History and development of bench measurement techniques for impedance evaluation

F. Caspers, A. Mostacci

After the introduction of the beam coupling impedance concept by V. Vaccaro it was realized soon that for highly relativistic beams a very close similarity exists between the TEM like field of the charged particles and the field of a wire in a coaxial structure. This is the basis and motivation of the coaxial wire method.

Early concepts of this method are shown including their shortcomings which had lead over a certain period to a poor reputation of the coax wire method since not all sources of errors and misinterpretation had been understood properly.

Transverse impedance measurements using two wires carrying currents with opposite polarity were already done on the late 70ths and the concept was extended to the evaluation of dipole and quadrupolar impedances by applying a single displaced wire and pair of wires.

Advanced and special methods are shown and briefly discussed together with few examples.

Electromagnetic wake fields and impedances in particle accelerators
Erice, 24-28 April 2014

OUTLINE

History and development of bench measurement techniques for impedance evaluation

The intuition

Historical highlights

Synthetic pulse and time domain gating

Mitigation options

Non standard techniques

Theoretical, numerical and experimental verifications

Examples of applications

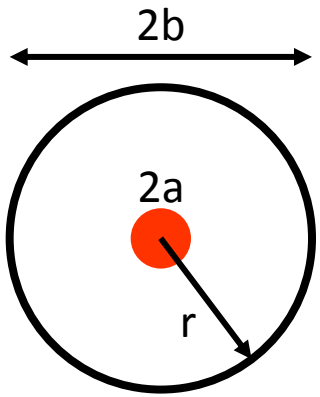
THE INTUITION

Ultra-relativistic beam field

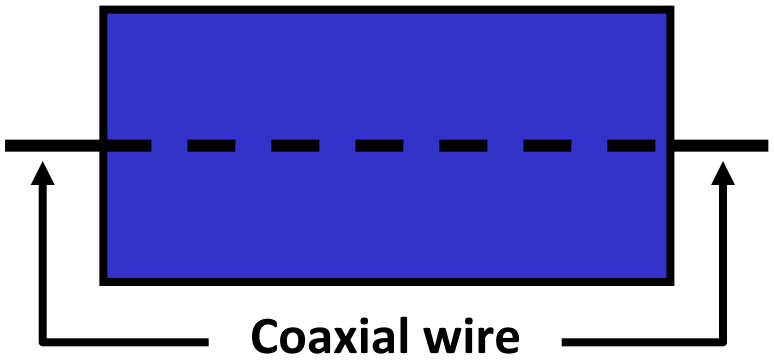
$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = \frac{Z_0 q}{2\pi r}\exp\left(-j\frac{\omega}{c}z\right)$$

TEM mode coax waveguide

$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = Z_0\frac{\text{const}}{r}\exp\left(-j\frac{\omega}{c}z\right)$$

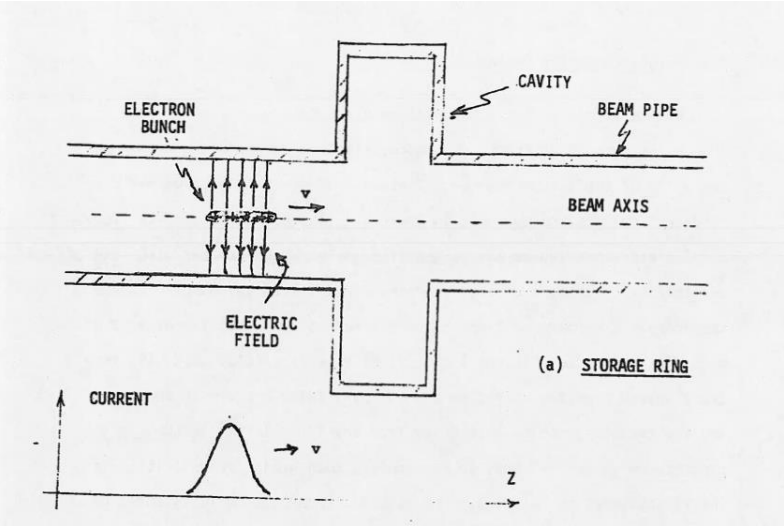


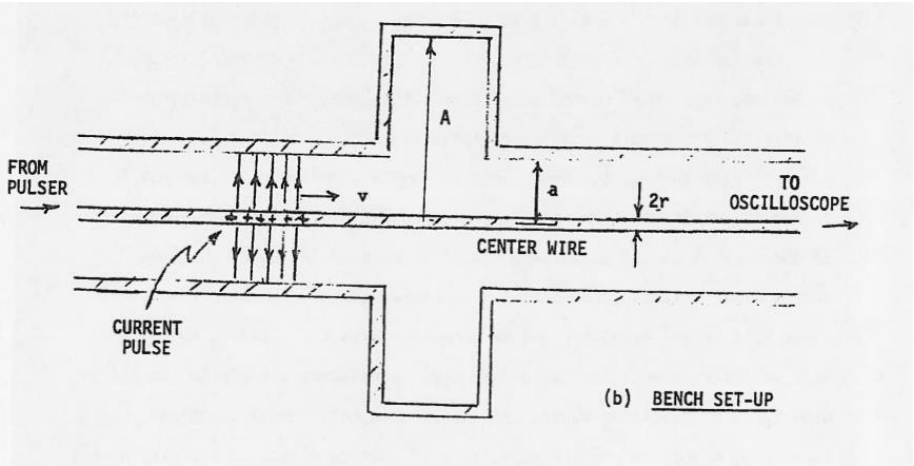
Device Under Test



Single wire centered/displaced
Two wires

THE INTUITION



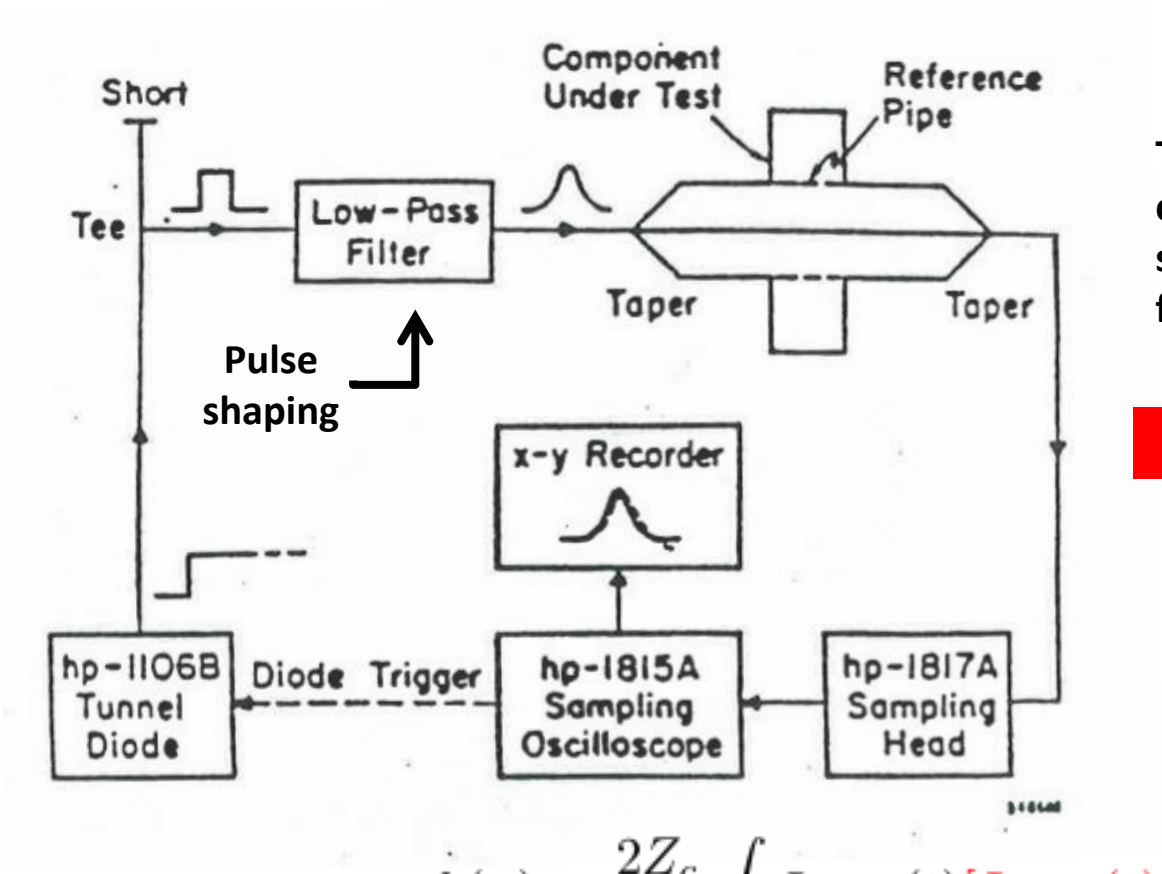


The field "slice" of a short pulse on a TEM line or a short bunch leads to essentially the same image current distribution on the inner surface of the beam pipe or inner surface of the outer conductor of the coaxial line.

The beam is loosing momentum due to some discontinuity and the pulse on the coaxial line is loosing amplitude.

M. Sands, J. Rees, SLAC Report PEP-95, 1974

LOSS FACTOR MEASUREMENT



Ansatz

The energy removed from the coaxial current pulse by the secondary fields is similar as for the bunch.

Time domain measurement

Charge in the pulse

$$Q = \int I_{REF}(t)dt$$

$$k(\sigma) = \frac{2Z_c}{Q^2} \int I_{REF}(t)[I_{REF}(t) - I_{DUT}(t)]dt$$

Gaussian pulse length
||
Gaussian bunch length

… difference!!

M. Sands, J. Rees, SLAC Report PEP-95, 1974

LOSS FACTOR MEASUREMENT

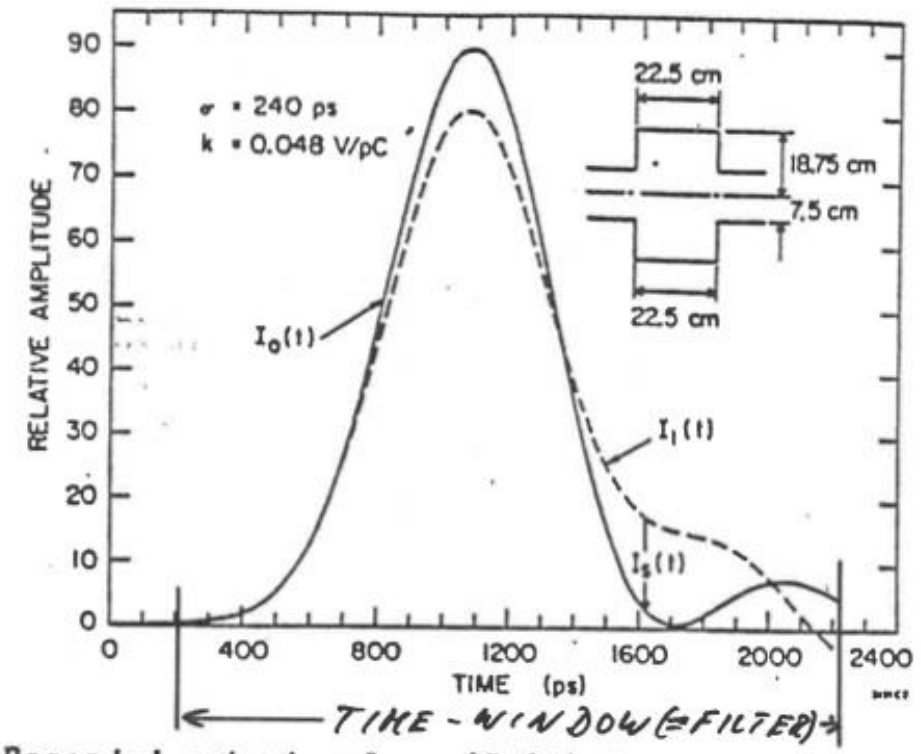
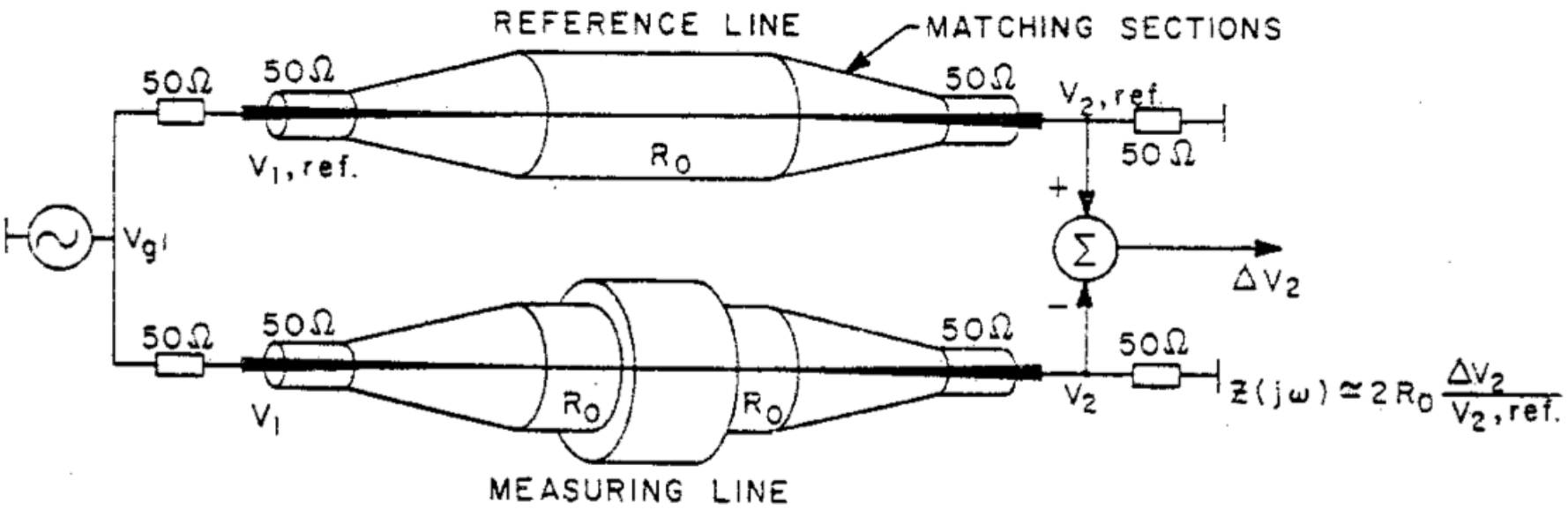


Fig. 3 - Recorded output pulses ($I_0(t)$ for the reference pipe and $I_1(t)$ for a cylindrical cavity having the dimensions shown (from ref. [2]).

The starting point of the DUT and REF pulse should coincide for rejecting imaginary impedance contribution (i.e. time delay).

F. Caspers, ESRF workshop, 1988

LONGITUDINAL IMPEDANCE MEASUREMENT



$$Z_{\parallel}(j\omega) \approx 2Z_c \frac{V_{2,REF} - V_{2,DUT}}{V_{2,REF}}$$

… difference!!

$$Z_{\parallel}(j\omega) \ll Z_c$$

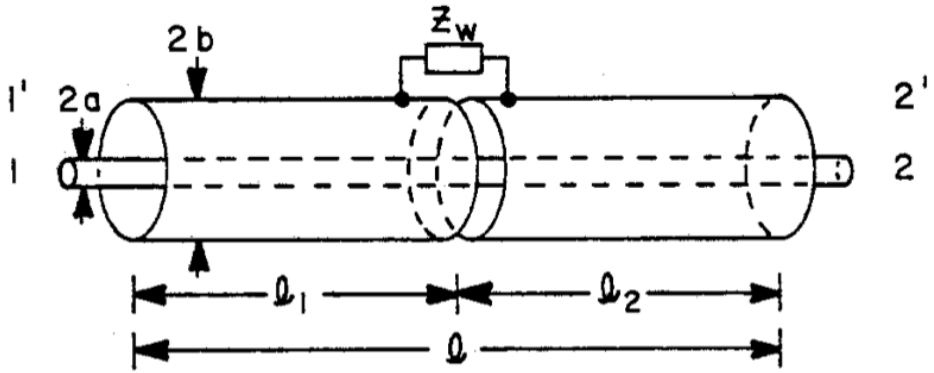
Frequency domain measurement

Imperfections in the matching sections are cancelled out by identical matching sections in the reference line.

It is a very simple version of a Network Analyzer …

H. Hahn, F. Pedersen, BNL Report 50860, 1978

HAHN-PEDERSEN FORMULA



Short gap in a circular beam pipe of uniform cross section.

Lumped element is fulfilled if DUT length << λ, beam pipe diameter

Coupling Impedance << Zc

Use of S-parameters and network analysers.

If the lumped element condition is "strictly" fulfilled we can measure several MOhm on a 50Ohm system via S21 (leading to 100dB attenuation, e.g. quartz resonator), but not via S11 (maximum 10kOhm on a 50Ohm system).

Transmission measurement more accurate than reflection measurement.

Hahn Pedersen

$$Z_{\parallel}(\omega) \approx 2Z_c \frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{DUT}} = Z_{HP}$$

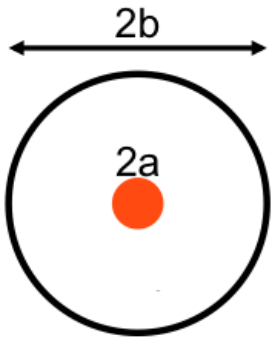
Sands Rees

$$Z_{\parallel}(\omega) \approx 2Z_c \frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{REF}}$$

HP formula available in the the conversion menu of modern VNA (norm. to 50 Ohm ...)

H. Hahn, F. Pedersen, BNL Report 50860, 1978

COAXIAL WIRE DIAMETER



$$Z_c = \frac{Z_{vac}}{2\pi} \ln\left(\frac{b}{a}\right)$$

Sands Rees

For a given coaxial wire current, the energy delivered to the DUT is proportional to Zc.

The transmitted pulse is only slightly modified relative to the incident pulse.

Hahn Pedersen

The transmission coefficient does not deviate too much from unity (within the frequency spectrum of the pulse).

$$S_{21}^{DUT} \approx S_{21}^{REF}\left(1 - \frac{Z_{\parallel}}{2Z_c}\right)$$

Reducing wire radius, increases Zc and reduces systematic error. BUT the desired term is reduced compared to unity and the small change in transmission may drown inaccuracy and random errors in measuring setup.

Very small DUT impedances may justify using a bigger wire diameter.

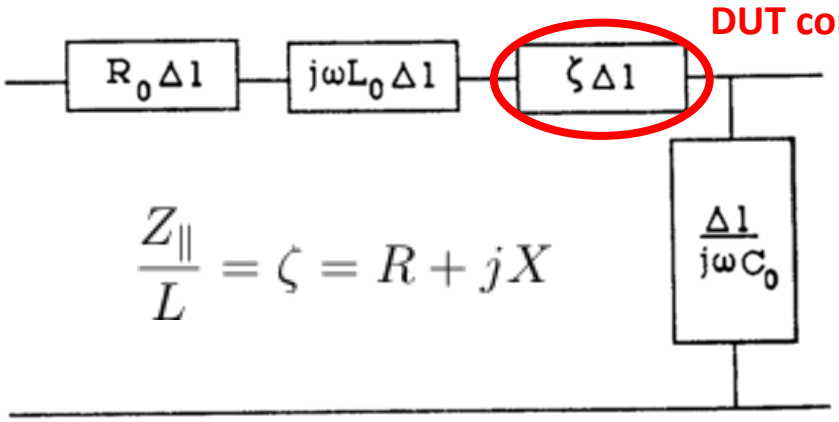
SYNTETHIC PULSE TECHNIQUE AND GATING (1985)

The coaxial wire method is widely used to simulate the image current and the electromagnetic field of a bunch. Measurements are usually performed in frequency (impedance) or time-domain (k-parameter). Some limits of validity and possible sources of error applying this simulation method are discussed. In general one may expect correct results if measurements are restricted to single localized impedances much smaller than the characteristic impedance of the coaxial line (beampipe with center wire). In case of more than one localised small impedance in a given beampipe time-filtering can be applied, provided there is sufficient spatial separation to reduce the problem to the case of isolated single impedances and to eliminate multiple reflections from nonmatched 50 ohm transitions at the end of the beampipe. The technique consists in generating a synthetic pulse in time domain via FFT, from measurements taken in the frequency domain. This leads to higher spectral power density than realtime or sampling pulse measurements thus giving higher dynamic range and better reproducibility. The impedance $Z(\omega)$ as well as the loss parameter k as a function of the bunch length ℓ can then be deduced by computations.

F. Caspers, IEEE Trans.Nucl.Sci.NS-32,1985

DISTRIBUTED IMPEDANCE

DUT + Coaxial Wire = TEM transmission line (with distributed parameters)



The DUT coupling impedance is modeled as a series impedance of an ideal REFerence line.

L.S. Walling et al., NIMA 281, 1989

V.G. Vaccaro, INFN TC-94/023, 1994

Coupling impedance is obtained from the REF and DUT characteristic impedances and propagation constants.

In the framework of the transmission line model, the DUT impedance can be computed from S-parameters (measured with VNA).

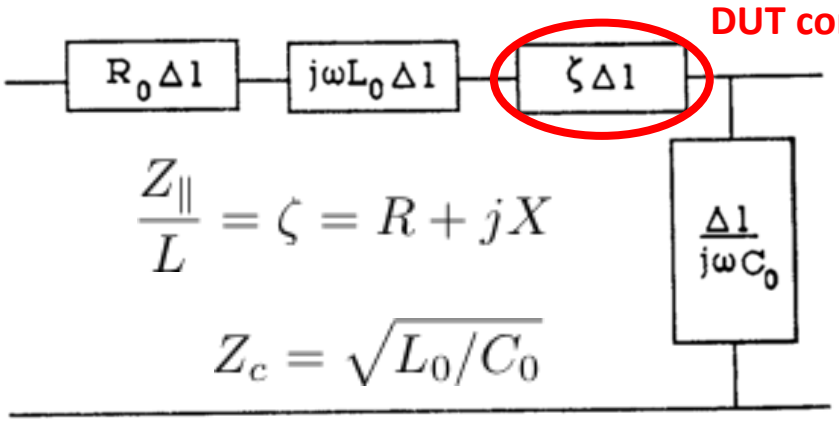
→ **Practical approximated formulae**

Already in Hahn/Pedersen paper (1978) a first attempt to deal with distributed impedance was made.

Review: F. Caspers in Handbook of Accelerator Physics and Engineering (2012)

DISTRIBUTED IMPEDANCE: LOG FORMULA

DUT + Coaxial Wire = TEM transmission line (with distributed parameters)



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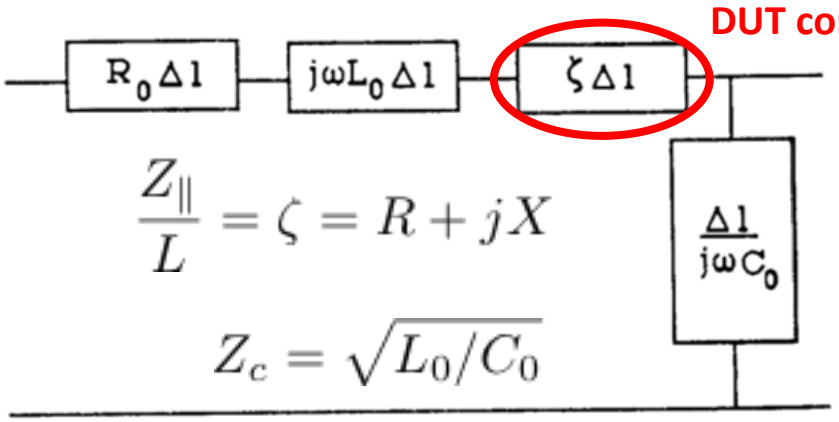
Coupling impedance is obtained from the REF and DUT characteristic impedances and propagation constants.

$$Z_{log} = -2Z_c \ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)$$

$$\frac{cX}{\omega Z_c} \ll 1$$

DISTRIBUTED IMPEDANCE: LOG FORMULA

DUT + Coaxial Wire = TEM transmission line (with distributed parameters)



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$$Z_{LOG} = -Z_c \ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)\left[1 + \frac{\ln\left(S_{21}^{DUT}\right)}{\ln\left(S_{21}^{REF}\right)}\right]$$

REF and DUT have impedance different from 50Ohm (tapers as matching network).

It is possible to get the S-parameters of the DUT and REF alone by additionally measuring the line given by the two contiguous adaptors.

RELATIONS BETWEEN FORMULAS

Distributed impedance

Lumped element:
DUT length << λ, pipe diameter

Improved log formula (Vaccaro, 1994)

$$Z_{LOG} = -Z_c \ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)\left[1 + \frac{\ln\left(S_{21}^{DUT}\right)}{\ln\left(S_{21}^{REF}\right)}\right]$$

High frequency/long DUT

Hahn-Pedersen formula (1978)

$$Z_{HP} = 2Z_c \frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{DUT}}$$

Exact in the frame of lumped element hypothesis

$$Z_{\parallel}(\omega) \ll Z_c$$

$$S_{21}^{DUT} \approx S_{21}^{REF}$$

Log formula (Walling et al, 1989)

$$Z_{log} = -2Z_c \ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)$$

$$S_{21}^{DUT} \to 1$$

$$\ln(x) \approx x - 1$$

Sands-Rees formula (1974)

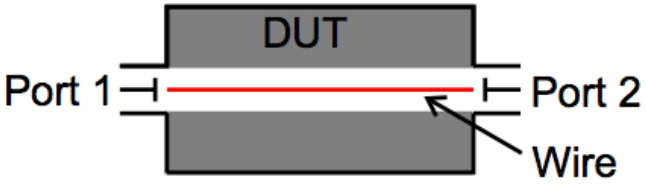
$$Z_{SR} = 2Z_c \frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{REF}}$$

Very versatile formula, also for lumped elements with reduced accuracy.

The wire method is strictly valid for frequencies below cut-off.

RESONANT METHODS FOR SMALL IMPEDANCES

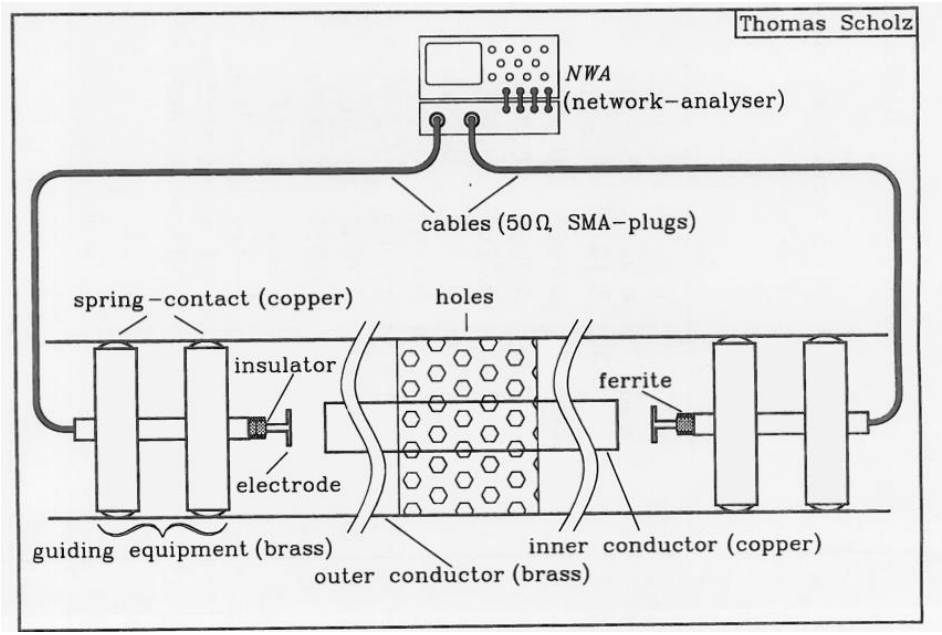
A reliable technique is to apply an inner conductor, which is capacitively (weakly) coupled and operates as a transmission resonator



The change in resonance frequency of this TEM line resonator (as compared to a reference measurement) indicates the imaginary part of the wall impedance (using the identical inner conductor), and a change in Q stands for the real part.

The advantage of capacitive coupling at either end is that there will be no doubts on contact reproducibility. We must check the weak coupling on each side via S11 and S22.

The coupling elements and other discontinuities in the set-up cause detuning too, thus increasing the uncertainty of the results of the imaginary part of the impedance.



F. Caspers, T. Scholz, Particle Accelerators, 1995

TRANSVERSE IMPEDANCE MEASUREMENTS

The transverse impedance is proportional (at a given frequency) to the change of longitudinal impedance due to lateral displacement of the beam in the plane under consideration (H or V): Panowsky-Wentzel theorem.

Two parallel wires are stretched across the DUT (odd mode) to get ONLY the driving/dipolar impedance (source particle on-axis, witness off-axis).

Panowsky-Wentzel

Two wires/loop

$$Z_\perp = \frac{Z_\parallel c}{\omega \Delta^2}$$

Δ **wire spacing (<10% of the DUT radius)**

$$Z_{\perp,LOG} = -\frac{Z_c c}{\omega \Delta^2} \ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)\left[1 + \frac{\ln\left(S_{21}^{DUT}\right)}{\ln\left(S_{21}^{REF}\right)}\right]$$

from improved log formula

$$Z_c = Z_{c,\mathrm{ODD}}$$

At low frequency:
λ>> DUT length → **Lumped element formula**

G. Nassibian, F. Sacherer, NIMA 159, 1979

SINGLE DISPLACED WIRE MEASUREMENTS

IF $Z_L = const + F^2(x_0)$ ⇒ $Z_T = \frac{c}{\omega}\left(\frac{dF}{dx_0}\right)^2$

Since

$Z_L(x_0) = Z_L(-x_0)$ ⇒ $Z_L(x_0) = Z_L(x_0 = 0) + a^2 x_0^2 + \ldots$

Then, assuming $F(x_0) \approx a\, x_0$

⇒ $Z_T = \frac{c}{\omega}\frac{Z_L(x_0) - Z_L(x_0 = 0)}{x_0^2}$

Measuring transverse impedance with a single displaced wire displaced of x0.

G. Nassibian, F. Sacherer, NIMA 159, 1979

COMMENTS

In the two wires bench set-up only “dipole field components”.

The odd mode wire pair is equivalent to a single wire over a metallic image plane (metallic half space).

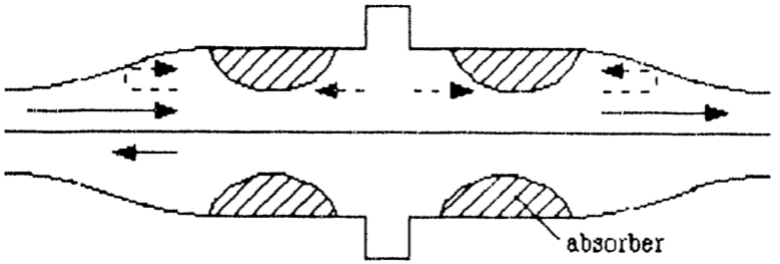
Some devices exhibit a strong azimuthal asymmetry in the image current distribution due to variation of the EM properties (e.g. ferrite in kickers) or to the cross section.

In order to get a more complete view of the transverse kick on the beam, it may be useful to characterize the device with a single displaced wire (no image plane).
H. Tsutsui, SL-Note-2002-034 AP

Only the sum (or respectively difference) of the driving and detuning impedances is measured with a single displaced wire.
E. Métral et al., THPCH059, EPAC06, 2006

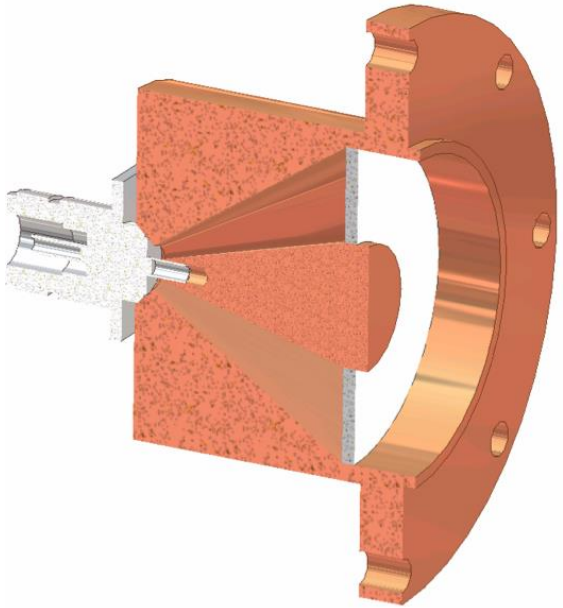
BEAM IMPEDANCE MEAS. ABOVE CUT-OFF

Already in the early days of loss factor measurements, the spectrum of the pulse had significant components beyond waveguide cut-off.



In the frequency domain, HOMs clearly show up as notches in the transmission. Those notches can be reduced by inserting microwave absorbing material (foam) near the tapers or end pieces of the test set-up.

One can omit the wire completely, playing on the fact that certain TM modes have a similar surface current distribution as the TEM field. The use of TEM-wave apparatus to small test resonators gave good results in the 10-19GHz frequency range.



The technique to operate without any wire limits of course the frequency range but permits waveguide mode, pulse-reflectometry to identify obstacles and band-limited impedance measurement in transmission.

T. Kroyer, PhD thesis, 2005

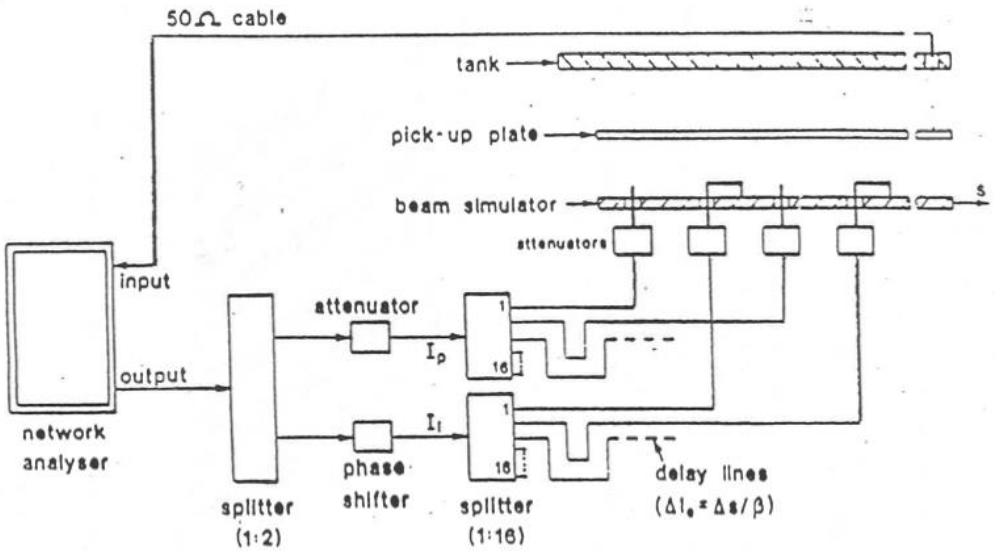
Lambertson, LBL Note 28190,1990

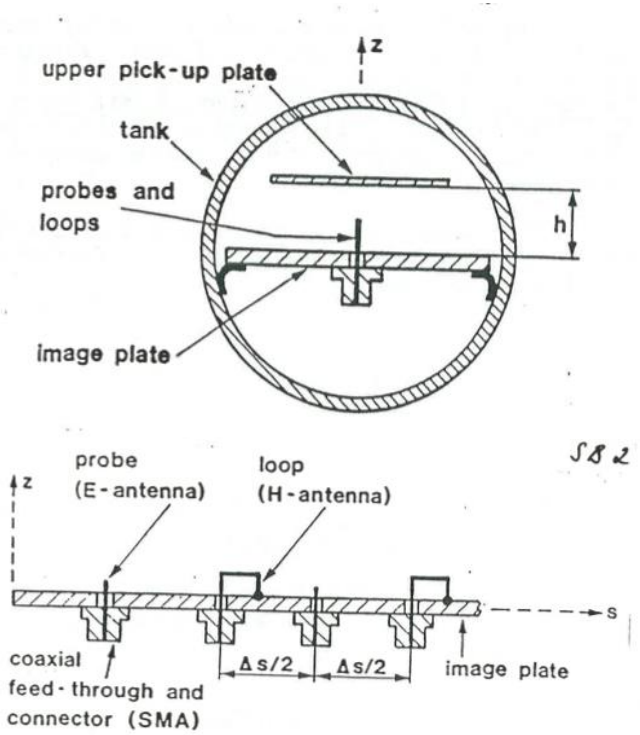
IMPEDANCE FOR SLOW BEAMS

For test bench simulations of slow beams a quasi-static approach has been developed, that permits dealing virtually any v/c value as well as independently any E/H ratio.

Each of those probes and loops is fed with an RF signal from some broadband (few MHz to some GHz) power divider, which arrives at the probe or loop via a thin coaxial cable of well defined delay with respect to its neighbour probe or loop.

The probes serve as E-field exciter and the loops as H-field exciter, but they are not used to radiate EM energy (near field use only).





F. Caspers et al, EPAC 90, 1990

MITIGATION OPTIONS

The classical mitigation technique is the de-Qing of resonances.

This is often done by damping resonances via insertion of lossy ferrites attached to the metallic walls which should not be seen directly from the beam.

The interesting fact here: the higher the reduction in Q and thus the damping from the ferrites , the better the performance (cavity driven from current source). Inserting more lossy material reduces power dissipation.

Also lossy dielectrics have been proposed and used. However ferrite are naturally the first choice as the interact with the magnetic fields of wall currents.

However often there is an issue with the heat removal from those ferrites in vacuo.

Thus the AMD (the ALL MODE DAMPER) i.e. some sort of coupling loop or pin to interact with as many modes as possible, is an alternative and the dissipation takes place in a load outside the vacuum.

In some cases minor changes in the geometry of the structure have been rather helpful.

MITIGATION OPTIONS

For kickers shielding strips on an alumina tube and thick film coating (pattern) on ferrite blocks was applied with good success Improvement of bellows or installation of shielding bellows and reduction of contact resistance can also be an option (in some cases).

In the presence of strong magnetic fields , ferrite type damping material should not be used ; instead resistively coated ceramic tubes are a good option (e.g. in the CERN SPS) In wire scanners adding a small and light weight wire loop around the movable fork can help.

THEOR. JUSTIFICATION AND ERRORS

Theoretical justifications of lumped element formula in R.L. Glucstern,R. Li, Particle accelerator, 1990 and A. Argan et al., PAC99, 1999.

$Z_{\parallel}$ **Beam coupling impedance**

$$\frac{Z_{HP}}{Z_{\parallel}} \simeq 1 + \frac{Z_{\parallel}}{4Z_c}\left[1 + \frac{j}{\Theta} - \frac{\left(1 - e^{-j\Theta}\right)e^{-j\Theta}}{\Theta^2}\right]$$

$$\frac{Z_{log}}{Z_{\parallel}} \simeq 1 + \frac{Z_{\parallel}}{4Z_c}\left[\frac{j}{\Theta} - \frac{\left(1 - e^{-j\Theta}\right)e^{-j\Theta}}{\Theta^2}\right]$$

$$\frac{Z_{LOG}}{Z_{\parallel}} \simeq 1 - \frac{Z_{\parallel}}{4Z_c}\frac{\left(1 - e^{-j\Theta}\right)e^{-j\Theta}}{\Theta^2}$$

H. Hahn, PRST-AB 3 122001 (2001)

$$\Theta = \beta L \longrightarrow L/\lambda$$

The error is always proportional to $\frac{Z_{\parallel}}{Z_c}$

Thin wire ⟶ **High Zc**

No lumped element

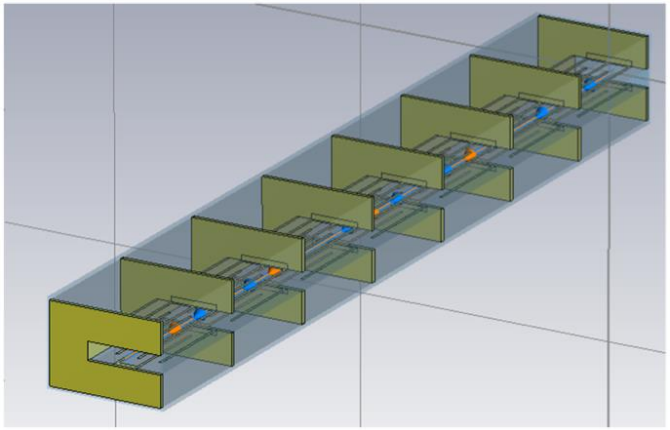
Applicable up to Θ ~ 1

E. Jensen, PS-RF-Note 2000-001 (2001)

Compares the three formulae to the exact transmission line solution.

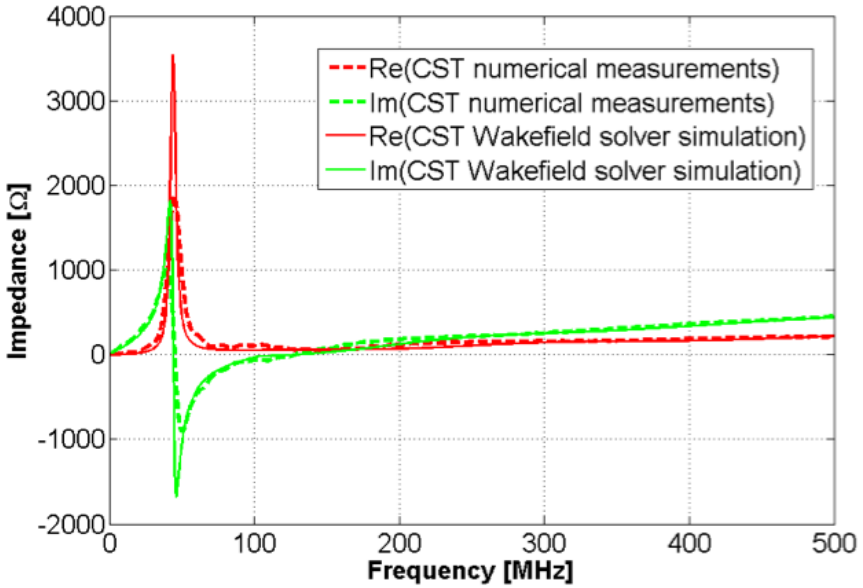
NUMERICAL INVESTIGATIONS OF WIRE METHOD

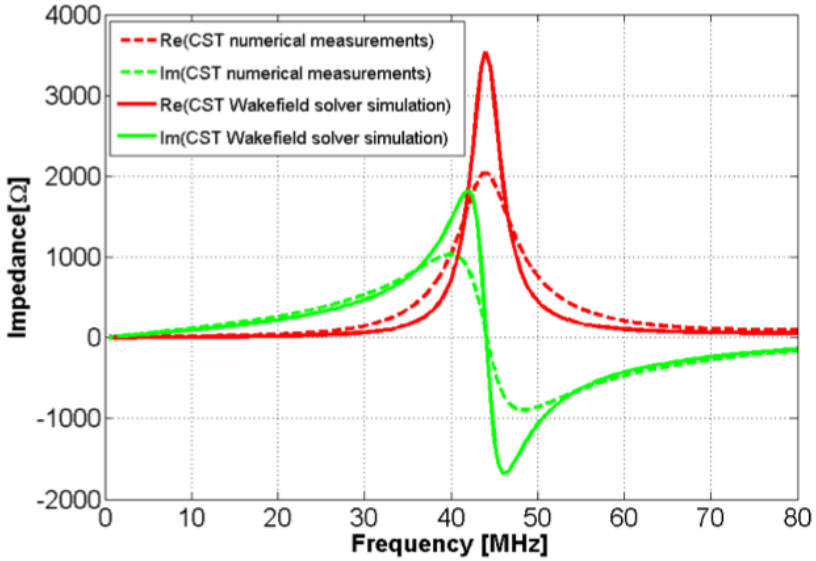
Simulation of the MKE SPS extraction kicker with serigraphy (7 cell).



Very good agreement in the "broadband" behaviour.

Reduction/widening of the peak may be due to the propagation losses in the coaxial line.





C. Zanini, EM simulations of CERN accelerator components and experimental applications, PhD thesis, 2013

EPA EXPERIMENT: BEAM SET-UP

Goal of the experiment: to investigate the transmission properties of a coated ceramic chamber with the CERN EPA electron beam.

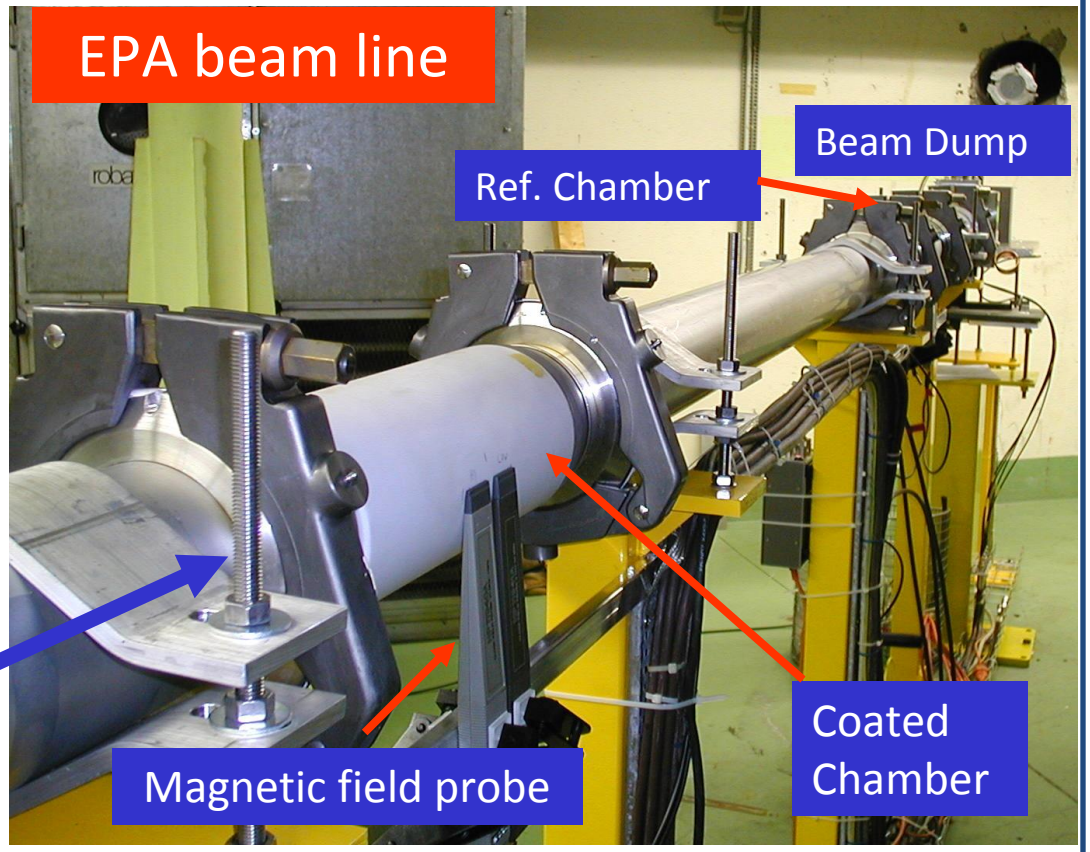
Titanium coating (1.5 μm)

Thickness << skin depth

DC resistance 1 Ohm

Reference chamber
(non coated)

500 MeV electron bunch
(7e10 particles, σ~ 1 ns)



EPA 1999: shielding properties

EPA 2000: effect of external shields

L. Vos et al., AB-Note-2003-002 MD

EPA EXPERIMENT: BENCH SET-UP

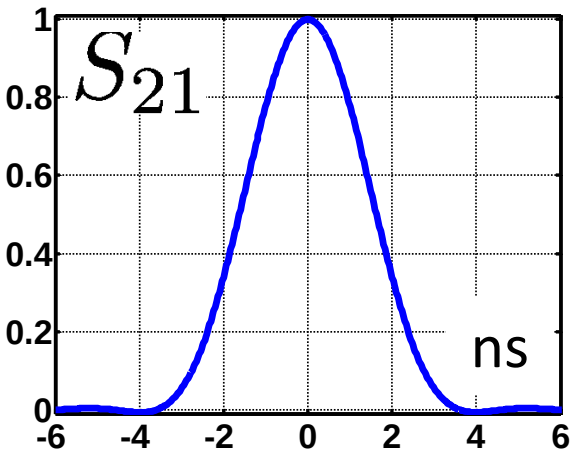
The same ceramic chambers used in the beam experiment have been measured within a coaxial wire set-up, using the same magnetic field probes.

Just like in the early days of coaxial wire techniques (Sand and Rees,1974)

VNA in time domain mode

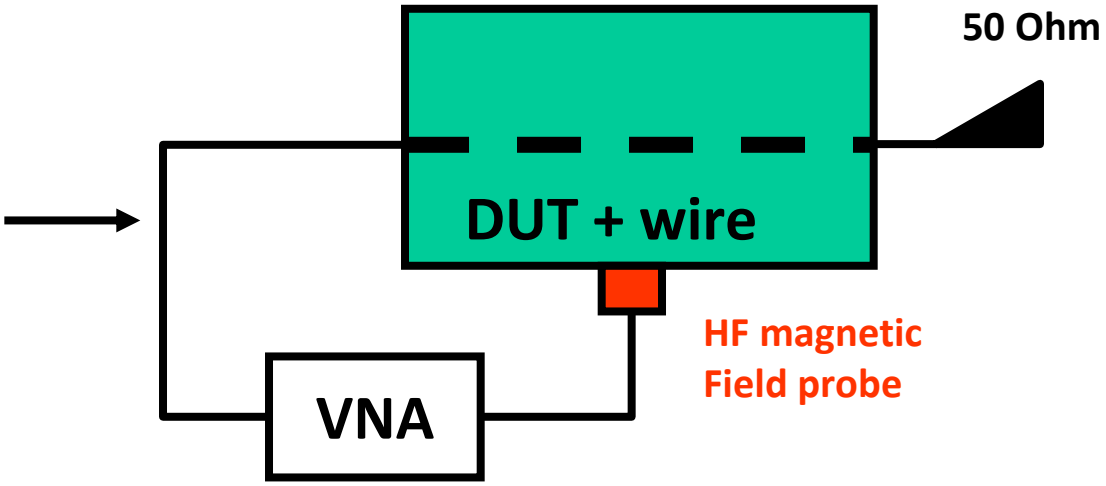
↓

Synthetic pulse (300 MHz BW)



wire diameter: 0.8 mm

Matching resistors: 240 Ohm



A. Mostacci et al., CARE workshop, 2004

BENCH VS BEAM MEASUREMENT IN EPA

Shallow cavity

Beam/wire axis

Vacuum chamber

External shield

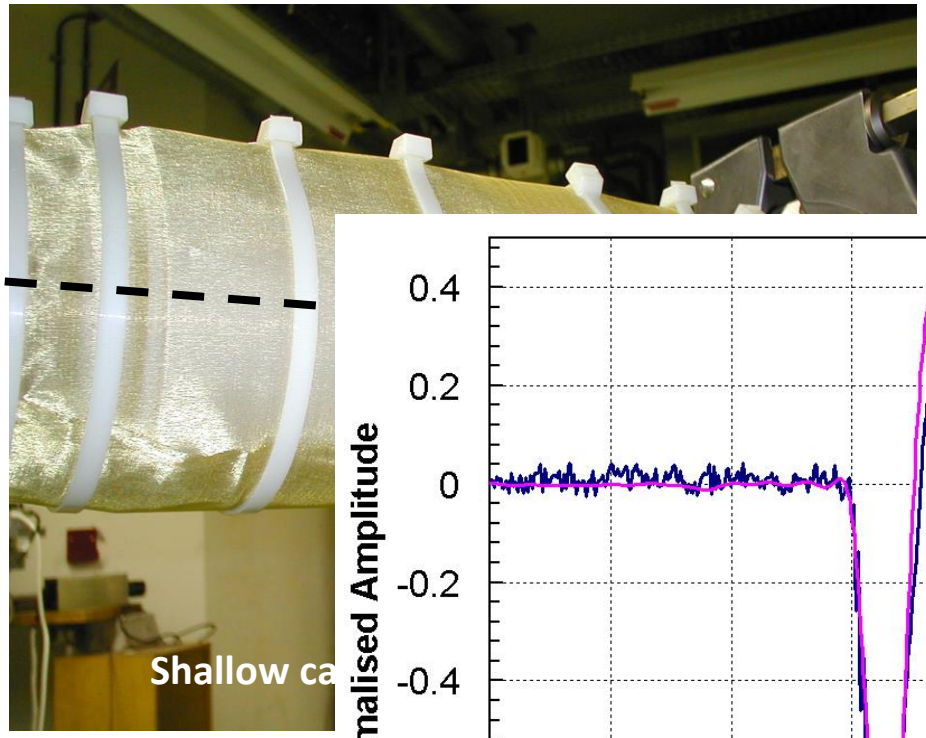
Titanium coating

The external shield is electrically connected to the vacuum chamber.

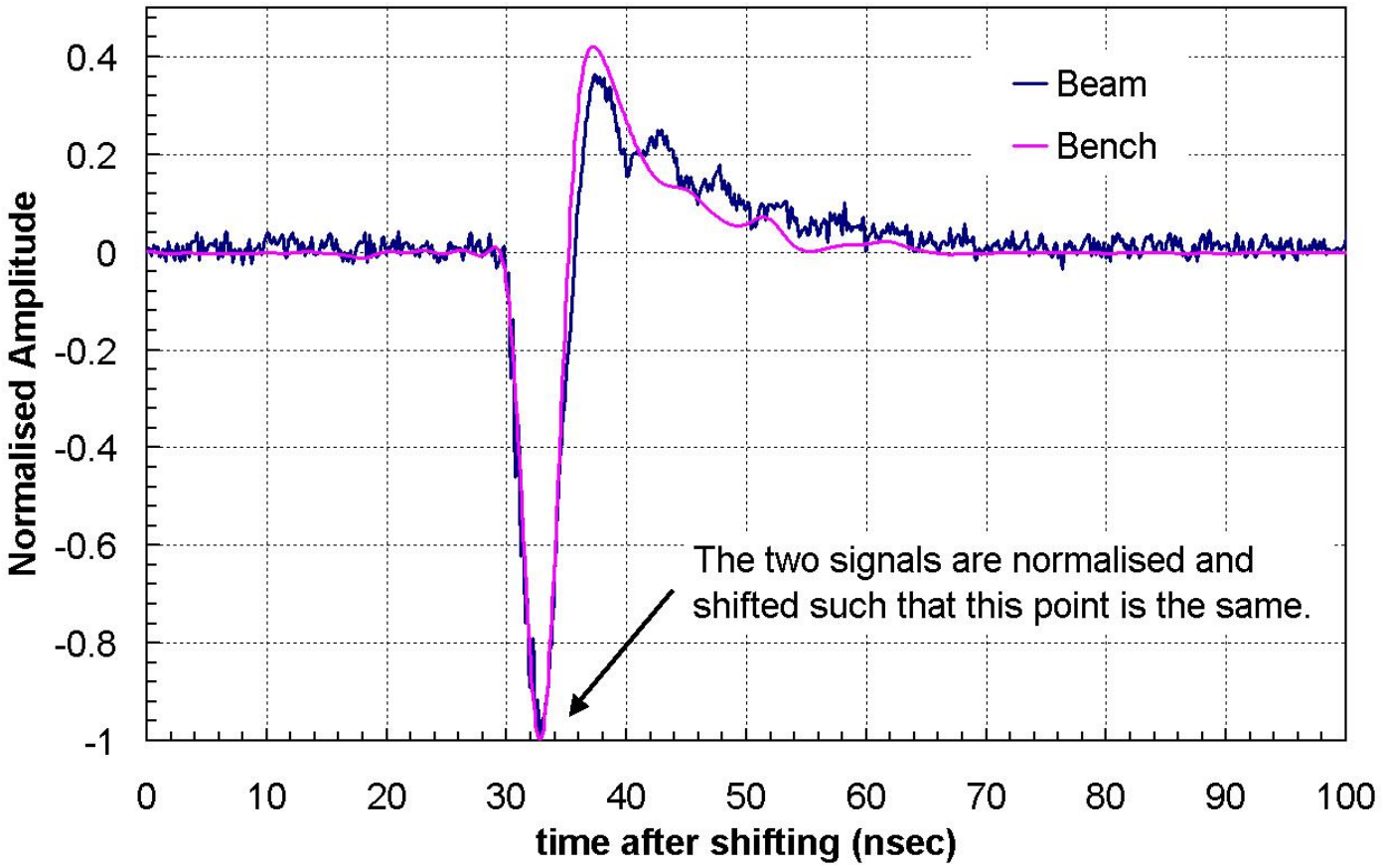
Ceramic chamber

Field probe

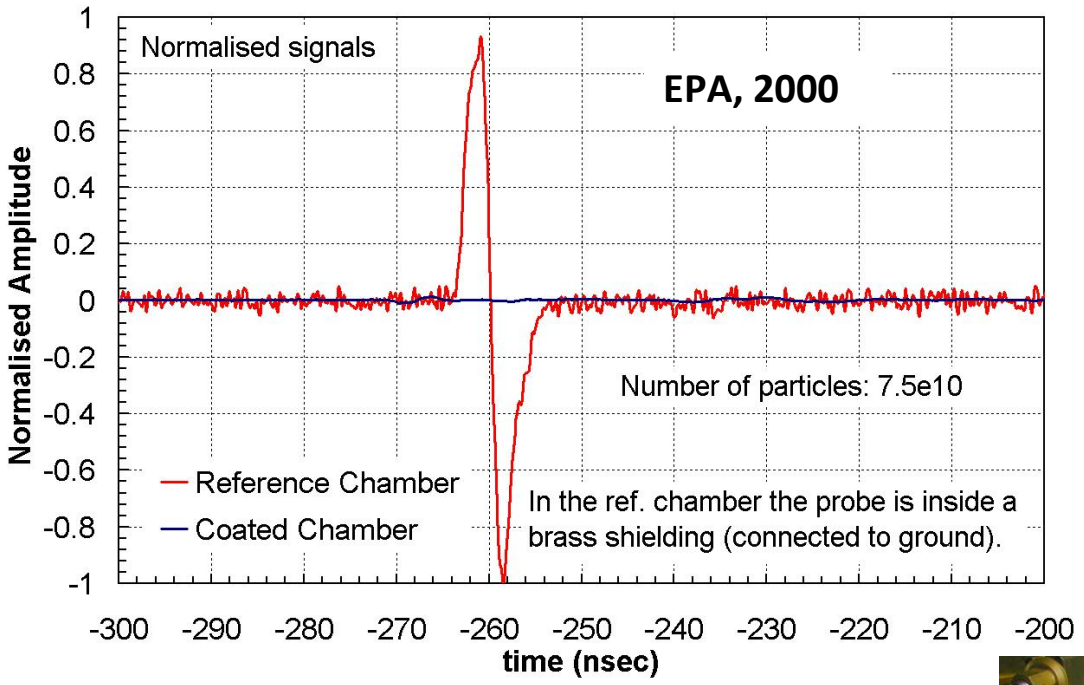
BENCH VS BEAM MEASUREMENT IN EPA



The external shield carries image currents and field penetrates the thin resistive (titanium) layer if this external bypass is present.

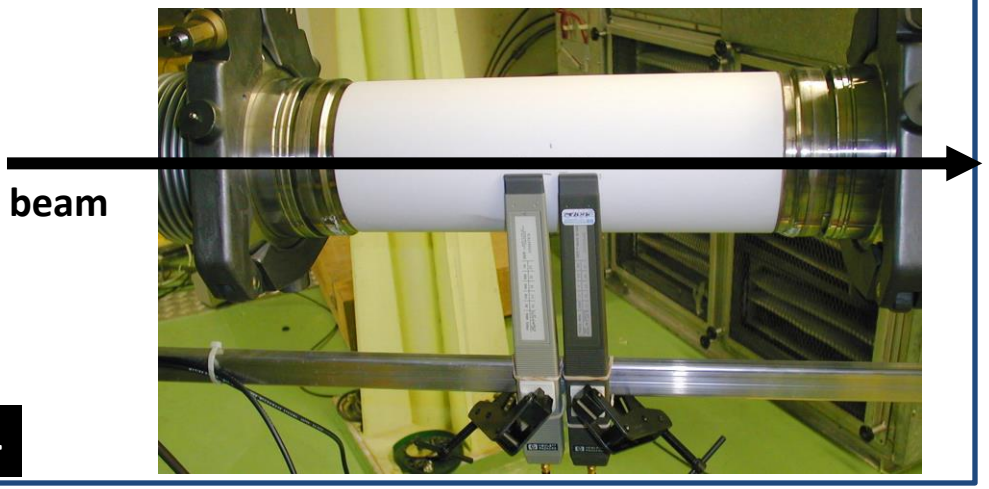


BENCH VS BEAM MEASUREMENT IN EPA



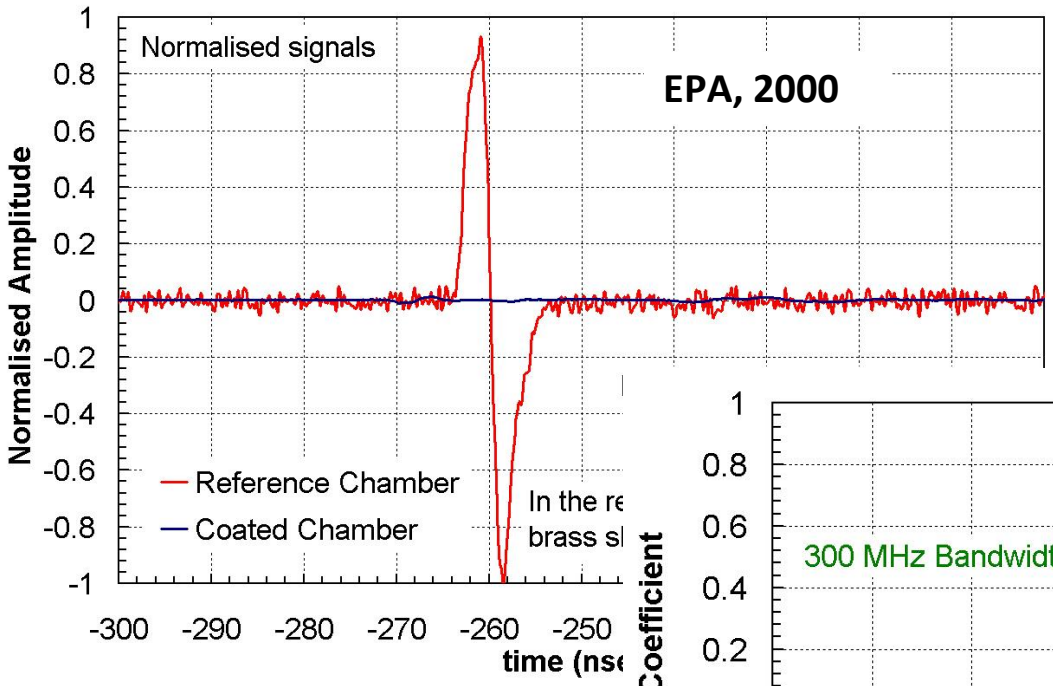
Coated chamber without any external bypass

Shielding properties of the coated chamber



A. Mostacci et al., CARE workshop, 2004

BENCH VS BEAM MEASUREMENT IN EPA



Coated chamber without any external bypass

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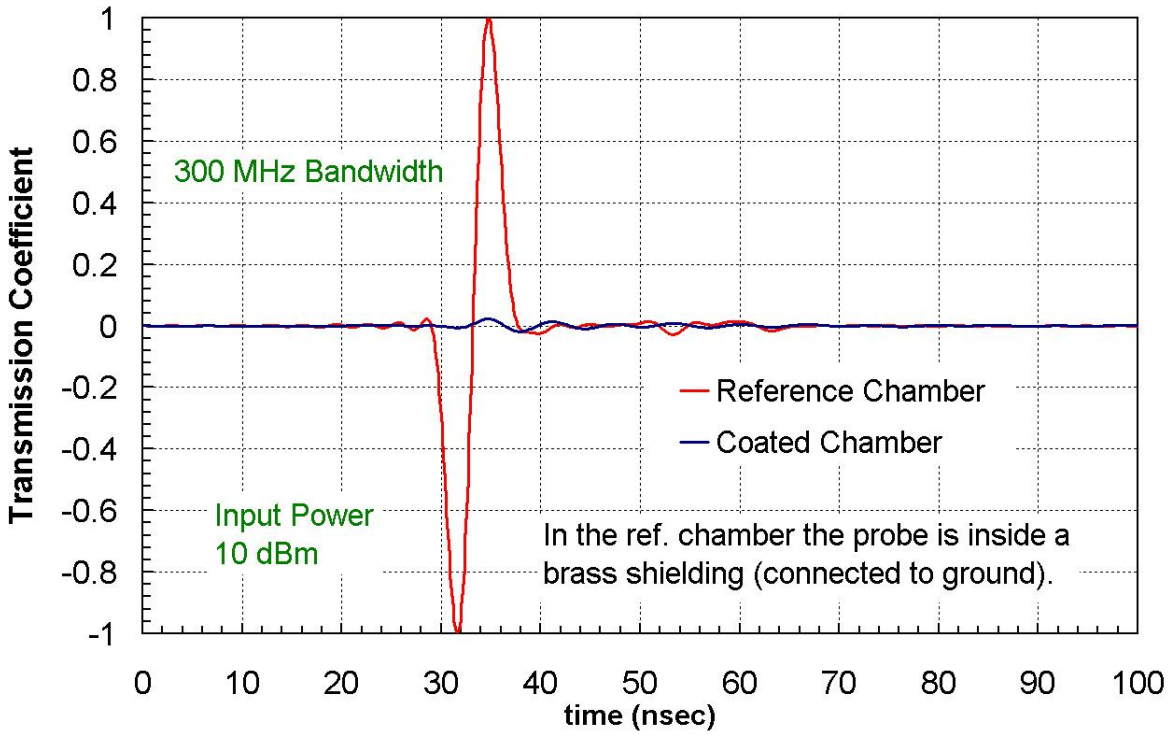
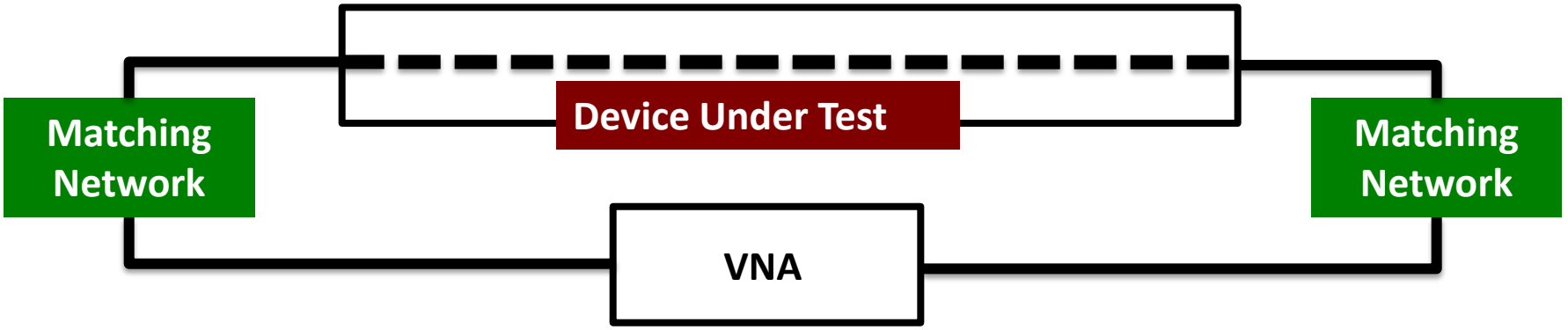


A. Mostacci et al., CARE wo

MATCHING NETWORKS



Matching sections are required to change impedance from 50Ohm to the much higher Zc required in the measured line.

Tapers are not the ultimate solution (strong reflections at low frequencies for distributed impedance transformers). Constant impedance tapers have no problem.

For transverse measurements, long impedance tapers are practically impossible.

Practical solution: a flat end plate with some resistive matching network.

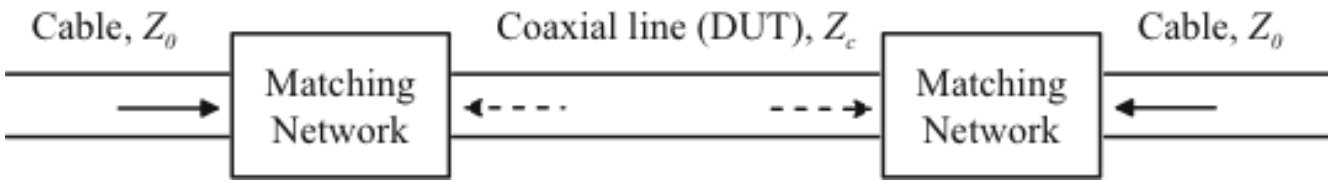
Tiny carbon resistors (0.05-0.1 W) can be used up to several GHz, rather than precision metal film resistors which often have a large inductance.

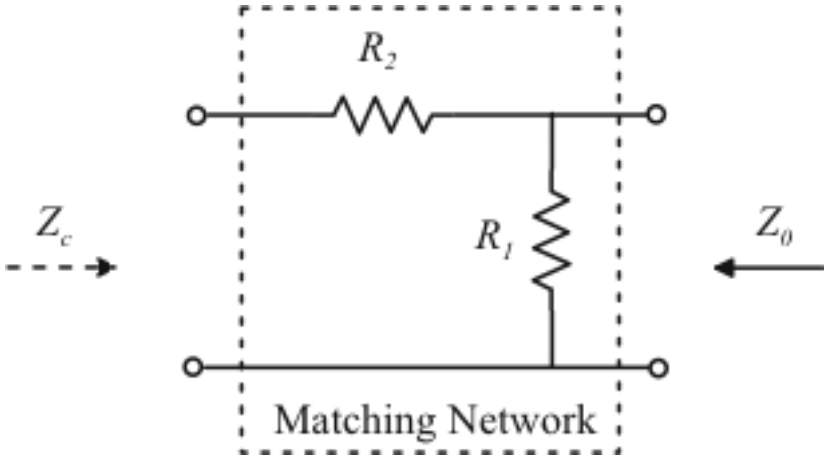
Use lossy foam for adsorbing high order modes where the resistor is ineffective.

A. Mostacci et al., NIMA 517, 2004

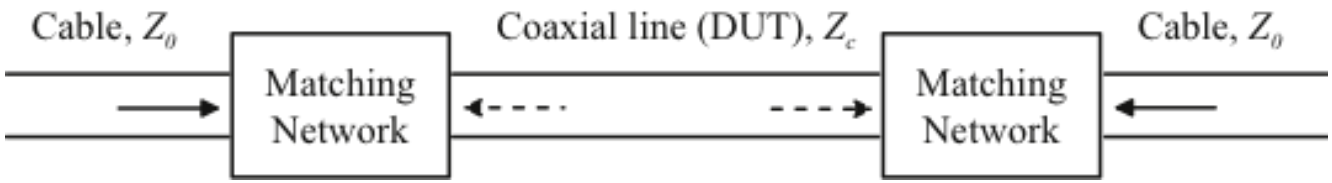
T. Kroyer et al., CERN AB-Note-2007-028, 2007

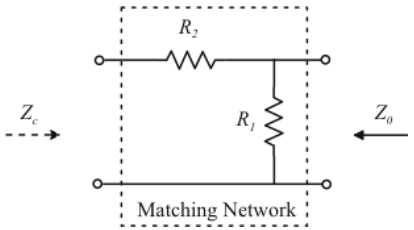
RESISTIVE MATCHING NETWORKS



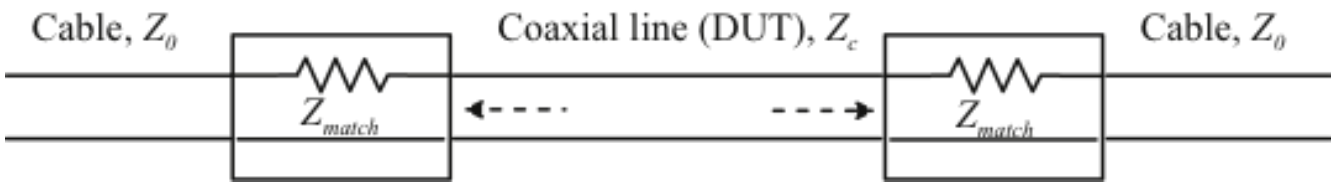


RESISTIVE MATCHING NETWORKS

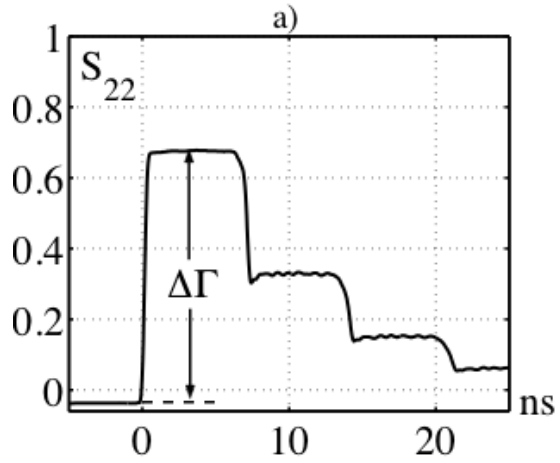




Practical solution

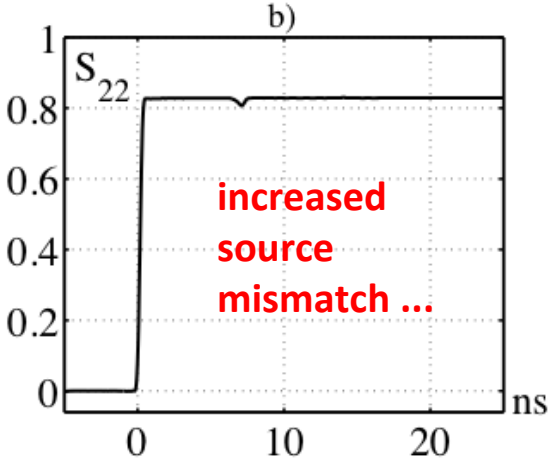


Coaxial line properties can be measured with Time Domain Reflectometry (TDR)



$$Z_c = Z_0 \frac{1 + \Delta\Gamma}{1 - \Delta\Gamma}$$

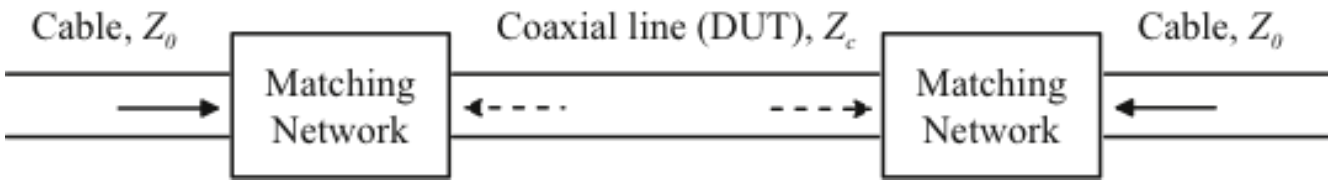
$$Z_{match} = Z_c - Z_0$$

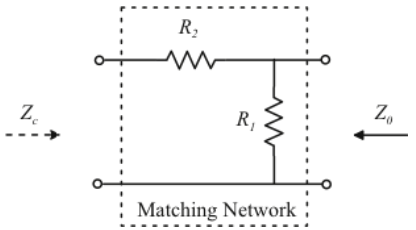


A. Mostacci et al., NIMA 517, 2004

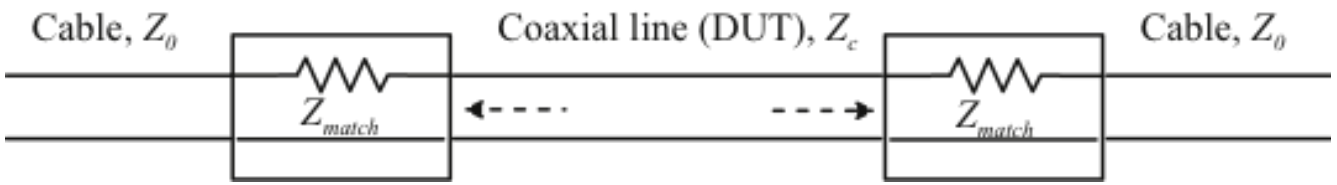
T. Kroyer et al., CERN AB-Note-2007-028, 2007

RESISTIVE MATCHING NETWORKS

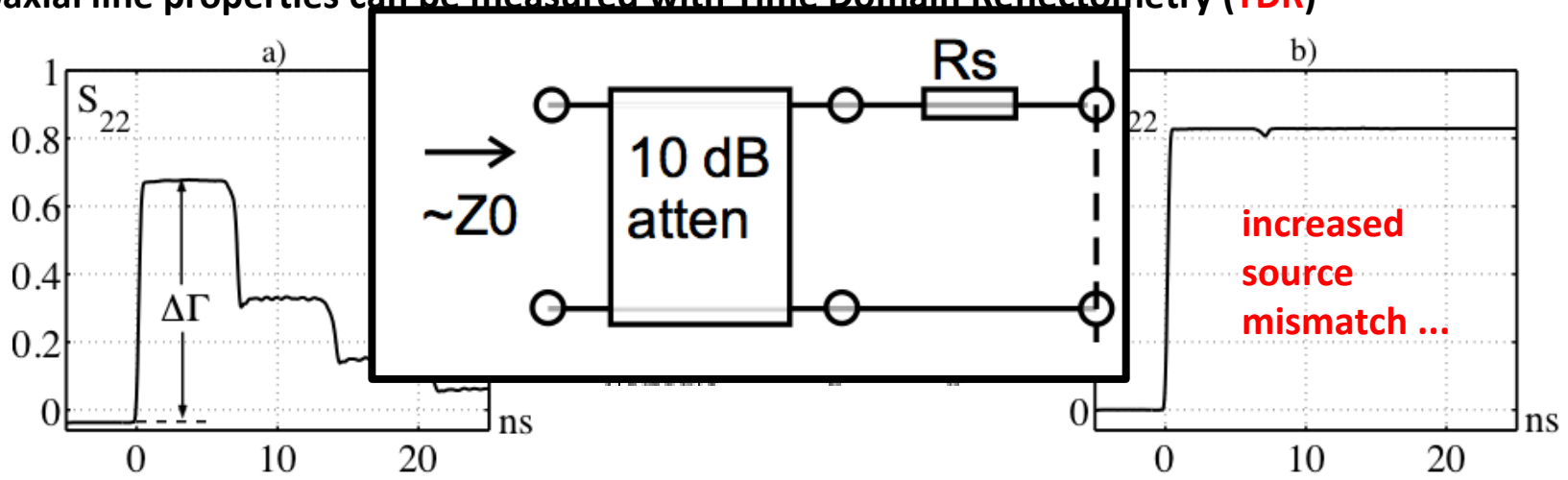




Practical solution



Coaxial line properties can be measured with Time Domain Reflectometry (TDR)

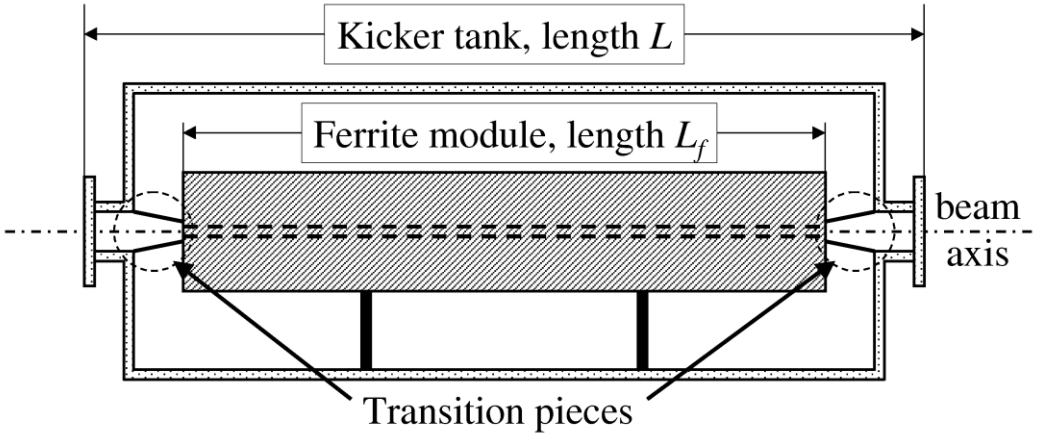


A. Mostacci et al., NIMA 517, 2004

T. Kroyer et al., CERN AB-Note-2007-028, 2007

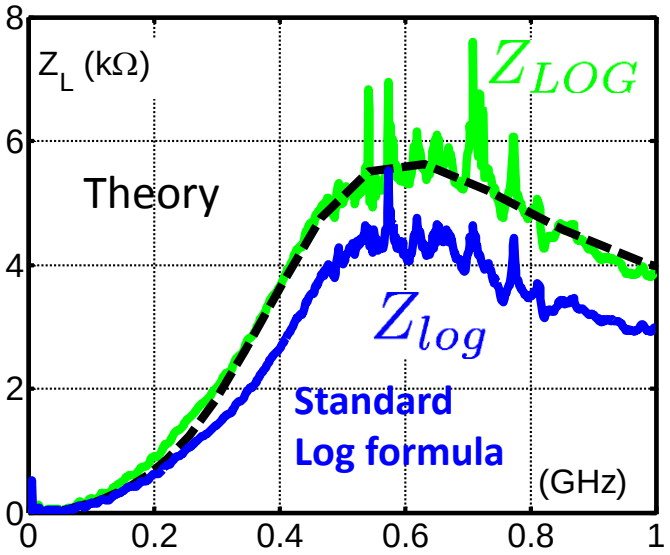
COMPARISON BETWEEN LOG FORMULAS

MKE kicker @ SPS: 7 cells module.



L=2.31 m **L_f=1.66 m**

Improved Log formula



Coupling impedance >> characteristic impedance (300 Ohm)

Correction to the improved LOG formula

$$Z_{LOG} = Z_{log}\left[1 + \frac{jc}{2\omega L_f}\ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)\right]$$

At low frequencies (λ ~ L), theory is closer to standard log formula.

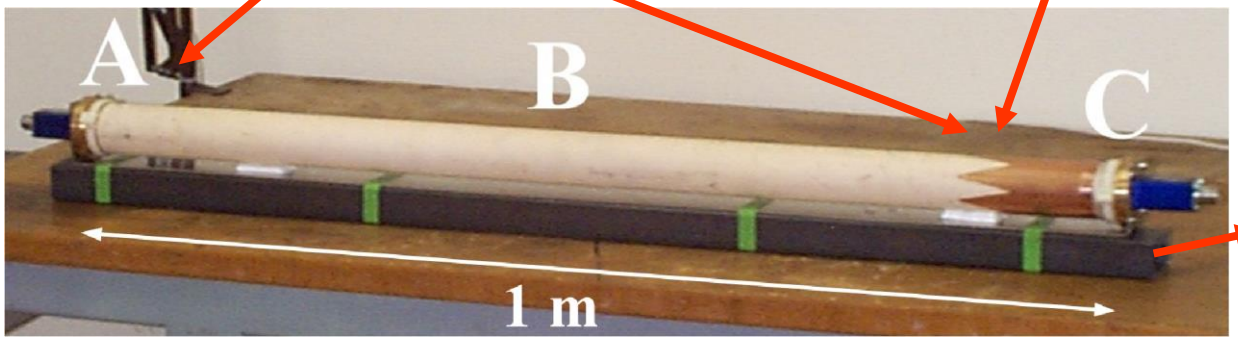
A. Mostacci, F. Caspers CERN-SL-2000-071

NUMERICAL SIMULATIONS AND WIRE METHOD

First prototypes of LHC kickers ...

RF contacts

Improvement of RF match towards HF.



PS-RF-Note 2002-156

rectangular steel profile

magnet cold conductor

Ceramic test chamber with 30 printed conducting strips (different widths) inside, using the same technology of the final LHC kicker.

Copper tape surrounding the right end of the ceramic tube in order to make a capacitor between the right port and the strip line (point C).

Numerical simulation of the bench measurement

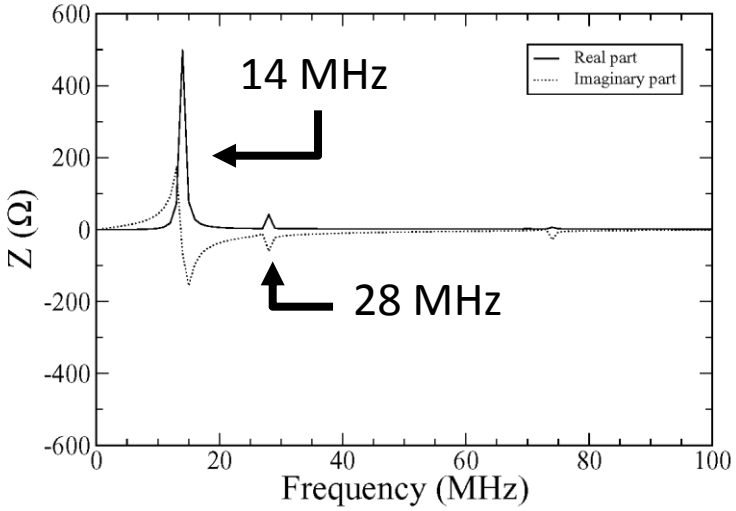
H. Tsutsui LHC Project Note 327 (2003)

Nowadays due to the availability of detailed models, as well as the reliability of RF codes, the simulation comparison is an important help.

SIMULATION OF WIRE MEASUREMENT

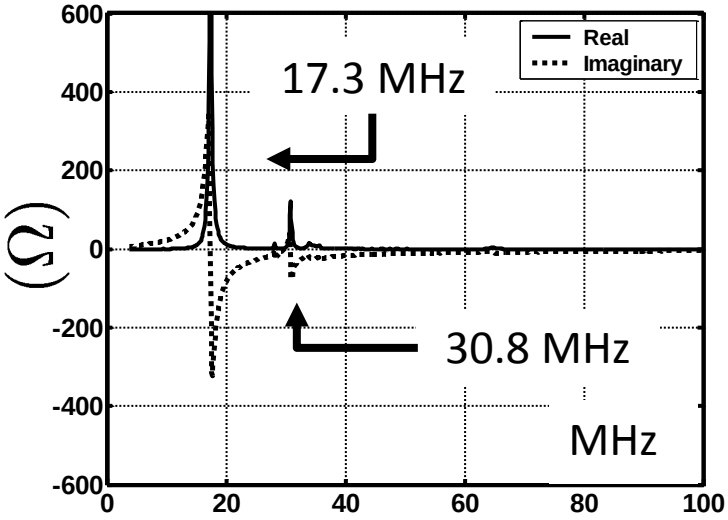
Numerical simulations

H. Tsutsui, LHC Project Note 327



RF measurement

PS-RF-Note 2002-156



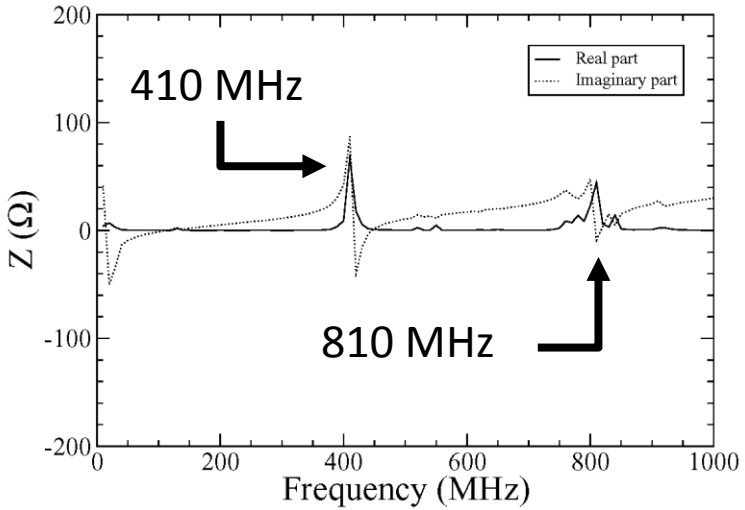
Resonance @ 17.3 MHz (700 Ohm) is due to the capacitor and the inductance created by the strip and the outer support. To dump it a ferrite ring was set (agreement between measurement and simulations).

Resonance @ 30 MHz is a transverse resonance and it may be related to slightly offset or not properly tightened wire.

SIMULATION OF WIRE MEASUREMENT

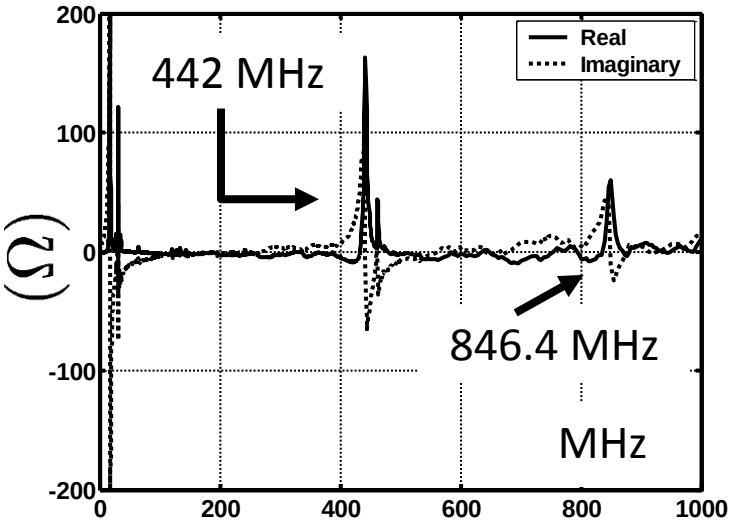
Numerical simulations

H. Tsutsui, LHC Project Note 327

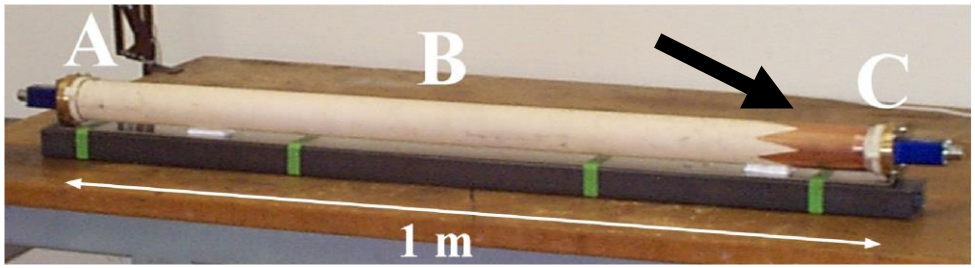


RF measurement

PS-RF-Note 2002-156

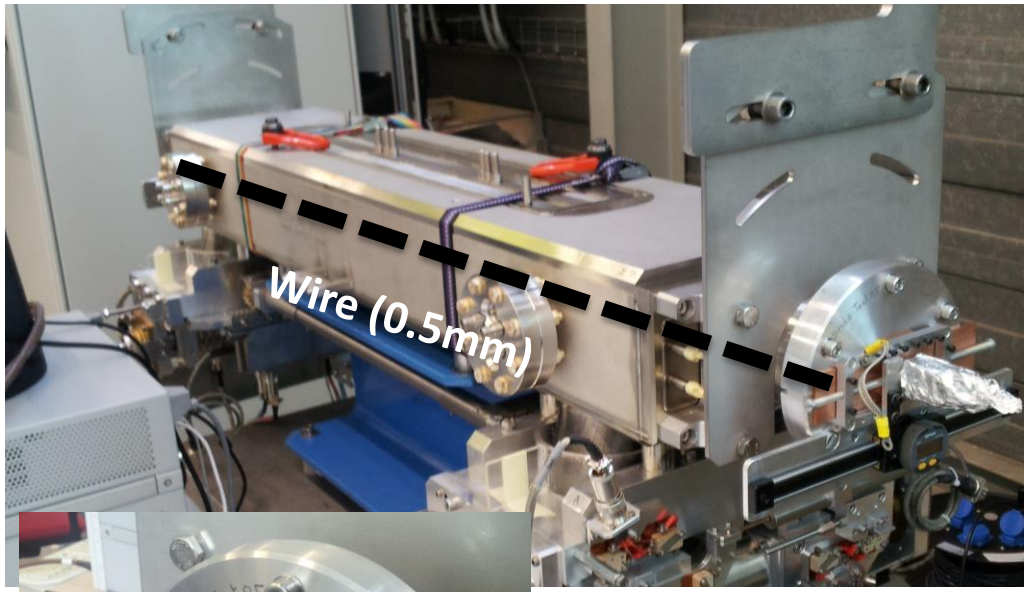


The 442.3 MHz and 846.4 MHz peaks are due to coaxial waveguide resonance at the copper tape.

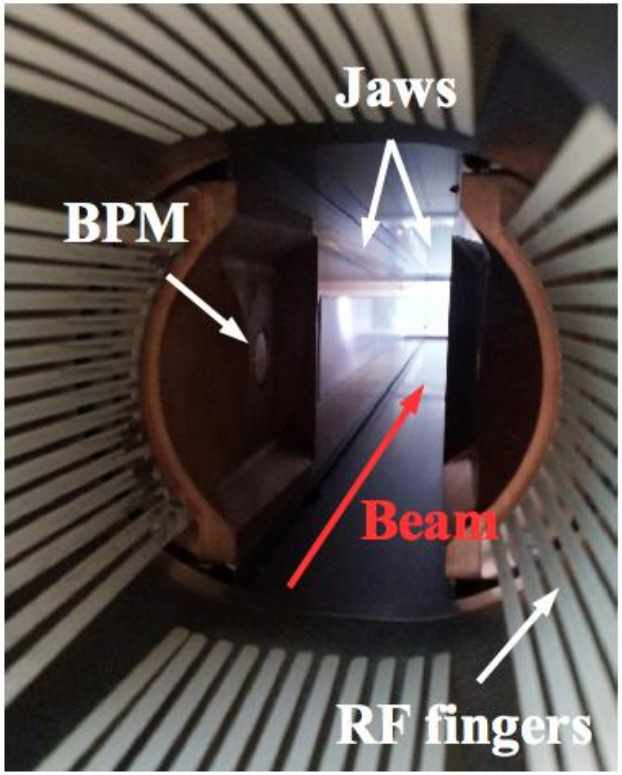


TDR AND WIRE MEASUREMENT

Characterisation of the z-dependency of the characteristic impedance of the wire.

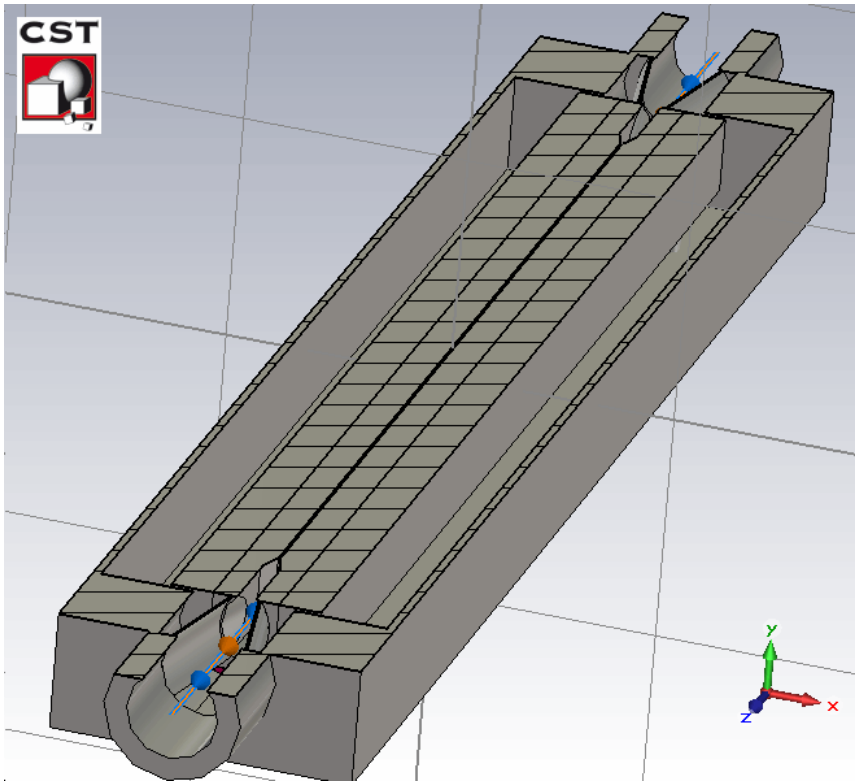


LHC collimator

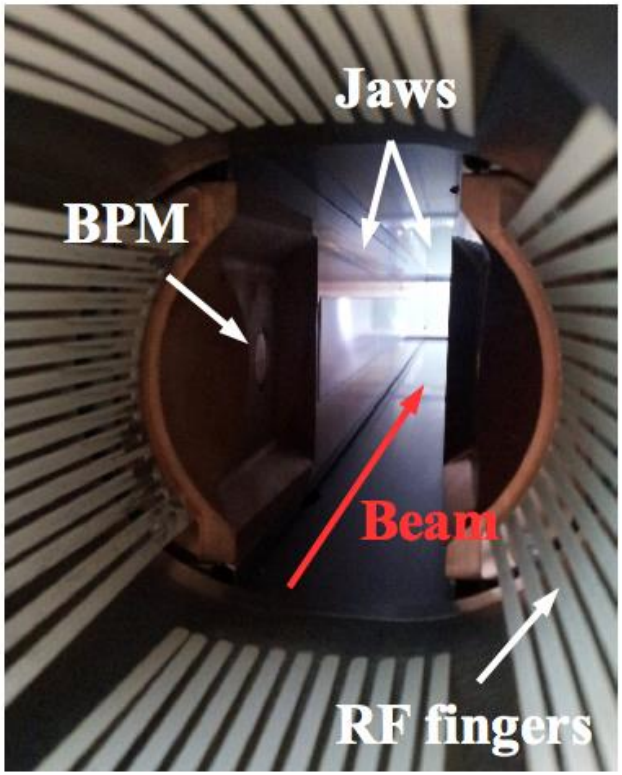


N. Biancacci et al., TCTP collimator meas., 2014

LHC TCTP COLLIMATOR

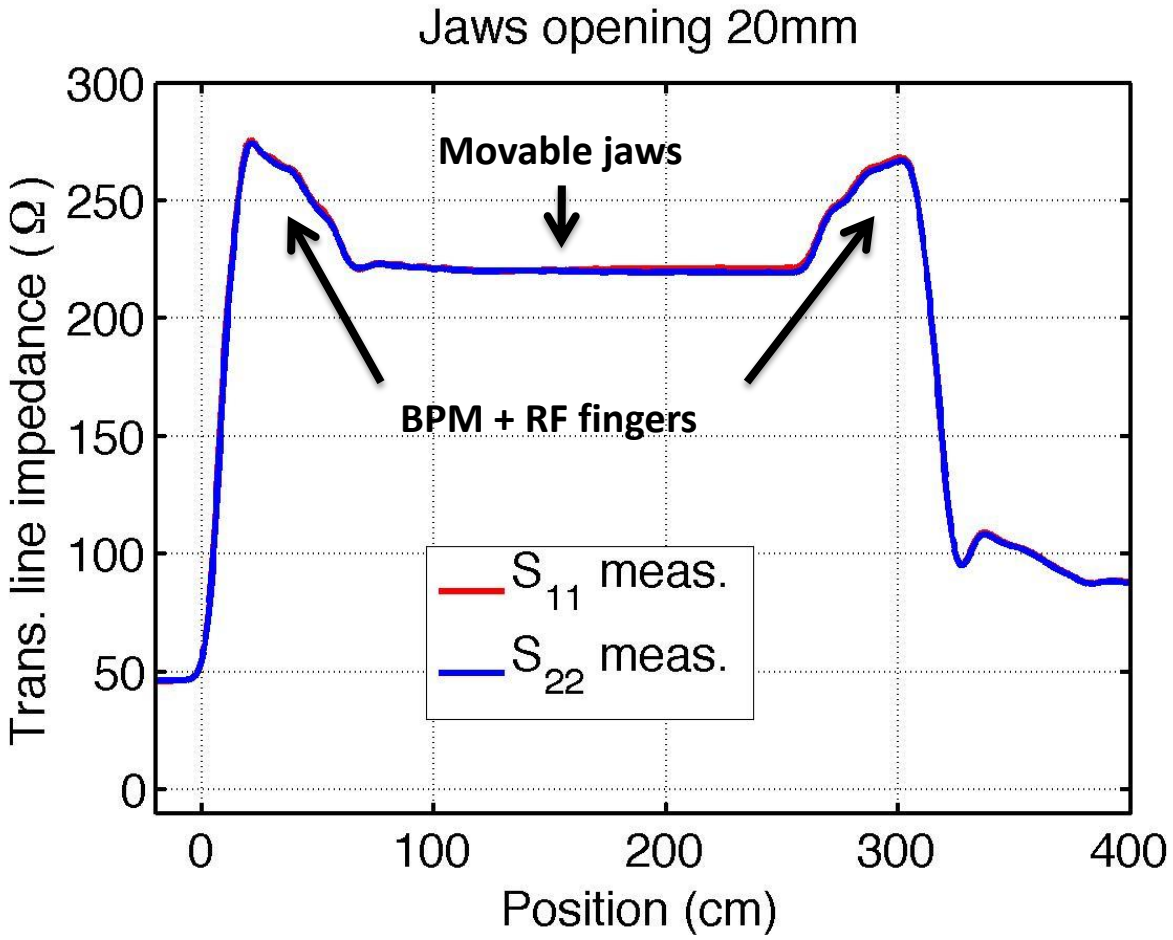


Courtesy of B. Salvant, CERN

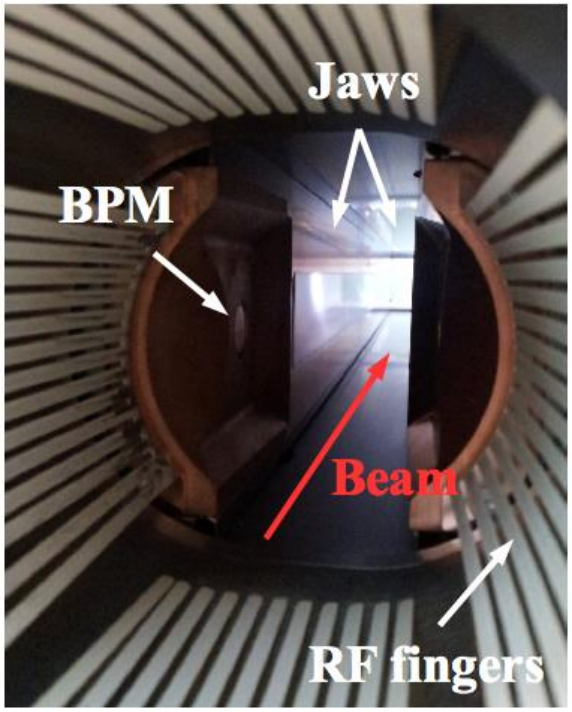


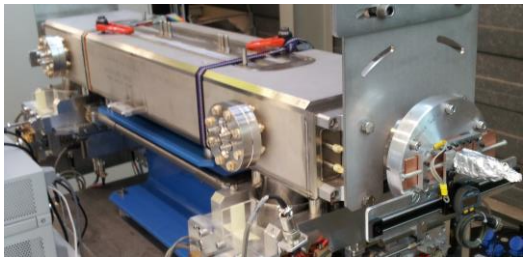
N. Biancacci et al., TCTP collimator meas., 2014

COAXIAL TRANSMISSION LINE



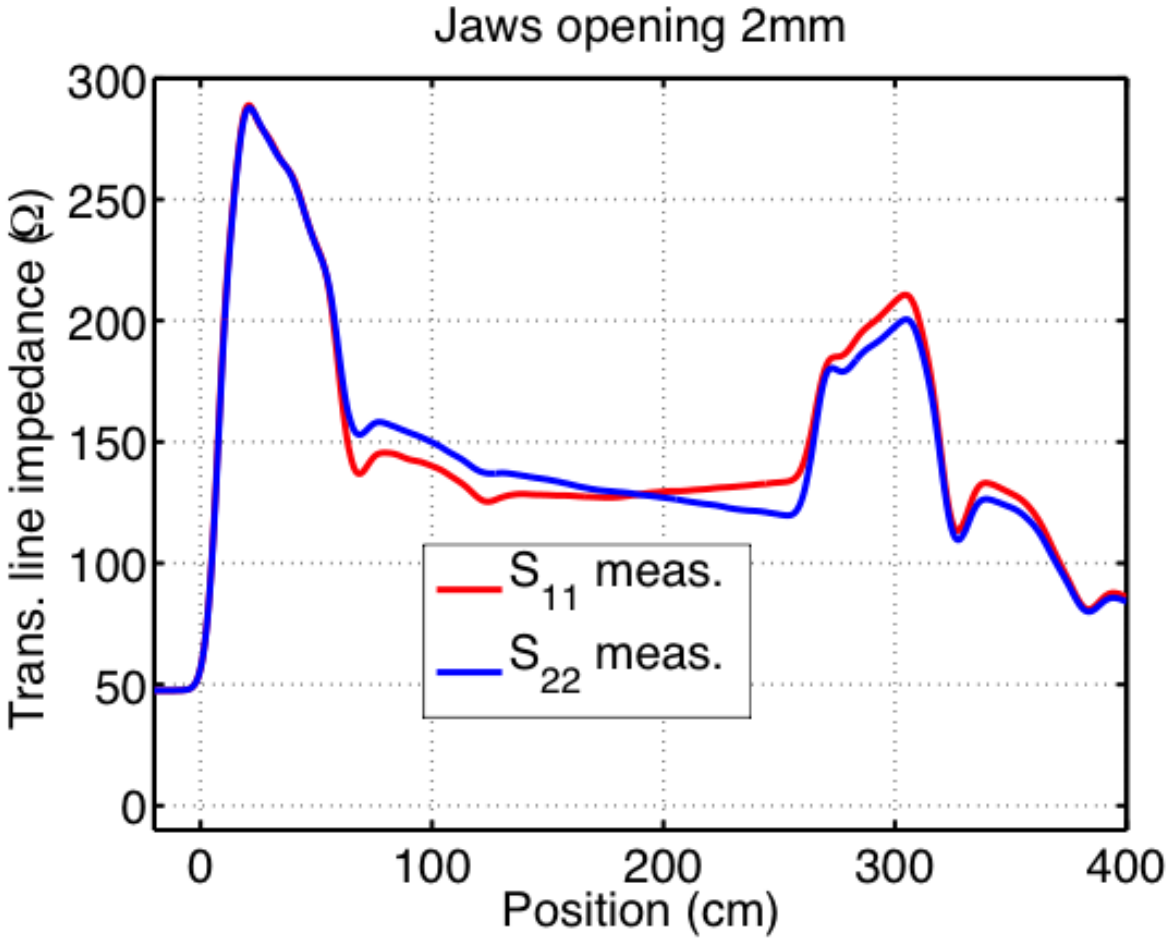
REFLECTION measurement

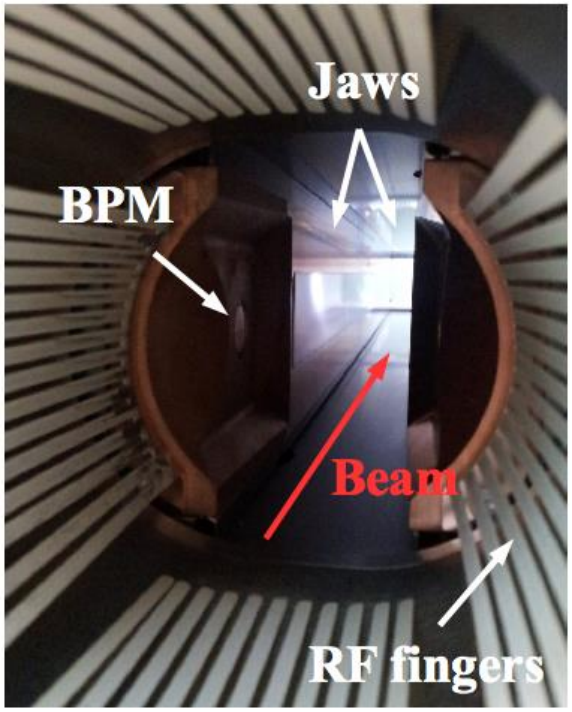


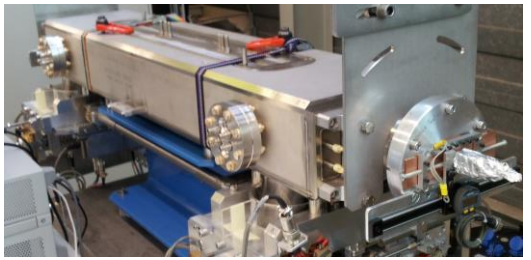


N. Biancacci et al., TCTP collimator meas., 2014

MEASURE OF JAWS ALIGNMENT



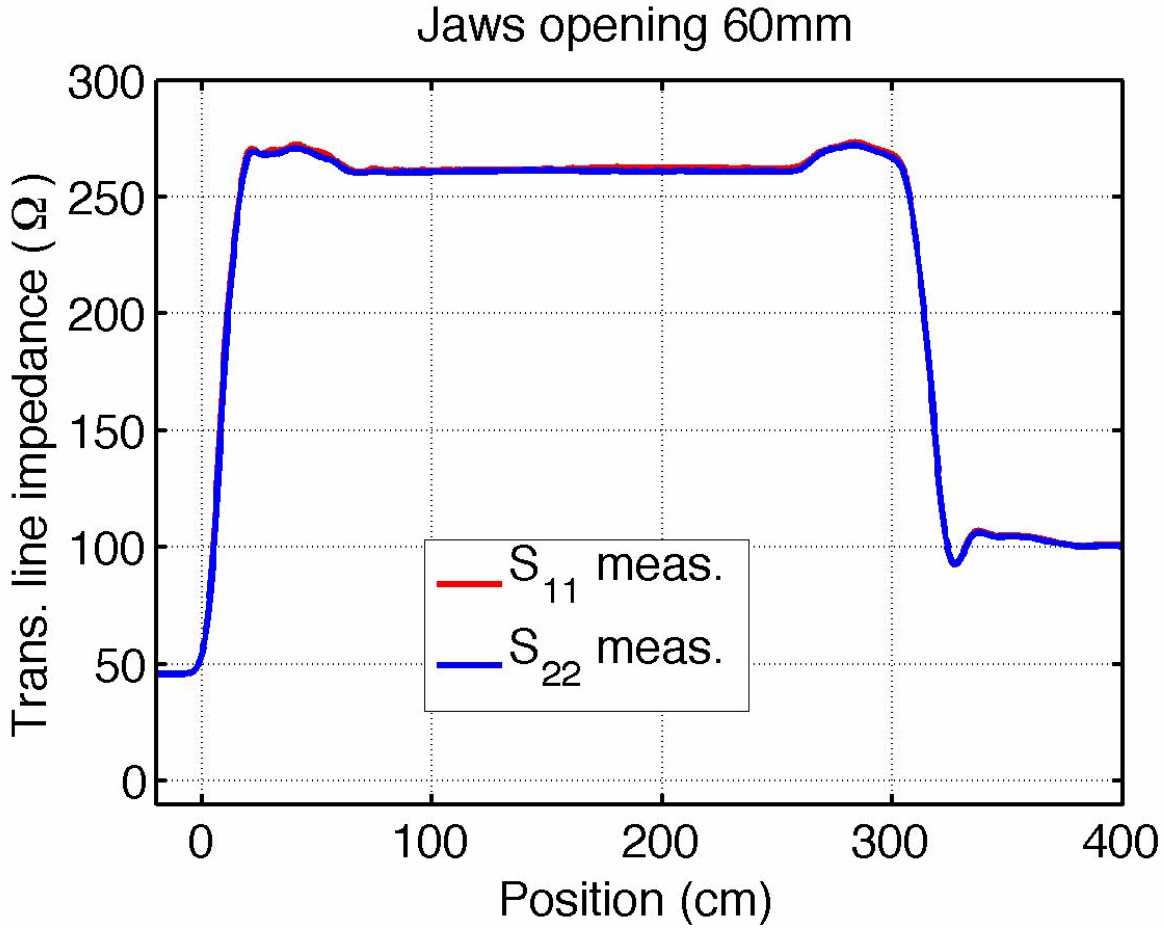


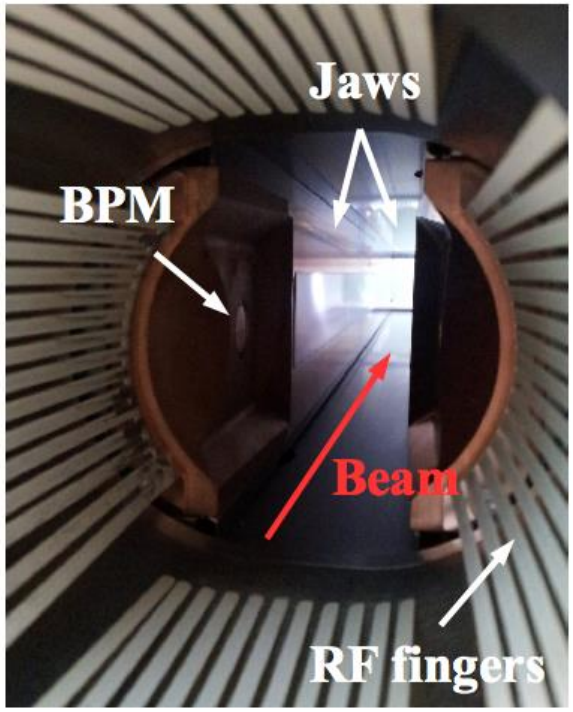


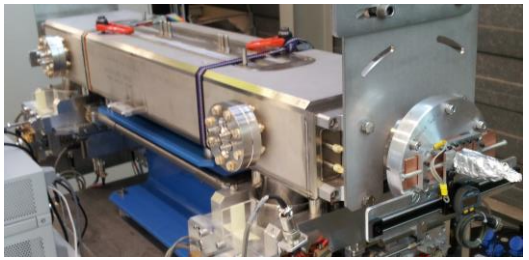
REFLECTION measurement

N. Biancacci et al., TCTP collimator meas., 2014

COAXIAL TRANSMISSION LINE PROPERTIES



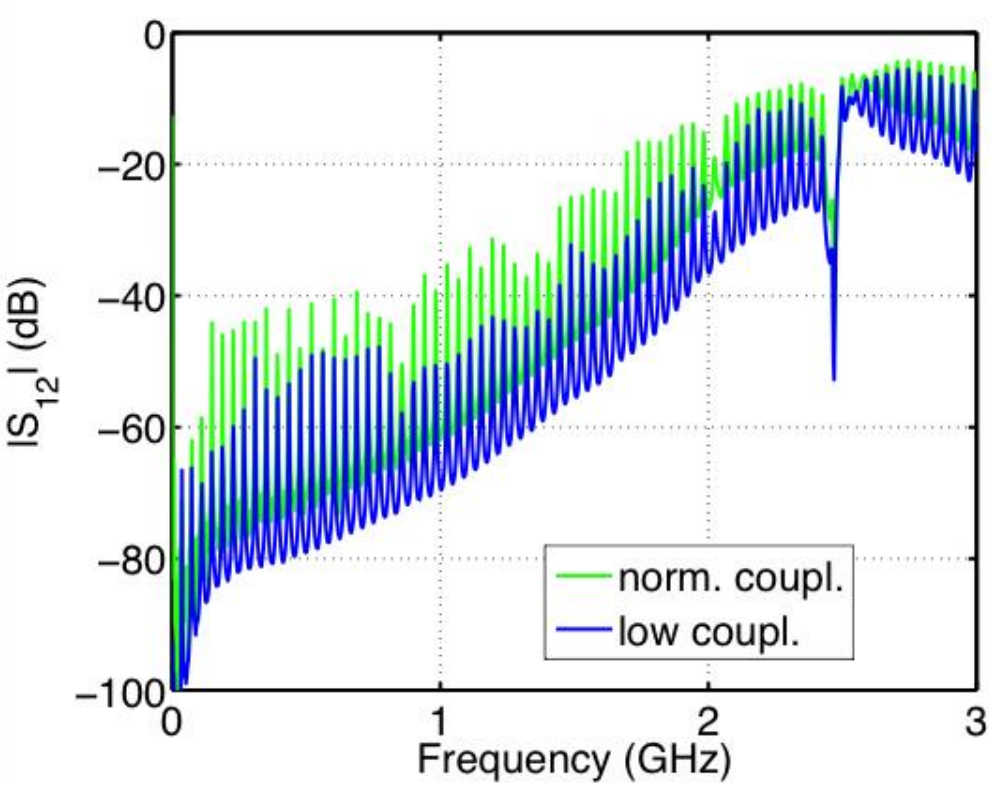


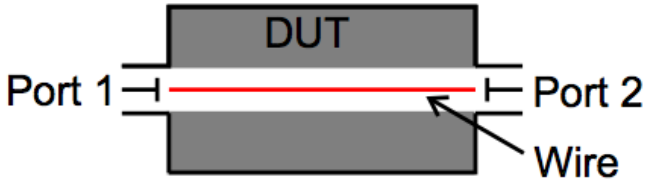


Matching in impedance measurement is critical.

N. Biancacci et al., TCTP collimator meas., 2014

COAXIAL RESONATOR METHODS





Frequency resolution is limited due to the length of the DUT.

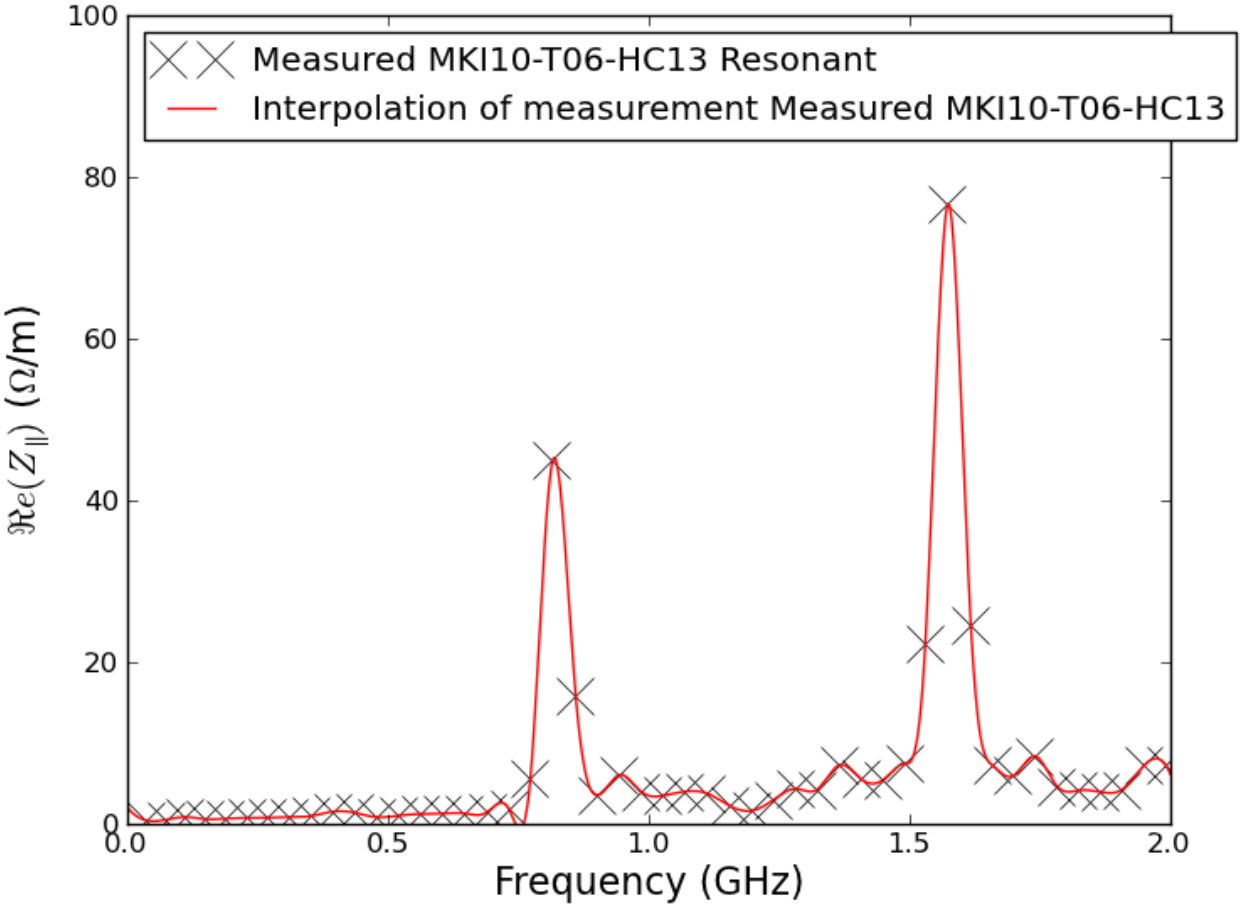
High-Q, narrowband resonances may be lost.

The Q of a lossy line resonator is independent from the length of the resonator.

The losses (i.e. the Q) include both that from the beam coupling impedance as well as that due to the finite resistance of the wire. Wire contribution must be removed.

See H. Day talk on LHC kickers, Monday 9.00

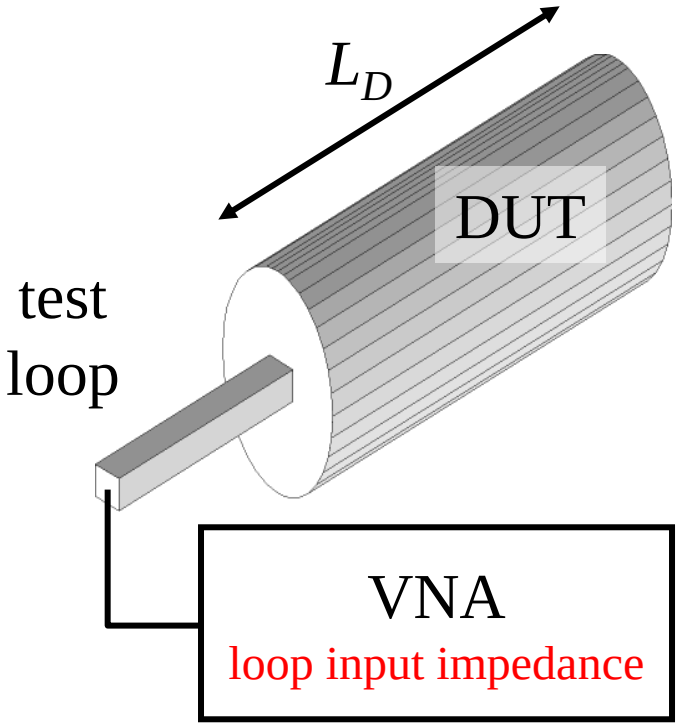
LHC INJECTION KICKERS



Extremely low impedance can be measured

See H. Day talk on LHC kickers, Monday 9.00

LOW FREQUENCY TRANSVERSE IMPEDANCE

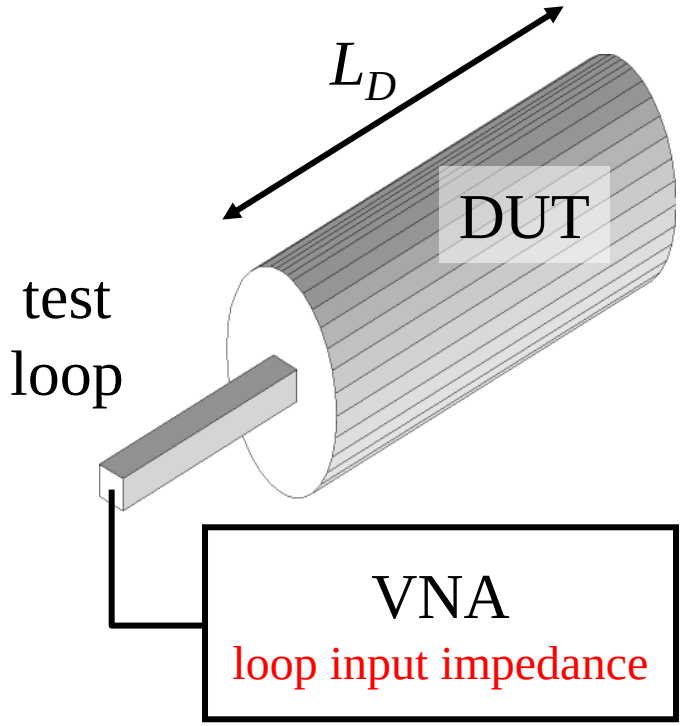


$$Z_T = \frac{c}{\omega}\frac{Z^{DUT} - Z^{perf.\ cond.}}{N^2\Delta^2}$$

Δ loop width ***N*** **# turns**

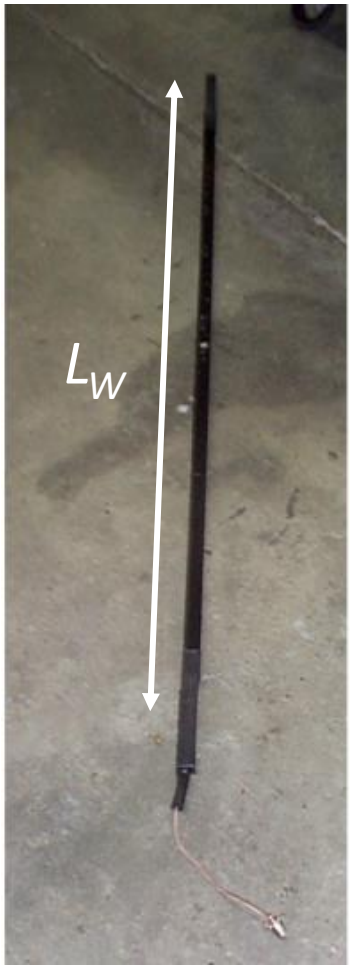
G. Nassibian, F. Sacherer, 1979

LOOP MEAUREMENT IN CIRCULAR BEAM PIPE



A "calibration" case: circular steel beam pipe

radius = 50 mm
σ = 1.3 10^6 S/m (SS)
wall thick. = 1.5 mm
L_D = 2 m

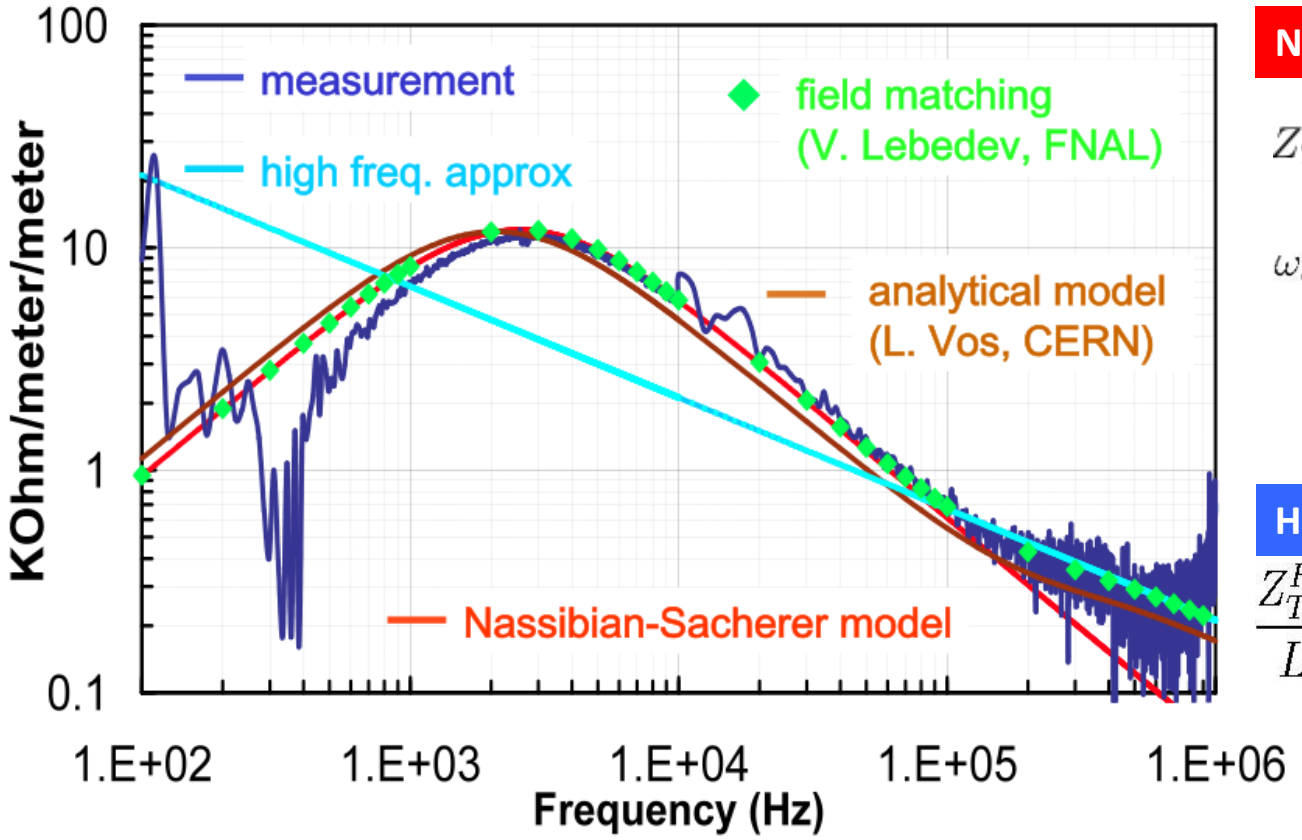


$$Z_T = \frac{c}{\omega}\frac{Z^{DUT} - Z^{perf.\ cond.}}{N^2\Delta^2}$$

L_W = 1.25 m
D = 22.5 mm
N **= 10**

Δ loop width ***N*** **# turns**

CIRCULAR RESISTIVE BEAM PIPE: REAL PART



NS model

$$Z_T = \frac{c}{4\omega b^2}\frac{R_W - j\omega L_W}{1+(\omega_c/\omega)^2}$$

$$\omega_c = \frac{R_W}{L_W} \qquad L_W = \frac{2\mu_0\mu_r}{\pi}L$$

$$R_W = 8\,\frac{L}{2\pi\, b\, d\, \sigma}$$

High frequency approx

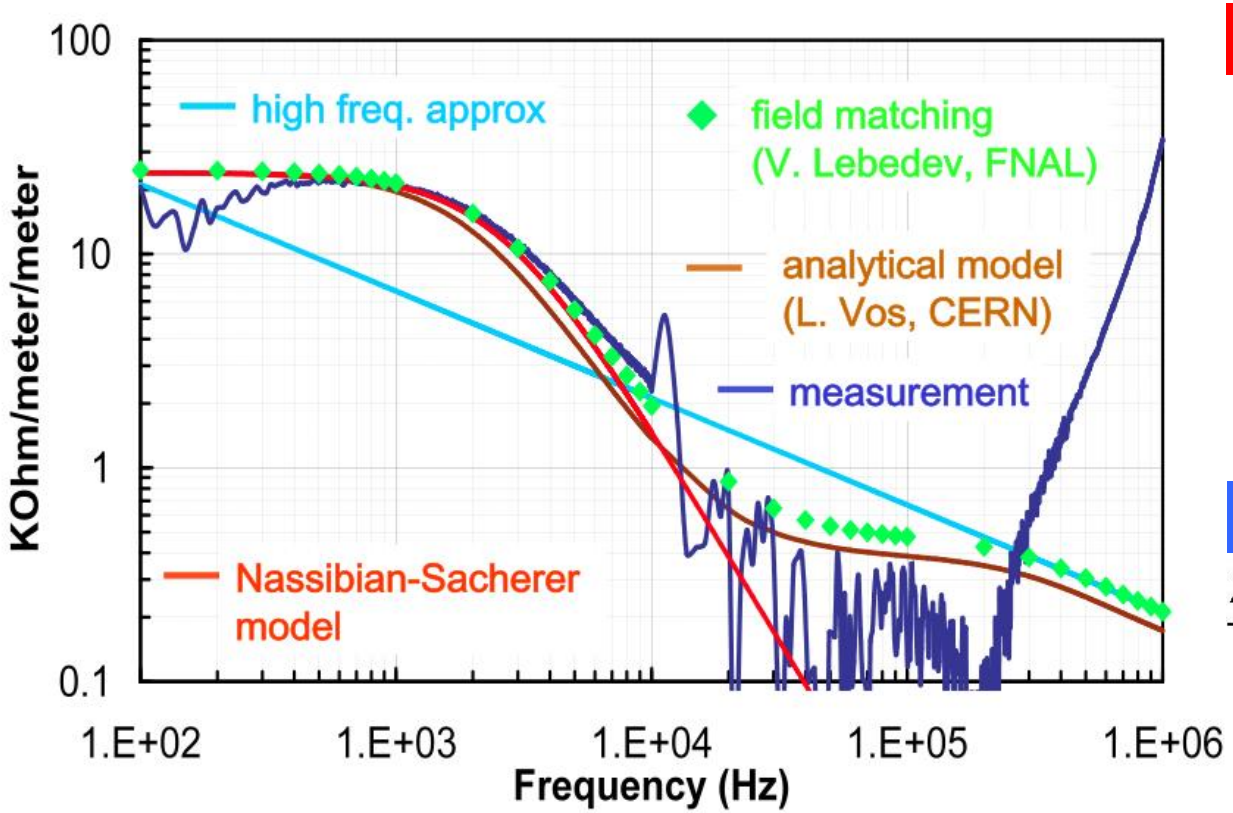
$$\frac{Z_T^{Re}}{L} = \frac{c}{\pi\, b^3\, \sigma\, \omega\, d} \qquad \delta \gg d$$

The reference measurement is done in a "perfectly" conducting pipe.

Real impedance vanishes at DC (no variation of the long. imp. with position).

A. Mostacci et al., CARE workshop, 2004

CIRCULAR RES. BEAM PIPE: IMAGINARY PART



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High frequency approx

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The reference measurement is done in a "perfectly" conducting pipe.

Loop self resonance limits the frequency range of this kind of measurements.

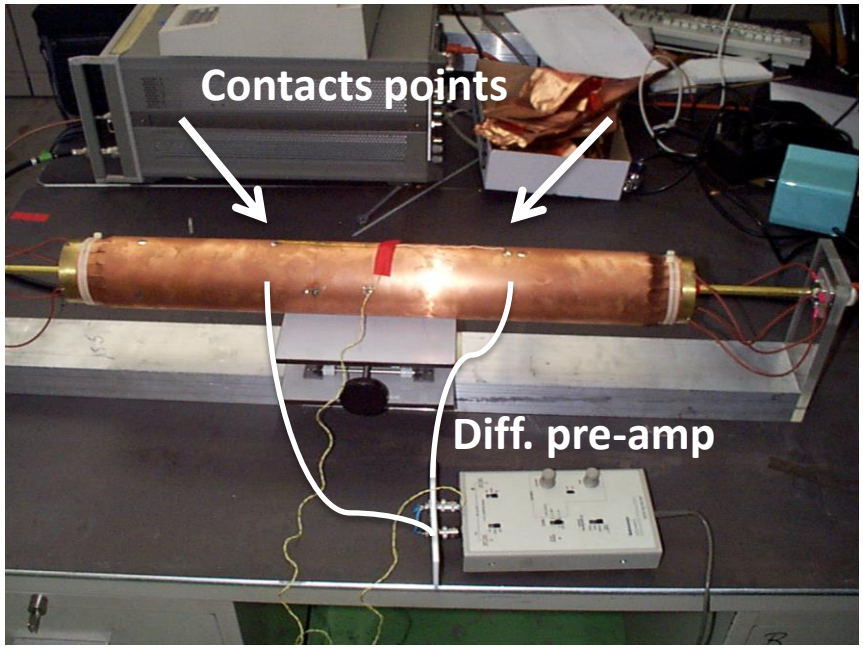
A. Mostacci et al., CARE workshop, 2004

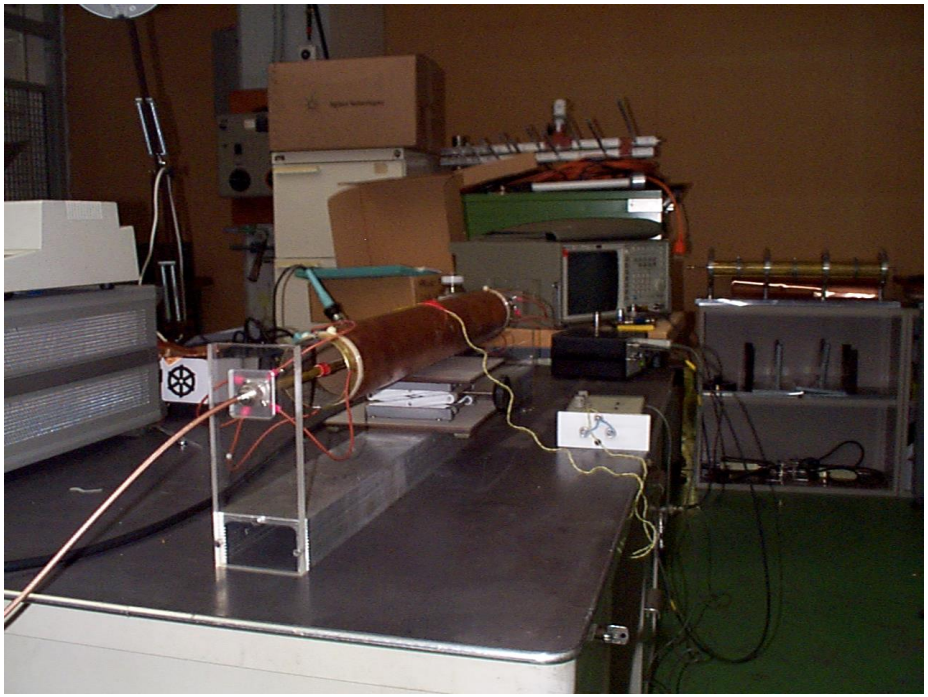
IMAGE CURRENTS AT LOW FREQUENCY

The decline of transverse real impedance at low frequency is referred to redistribution effect or inductive bypass effect.

Transverse impedance is essentially the dependency of the longitudinal impedance versus transverse displacement.

In coaxial line the return current density on the outer conductor at DC is independent on the position of the inner conductor and constant.





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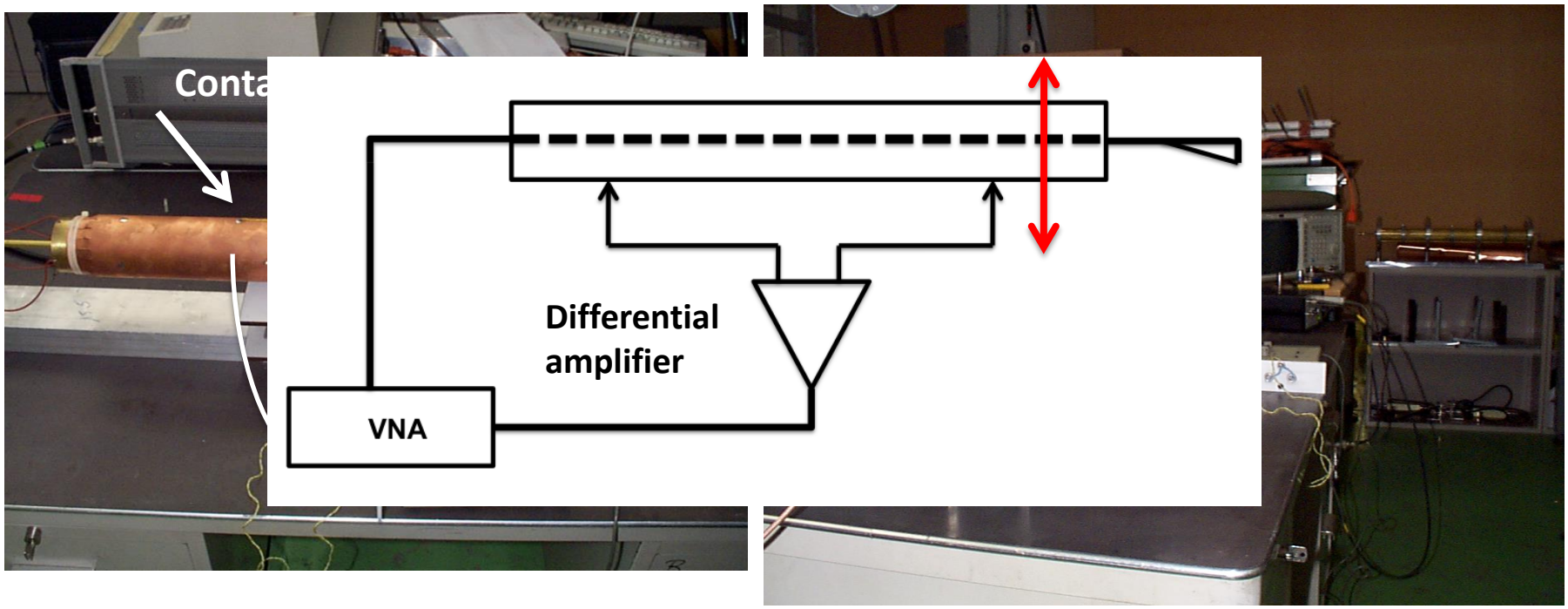
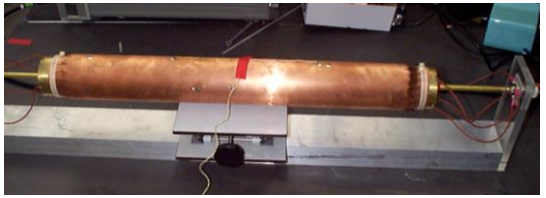


IMAGE CURRENTS AT LOW FREQUENCY

Skin depth = thickness at about 500kHz



Redistribution effect test structure
(84 mm diameter, copper 0.1 mm thick)

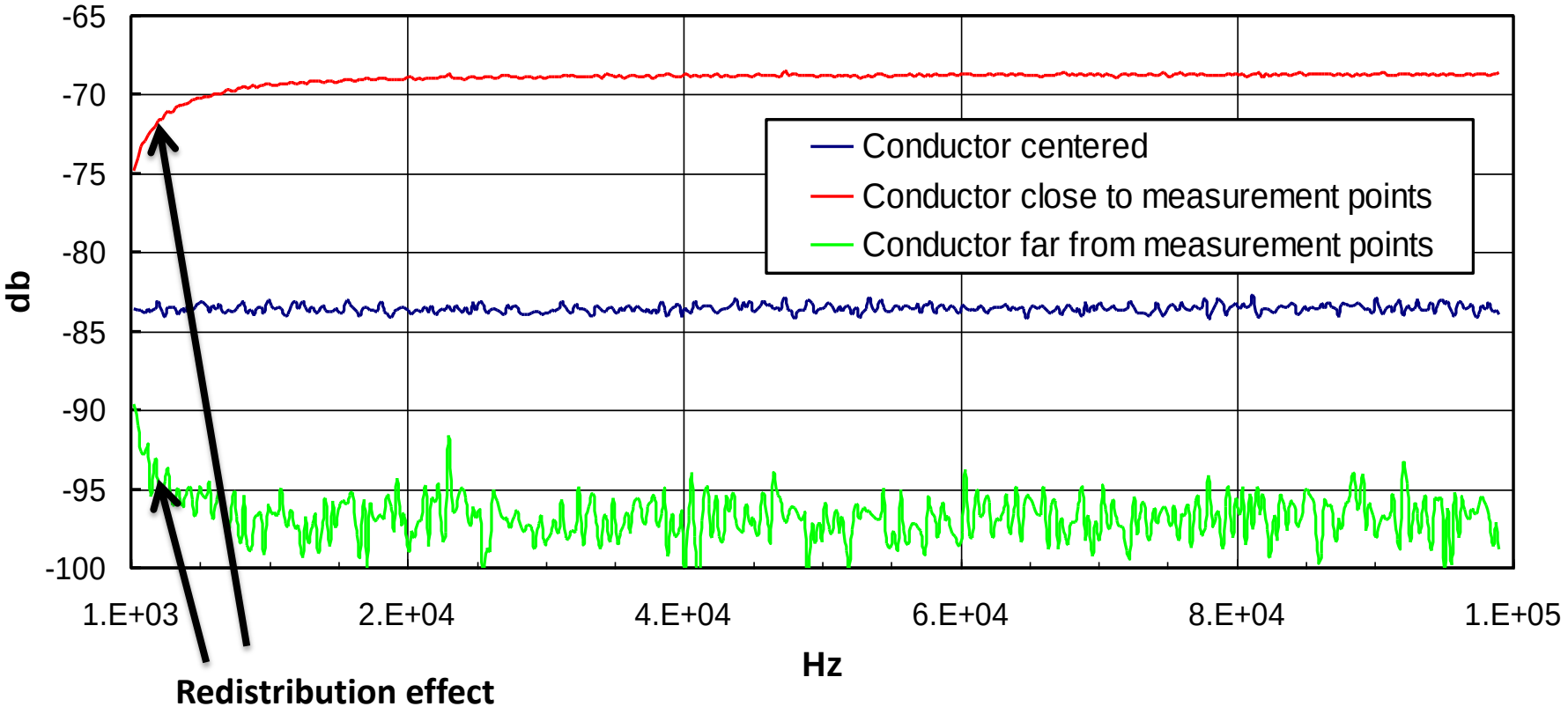
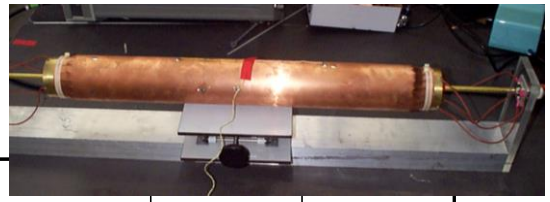


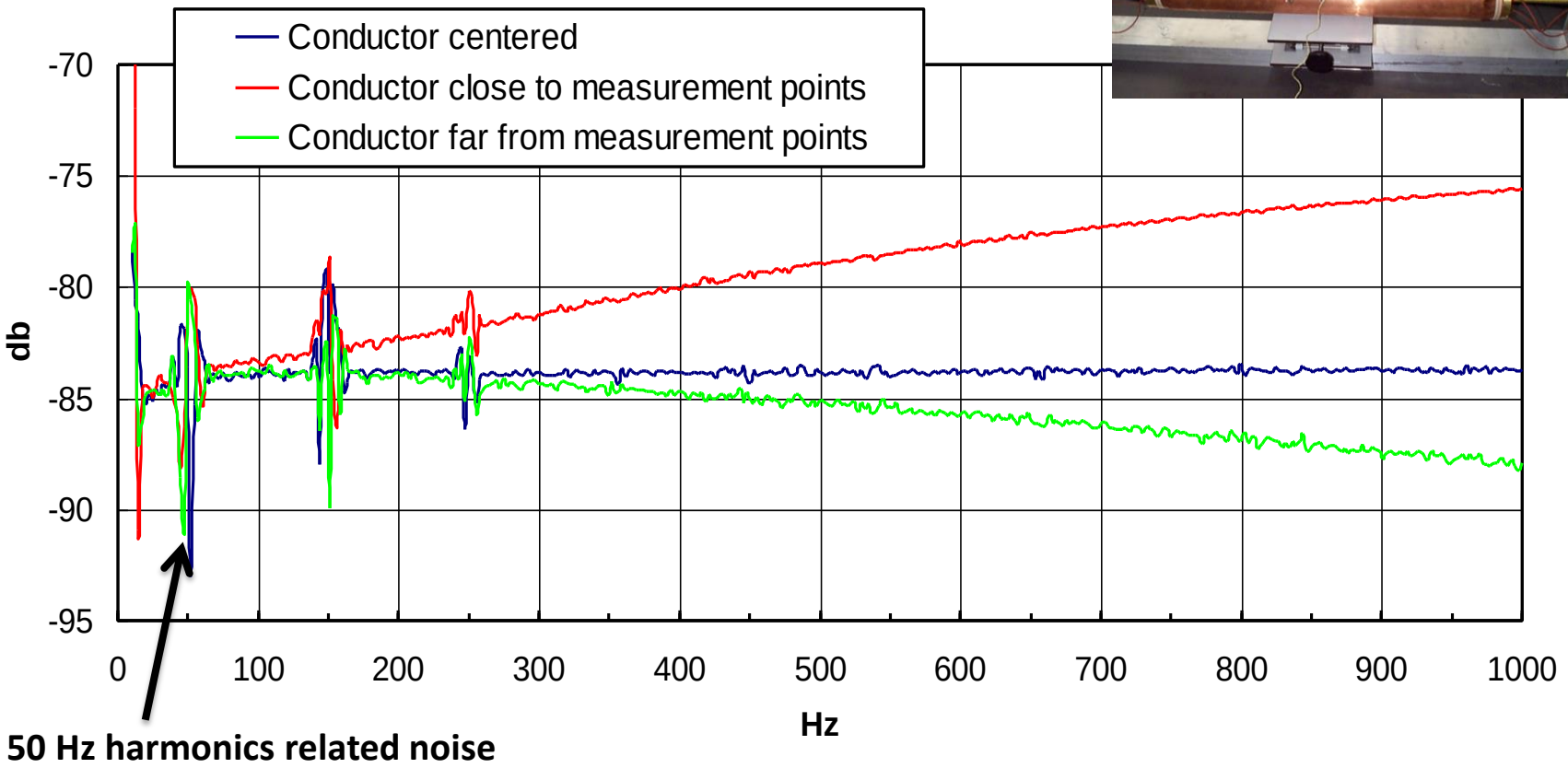
IMAGE CURRENTS AT LOW FREQUENCY

Skin depth = thickness at about 500kHz

The current density is decoupled from the radial electric field inside, unlike TEM case.

Redistribution effect test structure
(84 mm diameter, copper 0.1 mm thick)





50 Hz harmonics related noise

BEAM TRANSFER IMPEDANCE

BPM BUTTONS FOR THE PEP-II B-FACTORY

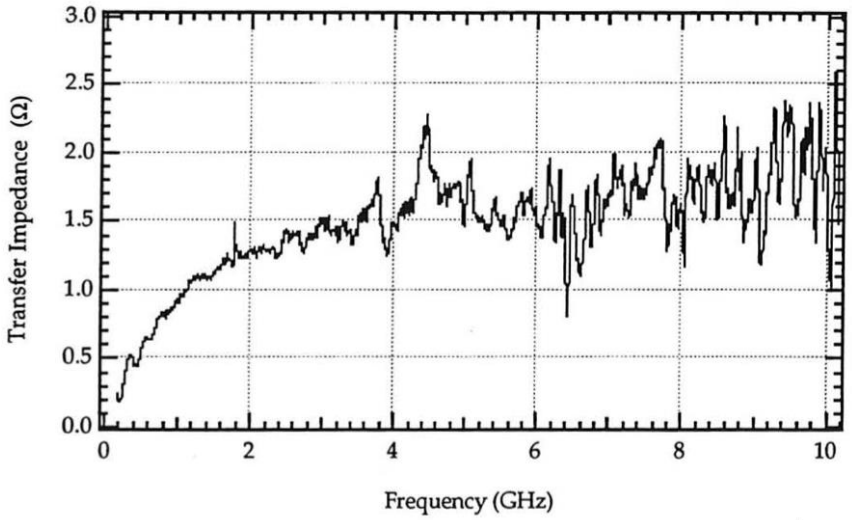
The transfer impedance measurement uses the coaxial wire and takes the output signal from the button in a S21 measurement.

Transmission from the vacuum chamber coaxial line to the button output.

$$|Z_{transfer}| = \sqrt{Z_c Z_{\text{button}}} \left| \frac{S_{21}^{\text{pickup}}}{S_{21}^{\text{through}}} \right|$$

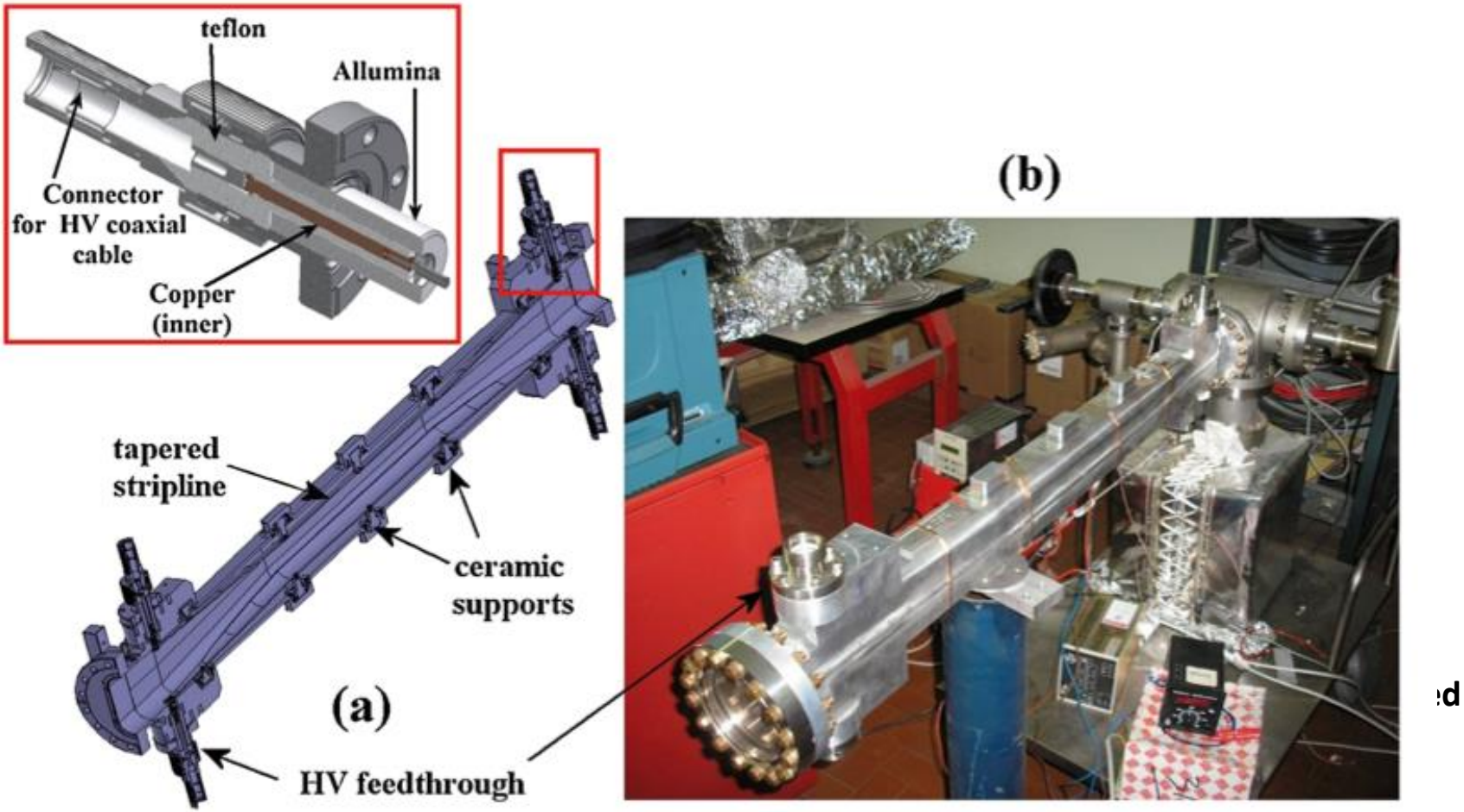
Coax line characteristic impedance

Transmission through the vacuum chamber line (coaxial).



J.N. Corlett., LBL-Note 37782, 1995

TRANSFER IMPEDANCE FOR DAΦNE KICKERS



D. Alesini et al., PRSTAB 111002, 2010

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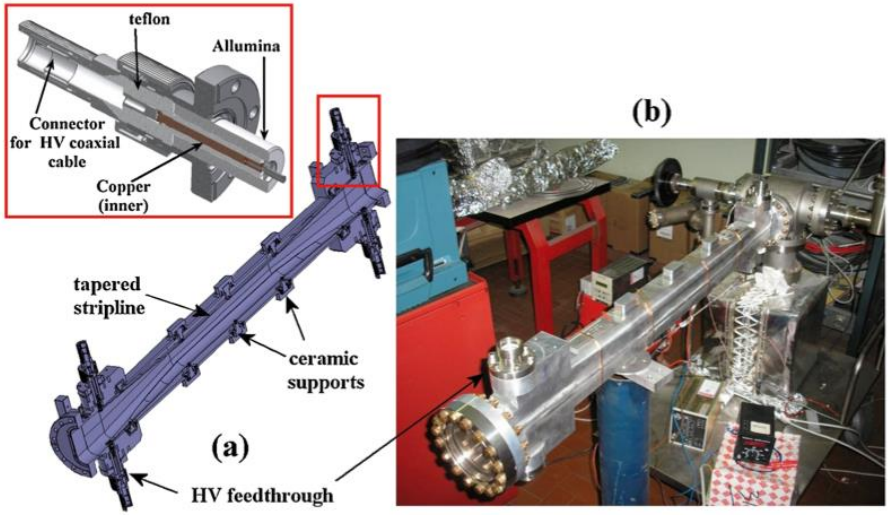

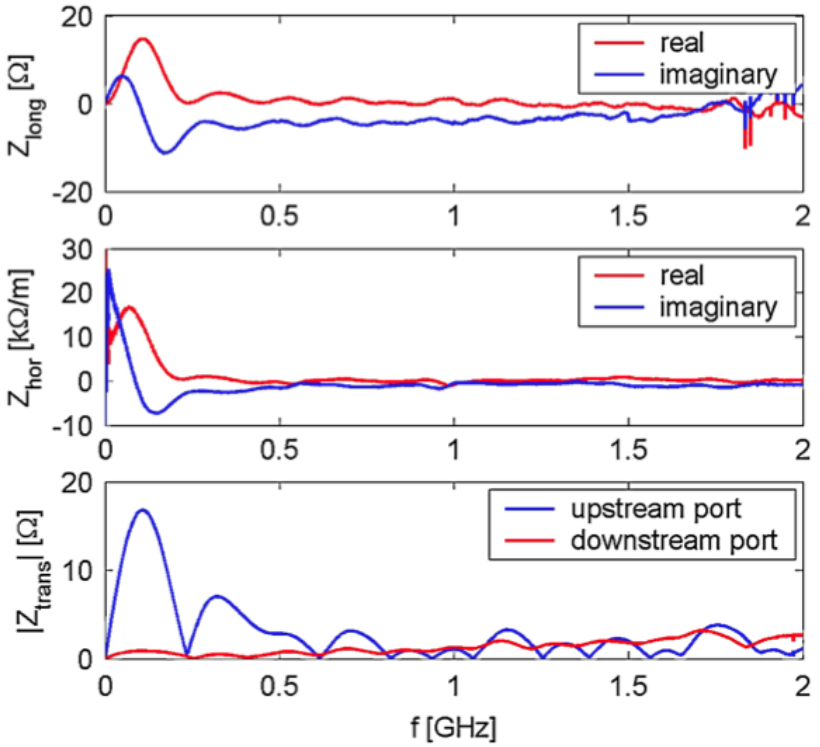

The transfer impedance allows the evaluation of the peak voltage and the average power induced by the beam into the kicker ports for a given beam current. The maxi- mum induced peak voltage on the upstream (output) ports is <100 V with a 6 nC bunch charge, while the average power induced on the ports is <10W with a 2 A beam.

Strong reduction of all impedances, with respect to not tapered strip-line kickers.

D. Alesini et al., PRSTAB 111002, 2010

SHUNT IMPEDANCE PERTURBATION MEAS.

Wire perturbs longitudinal cavity modes, e.g. lowering the Q and detuning the frequency: coaxial wire set-ups are not recommended for cavity measurements (only special cases, mainly transverse).

All the resonant frequencies are depleted because of power drained in the pipes by the TEM mode (Masullo et al, LINAC10, 2010)

Bead Pull measurement

The field in a cavity can be "sampled" by introducing a perturbing object and measuring the change in resonant frequency.

The object must be so small that the field do not vary significantly over its largest linear dimension: it is a perturbation method.

Shaped beads are used to enhance perturbation and give directional selectivity

Bead pull methods are not suitable to characterize heavily dumped mode, e.g. with low Q and/or with resonance shift not clearly measurable.
(Alesini et al, PRST 092001, 2004)

CONCLUSIONS

The coaxial wire method has been in use for more than 4 decades for impedance and loss factor determination on the bench.

Due to improvements in instrumentation (synthetic pulse, gating and calibration) and also better understanding of the theoretical limitations the results are reasonable and reliable these days provided that certain DOs, DONTs and CAVEATs are respected.

Practical solutions have been discussed.

In general the measurement should use the forward transmission coefficient S21 with subsequent evaluation of the impedance via lumped element or (improved) log formula. Although S11 measurements can give higher signals in certain cases their use is in general NOT recommended (Hahn Pedersen paper, 1978).

Transverse impedance measurements can be carried with a pair of wires (or a single wire over a metallic image plane) and the laterally displaced single wire.

Matching networks can be implemented with single, low inductance, small size, carbon resistor in "SUCO box" and a wideband coax attenuator on the 50Ohm side. In combination with adsorbing foam it can be used above cut-off.

Time domain reflectometry can be used to determine the characteristic impedance of the wire and subsequently select the adequate matching resistor.

CONCLUSIONS

For high sensitivity requirements resonant wire methods can be applied.

Wire measurements on cavities are in general not recommended (strong mode perturbation) unless for transverse modes.

The numerical simulation of the coaxial wire is rather easily possible now. Comparison with a real wire measurement is a very powerful tool to check the validity of the (usually simplified) DUT.

A priory the coaxial wire technique is only usable for simulation of (highly) relativistic beams. For slow beams special methods exist.

The method has also found wide range applications for PU and kicker performance evaluation and calibration measurements.

We acknowledge the collaboration and discussion with many colleagues at CERN and elsewhere over more than 30 years and enduring support.

THANK YOU FOR YOUR ATTENTION