







Transverse impedance in vacuum

- * Introduction
- * Reminder about crash programme for LHC collimators (started in 2003)
- Transverse impedance in matter
- Conclusions and next steps







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Limits performance of ALL machines (high intensity and/or high brightness)
* Beam instabilities => Increased beam size, beam losses





- ★ Beam instabilities => Increased beam size, beam losses
- * Excessive heating => Deformed / melted components, beam dumps





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- ✤ Beam instabilities => Increased beam size, beam losses
- * Excessive heating => Deformed / melted components, beam dumps
- Each equipment of each accelerator has an impedance (several complex functions of f) => To be characterized and minimized!







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A new physical regime was revealed by LHC collimators
=> Small aperture paired with large wall thickness ask for a different physical picture of resistive-wall effect than classical one





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In 2005, starting from Maxwell equations and using field matching, a consistent derivation of the transverse (resistive-)wall impedance of an infinitely long cylindrical beam pipe was performed for 2 layers (see https://ds.cem.ch/record/0505/fles/ab.2005/084.pdf) => Results valid for any beam velocity, frequency, conductivity, permittivity and permeability (and L >> b)





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Figure 6. Transverse wall impedance for the case of a (round) LHC collimator. Here, σ is the el conductivity and τ is the relaxation time.











Note: for a cylindrical beam pipe or two parallel plates, with any number of layers, the ImpedanceWake2D code was developed (see <u>https://gitlab.cern.ch/IRIS/IW2D</u>), which is valid when the length of the structure is (much) larger than the beam pipe radius (or half gap in the case of two parallel plates) => Nicolas Mounet, "The LHC Transverse Coupled-Bunch Instability", PhD thesis, EPFL, Lausanne, 2012







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• If the layer 1 is a PC, then
$$\alpha_{TM} = \frac{K_1(x_1)}{I_1(x_1)}$$
, with $x_1 = \frac{k b}{\gamma}$





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$$= Z_x^{\text{Total}}(f) = -\frac{jLZ_0I_1(x_0)K_1(x_0)}{\pi a^2\beta\gamma^2} + \frac{jLZ_0I_1^2(x_0)}{\pi a^2\beta\gamma^2}\frac{K_1(x_1)}{I_1(x_1)}$$





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$$Z_{x}^{\text{Total}}(f) = -\frac{jLZ_{0}}{2\pi a^{2}\beta\gamma^{2}} + \frac{jLZ_{0}}{2\pi b^{2}\beta\gamma^{2}} = -\frac{jLZ_{0}}{2\pi\beta\gamma^{2}}(\frac{1}{a^{2}} - \frac{1}{b^{2}})$$



Case of 1 layer of Perfect Conductor => Plot of indirect impedance











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$$\Rightarrow Z_{x}^{\text{Direct,Mat}}(f) = -\frac{jLZ_{0}I_{1}(x_{0})K_{1}(x_{0})}{\pi a^{2}\beta}\mu_{1}(\frac{1}{\epsilon_{1}\mu_{1}} - \beta^{2})$$





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$$\nu = k\sqrt{(1 - \mu_1 \beta^2 [\epsilon_b + \frac{\sigma}{j\epsilon_0 \omega}])}$$





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And now we can scan the effect of the material's conductivity σ , permittivity ϵ_b and permeability μ_1

$$\nu = k\sqrt{(1 - \mu_1\beta^2[\epsilon_b + \frac{\sigma}{j\epsilon_0\omega}])}$$

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 $L = 1 \text{m}; a = 0.1 \text{mm}; b = 1 \text{cm}; \beta = 0.5; \sigma = \sigma_{\text{DC}}; \epsilon_b = \mu_1 = 1$

MuCol

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$$\sigma = 0$$
 [S/m]





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$$\sigma = 10^{-3}$$
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$$\sigma = 10^{-2} \quad [\text{S/m}]$$





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$$\sigma = 10^{-1} \quad [\text{S/m}]$$



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Collaboration

MuCol



 $L = 1 \text{m}; a = 0.1 \text{mm}; b = 1 \text{cm}; \beta = 0.5; \sigma = \sigma_{\text{DC}}; \epsilon_b = \mu_1 = 1$

$$\sigma = 10^0$$
 [S/m]



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Highly Conductive Metals:

- Silver (Ag): 6.30 × 10⁷ S/m (Best conductor)
- Copper (Cu): 5.96 × 10⁷ S/m
- Gold (Au): 4.10 × 10⁷ S/m
- Aluminum (Al): 3.50 × 10⁷ S/m

Moderate Conductivity Metals:

- Tungsten (W): 1.79 × 10⁷ S/m
- Iron (Fe): 1.00 × 10⁷ S/m
- Beryllium (Be): 2.5 × 10⁷ S/m

Poorer Conductors (Still Metals):

- Titanium (Ti): 2.4 × 10⁶ S/m
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- Liquid hydrogen (LH₂): ?
- Lithium hydride (LiH): ?





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What will be the operational temperature and pressure? => "Exact" EM properties (vs. frequency) will be needed at some point and might need to be carefully measured! => Demonstrator?





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 Lithium hydride (LiH) => From Wikipedia (<u>https://en.wikipedia.org/</u> <u>wiki/Lithium_hydride</u>):

LiH is a diamagnetic and an ionic conductor with a conductivity gradually increasing from $2 \times 10^{-5} \Omega^{-1}$ cm⁻¹ at 443 °C to 0.18 Ω^{-1} cm⁻¹ at 754 °C there is no discontinuity in this increase through the melting point.^{13:36} The dielectric constant of LiH decreases from 13.0 (static, low frequencies) to 3.6 (visible-light frequencies).^{[3]:35} LiH is a soft







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$$\sigma = 10^{-1} \quad [\text{S/m}]$$









$$L = 1$$
m; $a = 0.1$ mm; $b = 2$ cm; $\beta = 0.5$; $\sigma = \sigma_{DC}$; $\mu_1 = 1$; $\epsilon_b = 10$

$$\sigma = 10^1$$
 [S/m]









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The transverse impedance in matter has been computed using the same formalism as the one developed in the past (2005) for the LHC collimators (see https://cds.cern.ch/record/877819/files/ab-2005-043.pdf, https://cds.cern.ch/record/877819/files/ab-2005-043.pdf, https://cds.cern.ch/record/877819/files/ab-2005-043.pdf, https://cds.cern.ch/record/895805/files/ab-2005-084.pdf and https://emetral.web.cern.ch/USPAS09course/WakeFieldsAndImpedances.pdf) => https://cds.cern.ch/USPAS09course/WakeFieldsAndImpedances.pdf) => https://cds.cern.ch/USPAS09course/WakeFieldsAndImpedances.pdf) => https://cds.cern.ch/USPAS09course/WakeFieldsAndImpedances.pdf) =>





A similar analysis can be done also for the longitudinal impedance

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 \star Check with a numerical solver such as WAKIS




Take-home messages



"Exact" EM

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 - Study the impact of the absorber's material and geometry, number of layers, interface with vacuum,...



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 - \star Check with a numerical solver such as WAKIS
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 - \star And then study the impact on beam dynamics

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Thank you for your attention!



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APPENDIX: 6D-cooling (RuihuZ: https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.28.04100)



TABLE I. Main parameters for the cooling cells in each stage. A and B denote the premerge and postmerge section, respectively. Liquid hydrogen is used as the wedge absorber material for all stages.

Stage	Cell length (m)	Stage length (m)	Pipe radius (cm)	Maximumon-axis B_z (T)	Integrated B_y (T · m)	Transverse beta (cm)	Dispersion (mm)	On-axis wedge length (cm)	Wedge apex angle (deg)	rf frequency (MHz)	Number of rf cells	rf cell length (cm)	Maximum rf gradient (MV/m)	rf phase (deg)
A1	1.8	104.4	28	2.5	0.102	70	-60	14.5	45	352	6	19	27.4	18.5
A2	1.2	106.8	16	3.7	0.147	45	-57	10.5	60	352	4	19	26.4	23.2
A3	0.8	64.8	10	5.7	0.154	30	-40	15	100	704	5	9.5	31.5	23.7
A4	0.7	86.8	8	7.2	0.186	23	-30	6.5	70	704	4	9.5	31.7	25.7
B1	2.3	50.6	23	3.1	0.106	35	-51.8	37	110	352	6	25	21.2	29.9
B2	1.8	66.6	19	3.9	0.138	30	-52.4	28	120	352	5	22	21.7	27.2
B3	1.4	84	12.5	5.1	0.144	20	-40.6	24	115	352	4	19	24.9	29.8
B4	1.2	66	9.5	6.6	0.163	15	-35.1	20	110	352	3	22	24.3	31.3
B5	0.8	44	6	9.1	0.116	10	-17.7	12.5	120	704	5	9.5	22.5	24.3
B6	0.7	38.5	4.5	11.5	0.0868	6	-10.6	11	130	704	4	9.5	28	22.1
B7	0.7	28	3.75	13	0.0882	5	-9.8	10	130	704	4	9.5	28.5	18.4
B8	0.65	46.15	2.85	15.8	0.0726	3.8	-7.0	7	140	704	4	9.5	27.1	14.5
B9	0.65	33.8	2.3	16.6	0.0694	3	-6.1	7.5	140	704	4	9.5	29.7	11.9
B10	0.63	29.61	2	17.2	0.0691	2.7	-5.7	6.8	140	704	4	9.5	24.9	12.2



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