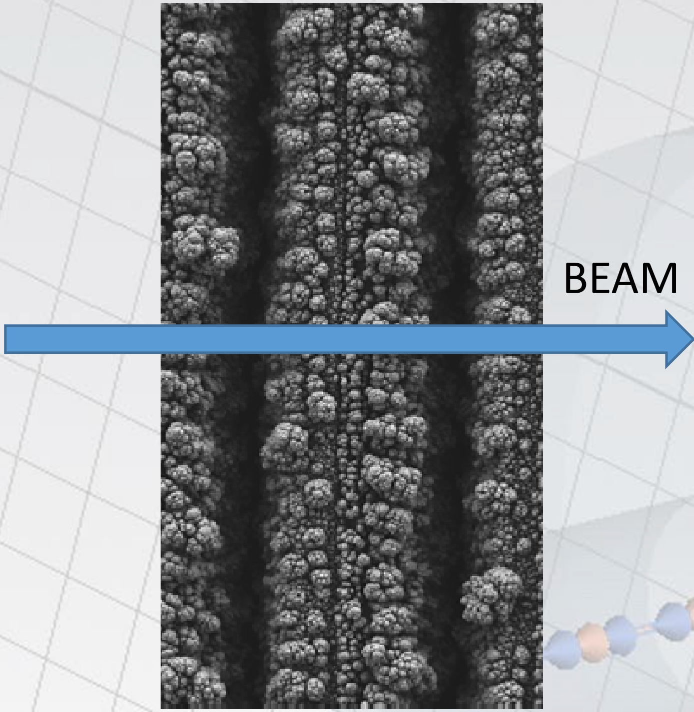
Laser-engineered surface structures (LESS)

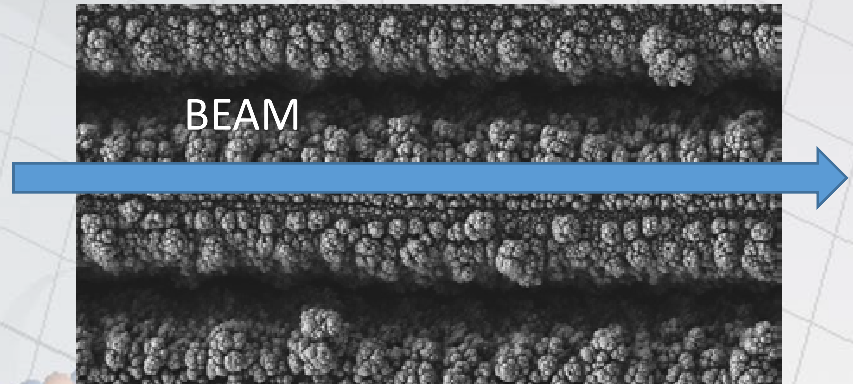
What is the beam impedance?

O. Berrig, N. Biancacci, F. Caspers, A. Grudiev, E. Metral, B.Salvant, G.Stupakov

LESS (laser-engineered surface structures)



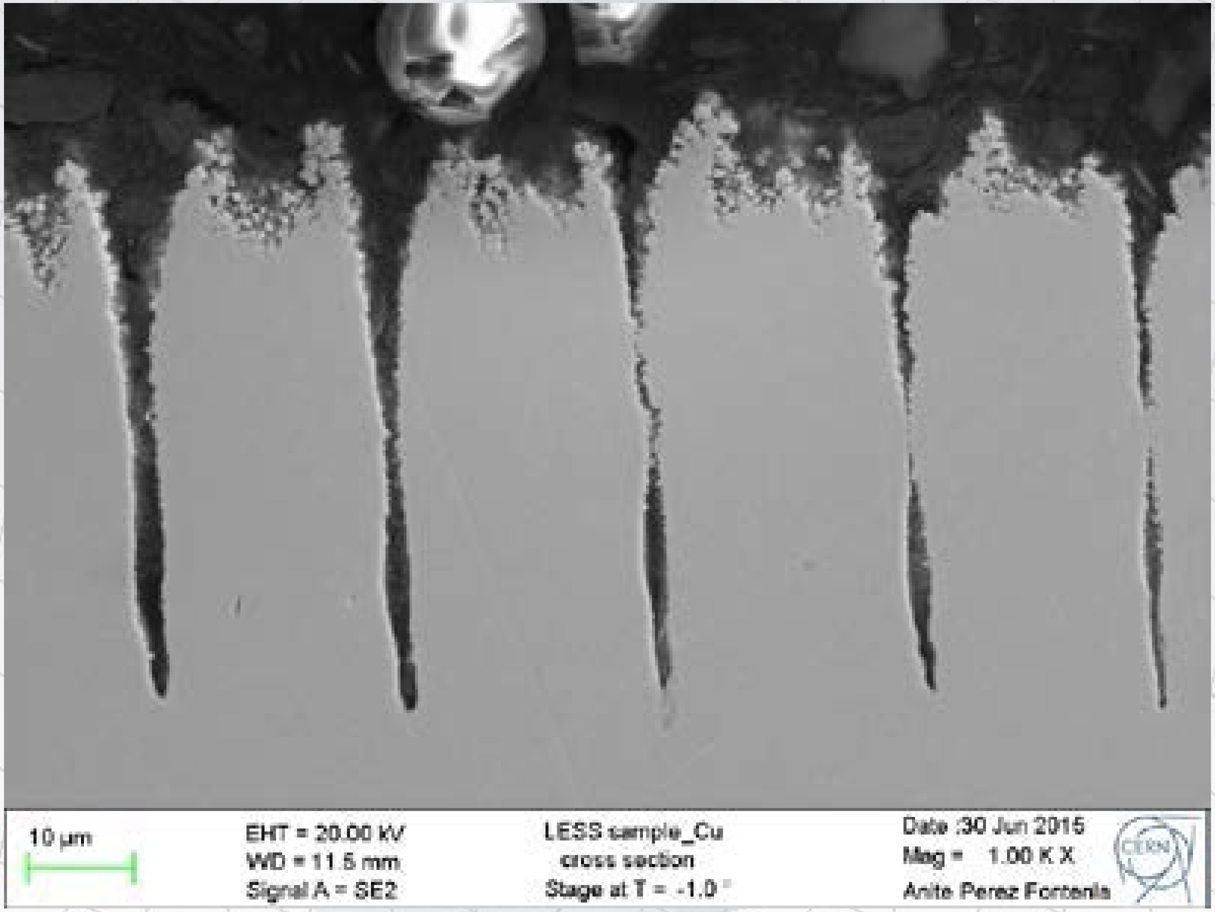
TRANSVERSE GROOVES



LONGITUDINAL GROOVES

http://indico.cern.ch/event/375755/attachments/749006/1027567/CERN_talk_26-Feb-2015-.pdf

In order to reduce the beam induced heating from electron-cloud in IP2 and IP8, it is proposed to make a surface treatment of the LHC vacuum chambers that will reduce the secondary electron yield and hence electron-cloud.



\\cern.ch\dfs\Divisions\EST\Groups\SM\ThinFilms\LESS\SEM_Dundee\EDMS-1533336_SEM_observation_of_laser-engineered_surface_structures.pdf

(S. Calatroni TE/VSC)

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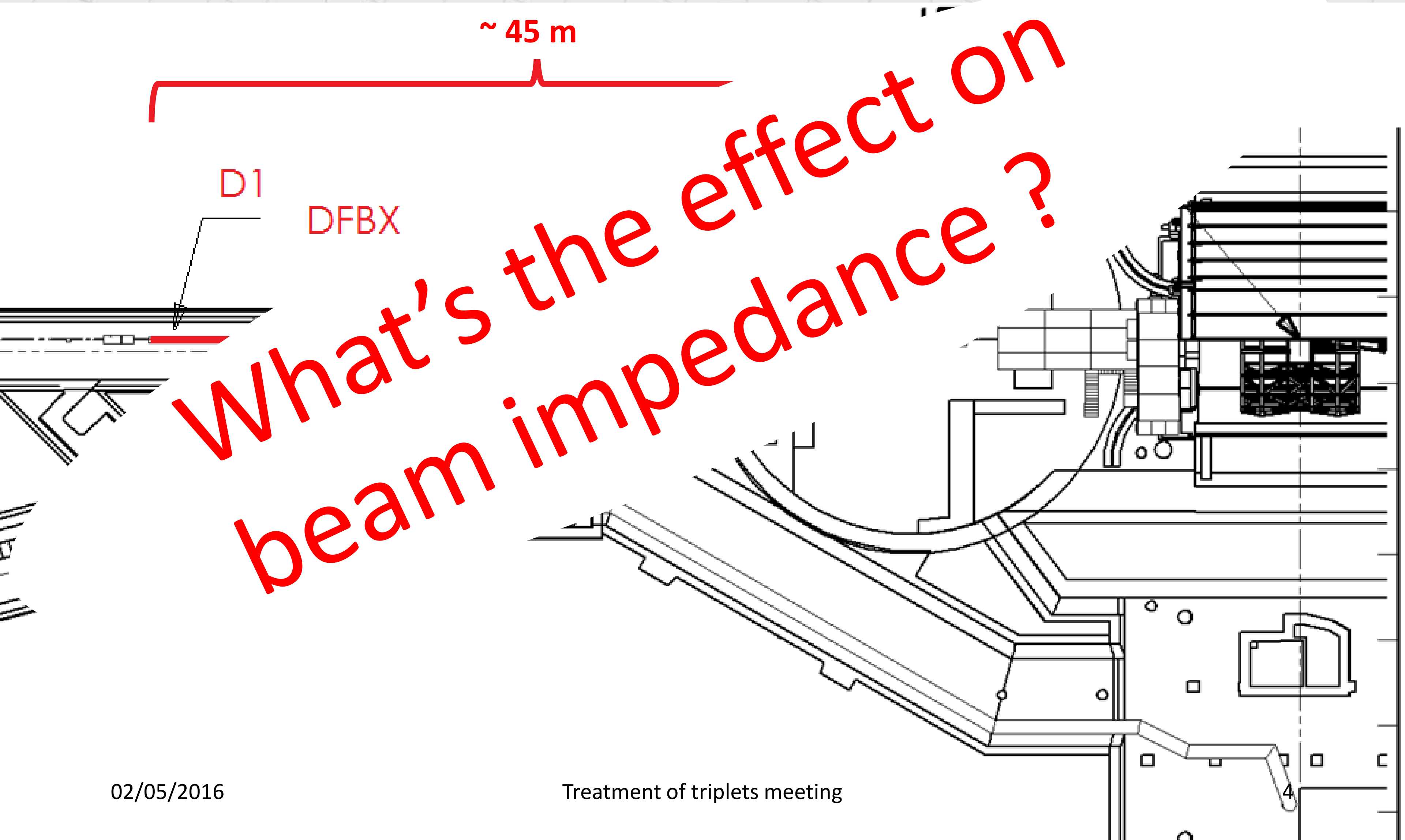
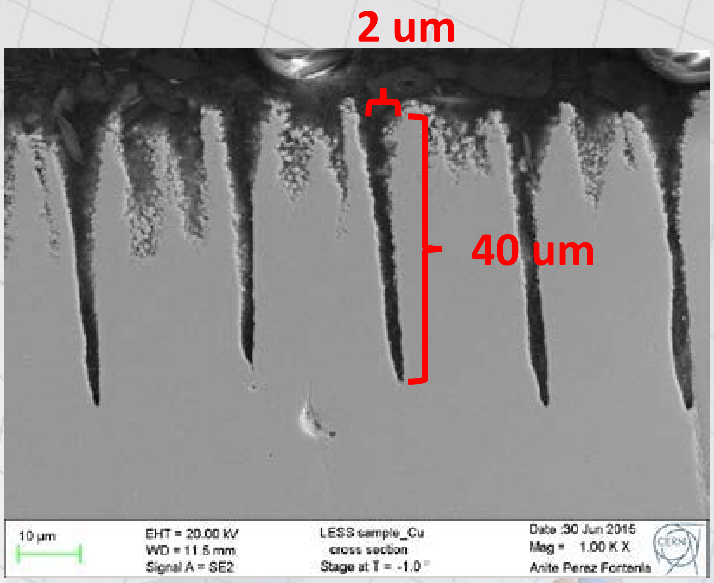


LESS (laser-engineered surface structures)



Area = 2 um · 40 um
= 80 10^{-12} m^2

The imaginary impedance is approximately proportional to the area of the grooves, see: https://cds.cern.ch/record/250977/files/p95.pdf S.S.KURENNOY and G.V. STUPAKOV

Since the area of the grooves is approximately equal to the area of the roughness, **we will in the following calculate the imaginary impedance of the grooves, and just double it to get the total imaginary impedance !**

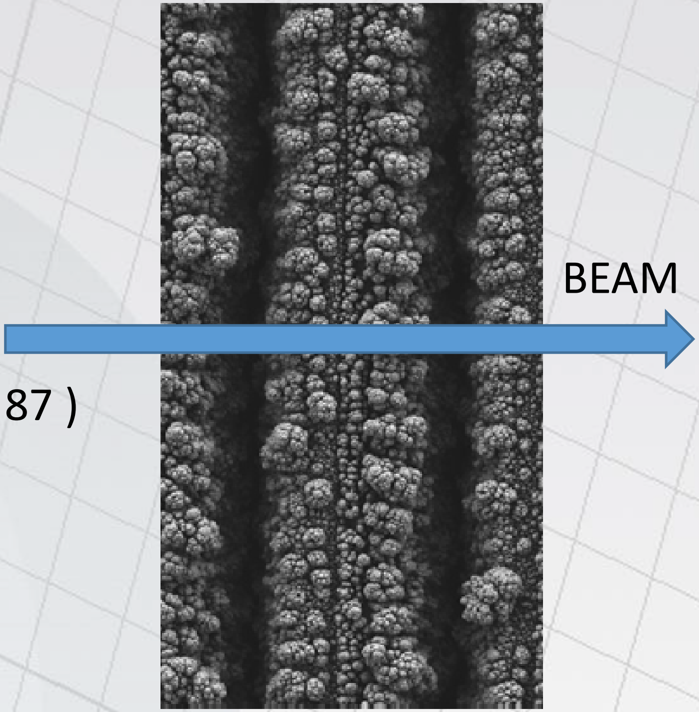
We will also not do calculations for longitudinal grooves, because they will in any case have impedances that are less than transverse grooves!

Imaginary impedance of transverse grooves

For the high energy LHC we can ignore the space charge impedance i.e. the first term with γ^2 in the denominator

$$Z_L / n \cong -j \cdot \frac{Z_0}{\beta \cdot \gamma^2} \cdot \left[\frac{1}{2} + \ln\left(\frac{b}{a} \right) \right] + j \cdot \frac{Z_0 \cdot \beta \cdot L}{2 \cdot \pi \cdot R} \cdot \ln\left(\frac{b'}{b} \right)$$

http://cdsweb.cern.ch/record/118026/files/p1.pdf (page 87)



ZL = Longitudinal impedance. It is a function of frequency ZL(f)

n = (f/frev)

frev = Revolution frequency. For the LHC it is 11.2455 kHz

β = Relativistic beta ~ 1 for LHC

Z0 = Intrinsic impedance (= $\mu_0 c \simeq 120\pi$)

b = Radius of the inner of the bellow. ***Calculations based on smallest distance to LHC beam screen***(=36.9/2 mm. http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html)

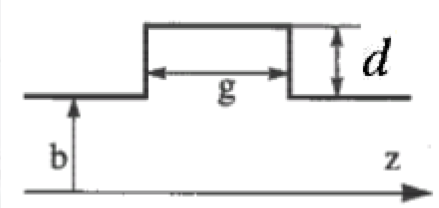
b' = Radius of the outer fold of bellow. 4 different cases: groove of 10,20,30 or 40 um deep.

L = Accumulated length of the bellow

R = Radius of the accelerator. For LHC it is (26659m / 2π)

Imaginary impedance of transverse grooves

$$Z_L/n \cong j \cdot \frac{Z_0 \cdot \beta \cdot L}{2 \cdot \pi \cdot R} \cdot \ln\left(\frac{b+d}{b}\right)$$



http://cdsweb.cern.ch/record/118026/files/p1.pdf (page 87)

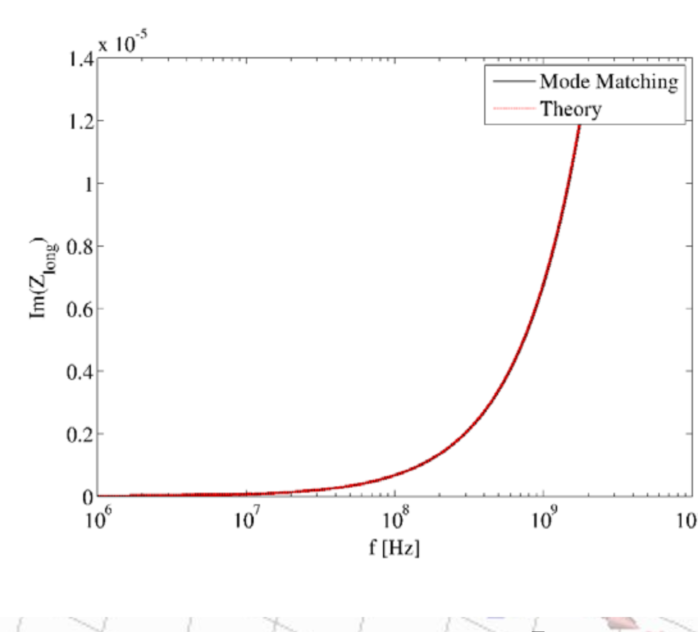
Derived for rectangular bellows

Corresponds to calculation by S. Kurennoy and G. Stupakov:
http://www.slac.stanford.edu/~stupakov/my_papers/low-freq_impedance.ps
See the comparison: \\cern.ch\dfs\Departments\AB\Groups\dropbox\berrig\LESS.cdf

Also corresponds to Chao: $$Z_L \approx -i\omega Z_0 \frac{gd}{2\pi bc}$$

http://www.slac.stanford.edu/~achao/WileyBook/WileyChapter2.pdf
(see formula 2.119)

Verified by mode matching technique by N.Biancacci:



Imaginary impedance of transverse grooves

$$Z_L / n \cong j \cdot \frac{Z_0 \cdot g \cdot d}{2 \cdot \pi \cdot R \cdot b}$$

RESULTS:
*LHC longitudinal impedance (flat top) is **96 mOhm***
*HL-LHC longitudinal impedance is **93 mOhm***

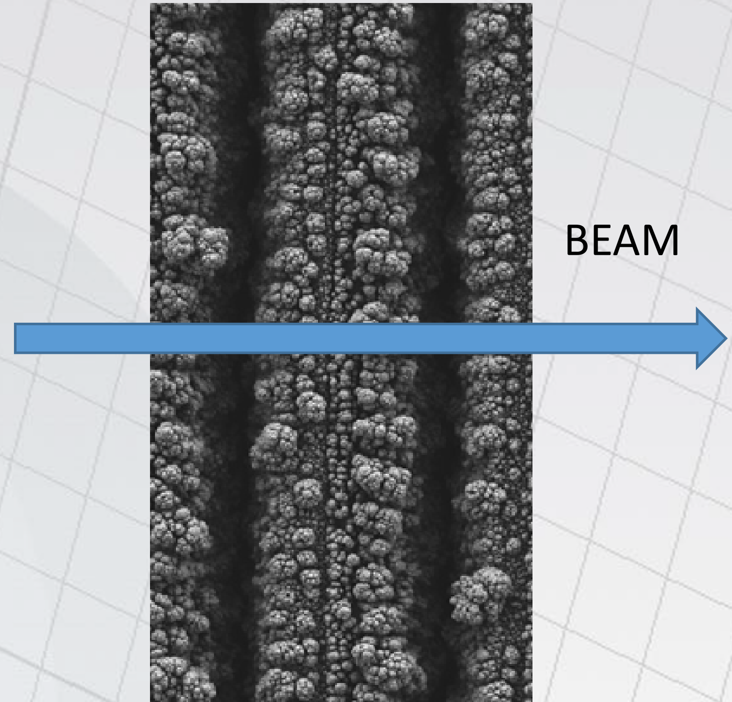
One groove (2 um wide for every 20 um)
1) 10 um groove Z_L/n = 0.10 mΩ
2) 20 um groove Z_L/n = 0.20 mΩ
3) 30 um groove Z_L/n = 0.30 mΩ
4) 40 um groove Z_L/n = 0.40 mΩ

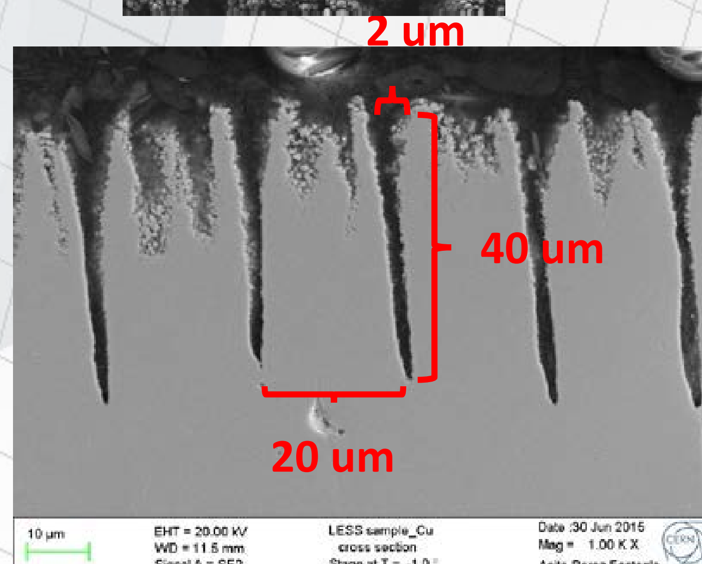
\\cern.ch\dfs\Departments\AB\Groups\dropbox\berrig\LESS.cdf

=> The deeper the grove, the worse!

Treating IP2 and IP8 on both left and right of the IP.

Equipment	Q1	Q2	Q3	DFBX	D1
Length treated [m]	7.9	14.0	9.7	2.6	10.8
Radius HOR [mm] Radius VER [mm]	20.2 25.0	25.2 30.0	25.2 30.0	30.5 35.3	30.5 35.3





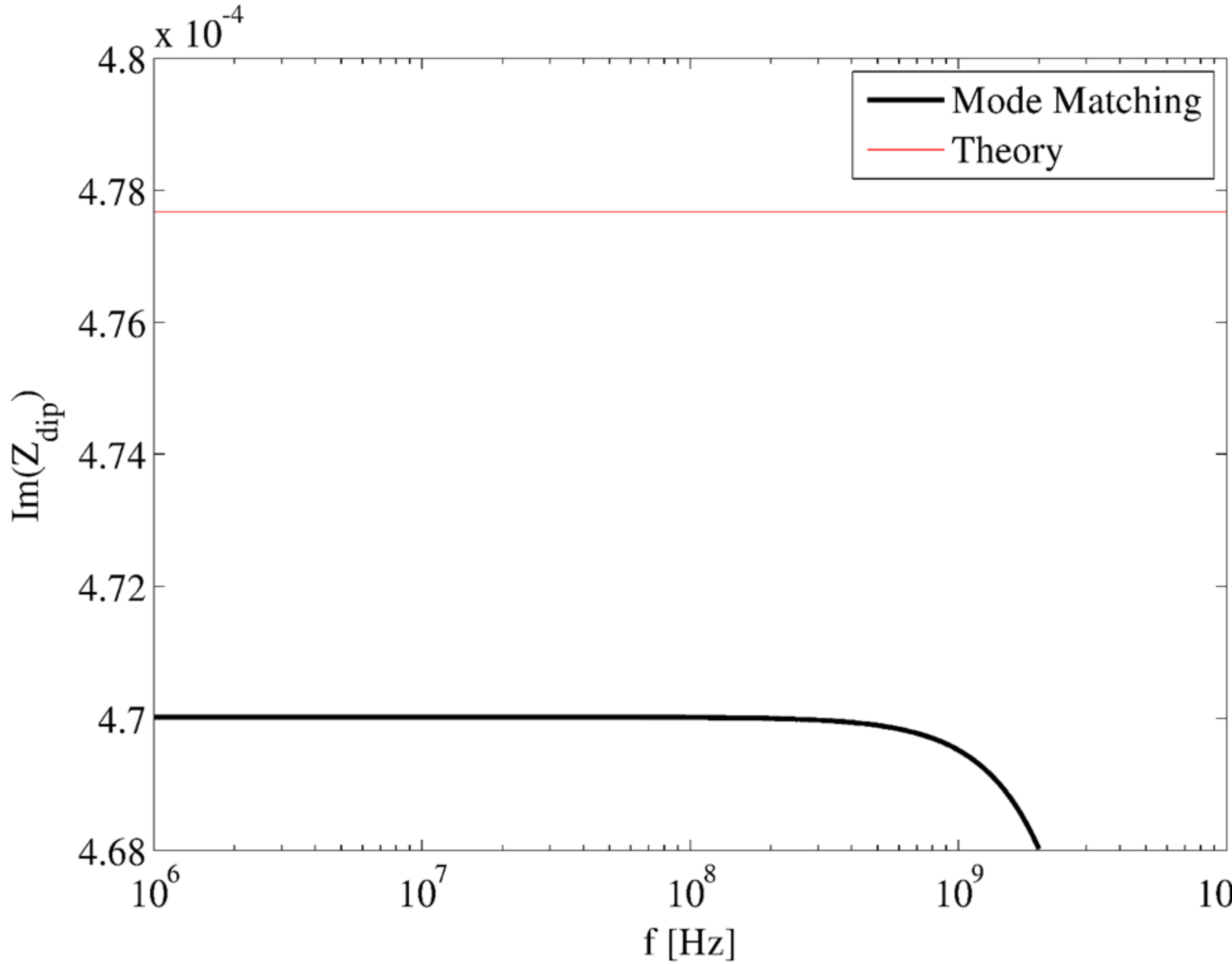
Impact on the imaginary part of transverse impedance?

$$Z_{\perp} = \frac{2c}{w \cdot b^2} \cdot Z_{\parallel}$$

← Classical thick wall formula for circular vacuum pipe

A.Wolski BEAM DYNAMICS p.503

Verified by N.Biancacci
with mode matching technique:



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A.Wolski BEAM DYNAMICS p.503

Additional impedance from grooves and roughness:
80 kOhm/m (Including a scaling factor of 4.1 for beta-functions)
Notice also that the beta-functions for LHC and HL-LHC in IP2 and IP8 are identical

LHC budget for transverse impedance:
Zx=28.8 MΩ/m (HOR) and **Zy=22.6MΩ/m** (VER)

HL-LHC budget for transverse impedance:
Zx=20.8 MΩ/m (HOR) and **Zy=17.8MΩ/m** (VER)

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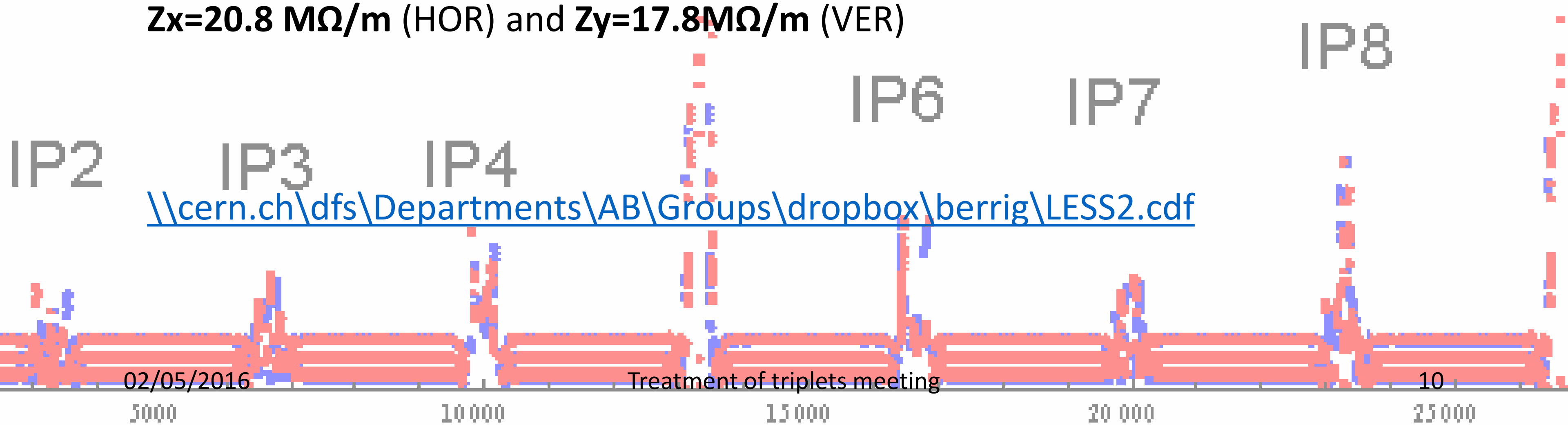


Evaluation of resistive part of the beam impedance (measurements at room temperature)

	Bulk Resistivity [Ω m]	Roughness r.m.s. RA [m]	Surface resistance at 7.8 GHz Calculated [Ω]	Measured [Ω]
Cu bulk	1.68×10^{-8}	4.09×10^{-7}	2.86×10^{-2}	**2.70×10^{-2}**
Cu(5μm)/Si	1.68×10^{-8}	9.08×10^{-9}	2.27×10^{-2}	**2.84×10^{-2}**
LESS-C	**1.68×10^{-8}**	-	-	**3.4×10^{-2}**

Increase by factor 1.5 (~3.4/2.27)

The calculated impedance is done with Hammerstad's correction coefficient:
Rs = Rs_ideal (T,RRR) · Ksr (roughness, skin depth(Rs_ideal(T,RRR)))
The correction coefficient is:

$$K_{sr} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4 \left(\frac{\Delta}{\delta_s} \right)^2 \right] \right)$$

Empirically, max=2

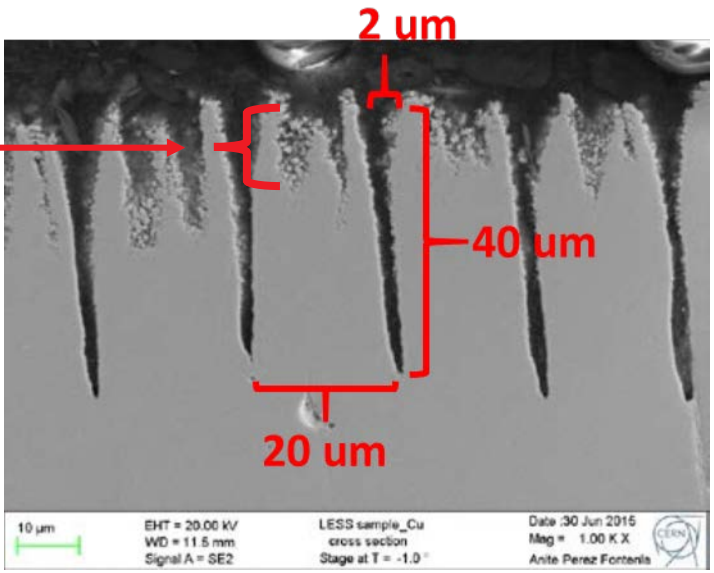
Example:
f=$7.8\cdot10^{9}$ Hz; w=2πf; μ=$1.256629\cdot10^{-6}$ Henry/m; ρ = $1.68*10^{-8}$ Ωm; Δ=$4.09*10^{-7}$ m; $\delta=\sqrt{\frac{2\rho}{w\mu}}$
Rs_Ideal=$2.27\cdot10^{-2}$Ω
Ksr= 1.25813050301
Rs=RsIdeal Ksr = $2.86\cdot10^{-2}$ Ω

http://indico.cern.ch/event/375755/attachments/749006/1027567/CERN_talk_26-Feb-2015-.pdf

Evaluation of resistive part of the beam impedance This time at 20 K, i.e. the condition in the triplets

Applying Hammerstad's correction coefficient to the triplets at 20 K with a roughness of 10 um

$$K_{sr} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4 \left(\frac{\Delta}{\delta_s} \right)^2 \right] \right)$$



Calculation for the triplets:

$f = 2.5 \cdot 10^9$ Hz; $w = 2\pi f$; $\mu = 1.256629 \cdot 10^{-6}$ Henry/m;

$\rho = 7.7 \cdot 10^{-10}\ \Omega$m (* conductivity copper at 20 K *)

$\Delta = 10\ \mu$m (* roughness for LESS *)

$\delta = \sqrt{\frac{2\rho}{w\mu}}$ (* skin depth *)

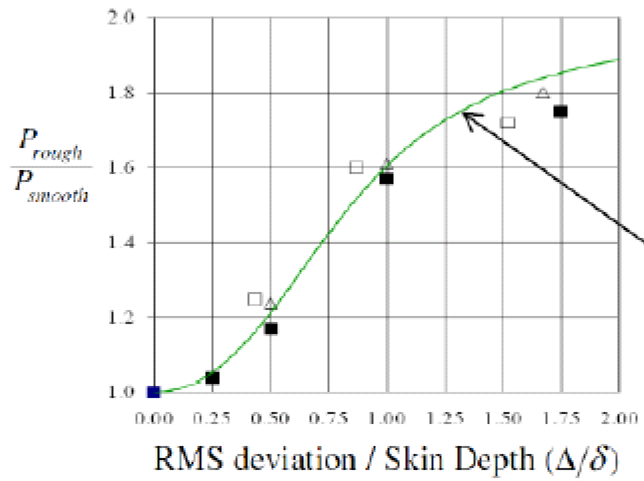
Ksr= 2.0 ← could be a factor **5** (* Private communication from F.Caspers *)

We will in the following use a factor **5** in order to be safe !

Evaluation of resistive part of the beam impedance
This time at 20 K, i.e. the condition in the triplets

Effect of Copper Roughness on Resistivity

Rs = Rs_ideal (T,RRR) * Ksr (roughness, skin depth(Rs_ideal(T,RRR)))



Hammerstad's correction coefficient

$$K_{sr} = 1 + \left(\frac{2}{\pi}\cdot\arctan\left[1.4\left(\frac{\Delta}{\delta_s}\right)^2\right]\right)$$

Empirical, Max = 2

http://cern-accelerators-optics.web.cern.ch/cern-accelerators-optics/LHC/Morgan_1949.pdf

http://cern-accelerators-optics.web.cern.ch/cern-accelerators-optics/LHC/roughness_resistivity_slides.pdf (G.Stupakov)

Heat dissipation before LESS treatment
(at 20 K, i.e. the condition in the triplets)

Power dissipated by the beam in the beam screen in mW/m (for 2 beams)

Beam screen	Radius (mm)	2012 4TeV 1374b 1.7e11 1.25 ns	2015 6.5 TeV 2248b 1.2e11 1.25 ns	Nominal 7TeV 2808b 1.15e11 1 ns	HL-LHC 7TeV 2748b 2.2e11 1.08 ns
Arc(*)	18.4	187	176	290	927
Current Q1(*)	24	143	135	222	710
Current Q2-Q3(*)	18.95	181	171	282	900
New Q1(**)	49	-	-	151	483
New Q2-Q3(**)	59	-	-	126	401

Valid for IP2 and IP8

(*) Assumes 1 weld (2mm wide) on the side of the beam screen
(**) Assumes 2 weld (4mm wide) on each side of the beam screen

https://indico.cern.ch/event/450955/ (B. Salvant)

What is the effect on beam heating?

$$P_{loss/m} = \frac{1}{C}\,\Gamma\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\, e}{2\,\pi}\right)^2\sqrt{\frac{c\,\rho\, Z_0}{2}}\;\sigma_t^{-3/2}$$

http://ibic2013.org/prepress/papers/thbl1.pdf
(E.Metral)

Where
C = 26658.883 m is the LHC circumference,
Γ = the Euler gamma function
M = the number of bunches (nominal LHC: M=2808)
b = the beam screen half height (assumed to be 18.4 mm)
N_b= the number of protons per bunch (nominal LHC N_b= 1.15 10^{11})
c = the speed of light
ρ = The resistivity (assumed to be 7.7 10^{-10} Ωm for copper at 20 K and 7 TeV)
Z_0 = the free-space impedance
σ_t =rms bunch length (expressed in unit of time) (nominal LHC: σ_t =0.25 ns)
NB! The power loss needs to be multiplied by 2, because there are 2 beams

Heat dissipation

Before LESS	After LESS
~0.9 W/m	**1.7 W/m**

⇧

The resistivity of the copper is increased by a factor **5** and therefore the power loss by the copper increases by a factor $\sqrt{5}\sim 2.24$. Since only the copper is treated and not the welds - and that the copper contributes to 70 % of the 0.9 W/m – then the heat dissipation after LESS treatment is 0.9*(1.0-0.7)+0.9*0.7*2.24 ~ 1.7 W/m

Power loss [W/m] (25ns, 2.2E11, 2748)	E-cloud IR2&8
Q1 (a/b) (SEY=1.1 - 2 beams)	2.3
Q2 (a/b) (SEY=1.1 - 2 beams)	3.4/5.4
Q3 (a/b) (SEY=1.1 - 2 beams)	3.9

https://indico.cern.ch/event/463028/contributions/1979637/attachments/1243503/1830017/63rdHiLumiWP2Meeting_EM_15-03-16.pdf
(E.Metral)

Impedance concerns

- Will the LESS treatment affect the RRR ? Answer from meeting: probably with a factor 2, corresponding to a factor √2 ~ 1.4 in effect. We consider that since we already have a safety factor 5 in the resistivity; then it includes the factor 2
- There is a weld of steel on the side of the beam screen. What if the steel is spread out on the surface of the copper as a result of the LESS treatment – will that increase the resistance? Answer from meeting: The weld will not be treated
- The nominal thickness of the copper layer is 75 um, but there are variations, which means that we can only guarantee 50 um copper coating. What is the LESS treatment occasionally goes deeper than 50 um? Answer from meeting: The grooves are not part of the scheme to reduce the SEY. They only provide material for the roughness. It is already planned to reduce the depth of the grooves

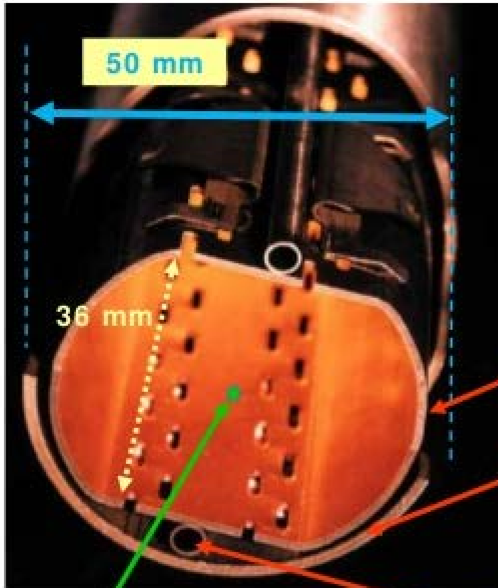
Other comments

- Depth of grooves – can we get the same SEY? Answer from meeting: The grooves are not part of the scheme to reduce the SEY. They only provide material for the roughness. It is already planned to reduce the depth of the grooves
- Angle of grooves – are perpendicular grooves best for reducing SEY?
- Is it the grooves themselves or the roughness of the surface that reduces SEY? Answer from meeting: It is only the roughness which is important
- Will the LESS treatment create dust? Answer from meeting: The concern about the dust is well known and could be a showstopper

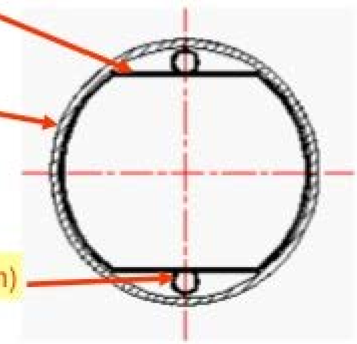
Conclusion

- Longitudinal grooves are better than transverse grooves i.e. less impedance
- Transverse grooves give an increase of ~ 0.4 % in the imaginary part of the longitudinal impedance (~0.4*100/95). The roughness adds another 0.4 %
  The total longitudinal impedance is increased by 0.8 %
- LHC: Zx=28.8 MΩ/m, Zy=22.6MΩ/m
  HL-LHC: Zx=20.8 MΩ/m, Zy=17.8MΩ/m.
  Transverse impedance increased 80 kΩ/m versus ~20M Ω/m i.e. ~0.4 % increase
- We assume that the LESS treatment gives a factor 5 increase in resistivity
- The factor 5 increase in resistivity gives a factor 2.24 increase in heat deposition. Giving roughly 1.7 W/m in heat deposition, which is lower that the heating from e-cloud: 2 – 4 W/m

Vacuum chamber



- The beams circulate in two ultra-high vacuum chambers, P ~ 10^{-10} mbar.
- A Copper beam screen protects the bore of the magnet from heat deposition due to image currents, synchrotron light etc from the beam.
- The beam screen is cooled to T = 4-20 K.



J. Wenninger LNF Spring School, May 2010 40

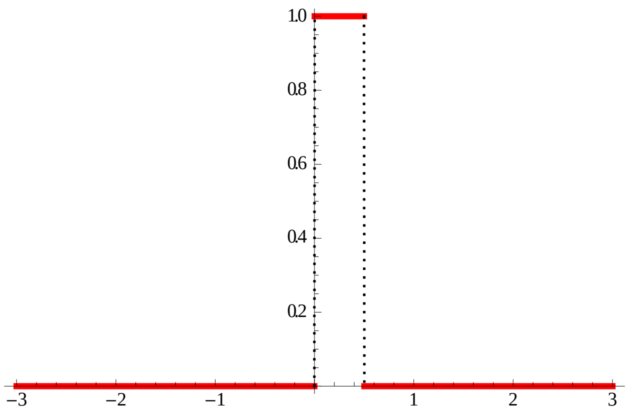
Table 2.4: LHC storage ring parameters

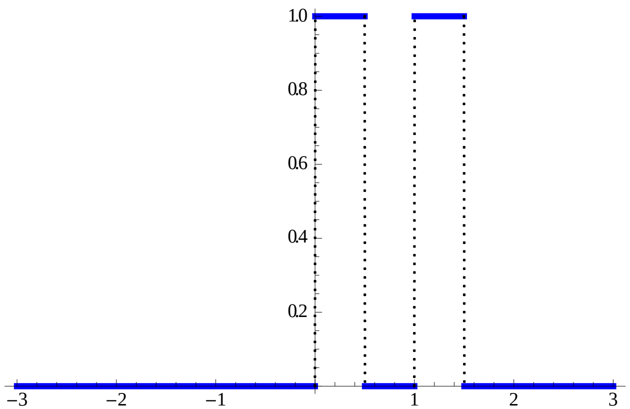
		Injection	Collision
Geometry			
Effective vacuum screen height (incl. tol.)	[mm]	44.04	
Effective vacuum screen width (incl. tol.)	[mm]	34.28	

Power loss is proportional to number of bunches

$$I1[t\_] := \begin{cases} 0 & t \leq 0.0 \\ 1 & 0.0 < t < 0.5 \\ 0 & \text{True} \end{cases}$$

$$I2[t\_] := \begin{cases} 0 & t \leq 0.0 \\ 1 & 0.0 < t < 0.5 \\ 0 & 0.5 \leq t \leq 1.0 \\ 1 & 1.0 < t < 1.5 \\ 0 & \text{True} \end{cases}$$





$$\text{Power1} = \frac{R}{T} \int_0^T I1[t]^2 \, dt$$

0.166666666667

$$\text{Power1} = \frac{R}{T} \int_0^T I2[t]^2 \, dt$$

0.333333333333

```
T = 3; (* We assume that the currents repeat, with the repetition time T *)
R = 1; (* Resistance *)
```

$$\frac{\Delta \mathscr{E}}{L} = \begin{cases} -\dfrac{2q^2}{b^2} & \text{if} \quad \sigma_z \ll \chi^{1/3} b, \\ -\dfrac{1}{2\pi}\Gamma\left(\dfrac{3}{4}\right)\dfrac{q^2}{b\sigma_z^{3/2}}\sqrt{\dfrac{c}{2\pi\sigma}} & \text{if} \quad \sigma_z \gg \chi^{1/3} b, \end{cases} \qquad (2.194)$$

http://www.slac.stanford.edu/~achao/WileyBook/WileyChapter2.pdf

$$P_{loss/m} = \frac{1}{C}\Gamma\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\, e}{2\,\pi}\right)^2 \sqrt{\frac{c\,\rho\, Z_0}{2}}\; \sigma_t^{-3/2}$$

http://ibic2013.org/prepress/papers/thbl1.pdf

(E.Metral)

Where

C = 26658.883 m is the average LHC radius,

Γ = the Euler gamma function

M = the number of bunches (nominal LHC: M=2808)

b = the beam screen half height (assumed to be 18.4 mm)

N_b= the number of protons per bunch (nominal LHC N_b= 1.15 10^{11})

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Z_0 = the free-space impedance

σ_t =rms bunch length (expressed in unit of time) (nominal LHC: σ_t =0.25 ns)