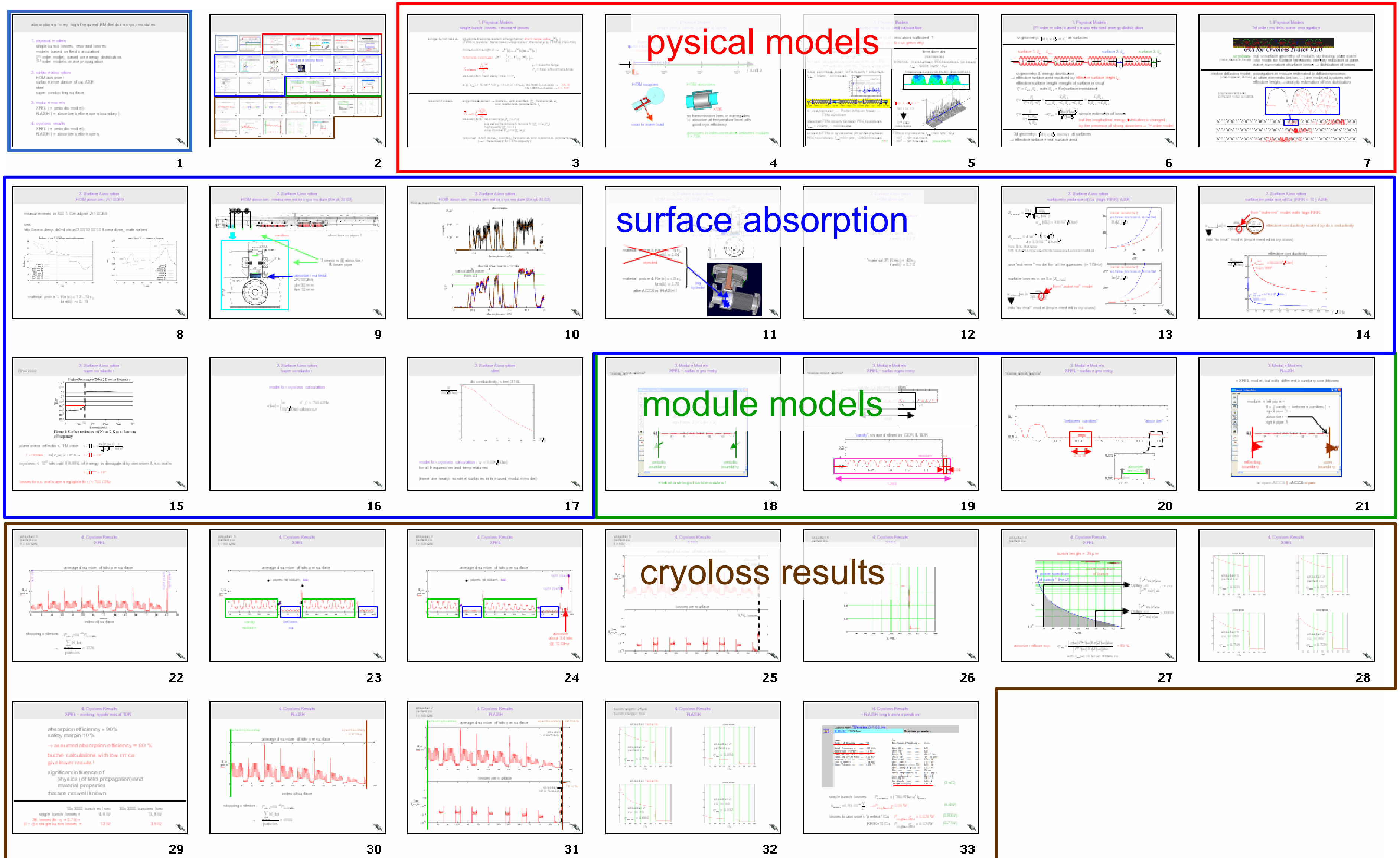
absorption of very high frequent EM-fields in cryo-modules

1. physical models
   single bunch losses, resonant losses
   models based on field calculation
   0^{th} order model: based on energy distribution
   1^{st} order models: wave propagation

2. surface absorption
   HOM absorber
   surface impedance of cu; ASE
   steel
   super conducting surface

3. module models
   XFEL (= periodic model)
   FLASH (= absorber before open boundary)

4. cryoloss results
   XFEL (= periodic model)
   FLASH (= absorber before open



pysical models
surface absorption
module models
cryoloss results
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1. Physical Models
single bunch losses, resonant losses

single bunch losses:

asymptotic approximation of longitudinal short range wake $w^{(\delta)}(s)$
(TESLA module: Novokhatski, Zagorodnov, Weiland; e.g. TESLA 2003-19)

finite bunch length $\sigma \rightarrow \quad w^{(\sigma)}(s) = \lambda^{(\sigma)}(s) \otimes w^{(\delta)}(s)$

total loss parameter $k_{\text{tot}}^{(\sigma)} = -\frac{1}{c}\int w^{(\sigma)}(s)\lambda^{(\sigma)}(s)ds$

$$P_{\text{single bunch}} = \frac{q^2 k_{\text{tot}}^{(\sigma)}}{T_b}$$

q = bunch charge
T_b = time of bunch distance

assumption: field decay time >> T_b

e.g. $k_{tot} \approx 1.53\cdot 10^{14}$ V/C, $q = 1$nC, $\sigma = 25\mu$m, 10x3000 bunches/sec $\rightarrow$ 4.6 W
30x3000 bunches/sec $\rightarrow$ 13.8 W

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resonant losses:

eigenmode solver $\rightarrow$ modes ν with qualities Q_ν, frequencies ω_ν
and modal loss parameters k_ν

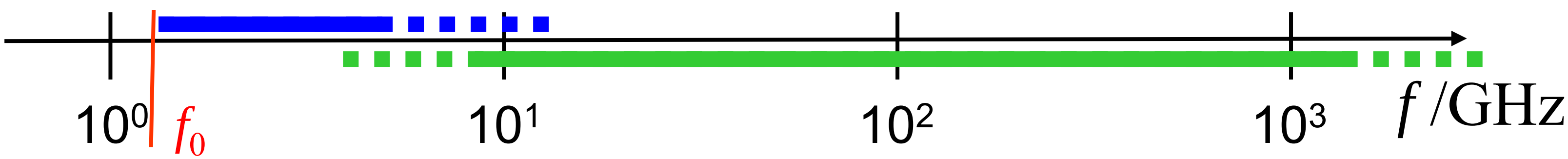
$$\overline{P}_{\nu,\text{res}} \approx I_b^2 \frac{4Q_\nu k_\nu}{\omega_\nu}$$

assumptions: resonance ($\omega_\nu T_b = n2\pi$)
low decay from bunch to bunch ($Q_\nu >> \omega_\nu T_b$)
high quality ($Q_\nu >> 1$)
long rf pulse ($T_{\text{rf}} >> 2Q_\nu/\omega_\nu$)

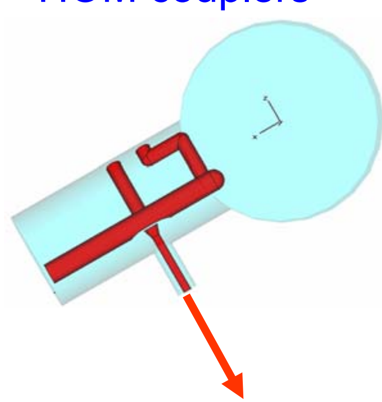
required: list of modes, qualities, frequencies and modal loss parameters
($\rightarrow$ J. Sekutowicz for TESLA cavity)

trapped &
quasi trapped modes:
~ resonant effects

propagating modes
~ single bunch effects

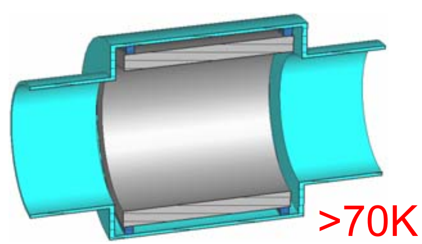


HOM couplers



coax to warm load

HOM absorbers



no transmission lines or waveguides
⇒ absorber at temperature level with
good cryo efficiency

absorbers in interconnections between modules
T > 70K

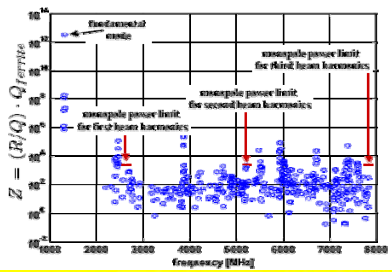
1. Physical Models
models based on field calculation

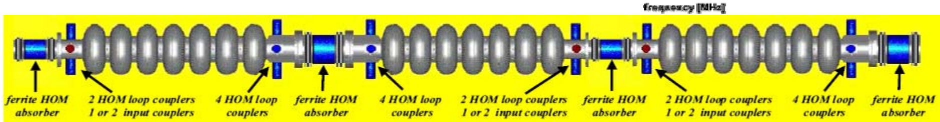
model with symmetry of revolution sufficient ?

doable (if at all) only for rz-geometry

eigenmode analysis (monopoles)	time domain (monopoles)
M.Liepe: Conceptual Layout of Cavity String ... ERL ...; 11th workshop of RF SC, Travemuende, 2003	M.Dohlus: 3 cells between PEC boundaries (no losses) t_{max} ~ 1000/1.3GHz ~ 1μs

lossy eigenmode solver; 3x7cell-cavity + absorbers:
f_{max} = 8GHz; ~ 400 modes

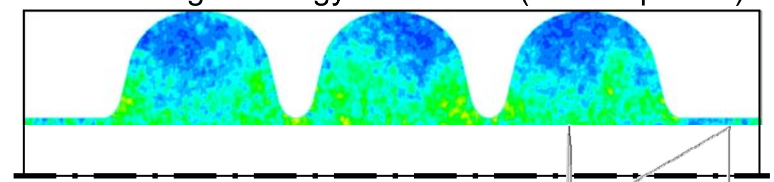




A. Joestingmeier, …: Photon Diffusion Model … TESLA 2000-11

idealized TESLA cavity between PEC boundaries:
f_{max} = 20 GHz; ~ 1400 modes

time averaged energy distribution (few snapshots)

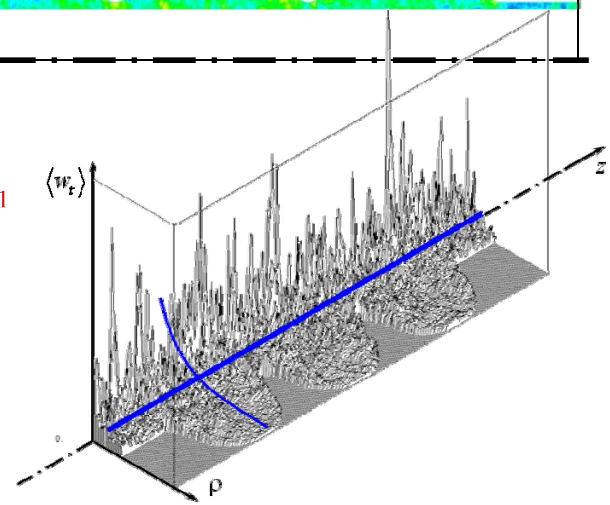


$\langle w(r,z,t)\rangle_t \propto r^{-1}$

for $r/\lambda >> 1$

↓

0th oder loss model



scaled to TESLA cryo-module (8 cavities) between PEC boundaries: f_{max}=100 GHz; ~ 280000 modes ???	TESLA cryo-module, f_{max}=100 GHz, 10μs ~ 10^7 … 10^8 meshcells ~ 10^7 … 10^8 timesteps **possible !!!**

0^{th} order model: based on unperturbed energy distribution

rz geometry: $\langle w(r,z,t)\rangle_t \propto r^{-1}$ at surfaces

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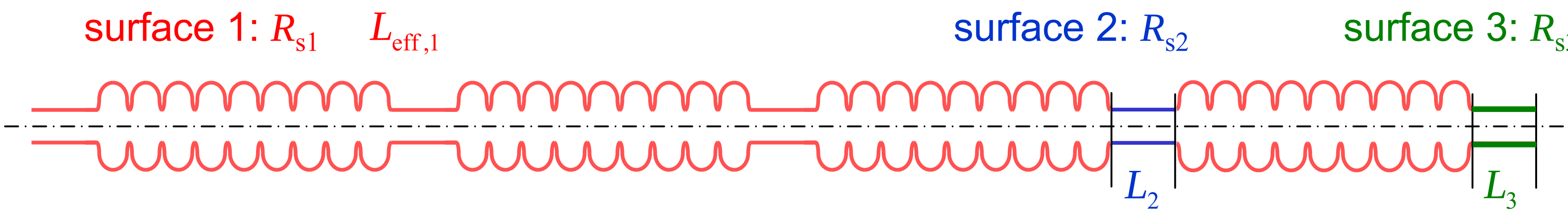

rz-geometry & energy distribution

$\rightarrow$ effective surface area replaced by effective surface length L_{eff}

effective surface length = length of surface in rz cut

$P_\nu \propto L_{eff,\nu} R_{s,\nu}$ with $R_{s,\nu}$ = Re{surface impedance}

$$\eta = \frac{P_3}{P_1 + P_2 + P_3} = \frac{L_3 R_{s,3}}{L_{eff,1} R_{s,1} + L_2 R_{s,2} + L_3 R_{s,3}} \approx \frac{L_3 R_{s,3}}{L_2 R_{s,2} + L_3 R_{s,3}}$$

$$\eta \approx \frac{1}{1 + \dfrac{L_2 R_{s,2}}{L_3 R_{s,3}}} \quad \rightarrow \eta_{eff} \approx \frac{\langle \eta(\omega) P(\omega) \rangle}{\langle P(\omega) \rangle}$$

simple estimation of losses

but the longitudinal energy distribution is changed by the presence of strong absorbers $\rightarrow$ 1^{nd} order model

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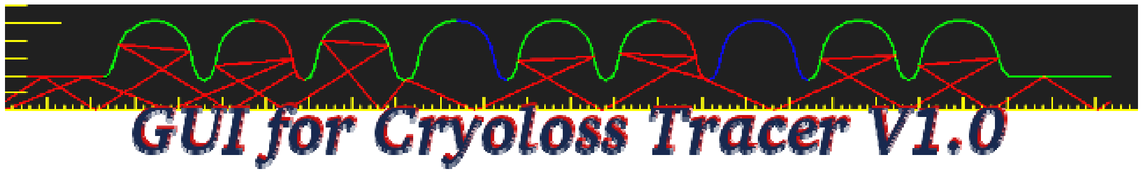
3d geometry: $\langle w(r,z,t)\rangle_t \approx const$ at surfaces

$\rightarrow$ effective surface = real surface area

1st order models: wave propagation



cryoloss: (Voss, Clemens, Dohlus) real rz-surface geometry of module; ray tracing; plane wave loss model for surface reflections; intensity reduction of plane wave; summation of surface losses → distribution of losses

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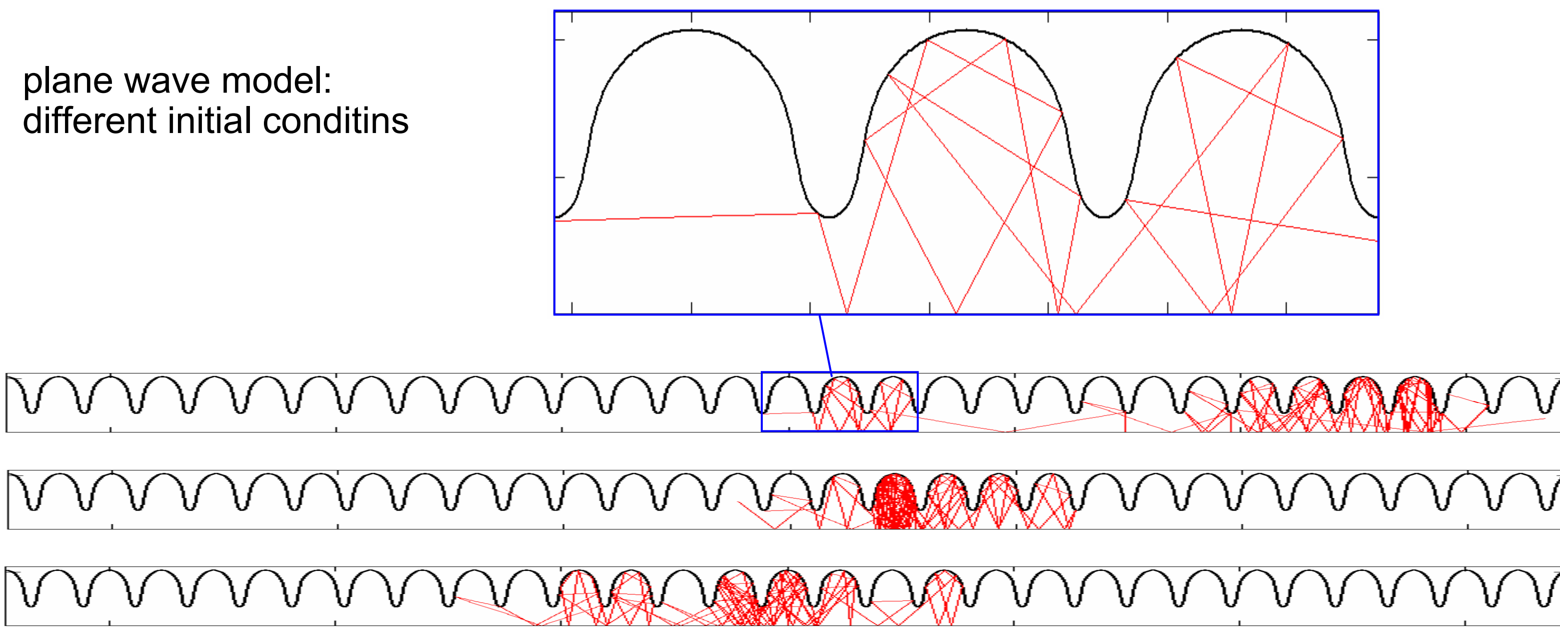
photon diffusion model: (Joestingmeier, Dohlus) propagation in module estimated by diffusion process; all other elements (bellow, …) are modeled by pipes with effective length; → analytic estimation of loss distribution

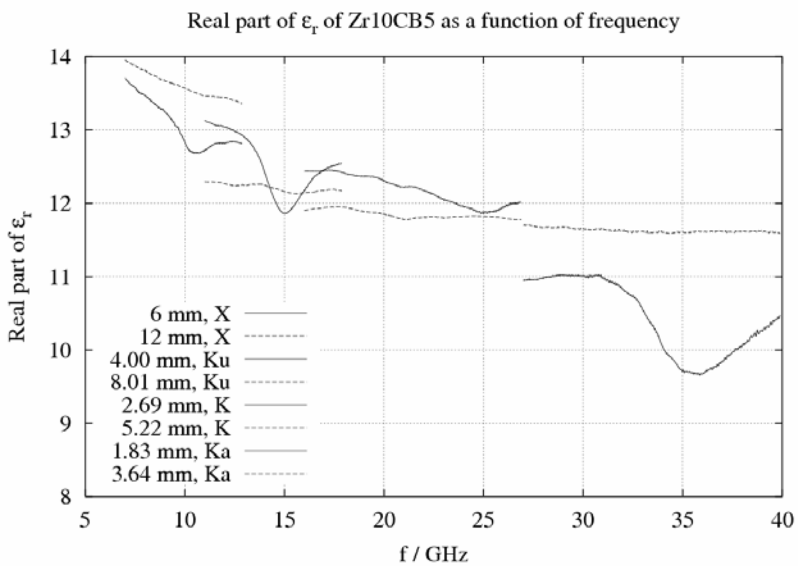
plane wave model:
different initial conditins

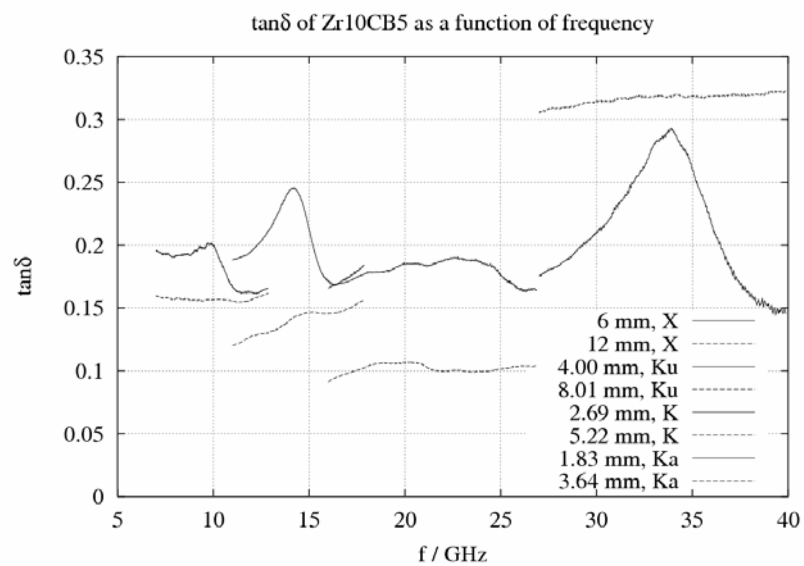


HOM absorber: Zr10CB5

measurements in 2001: Ceradyne Zr10CB5

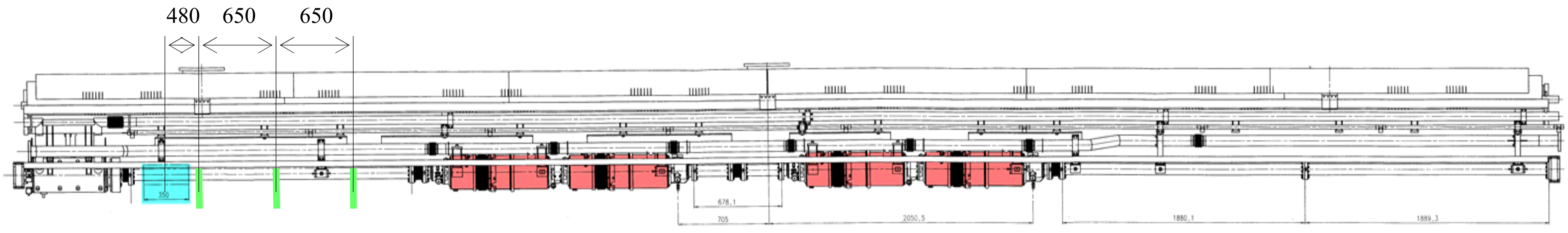
see:
http://www.desy.de/~dohlus/2001/2001.08.ceradyne_materialien/





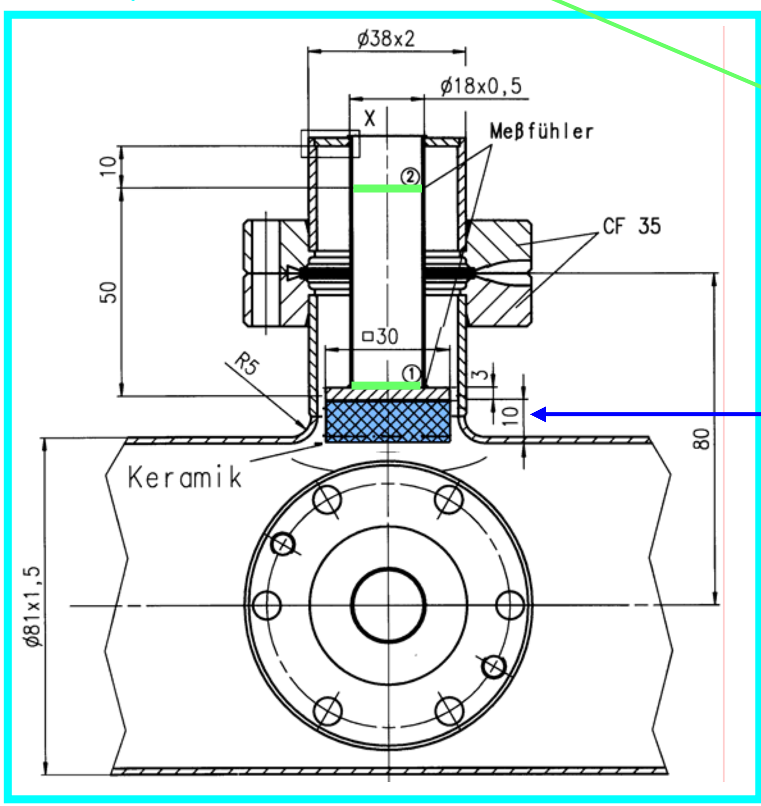
material probe 1: Re(ε) $\approx$ 12 ..14 ε_0
tan(δ) >$\approx$ 0.15

2. Surface Absorption
HOM absorber: measurement in cryo module (Sept. 2002)



cavities

steel beam pipes !

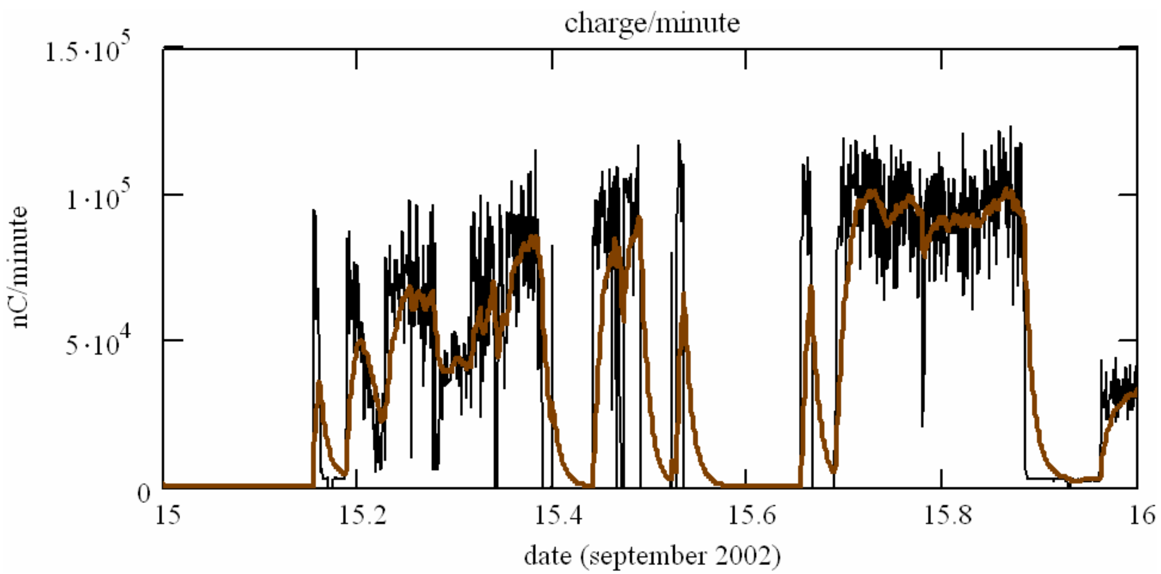


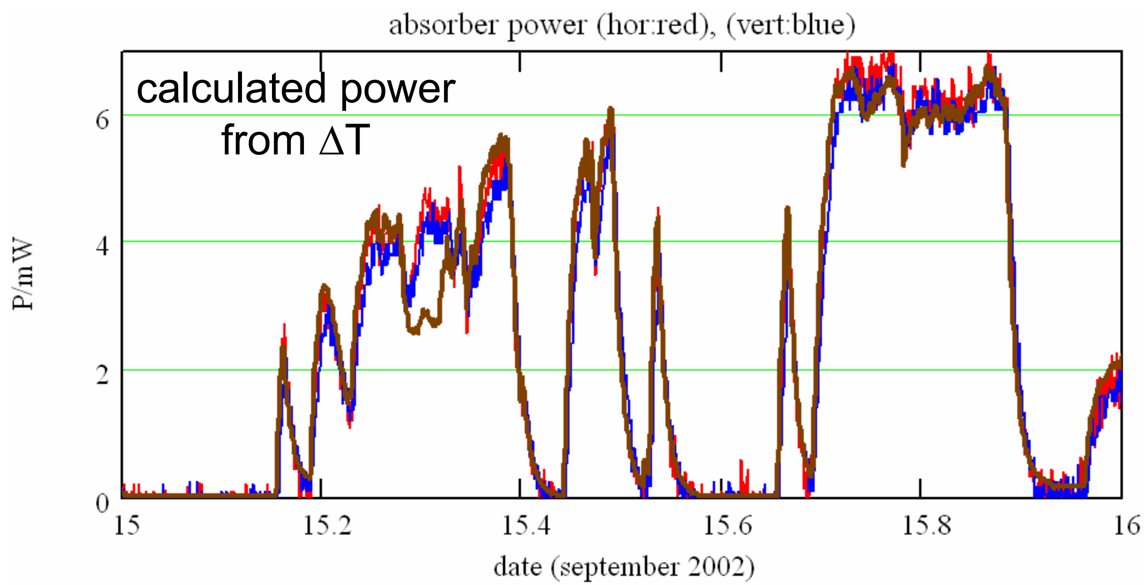
T sensors @ absorber & beam pipe

absorber material
ZR10CB5
d = 30 mm
h = 10 mm

2. Surface Absorption
HOM absorber: measurement in cryo module (Sept. 2002)

500 μs bunch train

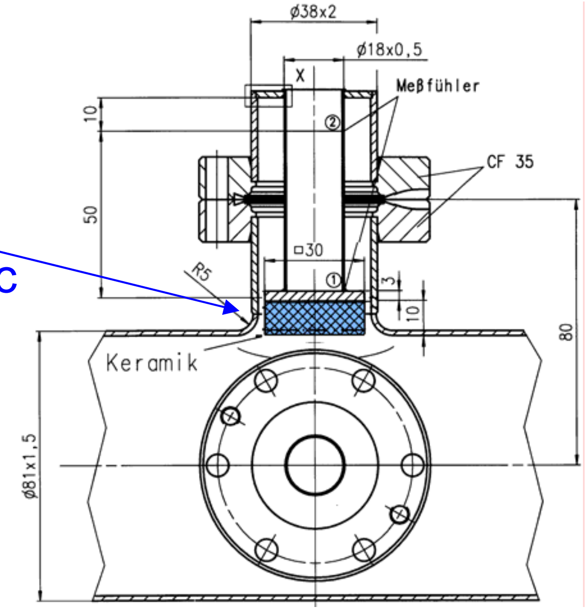




2. Surface Absorption
HOM absorber: Zr10CB5 – new probes

material probe 2: Re(ε) ≈ 16.5 ε_0
tan(δ) ≈ 0.20

small disc
d = 30



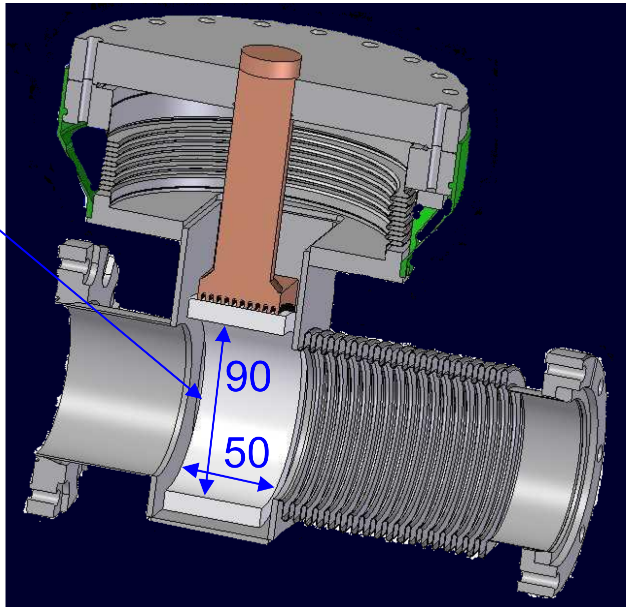
~~material probe 3: Re(ε) ≈ 14 ε_0~~
~~tan(δ) ≈ 0.04~~

rejected

material probe 4: Re(ε) ≈ 40 ε_0
tan(δ) ≈ 0.70

after ACC6 in FLASH !

big
cylinder



2. Surface Absorption
HOM absorber

model for cryoloss calculation:

"material 1": $\mathrm{Re}(\varepsilon) = 15\ \varepsilon_0$

$\tan(\delta) \approx 0.20$

"material 2": $\mathrm{Re}(\varepsilon) = 40\ \varepsilon_0$

$\tan(\delta) \approx 0.70$

2. Surface Absorption
surface impedance of Cu (high RRR), ASE

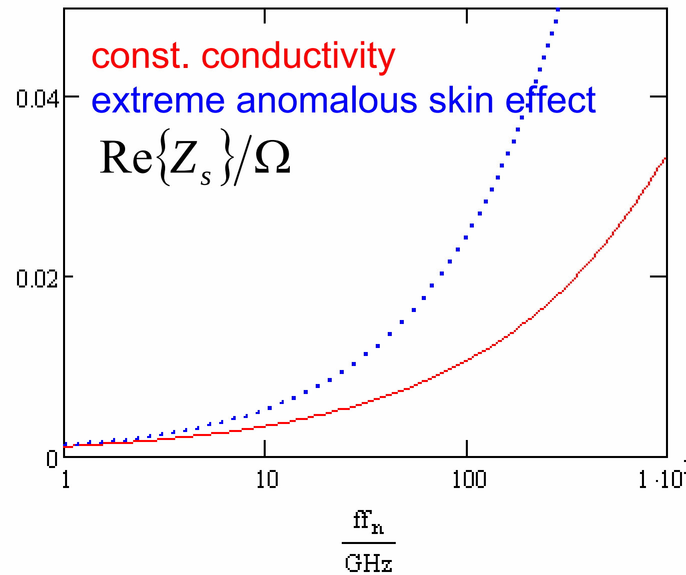
$$Z_{\text{s\_normal}} = \frac{1+i}{\sqrt{2}}\sqrt{\frac{\omega\mu_0}{\kappa_{cu}(4K)}}$$

$$\kappa_{\text{cu}}(4\text{K}) = 3.6\cdot 10^9/(\Omega m)$$

$$Z_{\text{s\_extreme}} = A\cdot\omega^{2/3}\cdot\left(1+i\sqrt{3}\right)$$

$$A = 3.3\cdot 10^{-10}\,\Omega\sec^{2/3}$$

from Boris Podobedov:
http://pubweb.bnl.gov/users/borisp/www/papers/anomskinrwtalk.pdf



use “extreme” model for all frequencies (> 1GHz)

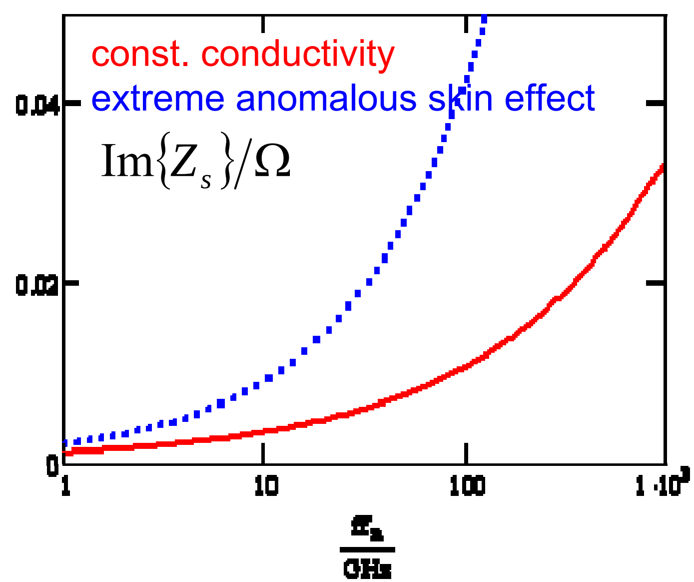
surface losses $\propto$ on $\mathrm{Re}\{Z_{\text{surface}}\}$

from “extreme” model

$$\kappa_{\text{effective}}(\omega) = \frac{\omega\mu_0}{2(\mathrm{Re}\{Z_s\})^2}$$

↓

into “normal” model (implemented in cryoloss)



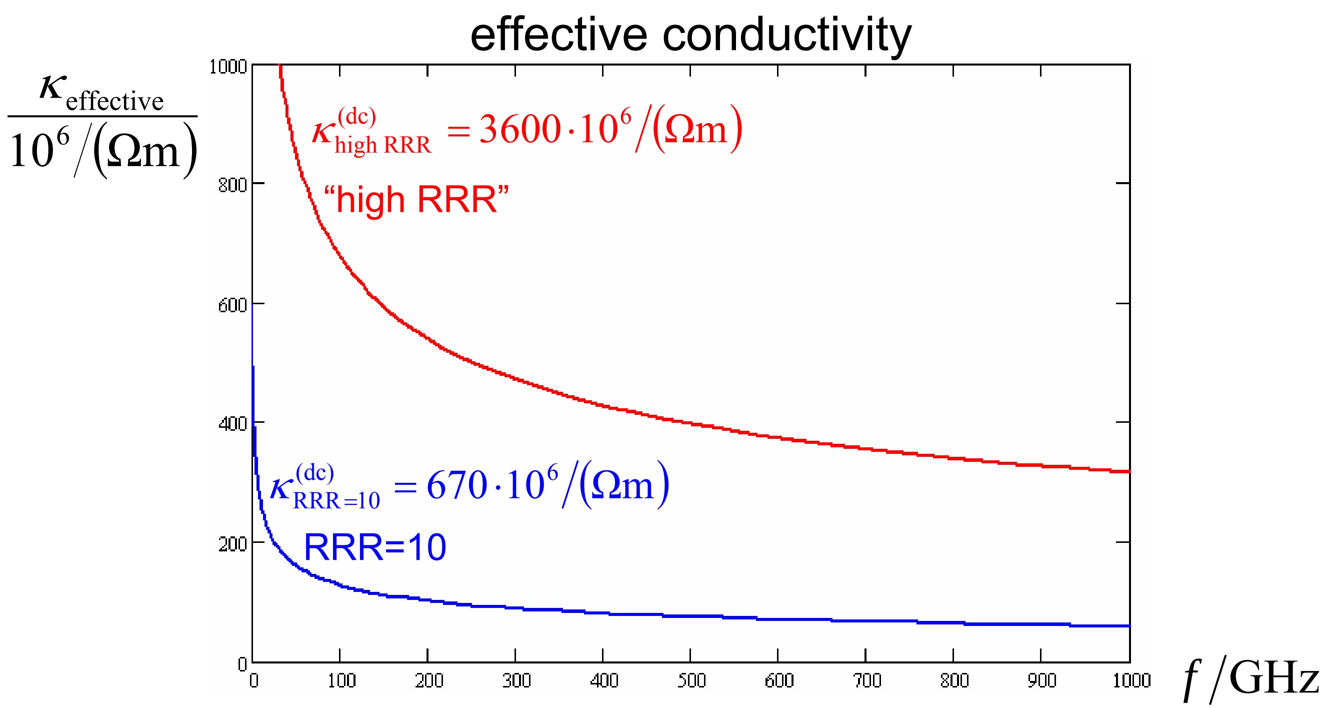
surface impedance of Cu (RRR ≈ 10), ASE

from “extreme” model with high RRR

$$\kappa_{\text{effective}}(\omega) = \frac{\omega\mu_0}{2\left(\mathrm{Re}\{Z_s\}\right)^2} \cdot \frac{\kappa^{(\mathrm{dc})}_{\mathrm{RRR}=10}}{\kappa^{(\mathrm{dc})}_{\text{high RRR}}}$$

effective conductivity scaled by dc conductivity

into “normal” model (implemented in cryoloss)



2. Surface Absorption
super conductor

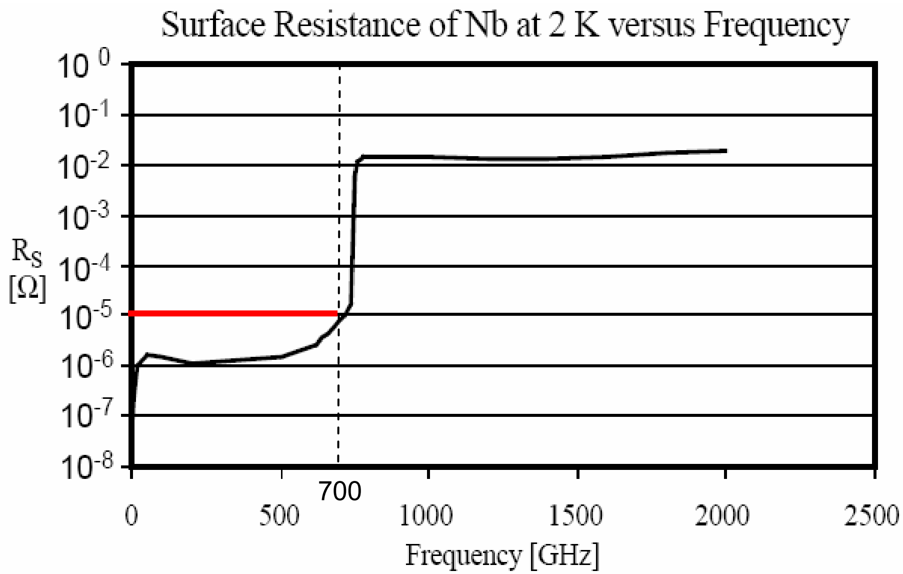


Figure 1: Surface resistance of Nb at 2 K as a function of frequency

plane wave reflection, TM case: $1-|r|^2 \approx 4\,\frac{\mathrm{Re}\{Z_s(\omega)\}}{\sqrt{\mu_1/\varepsilon_1}}\,\frac{1}{\cos\varphi}$

$f < 700\mathrm{GHz}\ :\ \mathrm{Re}\{Z_s(\omega)\} < 10^{-5}\,\Omega \rightarrow\ 1-|r|^2 \approx 10^{-7}$

cryoloss: < 10^4 hits until 99.99% of energy is dissipated by absorber & n.c. walls

$$1-|r|^{20000} \approx 10^{-3}$$

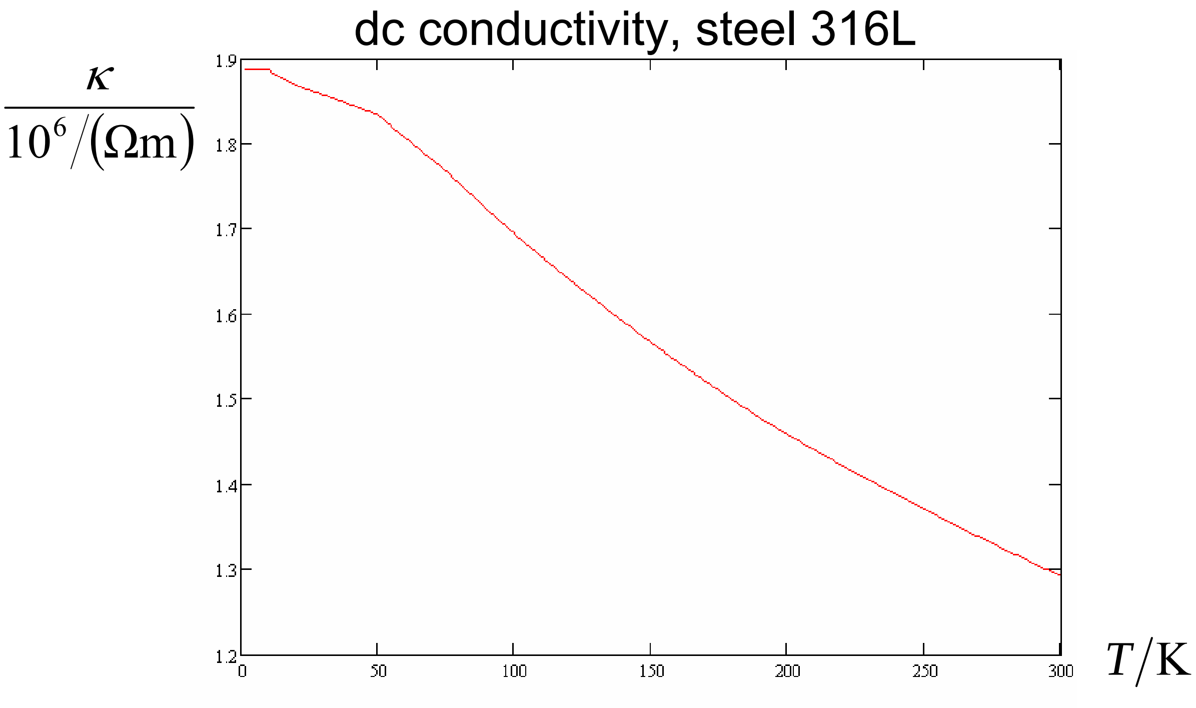
losses to s.c. walls are negligible for $f < 700$ GHz

2. Surface Absorption
super conductor

model for cryoloss calculation

$$\kappa(\omega) = \begin{cases} \infty & \text{if } f < 700\,\text{GHz} \\ 10^6/(\Omega\text{m}) & \text{otherwise} \end{cases}$$

2. Surface Absorption
steel

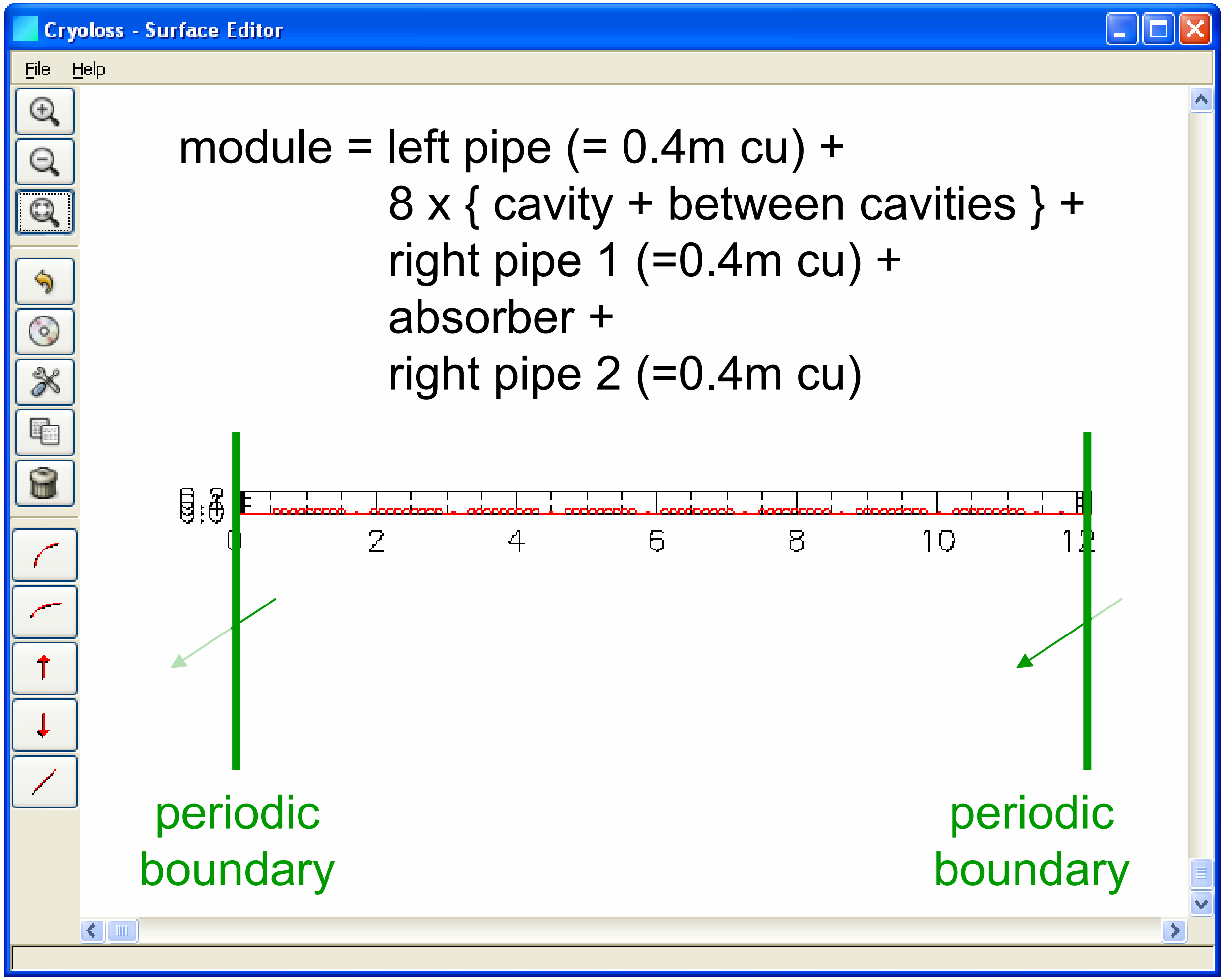


model for cryoloss calculation: $\kappa = 1 \cdot 10^6 / (\Omega \mathrm{m})$
for all frequencies and temperatures

(there are nearly no steel surfaces in the used module-model)

3. Module Models
XFEL – surface geometry

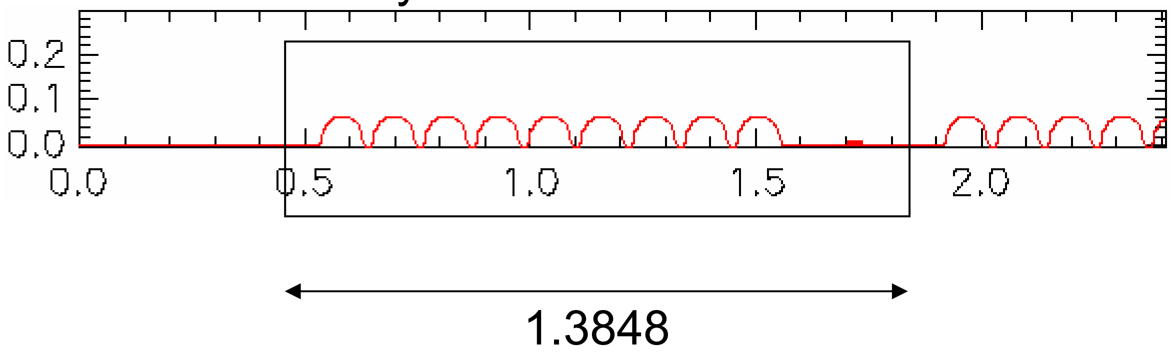
“module_bellows_geo2.cav”



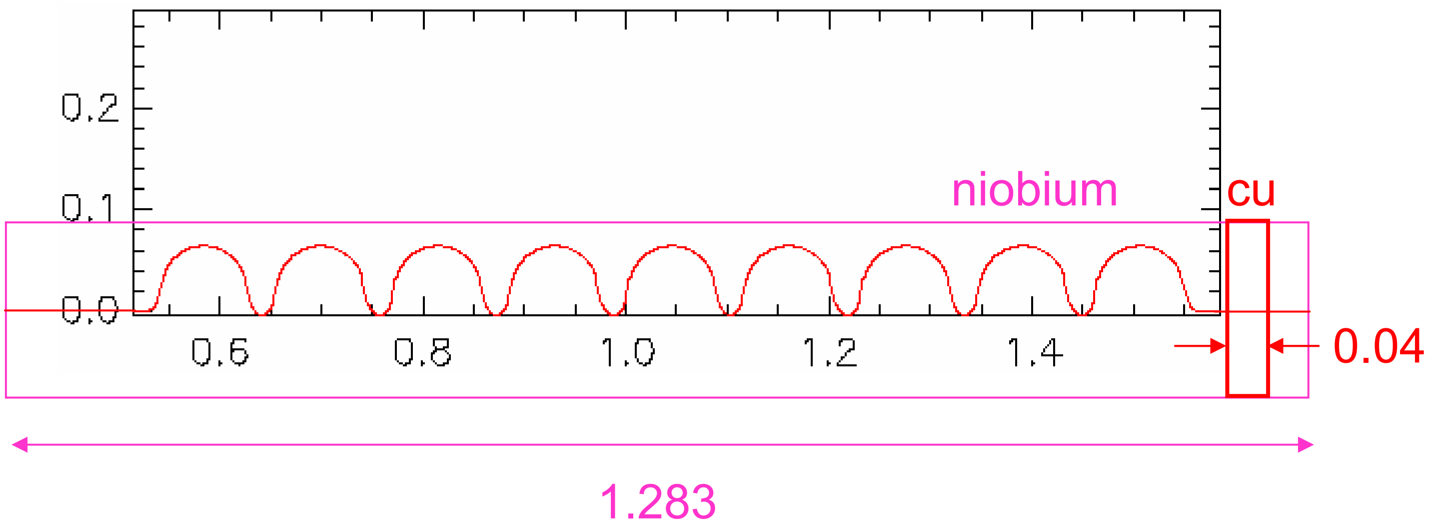
= infinite string of cold modules !

3. Module Models
XFEL – surface geometry

"cavity + between cavities"

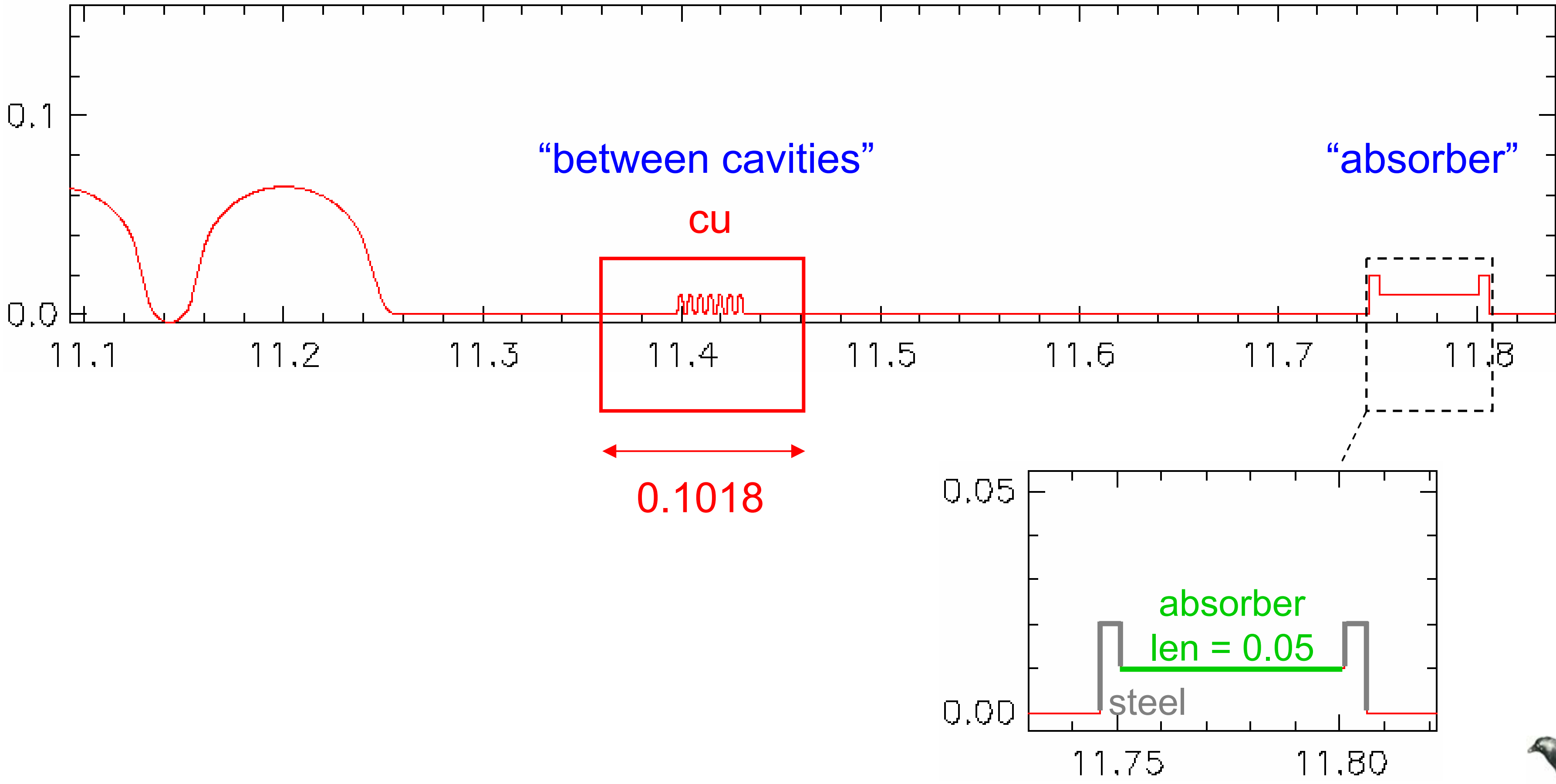


"cavity", shape defined in CDR & TDR



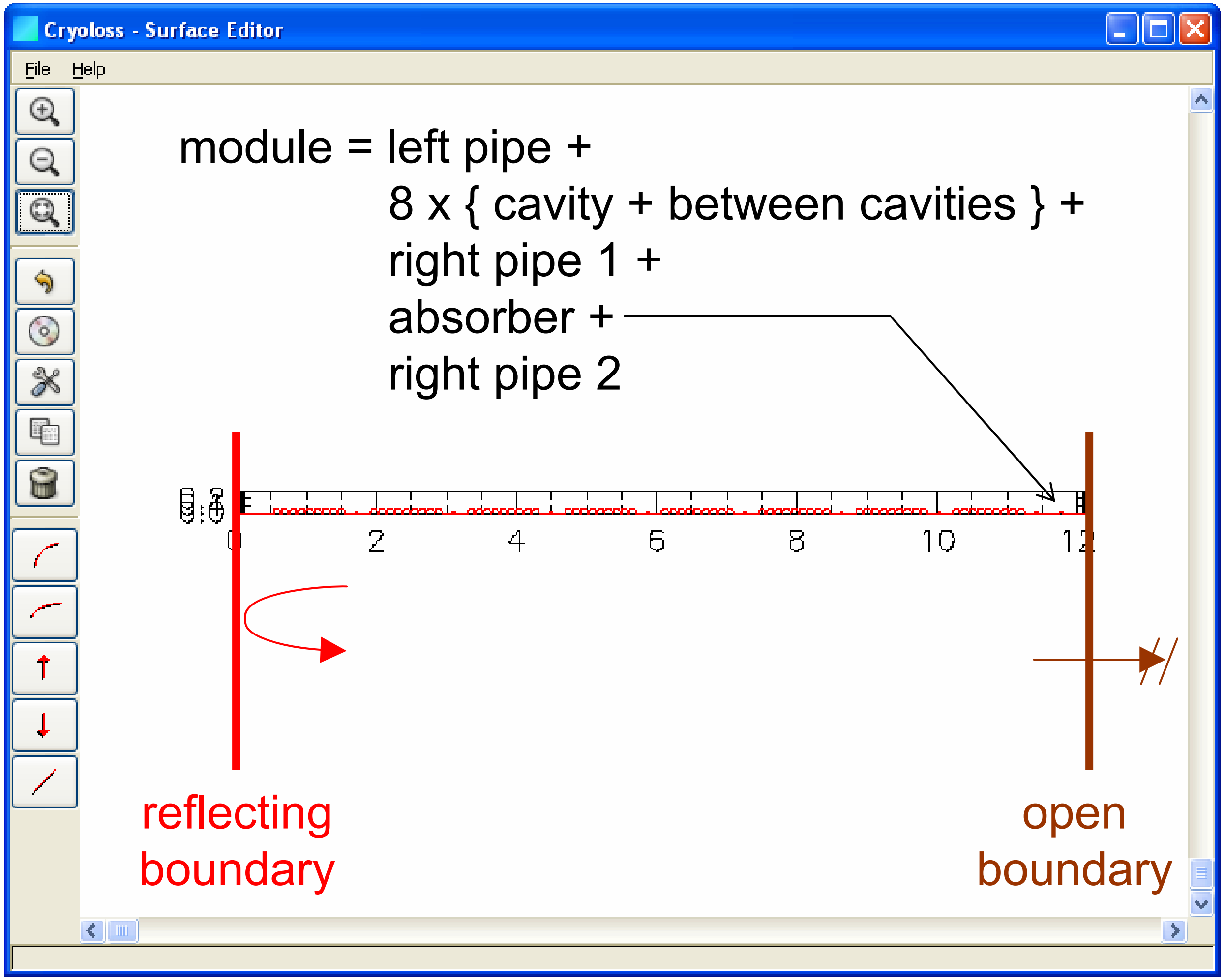
3. Module Models
XFEL – surface geometry

“module_bellows_geo2.cav”



3. Module Models
FLASH

= XFEL model, but with different boundary conditiones

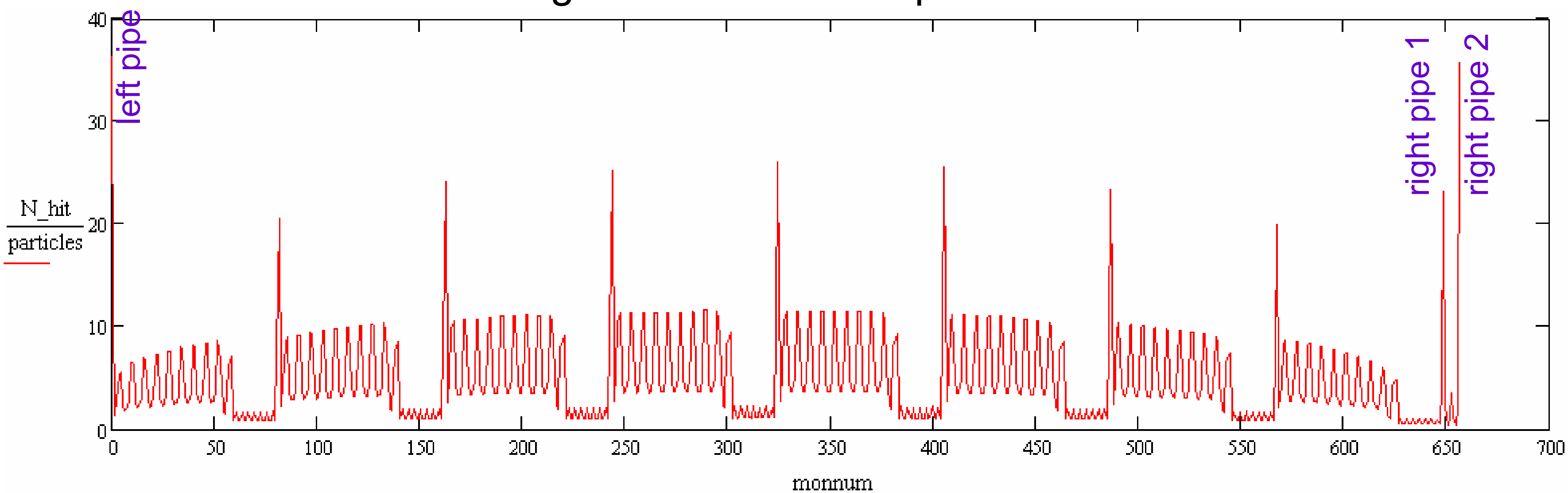


≈ **open–ACC5–|–ACC6–open**

absorber 1
perfect cu
f = 10 GHz

4. Cryoloss Results
XFEL

averaged number of hits per surface



index of surface

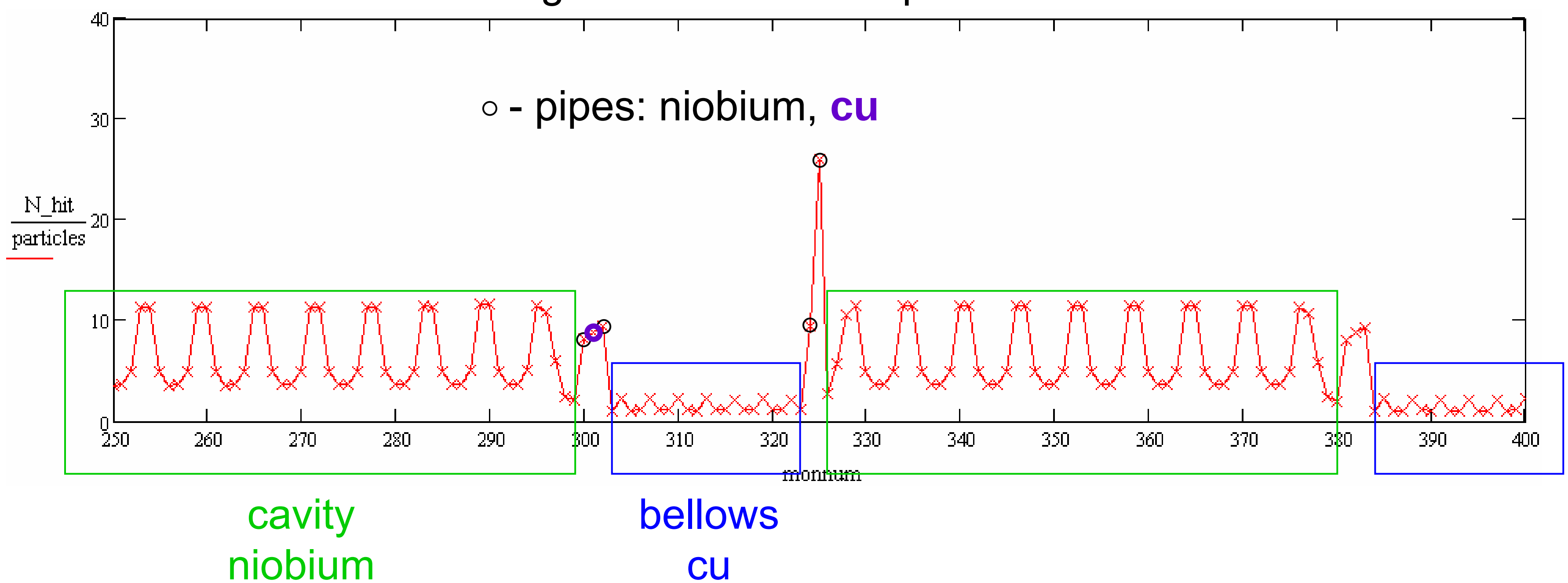
stopping criterion: $P_{\text{wave}} < 10^{-4} P_{\text{initial wave}}$

$$\rightarrow \quad \frac{\sum\limits_{\text{surfaces}} \text{N\_hit}}{\text{particles}} = 3226$$

absorber 1
perfect cu
f = 10 GHz

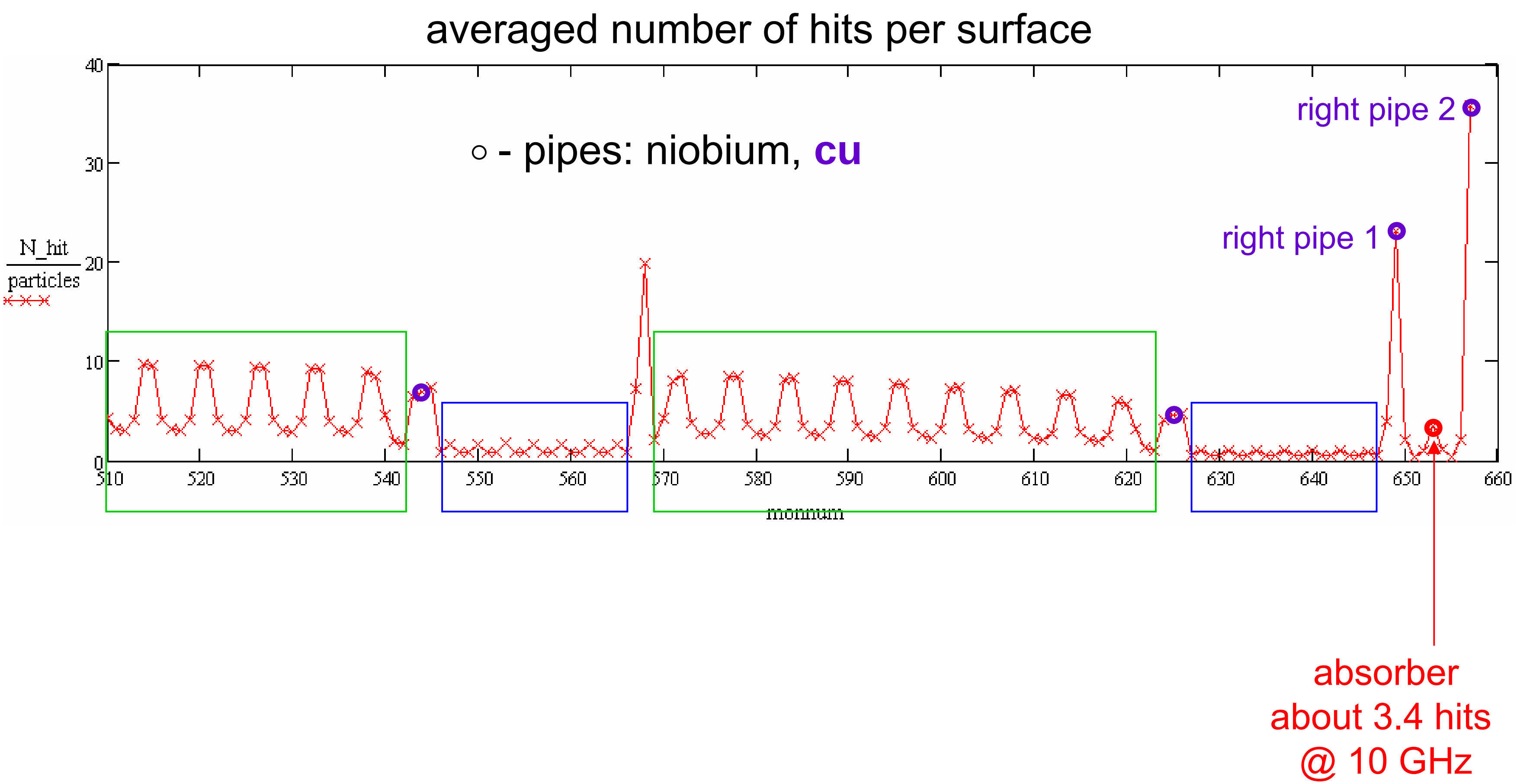
4. Cryoloss Results
XFEL

averaged number of hits per surface



absorber 1
perfect cu
f = 10 GHz

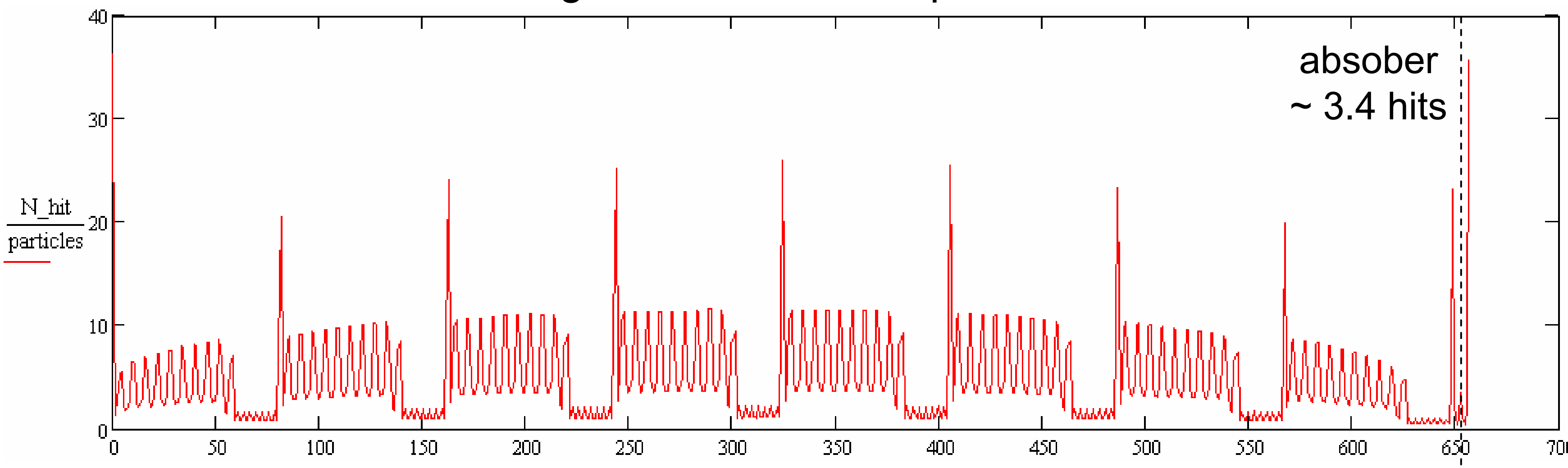
4. Cryoloss Results
XFEL



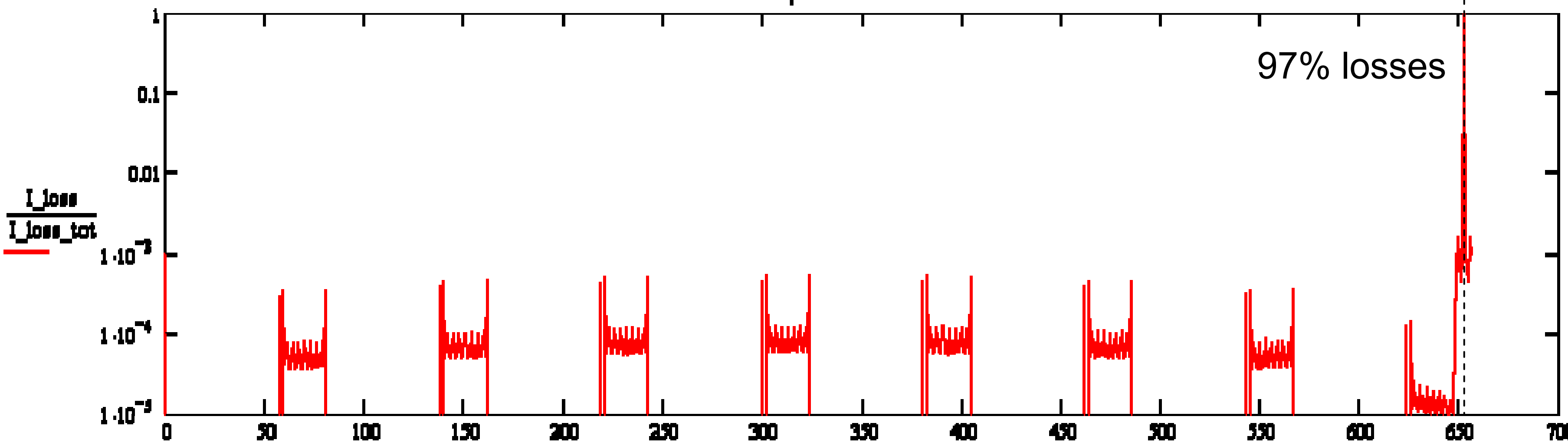
absorber 1
perfect cu
f = 10 GHz

4. Cryoloss Results
XFEL

averaged number of hits per surface

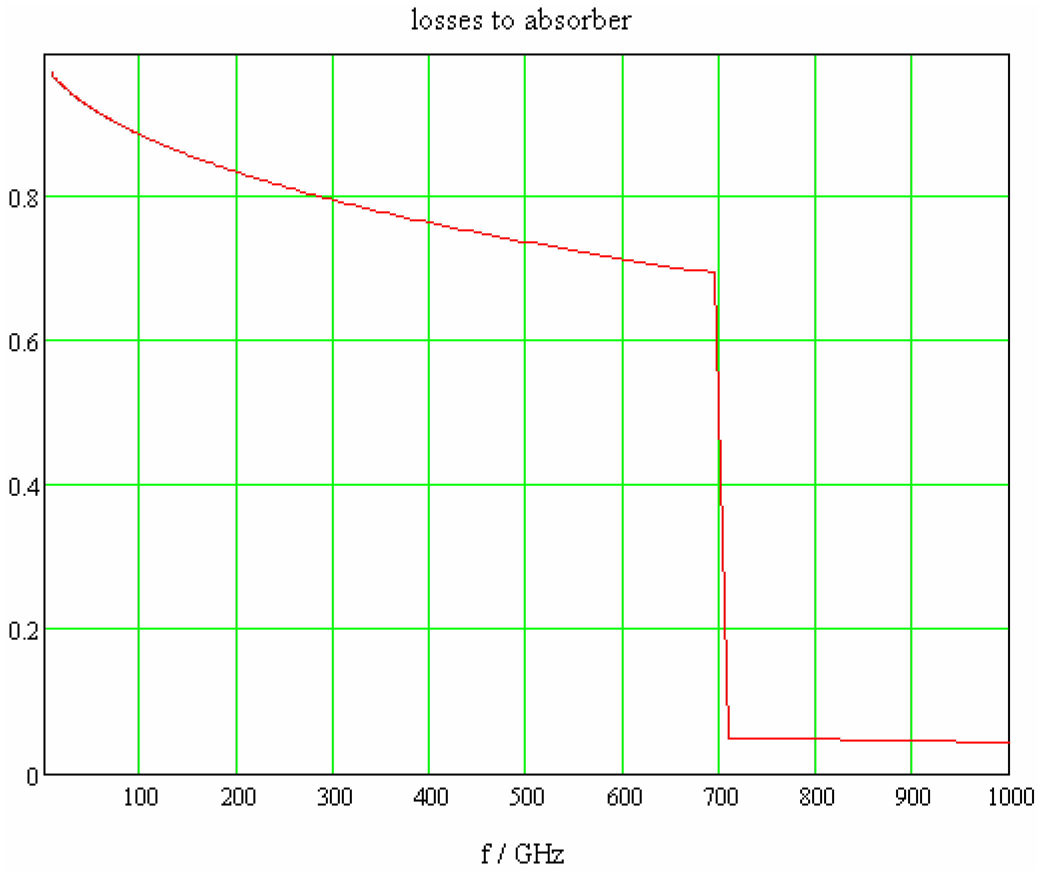


losses per surface



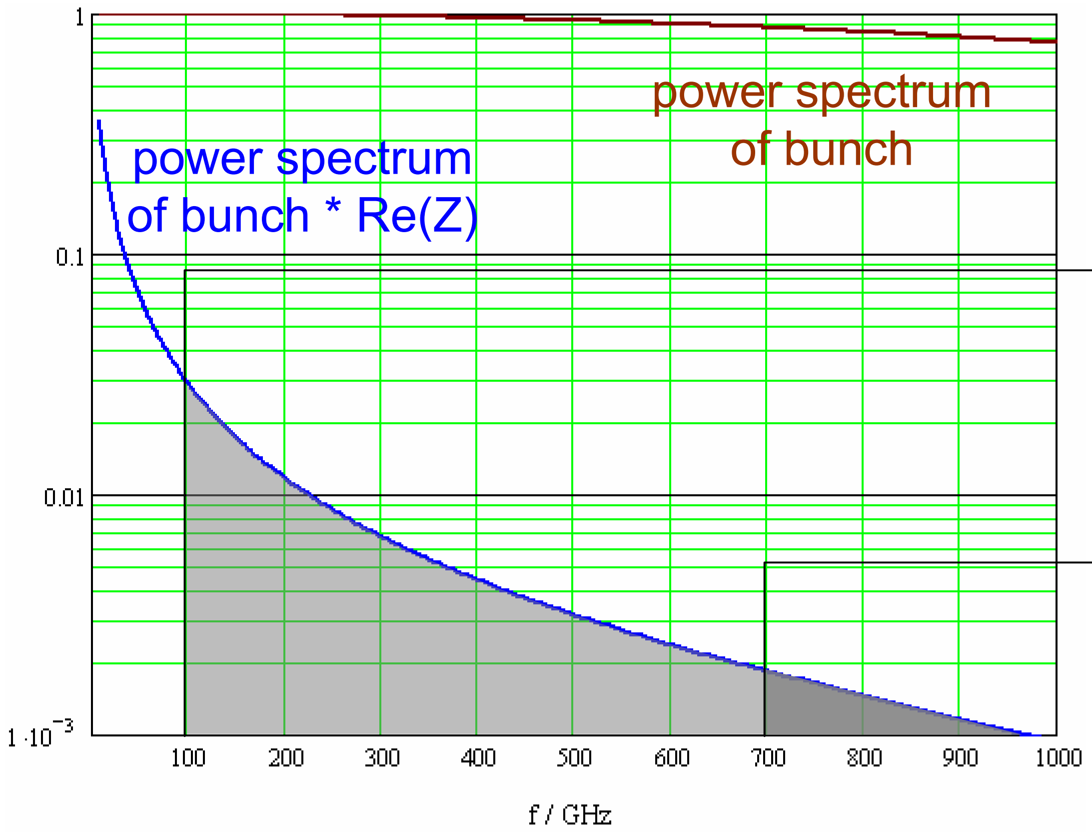
absorber 1
perfect cu

4. Cryoloss Results
XFEL



4. Cryoloss Results
XFEL

bunch length = 25 µm



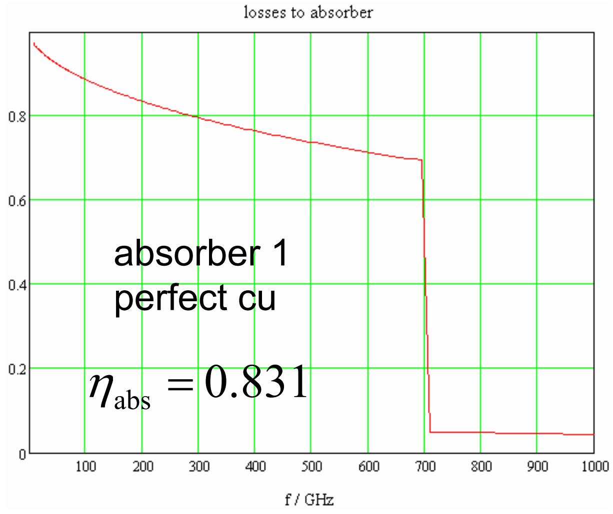
$$\frac{\int_{100\mathrm{GHz}\cdot 2\pi}^{\infty} P^{(\sigma)}\,\mathrm{Re}\{Z\}\,d\omega}{\int_{0}^{\infty} P^{(\sigma)}\,\mathrm{Re}\{Z\}\,d\omega} \approx 0.258$$

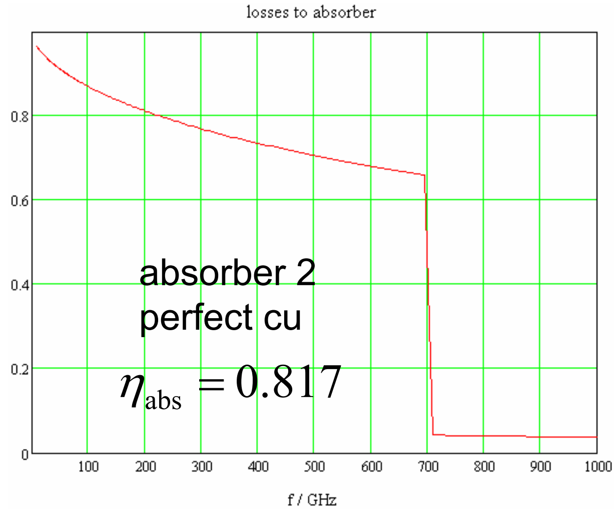
$$\frac{\int_{700\mathrm{GHz}\cdot 2\pi}^{\infty} P^{(\sigma)}\,\mathrm{Re}\{Z\}\,d\omega}{\int_{0}^{\infty} P^{(\sigma)}\,\mathrm{Re}\{Z\}\,d\omega} \approx 0.046$$

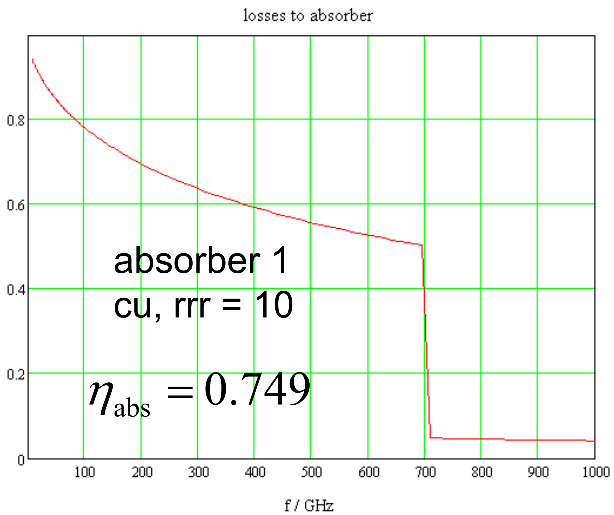
absorber efficiency: $\eta_{abs} = \frac{\int \eta(\omega) P^{(\sigma)}(\omega)\,\mathrm{Re}\{Z(\omega)\}\,d\omega}{\int P^{(\sigma)}(\omega)\,\mathrm{Re}\{Z(\omega)\}\,d\omega}$ = 83 %

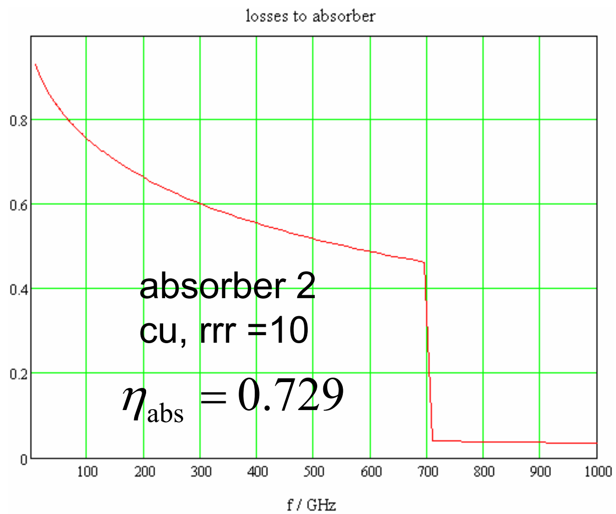
with $\eta_{abs}(\omega) = 0$ for $\omega > 700\mathrm{GHz}\cdot 2\pi$

4. Cryoloss Results
XFEL









4. Cryoloss Results
XFEL – working hypothesis of TDR

absorption efficiency ≈ 90%
safety margin 10%

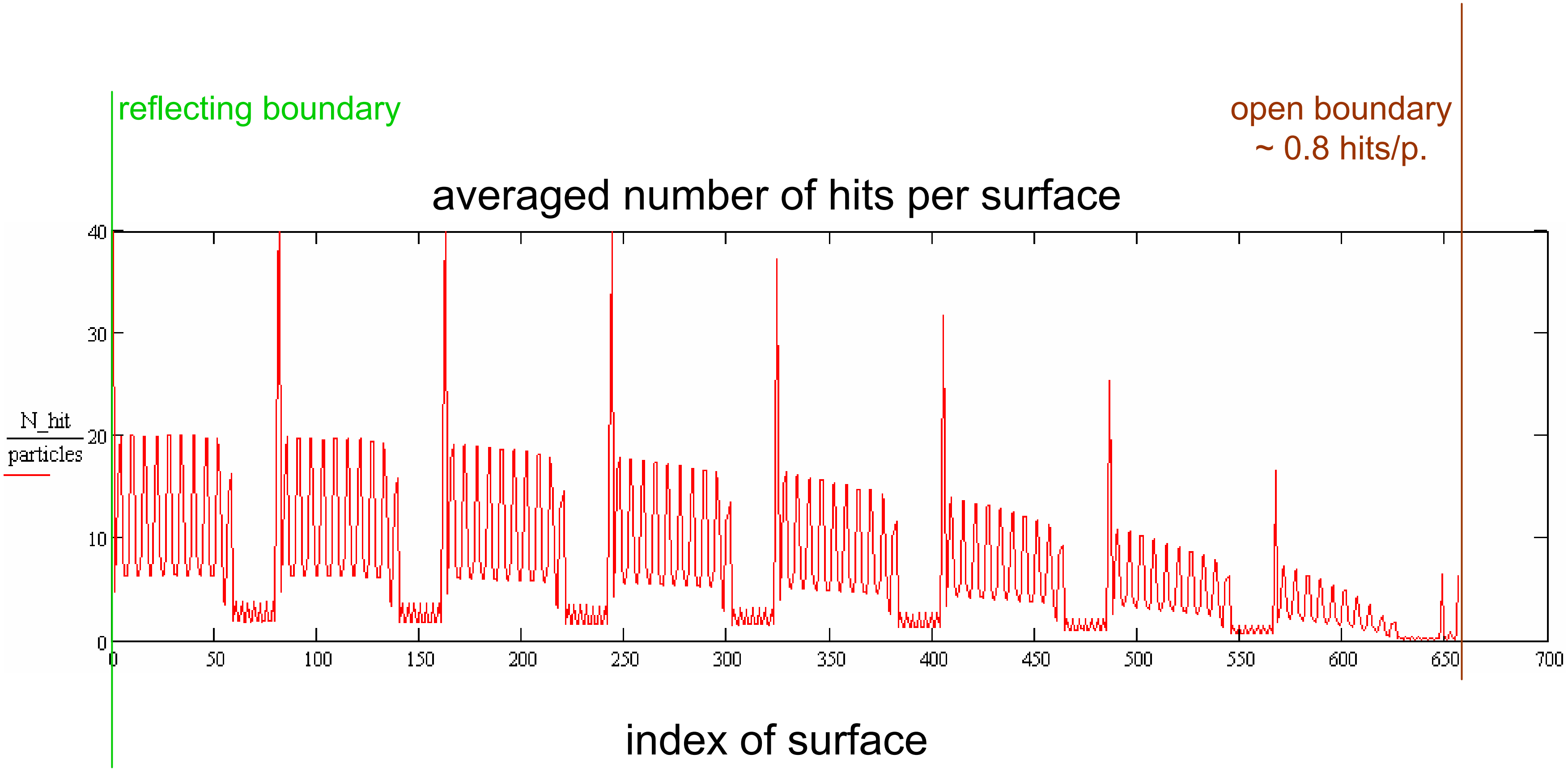
→ assumed absorption efficiency = 80 %

but the calculations with low rrr cu
give lower results !

significant influence of
    physics (of field propagation) and
    material properties
that are not well known

	10x3000 bunches / sec	30x3000 bunches /sec
single bunch losses =	4.6 W	13.8 W
2K losses (for η = 0.75) = $(1 - \eta)$ x single bunch losses =	1.2 W	3.5 W

4. Cryoloss Results
FLASH



stopping criterion: $P_{\text{wave}} < 10^{-4} P_{\text{initial wave}}$

$$\rightarrow \quad \frac{\sum_{\text{surfaces}} \text{N\_hit}}{\text{particles}} \approx 4100$$

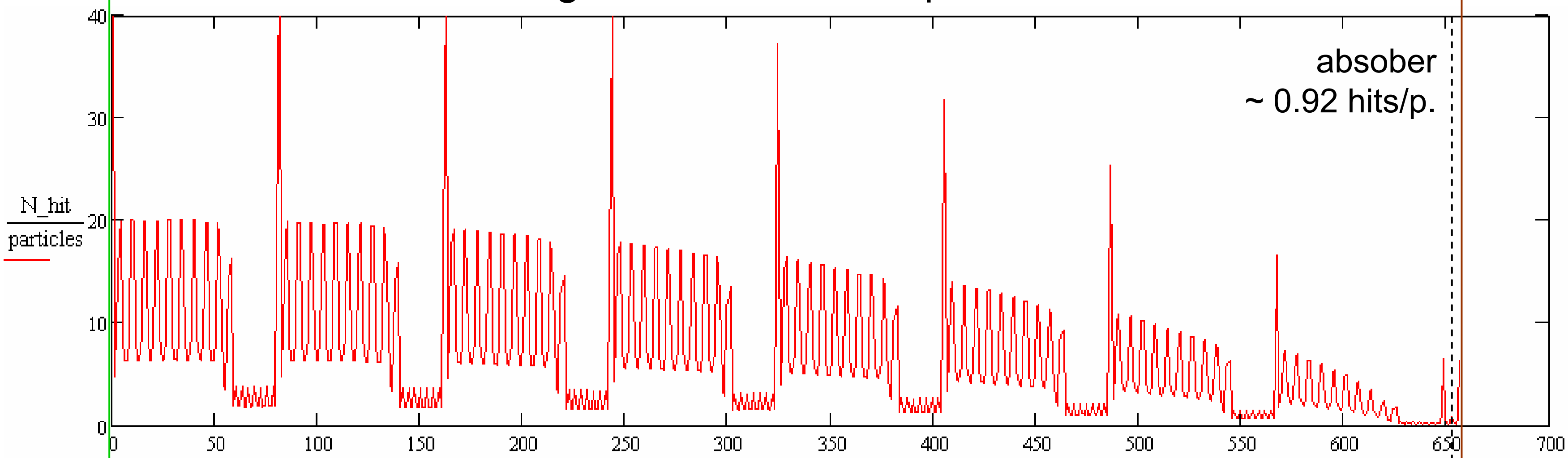
4. Cryoloss Results
FLASH

absorber 2
perfect cu
f = 10 GHz

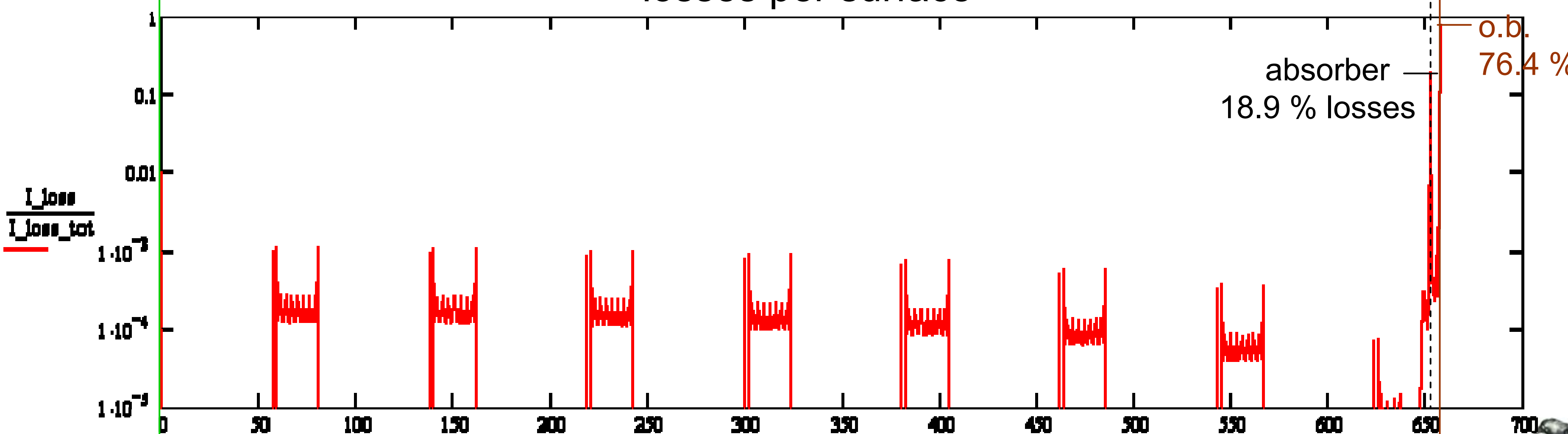
reflecting boundary

open boundary ~ 0.8 hits/p

averaged number of hits per surface



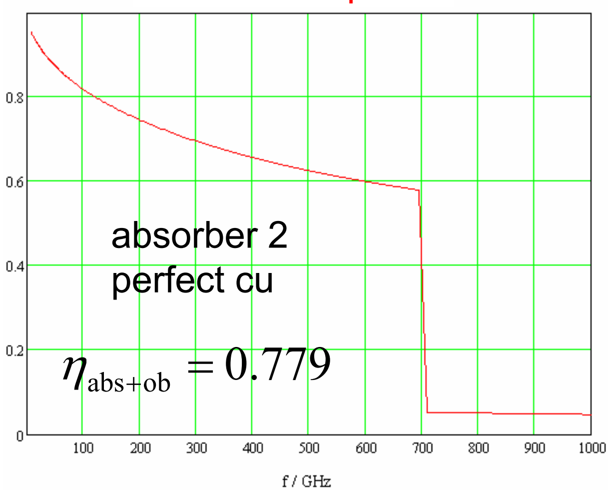
losses per surface

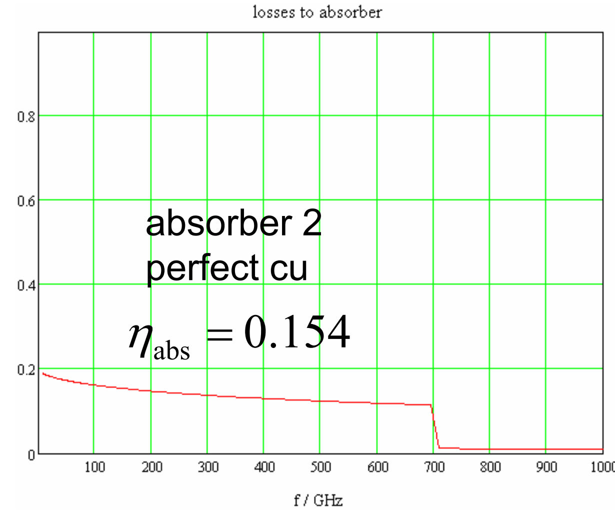


bunch length = 25 µm
bunch charge = 1nC

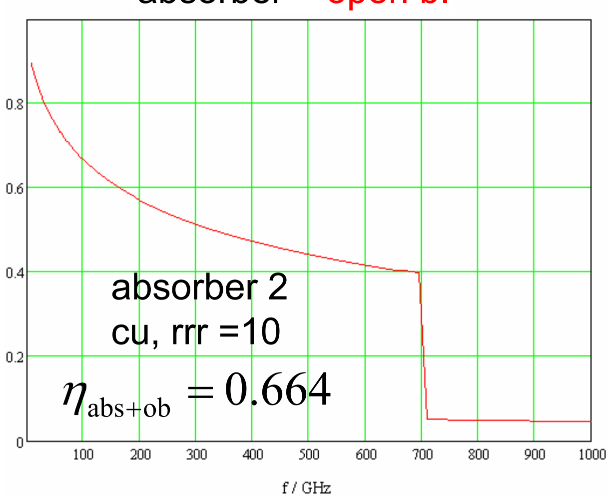
4. Cryoloss Results
FLASH

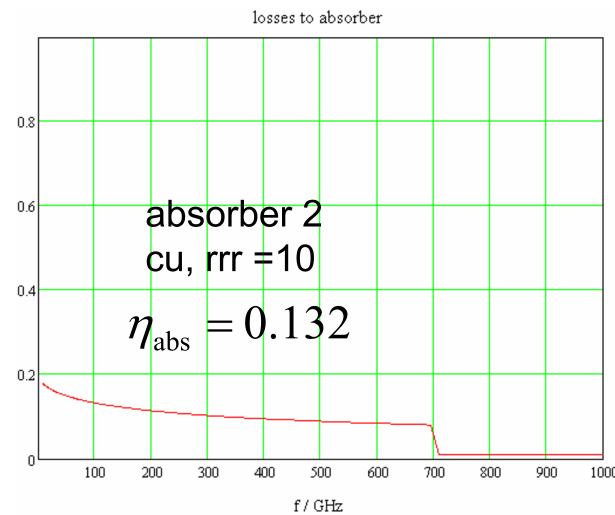
absorber + open b.





absorber + open b.





4. Cryoloss Results
+ FLASH long bunch operation

Logbook entry: /TTFelog/data/2007/42/21.10_a

21.10.2007 19:07 ttflinac **Main linac parameters**

```
Laser                                          Gun
Number of bunches ...... 780                   Feedforward/Feedback ... on/on

Bunch frequency ........ 1000 kHz              Pfwd SP ................ 3.35
Macropulse rep'rate .... 5.0 Hz                Pfwd RBV ............... 3.38
Flashlamp current ...... 2.20                  Phase SP ............... -96.47 deg
Flashlamp start time ... 2.29 ms               Phase RBV .............. -147.26 deg
Attenuator SP .......... 18144                 Pfwd (peak) ............ 3.563 MW
Iris diameter .......... 1.95 mm               Prefl (peak) ........... 1.343 MW
Piezo Voltage .......... 4.212 V               Pfwd (sample point 700)  3.382 MW
                                               Prefl (sample point 700) 0.012 MW
                                               Flat top ............... 850 us
                                               Water temperature SP ... 60.57 deg C
                                               Main solenoid .......... 294.04 A
                                               Bucking coil ........... -26.51 A
                                               Gun dipole ............. 0.000 A
                                               Charge 3GUN(T1) ........ 0.55 nC
```

(3 nC)

single bunch losses $P_{\text{single bunch}} = (780 \cdot 5\text{Hz})\, q^2 k_{\text{module}}$

$k_{\text{module}} \approx 1.53 \cdot 10^{14} \dfrac{\text{V}}{\text{C}}$ $\rightarrow P_{\text{single bunch}} \approx 0.18\ \text{W}$ (5.4W)

losses to absorber: “perfect” Cu $P_{\text{single bunch}} \eta_{\text{abs}} \approx 0.028\ \text{W}$ (0.83W)

RRR=10 Cu $P_{\text{single bunch}} \eta_{\text{abs}} \approx 0.024\ \text{W}$ (0.71W)

Supplement

SRF

RRR OF COPPER COATING AND LOW TEMPERATURE ELECTRICAL RESISTIVITY OF MATERIAL FOR TTF COUPLERS

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S. Prat, LAL, France

Abstract

In the frame of the R&D program on the TTF III main RF coupler, IPN Orsay developed in close collaboration with LAL institute, a dedicated facility for the electrical characterization of different materials at low temperature. This apparatus was used for measuring the electrical resistivity versus temperature (4.2 K- 300K) of various samples produced in the industry. These tests were performed in order to compare the RRR of the samples, qualify and find the optimum parameters for the coating process. Seven flat samples were tested in a saturated liquid helium bath under ~1013 mBar pressure: measurements were performed on bare 316L samples, nickel coated 316L samples, copper coated 316L samples with a nickel under layer. We investigated, in particular, the effect of vacuum annealing at 400°C on the RRR of the copper coating. Our experimental data are compared to previous results reported by other groups, empirical correlation and a good agreement was found. Finally, the tested samples fulfil the TTF III design parameters requirements in terms of heat loads to the refrigerator at 2 K, 4 K and 70 K.

Contribution to the SRF 2005, Ithaca, New York, USA

Work supported by the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

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Using the equation 4 and the data shown in Fig.10, we have deduced the electrical resistivity of the copper coating (Fig. 11).

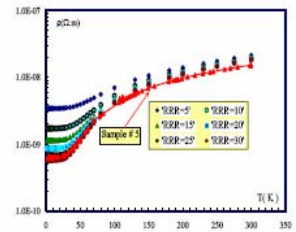

Fig. 11: Electrical resistivity of the copper coating

Our data are compared to the theoretical ρ_{Cu} versus T curve which was calculated using the following empirical correlation:

$$\rho(T) = RRR.\rho(273) + b.\exp\left(\sum_{i=0}^{i=4} a_i.\left(Ln(T)\right)^i\right) \quad (5)$$

Where: ρ (273) =1.7110^{-8}Ω.m is the electrical resistivity of copper at the ice point temperature T=273 K,
b and $a_{i(0<i<4)}$ are empirical constants given in the Table 4.

Table 4: Values of the empirical correlation parameters

Constant	Value
b	10^{-8} Ωm
a_0	-9.600976
a_1	-12.52445
a_2	8.309361

The shape of our experimental data and the theoretical curves given by expression (5) for different RRR values are similar. Moreover, the comparison of the data to the correlation lead to a theoretical RRR=25-30. Resolution of the electronics used for the tests is not sufficient for the precise measurement of the electrical resistivity of the nickel sub layer. Consequently we have to assume reasonable values of this parameter in order to deduce the RRR of copper coating from our experimental data. The summary of RRR measurements for all the samples tested are illustrated in Table 5.

For the samples without any heat treatment (i.e. as received), the RRR of Cu coating are in the range 20-46 if we use a realistic value of Ni RRR (i.e. RRRNi~1). Moreover the RRR data of sample #1 are in good agreement with the empirical correlation (5): the measured value of copper coating (RRR=20) is consistent with that given by the correlation (RRR=25-30). Furthermore, the vacuum annealing at 400°C during one hour increases the RRR of copper coating by a factor ~6.

Table 5: Summary of copper coating RRR results.

Sample	Ni effect neglected	RRRNi =1	RRRNi =300
#1 As received	19.8	20.4	11.2
#1 Vacuum Annealed@ 400° during 1h00	113	117	107
#5 As received	23.7	24	21
#6 As received	45.5	45.9	43

CONCLUSION

In the frame of the CARE-SRF project WP7 R&D program aimed at development and fabrication in the industry of thirty TTF III power couplers, we designed an apparatus dedicated to the measurement of the electrical resistivity of materials at low temperatures. Several stainless steel samples coated with copper were characterized at room temperature (adhesion and thickness of the coating, impurity content, roughness…). The electrical resistivity of different materials (stainless steel, Cu coating, Ni under layer) were measured in the range 4.2 K – 300 K. The RRR of Cu coating was deduced from these data: 1) for as received samples the RRR values are in the range 20-46, 2) the vacuum annealing at 400°C during one hour increases the RRR of copper coating by a factor ~6. Moreover, our electrical resistivity data are compared to previous results reported by other groups, theoretical values, empirical correlation and a good agreement was found. Finally, the tested samples fulfil the TTF III design parameters requirements in terms of heat loads to the refrigerator at 2 K, 4 K, and 70 K.

ACKNOWLEDGEMENTS

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

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