Update on IR HOM evaluations

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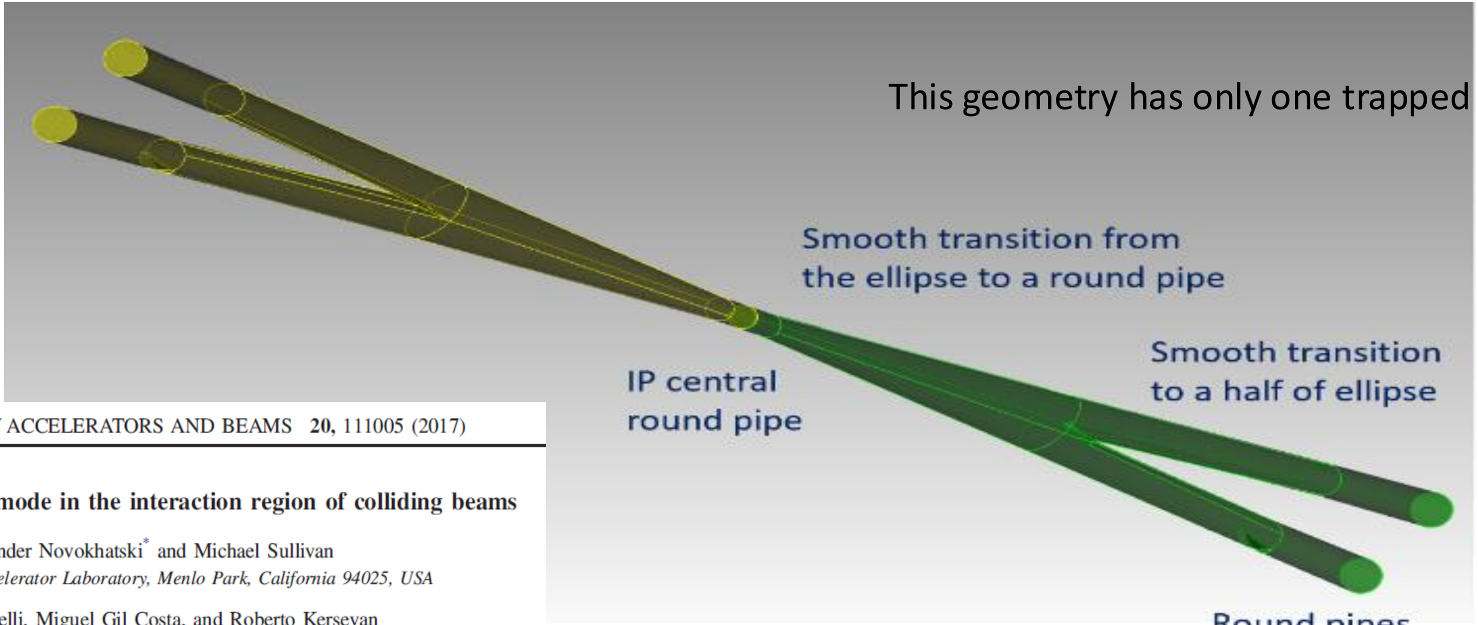
Outline

- The study of the wake field beam energy losses is very important for the design of the vacuum chamber of the FCC-ee Interaction Region.
- They are responsible for heating metal walls of the chamber.
- The shape of the chamber and the materials used in the chamber design determine the magnitude and distribution of the thermal load.
- We optimized the shape to make the impedance, which determines the wake field beam energy loss, as small as possible.
- The choice of materials is based on the needs of the detector.
- Here we present the results on the beam energy loss and the thermal load distribution for different beam energies.
- We suggest some possible improvements to reduce the thermal load and improve the vacuum conditions.

Low impedance FCC-ee IR vacuum chamber

We have developed special smooth transitions from two beam pipes into a mutual pipe. The incoming pipes have a diameter of 30 mm and the central IR pipe has a diameter of 20 mm.

This geometry has only one trapped mode.



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Unavoidable trapped mode in the interaction region of colliding beams

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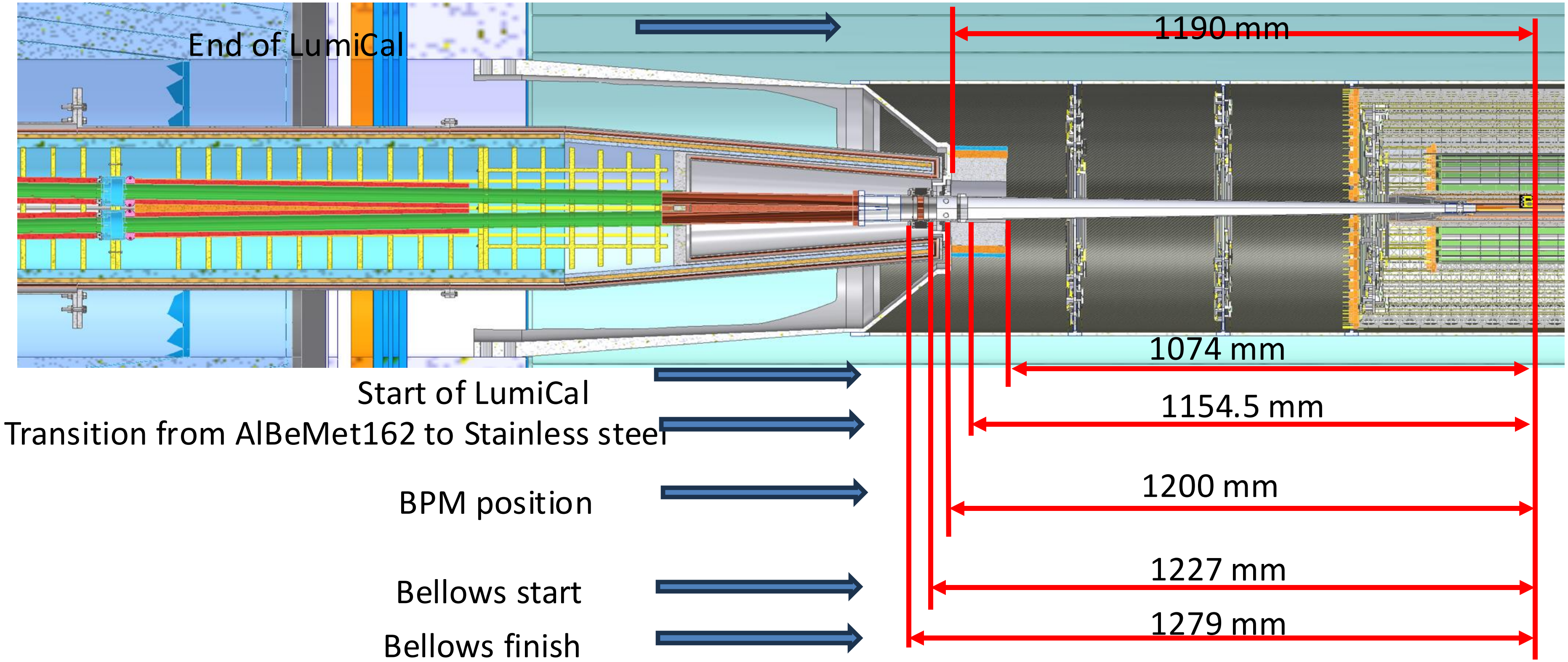
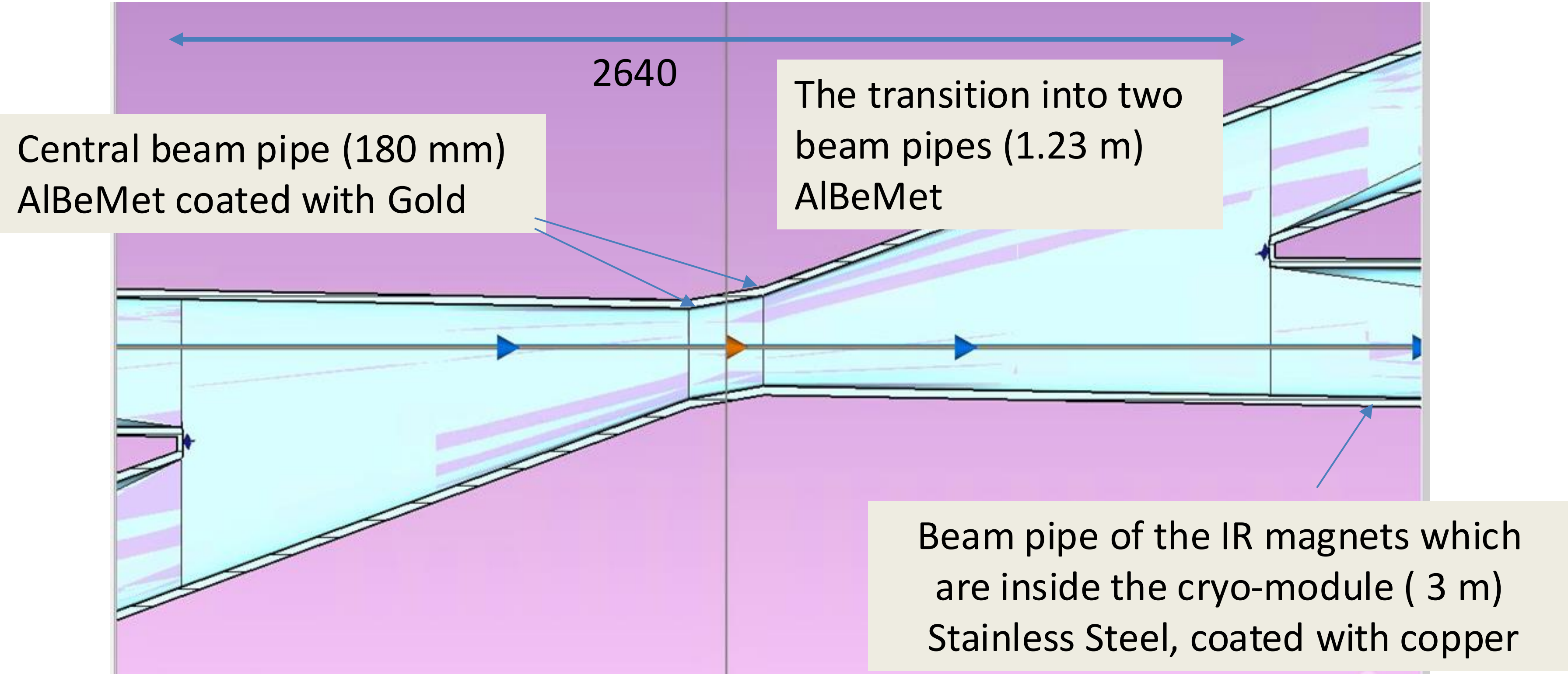
Francesco Fransesini "IR BEAM PIPES"

8th FCC Physics Workshop8th FCC Physics Workshop15/01/2025 CERN

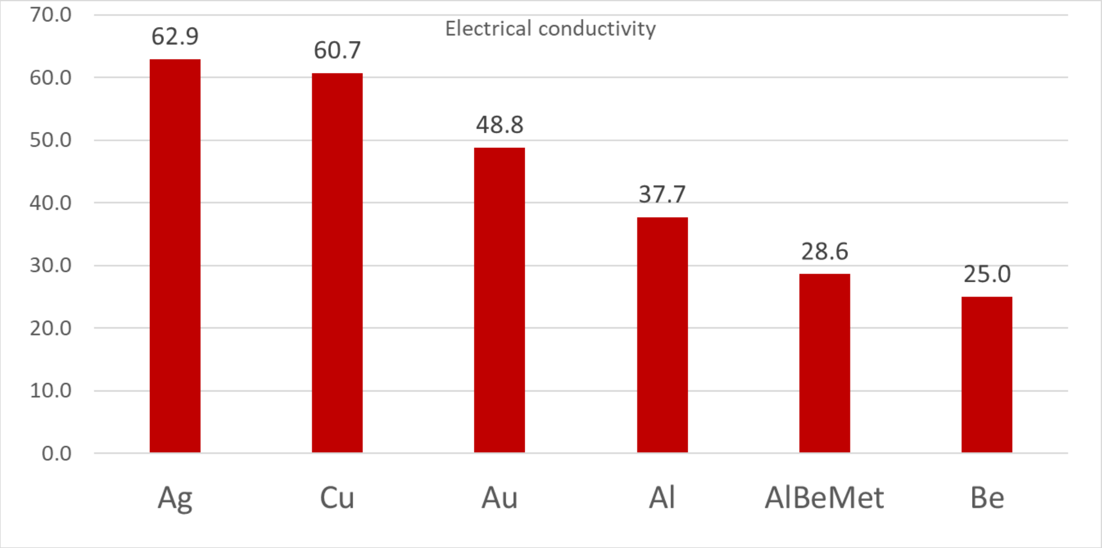


Material distribution in IR vacuum chamber



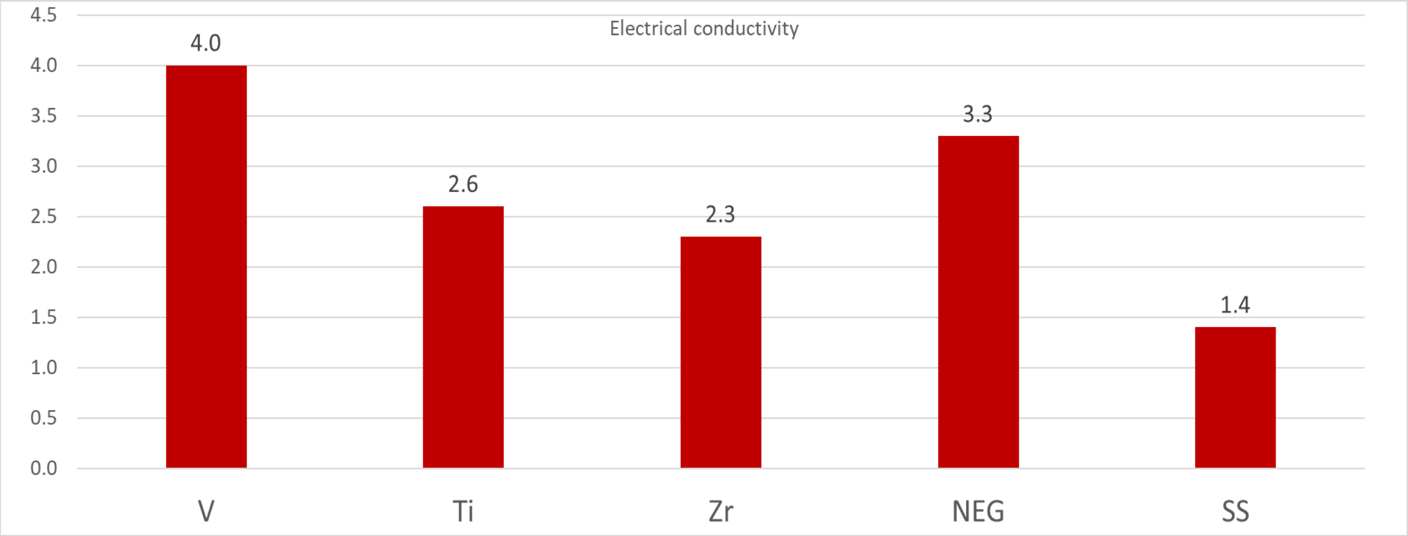
Electrical conductivity

				Silver	Copper	Gold	Aluminum		Beryllium
Element				Ag	Cu	Au	Al	AlBeMet	Be
Electrical conductivity	1.00E+06	/Ohm /m		62.9	60.7	48.8	37.7	28.6	25.0
Measured				63.0	58.0	41.0	35.0		25.0



Electrical conductivity of the materials used in NEGs

				Vanadium	Titanium	Zirconium	Non-Evaporable Getter	Stainless steel
Element				V	Ti	Zr	NEG	SS
							55% +20%+25%	
Electrical cond	1.00E+06	/Ohm /m		4.0	2.6	2.3	3.3	1.4
Measured							0.5 -1	1.45
Thermal conductivity		W /K /m		30.7	21.9	22.7	26.9	15

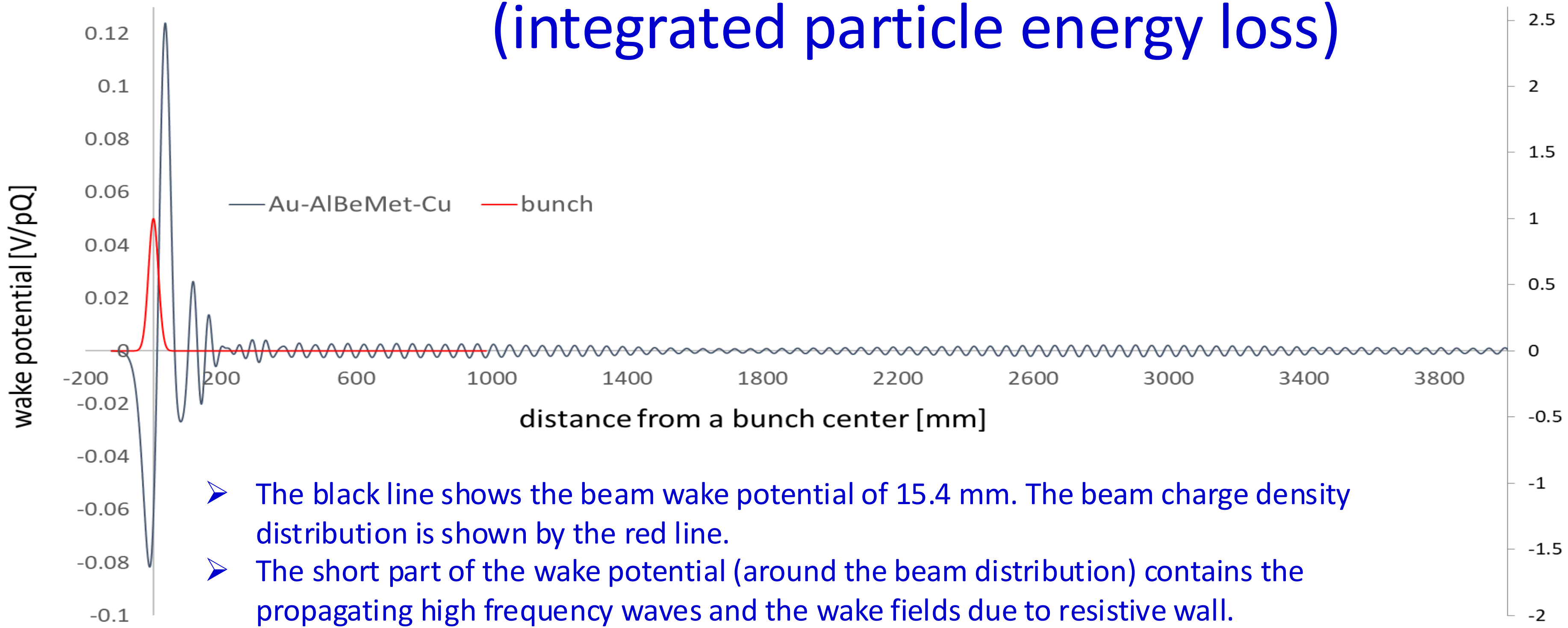


Due to coating roughness

CAD Model and calculating wake potential

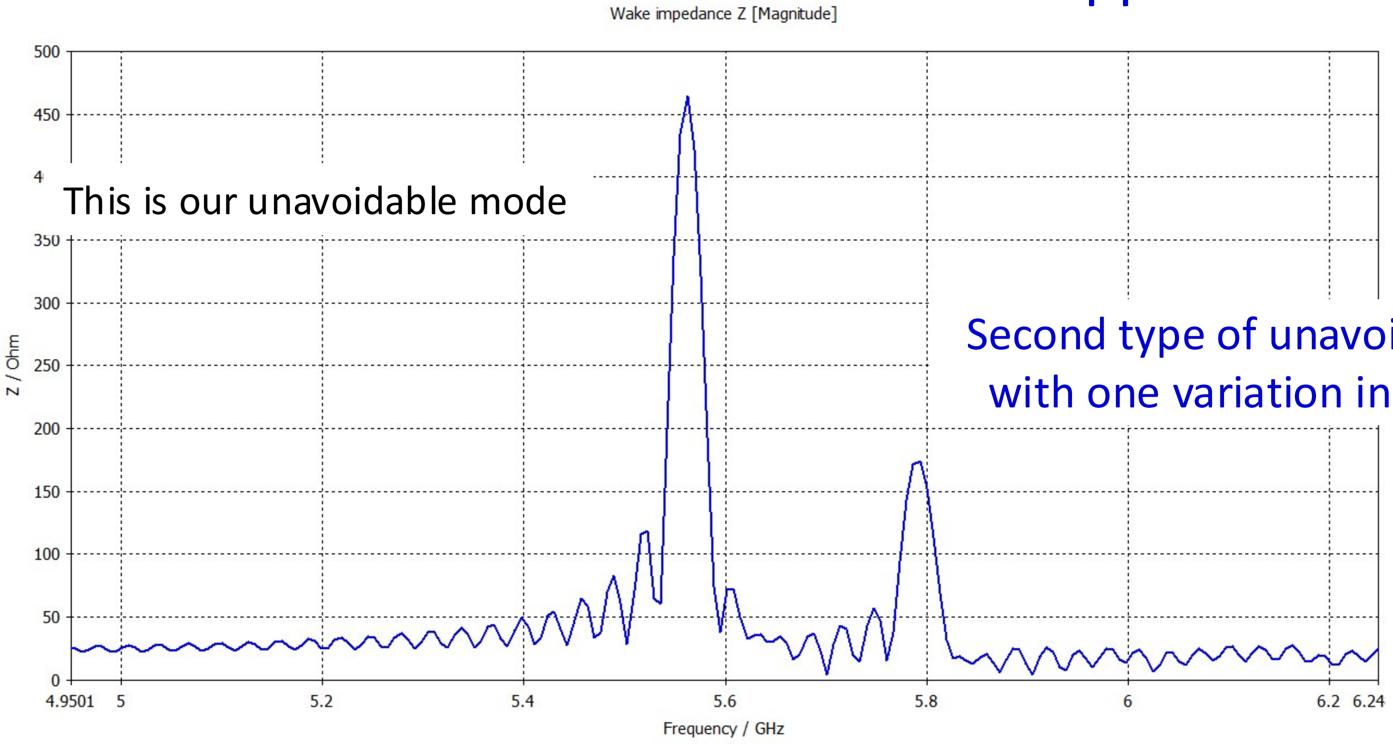
- To evaluate the electromagnetic interaction of the beam with the metal walls of the Interaction Region we calculate wake potential using CST code.
- To achieve best results in these calculations of a 10 m long interaction region we use a simplified real CAD model.
- We take away all unnecessary elements like bolts, nuts, shifts and everything that is outside of the vacuum chamber.
- As the amount of mesh points is limited, so we also need to take away all small details like sharp conners inside the vacuum chamber, of a size less than 1 mm.
- In this case we can make a good mesh with a homogeneous distribution and with a minimum as possible mesh size.
- We using CERN computers to run CST.

Wake field potential of a 15.4 mm bunch (integrated particle energy loss)



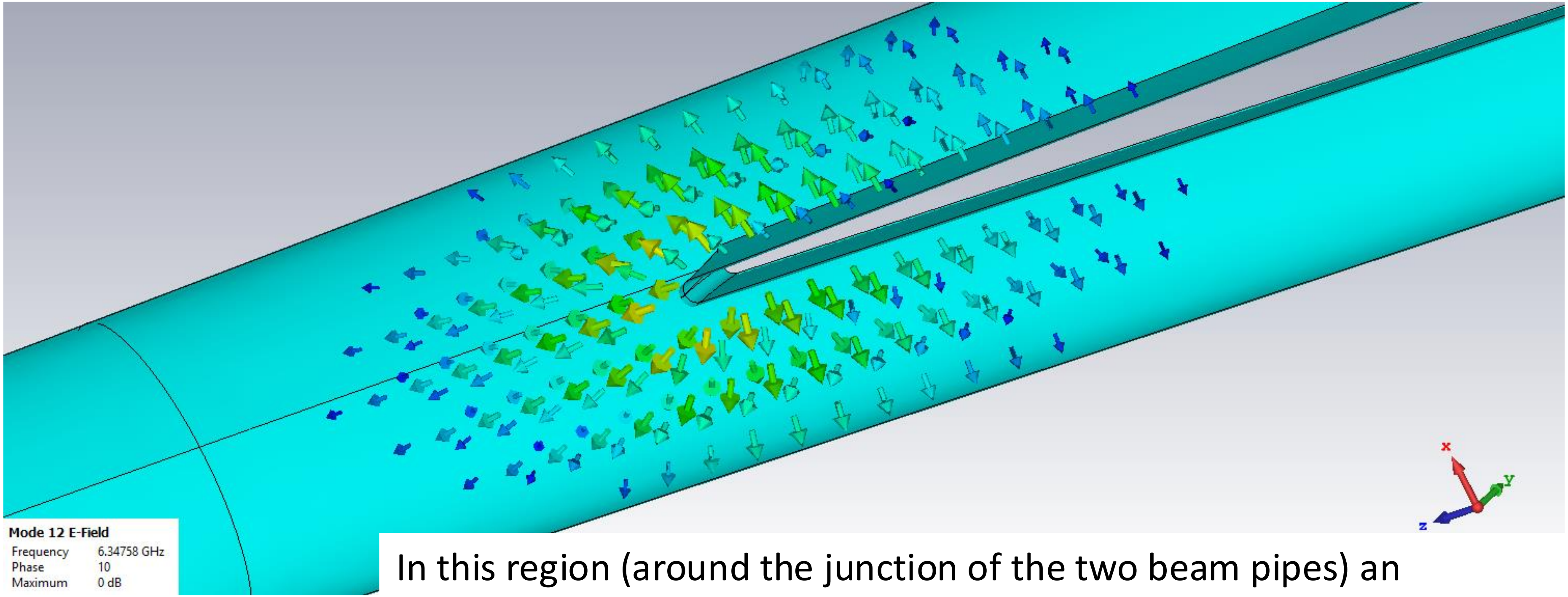
- The black line shows the beam wake potential of 15.4 mm. The beam charge density distribution is shown by the red line.
- The short part of the wake potential (around the beam distribution) contains the propagating high frequency waves and the wake fields due to resistive wall.
- The long part of the potential shows the beating waves of two trapped modes with very close frequencies

Spectrum of the wake potential
The IR chamber has two trapped modes



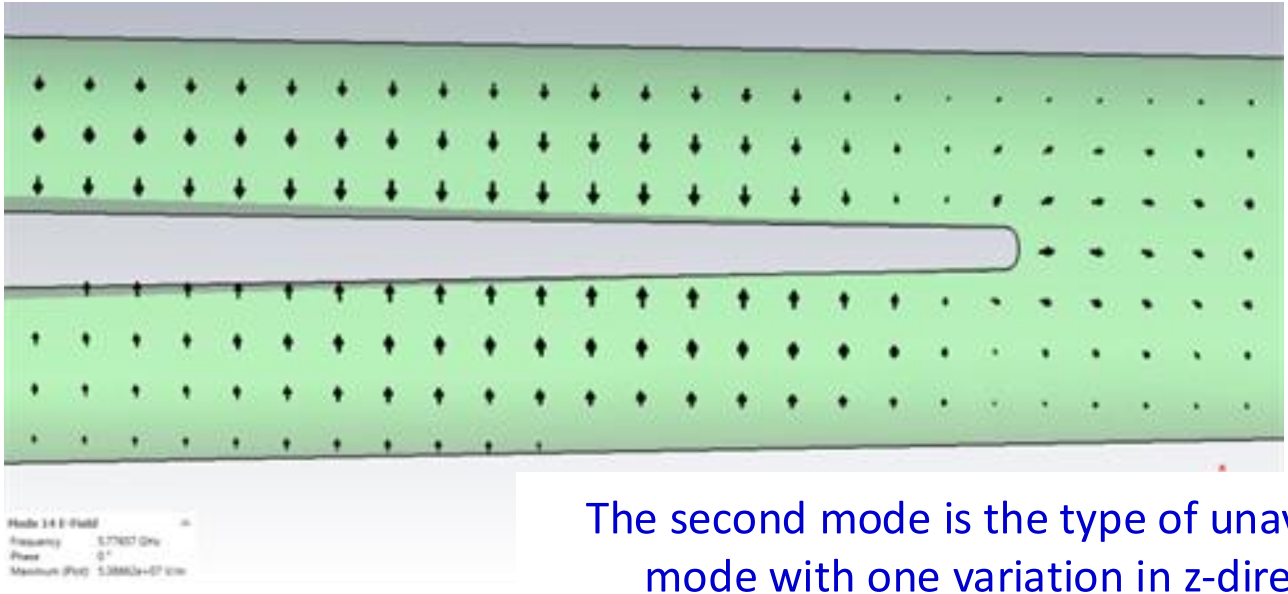
The second trapped modes appears due to lengthening the mutual pipe, needed for BPMs and bellows

The unavoidable trapped mode. Electric field distribution



In this region (around the junction of the two beam pipes) an additional heat loading may occur when some of the beam rotation harmonic is in resonance with the frequency of the trapped mode.

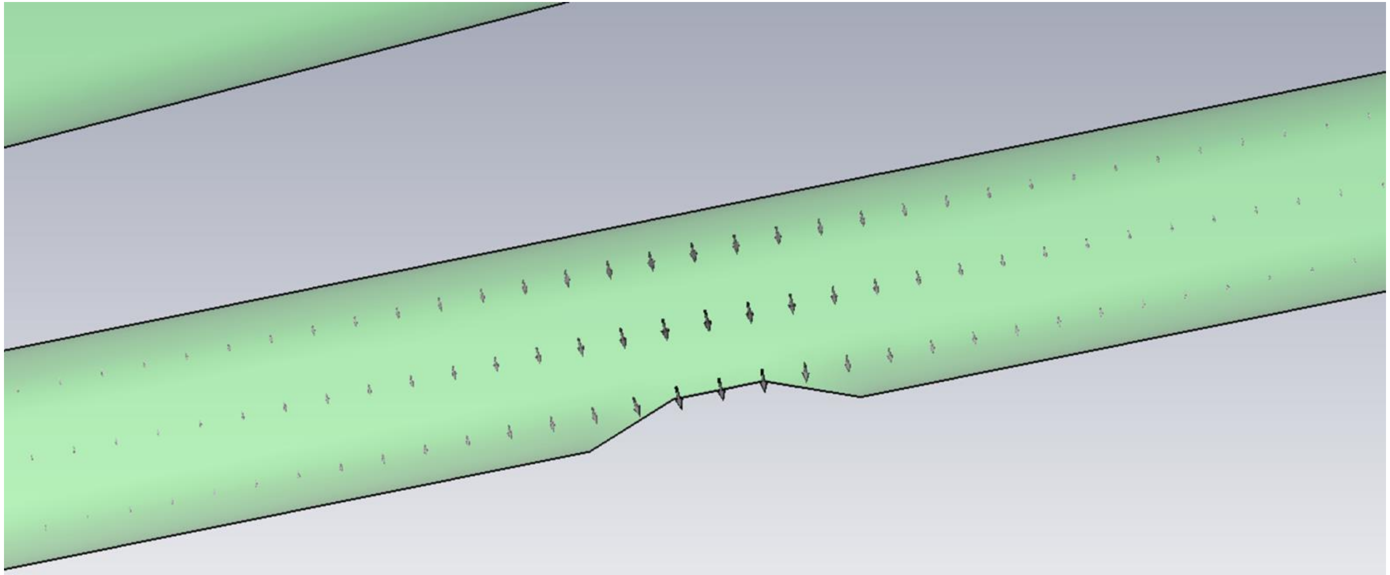
The second trapped mode



The second mode is the type of unavoidable mode with one variation in z-direction

Also, in this region an additional heat loading may occur when some beam rotation harmonic is in resonance with the frequency of the trapped mode.

Another trapped mode can be seen near the SR mask



This trapped mode can only be excited when its shape is not symmetric in the Z direction.

Heat load: electromagnetic power of the wake fields dissipated in chamber metal walls

In the electromagnetic simulation we calculate the loss factor needed to estimate the heat load. Loss factor strongly depends upon the bunch length

.

Here is a general formula to estimate the heat load from one beam

$$P = k\tau I^2$$

Power = Loss factor x bunch spacing x Current^2

$k\tau$ can be consider as an overall resistance of the beam pipe

For two colliding beams the power is usually doubled

I checked this formula practically during the PEP-II operation. It really works.

Beam Parameters available from the

FCC Feasibility Study Status
FCC Week, 10 June 2024
Michael Benedikt, Frank Zimmermann, CERN
on behalf of FCC collaboration & FCCIS DS team

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

Wake field power loss in FCC-ee Interaction Region (8.6 m long)

	Z	WW	H(ZH)	ttbar
Parameter				
beam energy [GeV]	45.6	80	120	182.5
beam current [A]	1.27	0.137	0.0267	0.0049
number of bunches/beam	11200	1780	440	60
SR energy loss per tun [MeV]	39.4	374	1890	10400
SR power loss [MW] for two beams	100.08	102.48	100.93	101.92
rms bunch length with SR/ BS [mm]	5.6 / 15.4			
Circumference [m]	90658.82	90658.82	90658.82	90658.82
average bunch spacing [ns]	28.20	177.46	717.92	5264.74
Energy beam power loss in IR [W]	**3202.51**	**234.49**	**36.03**	**8.90**
for two beams				

Where the wake fields generated in the IR, are absorbed?

- In the centrale IR beam pipe
- In the following transitions
- In the beam pipe conjunction, where trapped modes are located
- In BPMs
- In Bellows
- In beam pipes of the IR magnets located in cryo-modules
- Finally, all the rest part is absorbed in the beam pipes and vacuum elements of the FCC electron and positron rings

How much depth of the Gold coating we need for IR central pipe?

- When we coat the central beam pipe with Gold, we also decrease the heat load, because the Gold has a higher conductivity than Beryllium (ALBeMet) .
- What depth of the Gold layer is needed to make a Be pipe to be a Gold pipe?
- We can make an estimate using the electromagnetic skin depth

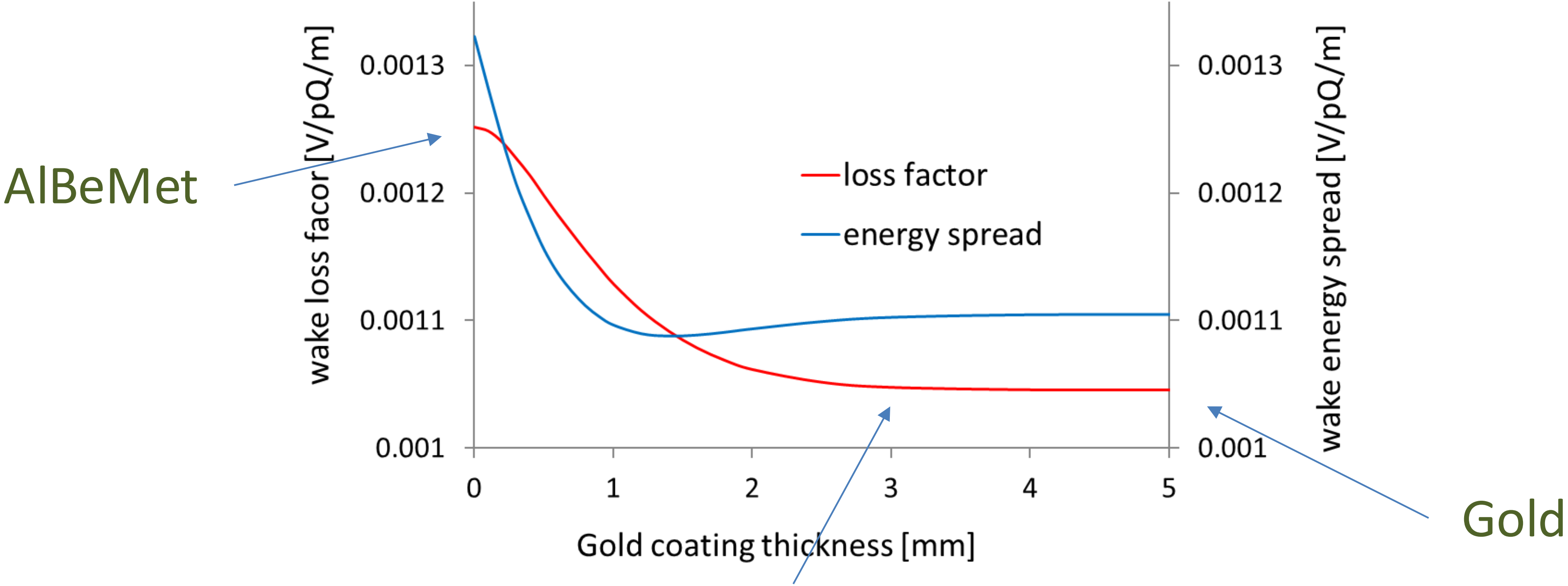
$$\delta = \sqrt{\frac{2c}{Z_0 \sigma \omega}} \qquad Z_0 = 120\pi\ [Ohm] \qquad \sigma \text{ is electrical conductivity}$$

$$\text{in our case } \frac{\omega}{c} = \frac{1}{\sigma_{bunch}} \qquad \delta = \sqrt{\frac{2\sigma_{bunch}}{Z_0 \sigma}}$$

for σ_{bunch}=15.4 mm and Gold σ=41*10^6 1/(Ohm*m)

$$\delta = 1.4\ \mu$$

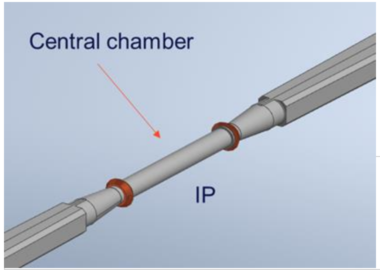
More accurate calculations show the "transition" of AlBeMet into a Gold



So, we need less than 3 micron of the Gold coating

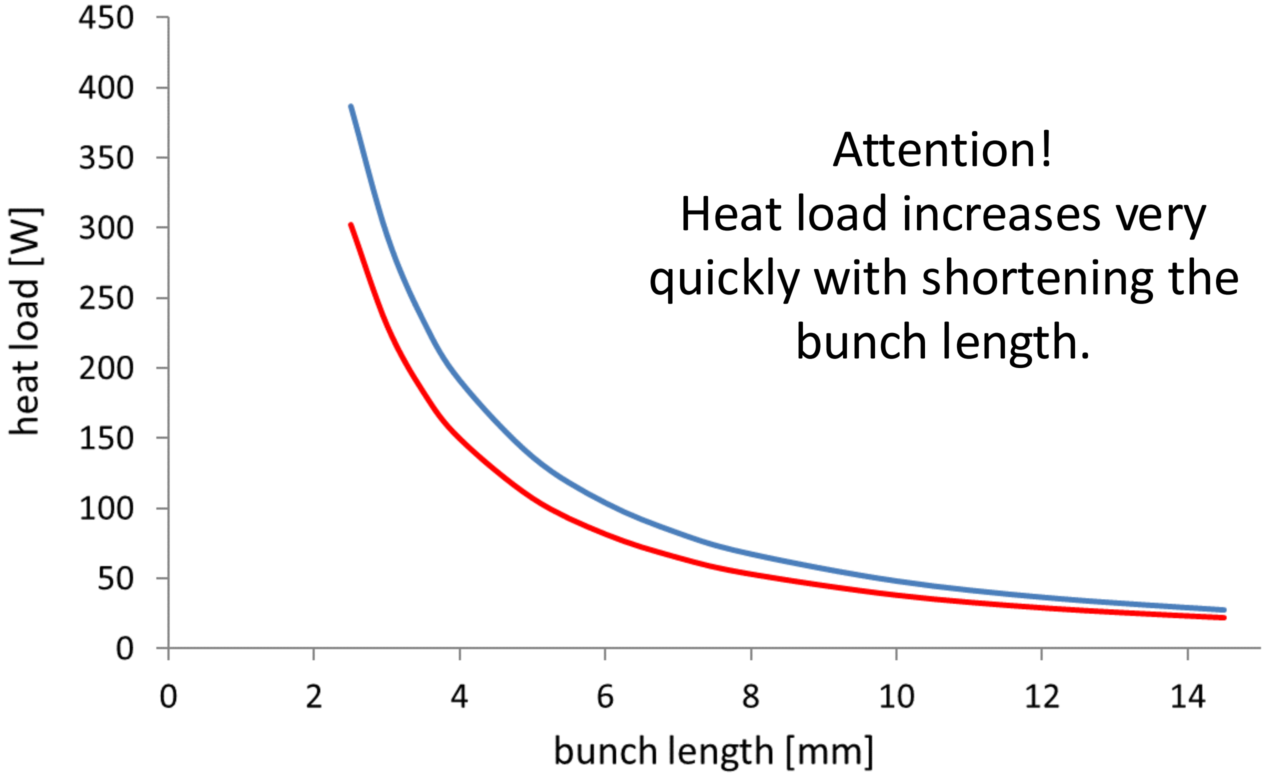
Also, we get less wake field energy spread important for beam dynamics

Heat Power (W) absorbed in the IR CENTRAL BEAM PIPE (180 mm long) for different materials



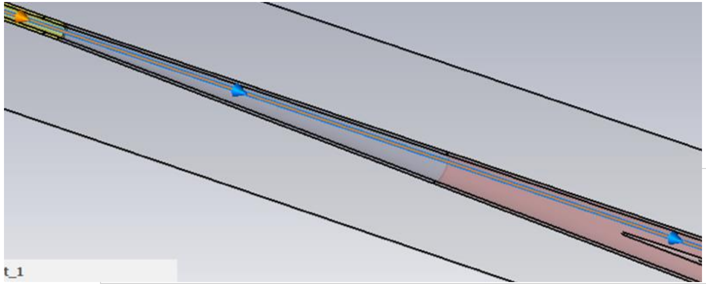
	Z	WW	H(ZH)	ttbar
Material				
AlBeMet coated by Gold	26.08	1.91	0.29	0.07
No coating. Only AlBeMet	30.75	2.25	0.35	0.09
No coating. Only Be	33.21	2.43	0.37	0.09

Heat load in the central part vs bunch length



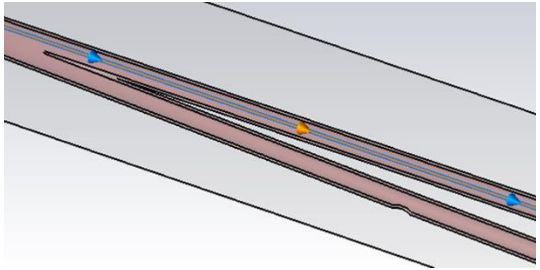
Attention!
Heat load increases very quickly with shortening the bunch length.

Heat Power (W) absorbed in the IR BEAM PIPE TRANSITION (1230 mm long) for different materials



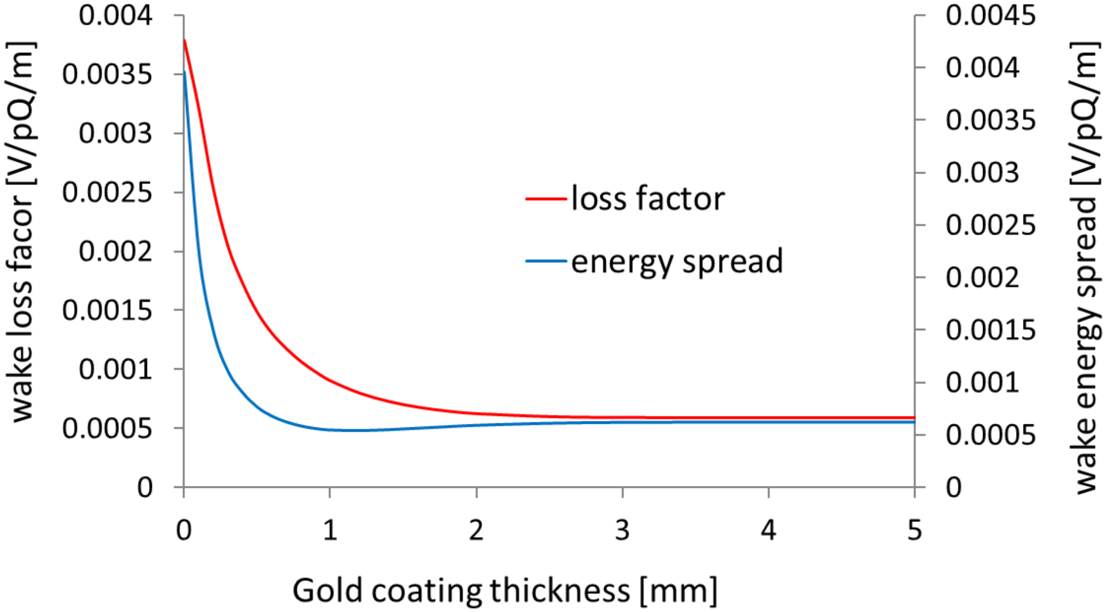
Material	Z	WW	H(ZH)	ttbar
AlBeMet	210.15	15.39	2.36	0.58
Beryllium	226.93	16.62	2.55	0.63
If we coat by Gold	178.23	13.05	2.01	0.50

Heat Power (W) absorbed in the IR CRYO-MODUL BEAM PIPE (3 m long) for different materials



	Z	WW	H(ZH)	ttbar
Material				
Stainless steel coated by 2 μ Cu	169.69	12.42	1.91	0.47
Stainless steel only	1034.19	75.72	11.64	2.87

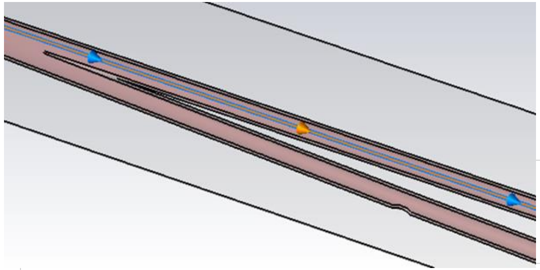
Stainless-Steel pipe coating with copper



Copper coating reduces wake field losses in a stainless-steel pipe by more than 6.5 times. We need only 2 micron of copper.

Additional wake energy spread also deceasing with copper coating

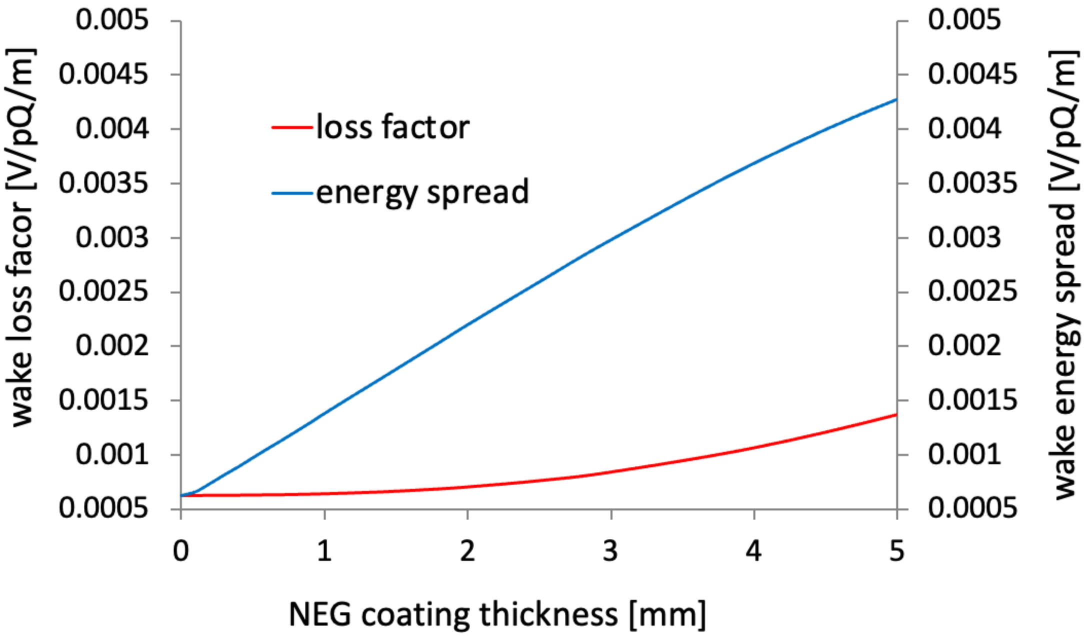
Heat Power (W) absorbed in the IR CRYO-MODUL BEAM PIPE (3 m long) for different materials



Material	Z	WW	H(ZH)	ttbar
Stainless steel coated by 2 μ Cu	169.69	12.42	1.91	0.47
Stainless steel only	1034.19	75.72	11.64	2.87
Stainless steel coated by 2 μ Cu + 2 μ NEG	190.95	13.98	2.15	0.53

If we can tolerate 190 W, then we can coat additionally by NEG and improve considerably vacuum condition in the IR

NEG on Cu on Stainless steel



- The heat load grows slowly with the NEG thickness up to 2 μ.
- Unfortunately, the beam energy spread grows linear and this is the main concern of the beam dynamics people, as it may decrease the threshold of instability.
- However, the effect from the IR is considerably smaller in comparison with the effect from the 100 km long beam pipe and can be tolerated.
- But the IR will get good pumping and good vacuum.

Summary and last remarks

- We analyzed the heat load distribution inside the IR vacuum chamber due to the wake field excitation for the last FCC-ee beam parameters and material distribution. The total wake field loss power for Z-energy is 3.2 kW which included heat power in the IR of 800 W.
- We calculated the thickness of the Gold coating in the central beam pipe necessary for decreasing the heat load. It is less than 3 micron
- We also calculated the thickness of the Copper coating on the stainless-steel pipe necessary for decreasing the heal load. It is 2 micron.
- We suggest to coat the copper coating of the stainless-steel pipe with NEG (Non-Evaporable Getter) by 2 micron. This will not bring more heat but make considerably better the vacuum condition in the FCC-ee interaction region and good for all other ring energies.

Summary and last remarks

- This work must continue, as for higher energies the bunch length is much smaller, and heat load can go up considerably.
- Unfortunately, I have lost the CAD support to perform the next very important steps in the design of the HOM absorber bellows, BPM and SR masks. These elements will bring additional beam energy losses and increase the heat load. They are important for the full study of the FCC-ee vacuum IR chamber.
- In addition, there are some important beam dynamics issues such as wake field kick near the crotch and especially in the bellows.
- I need to ask another people for the CAD design to continue this study.

Acknowledgement

We would like to thank Frank Zimmermann and John Seeman for their great support and help with this activity.

Thank you.