RF beam diagnostics
1^{st} part

A. Mostacci

With the help of
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OUTLINE

RF beam diagnostics – 1st lecture

Introduction

Definitions (from metrology)

Field from a relativistic moving charge

Beam intensity diagnostics

Current transformers

Passive Cavity based devices

Beam transverse position diagnostics

Transmission line beam position monitor

Cavity beam position monitor

Longitudinal diagnostics

Only few selected examples

- It is impossible to cover all.
- to show general principles.
- to link to the hands on session (bench measurement).

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BASIC DEFINITIONS

Measurement accuracy

closeness of agreement between a **measured quantity value** and a **true quantity value** of a **measurand**

Calibration

Hopefully once!!!

Measurement uncertainty

non-negative parameter characterizing the dispersion of the **quantity values** being attributed to a **measurand**, based on the information used.

Precision

Hopefully always!!!

Resolution (of the measurement system)

smallest change in a **quantity** being measured that causes a perceptible change in the corresponding **indication**

It depends on noise

Sensitivity of a measuring system

quotient of the change in an **indication** of a **measuring system** and the corresponding change in a **value** of a **quantity** being measured.

International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)

OIML

Organisation Internationale de Métrologie Légale

International Organization of Legal Metrology

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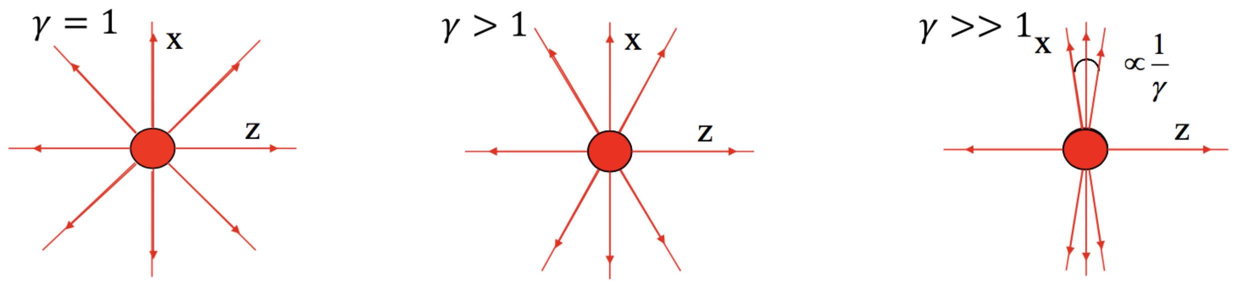
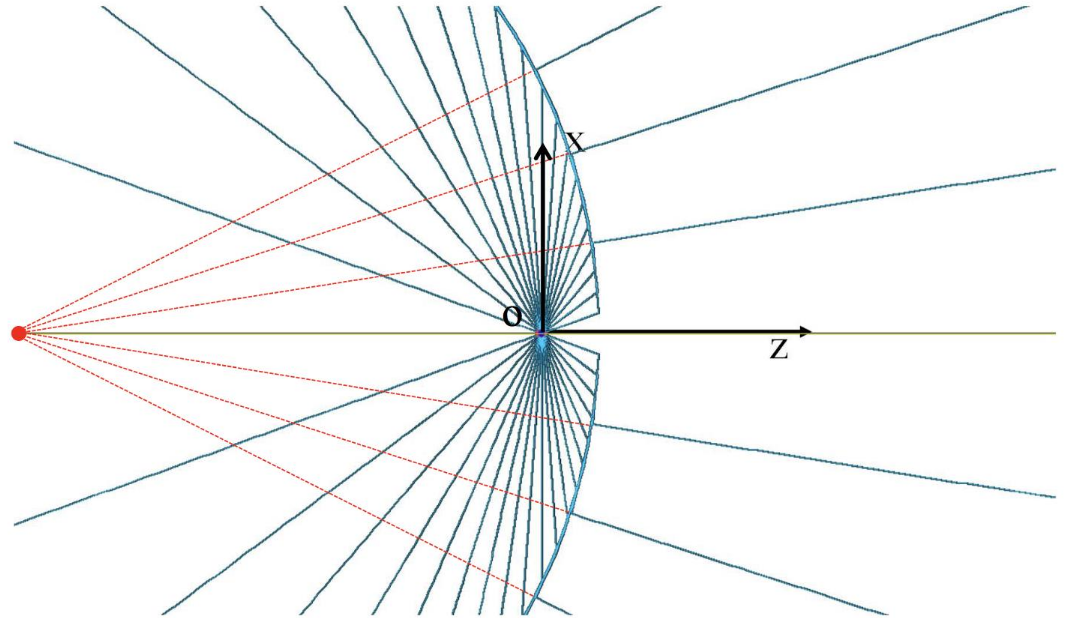
FIELD OF A MOVING CHARGE





Courtesy of M. Migliorati

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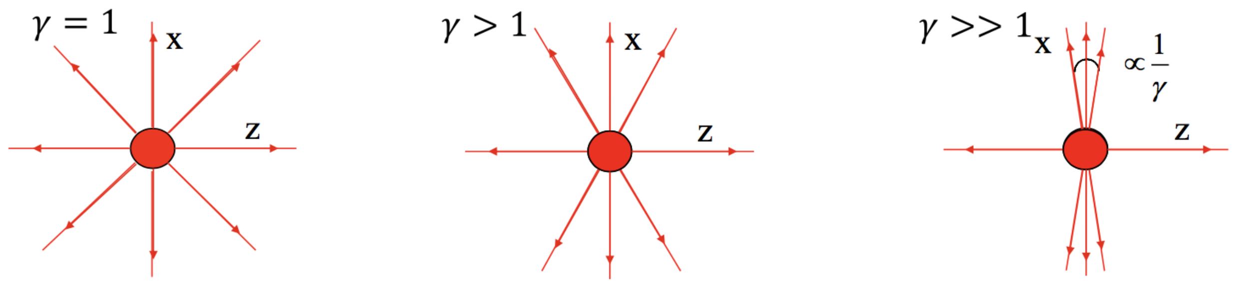
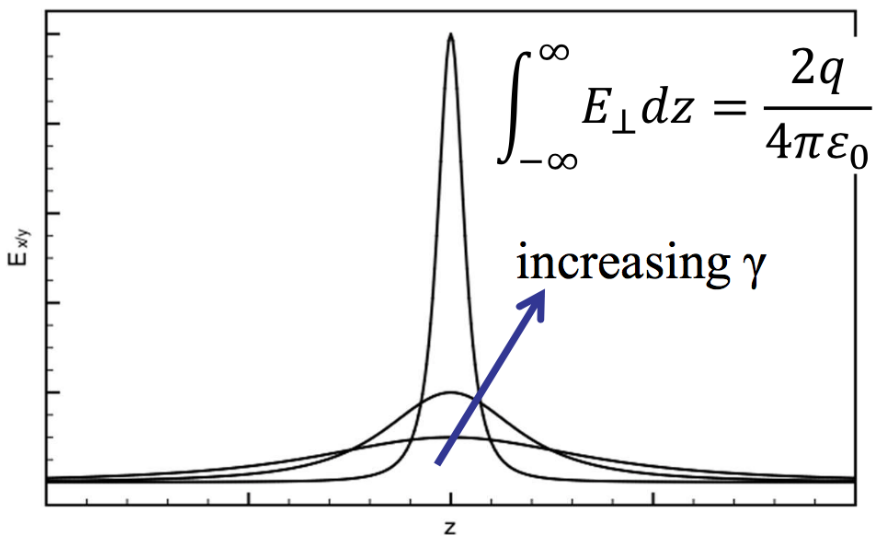
FIELD OF A MOVING CHARGE





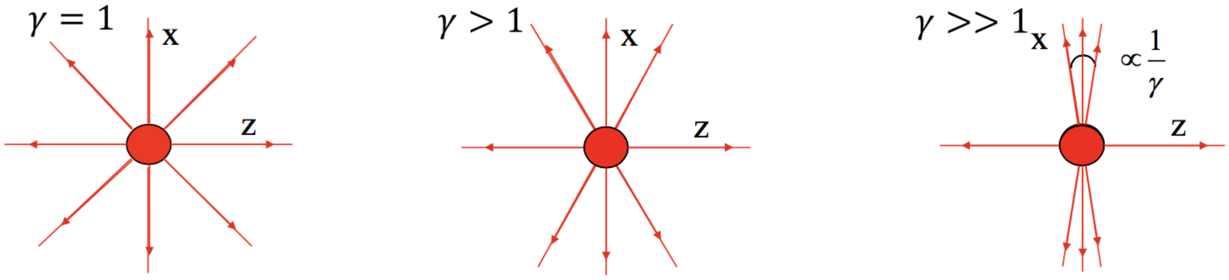
$$\int_{-\infty}^{\infty} E_\perp dz = \frac{2q}{4\pi\varepsilon_0}\frac{1}{r} \quad \text{independent on } \gamma \quad (3)$$

$$\Rightarrow \quad E_\perp = \frac{2q}{4\pi\varepsilon_0}\frac{1}{r}\delta(z - ct)$$

$$\vec{B}_\perp = \frac{\vec{v} \times \vec{E}}{c^2}$$

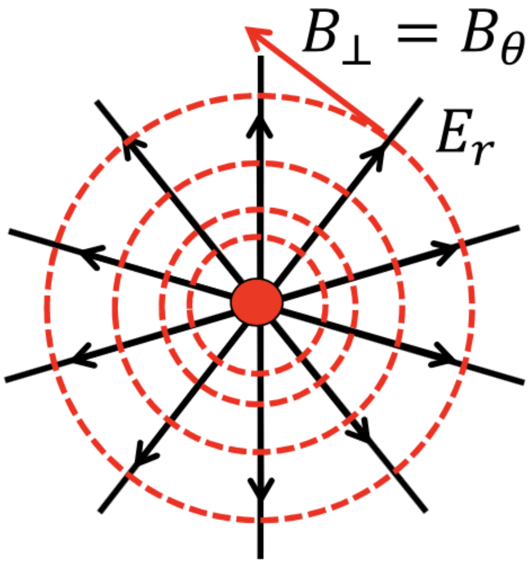
Courtesy of M. Migliorati

FIELD OF A MOVING CHARGE



$$E_\perp = \frac{2q}{4\pi\varepsilon_0}\frac{1}{r}\delta(z - ct)$$

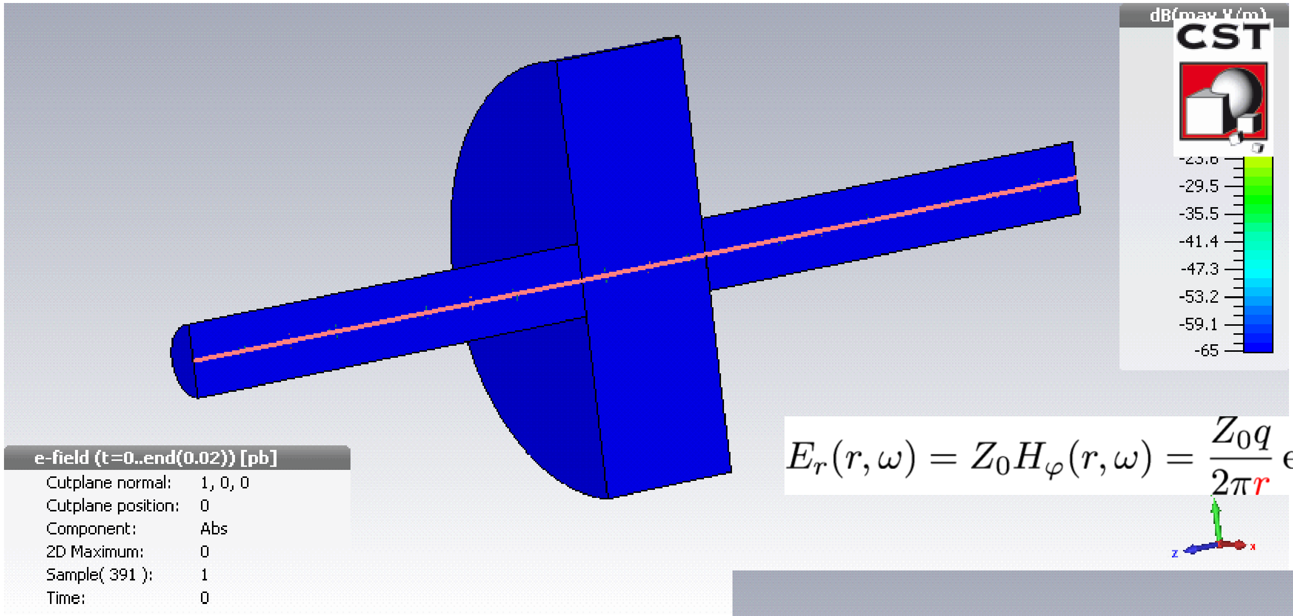
$$B_\perp = B_\theta = \frac{vE_r}{c^2} = \frac{\beta E_r}{c}$$



Only Transverse Electric Magnetic (TEM) field components

Courtesy of M. Migliorati

PRIMER OF BENCH MEASUREMENTS



Electron beam travelling on axis

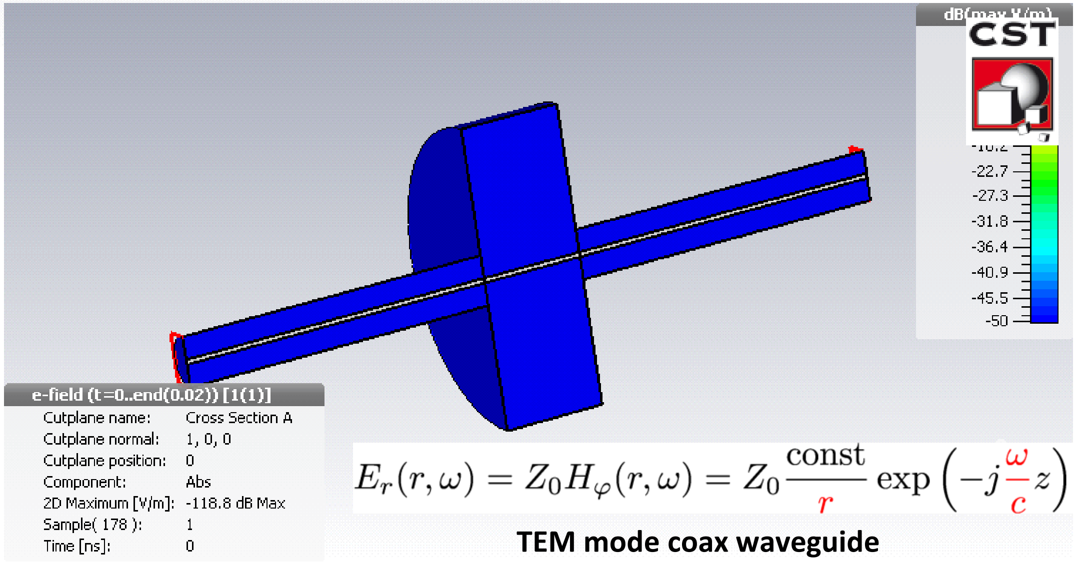
Cavity mode excitation

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

Ultra-relativistic beam field

Electric pulse traveling on the wire

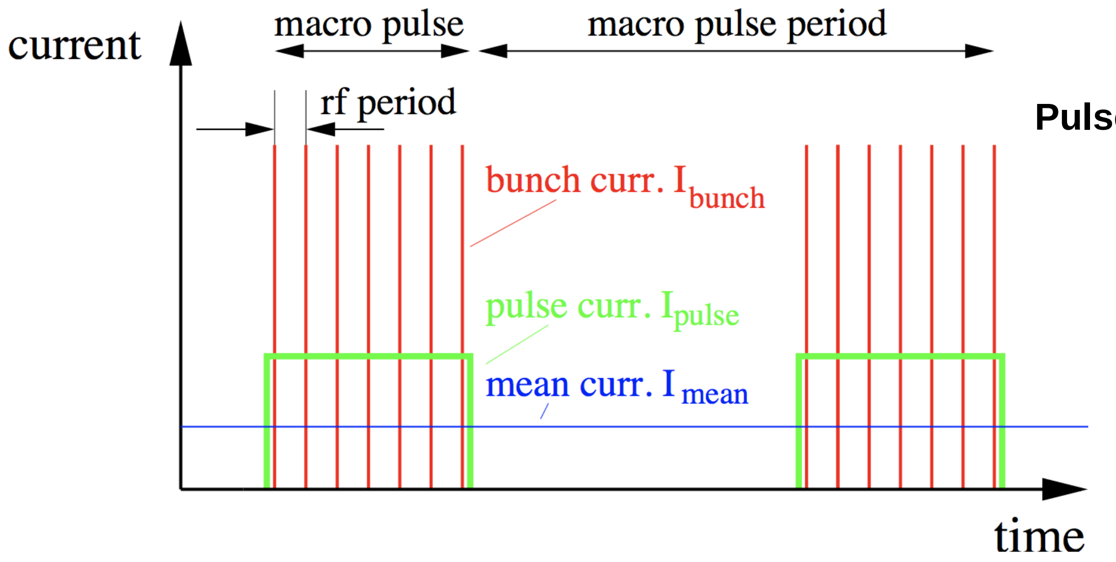
Cavity mode excitation and power reflection



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

TEM mode coax waveguide

BEAM INTENSITY: Charge and/or current



Pulsed LINAC

I_{mean} **long time average (Ampere)**

I_{pulse} **average on the beam delivery (Ampere)**

I_{bunch} **Current with the bunch (charge or number of particles)**

Courtesy of P. Forck

BEAM INTENSITY MEASUREMENTS

BEAM INTENSITY: Charge and/or current

Linac

Transformer (dc, pulsed)

Faraday Cup

Particle Detector (e.g. scintillators)

Normalised pick-up signal

Ring

Transformer (dc, pulsed)

Normalised pick-up signal

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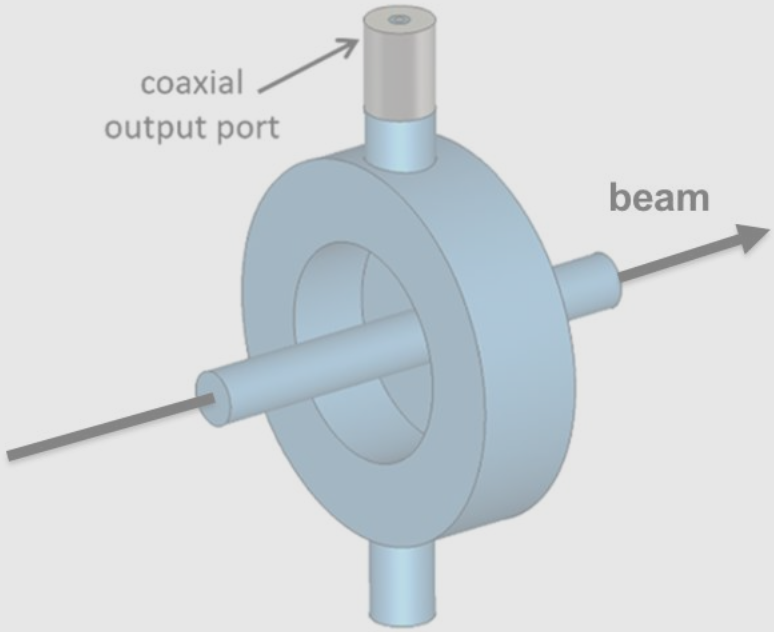
BEAM INTENSITY

Current Transformers

Widespread, commercial devices

Passive cavity



Research group design

Pulsed beam

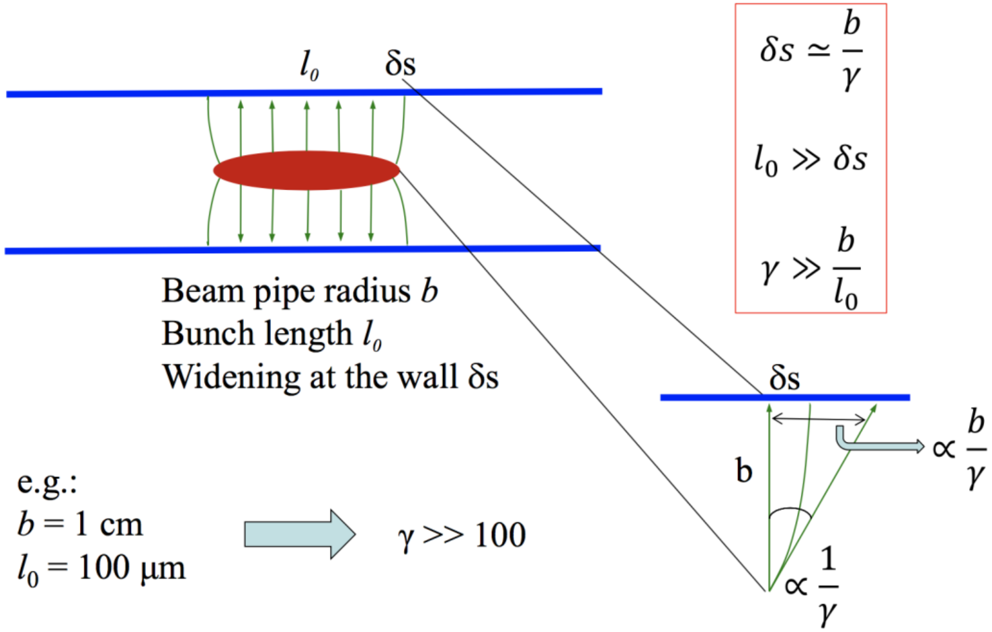
B FIELD PROPERTIES

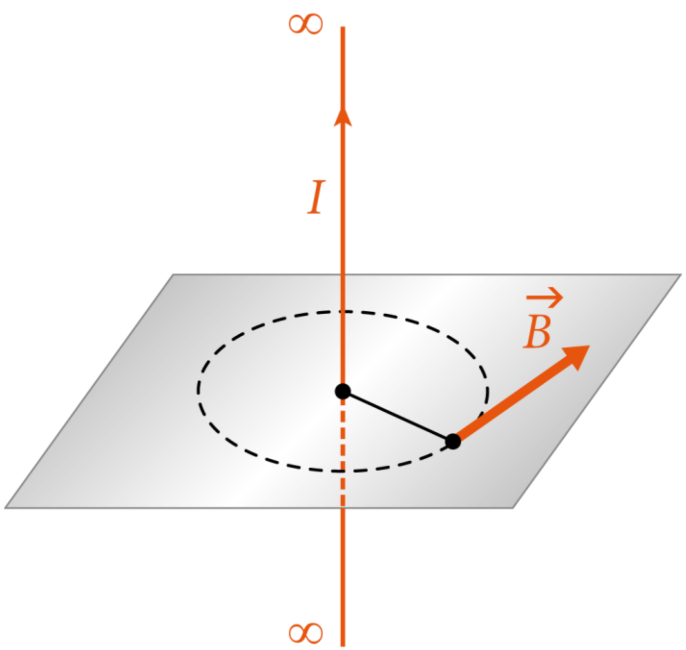
Current transformers detects of beam magnetic field.

No dependence on beam energy.

$$\sigma_z \gg \frac{b}{\gamma}$$

Bunched beam has the same B field of an infinite current





$$\vec{B} = \mu_0 \frac{I_{beam}}{2\pi r} \hat{\varphi}$$

Courtesy of M. Migliorati

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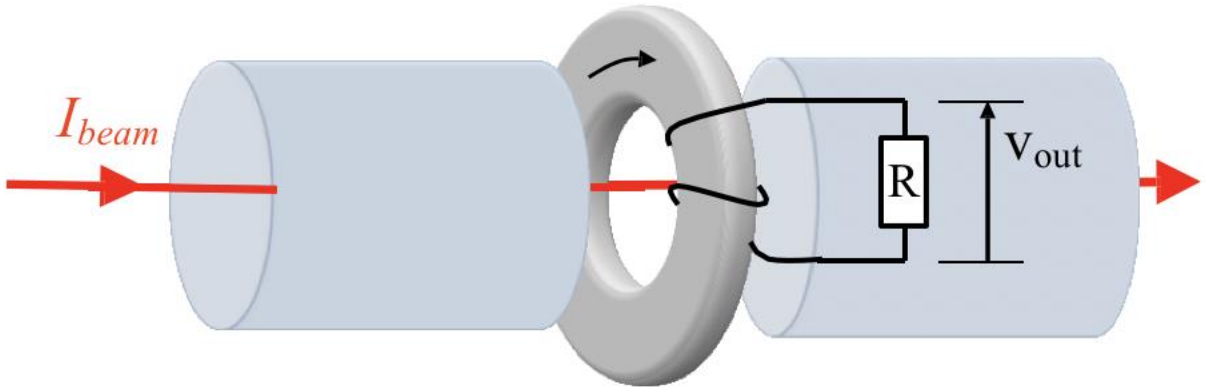
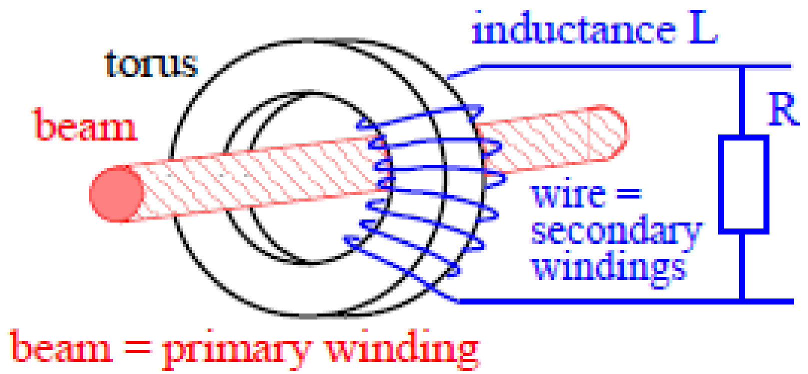
CURRENT TRANSFORMER – PULSED BEAM

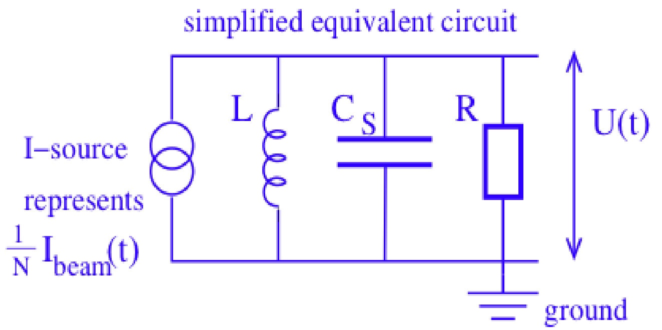
Non destructive measurement

Courtesy of P. Forck

Typical detection threshold in uA range due to noise limitation.







$$L = \frac{\mu_0 \mu_r}{2\pi} \cdot l N^2 \cdot \ln \frac{r_o}{r_i}.$$

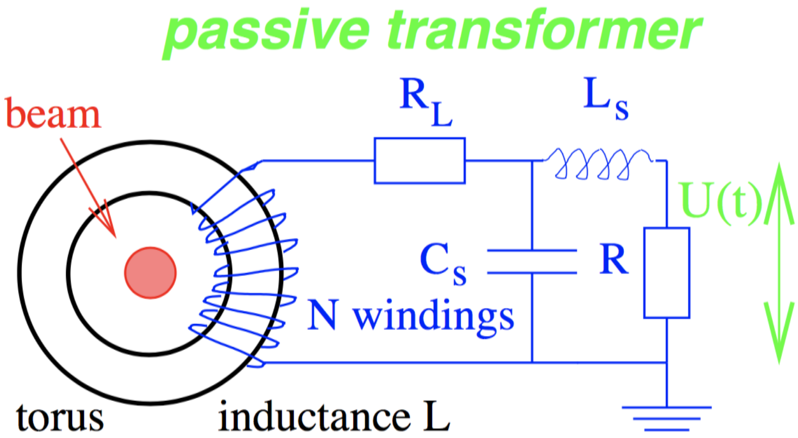
$$U = R \cdot I_{sec} = \frac{R}{N} \cdot I_{beam}$$

Sensitivity

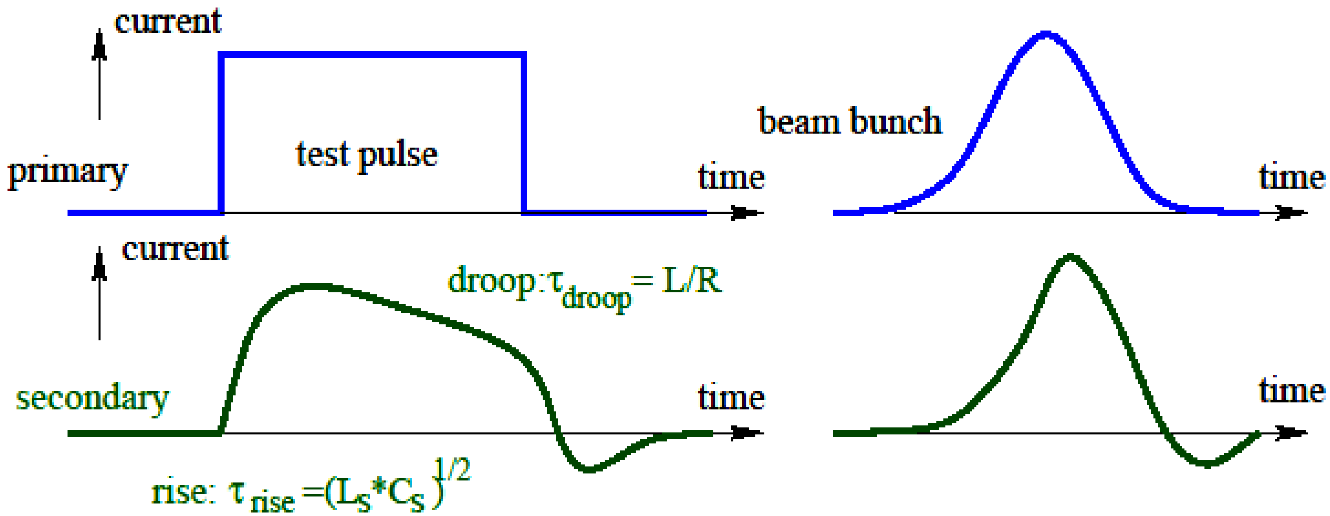
$$U = S \cdot I_{beam}$$

FAST CURRENT TRANSFORMER - FCT

Courtesy of P. Forck



$$U(t) = \frac{R}{N} \cdot e^{-t/\tau_{droop}} \cdot I_{beam}$$



FAST CURRENT TRANSFORMER PARAMETERS

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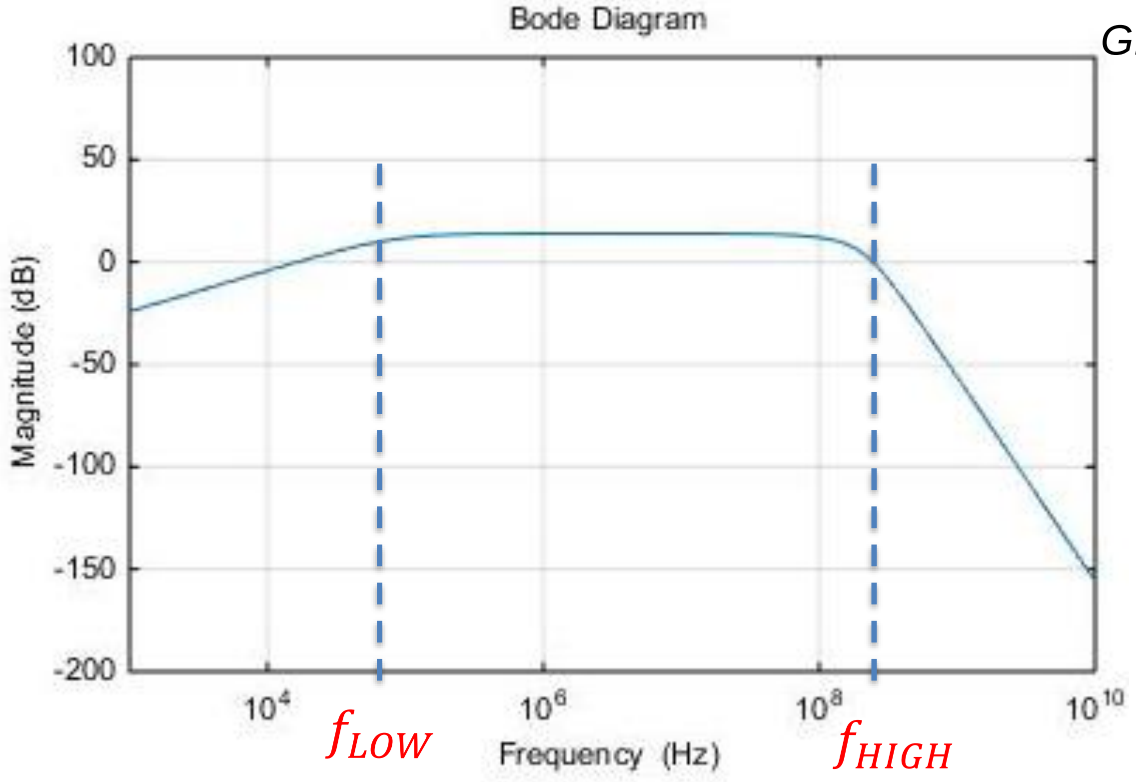

f_{LOW} ↓ τ_{droop} ↑ $droop$ ↓

f_{HIGH} ↑ τ_{rise} ↓ faster response

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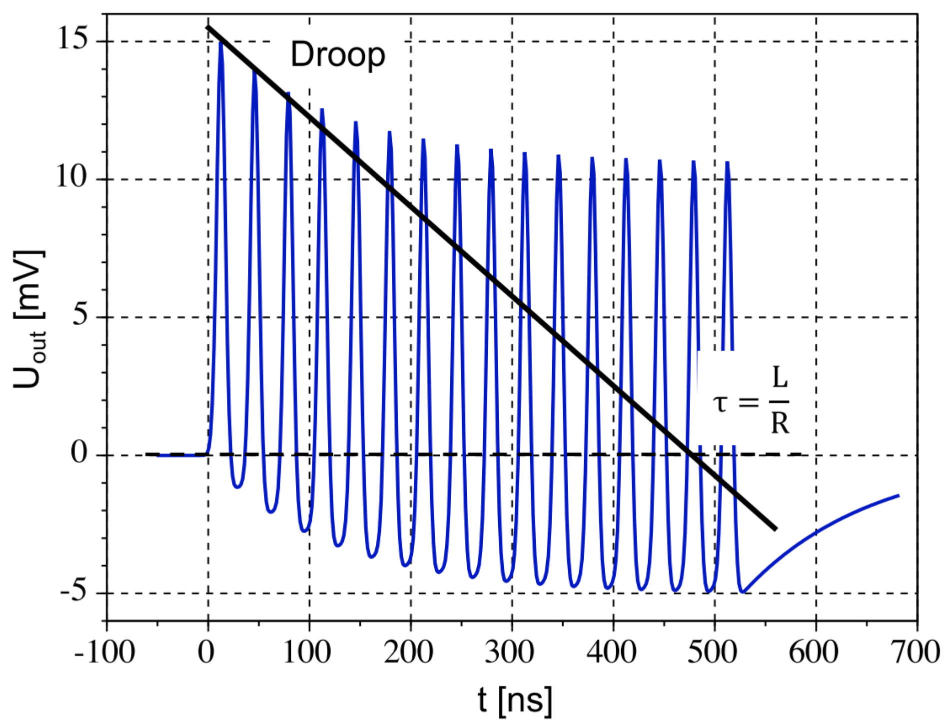
FAST CURRENT TRANSFORMER PARAMETERS

G. Franzini - INFN



f_{LOW} ↓ τ_{droop} ↑ $droop$ ↓

f_{HIGH} ↑ τ_{rise} ↓ faster response

FCT FROM INDUSTRIAL SUPPLIER

In-flange FCT

In-air FCT

From Instrument manual

FCT main advantages

- The FCT displays the beam current with a minimum of distortion up to very high frequency. It is therefore, primarily, an instrument to be used with an oscilloscope.
- Very low ringing when it is properly installed (See: "Installation on the vacuum chamber" in this manual).

FCT limitations

- The FCT, like all transformers, differentiates the signal. When the observed pulses are longer than a few microseconds, the output droop of the FCT becomes excessive.
- The FCT has eddy current loss up to a few percent. Eddy current losses are frequency dependent, increase towards the higher frequencies. Yet, the FCT is still the best instrument to visualize a short, fast pulse on an oscilloscope when non-contact measurement is a necessity: particle beams, high voltage, etc.

Wideband models (standard)

Sensitivity (nominal)	0.25	0.5	1.25	2.5	5.0	V/A
Turns ratio (old reference)	100:1	50:1	20:1	10:1	5:1	
Rise time (typ.)*	0.60	0.30	0.23	0.30	0.39	ns
Droop	< 1	< 3	< 6	< 10	< 32	%/µs
Upper cutoff frequency -3dB typ. *	0.58	1.17	1.50	1.17	0.90	GHz
Lower cutoff frequency -3dB typ. *	< 1.6	< 5	< 9.5	< 16	< 50	kHz
L/R time constant (min.)	100	35	17	10	5	µs
Max. charge/pulse	8100	2000	324	81	20	µC
Max. rms current (f > 10 kHz)	2.7	2.7	2.7	2.7	2.7	A
Max. peak current (pulse = 1 ns)	2	0.4	0.2	0.1	0.1	kA
For 10 V/A sensitivity specifications, please ask						

* Depends on FCT sensor dimensions and selected options

Low droop (-LD) models on option

Sensitivity (nominal)	0.25	0.5	1.25	2.5	5.0	V/A
Turns ratio (old reference)	100:1	50:1	20:1	10:1	5:1	
Rise time (typ.)*	1.00	0.54	0.40	0.50	0.78	ns
Droop	< 0.05	< 0.2	< 1	< 3	< 8	%/µs
Upper cutoff frequency -3dB typ. *	350	650	850	700	450	MHz
Lower cutoff frequency -3dB typ. *	< 0.08	< 0.32	< 1.6	< 5	< 13	kHz
L/R time constant (min.)	2000	500	100	35	12	µs
Max. charge/pulse	8100	2000	324	81	20	µC
Max. rms current (f > 10 kHz)	2.7	2.7	2.7	2.7	2.7	A
Max. peak current (pulse = 1 ns)	2	0.4	0.2	0.1	0.1	kA
For 10 V/A sensitivity specifications, please ask						

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FCT SPECIFICATIONS

Turns ratio / Model	20:1	5:1	20:1 –low droop	5:1 –low droop
Sensitivity (V/A)	1.25	5.0	1.25	5.0
Rise time (ns)	0.23	0.39	0.4	0.78
Droop (%/μs)	< 6	< 32	<1	< 8
Upper cutoff frequency (GHz)	1.50	0.9	0.85	0.45
Lower cutoff frequency (kHz)	< 9.5	< 50	< 1.6	< 13
L/R time constant (min.) (μs)	17	5	100	12
Max. charge/pulse (μC)	324	20	324	20
Max. rms current (A)	2.7	2.7	2.7	2.7
Max. peak current (pulse = 1 ns) (kA)	0.2	0.1	0.2	0.1

Based on the duration and shape of the bunch (i.e., its frequency content), the most suitable model can be chosen. For instance, a low risetime (i.e., high upper cut-off) may be desired to track fast variations (short bunches) at the expense of reduced sensitivity, etc.

Models with the low droop option decrease both the lower and upper cut-off frequencies. Consequently, they decrease droop but increase risetime. Therefore, they are used for longer duration bunches with slower variations.

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ACTIVE CURRENT TRANSFORMER

By using an operational amplifier in the output stage, it is possible to significantly reduce the lower cut-off compared to the FCT and, consequently, decrease the droop time.

The ACCT is therefore employed for long-duration impulses (µs-ms). Typically, an amplifier with limited bandwidth (e.g., 1 MHz) is used to reduce high-frequency noise resulting in a high risetime (e.g. 350 ns).

In-flange ACCT **In-air ACCT**

ACCT ADVANTAGES COMPARED TO OTHER CTs

The ACCT can measure low AC currents accurately. Other current transformers cannot do it for the following reasons:

- A passive CT capable of passing say 50-60 Hz with less than 1% error must have a -3dB lower cutoff frequency below a few Hertz. This imposes a large number of turns, typically 500 turns. Therefore, the sensitivity is in the order of 0.1 V/A in a high impedance load.
- If 10 mA current is measured with this transformer, the output is a mere 1mV, which cannot be measured on an oscilloscope or voltmeter. The situation is not much better at 100 mA current.
- Amplifying the signal from this CT does not help much, because the noise is amplified as well.

Therefore, the ACCT is much superior to other CTs for pulses longer than tens of µs: It measures accurately down to 10 mA full scale, even down to 1 mA. It delivers a strong voltage signal, with accuracy better than 1%.

Full scale range	Any value from ±1mA to ± 2A, factory preset range.
Lower cutoff (-3dB)	<3Hz
Droop	<2%/ms
Upper cutoff (-3dB)	1MHz
Risetime	350ns (10% - 90%)

Resolution

Ranges	1mA	10mA	100mA	1A
ACCT-E-RM	<1.5µArms	<1.5µArms	<5µArms	<40µArms
ACCT-E-RM-3R	<5µArms	<5µArms	<8µArms	<25µArms
With LN option				
ACCT-E-RM	<0.5µArms	<0.5µArms	N/A	
ACCT-E-RM-3R	<1.5µArms	<1.5µArms		

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ACCT-E-RM-3R	<5µArms	<5µArms	<8µArms	<25µArms
With LN option				
ACCT-E-RM	<0.5µArms	<0.5µArms	N/A	
ACCT-E-RM-3R	<1.5µArms	<1.5µArms		

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INTEGRATING CURRENT TRANSFORMER

The FCT is a pure and simple transformer that, within a certain bandwidth, allows measuring the current of the bunch while also reconstructing its temporal profile.

On the other hand, the ICT uses passive components (R, L, C) mounted on the device that completely deform the bunch profile, elongating it while guaranteeing that the integral of the output signal is proportional to the bunch charge.

It is used when the bunch is short (i.e. ps level) and FCTs would not be able to measure it. For instance in high brightness LINAC the 1ps signal from the bunch is increased up to 5ns.

ICTs are used to measure the charge of bunches when they are very short (i.e., ps level).

CTs sensitivity is in V/A, while ICTs sensitivity is given in Vs/C, emphasizing the fact that the charge of the bunch is measured by calculating the integral of the output signal.

In-flange ICT

In-air ICT

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ICT SPECIFICATIONS

In-flange ICT

In-air ICT

Beam Charge Monitor - Integrate-Hold-Reset

Full scale ranges	Selectable in a range of 50:1 by TTL
Most sensitive range	800 pC, using 5 Vs/C ICT
Least sensitive range	400 nC, using 0.5 Vs/C ICT
Range control	Full scale and polarity (4 TTL bits)
Noise on single bunch	0.55 pCrms, limited by dynamic range
Dynamic range	>35'000, limited by resolution
Output	±8 V, available 50 µs after trigger, held for 400 µs (up to 10 ms on option)

It corresponds to a precision of 1pC

ICT Specifications

Sensitivity (nominal)	0.5	1.25	2.5	5.0	10.0	Vs/C
Turns ratio (old reference)	50:1	20:1	10:1	5:1	2x 5:1	
Output pulse (full length)	70	70	70	70	70	ns
Droop	< 3	< 6	< 10	< 32	< 157	%/µs
Droop with Low Droop option	< 0.2	< 1	< 3	< 8	< 32	%/µs
Max. charge/pulse	2000	324	81	20	5	µC
Max. rms current (f > 10 kHz)	2.7	2.7	2.7	2.7	2.7	A
Max. peak current (pulse = 1 ns)	0.4	0.2	0.1	0.1	0.1	kA
For 10 Vs/C sensitivity specifications, please ask						

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PERFORMANCE COMPARISON

	FAST CURRENT TR..	ACTIVE CURRENT TR. (ACCT)	INTEGRATING CURRENT TR.
Turns Ratio	10:1	...	5:1
Sensitivity	2.5 V/A	Depends on the amplifier	5 Vs/C
Low cutoff frequency	16 kHz	3 Hz	5.3 kHz
Up cutoff frequncy	1.17 GHz	1 MHz	191 MHz
Rise time	0.3 ns	350 ns	1.5 ns
Droop	10 %/µs	2%/ms	3.6 %/µs
Output Pulse Length	Depends on bunch length	Depends on bunch length	5 ns
Uncertainty (typical)	...	1.5µArms (in 1A range)	~0.55 pCrms
Accuracy	Depends on eddy currents (up to few percents)	~1%	

.. from datasheet **… measured @LNF**

Datasheet parameters can vary within the same category from model to model. Therefore, they should be considered as orders of magnitude.

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ACCURACY AND RESOLUTION OF CTs

Accuracy

The accuracy can depend on several factors, including eddy currents (which, in turn, depend on the frequency content of the bunch), offset (of the measurement electronics), accuracy in device calibration/construction, and temperature.

Data on accuracy is rarely available, but when provided, it is typically presented with an order of magnitude of around 1-2% of the measured quantity (current or charge). This data has been verified against some articles.

Uncertainty

The uncertainty typically depends on the active components (such as amplifiers in the case of ACCT) and the measurement electronics. For example, in the case of SPARC high brightness LINAC, ICT uncertainty is in the order of 0.5/1 pC (measured as the rms value of noise in the measurements).

For ACCT, a value of 1.5 µArms is reported for a 1A range.

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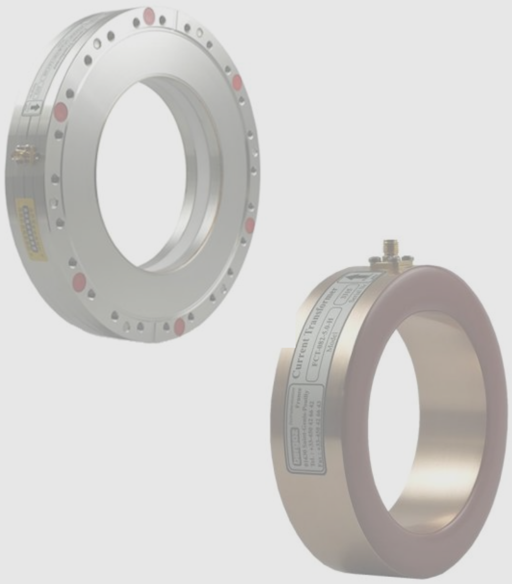
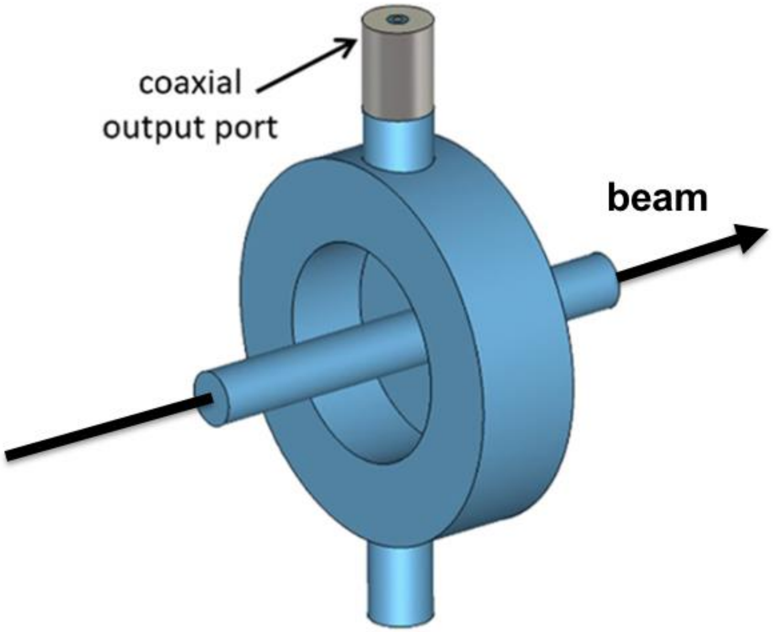
BEAM INTENSITY

Current Transformers



Widespread, commercial devices

Passive cavity



Research group design

Pulsed beam

CAVITY BEAM INTENSITY MONITOR

Passive Cavity Beam Intensity Monitor for 35MeV Pulsed Proton Beams for Medical Applications

Example

Problem

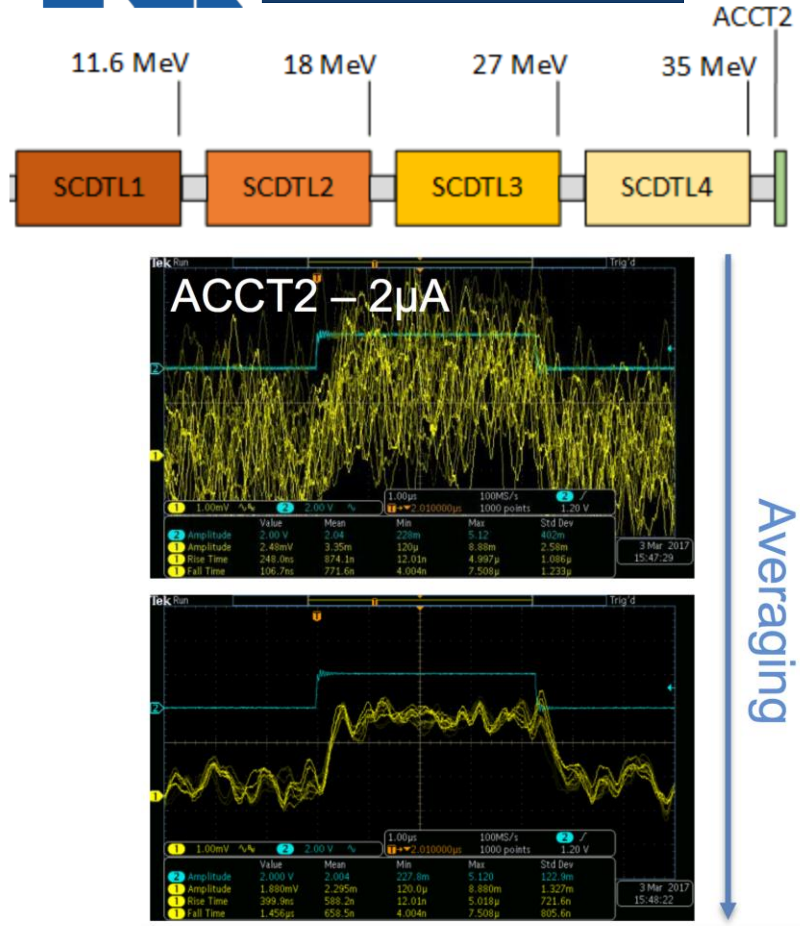
Non destructive measurement

Single pulse measurement

With CT averaging is necessary to extract signal from noise but losing single pulse information

Sensitive, compact, non interceptive detector between sections to be used in commissioning

TOP-IMPLART linac



CAVITY BEAM INTENSITY MONITOR

Example

Passive Cavity Beam Intensity Monitor for 35MeV Pulsed Proton Beams for Medical Applications

Problem

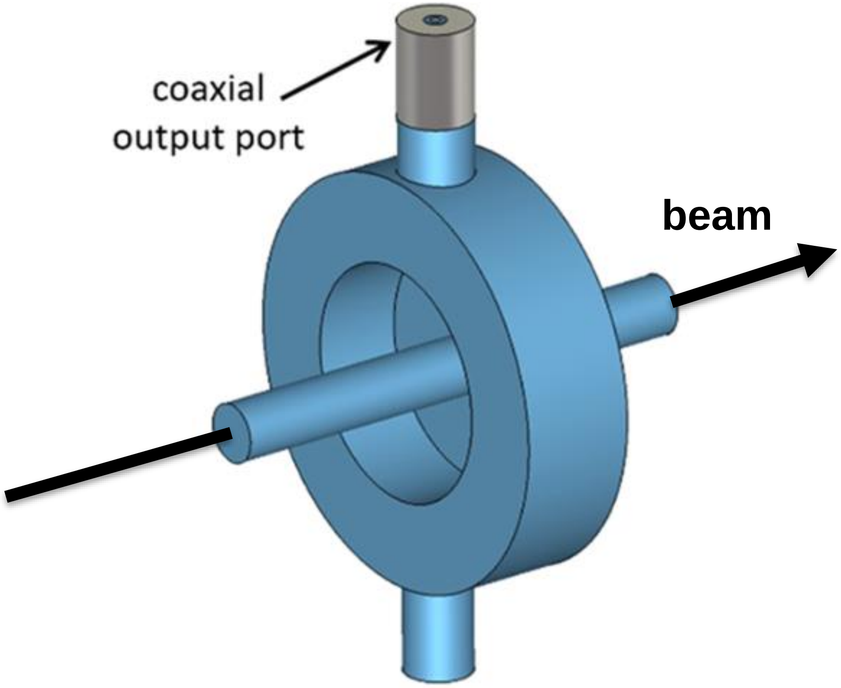
Non destructive measurement

Single pulse measurement

With CT averaging is necessary to extract signal from noise but losing single pulse information

Sensitive, compact, non interceptive detector between sections to be used in commissioning

Solution



Short TM010 cavity

EXTRACTED POWER

RF power extracted from a resonant cavity excited by a pulse with a train of bunches

$$P_{meas} = 4I_{beam}^2 e^{-\omega_b^2\sigma_t^2} R_{shunt}T^2Q_0 \frac{\beta}{(1+\beta)^2}\left[1+4\,Q_L^2\left(\frac{\omega_0-\omega_b}{\omega_0}\right)^2\right]^{-1}$$

Beam **Cavity** **Coupling** **Detuning**

T_b **Bunch spacing**

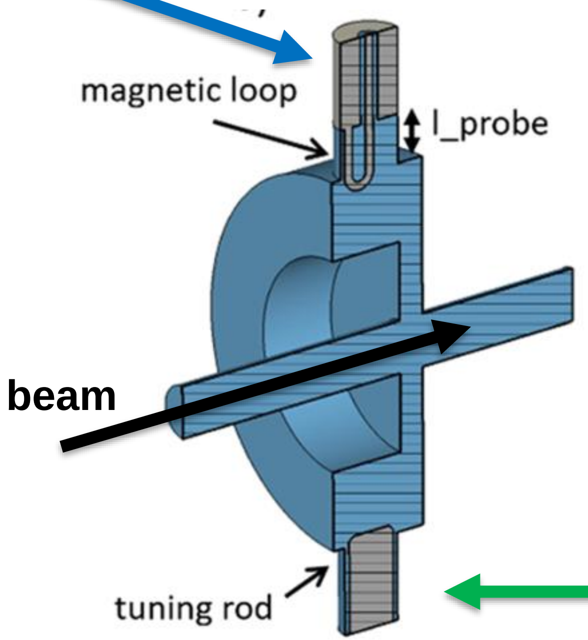
I_{beam} **Average current**

$$\omega_b = \frac{2\pi}{T_b}$$

f_0 **Resonant frequency**

$$\omega_0 = 2\pi f_0$$

T **Transit time factor**



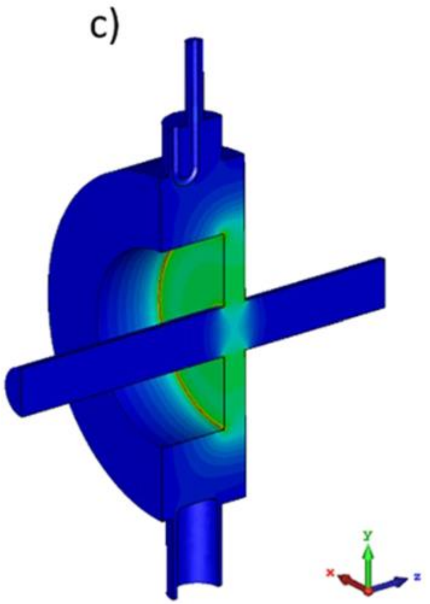
F. Cardelli et al., **Design and test of a compact beam current monitor based on a passive RF cavity for a proton therapy linear accelerator**, Rev. Sci. Instrum. 92, 113304 (2021); https://doi.org/10.1063/5.0062509

EM DESIGN OF THE CAVITY

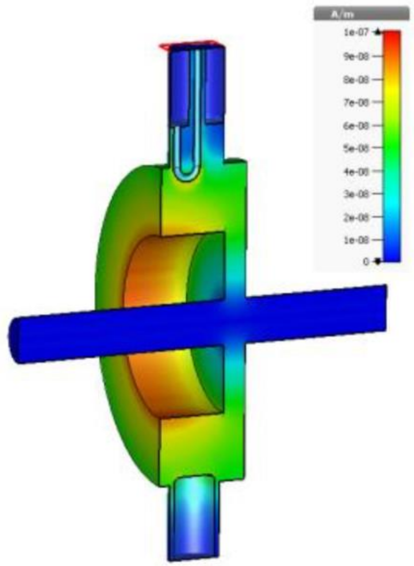
Example

Design goal:

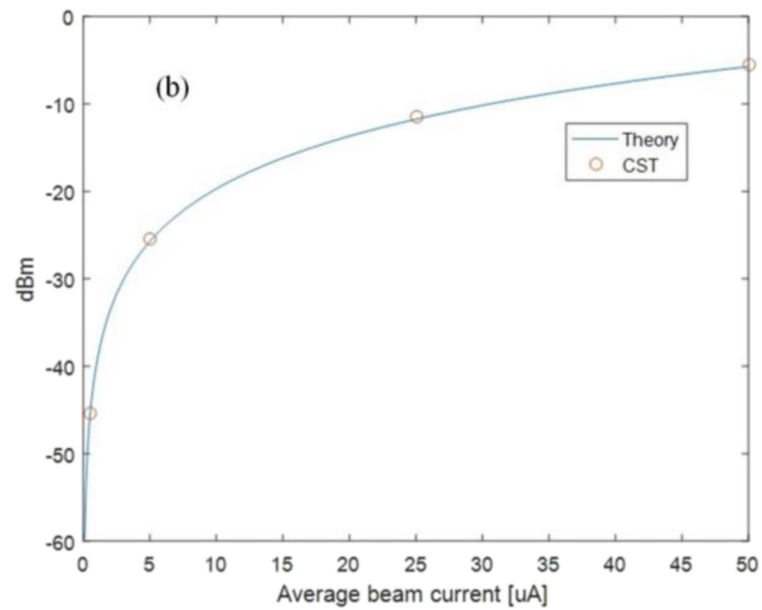
re-entrant cavity 12mm long with filling time between 100 and 200 ns, maximizing shunt impedance and transit time factor



Electric Field (CST)



Magnetic Field (CST)

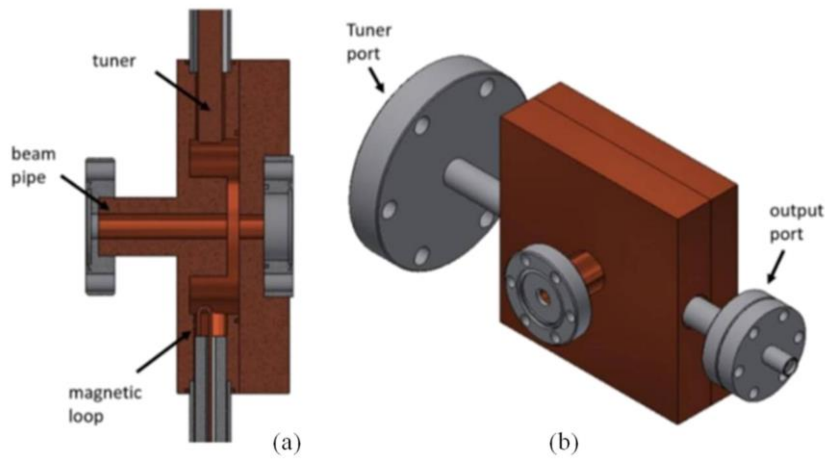


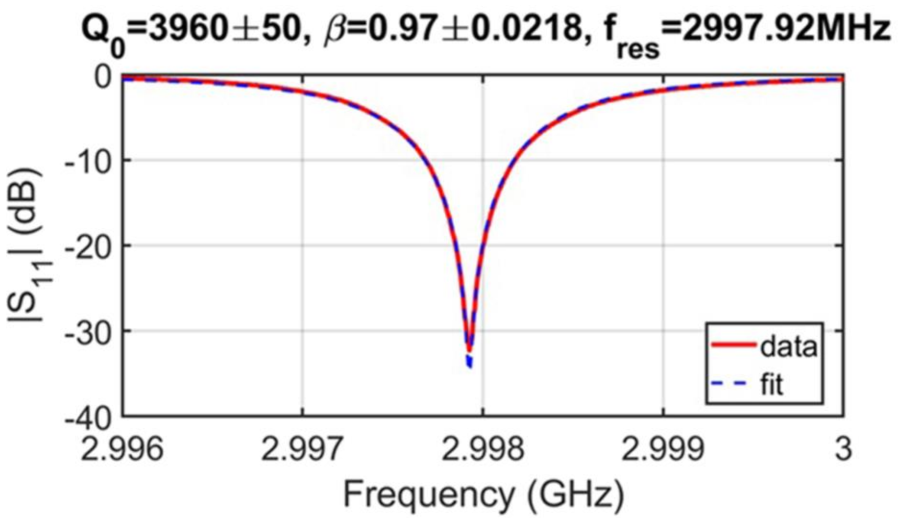
RF output power variation with respect to the beam current (PIC-CST module vs theory)

F. Cardelli et al., **Design and test of a compact beam current monitor based on a passive RF cavity for a proton therapy linear accelerator**, Rev. Sci. Instrum. 92, 113304 (2021); https://doi.org/10.1063/5.0062509

CAVITY MEASUREMENT

Example





Parameter	Unit	Design value	Measured value
f_0	MHz	2997.92	2997.92
Q_0	···	4257	3960
Q_{load}	···	2129	2010
β	···	1	0.97
$\tau = 2Q_{load}/\omega$	ns	225	213
R_S/Q_0	Ohm	60	···

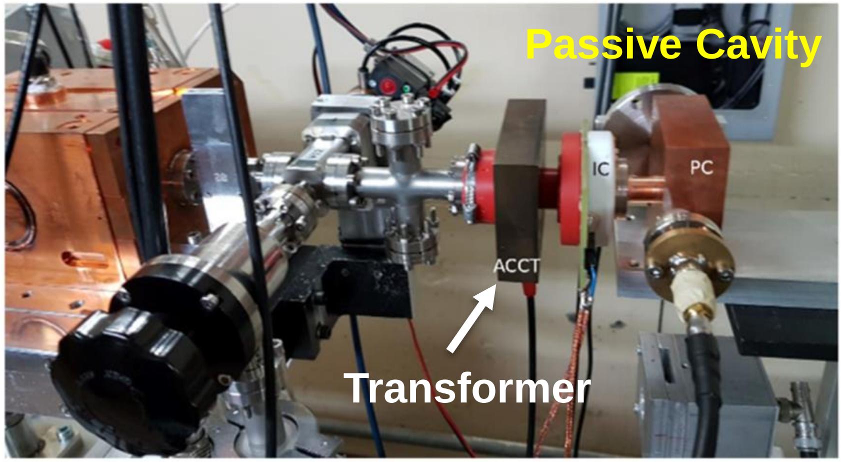
$$S_{11} = \frac{\beta - 1 - jQ_0\delta}{\beta + 1 + jQ_0\delta}$$

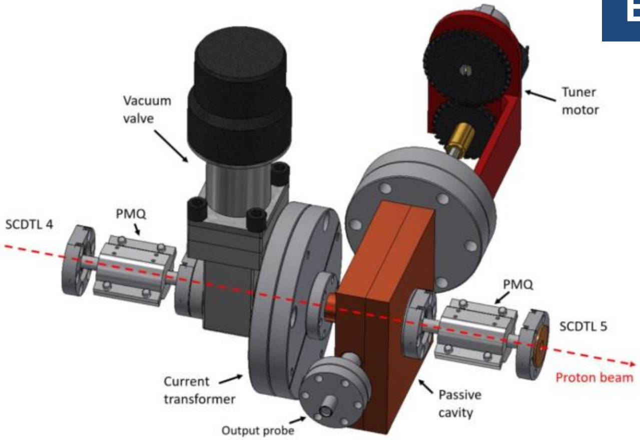
$$\delta = \frac{f}{f_{res}} - \frac{f_{res}}{f}$$

F. Cardelli et al., **Design and test of a compact beam current monitor based on a passive RF cavity for a proton therapy linear accelerator**, Rev. Sci. Instrum. 92, 113304 (2021); https://doi.org/10.1063/5.0062509

BEAM MEASUREMENT

Example





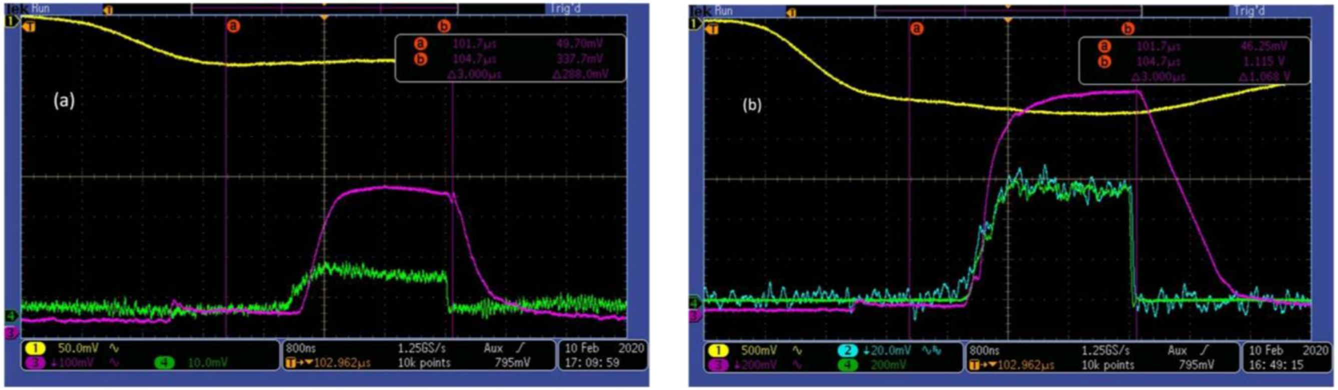
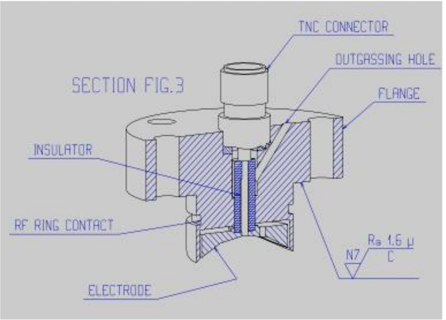


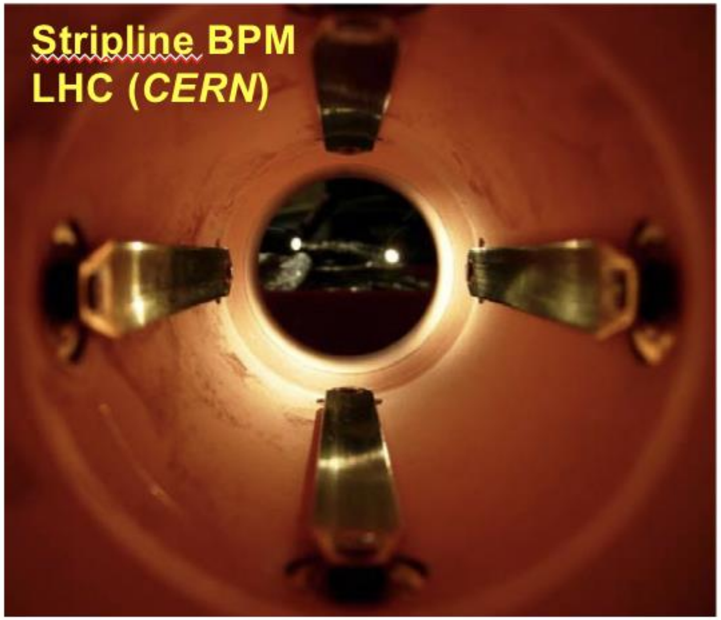
FIG. 14. Beam current profile measurement at the end of the fourth SCDTL structure reads with an oscilloscope for two different values of the current injected into SCDTL structures: (a) AC transformer at SCDTL-1 input (yellow, scale = 50 μA/div), Faraday cup (green, scale = 0.5 μA/div), and passive cavity (purple). (b) AC transformer at SCDTL-1 input (yellow, scale = 500 μA/div), Faraday cup (green, scale = 10 μA/div), current transformer (blue, scale = 10 μA/div), and passive cavity (purple).

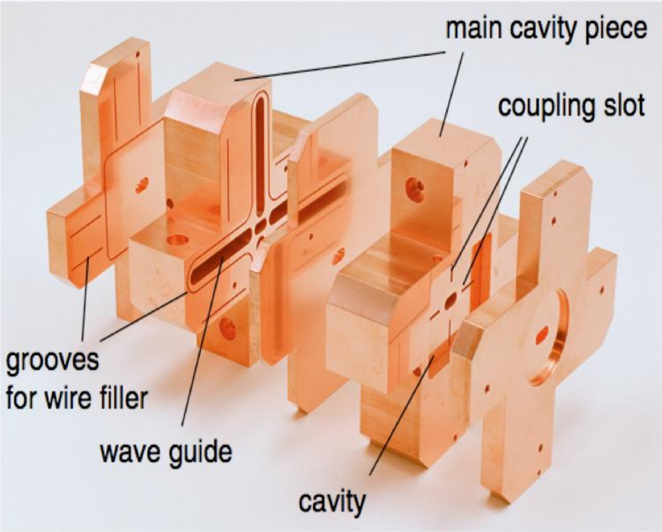
F. Cardelli et al., **Design and test of a compact beam current monitor based on a passive RF cavity for a proton therapy linear accelerator**, Rev. Sci. Instrum. 92, 113304 (2021); https://doi.org/10.1063/5.0062509

BEAM POSITION MONITOR



LHC Button BPM (*CERN*)

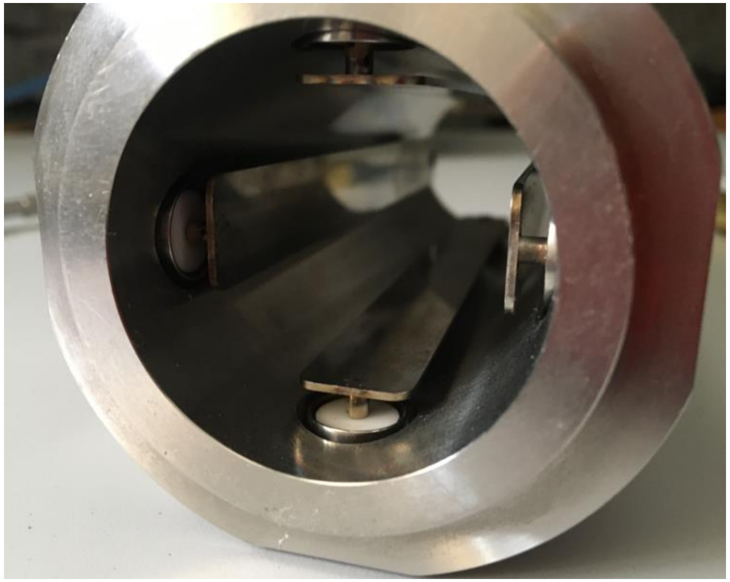




Courtesy of M. Wendt

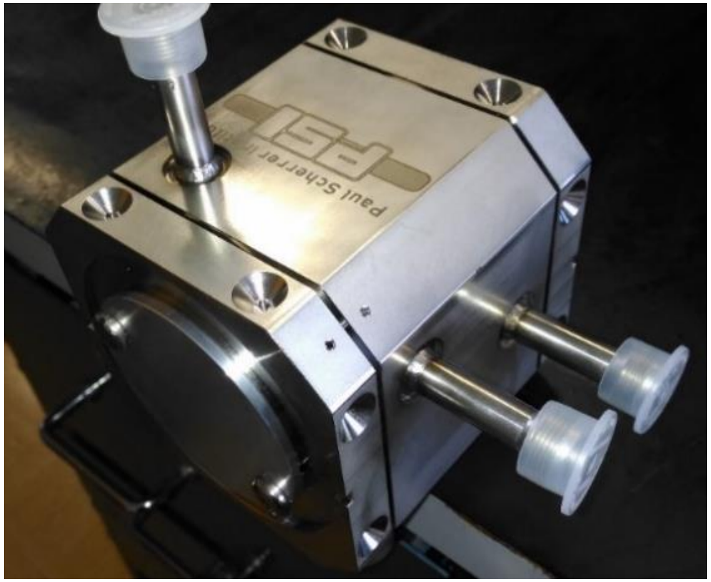
TRANSVERSE POSITION MEASUREMENT

Strip line BPM



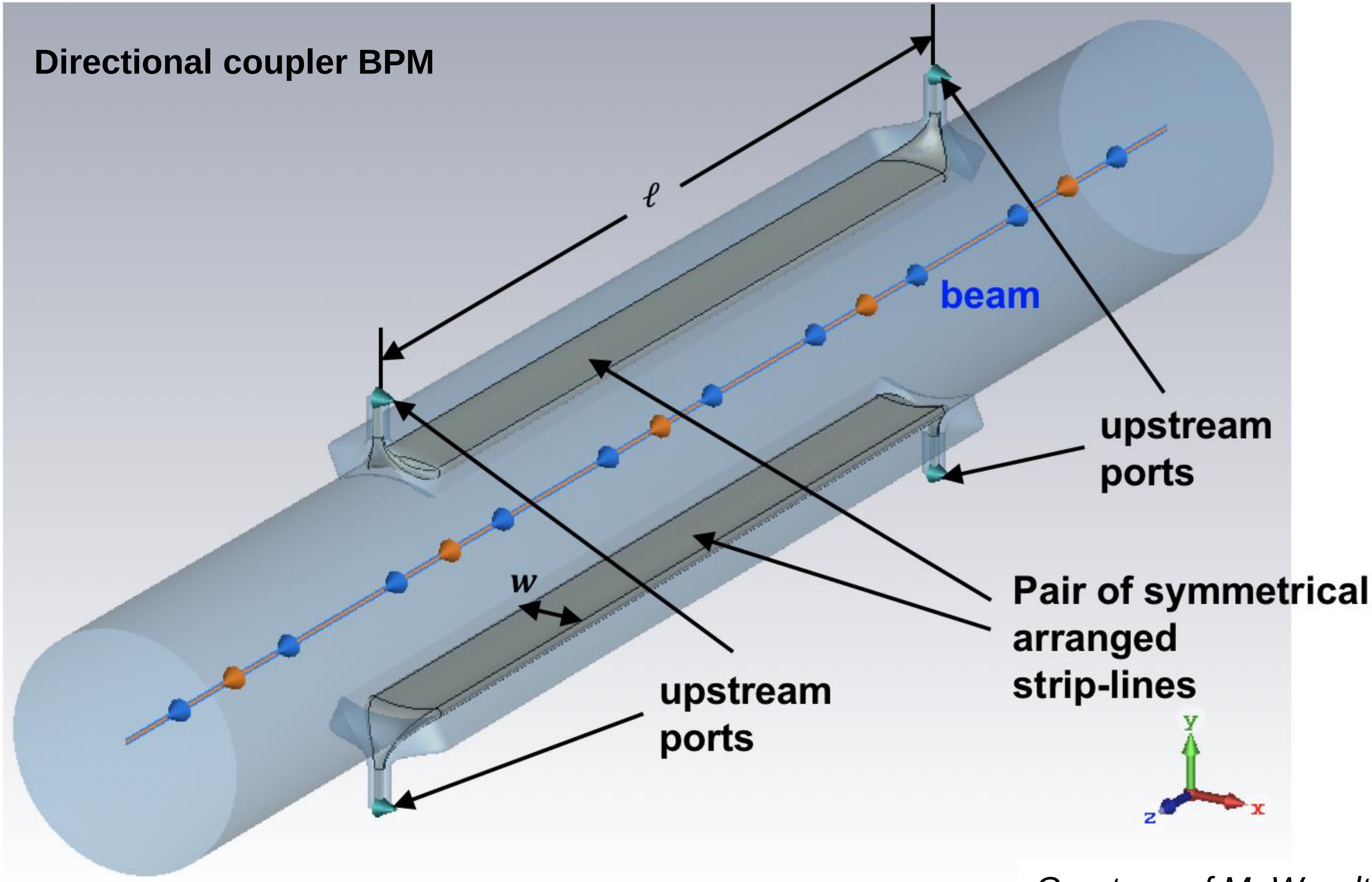
Transmission line pick-up

Cavity BPM



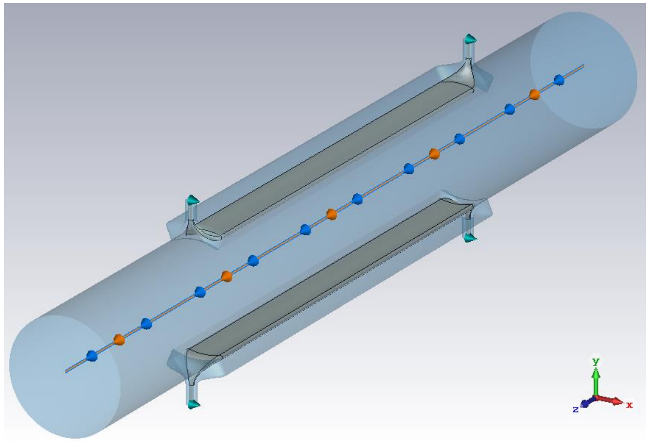
Resonant pick-up

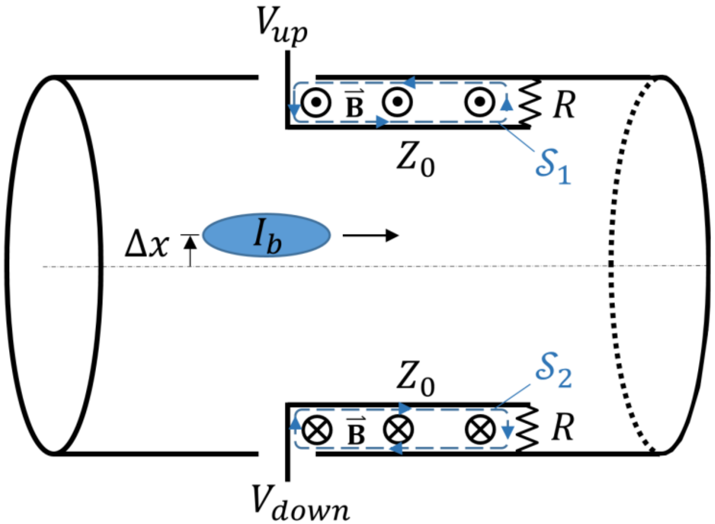
STRIPLINE BEAM POSITION MONITOR

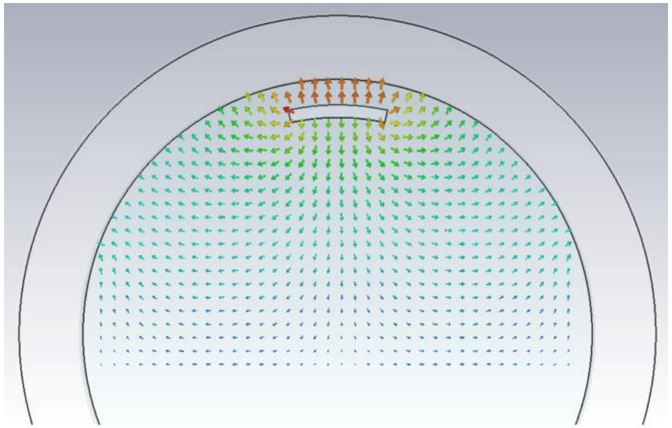


Courtesy of M. Wendt

STRIPLINE BPM BASICS







Strip transmission-line of characteristic impedance $Z_0 = 50\ \Omega$

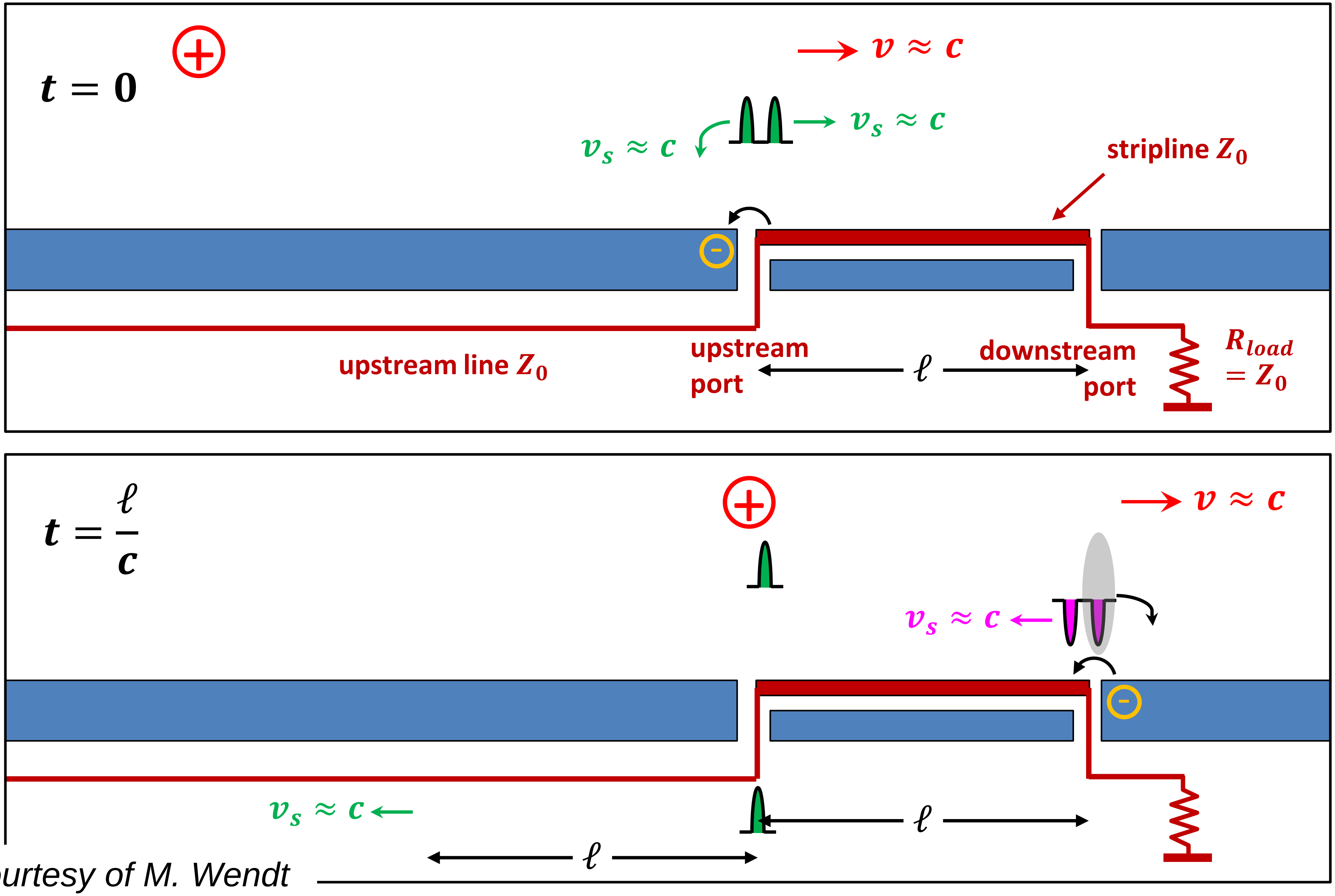
TEM signal (except near the ports)

Electric + Magnetic coupling to the beam field

Ability of detecting beam direction

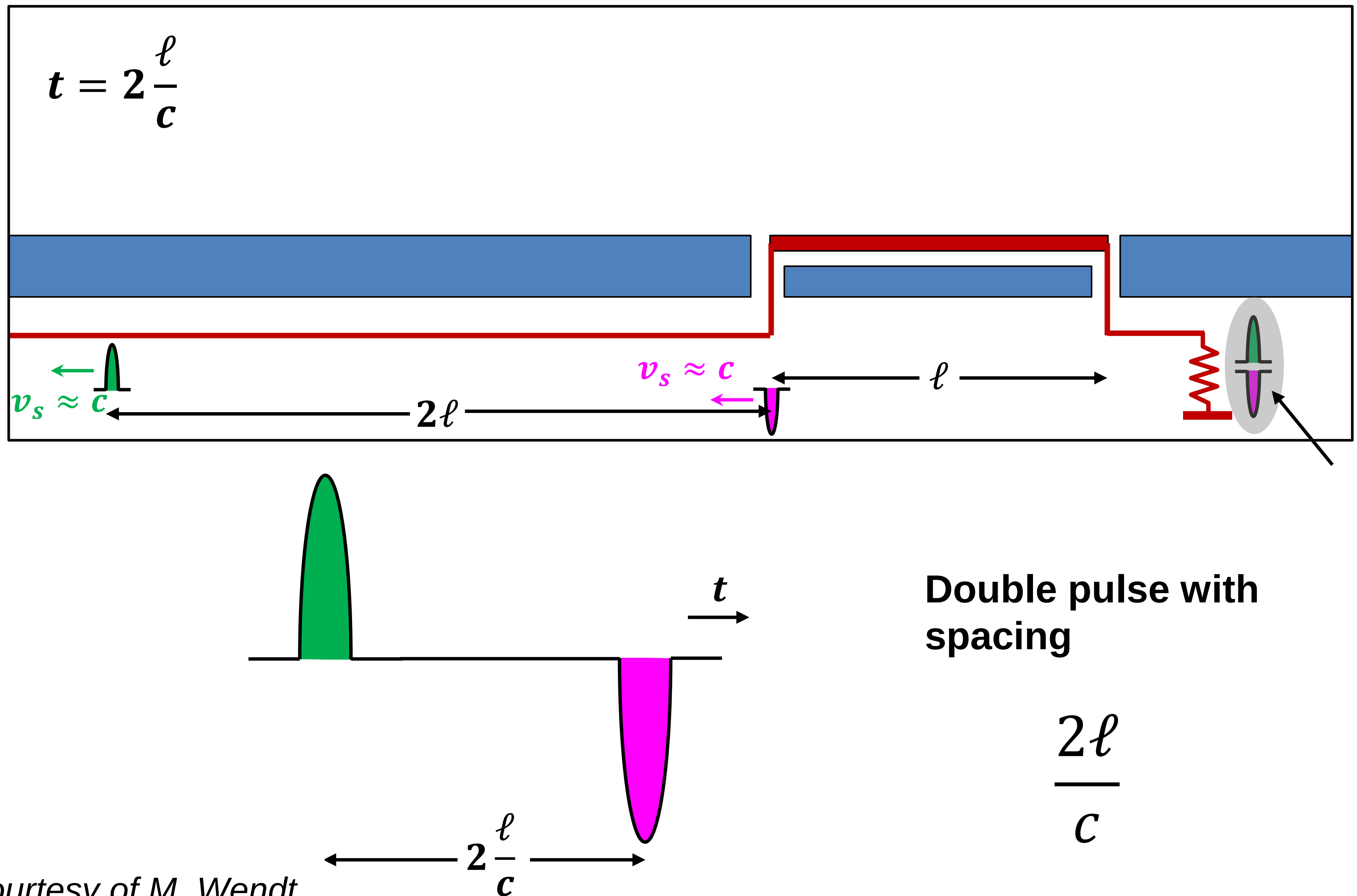
Courtesy of M. Wendt

STRIPLINE BPM PRINCIPLE



Courtesy of M. Wendt

STRIPLINE BPM PRINCIPLE



Double pulse with spacing

$$\frac{2\ell}{c}$$

Courtesy of M. Wendt

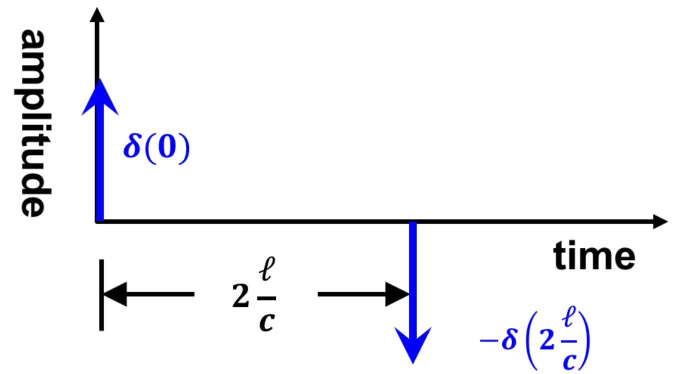
TRANSFER IMPEDANCE

- **Time domain impulse response: δ-doublet pulse**

characteristic impedance typically 50 Ω

$$z(t) = \phi \frac{Z_0}{2}\left[\delta(t) - \delta\left(t - 2\frac{\ell}{c}\right)\right]$$

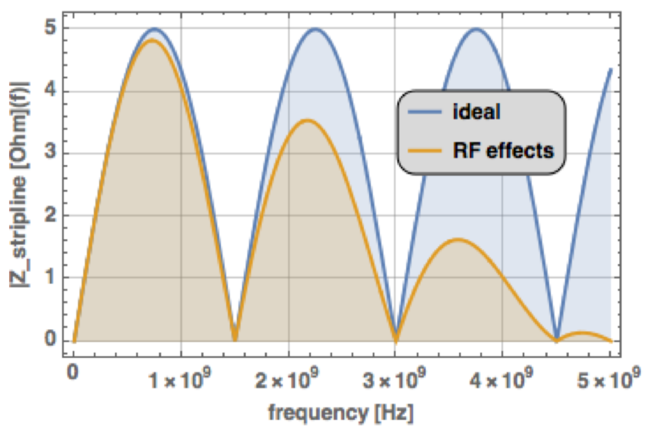
coverage factor



- **Frequency domain transfer impedance**

$$Z(\omega) = j\phi Z_0 e^{j\frac{\pi}{2}} e^{-j\omega\frac{\ell}{c}} \sin\left(\omega\frac{\ell}{c}\right)$$

$Z_0 = 50\Omega, \ell = 100\ mm, \phi = 0.1$



Courtesy of M. Wendt

SHORT CIRCUITED STRIPLINE

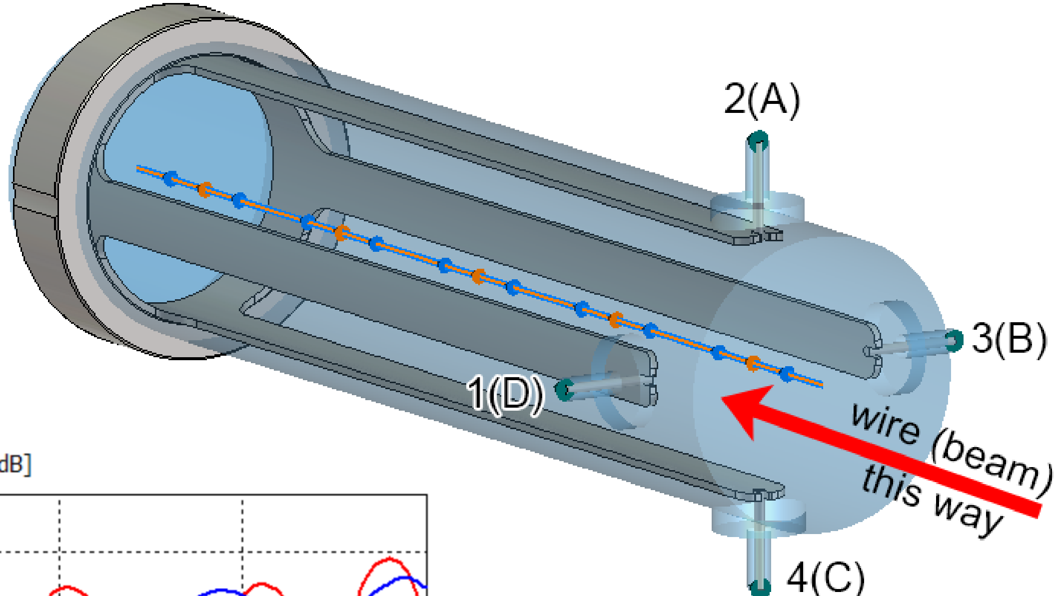
Simplified design: short circuited connector

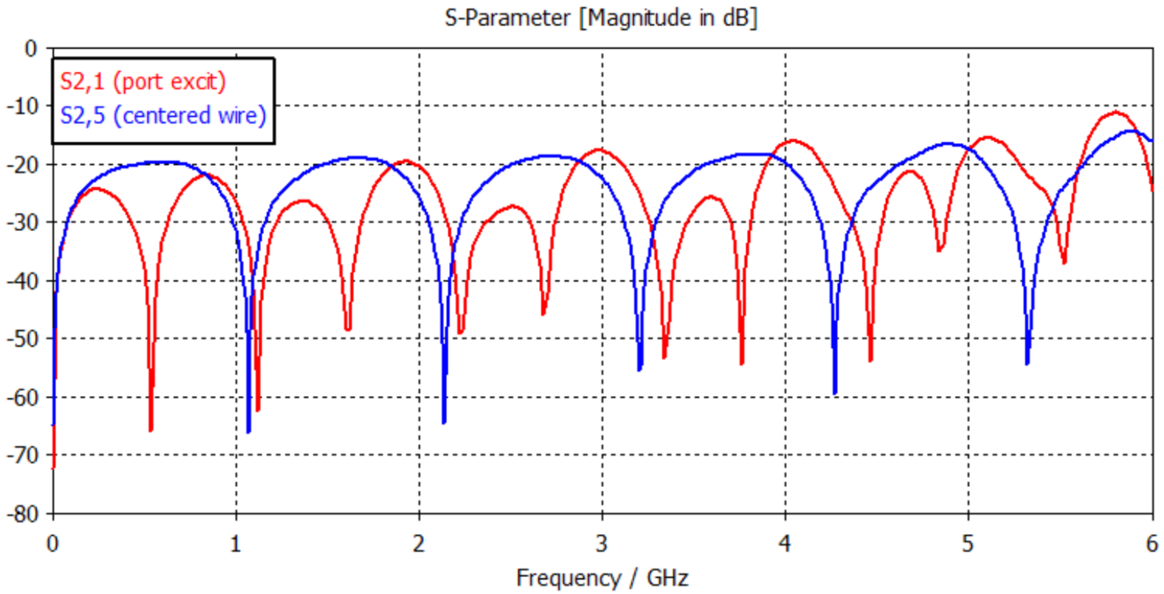
Example

50Ω vacuum feedthroughs are difficult to make

Compton source Linac design

No directivity

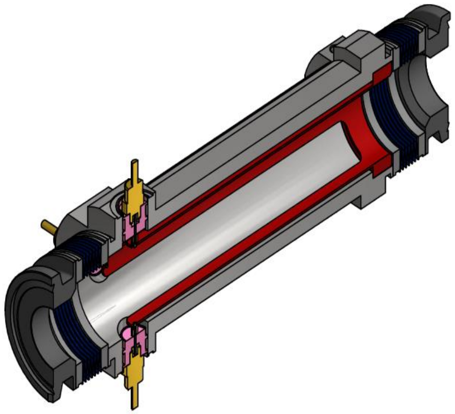


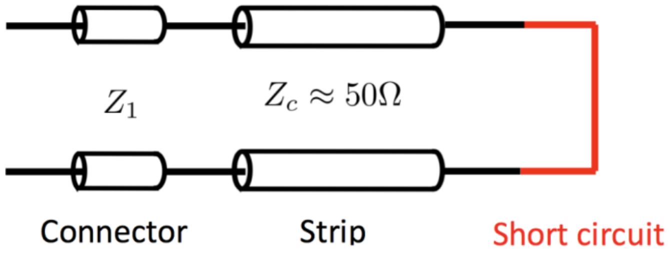


Simulation of wire bench measurement

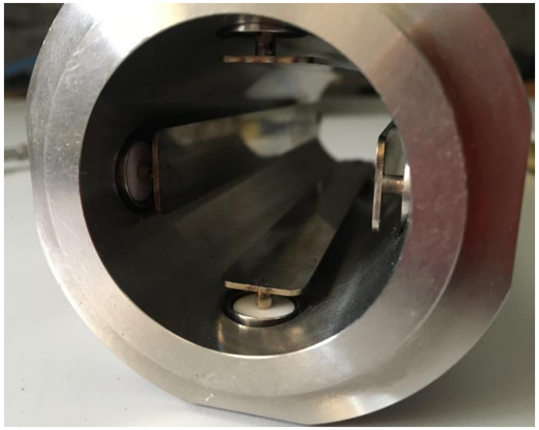
SHORT CIRCUITED STIPLINE BPM

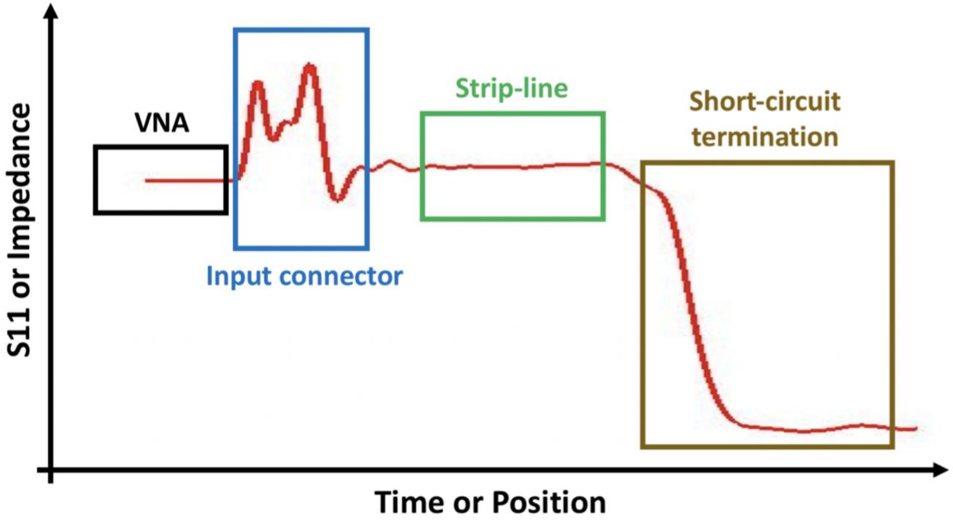
Example





TDR measurement with Network analyser



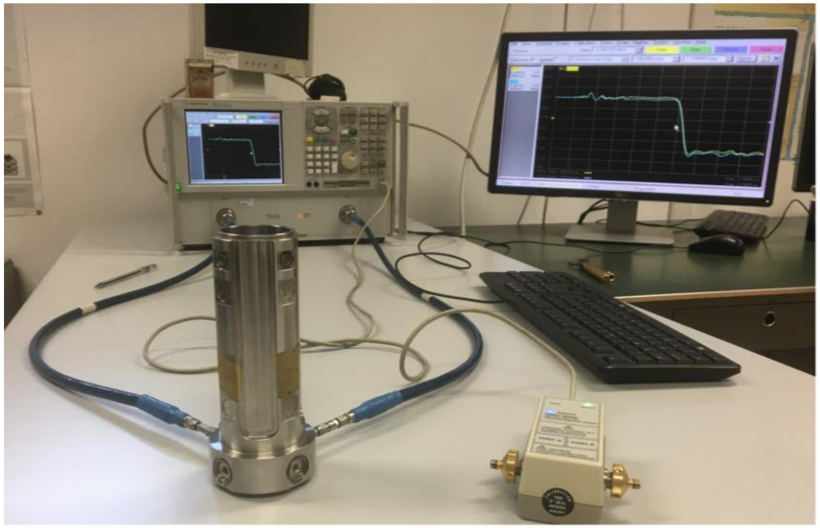


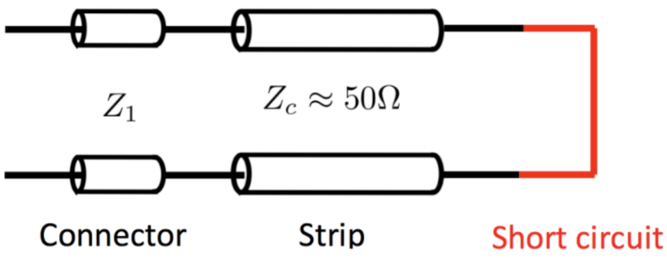
Andrea Mostacci
(Sapienza University, INFN-Roma)

The CERN Accelerator School

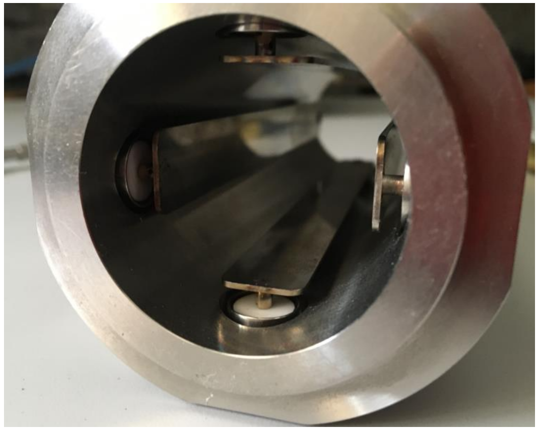
SHORT CIRCUITED STIPLINE BPM

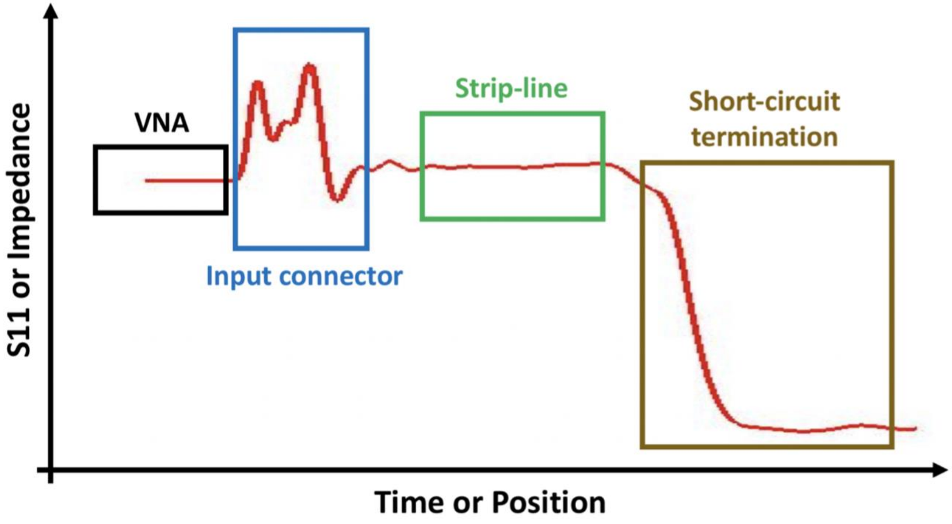
Example





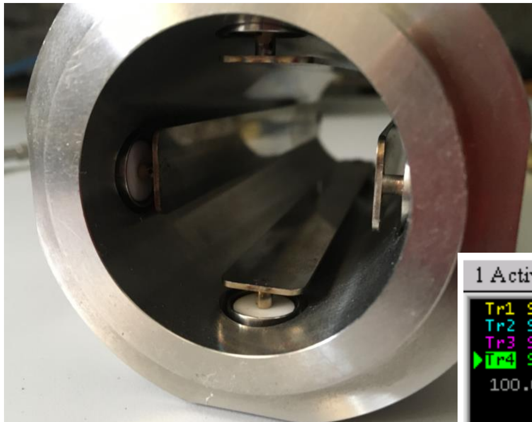
TDR measurement with Network analyser

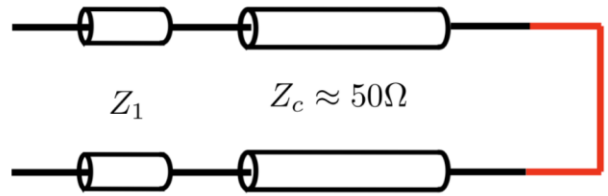


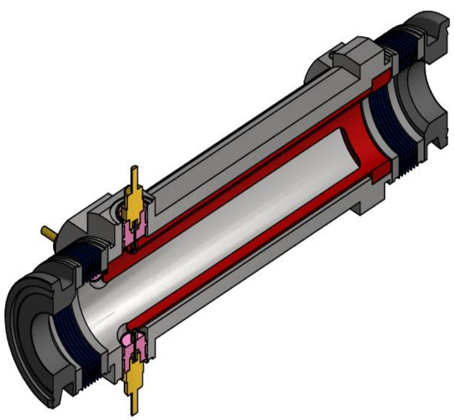


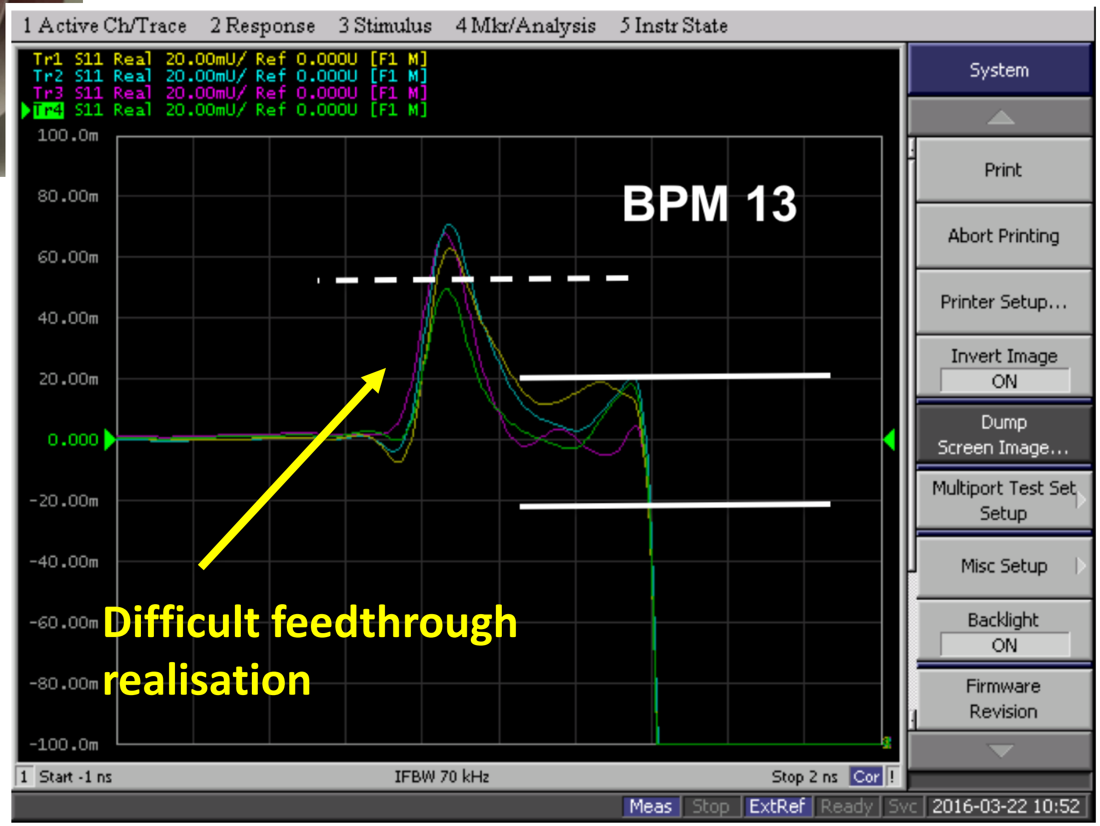
ACCEPTANCE TEST OF BPM

Example









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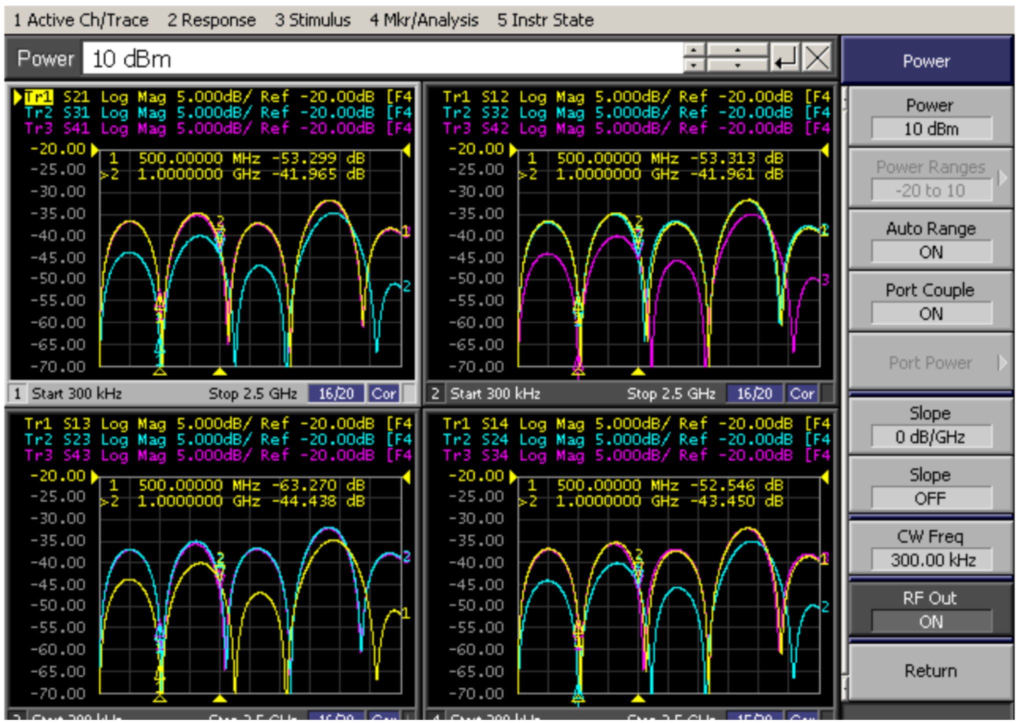
OFFSET CALIBRATION

Accuracy

Lambertson method uses the coupling between strips to determine the gain factors of each electrode; the ratios between gain factors then provide the difference between the mechanical and electrical centres.



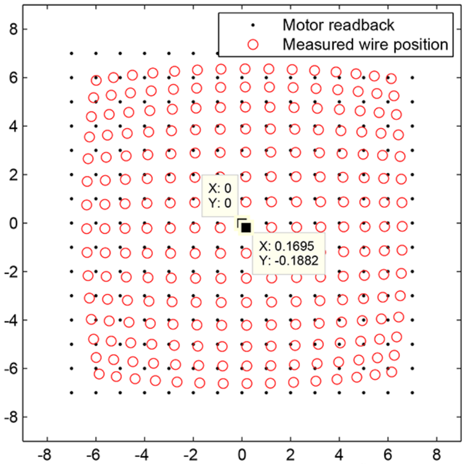
	x_e, μm	y_e, μm
BPM-01	132 ± 0	-238 ± 8.5
BPM-02	25 ± 0.15	-134 ± 10.4
BPM-04	165 ± 0.7	-157 ± 10

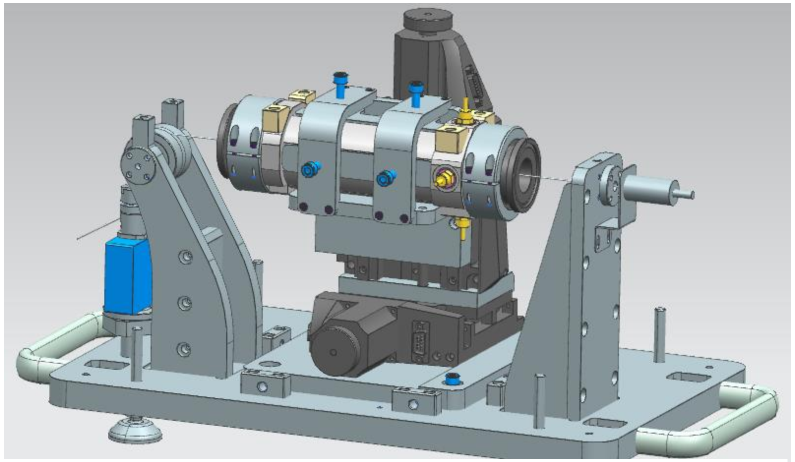
A. A. Nosych et al., **Measurements and calibration of the stripline BPM for the ELI-NP facility with the stretched wire method**, IBIC2015, Melbourne, Australia.

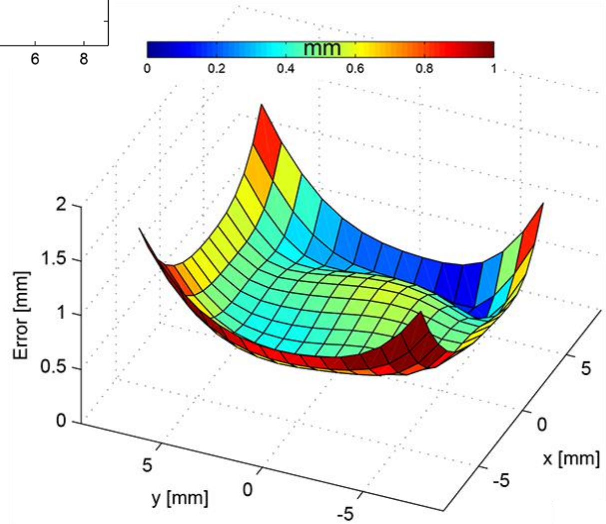
NON LINEAR RESPONSE OF BPM

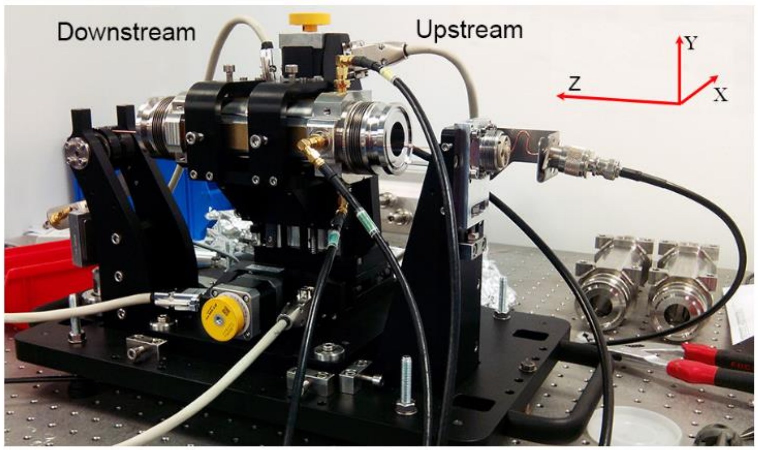
Accuracy

Wire scan bench measurement using readout electronics







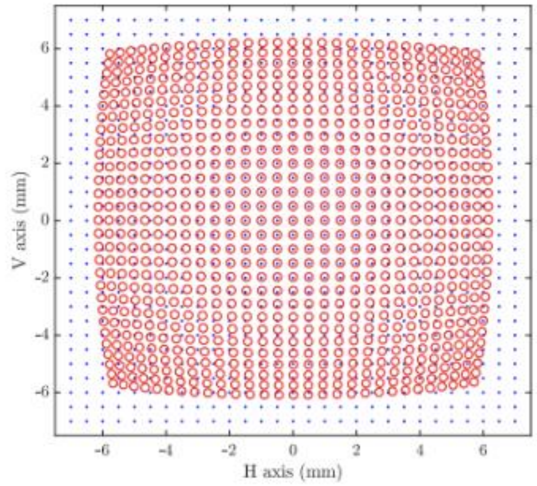


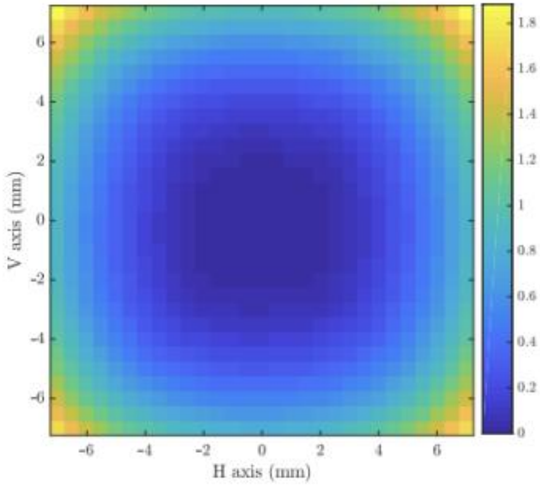
A. A. Nosych et al., **Measurements and calibration of the stripline BPM for the ELI-NP facility with the stretched wire method**, IBIC2015, Melbourne, Australia.

CORRECTION OF NON LINEAR RESPONSE

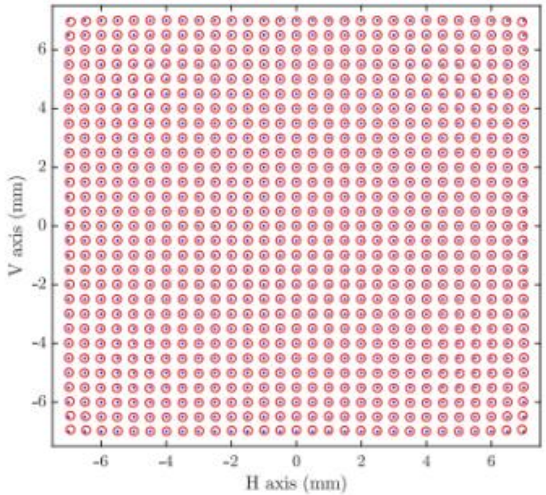
Accuracy

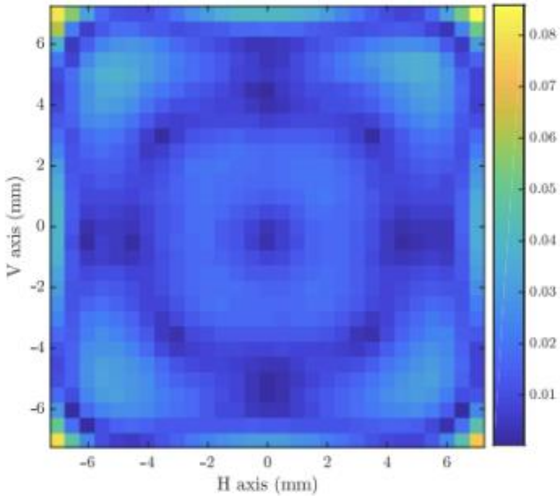
(Polynomial) correction algorithm can be applied





1.85mm





0.084mm

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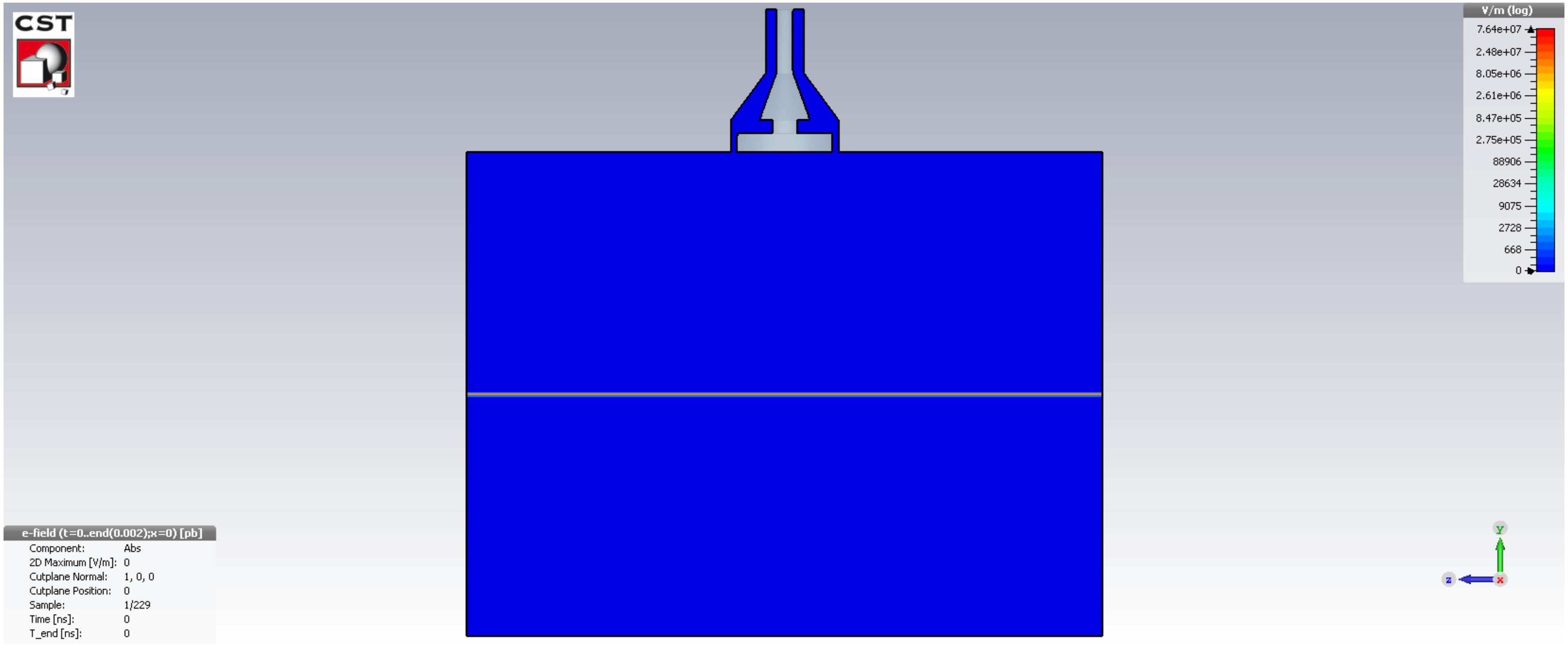
WAKE FIELDS IN BPMs

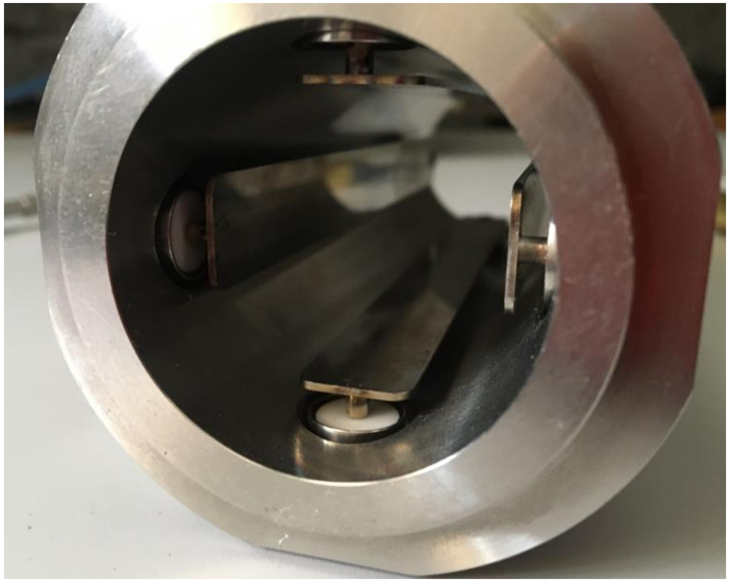
Maybe relevant for novel low emittance rings …



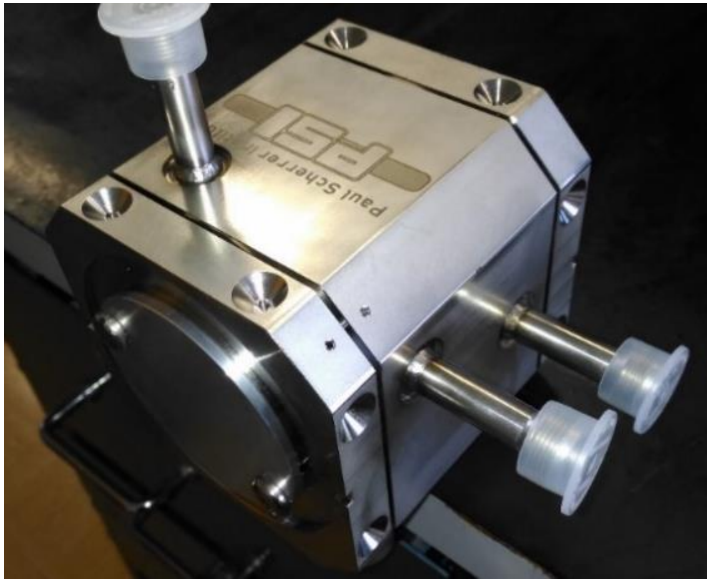
Courtesy of G. Castorina - Sapienza

TRANSVERSE POSITION MEASUREMENT

Strip line BPM



Cavity BPM



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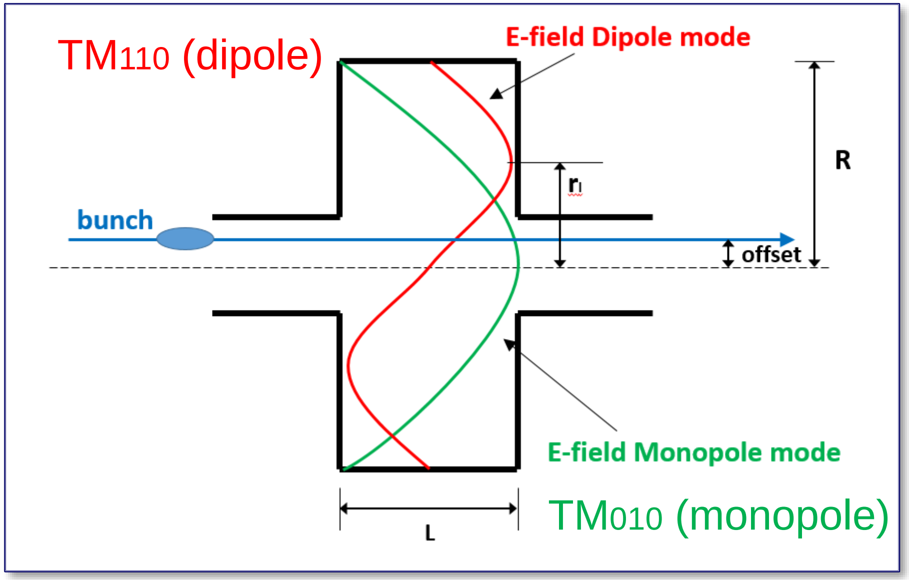
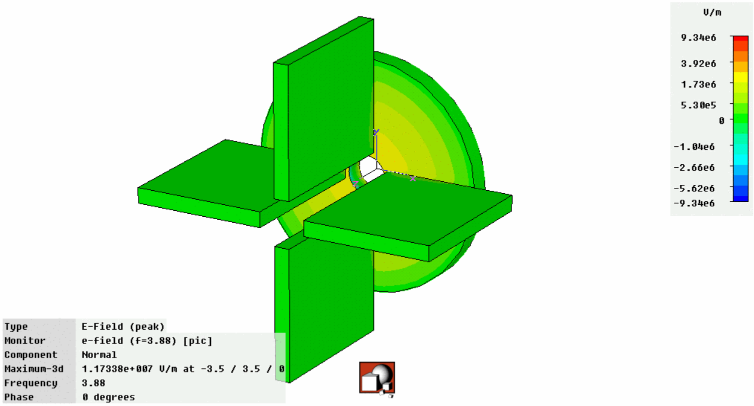
FIELD EXCITED BY A OFFSET BUNCH IN CAVITY

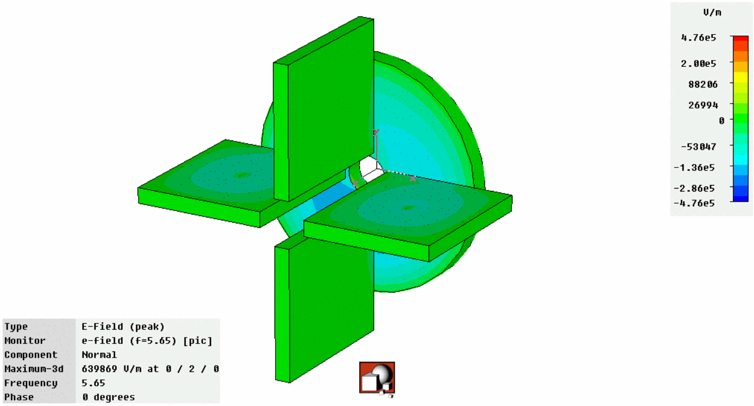
PILLBOX CAVITY



monopole mode



dipole mode



Different modes have different oscillating frequencies

Courtesy of *D. Lipka*

G. Franzini - INFN

Andrea Mostacci
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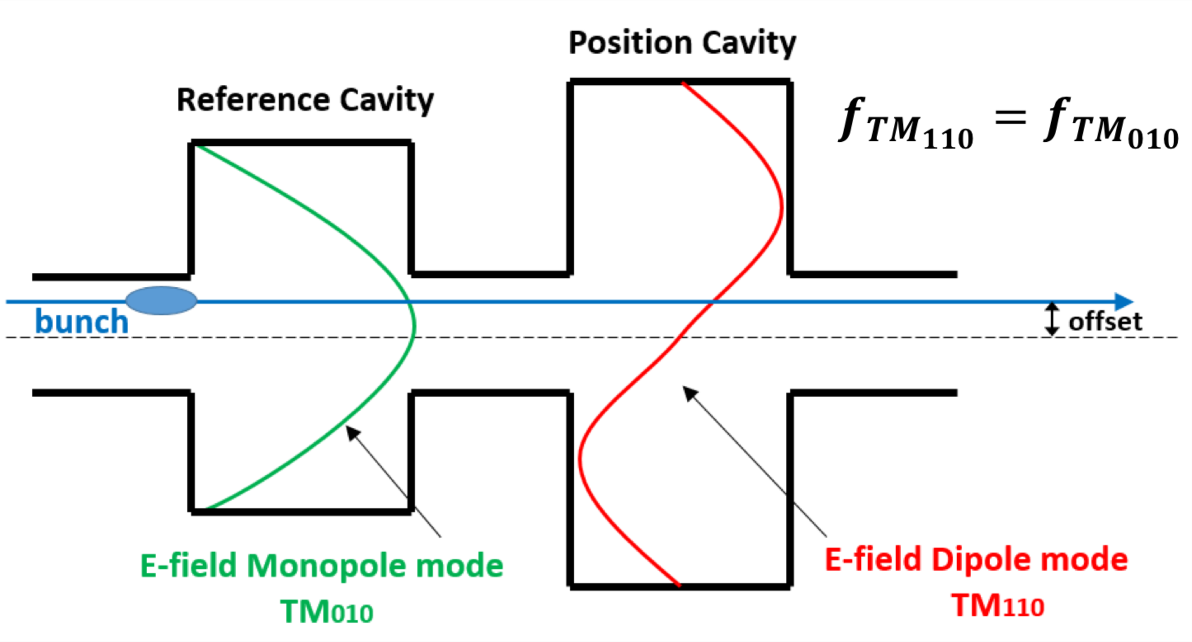
CAVITY BPM - TWO PILLBOX RESONATORS

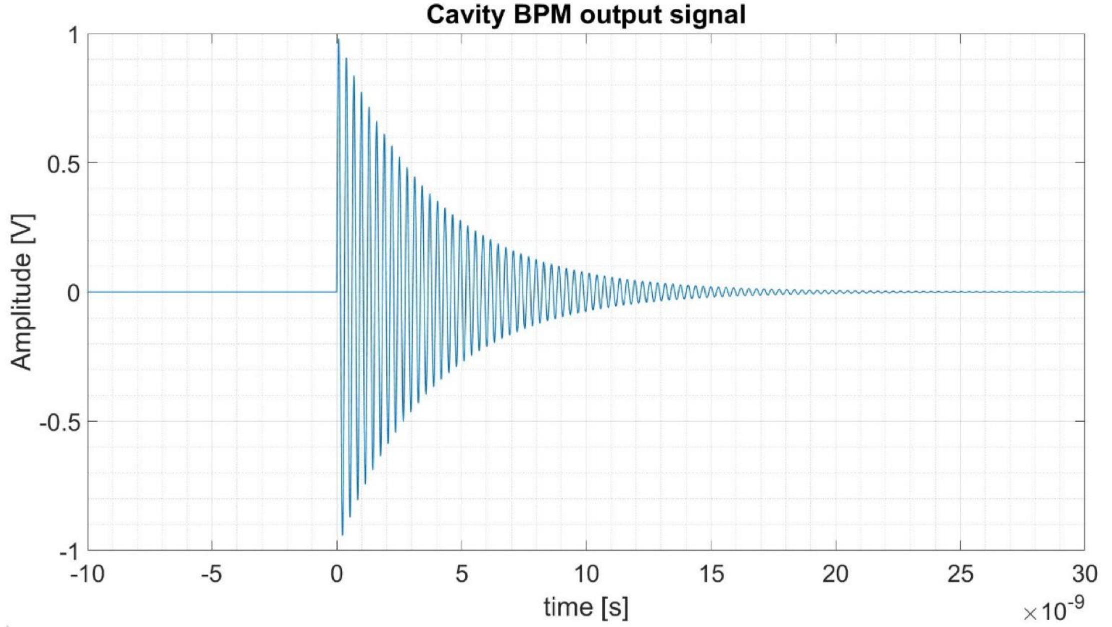


- ***Monopole mode** is proportional to the **bunch charge**.*
- ***Dipole mode** is proportional to the **bunch charge and bunch offset**.*

Extracting Dipole and Monopole mode signals is possible to measure the beam offset independently by the beam charge as well as offset sign. The working frequency is driven by the electronics.

G. Franzini - INFN

CAVITY BPM OUTPUT SIGNALS



$$V_{out}(t) = A \cdot \sin(2\pi f_{res} t + \theta) \cdot e^{-t/\tau} \rightarrow \tau = \frac{Q_L}{\pi f_{res}}$$

A is proportional to beam charge for TM_{010} and proportional to charge and beam offset for TM_{110}.

- The two cavities are designed to produce signals with the **same frequency and decay constant (τ)** respectively for monopole and dipole mode.
- **Three signals per bunch are extracted:** horizontal and vertical polarization of the dipole mode (**X** and **Y**) and the monopole mode (**I**).

G. Franzini - INFN

CAVITY BPM FOR MULTIBUNCH OPERATION

Example

General Pickup Parameters

Parameter	Value
Material	Stainless Steel 316LN
Length [mm]	100
Inner Aperture [mm]	16
Distance from Pos. To Ref. Resonator [mm]	60

Position Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	**40**
TM_{110} Frequency [GHz]	**3.284**
TM_{010} Frequency [GHz]	2.252
Position Signal [V/mm/nC]	**7.07**
Angle Signal [μm/mrad]	4.3

Reference Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	**40**
TM_{010} Frequency [GHz]	**3.284**
Charge Signal [V/nC]	**135**
Angle Signal [μm/mrad]	4.3

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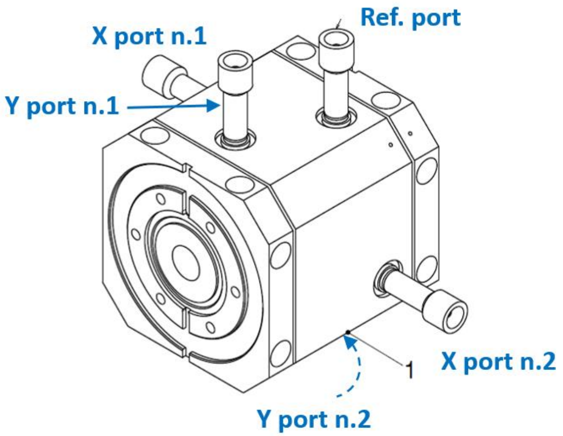
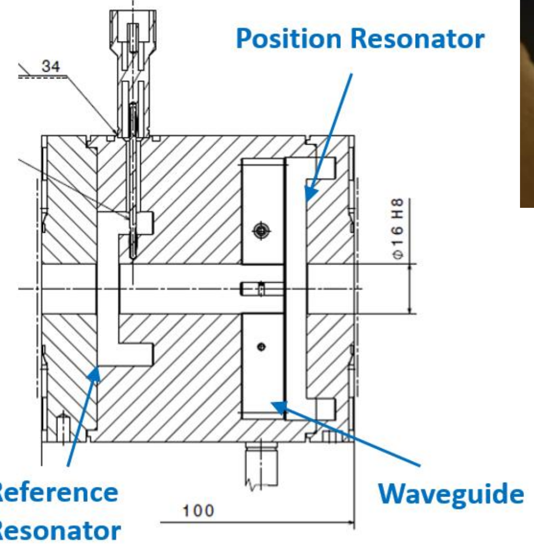
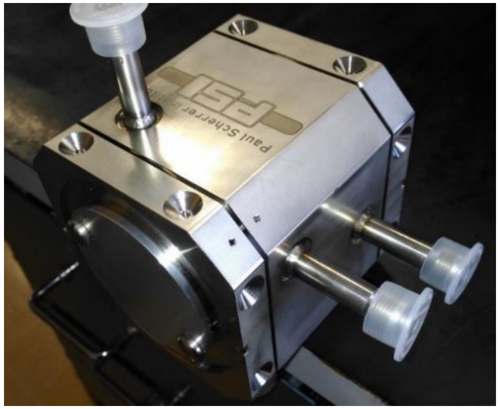
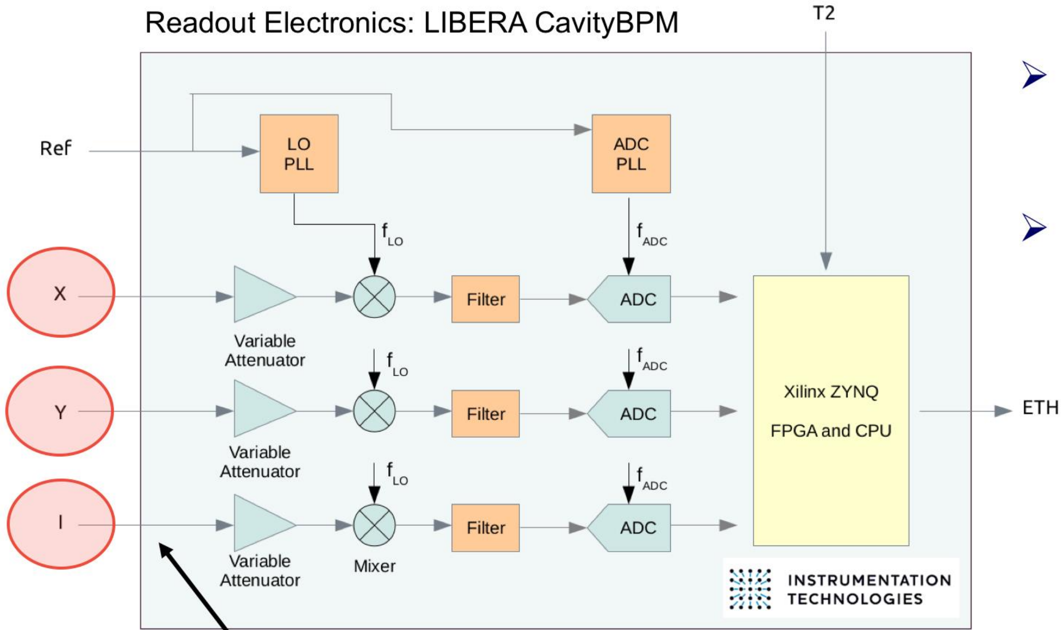




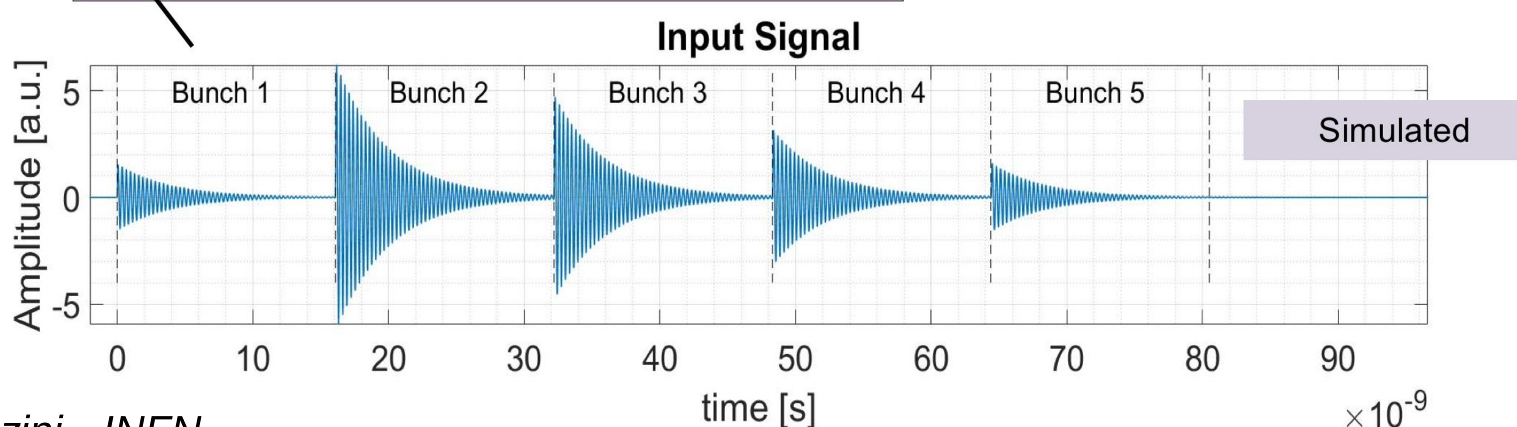


CAVITY BPM - SIGNAL PROCESSING (1/3)

Example



- RF signals (X, Y, I) use three identical and independent channels.
- They are filtered and attenuated by means of three configurable attenuators (0 / 32 dB).



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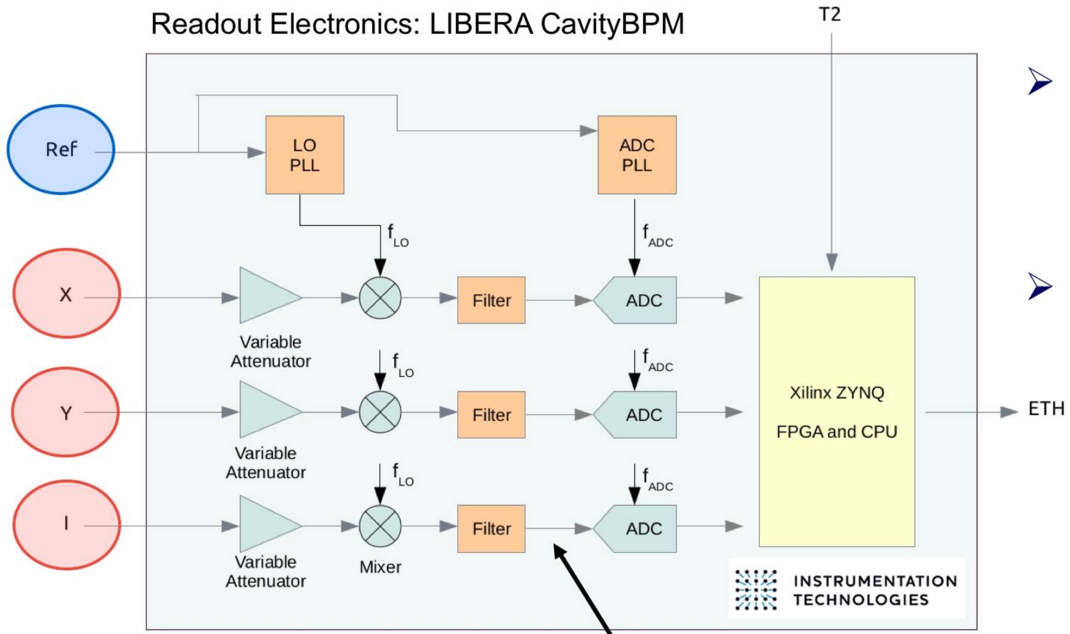
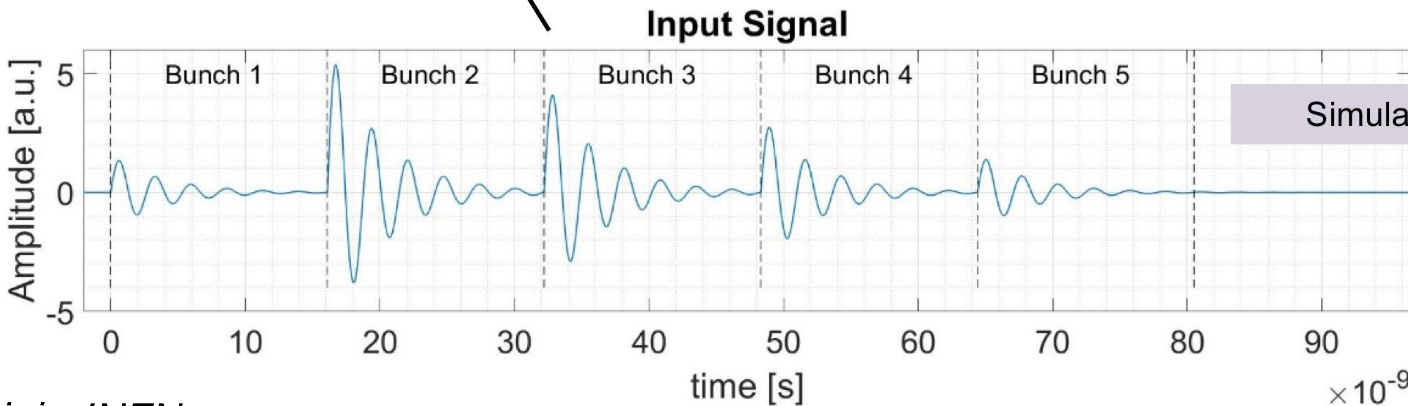
CAVITY BPM - SIGNAL PROCESSING (2/3)

Example



- Reference signal (62.1 MHz) is used to generate f_{LO} (for the mixer) and f_{ADC} for the ADC clock.
- Signals are down-mixed from 3.284 GHz to 375 MHz.



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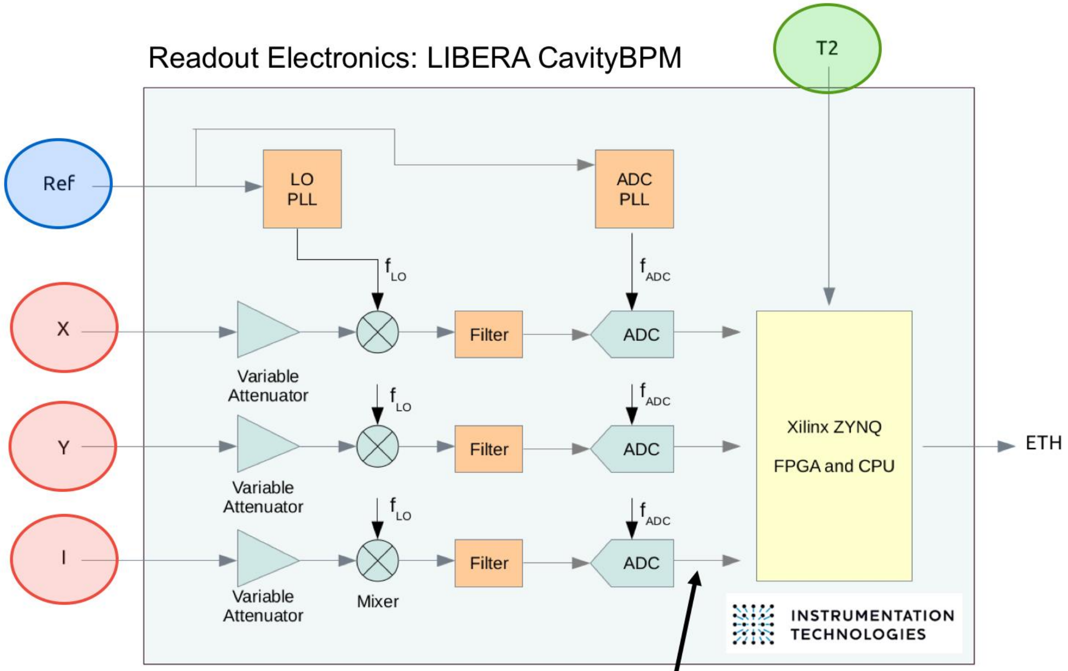
CAVITY BPM - SIGNAL PROCESSING (3/3)



$$V_{X_b} = \sqrt{\sum_{bth\ bunch\ window} {x_n}^2}$$

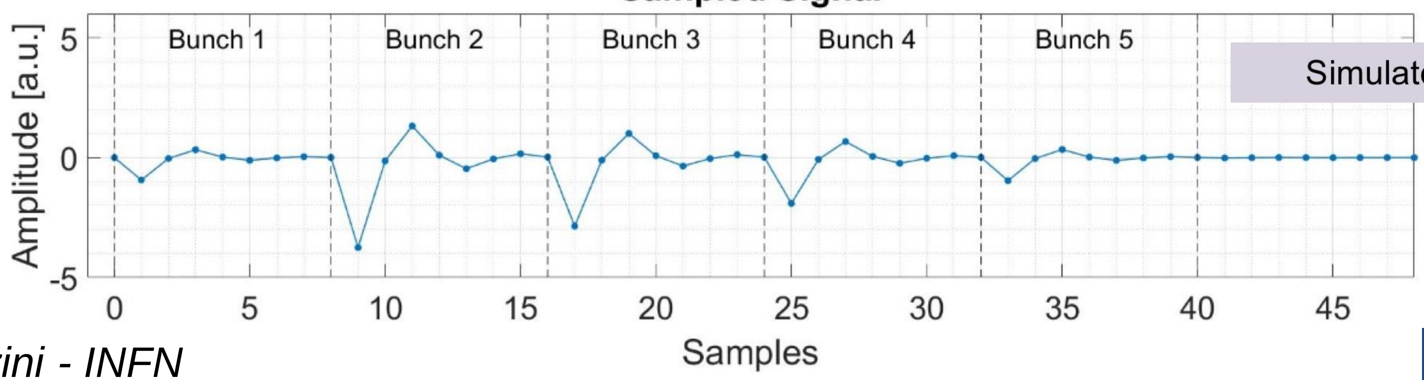
$$V_{Y_b} = \sqrt{\sum_{bth\ bunch\ window} {y_n}^2}$$

$$V_{I_b} = \sqrt{\sum_{bth\ bunch\ window} {i_n}^2}$$

Calc. beam position

$$X_b = K_x \frac{V_{X_b}}{V_{I_b}} \qquad Y_b = K_y \frac{V_{Y_b}}{V_{I_b}}$$

Sampled Signal



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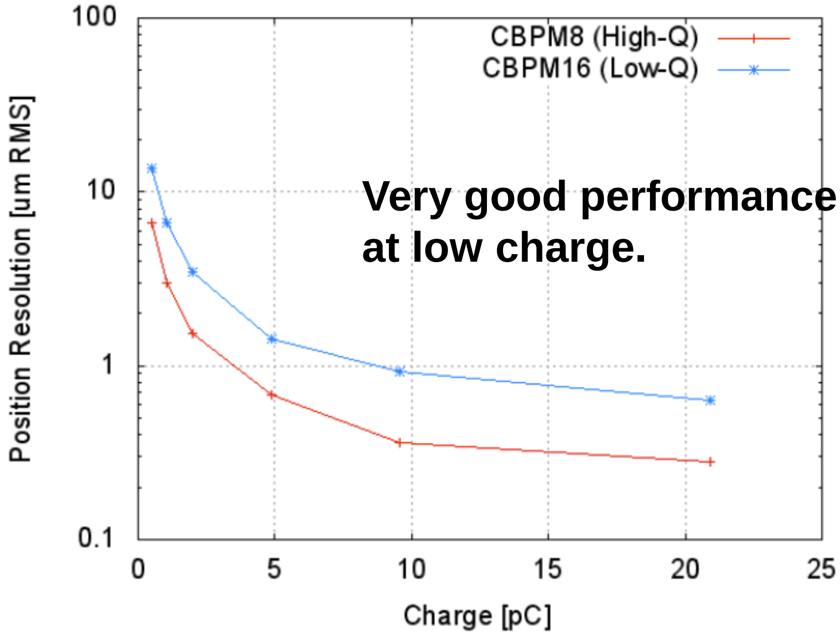
Example

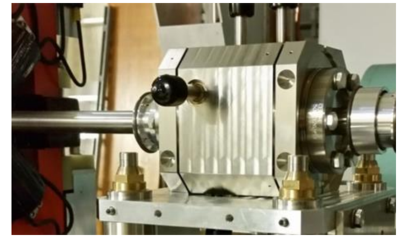
CBPM MEASUREMENTS AT SWISSFEL

Measurement obtained by correlating the reading of three adjacent CBPMs of the same type with similar offset.



Very good performance at low charge.

CBPM16



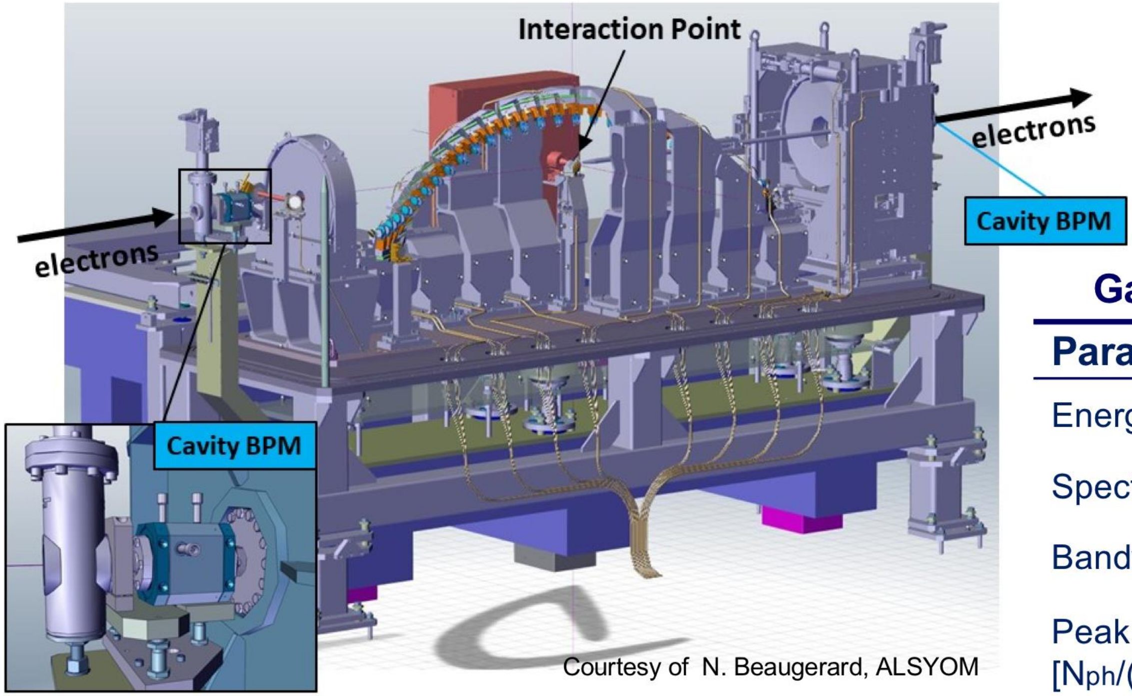
CBPM8

Model	CBPM16	CBPM8
Length	100 mm	100 mm
Inner Aperture	16 mm	8 mm
Typ. Pos. Range	±5 mm	±1 mm
Charge Range	10-200 pC	10-200 pC
Bunch Spacing	28 ns	10 ms
Q_L	40	1000
Frequency	3.2844 GHz	4.9266 GHz

B. Keil et al., **First beam commissioning experience with the SwissFEL CAVITY BPM SYSTEM**, IBIC2017, Grand Rapids, MI, USA

CAVITY BPM IN COMPTON MACHINES

Example



Gamma Beam Specifications

Parameter	Value
Energy [MeV]	0.2 – 19.5
Spectral Density [ph/(s·eV)]	0.8 – $4 \cdot 10^4$
Bandwidth rms [%]	≤ 0.5
Peak brilliance [N_{ph}/(s·mm^2·mrad^2·0.1%)]	10^{20} – 10^{23}

- By using an **optical re-circulator**, a single **laser pulse** will collide with a multi-bunch (up to 32) **electron beam** at the interaction point, generating **the gamma beam by Compton back-scattering.**
- **Two Interaction Point modules are foreseen.** One at low energy ($E_{el.}$ ≤ 280 MeV), the other at high energy ($E_{el.}$ ≤ 720 MeV).

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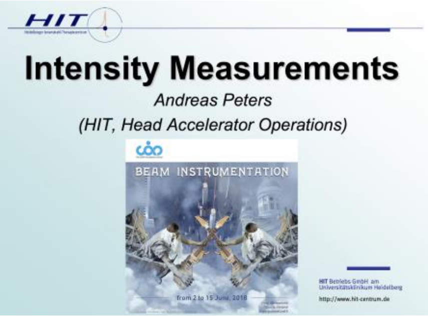
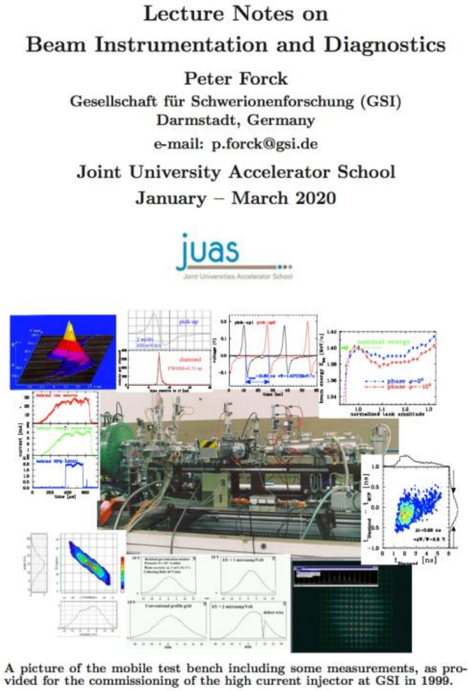
REFERENCES

Beam Instrumentation CAS 2018



A beam instrumentation primer


Lecture Notes on
Beam Instrumentation and Diagnostics
Peter Forck
Gesellschaft für Schwerionenforschung (GSI)
Darmstadt, Germany
e-mail: p.forck@gsi.de
Joint University Accelerator School
January – March 2020
juas

A picture of the mobile test bench including some measurements, as provided for the commissioning of the high current injector at GSI in 1999.

Bergoz Instruments manual – www.bergoz.com

P. Nenzi, et al. Development of a Passive Cavity Beam Intensity Monitor for Pulsed Proton Beams for Medical Applications, IBIC'19, 9 September 2019, Malmö, Sweden

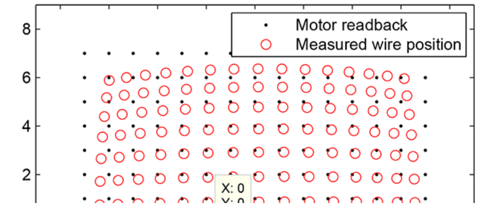
CONCLUSION

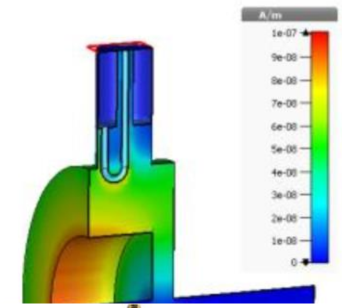
Accuracy and calibration procedures

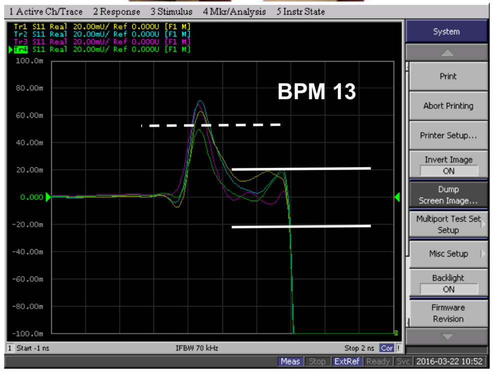
Primer of cavity based beam measurement

Example of industrially available diagnostics

Use of bench measurement in diagnostics set-up







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