Beam-Wall Interaction in the LHC Liner: a former PhD student experience

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Francesco as my PhD thesis supervisor

I had the honor to be one of Francesco's students.

Constant in-depth discussions during all my thesis work.

… I learnt from him a <u>method</u>.

He was always looking for the physical insight of results, first condition for them to be correct.

The first step to assess a result was to always look for a counter-example.

The need (and the pleasure) to understand in depth the issues that we were dealing with.

Ability of highlighting the critical points in my work and recommending clever following steps.

Warm atmosphere for young people in the group.

Francesco believed in the need of the SL-AP group of preserving and transmitting AP know-how. When he became group leader, training of students was explicitly declared in the SL-AP group mandate.

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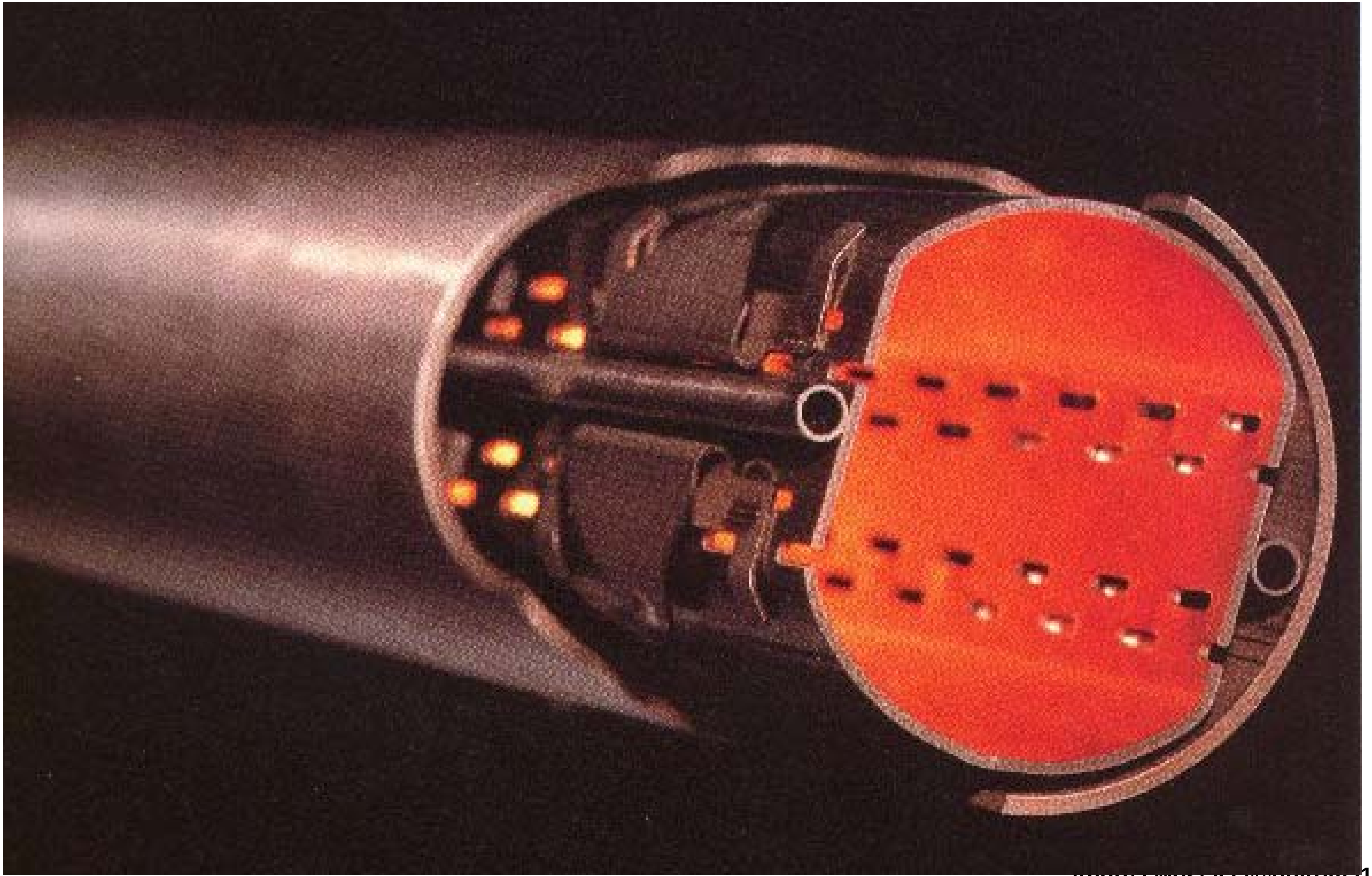
LHC beam pipe



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LHC beam pipe

Pumping holes.

EM coupling, through holes, between a cylindrical and a coaxial waveguide.

Artificial (saw-tooth) roughness.

Interaction between the beam and a surface (synchronous) wave in a (rectangular) beam pipe with “small” periodic corrugations.

Weldings.

Currents distribution in a (metallic) beam pipe whose conductivity varies with the azimuth (ultrarelativistic beam).

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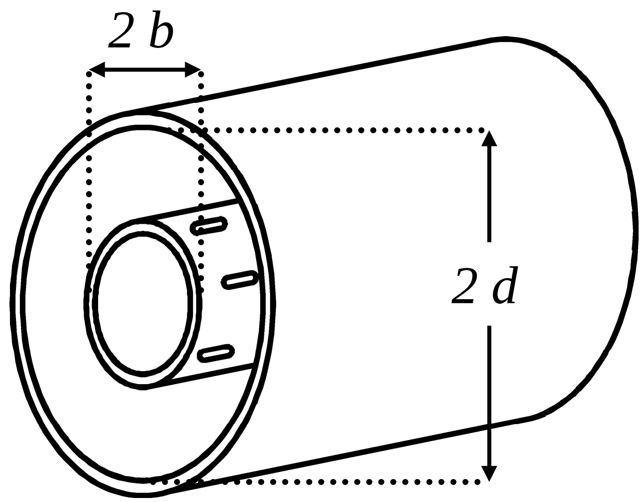
Pumping holes in a coaxial beam pipe

- *Ohmic losses in the coaxial region:*

$$\alpha(\omega) = \frac{1}{2\,Z_0\,\ln(d/b)}\left(\frac{\sqrt{\rho_b}}{b}+\frac{\sqrt{\rho_d}}{d}\right)\sqrt{\frac{\mu\,\omega}{2}} = a\sqrt{\omega}.$$

b *internal radius* *d* *external radius* ρ *resistivity*



- *Holes and equivalent dipoles (Modified Bethe Theory).*
- *Polarizability including also the wall thickness.*
- *Coupling impedance (beam stability).*
- *Loss Factor k(σ) (energy losses).*
- *Power lost per unit length: P.*

$$P = \frac{c\,Q^2 k(\sigma)}{S_b L}$$

S_b bunch spacing

L device length

σ r.m.s bunch length

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Pumping holes: loss factor

- *Randomising the position of the holes does not affect the loss factor.*

- *Limit of negligible ohmic losses (N equispaced holes, at distance D) :*

$$k(\sigma) = \frac{Z_0\sqrt{\pi}c\,(\alpha_m + \alpha_e)^2}{128\pi^4 b^4 \ln(d/b)\sigma^3}\left[N^2 + \left(\frac{\sigma}{D}\right)^2 \frac{(\alpha_m - \alpha_e)^2}{(\alpha_m + \alpha_e)^2}\right].$$

magnetic polarizability → α_m

electric polarizability → α_e

- *Ohmic losses in the coaxial region:*

$$k(\sigma) = \frac{Z_0\,(\alpha_m + \alpha_e)^2}{16\pi^4 b^4 \ln(d/b)c^2}\left[\frac{\sqrt{\pi}}{8}\left(\frac{c}{\sigma}\right)^3 N + \frac{1}{2}\Gamma\left(\frac{5}{4}\right)\frac{c^{5/2}}{aD\sigma^{5/2}}N + \frac{I_3}{a^2D^2}\right].$$

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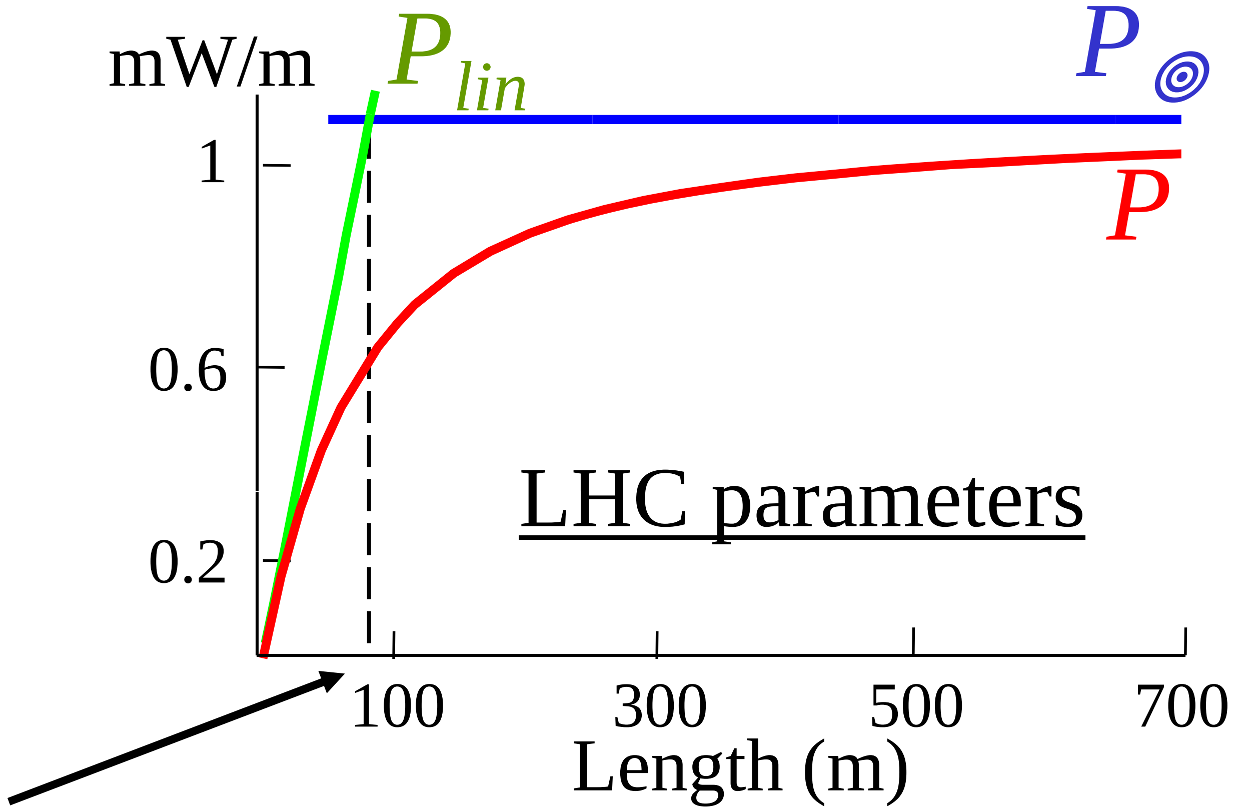
Pumping holes: power lost per unit length

P_{lin} no attenuation

$P_{◎}$ limit value

P "exact" formula



$$\omega_c = c/\sigma$$

$$L_\alpha = 4\frac{\Gamma(5/4)}{\sqrt{\pi}}\frac{1}{\alpha(\omega_c)}$$

A. Mostacci, L. Palumbo and F. Ruggiero, Physical Rev. ST-AB (December '99).

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Pumping holes: impact on the liner design

Around LHC nominal values (♦):

$$P_\infty \approx P_0 \, Exp\left(-1.75\pi \, T/W\right),$$

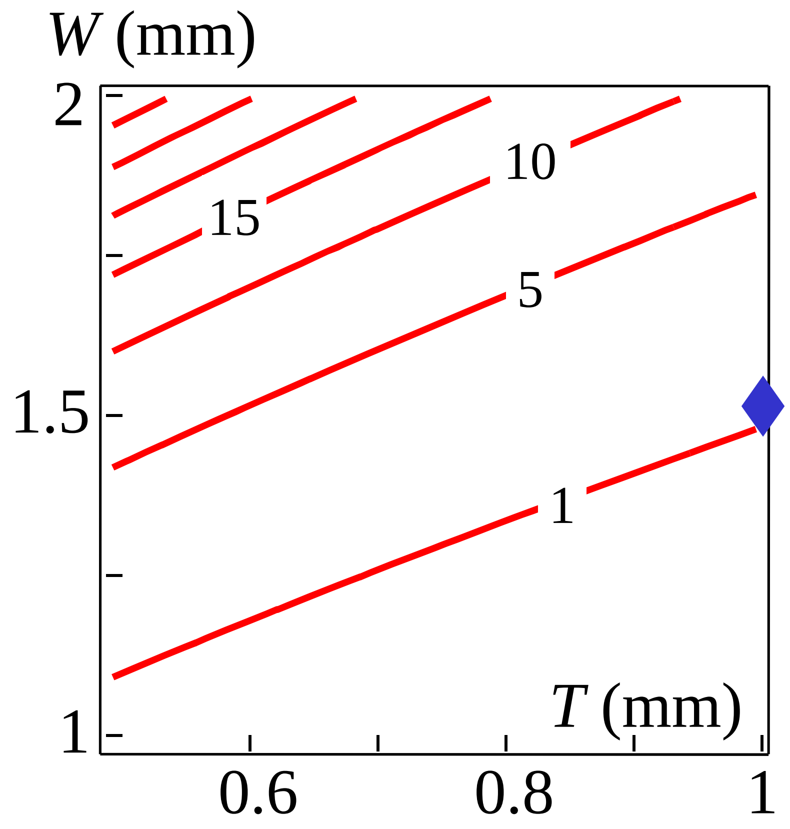
$$P_0 = 42\, mW/m \left(\frac{W}{1.5\, mm}\right)^4.$$

W slot width (rectangular)

T wall thickness

Power loss per unit length is negligible for holes of the nominal dimensions.

Curves of constant power per unit length (mW/m)



A. Mostacci and F. Ruggiero, LHC Project Note 195 (August '99).

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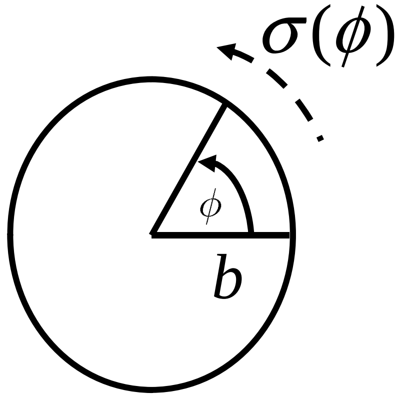
Beam pipe with azimuthally varying conductivity

- *Cylindrical geometry (circular cross section).*



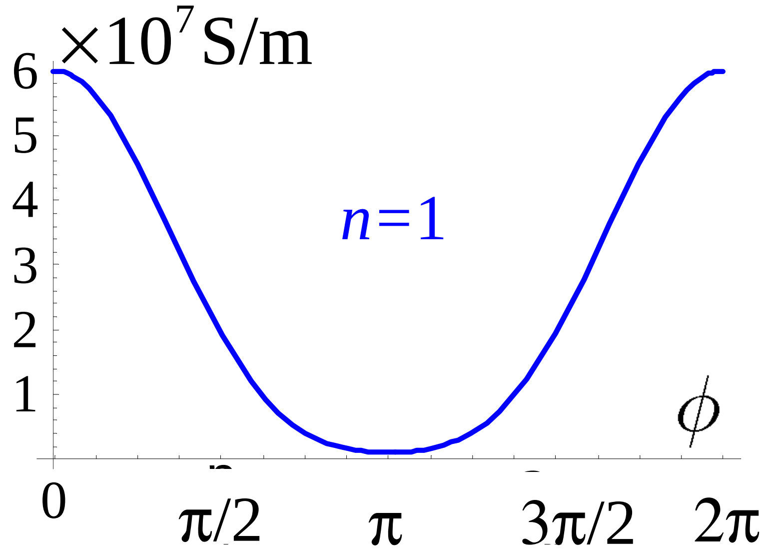
$$\Pi_z = -\frac{j}{2\pi^2}\frac{Z_0}{k}\sum_{m=0}^{\infty} F_m I_m\left(\frac{kr}{\beta\gamma}\right) K_m\left(\frac{kb}{\beta\gamma}\right)\cos(m\phi)e^{jzk/\beta}.$$

$$\widetilde{\Pi}_z = \frac{j}{2\pi^2}\frac{\beta\gamma}{k}\sum_{m=1}^{\infty} \widetilde{F}_m I_m\left(\frac{kr}{\beta\gamma}\right) K'_m\left(\frac{kb}{\beta\gamma}\right)\sin(m\phi)e^{jzk/\beta}.$$

- *Leontovich conditions (SIBCs):*

$$\boldsymbol{n} \times (\boldsymbol{n} \times \boldsymbol{H}) = Y(\omega, \phi)\, \boldsymbol{n} \times \boldsymbol{E},$$

$$Y(\omega,\phi) = \sqrt{\frac{j\sigma(\phi)}{\omega\mu_0}} = Y_0(\omega)\left[1 + \frac{Y_n}{Y_0}\cos(n\phi)\right].$$



following an approach proposed in
F. Ruggiero, Phys. Rev. E, Vol. 53, 3, 1996

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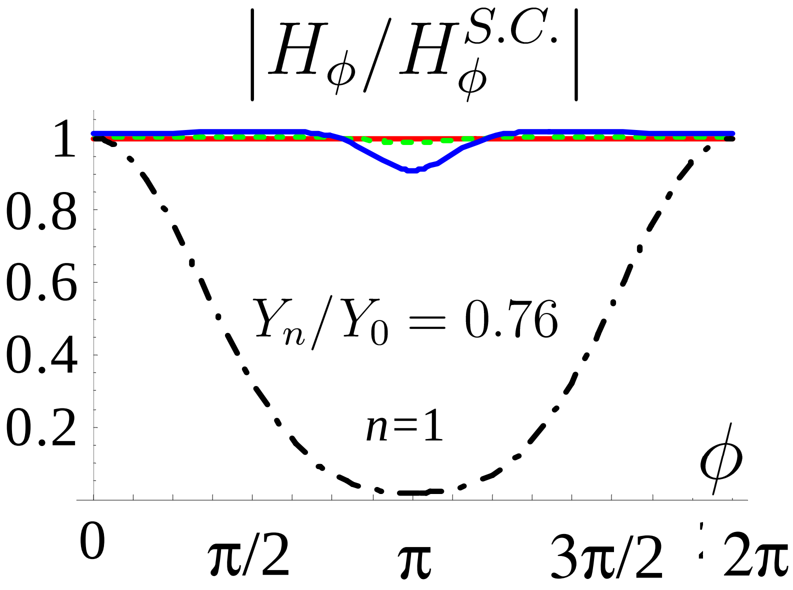
Azimuthally varying conductivity: solution (I)

- *Ultrarelativistic limit.*
- *From B.C, we get a system for the coefficients* $F_m, \tilde{F}_m$ *(truncation).*
- *Semi-analytic solution.*
- *A posteriori check of B.C.*

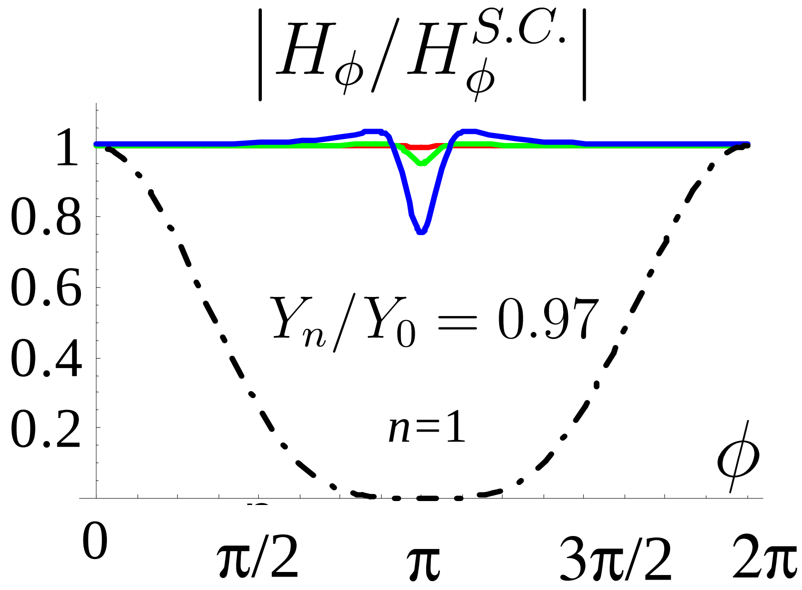


Stainless steel / "warm" copper

1 GHz

1 MHz

20 kHz



Stainless steel / "cold" copper

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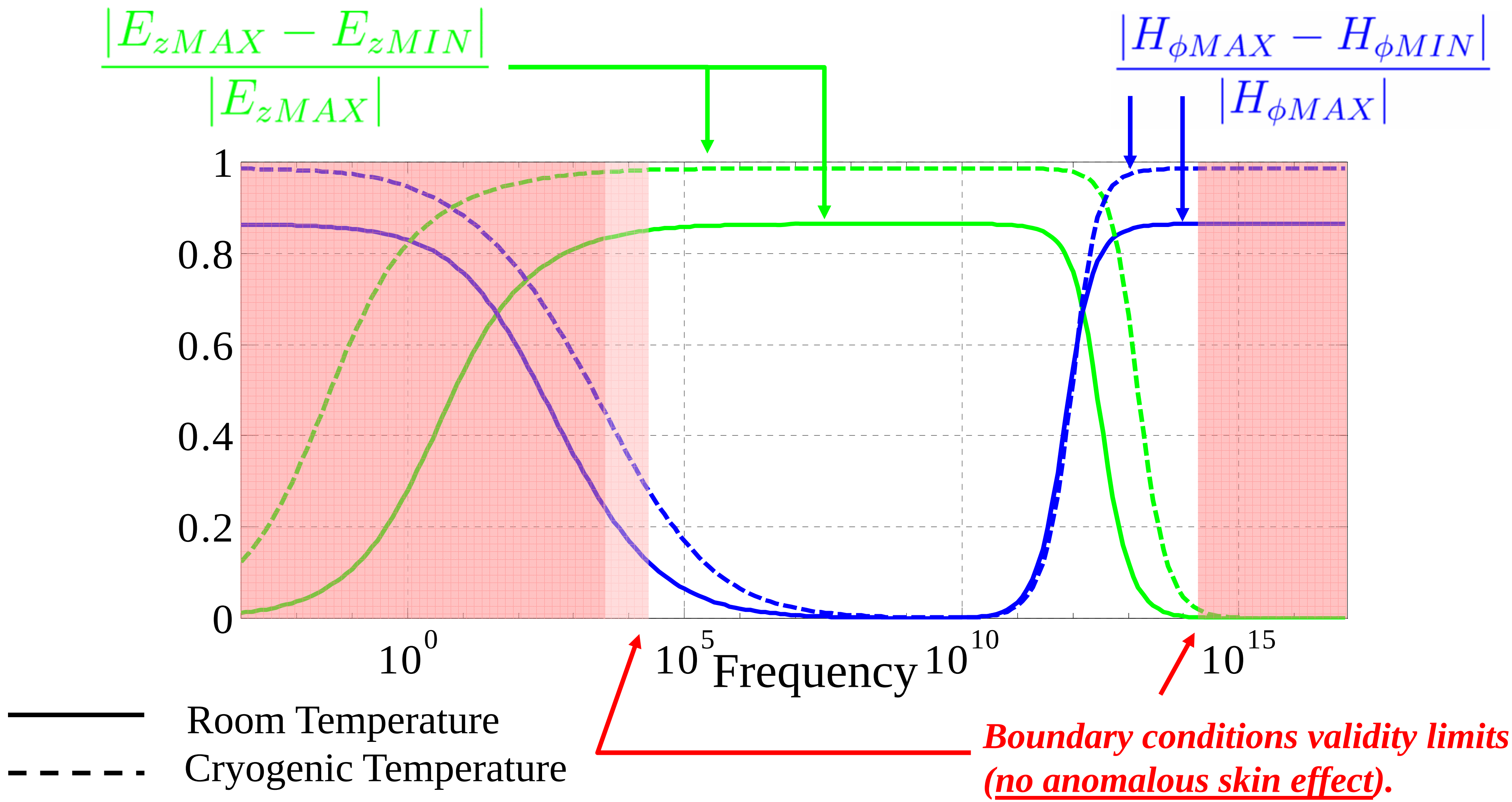
Azimuthally varying conductivity: solution (II)



Surface currents are constant over the azimuth (at all the relevant frequencies). The losses in the welding is 5 % of the ones in the copper at room temperature (50% at cryogenic temperatures).

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Azimuthally varying conductivity: validity of the BC

- *Leontovitch boundary condition is a 1st order condition (SIBC).*

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

Skin Depth

Higher Frequency Limit → $\lambda >> \delta$ → 200 THz (S.S.)

Lower Frequency Limit

- *Cryog. Temp.* → *Variations of the material properties slow on a scale of δ.* → 20 kHz
- *Room Temp.* → *curvature* $>> \delta$ → 5 kHz (S.S.)

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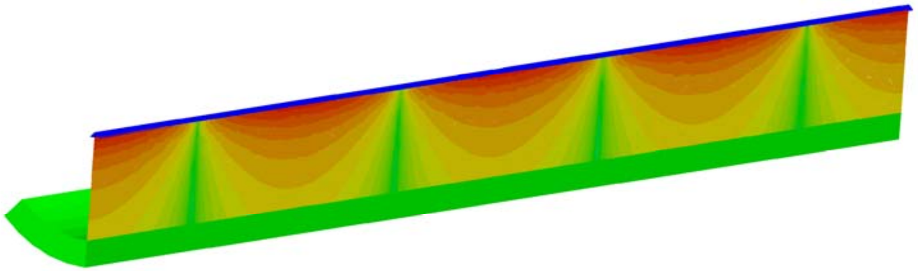
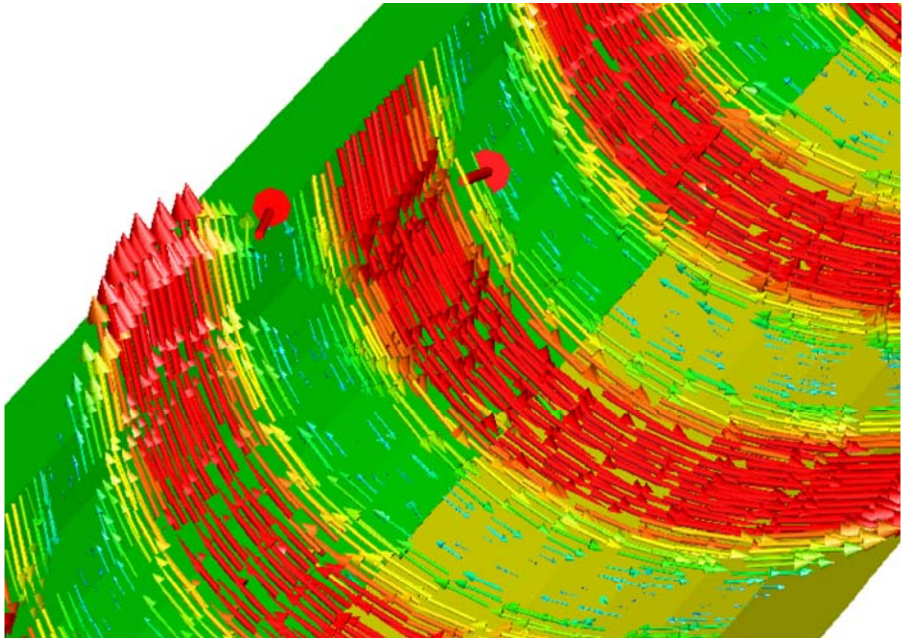
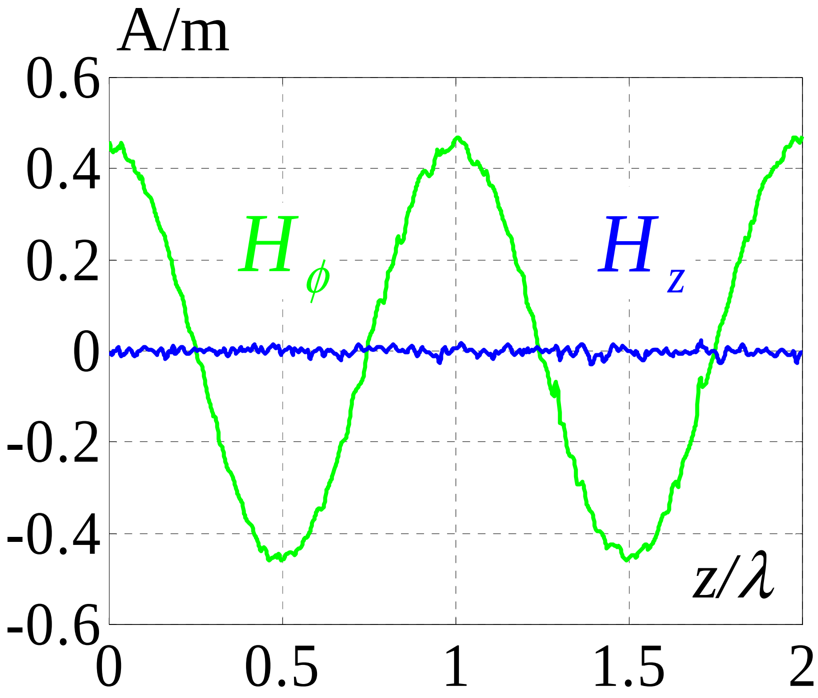
Azimuthally varying conductivity: simulation (HFSS)

- *Wire method.*
- *f = 1 GHz, P = 1 W.*
- *No solution inside the conductor.*







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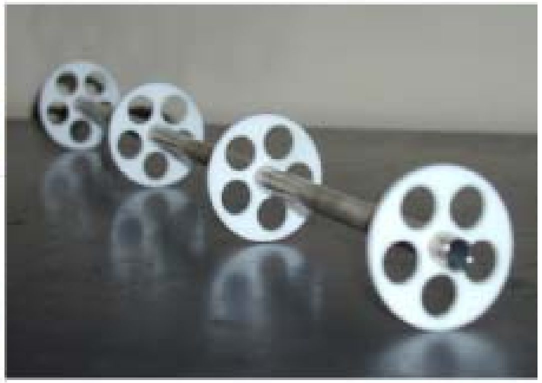
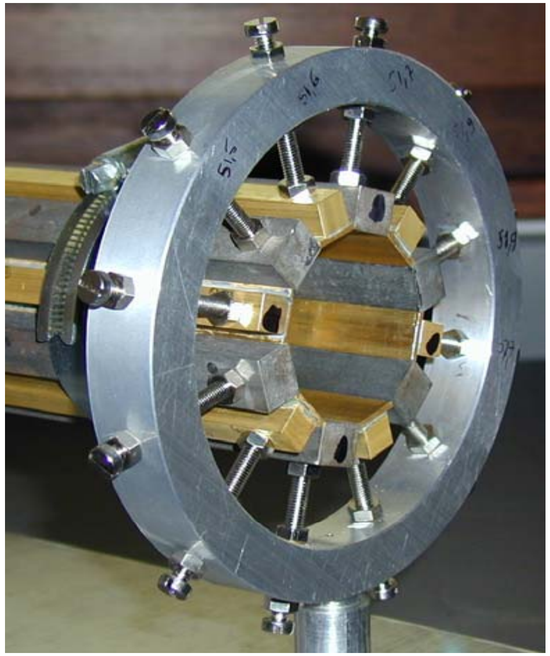
Azimuth. varying conductivity: Q measurements (I)



Coaxial resonator:

Q measurements in

various configurations.



F. Caspers, A. Mostacci, L. Palumbo and F. Ruggiero, LHC Project Note 493 (August ‘01).

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Azimuthally varying conductivity: Q measurements (II)

Power dissipated in a brass bar.

$$P_0 = P_{INNER} + 12P^{BRASS} \qquad P_N = P_{INNER} + (12-N)P^{BRASS} + \sum_{j=1}^{N} P_j^{STEEL}$$

Power dissipated in the inner conductor.

Power dissipated in the steel bar j.

$$P_0 - P_N = \sum_{j=1}^{N} P^{BRASS} - P_j^{STEEL} = \sum_{j=1}^{N} P_0 - P_1^j$$

$$Q = 2\pi f_0 \frac{W}{P}$$

$$\frac{Q_0 - Q_N}{Q_N} = \sum_{j=1}^{N} \frac{Q_0 - Q_1^j}{Q_1^j}$$

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Azimuth. varying conductivity: theory validation

$$\frac{Q_0 - Q_N}{Q_N} = \sum_{j=1}^{N} \frac{Q_0 - Q_1^j}{Q_1^j}$$

Q_N *N steel bars*

Q_1^j *steel bar j*

$$u_c(f) = \frac{\overline{Q}_0}{\overline{Q}_N}\sqrt{\left[\frac{u\left(Q_0\right)}{\overline{Q}_0}\right]^2 + \left[\frac{u\left(Q_N\right)}{\overline{Q}_N}\right]^2}$$

$$u_c(g) = \sqrt{\left[\sum_{j=1}^{N} \frac{u\left(Q_0^j\right)}{\overline{Q}_1^j}\right]^2 + \sum_{j=1}^{N}\left(\frac{\overline{Q}_0}{\overline{Q}_1^j}\right)^2\left[\frac{u\left(Q_1^j\right)}{\overline{Q}_1^j}\right]^2}$$

	$\overline{f} = (\overline{Q}_0 - \overline{Q}_N)/\overline{Q}_N$	$u_c(f)$	$\overline{g} = \sum_{j=1}^{N}(\overline{Q}_0 - \overline{Q}_1^j)/\overline{Q}_1^j$	$u_c(g)$
2 steel bars @ 288 MHz	**0.704**	0.02	**0.687**	0.03
2 steel bars @ 1.16 GHz	**0.589**	0.01	**0.579**	0.02
3 steel bars @ 288 MHz	**1.037**	0.02	**1.041**	0.03
3 steel bars @ 1.16 GHz	**0.877**	0.01	**0.880**	0.02

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Francesco's legacy

Respect and promote young people's work.

Intellectual honesty and rigour.

Many small and practical tips which I still pass on to our students.

Ability to give meaningful comments or suggestions on many technical aspects of several accelerator physics problems.

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I am proud to have been one of Francesco's students.

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