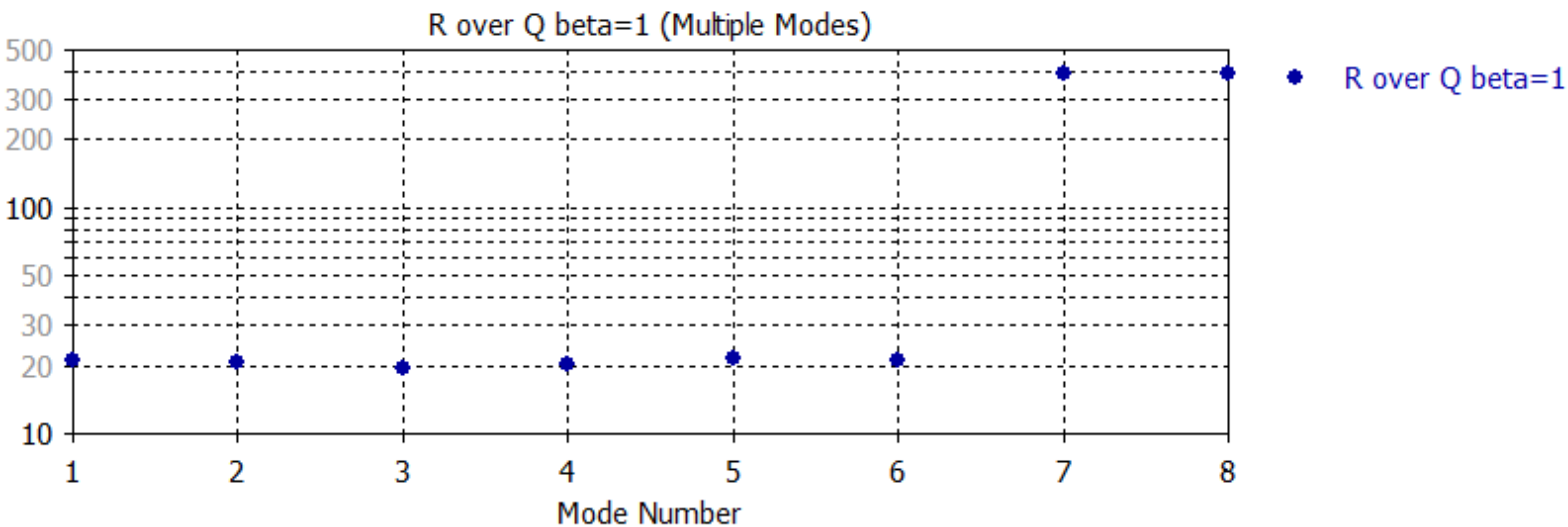


… by the way: Which kind of experiment gives this information for a real-world-cavity ?

We get :

4.) a lot of further fancy post-processing information

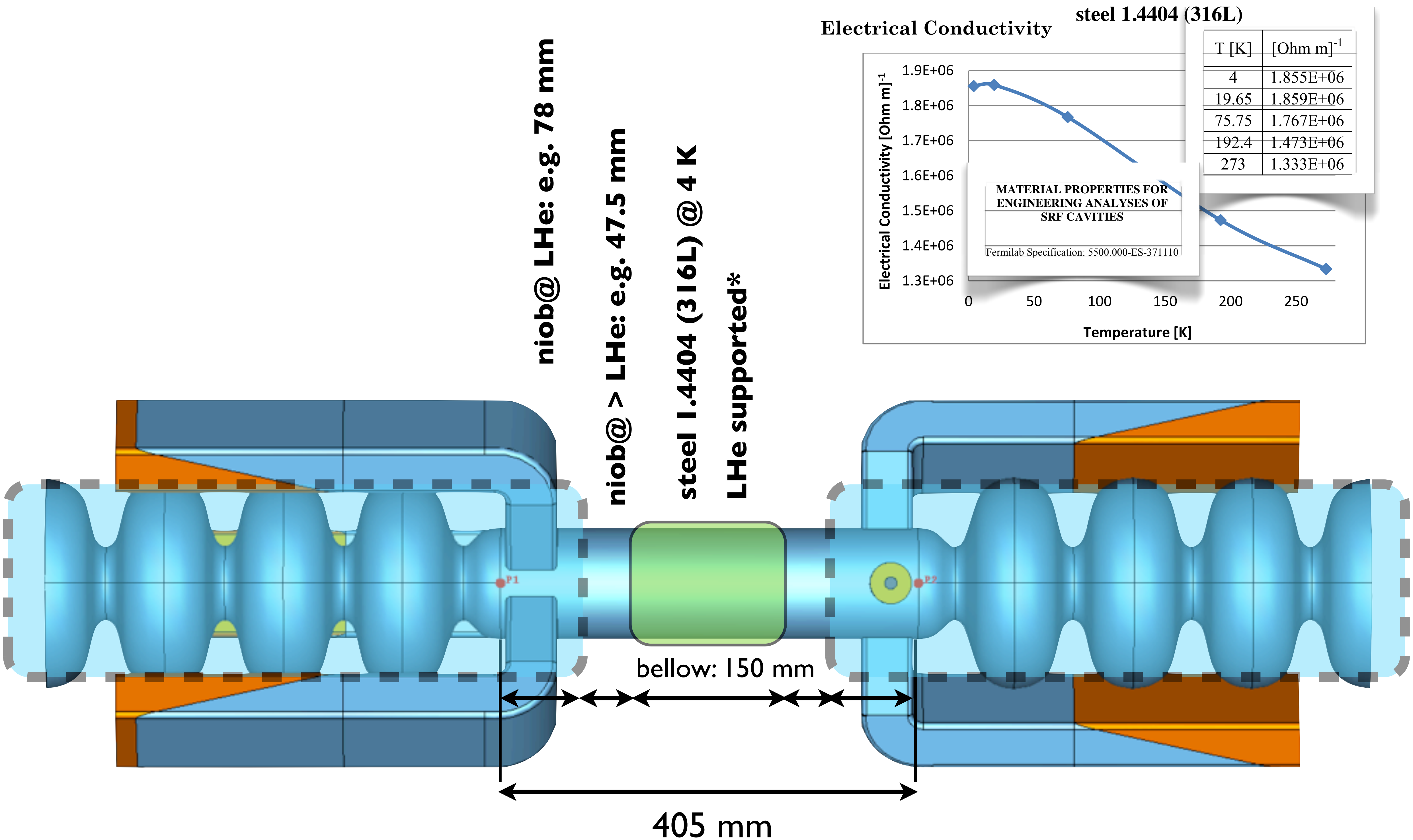
(numerical) field flatness



… by the way: Is the R/Q-value depending on the test particle's velocity ?

An engineering question, based on eigenmodes:

Cavity-cavity-connection: Something similar to this ...

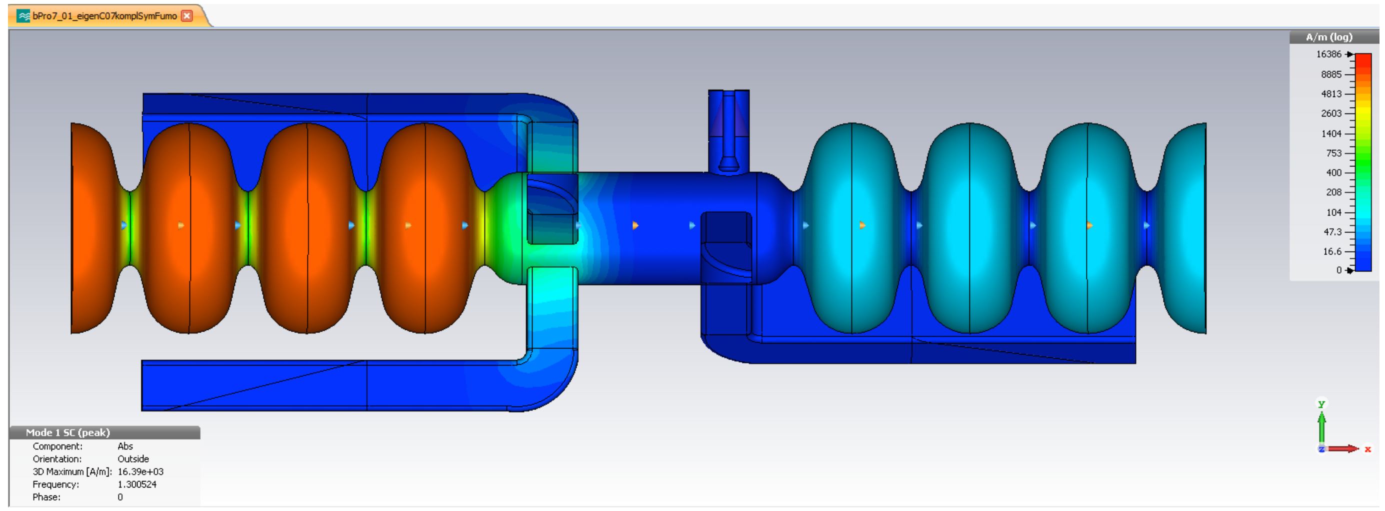


Questions and inputs:

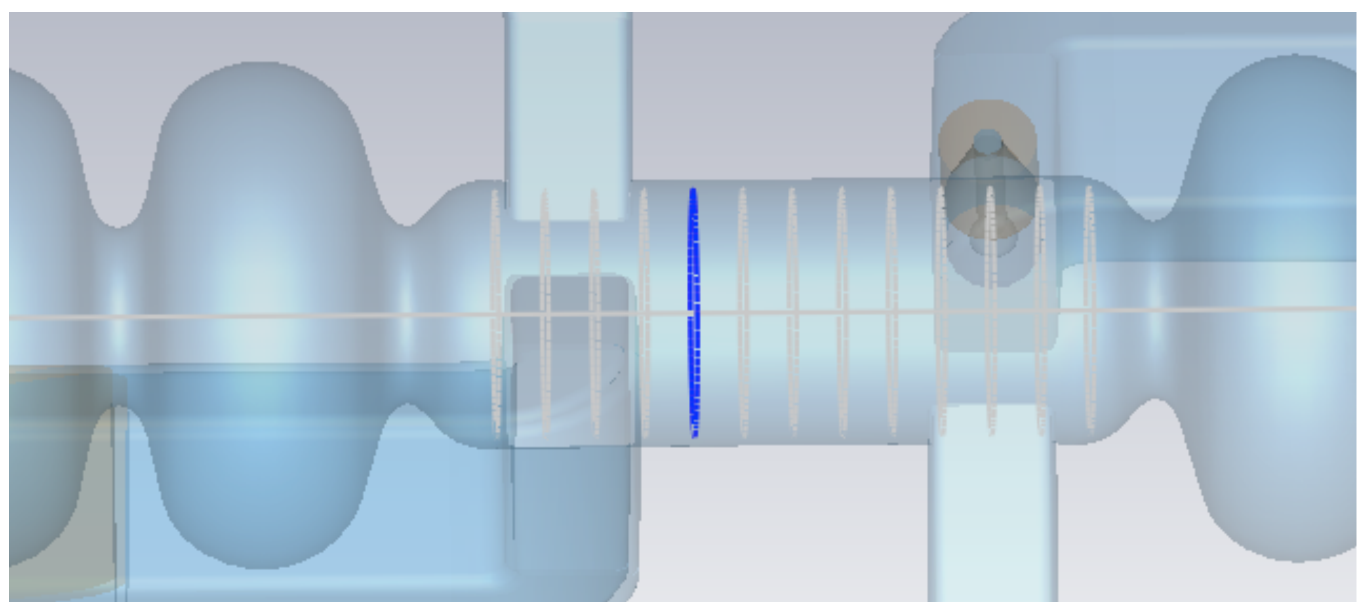
- How far to extend superconducting material from accelerating cavities into beam pipe?
- What is going to happen outside the LHe-vessel?
- Fundamental mode surface resistance $R_s(T)$ and thermal conductivity $\lambda(T)$ strongly depend on temperature. ⇒ Severely non-linear problem
- 1-dimensional approach to keep effort reasonable but gain "feeling" (also provide benchmark for any 3-dim).
- Include distributed fundamental mode losses, concentrated heat flux from "nc bellow" and fixed temperature boundary at "LHe bath".

Fundamental Loss Calculations

– eigenmode computation of fundamental mode, H_{tan} @ surface = j_{surf}

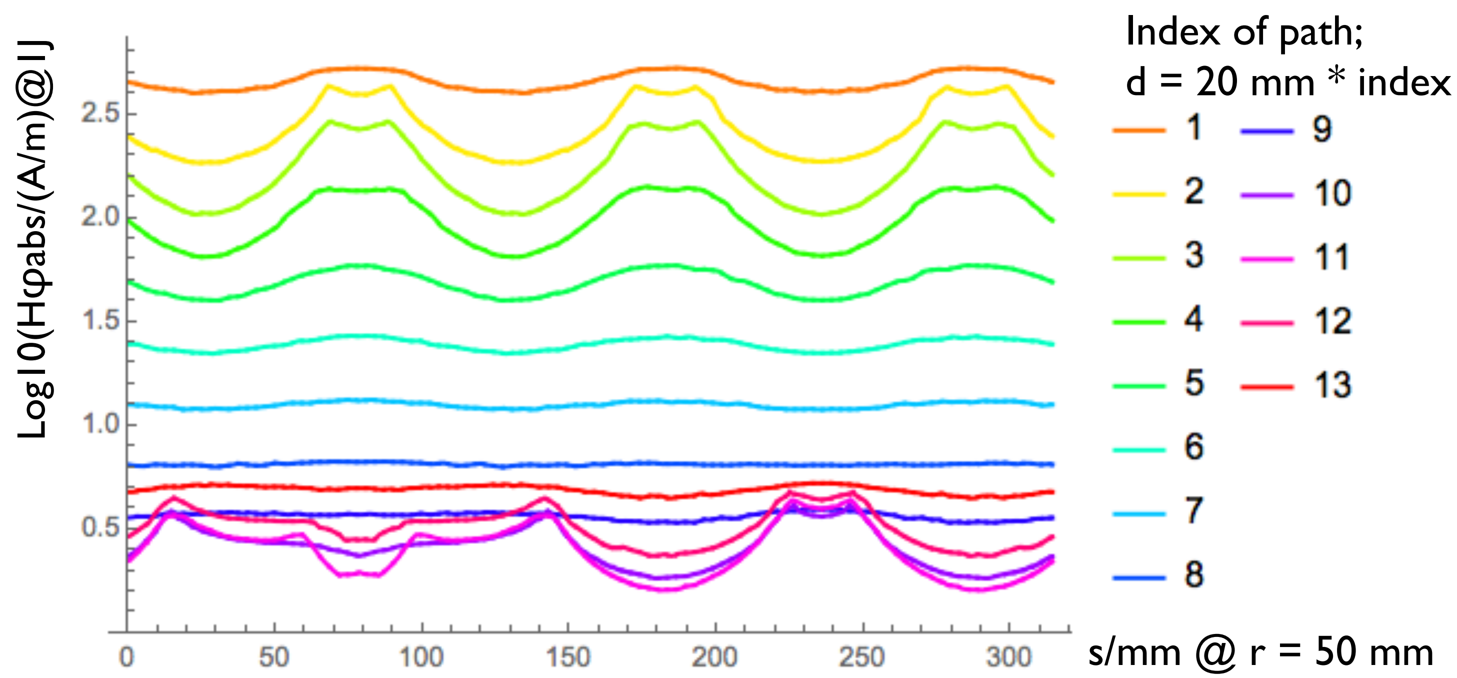


– sampling along axially equidistant circular paths, close to inner surface

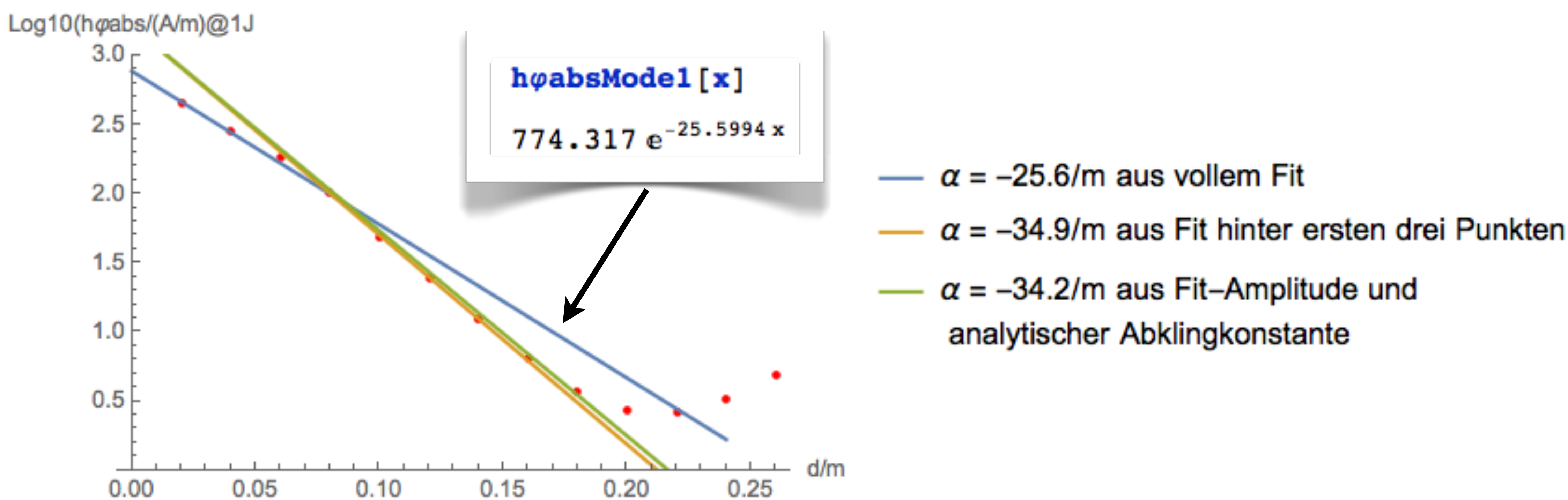


Fundamental Loss Calculations II

– taking average of circumferential field profiles to eliminate disturbances by WGs



– fit exponential dependence to sampled (average) values; compare to analytics



Fundamental Loss Calculations III

– scale field amplitude from CST-convention: "stored energy = 1 J"

CST - with transittime factor: energy gain of 1.8005 10^6 Volt in 3,5 cells.
calculation for 25 MV/m:

$$\texttt{feldSkalier} = \frac{25 \times 10\hat{}6\ \texttt{Volt} / \texttt{Meter} * 0.8\ \texttt{Meter}}{2 * 1.8005 \times 10\hat{}6\ \texttt{Volt}}$$

5.55401

```
hφ[x_] := feldSkalier * hφabsMode1[x]
```

$$\texttt{linienLeistung[rs\_, x\_]} := 2\,\pi\, 0.055\ \texttt{Meter}\ \frac{rs}{2}\ (\texttt{h}\varphi\texttt{[x] Ampere / Meter})\hat{}2$$

– for steel parts determine surface impedance from conductivity, frequency (, permeability)

normaler Skineffekt liefert

$$\texttt{rSur}[\omega\_,\ \mu r\_,\ cond\_] := \sqrt{\frac{\omega\ \mu r\ 4\,\pi\, 10\hat{}-7\ \texttt{Volt Sekunde}}{2\ cond\ \texttt{Ampere Meter}}}$$

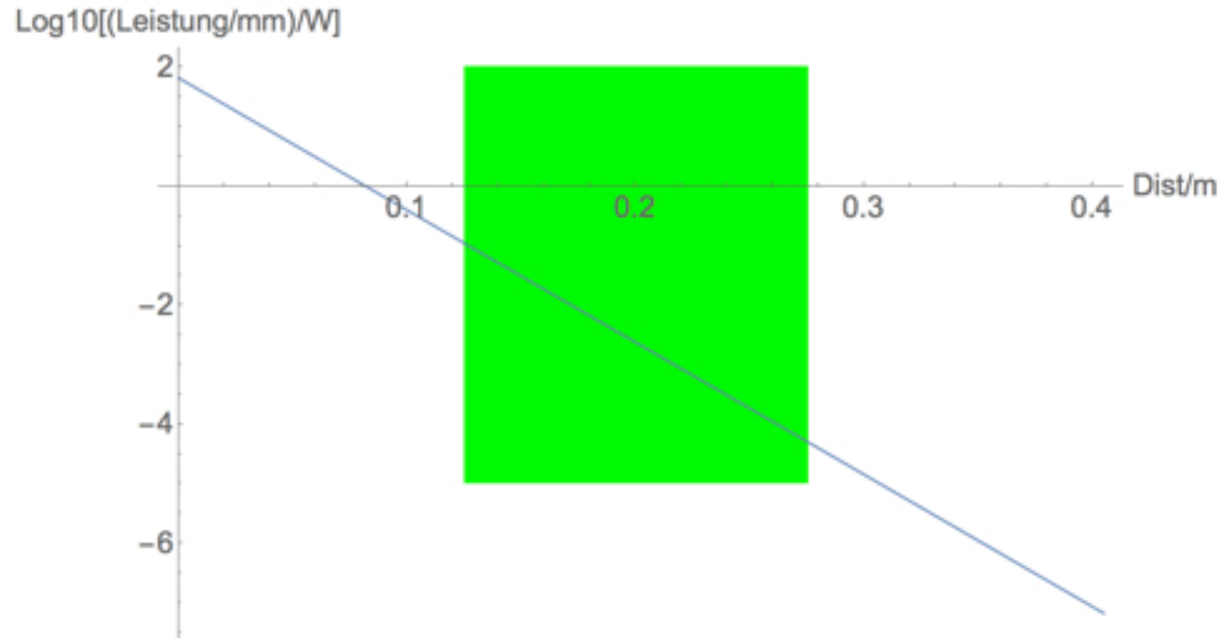
$$\frac{0.02096\grave{}\ \texttt{Volt}}{\texttt{Ampere}}$$

… by the way: Is stainless steel „magnetic“ ?

H.-W. Glock, HZB

Fundamental Loss Calculations IV

- dissipated fundamental power (no wakes) per mm straight beam pipe length @ 25 MV/m, steel 316L, excited by ONE cavity



- integrated over bellow (ignoring corrugation): 2.1 Watt

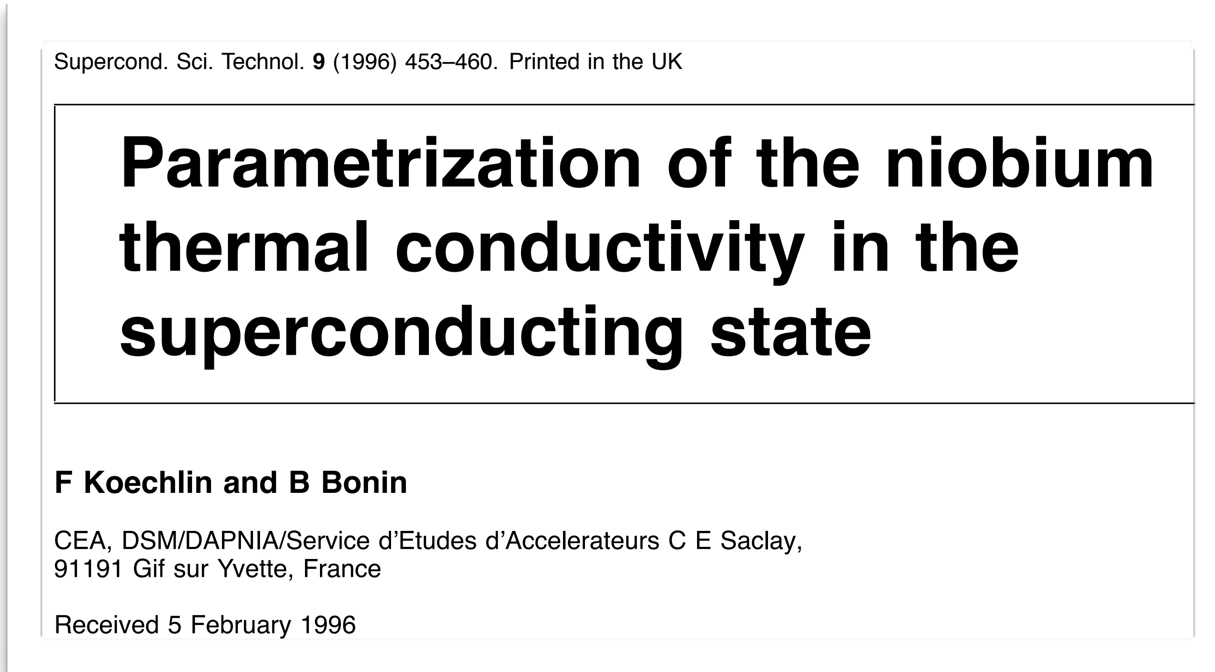
```
intPowSteel4K[{0.078 + 0.0475, 0.078 + 0.0475 + 0.150} Meter]
2.11771 Ampere Volt
```

- hypothetically 20 mm closer to the cavity: 5.9 Watt

```
intPowSteel4K[{0.078 + 0.0475 - 0.02, 0.078 + 0.0475 + 0.150 - 0.02} Meter]
5.89623 Ampere Volt
```

… by the way: What is the Carnot efficiency for a refrigerator cooling from 300 K to 2 K ?

Temperature-dependent thermal conductivity of niobium



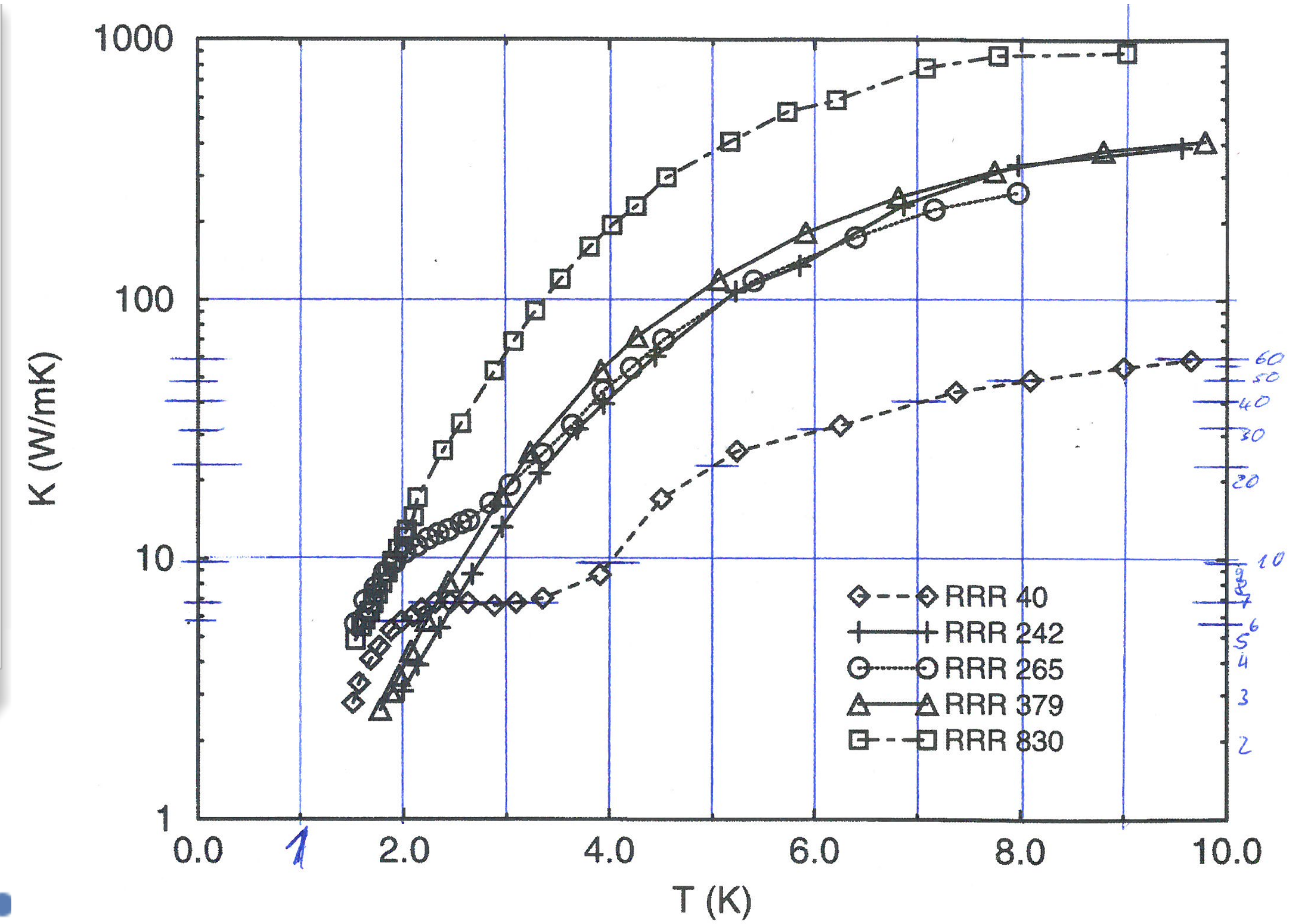
Supercond. Sci. Technol. **9** (1996) 453–460. Printed in the UK

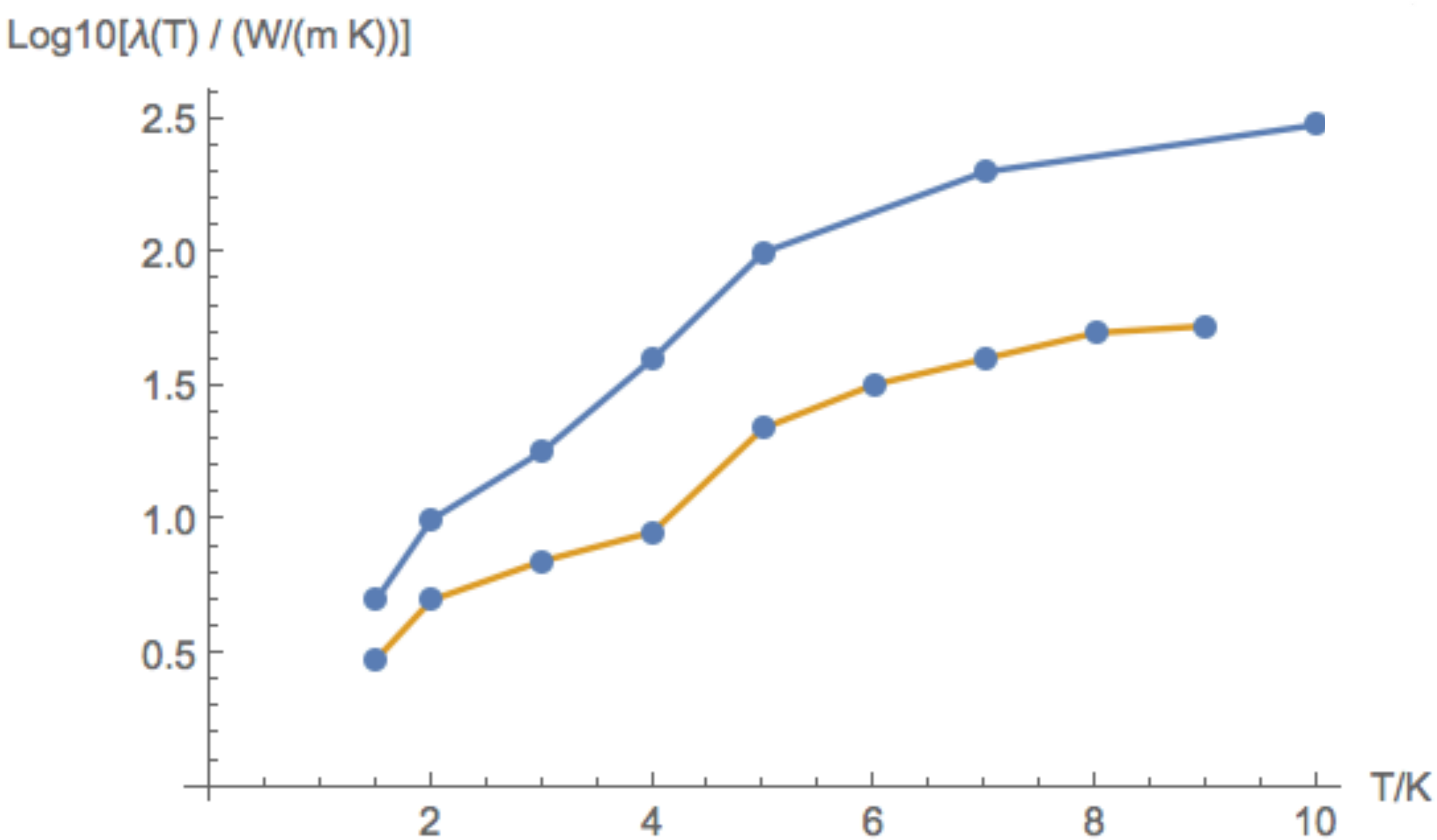
Parametrization of the niobium thermal conductivity in the superconducting state

F Koechlin and B Bonin

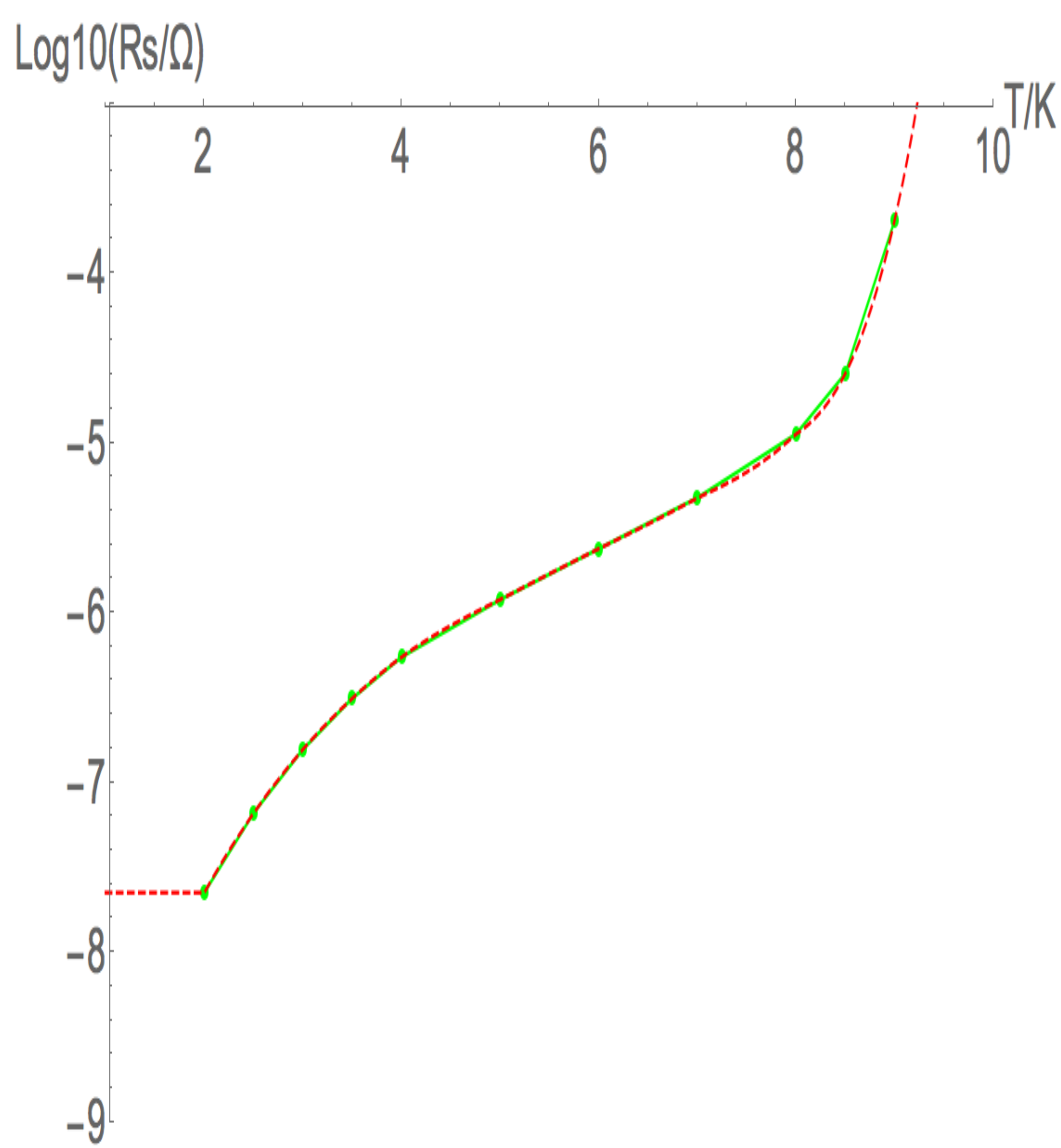
CEA, DSM/DAPNIA/Service d'Etudes d'Accelerateurs C E Saclay, 91191 Gif sur Yvette, France

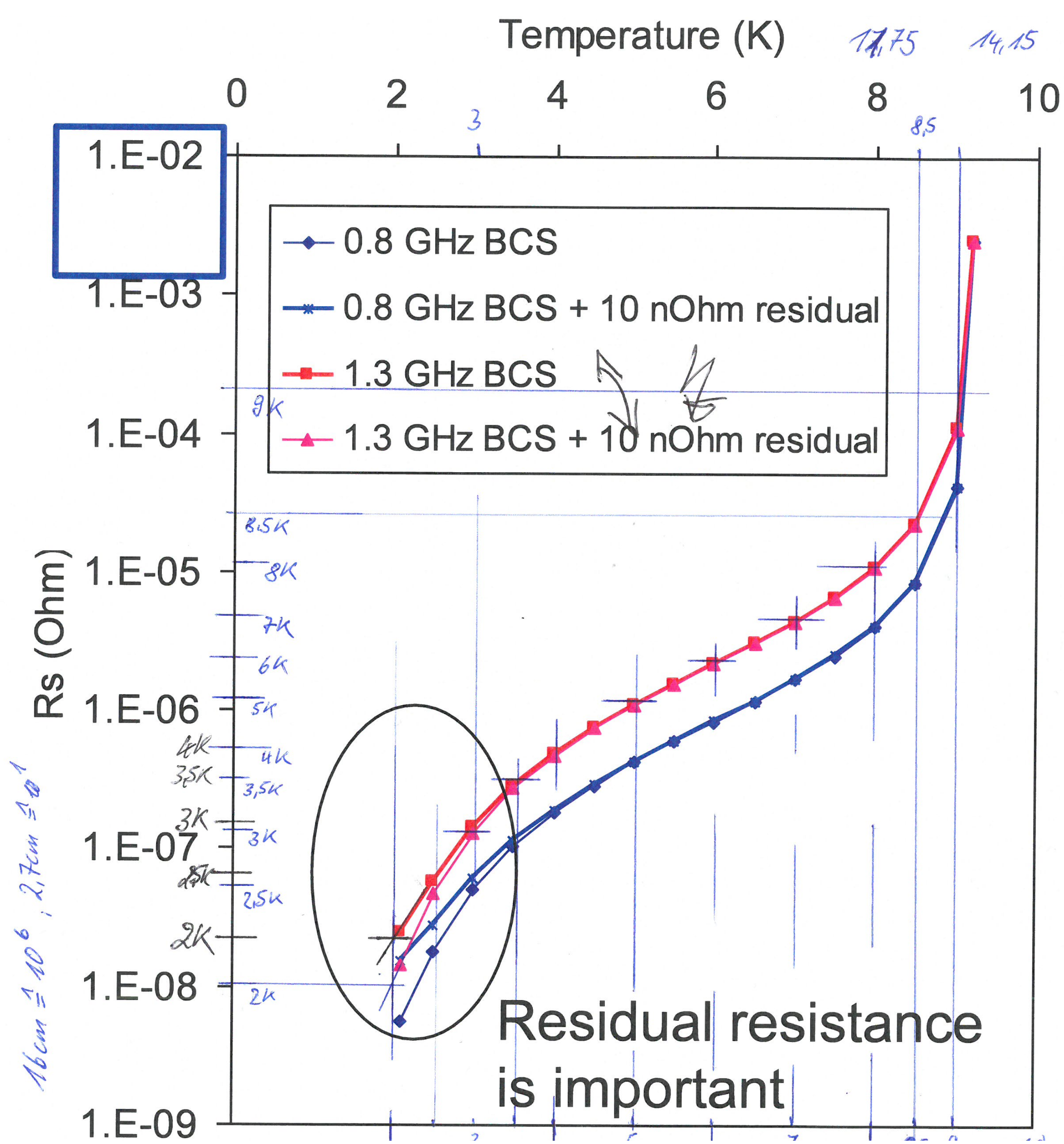
Received 5 February 1996





Temperature-dependent surface resistance of niobium

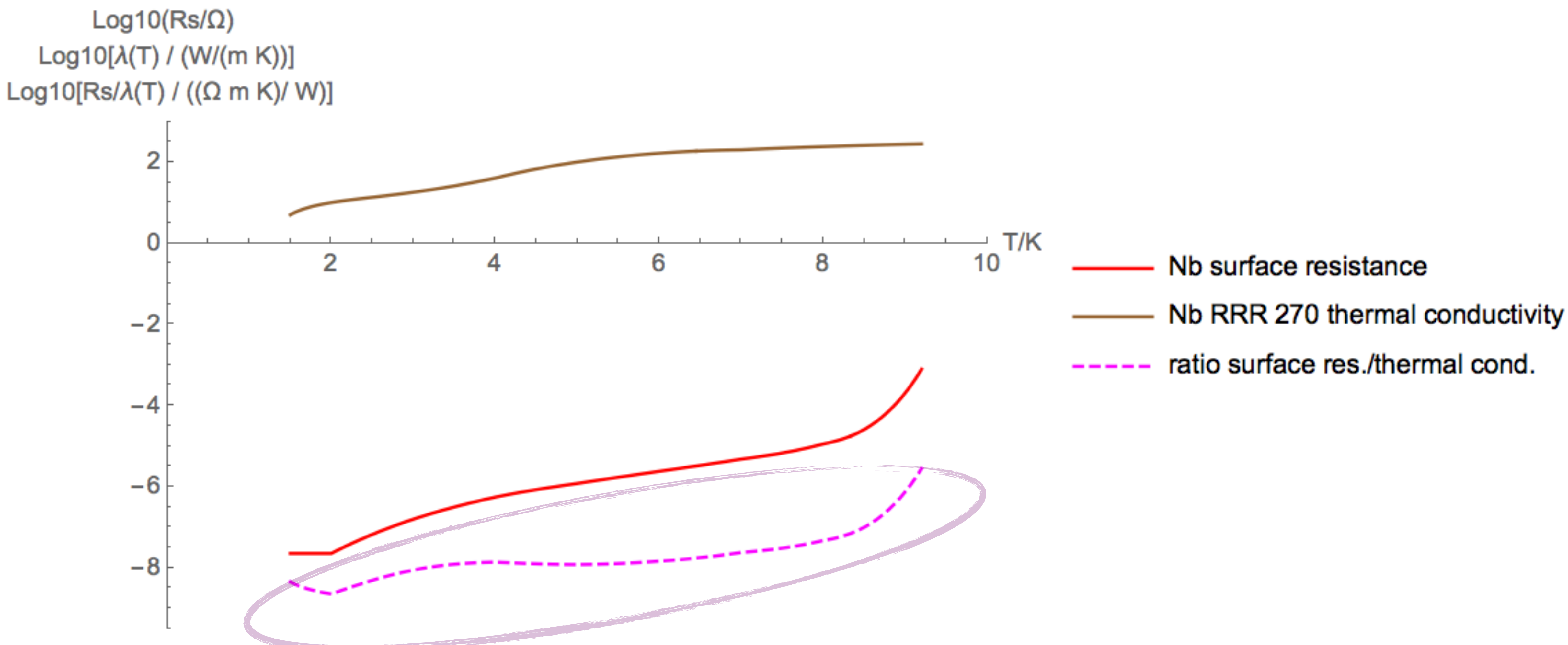




author ??, very recommendable source: uspas.fnal.gov/materials/13Duke/SCL_Chap1.pdf

data close to Halbitter SRIMP, now online https://www.classe.cornell.edu/~liepe/webpage/researchsrimp.html

Temperature-dependent Nb surface resistance and thermal conductivity



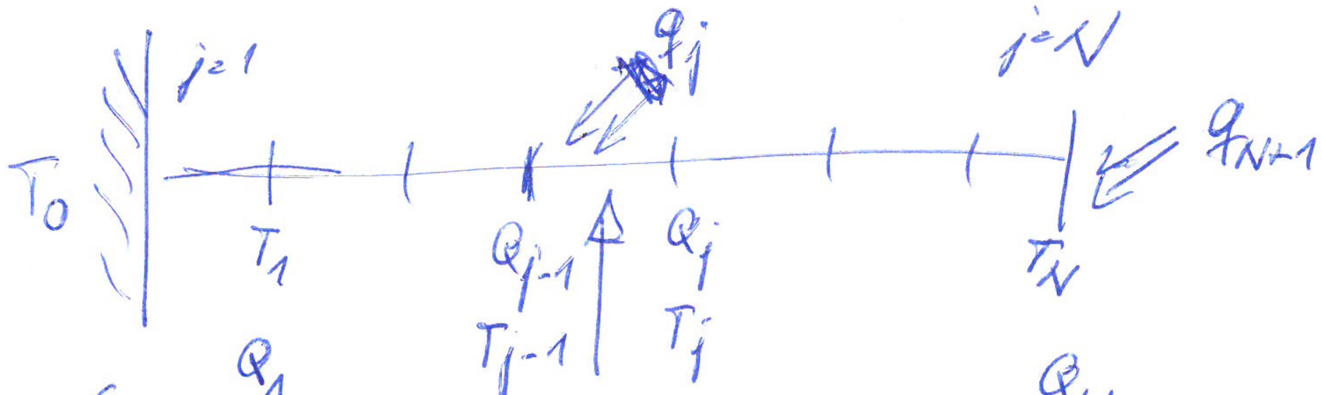
surface resistance ~ dissipated power grows faster than thermal conductivity ⇒ the colder, the cooler

1-dimensional model of stationary heat flux

T1

25.11.15

Alles Stationär.



Element j :

$$Q_{j-1} = Q_j + q_j$$

$q_j > 0$ für deponierte Wärmeleistung

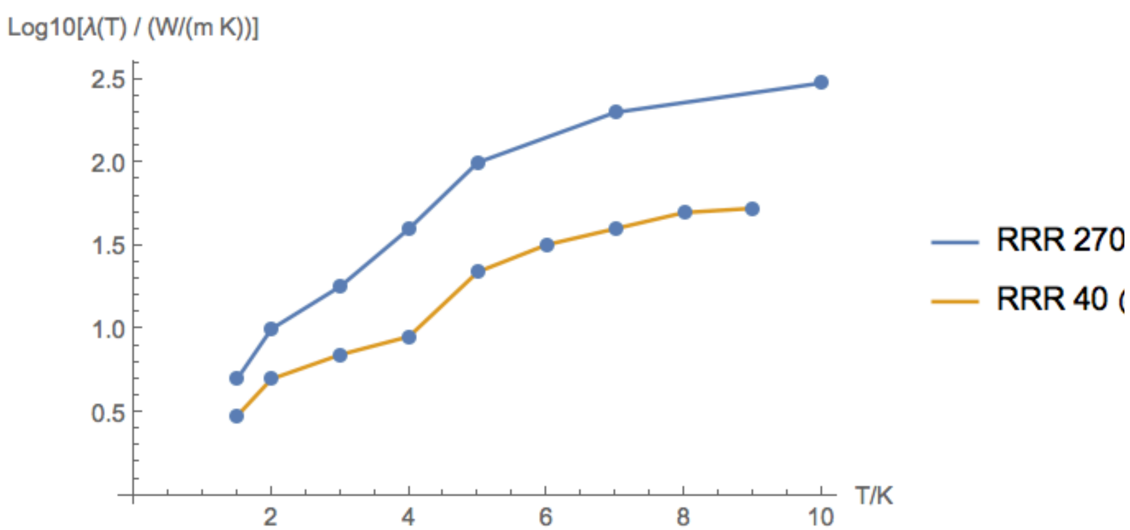
$$T_j = T_{j-1} + Q_j \cdot \frac{l_j}{\lambda_j A_j} + q_j \frac{l_j}{2 \lambda_j A_j}$$

positiver Wärmestrom bedeutet $T_j > T_{j-1}$

T_0: kalt, T_N warm

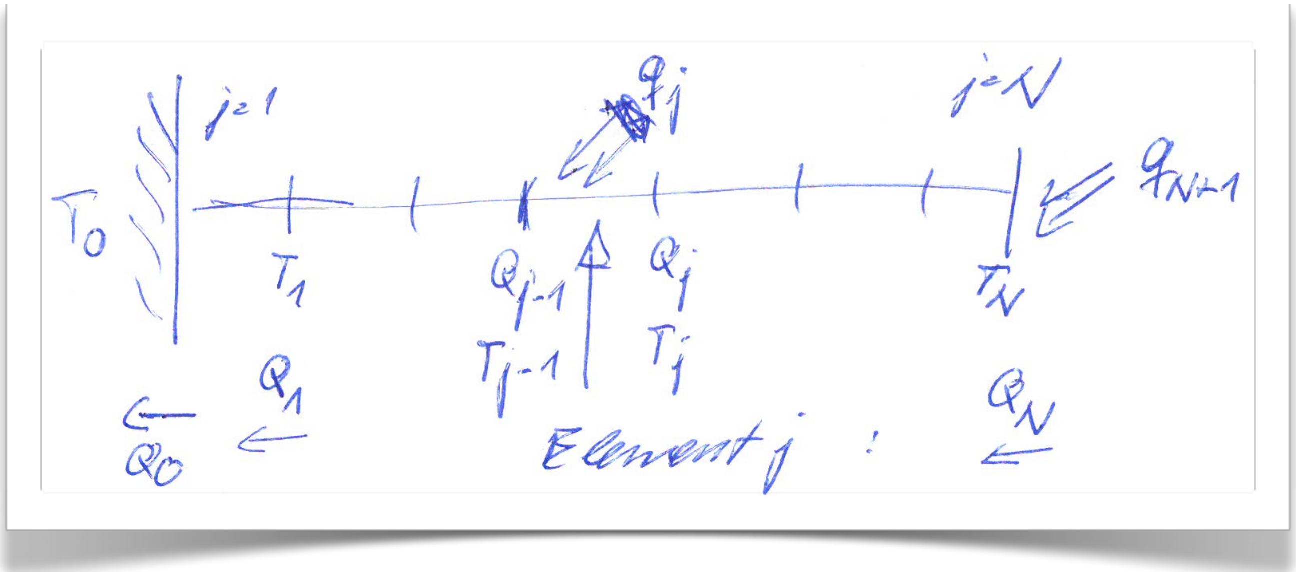
zusätzlicher Wärmeeintrag wird nur auf halber Länge gezählt

$$\lambda_j = \lambda_j\left(\frac{T_j + T_{j-1}}{2}\right)$$



H.-W. Glock, HZB

1-dimensional model of stationary heat flux



essentially a series of *heat flux resistors*, unfortunately strongly temperature-dependent

and a chain of *heat flux sources*, temperature- and EM-field-dependent

$$\Rightarrow T_1 = T_0 + \frac{l_1}{\lambda_1\left(\frac{T_0+T_1}{2}\right) A_1} \cdot \left(\frac{q_1}{2} + \sum_{j=2}^{N+1} q_j \right)$$

$$T_2 = T_1 + \frac{l_2}{\lambda_2(T_1+T_2)\, A_2} \left(\frac{q_2}{2} + \sum_{j=3}^{N+1} q_j \right) =$$

$$= T_0 + \frac{l_1}{\lambda_1\left(\frac{T_0+T_1}{2}\right) A_1} \left(\frac{q_1}{2} + \sum_{j=2} q_j \right) + \frac{l_2}{\lambda_2(T_1+T_2)\, A_2} \left(\frac{q_2}{2} + \sum_{j=3}^{N+1} q_j \right)$$

$$T_3 = T_2 + \frac{l_3}{\lambda_3\left(\frac{T_2+T_3}{2}\right) A_3} \left(\frac{q_3}{2} + \sum_{j=4}^{N+1} q_j \right) = \Rightarrow$$

$$\Rightarrow T_3 = T_0 + \frac{l_1}{\lambda_1\left(\frac{T_0+T_1}{2}\right) A_1} \left(\frac{q_1}{2} + \sum_{j=2}^{N+1} q_j \right) + \frac{l_2}{\lambda_2\left(\frac{T_1+T_2}{2}\right) A_2} \left(\frac{q_2}{2} + \sum_{j=3}^{N+1} q_j \right) + \frac{l_3}{\lambda_3\left(\frac{T_2+T_3}{2}\right) A_3} \left(\frac{q_3}{2} + \sum_{j=4}^{N+1} q_j \right)$$

$$t0 + \frac{l1\left(\frac{q1}{2}+q2+q3+q4+q5\right)}{a1\,\lambda fu\left[\frac{t0+\tau 1}{2}\right]}$$

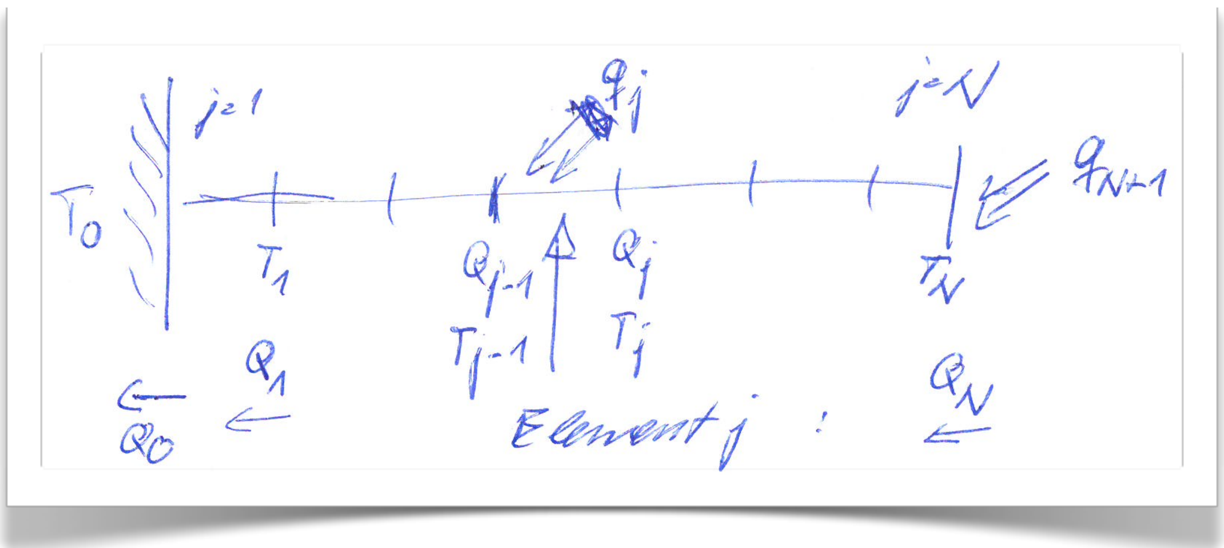
$$t0 + \frac{l1\left(\frac{q1}{2}+q2+q3+q4+q5\right)}{a1\,\lambda fu\left[\frac{t0+\tau 1}{2}\right]} + \frac{l2\left(\frac{q2}{2}+q3+q4+q5\right)}{a2\,\lambda fu\left[\frac{\tau 1+\tau 2}{2}\right]}$$

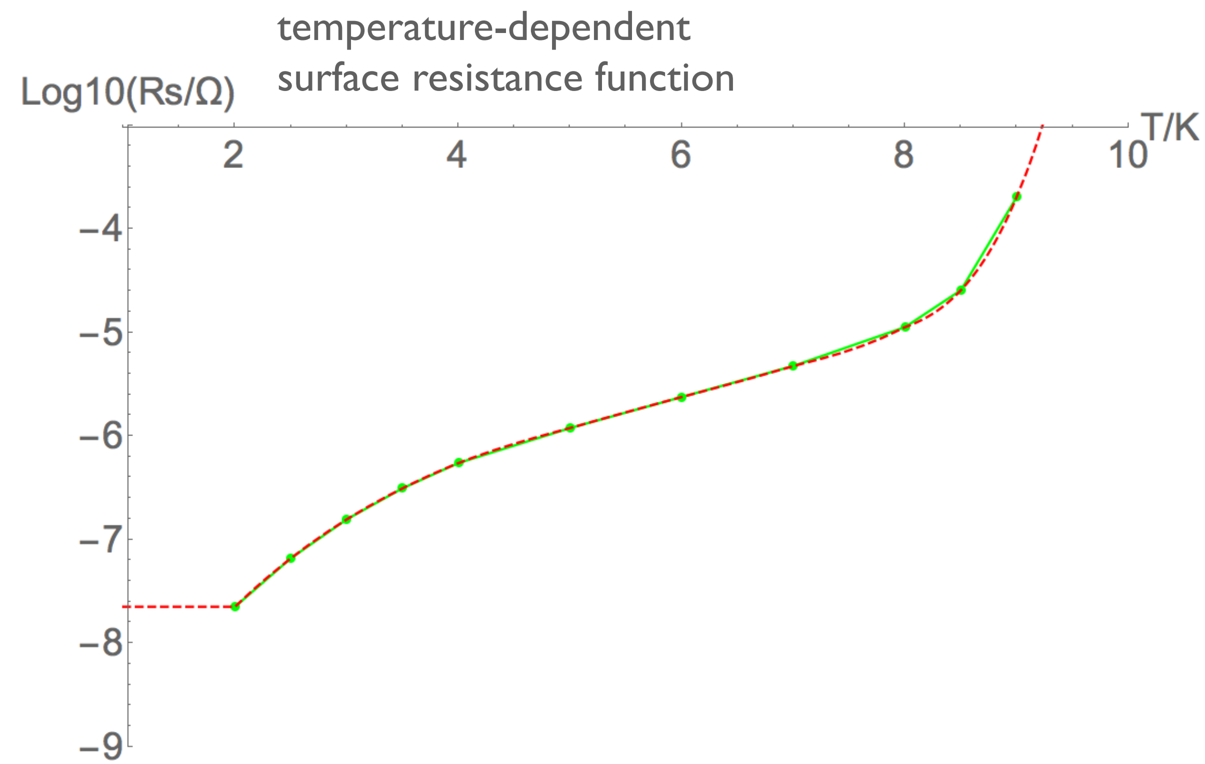
$$t0 + \frac{l1\left(\frac{q1}{2}+q2+q3+q4+q5\right)}{a1\,\lambda fu\left[\frac{t0+\tau 1}{2}\right]} + \frac{l2\left(\frac{q2}{2}+q3+q4+q5\right)}{a2\,\lambda fu\left[\frac{\tau 1+\tau 2}{2}\right]} + \frac{l3\left(\frac{q3}{2}+q4+q5\right)}{a3\,\lambda fu\left[\frac{\tau 2+\tau 3}{2}\right]}$$

$$t0 + \frac{l1\left(\frac{q1}{2}+q2+q3+q4+q5\right)}{a1\,\lambda fu\left[\frac{t0+\tau 1}{2}\right]} + \frac{l2\left(\frac{q2}{2}+q3+q4+q5\right)}{a2\,\lambda fu\left[\frac{\tau 1+\tau 2}{2}\right]} + \frac{l3\left(\frac{q3}{2}+q4+q5\right)}{a3\,\lambda fu\left[\frac{\tau 2+\tau 3}{2}\right]} + \frac{l4\left(\frac{q4}{2}+q5\right)}{a4\,\lambda fu\left[\frac{\tau 3+\tau 4}{2}\right]}$$

$$t0 + \frac{l1\left(\frac{q1}{2}+q2+q3+q4+q5\right)}{a1\,\lambda fu\left[\frac{t0+\tau 1}{2}\right]} + \frac{l2\left(\frac{q2}{2}+q3+q4+q5\right)}{a2\,\lambda fu\left[\frac{\tau 1+\tau 2}{2}\right]} + \frac{l3\left(\frac{q3}{2}+q4+q5\right)}{a3\,\lambda fu\left[\frac{\tau 2+\tau 3}{2}\right]} + \frac{l4\left(\frac{q4}{2}+q5\right)}{a4\,\lambda fu\left[\frac{\tau 3+\tau 4}{2}\right]} + \frac{l5\,q5}{2\,a5\,\lambda fu\left[\frac{\tau 4+\tau 5}{2}\right]}$$

1-dimensional model of stationary heat flux: sources





ferner $q_k = B_k \cdot R\left(\frac{T_{k-1}+T_k}{2}\right) \cdot \overline{H^2}_{tan,k}$

Innen Fläche

Oberflächenwiderstand @1,3GHz

über B_k gemittelte quadrierte Oberflächenstromdichte

```
linienLeistung[rs_, x_] := 2 π 0.055 Meter rs/2 (hφ[x] Ampere / Meter)^2
```

beam pipe radius

```
liLeiD110[rs_, x_] := 2 π 0.055 rs/2 hφ[x]^2
```

position-dependent surface current density (cf. page 7)

temperature-dependent surface resistance function

artificial power scaling factor for easing convergence

```
qvec = liLeiD110[nbBCS1p3GHzIP[#[[1]]], #[[2]] ] * #[[3]] * powerscale & /@
  Transpose[{(tkvec + tksupvec) / 2, absLkvec, lkvec}];
```

average temperature of segments

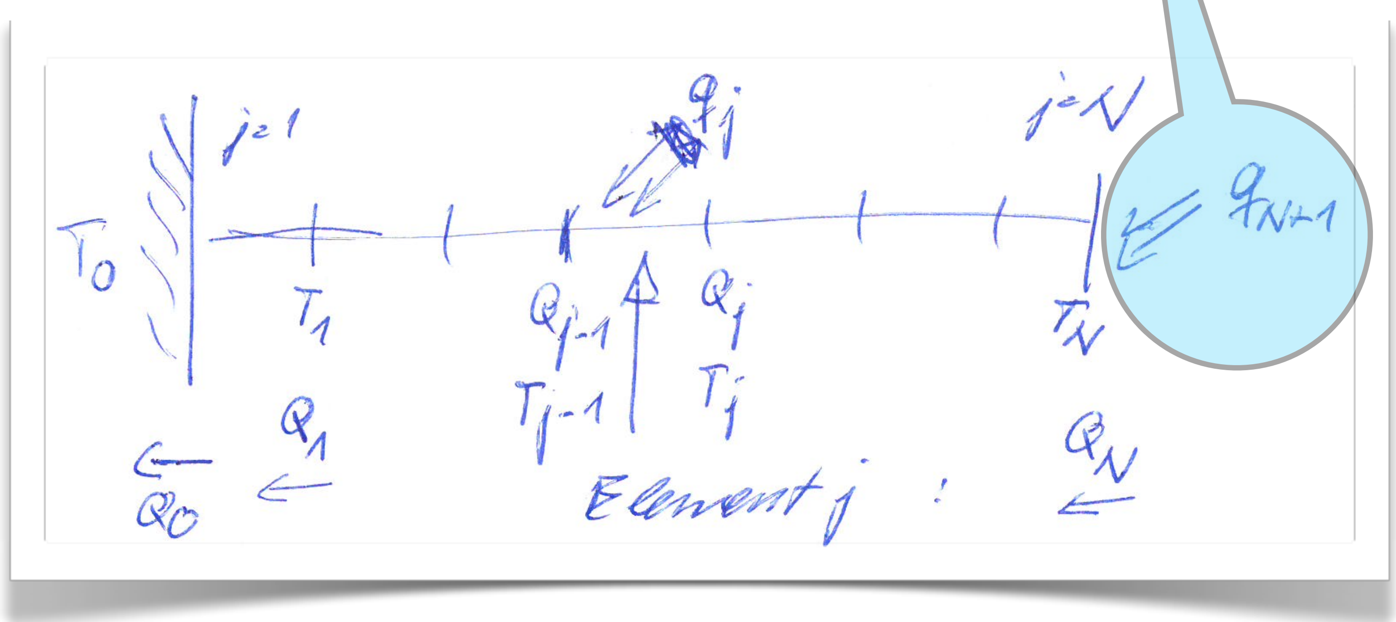
distances to reference plane

lengths of individual segments

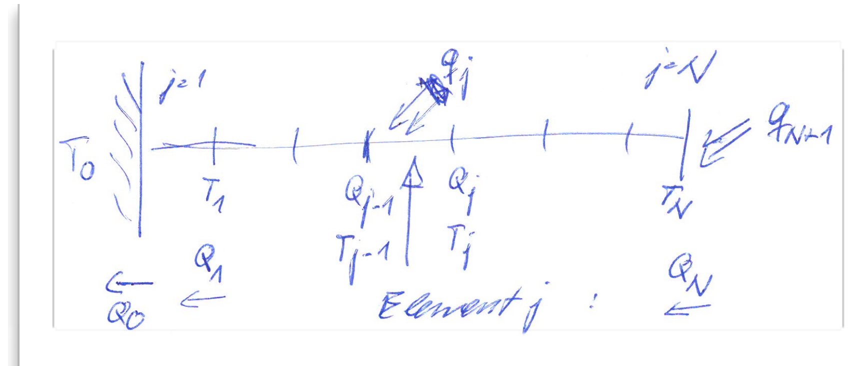
1-dimensional model of stationary heat flux: sources II

```
qvec = liLeiD110[nbBCS1p3GHzIP[#[[1]]], #[[2]] ] * #[[3]] * powerscale & /@
  Transpose[{(tkvec + tksupvec) / 2, absLkvec, lkvec}];
qvec = qvec + Join[Table[0, {Length[qvec] - 1}], {poweradd}];
```

additional power incident at the chain's end



1-dimensional model of stationary heat flux: iterator




```
In[103]:= increment = 0.001
```

define the power growth rate during iteration

```
Out[103]= 0.001
```

```
In[174]:= iteRad = NestList[
```

do everything repeatedly and store all intermediate steps

```
    {setSystemTkQkD110U25MV[
```

compute new temperature distribution based on ...

```
        #[[1]],
```

... old temperature distribution ...,

```
        2,
```

... T_0 at leftmost boundary, here T0 = 2K, ...

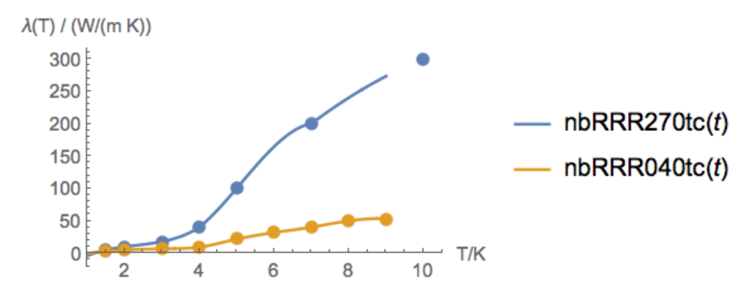
```
        Table[0.001, {100}],
```

... interval lengths, here 100 intervals of 1 mm length, ...

```
        Table[π * (0.058² - 0.055²), {100}],
```

... table of interconnecting surfaces, here all 3 mm thick pipes of 55 mm inner radius, ...

```
        nbRRR270tc,
```



... temperature dependent thermal conductivity, here of Nb RRR 270, ...

```
        1,
```

... overall scaling of powers, here no scaling ...

```
        8,
```

... additional power at the chain's end, here 8 W ...

```
        #[[2]]],
```

... iteration dependent scaling of power.

```
      If[#[[2]] + increment > 1, 1, #[[2]] + increment]
```

increment power scaling in every step by 1 ‰

```
    } &,
    {Table[2, {100}], 0.001},
```

start iteration with overall temperature of 2 K for all 100 segments, initial power scaling 0.001

```
    1100];
```

do 1100 steps

```
(Flatten[{#[[2]], #[[1]]}] & /@ iteRad)[[1 ;; -1 ;; 50, 1 ;; -1 ;; 10]] // TableForm
```

write iteration-dependent scaling as first entry; show every 50th iteration; show every 10th segment

1-dimensional model of stationary heat flux: typical result

write iteration-dependent scaling as first entry

all temperatures in K

show every 10th segment

show every 50th iteration

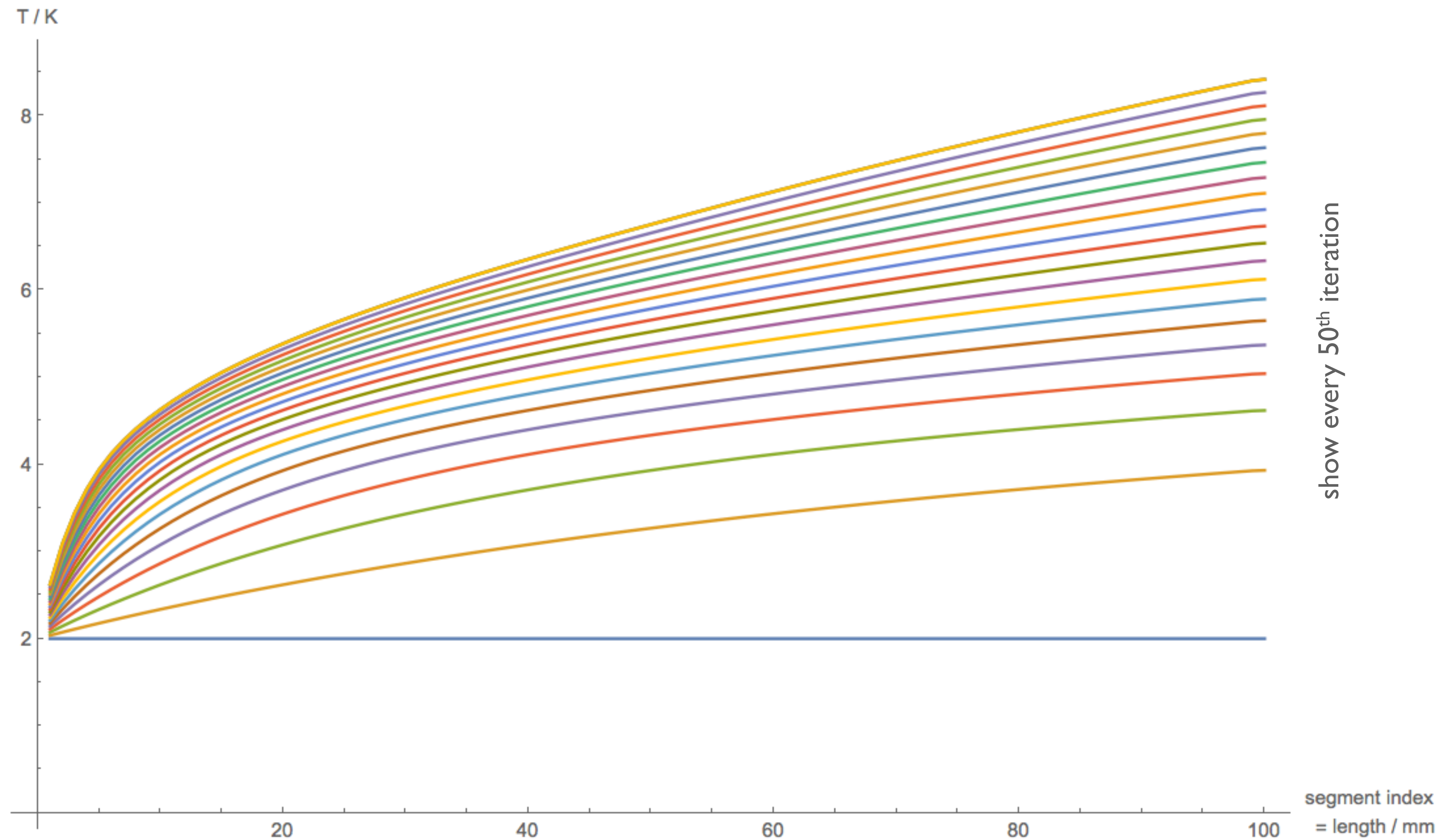
Out[175]//TableForm=

0.001	2	2	2	2	2	2	2	2	2	2
0.051	2.336	2.61874	2.86418	3.07858	3.26711	3.43336	3.58055	3.71168	3.82939	3.93078
0.101	2.61829	3.07693	3.43034	3.70743	3.93064	4.11478	4.26788	4.39987	4.51684	4.6175
0.151	2.86317	3.42982	3.82358	4.11331	4.3343	4.5149	4.66992	4.80722	4.93142	5.04005
0.201	3.07698	3.70647	4.11295	4.3975	4.61986	4.80647	4.96965	5.11618	5.25023	5.36855
0.251	3.26491	3.92938	4.3338	4.61979	4.849	5.0445	5.21748	5.37426	5.51884	5.64731
0.301	3.4306	4.11328	4.51438	4.80645	5.04457	5.25002	5.43339	5.60083	5.75624	5.89517
0.351	3.57727	4.26633	4.6696	4.96986	5.2178	5.43364	5.62771	5.80604	5.97256	6.12226
0.401	3.70796	4.39841	4.80716	5.11672	5.37494	5.60144	5.80641	5.99589	6.17385	6.33479
0.451	3.82545	4.51555	4.9317	5.25115	5.51991	5.75726	5.97334	6.17427	6.36413	6.53689
0.501	3.93171	4.62159	5.04625	5.37595	5.65544	5.90382	6.13126	6.34403	6.54636	6.73176
0.551	4.0287	4.71892	5.15284	5.49303	5.7834	6.04299	6.28211	6.50721	6.72278	6.92189
0.601	4.11641	4.80925	5.25291	5.60376	5.90515	6.1762	6.42739	6.66545	6.89523	7.1085
0.651	4.19648	4.89389	5.34761	5.70925	6.02183	6.3046	6.56834	6.82015	7.06508	7.28874
0.701	4.27033	4.97376	5.43779	5.81034	6.13429	6.42912	6.70599	6.97251	7.23001	7.46296
0.751	4.33879	5.04941	5.52396	5.90755	6.24309	6.55039	6.8411	7.12231	7.38975	7.63182
0.801	4.40337	5.12181	5.60696	6.00171	6.34908	6.66931	6.97471	7.26792	7.54506	7.79612
0.851	4.46405	5.19102	5.68694	6.09301	6.4525	6.78623	7.10644	7.40956	7.69627	7.9562
0.901	4.52151	5.25754	5.76436	6.1819	6.55386	6.90175	7.23485	7.5477	7.84385	8.11254
0.951	4.57668	5.32199	5.83975	6.26893	6.65373	7.01658	7.36043	7.68288	7.98836	8.26571
1	4.62906	5.38413	5.913	6.35406	6.75218	7.12951	7.48319	7.81515	8.12987	8.41581
1	4.62826	5.38322	5.912	6.353	6.75106	7.12834	7.48195	7.81384	8.12849	8.41437
1	4.62826	5.38322	5.912	6.353	6.75106	7.12834	7.48195	7.81384	8.12849	8.41437

iteration stabilizes well after 1000 steps with increasing power and 100 more steps with constant power (probably also less steps sufficient); computing takes a few seconds

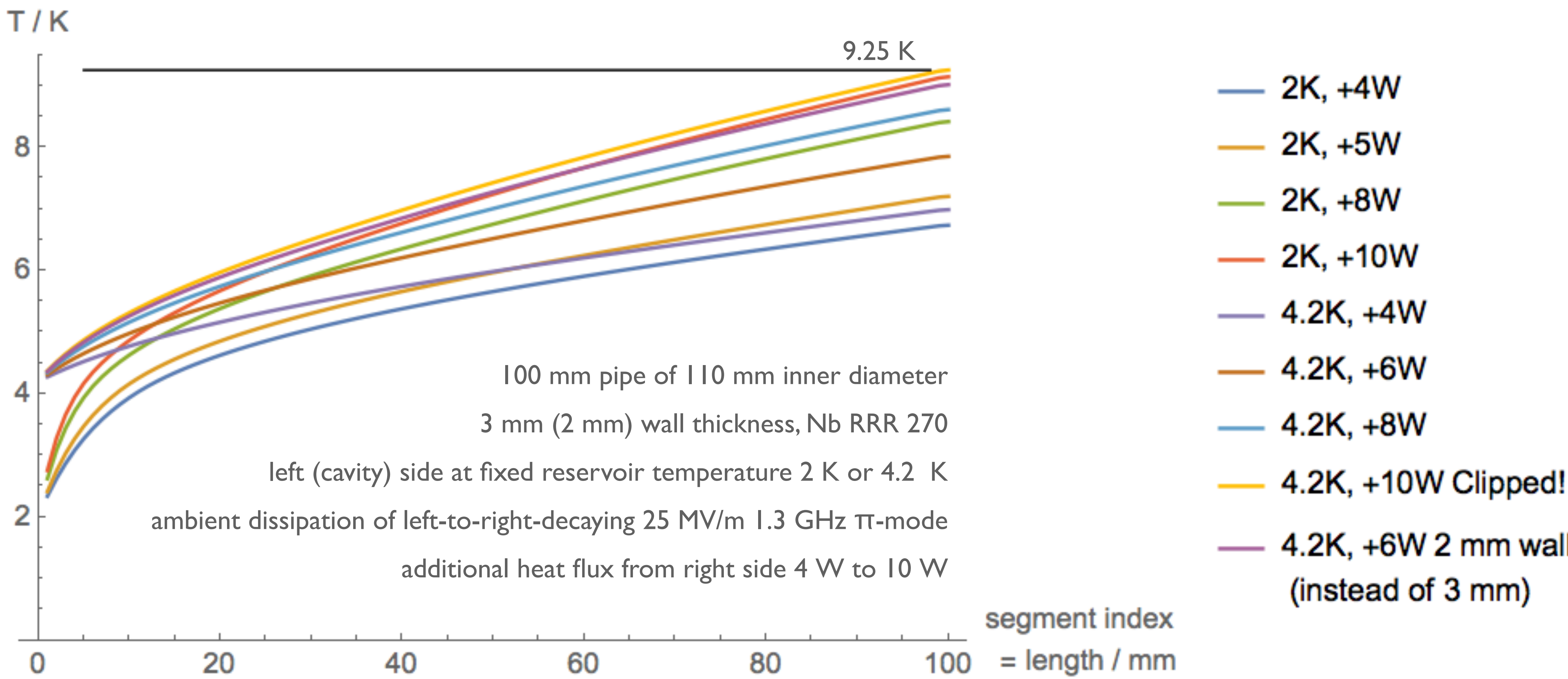
1-dimensional model of stationary heat flux: typical result

```
ListPlot[(#[[1]] & /@ iteRad)[[1 ;; -1 ;; 50]], Joined → True, AxesLabel → {"segment index \n = length / mm", "T / K"}]
```



iteration stabilizes well after 1000 steps with increasing power and 100 more steps with constant power (probably also less steps sufficient); computing takes a few seconds

1-dimensional model of stationary heat flux: different scenarios



Superconducting limit (almost) reached either by:

– 10 W additional power, 2 K reservoir temperature

– 8 W additional power, 4.2 K reservoir temperature

– 6 W additional power, 4.2 K reservoir temperature, 2 mm wall thickness

Conclusions:

fundamental mode decay in a D110 mm circular pipe *causes ~ 4 W additional losses* if the inner 150 mm (of 405 mm) are made of stainless steel

a straight beam pipe of 100 mm length and attached to the 25 MV/m, 1.3 GHz π-mode *can be bridged remaining superconducting* without additional cooling if

– a high RRR (here 270) is used

– wall thickness of 3 mm is used

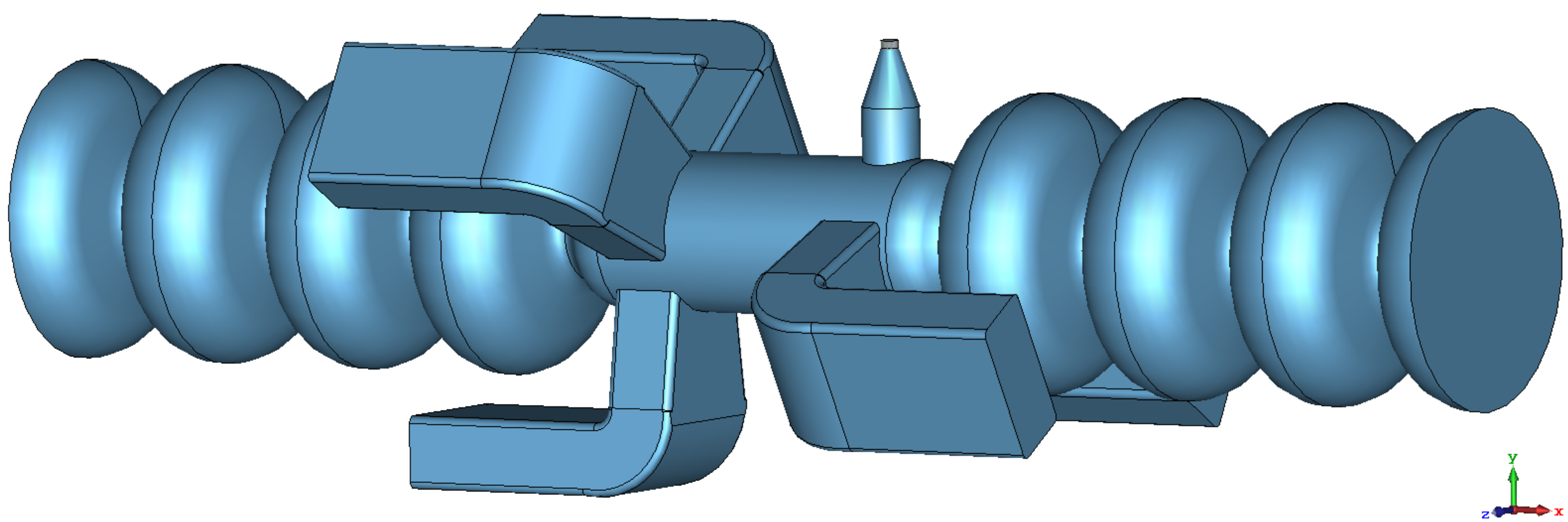
– cavity side has reservoir temperature of 2 K (or lower)

– additional heat load remains below 10 W

higher

… so, let us compute some eigenmodes of a:

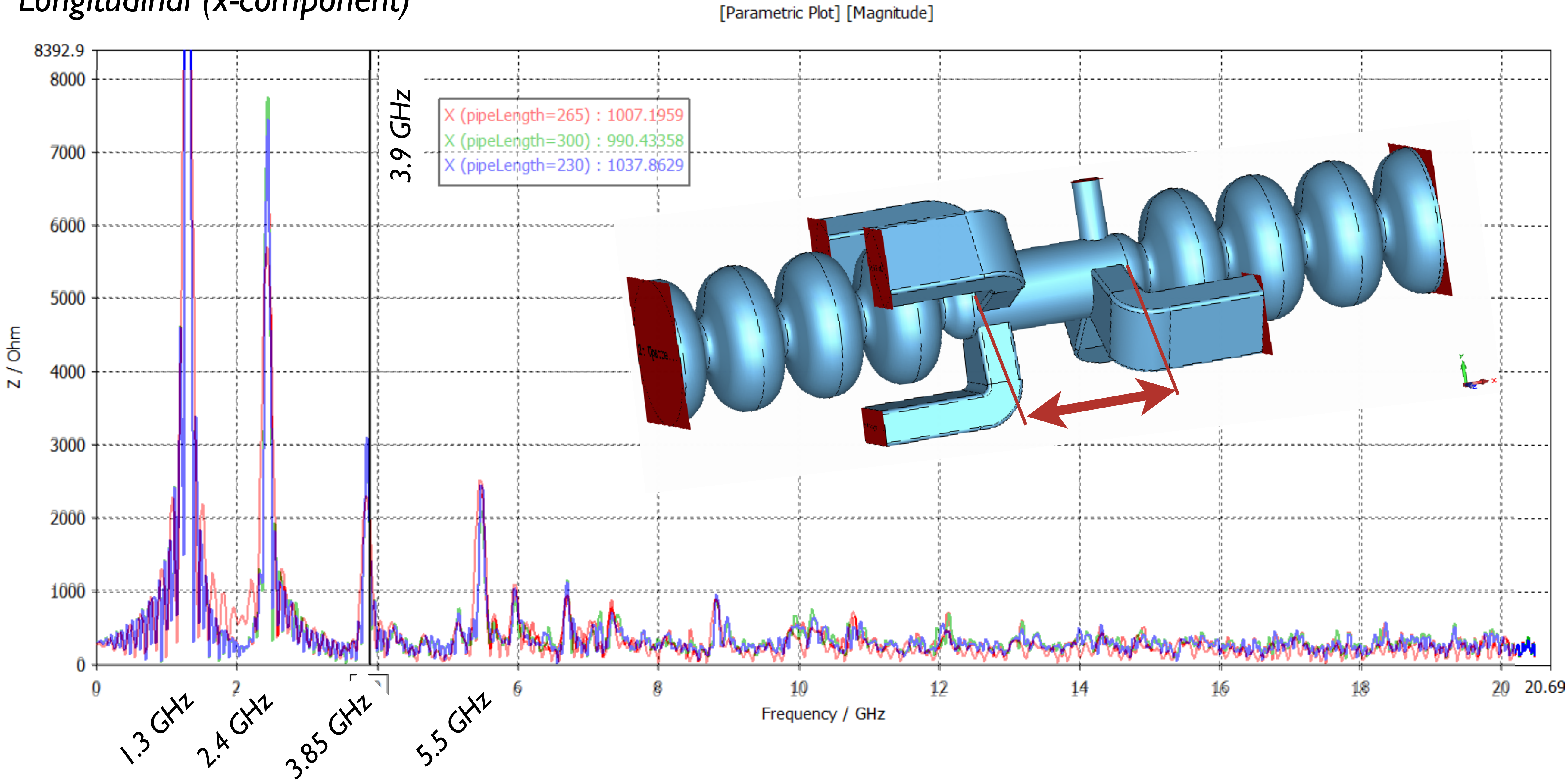
- *7-cell elliptical cavity*
- *strongly HOM-damped with 5 waveguides*
- *a fundamental power coupler*
- *and a beam pipe*



– *which is going to be placed in a chain of identical neighbors, so we would like to study the beam-pipe-coupling as well*

A wake-solver result: Impedance Simulations with variation of pipe length

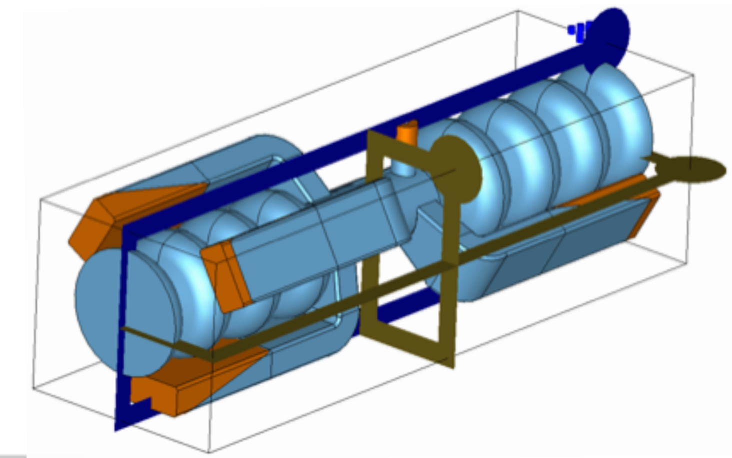
Longitudinal (x-component)

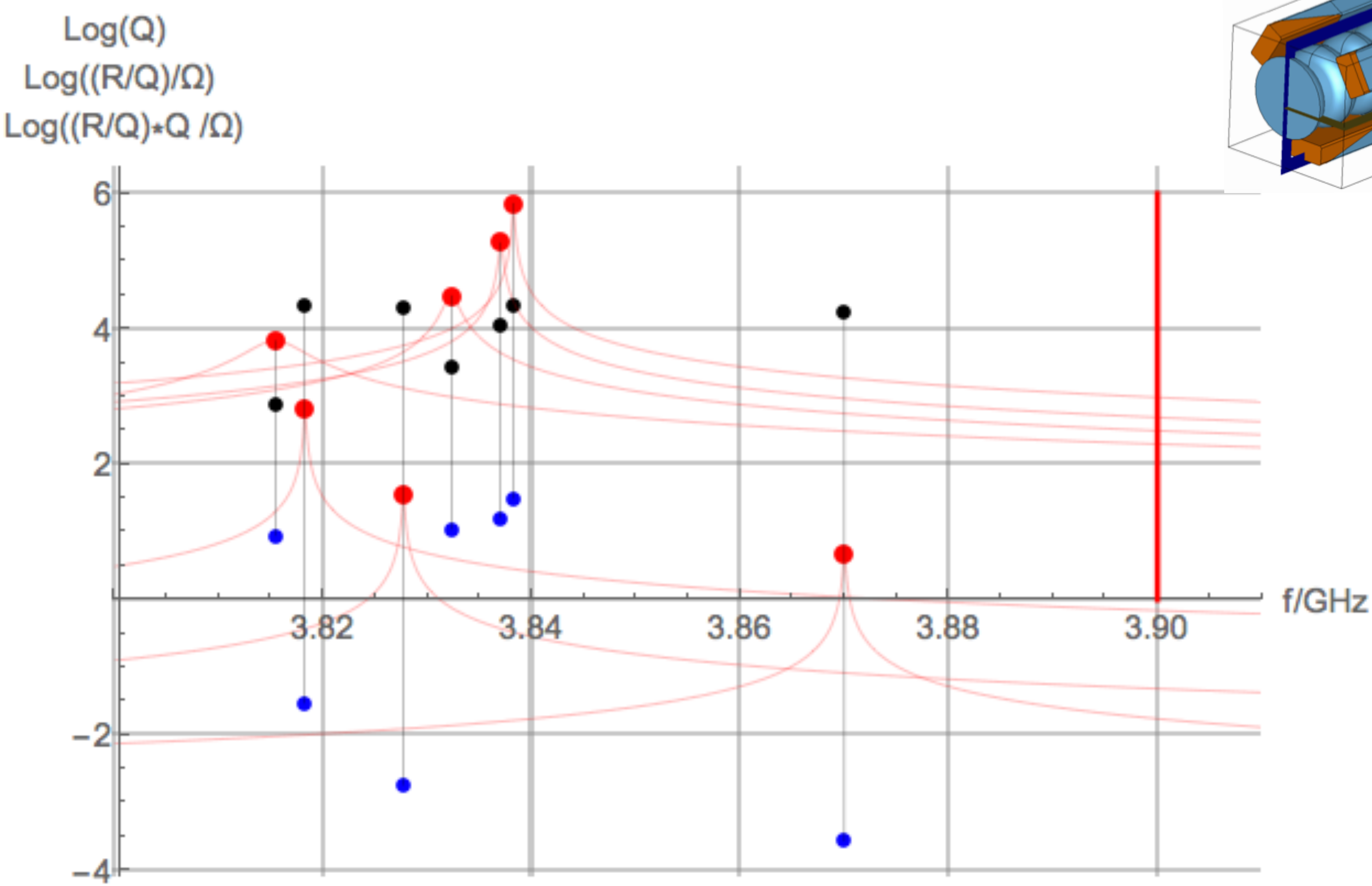


– longitudinal impedance independent on pipe length ⇒ no pipe-trapped fields contributing

– few, but significant peaks; none of them on bERLinPro's beam harmonics N · 1.3 GHz, but two very close (@ ≈ 3.85 GHz, ≈ 5.15 GHz)

Eigenmode computations close to 3.9 GHz



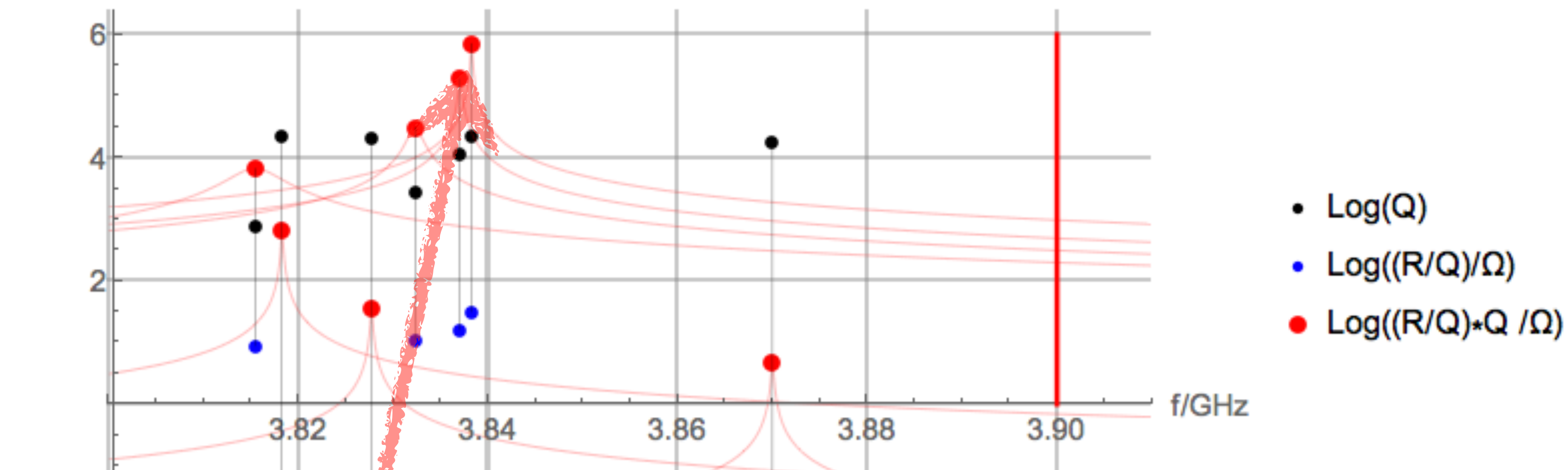


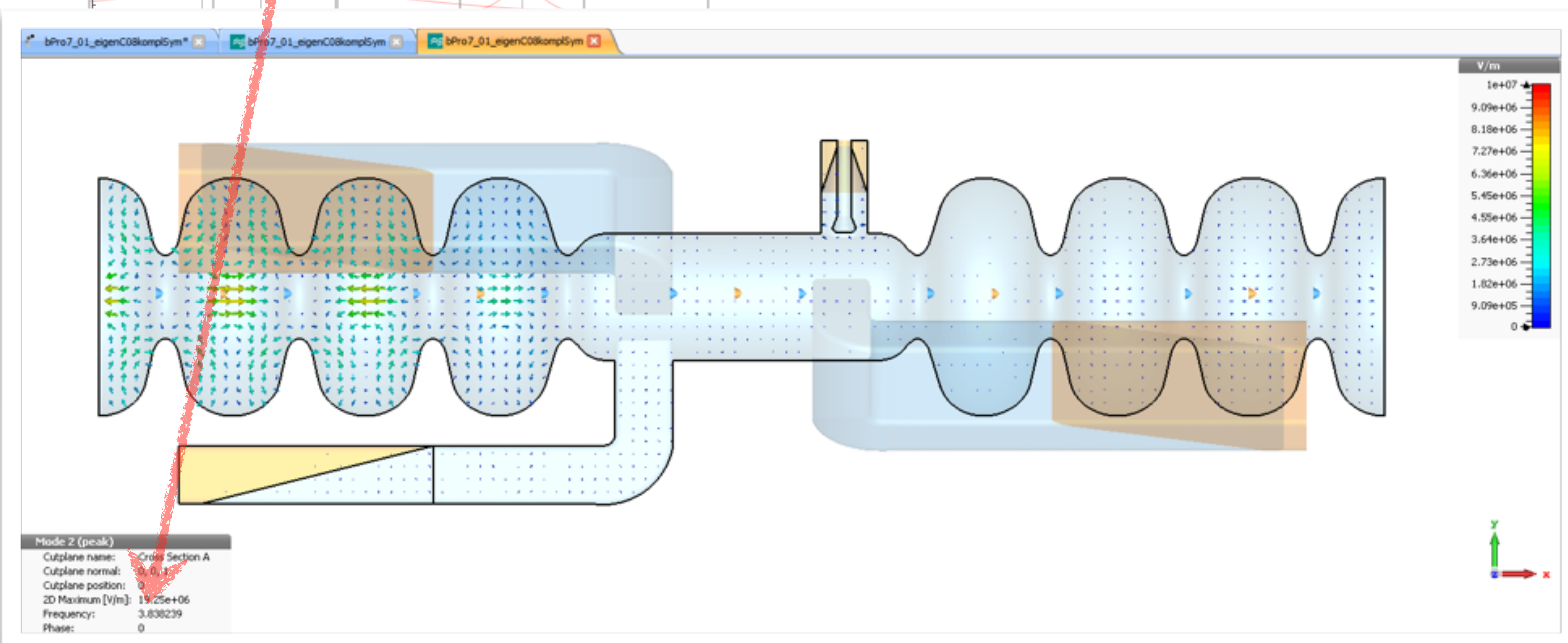
– no Q's > 2.5 $\cdot 10^4$ observed

– set of relevant (R/Q)'s ~ 10 ... 30 Ω found

– close, but not too close to 3.900 GHz

Eigenmode computations close to 3.9 GHz

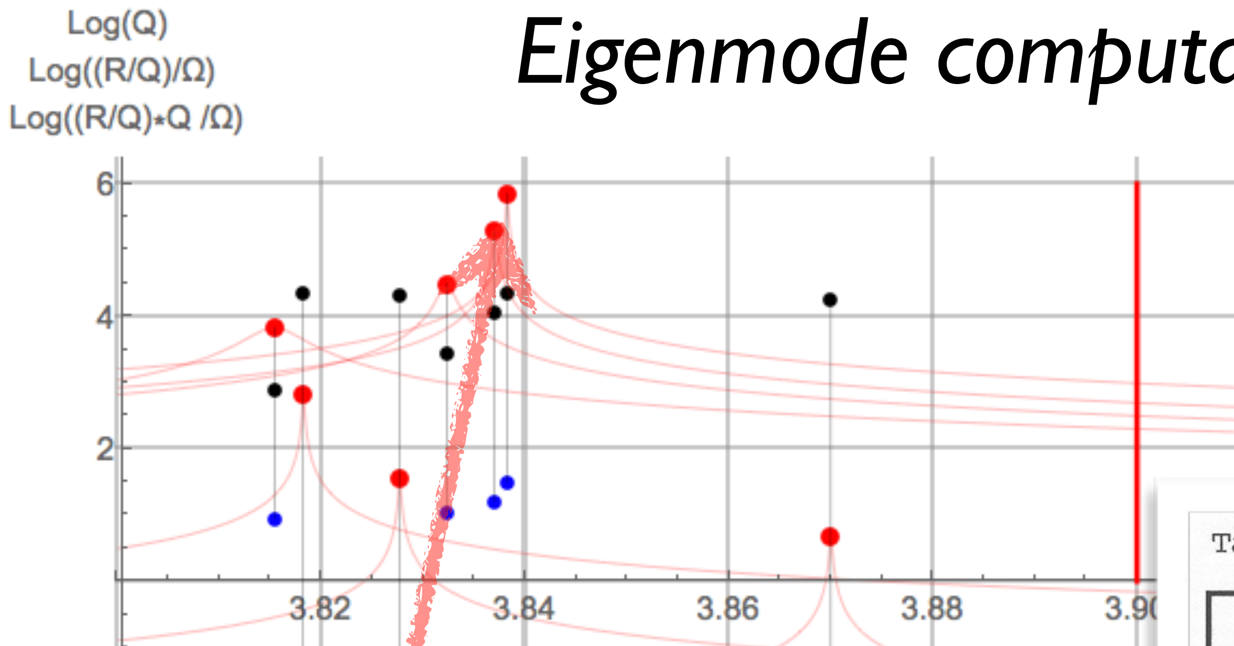


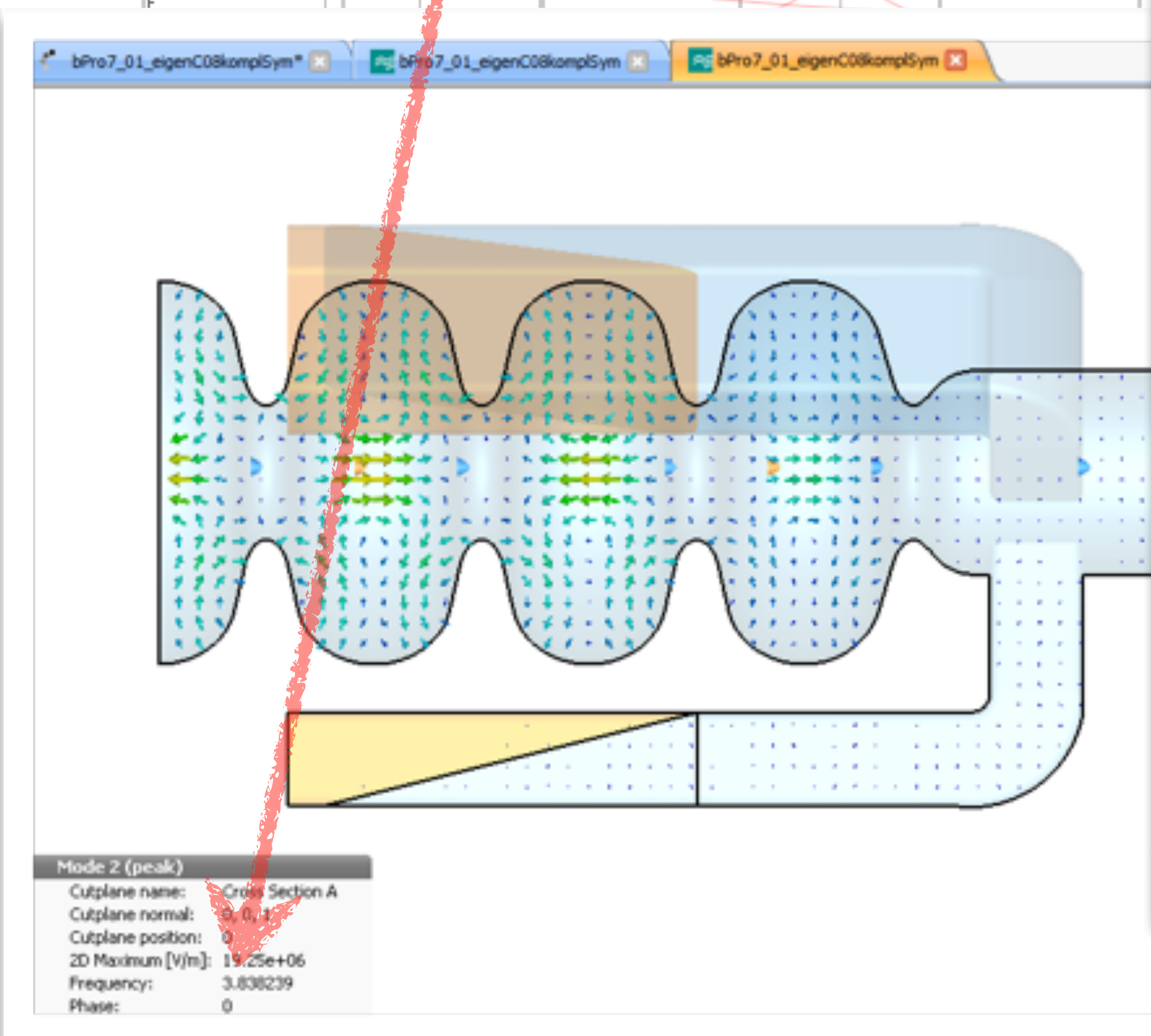


– $TM_{\varphi=0,\, r=1,\, z=2}$ –type: monopole, on axis longitudinal E-field

– f = 3.838239 GHz, Q = $2.286 \cdot 10^4$, R/Q = 31.4 Ω

Eigenmode computations close to 3.9 GHz





HIGHER ORDER MODE COUPLER FOR TESLA

TESLA-Report 1994-07

Jacek Sekutowicz

DESY, Notkestraße 85, 22607 Hamburg, FRG

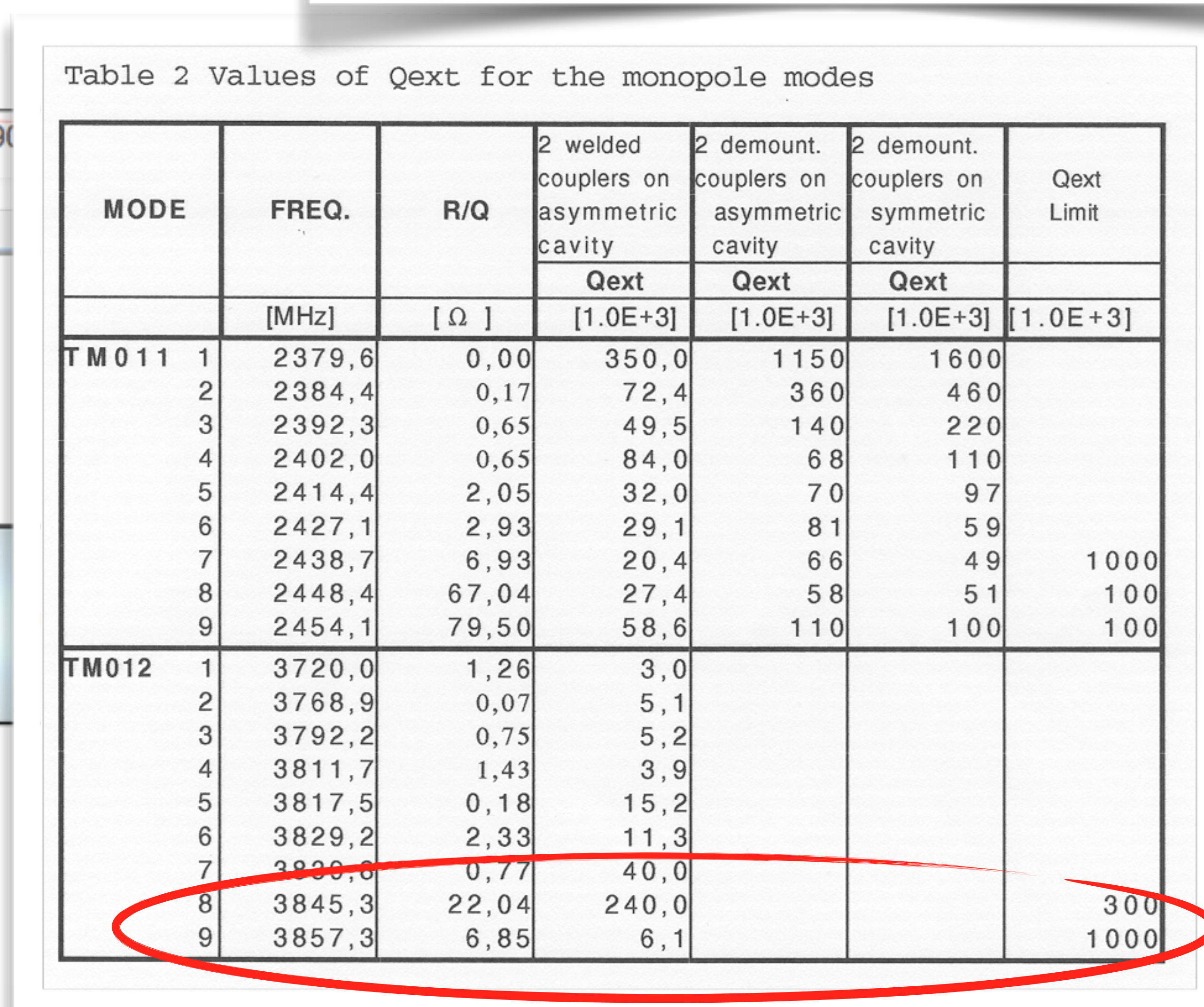


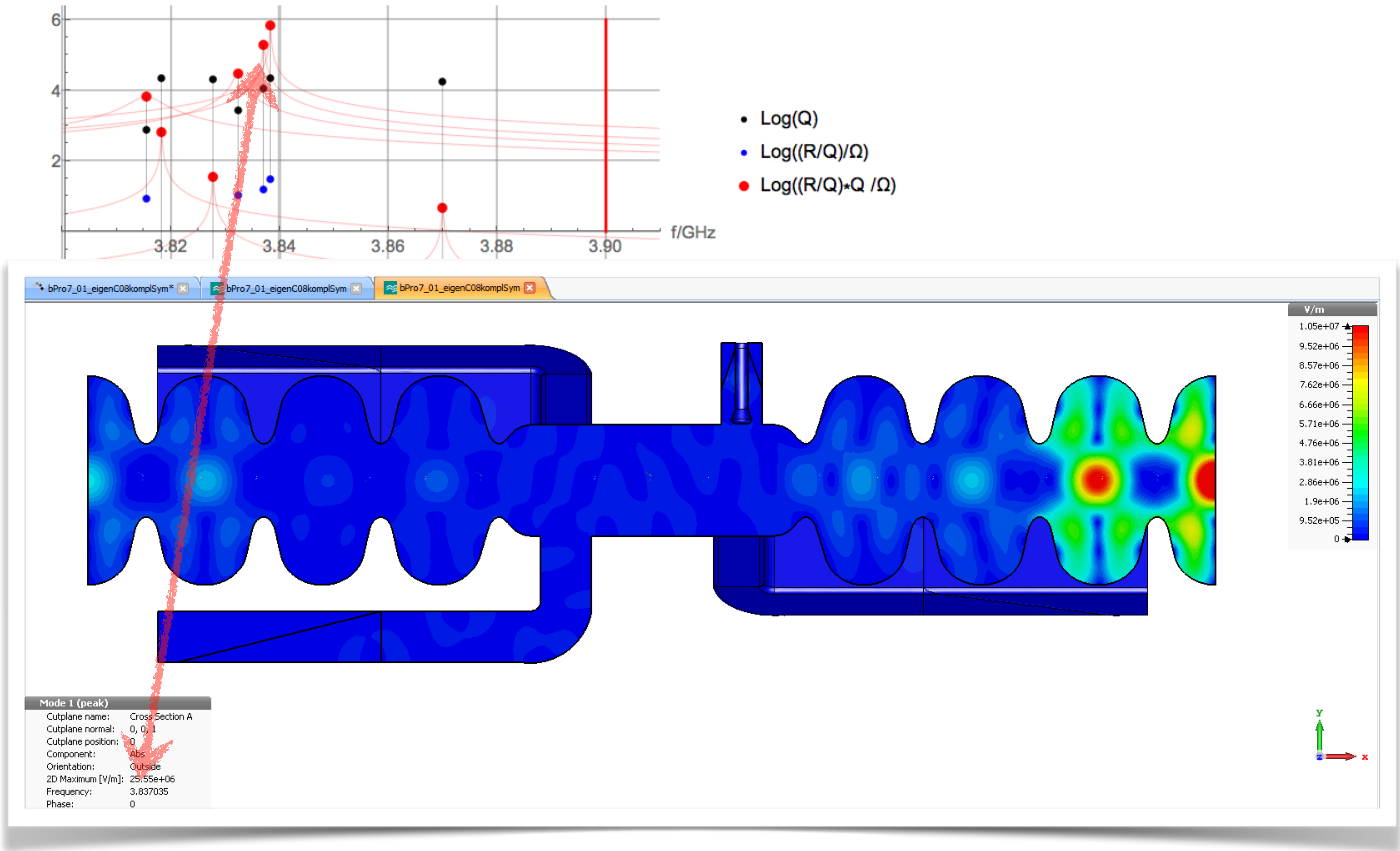
Table 2 Values of Qext for the monopole modes

MODE		FREQ.	R/Q	2 welded couplers on asymmetric cavity	2 demount. couplers on asymmetric cavity	2 demount. couplers on symmetric cavity	Qext Limit
				Qext	Qext	Qext	
		[MHz]	[Ω]	[1.0E+3]	[1.0E+3]	[1.0E+3]	[1.0E+3]
TM011	1	2379,6	0,00	350,0	1150	1600	
	2	2384,4	0,17	72,4	360	460	
	3	2392,3	0,65	49,5	140	220	
	4	2402,0	0,65	84,0	68	110	
	5	2414,4	2,05	32,0	70	97	
	6	2427,1	2,93	29,1	81	59	
	7	2438,7	6,93	20,4	66	49	1000
	8	2448,4	67,04	27,4	58	51	100
	9	2454,1	79,50	58,6	110	100	100
TM012	1	3720,0	1,26	3,0			
	2	3768,9	0,07	5,1			
	3	3792,2	0,75	5,2			
	4	3811,7	1,43	3,9			
	5	3817,5	0,18	15,2			
	6	3829,2	2,33	11,3			
	7	3830,6	0,77	40,0			
	8	3845,3	22,04	240,0			300
	9	3857,3	6,85	6,1			1000

– $TM_{\varphi=0,\, r=1,\, z=2}$ –type

– f = 3.838239 GHz, Q = $2.286 \cdot 10^4$, R/Q = 31.4 Ω

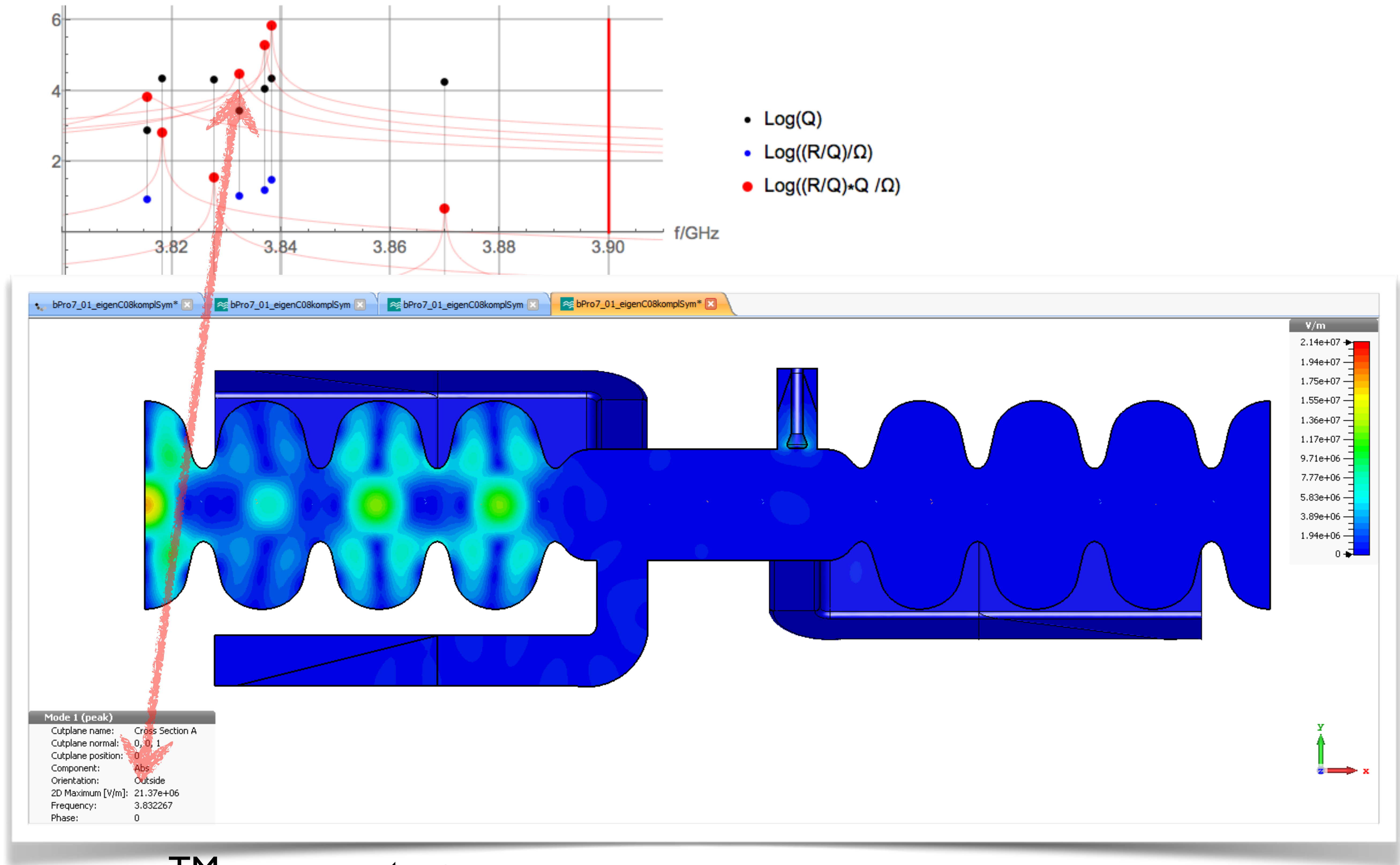
Eigenmode computations close to 3.9 GHz



– $TM_{\varphi=0, r=1, z=2}$ –type

– f = 3.837035 GHz, Q = $1.166 \cdot 10^4$, R/Q = 16.2 Ω

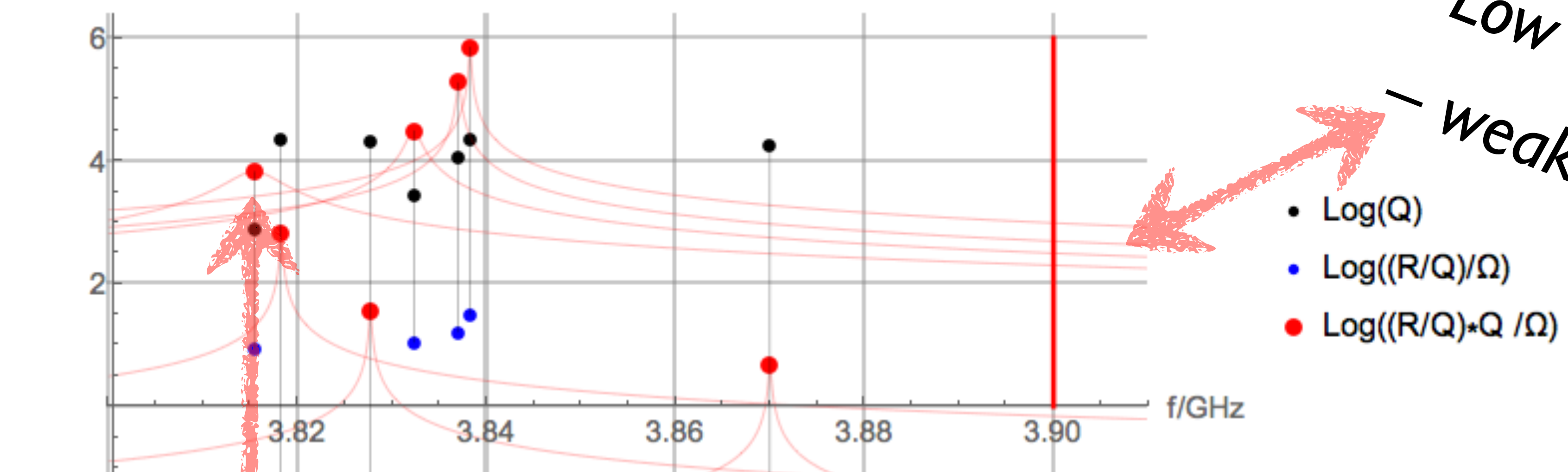
Eigenmode computations close to 3.9 GHz



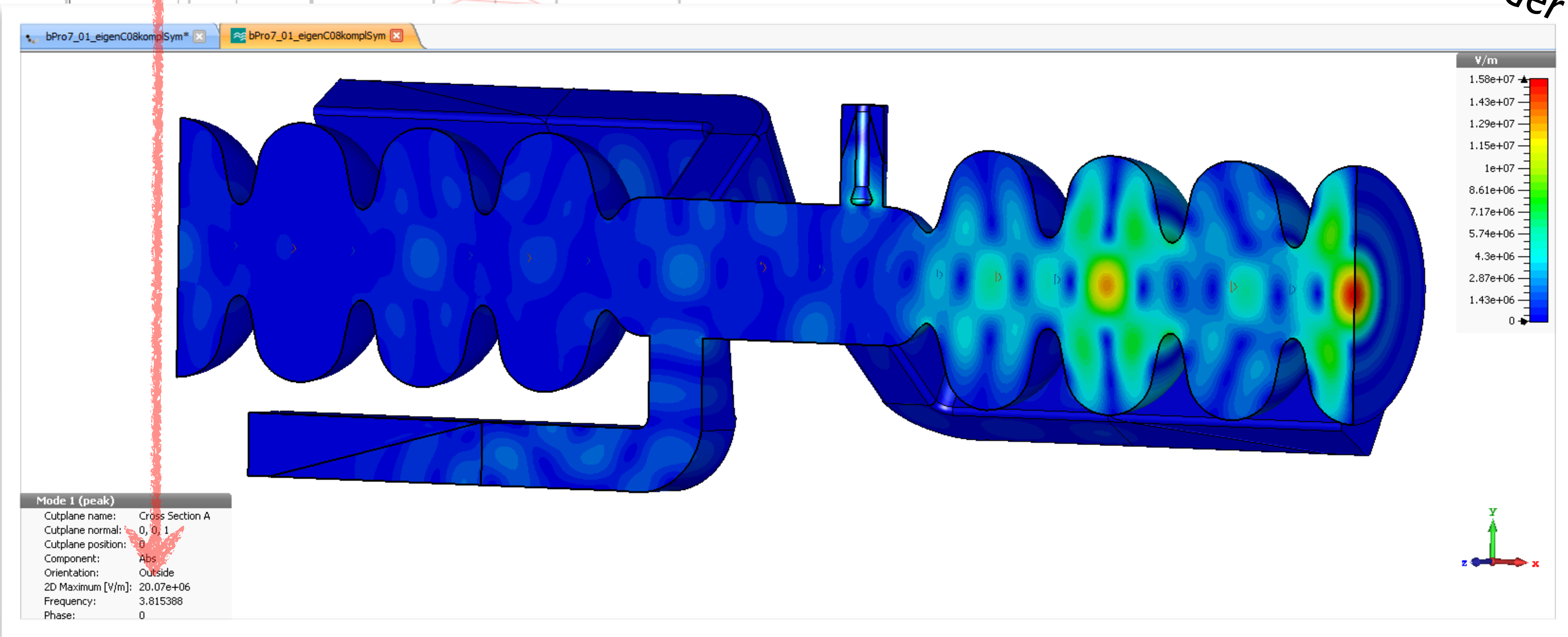
– $TM_{\varphi=0,\, r=1,\, z=2}$ –type

– f = 3.832267 GHz, Q = 2802, R/Q = 11.1 Ω

Eigenmode computations close to 3.9 GHz



Low Q's are not necessarily harmless – weaker reaction, but covering broader spectrum !



– $TM_{\varphi=0,\, r=1,\, z=2}$ –type

– f = 3.815388 GHz, Q = 758, R/Q = 8.85 Ω:

The tool box: You should have …

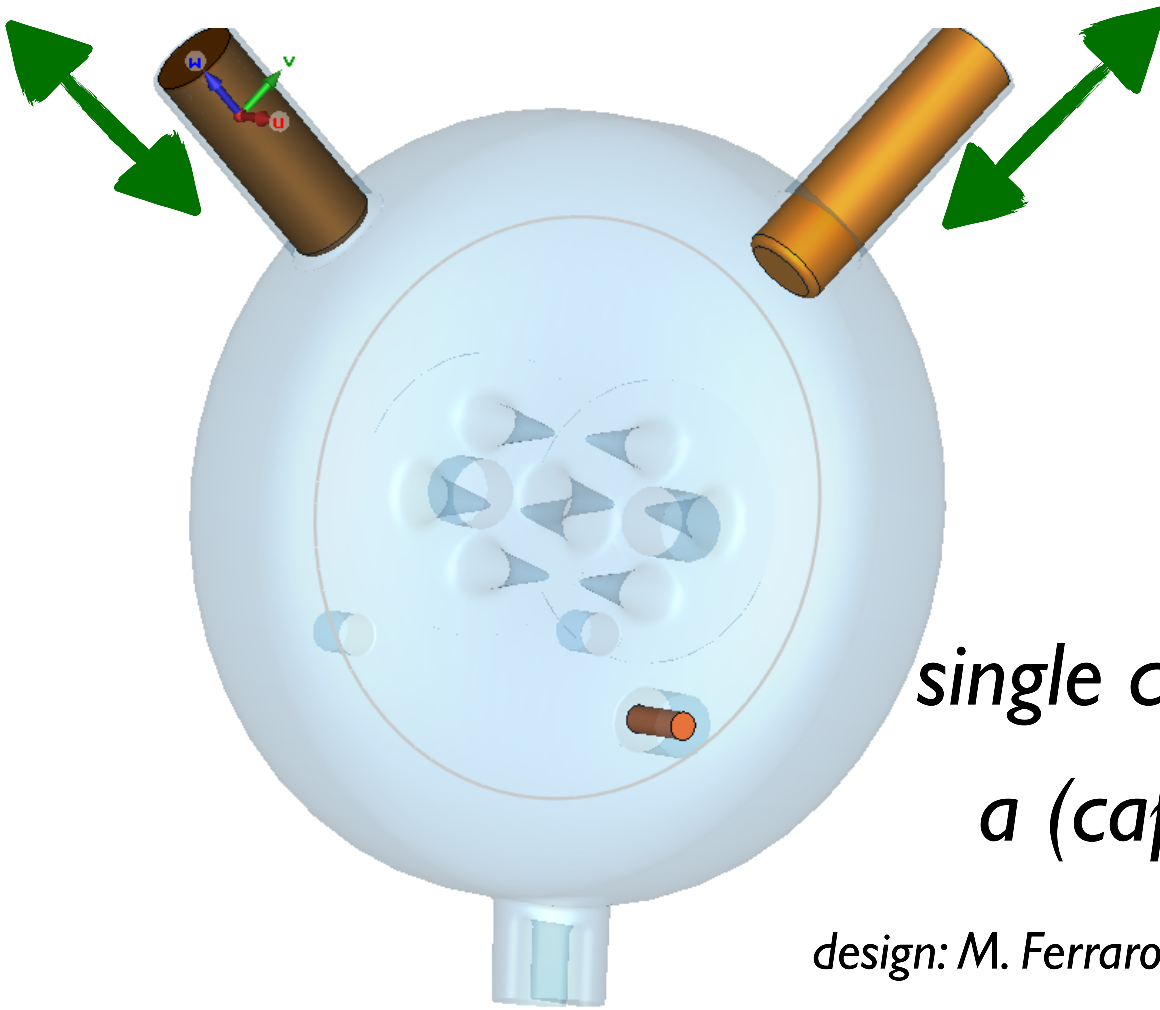
a *<u>frequency domain solver</u>* to compute the reaction of a cavity or an open structure on externally given driving excitations

„Frequency-domain“-field solver:

1. *Excites a cavity-like or waveguide-like structure (or anything between) with at least one port through a monochromatic wave of given frequency and simulates the stationary (not: static!) response.*
2. *Such a response is …*
   a) *the electromagnetic field inside the structure, and …*
   b) *the scattered waves at the port of excitation and at all other ports. By normalization with the incident wave amplitude, (complex-valued) S-parameters are computed.*
3. *It also computes (typically) the appropriate waveguide modes of the port(s) as solutions of 2-dimensional eigen-problem(s).*
4. *Frequency spectra are computed by repetition (slow) or (sophisticated) model-order-reduction-miracles.*

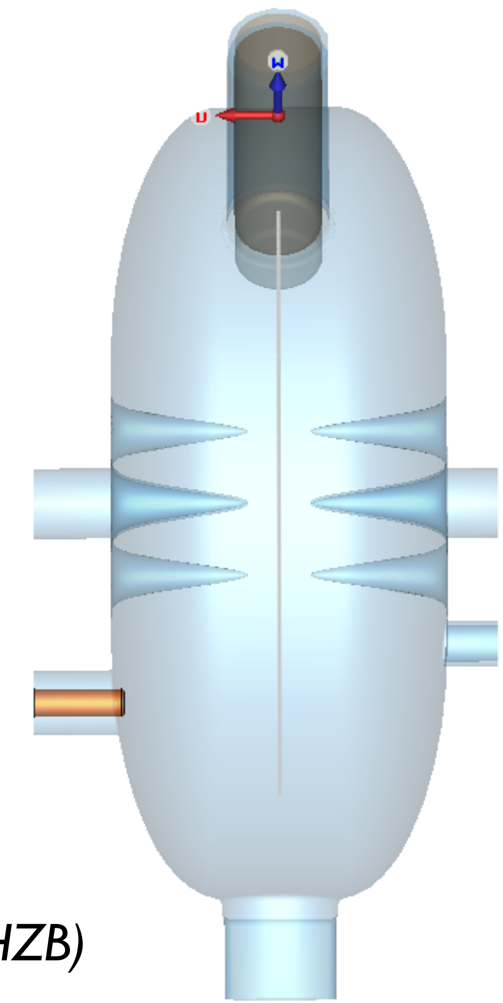
Example:

Double-plunger-tuned Cu cavity for transversal deflection



single coaxial port feeding

a (capacitive) antenna



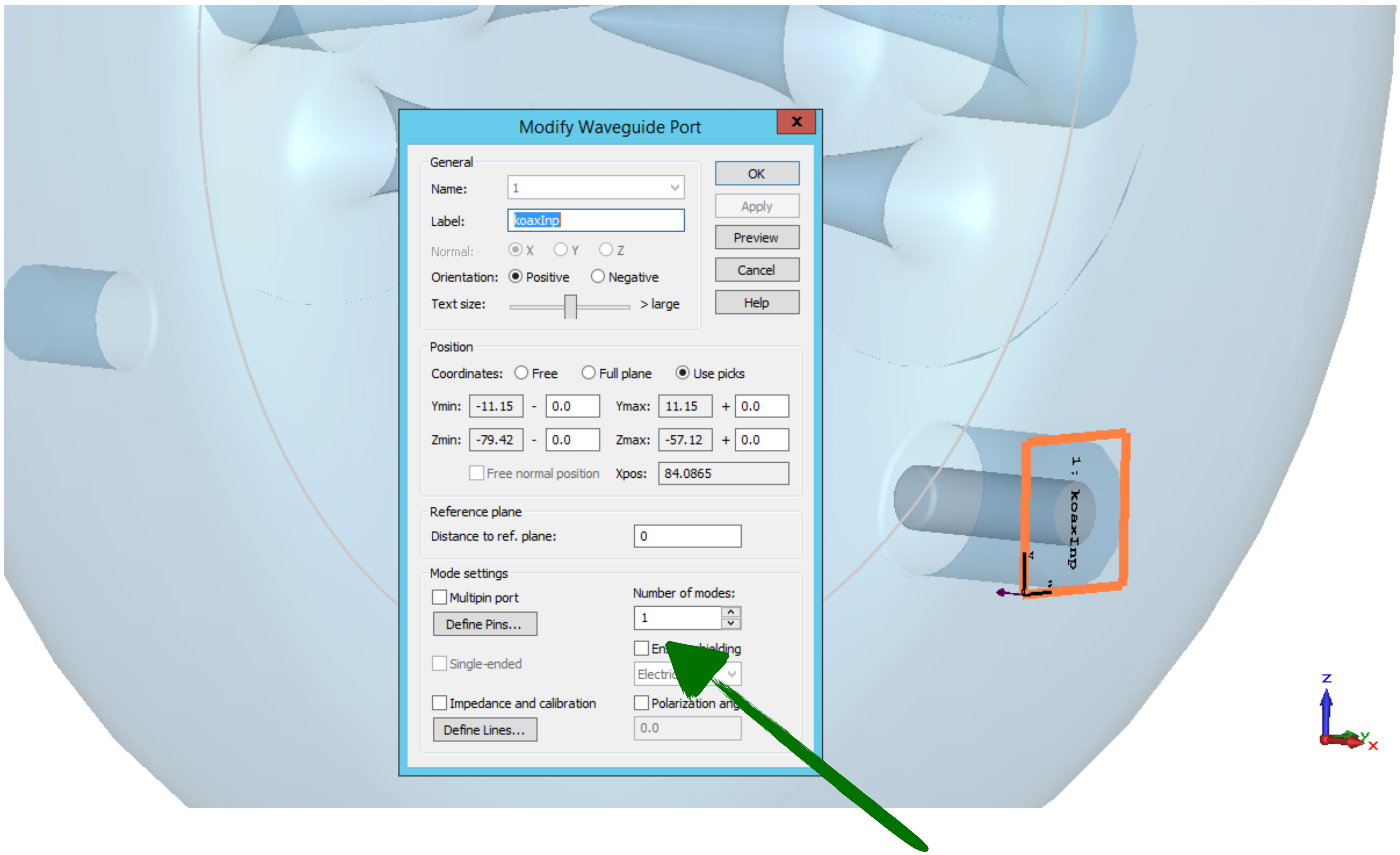
design: M. Ferrarotto (TU Dortmund), F. Pfloksch (HZB)

Task: Determine the internal field patterns and input reflection depending on plunger depths and antenna length.

(we will skip the multi-dimensionality, handled in practice by geometry parameters)

… by the way: What determines the TEM-impedance of a vacuum coaxial line ?

Frequency-domain-solver definitions 1: Port location(s) and parameters



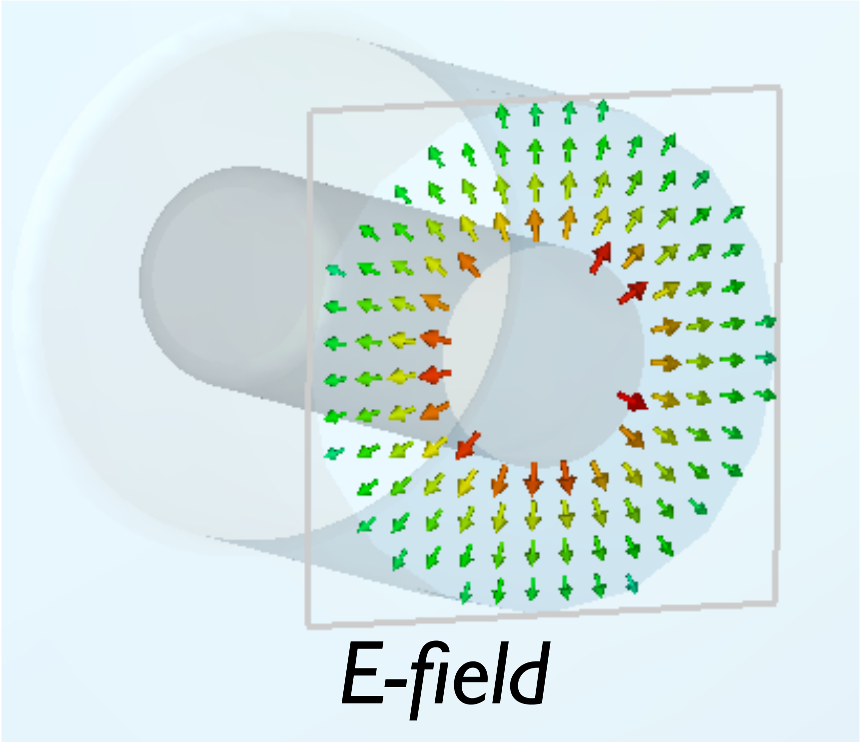
most essential: How many modes to be considered.

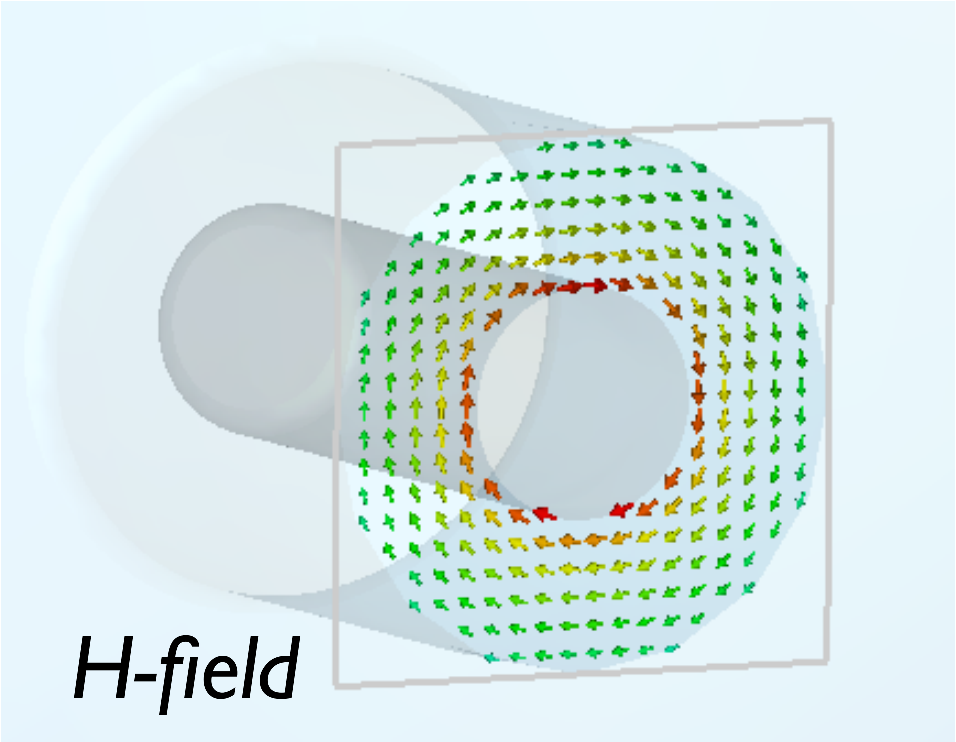
… by the way: What is the cut-off frequency of a TEM mode ?

Frequency-domain-solver outcome 1:
Mode pattern(s) at the port(s)

Port1 e1 (peak)	
Frequency:	1.29964
Phase:	0
Dist. -40dB:	1.014e+06
Line Imp. [Ohms]:	49.45
Alpha [1/m]:	0.004539
Wave Imp. [Ohms]:	376.3
Beta [1/m]:	27.25
Accuracy:	4.663e-17
Mode type:	TEM
Maximum:	1781
Plane at x	84.09

3D Schematic 1D R

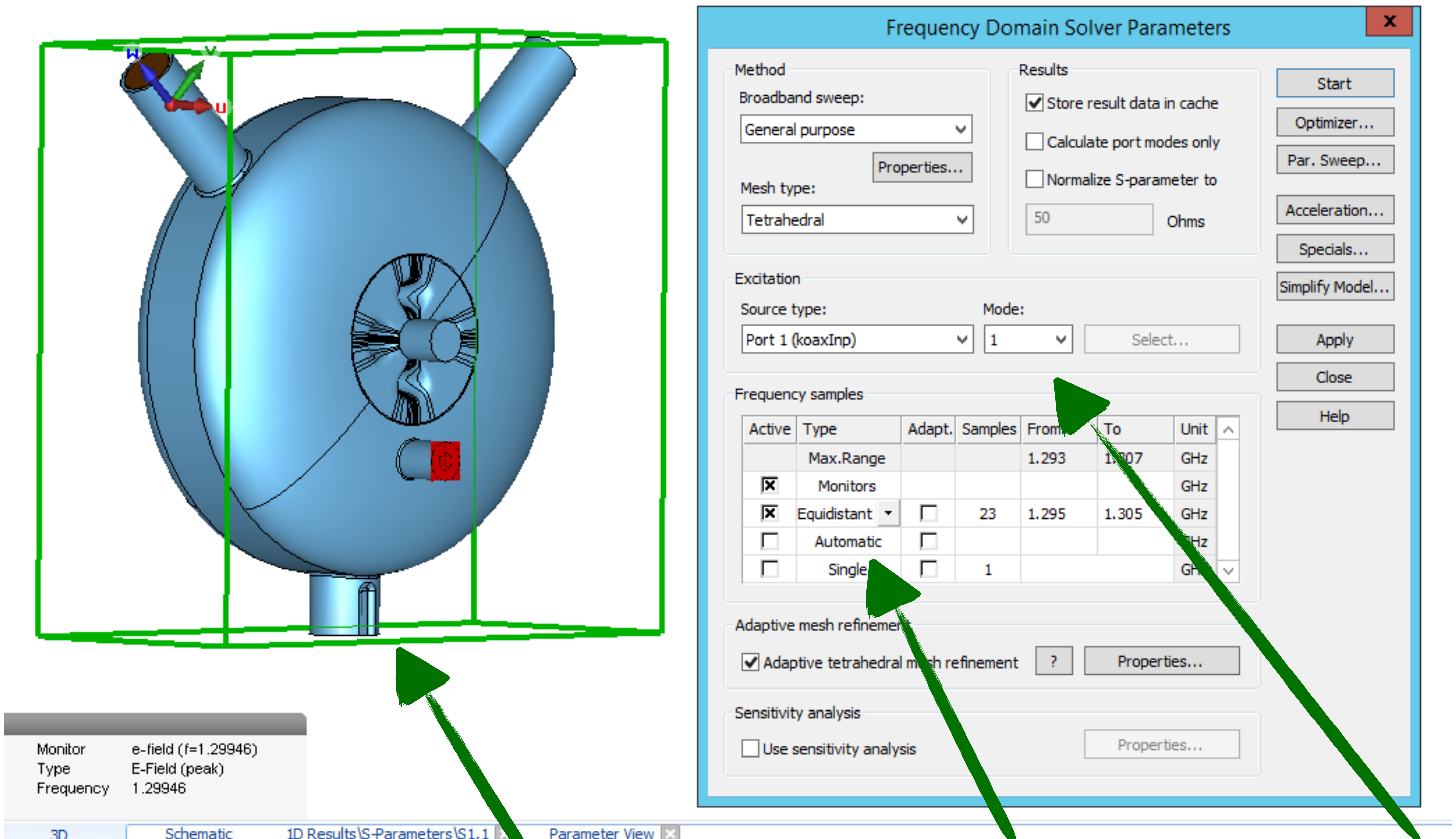




… by the way: What is the ratio E/H in free space ?

Frequency-domain-solver definitions II:

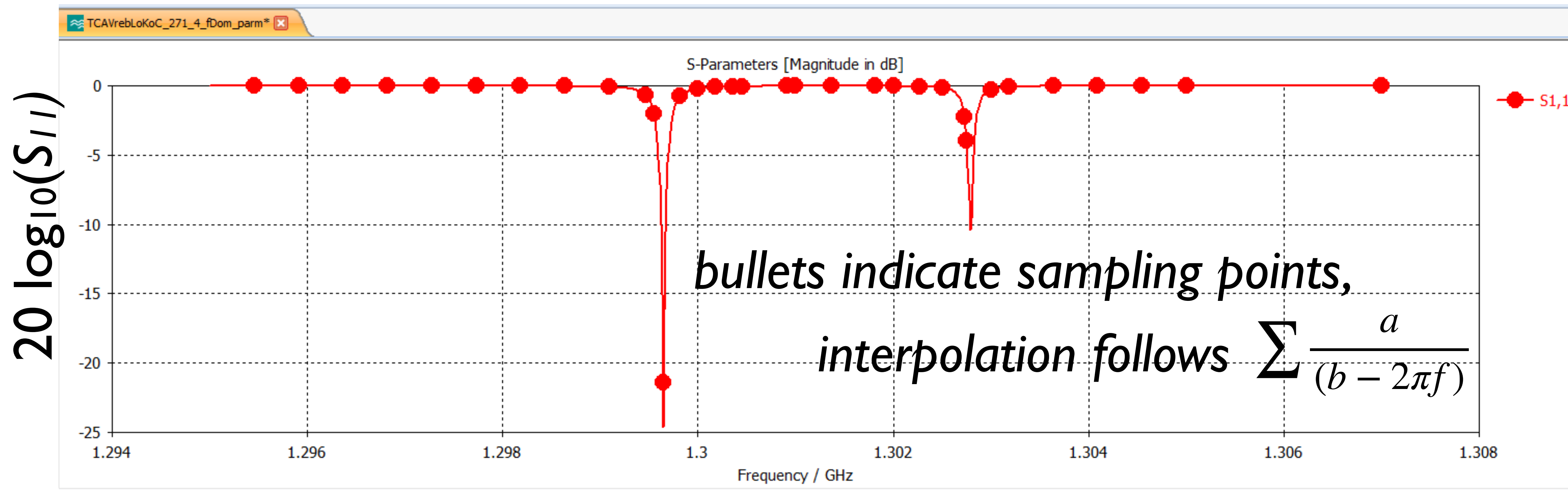
Frequency sampling points/ranges, fields to keep, excitations



stored volume *frequencies* *excitations*

… by the way: How to compute a stationary H-field from a given E-field ?

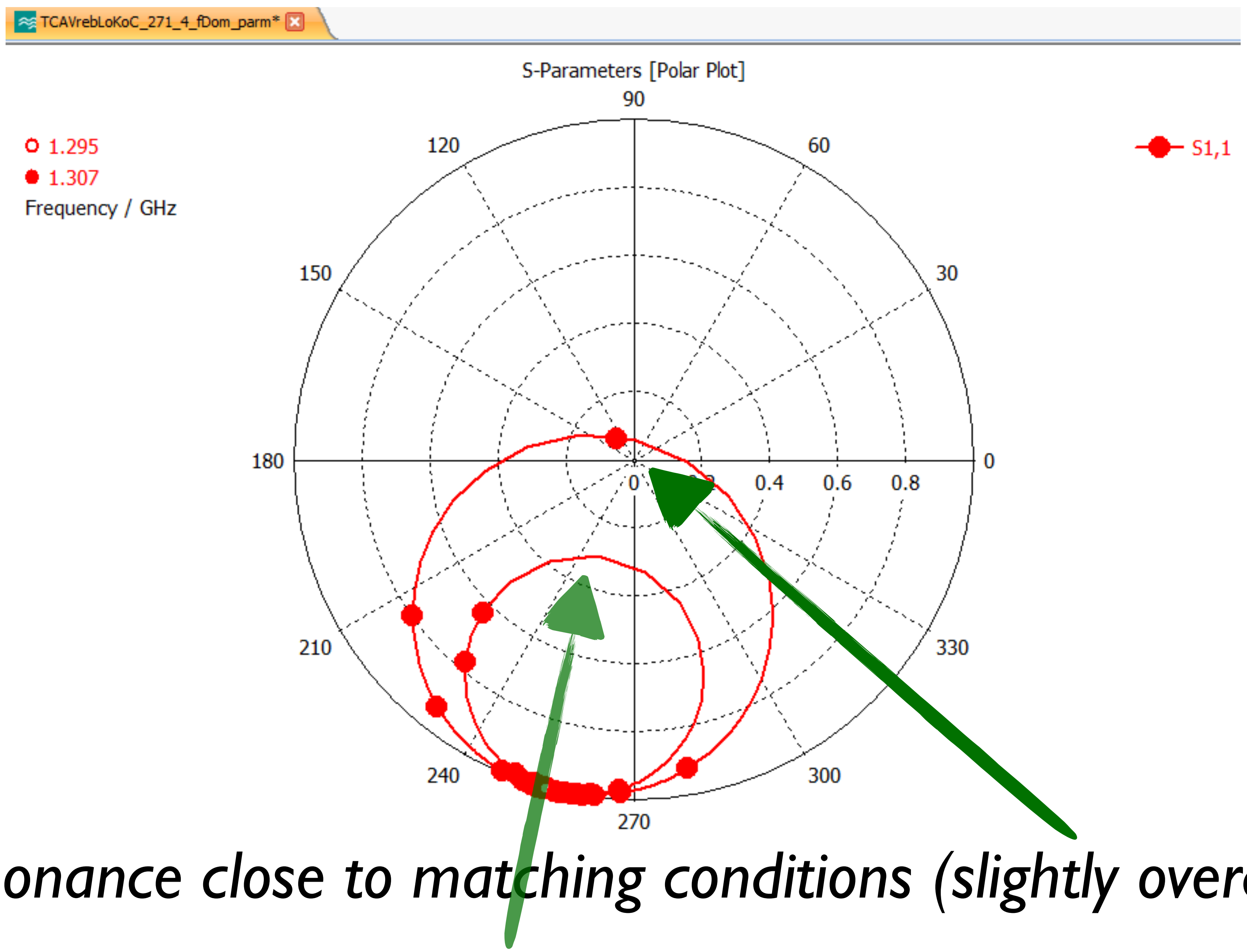
Frequency-domain-solver outcome II: Scattering parameters – in case of single-moded one-port device only S_{11} exists



Cavity dissipates most energy in the wall, if in resonance, i.e. minima of S_{11} (1.2996 GHz and 1.3028 GHz)

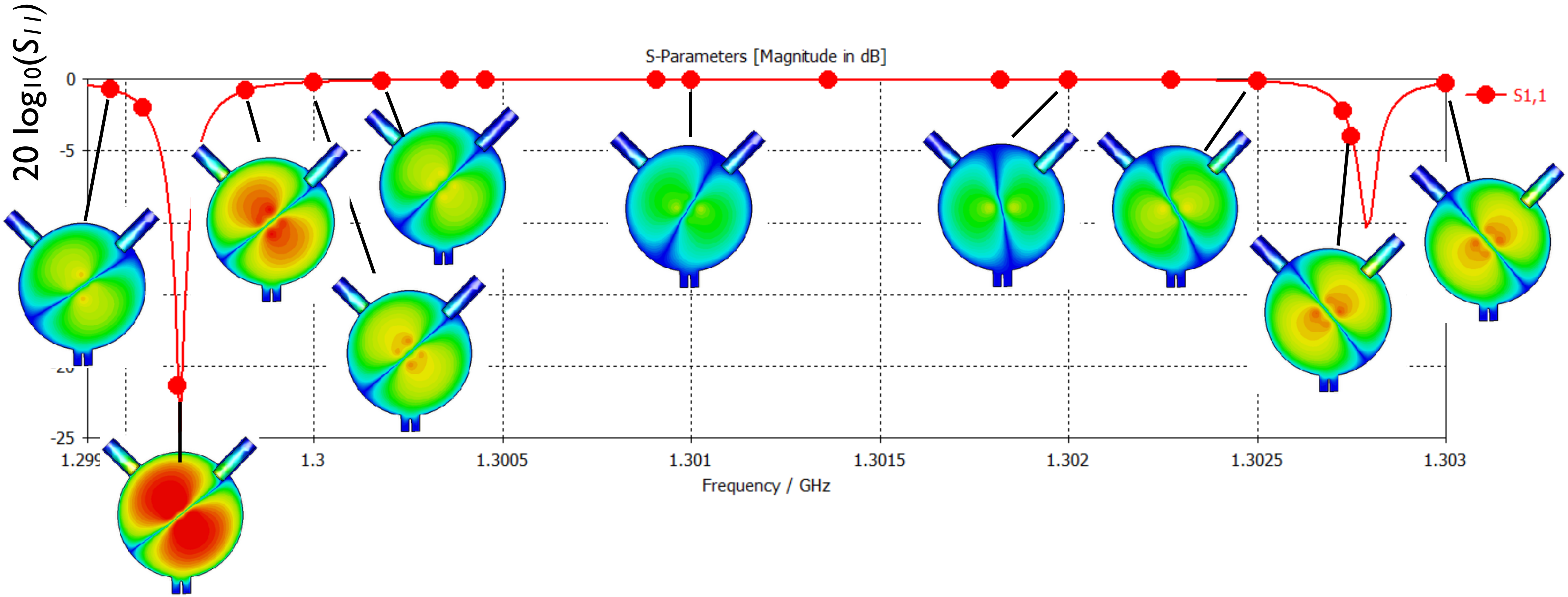
… by the way: How much of the energy is reflected if $|S_{11}| = -3$ dB ?

Frequency-domain-solver outcome III: Complex-valued scattering parameters in polar representation



One resonance close to matching conditions (slightly overcoupled), second not accordingly matched

Frequency-domain-solver outcome IV: Field patterns for different driving frequencies



Driven field pattern shifts its orientation and takes different amplitudes depending on the frequency.

… by the way: What is a degenerated mode ?

The tool box: You should have …

a ***wakefield solver*** to observe the time-domain reaction of a beam line element on a driving bunch

„Wake"-field solver:

1. *Excites a cavity-like or waveguide-like structure (or anything between) with (typically) one traversing gaussian bunch of given length and simulates the time-dependent response.*
2. *Such a response is …*
   a) *the electromagnetic field inside the structure, and …*
   b) *the outgoing waves at all ports, and …*
   c) *the integral force, that would be experienced by witness charges following the bunch in fixed distances („wake potentials")*
3. *It also computes (typically) the appropriate waveguide modes of the port(s) as solutions of 2-dimensional eigen-problem(s).*
4. *Fourier-transformation of the wake potentials give „beam impedances", integral deposited energy „loss factors".*

Again for comparison: „Frequency-domain"-field solver:

1. *Excites a cavity-like or waveguide-like structure (or anything between) with at least one port through a monochromatic wave of given frequency and simulates the stationary (not: static!) response.*
2. *Such a response is …*
   a) *the electromagnetic field inside the structure, and …*
   b) *the scattered waves at the port of excitation and at all other ports. By normalization with the incident wave amplitude, (complex-valued) S-parameters are computed.*
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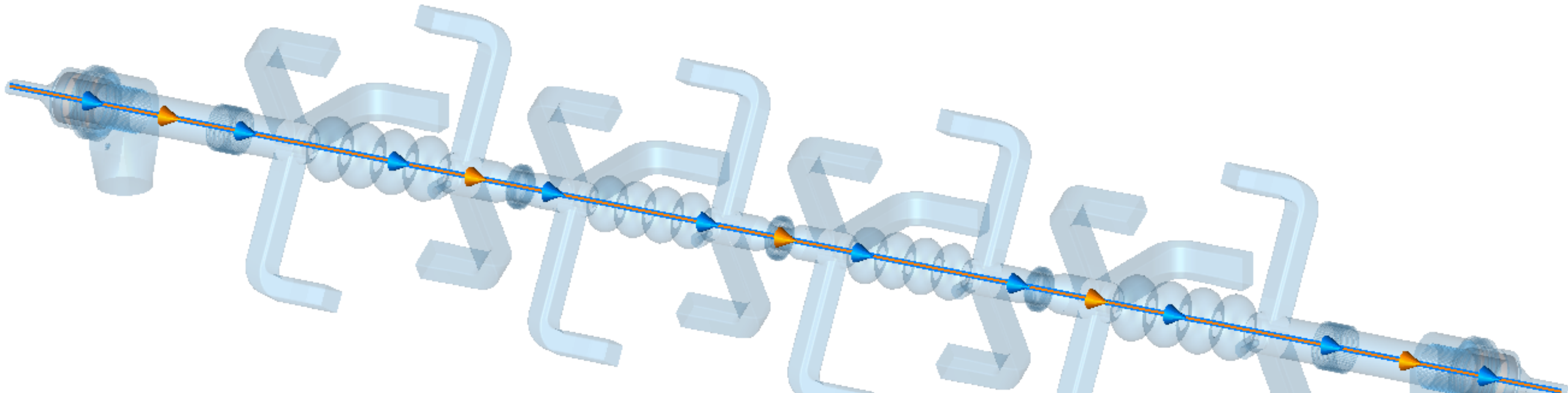
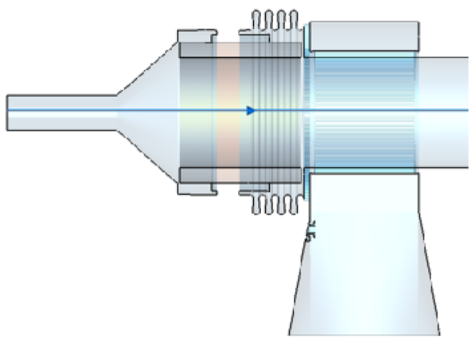
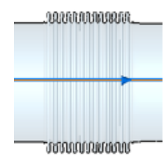
3. *It also computes (typically) the appropriate waveguide modes of the port(s) as solutions of 2-dimensional eigen-problem(s).*
4. *Fourier-transformation of the wake potentials give „beam impedances", integral deposited energy „loss factors".*

Example (a really big one): BESSY-VSR-upgrade module

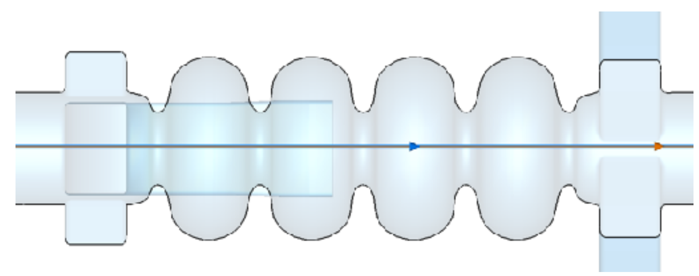




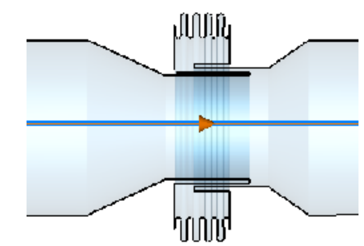
Warm End Group
(not recent design)
– *absorber*
– *cross section adaption*
– *mech. compensation*
– *pumping*



Module End Bellow
(not recent design)
– *mech. compensation*
– *thermal insulation*



Cavity 1.5 / 1.75 GHz
– *alternating bunch lengthening/shortening*

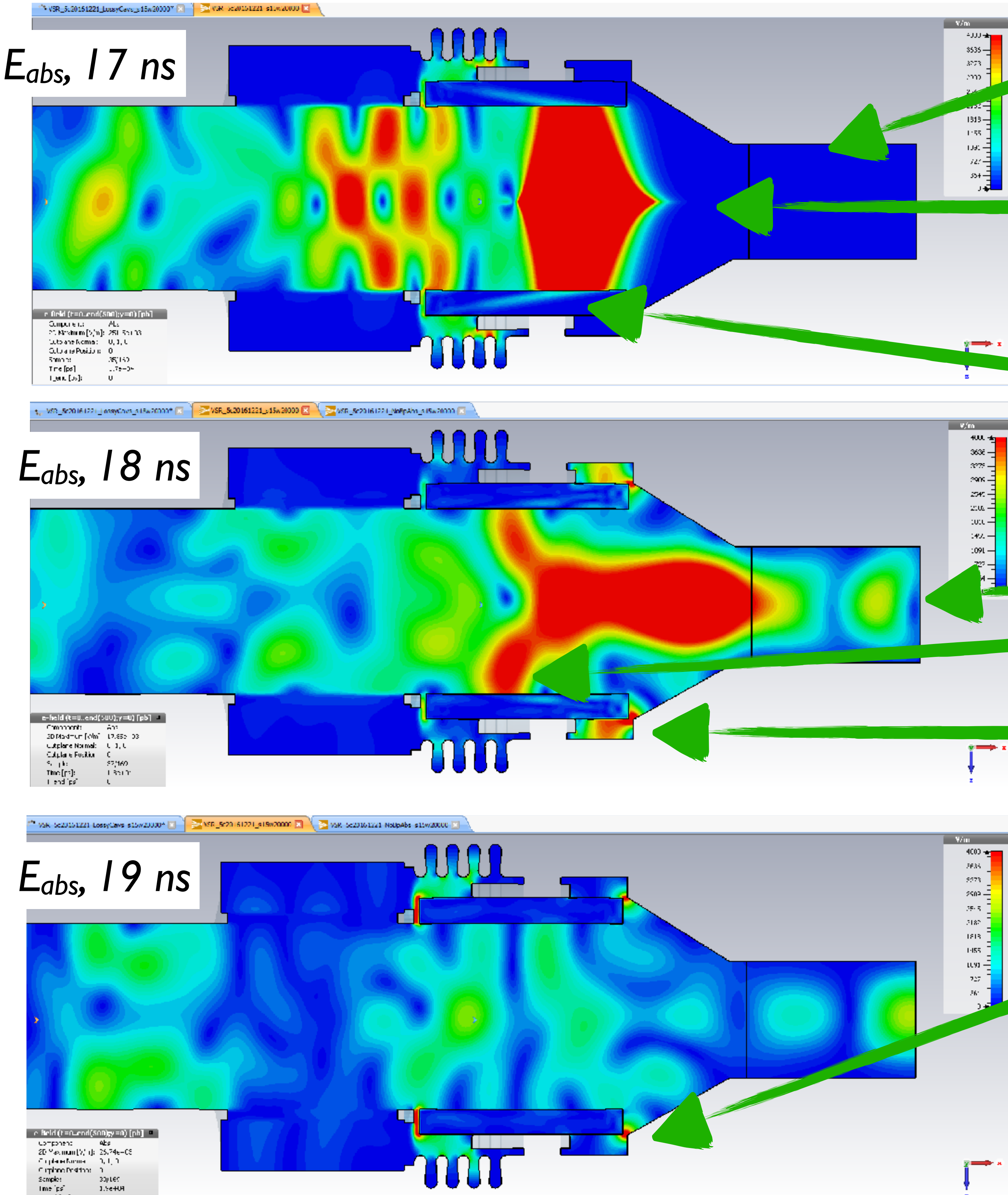


Shielded Belows
– *mech. compensation*
– *synchrotron light collimation*
– *while not affecting cavity Qs*

Task: Determine the power to be damped in the waveguides and endgroups when operating in 300 mA CW synchrotron operation

… by the way: How many bunches with 4 ns spacing are together in a structure of 5 m length ?

How do wake fields look like (e.g. at the module end)?



field-free volume ahead the bunch (ideally only if $v_{bunch} = c_0$)

strong fields accompany the bunch (Lorentz-transformed space charge field: radial E, circular H)

Czerenkov radiation cone in dielectric

scattered fields propagate up- and downstream

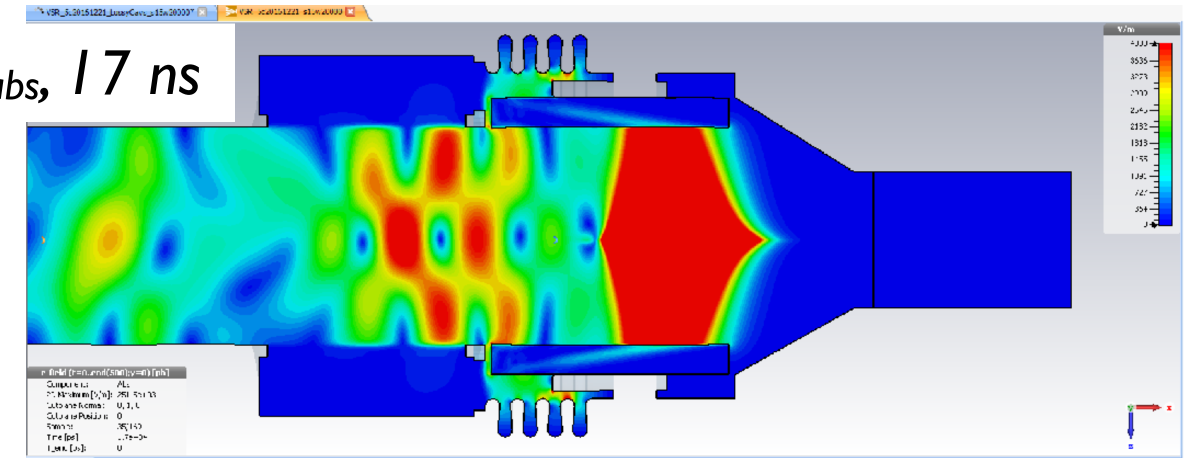
localized field patterns („modes“) ring and …

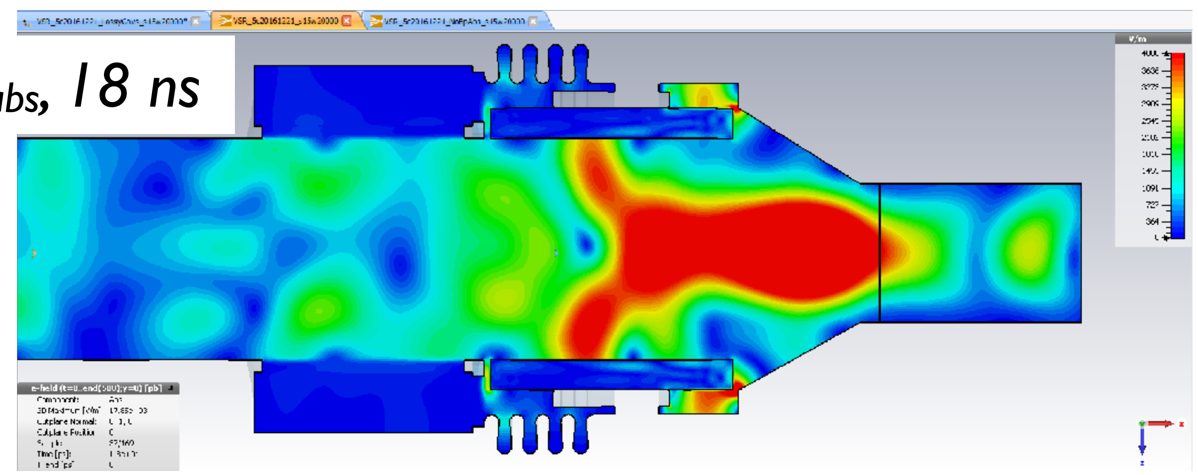
… decay; Q depending on energy sinks = ports, wall losses, dielectric losses)

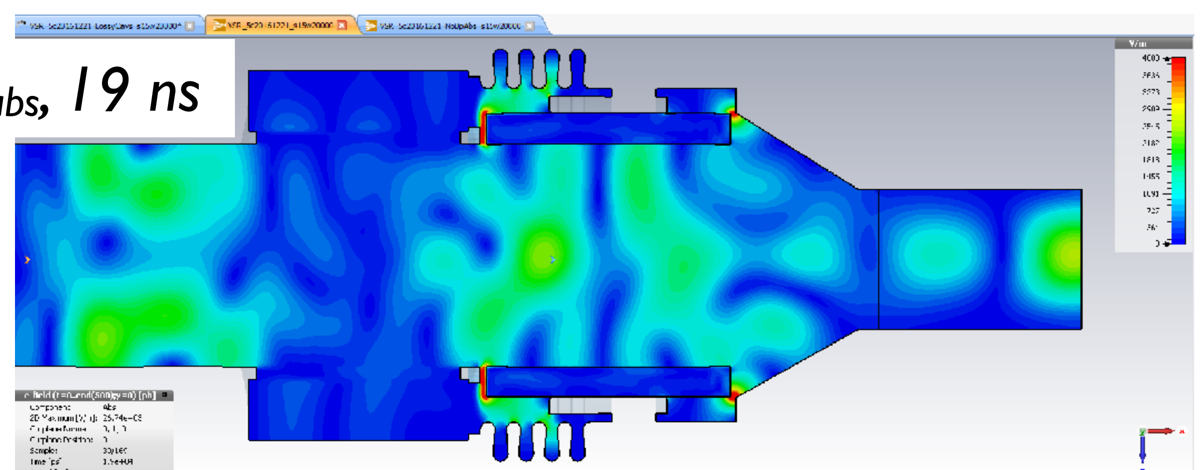
H.-W. Glock, HZB

Side note: How damps the dielectric absorber the fields?

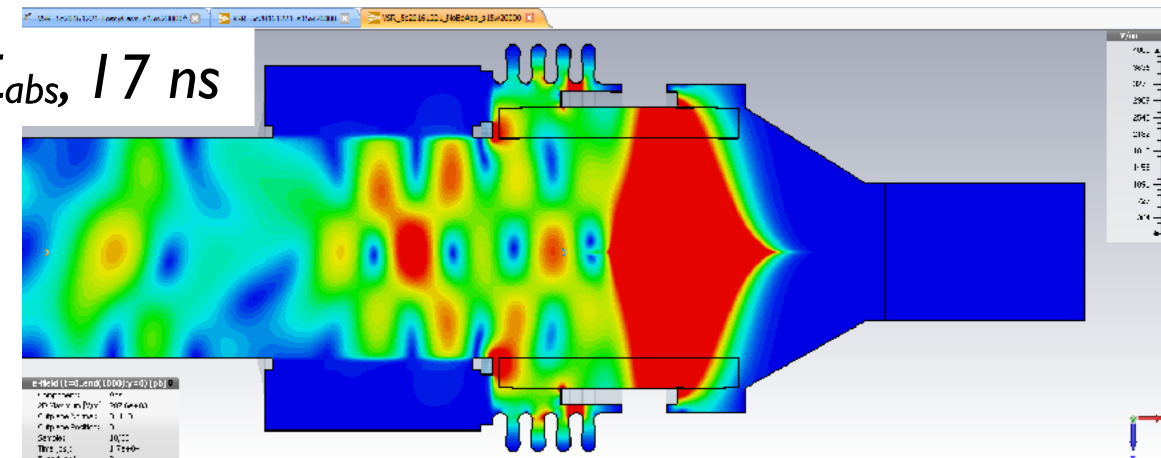
dielectric $\varepsilon_r = 45$, $\mu_r = 1$, *tan* $\delta = 0.44$ *@ 2.0 GHz*

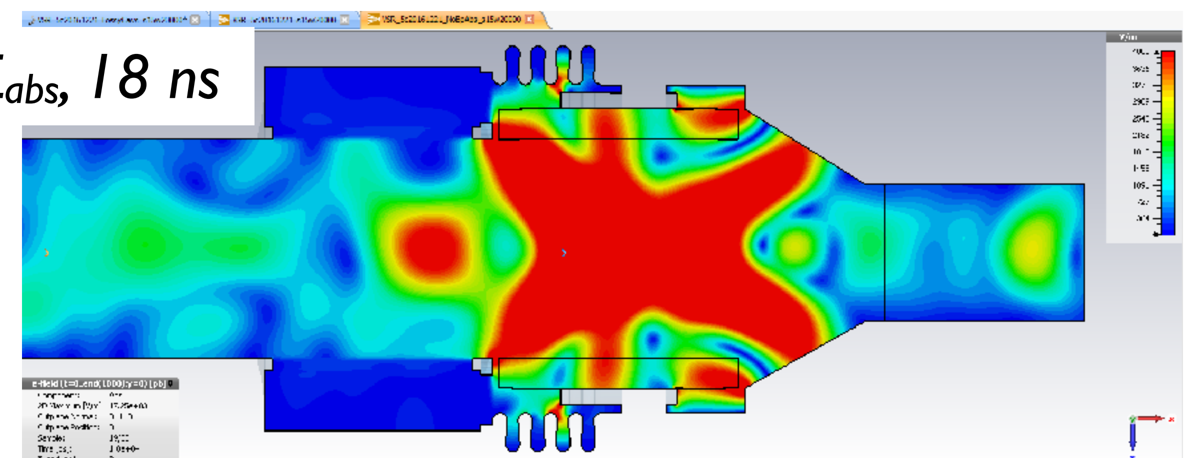


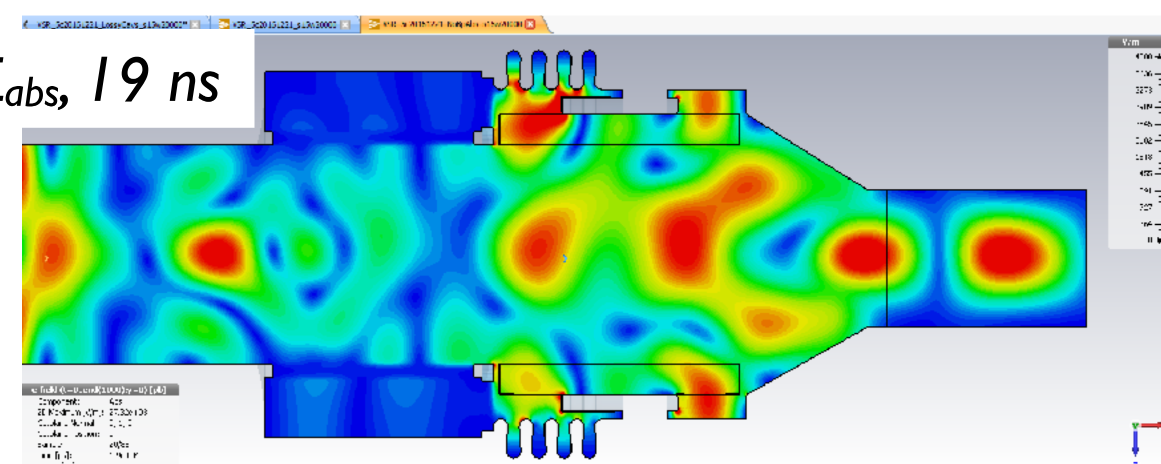




vacuum $\varepsilon_r = 1$, $\mu_r = 1$, *tan* $\delta = 0$







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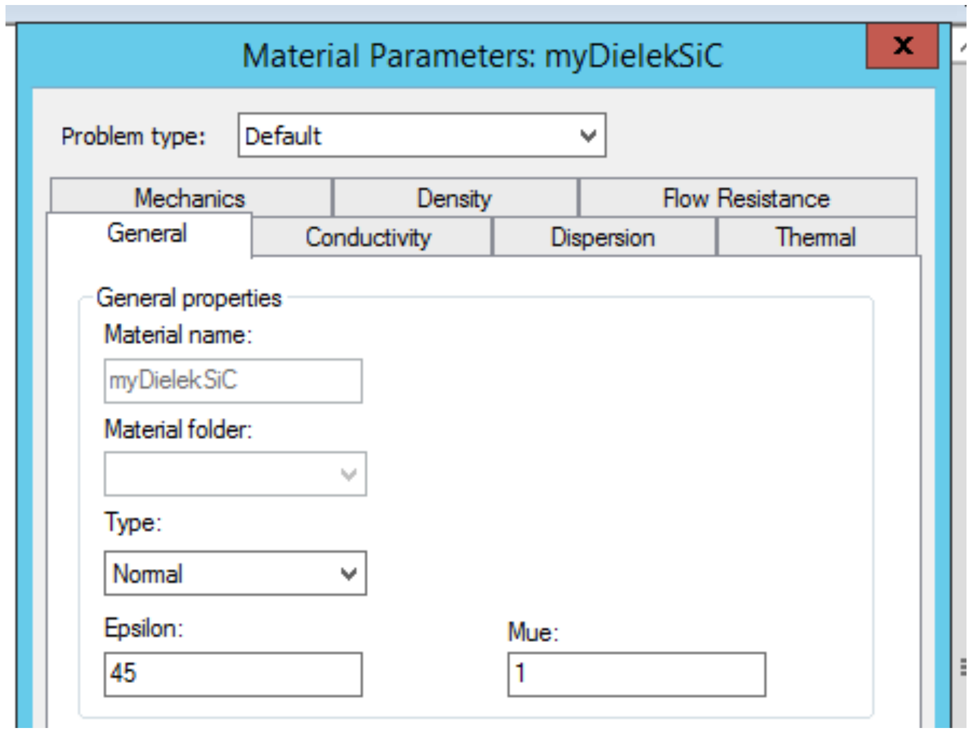
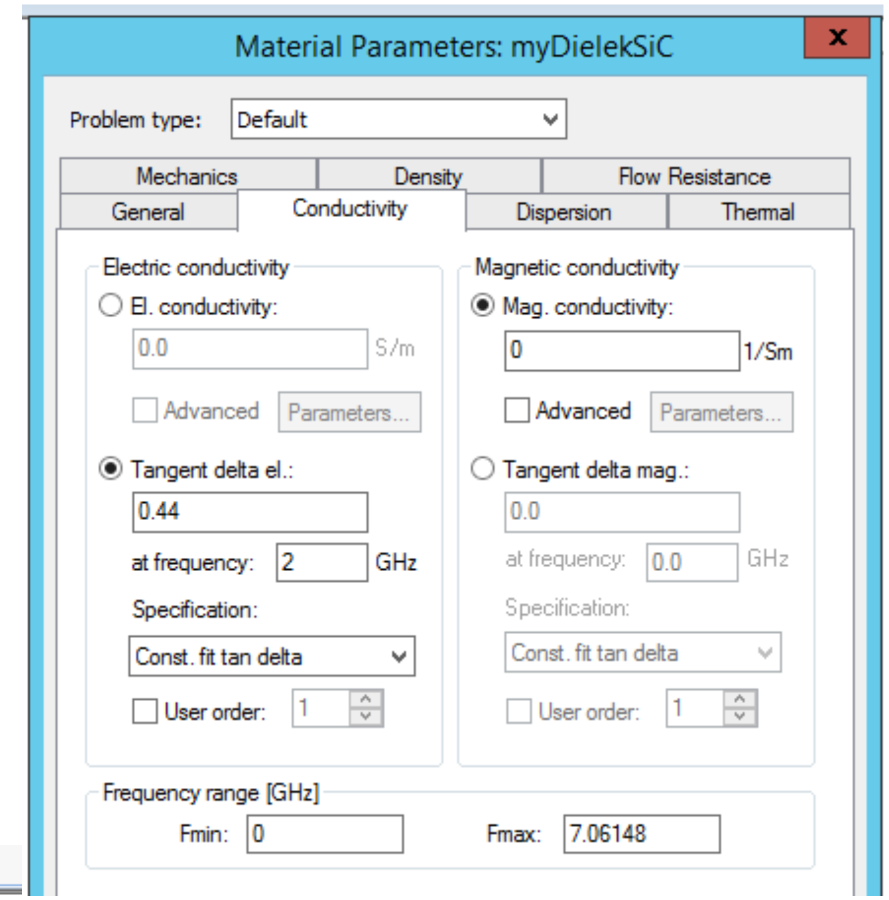
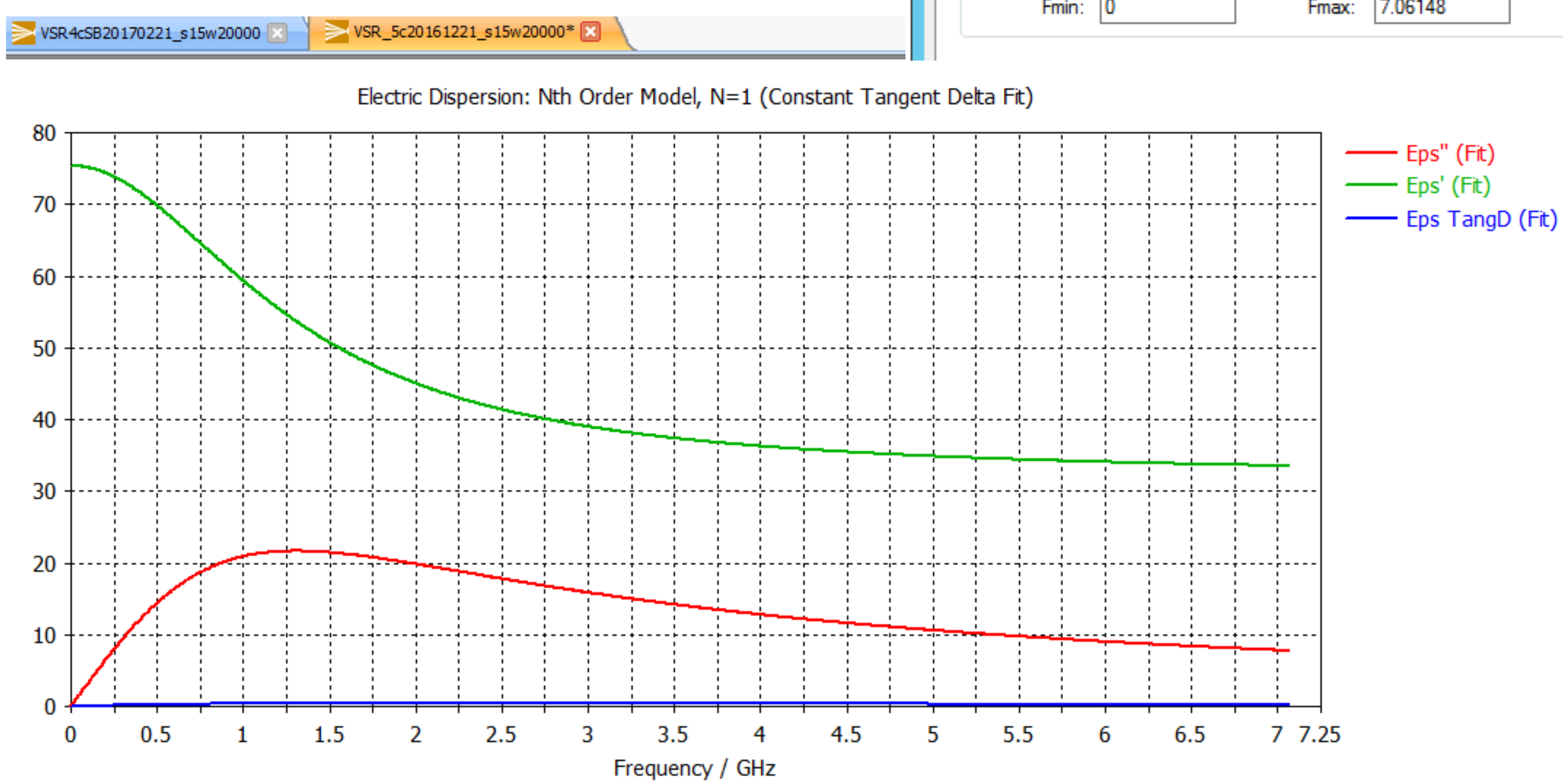
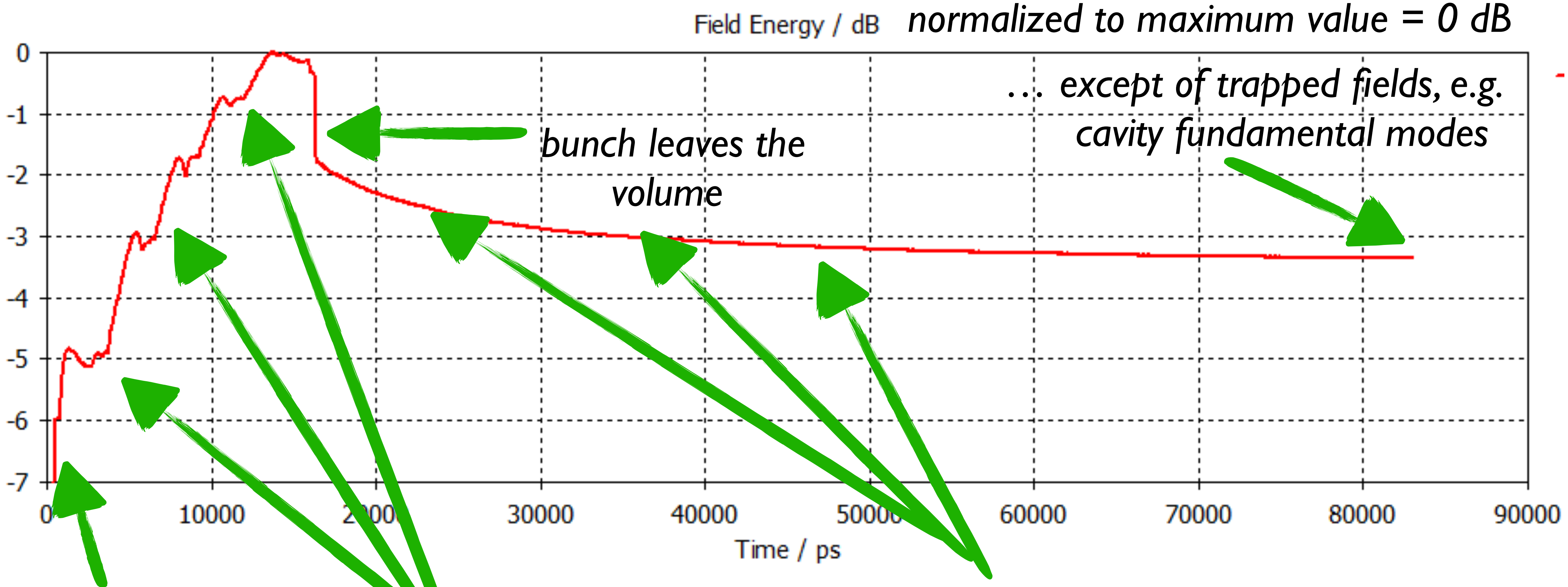
Side note II: Definition of dispersive materials needs care !







How develops the total energy in the system?



normalized to maximum value = 0 dB

bunch leaves the volume

…. except of trapped fields, e.g. cavity fundamental modes

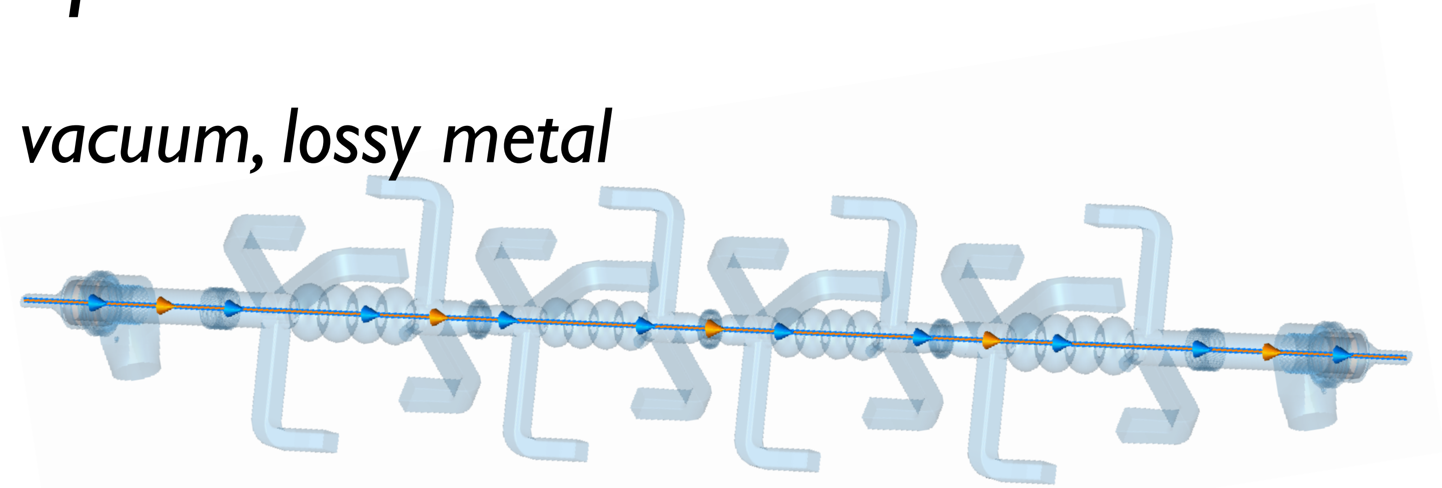
bunch enters the volume

field energy decays through ports, wall losses, dielectric losses …

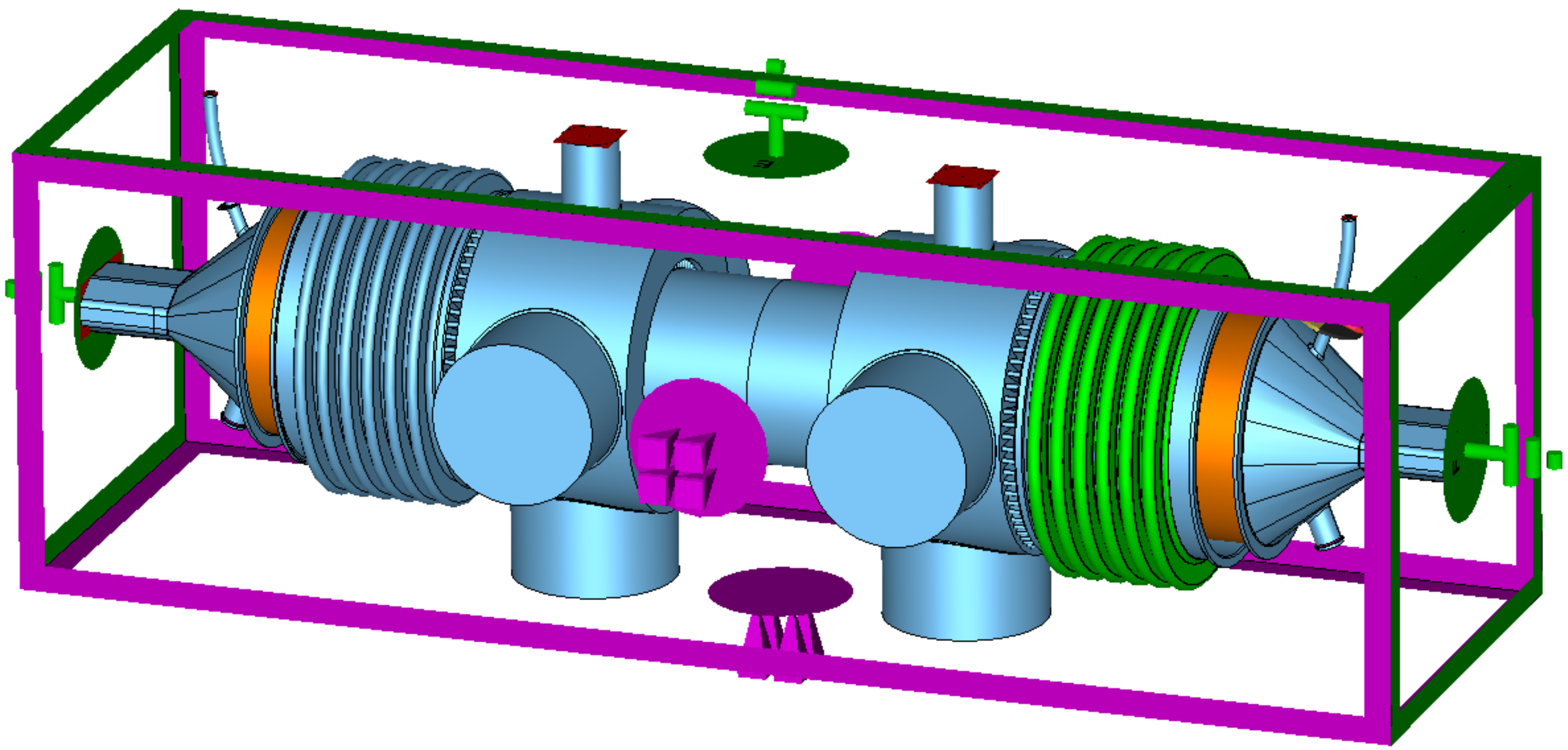
scattering of field energy into the structure;
re-fed out of infinite kinetic energy of STIFF bunch;
all loss mechanisms apply simultaneosly

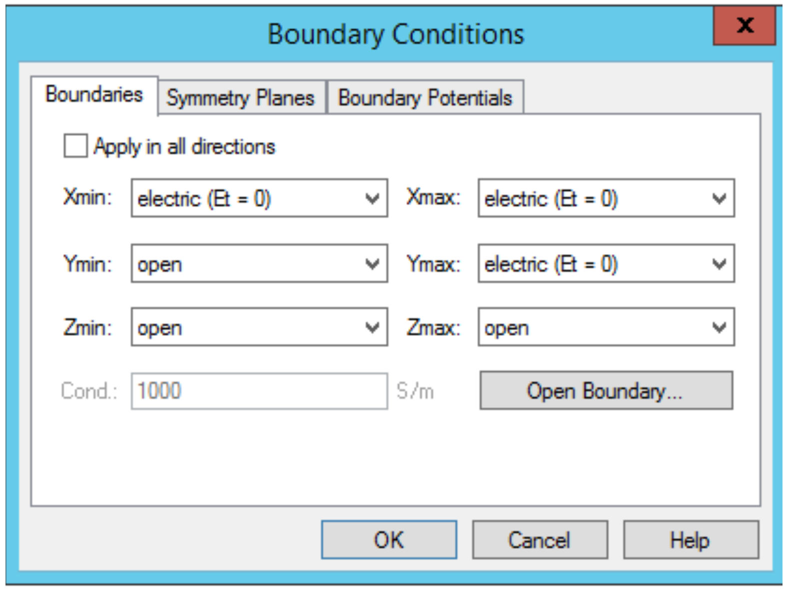
So, what to tell the wakefield solver ?

1. the geometry, i.e. the inner vacuum, lossy metal walls, dielectrics



2. the boundary conditions, esp. at the beam pipes (preferably waveguide ports overlaying PEC) and large openings like pumping ports (preferably open boundary)

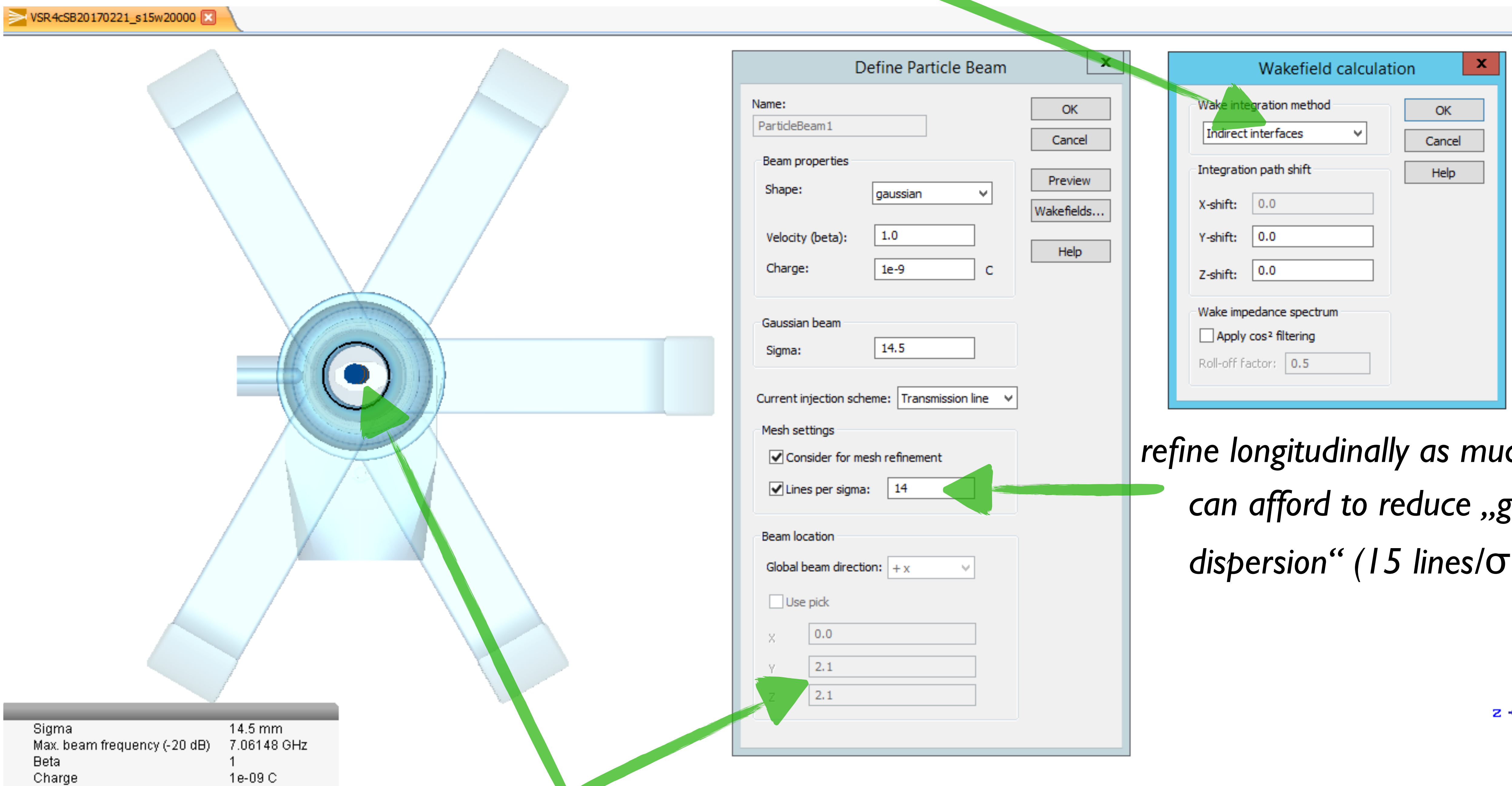




So, what to tell the wakefield solver ?

3. *the beam parameters*

3a. *the wake integration scheme (avoid „direct“ unless v < c_0 or you can afford very long beam pipes !)*

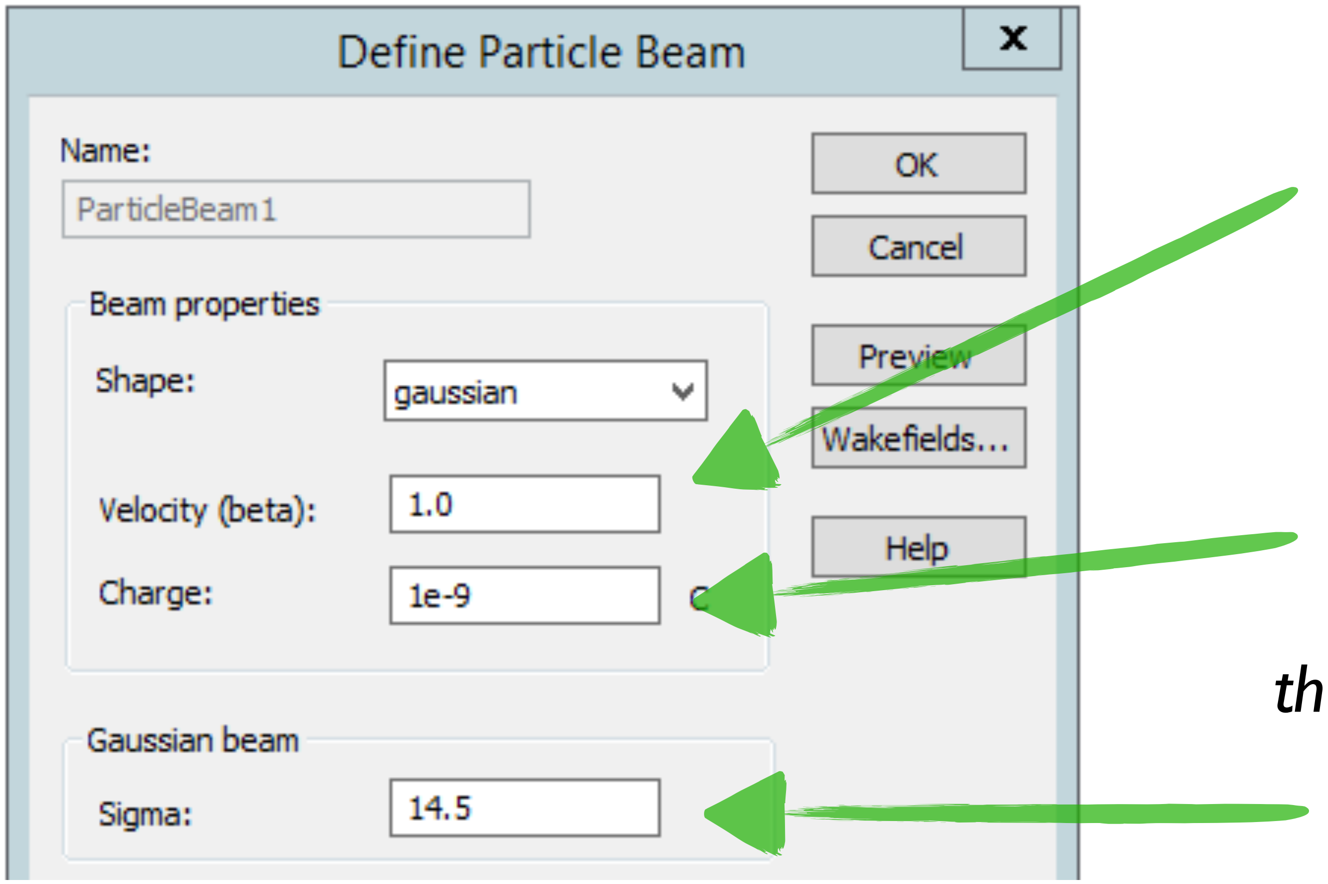


refine longitudinally as much you can afford to reduce „grid dispersion“ (15 lines/σ is ok)

put it slightly off-axis to excite also dipole (quadrupole …) modes

So, what to tell the wakefield solver ?

3. *the beam parameters (cont.)*



things get difficult if $v < c_0$

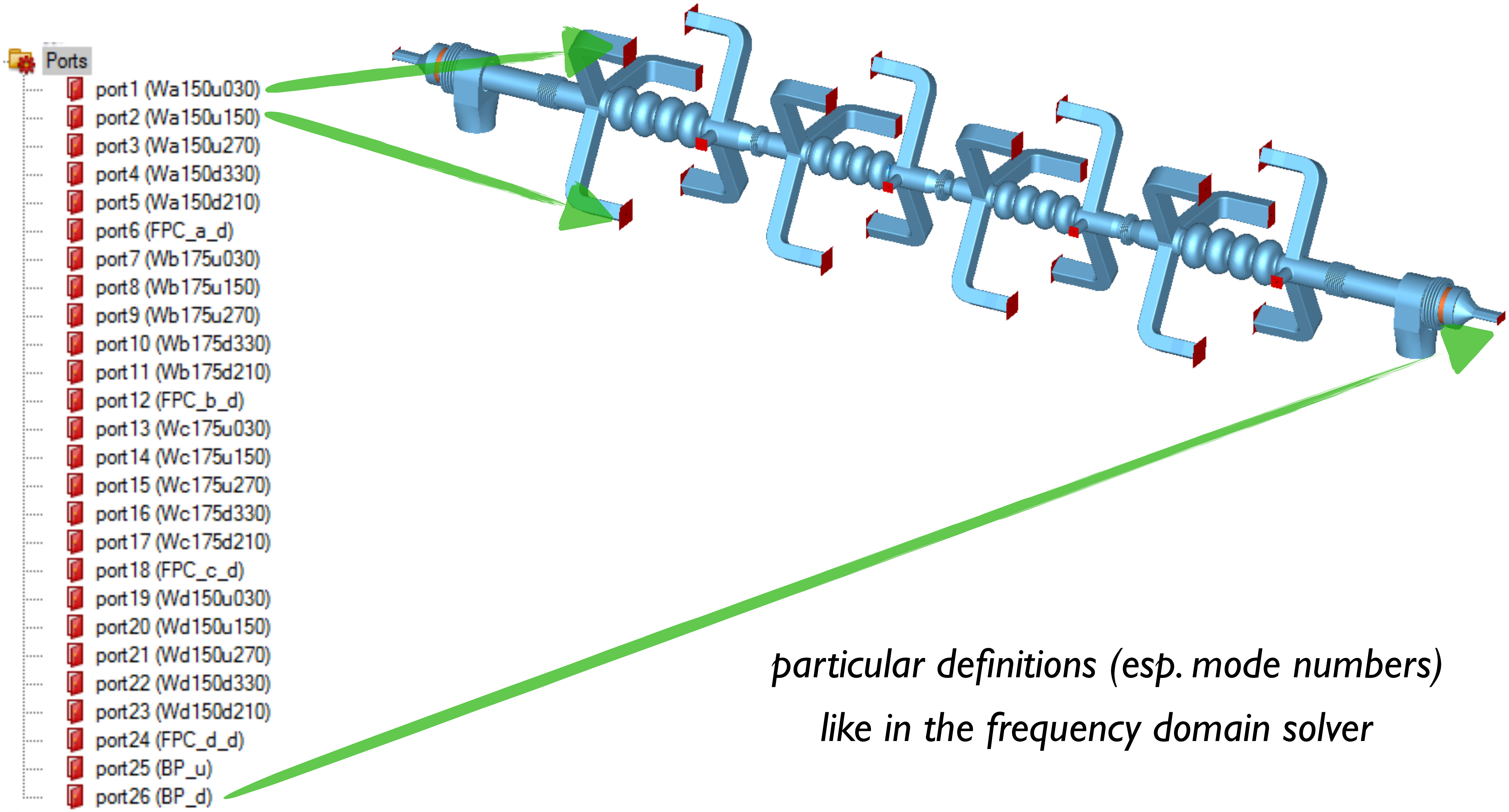
relevant only for absolute field amplitudes

the longer the bunch, the lower the frequency range covered: σ = 14.5 mm correspond to ~ 7 GHz

… by the way: How scale wake fields if the bunch charge is doubled ?

So, what to tell the wakefield solver ?

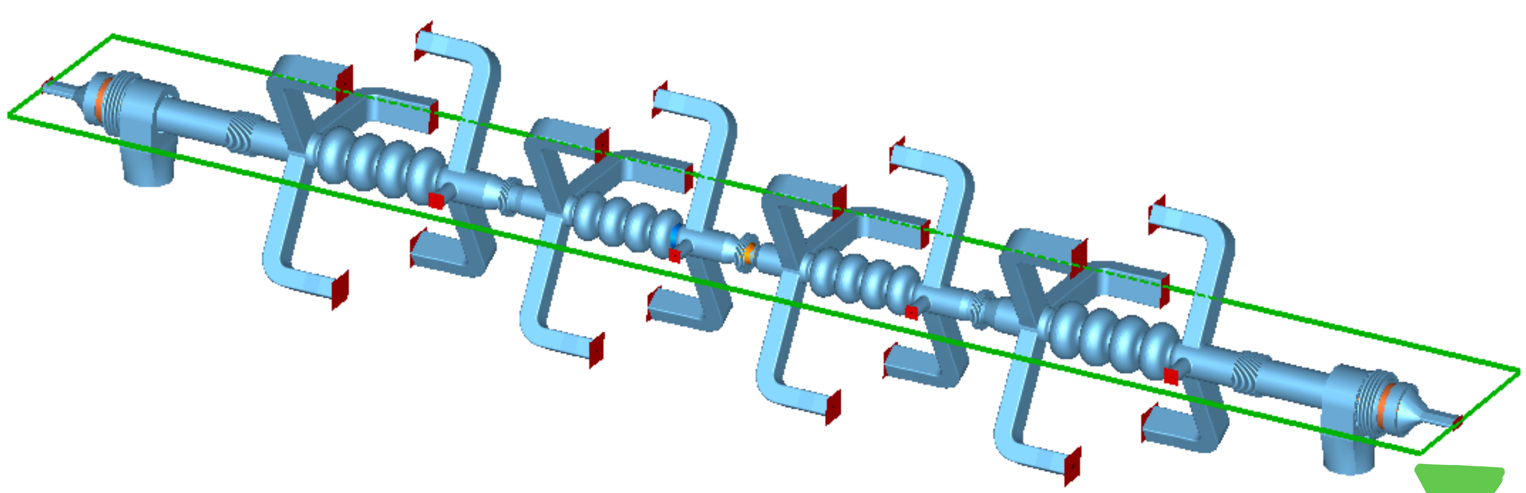
4. the ports

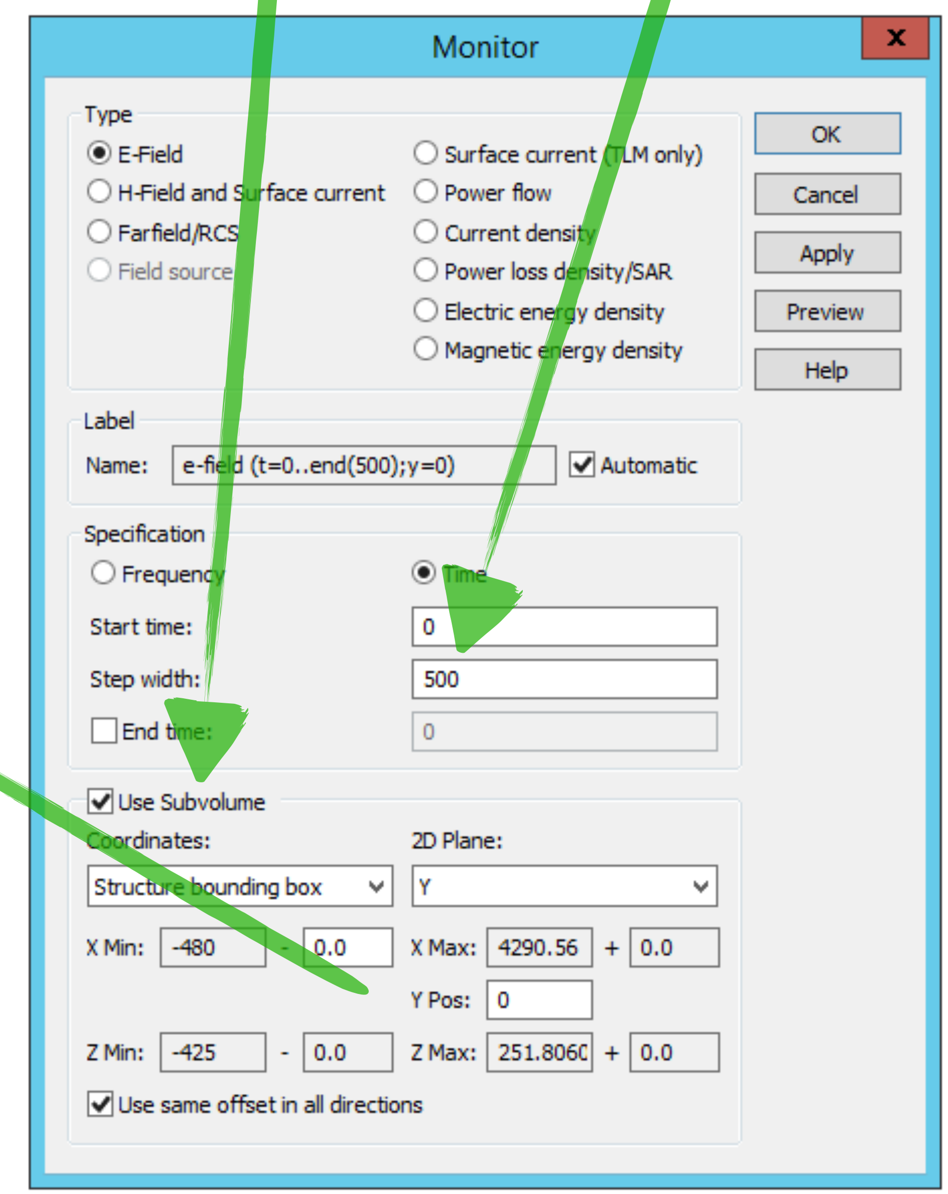


particular definitions (esp. mode numbers)
like in the frequency domain solver

So, what to tell the wakefield solver ?

5. *the field monitors (very carefully = reduce volume or planes only, wide time stepping, otherwise you can fill up any storage medium)*

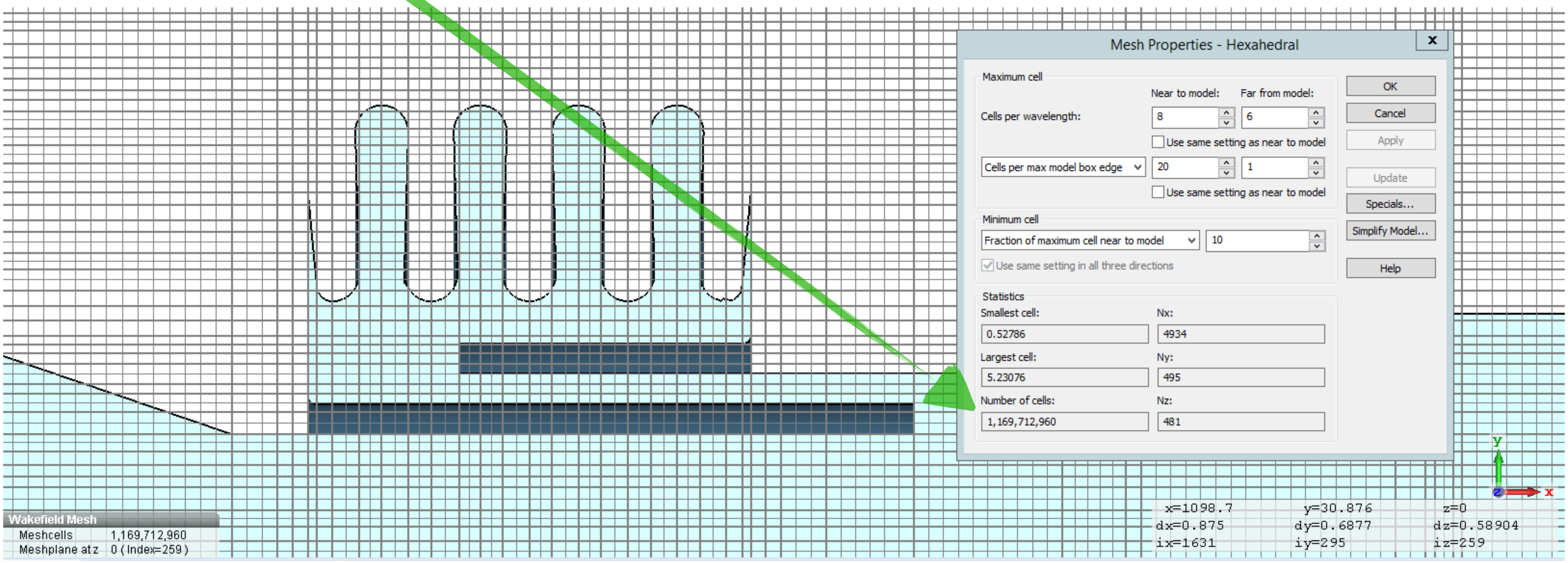




So, what to tell the wakefield solver ?

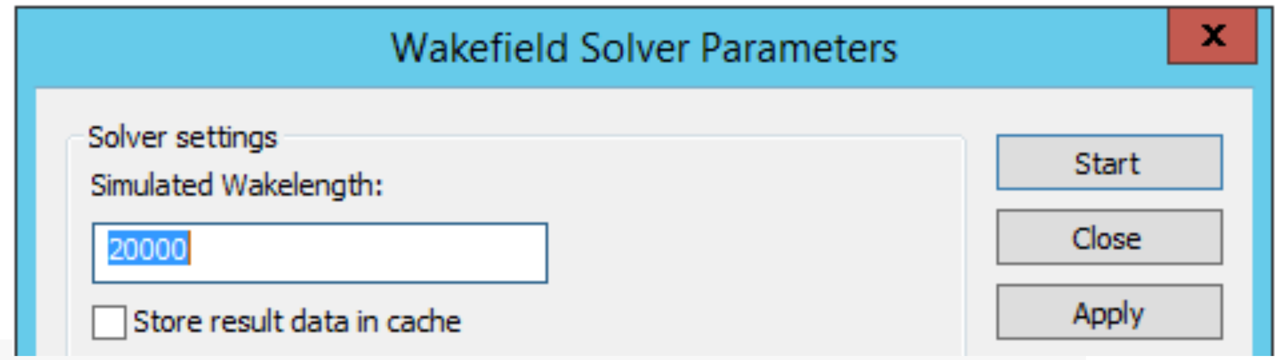
6. *check the mesh (hex-mesh only, constructed automatically and appropriate for the beam, but all geometrical details need to covered)*

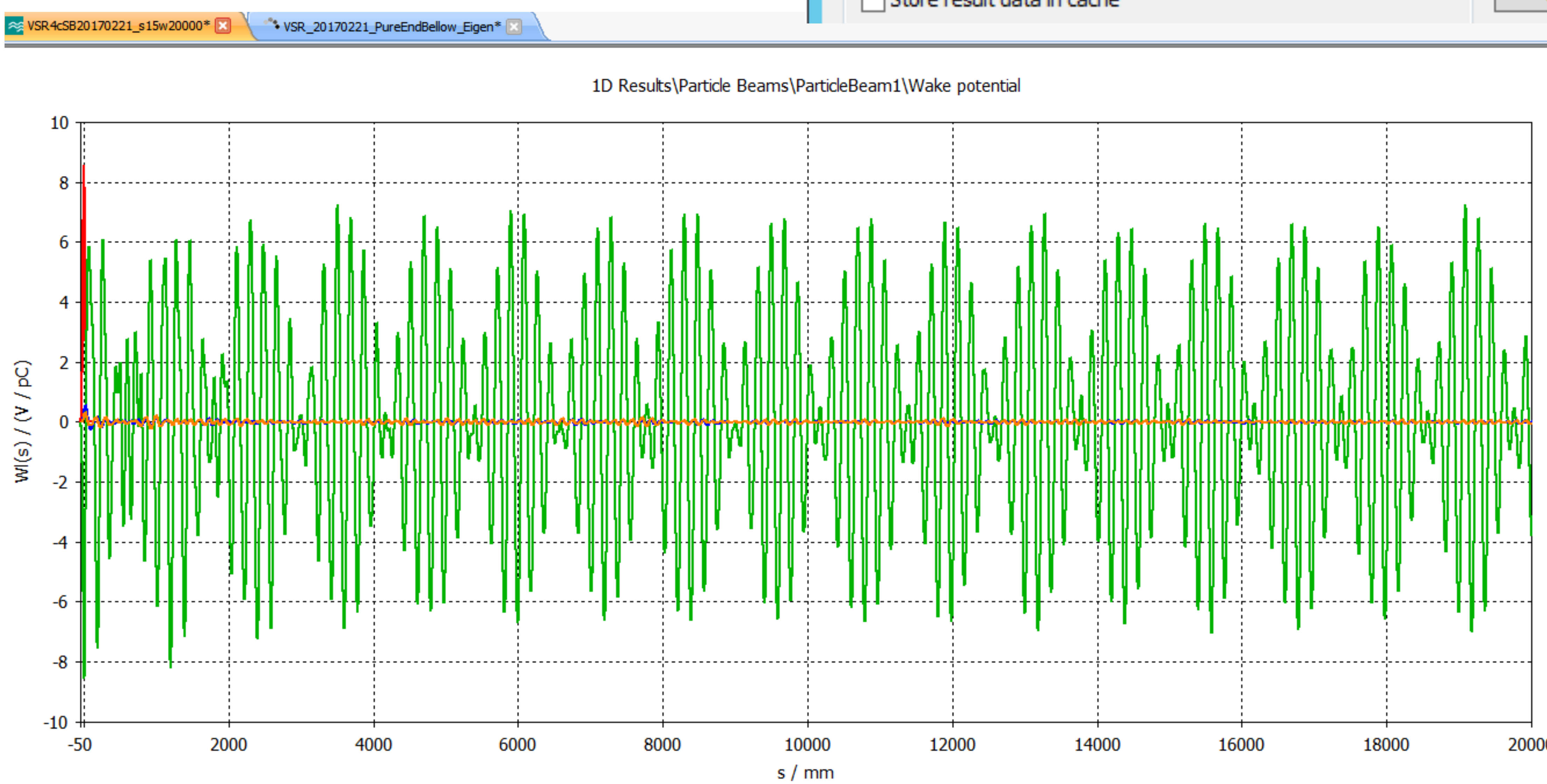
N_{cells} ~10^9 is close to the limit of 256GB / 12 core workstation; lengthen bunch as N_{cells} ~ $(1/\sigma)^3$; computing time ~ $(1/\sigma)^4$



So, what to tell the wakefield solver ?

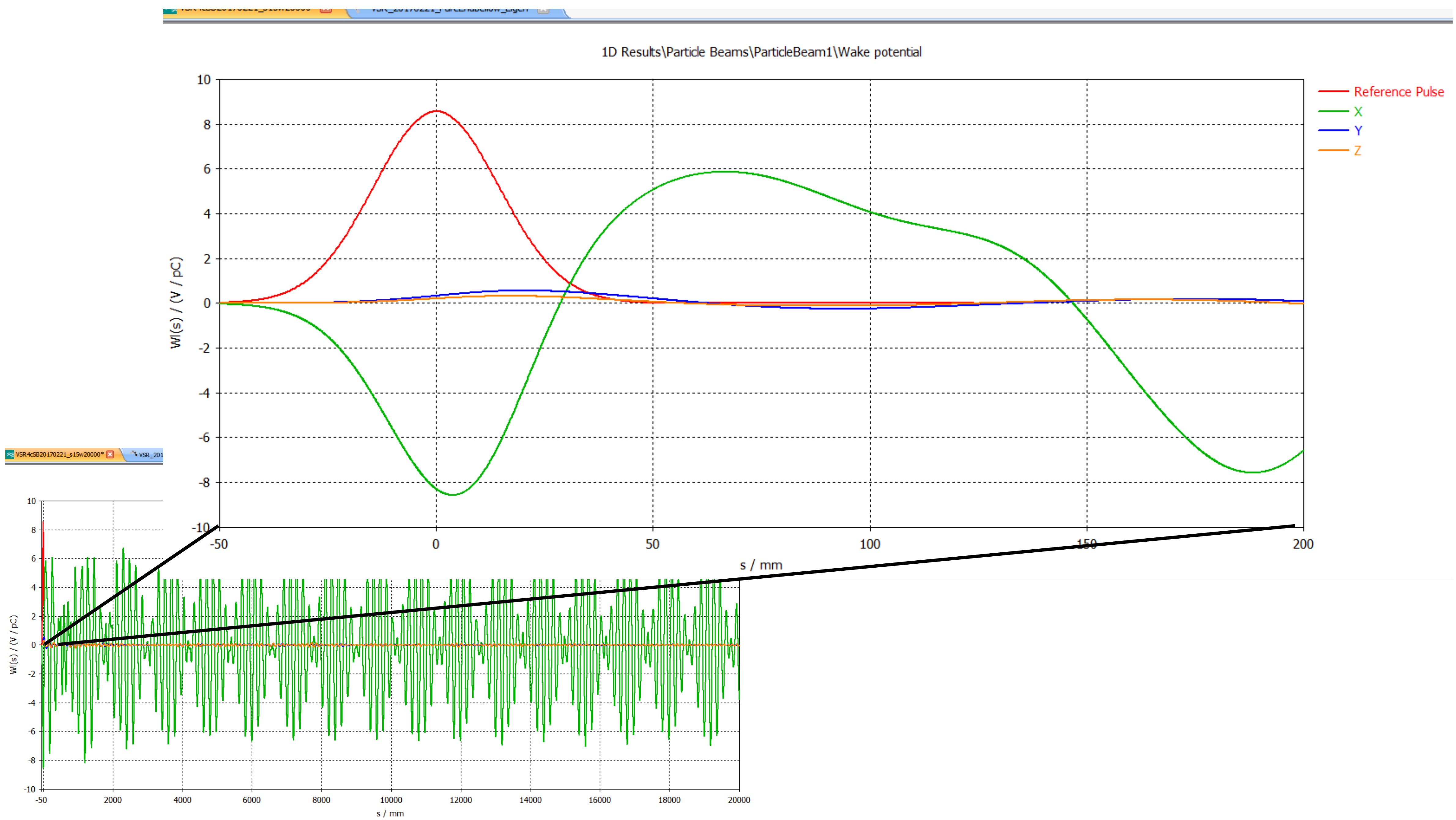
7. *the wake integration length L_{wake}. This determines the resolution of the impedance spectrum by $\Delta f = c_0 / L_{wake}$. L_{wake} = 20 m corresponds to $\Delta f \approx 12$ MHz*





So, what to tell the wakefield solver ?

7b. *If you only need a loss factor 200 mm wake length are sufficient, as k_{loss} is determined by the short range effect only.*



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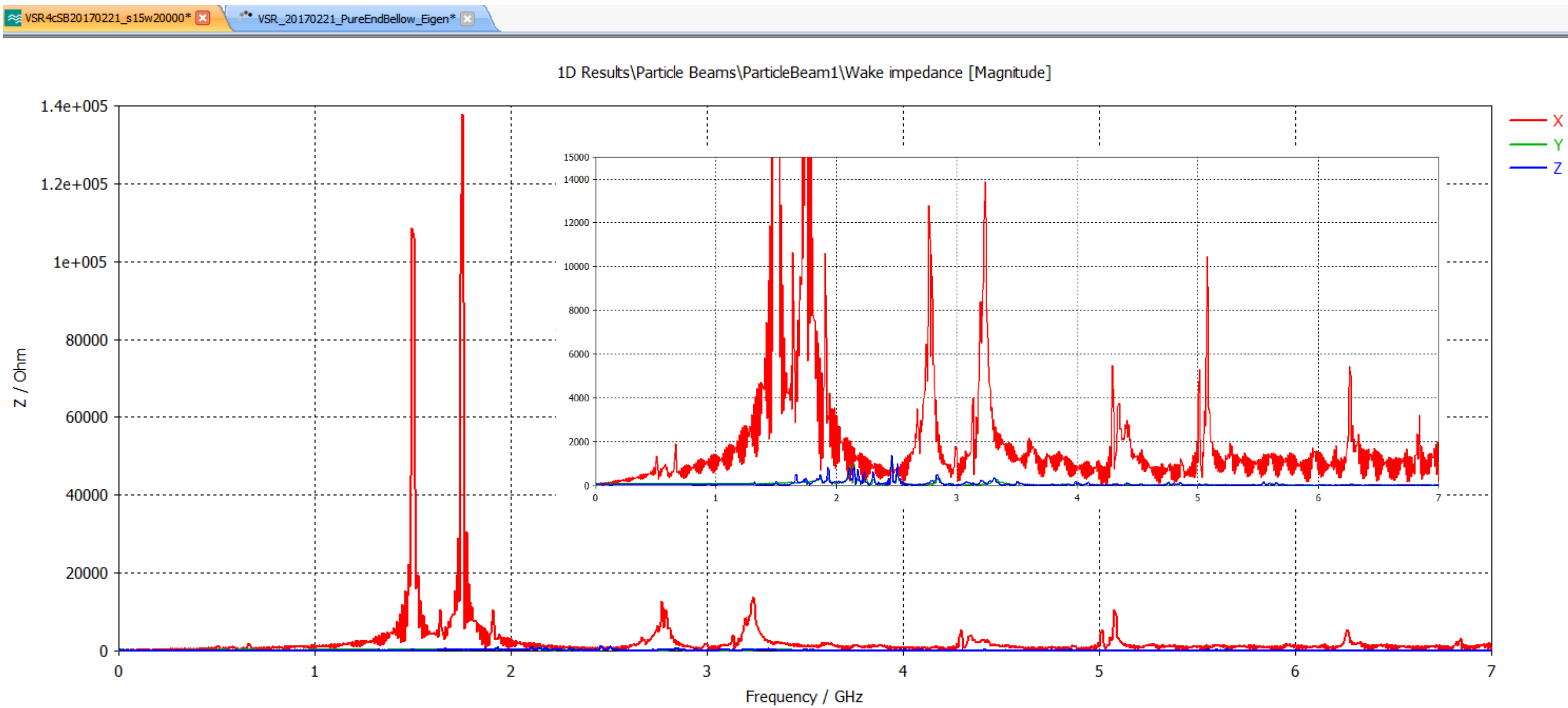
And what do you get out - most we already saw

– *except of the impedance*



… by the way: Which cavity modes should show the highest impedances ?

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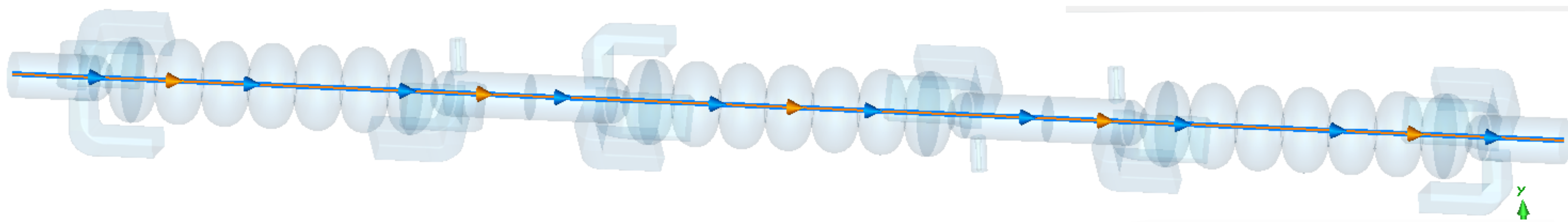
Supplement:

Continuous-Wave HOM Load Power Computations

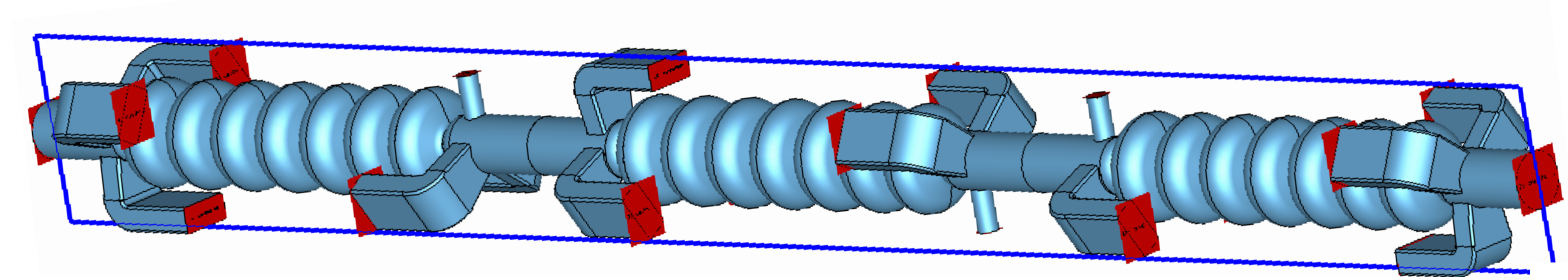
Based on Single-Bunch Wake Simulations

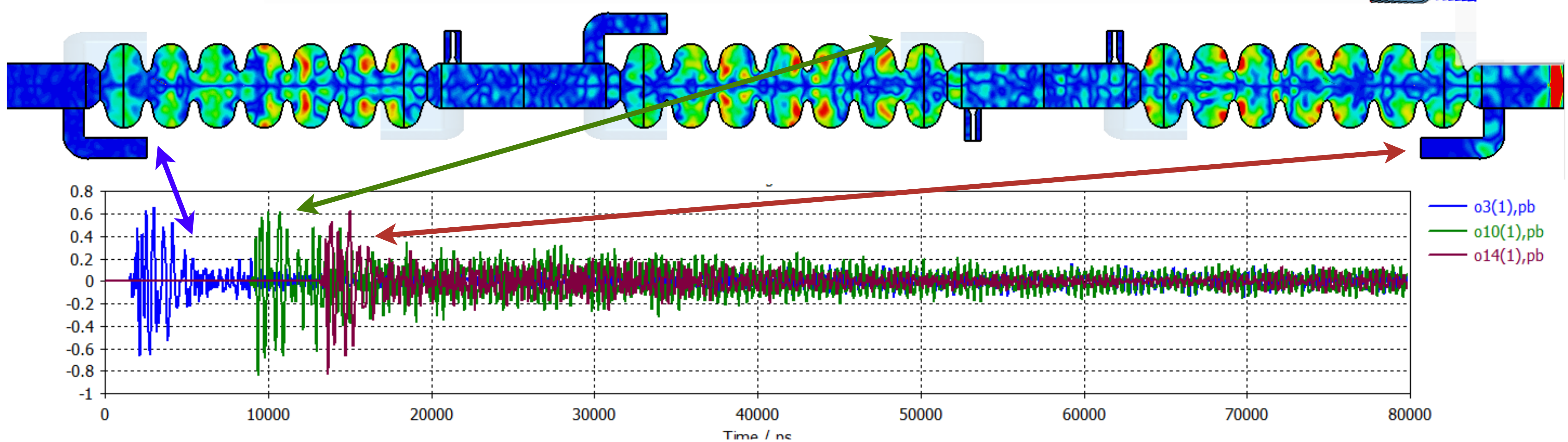
CST wake-to-absorber calculations (here bERLinPro Linac):

1.) numerically pass a single bunch ((reasonably) off-axis) through the cavity (chain)



2.) monitor (sufficiently many) waveguide mode amplitudes (dimension $W^{1/2}$) at all ***ports****:*

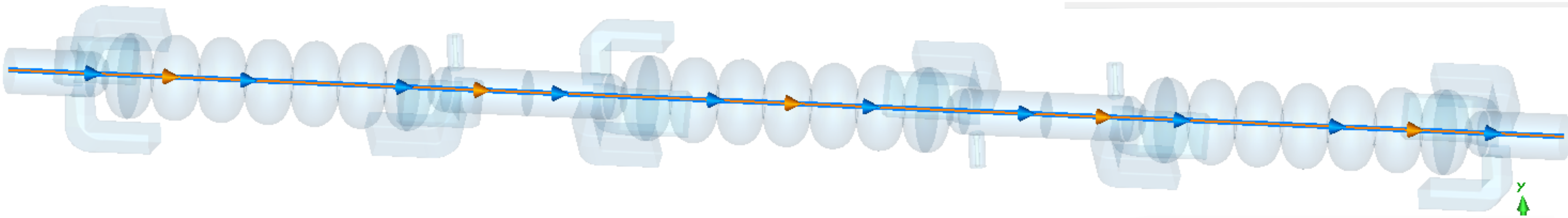




3.) ⇒ (single bunch) time domain port amplitudes

CST wake-to-absorber calculations:

1.) numerically pass a single bunch ((reasonably) off-axis) through the cavity (chain)



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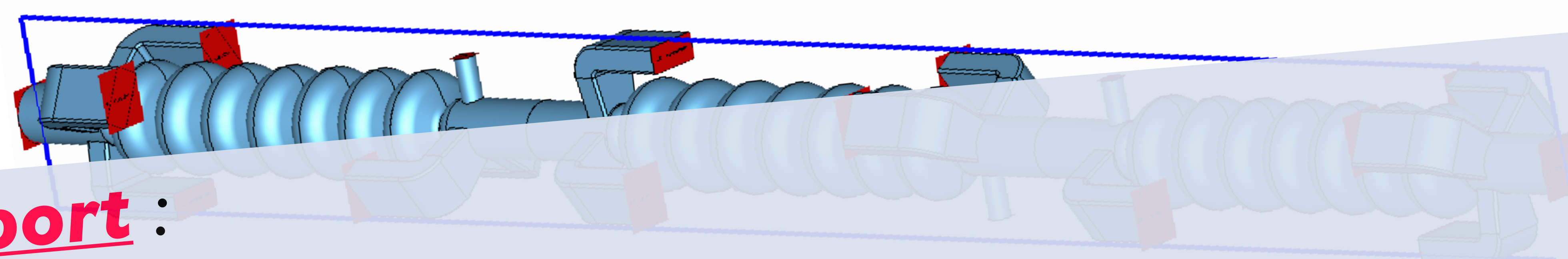
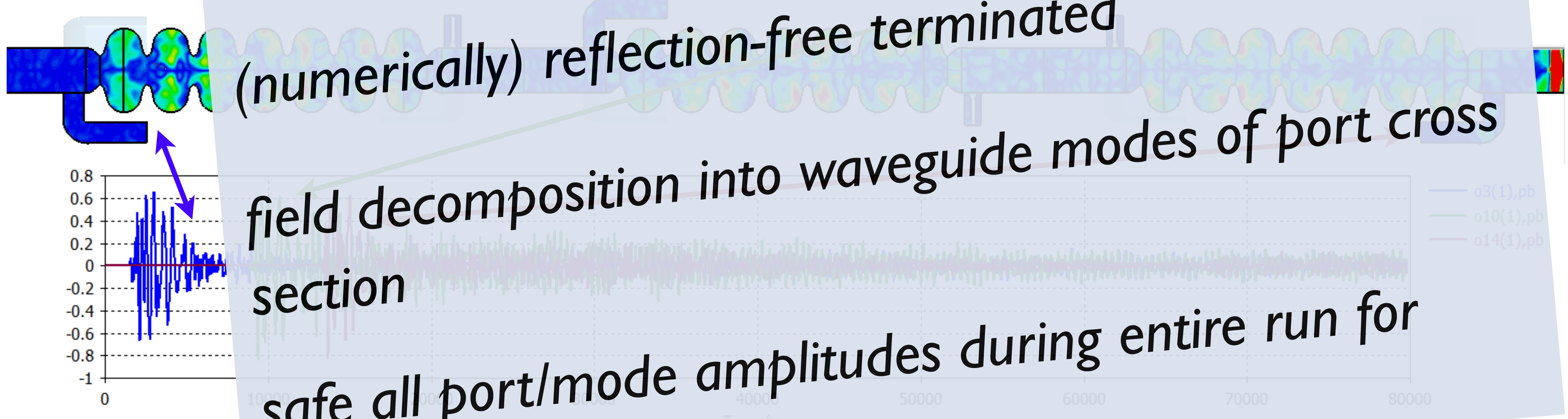


port :

(numerically) reflection-free terminated

field decomposition into waveguide modes of port cross section

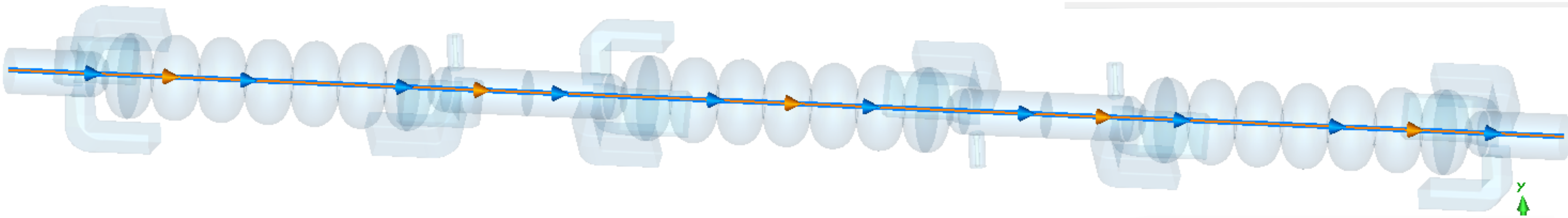
safe all port/mode amplitudes during entire run for every time step



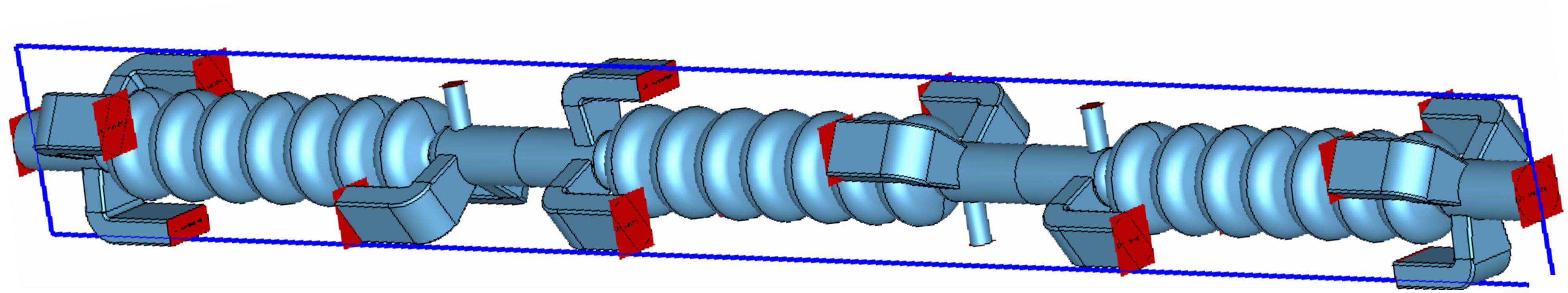
3.) ⇒ (single bunch) time domain port amplitudes

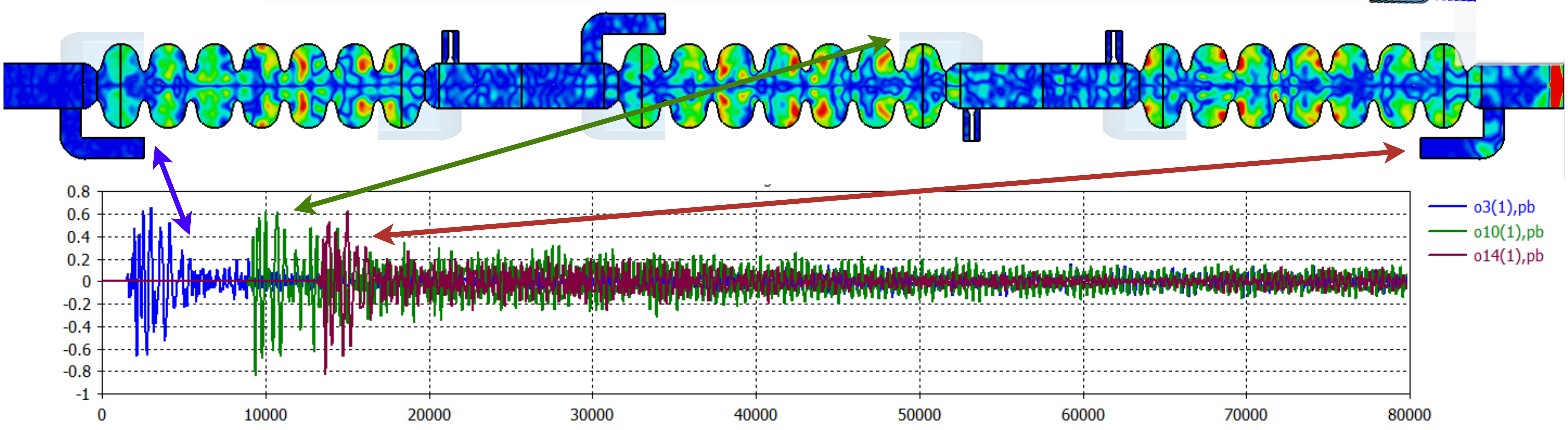
CST wake-to-absorber calculations:

1.) numerically pass a single bunch ((reasonably) off-axis) through the cavity (chain)



2.) monitor (sufficiently many) waveguide mode amplitudes (dimension $W^{1/2}$) at all ***ports****:*





3.) ⇒ (single bunch) time domain port / mode amplitudes

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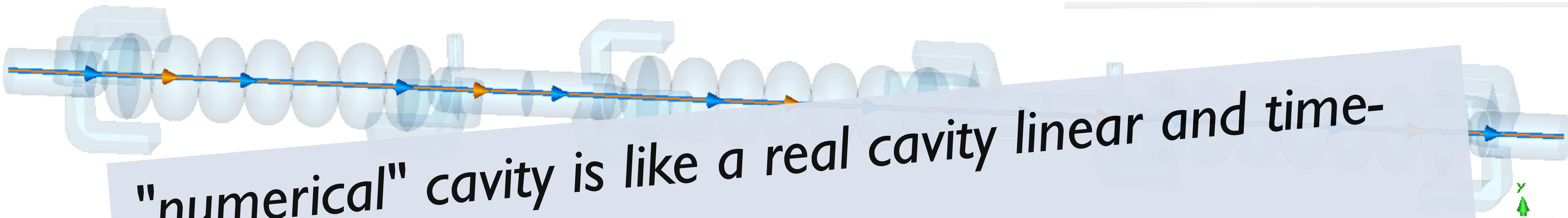
CST wake-to-absorber calculations:

1.) numerically pass a single bunch ((reasonably) off-axis) through the cavity (chain)



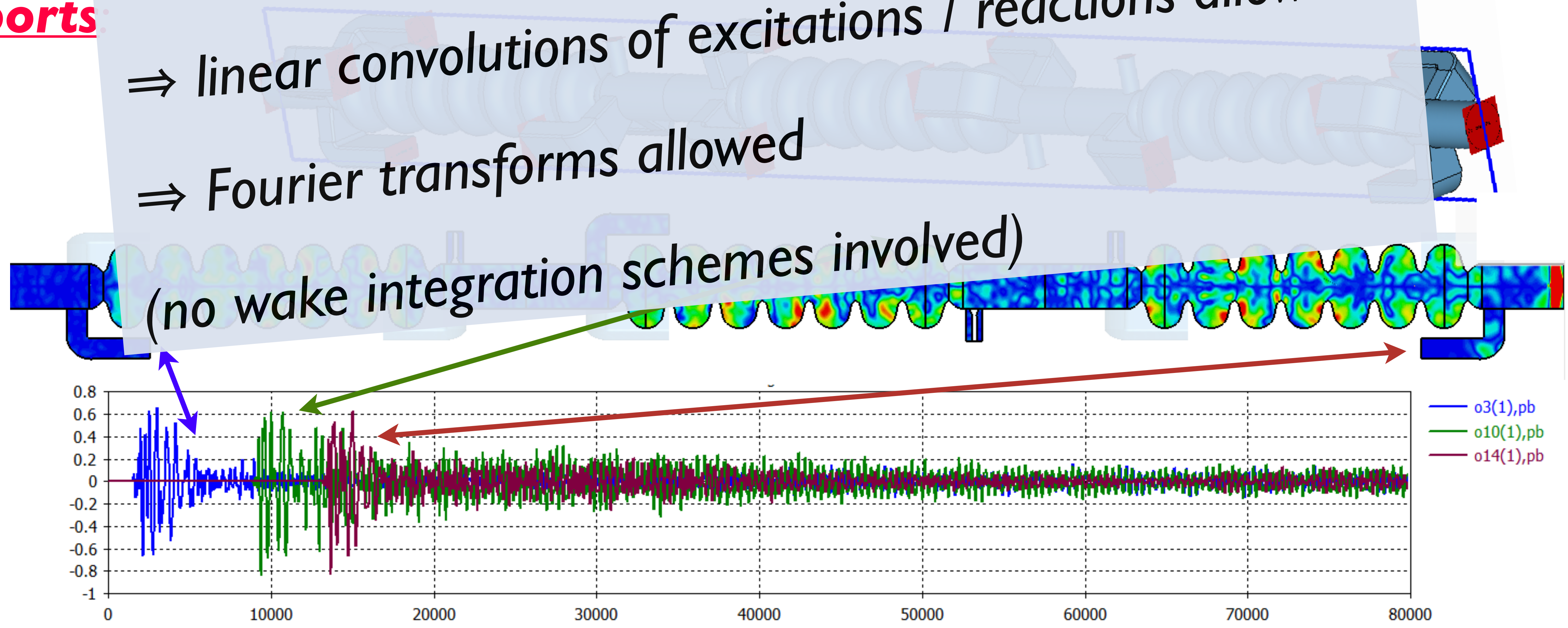
*2.) monitor (sufficiently many) waveguide mode amplitudes (dimension $W^{1/2}$) at all **ports**:*

"numerical" cavity is like a real cavity linear and time-invariant

⇒ linear convolutions of excitations / reactions allowed

⇒ Fourier transforms allowed

(no wake integration schemes involved)



3.) ⇒ (single bunch) time domain port amplitudes

How do we get the

<u>multi-bunch</u> port/mode power P_{pm} (averaged over ΔT)

from the <u>single-bunch</u> exited port/mode amplitude A_{pm}?

1.) Fourier-transform A_{pm} and interpolate it on frequency points $(j/\Delta T)$

$$\alpha_{pm}(j) = \mathrm{Interpolate}\{\ \mathrm{DiscreteFourierTr.}\{A_{pm}\}\ @\ (j/\Delta T)\ \},\quad j = 1 \ldots N_{max}, \quad N_{max} = f_{max} \cdot \Delta T$$

2.) Sample a single Gaussian bunch current of simulated σ, zero-padded to ΔT. Fourier-transform, take the first N_{max} values:

$$\gamma(j) = \mathrm{DiscreteFourierTr.}\{\mathrm{Gauss}_\sigma + 000\}$$

3.) Sample the given train of (Gaussian?) bunch currents. Fourier-transform, take the first N_{max} values:

$$\beta(j) = \mathrm{DiscreteFourierTr.}\{\mathrm{bunchtrain}\}$$

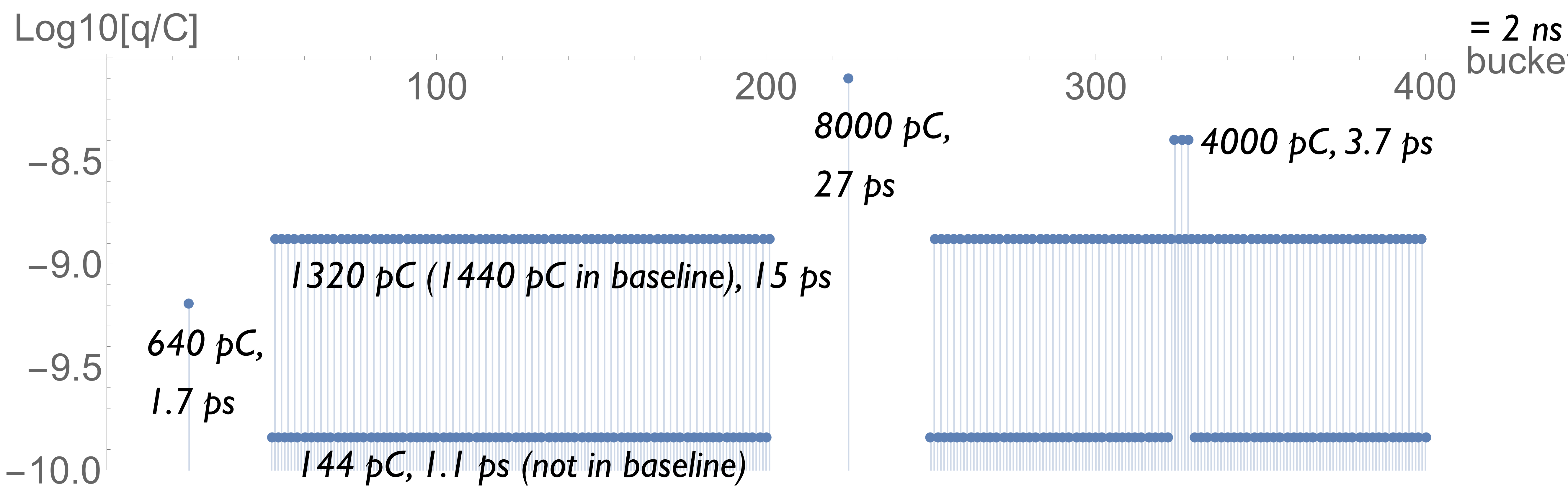
4.) Compute for each frequency step j the excitation-scaled, frequency-domain port / mode amplitude:

$$\tilde{A}_{pm}(j) = \beta(j)\ /\ \gamma(j) \cdot \alpha_{pm}(j)$$

5.) Compute for each frequency step j (of width $1/\Delta T$), the frequency-domain port / mode power $P_{pm}(j)$:

$$P_{pm}(j) = \tilde{A}_{pm}(j) \cdot \tilde{A}^*_{pm}(j)$$

VSR (Variable pulse length Storage Ring) beam time structure:



All bunches Gaussian shaped, sampled with 0.1 ps time step,

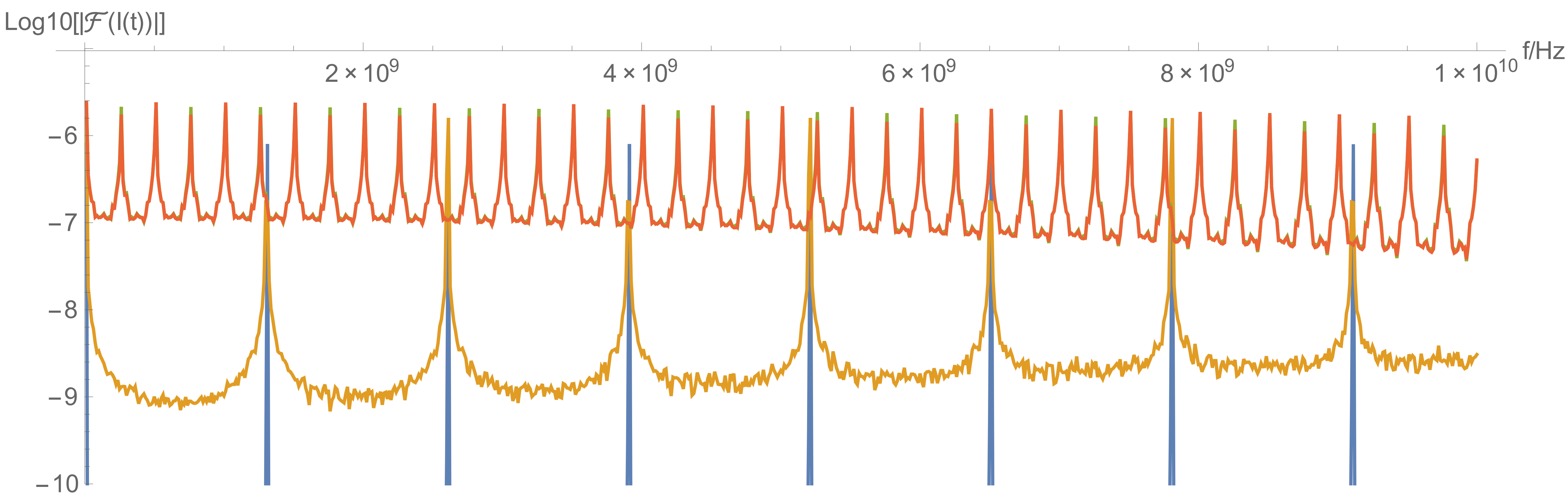
time signal of ΔT = 8 µs length = 80 Mio sampling points Discrete-Fourier-transformed.

VSR — NO: beam dynamics, phase shifts, noise

bERLinPro — σ = 2 ps, 1.3 GHz cw, recirculation, white noise charge jitter ± 2%, phase jitter ± 1°, assumed gapping: 2080 bunches + 520 empty buckets

Spectral amplitude comparison up to 10 GHz:

bERLinPro / bERLinPro-worst case / VSR-baseline / VSR-extended



bERLinPro: recirculation not included, therefore n × 1.3 GHz

bERLinPro-w.c.: recirculation included ⇒ n × 2.6 GHz, but also gaps ⇒ (weaker) n × 2.6 GHz + 1.3 GHz

VSR: 4 ns-gaps dominant ⇒ n × 250 MHz

VSR-extended: interlaced 1.1 ps – low charge does not hurt, but n × 500 MHz a little bit more exposed

- bERLinPro cw beam NO repetition, NO jitter
- bERLinPro cw beam with repetition, 2080 bunches + 520 gaps, jitter +-1°, q +-2%
- bessy VSR beam NO 1.1 ps, no jitter
- bessy VSR beam WITH 1.1 ps, no jitter

Interpolation of port signal spectra ... unfortunately needed:

Typical workstation (12 cores, 256 GB RAM),

wake simulation acting on ~ 10^9 mesh cells (hexagonal grid),

response times ~ 10^1 days :

⇒ ~ 20 m wake length

⇒ ~ 80 ns integration time

⇒ ~ 12.5 MHz frequency resolution

REMEMBER: Beam spectra available e.g. with 125 kHz

Interpolation of port signal spectra ... unfortunately needed:

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⇒ ~ 20 m wake length

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REMEMBER: Beam spectra available e.g. with 125 kHz

Interpolation options:

⇒ linear – in tests significant power deficit

⇒ black-box spline x^{th} order – we use x = 5, seems acceptable

⇒ pole fitting – recommendable

Interpolation of port signal spectra ... unfortunately needed:

Typical workstation (12 cores, 256 GB RAM),

wake simulation acting on ~ 10^9 mesh cells (hexagonal grid),

response times ~ 10^1 days :

Interpolating the spectrum of the port signals means a virtual prolongation of missing wake integration time.

⇒ ~ 20 m wake length

⇒ ~ 80 ns integration time

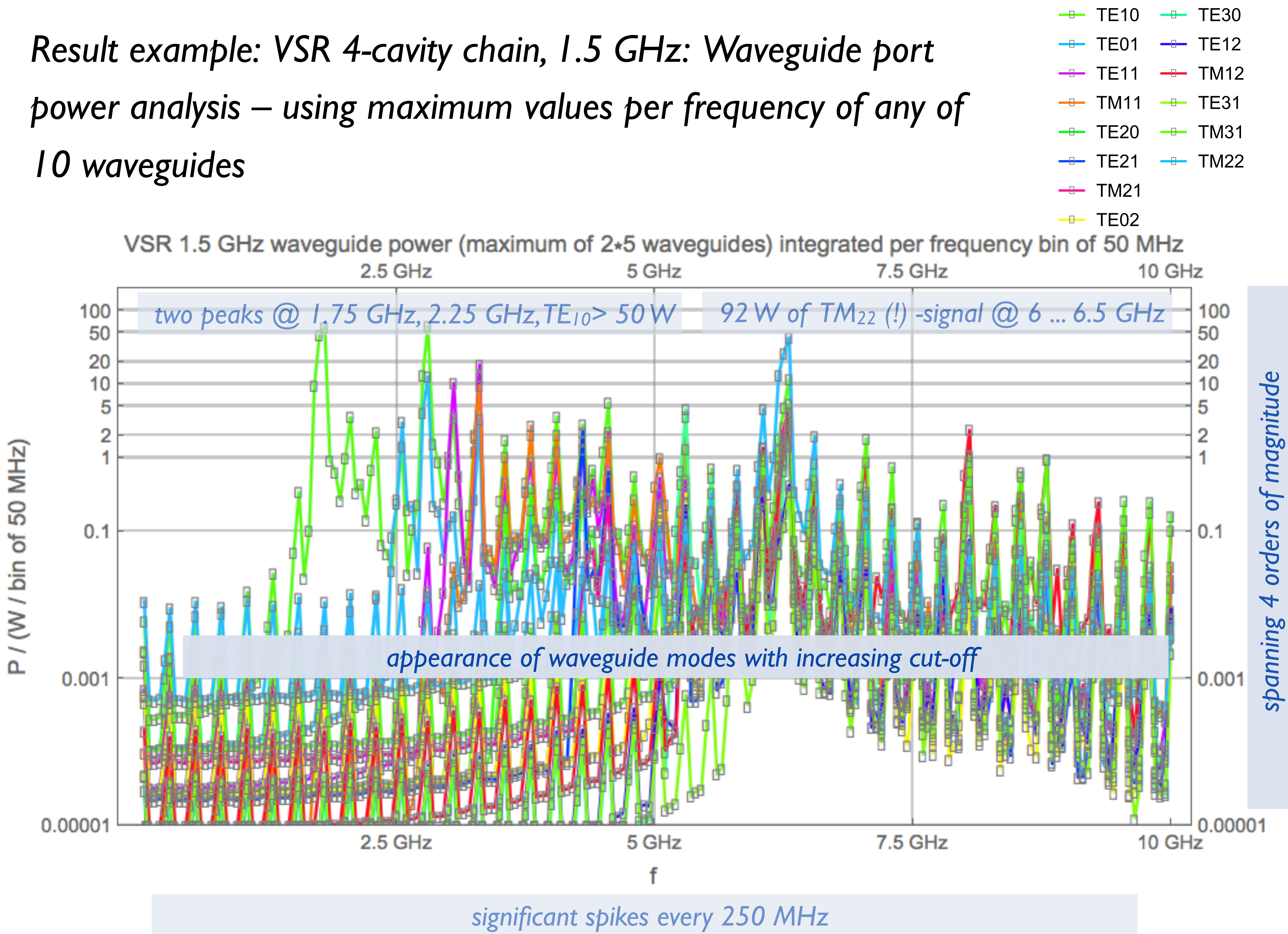
⇒ ~ 12.5 MHz frequency resolution

REMEMBER: Beam spectra available e.g. with 125 kHz

Interpolation options:

- *⇒ linear* – *in tests significant power deficit*
- *⇒ black-box spline x^{th} order* – *we use x = 5, seems acceptable*
- *⇒ pole fitting* – *recommendable*

Result example: VSR 4-cavity chain, 1.5 GHz: Waveguide port power analysis – using maximum values per frequency of any of 10 waveguides



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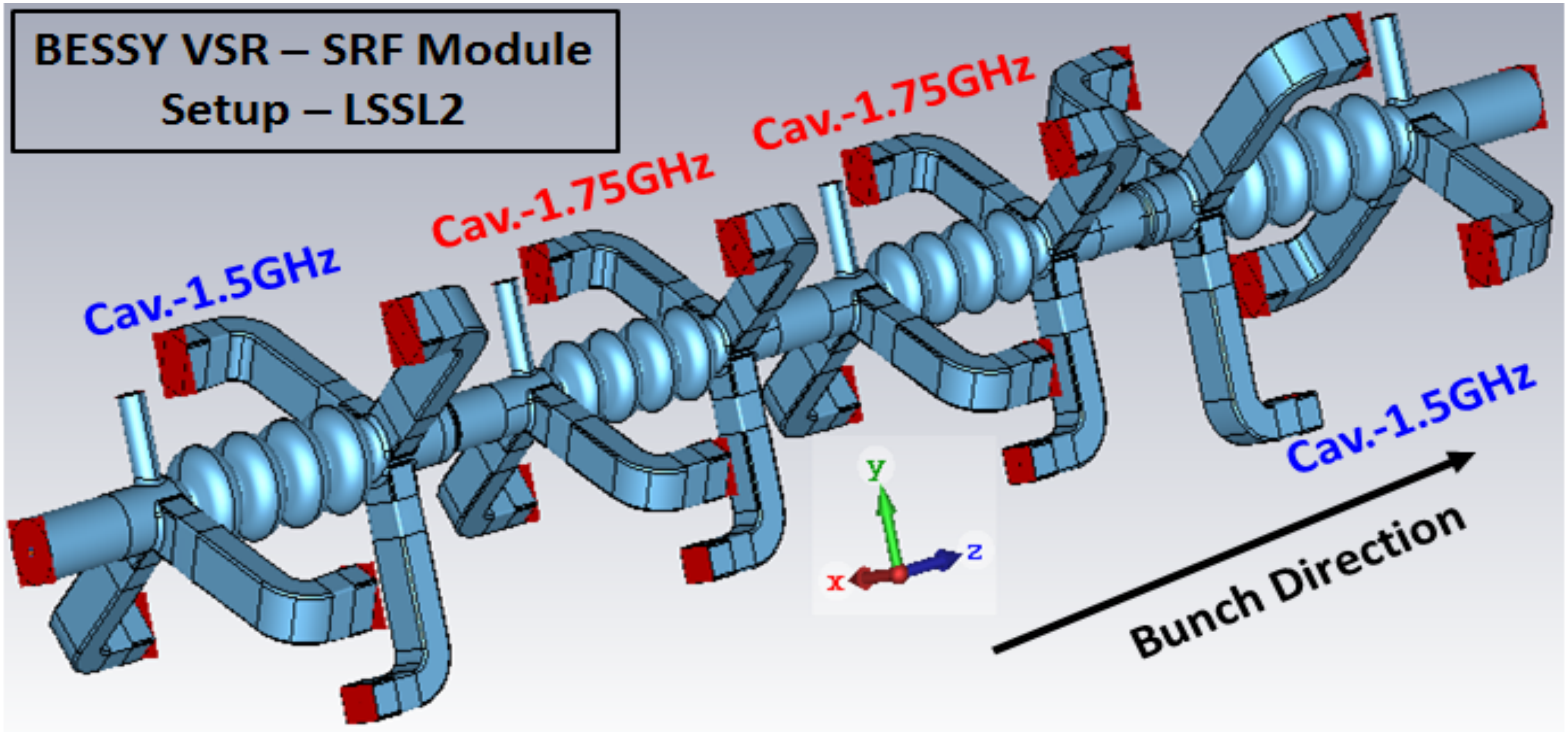
Full String Wake Simulations in Various Setups

results, slide courtesy of Andranik Tsakanian

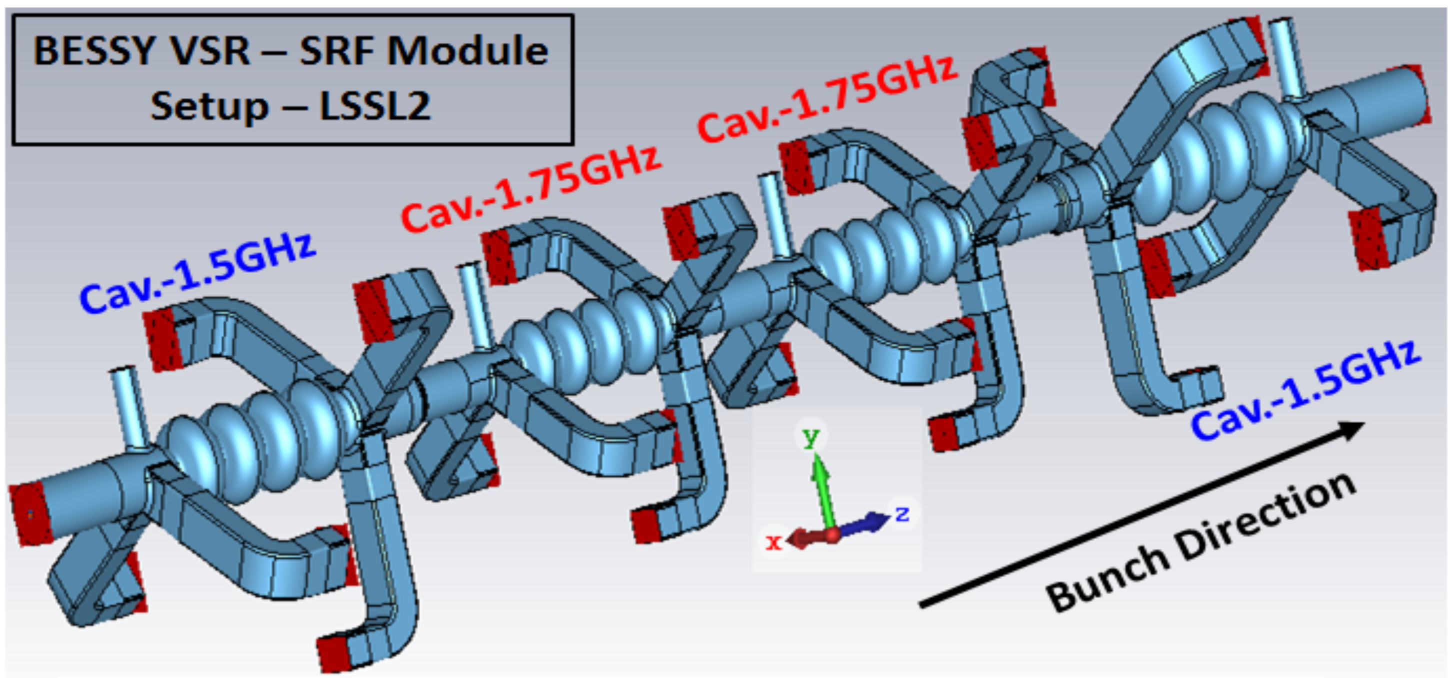


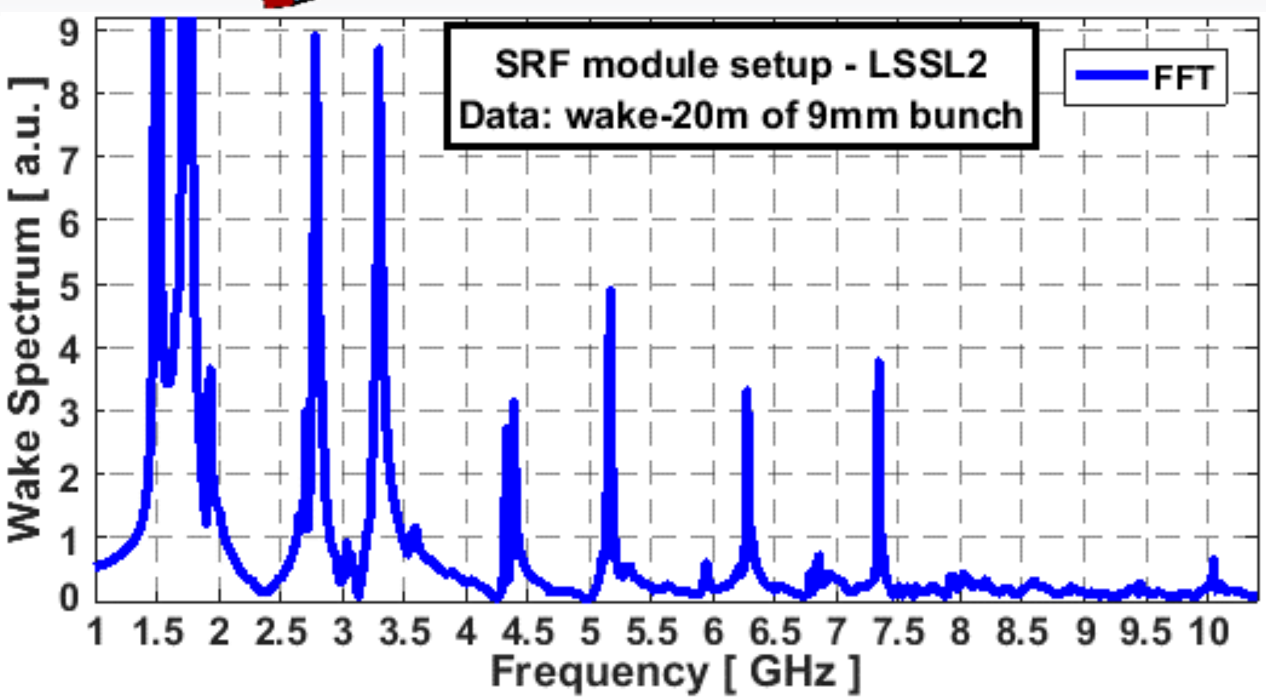
... to reduce and equilibrate power flow in HOM loads

... especially to reduce power flow in fundamental power couplers to avoid issues of the ceramic windows.

HOM Power Levels in Entire Module

results, slide courtesy of Andranik Tsakanian





VSR Module Power Levels: Baseline Filling Patern

HOM Power [W]

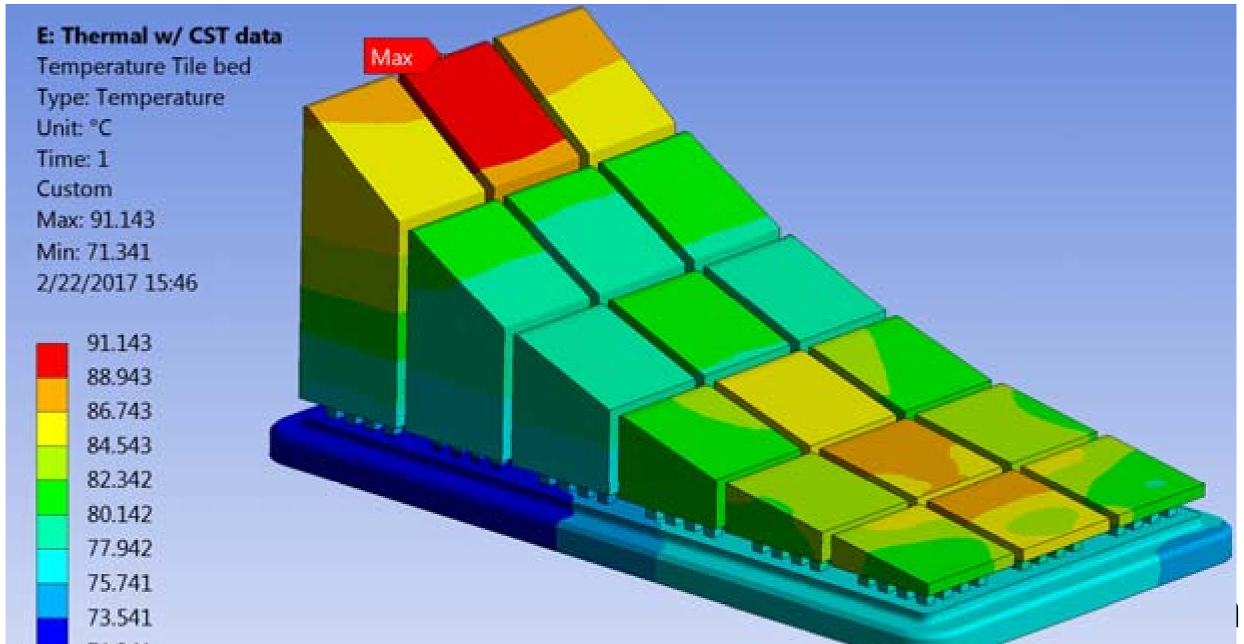
Port	LSSL1	LSSL2	SSLL1	SSLL2
1	28,9	28,9	102,2	58,6
2	102,2	102,1	216,0	217,4
3	102,2	102,1	216,0	217,4
4	157,0	157,1	178,7	179,0
5	157,0	157,1	178,7	179,0
6	195,6	195,5	204,6	231,7
7	46,3	45,8	25,7	25,4
8	230,3	230,1	140,2	140,1
9	230,3	230,1	140,2	140,1
10	163,2	163,7	165,5	165,9
11	163,2	163,7	165,5	165,9
12	221,8	221,3	225,7	223,6
13	52,6	53,0	53,1	52,4
14	249,6	247,2	254,2	251,8
15	249,6	247,2	254,2	251,8
16	185,2	163,9	195,2	171,1
17	185,2	163,9	195,2	171,1
18	240,9	199,9	263,6	207,6
19	96,2	24,2	59,7	23,7
20	201,5	115,1	210,2	116,2
21	201,5	115,1	210,2	116,2
22	86,0	159,5	90,0	167,6
23	86,0	159,5	90,0	167,6
24	97,3	202,8	96,5	208,5
25	246,6	246,1	227,6	225,0
26	269,4	330,2	299,0	357,7
Total	4245 W	4225 W	4457 W	4432 W

Ports 1–6: 1.5 GHz; Ports 7–18: 1.75 GHz Cavities; Ports 19–24: 1.5 GHz; Ports 25–26: Beam pipes

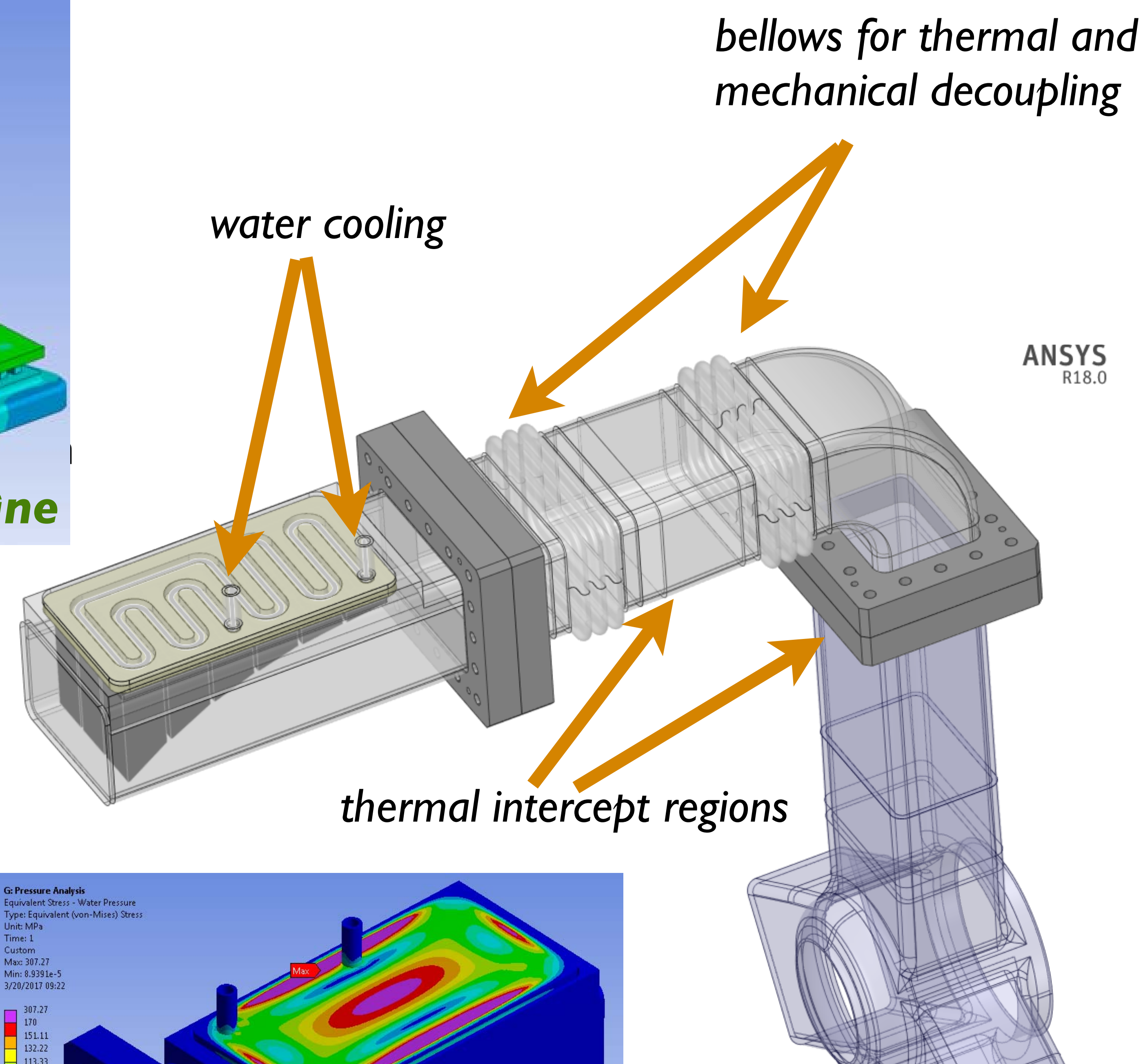
... we have to face ~5 kW of RF power to be dumped.

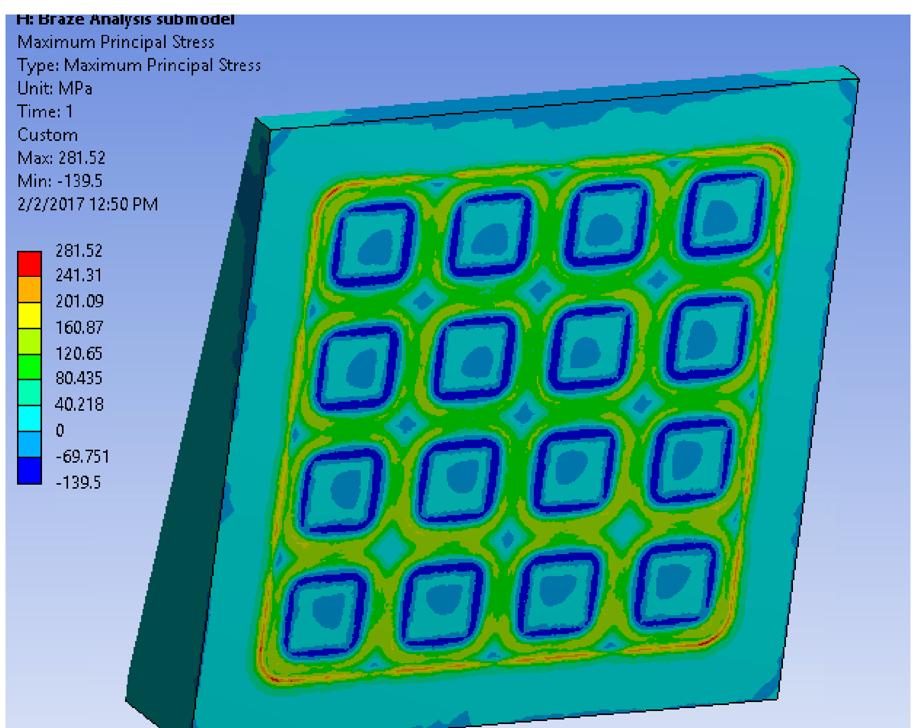
Warm absorber / waveguides

modeling, simulation, viewgraphs
courtesy Fredrik Fors, Jiquan Guo, JLab

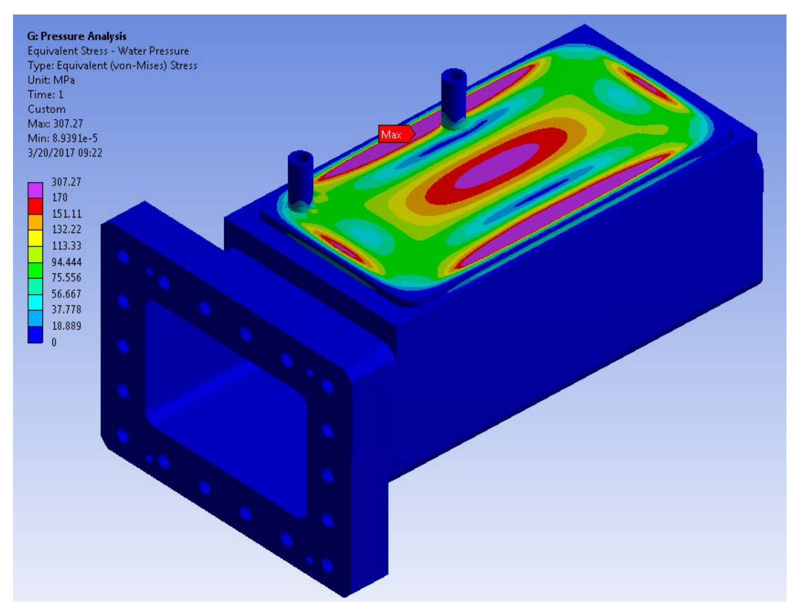


temperature distribution numerically fine





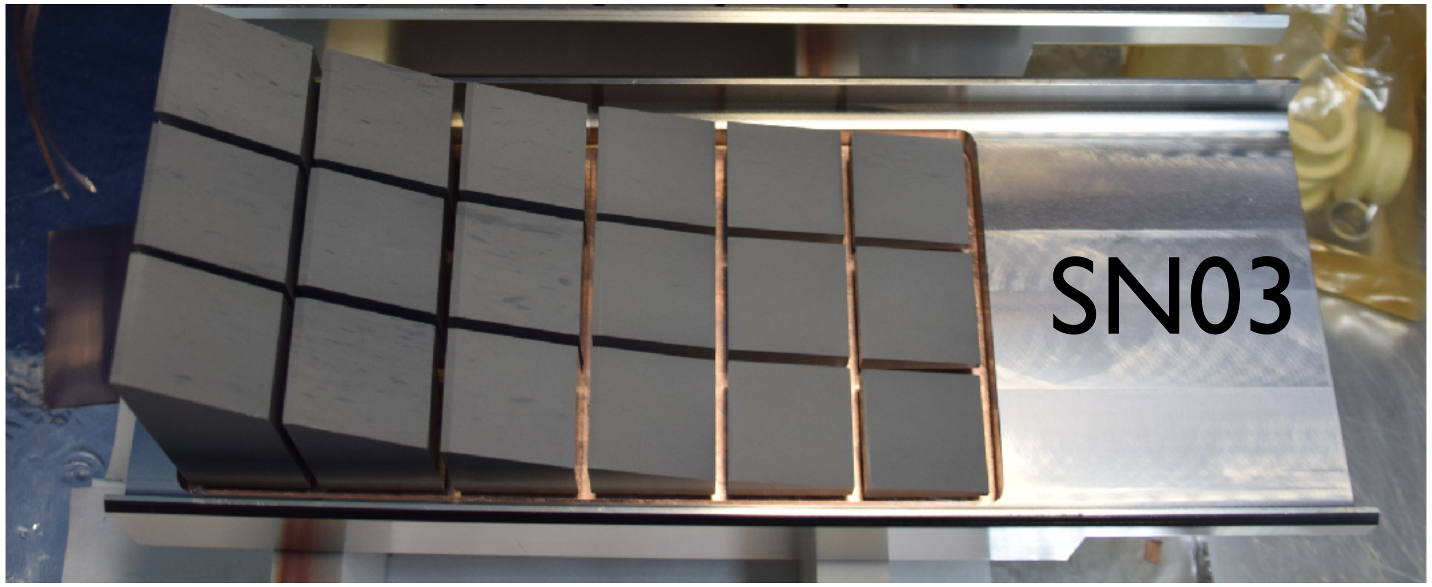
absorber tile stress numerically fine

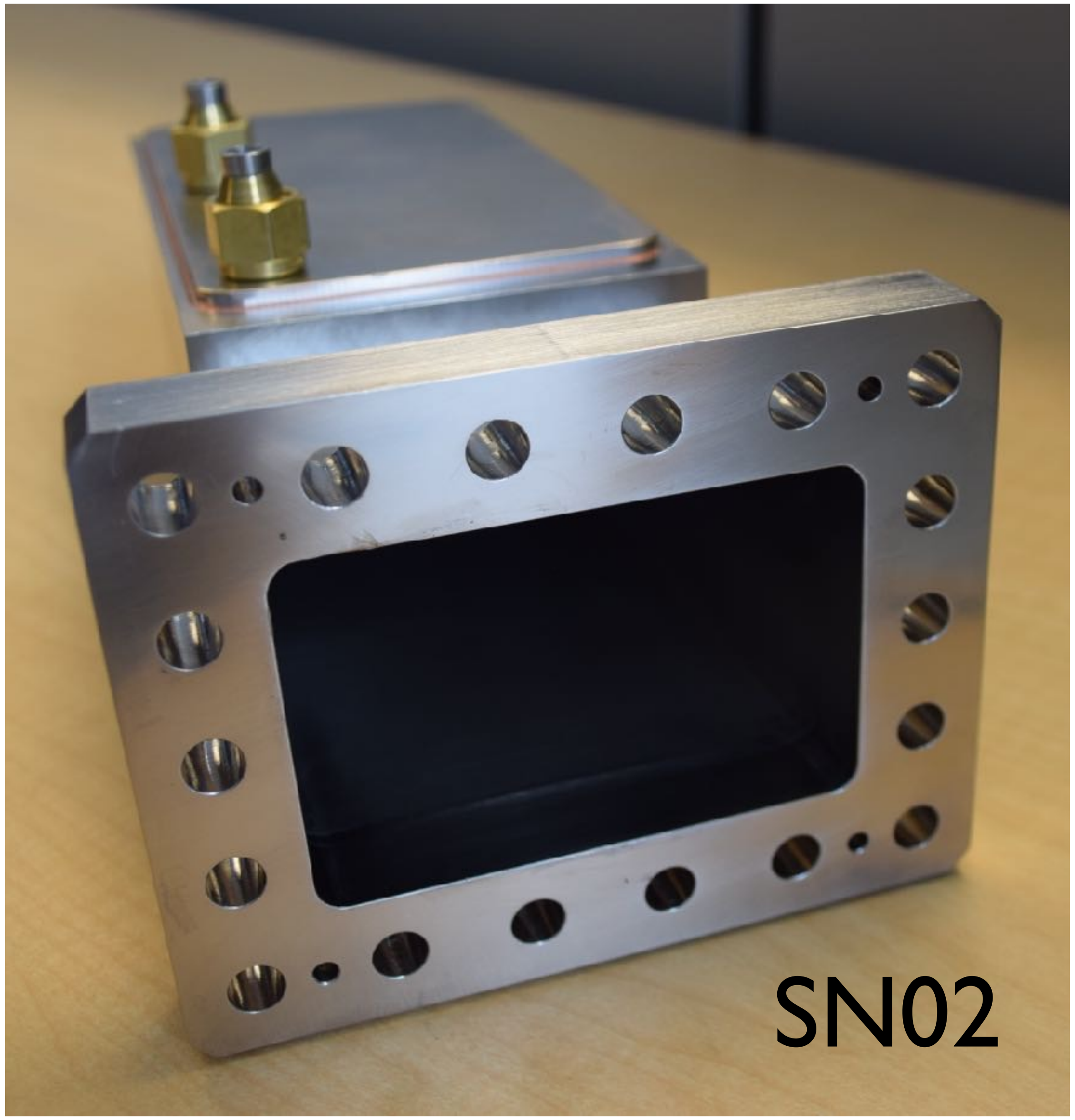


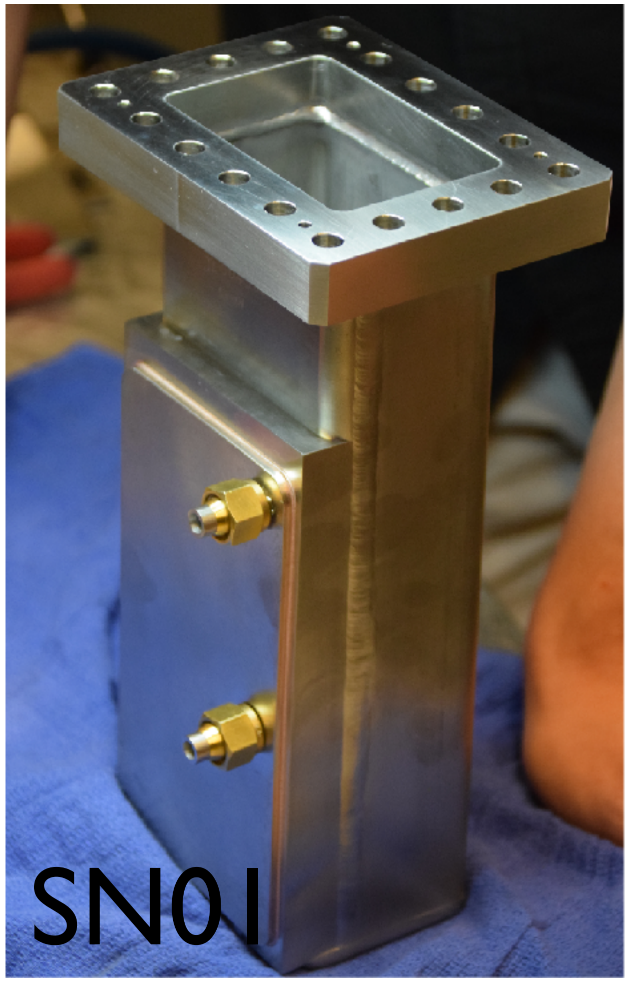
mechanical stress numerically fine

We do have

- *2 VSR load prototypes (1.5 GHz) welded (including top, flange)*
- *1 VSR load prototypes (1.5 GHz) not welded*

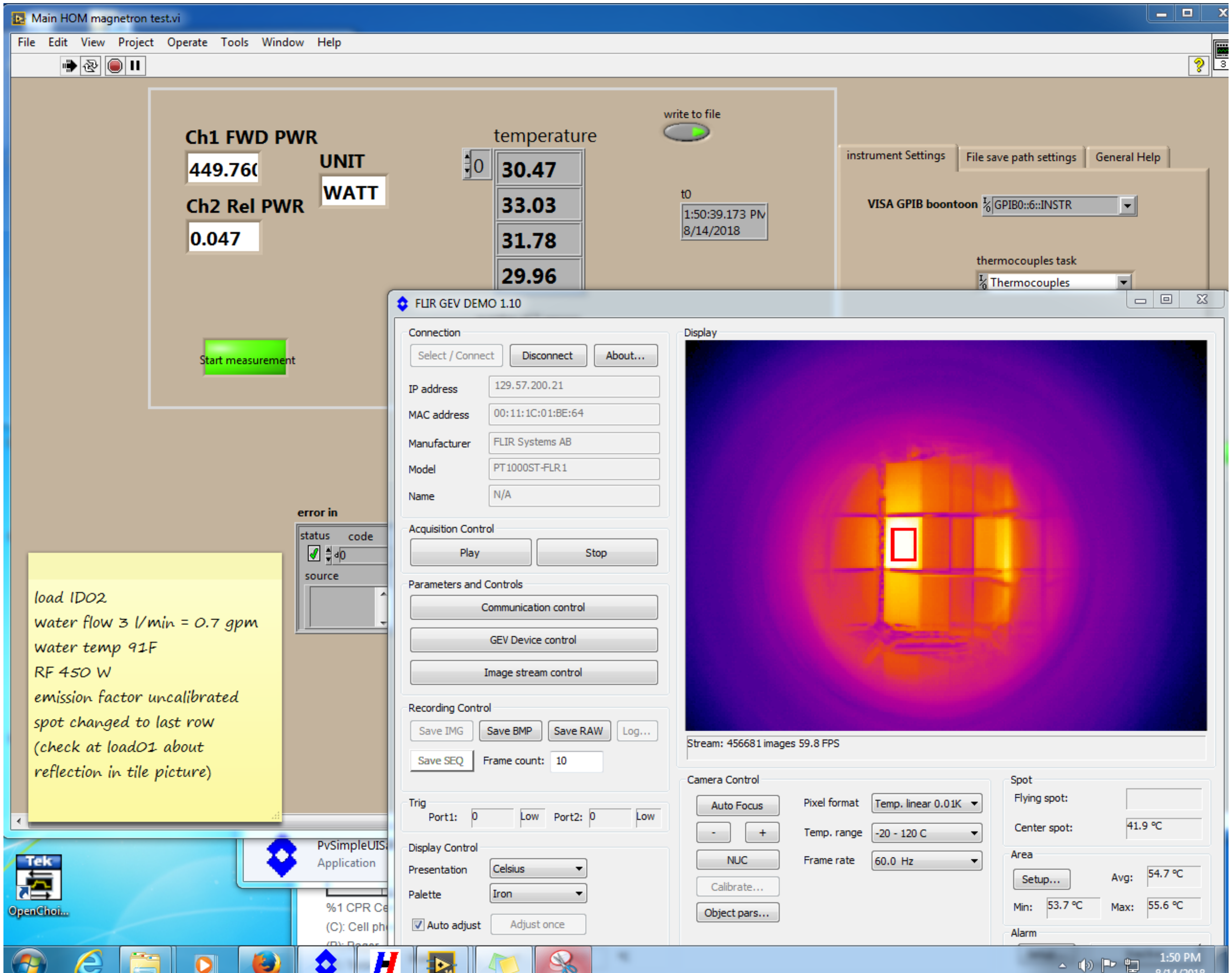






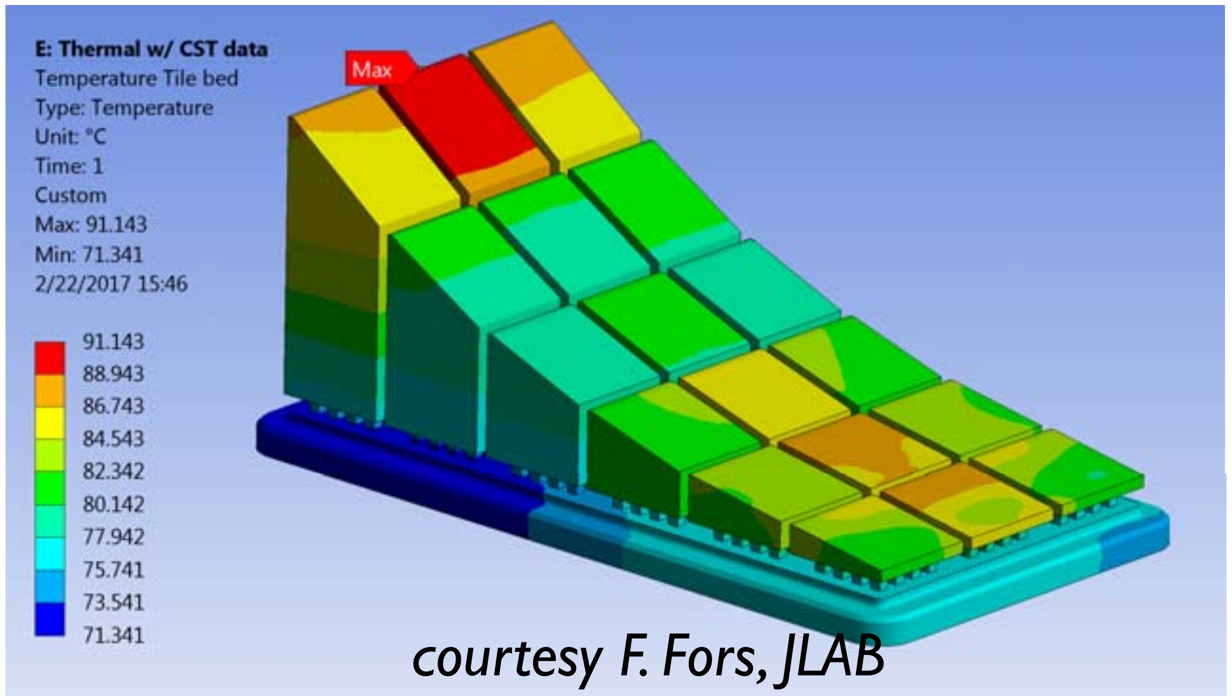
High-power RF test

– ceramic temperatures ≤ 56 °C (uncal.), water ≤ 32 °C (@ 30 °C inlet, 3 L/min) @ 450 W (design)



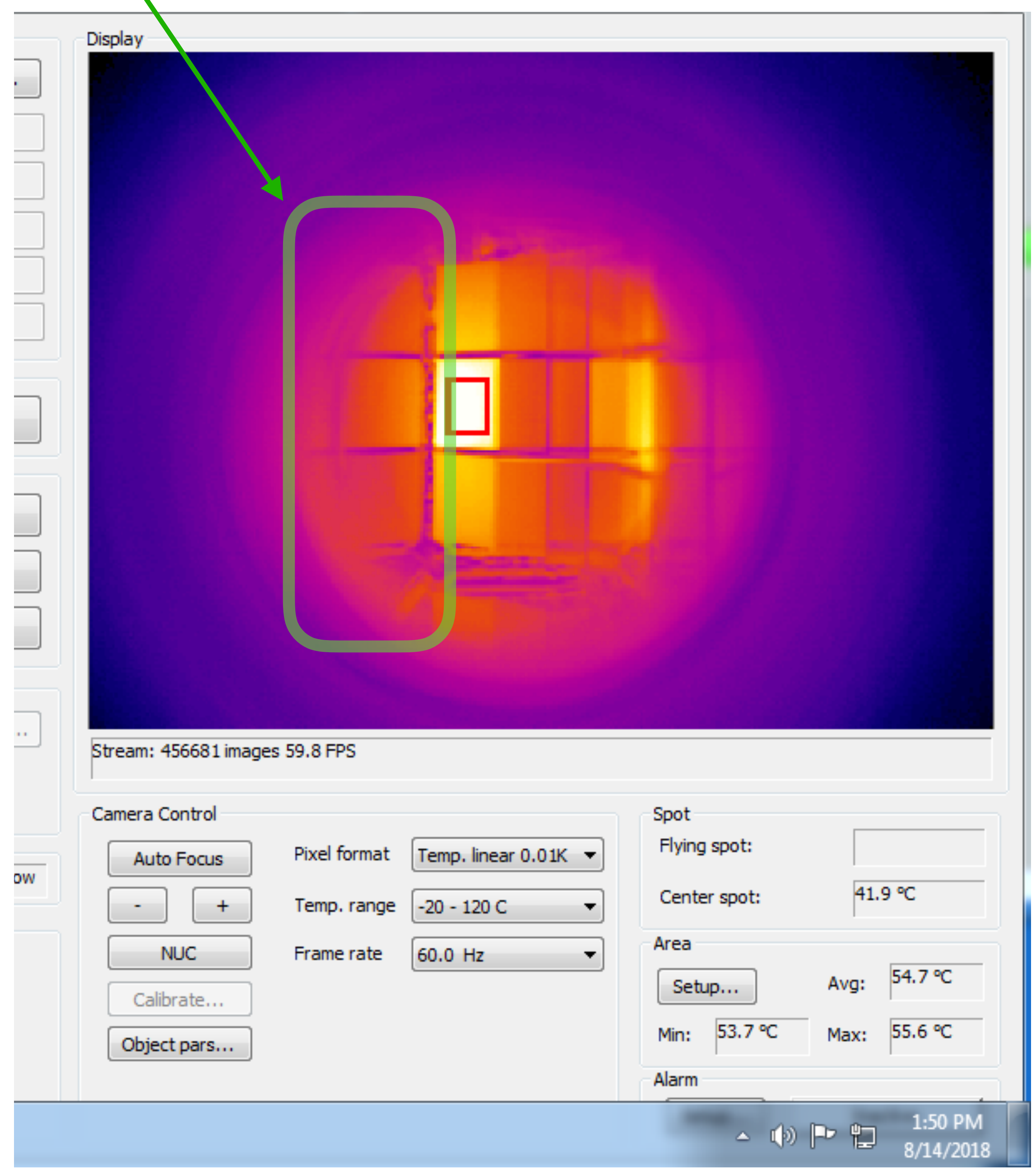
High-power RF test

– good coincidence with simulation result (leftmost row is reflection at waveguide inner surface)



Thermal analysis results

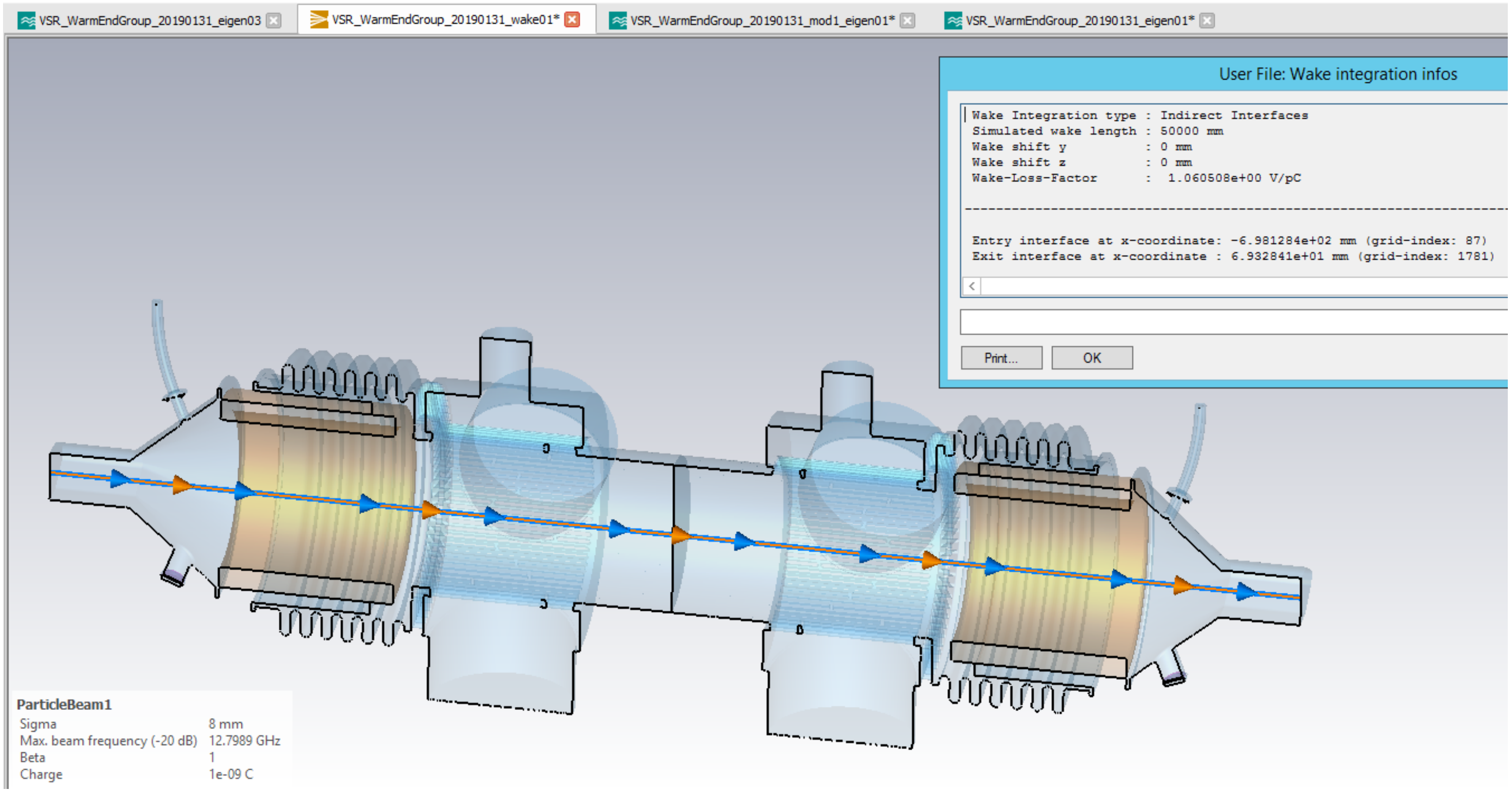
optical reflection of last row



- temperature level of copper backplate unexpectedly high @30°C cooling water
- temperature gradient from backplate to ceramic in good coincidence with measurement

Supplement:

The Warm End Group as Example for Rescaling of Dielectric Losses



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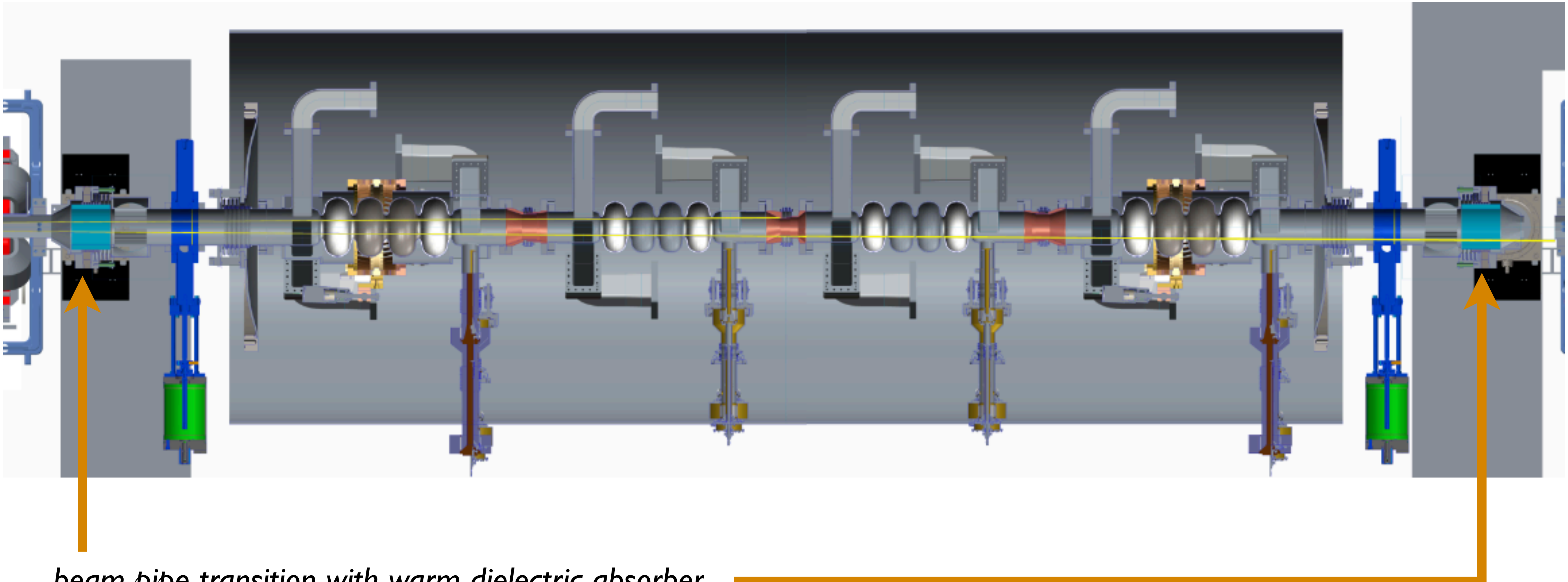
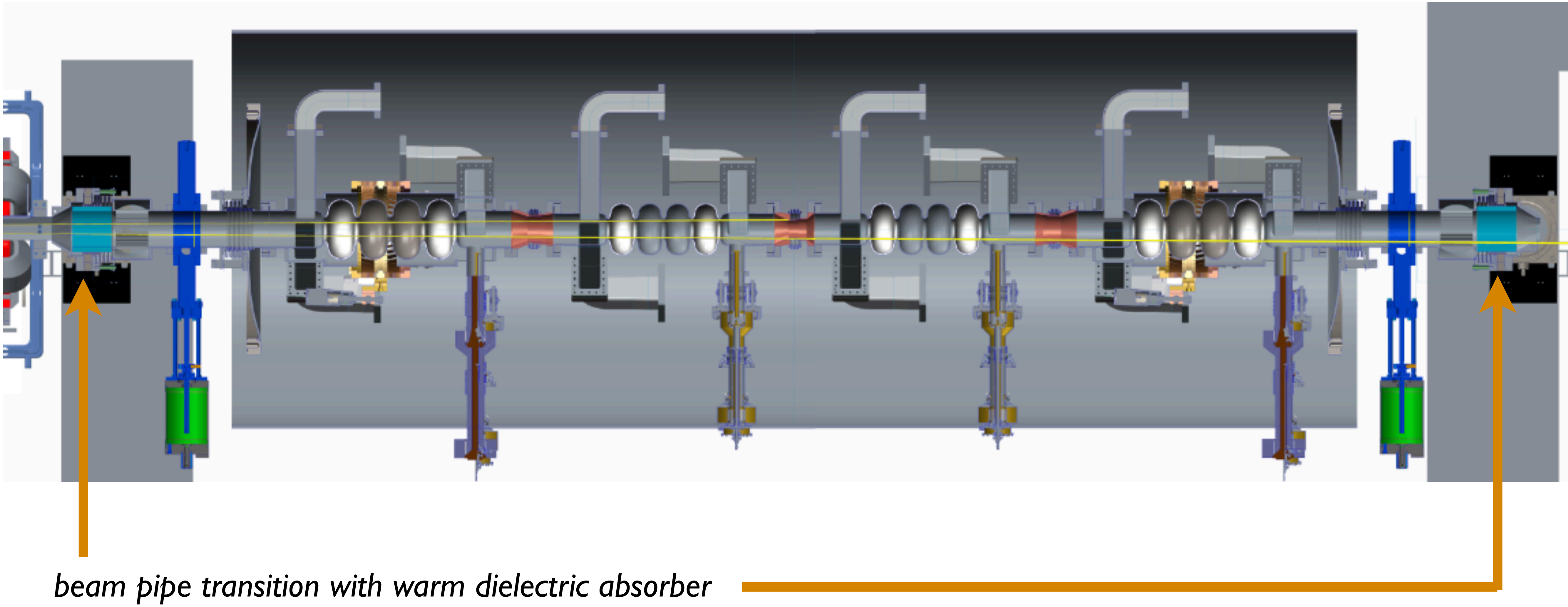
Beam pipe transitions with warm dielectric absorbers etc.

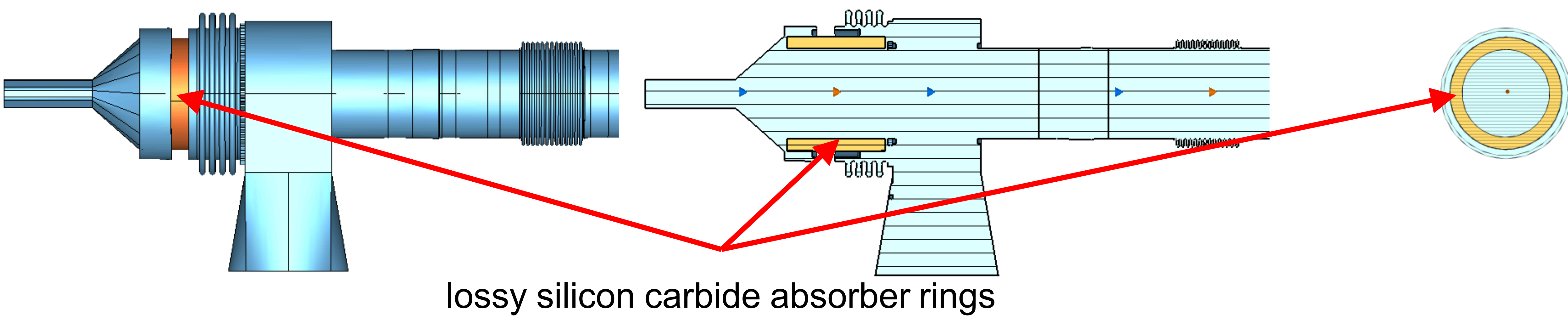


beam pipe transition with warm dielectric absorber

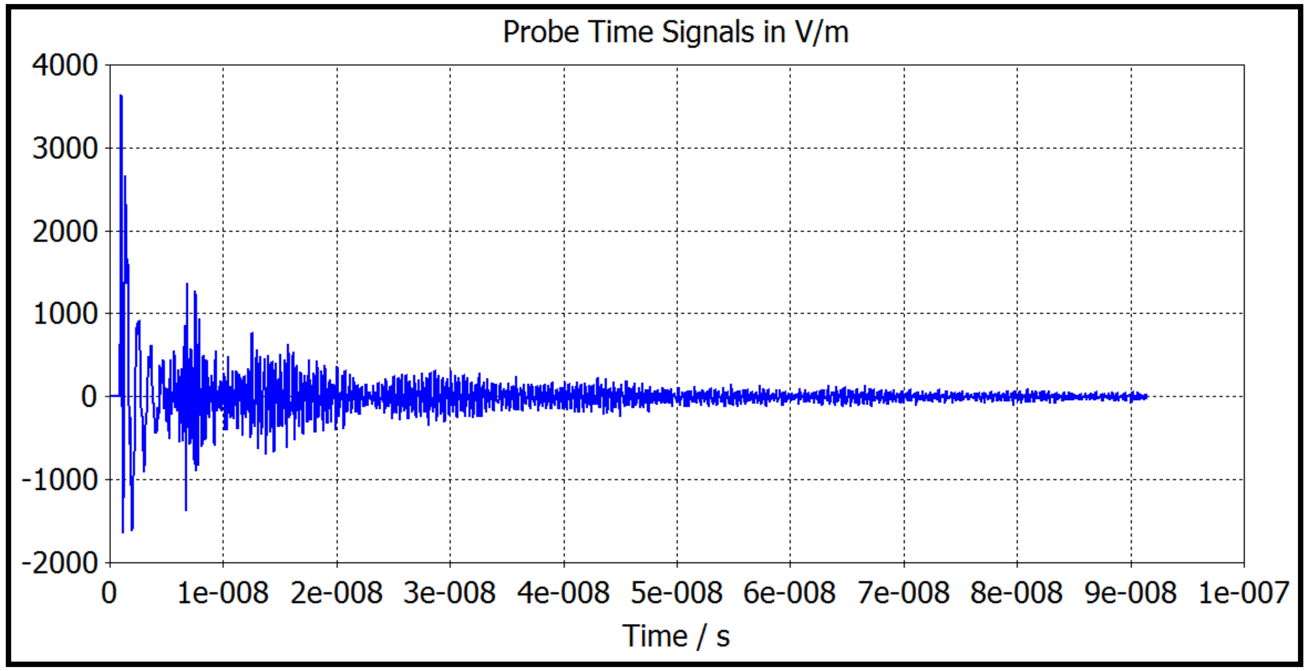
- *space restrictions enforce step-like beam pipe cross section transitions ⇒ local wake power generation*
- *significant (~ 1... 2 kW) HOM power known to travel outwards the module*
- *further functionality: longitudinal compensation, attached getter pump dome, shutter valves (in vicinity), moveable collimator for synchrotron light (upstream only)*
- *use of dielectric absorbers identical to bERLinPro gun and booster devices very preferred (but water cooling applied)*

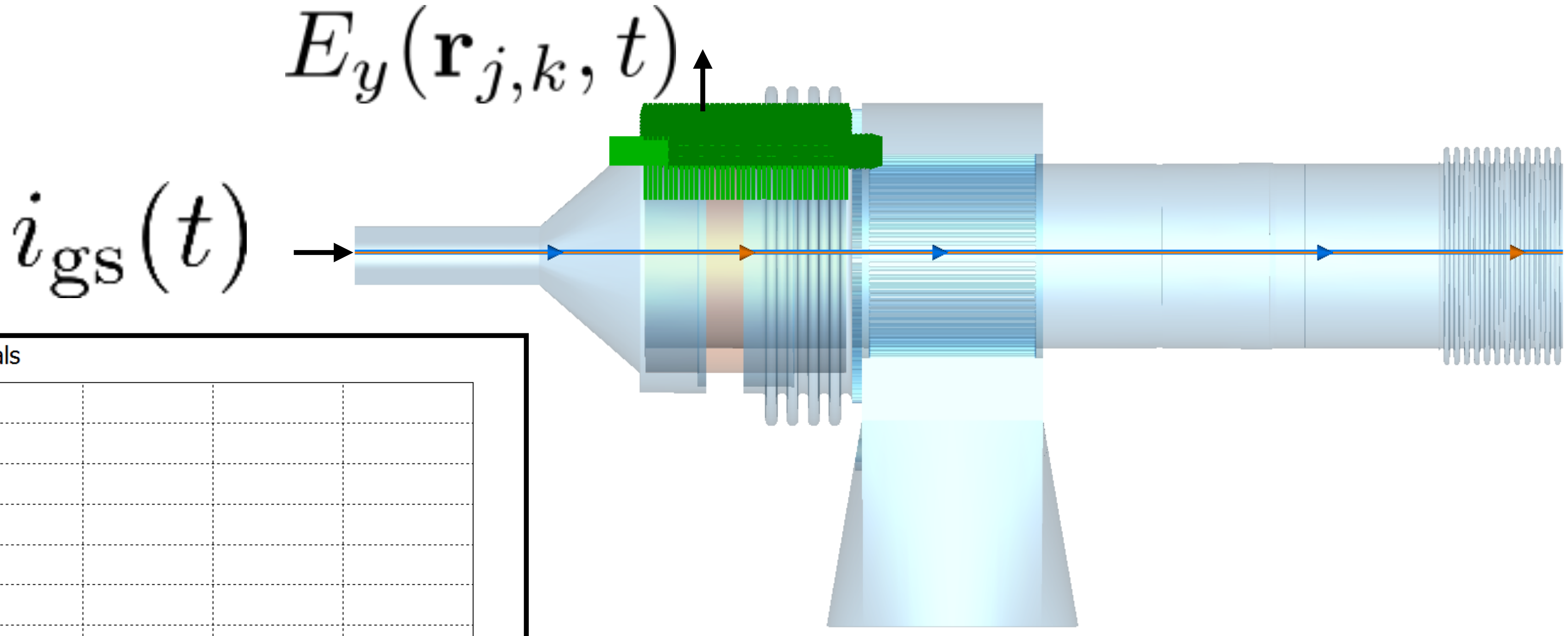
Beam pipe transitions with warm dielectric absorbers (bulk dielectric available)

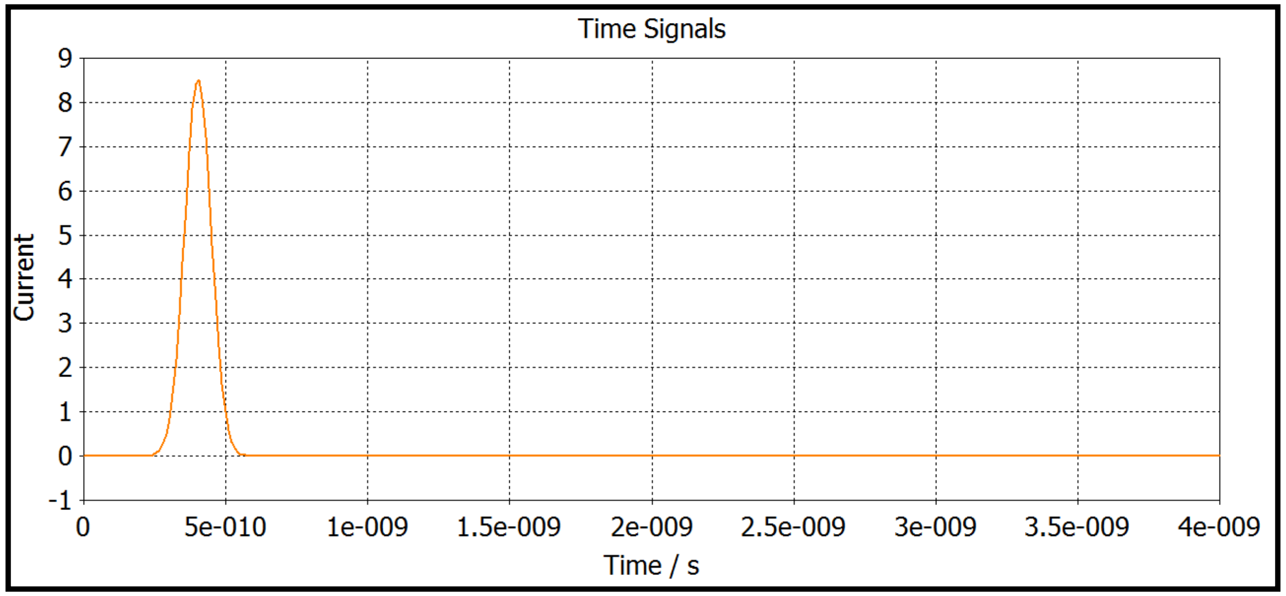




- excitation of the structure using broadband Gaussian bunch
- monitor electric field strengthes arising from Gaussian bunch excitation using time domain field probes





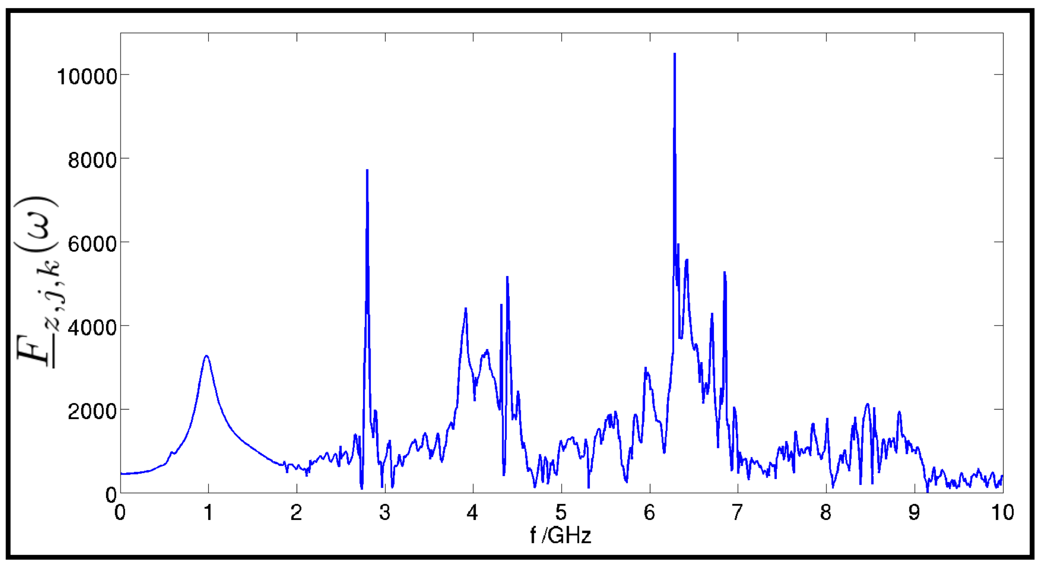


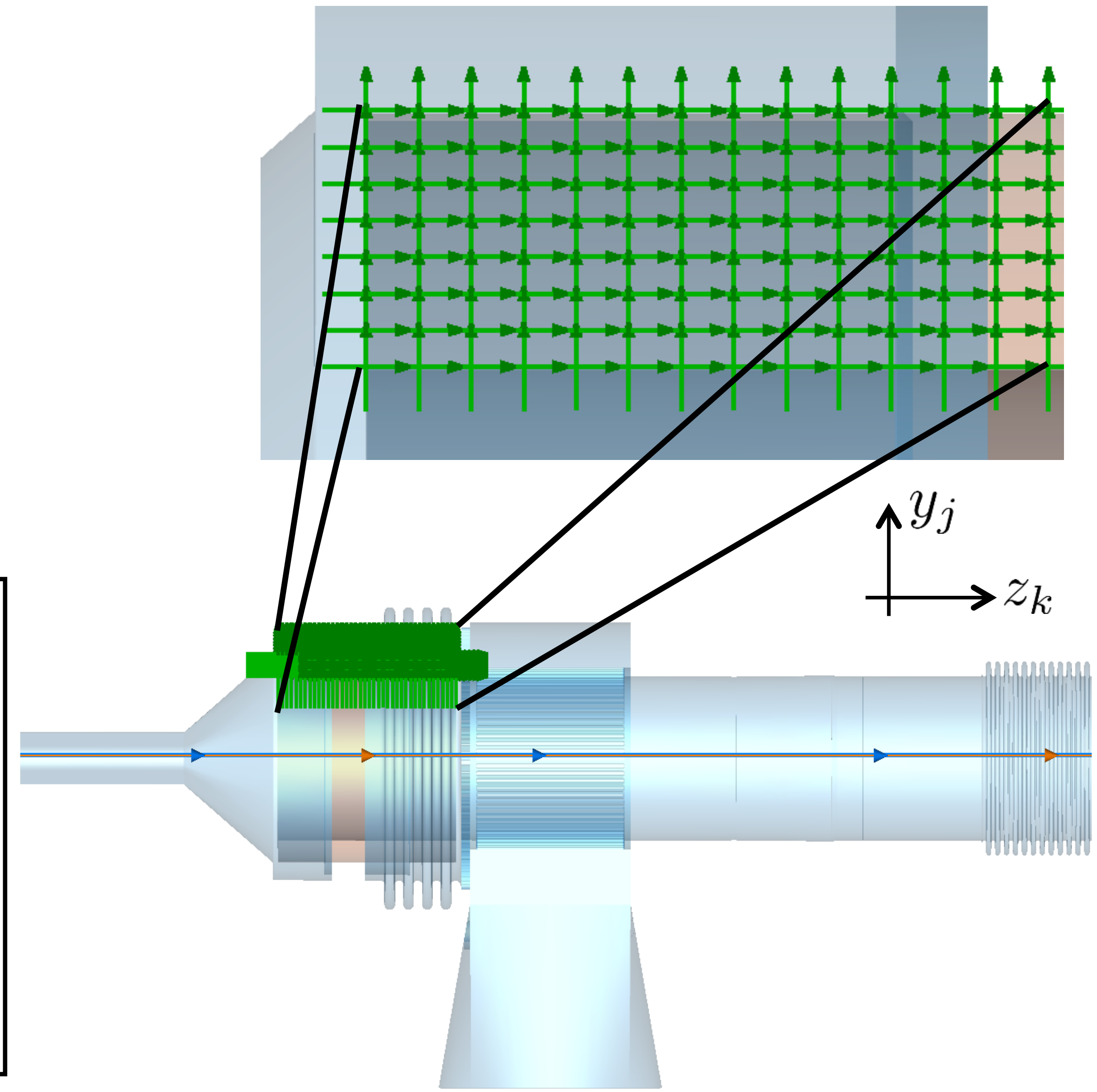
method, results, slides courtesy of Thomas Flisgen

$$\underline{F}_{x,j,k}(\omega_n) = \frac{\mathrm{FFT}[E_x(\mathbf{r}_{j,k},t)]}{\mathrm{FFT}[i_{\mathrm{gs}}(t)]}$$

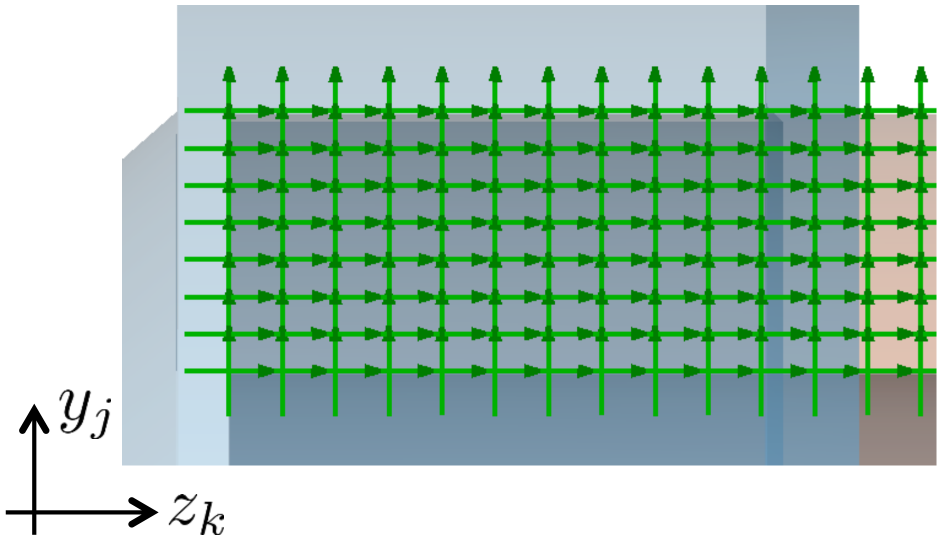
$$\underline{F}_{y,j,k}(\omega_n) = \frac{\mathrm{FFT}[E_y(\mathbf{r}_{j,k},t)]}{\mathrm{FFT}[i_{\mathrm{gs}}(t)]}$$

$$\underline{F}_{z,j,k}(\omega_n) = \frac{\mathrm{FFT}[E_z(\mathbf{r}_{j,k},t)]}{\mathrm{FFT}[i_{\mathrm{gs}}(t)]}$$





transfer function(s) translate(s) beam current into field components



Evaluation of the electric field strengths at the locations of the field probes by means of:

$$\underline{\mathbf{E}}_n(\mathbf{r}_{j,k}) = \begin{pmatrix} \underline{F}_{x,j,k}(\omega_n) \\ \underline{F}_{y,j,k}(\omega_n) \\ \underline{F}_{z,j,k}(\omega_n) \end{pmatrix} \underline{I}_{\mathrm{vsr}}(\omega_n)$$

Approximation of the volume integrals by surface integrals assuming rotational symmetry:

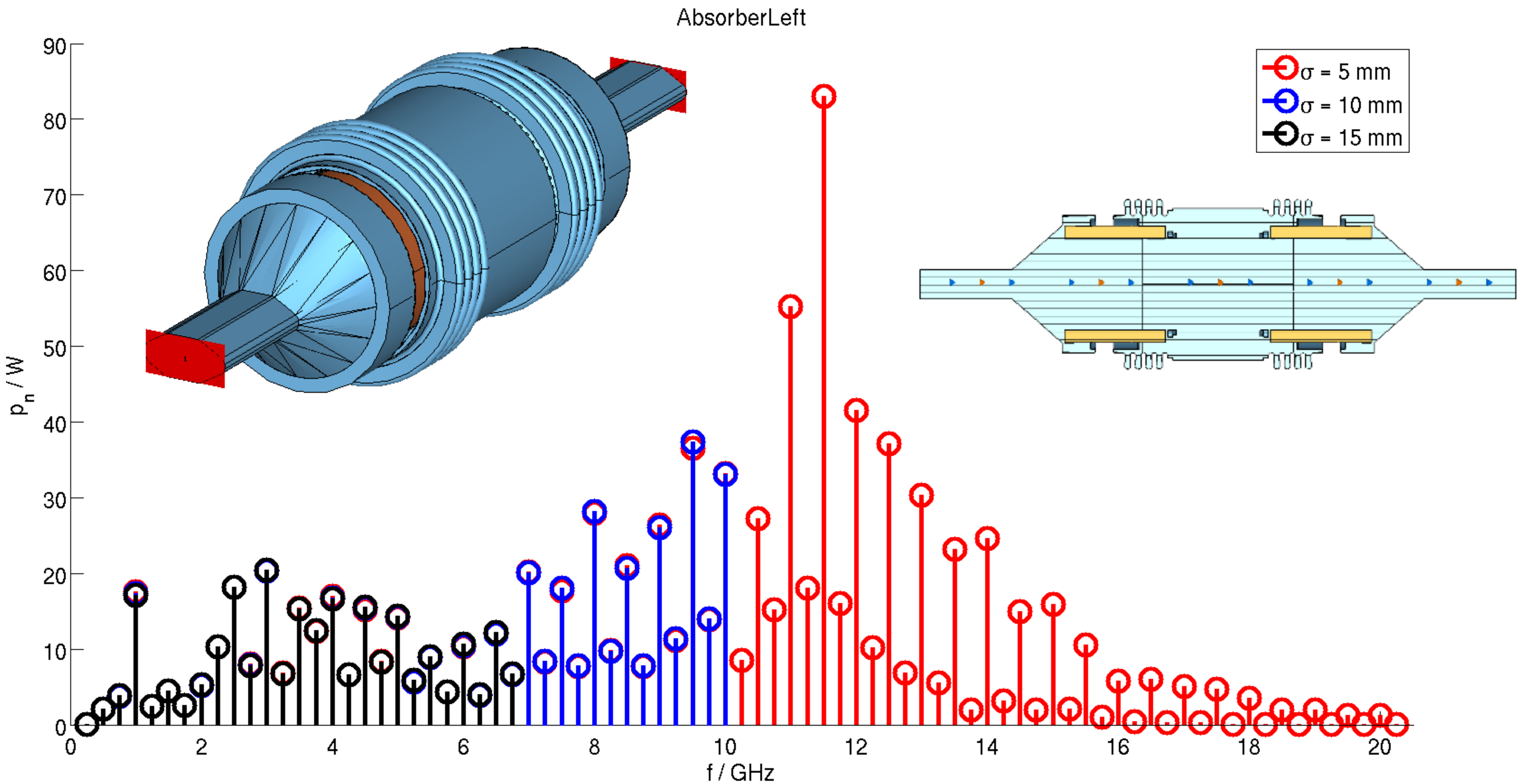
$$p_n = \iiint\limits_{\mathbf{\Omega}_{\mathrm{abs}}} \frac{1}{2} \omega_n \, \varepsilon''(\omega_n) \, |\underline{\mathbf{E}}_n(\mathbf{r})|^2 \, \mathrm{d}V$$

$$= \pi \int\limits_{y_{\min}}^{y_{\max}} \int\limits_{z_{\min}}^{z_{\max}} r \, \omega_n \, \varepsilon''(\omega_n) \, |\underline{\mathbf{E}}_n(\mathbf{r})|^2 \, \mathrm{d}y \mathrm{d}z$$

final determination of the 2D integrals using trapeziodal rule.

approximation for spectral- and spatial-distributed dielectric wake loss for periodic beams

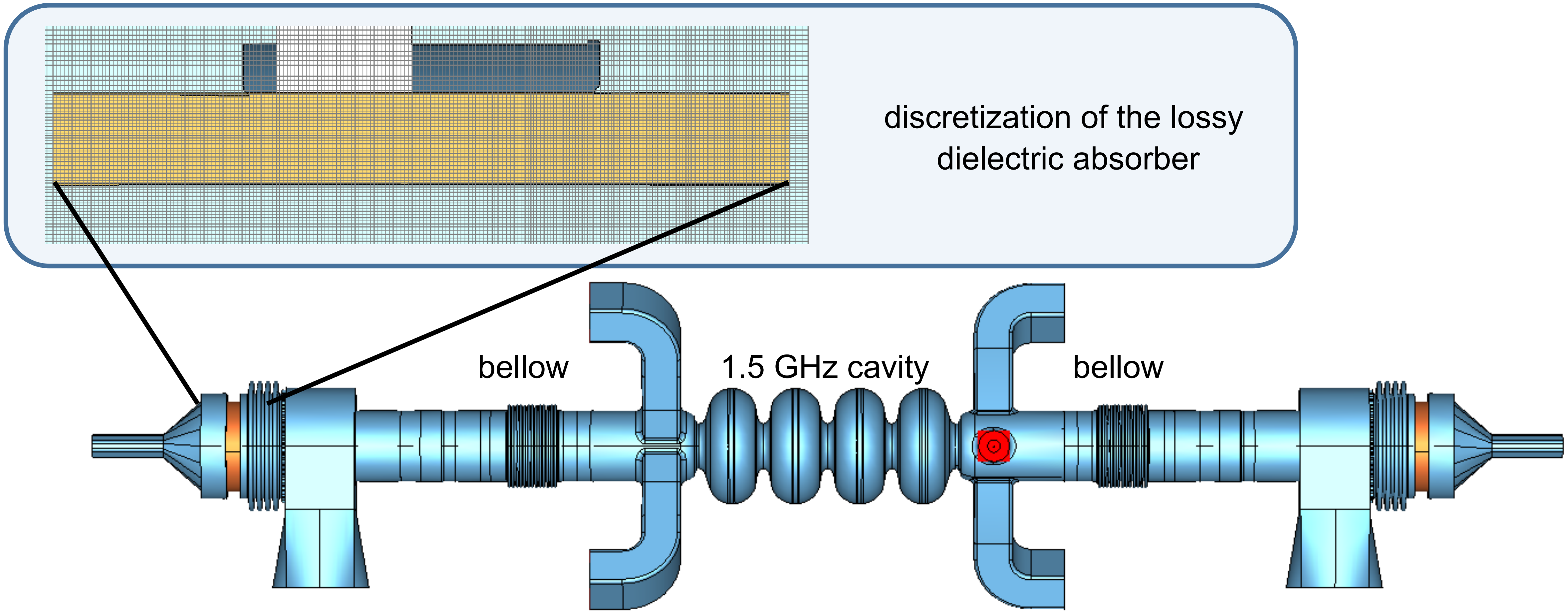
TEST STRUCTURE TO INVESTIGATE LOSSES AT HIGHER FREQUENCIES



Filling Pattern	Power Left Absorber σ = 15 mm / 10 mm / 5 mm			Power Right Absorber σ = 15 mm / 10 mm / 5 mm		
VSR Baseline	282 W	549 W	1064 W	446 W	861 W	1353 W

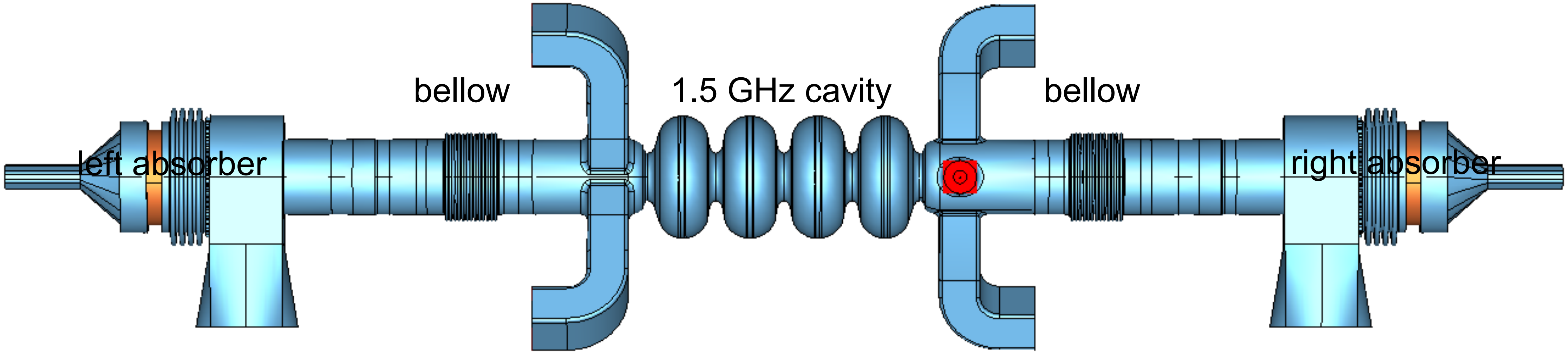
simulations should reach at least 15 GHz, better 20 GHz, but ...

DIELECTRIC LOSSES IN SIMPLIFIED "STRING"



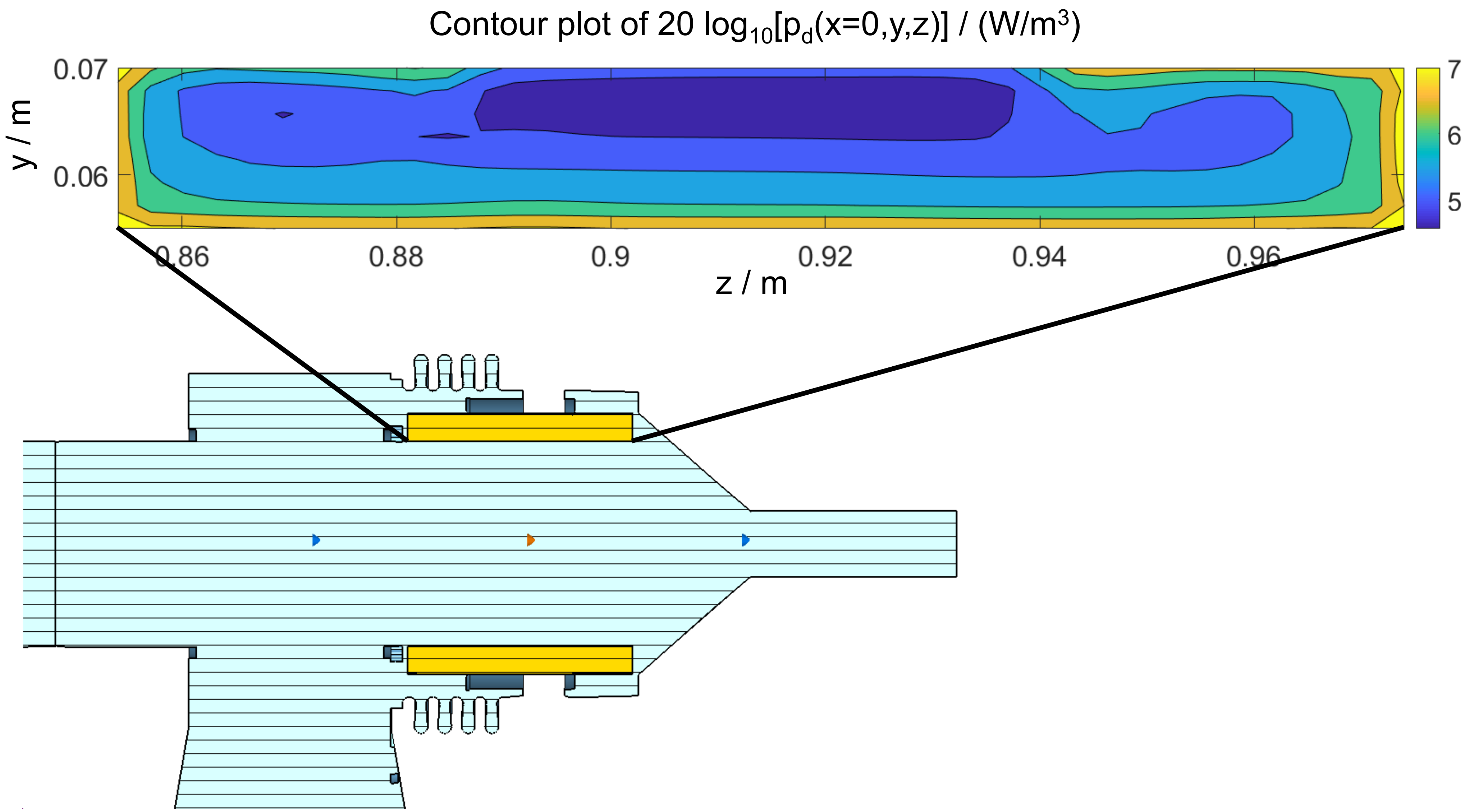
	σ / mm	f_{max} / GHz	N_{mesh}	T_{comp}
Model 1	14	7.3136	426,809,958	2 d 20 h 12 min
Model 2	10	10.2391	1,075,099,752	7 d 3 h 11 min

- 112 2D port modes
- 320 field probes for E_x, E_y, and E_z per beam pipe absorber
- transversal offset of the bunch $\Delta x = \Delta y = 2.1$ mm



Filling Pattern	Power Left Absorber	Power Right Absorber
baseline	801 W	1371 W
extended	716 W	1250 W

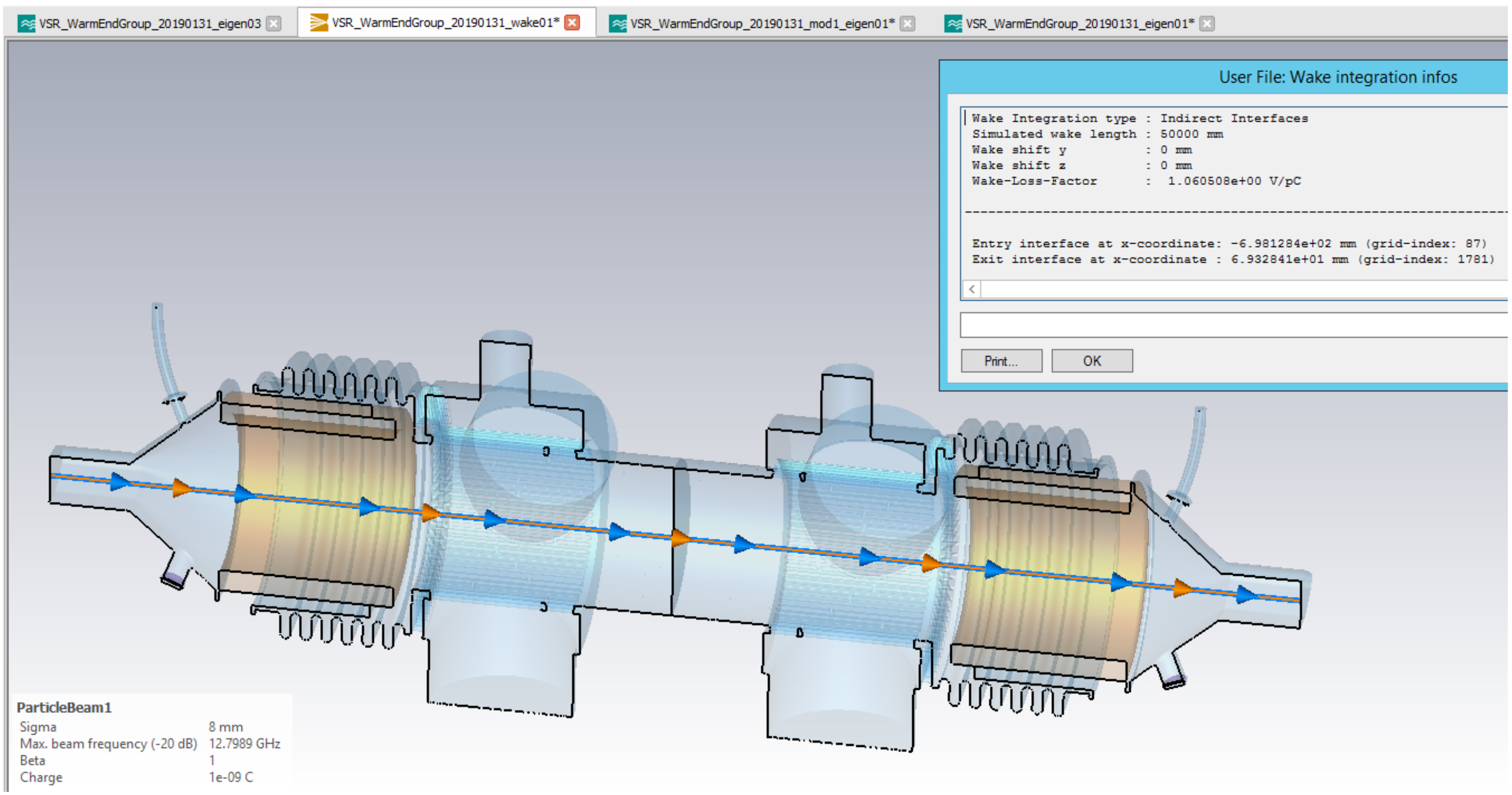
- losses are in the expected order ☺ but depend heavily on the considered frequency range ☹
- losses arising from baseline fill pattern are slightly higher than from extended pattern
- losses in the right absorber are ≈ 1.7 times higher than in the left absorber



dissipation strongly concentrated close to surface; stress ??
with contigency, we expect 2 kW per absorber

Supplement:

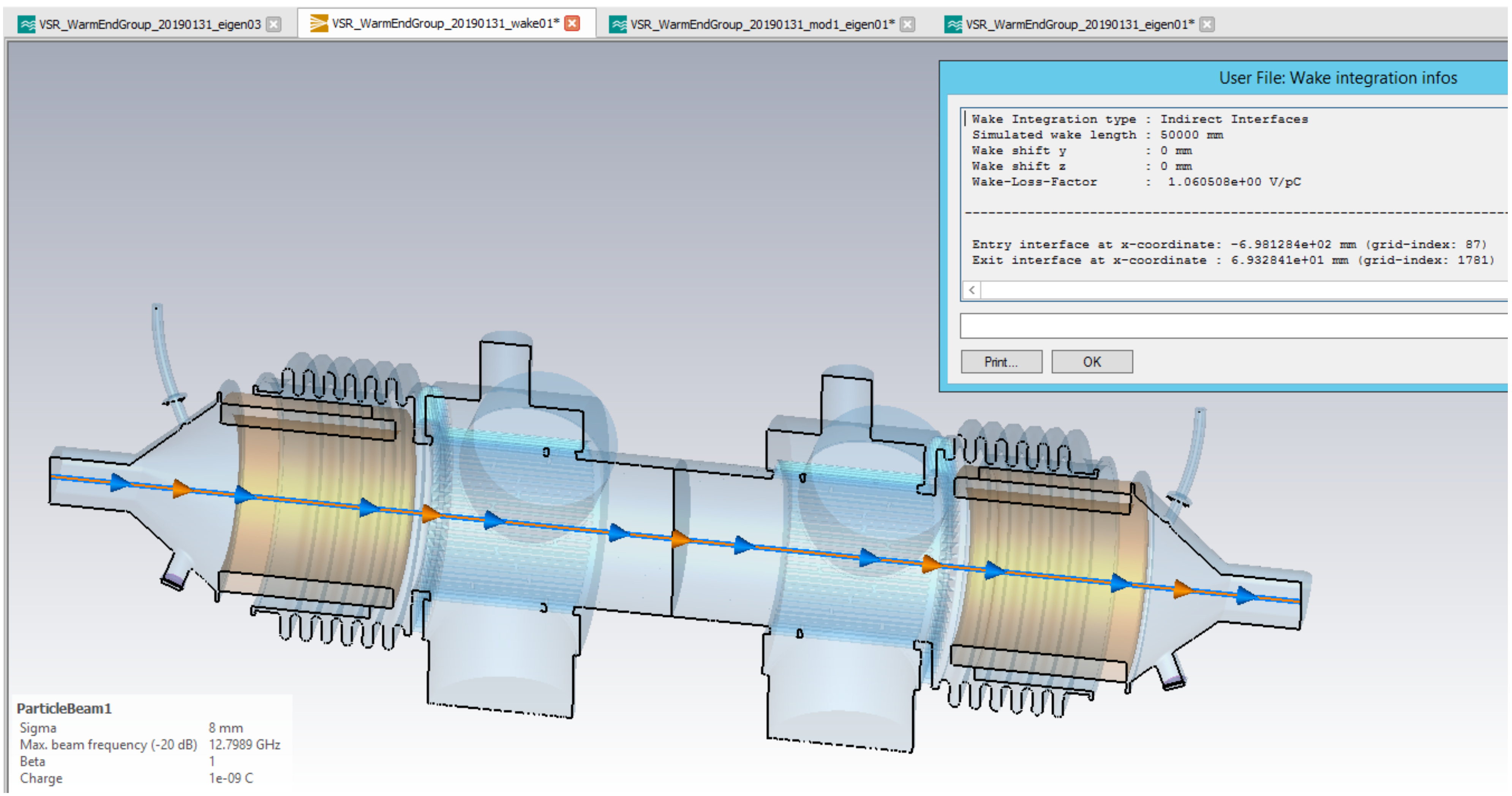
Redesign of the Warm End Group based on wake and eigenmode simulations



H.-W. Glock, HZB

Warm end group *(without additional synchrotron light collimator)*

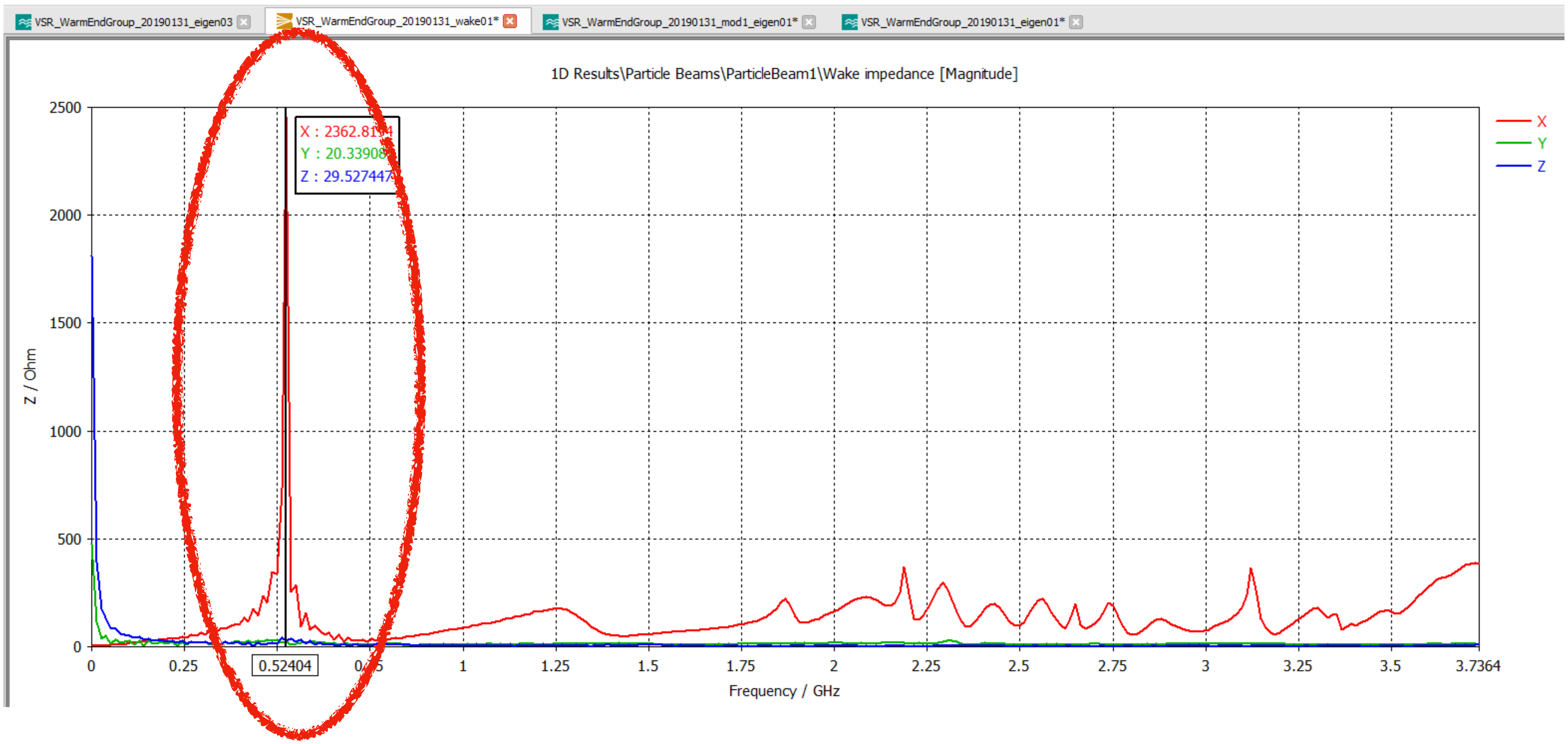
- *engineered (NW) with several modifications: 3 +1 pumping ports, increased gap and compensation capabilities for mounting, "decoherent" slots, IR monitoring window, RF pick-up, etc. .*
- *check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *…, which needs to be avoided, options under numerical evaluation*



H.-W. Glock, HZB

Warm end group

– *check-up wake run revealed dangerous resonance very close 500 MHz, …*



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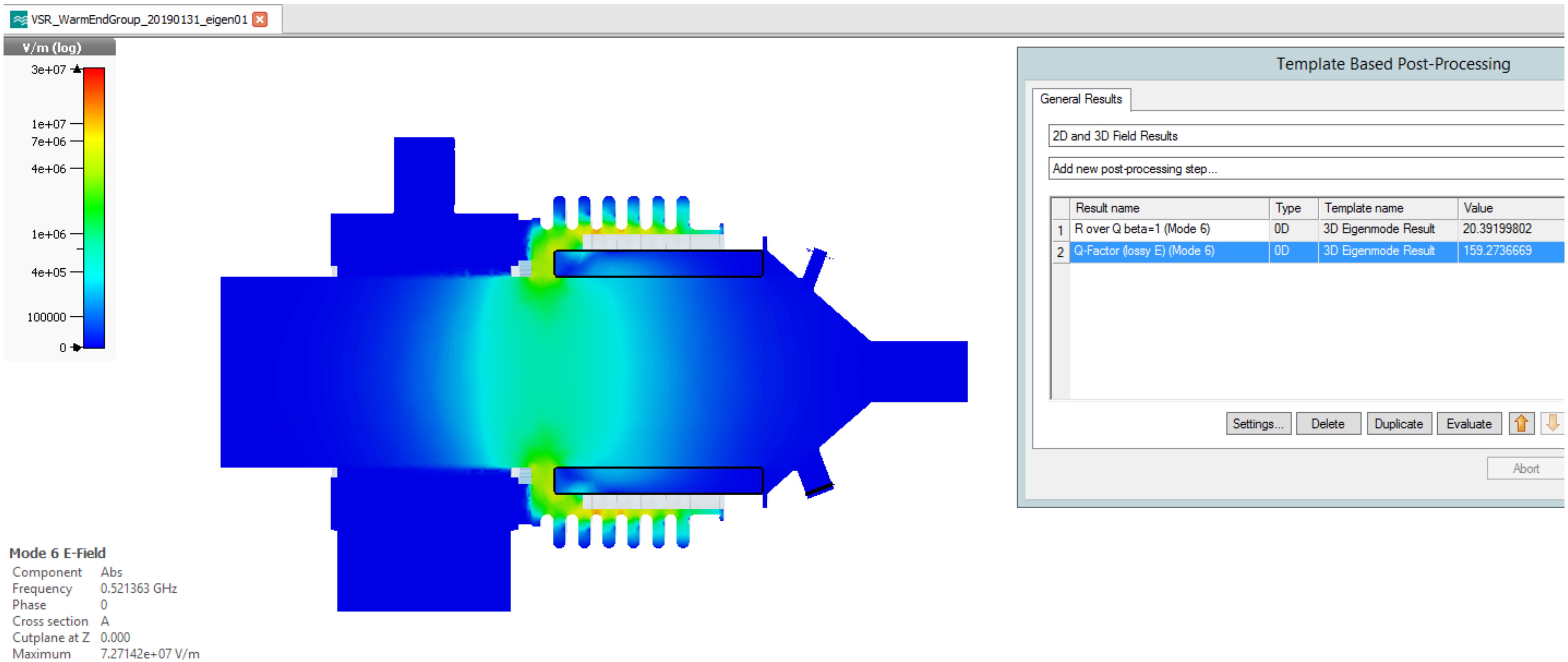
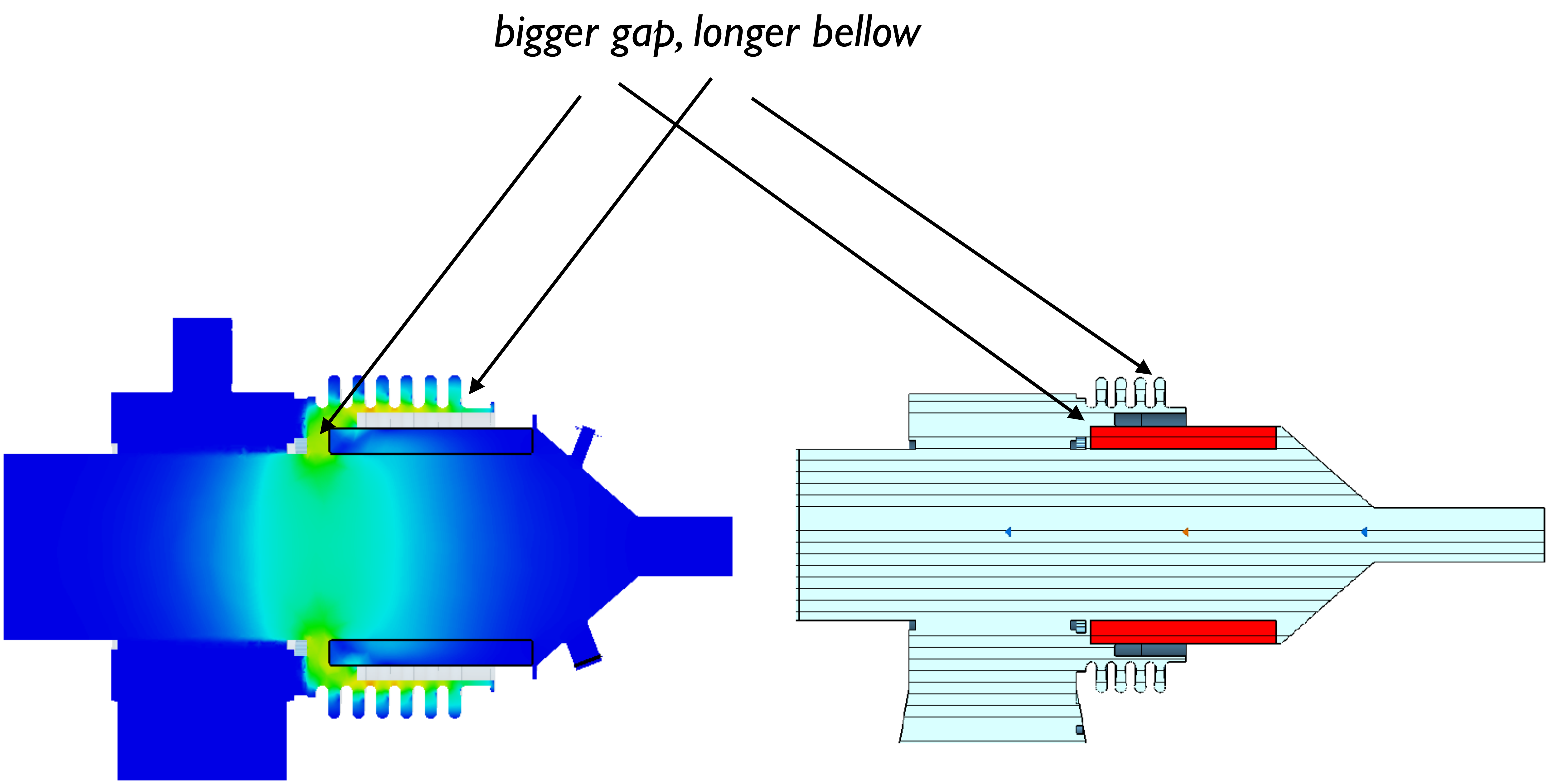
Warm end group

- *check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *confirmed by eigenmode run: 521 MHz, R/Q = 20.4 Ω, Q = 159*



Warm end group – what made the difference ?



new design

previous design

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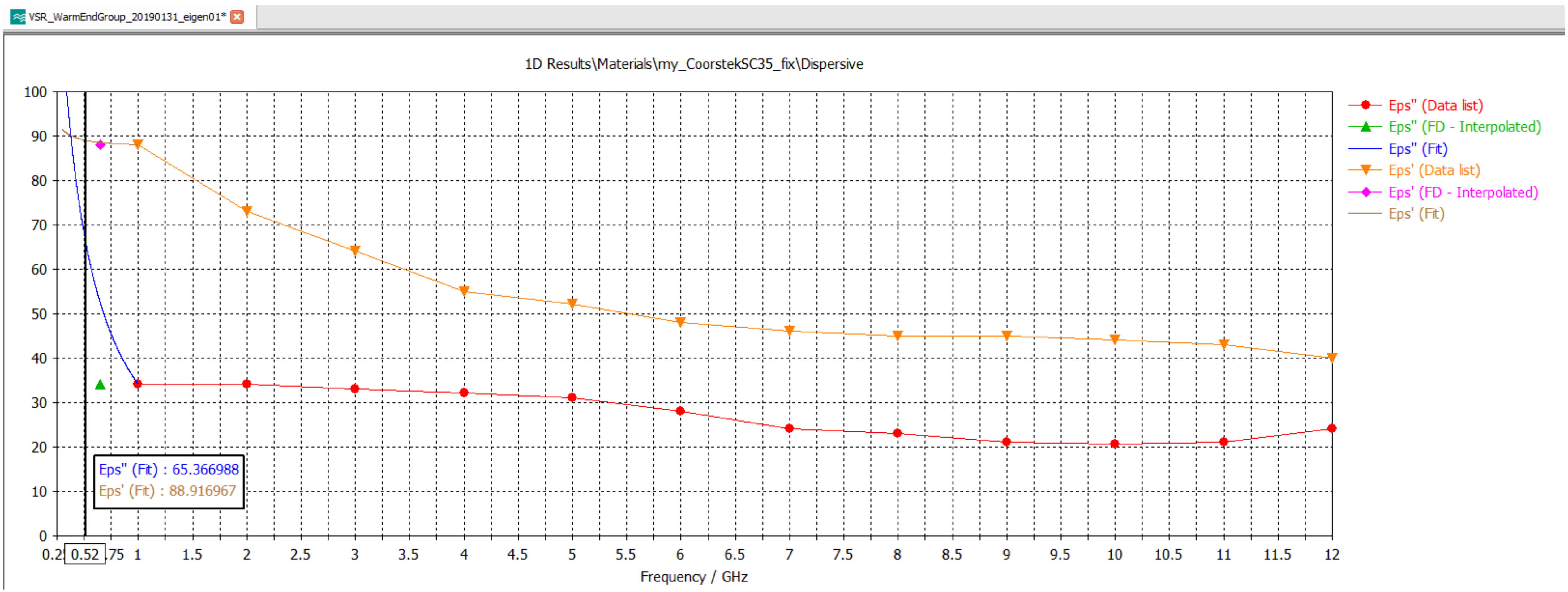
Warm end group

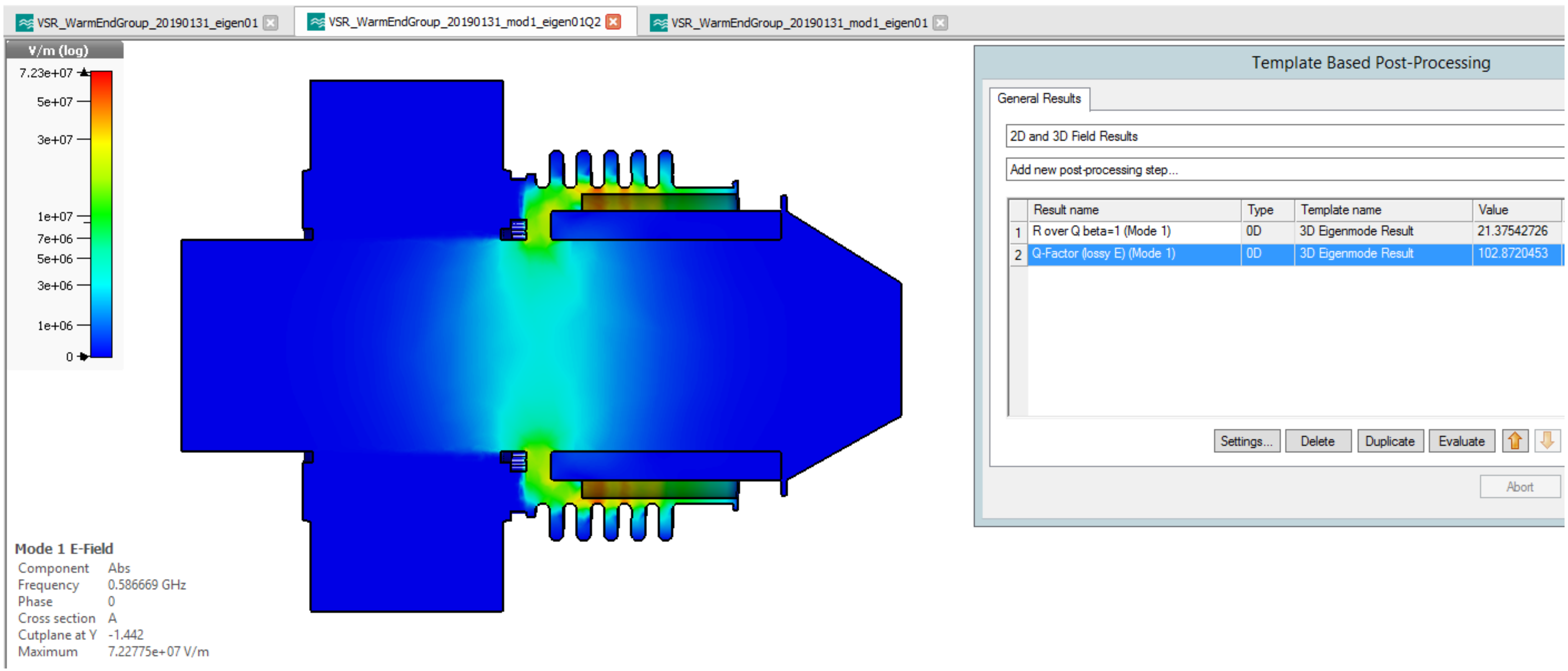
- *– check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *– confirmed by eigenmode run: 521 MHz, R/Q = 20.4 Ω, Q = 159*
- *– but: dielectric material parameters (cf. Eichhorn priv.com.) may vary*



H.-W. Glock, HZB

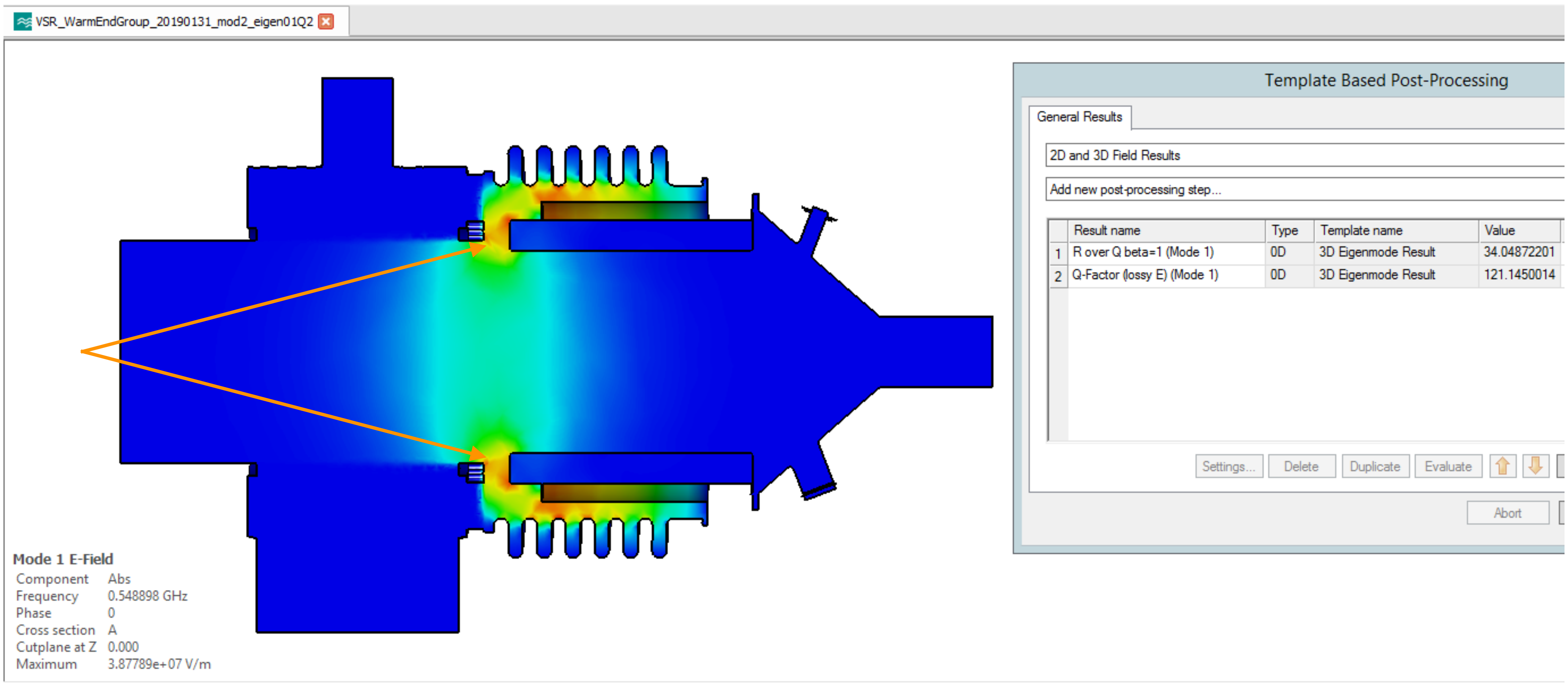
Warm end group

- *check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *…, which needs to be avoided, options under numerical evaluation*
- *Mod 1: one less convolution: 587 MHz, 21.3 Ω, Q = 103, $E_{peak@1J}$ 7.2 MV/m*



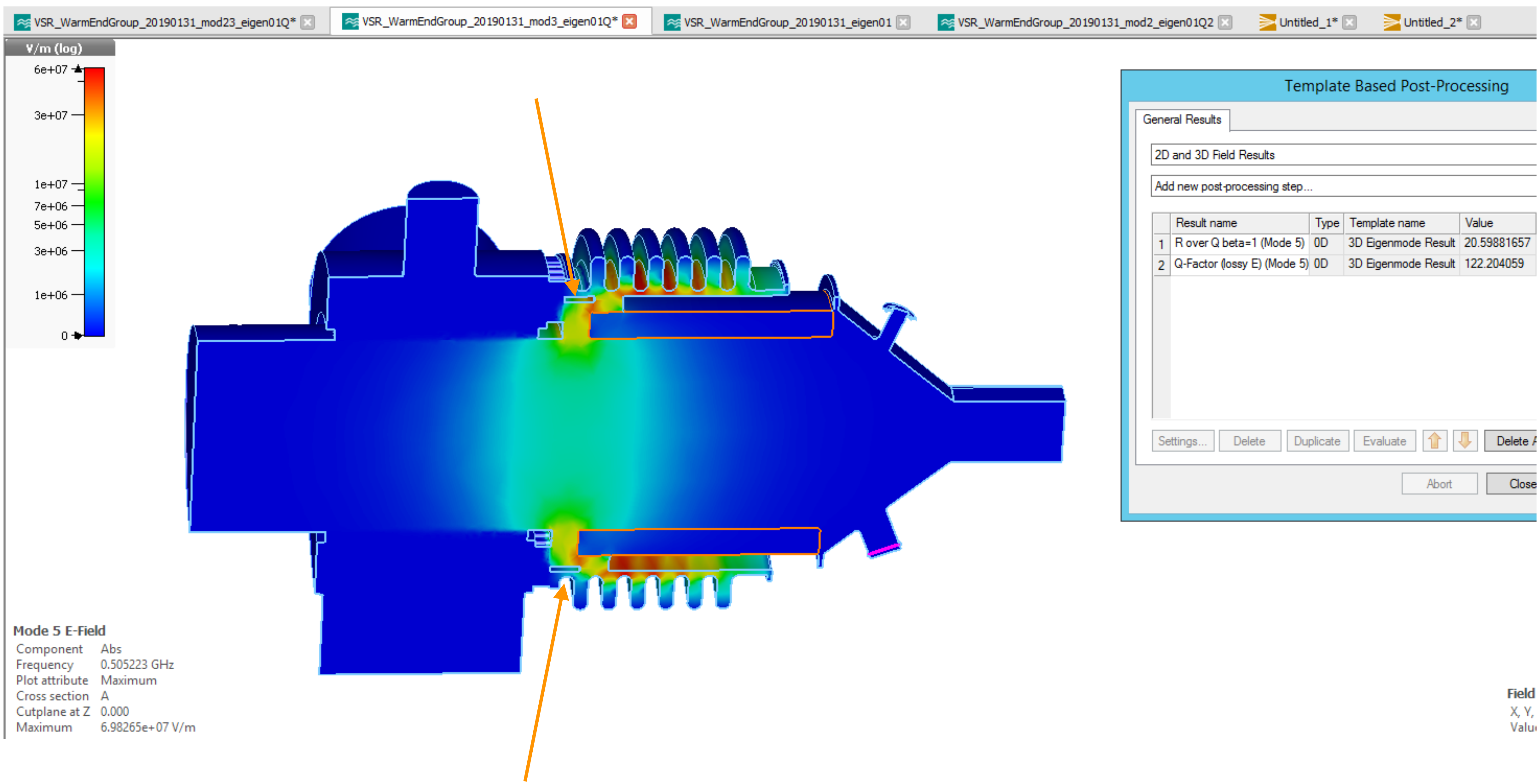
Warm end group

- *check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *…, which needs to be avoided, options under numerical evaluation*
- *Mod 2: reduce diameter of toroid and jacket by 10 mm: 549 MHz, R/Q = 34 Ω, Q = 121,* $E_{peak@1J}$ *3.9 MV/m*



Warm end group

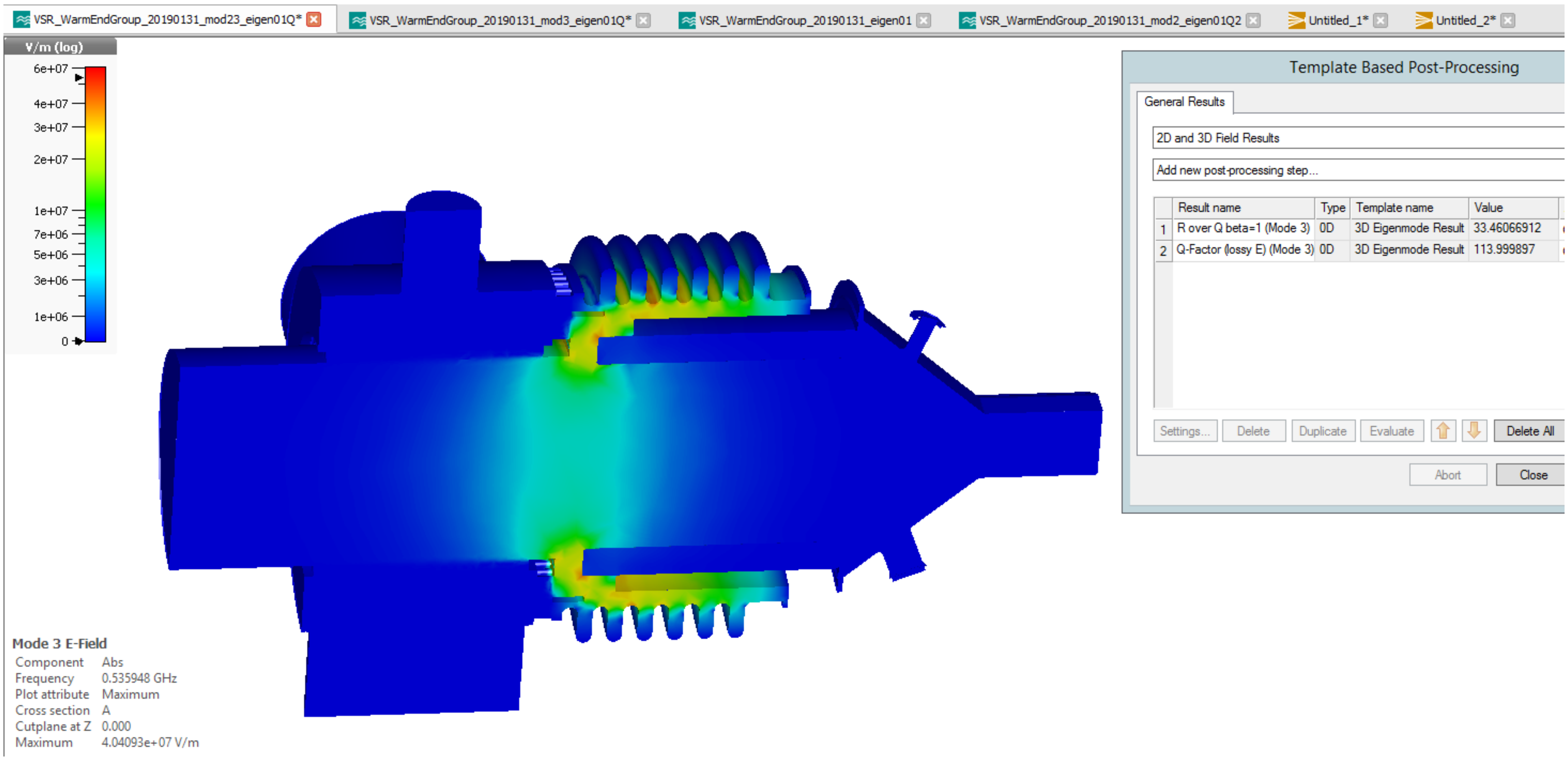
- check-up wake run revealed dangerous resonance very close 500 MHz, …
- …, which needs to be avoided, options under numerical evaluation
- Mod 3: introduce a small shielding ring at the pumping grid: 505 MHz,
  $R/Q = 20.6\ \Omega$, $Q = 122$, $E_{peak@1J}$ 7.0 MV/m



H.-W. Glock, HZB

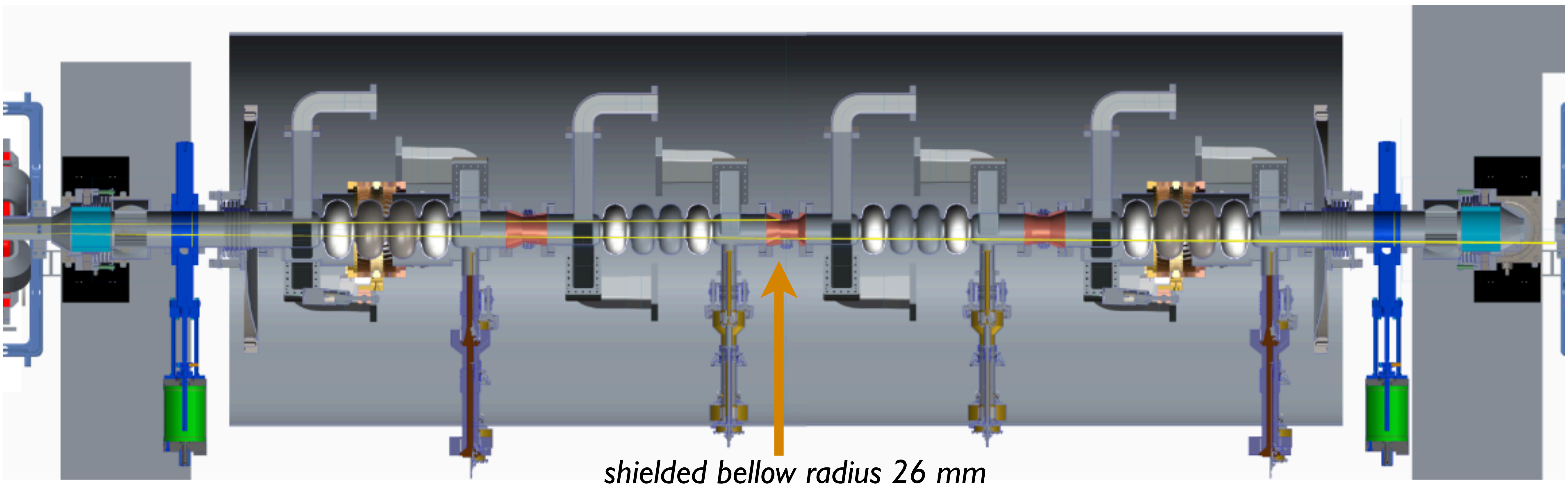
Warm end group

- *check-up wake run revealed dangerous resonance very close 500 MHz, …*
- *…, which needs to be avoided, options under numerical evaluation*
- *Mod 23: combine mod 2 and mod 3: 536 MHz, R/Q = 33.5 Ω, Q = 114, $E_{peak@1J}$ 4.0 MV/m*



Supplement:

Design Aspects of the Collimating Shielded Bellow

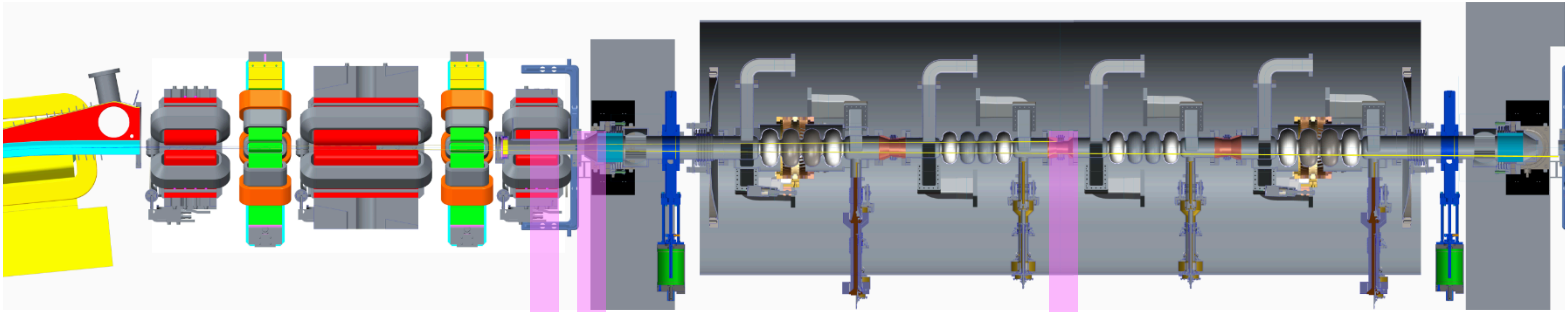


shielded bellow radius 26 mm
with taper, collimating
synchrotron light

Synchrotron light power deposition

data courtesy Markus Ries

mandatory to fetch power outside the module or at 5K-level



collimator in quad: 16 mm off axis

moveable collimator in taper:

≤16 mm off axis

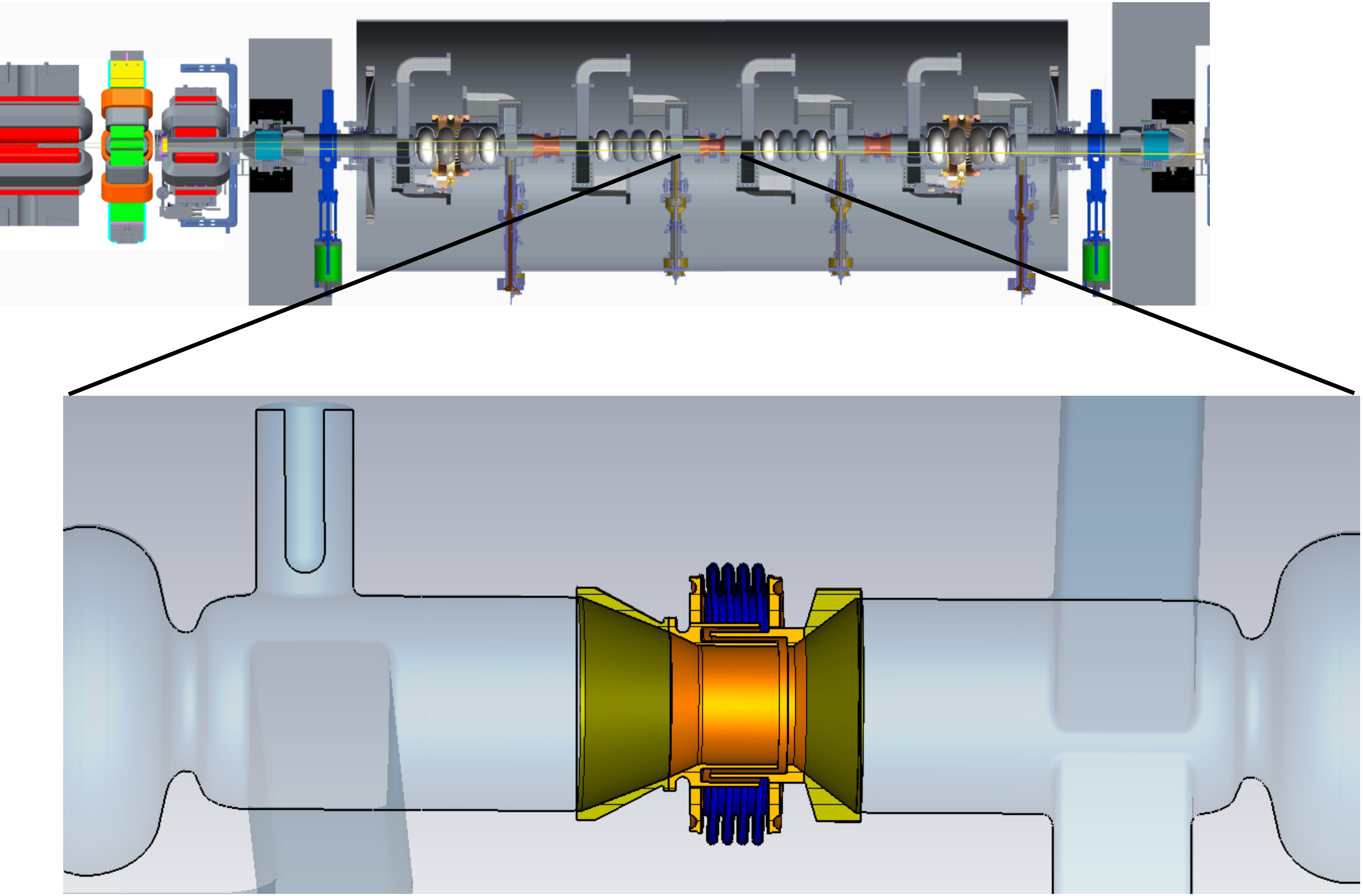
collimating shielded bellow:

26 mm radius

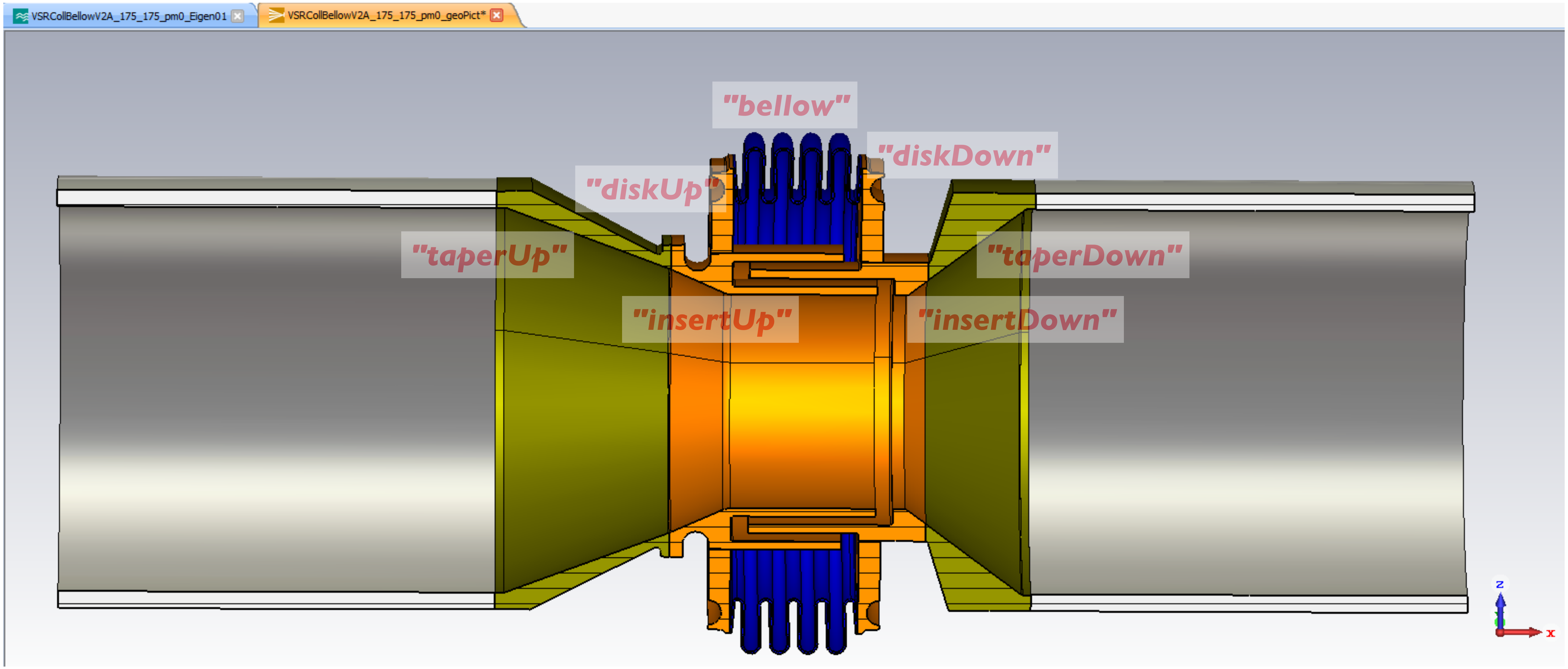
P_{rad} @ ...	... collimator in quadrupole	... on moveable collimator	... collimating bellow	... leaving cold module
moveable not activated	63 W	0 W	11 W	15.3 W

data courtesy Markus Ries

Collimating shielded bellow, inner radius 26 mm



Collimating shielded bellow, inner radius 26 mm



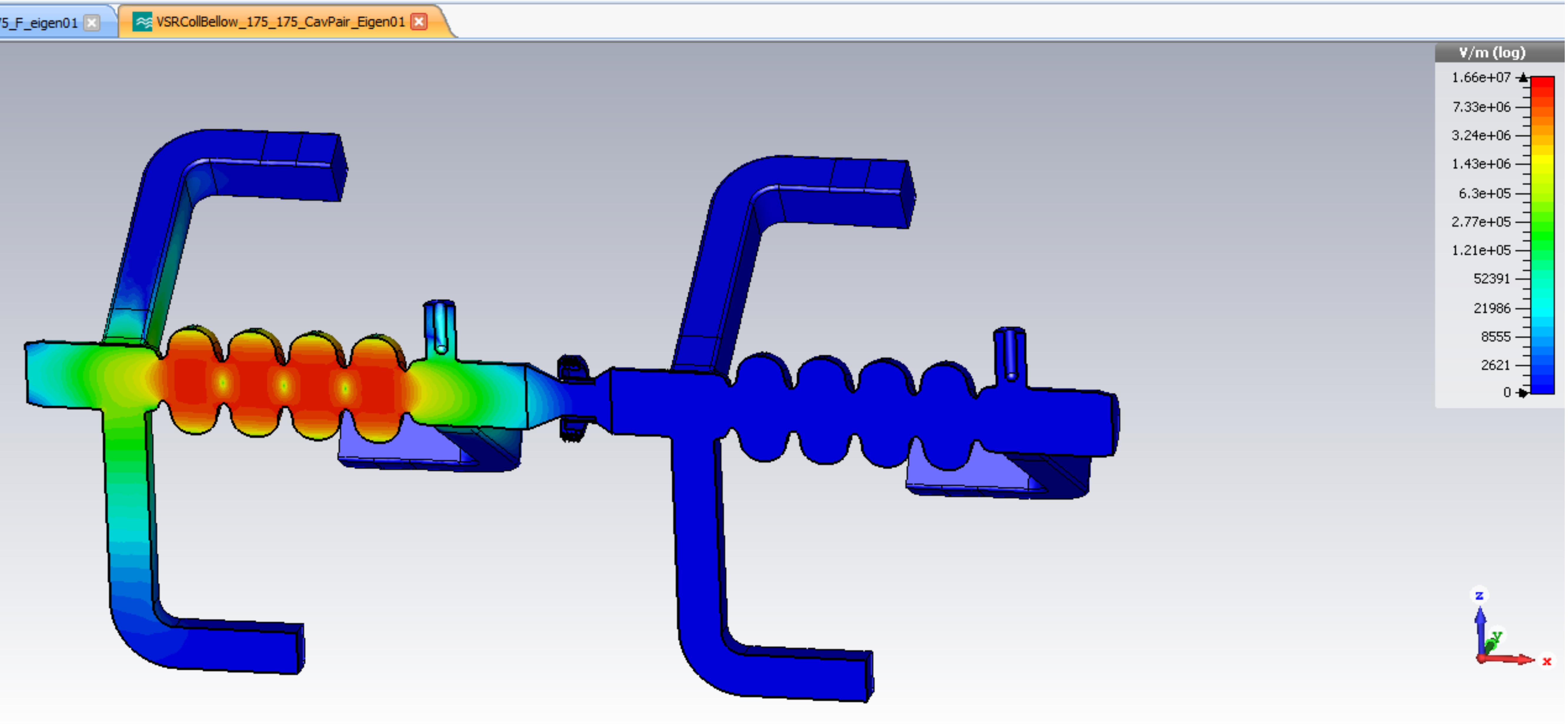
– *seven sections for spatial resolution of power loss:*

massive copper

stainless steel

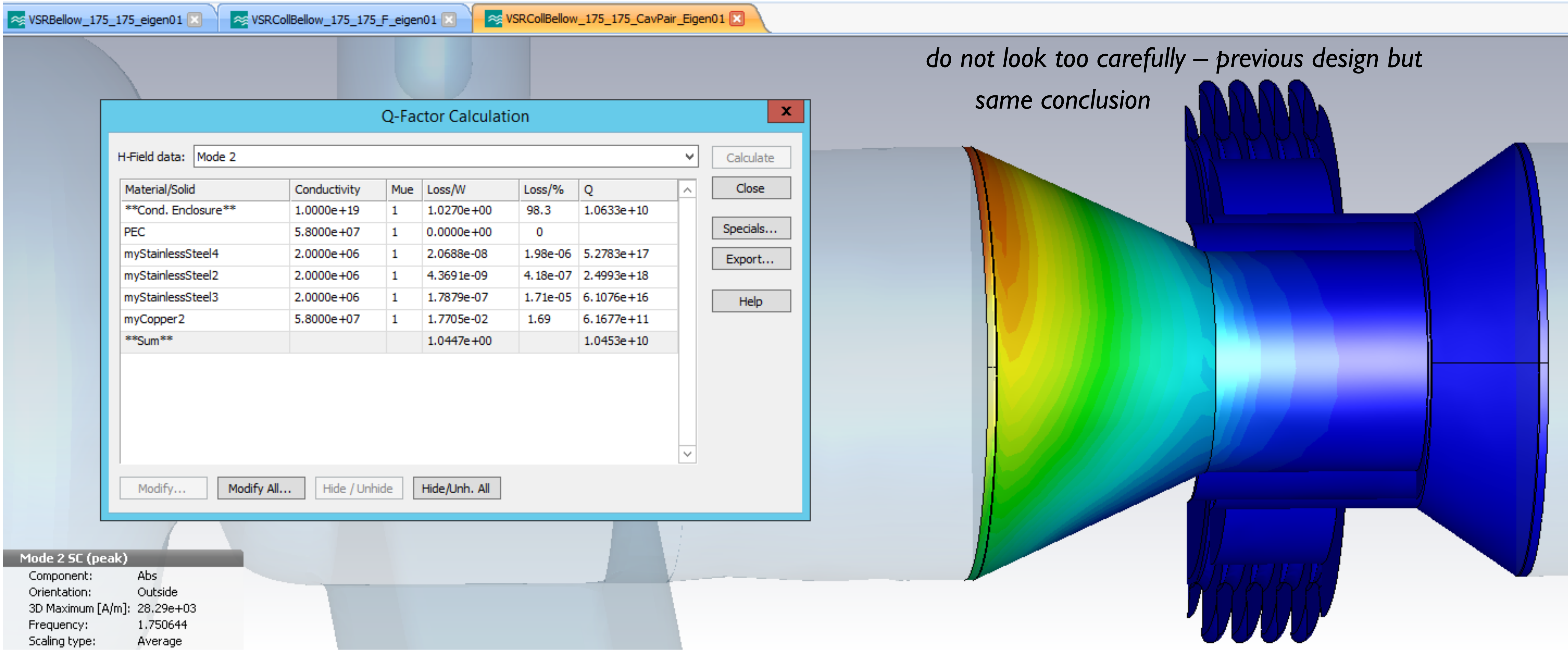
stainless with inner copper coating / plating

Collimating shielded bellow, fundamental mode losses



some part of evanescent fundamental mode reaches bellow
(from either side; here logarithmic color scaling)

Collimating shielded bellow, fundamental mode losses

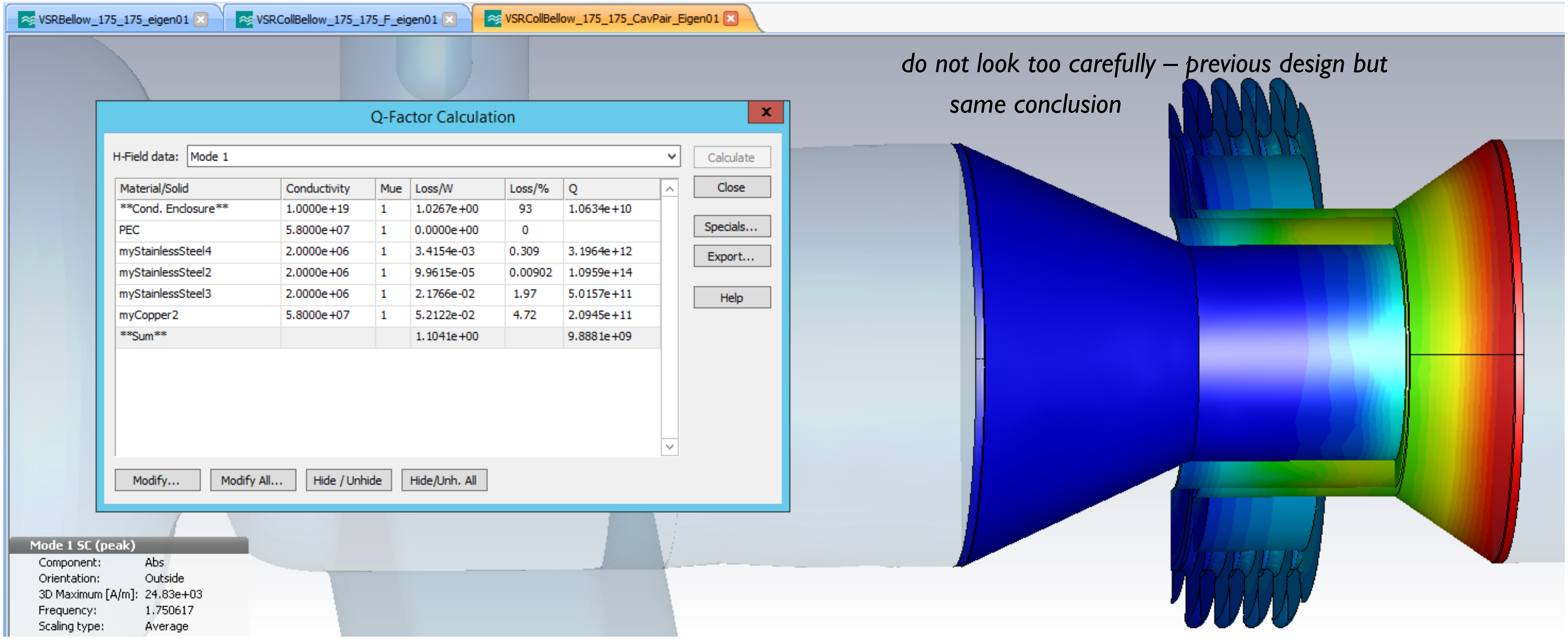


some part of evanescent fundamental mode reaches bellow (from either side; here logarithmic color scaling)

"left side": $Q_{load,bellow} = 6.1 \cdot 10^{11}$, $P_{loss\ Cu\ @7MV/cav} = 0.28\,W$, $P_{loss\ Steel\ @7MV/cav} \approx 0\,W$

3	R over Q beta=1 (Mode 1)	0D	3D Eigenmode Result	380.7802724
4	R over Q beta=1 (Mode 2)	0D	3D Eigenmode Result	380.8026181
5	Voltage beta=1 (Mode 1)	0D	3D Eigenmode Result	2.0384628689e+06
6	Voltage beta=1 (Mode 2)	0D	3D Eigenmode Result	2.0391897604e+06

Collimating shielded bellow, fundamental mode losses



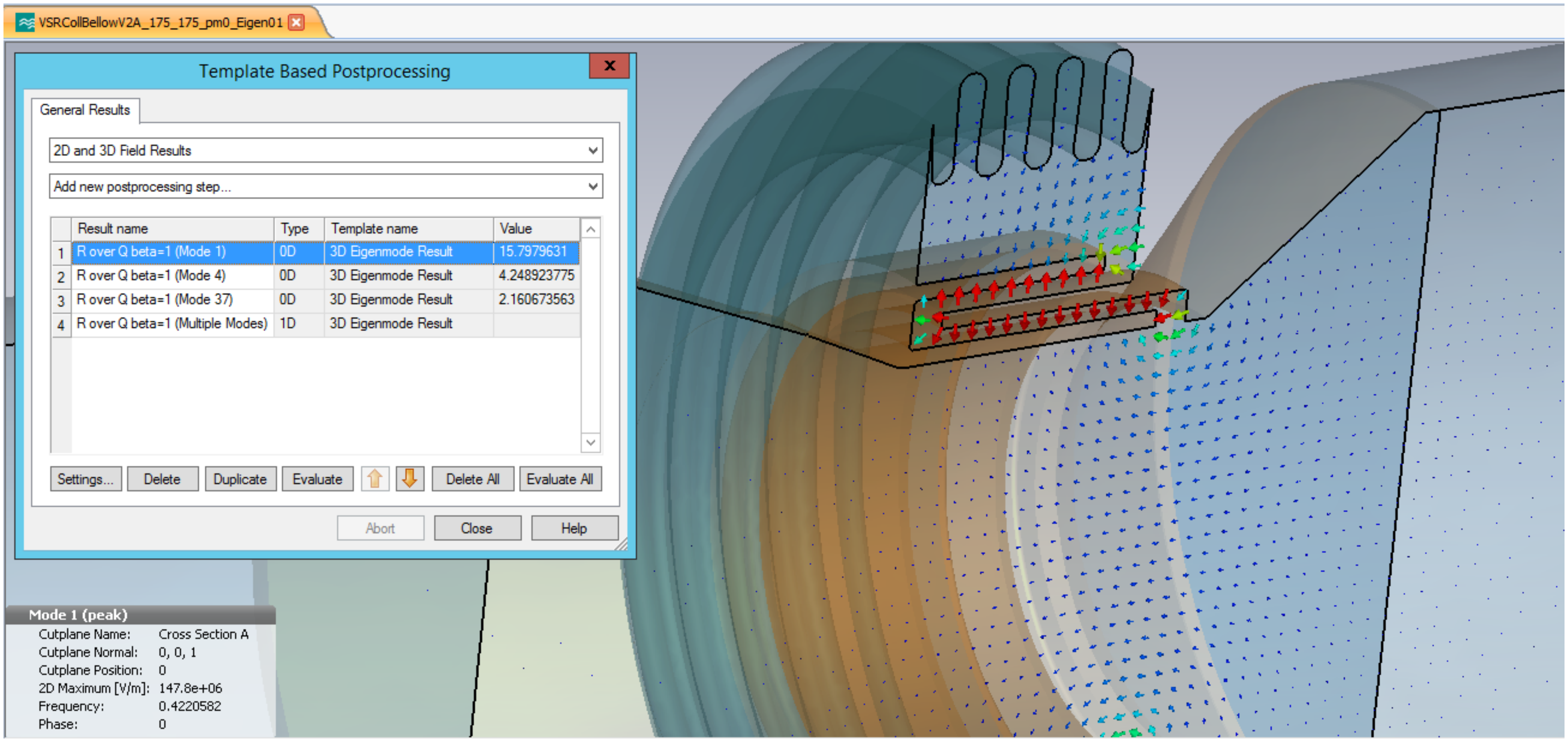
some part of evanescent fundamental mode reaches bellow (from either side; here logarithmic color scaling)

"right side": $Q_{load,bellow} = 2.09 \cdot 10^{11}$, $P_{loss\ Cu\ @7MV/cav} = 0.83$ W, $P_{loss\ Steel\ @7MV/cav} = 0.35$ W

3	R over Q beta=1 (Mode 1)	0D	3D Eigenmode Result	380.7802724
4	R over Q beta=1 (Mode 2)	0D	3D Eigenmode Result	380.8026181
5	Voltage beta=1 (Mode 1)	0D	3D Eigenmode Result	2.0384628689e+06
6	Voltage beta=1 (Mode 2)	0D	3D Eigenmode Result	2.0391897604e+06

⇒ total fundamental mode loss: 0.28 W + 0.83 W + 0.35 W = 1.46 W ≈ 1.5 W

Collimating shielded bellow: Parasitic modes I – 422 MHz



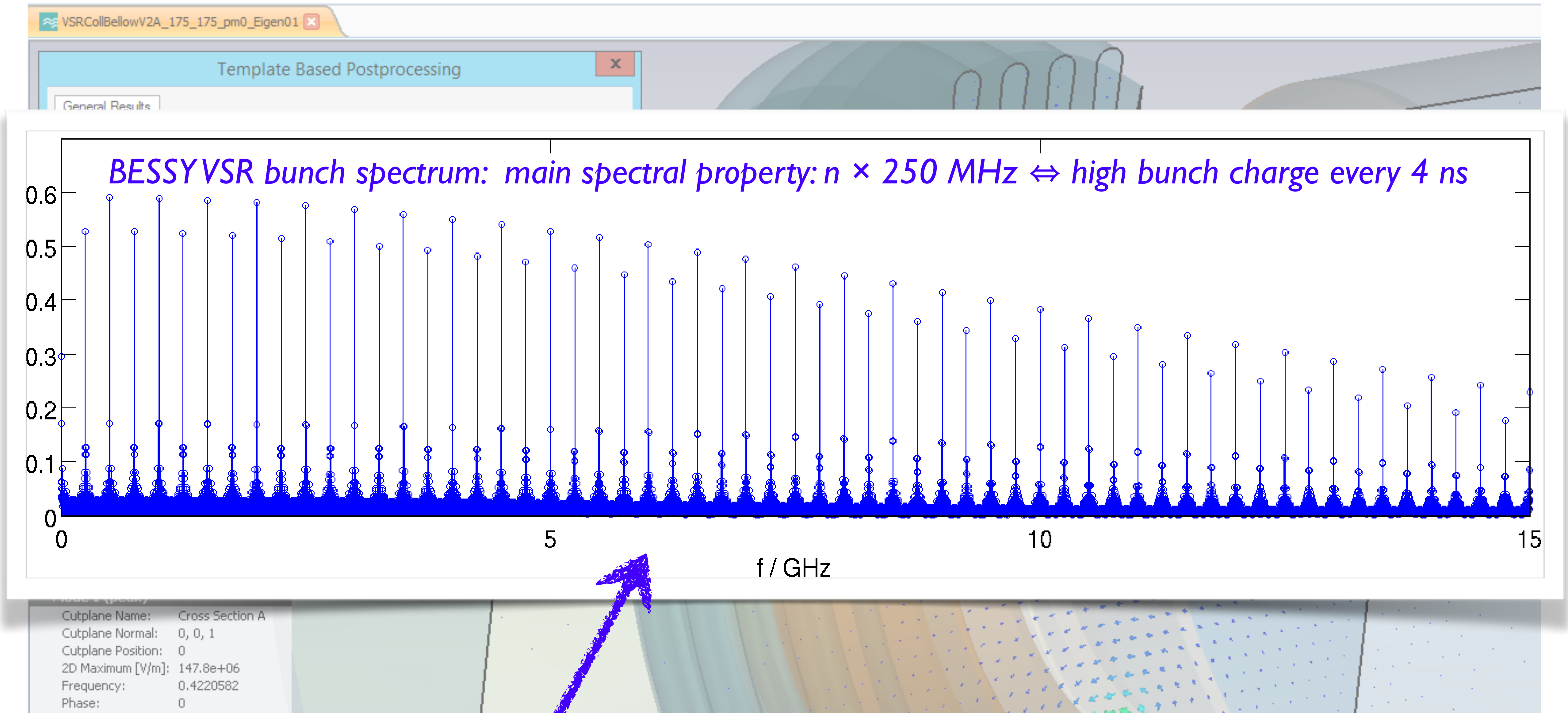
λ/4-line-like field pattern, accessing beam, R/Q = 15.80 Ω, Q = 497,

not relevant with standard fill patterns, but in case of single puls mode (20 mA):

$P_{beamloss}$ = 6.70 W, mainly dissipated in steel bellow:

Bellow	5.52429 Watt
InsertUp	0.541045 Watt
taperUp	0.
taperDown	0.
DiskDown	0.188161 Watt
DiskUp	0.179456 Watt
InsertDown	0.262487 Watt

Collimating shielded bellow: Parasitic modes I – 422 MHz



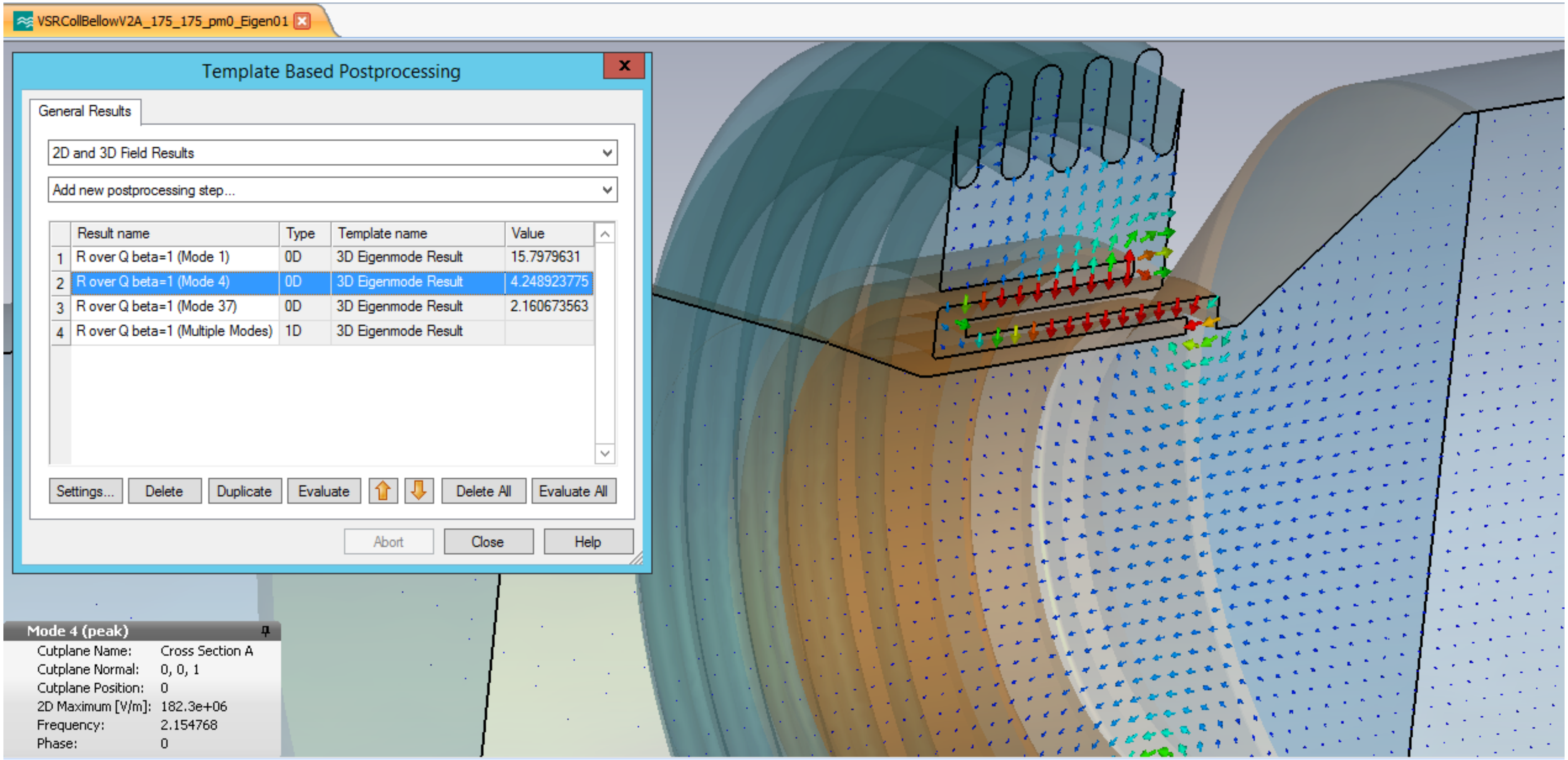
λ/4-line-like field pattern, accessing beam, R/Q = 15.80 Ω, Q = 497,

not relevant with standard fill patterns but in case of single puls mode (20 mA):

$P_{beamloss}$ = 6.70 W, mainly dissipated in steel bellow:

Bellow	5.52429 Watt
InsertUp	0.541045 Watt
taperUp	0.
taperDown	0.
DiskDown	0.188161 Watt
DiskUp	0.179456 Watt
InsertDown	0.262487 Watt

Collimating shielded bellow: Parasitic modes II – 2.155 GHz



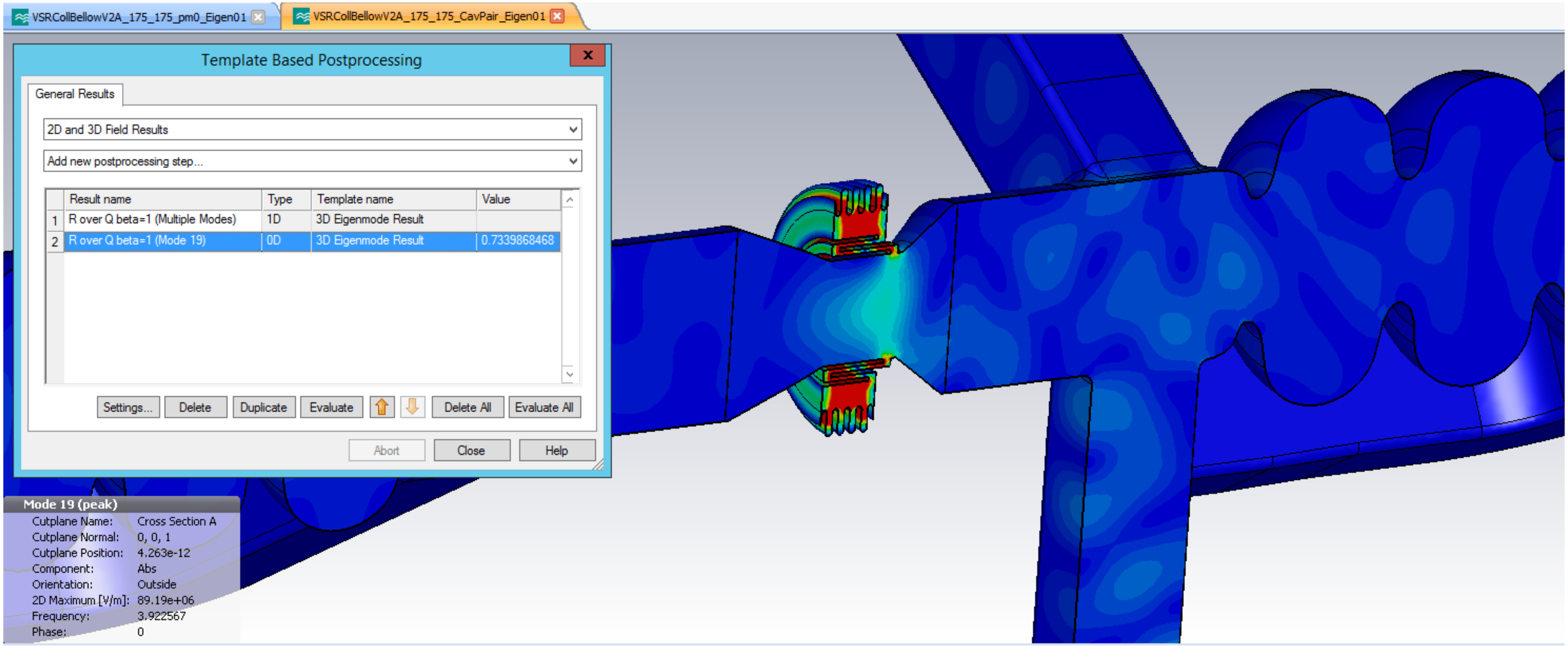
3λ/4-line-like field pattern, accessing beam, R/Q = 4.25 Ω, Q = 1490

not relevant with standard fill patterns, but in case of single puls mode (20 mA):

$P_{beamloss}$ = 9.16 W, mainly dissipated in copper inserts:

Bellow	1.19021 Watt
InsertUp	4.69675 Watt
taperUp	0.
taperDown	0.
DiskDown	0.
DiskUp	0.0539257 Watt
InsertDown	3.21357 Watt

Collimating shielded bellow: Parasitic modes III – 3.923 GHz



distributed field pattern, accessing beam, R/Q = 0.734 Ω, Q = 1038 (*no HOM dampers*)

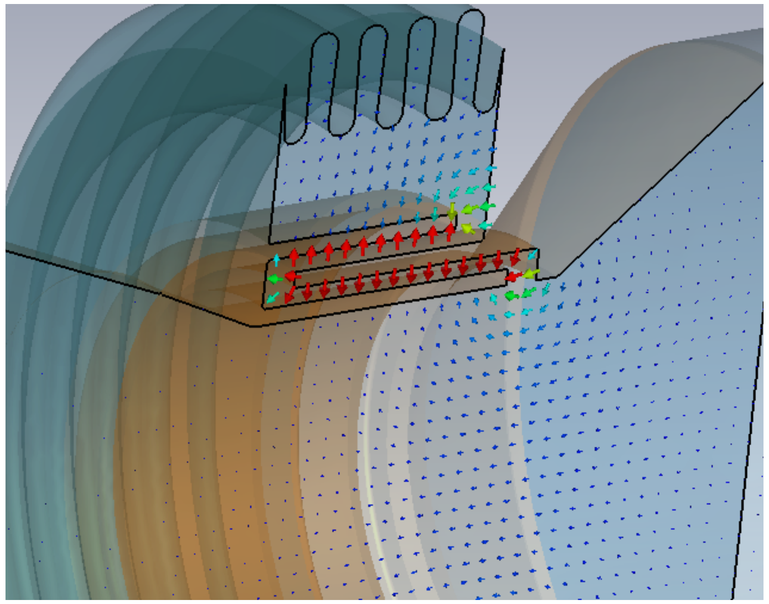
not relevant with standard fill patterns, in case of single puls mode (20 mA):

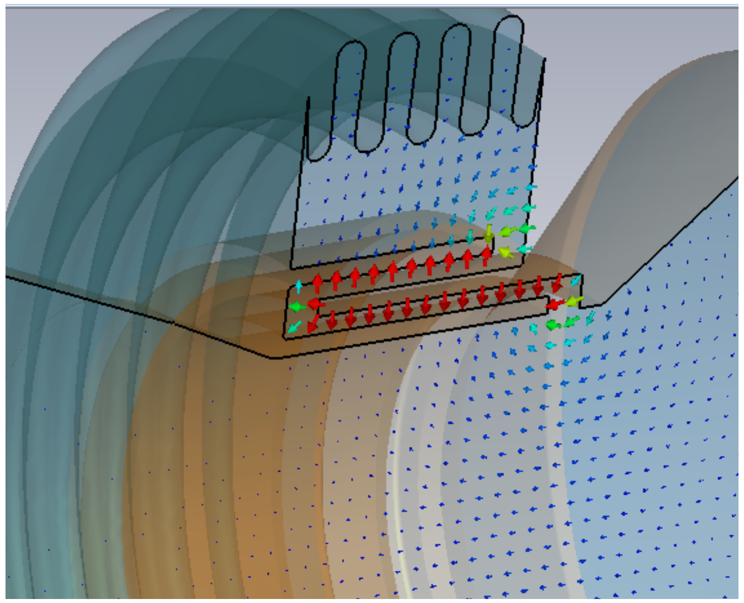
$P_{beamloss}$ *= 2.90 W, mainly dissipated in steel bellow:*

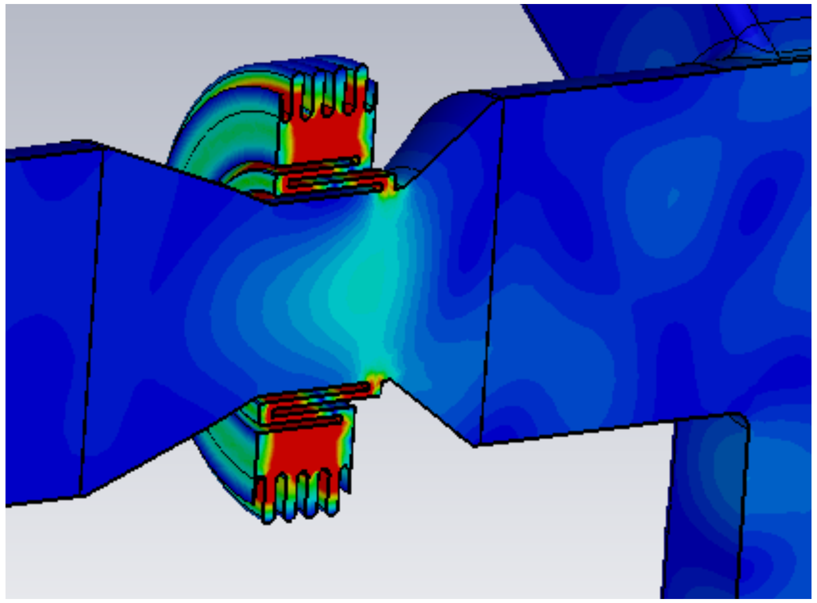
Bellow	2.50393 Watt
InsertUp	0.140266 Watt
taperUp	0.
taperDown	0.
DiskDown	0.0591205 Watt
DiskUp	0.0570919 Watt
InsertDown	0.125486 Watt

this and higher modes are well coupled to the absorbers

Collimating shielded bellow: Length dependence of parasitic modes







-2 mm	± 0	+ 2mm
415.8 MHZ	422.1 MHz	423.0 MHz
14.3 Ω	15.8 Ω	17.1 Ω

-2 mm	± 0	+ 2mm
2125.1 MHZ	2154.8 MHz	2135.4 MHz
4.3 Ω	4.2 Ω	4.2 Ω

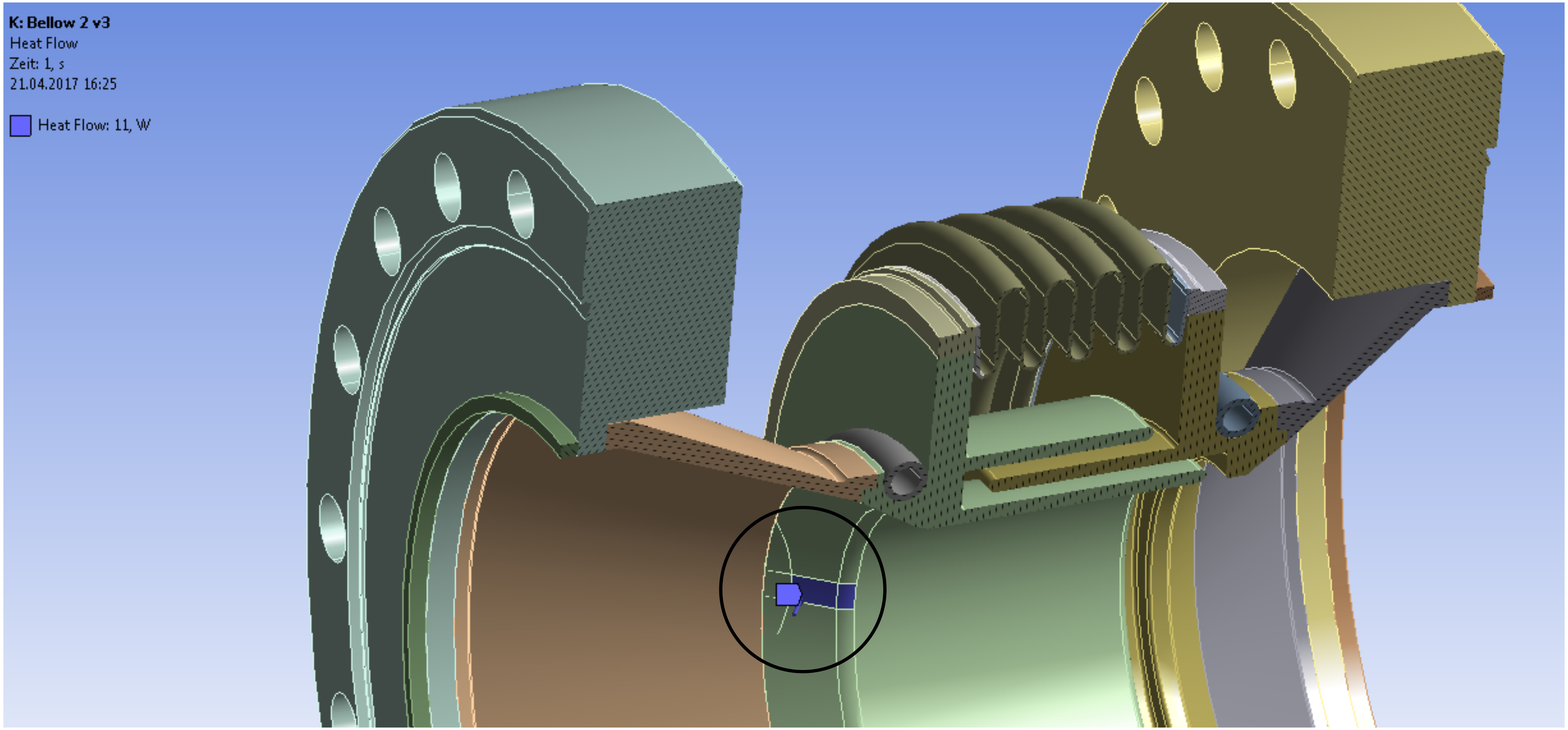
-2 mm	± 0	+ 2mm
3976.4 MHZ	3928.0 MHz	3784.4 MHz
5.2 Ω	2.2 Ω	2.2 Ω

(computed without cavities; influenced by finite beam pipes)

– *no issues from stretching / shortening*

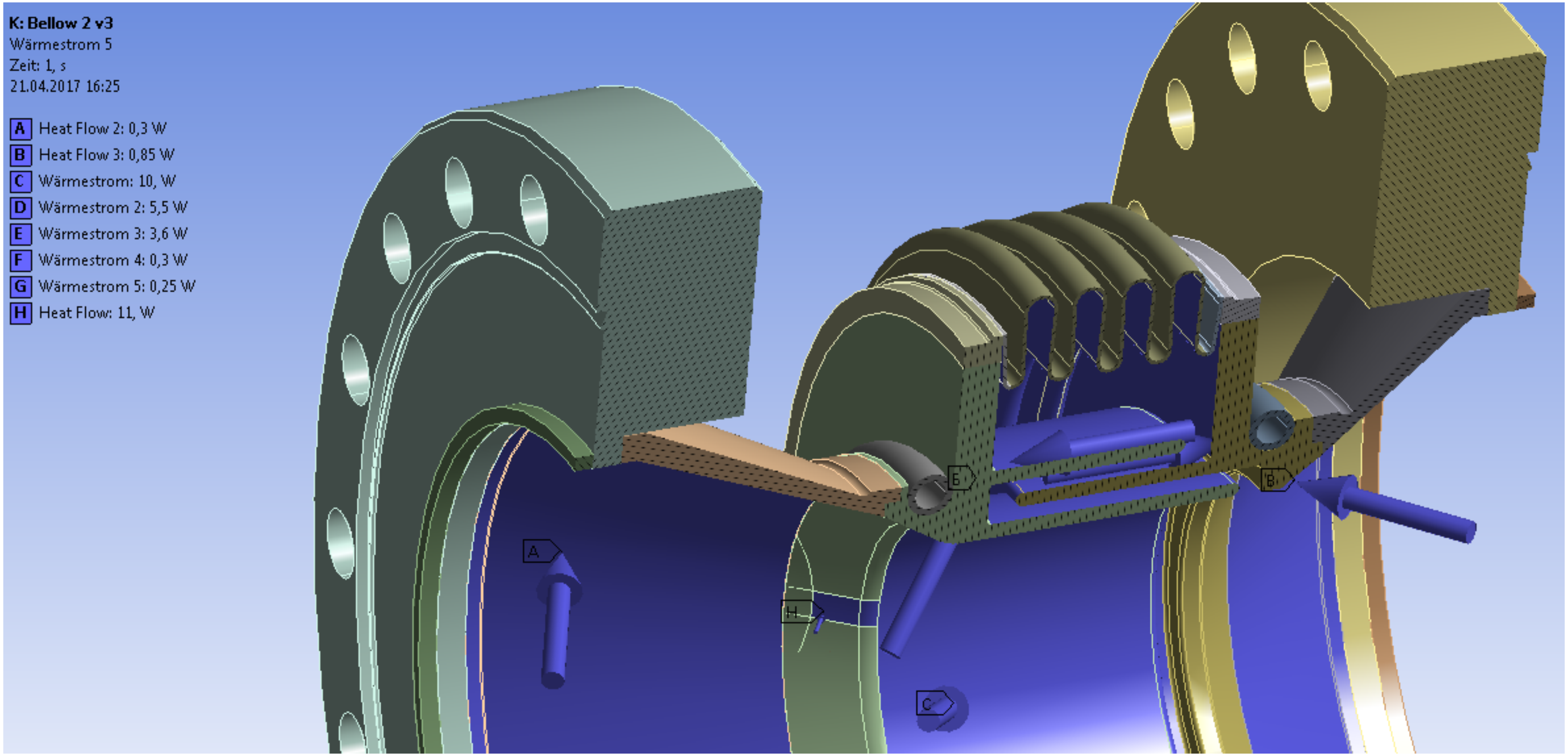
– *not necessarily monotonous dependence*

Thermal simulation of collimating shielded bellow: Synchrotron light



Incidence of synchrotron light beam of ~ 2 x 2 mm² cross section and 11 W power

Thermal simulation of collimating shielded bellow:
Fundamental + parasitic modes + synchrotron light



Total dissipated power of 31.8 W, assuming

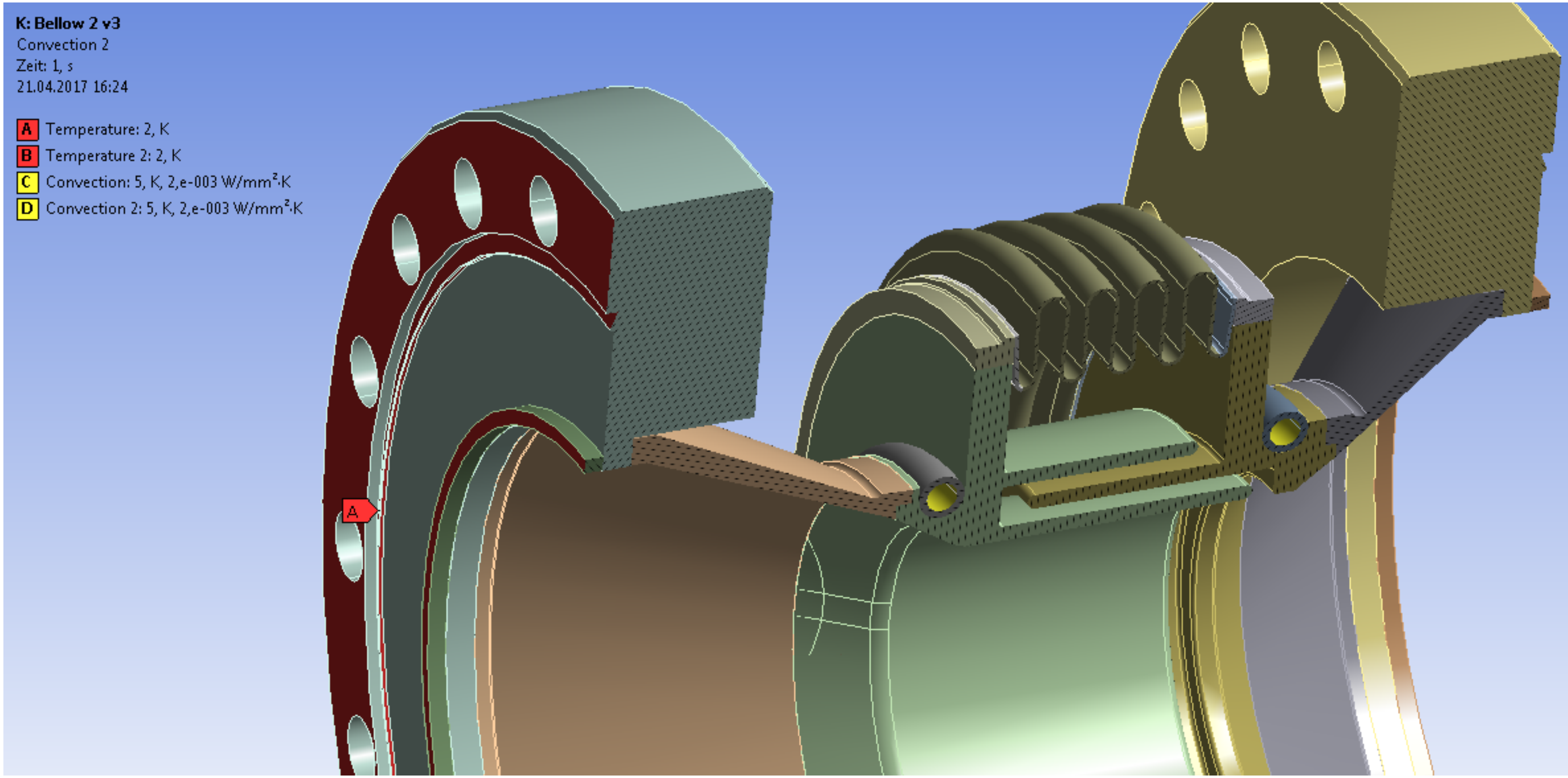
– all beam-deposited wake power is absorbed locally

– synchrotron light is fully absorbed

– homogeneous rf dissipation over surface elements

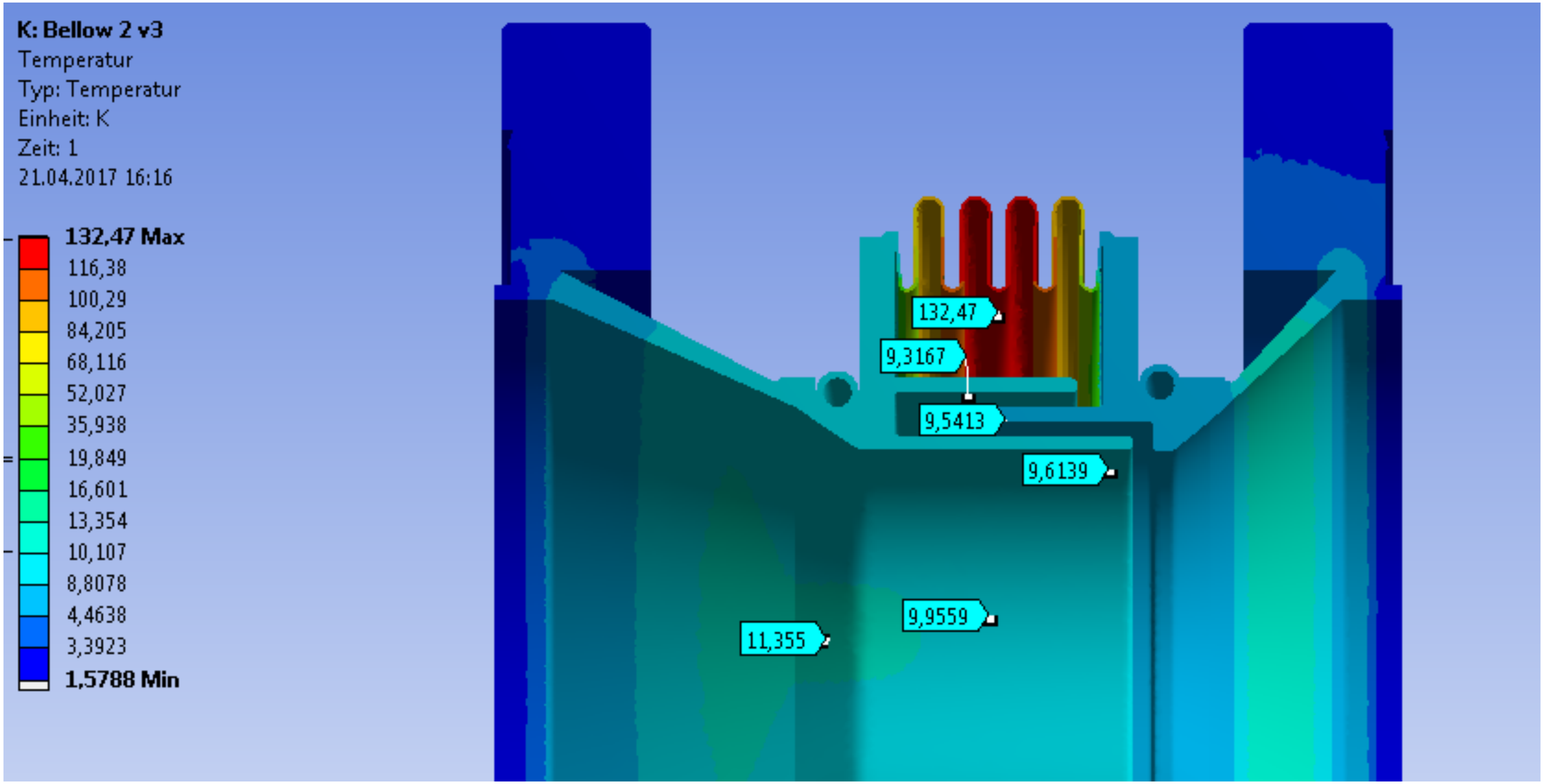
Thermal simulation of collimating shielded bellow:

Temperature and convective boundaries = heat sinks



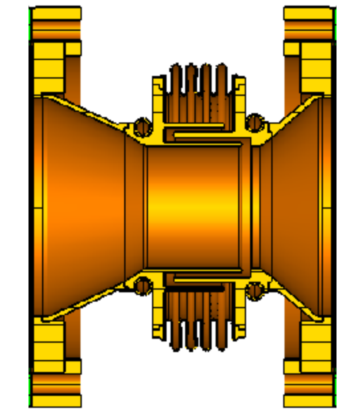
- *2 K boundaries on contact planes to the neighboring cavities*
- *5 K boundaries with 0.002 W/(mm^2 K) convective heat transfer to circular pipes*

Thermal simulation of collimating shielded bellow: Temperature distribution

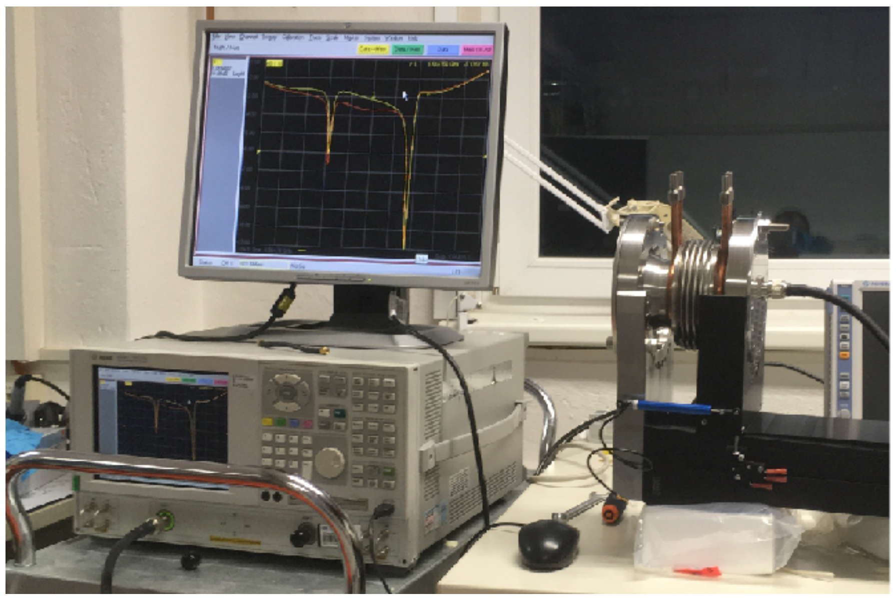


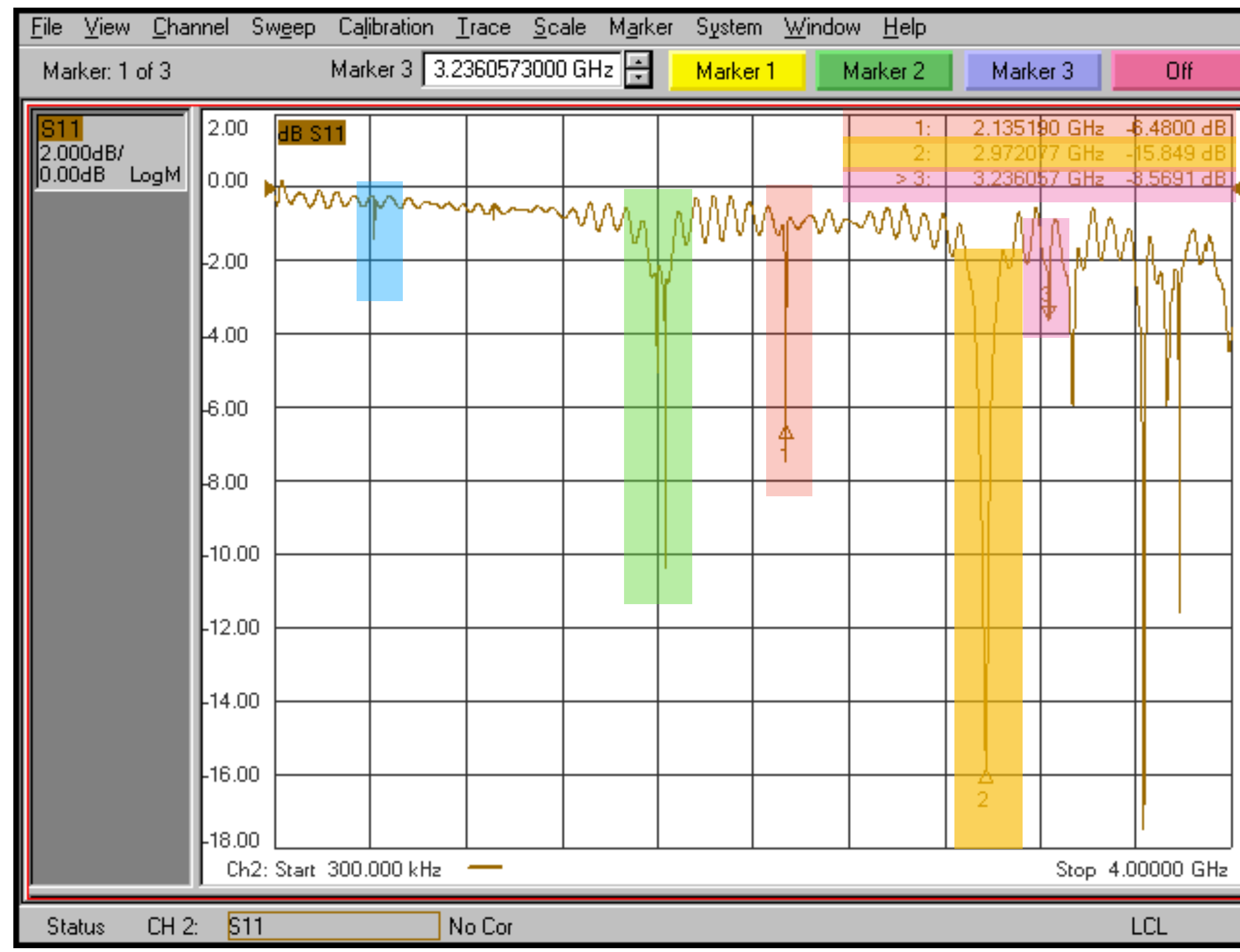
- *synchrotron light power well distributed by copper*
- *total heat flux to the cavities < 1 W*
- *in (rare) single bunch operation bellow exceeds 130 K, outgassing triggered ...*
- *... but labyrinth could work as cold gas trap*

Collimating Shielded Bellow (CsB)



- *prototype in house*
- *network analyzer measurements at default length done, results in (very) good agreement with simulations (dedicated run with closed beam pipes)*





Eigenmode solver results:

Mode	Frequency	Accuracy
1	0.422017503820 GHz	4.815e-09
2	1.61651890959 GHz	1.505e-09
3	1.61660683476 GHz	1.848e-09
4	2.15390260456 GHz	5.946e-07
5	2.66492439661 GHz	7.97e-07
6	2.66507610941 GHz	8.177e-07
7	2.92504757426 GHz	3.033e-07
8	3.07292294057 GHz	3.693e-09
9	3.07302474842 GHz	4.112e-09
10	3.10802492374 GHz	6.663e-09
11	3.22143179174 GHz	4.217e-08
12	3.22143792905 GHz	3.796e-08

Conclusion, summary and recommendation:

„Ihr wißt, auf unsern deutschen Bühnen
Probiert ein jeder, was er mag;
Drum schonet mir an diesem Tag
Prospekte nicht und nicht Maschinen.
Gebraucht das groß, und kleine Himmelslicht,
Die Sterne dürfet ihr verschwenden;
An Wasser, Feuer, Felsenwänden,
An Tier und Vögeln fehlt es nicht.
So schreitet in dem engen Bretterhaus
Den ganzen Kreis der Schöpfung aus,
Und wandelt mit bedächt'ger Schnelle
Vom Himmel durch die Welt zur Hölle.“

J. W. von Goethe, Faust: Eine Tragödie