Measurement of Cavity BPM Performance

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4. Summary and Outlook

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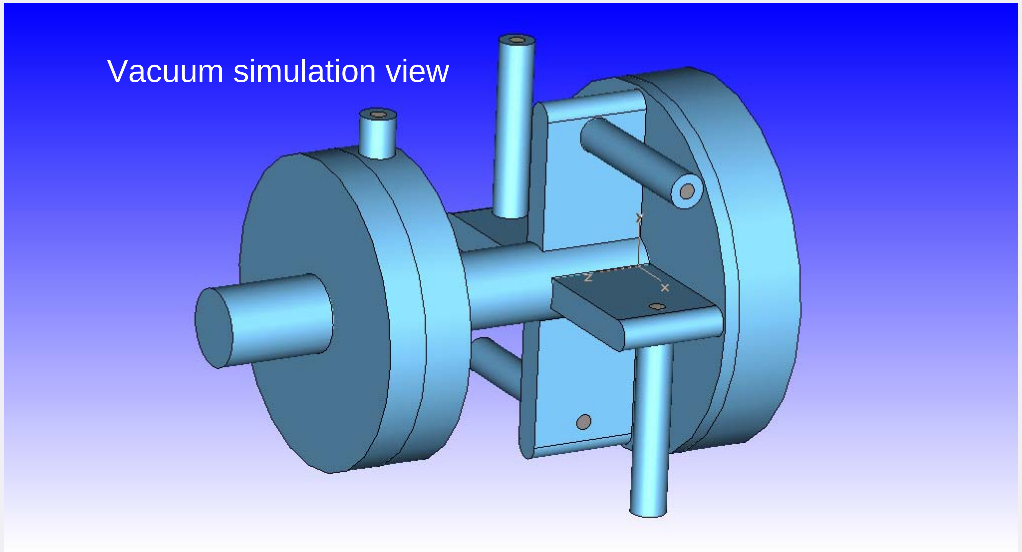
Sorry for forgetting somebody!

Goal

Measurement of

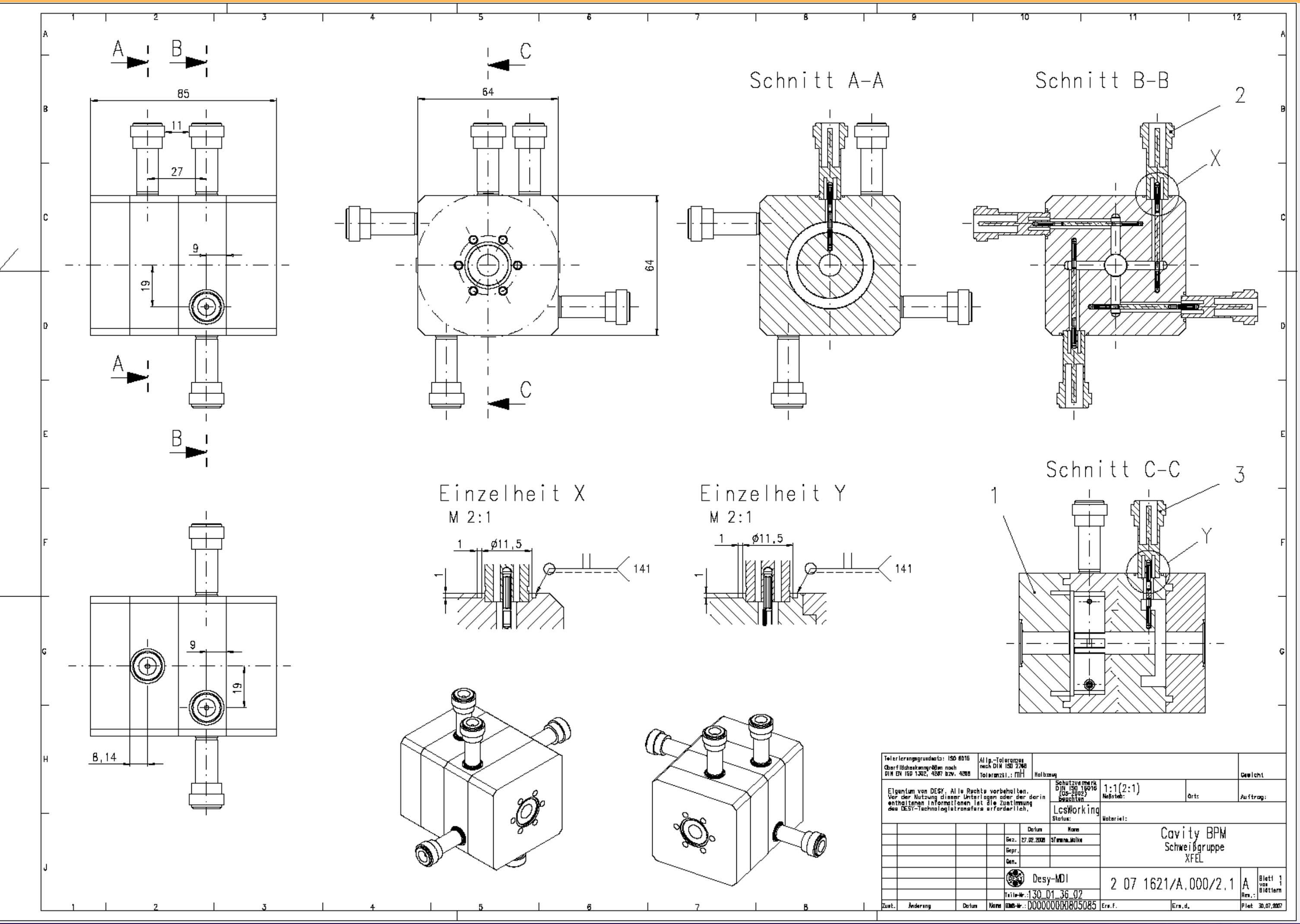
- Resonance frequency
- Bandwidth
- Loaded quality factor
- Orthogonal coupling
- Slope Voltage/Offset and Voltage/Charge

Compare with expectation to improve next generation



Reference and Dipole resonator

Drawing of Cavity BPM



Design frequency of Dipole and Reference resonator = 4.4 GHz

Origin by T. Shintake; SPring-8

Photos

Produced 3 Cavity BPM:

BPM I

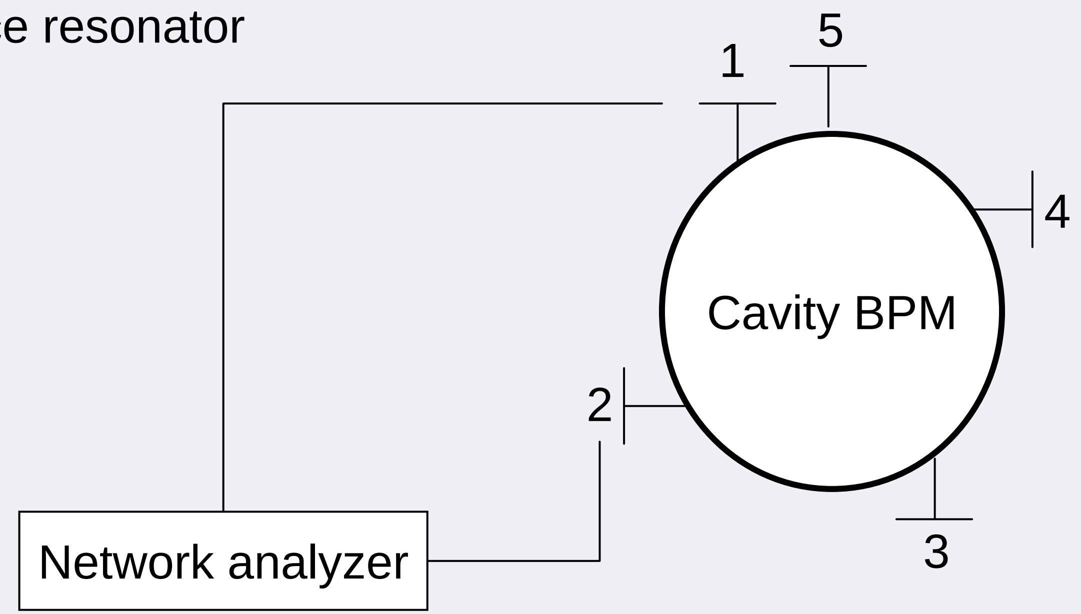
BPM II

BPM III

Measurement setup with Network Analyzer

Port 1 – 4: Dipole resonator

Port 5: Reference resonator



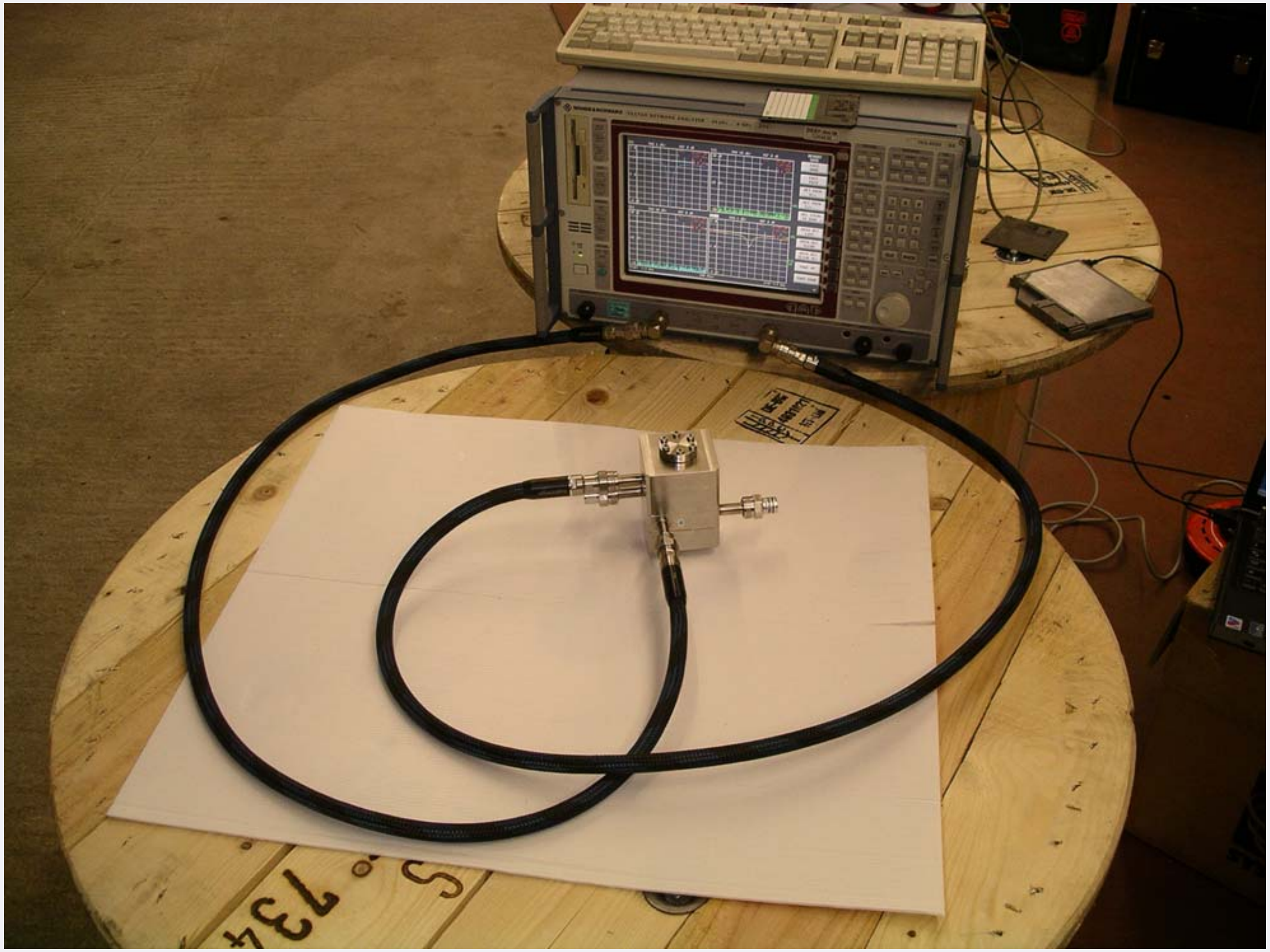
2 channel network analyzer (NWA), measurement of scattering matrix (S-parameter: S11, S22 [reflection] and S12, S21 [transmission])

Other ports terminated with 50 Ohm

NWA: Rohde & Schwarz

Up to 8 GHz

N-Cal-Kit from PSI



Transmission Data: Analysis

Time domain

$$U(t) = U_{out} e^{-\frac{t}{\tau}} \cos(\omega_R t)\Theta(t)$$

$$\omega_R = 2\pi f_R$$

$$f_R = resonance\ \ frequency$$

$$\tau = \frac{Q_L}{\pi f_s},\ decay\ time$$

$$Q_L =,\ loaded\ \ quality\ \ factor$$

$$BW = \frac{f_S}{Q_L},\ bandwidth$$

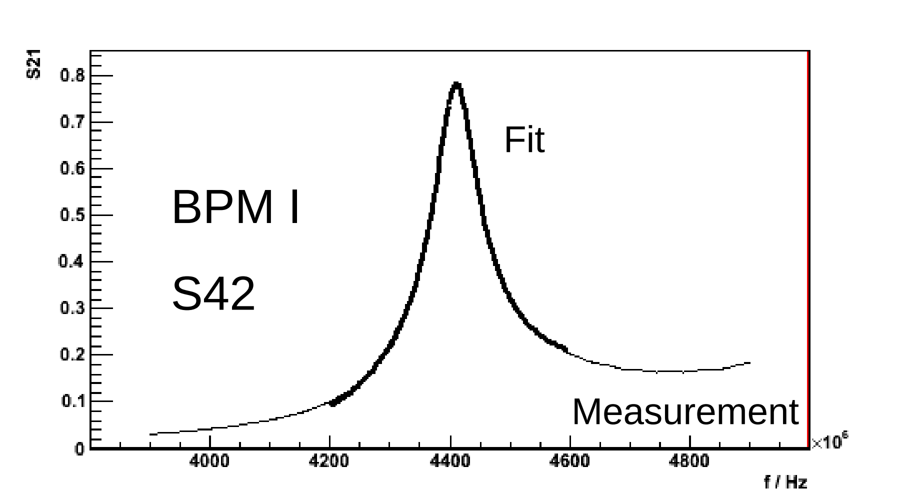
$$U_{out} \propto beam\ offset$$

Fourier transformation

Frequency domain

$$F(\omega) = \frac{U_{out}}{\sqrt{2\pi}} \frac{\frac{1}{\tau} + i\omega}{\left(\frac{1}{\tau} + i\omega\right)^2 + \omega_R^2}$$

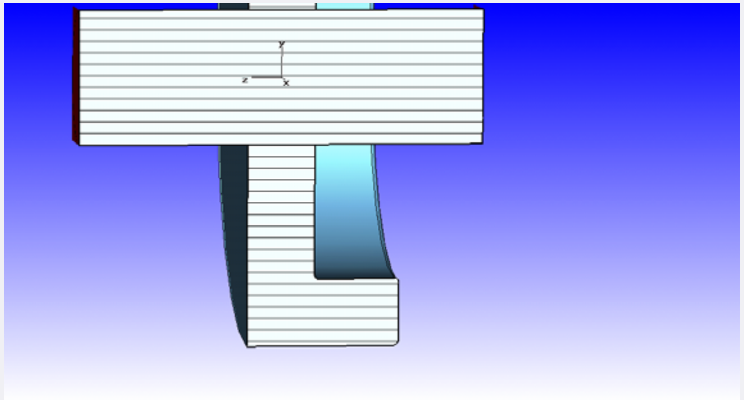
Adapting $|F(\omega)|$ to transmission data gives resonance frequency and loaded quality factor



Dipole resonator: Results

Parameter	Expected	BPM I	BPM II	BPM III
f_R / MHz	4400±17	4408.7 ± 0.6	4419.0 ± 0.5	4414.5 ± 0.6
BW / MHz	74	70.1 ± 2.2	66.7 ± 0.7	72.9 ± 1.5
Q_L	60	63.0 ± 2.0	66.3 ± 0.7	60.6 ± 1.3

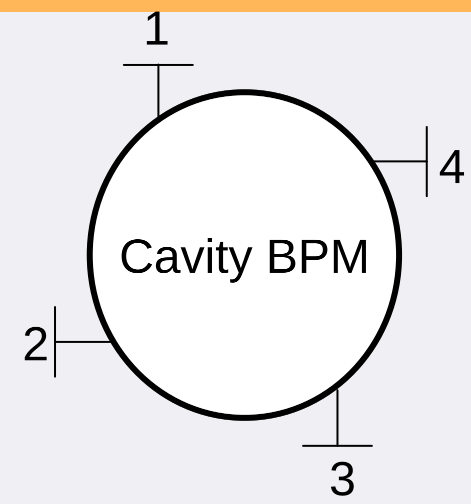
For resonance frequency the reflection data of dipole resonator used too,
Systematic shift of frequency to higher values because of roundings



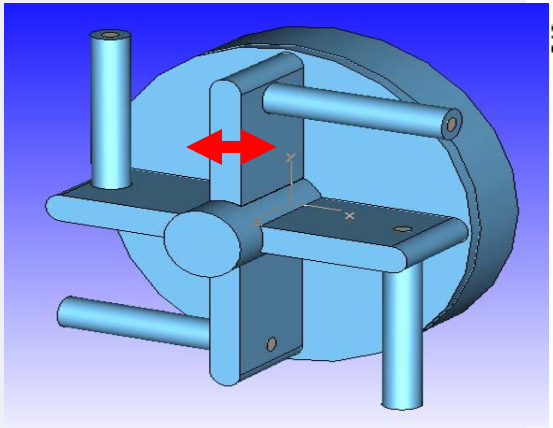
Orthogonal Coupling

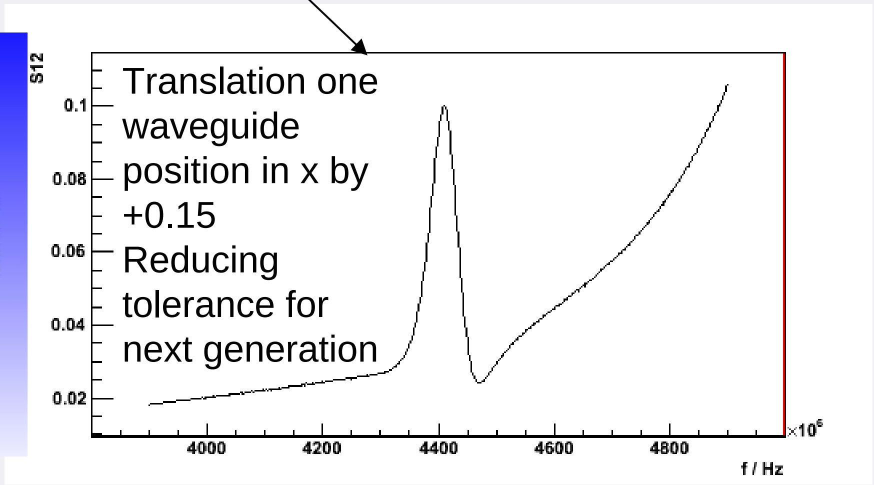
expected: -28 dB

Ports	BPM I / dB	BPM II / dB	BPM III / dB
1-2 3-4	-30.9 ± 0.1	-30.7 ± 0.3	-20.0 ± 0.2
1-4 2-3	-27.0 ± 0.1	-28.8 ± 0.3	-27.5 ± 0.5



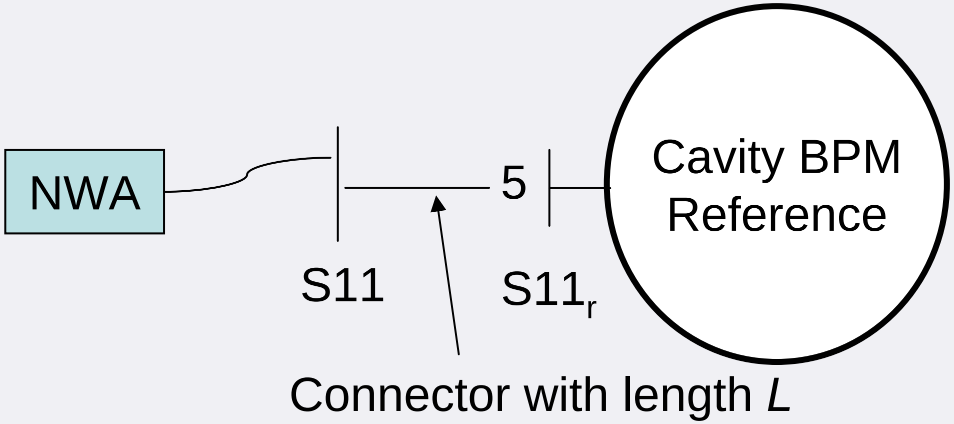
BPM III is installed in beamline for beam measurement, possible to measure coupling with fast oscilloscope





Reference Resonator: Analysis

Only Reflection S11 because one port on this resonator



$$S11_r = S11 e^{j2\beta L}$$

$$\beta = \frac{2\pi}{v_p}$$

$$v_p = \frac{c}{\sqrt{\varepsilon_r}}$$

c – light velocity

ε_r – dielectric

$$Z_r = 50\Omega \frac{1 + S11_r}{1 - S11_r}$$

Measured S11 -> recalculate to $S11_r$ -> recalculate to impedance *Z*

Adjust *L* until $Re(Z_r)$ constant, point of intersection between *Re* and |*Im*| gives bandwidth for Q_L with Z_r + 50 Ohm

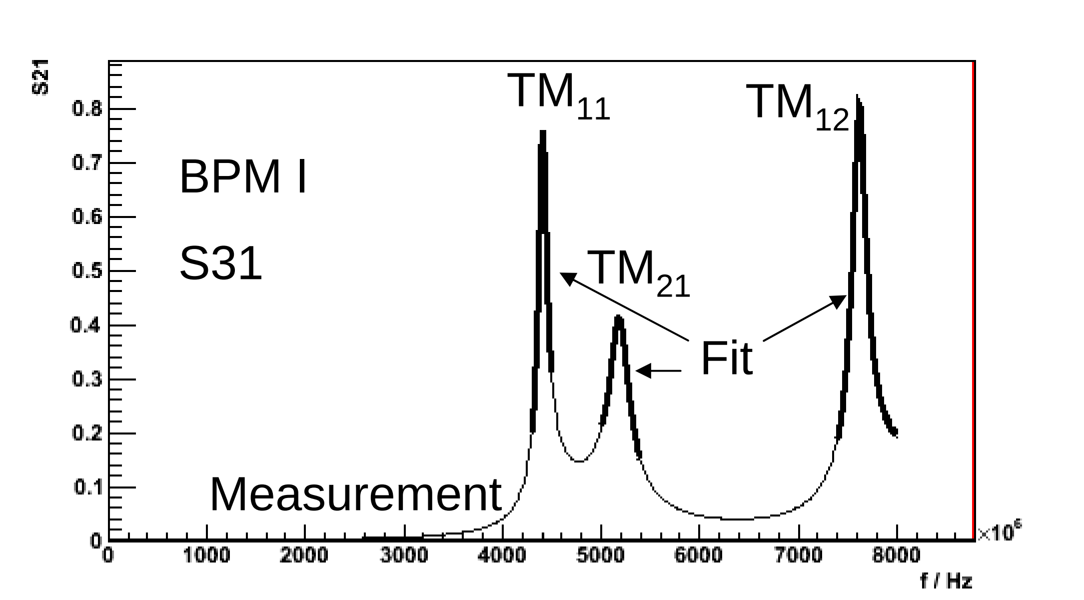
Reference Resonator: Results

Parameter	Expected	BPM I	BPM II	BPM III
f_R / MHz	4400 ± 16	4410.6 ± 0.2	4412.0 ± 0.1	4411.5 ± 0.1
BW / MHz	70	67.75 ± 0.95	69.59 ± 0.92	70.63 ± 0.36
Q_L	62	65.11 ± 0.91	63.41 ± 0.85	62.46 ± 0.32

Systematic shift of frequency to higher values

because rounding causes this shift

Transmission Data broad frequency range



Adapting $|F(\omega)|$ to broad frequency range transmission data gives resonance frequency and loaded quality factor for higher order modes

Global fit does not describe background perfectly, therefore range per mode restricted

Transmission Data broad frequency range: Results

Mode	Parameter	Expected	BPM I	BPM II
TM_{11}	f_R / MHz	4400 ± 17	4409.0 ± 0.7	4419.2 ± 0.4
	Q_L	60	62.8 ±1.9	65.4 ± 0.4
TM_{21}	f_R / MHz	5192	5183.1 ± 0.4	5191.5 ± 0.4
	Q_L	30	29.2 ± 0.2	29.9 ± 0.2
TM_{12}	f_R / MHz	7612	7623.6 ± 3.2	7618.2 ± 1.0
	Q_L	54	61.6 ± 0.3	60.3 ± 1.8

Measured values shown

Result: Agreement with short range TM_{11}, therefore broad range can be used too

Reflection Data:

Too few data points to get result of quality factor

Summary Network Analyzer Measurement

- Measured frequency, loaded quality factor of dipole and reference resonator
- Measured orthogonal coupling of dipole resonator
- Frequency shifted to higher values due to rounding
- Orthogonal coupling of BPM III higher because of mechanical tolerances

BPM III in Beamline

Beam Measurement with Oscilloscope (6 GHz, 20GS/s), 123 m cable between BPM and Oscilloscope

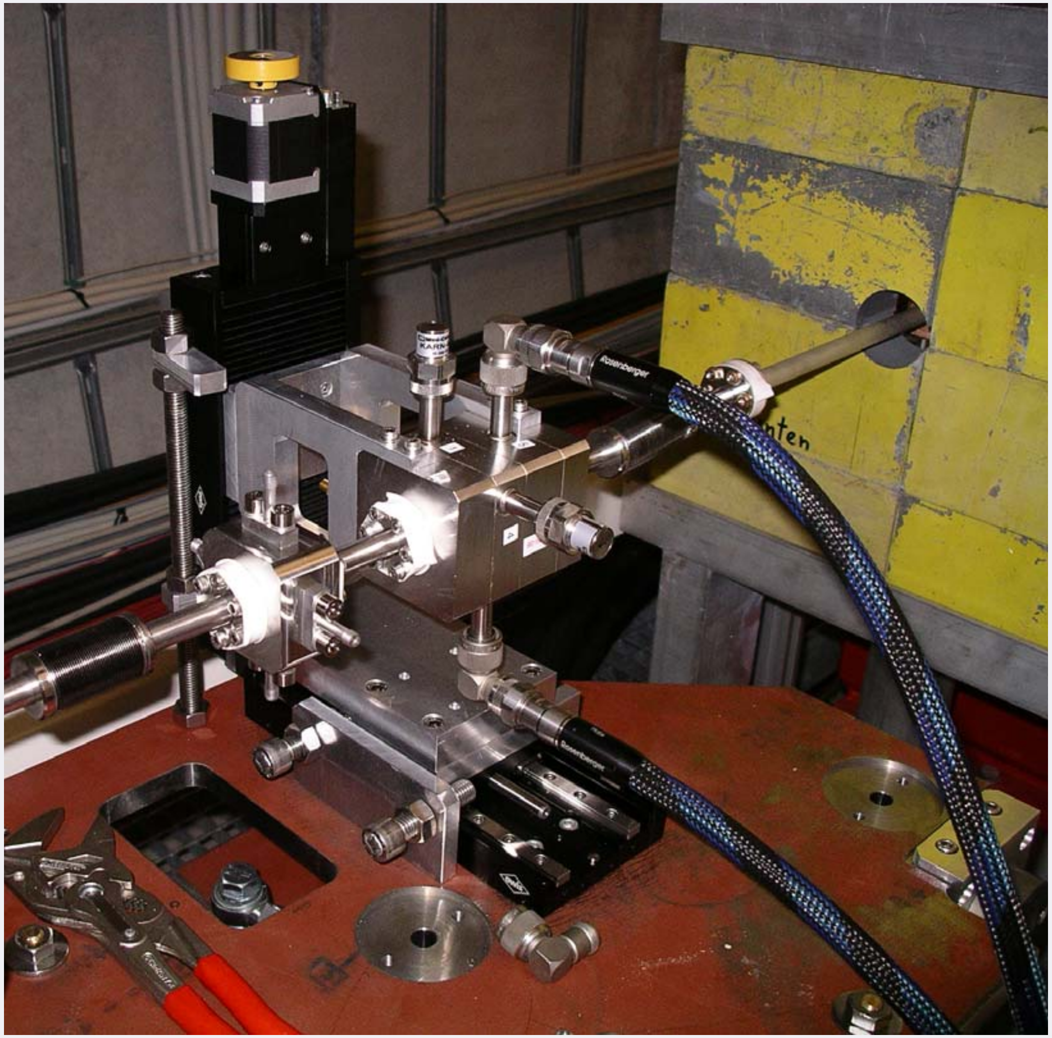
Available: stepper motor in both transverse directions (x, y)

Test of movement range, boundaries determined by beam loss monitor:

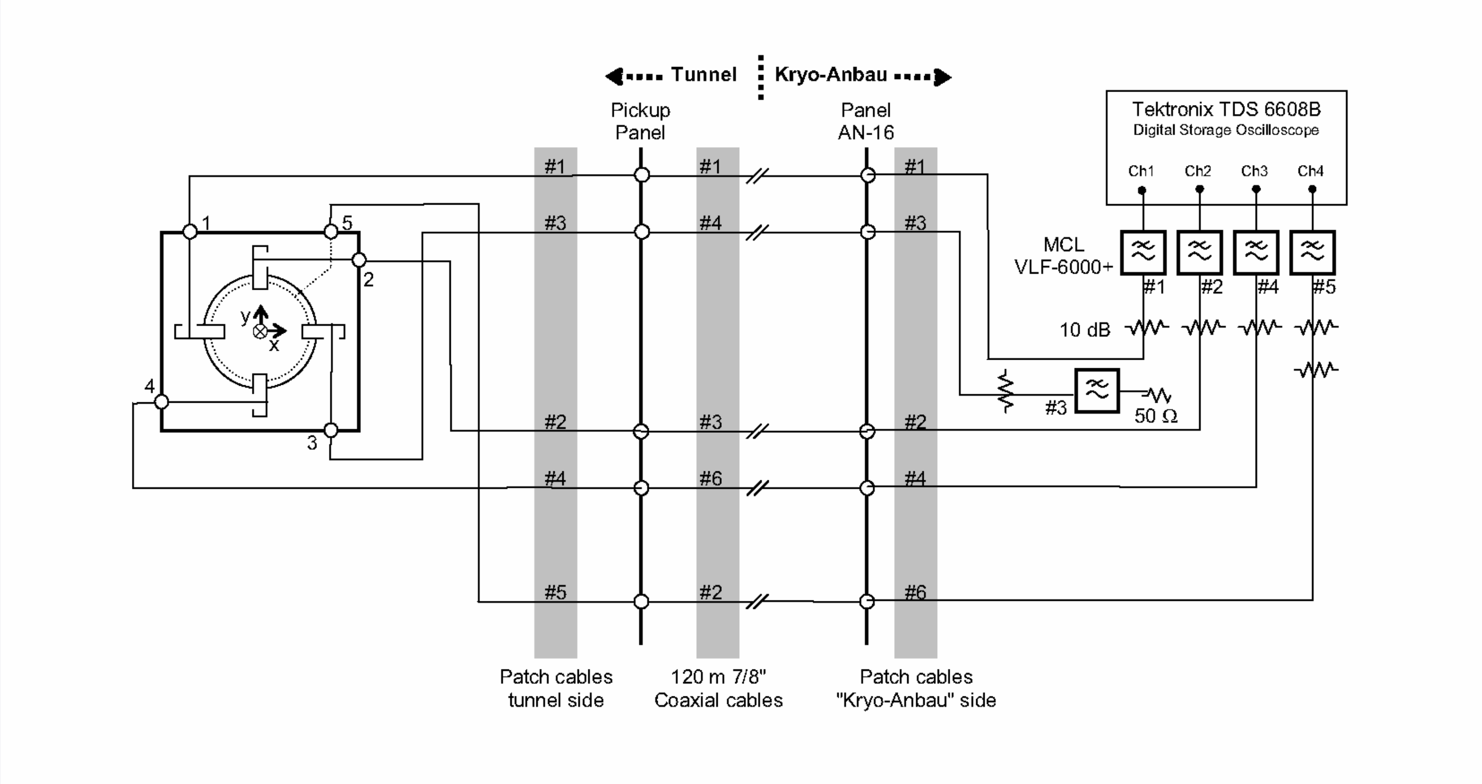
Horizontal: between -1.57 and 2.05 mm

Vertical: between -2.82 and 0.97 mm

SASE not affected!



Setup



Reference resonator signal always on channel 4
Free port terminated with 50 Ohm load

Attenuation and Phase shift of cables and filters

Table: Summary of signal losses and phase differences in [dB] and [°].

Signal (pickup port nr.)	Patch cable tunnel side [dB] ∠ [°]	120 m 7/8" Coaxial cable from [2]	Patch cable "Kryo-Anbau" side	Low pass filter	Total
1 D_Y	1.50 ∠ 0	10.5 ∠ 0	1.70 ∠ 0	0.49 ∠ 0.0	14.2 ∠ 0.0
2 D_X	1.35 ∠ 3	10.5 ∠ −2.5	1.45 ∠ −5	0.47 ∠ −0.9	13.8 ∠ −5.4
3 D_Y	1.60 ∠ −5	10.5 ∠ 17	1.50 ∠ 8	0.45 ∠ 0.8	14.1 ∠ 20.8
4 D_X	1.55 ∠ 6.5	10.0 ∠ −14	1.50 ∠ 4	0.44 ∠ 3.5	13.5 ∠ 0.0
5 Ref	1.52 ∠ 2.5	9.8 ∠ −7	1.65 ∠ 10	0.54 ∠ −0.9	13.5 ∠ 4.6

In addition 10 dB attenuator for Dipole signals and 20 dB for Reference signal

Fit function

To increase oscilloscope resolution for amplitude a fit is applied to the time signal, in addition resonance frequency and loaded quality factor is observed:

$$U(t) = U_{out} e^{-\frac{t-t_s}{\tau}} \cos(\omega_R t + \phi)\Theta(t_{trigger} + t_s)$$

$$\omega_R = 2\pi f_R$$

f_R *resonance frequency*

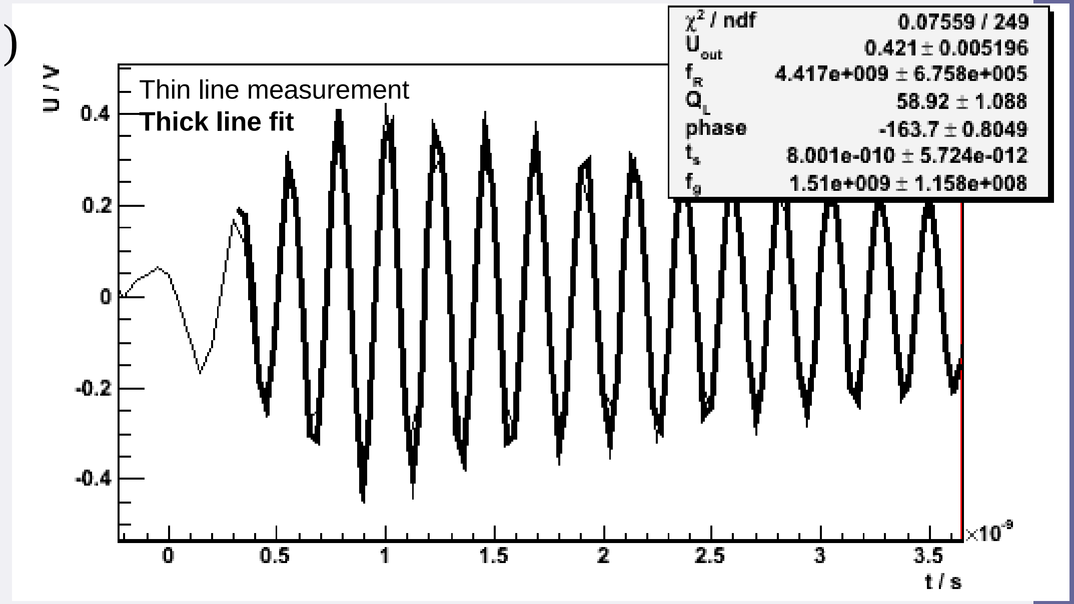
$$\tau = \frac{Q_L}{\pi f_s}, \text{ decay time}$$

Q_L *loaded quality factor*

$U_{out} \propto$ *beam offset*

ϕ *phase offset*

t_s *end of transient oscillation*

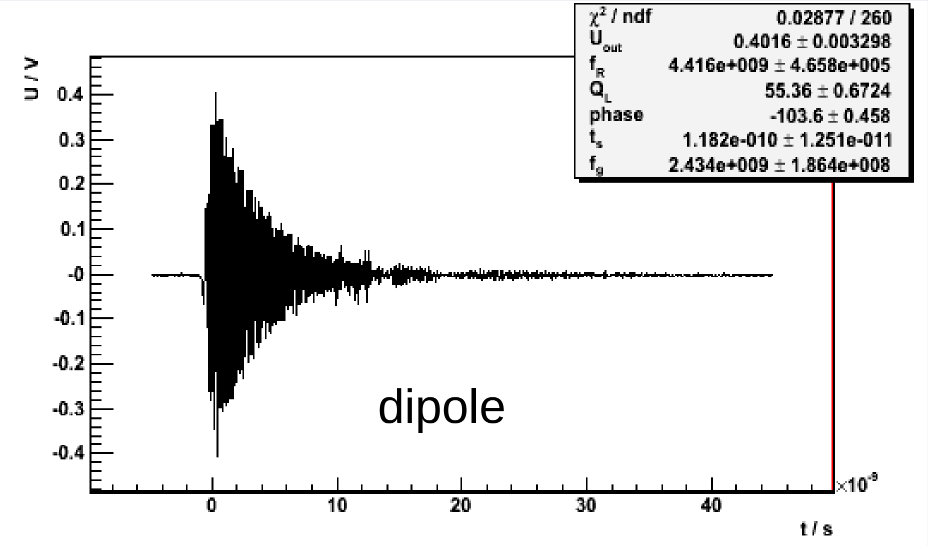


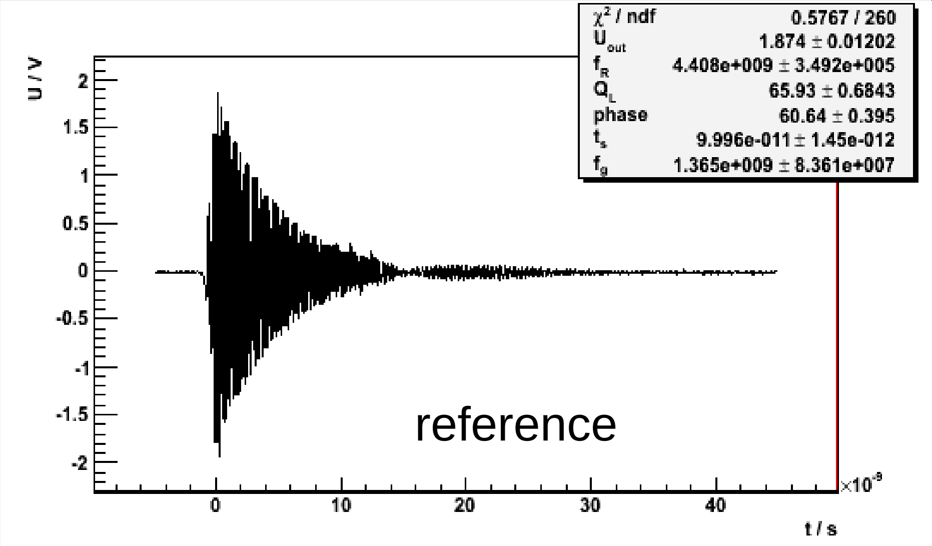
For time between $t_{trigger}$ and t_s (transient oscillation):

$$U(t) = U_{out} e^{(t-t_s) f_g} \cos(\omega_R t + \phi)$$

f_g *gradient frequency*

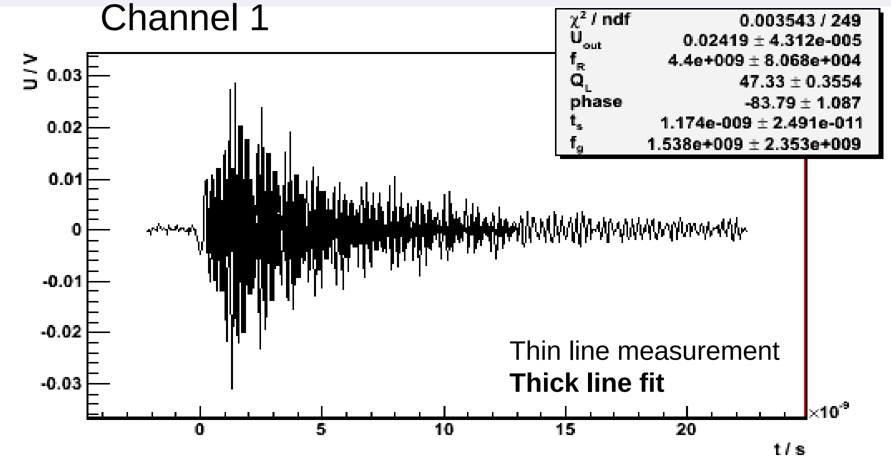
Fit maximum range

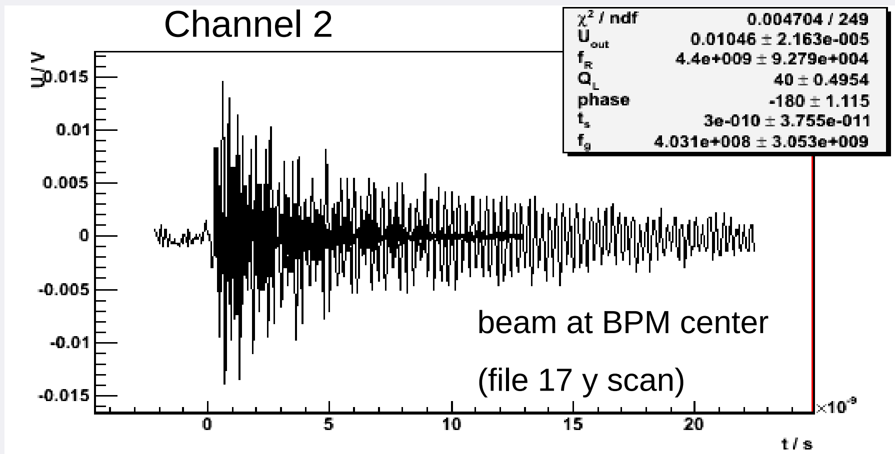


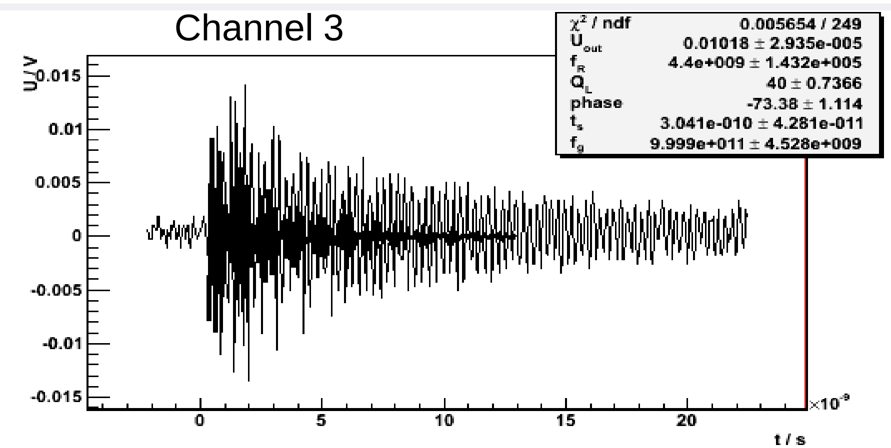


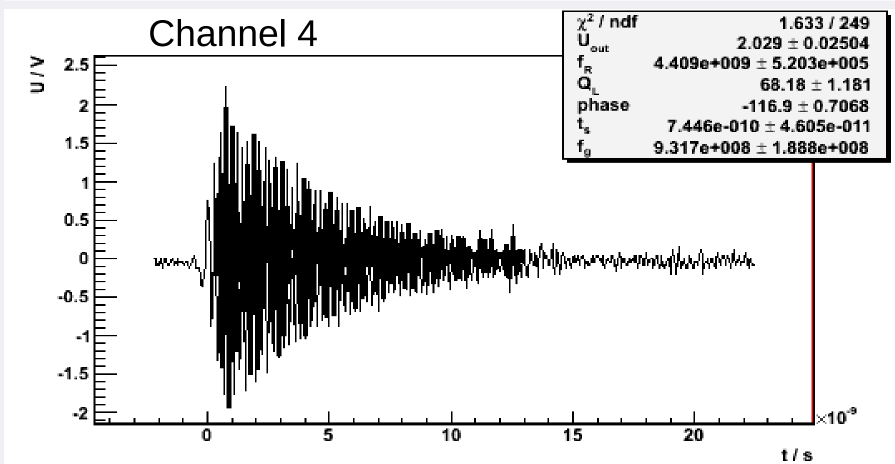
- t = 14 ns shows an additional oscillation: reflection between patch cable in tunnel (1.5 m long connected on BPM) and 7/8'' coaxial cable
- therefore time of fit limited to t_{max} = 13 ns

Fit at small offsets



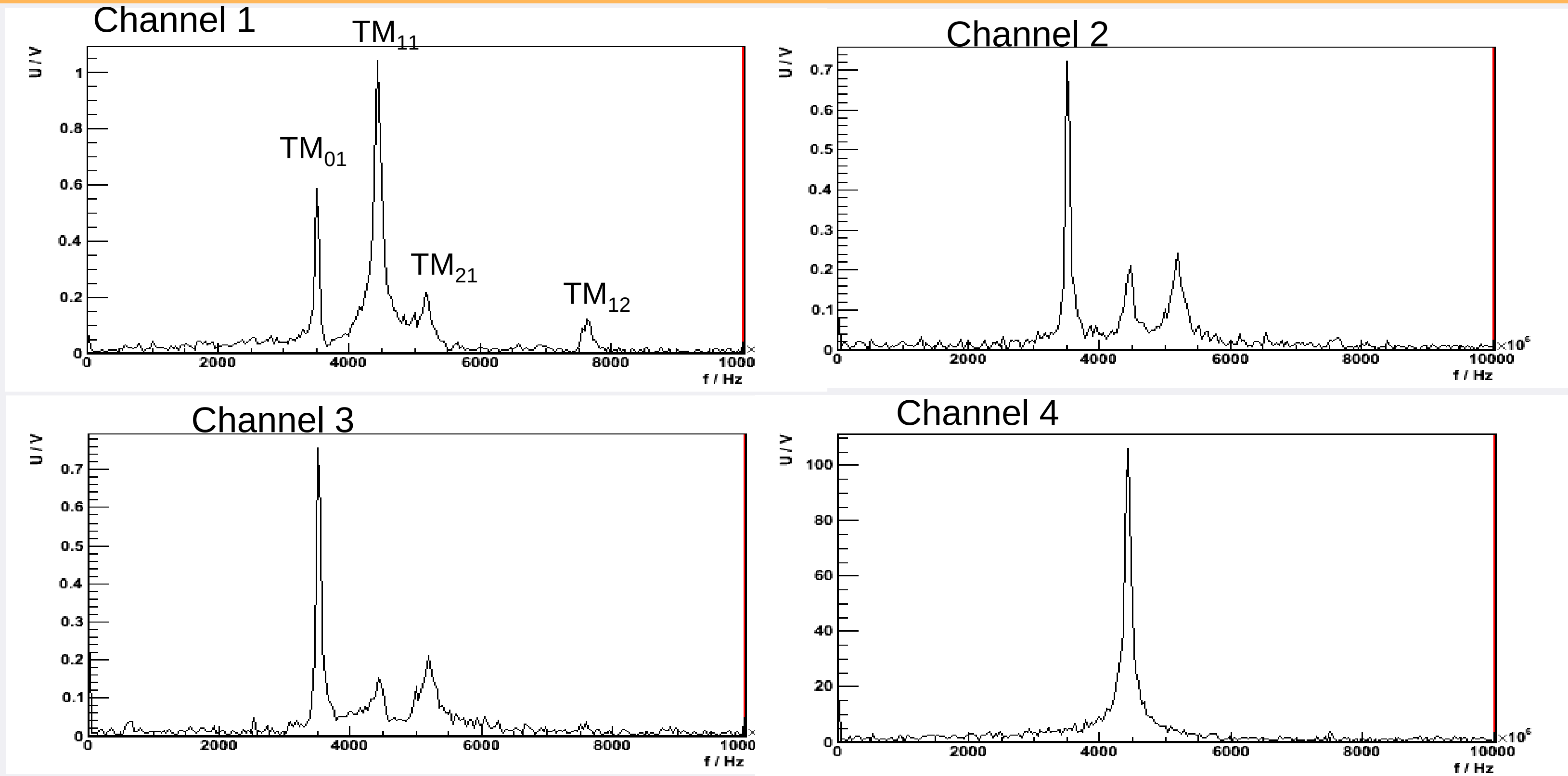






For small offsets the fit does not describe to the data perfectly, frequency and loaded quality factor at boundary

Frequency Domain

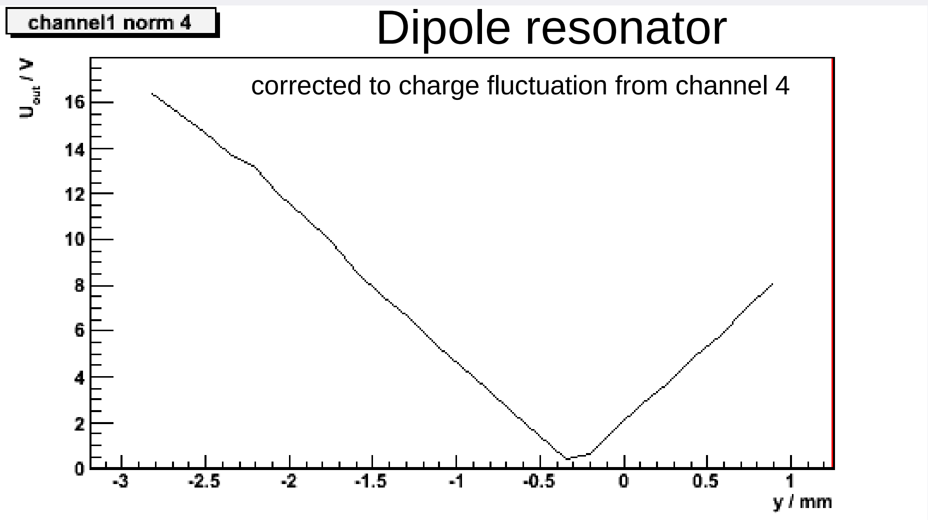


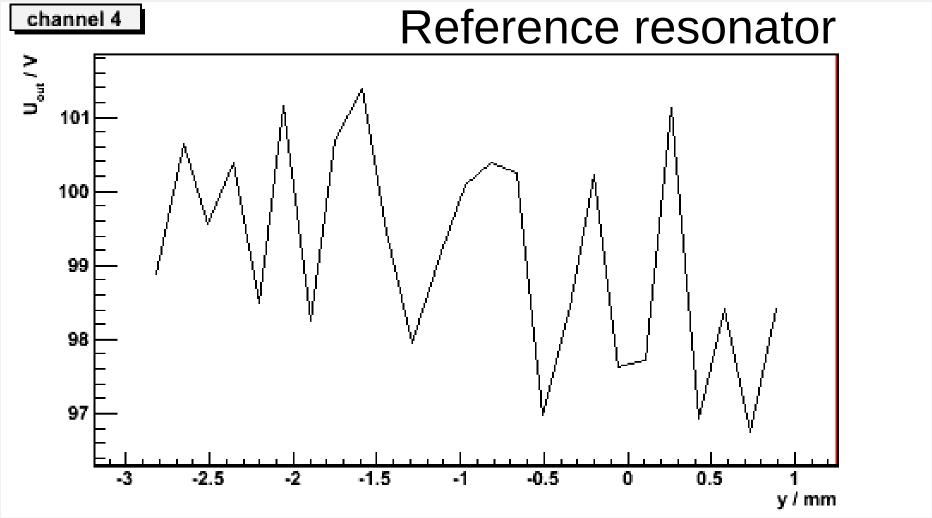
Because other frequencies contribute to the signal

But amplitudes from fit are useful at small offsets too; resonance frequency and loaded quality factor are taken outside of the beam offset minimum

Vertical Scan

Charge about 0.65 nC, Voltage corrected to attenuation





Dipole resonator:
f_R = 4417.7 ± 0.8 MHz
Q_L = 56.7 ± 1.8

Left slope: -6.63 V/mm
Right slope: 6.71 V/mm

Reference resonator:
f_R = 4407.4 ± 0.9 MHz
Q_L = 68.8 ± 1.1

U_{mean} = 99.1 ± 1.3 V

Errors are standard deviation

Scan Results in horizontal and vertical direction: Slope

	Charge Toroid / nC	|Slope| / V/mm	|Slope| / V/(mm nC)	U_{ref} / V	U_{ref} / V/nC
X scan	0.653 ± 0.010	6.62 ± 0.19	10.13 ± 0.33	100.2 ± 1.2	153.4 ± 3.0
Y scan	0.662 ± 0.009	6.67 ± 0.06	10.08 ± 0.15	99.1 ± 1.3	149.8 ± 2.8
Average 20 Pulses X scan	0.656 ± 0.009	6.12 ± 0.16	9.33 ± 0.28	91.2 ± 1.3	138.9 ± 2.8
Average 20 Pulses Y scan	0.649 ± 0.010	5.78 ± 0.29	8.91 ± 0.47	84.7 ± 1.2	130.5 ± 2.8

Simulation: 9.8 V/(mm nC) 92.6 V/nC

Toroid charge almost constant but reference and dipole data decreasing

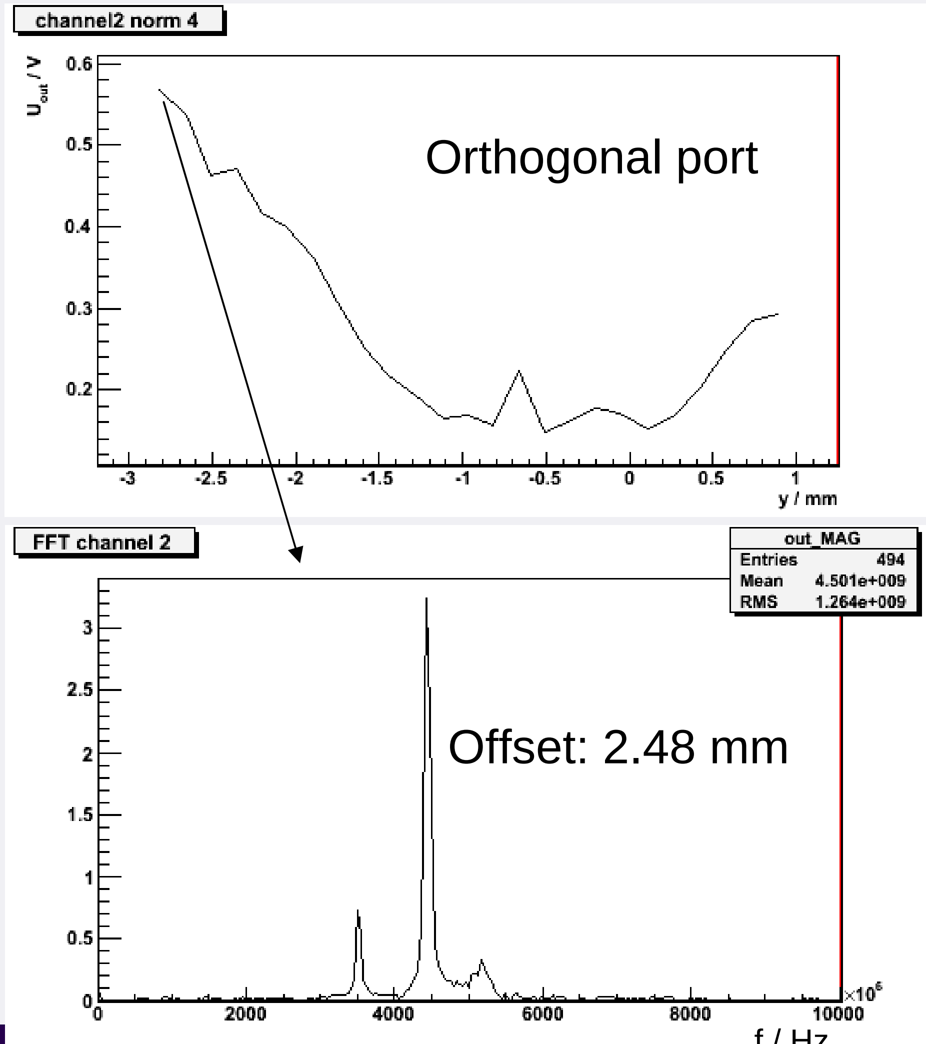
Measurement has to be repeated

Scan Results in horizontal and vertical direction: *f*, *Q*

Dipole resonator:	NWA Measurement:	Expected:
f_R = 4416.8 ± 0.6 MHz	4414.5 ± 0.6 MHz	4400 ± 17
Q_L = 57.0 ± 0.9	60.6 ± 1.3	60
Reference resonator:		
f_R = 4407.8 ± 0.1 MHz	4411.5 ± 0.1	4400 ± 16
Q_L = 67.1 ± 0.4	62.46 ± 0.32	62

Frequency domain measurement with higher resolution; here only statistical uncertainty

Crosstalk



Slope of orthogonal Ports shows increase of signal (crosstalk)

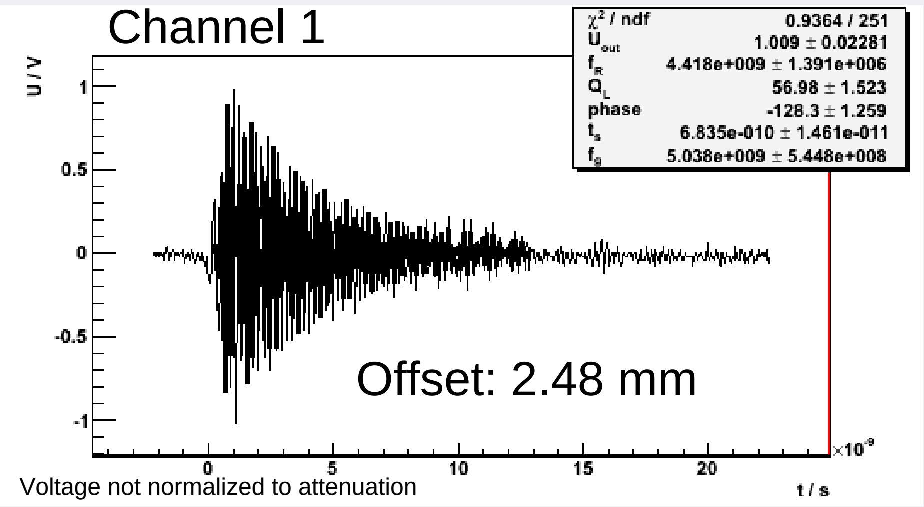
Result: -29 dB for all measured orthogonal Ports

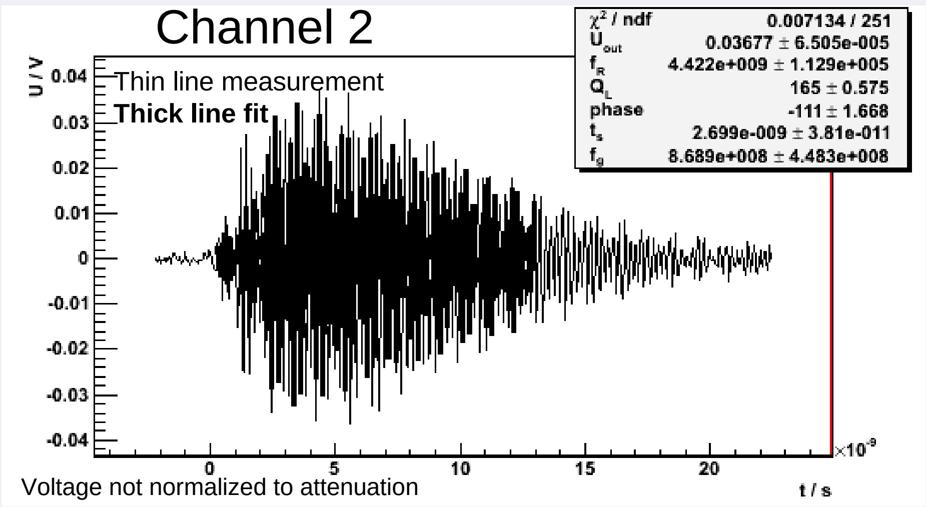
Analysis of time data to frequency domain gives slope, results in a crosstalk of -23 dB

NWA Measurement: -20 and -27.5 dB

Crosstalk in time and frequency domain

Question: crosstalk in time domain smaller compared to frequency domain?





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Reason: larger loaded quality factor on orthogonal port gives larger signal in frequency domain

Result: Crosstalk depend on analysis/electronics!

Summary Beam Measurement and Outlook

- Measured time signals from cavity BPM: dipole and reference resonator
- Slope of Reference Cavity higher as expected
- Measurements has to be repeated with monitoring charge synchronously
- Crosstalk

- Next prototypes: 3.3 GHz (cooperation decision)
- Number: 3 for resolution measurement installed at FLASH each with stepper motor in both transverse directions
- Status: Design
- Date of installation: Christmas 2008, measurement until April 2009