# Finding the thermal distribution of wake losses

Using time domain simulation, combined domain analysis, and thermal simulation, to predict the heating of diagnostic components

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Diamond Light Source

# Why are we worried?

- Diagnostics systems are *designed* to couple to the beam.
- Wake loss factor is large enough to give uncomfortably large amounts of energy being lost from the beam.
- We plan to go to higher currents and shorter bunches.

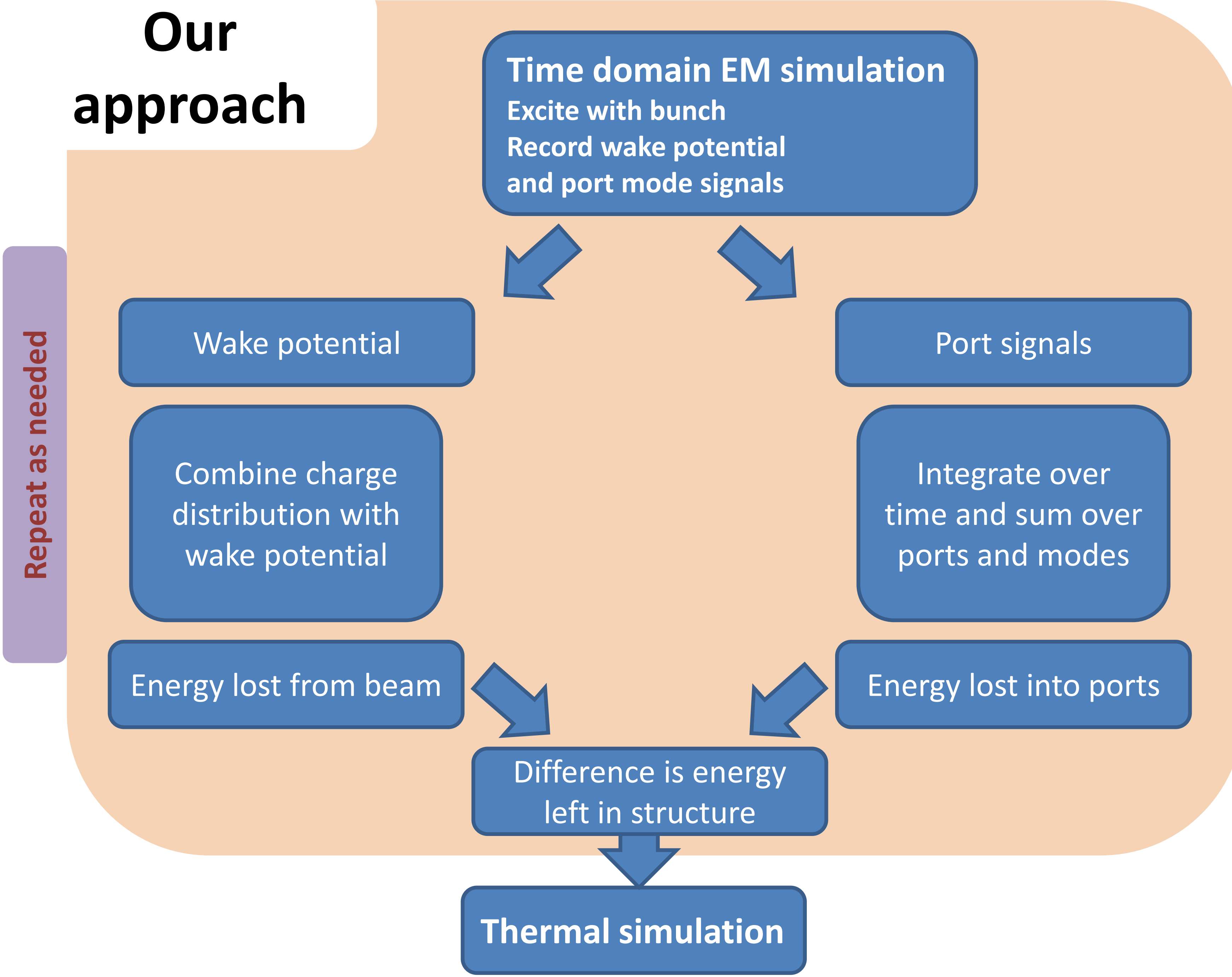
- Current settings imply 189W lost in striplines
- Planned settings imply 313W lost in striplines

# What next?

- **EM simulation** ->Where does the energy go?
  - Dissipated into the structure?
  - Transmitted down the beam pipe?
  - Transmitted out of measurement ports?

- **Thermal simulation** ->Does it cause a heating problem?

# Our approach



# One structure... many simulations

**As a minimum**

- Full lossy (finite conductivity, complex permittivity)
- No losses (PEC, real permittivity)

**Then**

- Lossy with the component of interest made lossless.

# The EM models

**2 stipulations**

- The mesh must be fine enough to have stable results (absolute)
- The simulation must have run long enough for the majority of energy to have left the structure (somewhat flexible)

**From EM simulation get:**

Wake loss factor, Wake impedance

Wake potential

Port/mode signals

Bunch charge distribution

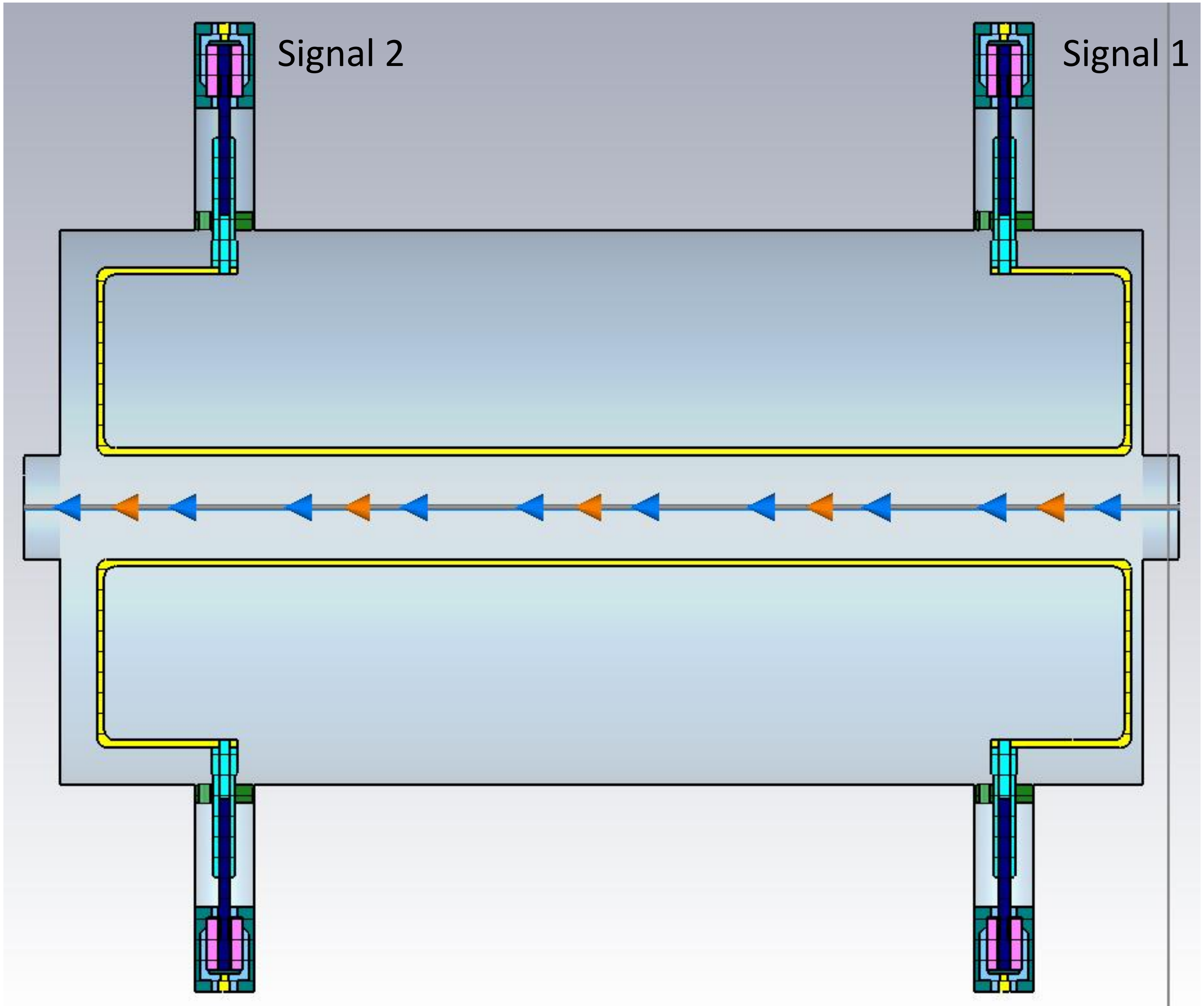
Energy in structure

| Result | Time domain | Frequency domain |
|---|---|---|
| Wake loss factor | | |
| Wake impedance | | |
| Energy lost from beam | | |
| Energy out of measurement ports | | |
| Energy out of beam pipe | | |
| Port spectra | | |
| Beam loss spectra | | |

| Check | Time domain | Frequency domain |
|---|---|---|
| Does the energy decay? | | |
| Total port power < energy lost from beam | | |
| Sum of port spectra < bunch loss spectra at all frequencies. | | |

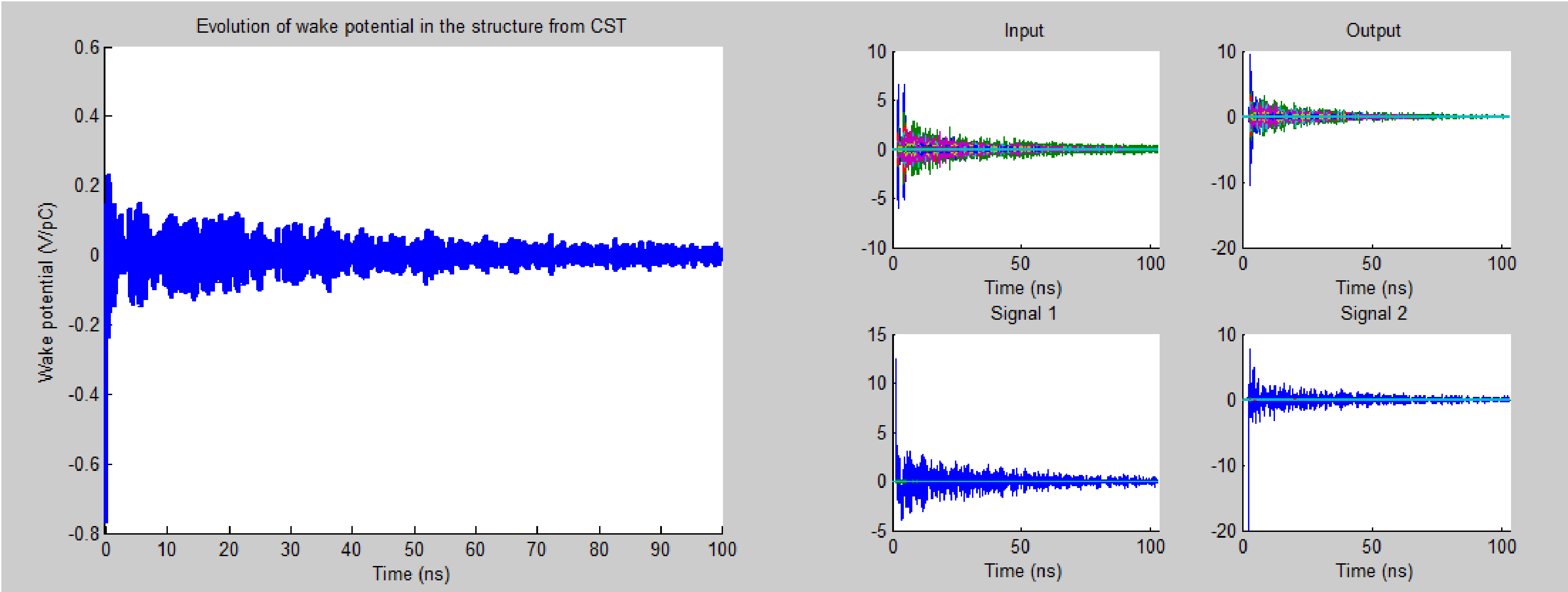
~14hrs per simulation

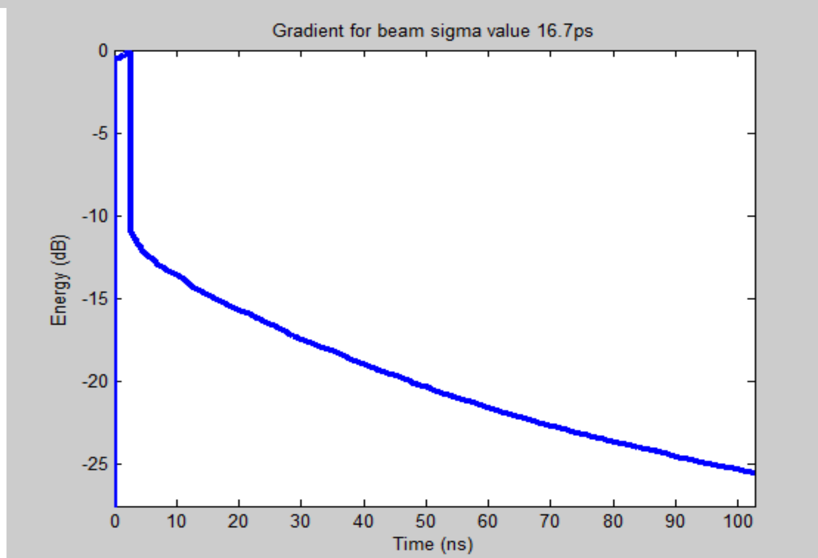
# Example: Striplines

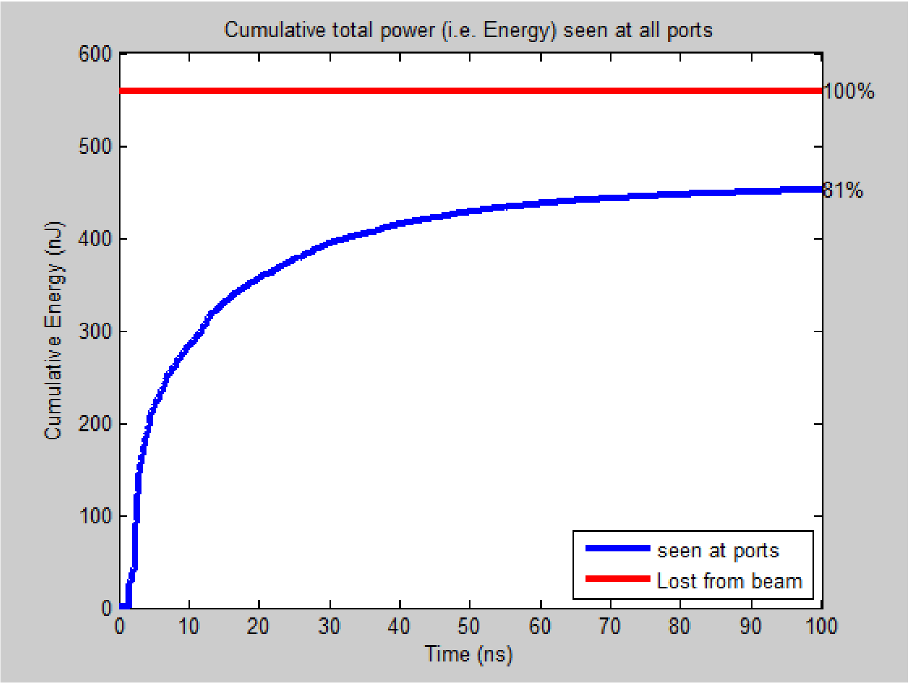


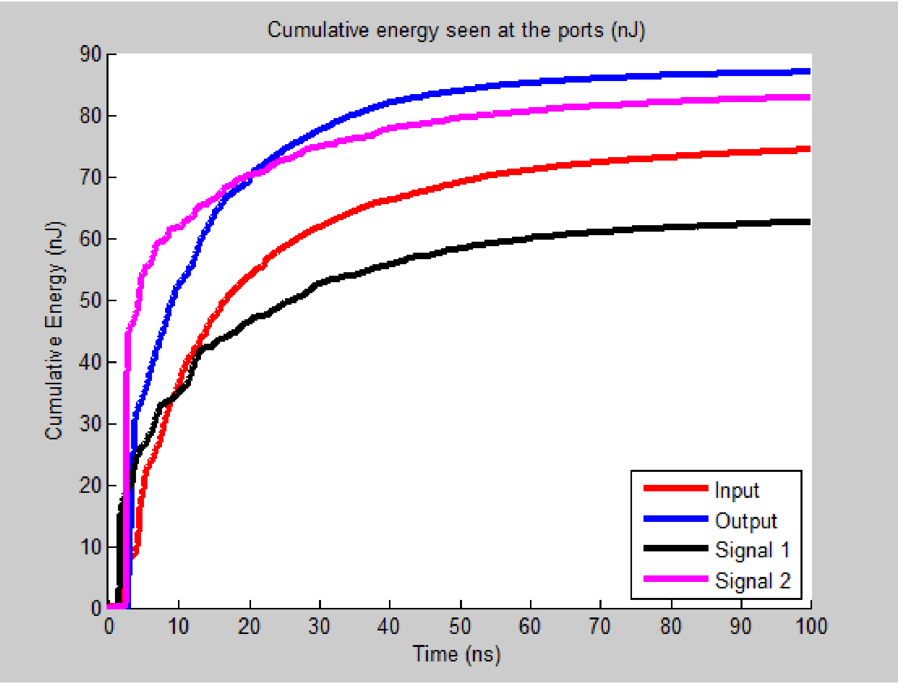

Output

Input

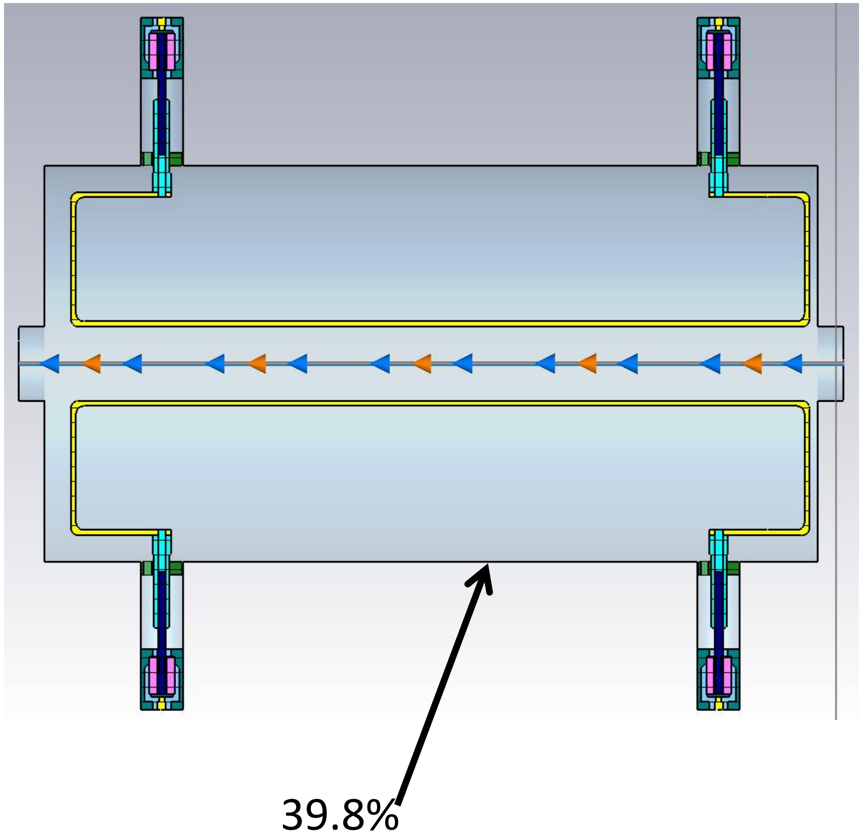

Evolution of wake potential in the structure from CST
Wake potential (V/pC)
Time (ns)
Input
Output
Signal 1
Signal 2
Time (ns)

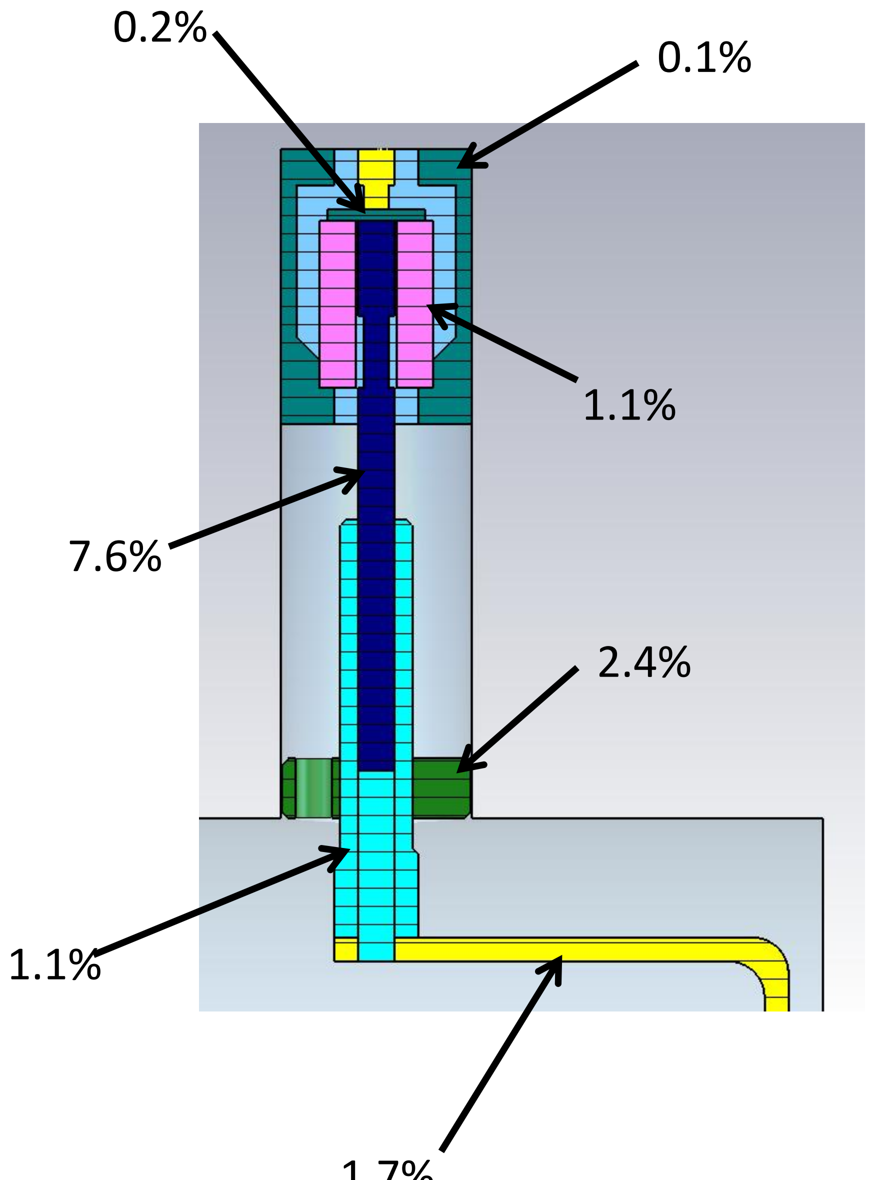

Gradient for beam sigma value 16.7ps
Energy (dB)
Time (ns)



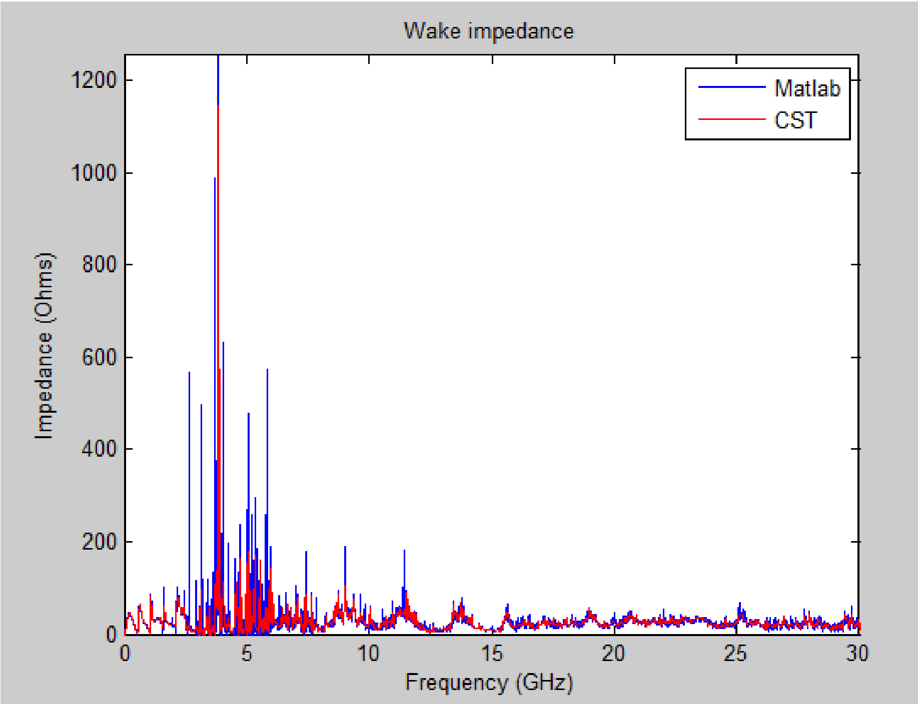

1nC 16ps bunch

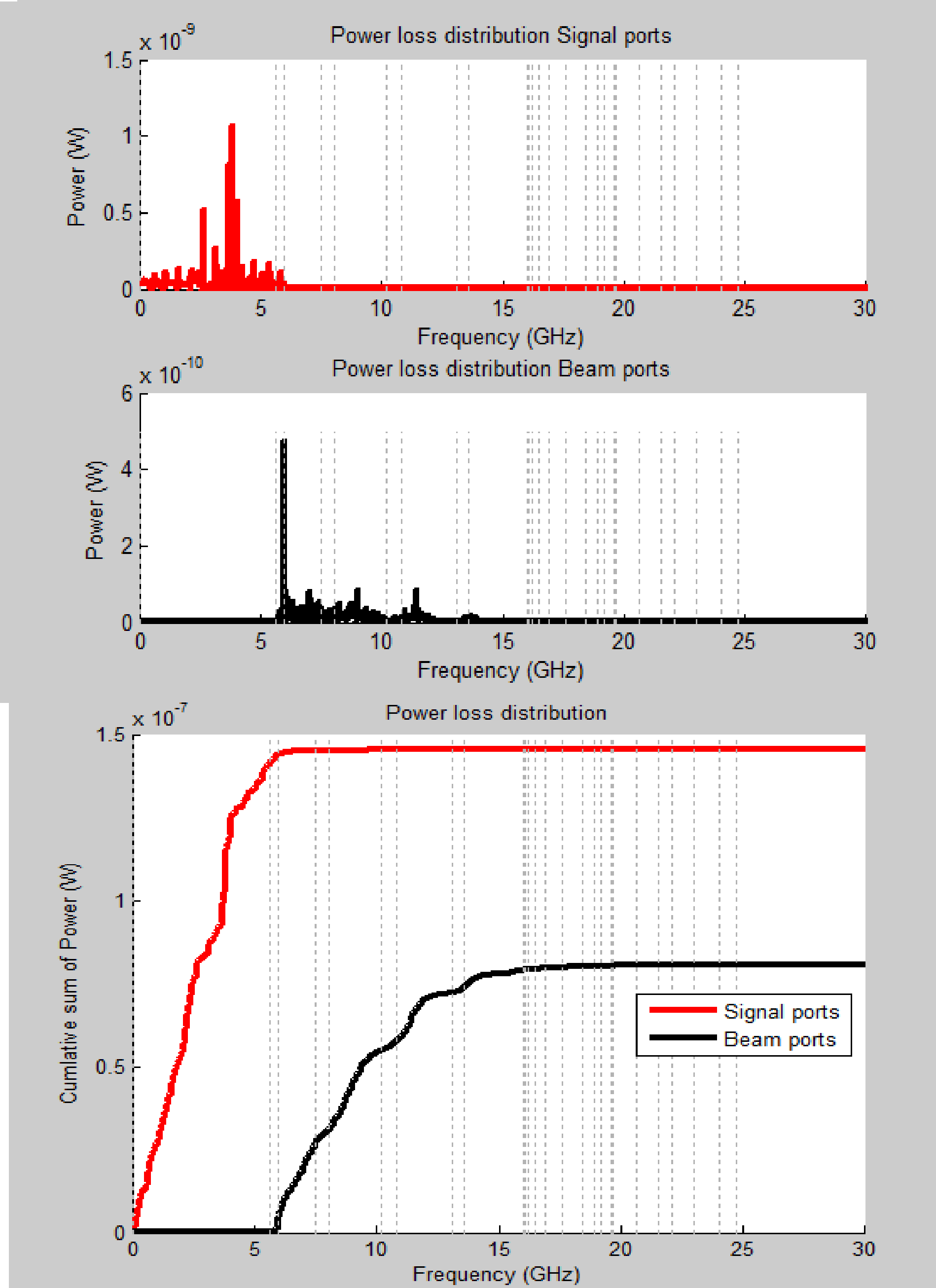



4% discrepancy between Component losses and Total losses.

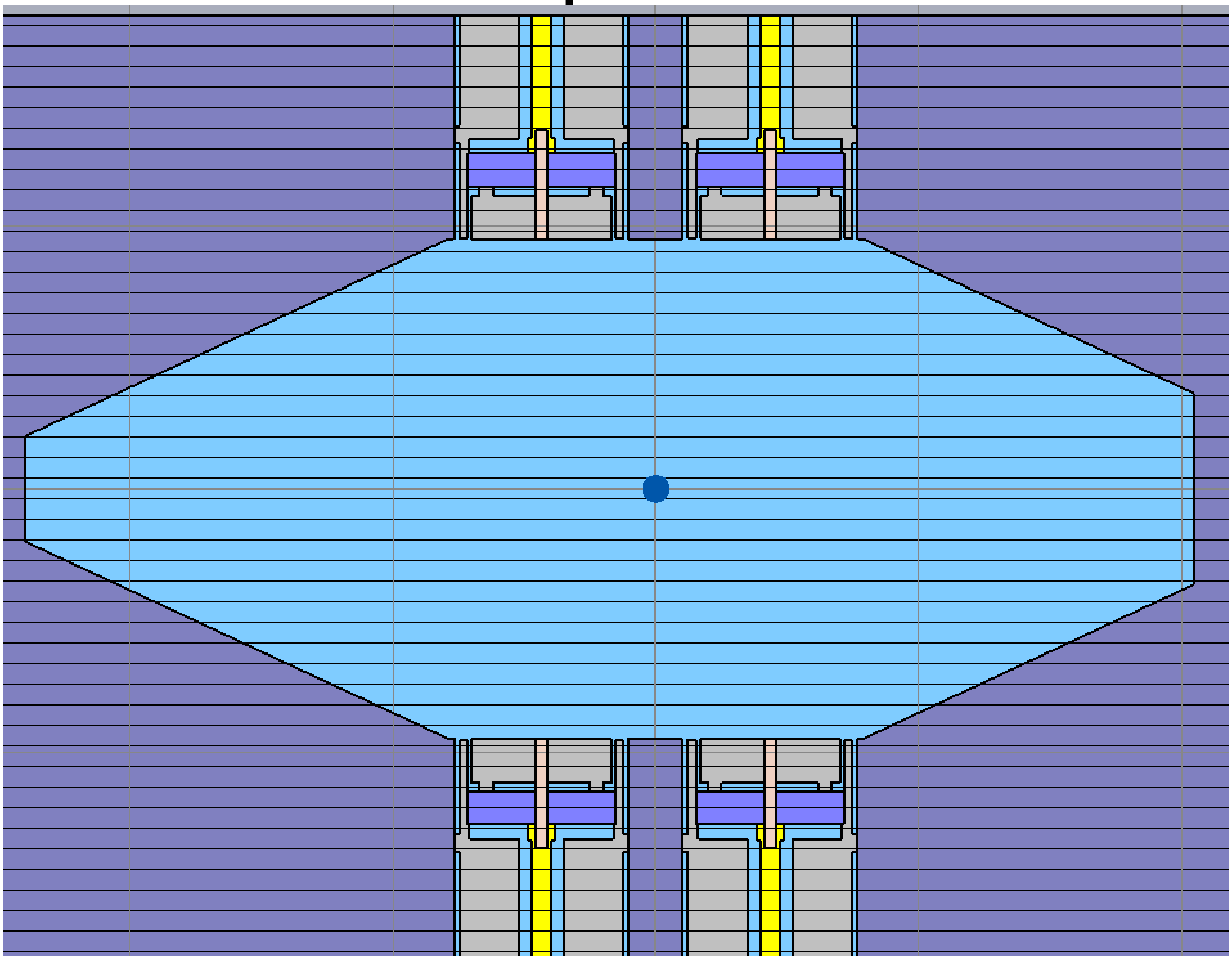
# Example:Striplines



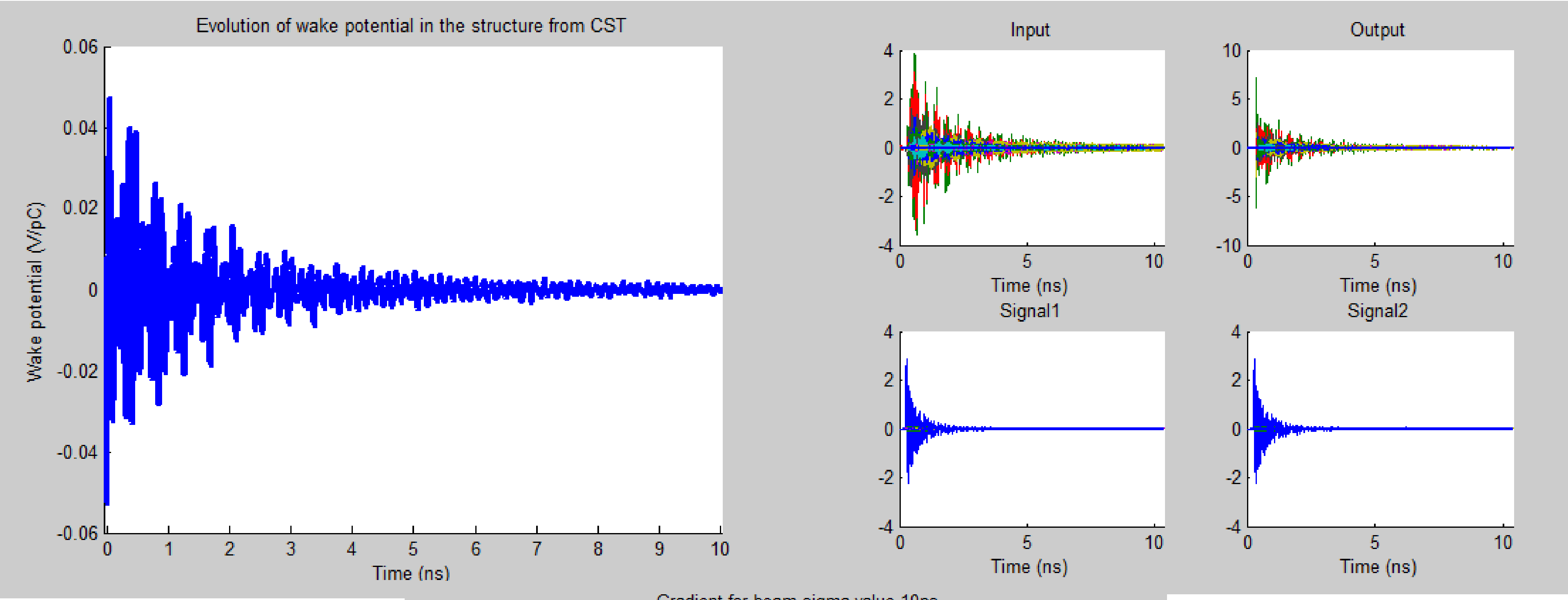



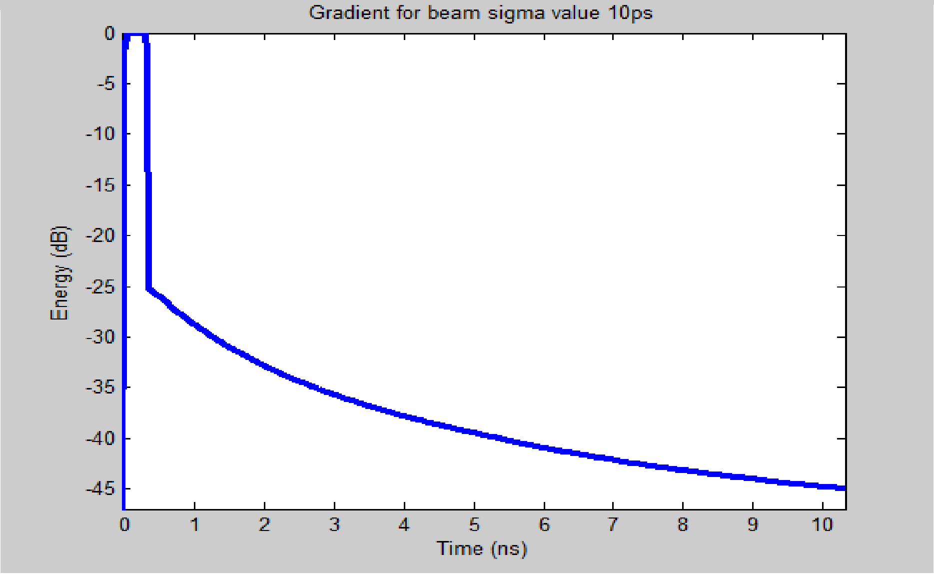
7 hrs lossy/component
46hrs lossless

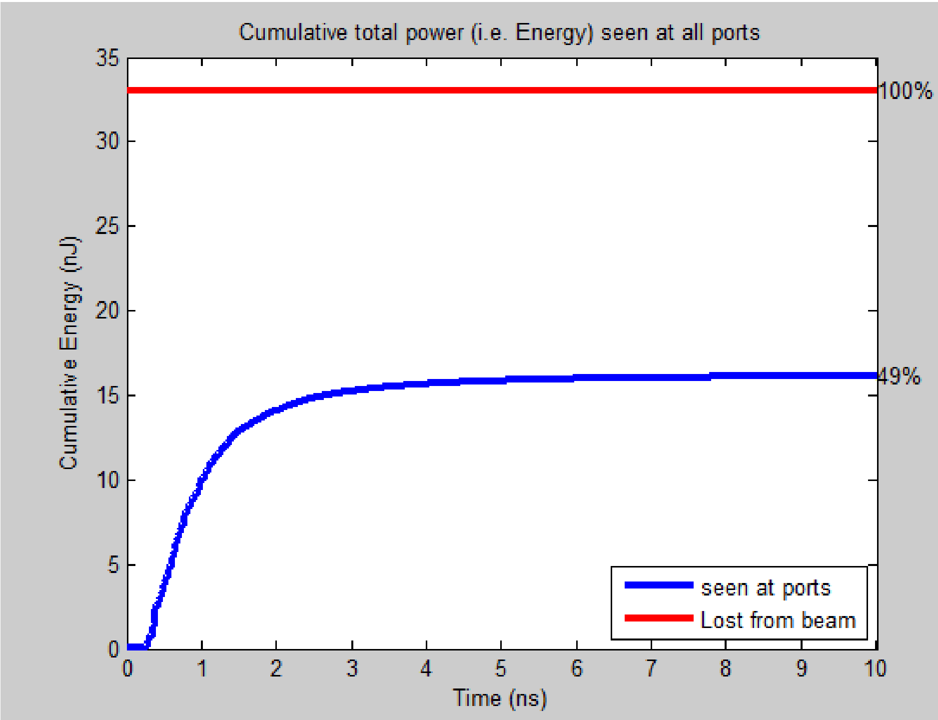
# Example: BPM

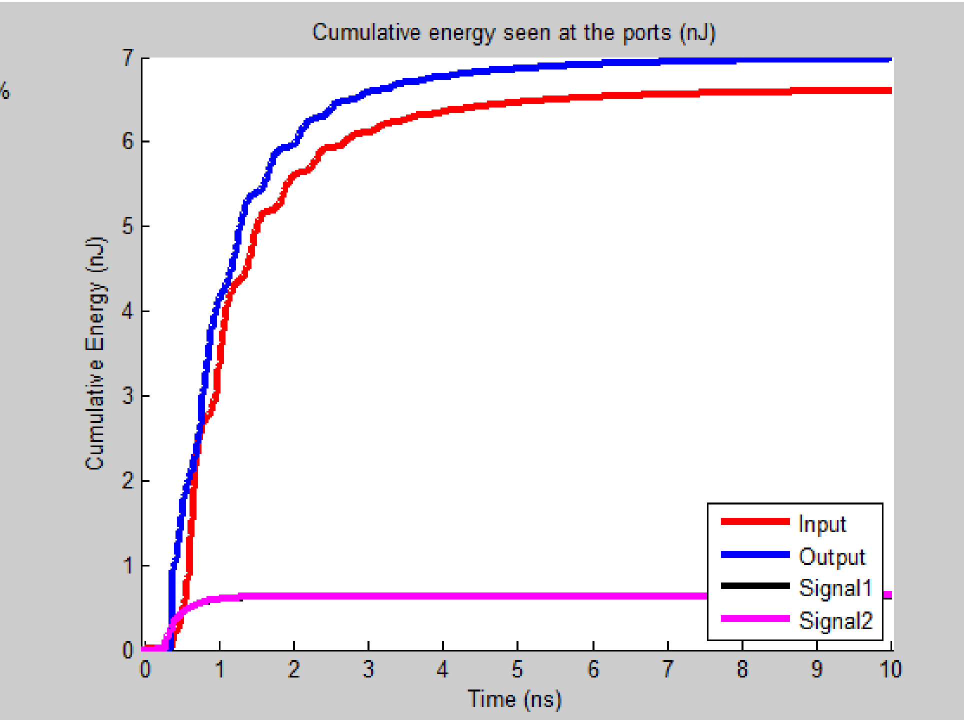


# Example:BPM

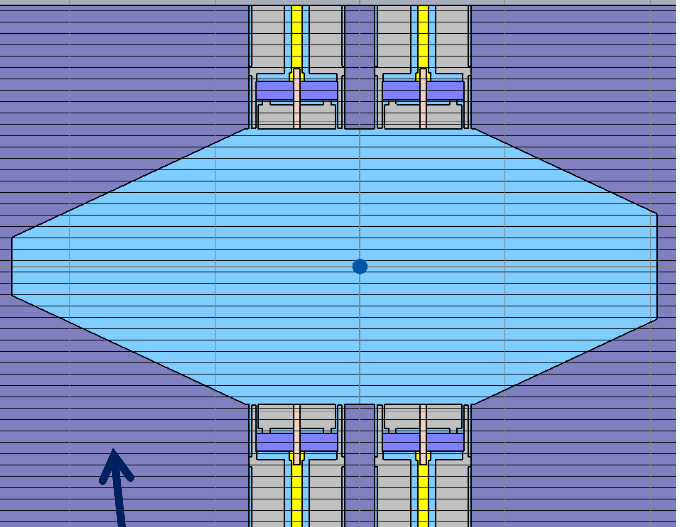

Evolution of wake potential in the structure from CST
Wake potential (V/pC)
Time (ns)
Input
Output
Signal1
Signal2
Time (ns)

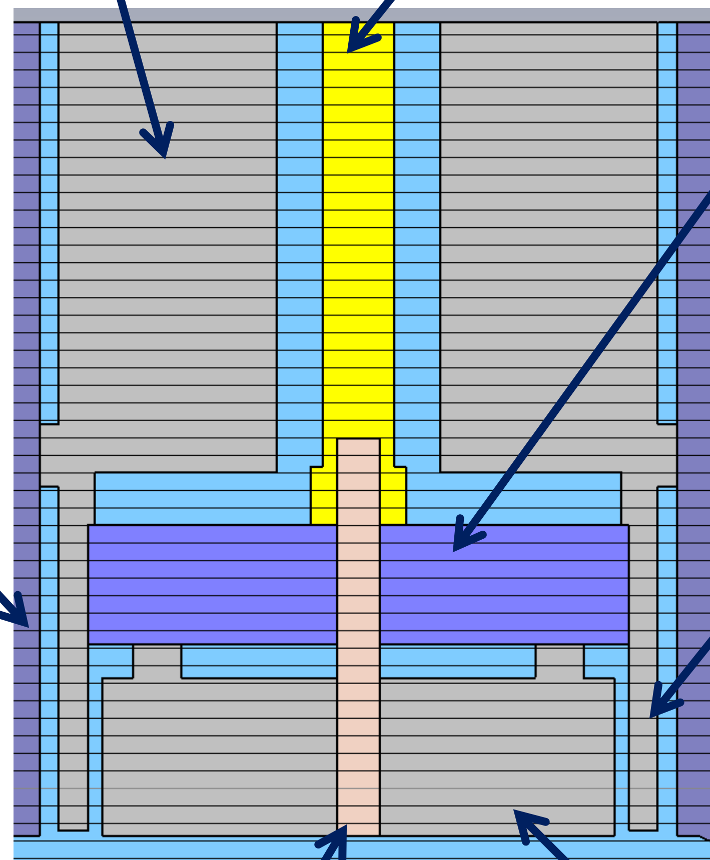

Gradient for beam sigma value 10ps
Energy (dB)
Time (ns)



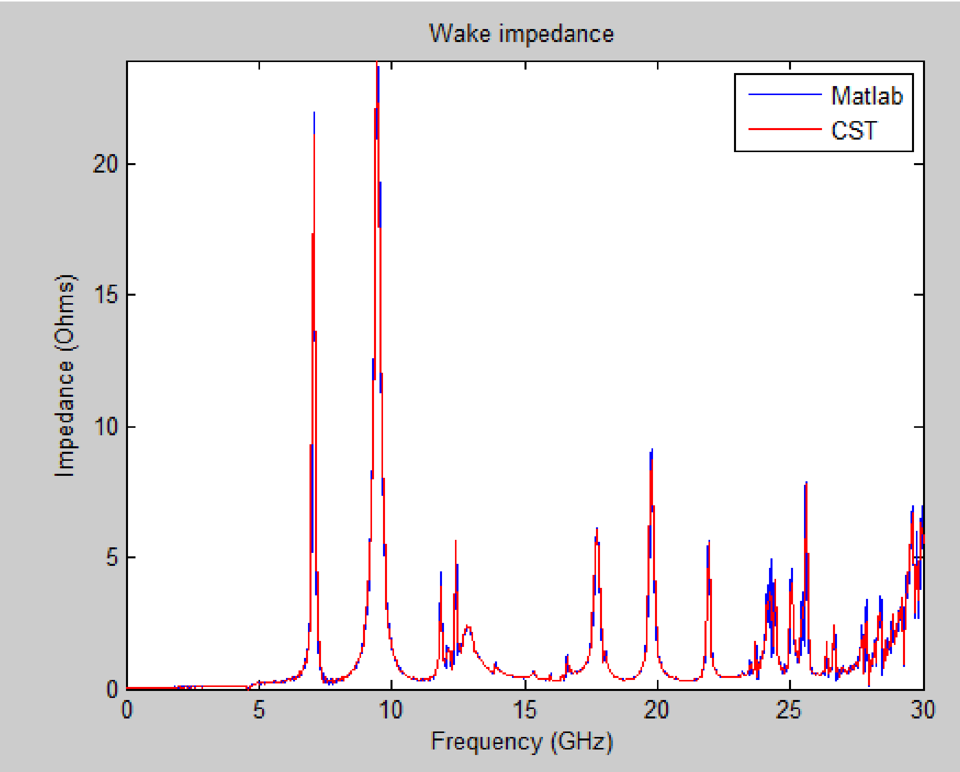

1nC 10ps bunch

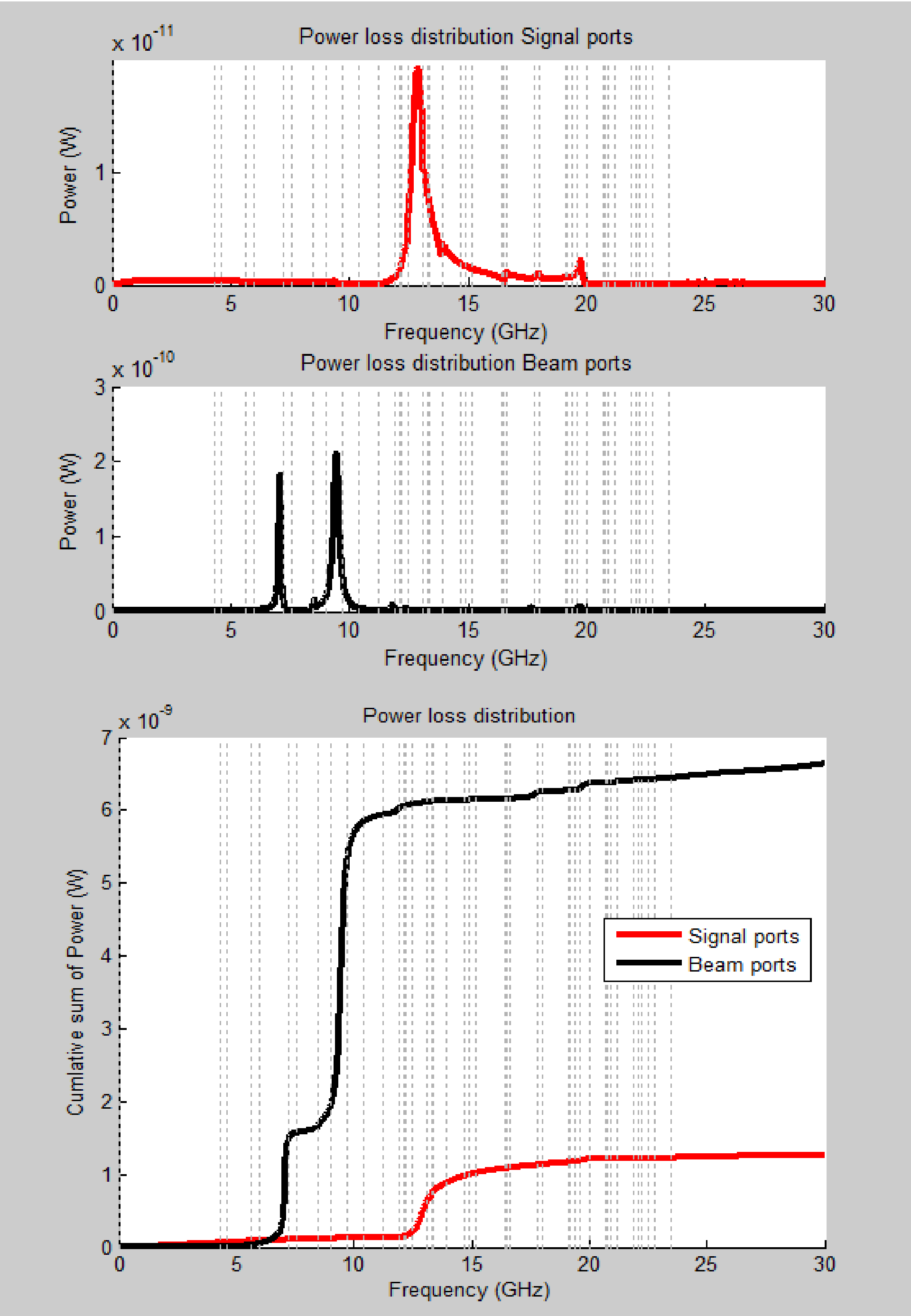



18% discrepancy between Component losses and Total losses.

# Example:BPM

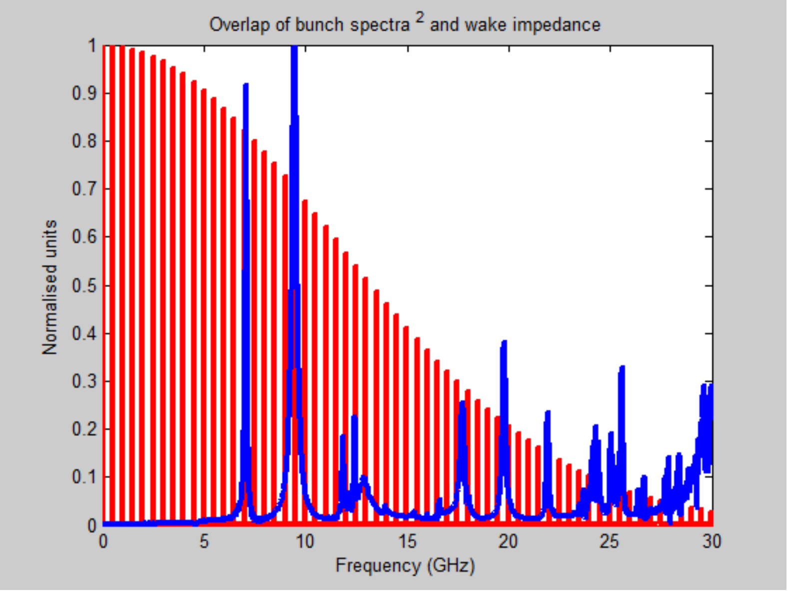

Wake impedance
Matlab
CST
Impedance (Ohms)
Frequency (GHz)


Power loss distribution Signal ports
x 10^-11
Power (W)
Frequency (GHz)
Power loss distribution Beam ports
x 10^-10
Power (W)
Frequency (GHz)
Power loss distribution
x 10^-9
Cumlative sum of Power (W)
Signal ports
Beam ports
Frequency (GHz)

# Extensions

We have the wake impedance which is the response of the structure **only**.
We can now multiply it with different spectra...

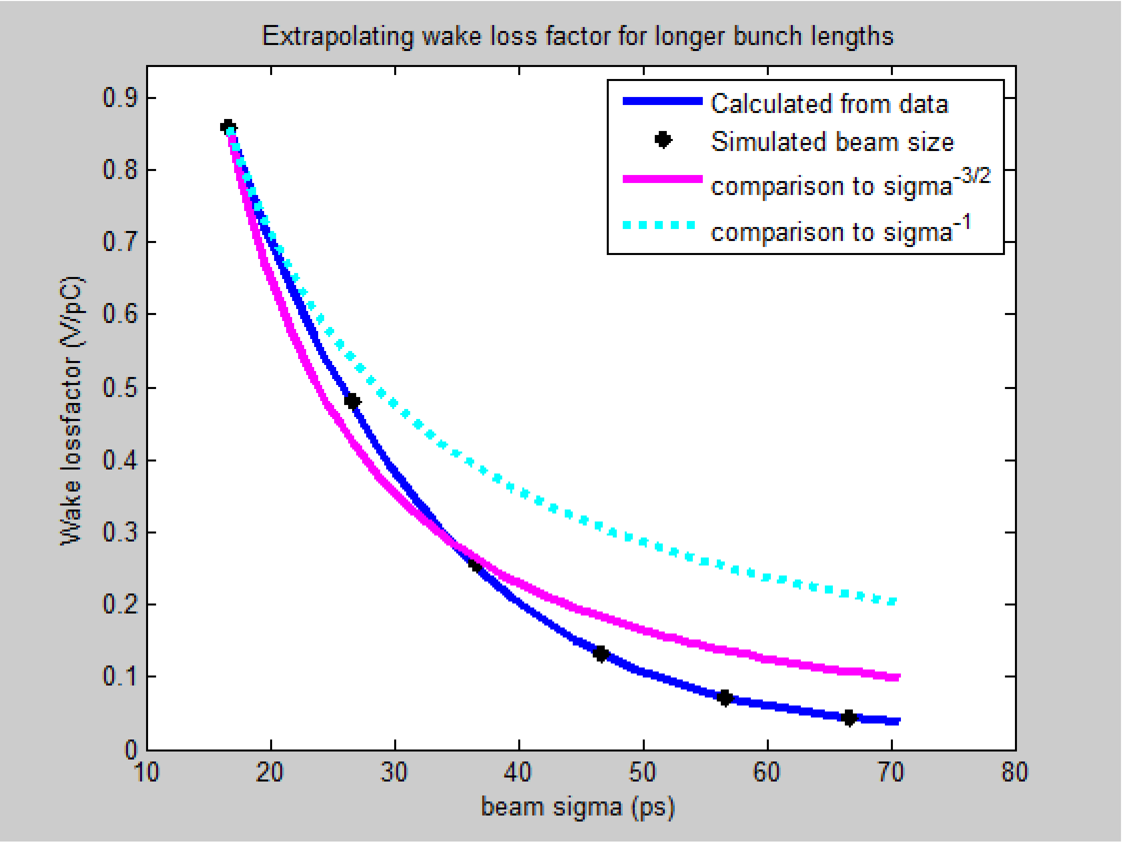
- multiple bunches
- Different bunch lengths
- Machine parameter studies




Have to use reconstructed wake impedance as it has better fidelity.

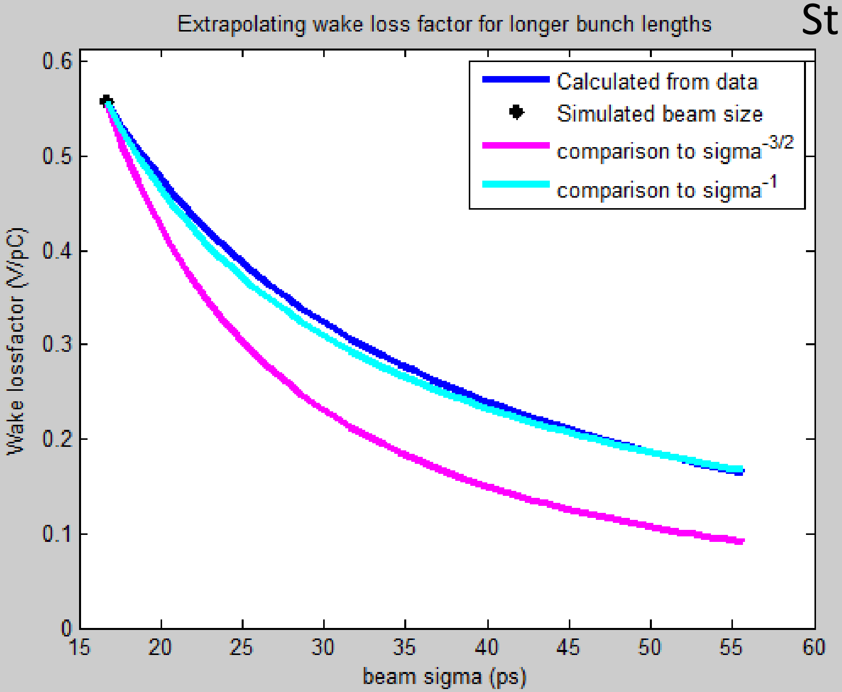
# Are the extensions valid?

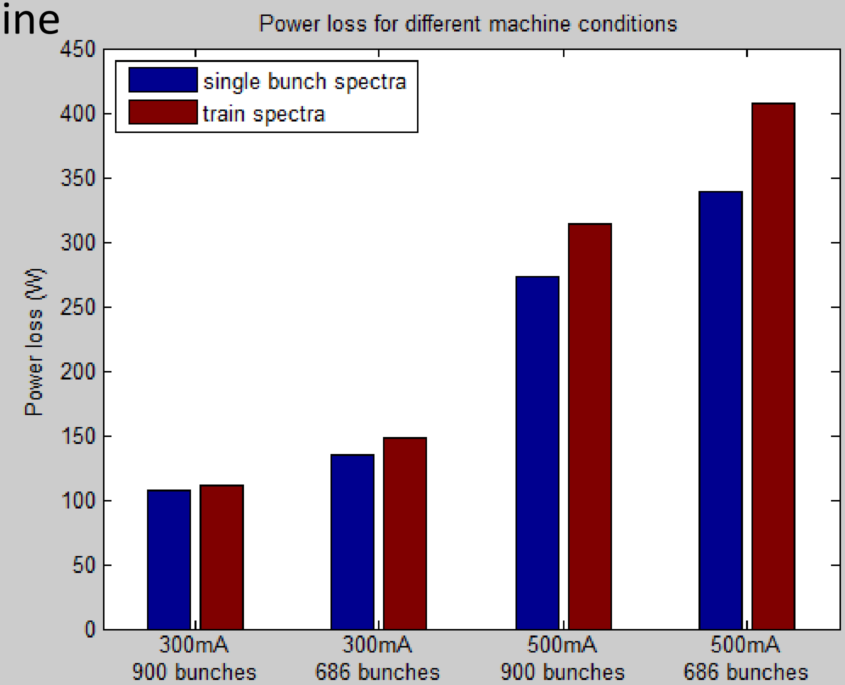
We can only check single bunch variation ... however the multi bunch extension uses the same technique just with different beam spectra.



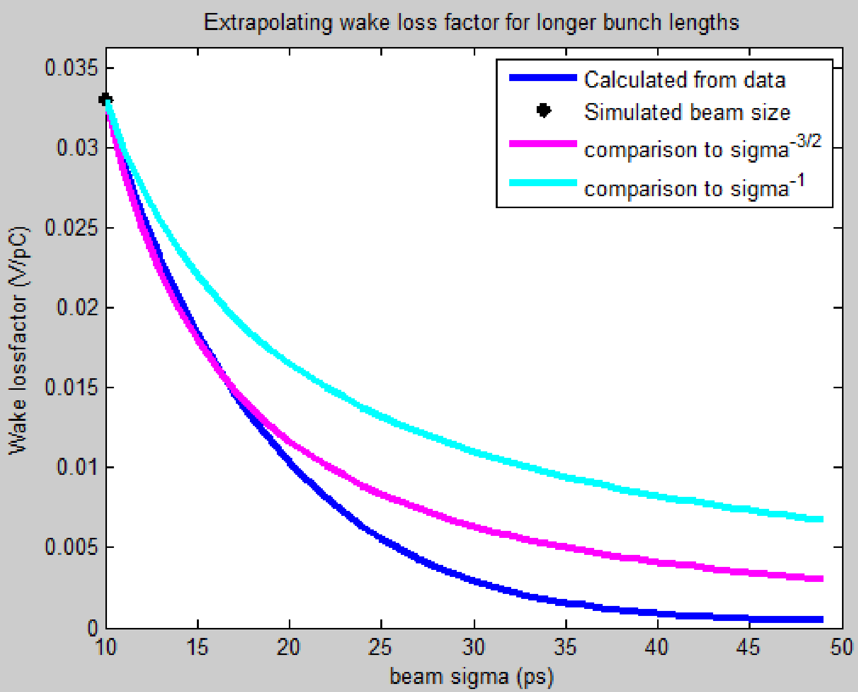

Structure is simplified stripline

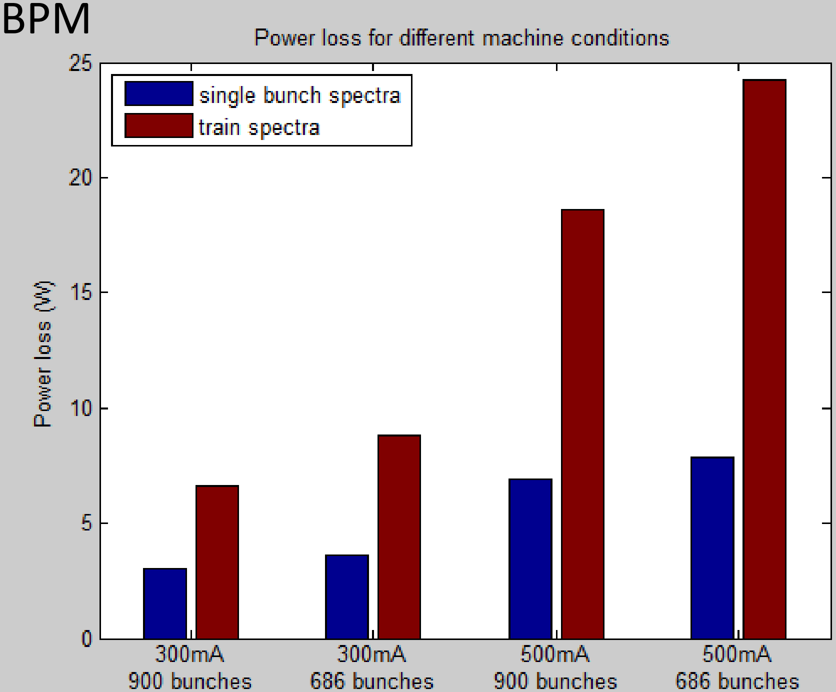
# Stripline

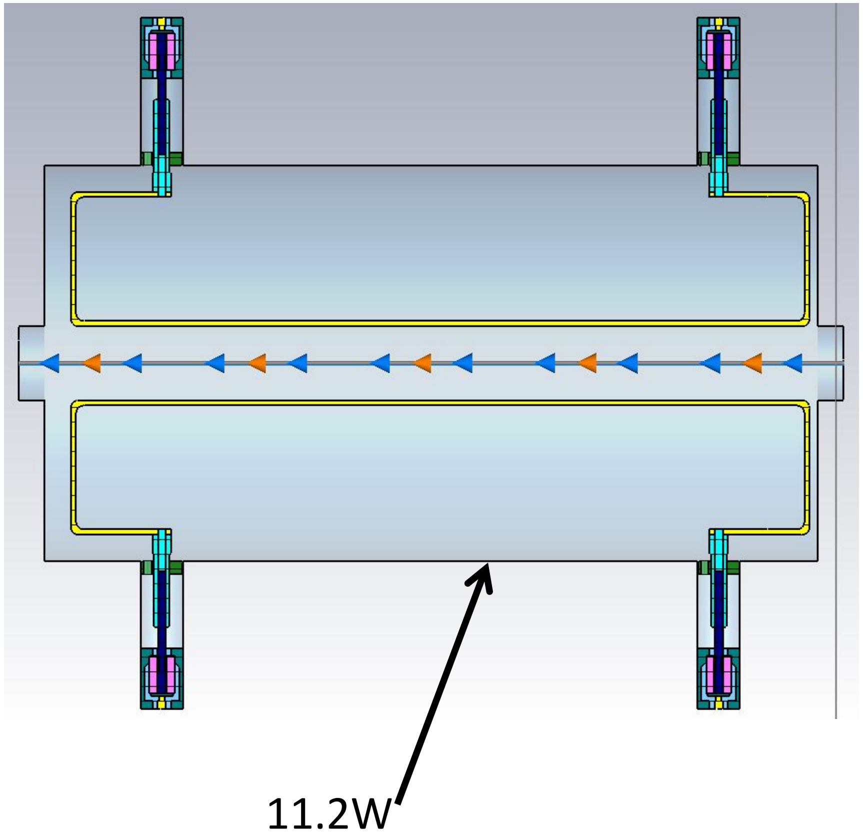



# Arc BPM

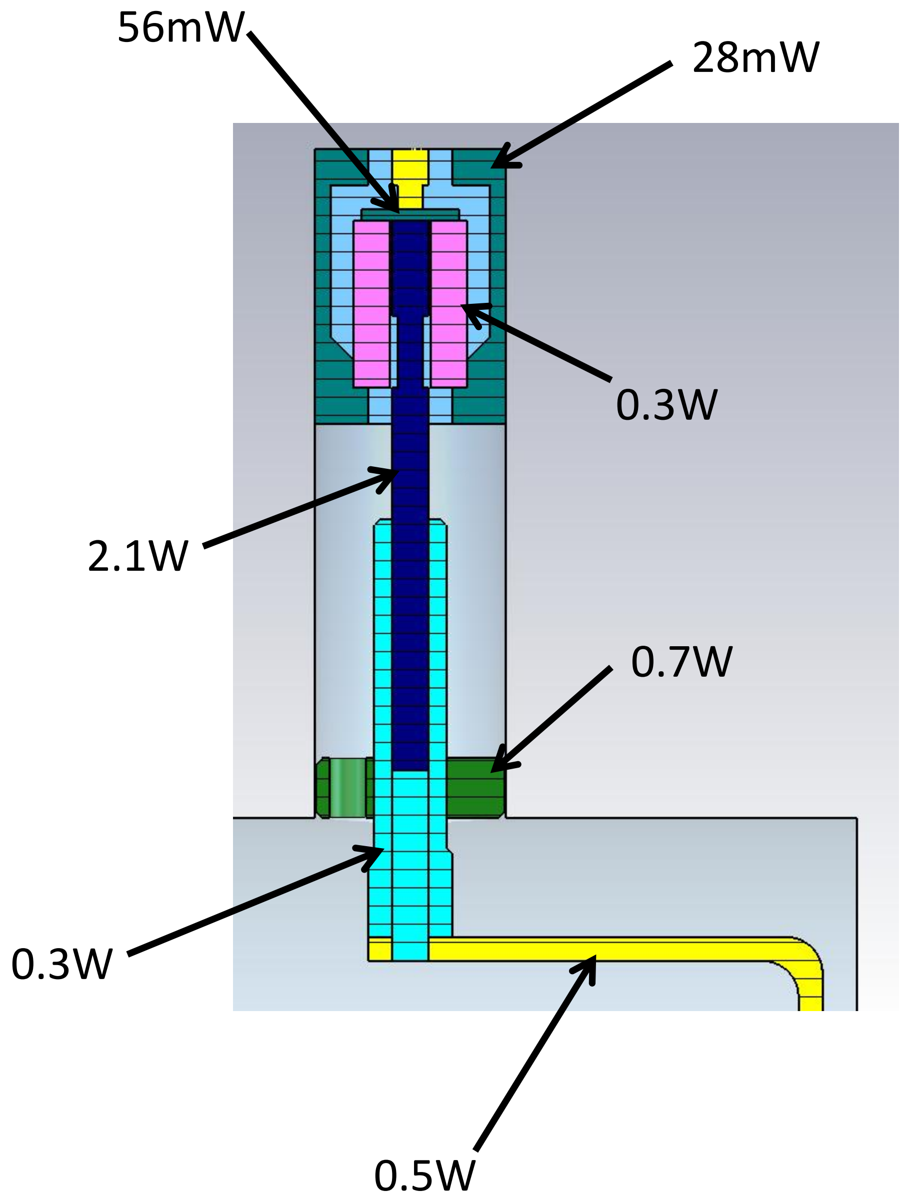





## Current running conditions

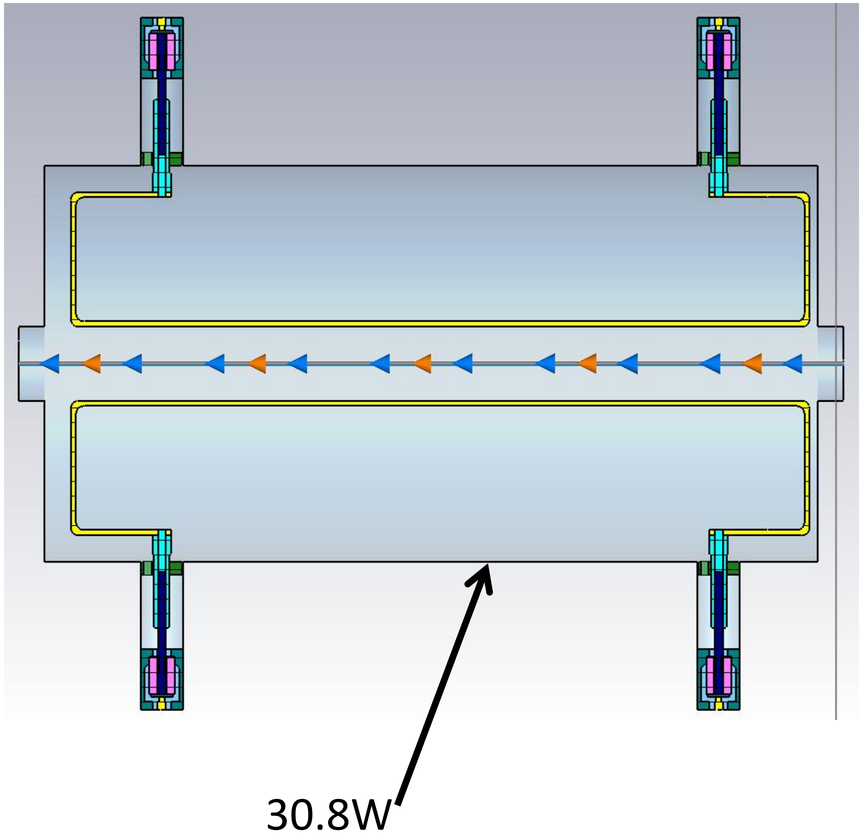
(300mA 686 bunch fill)




Beam loss 148W

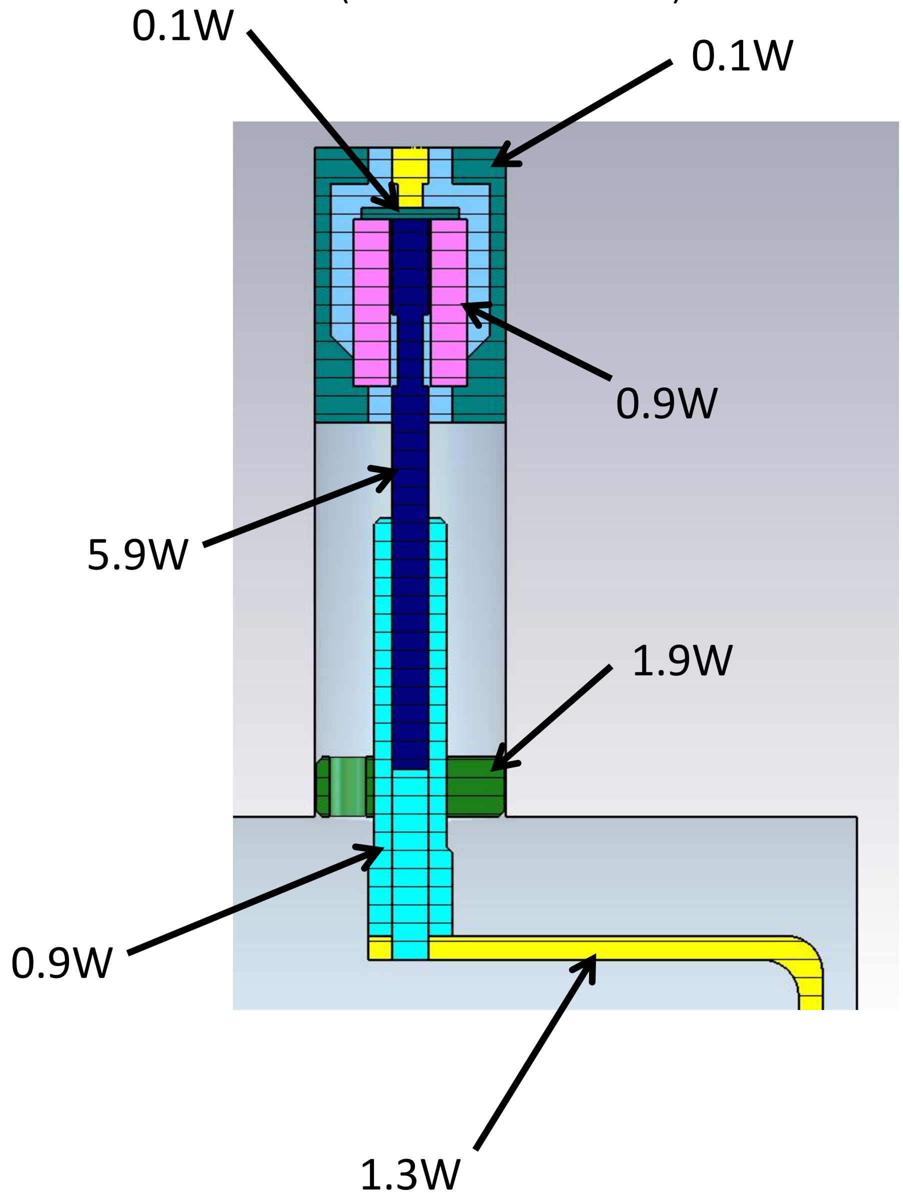
Total structure loss 28.1W

1.1W not accounted for



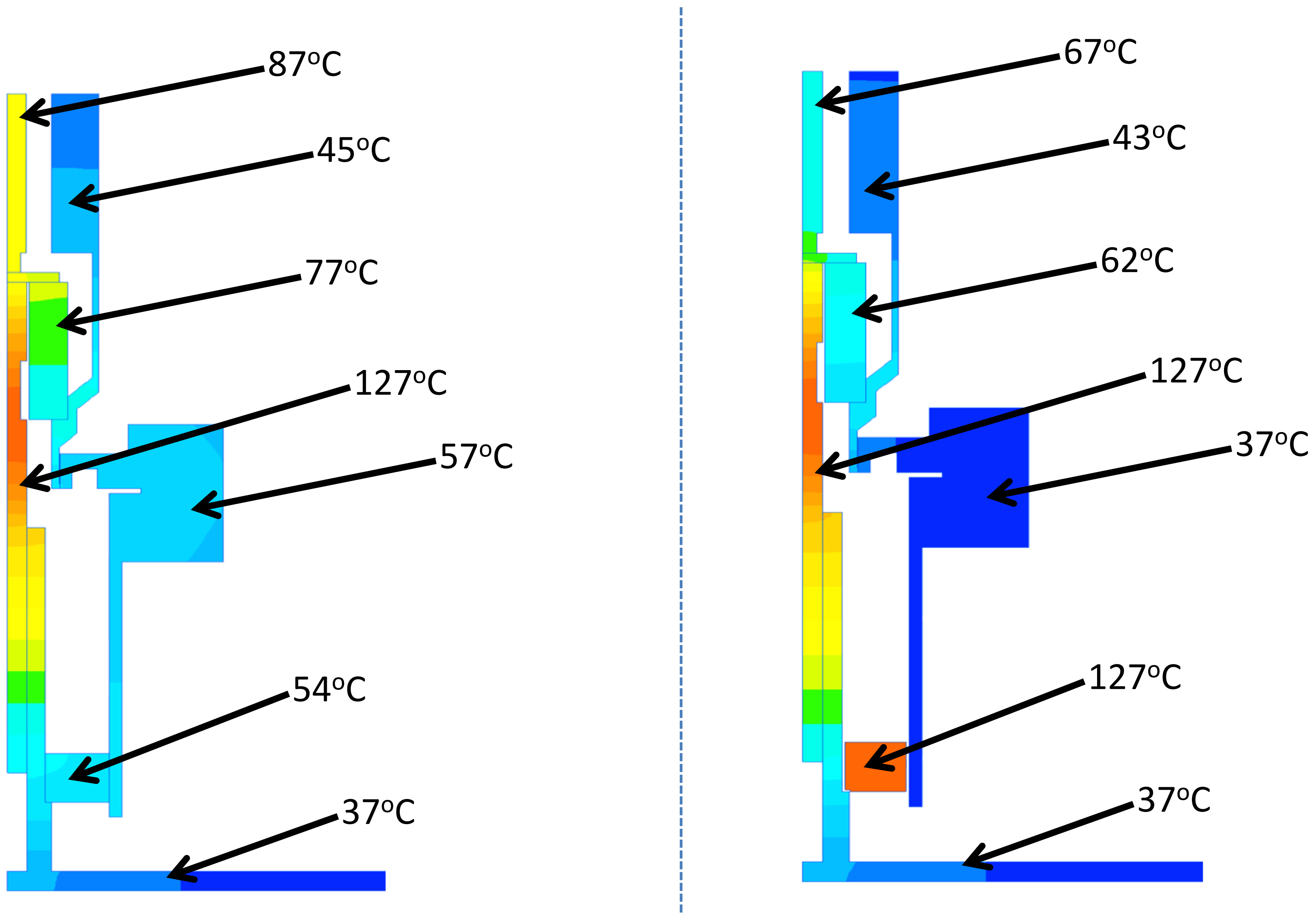

## Proposed running conditions

(500mA 686 bunch fill)

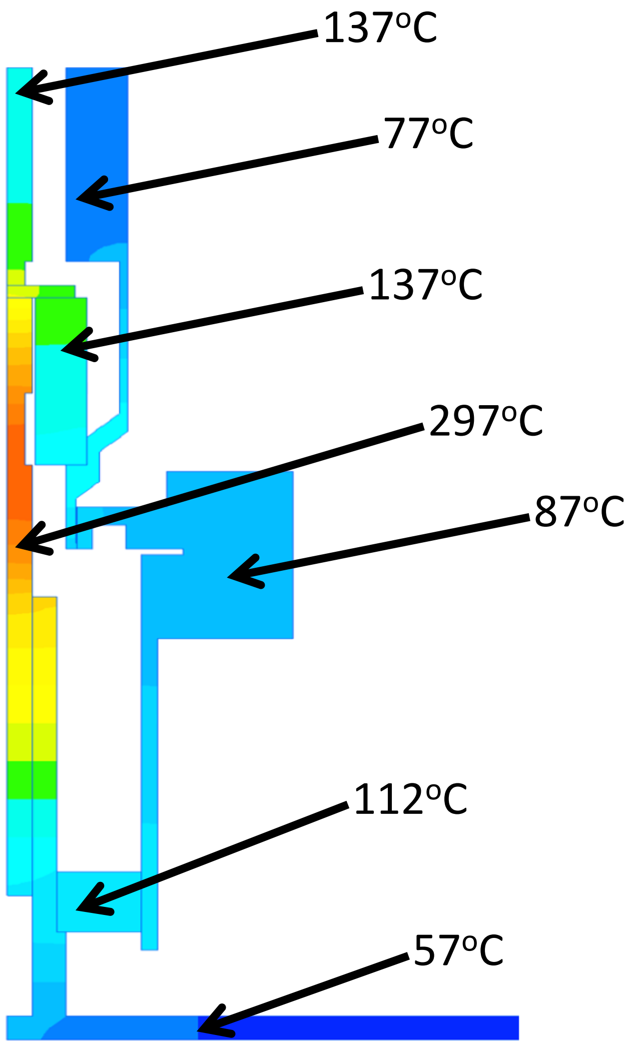


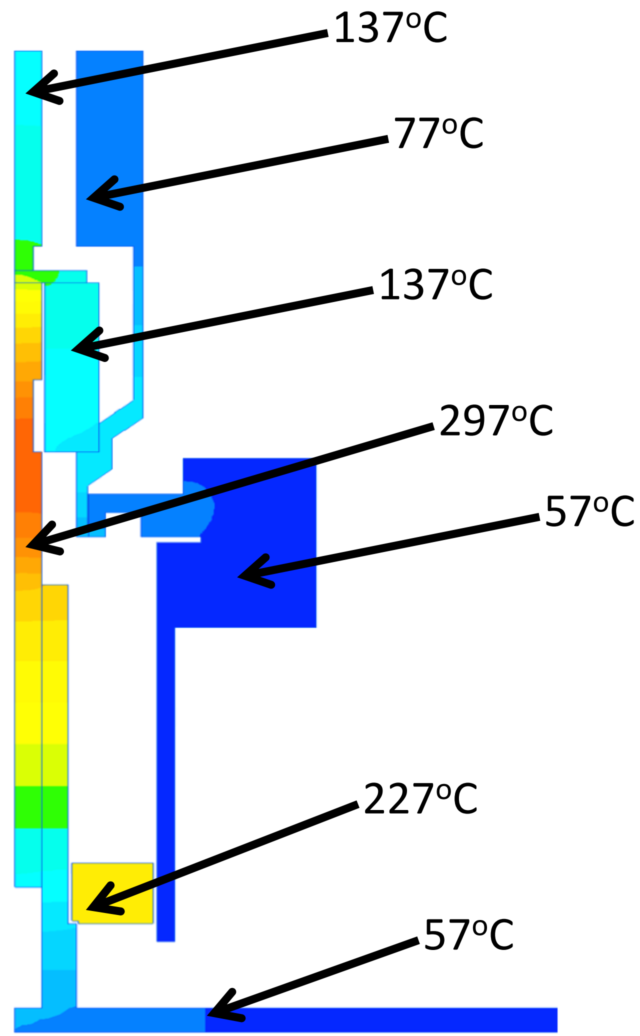

Beam loss 407W
Total structure loss 77.3W
3.1W not accounted for

# Thermal simulation 300mA

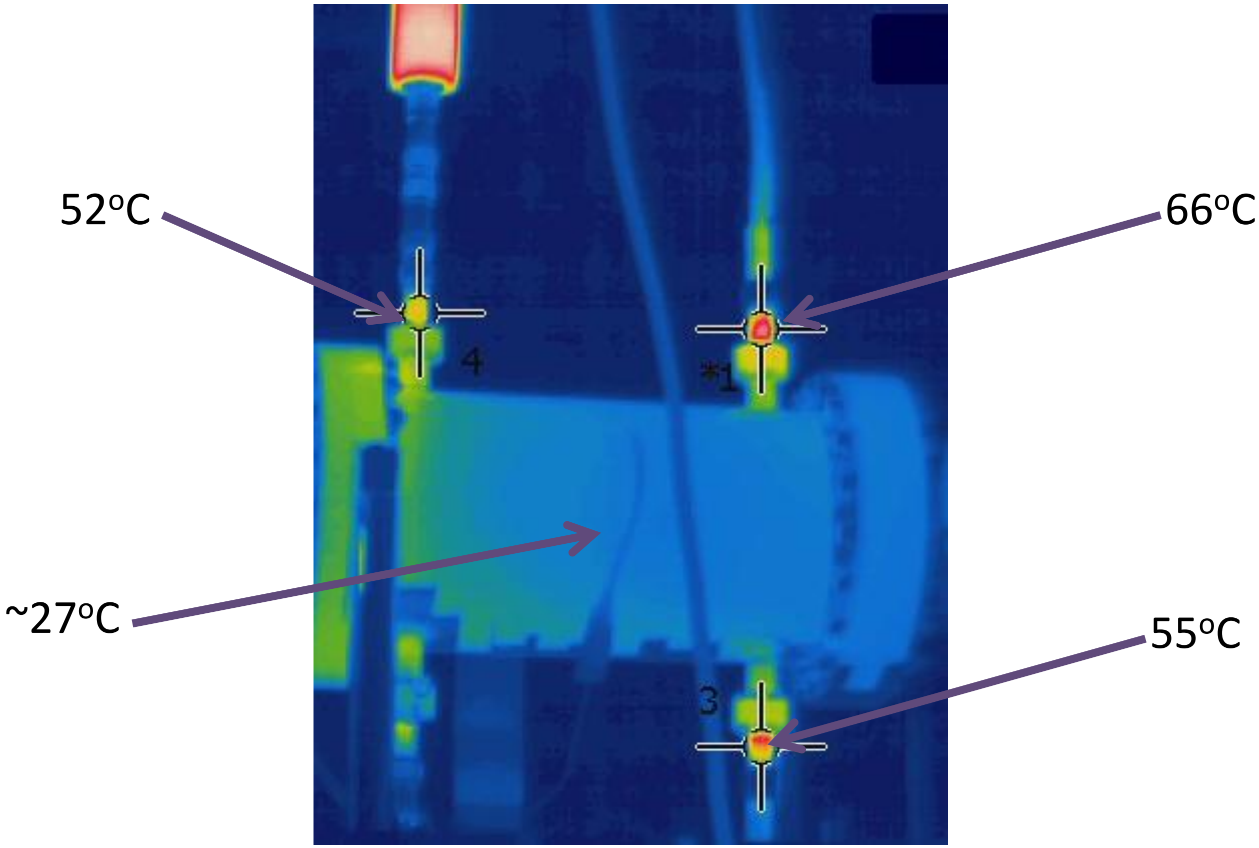


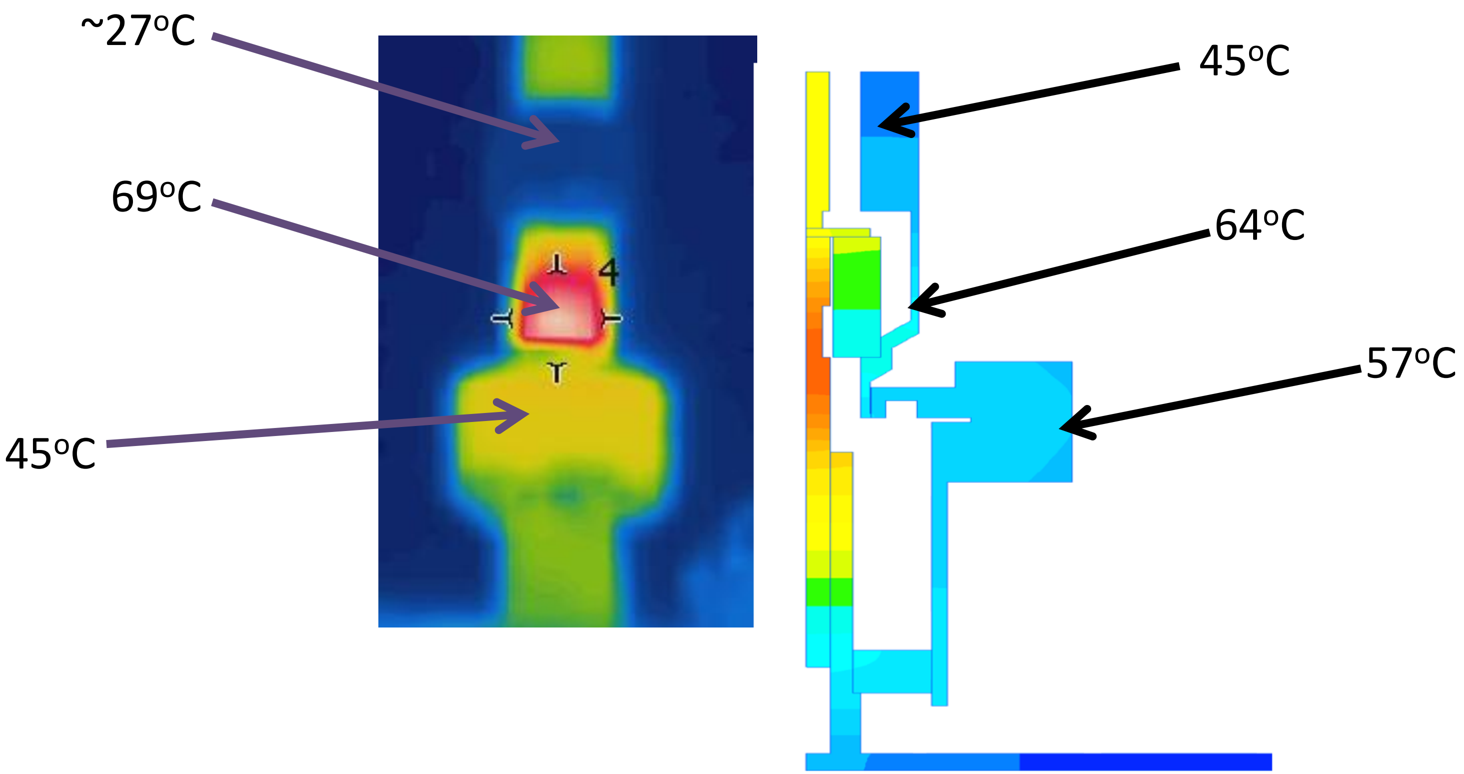
# Thermal simulation 500mA



# Comparison with real world data

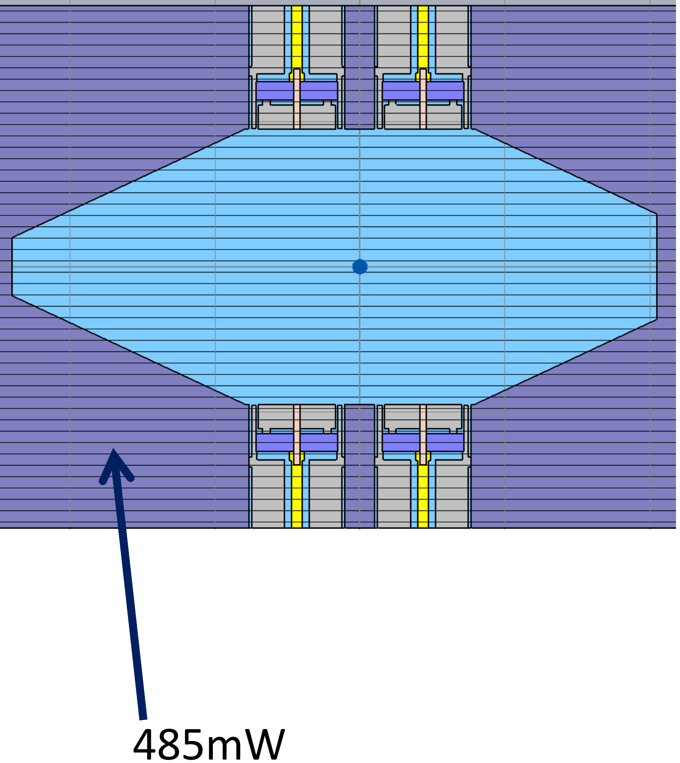


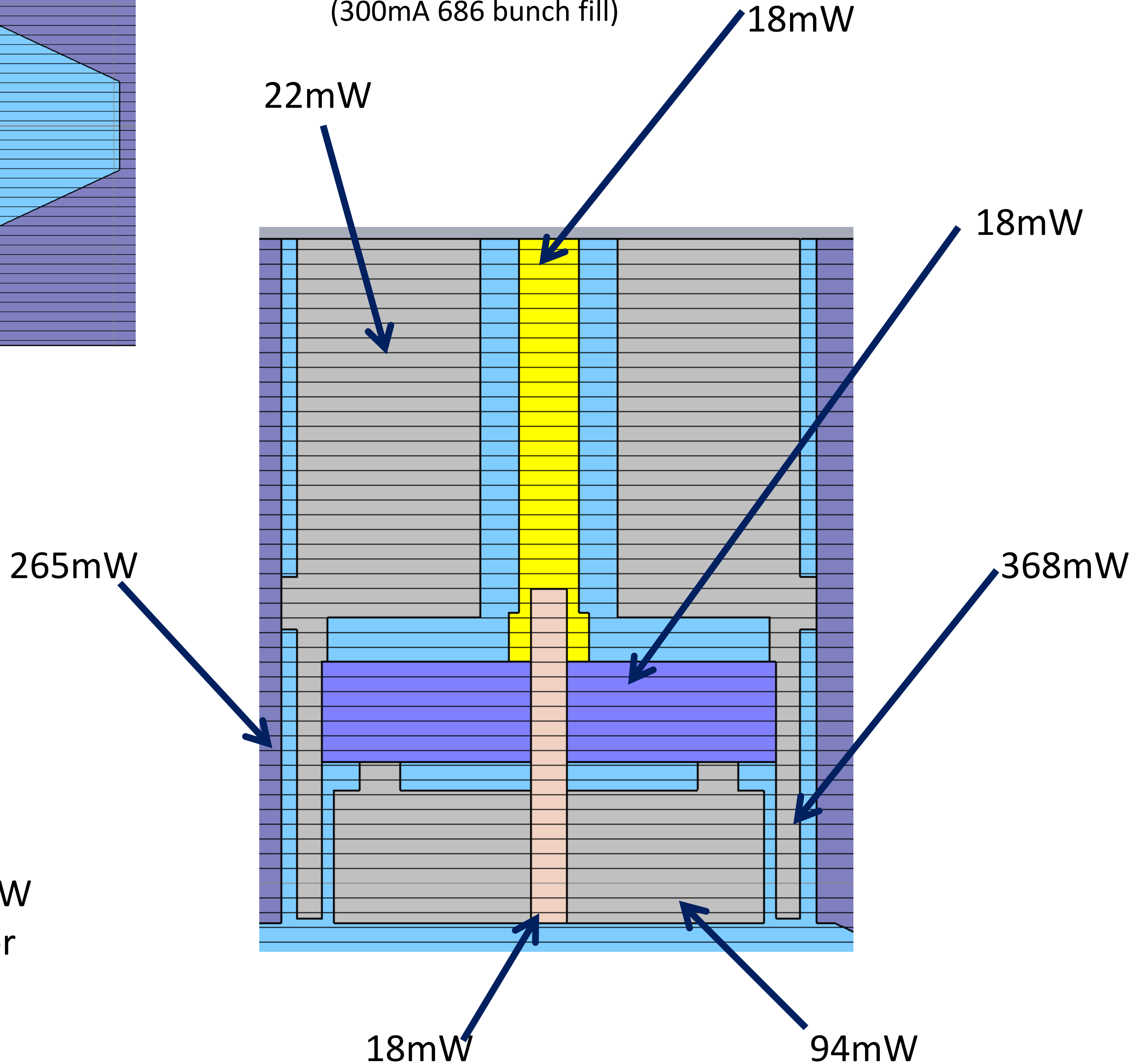

~27°C
69°C
45°C
45°C
64°C
57°C

Example:BPM

## Current running conditions

(300mA 686 bunch fill)

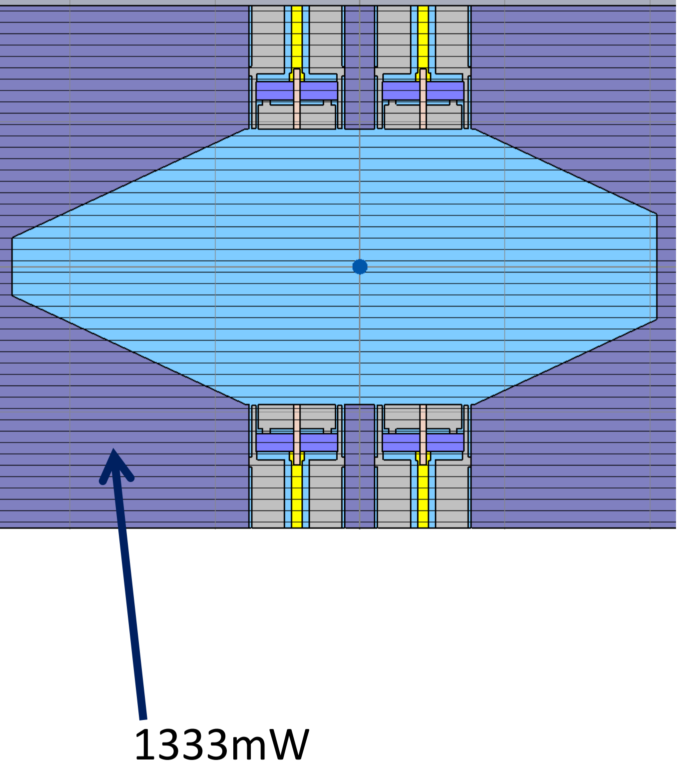


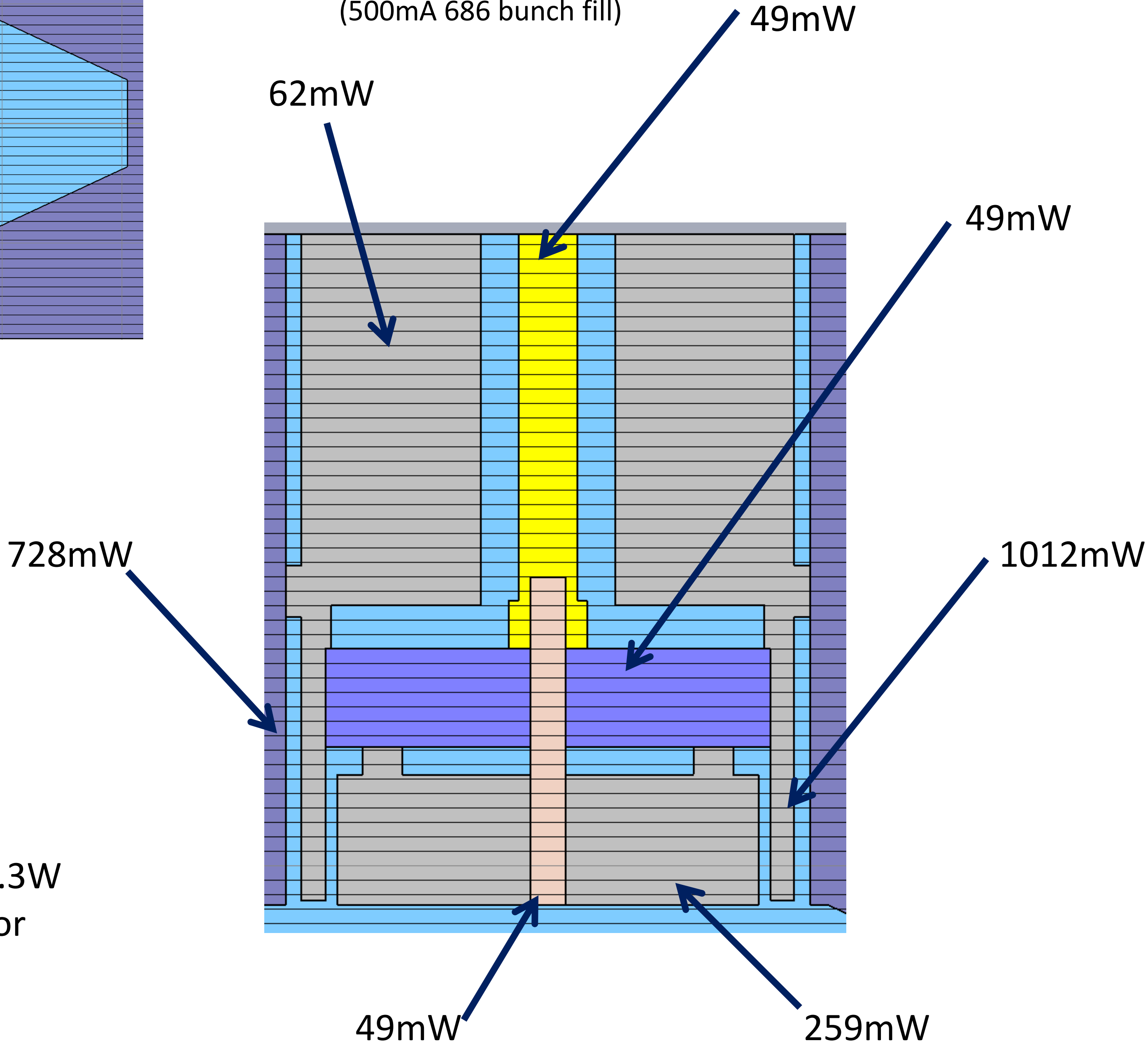




Beam loss 8.8W
Total structure loss 4.5W
0.8W not accounted for

**Proposed running conditions**

(500mA 686 bunch fill)



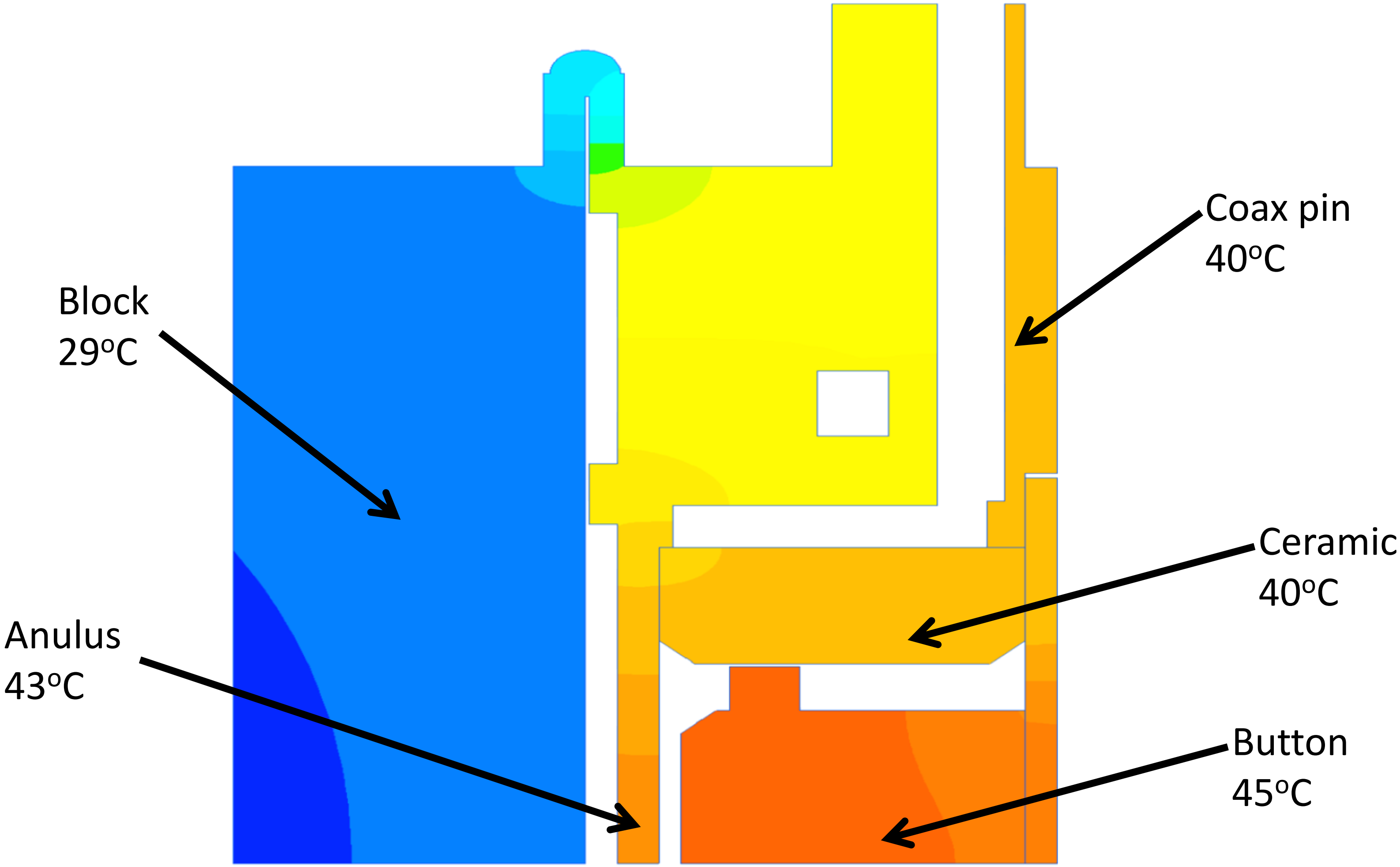




Beam loss 24.2W

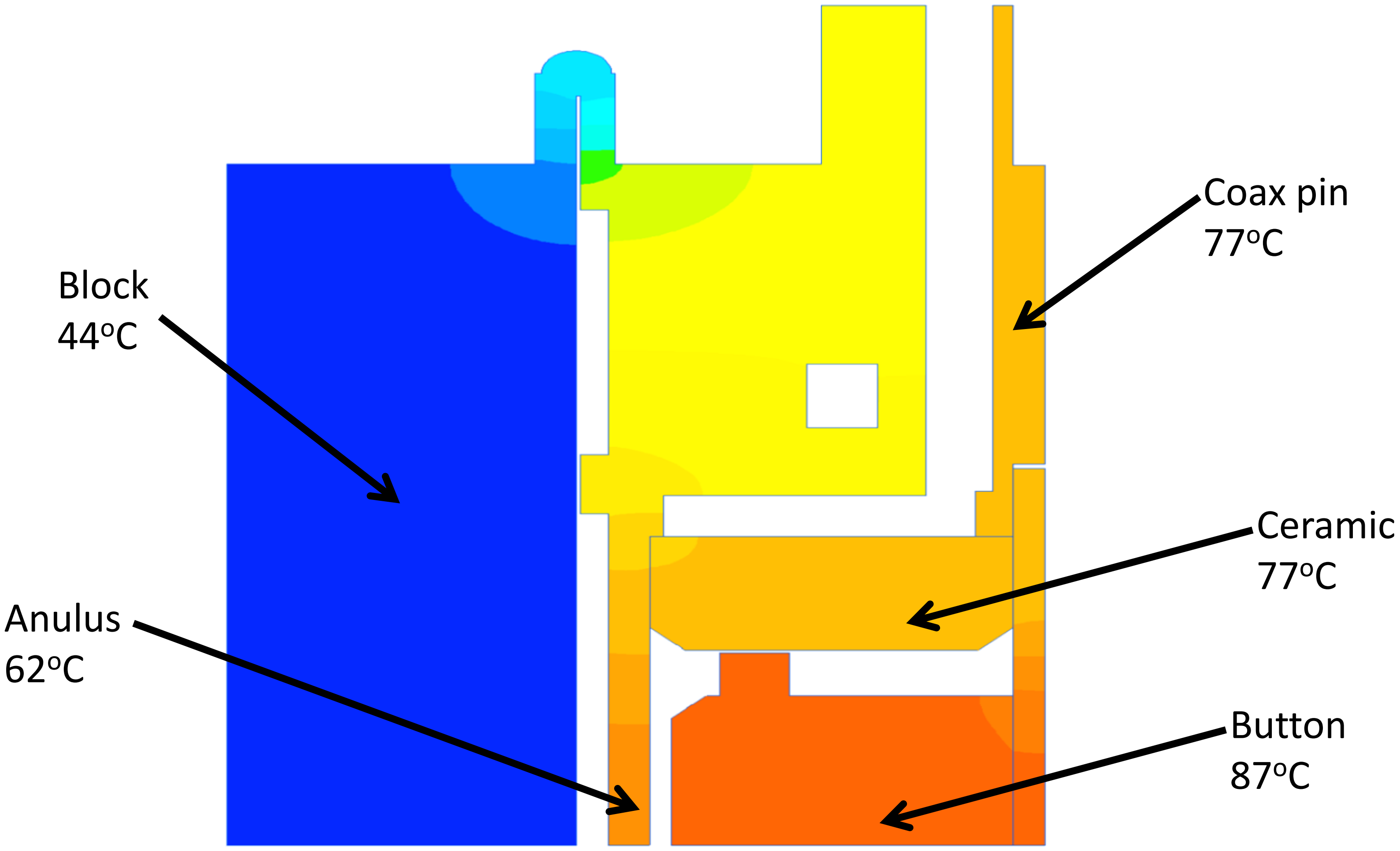
Total structure loss 12.3W

2.2W not accounted for

# Thermal simulation 300mA

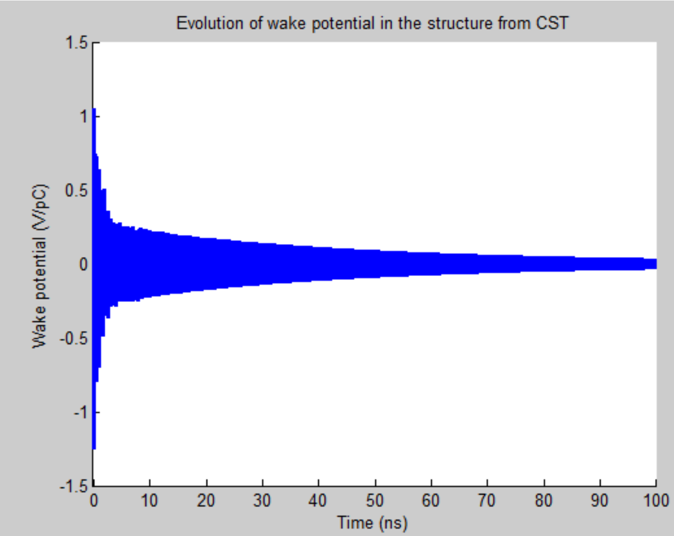


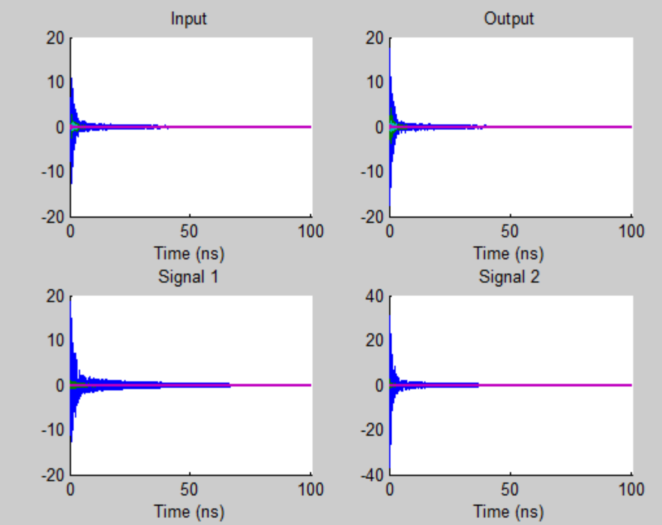
# Thermal simulation 500mA

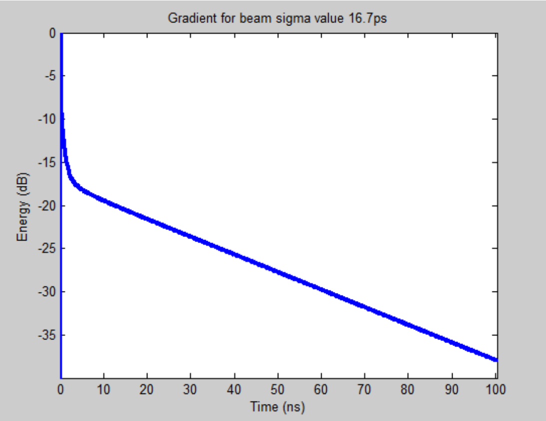


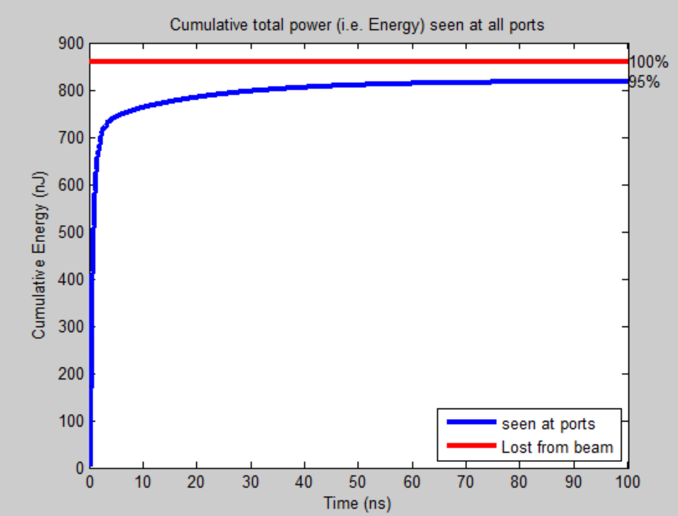
$K_{loss}$ = 858 mV/pC
Bunch length 5mm
Simulation time = 1h x4
16core 3.1GHz CPU 64GB ram, 128GB SSD

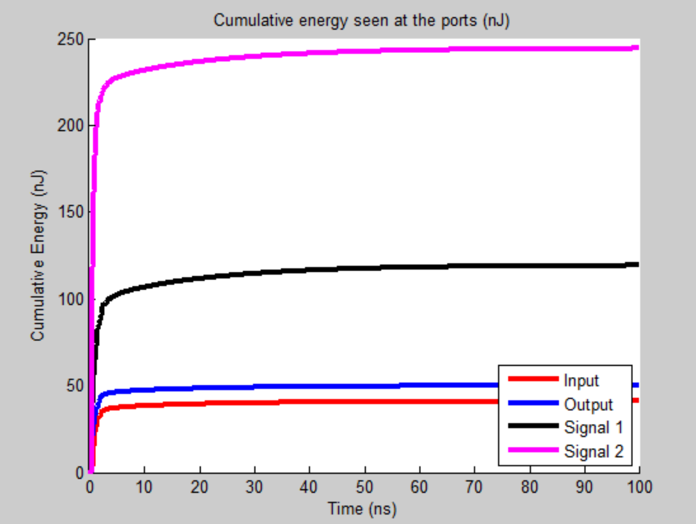
# 'Homework'



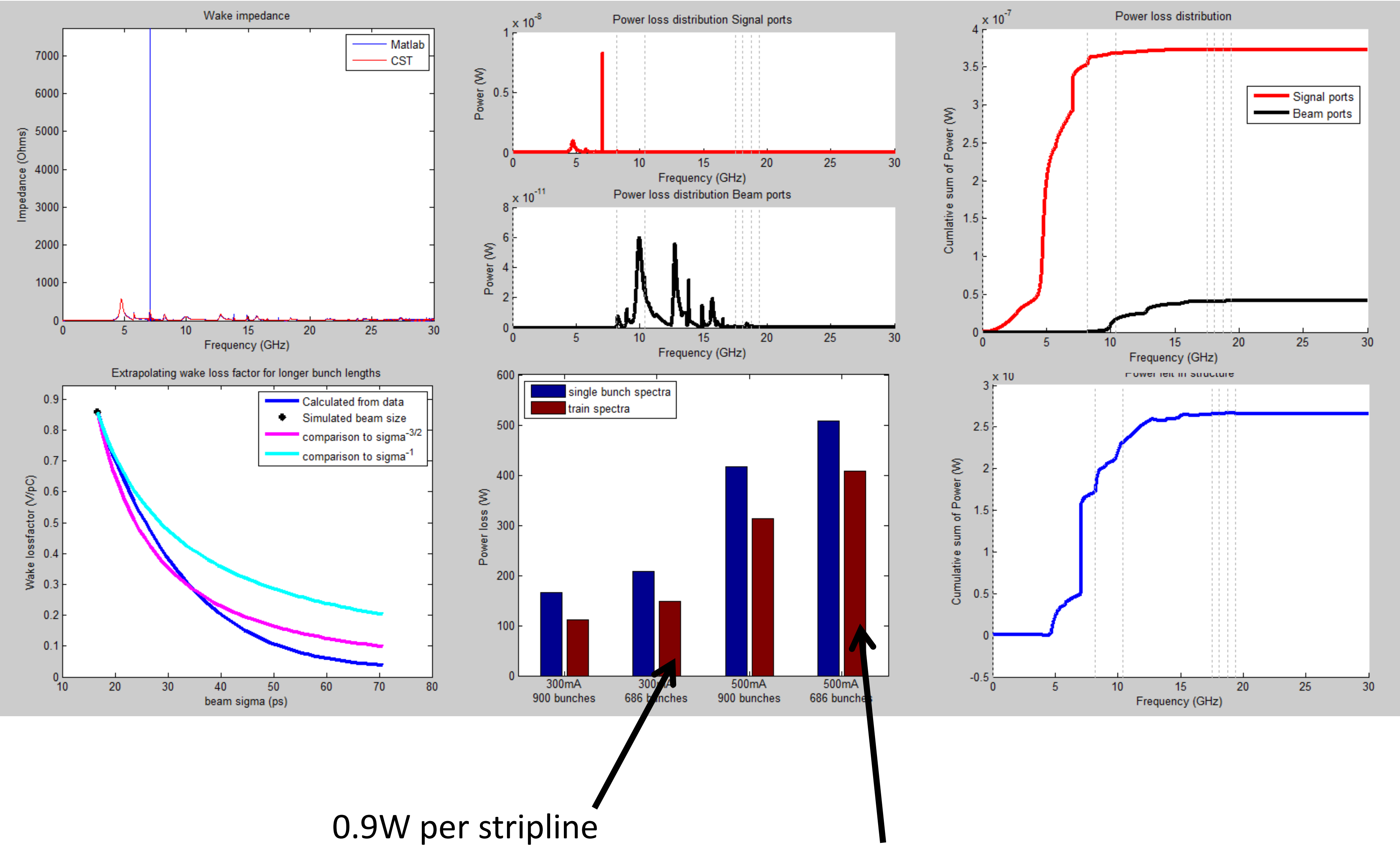




11% down the beam pipe
84% into the signal ports
5% left in structure

**Losses in structure**
25% Striplines
70% vessel
5% error




0.9W per stripline

2.5W per stripline

# Improvements to be done

- Combining all extensions
- Signal extensions – allows shorter simulations

- 3D thermal simulation

- More comparisons with real world data.
  - Thermal
  - Output signals

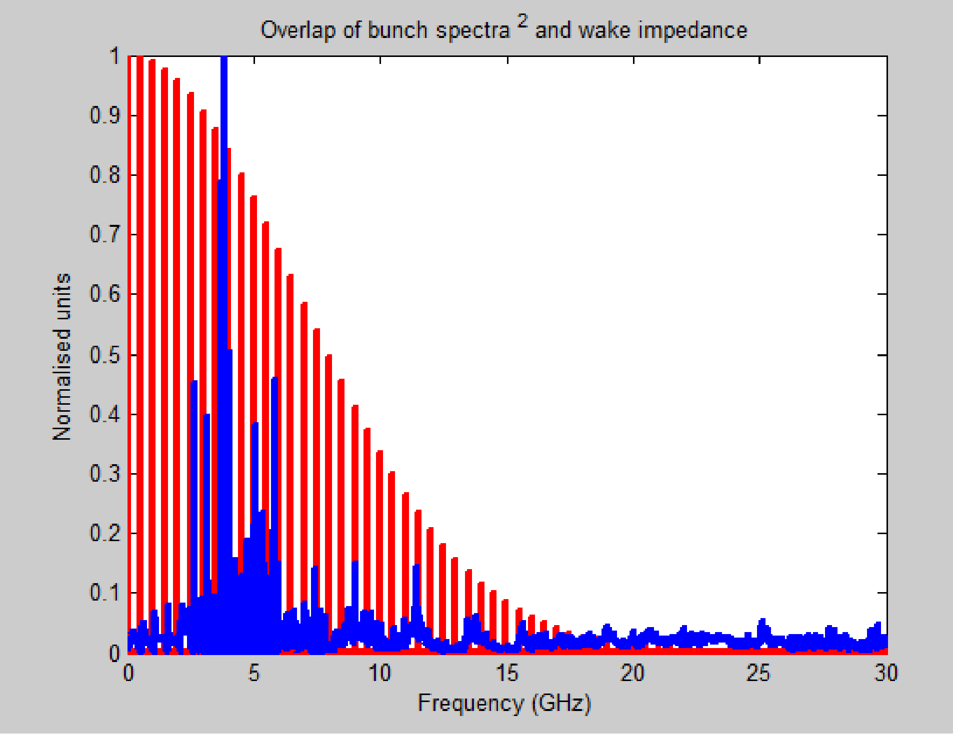
# Final thoughts

- For all the structures tested so far, a large fraction of the power is sent down the beam pipe. This will act as an additional heat load on nearby structures. Does this mean we should model adjacent models together?

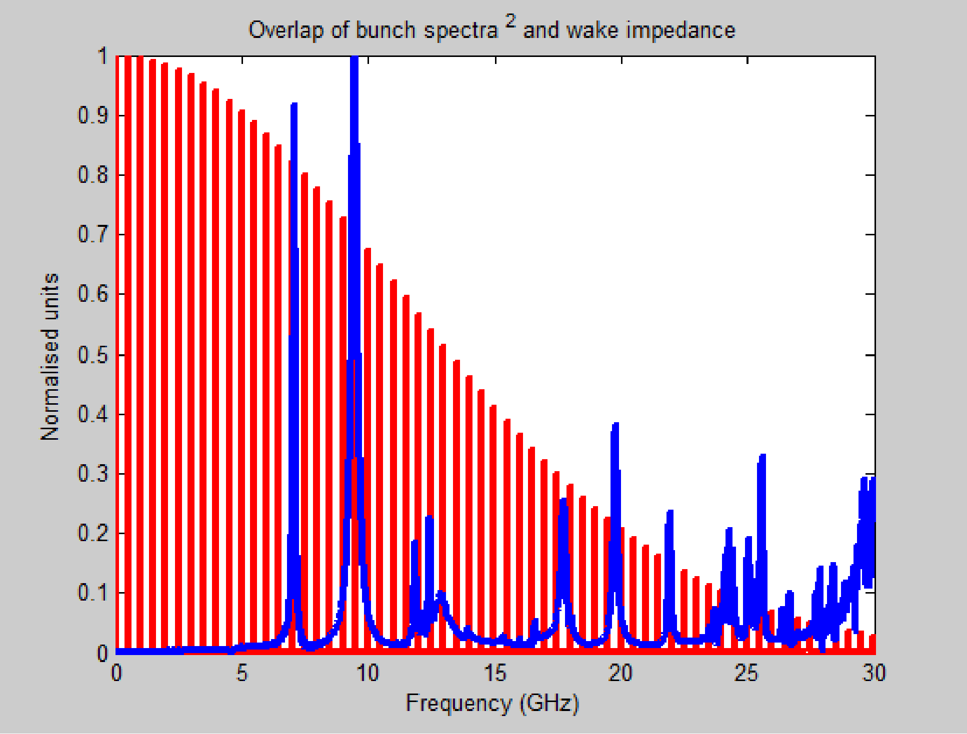
# Additional details

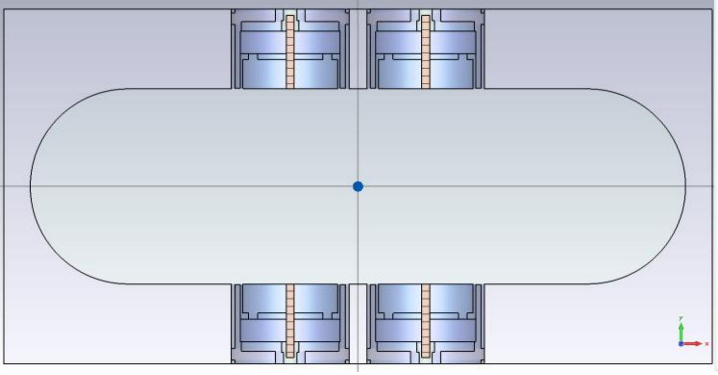
# Spectral overlap

Stripline




BPM

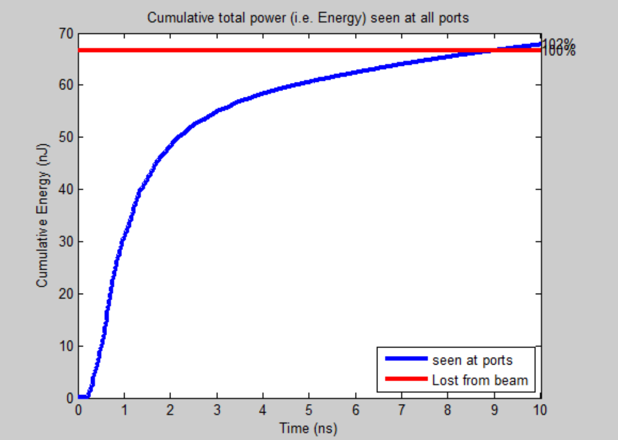


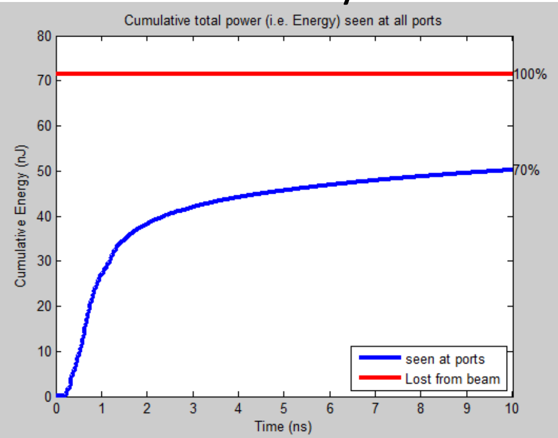


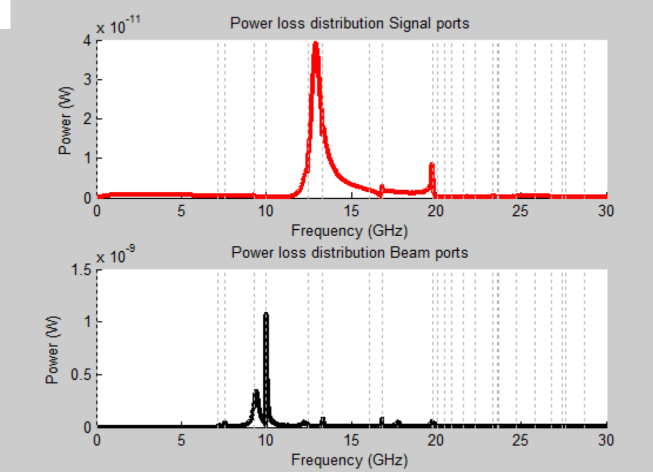
# Primary BPM

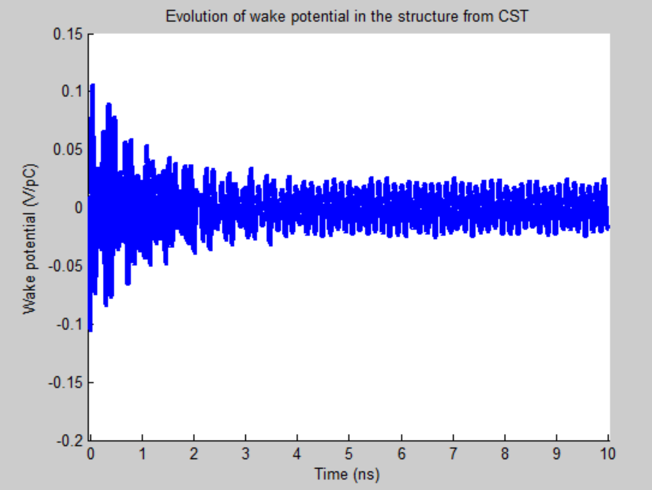
PEC

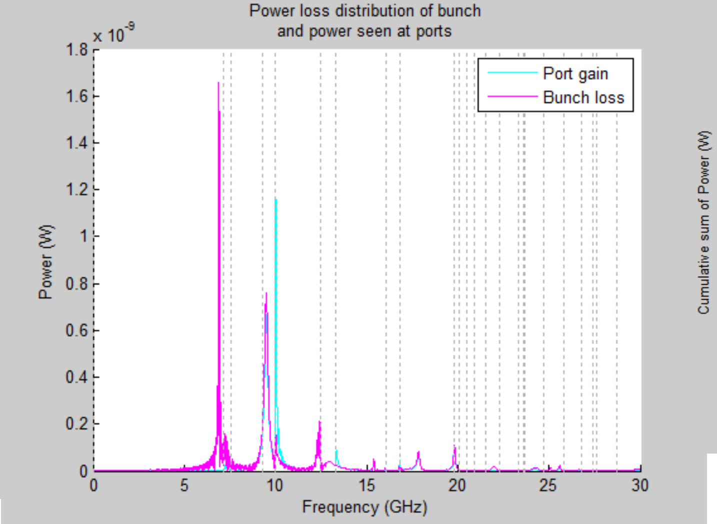
Lossy

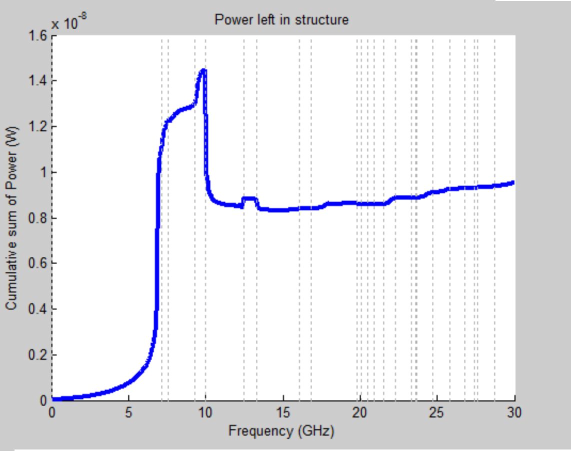


# Analysis details – Time domain

$$\text{normalised charge} = \frac{\text{Charge distribution data}}{\text{model charge}}$$

$$\text{wake loss distribution} = \text{normalised charge} * \text{Wake Potential}$$

$$\text{wake loss factor} = -\sum_{\text{time}} \text{wake loss distribution} * \text{time step size}$$

$$\text{loss from bunch} = \text{wake loss factor} * \text{model charge}^2$$

- Port signals

$$\text{energy}_{ports,modes} = \sum_{\text{time}} \text{signals}^2_{ports,modes} * \text{time step size}$$

- By using a cumulative sum one can see the evolution of the power deposition (does it all get dumped quickly, or in a more gradual way).

$$\text{fractional loss down the beam pipe} = \frac{\text{port1 energy} + \text{port2 energy}}{\text{loss from beam}}$$

# Analysis details – Frequency domain

- Zero pad in time domain
- FFT time data

$$\text{bunch spectra} = \frac{FFT(\text{charge distribution})}{\text{number of sample points}}$$

$$\text{FFT of scaled wake potential} = \frac{FFT(\text{Wake Potential} * \text{model charge})}{\text{number of sample points}}$$

$$\text{Wake Impedance} = -\Re\left(\frac{\text{FFT of scaled wake potential}}{\text{bunch spectra}}\right)$$

$$\text{bunch power} = \sum_{\text{frequency}} \left(|\text{bunch spectra}|^2 * \text{Wake Impedance}\right)$$

- Zero the wake impedance when the power in the bunch is small.

(combats numerical noise).

$$\text{energy for 1 bunch} = \text{bunch power} * \text{simulation time}$$

$$\text{wake loss factor} = \frac{\text{energy for 1 bunch}}{\text{model charge}^2}$$

- Using the ports

$$\text{Total power spectrum} = \sum_{\text{port}} \sum_{\text{mode}} |FFT(\text{port signals})|^2$$

$$\text{Total power from all ports} = \sum_{\text{time}} |\text{Total power spectrum}|$$

# Machine parameters to bunch parameters

$$\text{bunch charge} = \frac{\text{beam current}}{\frac{1}{\text{pulse gap}} * \frac{\text{fill pattern}}{936}}$$

$$\sigma = 3.87 + 2.41\left(\frac{\text{beam current}}{\text{fill pattern}}\right)^{0.81}\sqrt{\frac{2.5}{\text{RF Volts}}}$$

# Pulse equations

**Single pulse**

$$\text{pulse} = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\text{Wake Potential timescale}^2}{2\sigma^2}} \text{model charge}$$

**Train**

$$\text{pulse} = \sum_{n=1}^{N} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\text{Wake Potential timescale} + (\text{gap} * \text{n}))^2}{2\sigma^2}} \text{model charge}$$