Shortly it will be fifty, but it does not look like it

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Outline

- ***Giordano Bruno in Oxford***
- ***Historical Foreword***
- ***The birth of the Coupling Impedance***
- ***The Universal Maps of Stability***
- ***The Stretched Wire Method***
- ***Telescopic Measurements on a Canonical Structure***
- ***The best production***

AN ILLUSTRIOUS PREDECESSOR

- Giordano Bruno was born in Nola (close to Naples) in 1548. He was an excommunicated Dominican friar. In April 1583, Bruno went to England as a guest of the French ambassador. There he became acquainted with the poet Philip Sidney (to whom he dedicated two books). He denied several core Catholic doctrines (including the Trinity, the divinity of Christ, the virginity of Mary…).

The earliest depiction of Bruno published in 1715 in Germany,

AN ILLUSTRIOUS PREDECESSOR

He also lectured at Oxford, and unsuccessfully sought a teaching position there. His views were controversial with George Abbot, who later became Archbishop of Canterbury.

Abbot mocked Bruno for supporting "the opinion of Copernicus that the earth did go round, and the heavens did stand still; whereas in truth it was his own head which rather did run round, and his brains did not stand still"

(Frances A. Yates: Giordano Bruno and the Hermetic tradition (1964))

AN ILLUSTRIOUS PREDECESSOR

- He proposed that the stars were just distant suns surrounded by their own exoplanets and raised the possibility that these planets could even foster life of their own (a philosophical position known as cosmic pluralism).
- In 1693, back in Italy, he was imprisoned by order of Inquisition.

At that time: the 50's

- Phase Stability -> Cosmotron reaches its full energy in 1953 (3.3 GeV) at BNL
- Strong Focusing -> PS in 1959 (28 GeV) at CERN and AGS in 1960 (33 GeV) at BNL.

At that time: Beginning of 60's

At that time: Beginning of 60's

- Even before the successful achievements of PS and AGS, the scientific community was aware of another step needed to revolution the accelerator techniques. Indeed, the impact of particles against fixed targets is very inefficient from the point of view of the energy actually available for new experiments: much more efficient could be the **head on collisions** between high-energy particles.

BUT THERE IS A REAL NEED OF COLLIDERS?

- With increasing energy, the energy available in the Inertial Frame with fixed targets is incomparably smaller than in the head-on collision (HC), as Wideroe thought some decades before. If we want the same energy in IF, using fixed targets one should build gigantic accelerators. In the fixed target case (FT), according to relativistic dynamics, an HC-equivalent beam should have the following energy:

$$E_{FT} = 2\gamma_{HC} E_{HC}$$

The price to pay for colliders:
large current beams
highly collimated beams
and drawback involved

Collider Contest: Frascati vs Princeton

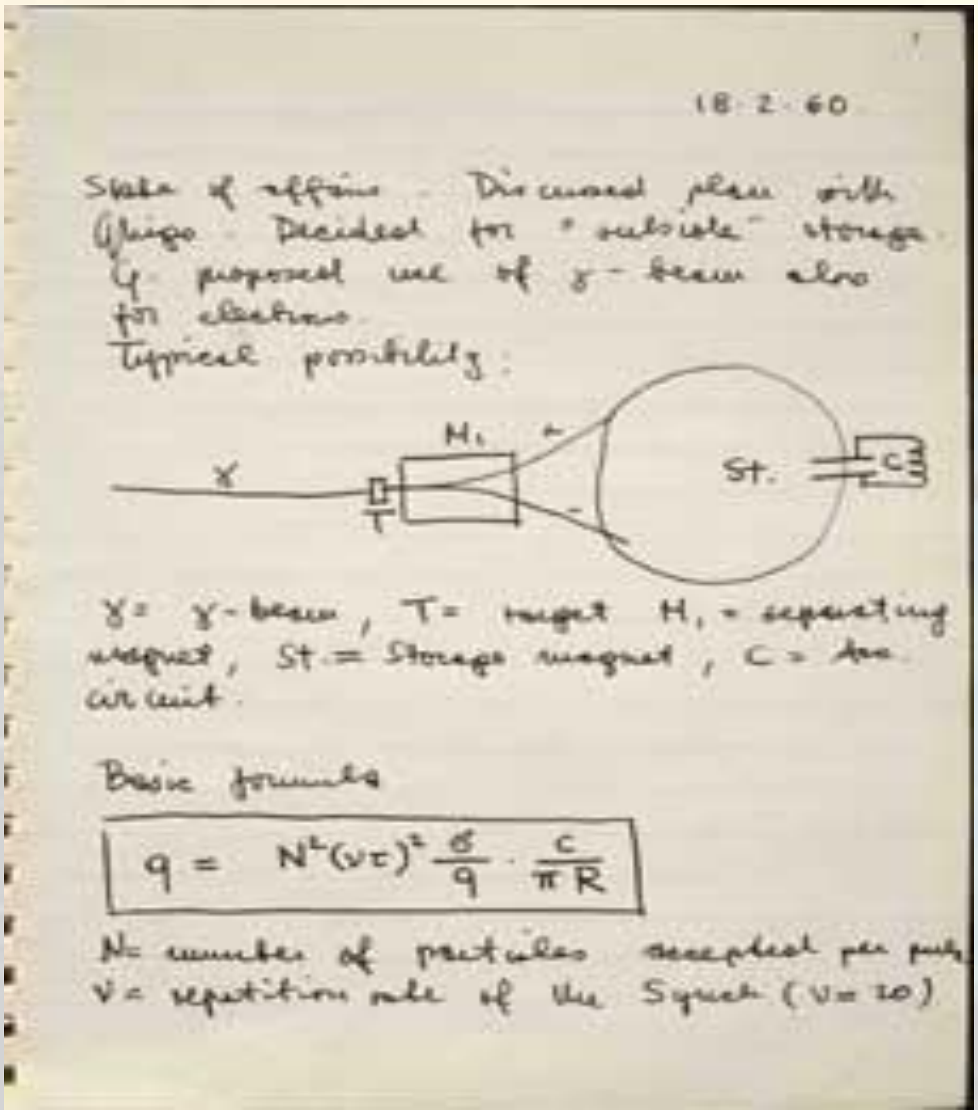
- A contest between Princeton and the Frascati Laboratories started. Princeton chose a eight-shaped structure: two circular rings in which electrons and positron were circulating with the same orientation, meeting at the collision point. Frascati team was even more audacious: they used a single ring with "counter-rotating" beams of electrons and positrons..

Collider Contest: Frascati vs Princeton

- The enterprise began on March 7, 1960. When Bruno Touschek held a seminar at Frascati Laboratories by which he was proposing to build an electron-positron storage ring, according to **Wideroe**'s visionary ideas concerning storage rings and colliders. On March 14, a preliminary study demonstrated the feasibility of the proposal. The storage ring was called ADA (Anello Di Accumulazione = Storage Ring).
- The total cost of the project (converted from Liras) was around 4.000 €.
- Although Frascati started for last, it came first: it was 1960, when the era of the colliders has begun. This success had great *prominence internationally*

The Contest: Frascati vs Princeton

A page from Touschek's notebook

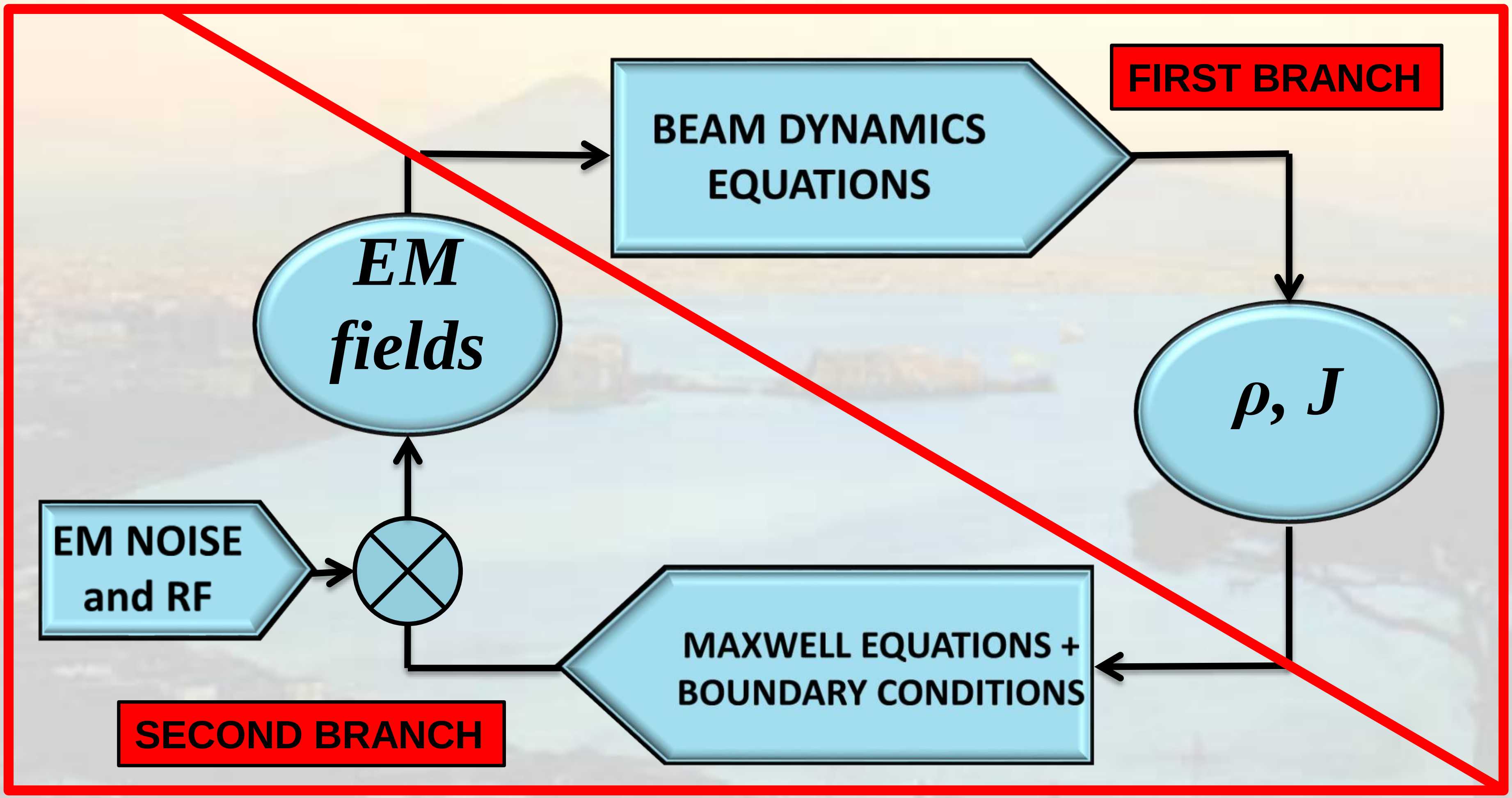


ADA

Beware

- Early ’60s: MURA 50 MeV (as well as other accelerators) exhibited instabilities consisting in a coherent self bunching and vertical coherent oscillation during particle storing. The phenomenon seemed to be related to the amount of current stored. The accumulated current could not go beyond a certain limit. Above this threshold there was evidence of coherent transverse instabilities, which were interpreted as due to the presence of electrodes.

Beam-equipment e-m interaction and Dynamics: the Flow Chart (circular accelerators)



Somebody leads the way

- Sessler et alii tackled this problem resorting to Vlasov equation. They showed that the beam could undergo to modulational instabilities if the finite conductivity of the pipe is taken into account.

Somebody leads the way

- In the absence of frequency spread the growth rate is proportional to $(N/\sigma)^{1/2}$ in the longitudinal case and to $N/\sigma^{1/2}$ in the transverse case.
- A criterion of stability was established which seemingly does not depend on σ. The authors preconized that it could depend on certain geometrical properties of the accelerator.
- These studies, even though the authors cautiously claim to be possibly related to the observed phenomena, represent an epochal breakthrough in coherent instabilities understanding.

Concern

- This evidence produced in the scientific community the conviction that in the beam dynamics the interaction with the surrounding equipment should not be neglected (e.m. field produced by image currents).
- On 1966 the design of a large Intersecting proton Storage Ring (ISR) started. It was supposed to accumulate at 31GeV the largest current ever reached. This is the equivalent of a 2000 GeV beam hitting a stationary target.
- Among other, it was foreseen a large number of clearing electrodes, pick-ups and variety of lumped components.

Concern and Call for Help

- Inside the designers community ther was very much concern about the successful achievement of the design.
- On August 1966, on leave of absence from Berkeley, Andy Sessler (2013 Fermi award) joined CERN for one year.
- Claudio Pellegrini (2014 Fermi award),Fernando Amman (director of Laboratori di Frascati), Ernest Courant (1986 Fermi award), Krinskii, Dikanski, Auslander were paying visits at CERN for discussions on ISR design.

The Fluke of my Life

- On June 1966 I was hired from CERN with a three year contract.
- On August, when Andy came, I was committed to him. I discovered new horizons.
- I was already acquainted with his work.

An Impedance is in the Air

- I was assigned the task to introduce in Vlasov equation the contribution of a lumped element, e. g. cavity of impedance Z_c (and/or pickups).

An Impedance is in the Air
The Banality of Invention

- Vlasov: $\frac{d\psi}{dt} + \dot{\theta}\,\frac{d\psi}{d\theta} + e\langle 2\pi R\ E_\theta\rangle \frac{d\psi}{dW} = 0$

$\psi(W, \theta, t)$ is the particle distribution function

- Perturbative solution
- $\psi(W, \theta, t) = \psi_0(W) + \psi_1(W)\exp[-i(\omega t - n\theta)]$
- $I_1 = -i\beta c e^2 \langle 2\pi R E_\theta\rangle \int \frac{d\psi_0}{dW} \frac{dW}{(\omega - n\omega_0)}$
- $I_1 = e\beta c \int \psi_1(W) dW$ is the perturbed current; $\omega_o = \dot{\theta}$

An Impedance is in the Air
The Banality of Invention

- The term $\langle 2\pi R E_\theta \rangle$ was calculated for a smooth vacuum chamber with constant resistivity. Its explicit expression had an awkward feature.
- The idea was to expand the impressed field distribution at the cavity gaps in waves along the circumference and to take the one which was riding along with the particle.
- In this way the factor

  $\langle 2\pi R E_\theta \rangle$ is replaced by the factor

  $\langle 2\pi R E_\theta \rangle$- $I_1 Z_c$

An Impedance is in the Air
The Banality of Invention

- I felt uneasy, as an engineer, to tackle a problem expounded in that unfamiliar feature: the imaginary unit i was quite misleading.
- free space impedance $4\pi/c$. NO!!!.

An Impedance is in the Air
The Banality of Invention

- I discussed with Andy to try to express the beam interaction with the vacuum chamber ($\langle 2\pi R E_\theta \rangle$- $I_1 Z_c$) in MKS units in order to compare it to lumped element impedance. It was a choice to make my life easier.
- The Andy idea was than to generalize this concept also for more complicated circuits.

An Impedance is in the Air
The Banality of Invention

- “It was emphasized that Z described the impedance of the wall elements and was, thus, amenable to computation--or measurement--by means of all the standard techniques employed in electrical engineering. This "engineering technique" was applied to a number of problems - such as helical insert - and allowed complicated structures to be readily analysed, such as pickup electrodes.” Sessler PAC71

An Impedance is in the Air
The Banality of Invention

Now, I have the impression that the coupling impedance was a concept which was just waiting to be introduced:

I was at the right moment in the right place with the right people.

Sophie Marceau

La Boom - The Party – Il tempo delle mele (1980)

Shortly she will be fifty, but she does not look it

- Andy Sessler proposed that I could write a paper concerning the cases we have already discussed…

ISR-RF/66-35
November 18, 1966

LONGITUDINAL INSTABILITY OF A COASTING BEAM ABOVE TRANSITION, DUE TO THE ACTION OF LUMPED DISCONTINUITIES.

by V.G. Vaccaro

1. Generalities

We assume that the electrical action on an ion beam, of a discontinuity in a tank is that of an impedance. We still consider the case in which this discontinuity is sufficiently small compared with the wavelength of the perturbation, to be considered as concentrated.

REFERENCES

1) V.K. Neil and A.M. Sessler

Longitudinal Resistive Instabilities of Intense Coasting Beams in Particle Accelerator

Rev. Sci. Instr. 36, 429 (1965)

1) A.M. Sessler and V.G. Vaccaro

Longitudinal Instabilities of Azimuthally Uniform Beams in Circular Vacuum Chambers of Arbitrary Electrical Proprieties

(in preparation).

Distribution: (closed) AR and ISR Scientific Staff.

- …and that we had to produce a more general paper.

CERN 67-2
ISR-Division
February 6, 1967

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

LONGITUDINAL INSTABILITIES OF AZIMUTHALLY UNIFORM BEAMS IN CIRCULAR VACUUM CHAMBERS WITH WALLS OF ARBITRARY ELECTRICAL PROPERTIES

by

A. Sessler and V. Vaccaro

Further developments

- A collaboration starts with Sandro Ruggiero and, later on, with Kurt Huebner, which last for almost two years.
- More than twenty paper written on coupling Impedance an Dispersion Relation.

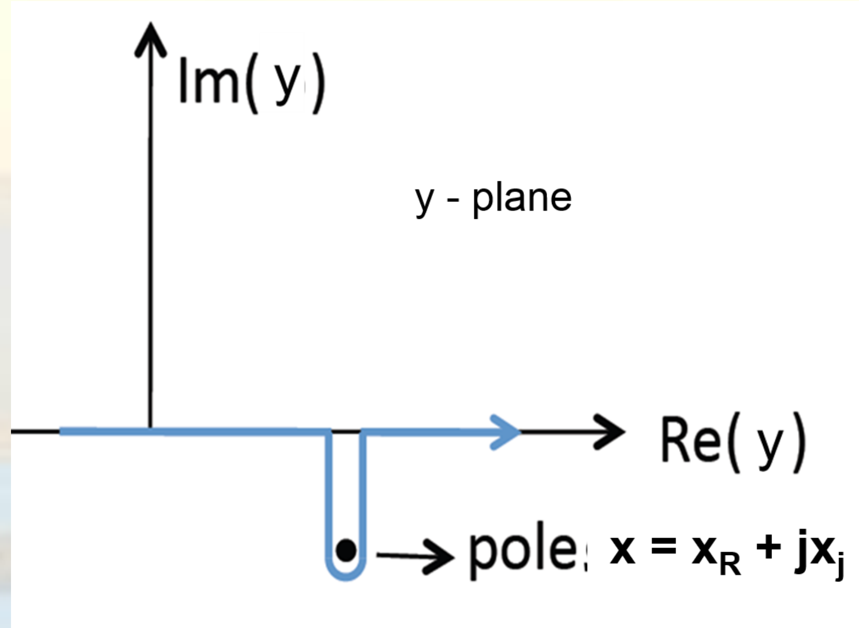
My preferred child: The Universal Maps of Stability

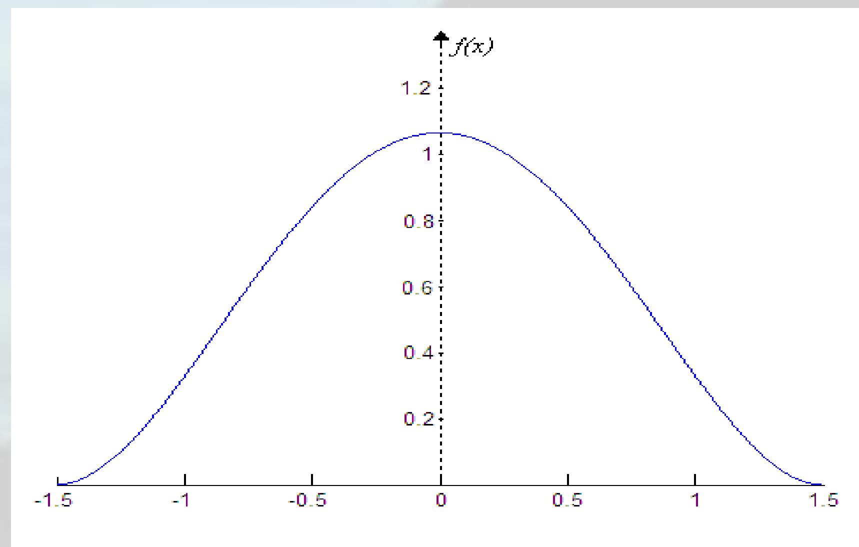
- Given a certain value of coupling impedance it was (at that time) almost impossible to solve the dispersion relation.
- We (Sandro and I) thought that it could be interesting to draw maps of stability, better to say ”maps of instability”.

The Universal Map of stability

The variables in the dispersion relation (DR) can be modified in order to let them be dimensionless. Assuming x as a complex variable, DR is a conformal transformation from x-plane to y-plane.

$$Z(x) = 1 \Big/ Y_b \int \frac{df_0}{dy} \frac{1}{y-x} dy$$





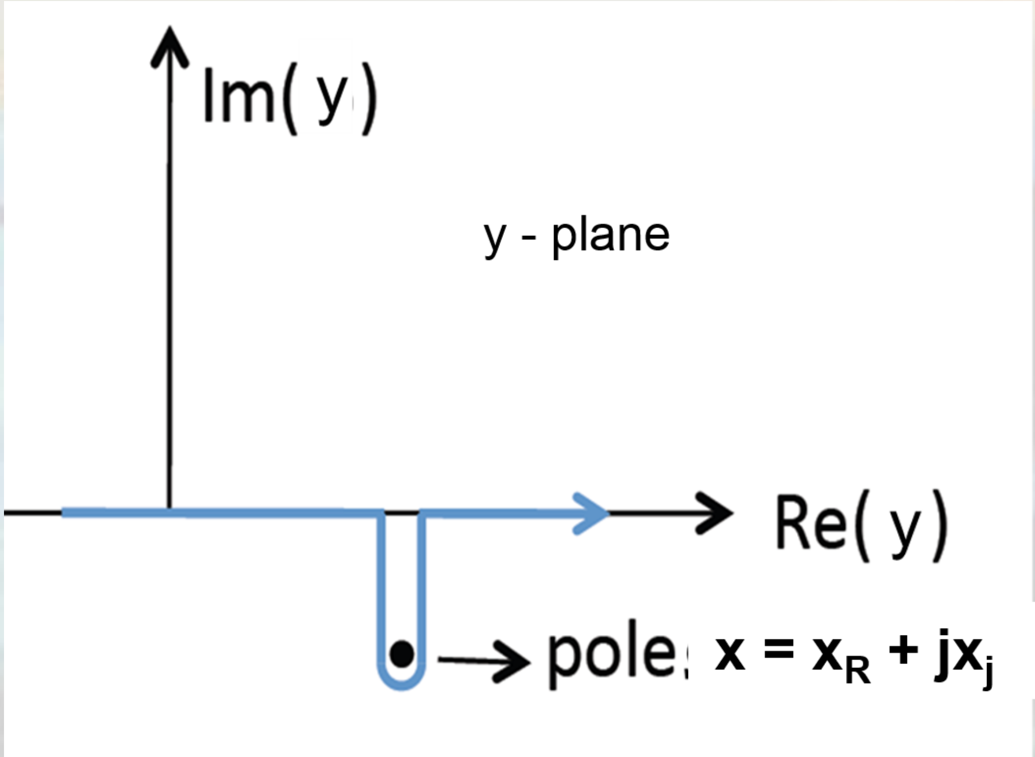
The universal maps

Let us consider ⇒

$$Z(x) = \frac{-Y_B^{-1}}{\int_{-\infty}^{+\infty} \frac{df_0(y)}{dy} \frac{1}{x-y} dy}$$

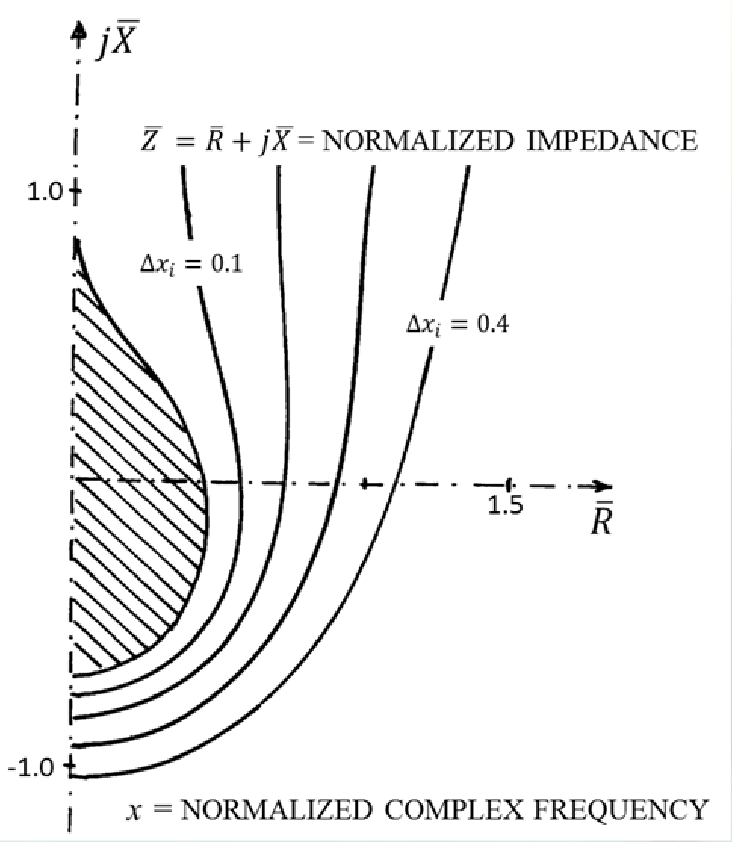
This explicit form allow us to calculate the value of $Z(x)$ for any given value of x. The procedure consists in assign a value of x, the imaginary part of which is negative (a diverging instability). In order to calculate the integral, the integration path may be supposed to approach the real y-axis from lower half plane. This integral is then equal to the principal values plus the residual in the pole.

GO TO THE NEXT SLIDE.



The universal maps

$$\overline{Z}(\Omega)=\overline{R}+j\overline{X}=\frac{-Y_B^{-!}}{\left(2\pi j\left.\frac{df}{dy}\right|_{y=x}+\int_{-\infty}^{+\infty}\cdots\cdots dy\right)}$$



The picture on the right tells us that the mapping of lower half $y - plane$ into the $Z - plane$ covers this plane almost entirely. Only a small portion (dashed) is left. It is worth of note that this domain is not covered by an analogous mapping of lower half plane. This domain is interpreted as a region of stability.

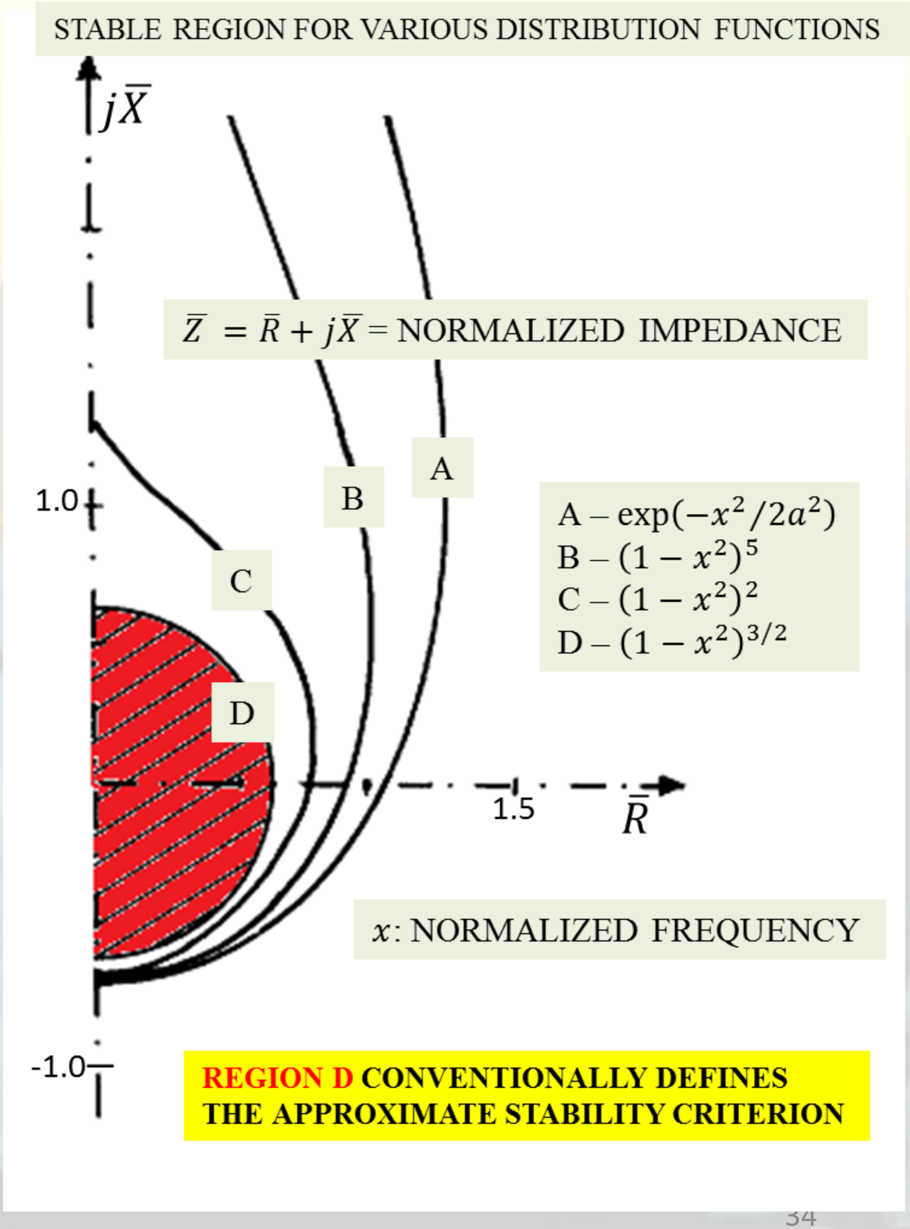
If the accelerator has an impedance which is for any frequency inside this domain, the beam is longitudinally stable

The universal maps

The picture yields the results of the mapping relevant to the stability boundaries for different distribution functions .
The domain in red represents the most conservative approximation of the calculations from realistic distribution functions.
IMPEDANCE BUDGET

$$\left|\frac{Z}{n}\right| \le F\,\frac{m_0 c^2 |\eta|}{e\gamma}\left(\frac{(\Delta\beta\gamma)^2}{I_0}\right)$$

$$\left|\frac{Z}{n}\right| \le F\,\frac{m_0 c^2 \beta^2 \gamma |\eta|}{e\, I_0}\left(\frac{\Delta p}{p}\right)^2$$



Pursuances and Consequences

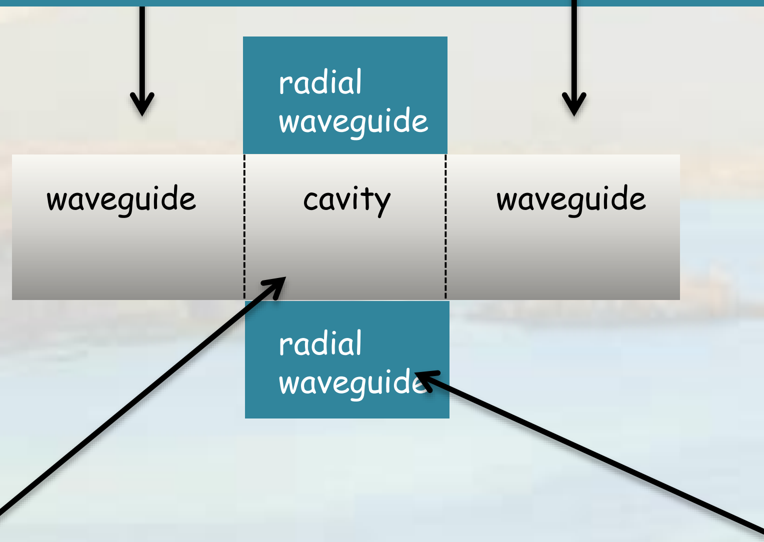
Afterwards many interesting development.

- Hereward gave the definition of transverse coupling impedance.
- Sacharer studied coupled beam instabilities and gave criterions for this case.
- Sacharer and Nassibian made coupling impeadance measurements of a kicker by means of the stretched wire method (Sand and Rees)

Mode Matching Method: a benchmarking Tool

Representation of a circular cross section subdivided in subsets.

Expansion of e.m. field in the waveguides by means of orthogonal wave modes



Expansion of e.m. field in the cavity by means of an orthonormal set of eigenmodes

Expansion of e.m. field in the radial waveguide by means of radial wave modes

Cavity Eigenvector properties

The Eigenvectors are always associated to boundary conditions Dirichlet, Neumann or mixed:

Divergenceless Eigenvectors (dynamic modes):

$$\nabla\times\vec{e}_n = k_n\vec{h}_n \;\Rightarrow\; \nabla\cdot\vec{h}_n = 0; \qquad \nabla\times\vec{h}_n = k_n\vec{e}_n \;\Rightarrow\; \nabla\cdot\vec{e}_n = 0$$

Irrotational Eigenvectors (static modes):

$$\vec{f}_n = \nabla\phi_n \;\Rightarrow\; \nabla\times\vec{f}_n = 0; \qquad \vec{g}_n = \nabla\phi_n \;\Rightarrow\; \nabla\times\vec{g}_n = 0$$

The boundary condition are relevant to the tangential component of the Electric field.

$$\begin{cases} \vec{E} = \sum_n V_n\vec{e}_n + \sum_n F_n\vec{f}_n \\ \vec{H} = \sum_n I_n\vec{h}_n + \sum_n G_n\vec{g}_n \end{cases}$$

In a more compact form the static modes may be considered as dynamic modes with k_n=0.

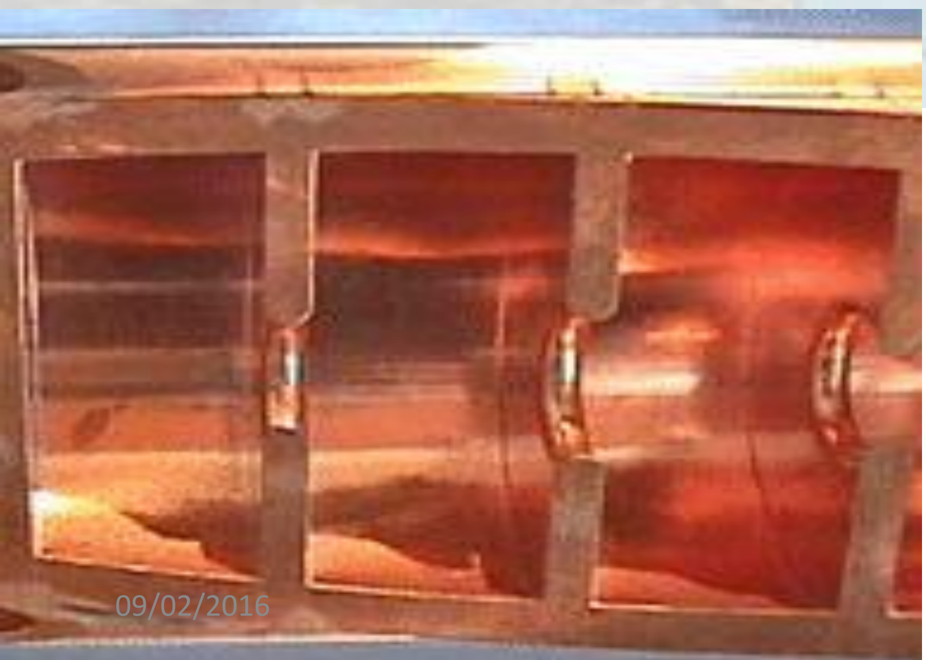
$$\vec{E} = \sum_n V_n\vec{e}_n$$

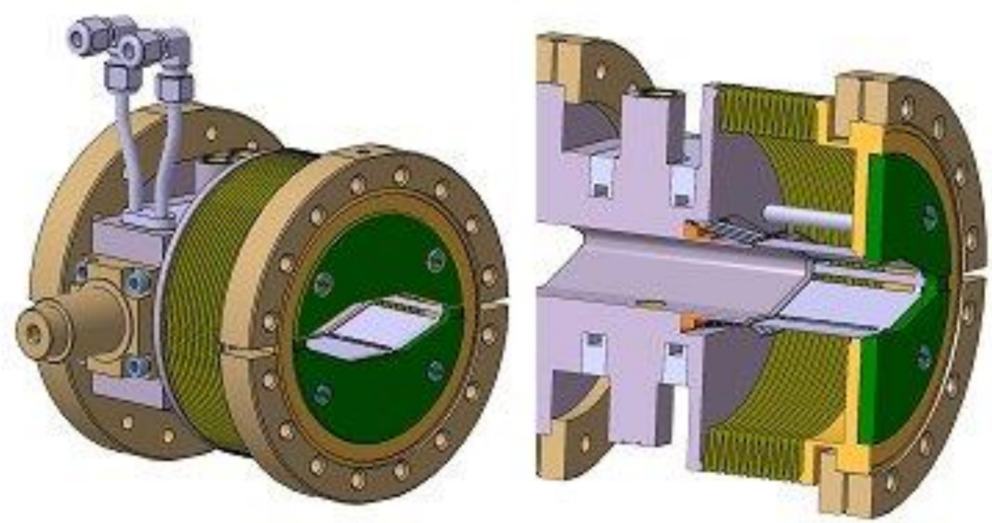
$$\vec{H} = \sum_n I_n\vec{h}_n$$

Insertions

- The variation of the cross section in accelerators cannot be avoided.

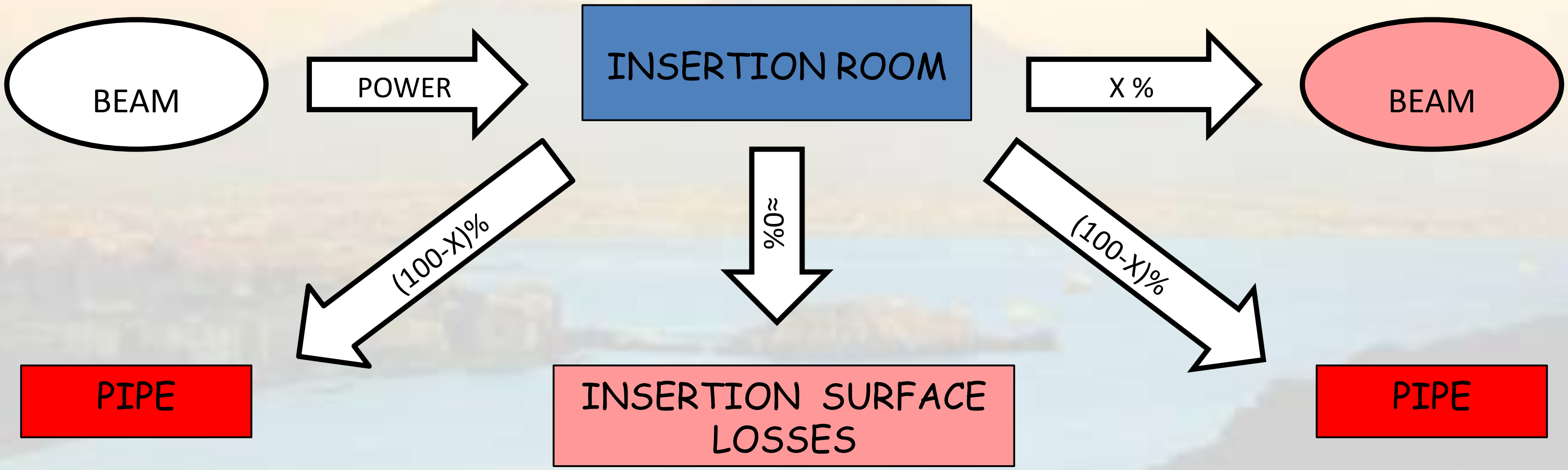
- example: the accelerating cavities and bellows.





A B O V E P I P E C U T O F F

INSERTION with LOSSY WALLS



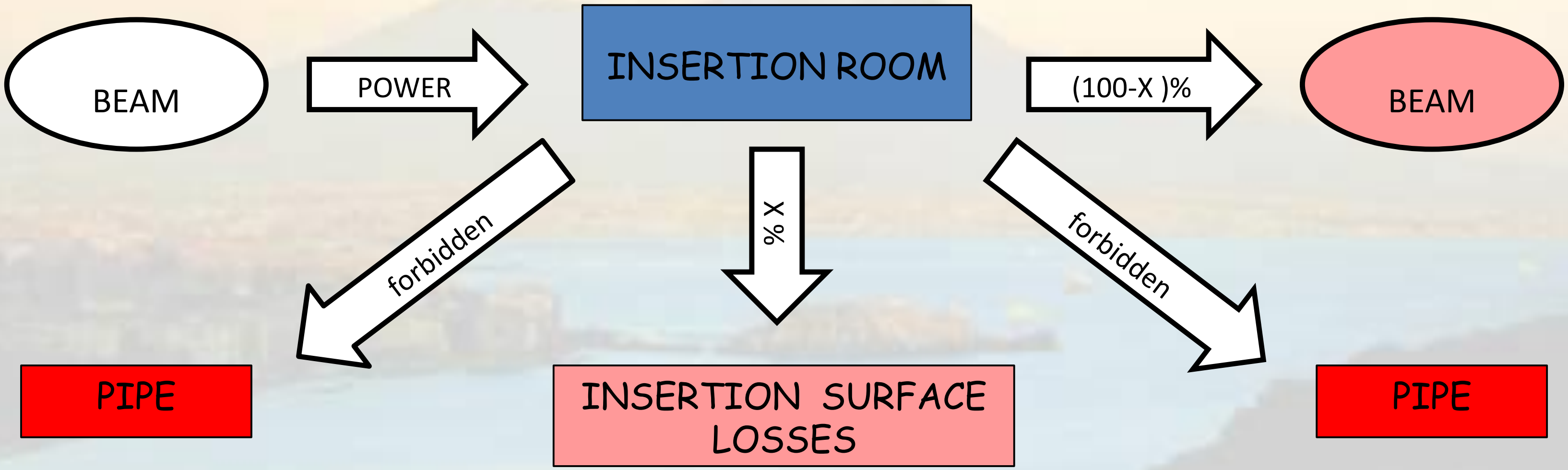
Negligible losses in the insertion :

Most of power flows toward infinite in the pipes.

Broad Band Impedance insensitive to cavity conductivity

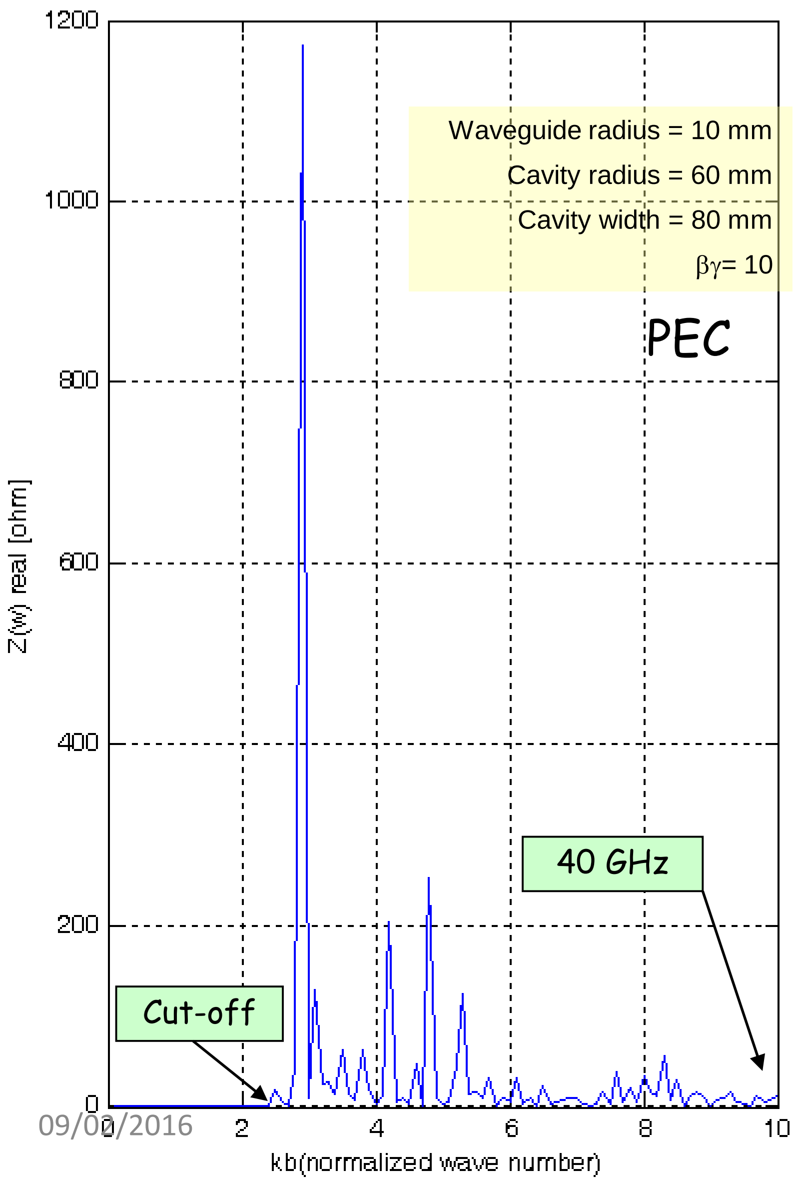
BELOW PIPE CUTOFF

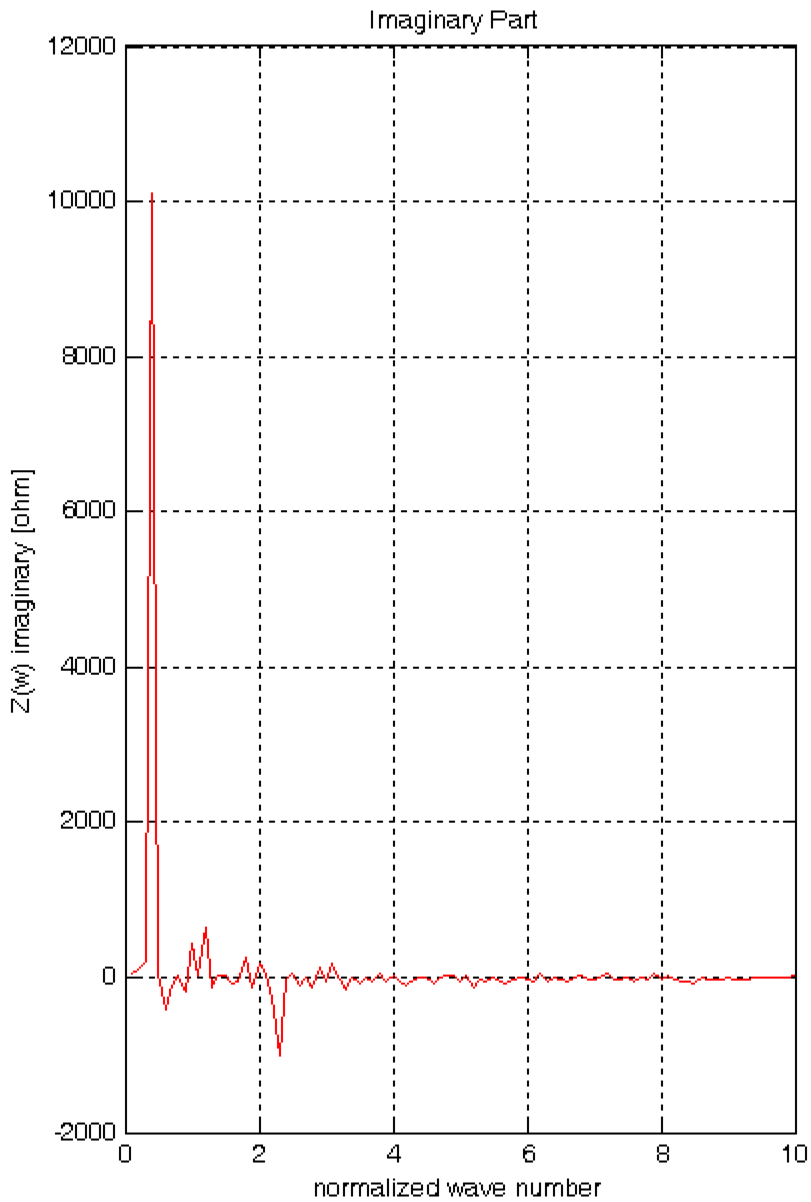
INSERTION with LOSSY WALLS



In general (X% very small) very high Q resonances sensitive to the wall conductivity.
The coupling resistance can be different from zero.
Lossless case (X% = 0) the resistance is null

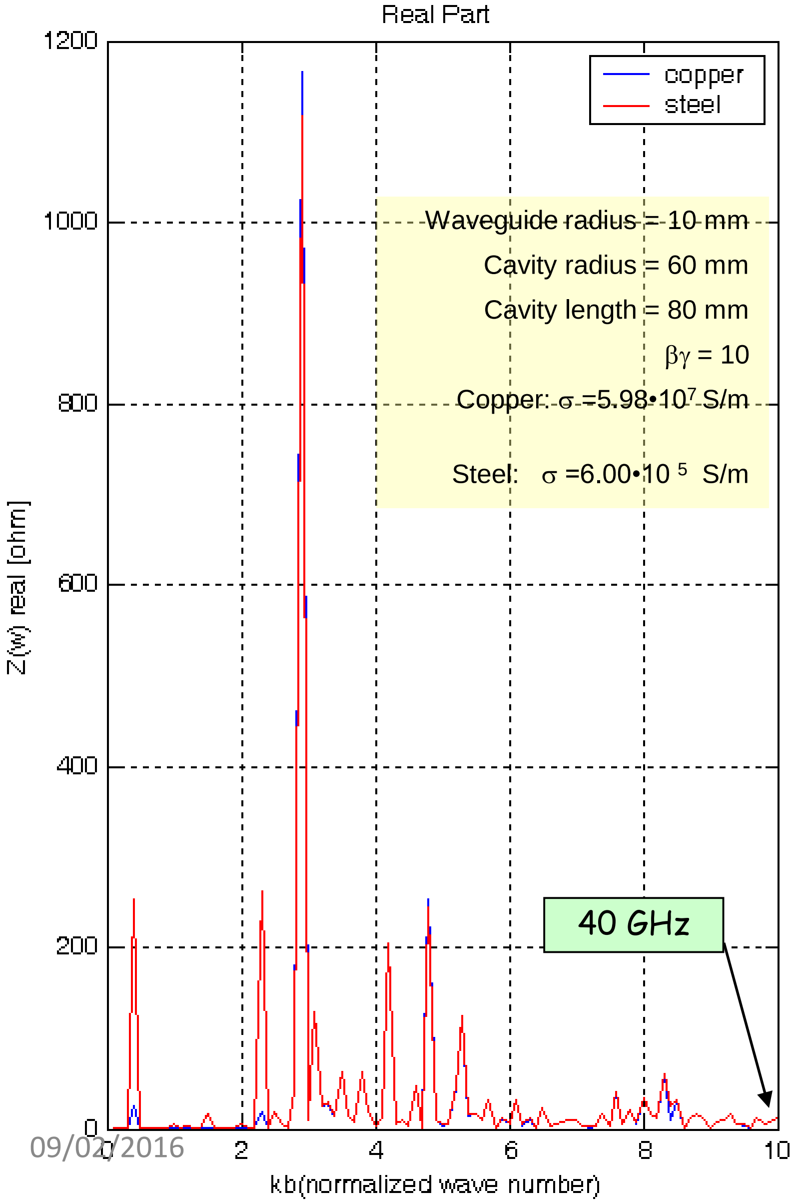
Analysis of a PEC Pillbox

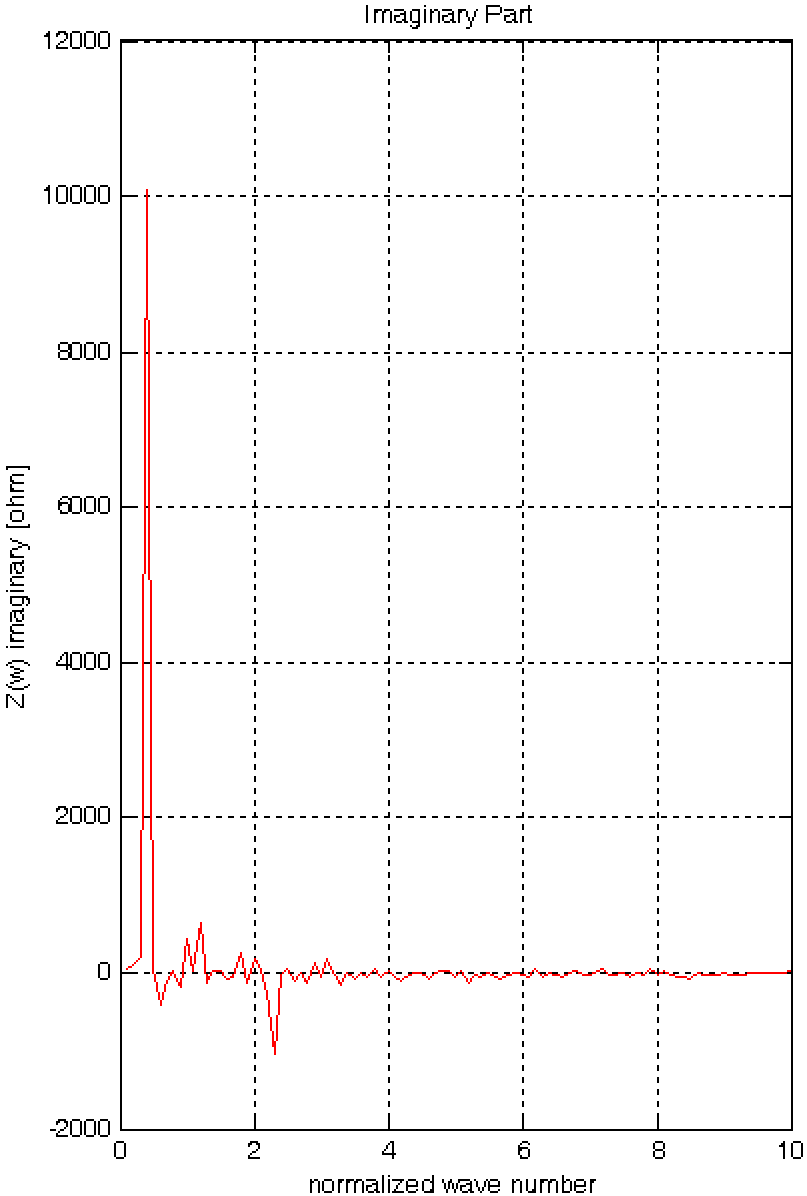




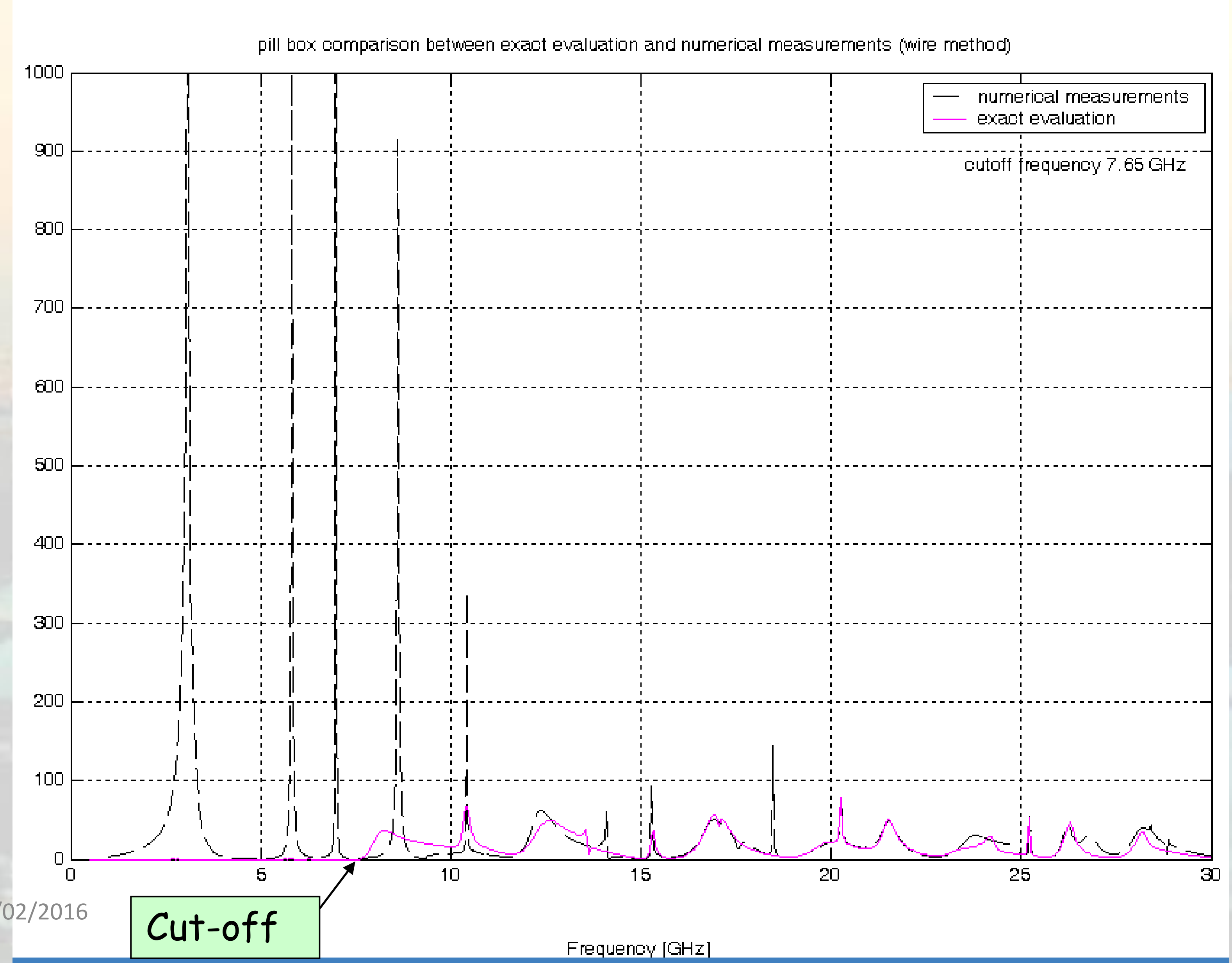
09/02/2016

Analysis of a Lossy Pillbox



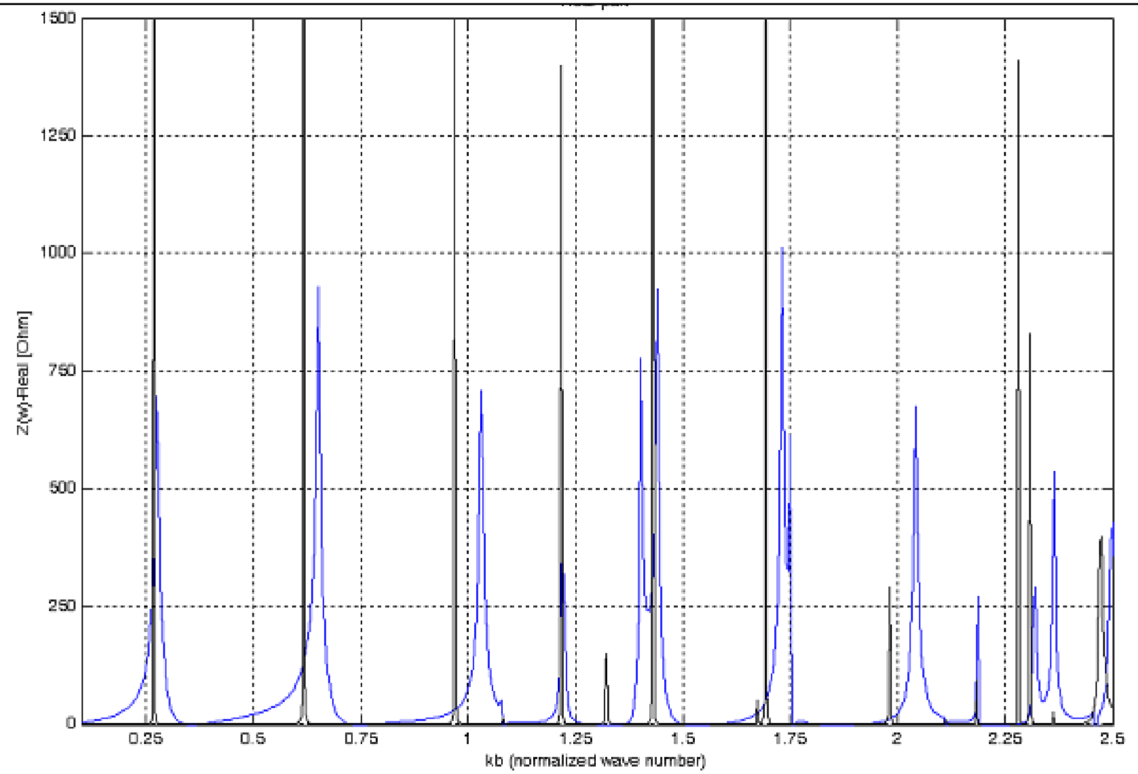


Wire Method vs Exact Evaluation



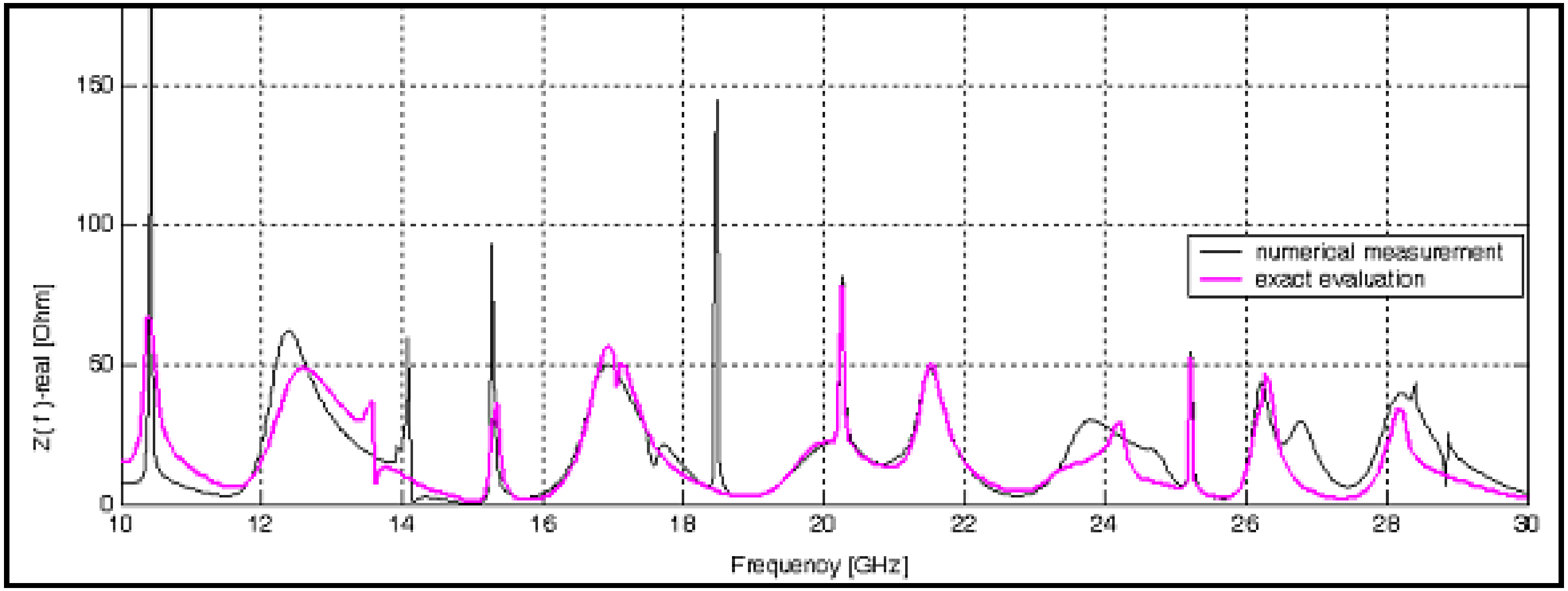
Virtual measurement with stretched wire vs MMT exact evaluation

Pipe radius = 4mm; Pillbox radius = 36mm;
Pillbox length = 12mm



Virtual measurement with stretched wire vs MMT exact evaluation

Pipe radius = 10mm; Pillbox radius = 60mm;
Pillbox length = 80mm



Tables of some results

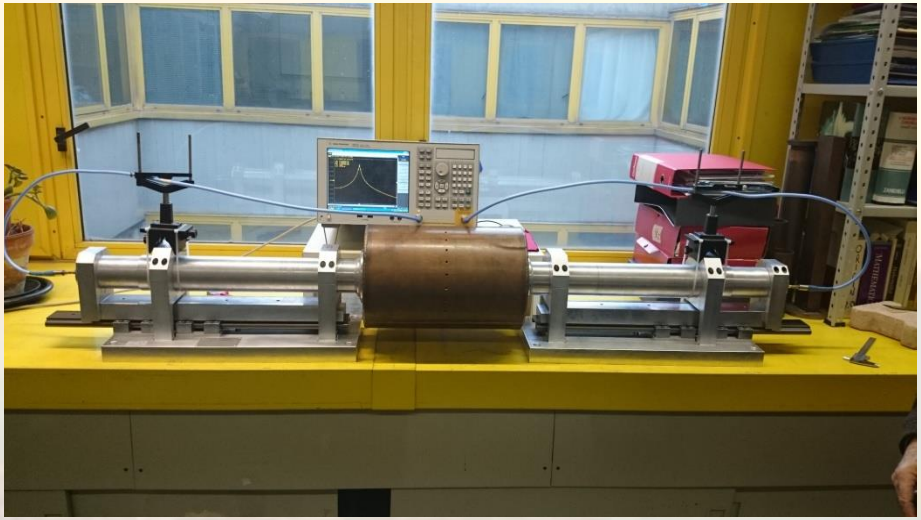
MATERIAL	$Re(Z_c)$ [kΩ]	Q	Q_{SF}	$Re(Z_c/Q)$ [Ω]	f [GHz]	f_{SF} [GHz]
Copper	250	8920	7689	28.0	3.196	3.196
Stainless Steel	79	2820	2500	28.1	3.197	3.196

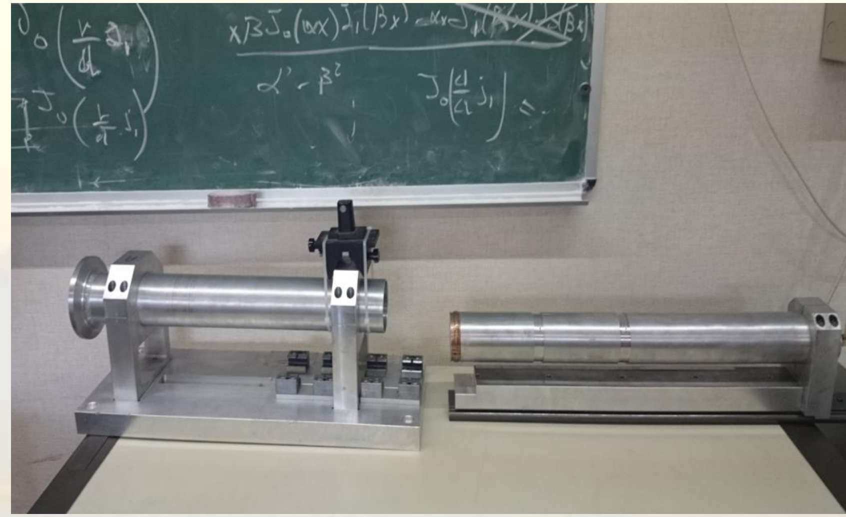
Table 1. fundamental parameters for two well-known materials, Copper and Steel, determined by Mode Matching Technique and SuperFish code applied to a pillbox cavity: b = 4 mm; c = 36 mm; 2L = 12 mm; βγ > 1000

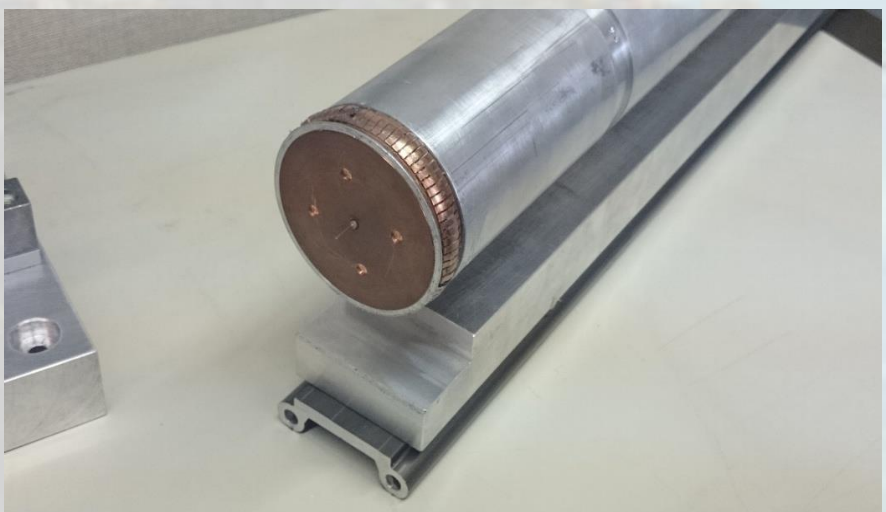
Method	**$Re(Z_c)$** [kΩ]	**Q**	**$Re(Z_c/Q)$** [Ω]
Exact evaluation	250	8920	28.0
Wire Method	1.27	300	4.25

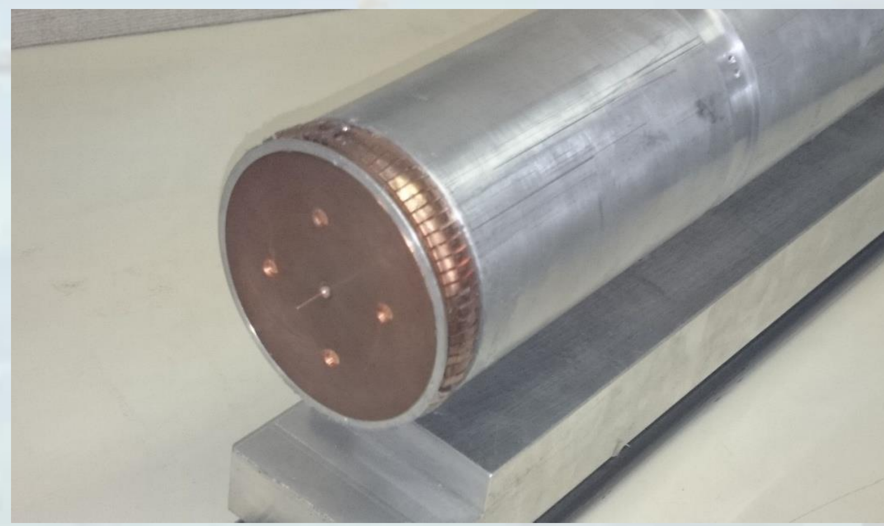
Table 3. Comparison between the main parameters obtained by Numerical Wire Measurements and Exact Evaluation applied to a pillbox cavity: b = 15 mm; c = 43 mm; 2L = 30 mm; βγ > 1000

The new telescopic set-up

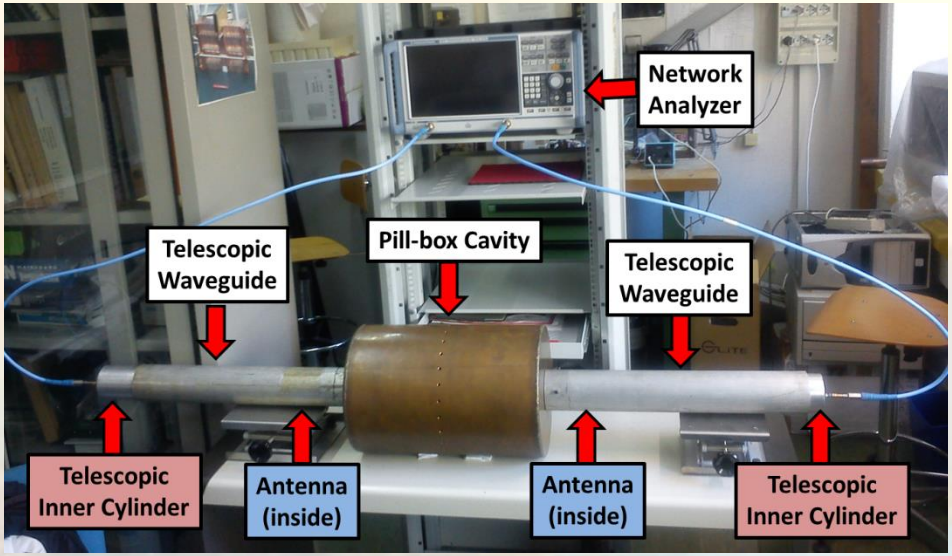


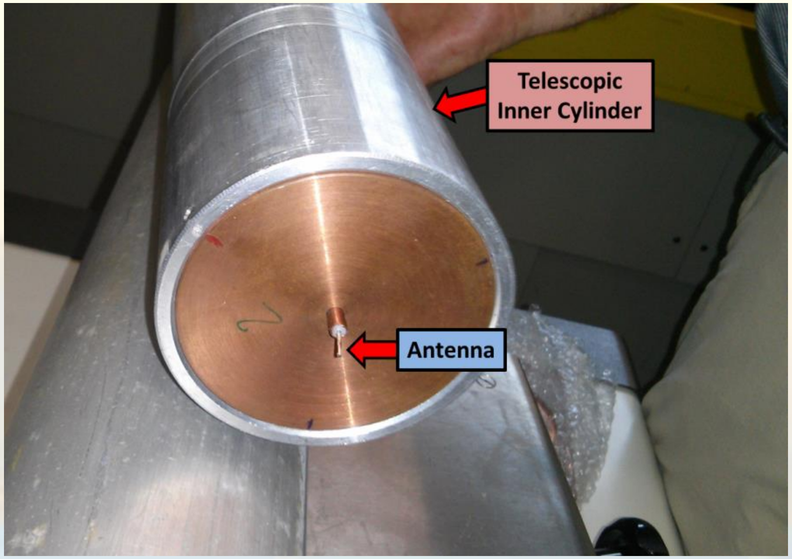


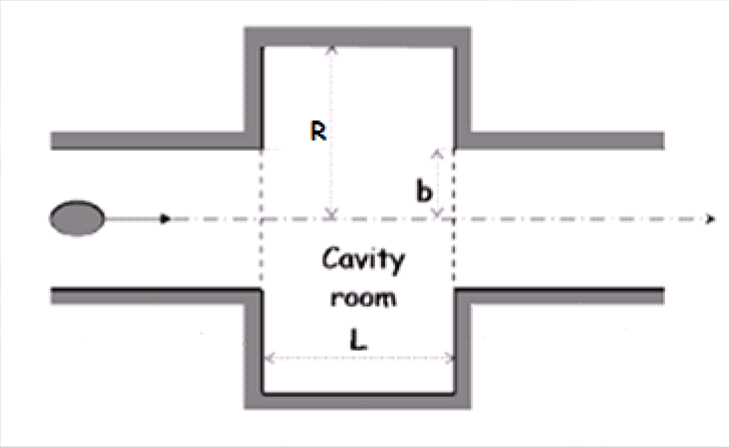




The telescopic measurement device



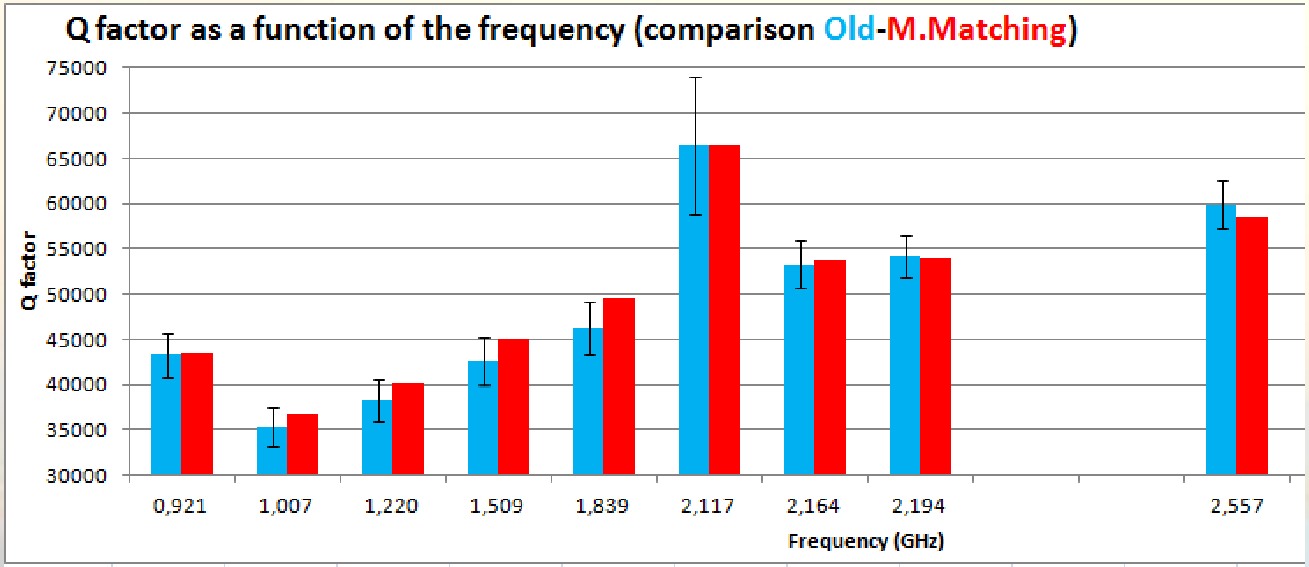


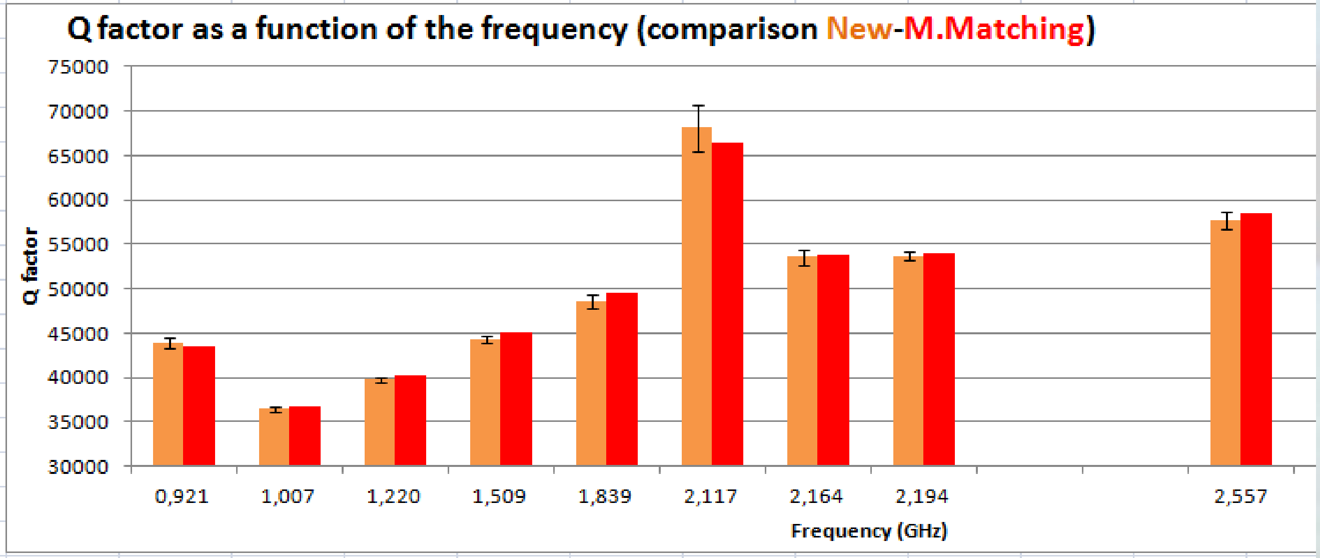


Parameter	Description
R	*125mm*
b	*34mm*
L	*375mm*
Conductivity	*5.96 e7 S/m*

$$f_{co} = \frac{x_{1,0} \cdot c}{2\pi b} = 3.377 GHz$$

Compare Mode Matching and measures





Hybrid (Numerical-experimental) method

The method with antennas does not still allow to measure the value of the coupling impedance below the cut-off frequency. The idea is to combine the *Q-factor* measured with antenna method and the R_{sh}/Q simulated using CST eigenmode solver in order to evaluate the shunt resistance *Rsh* for each resonant mode with following formula:

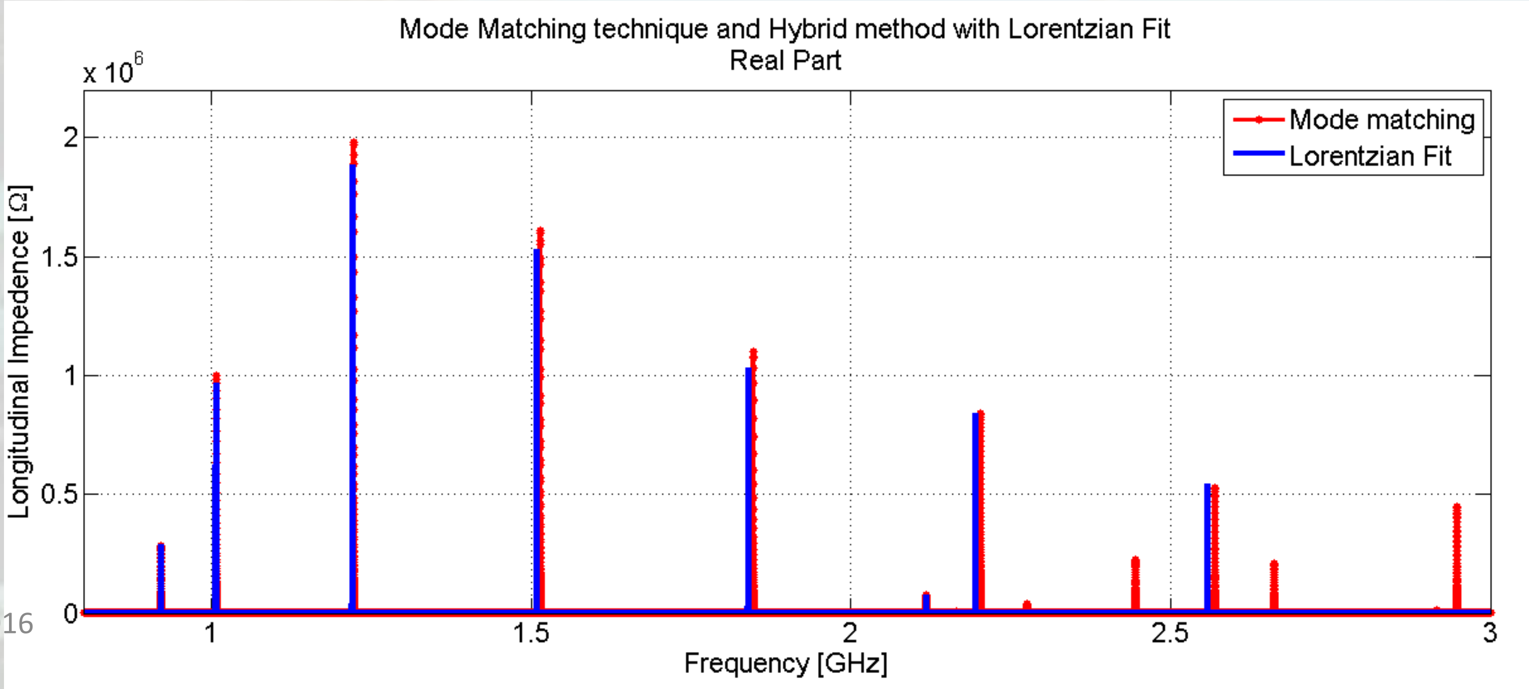
$$Q_m(f_n) \cdot \left(\frac{R_{sh}(f_n)}{Q(f_n)} \right)_{sim} = R_{sh}(f_n)$$

Is interesting to notice that the value of Q_m depends even on the EM properties of the material inside the structure (roughness, etc.). On the other hand the ratio $(R_{sh}/Q)_{sim}$ depends only on structure geometry

Hybrid (Numerical-experimental) method

A Lorentzian fit has been used to connect the values of resonance frequency, Q-factor and shunt resistance to the coupling impedance value, using the formula:

Lorentzian fit:
$$Z_{||}(f) = \sum_n \frac{R_{sh}(f_n)}{1 + jQ_m(f_n)\left(\frac{f}{f_n} - \frac{f_n}{f}\right)}$$



Giordano Bruno: epilogue

- After seven years of jail. The Inquisition found him guilty of heresy, found guilty of heresy and condemned to be burned on the stake. The verdict was executed on April, 17, 1600.
- He never abjured

My best scientific production

- Luigi Palumbo (U. Rome)
- Godehard Wuestefeld (Bessy)
- Caterina Biscari (Alba)
- Eliana Gianfelice (Fermilab)
- M. Rosaria Masullo (INFN)
- Augusto Lombardi (INFN)
- Antonio Palmieri (INFN)
- Roberto Losito (CERN)
- Giovanni Rumolo (CERN)
- Alessandro D'Elia (ESRF)
- Marco Panniello (INFN)
- Claudio Serpico (Elettra))
- Carlo Zannini (Adam)
- Giovanni De Michele (Adan
- Andrea Passarelli (CERN)
- Renato Prisco (Lund)
- Nicolò Biancacci (CERN)

This presentation is dedicated to the memory of

Andy Sessler

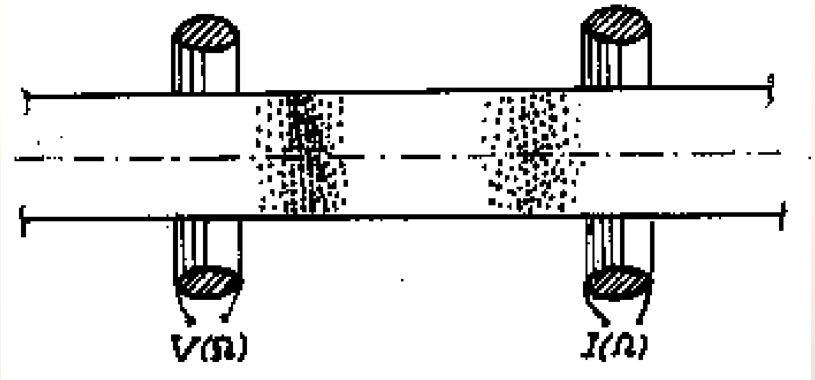
Sandro Ruggiero

Thank you, and keep up the good work

Instabilities for pedestrians

The gedanken experiment.

An ideal device, fed by a voltage $\Delta V(\Omega)$, produces a small longitudinal density perturbations in the current I at a frequency Ω



$$I = I_0 + \Delta I(\Omega)$$

Suppose that there is no interaction with surrounding medium and measure the perturbation by means of a reciprocal device which may define the perturbed current $\Delta I(\Omega)$

$$\Delta I(\Omega) = Y_B(\Omega)\,\Delta V(\Omega)$$

where the BEAM ADMITTANCE $Y_B(\Omega)$ depends on the beam properties: charge/mass, focusing properties etc. Of course the perturbed current is proportional to the d.c. current I_0

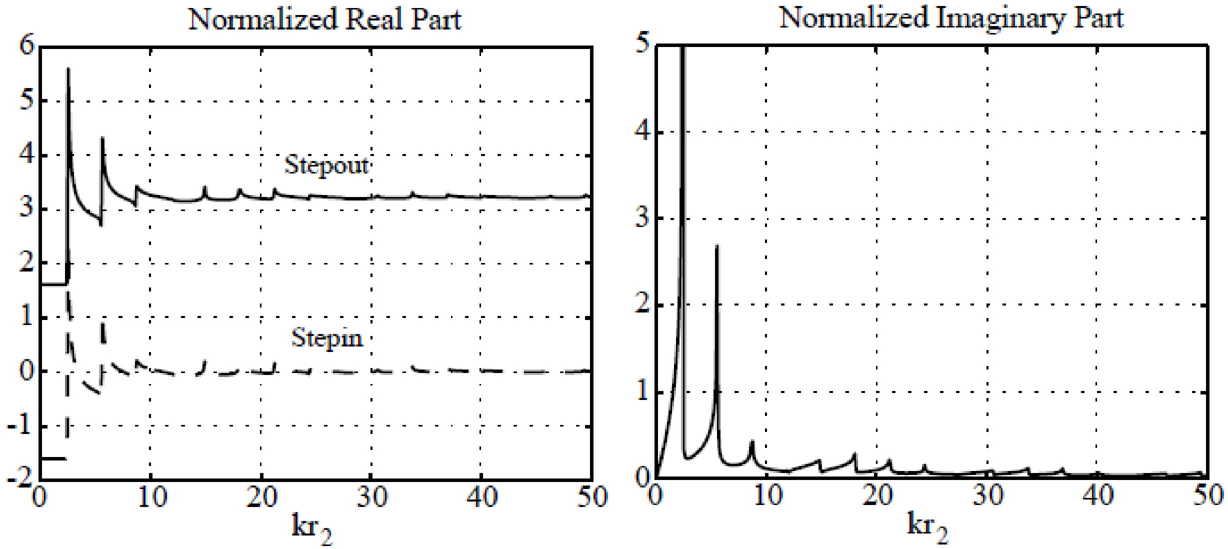


Fig. 27. – Normalized impedance in the case $\beta\gamma = \infty$ and $w = 0.2$ (the normalization constant is $2\pi/\zeta_0$).

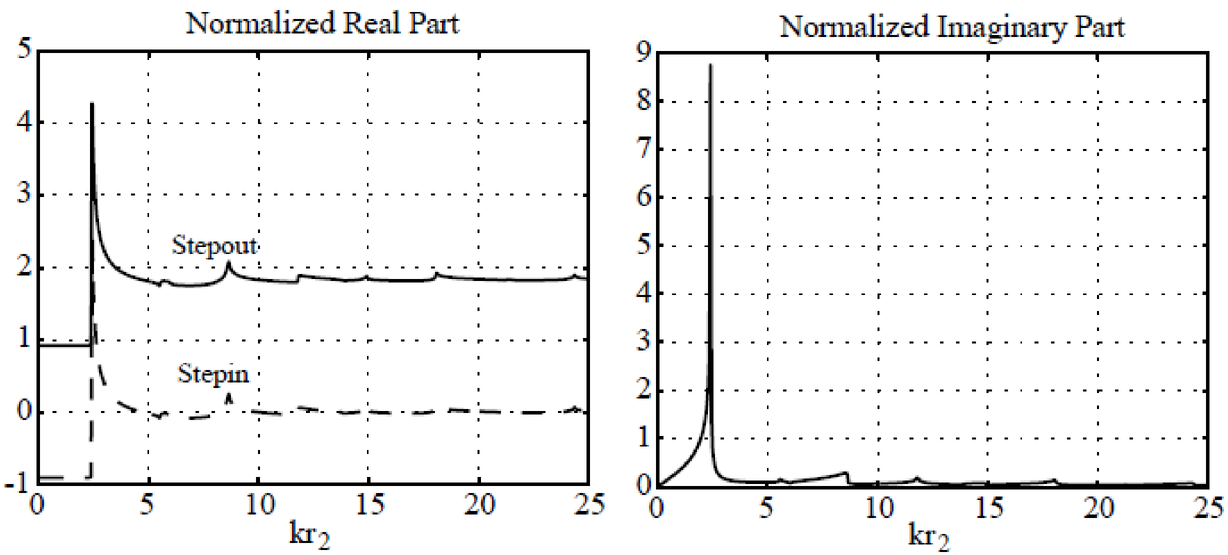


Fig. 28. – Normalized impedance in the case $\beta\gamma = \infty$ and $w = 0.4$ (the normalization constant is $2\pi/\zeta_0$).

Instabilities for pedestrians

Taking into account the e.m. interaction on one turn of the beam with the environment, this interaction will produce e.m. forces having the same space and time distribution as the perturbation. These forces can be represented by an equivalent voltage $\Delta V_1'(\Omega)$ which can be meant as produced by the current $\Delta I(\Omega)$, loading an ***IMPEDANCE.*** This impedance, $Z_M(\Omega)$, represents the overall interaction with surrounding equipment.

$$\Delta V_1'(\Omega) = Z_M(\Omega)\Delta I(\Omega)$$

$$\Delta V_1'(\Omega) = Z_M(\Omega) Y_B(\Omega) \Delta V(\Omega)$$

This voltage now acts back again on the beam, producing an additional perturbation, and so on. After *m* turns we have:

$$\Delta V_m'(\Omega) = [Z_M(\Omega) Y_B(\Omega)]^m \Delta V(\Omega)$$