Beam heat load due to geometrical and resistive wall impedance in COLDDIAG

Sara Casalbuoni, Mauro Migliorati, Andrea Mostacci, Luigi Palumbo, Bruno Spataro

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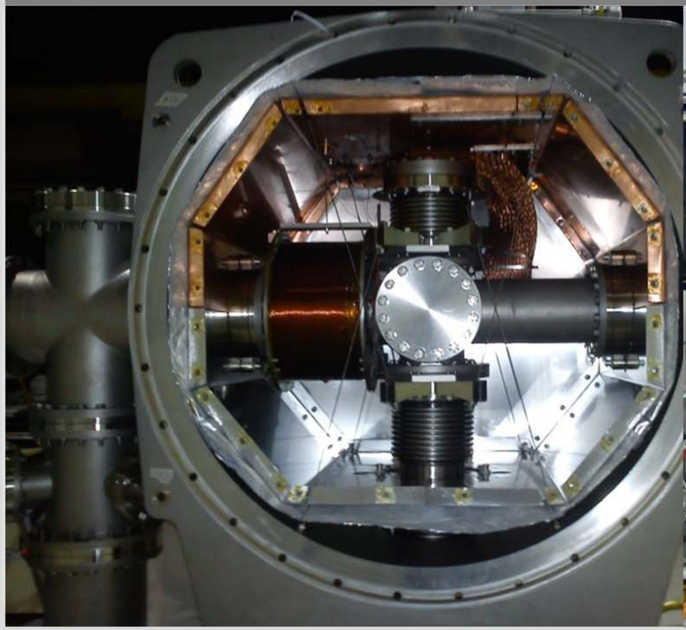

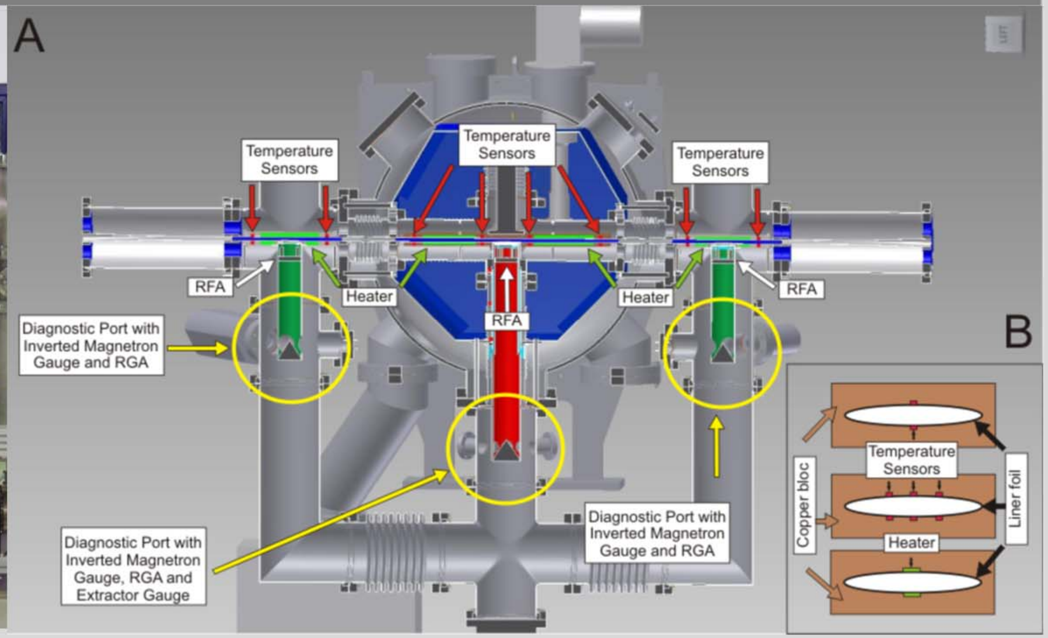

Outline

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Aim of COLDDIAG (COLD vacuum chamber for DIAGnostics)

- **Measure the beam heat load on a cold bore simulating the liner of superconducting IDs with different operating conditions**

- **Gain a deeper understanding in the beam heat load mechanisms.**

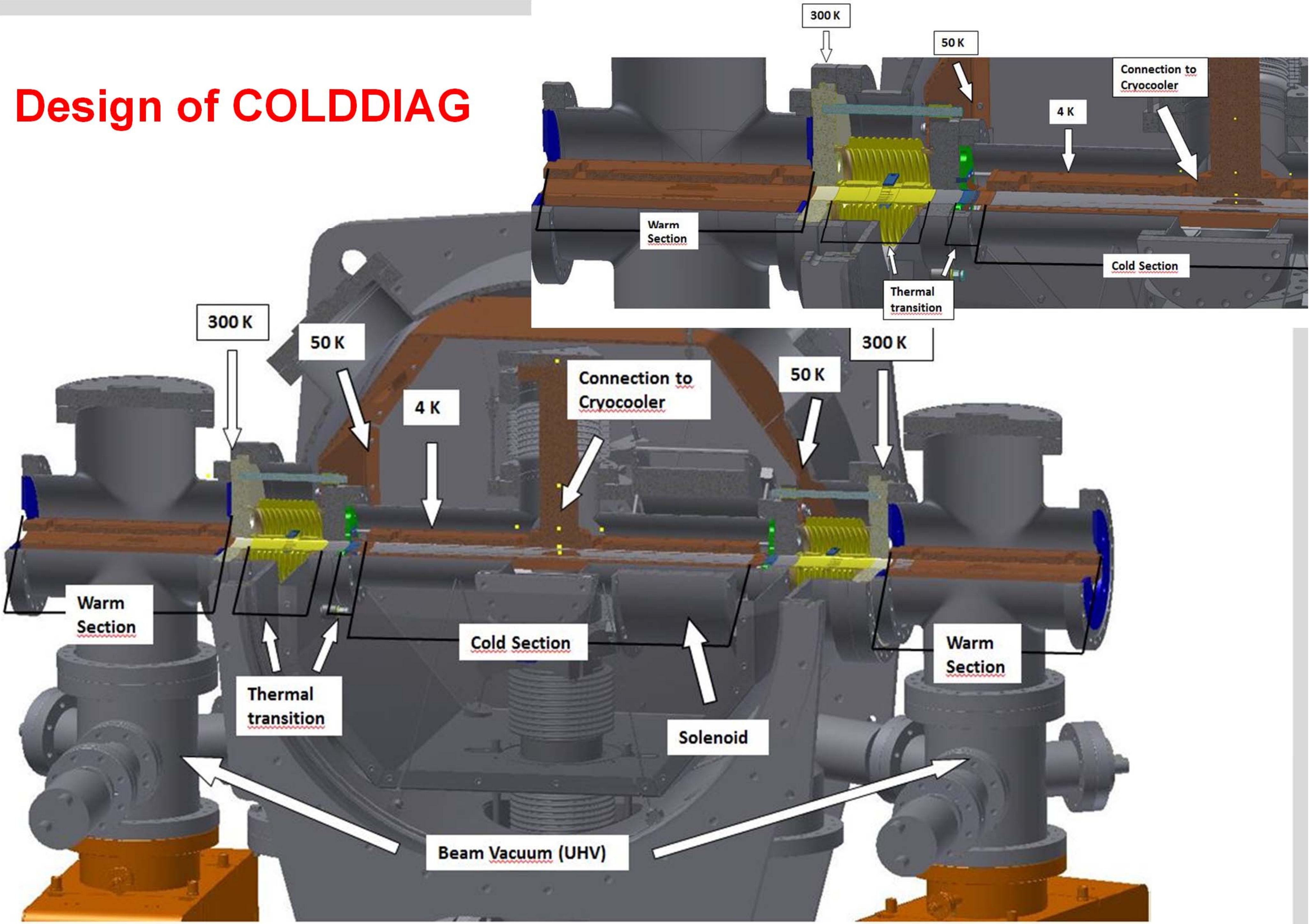
  Different mechanisms depend in different ways from parameters as beam current, energy, bunch length and filling pattern. Using this we can try to distinguish between the different mechanisms.

- **Additional diagnostics to temperature sensors including possibility to inject different gases and two warm sections to study the influence of the cryosorbed gas layer on the beam heat load.**

Possible beam heat load sources

- **Synchrotron radiation from upstream magnets**
- **Geometrical and resistive wall impedance**
- **Electron and/or ion bombardment**

Design of COLDDIAG



Design of COLDDIAG

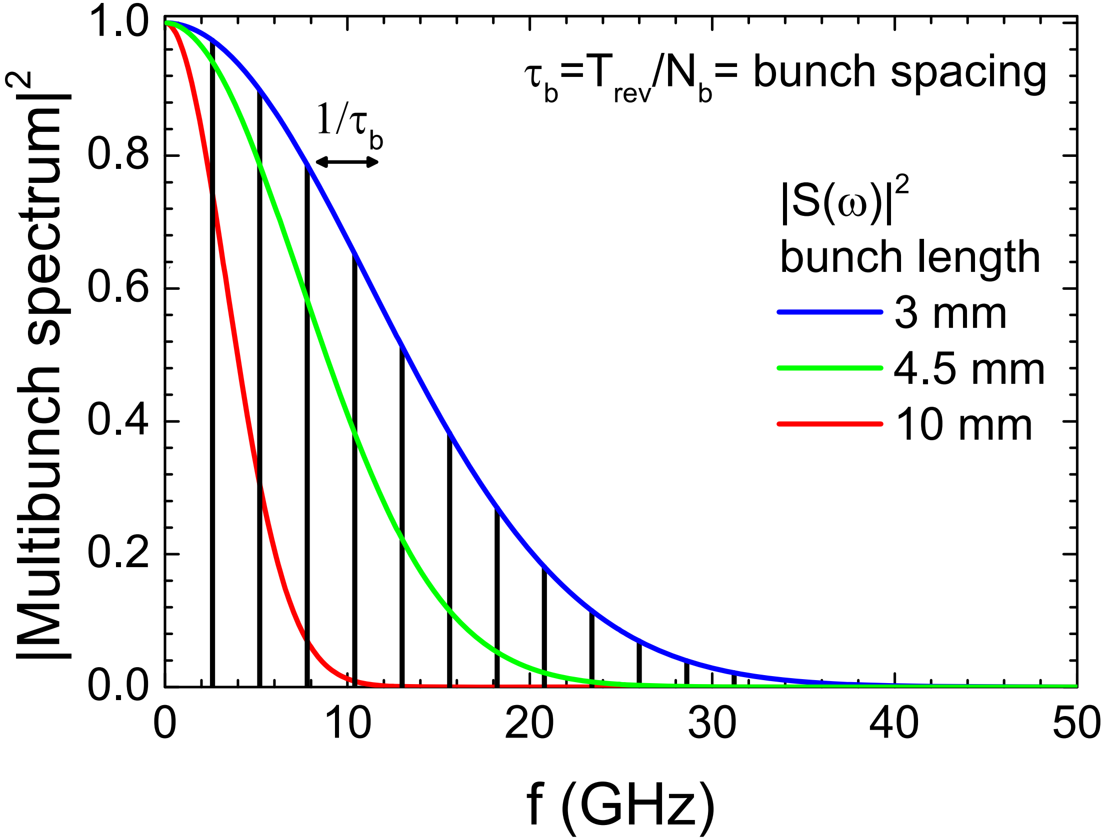
- **Two warm section to observe influence of synchrotron radiation and effect of cryosorbed gas layer**
- **Liner exchangable. Liner at DLS: Solid copper with elliptical cross section 60mmx10mm and 50 µm plated pure copper**
- **Thermal transition 4-50K: minimize heat intake to 4K => unavoidable steps due to mechanical tolerances**
- **Thermal transition 50-300K: bellows with RF fingers to compensate for thermal shrinkage**
- **Diagnostic ports to extract gas and electrons for measurements of pressure, gas content and charged particles**

A huge effort has been made to keep the mechanical tolerances below 10 µm along the middle of the beam pipe ±10 mm

Model

For equispaced gaussian bunch distribution

$$P_{\text{RF effects}} = I^2 \sum_{n=-\infty}^{+\infty} \operatorname{Re} Z_{\parallel}(nM\omega_{rev}) \exp\left(-\left(\frac{\sigma_z nM\omega_{rev}}{c}\right)^2\right) \xrightarrow[nM\omega_{rev}\to\omega]{M\omega_{rev}\to d\omega} \frac{I^2}{M} \cdot T_{rev} \cdot k_L$$



$$k_L = \frac{1}{\pi}\int_0^{\infty} \exp\left(-\left(\frac{\sigma_z \omega}{c}\right)^2\right) \cdot \operatorname{Re} Z_{\parallel}(\omega)\, d\omega$$

I = stored average beam current

M = total number of bunches per revolution

$T_{rev} = \frac{2\pi}{\omega_{rev}}$ = revolution period

Model

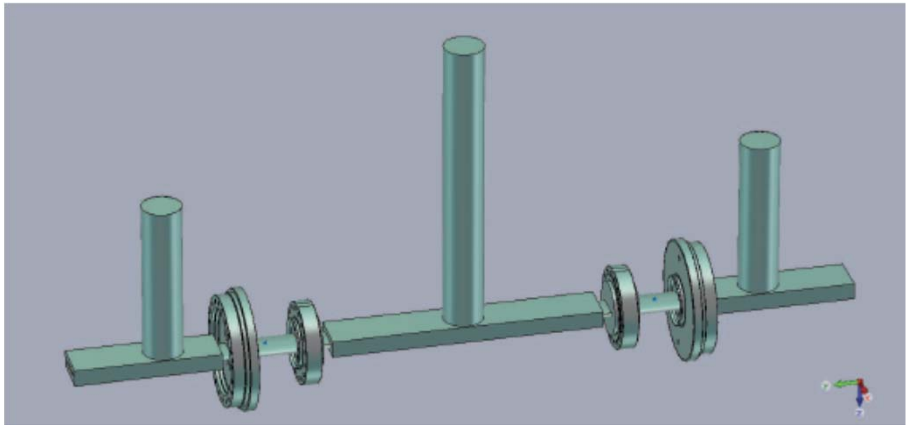
- **The total power lost by the beam represents an upper limit of the power dissipated in the structure since, excluding the case of resistive wall, it is not possible to exactly determine where this power is deposited.**

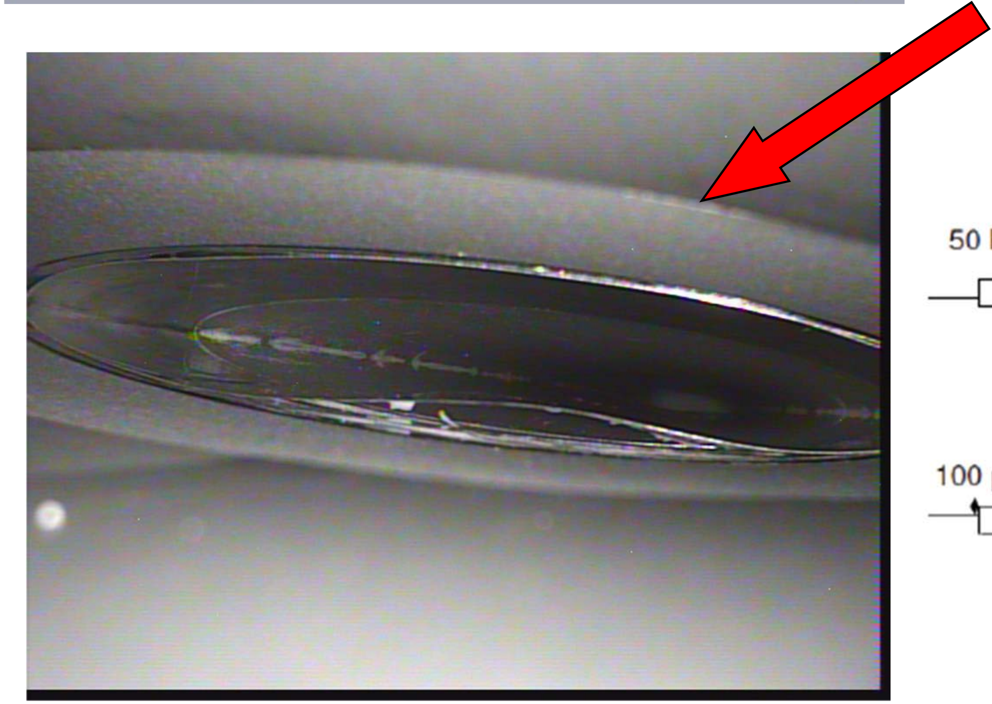
- **In the case of resistive wall the power is dissipated in the first few μm of the vacuum chamber.**

- **For wakefields induced by geometrical changes of the cross section of the vacuum chamber the power can be transferred from the beam to the vacuum pipe propagating modes, and it could be deposited in the chamber itself, could be exchanged in the interaction with other bunches, or could be deposited somewhere else in the accelerator.**

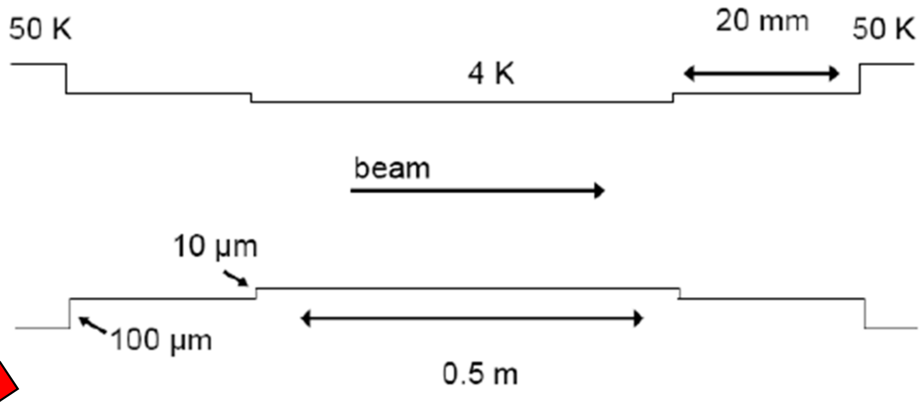
Geometry used for simulations

COLDDIAG model used in CST*

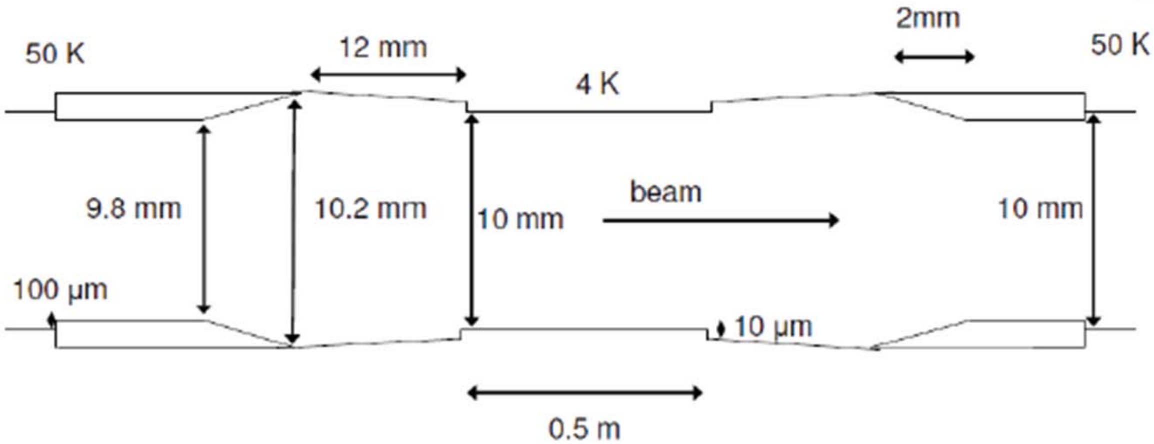




First installation



Second installation



***CST AG, Darmstadt, Germany, http://www.cst.com**

Beam parameters

- **Bunch length at the DLS for an average beam current I = 250 mA, a RF voltage V_{RF} = 2.5 MV and different filling patterns* with bunch current I_{bunch}**

N_b	I_{bunch} (mA)	σ_z (mm)
900	0.28	4.5
700	0.36	4.7
500	0.5	5.0
300	0.83	5.7
100	2.5	8.6

***G. Rehm, private communication.**

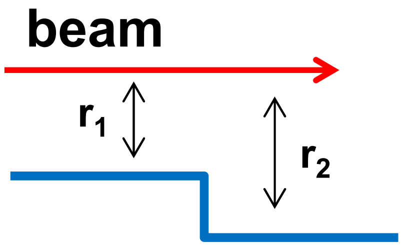
Beam power losses due to step transitions

Step in

Circular beam pipe above cut off $Re[Z_{||}(\omega)] \approx 0$

Step out

Circular beam pipe above cut off



$$R_{\text{step out}} = Re\left[Z_{||}(\omega)\right] = \frac{Z_0}{\pi}\ln(r_2/r_1)$$

Overestimation of the loss factor due to the step-out

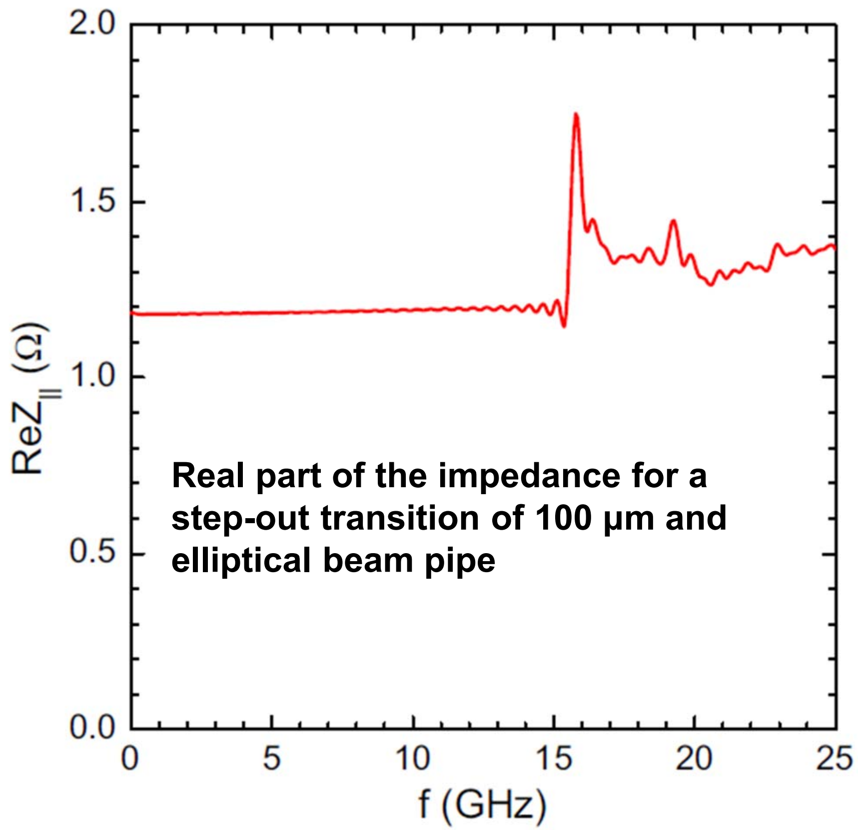
$$k_{1\ \text{step out}} = \frac{Z_0 c}{2\pi^{3/2}\sigma_z}\ln(r_2/r_1)$$

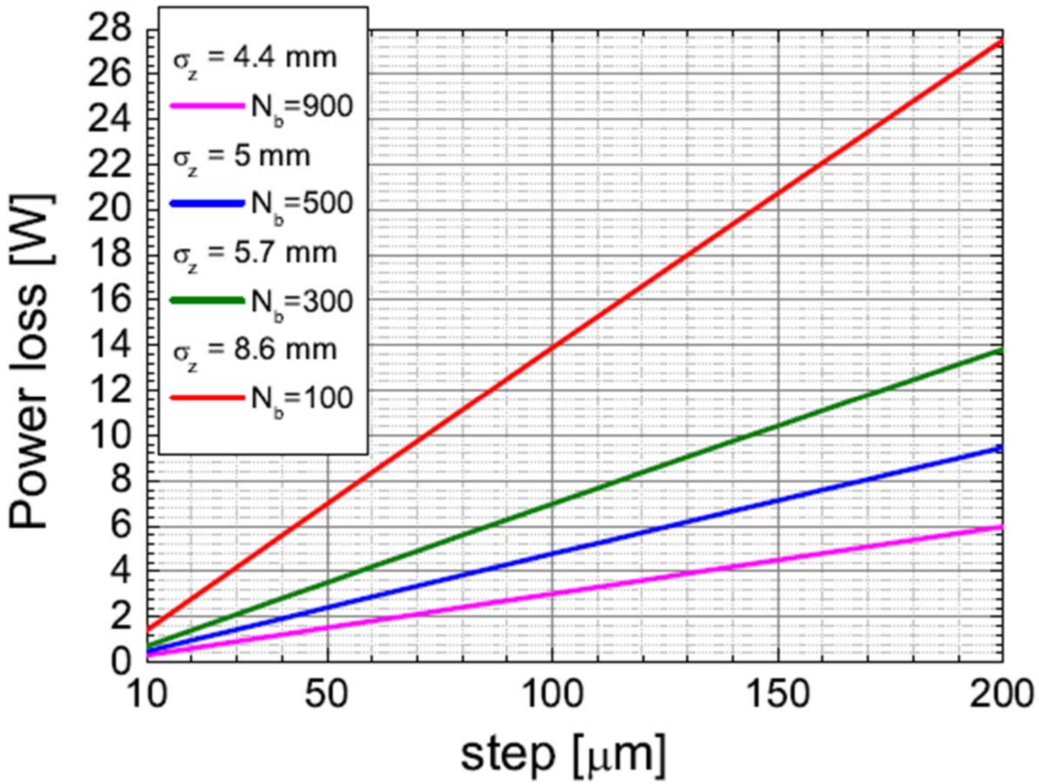
r_1= 5 mm r_2= 5.1 mm k_l=6.7x10^{-2} V/pC

r_1= 30 mm r_2= 30.1 mm k_l=1.1x10^{-2} V/pC

Beam power losses due to step transitions

No theory for step out with elliptical beam pipe.
In our case the steps are very small compared to the pipe dimensions.
Simulations could produce unreliable results due to the small dimensions of the meshes necessary for the computation, and to the limited number of them available for computer memory limitations.
Moreover, since the wakefield is very small, the effect could be hidden by the numerical noise.





The beam power losses due to the steps of 10 μm at the edges of the cold liner, that could contribute to its heating, are of the order of 1 W or less for all filling patterns.

Beam power losses due to tapers

- The total energy loss may drastically be reduced by using tapers instead of abrupt step transitions.

- For symmetric tapers with finite length, the diffraction model for short bunches (f < c/σ_z) and circular pipe predicts the following formula for the loss factor*:

$$k_{1\ \mathrm{taper}} = \frac{Z_0 c}{2\sigma_z \pi^{3/2}} (1 - \tilde{\eta}_1) \ln \frac{r_2}{r_1}$$

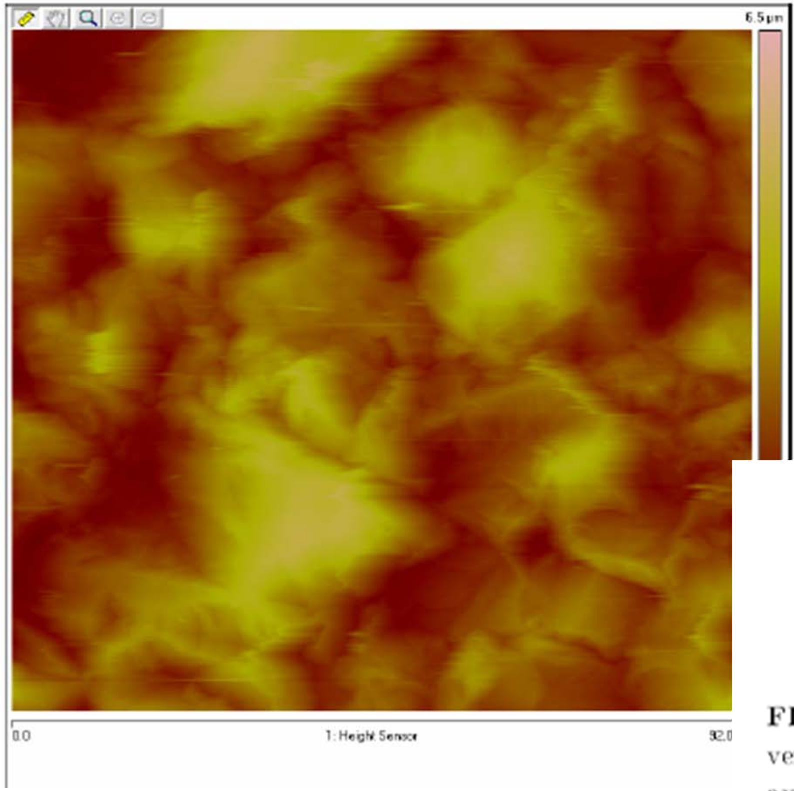
$$\tilde{\eta}_1 = Min[1, L_{\mathrm{taper}} \sigma_z / (r_2 - r_1)^2]$$

In our case $\tilde{\eta}_1$ = 1. For the worst case of the shorter taper L_{taper} = 2 mm, r_1 = 9.8 mm, σ_z= 8.6 mm, $L_{taper}\sigma_z/(r_2 - r_1)2$ = 107.5)

***S. A. Heifets and S. A. Kheifets, *Rev. Mod. Phys.* 63 (1991) 631**

Beam power losses due to surface roughness

AFM image 92 µm x 92 µm (courtesy of H. Hölscher and R. Thelen, Institute of Microstructure Technology at the KIT).



Surface of 50 µm galvanized copper

Results

Image Raw Mean	-47.5 nm
Image Mean	0.000093 nm
Image Z Range	7693 nm
Image Surface Area	10460 µm²
Image Projected Surface Area	8460 µm²
Image Surface Area Difference	23.6 %
Image Rq	1408 nm
Image Ra	1118 nm
Image Rmax	7693 nm

h~1 µm and g ~30-40 µm

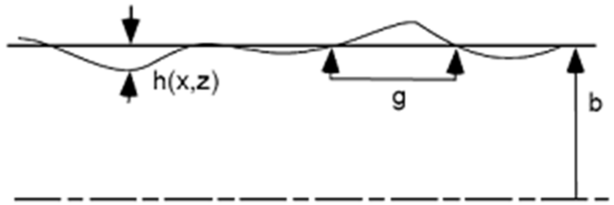


FIGURE 2. The profile of a rough surface. Shown are the height $h(x,z)$, the typical transverse size of the bumps g, and the pipe radius b. Note that the roughness here is not assumed axisymmetric. **G. Stupakov, Phys. Rev. ST Accel. Beams 1 (1998) 064401**

The bunch of few mm is too long to see the corrugation on the surface of the COLDDIAG liner. The contribution of the surface roughness to the impedance is relevant only for bunches with a length of the order of magnitude of the surface corrugations, which is not our case.

Beam power losses due to resistive wall

Resistive wall

L = length COLDDIAG

$2b$ = gap

$$\mathrm{Re}Z_{\parallel}(\omega) = \frac{L}{\pi \cdot 2b} \cdot R_{Surf}(\omega)$$

Cylindrical = Rectangular beam pipe
W. Chou and F. Ruggiero, LHC Project Note 2 (SL/AP),CERN-Geneva, 9/8/1995.
E. Wallén, G. Le Blanc, Cryogenics,44, 879 (2004).

elliptical vacuum beam pipe

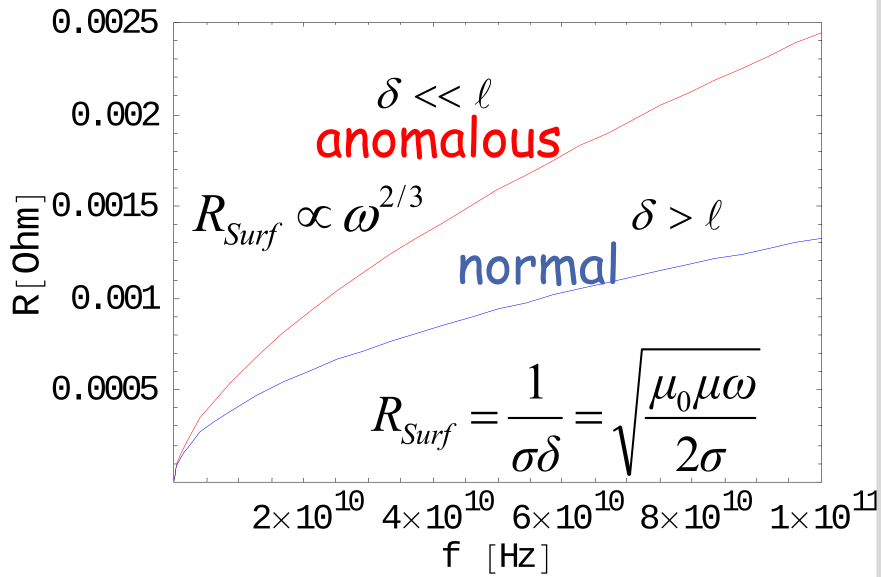
$$\mathrm{Re}Z_{\parallel}(\omega) = F(q) \cdot \frac{L}{\pi \cdot 2b} \cdot R_{Surf}(\omega) \qquad q = \frac{r_2 - r_1}{r_2 + r_1}; \quad F(q) \cong 1$$

R.L. Gluckstern, J. van Zeijts and B. Zotter, *Phys. Rev.* E 47 (1993) 656.

$$R_{Surf}(\omega) = R_{\infty}(\omega)(1 + 1.157\,\alpha^{-0.276}) \qquad \alpha \geq 3 \qquad \text{for Cu} \left(\ell / \sigma_{RT} \right) = 6.8 \times 10^{-16}\,\Omega\mathrm{m}^2$$

$$\alpha = \frac{3}{2}\left(\frac{\ell}{\delta(\omega)}\right)^2 = \frac{3}{4}\mu_r \mu_0 \sigma (4.2\,^{\circ}\mathrm{K})\,\omega \ell^2$$

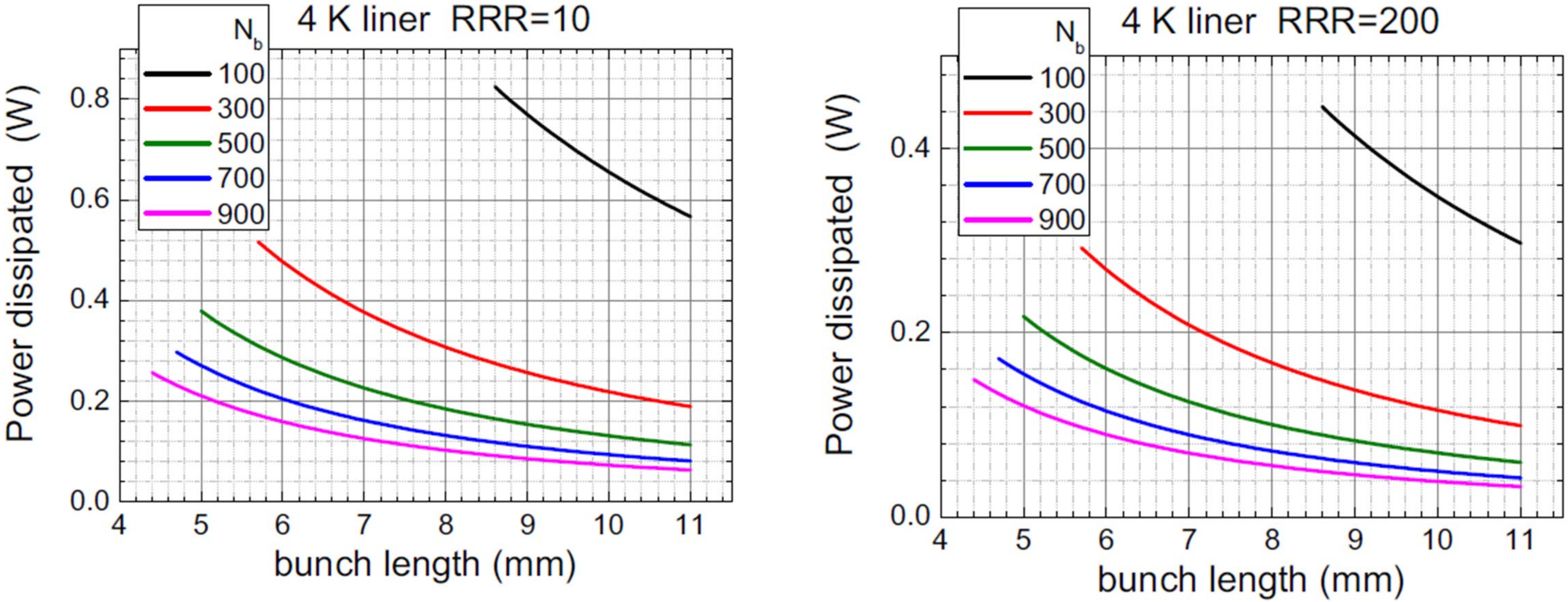
$$R_{\infty}(\omega) = \left(\frac{\sqrt{3}}{16\pi} \frac{\ell}{\sigma_{RT}} (\mu_r \mu_0 \omega)^2 \right)^{1/3} \qquad \sigma_{\mathrm{RT}} = 5.8 \times 10^7\,\Omega^{-1}\mathrm{m}^{-1}$$



- **H. London, Proc. Royal Society (London), A176, 522 (1940).**
- **A.B. Pippard, Proc. Royal Society (London), A191, 385 (1947).**
- **G.E.H. Reuter and E.H. Sondheimer, Proc. Royal Society (London), A195, 336 (1948).**
- **R.G. Chambers, Proc. Royal Society (London), A215, 481 (1952).**

Beam power losses due to resistive wall

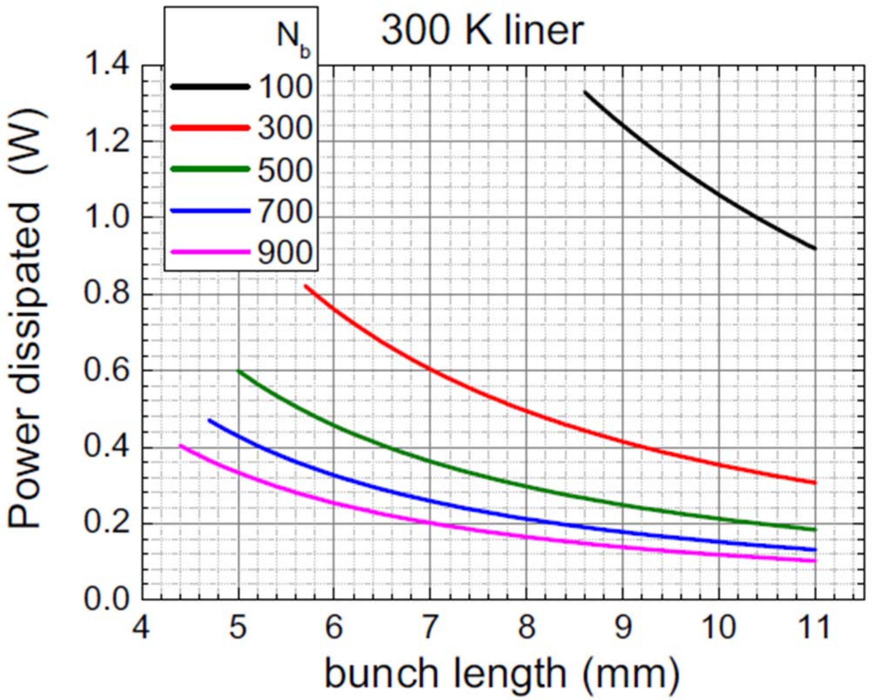
The beam heat load due to the resistive wall impedance in 0.5 m long cold liner as a function of the bunch length, for different filling patterns and for *I* = 250 mA.

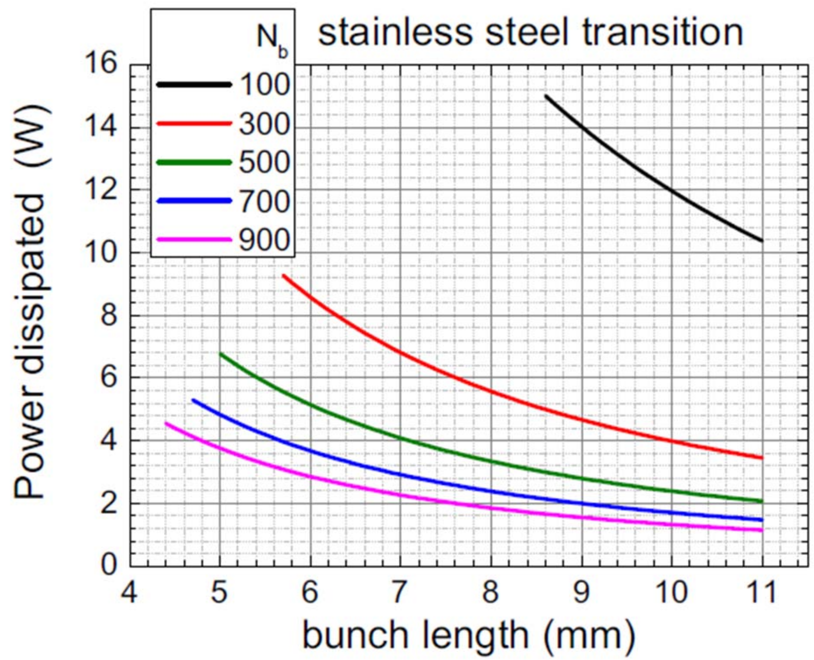


In the cold liner the power dissipated due to resistive wall heating is for all filling patterns below 1 W

Beam power losses due to resistive wall

The beam heat load due to the resistive wall impedance on <u>each of the warm liners 0.27 m</u> long and in the <u>stainless steel transition parts from 50 K to 300 K, 0.4 m</u> long, as a function of the bunch length, for different filling patterns and for *I* = 250 mA.

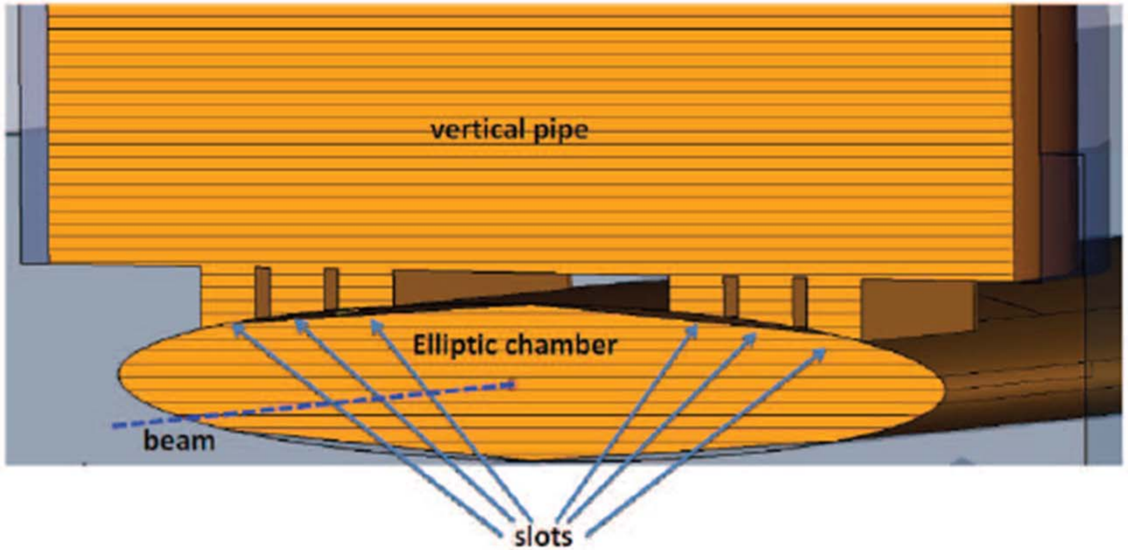


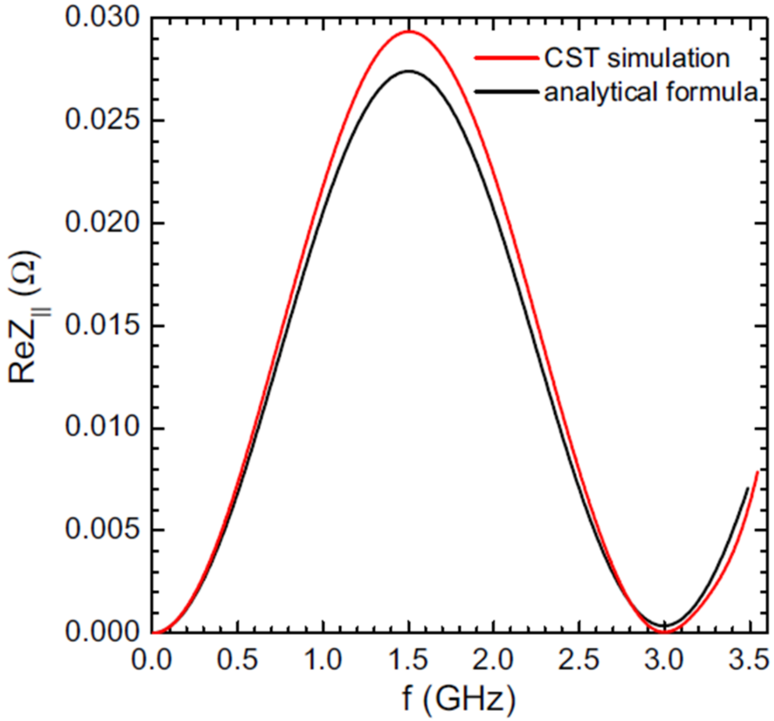


In the warm parts, even if shorter, the losses are higher, but still below 1.5 W.
The dissipated power in the stainless steel sections reaches at maximum 15 W but it is intercepted by the 50 K shield. It is then cooled down by the first stage of the cryocooler, which is loaded with about 30 W with no beam and has enough cooling capacity.

Beam power losses due to coupling slots

Analytical expression not existing in the literature, so CST simulations have been performed.





CST simulations are, in this situation, very subtle due to the high number of required meshes and to the low value of resulting impedance and loss factor that could be strongly affected by numerical noise.

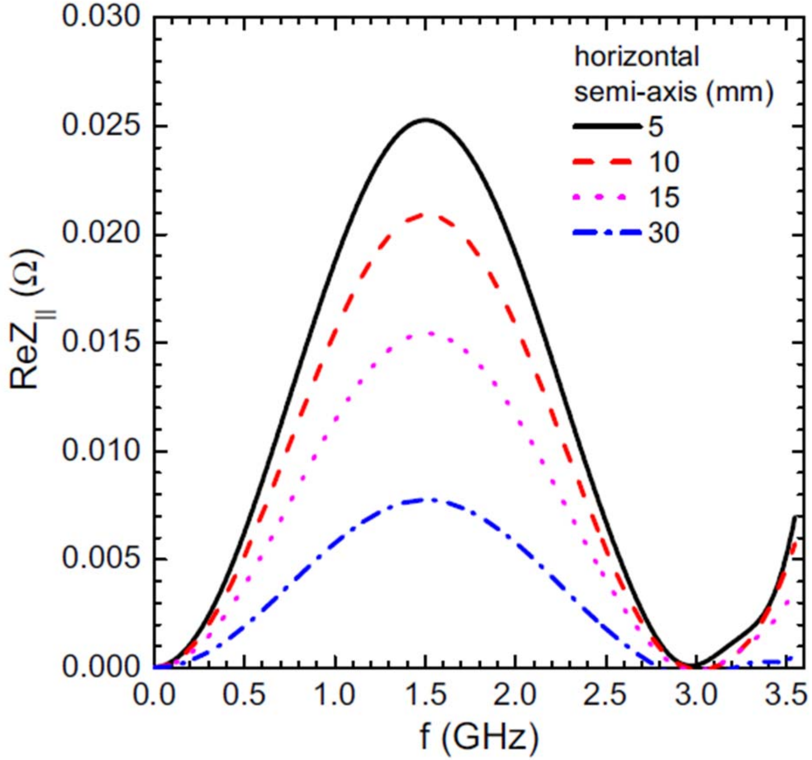
For this purpose we have divided the problems into three separate and consequential steps.

First step:
circular coaxial geometry with an internal pipe of radius b = 5 mm, an external pipe of radius d = 1 cm, with a slot L = 5 cm long and w = 4 mm wide, and with a bunch 5 cm long.

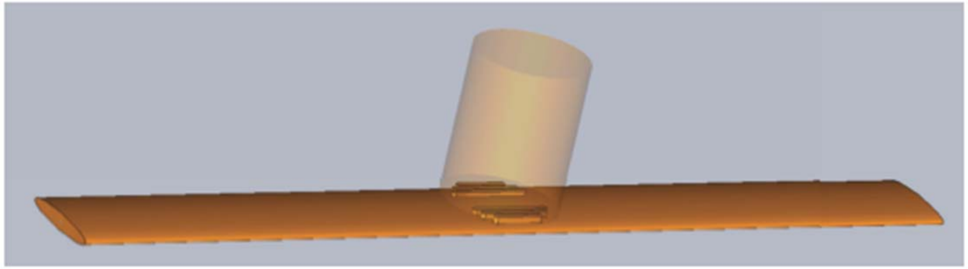
Analytical formula from:
S. De Santis, A. Mostacci, L. Palumbo and B. Spataro, Phys. Rev. E 58 (1998) 6565.

Beam power losses due to coupling slots

Second step:
modified ellipticity of the vacuum chamber



Third step:
real geometry



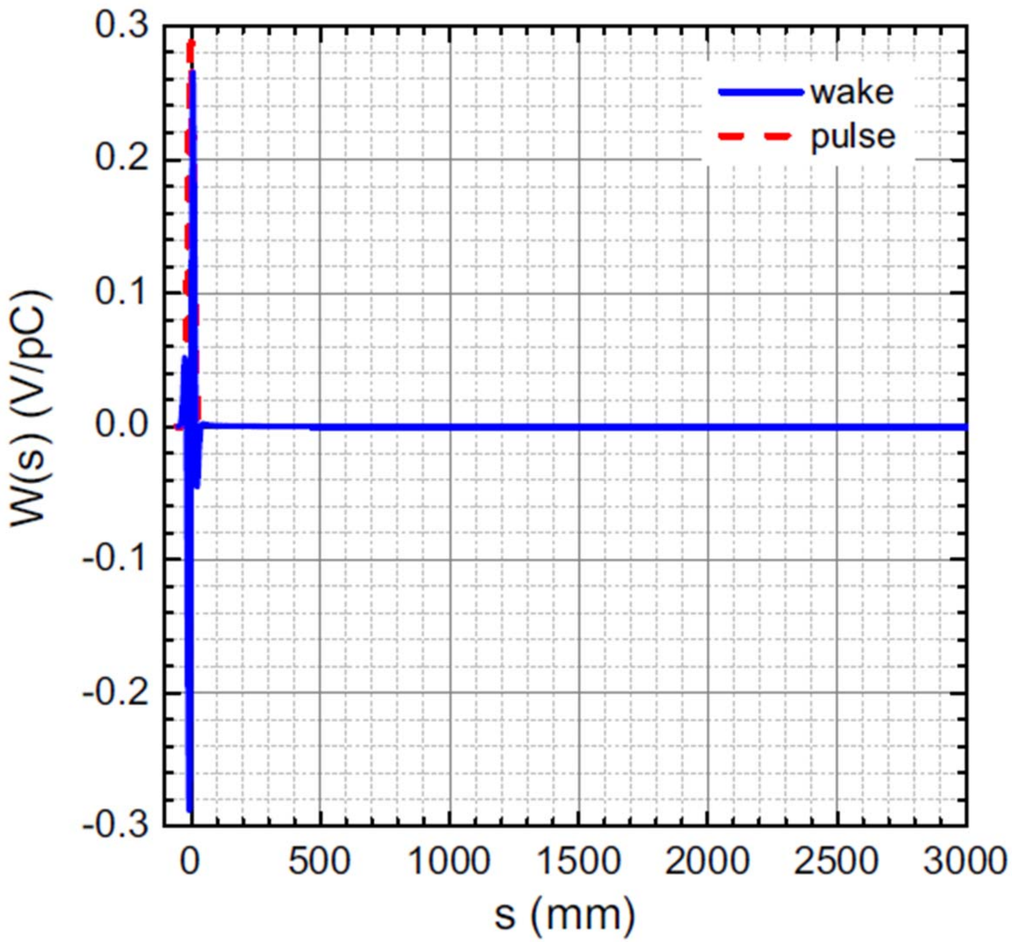
With a 5 mm Gaussian bunch, the power lost is always smaller than 4 mW for all filling patterns.

The losses and the consequent beam heat load due to the slots can be neglected in comparison to those due to the resistive wall and step transitions.

Long range wake fields

Existence of trapped resonant modes with high quality factor?

Longitudinal, long range wake potential for the entire COLDDIAG structure for a 1 cm bunch length.



Even if, with such a configuration, mesh problems show up, we wanted to understand if a perturbation in the wake behavior could suggest the existence of trapped resonant modes with high quality factor.

No trapped modes are excited by a 1 cm bunch length, since the wakefield behind the bunch is zero.

Simulations in the frequency domain with CST have confirmed the above results.

Conclusions

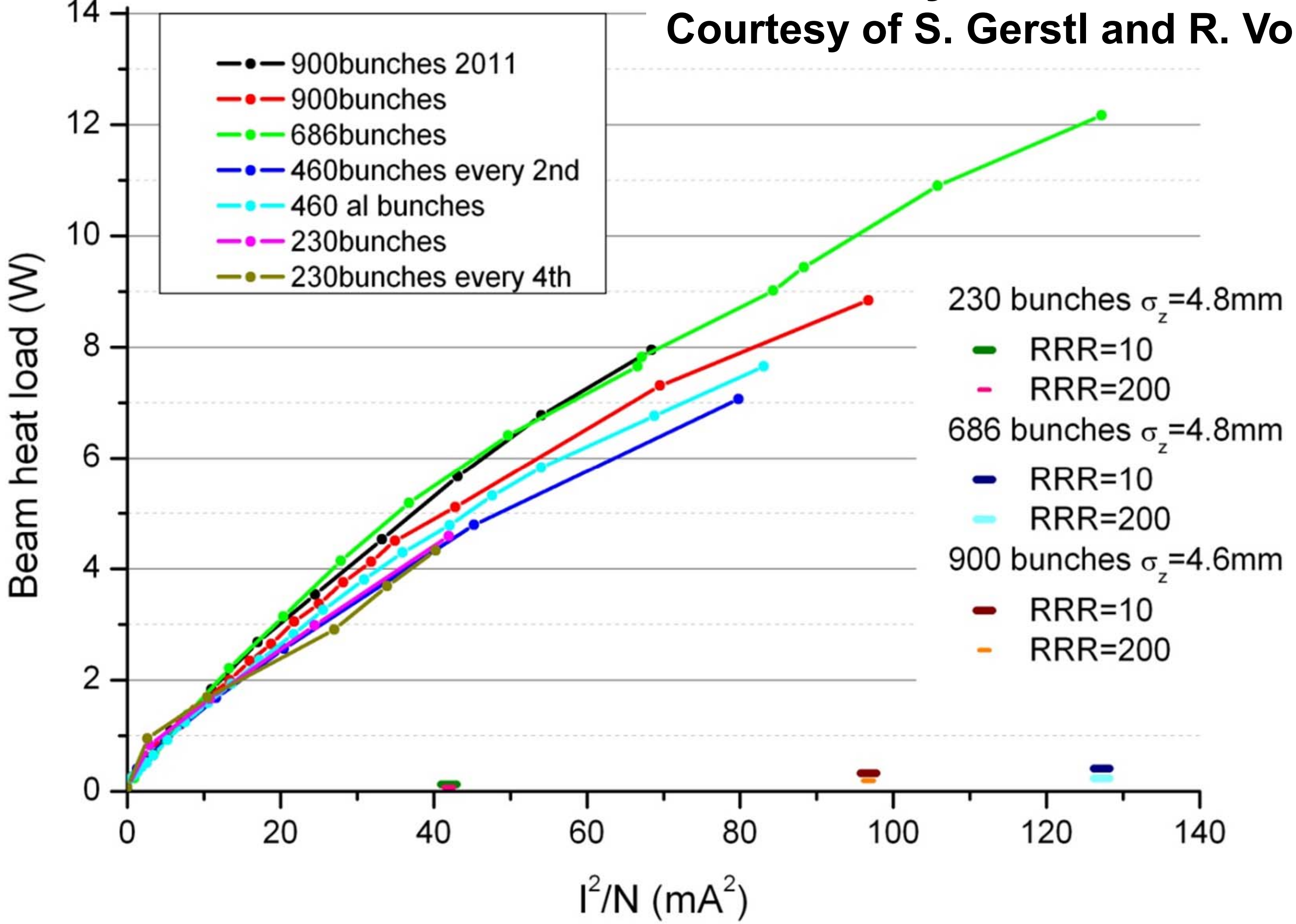
Karlsruhe Institute of Technology

- **Analytical results and numerical simulations of the beam heat load contribution due to geometrical and resistive wall impedances to the COLDDIAG installed at the DLS.**
- **Impedance contribution from the surface roughness and tapers negligible.**
- **Cold liner:**
  - **<u>Step</u>. An upper limit of about 1.5 W of a possible power dissipated on the cold liner has been estimated for the worst case of 100 bunches. <u>This power is not necessarily dissipated in the step.</u>**
  - **<u>Resistive wall.</u> For all filling patterns below 1 W.**
- **Warm regions:**
  - **<u>Steps</u> of 100 µm originated by the connection of the copper liner to the outer flanges, a maximum contribution of 14 W for 100 bunches and of 3 W for 900 bunches, is expected.**
  - **<u>Resistive wall.</u> For all filling patterns below 1.5 W.**
- **Stainless steel thermal transition sections:**
  - **<u>Resistive wall.</u> Maximum dissipated power of 15 W for 100 bunches, but the 50 K shield should be able to intercept the corresponding beam heat load.**
- **Power losses of the pumping slots included in the structure are negligible and <u>no resonant mode is trapped in the structure</u>.**

Outlook

Preliminary data !

Courtesy of S. Gerstl and R. Voutta



- **From these preliminary data, we would conclude that the beam heating due to geometrical and resistive wall impedances is not the main mechanism responsible for the beam heat load.**

Outlook

- **The COLDDIAG measurements and their analysis is work in progress and will continue both on the experimental and theoretical sides.**

  - **The electron/ion cloud effects should be investigated in detail.**

  - **A dedicated calibration without beam to study the influence of the increase in temperature of the shield on the temperature of the liner could be performed.**

  - **Sensitivity analysis study on mechanical tolerances that could destroy some hypothesis under which the results of beam heat load due to geometrical and resistive wall impedance have been obtained, as, for example, the presence of asymmetry in the tapered sections and in the steps.**

Acknowledgments

Thanks to:

N. Glamann and S. Gerstl (KIT) for providing the different CAD models used in the numerical simulations

R. Bartolini (DLS) for the informations on the beam parameters and different operation modes of the DLS

G. Rehm (DLS) for useful discussions, in particular for suggesting to include the effects of the surface roughness

Thank you for your attention!