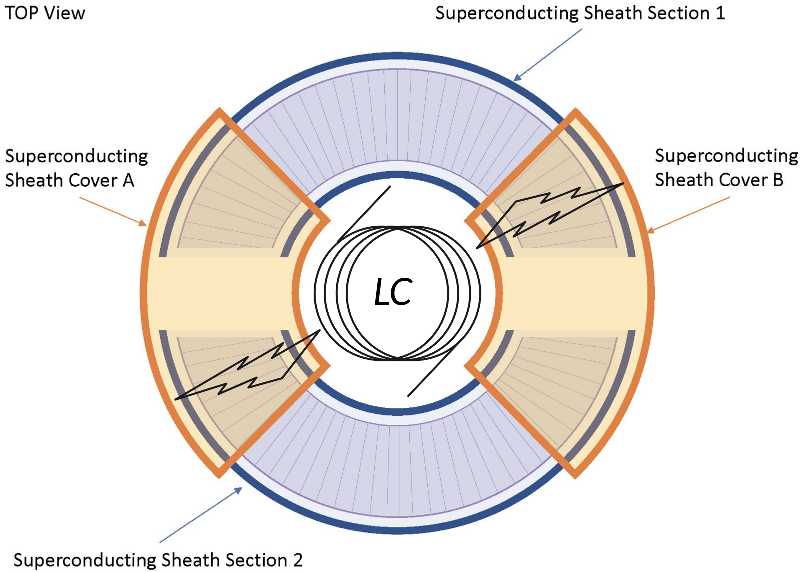
EM losses in sheath & magnet

DM Radio collaboration meeting 08/13/2020
Alex Droster, (soon-to-be) 3rd year grad student @UC Berkeley

Background



- Pick up loop in the center will sample lossy material in the sheath
- How much? What designs can mitigate this?
- Simulations with Ansys HFSS

Simulation campaign

- Pickup resonator modeling (Joe Singh)
  - Circuit model parameters, optimization of coupled energy
- Sheath Inductance (Chiara Salemi, Nicholas Rapidis)
  - COMSOL modeling to calculate sheath inductance, optimization of available energy
- Sheath RF modeling (me, Alex Droster)
  - HFSS simulations of TEM + TE + TM modes within sheath, lossy materials within sheath, parasitics
- Magnet (Alex Sebastian Leder)
  - OPERA simulations of DC magnetic field profiles, fringe fields
- Thermal (Maria Simanovskaia)
  - Ansys and COMSOL modeling of mandrel cooling, thermal design, cooldown time

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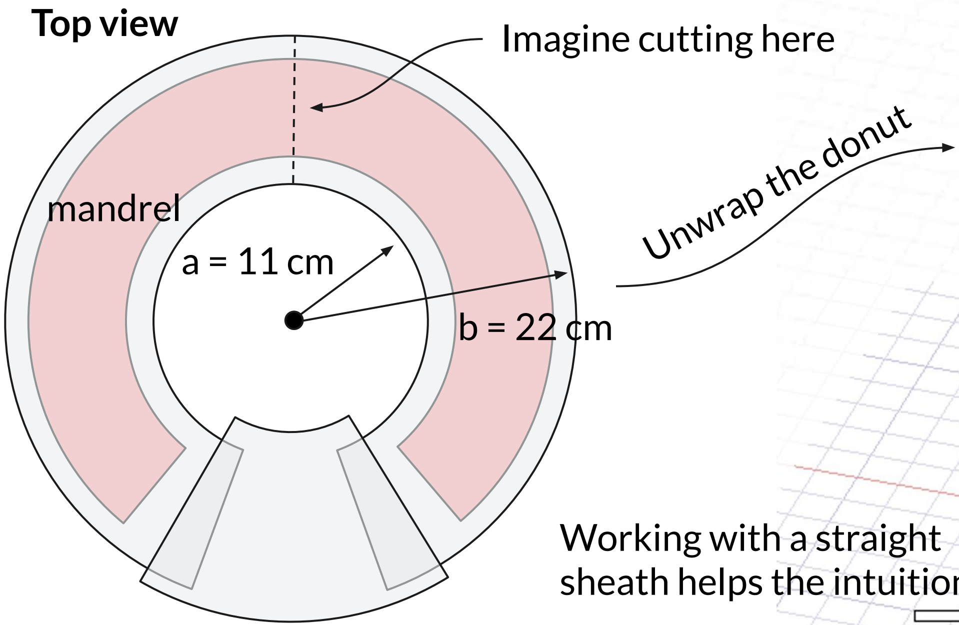
Losses in any given design inform end-to-end sensitivity

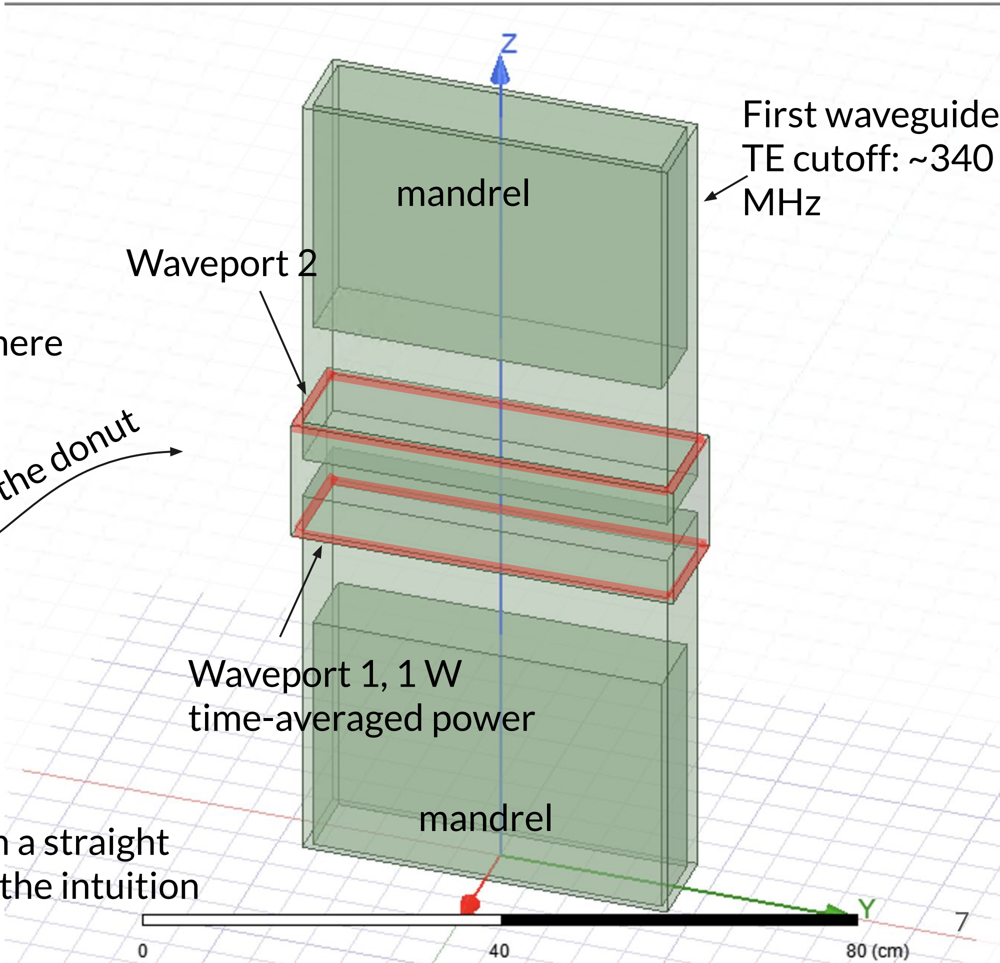
Sheath RF simulations in HFSS inform: magnet dimensions in OPERA sims, Sheath dimensions in COMSOL sheath inductance sims, coupled energy in pickup resonator modeling...

What is loss in a material?

- Loss refers to energy dissipated into a material ("lossy medium") in the form of heat
- In the quasi-static limit, loss in a conductor is due to magnetic fields
  - Surface currents/"Eddy currents" create loss due to Ohmic heating: $P_{loss}=(1/2\sigma\delta)\int|n\times H_t|^2dS$
- There are a handful of ways to calculate loss in HFSS-- I've spent a lot of time validating them!
- The magnet mandrel (metal "frame" around which the wires are wound) is not superconducting, therefore it is lossy.

Unwrapped sheath

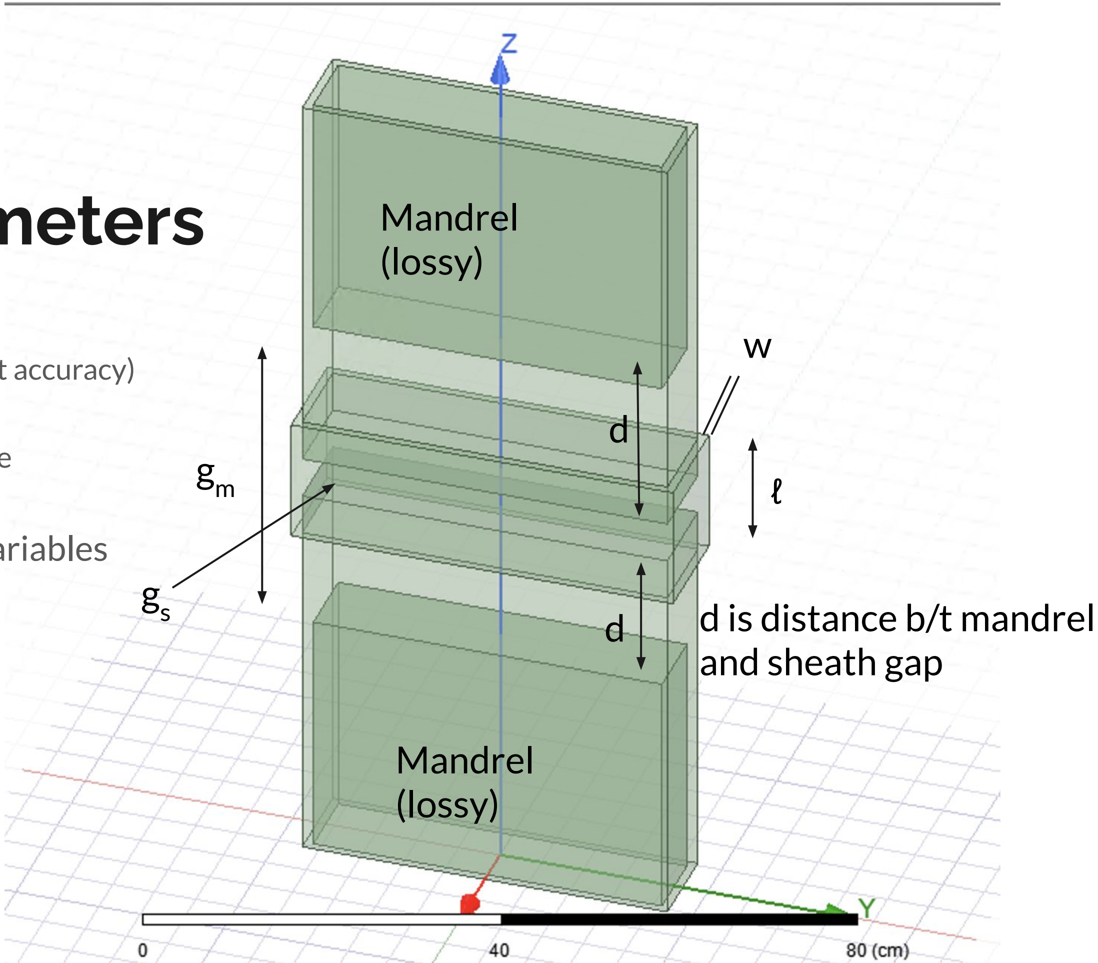




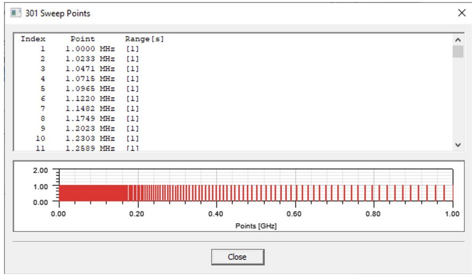
Working with a straight sheath helps the intuition

Simulation parameters

- Solver type: Driven Modal
  - Discrete solver (slowest but best accuracy)
- Frequencies: 1 MHz - 200 MHz
  - Log steps; 100 steps each decade
- 1 W input power on waveport 1
- Parametric sweep of geometric variables



Log distributed frequency steps



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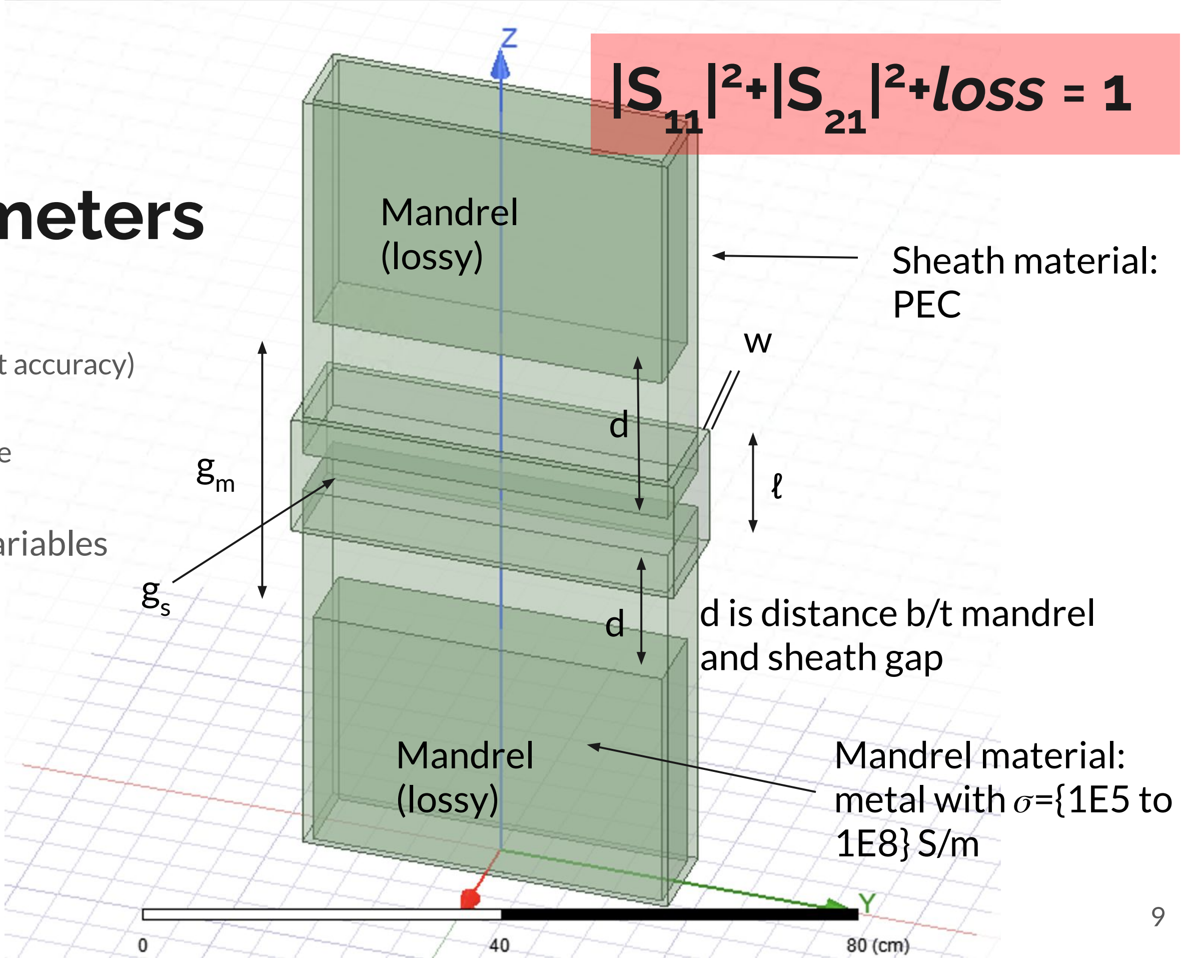
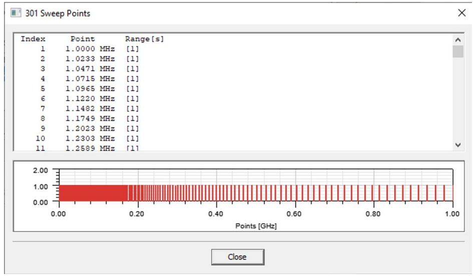
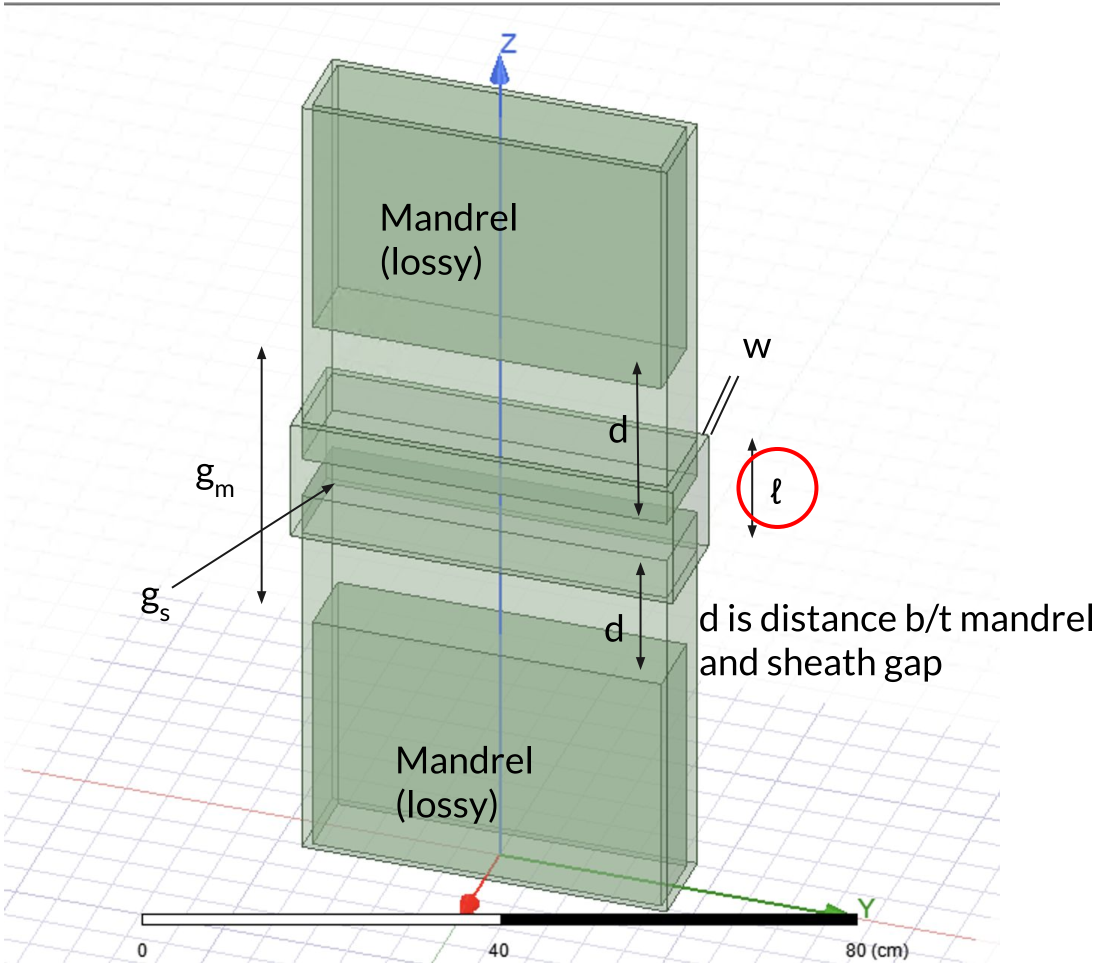
$$|S_{11}|^2+|S_{21}|^2+\mathit{loss} = 1$$



Log distributed frequency steps



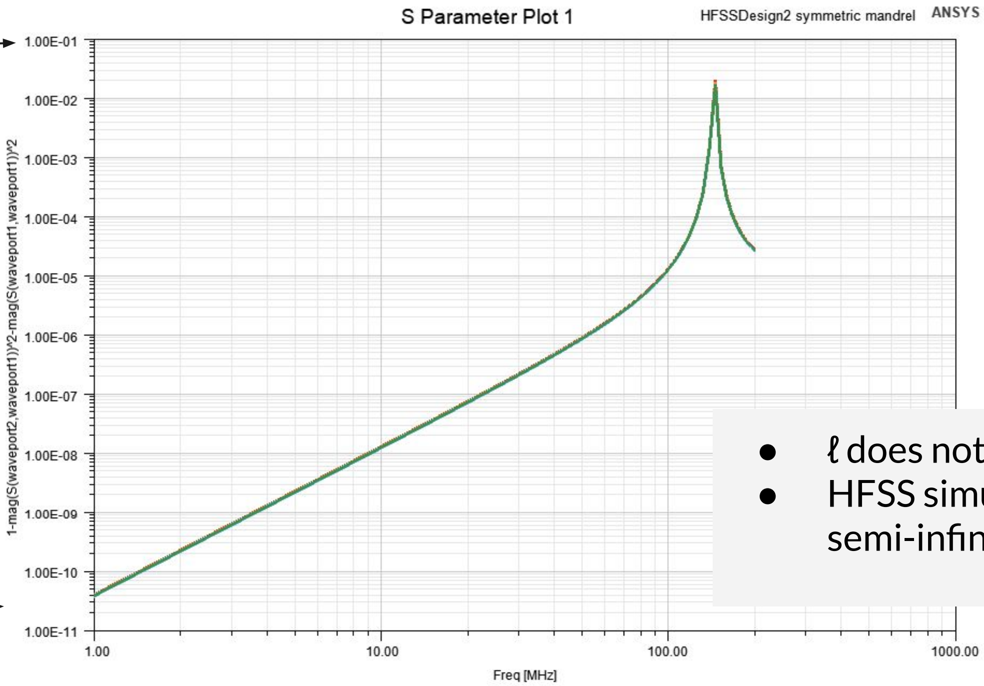

Z
Mandrel
(lossy)
w
d
ℓ
g_m
g_s
d
d is distance b/t mandrel
and sheath gap
Mandrel
(lossy)
Y
0
40
80 (cm)

Loss as a function of frequency and ℓ

High loss

Low loss

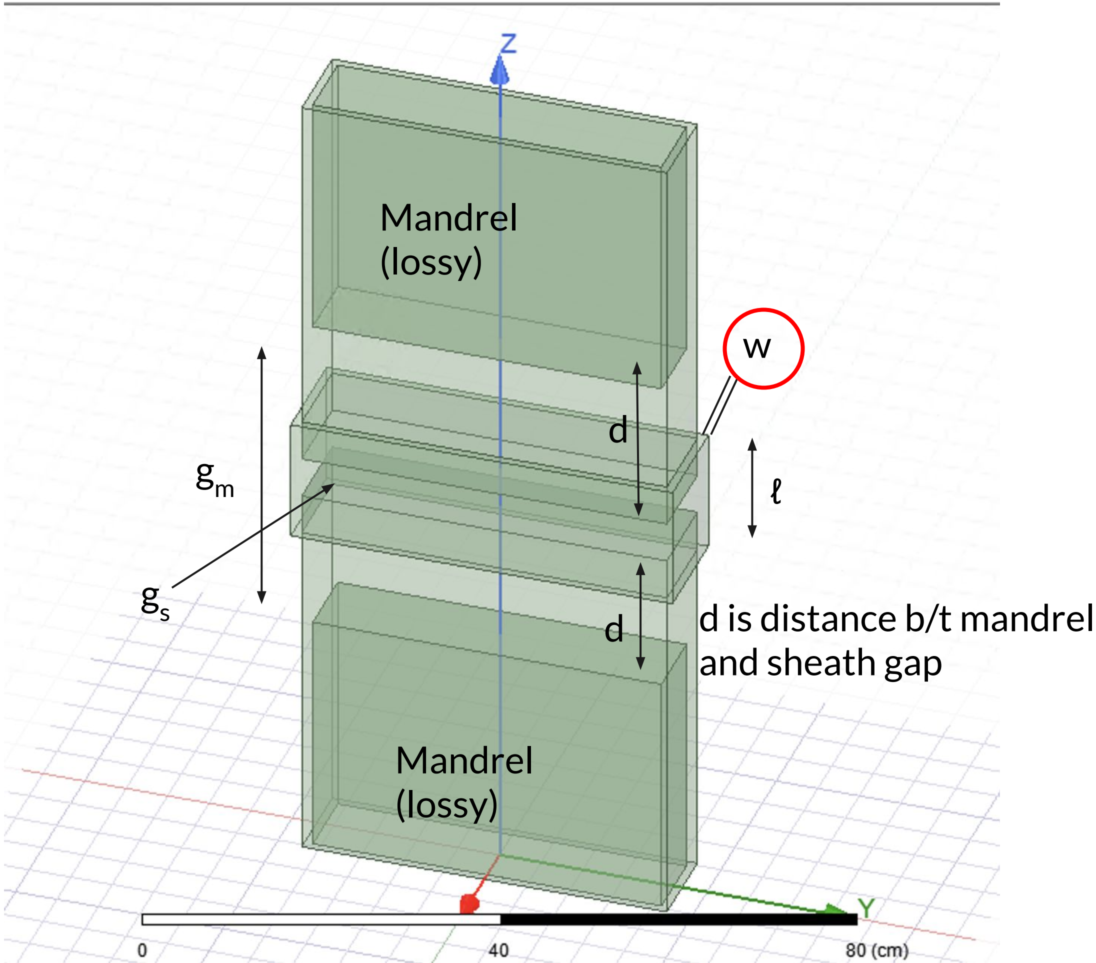
Loss [Watts]



ℓ = 2.5 cm

ℓ = 7.5 cm

- ℓ does not affect loss
- HFSS simulates waveports as attached to semi-infinite waveguides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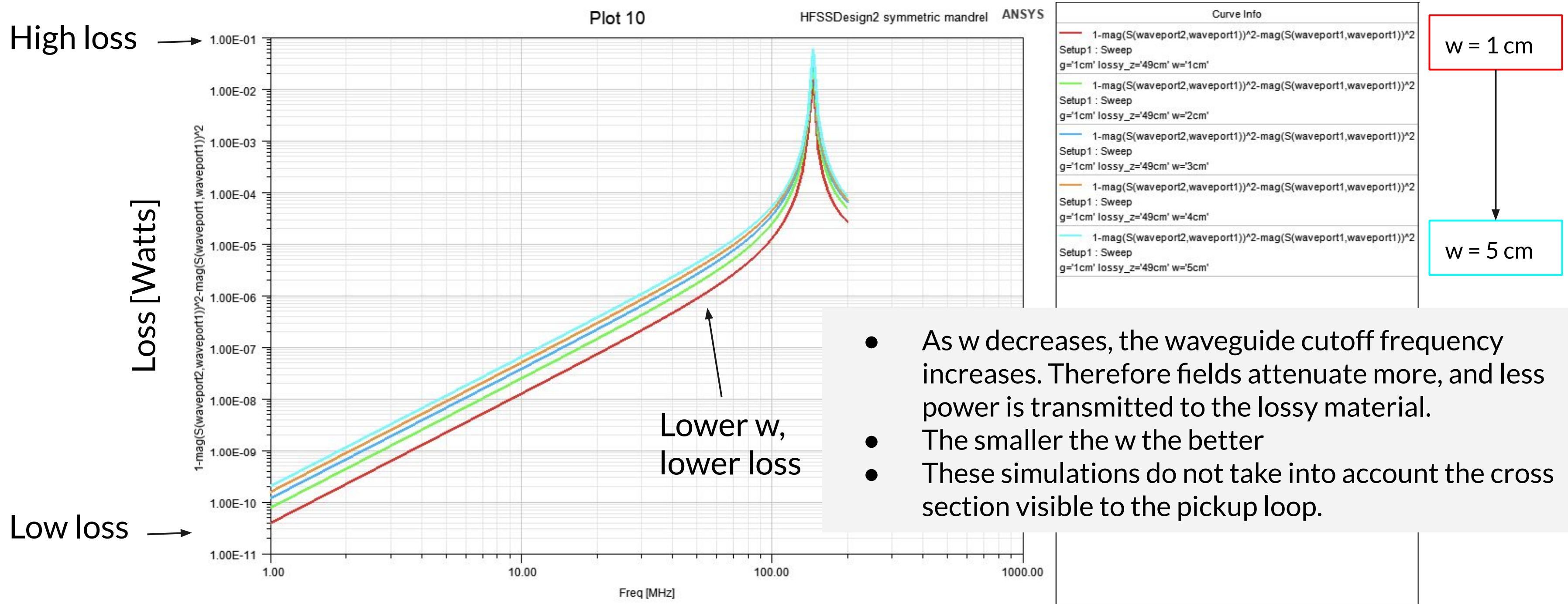
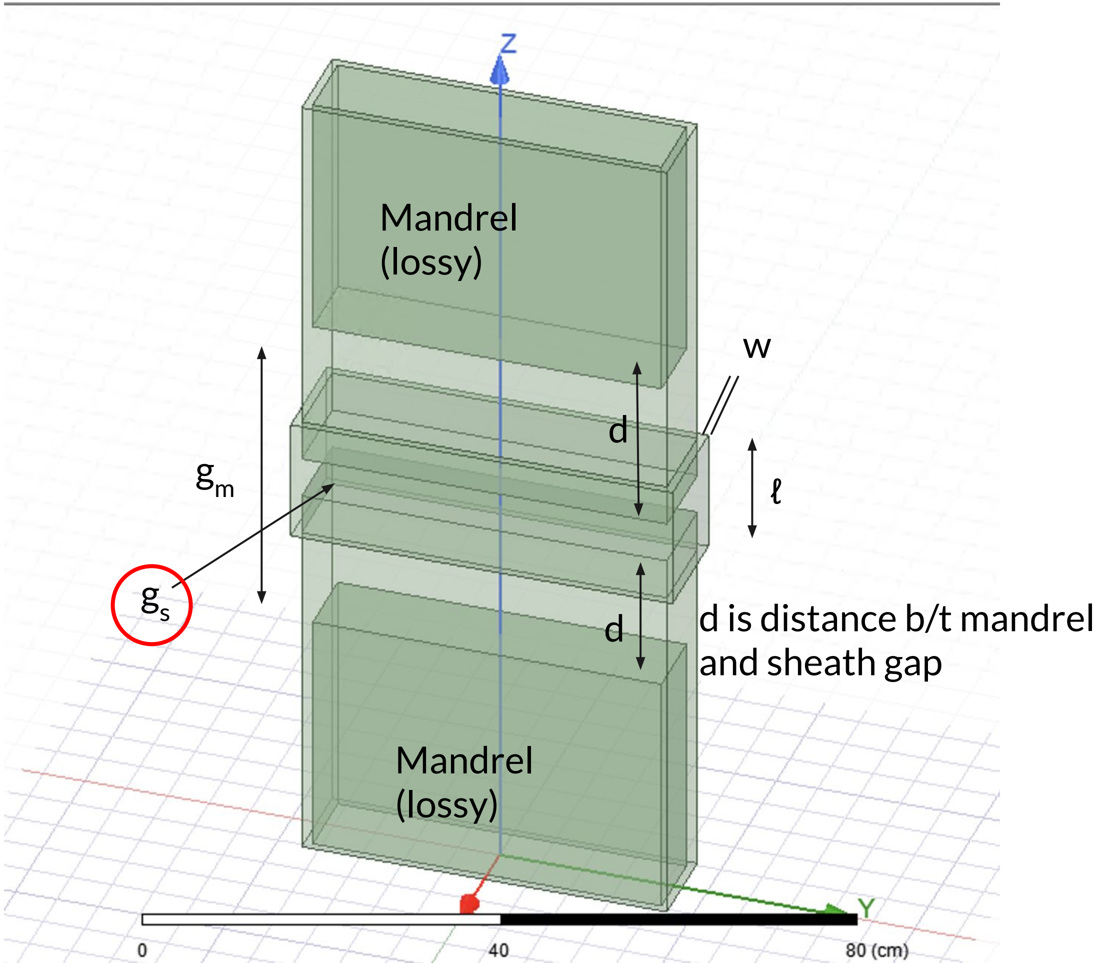
Y
0
40
80 (cm)

Loss as a function of frequency and w



- As w decreases, the waveguide cutoff frequency increases. Therefore fields attenuate more, and less power is transmitted to the lossy material.
- The smaller the w the better
- These simulations do not take into account the cross section visible to the pickup loop.



Z
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w
d
g_m
ℓ
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d is distance b/t mandrel
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Mandrel
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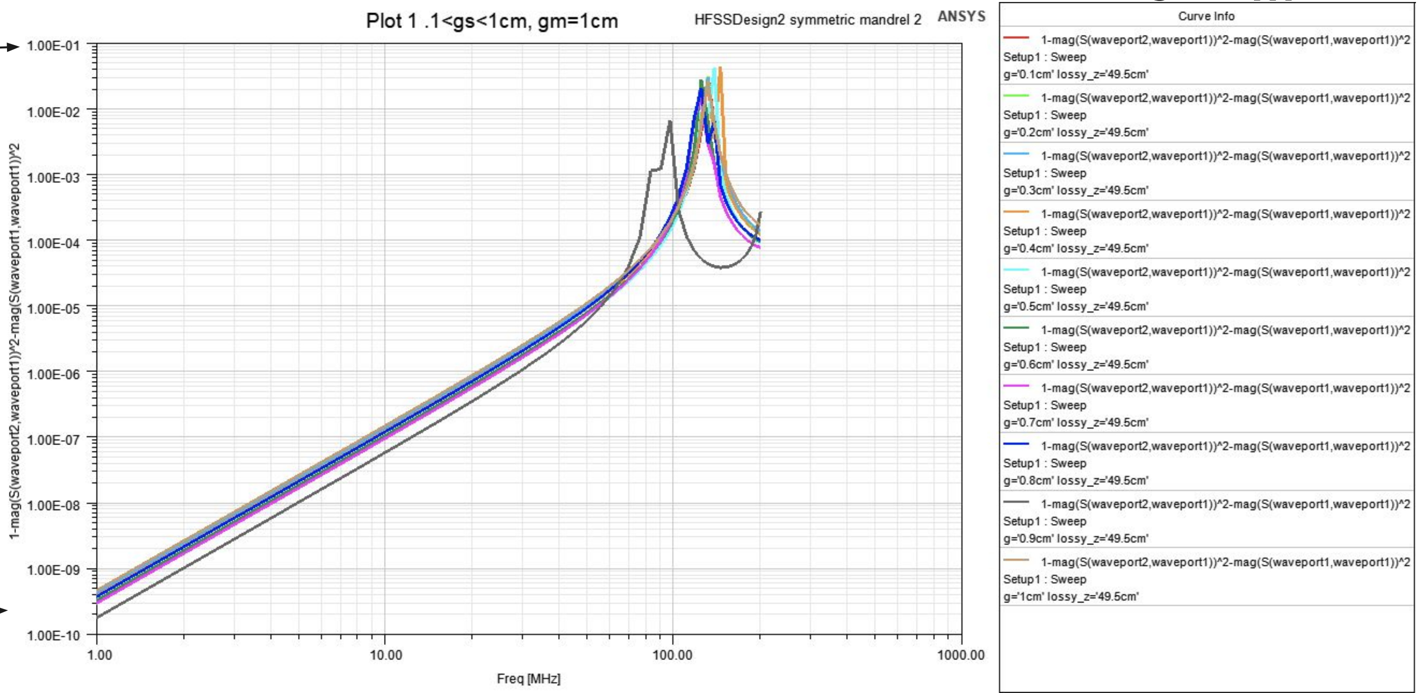
Y
0
40
80 (cm)

Loss as a function of frequency and g_s (g_m=1 cm)

High loss

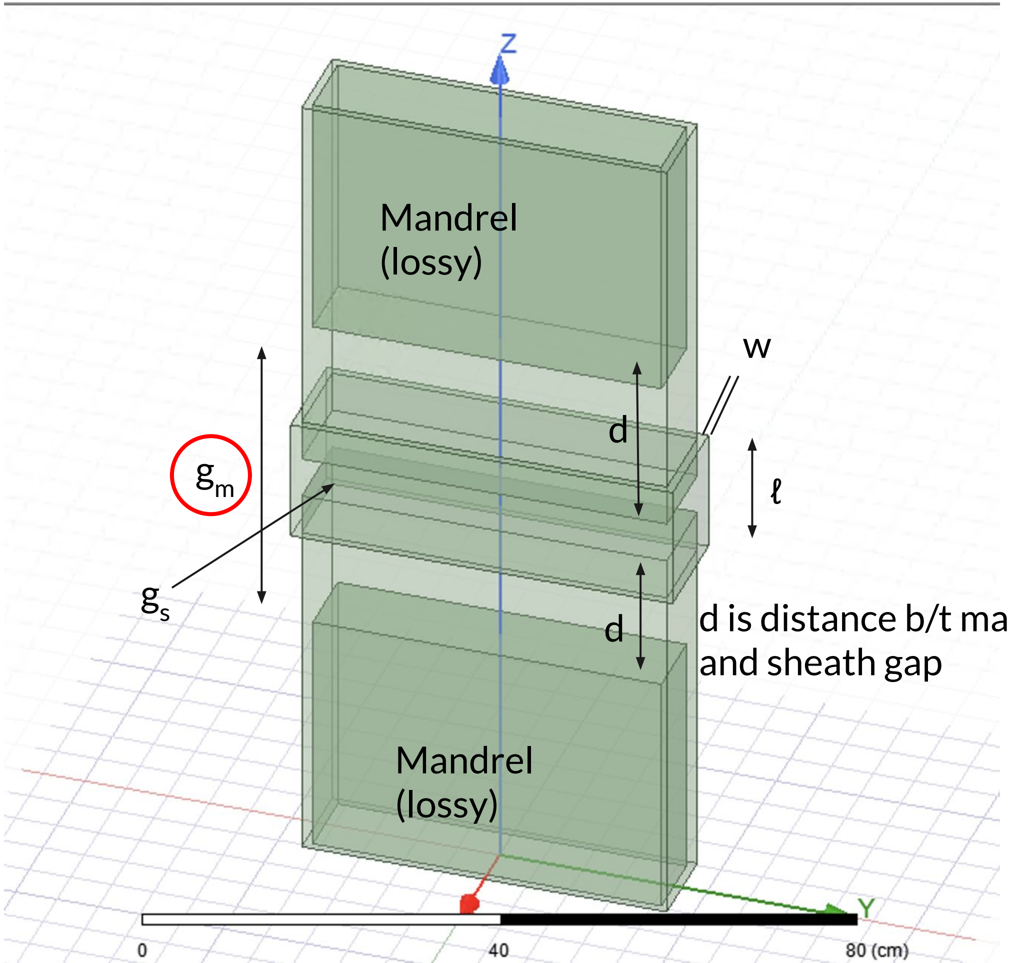
Low loss

Loss [Watts]



g_s = 0.1 cm

g_s = 1 cm



Z
Mandrel
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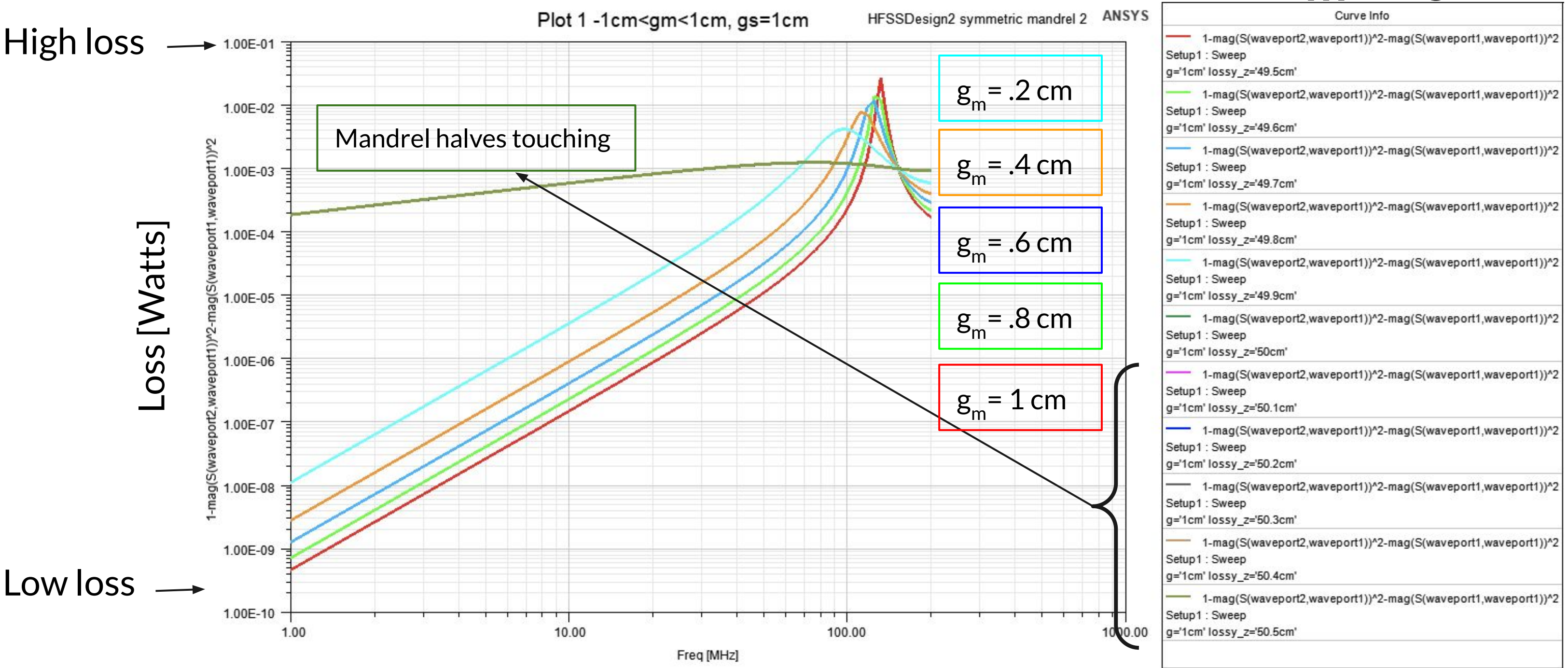
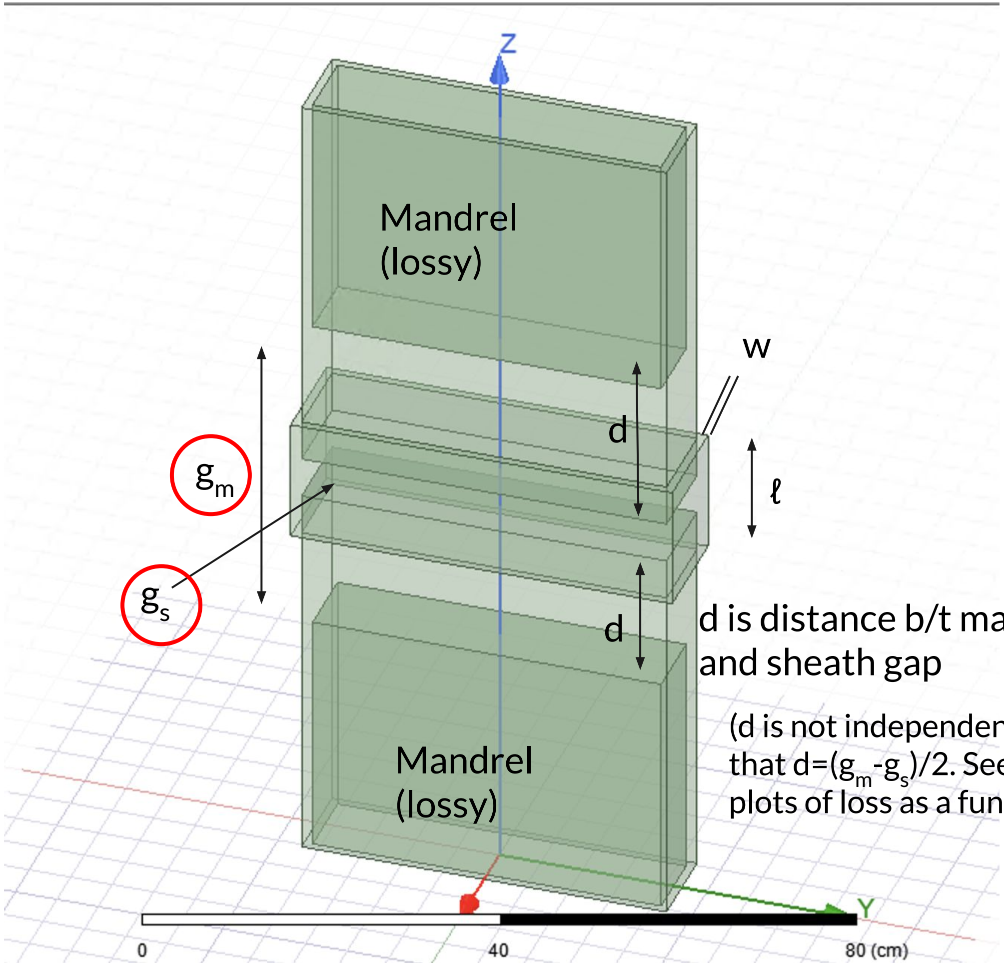
Loss as a function of frequency and g_m (g_s=1 cm)



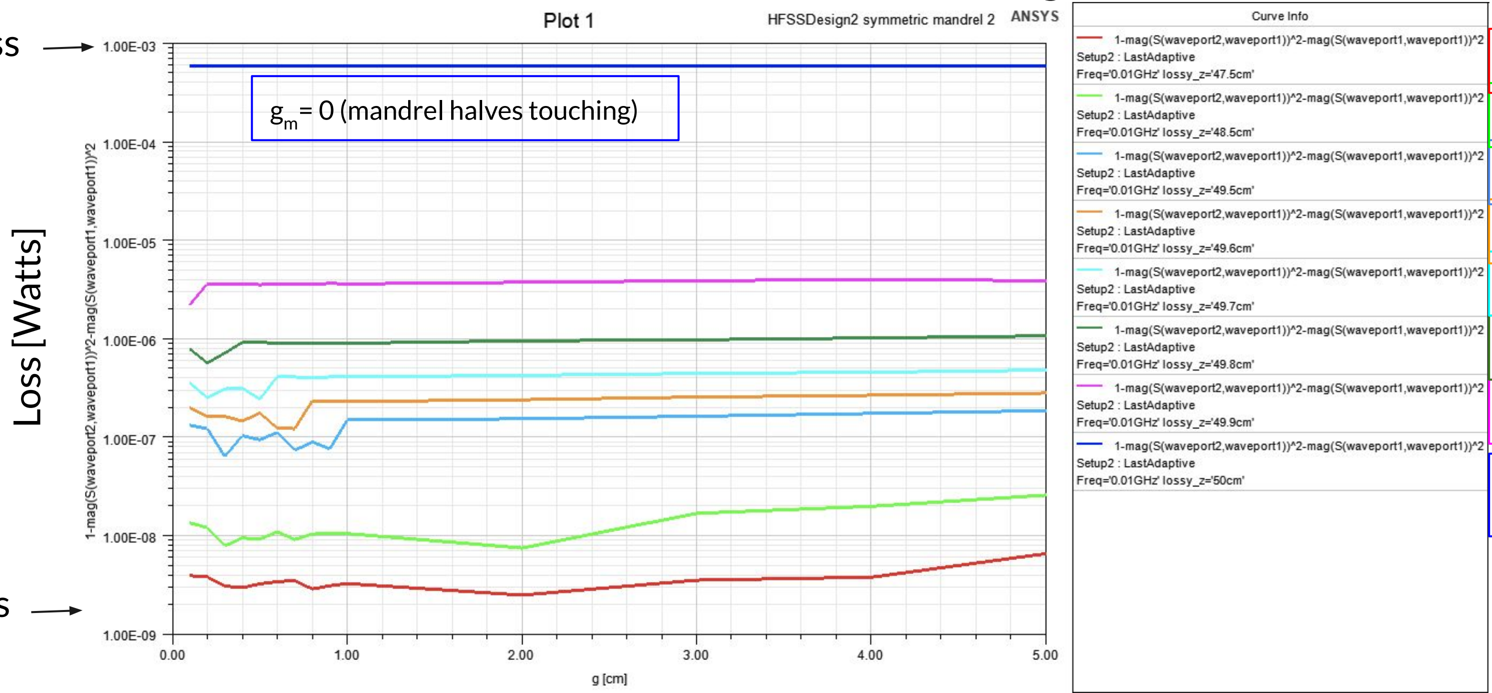


d is distance b/t mandrel and sheath gap

(d is not independent of g_m and g_s. Note that $d=(g_m-g_s)/2$. See bonus slides for plots of loss as a function of d)

Loss @10 MHz as a function of g_s (x-axis) and g_m

High loss →



Low loss →

g_m = 5 cm

g_m = 3 cm

g_m = 1 cm

g_m = 0.8 cm

g_m = 0.6 cm

g_m = 0.4 cm

g_m = 0.2 cm

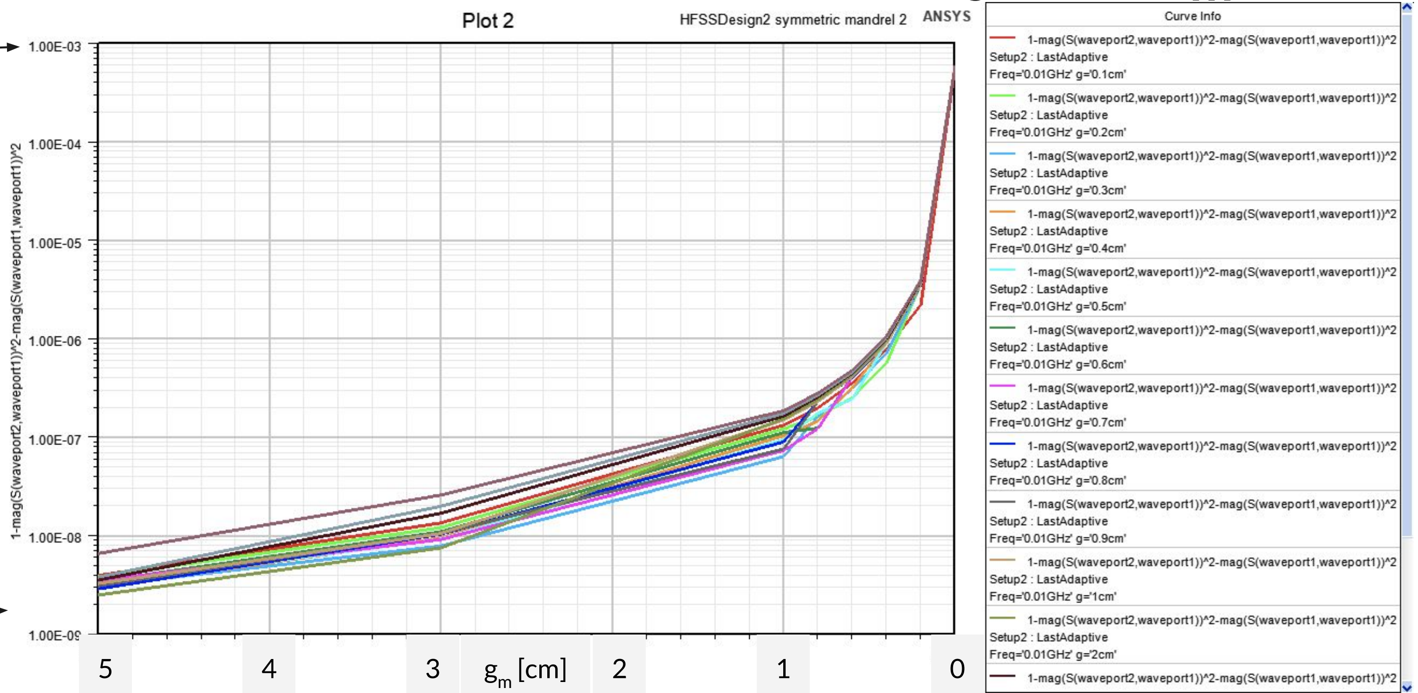
g_m = 0 (mandrel halves touching)

Loss @10 MHz as a function of g_s and g_m (x-axis)

High loss →

Loss [Watts]

Low loss →

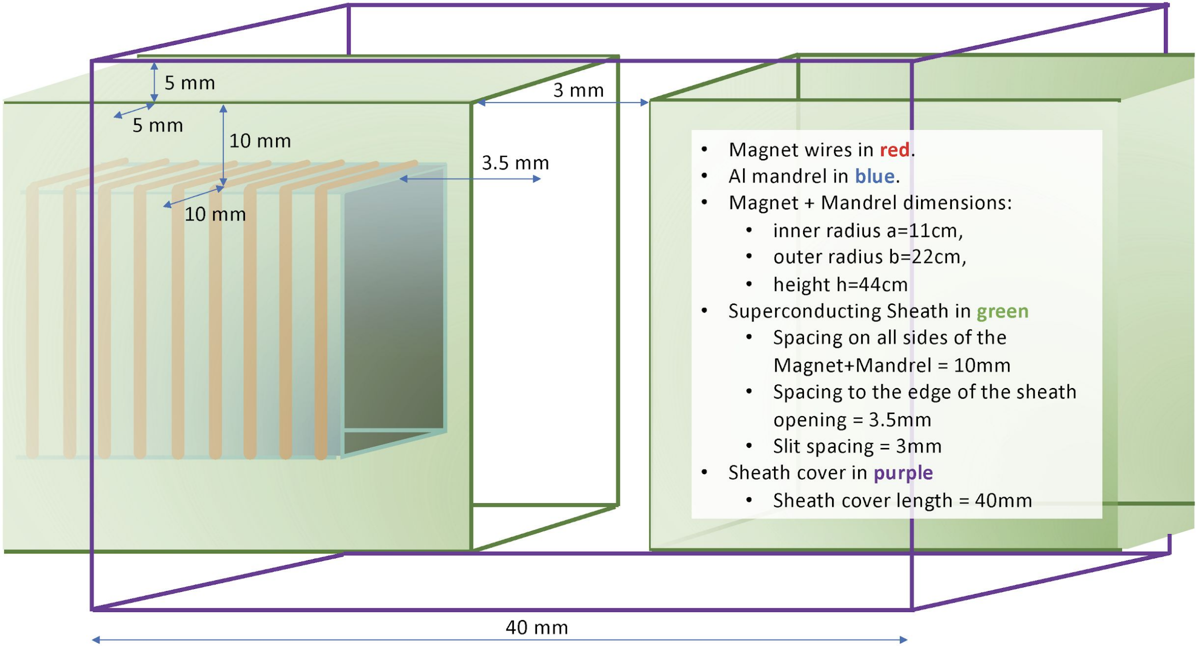


g_s=.1 cm

↓

g_s=5 cm

DM Radio 50 L Geometry

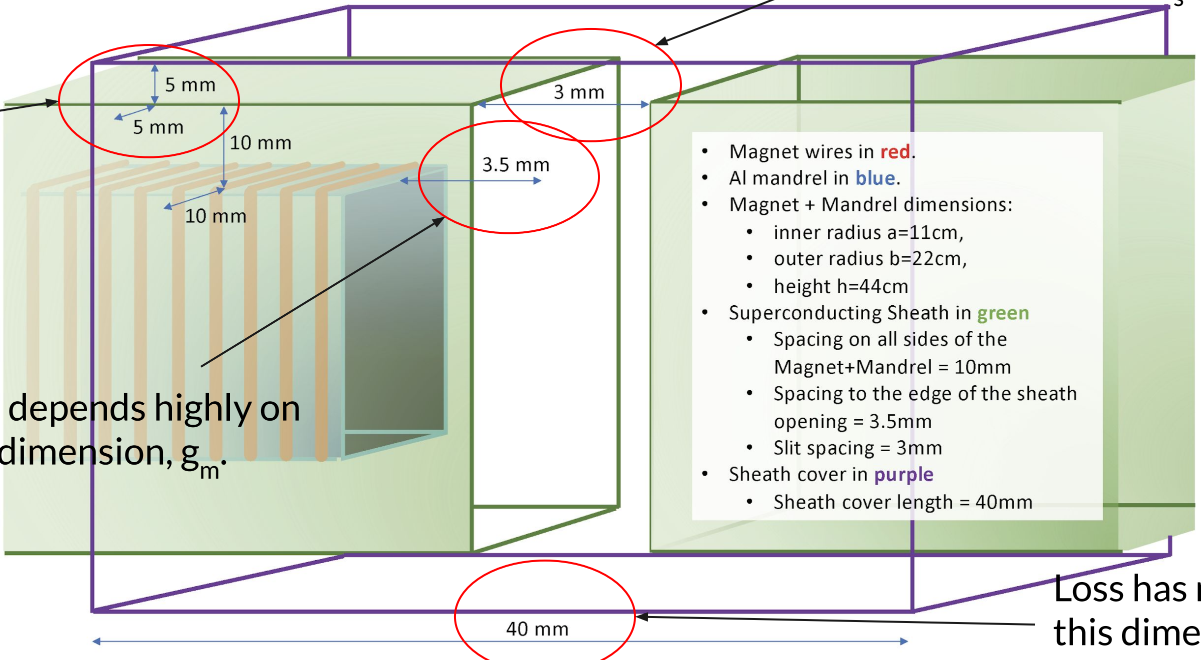


- Magnet wires in **red**.
- Al mandrel in **blue**.
- Magnet + Mandrel dimensions:
  - inner radius a=11cm,
  - outer radius b=22cm,
  - height h=44cm
- Superconducting Sheath in **green**
  - Spacing on all sides of the Magnet+Mandrel = 10mm
  - Spacing to the edge of the sheath opening = 3.5mm
  - Slit spacing = 3mm
- Sheath cover in **purple**
  - Sheath cover length = 40mm

DM Radio 50 L Geometry

Loss has weak dependence on this dimension, g_s

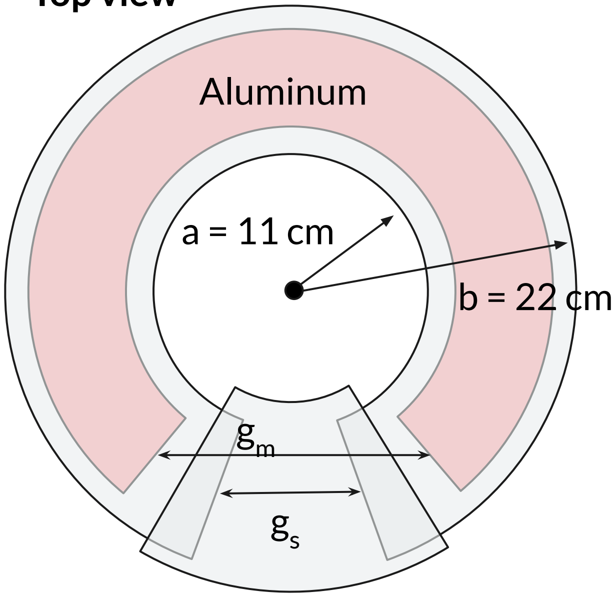
Loss has weak dependence on w, the smaller the better



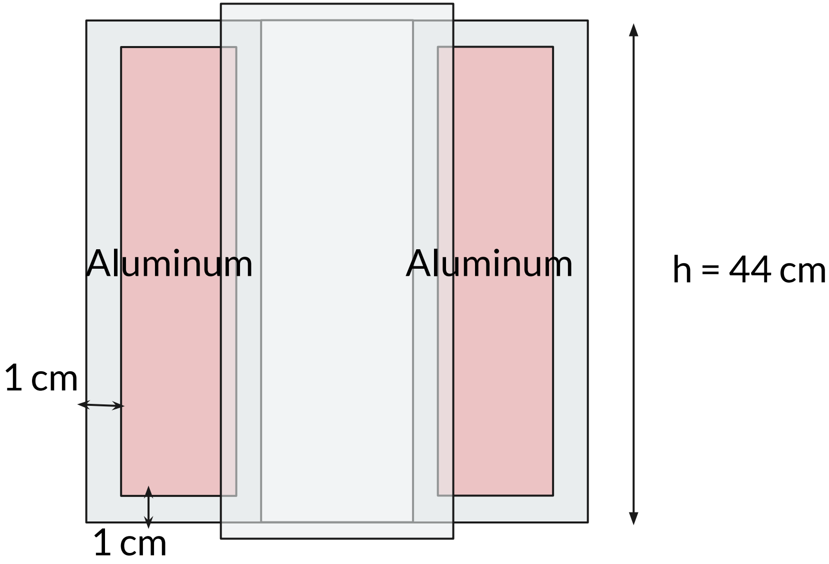
Loss has no dependence on this dimension, ℓ

Toroidal model with lossy material

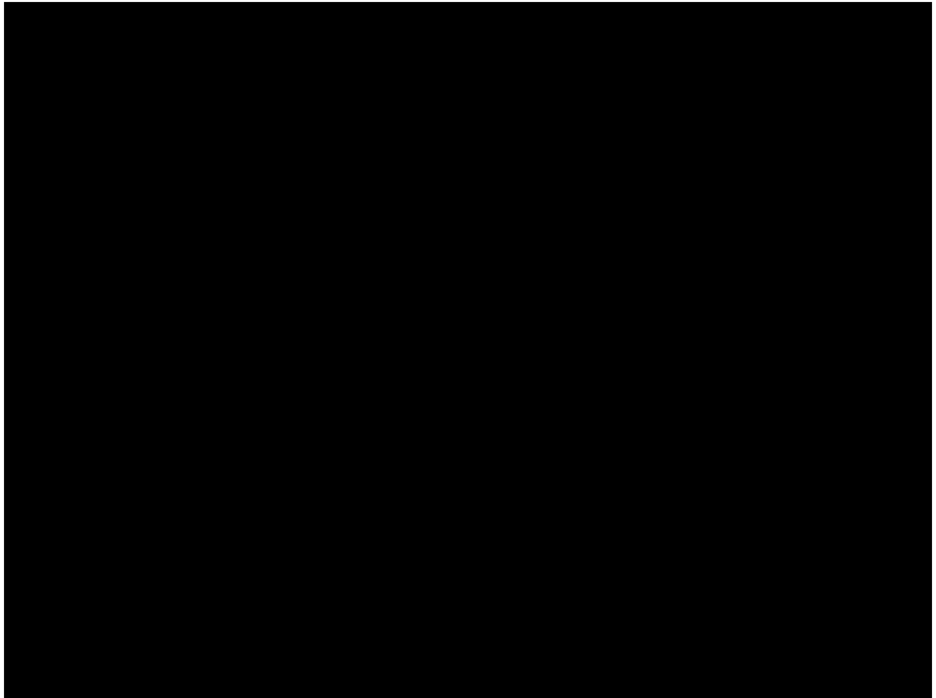
Top view



Side view

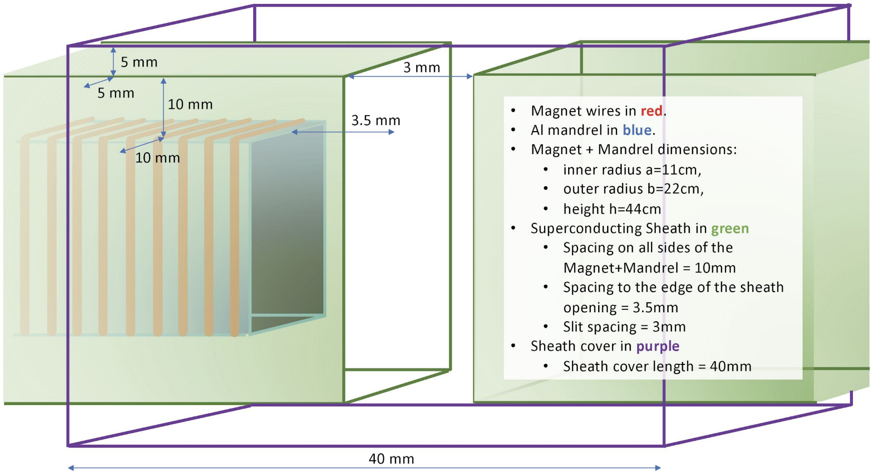


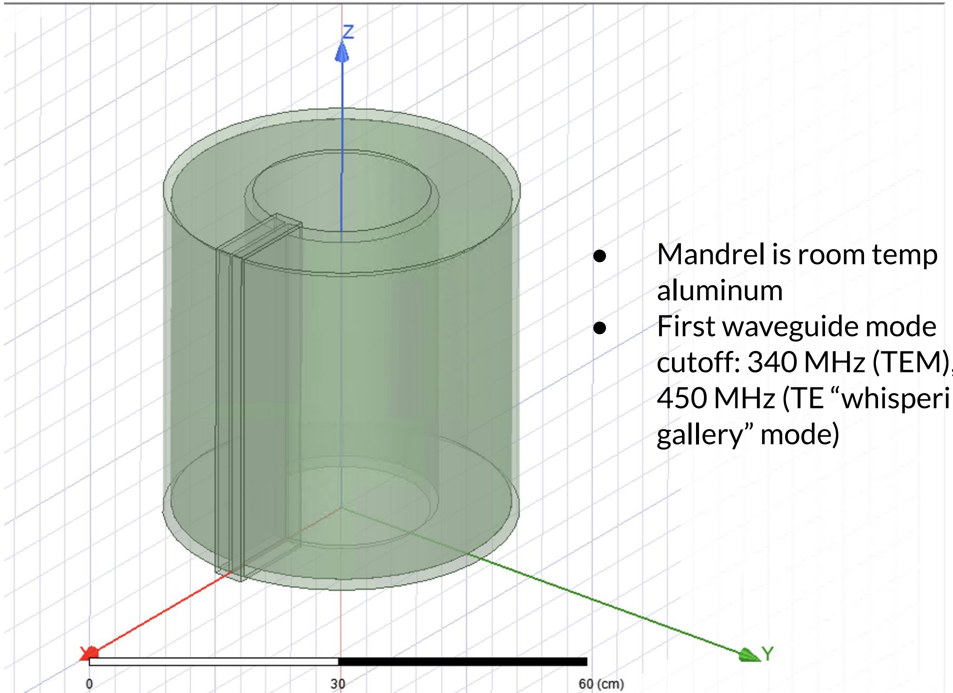
Fun animation



(outdated geometry)

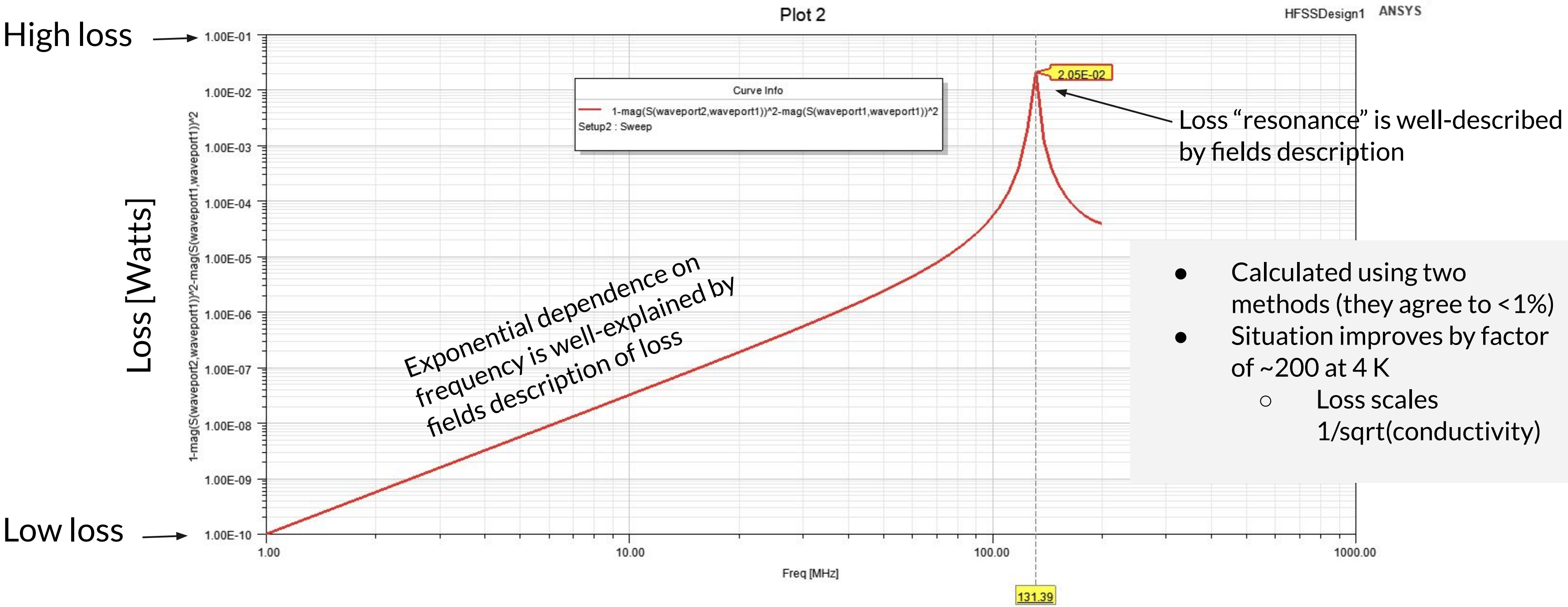
Geometry





- Mandrel is room temp aluminum
- First waveguide mode cutoff: 340 MHz (TEM), 450 MHz (TE "whispering gallery" mode)

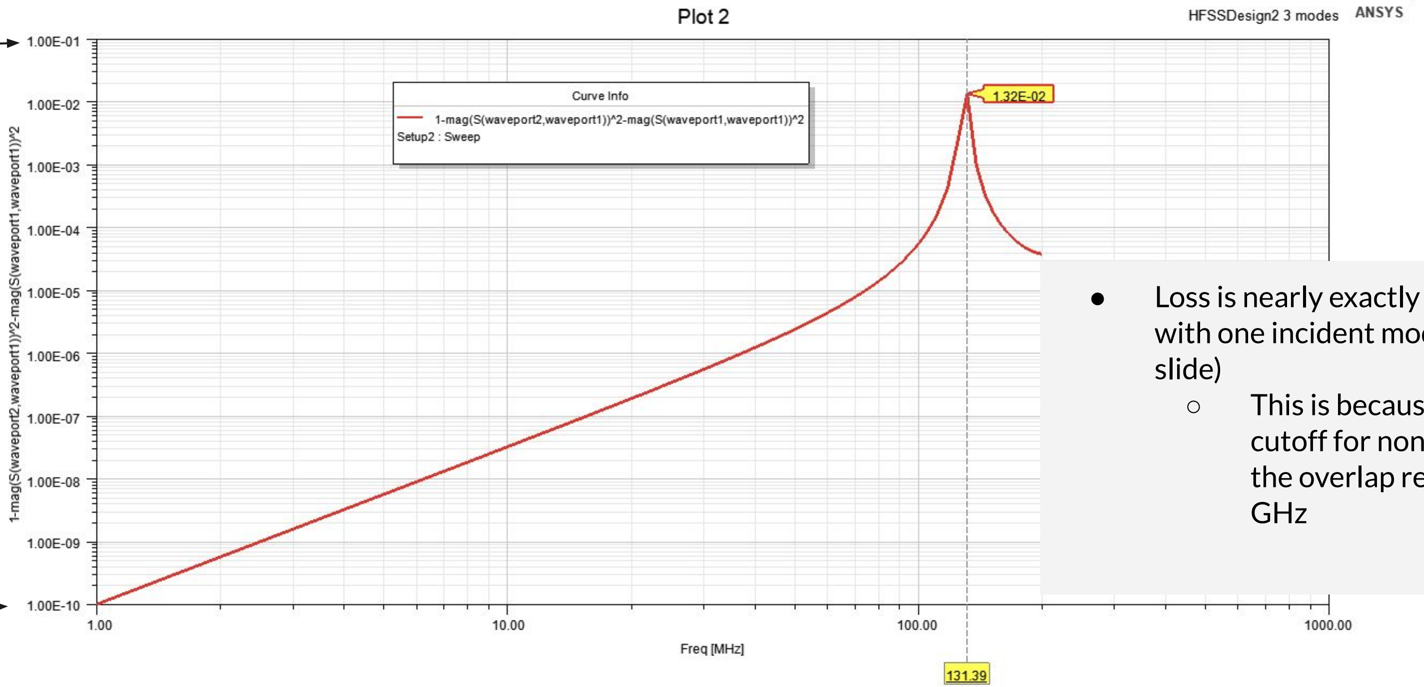
Loss as a function of frequency (1 mode (TEM))



- Calculated using two methods (they agree to <1%)
- Situation improves by factor of ~200 at 4 K
  - Loss scales 1/sqrt(conductivity)

Loss as a function of frequency (3 modes (TEM+2TE))

High loss



Loss [Watts]

Low loss

- Loss is nearly exactly the same as with one incident mode (previous slide)
    - This is because the waveguide cutoff for non-TEM modes in the overlap region is ~1-2 GHz

Conclusions & Future work

Conclusions

- The parameter that most affects loss is g_m, the gap in the mandrel
    - Loss does not depend on ℓ, at least in simulation (may matter in real life (see “future work”))
    - Loss has weak dependence on w and g_s
- g_m=1 cm and g_s=0.5 cm have been chosen for the DM Radio 50 L version 0 dimensions.

Future Work

- I will incorporate pickup loop into simulations, and use this as source of power instead of waveports
    - Requires lumped elements (L, C, etc...) in HFSS
    - Find voltage/capacitance across various parts of the design (useful for DM Radio m^3)
    - This will allow me to incorporate the other gap in the sheath/mandrel
- More realistic mandrel
    - Insulators/dielectrics
- Parasitic resonance

Appendix

Field equations that determine loss

For a rectangular waveguide with dimensions a, b, fields of the TE_{10} mode are

$$H_z = H_0 \cos(\frac{\pi x}{a}) e^{i(kz-\omega t)}$$

$$H_x = -\frac{ika}{\pi} H_0 \sin(\frac{\pi x}{a}) e^{i(kz-\omega t)}$$

$$E_y = \frac{i\omega a\mu}{\pi} H_0 \sin(\frac{\pi x}{a}) e^{i(kz-\omega t)}$$

(Jackson)

HFSS puts 1 W of time-averaged power on the waveport. Therefore we solve for H_0 as follows:

1 W = $P = \frac{1}{2}\int_S \vec{E} \times \vec{H}^* \cdot d\vec{S} = \ldots = \frac{1}{2} H_0^2 \frac{ka^2\mu\omega}{\pi^2} \frac{a}{2} b$

$$\Rightarrow H_0 = \sqrt{(1W)\frac{4\pi^2}{ka^3 b\mu\omega}}$$

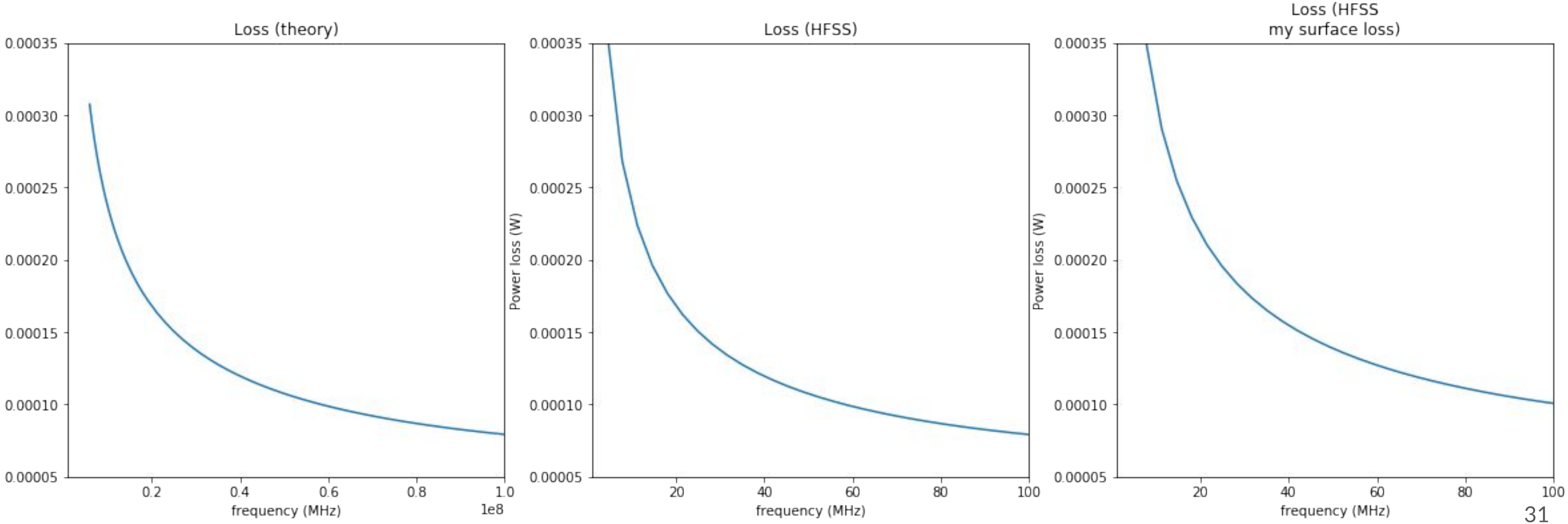
Power loss in a good conductor is given as follows:

$$P_{\text{loss}} = \frac{1}{2\sigma\delta} \oint_C |\hat{n} \times H_t|^2$$

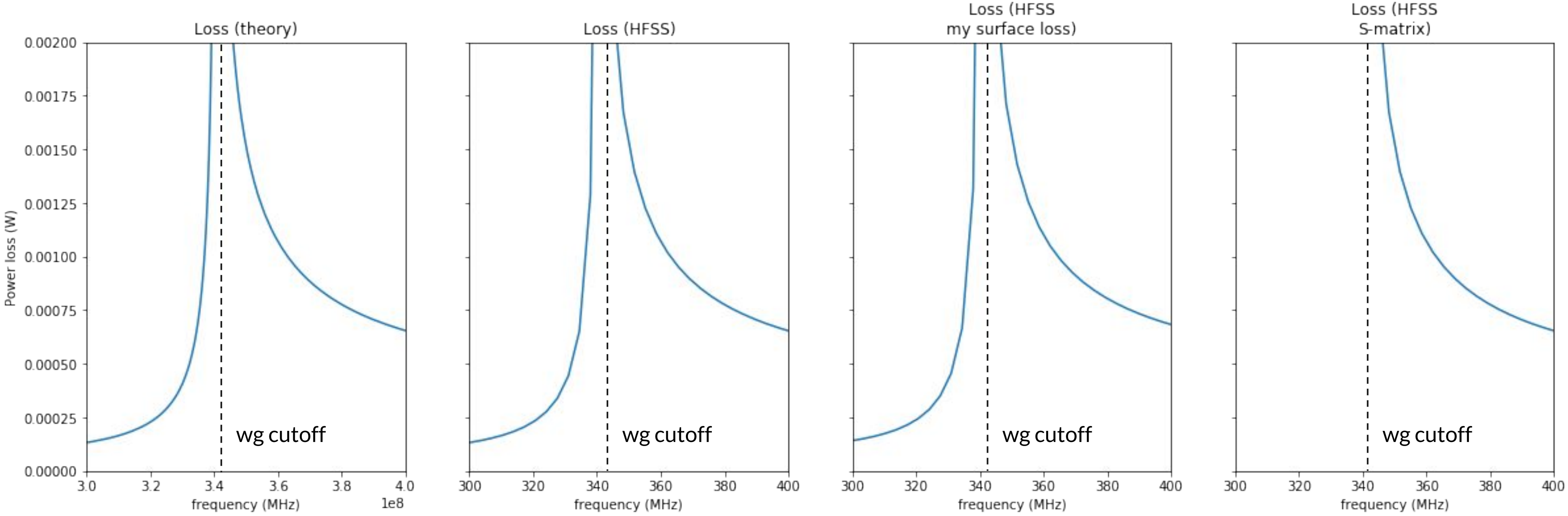
(Jackson)

$$\propto \frac{1}{\delta} H_0^2 \propto \frac{1}{k\sqrt{\omega}}$$

Rectangular waveguide - loss 1-100 MHz



Rectangular waveguide - loss 300-400 MHz



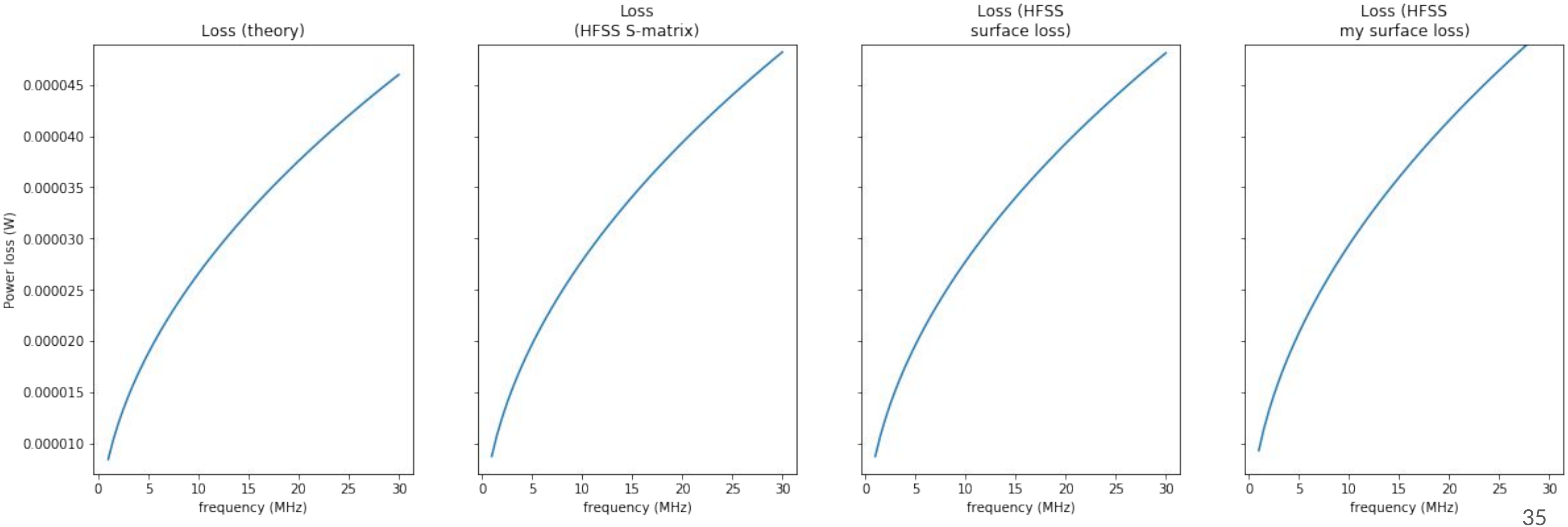
Calculating loss in HFSS

- For a good conductor, one may calculate loss according to the surface impedance $Z_s = (1-i)/\sigma\delta$ with the following formula:
  - $P_{loss}=\int(1/Z_s)^*|n\times H_t|^2$
- One may calculate loss in HFSS via a few methods:
  - $1-|S_{21}|^2-|S_{11}|^2$
    - Only works for propagating modes (above cutoff frequency). I call this method **"S-matrix"**
  - Using HFSS internal fields calculator
    - "Surface_loss_density" (this is what the documentation suggests). **I simply call this method "HFSS"**
    - I can manually integrate the fields according to $P_{loss}=\int(1/Z_s)^*|n\times H_t|^2$. **I call this "my surface loss"**

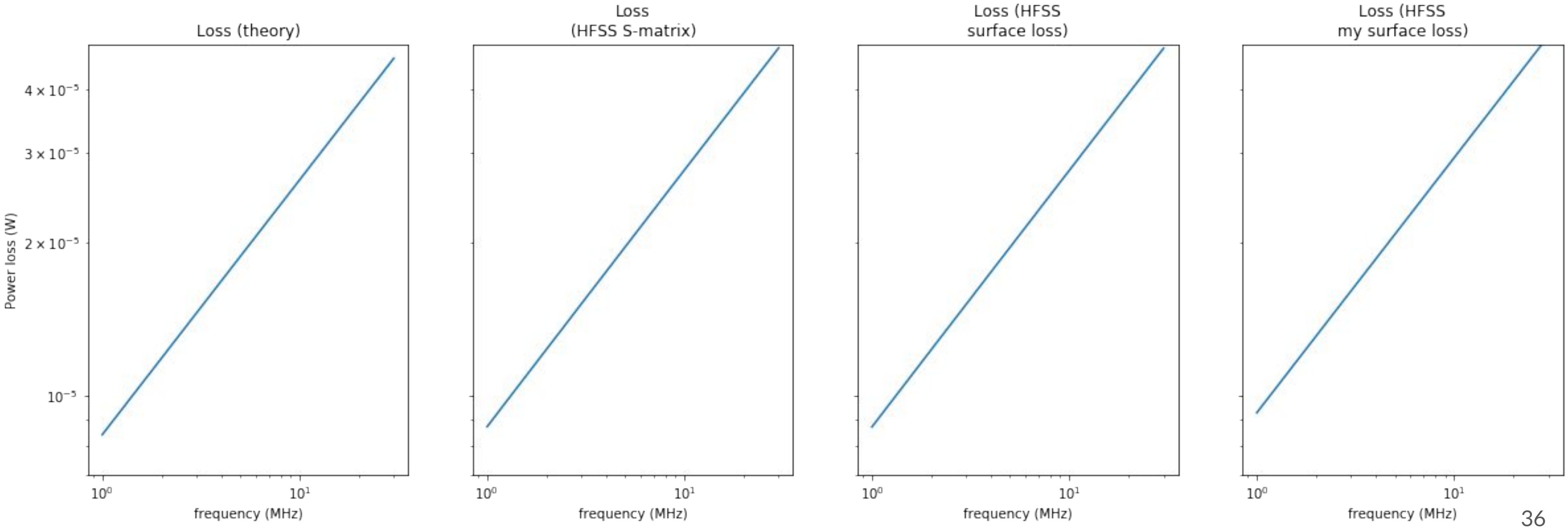
Calculating loss in HFSS

- I examined the following three methods:
    - $1-|S_{21}|^2-|S_{11}|^2$
        - Only works for propagating modes (above cutoff frequency)
    - "Surface_loss_density" (this is what the documentation suggests)
    - I can manually integrate the fields according to $P_{loss}=\int(1/Z_s)^*|n\times H_t|^2$
- I examined two geometries:
    - Coax TEM mode
        - No cutoff frequency, so I tried all 3 above methods
    - Rectangular waveguide
        - Cutoff ~340 MHz, so below cutoff I can only use fields calculator methods below cutoff

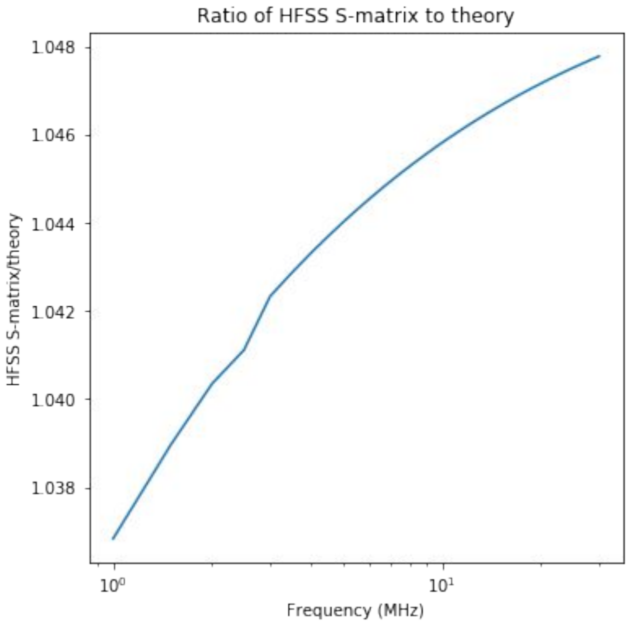
Coax - loss 1-30 MHz

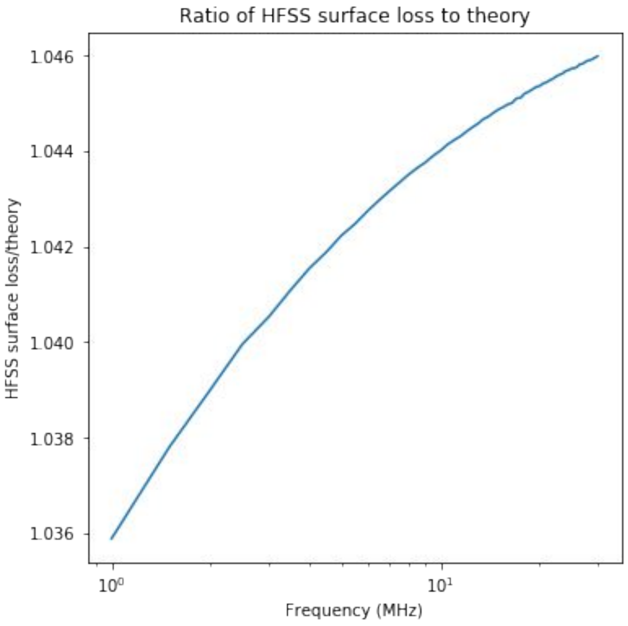


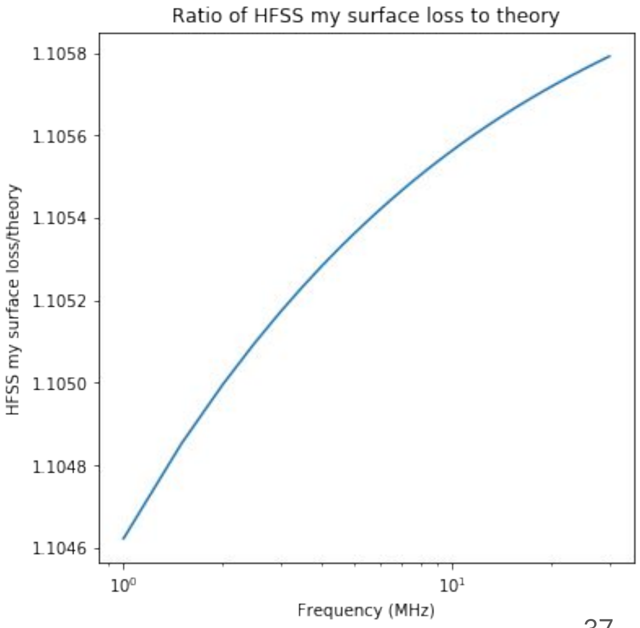
Coax - loss (log log plots) 1-30 MHz



Coax - Ratio to theory



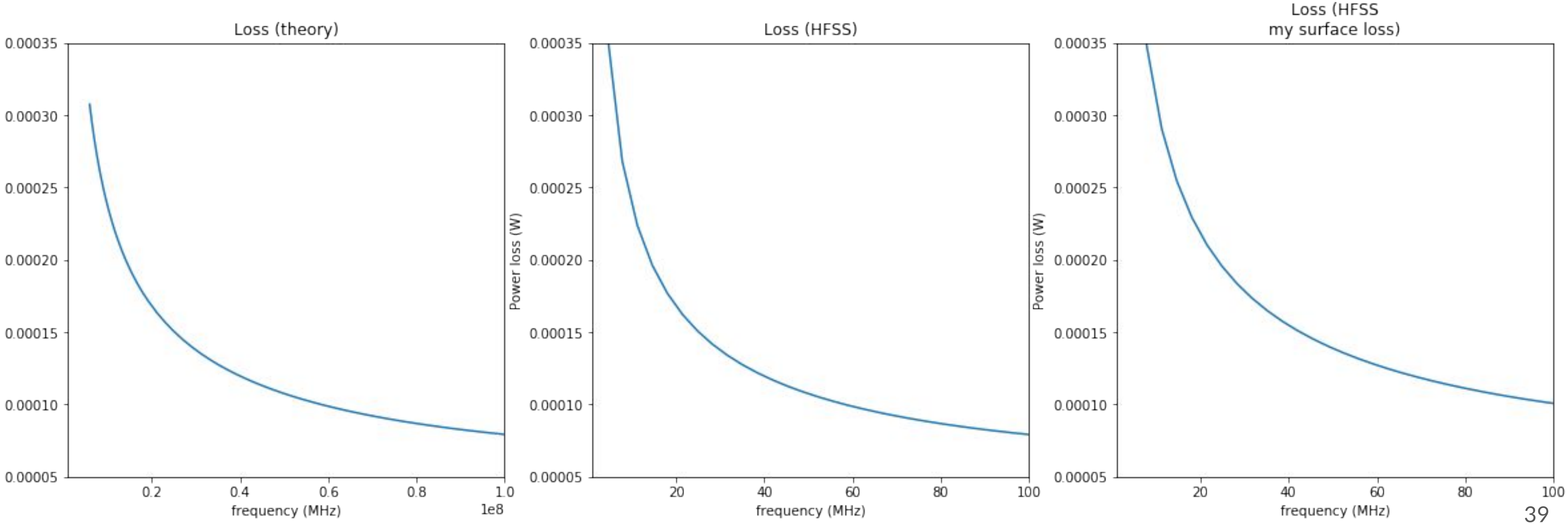




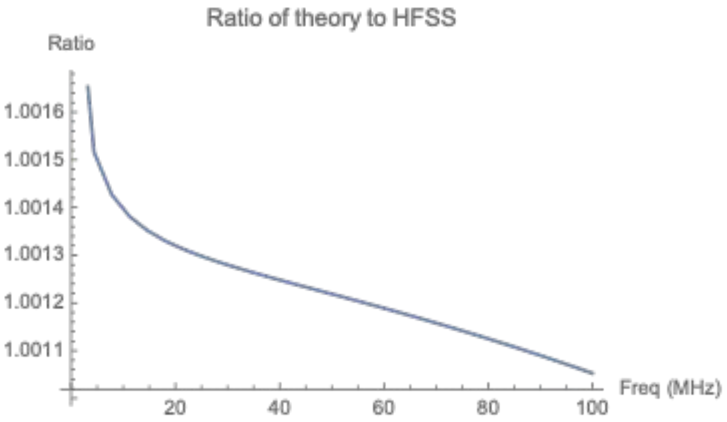
Coax - conclusion

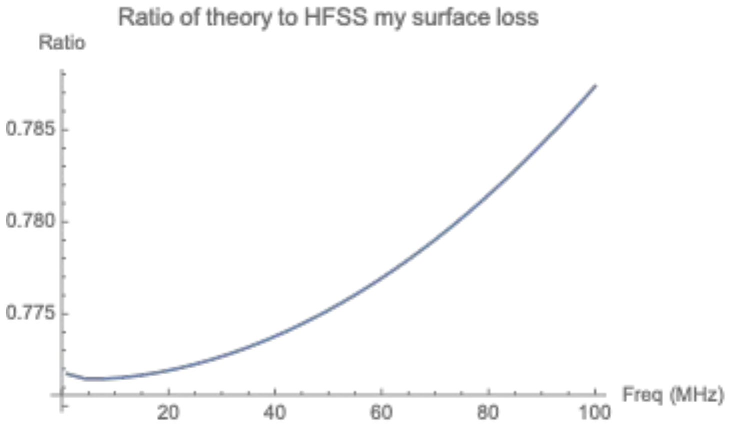
- S-matrix method agrees to <5% (**good**)
- HFSS built-in “surface_loss_density” method agrees to <5% (**good**)
- My surface loss method agrees to <11% (**OK**)

Rectangular waveguide - loss 1-100 MHz

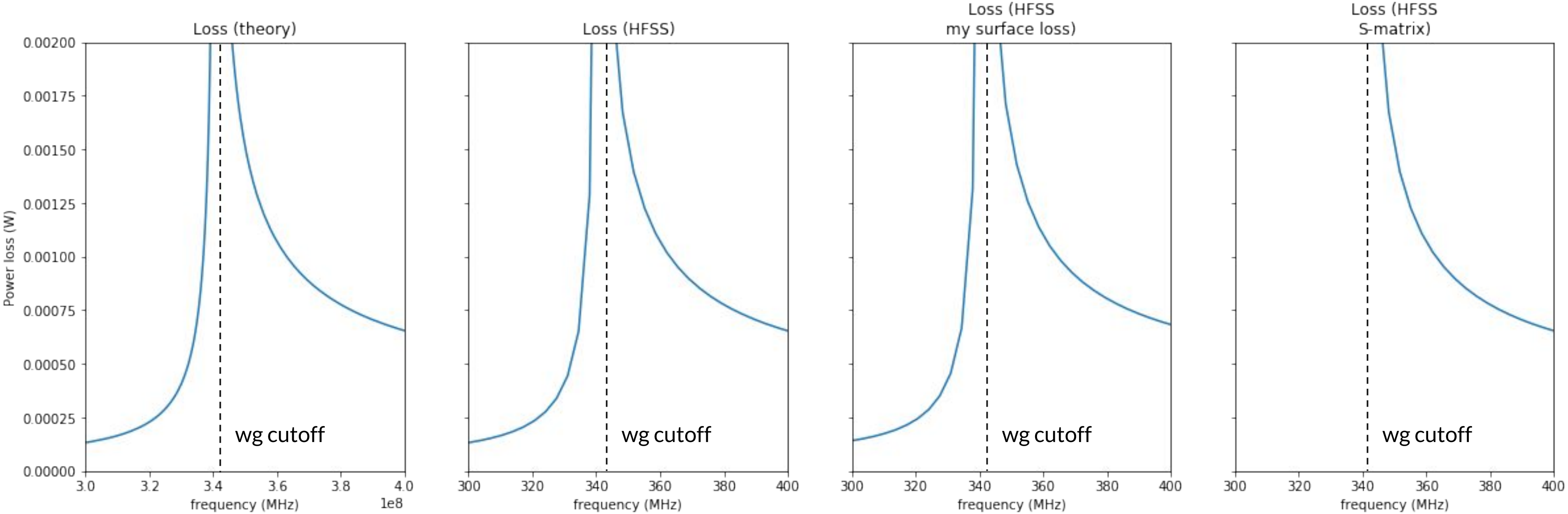


Rectangular waveguide - ratio with theory 1-100 MHz

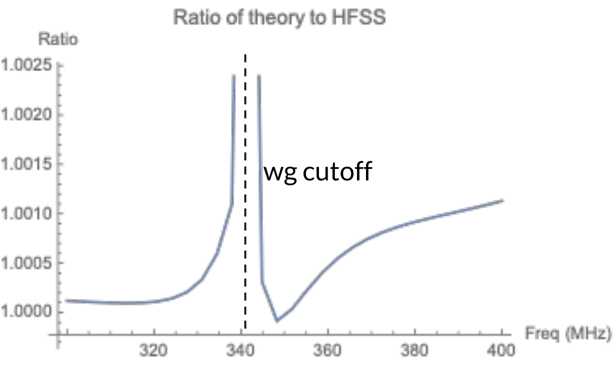


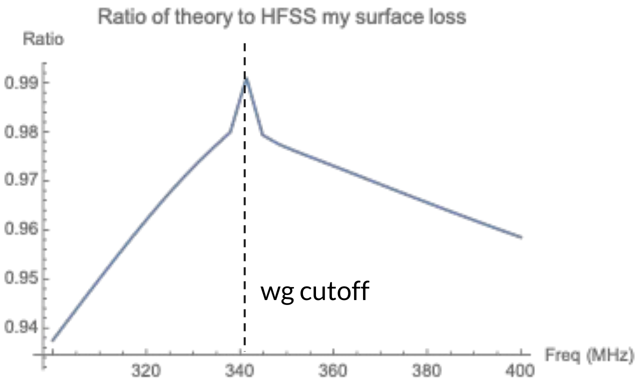


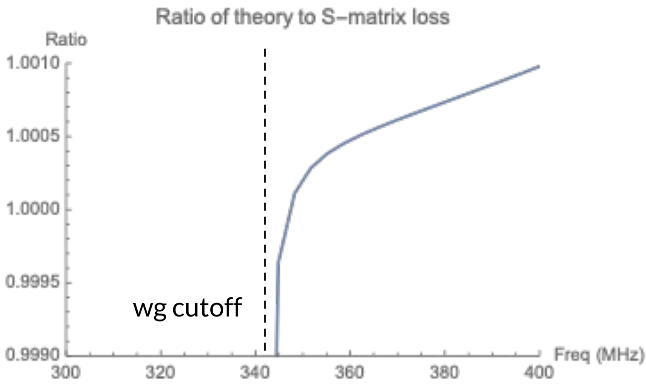
Rectangular waveguide - loss 300-400 MHz



Rectangular waveguide - ratio with theory 300-400 MHz





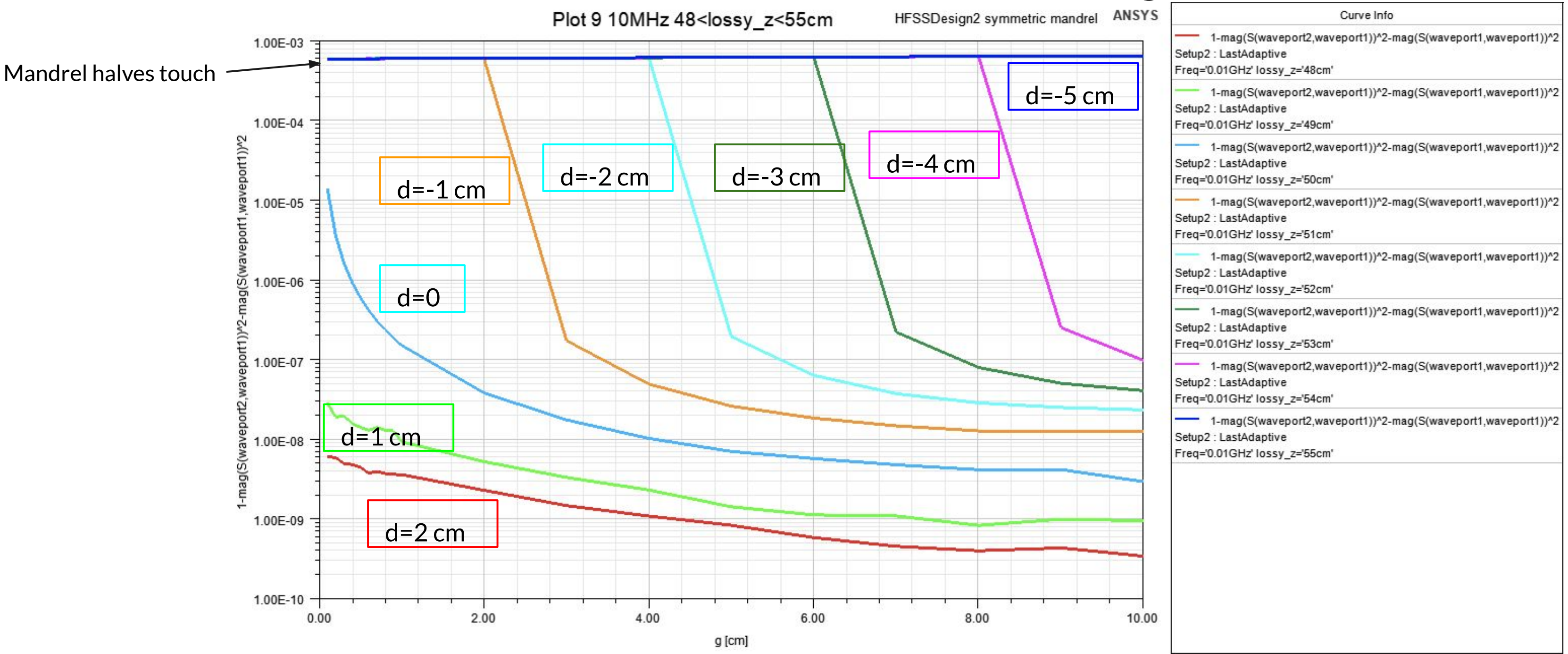


Rectangular waveguide - conclusions

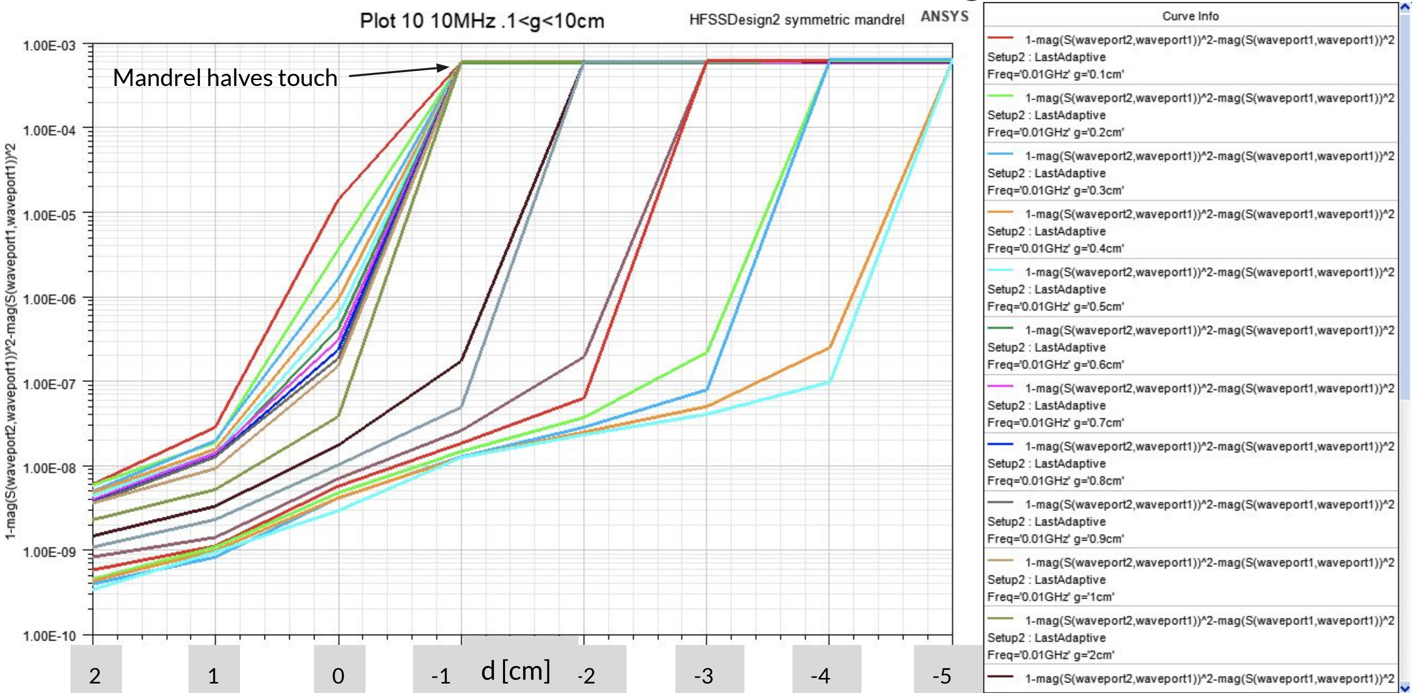
- Above cutoff, S-matrix method agrees to <0.1% (**good**)
- HFSS built-in “surface_loss_density” method agrees to
  - <.2% at all frequency ranges (1-100 MHz & 300-400 MHz) (**good**)
- My surface loss method agrees to
  - <23% in 1-100 MHz range (**bad**)
  - <6% in 300-400 MHz range (OK)

d?

Loss @10 MHz as a function of g_s (x-axis) and d



Loss @10 MHz as a function of g_s and d (x-axis)



Conductivity?

Loss as a function of conductivity: theoretical dependence on σ: $P \propto 1/\sqrt{\sigma}$

- Loss comes from electric fields moving around electrons (in non-ferrite materials)
- For a wave incident upon a conductor, loss comes from the electric field and the electric field induced by a time-varying magnetic field (Faraday's law)
- In the quasi static limit, the loss from Faraday's law is dominant, so it suffices to consider induced electric fields/currents
- Jackson 5.18A and Jackson 8.1 provide a good way to find loss power loss in a conducting medium. Assuming a wave propagating in the z direction,

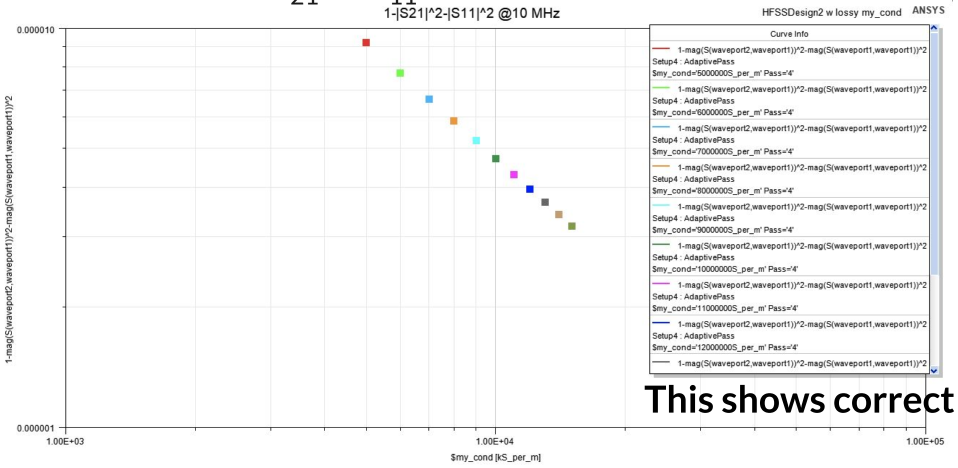
$$H_x(z,t) = H_0 e^{-z/\delta} \cos(z/\delta - \omega t) \qquad E_y(z,t) = \frac{1}{\sigma}\frac{\mathrm{d}H_x}{\mathrm{d}z} \qquad J_y = \sigma E_y \qquad P_{\text{loss}} = \frac{1}{2}\int \vec{J}\cdot\vec{E} = \frac{1}{2}\int \mu\omega H_0^2 e^{-2z/\delta}$$

Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$

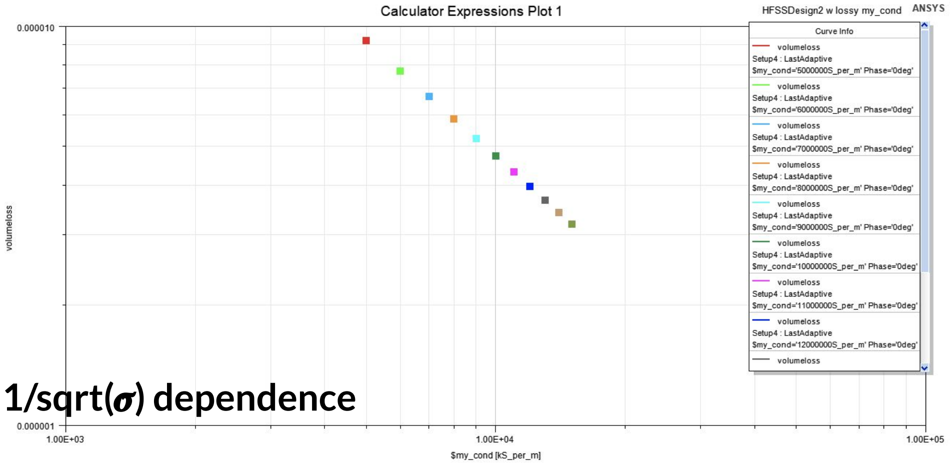
$$\boxed{P_{\text{loss}} = \frac{1}{4}|H_0|^2\sqrt{\frac{\mu\omega}{2\sigma}}}$$

Power loss as a function of conductivity at 10 MHz

Method 1: conservation of energy.
Loss = $(1-|S_{21}|^2-|S_{11}|^2)$*(1 W input power)



Method 2: Ohm's law. Loss = $(1/2)\int\sigma|\mathbf{E}|^2 dV$

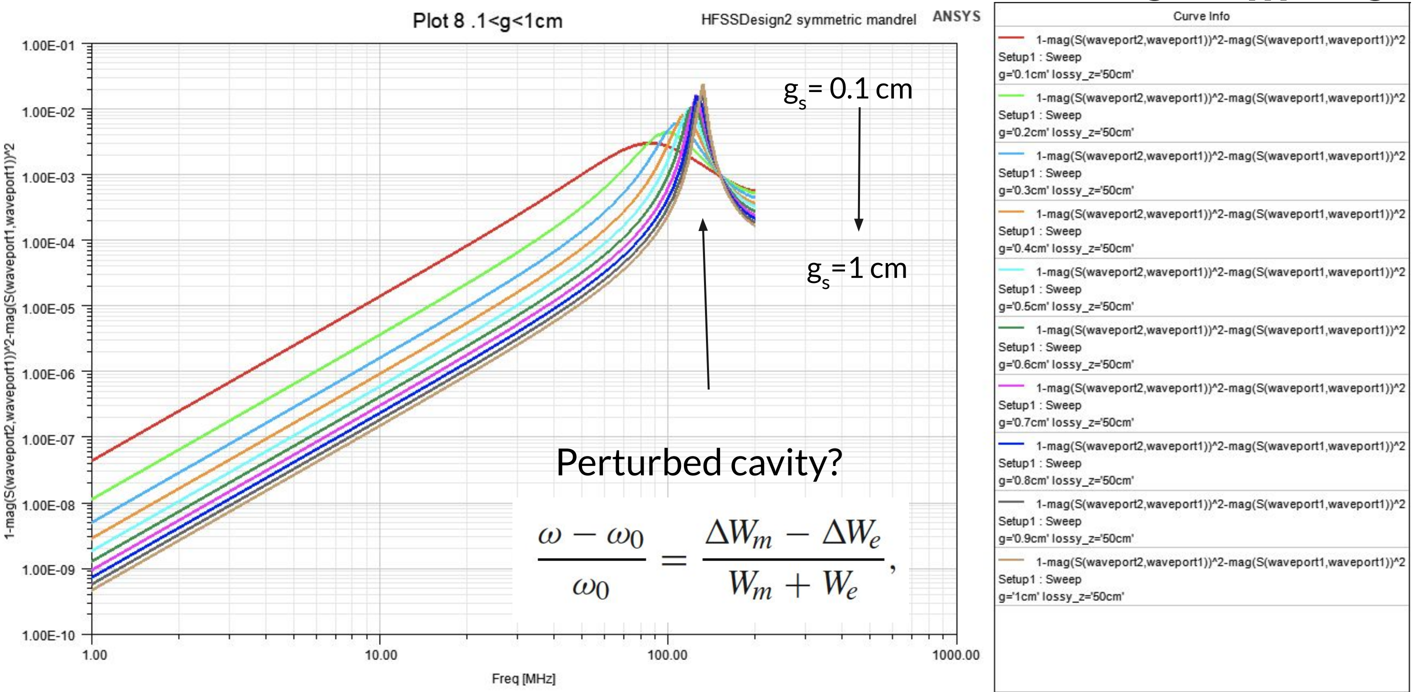


This shows correct 1/sqrt(σ) dependence

x-axis is conductivity of lossy material, not frequency!

Perturbed cavity?

Loss as a function of frequency and g_s (g_m=g_s)



Perturbed cavity?

$$\frac{\omega - \omega_0}{\omega_0} = \frac{\Delta W_m - \Delta W_e}{W_m + W_e},$$

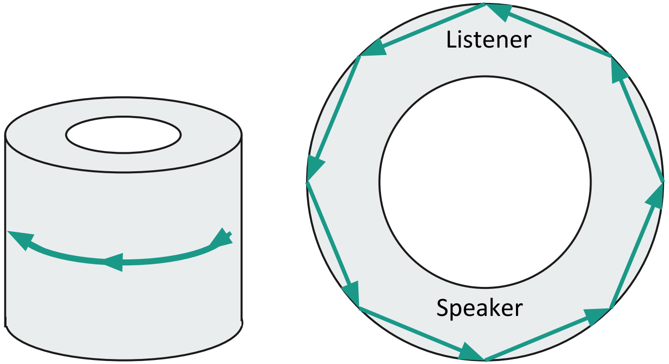
Whispering gallery?

“Whispering gallery” modes

- First theoretically described by Lord Rayleigh in 1896 to explain sound waves in the whispering gallery of St. Paul’s Cathedral

Whispering gallery modes
Lord Rayleigh, “The Theory of Sound, Vol.2”, (1896); Phil. Mag. 20,1001 (1910); ibid. 27,100 (1914); Proc. Royal Institution of Great Britain, January, 1904.

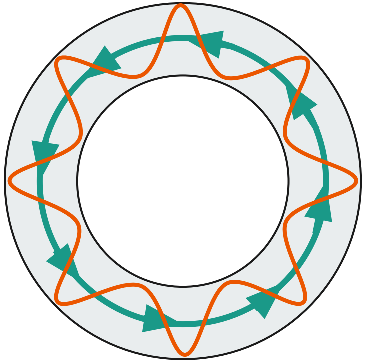
Acoustic case:



Electrostatic case:

Wavevector, *k*:

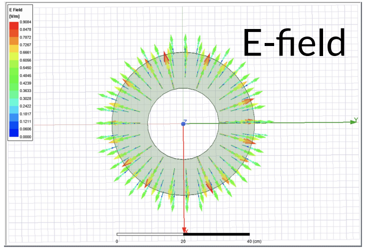
E-field (TE mode):
B-field (TM mode):

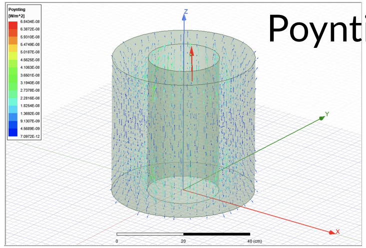


Prediction: $f_{np} = \omega_{np}/2\pi = 448\ MHz, 673\ MHz, 742\ MHz, \ldots$

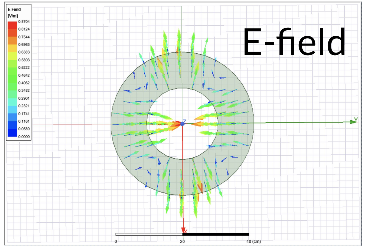
Simulation in Ansys HFSS

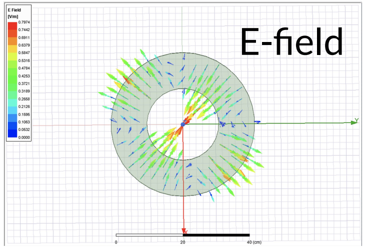
- Mode at **341 MHz** (TEM mode) (not whispering gallery)



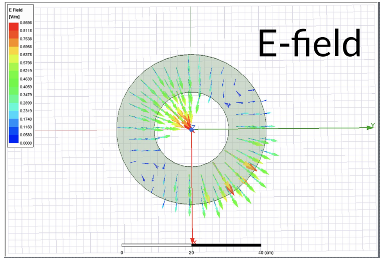


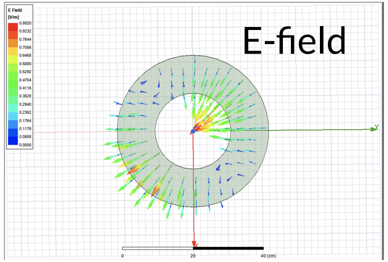
  - 2X modes at **674 MHz** (TE mode)

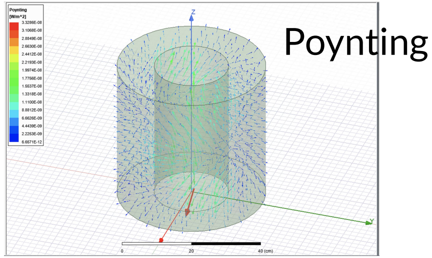


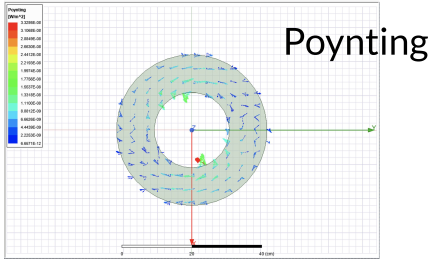


- 2X mode at **450 MHz** (TE modes)









These are the predicted whispering gallery modes!