# Overview of BPM button design and operational issues: BESSY II & VSR

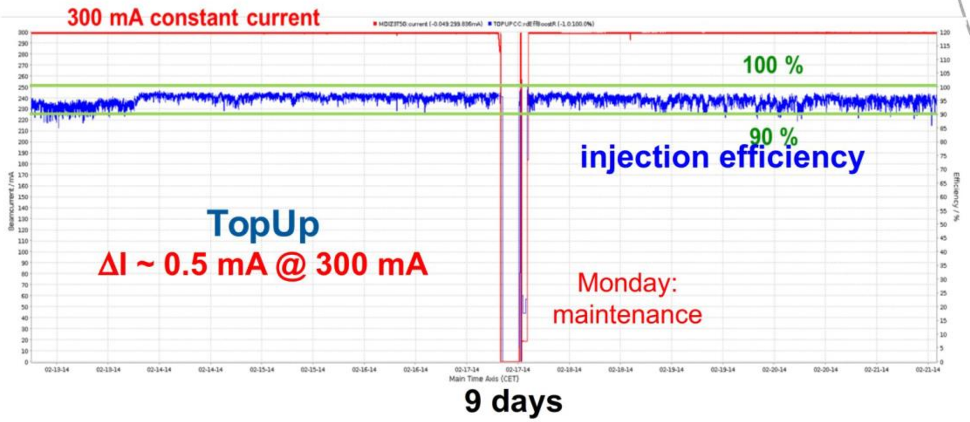
**J.-G. Hwang**, G. Schiwietz, M. Ries, A. Schälicke, F. Falkenstern, V. Dürr, D. Wolk
BESSY II, Helmholtz-Zentrum Berlin (HZB)

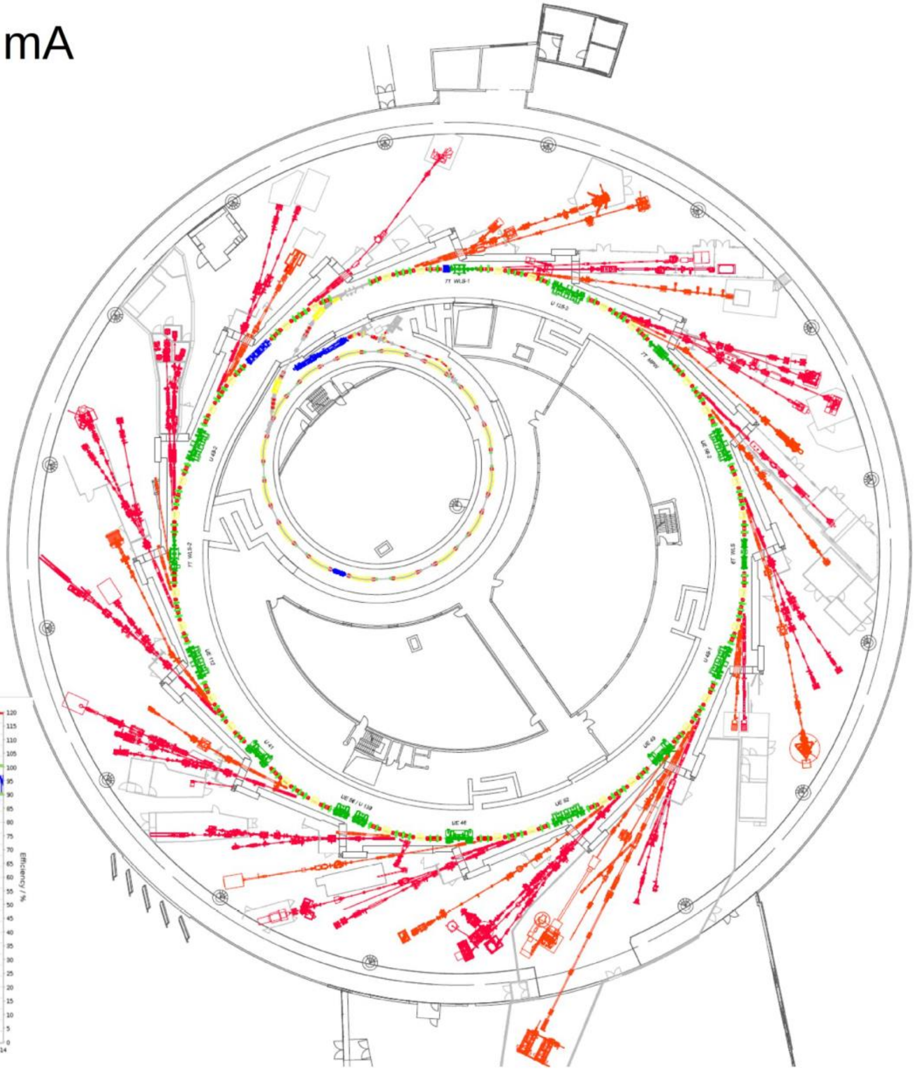
# BESSY II : 3rd generation light source (UV / XUV / soft X-ray)

Successor of BESSY I, construction 1992 – 1998, user operation 1999

- Energy / Current 1.7 GeV / 300 mA
- Circumference 240 m (DBA)
- Emittance 5 nm rad
- Pulse length 15 ps
- Straight sections 16 / 14
- Undulat./MPW+WLS 12 / 1+2
- Beamlines (ID, Bend) 30, 20

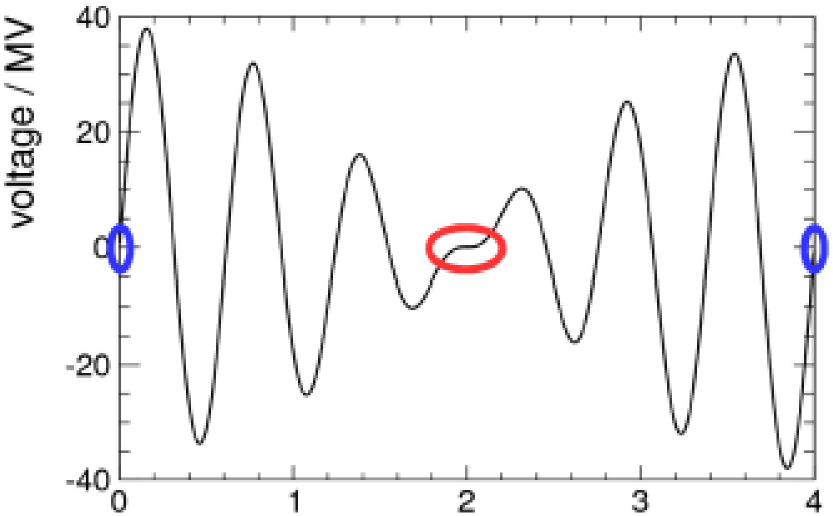
5000 h user operation and
3000 user visits / year



# BESSY Variable pulse-length Storage Ring (BESSY VSR)

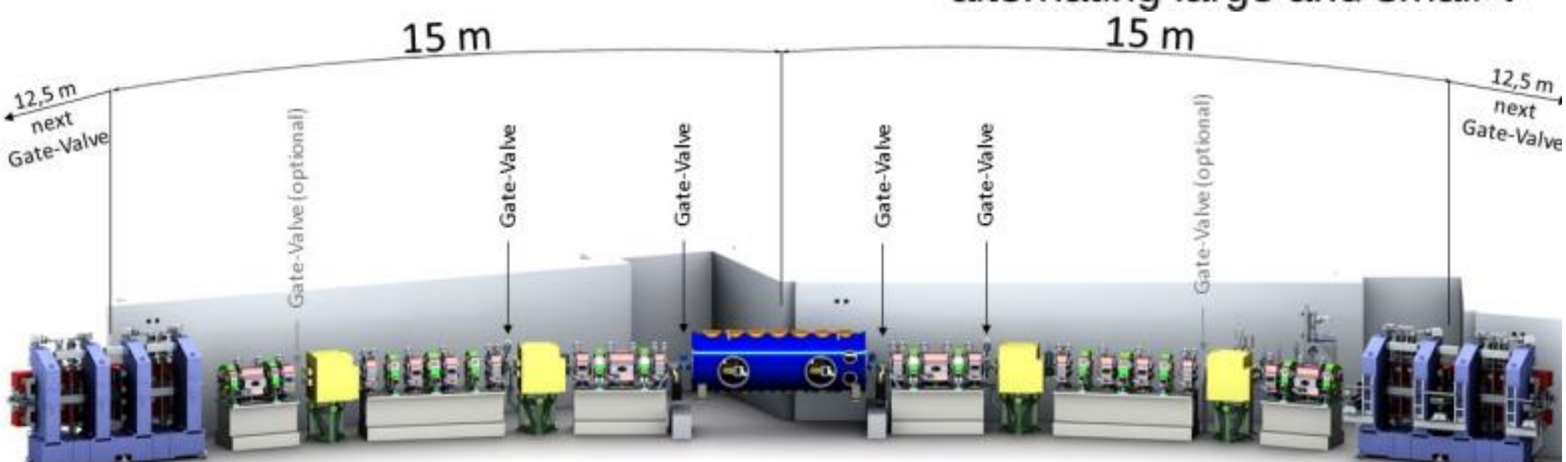
## Short and long bunches simultaneously




A. Jankowiak, J. Knobloch, *et al.*,
"Technical Design Study BESSY VSR",

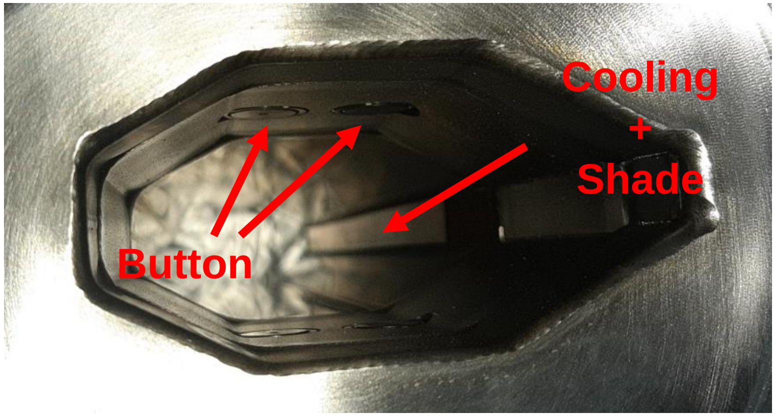
## Cavity system for gradient manipulation

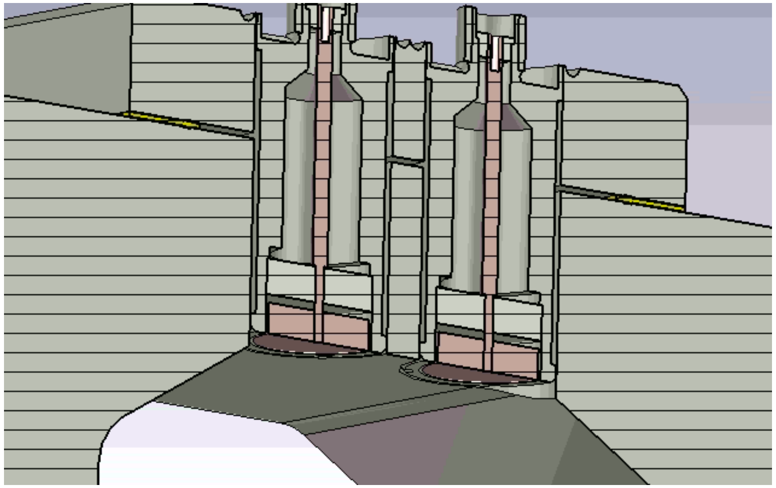
- Normal installed rf cavity
  V' = 2π 0.5 1.5 GHz MV
- 1st SC RF cavity, 3rd harmonic
  V' = 2π 1.5 20 GHz MV
- 2nd SC RF cavity, 3.5th harmonic
  V' = 2π 1.75 17 GHz MV
- In total V'(BII) = 0.75 GHz MV
  V'(VSR) = 60.0 GHz MV
- Voltage beating results in alternating large and small V'




**Refurbishment of vacuum system including BPMs**

construction 1992 – 1998



### 20 years-old "Mature" button-BPM

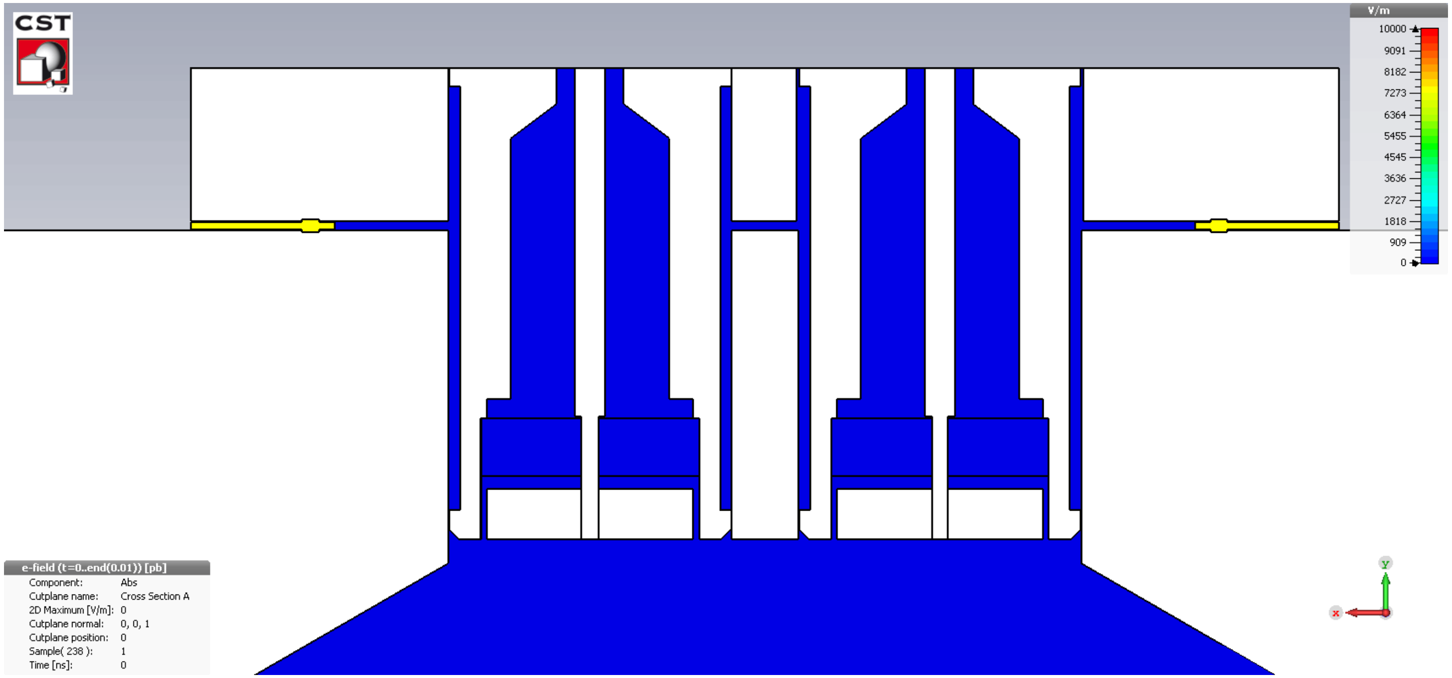
Rectangular-type Flange for easy **swap out**
SUS(housing) – Molybdenum (Button)
(* to reduce the power on button)
Insulator : **Alumina**
Chamber : **69 (H) x 35 (V) mm**
Button diameter : **10.6 mm**
H-Gap : 400 µm
Distance between two buttons : **18.3 mm**
**(7.7 mm)**

Shade is placed on the side to mitigate heat caused by synchrotron radiation.

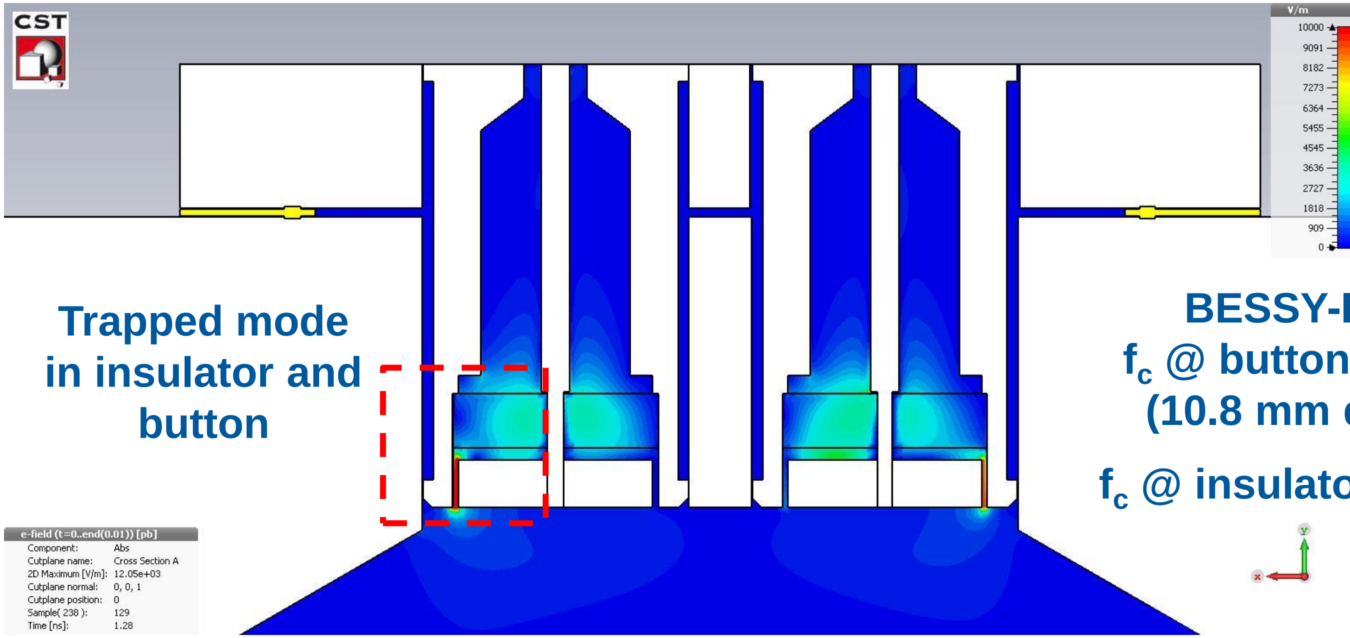
**Issues for new BESSY VSR straight**

1. Button size for small chamber
2. Short bunch length in VSR scheme
3. Signal contamination by preceding bunches

# Trapped mode in insulator in mature BPM

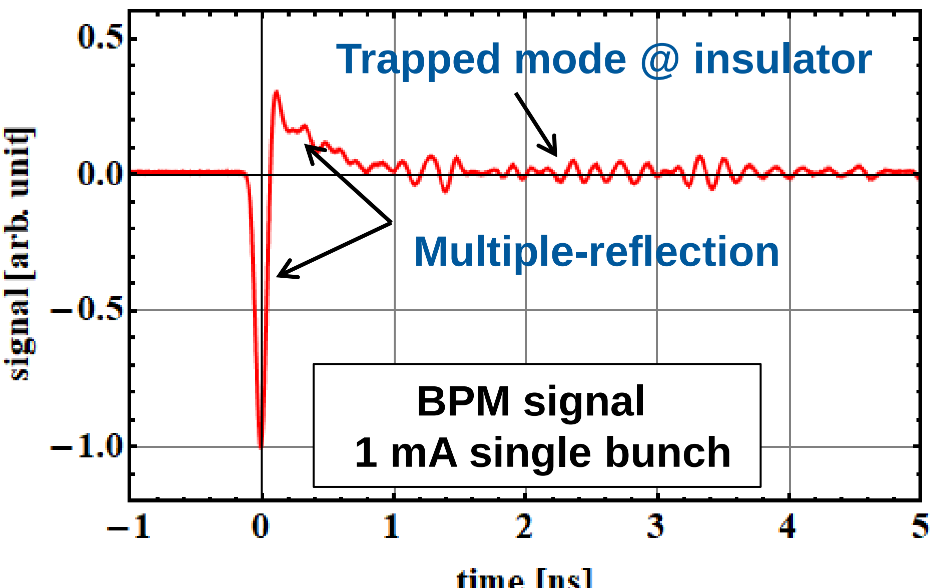


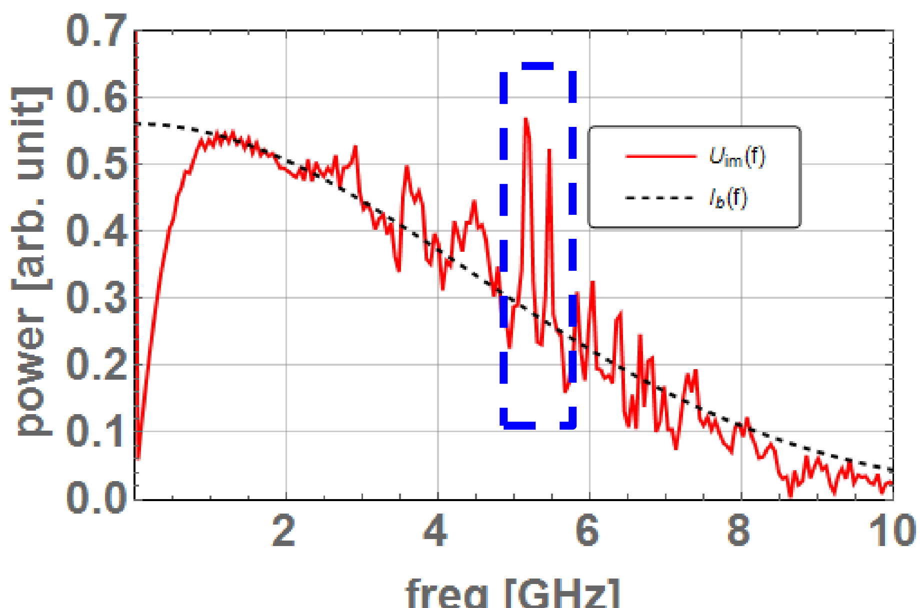
# Trapped mode in insulator in mature BPM



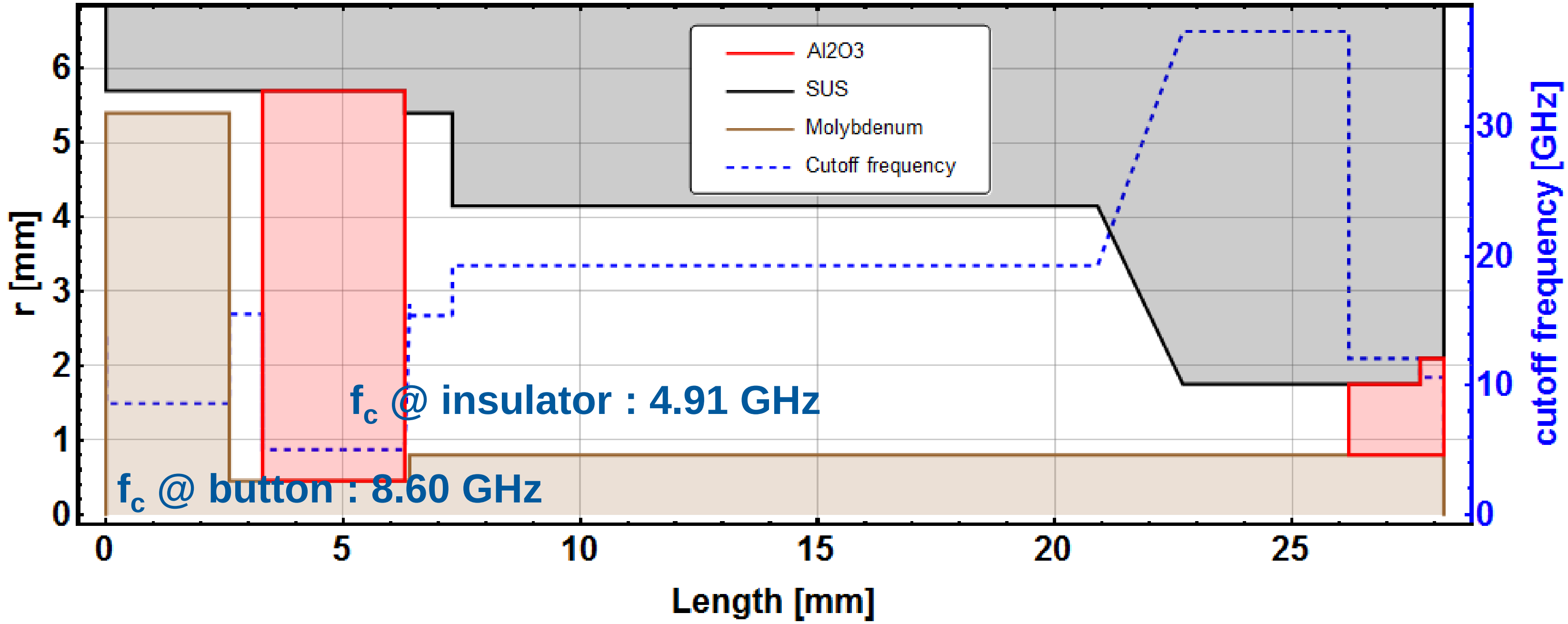

**BESSY-II button**
$f_c$ @ button : 8.60 GHz
(10.8 mm diameter )

$f_c$ @ insulator : 4.91 GHz



# Trapped mode in insulator in mature BPM

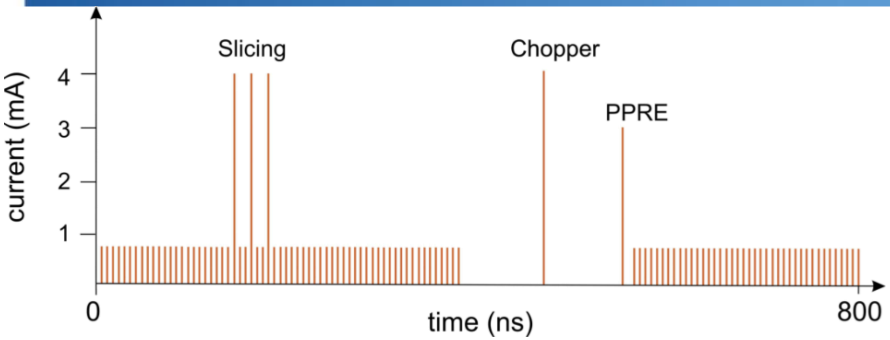


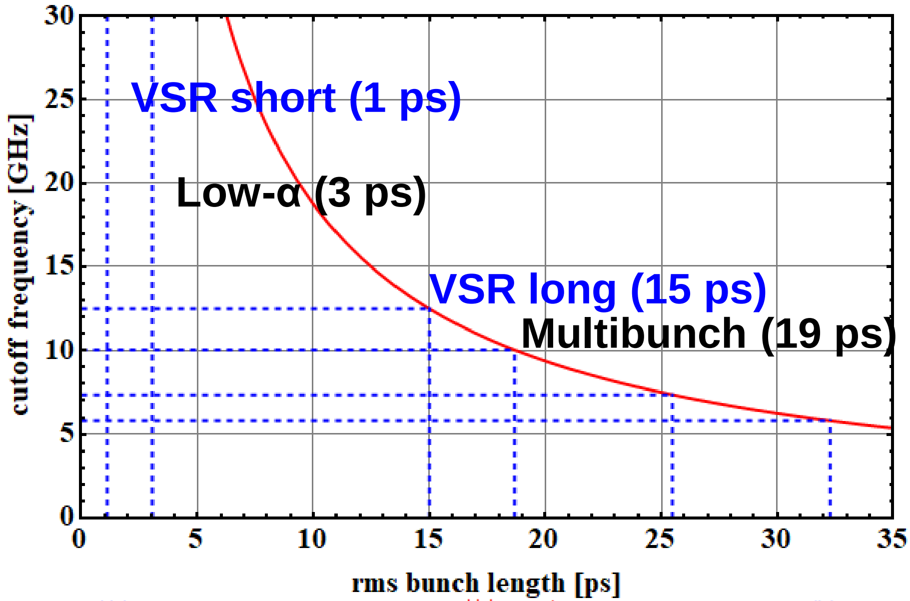

Since it may cause multiple modes with different phase velocities to propagate, interfering with each other, above a certain cutoff frequency, it is usually undesirable to transmit signals.

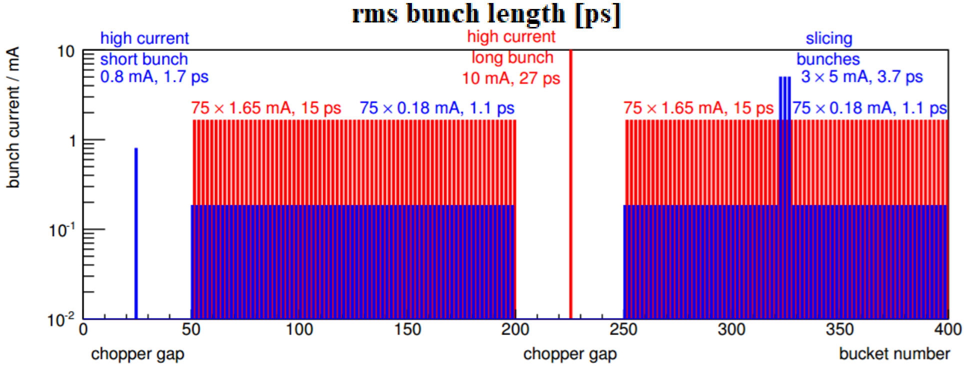
$$f_c^{H_{m1}} \approx \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{\pi} \frac{m}{(r_i + r_o)}$$

where $r_i$ and $r_o$ are the outer radius of inner conductor and the inner radius of outer conductor, respectively.

# Heating consideration in mature BESSY II




In case of M equi-spaced and equi-populated bunched, the power loss can be written*

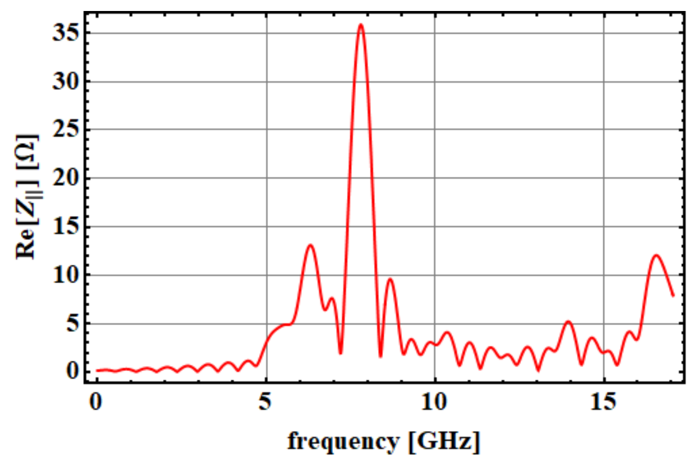
$$P_{loss} = M I_b{}^2 Z_{loss}$$

with

$$Z_{loss} = 2\,M \sum_{p=0}^{\infty} Re[Z_{||}(pM\omega_0)]\, e^{-(p\sigma M\omega_0)^2}$$

where $I_b$ is the bunch current, $\omega_0 = 2\pi f_{rev}$, σ is the bunch length.

In BESSY II, the beam current and harmonic number in the storage ring are 300 mA and 400, respectively.




In the conservative estimation, the power loss in whole BPM block is 9.5 W (0.48 W in button).

*** E. Metral, in proceedings of IBIC 2013, THBL1.**

# Heating consideration in mature BESSY II

Since the conductivities ratio is about 20 for steel and molybdenum, the button made of molybdenum will receive about 20% of the total power dissipated in the stainless steel button*.

| | $\sigma_t$ [ps] | $I_{avg}$ [mA] | $P_{total}$ [W] | $P_{button}$ [W] |
|---|---|---|---|---|
| BESSY II | 19 | 300 | 9.5 | **0.48** |
| Low-alpha | 3 | 100 | 3.0 | 0.15 |
| VSR long | 15 | ~ 260 | 9.9 | 0.5 |
| VSR short | 1.1 | ~ 40 | 0.5 | 0.03 |

From the conservative estimation, the power loss in the button at VSR operation is VSR long + VSR short = **0.53 W** which is 10 % higher than BESSY II operation.

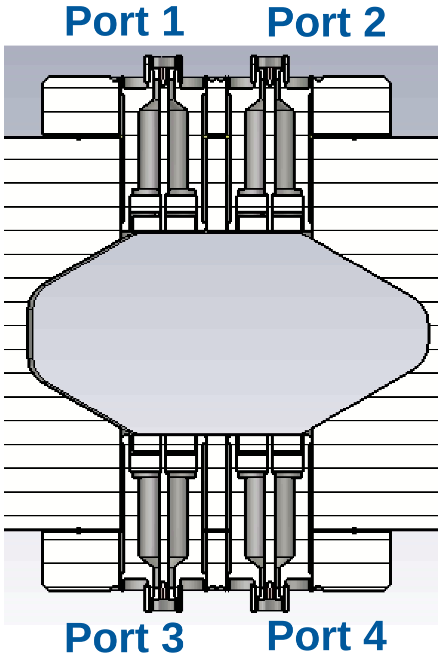
Since the 20-years old "Mature" button BPM was well designed and the BESSY II storage ring operates on relatively low current and long bunch length, the noticeable issues with the heating of the button has not been.

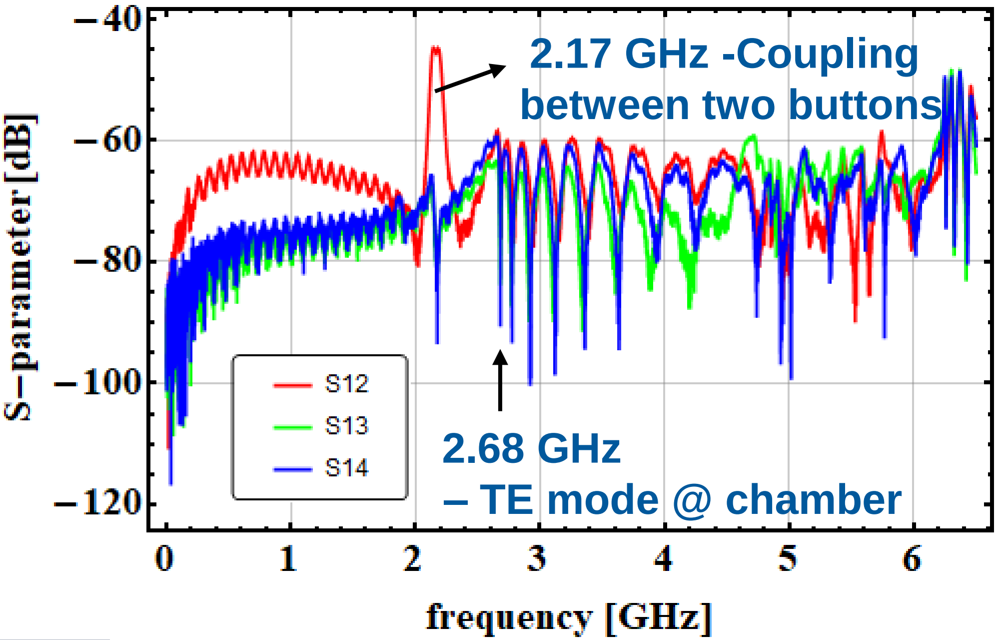
Therefore, it is the reference point for "New" BPM design.

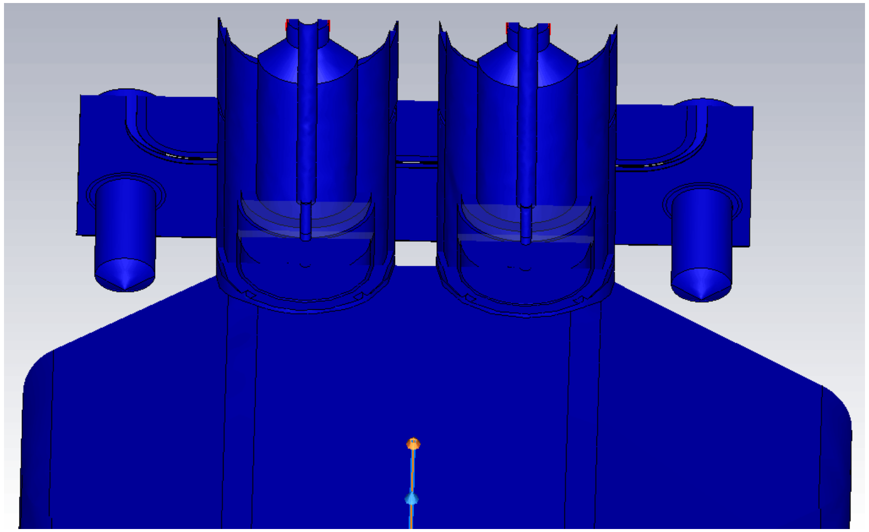
$$P_{button} = 0.48\ \mathrm{W}$$

*** I. Pinayev and A. Blednykh in proceedings of PAC09, TH5RFP014.**

# Heating consideration in mature BESSY II

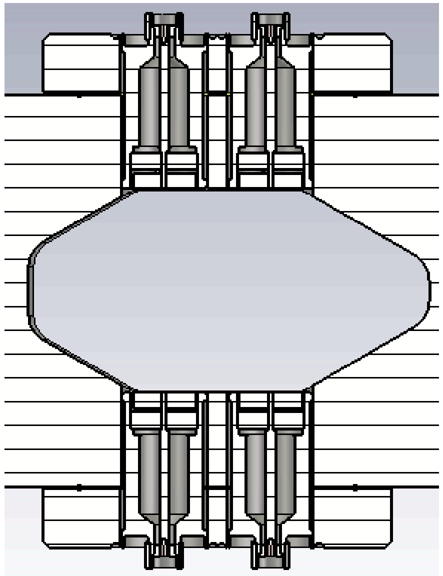


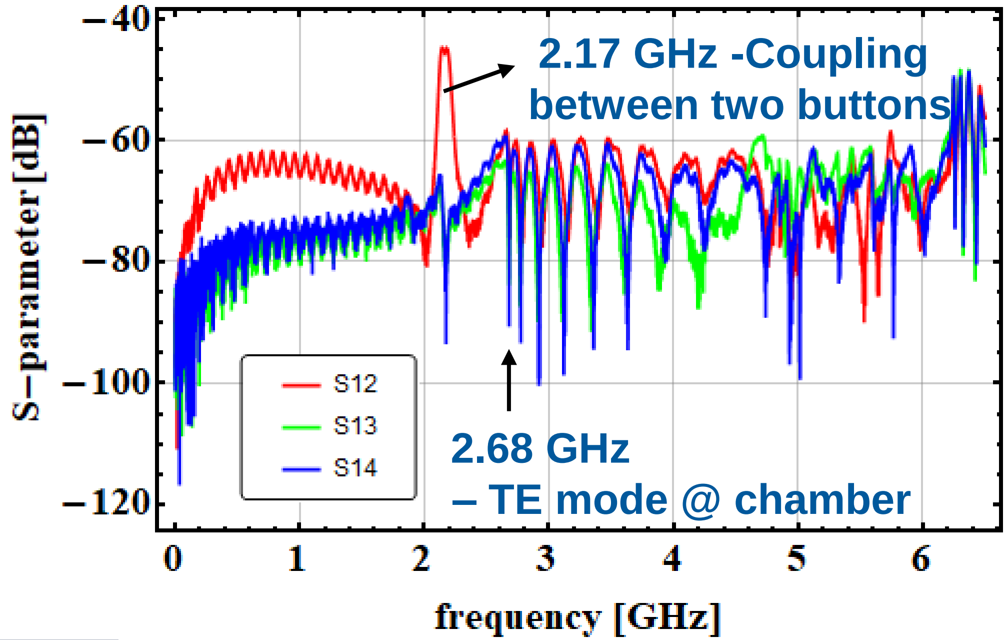



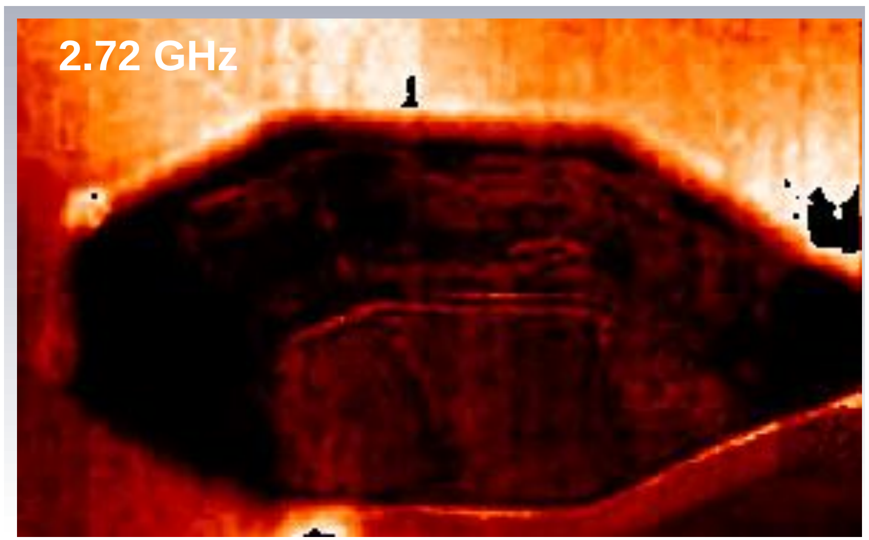




@ resonance (BG Subtracted)

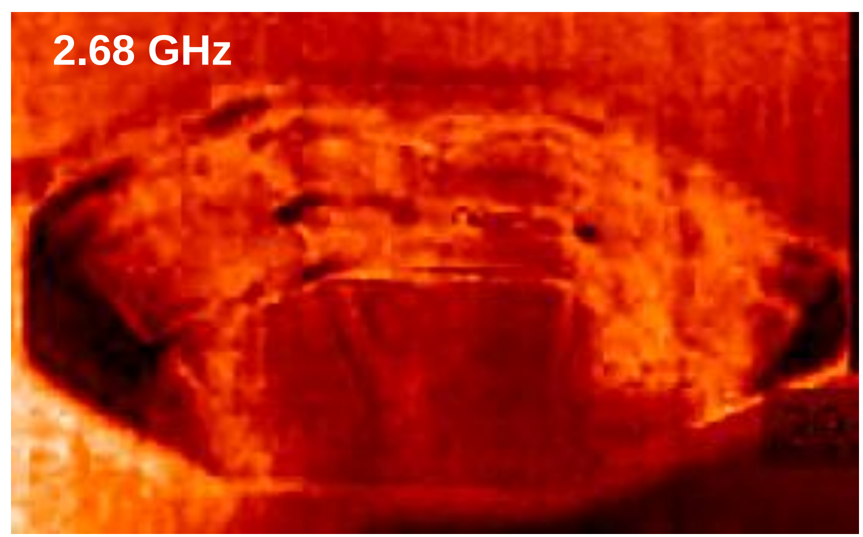
# Heating consideration in mature BESSY II



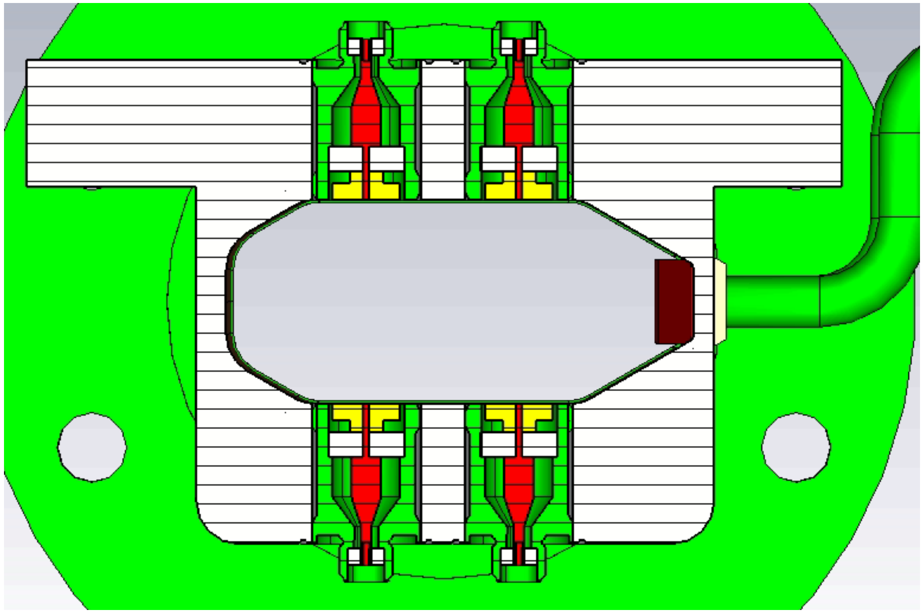




@ off-frequency (BG Subtracted)




@ resonance (BG Subtracted)

# New button-type Beam Position Monitor



Contacted Vendors for 10 buttons + test chamber with SiO2

1. **Friatec : No experiences on glass**
2. PMB : Preferred Al2O3 due to mechanical stability
3. BC-tech : No response

All vendors can not ensure + BESSY II is user machine → **Alumina**

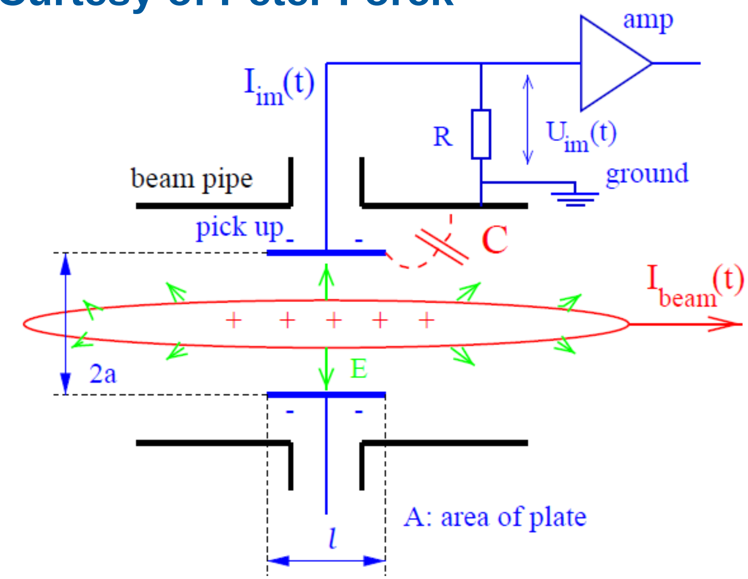
**Suggestion of Glass sealing technique using "SiO2" from button workshop.**

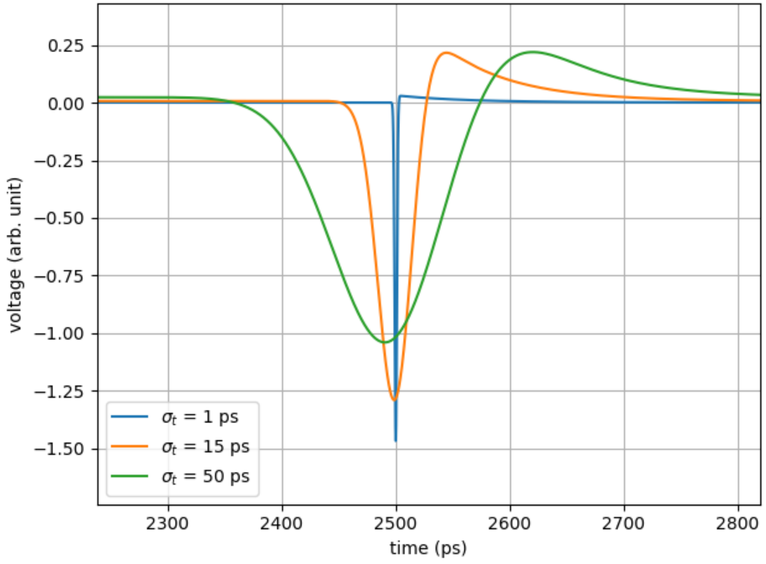
## New BPM design considerations

1. Fit into small chamber dimension : 69 (H) x 35 (V) → 55 (H) x 24 (V) mm
   → small button head : Wakefield↓ and signal ↓
2. Mitigate signal inference between bunches for BbB system.
   → **Low Permittivity insulator : SiO2 / Cutoff frequency ↑**
3. Mitigate internal reflection
   → Button structure : impedance matching
4. Improve the crosstalk → Distance between buttons ↑ : Resolution ↓
5. Trapped mode in gap @ button lodging hole → **Gap ↓ (* 30 ~ 40 um)**

# New button-type Beam Position Monitor (Button head)

Curtesy of Peter Forck




As the signal we use the voltage drop at a resistor R

$$U_{im} = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)$$

where $I_{beam} = I_0\, e^{-iwt}$ and $Z_t = \frac{1}{\beta c}\frac{1}{C}\frac{A}{2\pi a}\frac{i\omega RC}{1+i\omega RC}$ .

Since $f = 1/2\pi\sigma_t$, the width of transformed beam current in frequency domain

| $\sigma_t$ (ps) | $f$ (Ghz) |
|---|---|
| 1 | 159 |
| 20 | 7.96 |

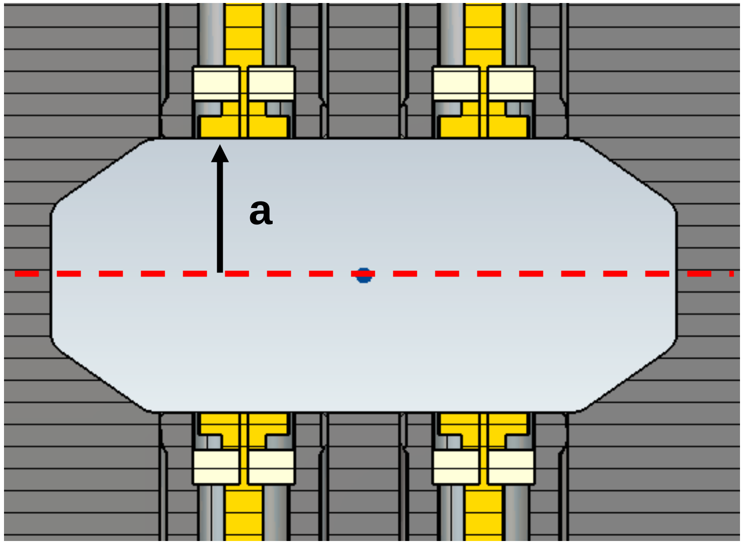
$$Z_t \propto \frac{i\,\omega/\omega_{cut}}{1+i\,\omega/\omega_{cut}} \rightarrow 1 \quad \text{for } f \gg f_{cut}$$
$$\rightarrow i\frac{\omega}{\omega_{cut}} \quad \text{for } f \ll f_{cut}$$

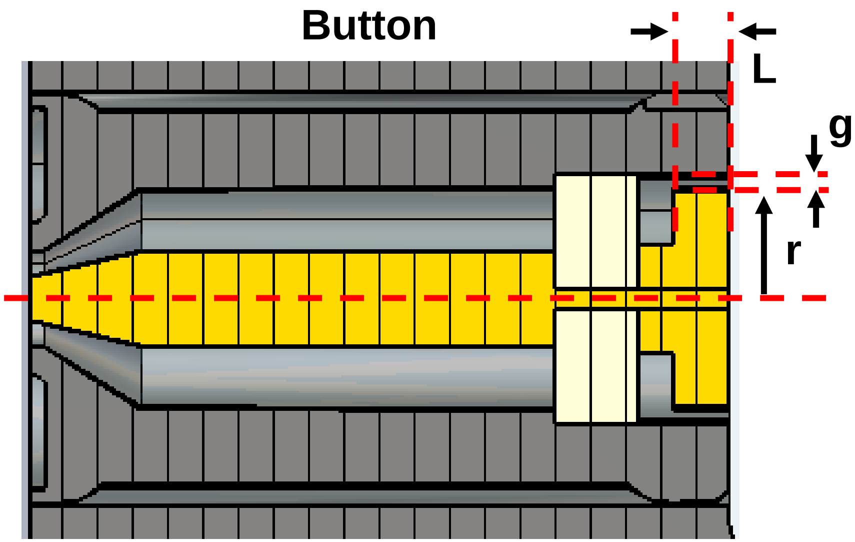
Then resulting voltage drop is

$$U_{im} = \frac{1}{\beta c\, C}\frac{A}{2\,\pi\, a} I_{beam} \quad \text{for } f \gg f_{cut}$$
$$= \frac{R}{\beta c}\frac{A}{2\,\pi\, a}\frac{dI_{beam}}{dt} \quad \text{for} f \ll f_{cut}$$

In our case, $f_{cut}$ ~ 3.2 GHz for about 1 pF capacitance.

# New button-type Beam Position Monitor (Button head)



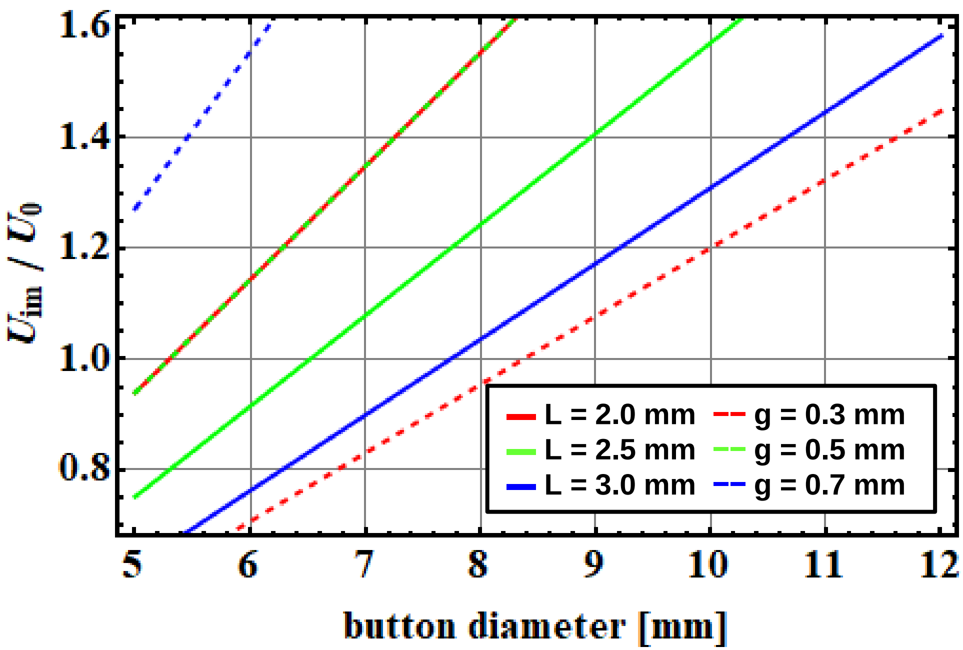

The resulting voltage drop is

$$U_{im} = \frac{1}{\beta c\, C}\frac{A}{2\,\pi\, a} I_{beam}$$

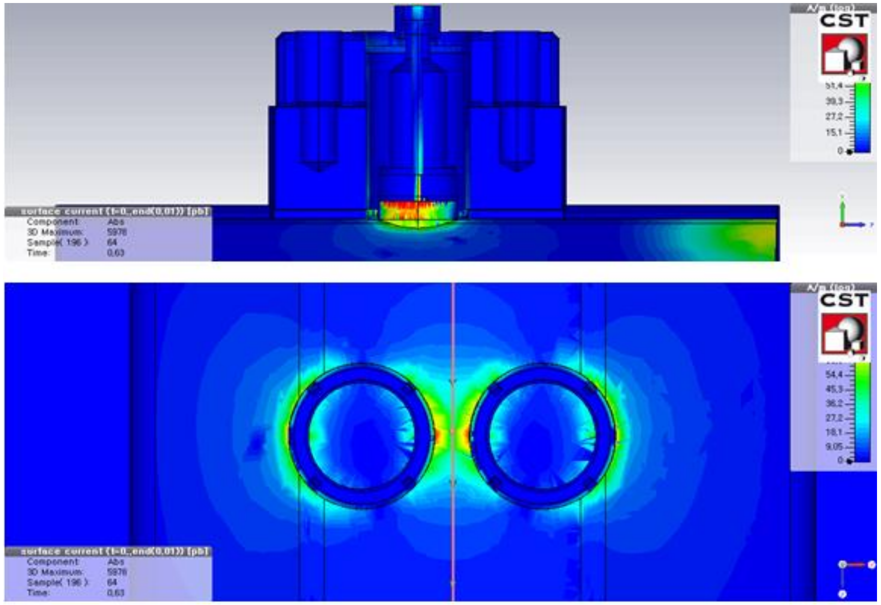
For high energy electron beams ($\beta \sim 1$) , $A = \pi r^2$, and the capacitance of coaxial structure ( $C = {}^{2\pi\varepsilon L}/_{\ln[(r+g)/r]}$ ), the voltage is given by

$$U_{im} = \frac{1}{c}\frac{r^2}{2\,a}\frac{\ln[(r+g)/r]}{2\,\pi\varepsilon\, L} I_{beam}$$

where a is radius of the chamber, $\varepsilon$ is the permittivity.



# New button-type Beam Position Monitor (loading hole)




Coaxial cavity type modes $TE_{m1p}$-mode ($H_{m1p}$-mode) where *m* and *p* are *1, 2, 3, k* (field variation in azimuthal and longitudinal directions). These modes then can be seen by the beam at frequencies defined by the cut-off frequency.
The cut-off frequency for $H_{m1}$-mode like in a coaxial waveguide can be defined as[†]

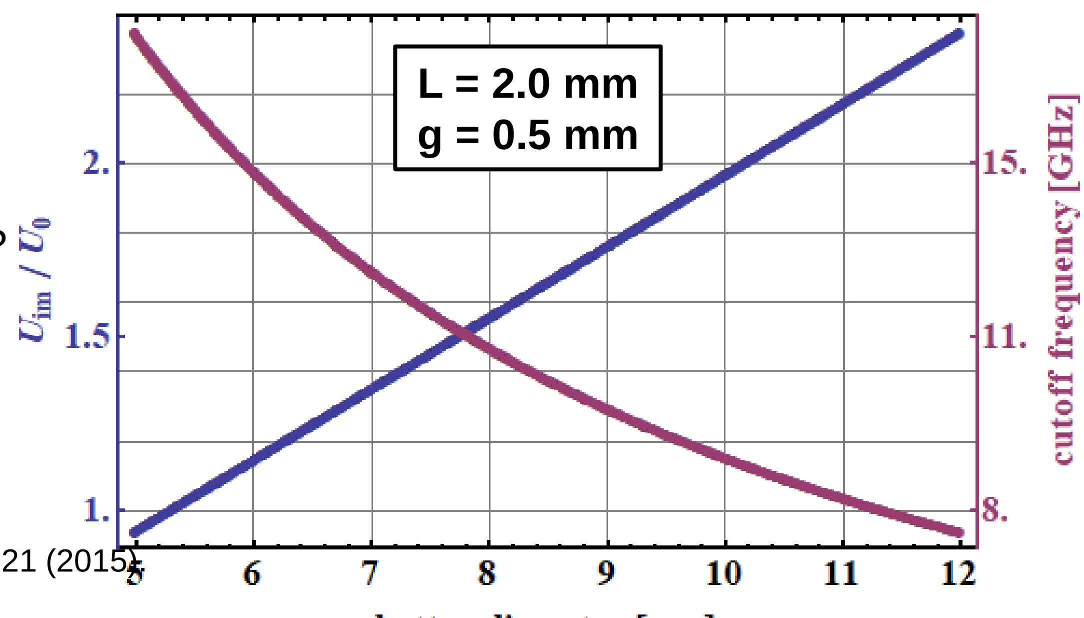
$$f_c^{H_{m1}} \approx \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{\pi} \frac{m}{(2r+g)}$$

where r is the radius of button size and g is gap between button and chamber.

**Large button**

**- Signal strength ↑**

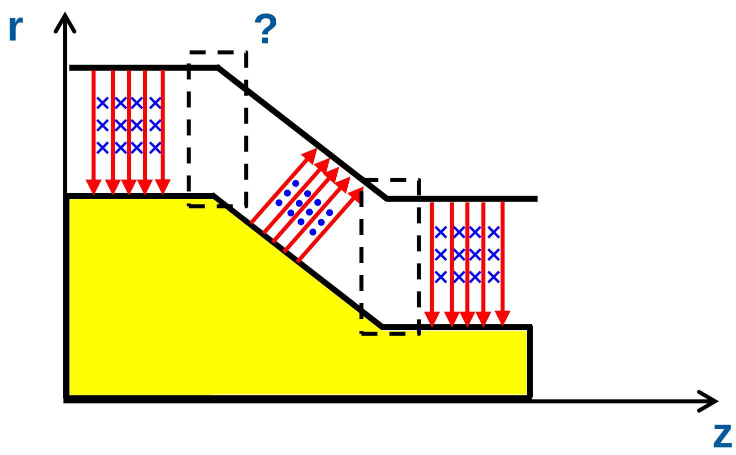
**- Cutoff frequency ↓**

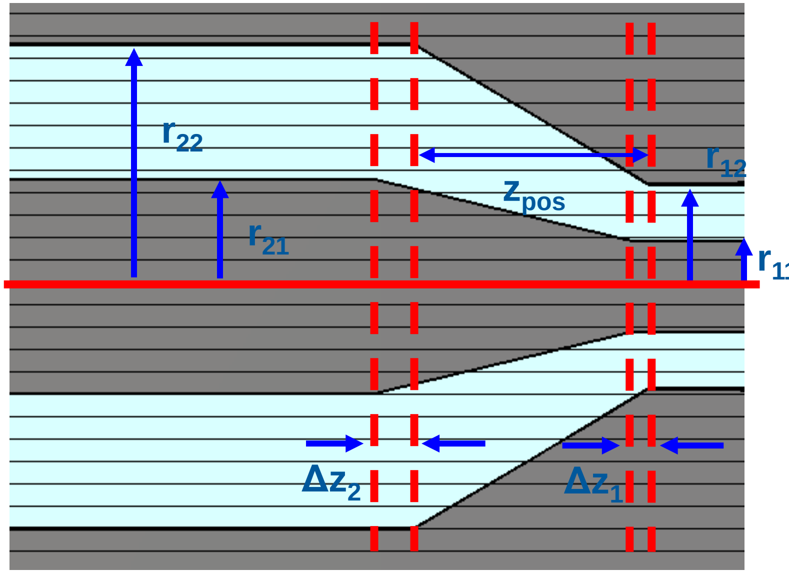



What is meant by the cutoff frequency $f_c$?
-The desirable TEM mode is allowed to propagate at all frequencies, but at frequencies above $f_c$ the first higher-order mode called TE11 is also allowed to propagate*.

† A. Blednykh et. al., Proceedings of IPAC15, MOPMN021 (2015)
*https://www.microwaves101.com/encyclopedias/coax

# New button-type Beam Position Monitor (impedance matching)



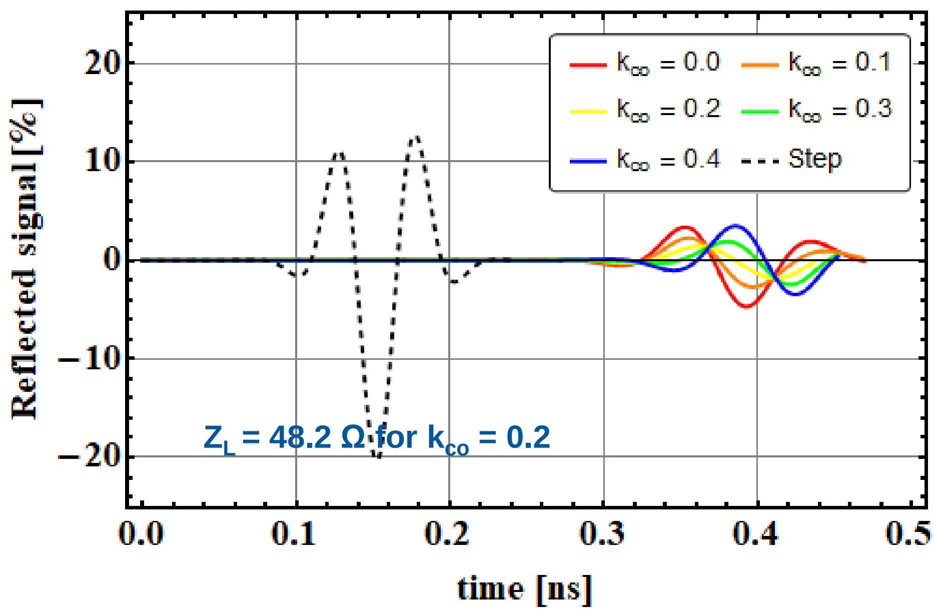



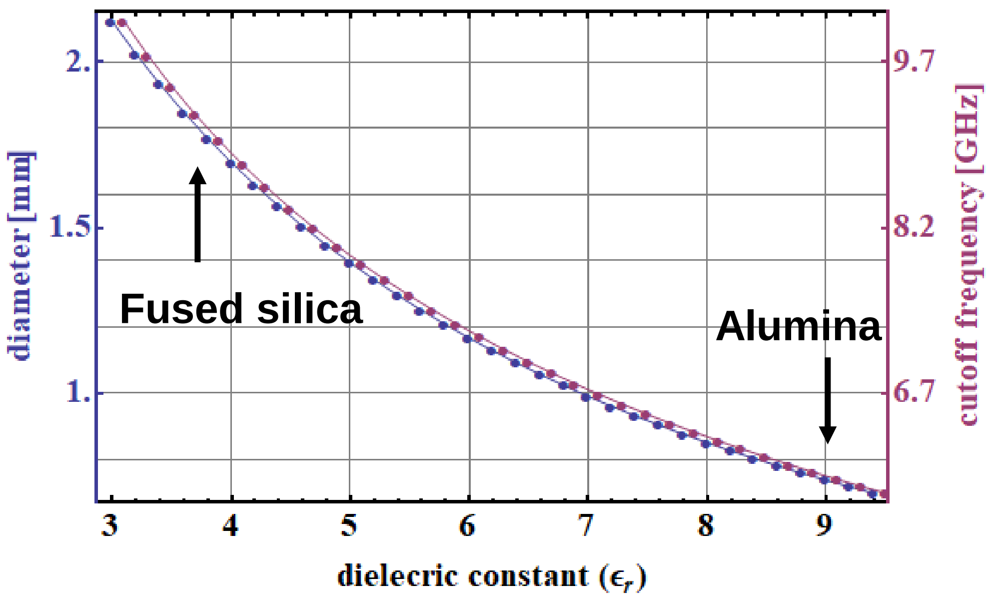

Since the wave direction is varied due to the angle (radius change), the optimization of the relative edge position between inner and outer conductor is required.

$$\Delta z_1 = k_{co} \frac{(r_{22} - r_{21})}{z_{pos}} (r_{21} - r_{11})$$

$$\Delta z_2 = k_{co} \frac{(r_{22} - r_{21})}{z_{pos}} (r_{22} - r_{12})$$

, where $k_{co}$ is a coefficient. The numerical calculation is performed for various $k_{co}$.






**Dielectric constant of materials of useable insulator**

- **Zirconia : 10 ~ 23**
- **Aluminum oxide : 9.0 ~ 9.8**
- **Magnesium oxide : 9.0 ~ 10.1**
- **Aluminum nitride : 9.0**
- **Nitride : 7.5**
- **Silicon nitride : 7.5**
- **Diamond : 5.7**
- **Fused silica : 3.82**

**The cut-off frequency for $H_{m1}$-mode like in a coaxial waveguide can be defined as†**

$$f_c^{H_{m1}} \approx \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{\pi} \frac{m}{(2r+g)}$$

**where r is the radius of button size and g is gap between button and chamber.**

**The impedance of coaxial line is given by**

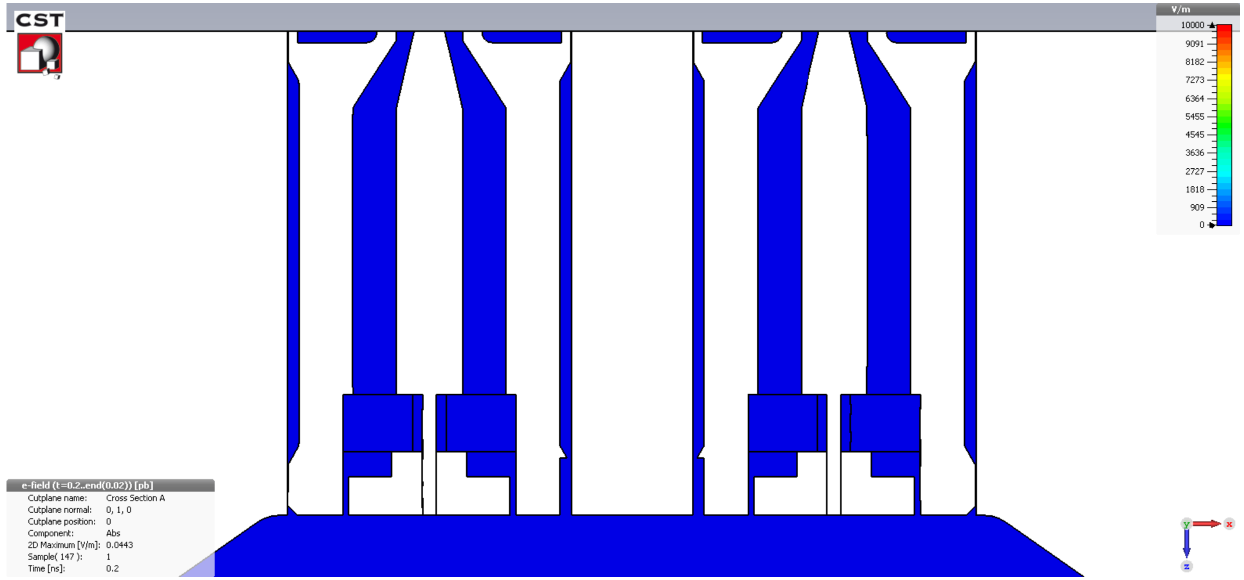
$$Z = \frac{Z_0}{2\,\pi} \frac{1}{\sqrt{\varepsilon_r}}\, ln(D/d)$$

**where $Z_0$ is the impedance of free space, $\varepsilon_r$ is dielectric constant, D is outer diameter, d is inner diameter.**

# New button-type Beam Position Monitor (insulator)

The mode decays proportional to

$$|H(t)| = e^{-\frac{\omega}{2Q}t}$$



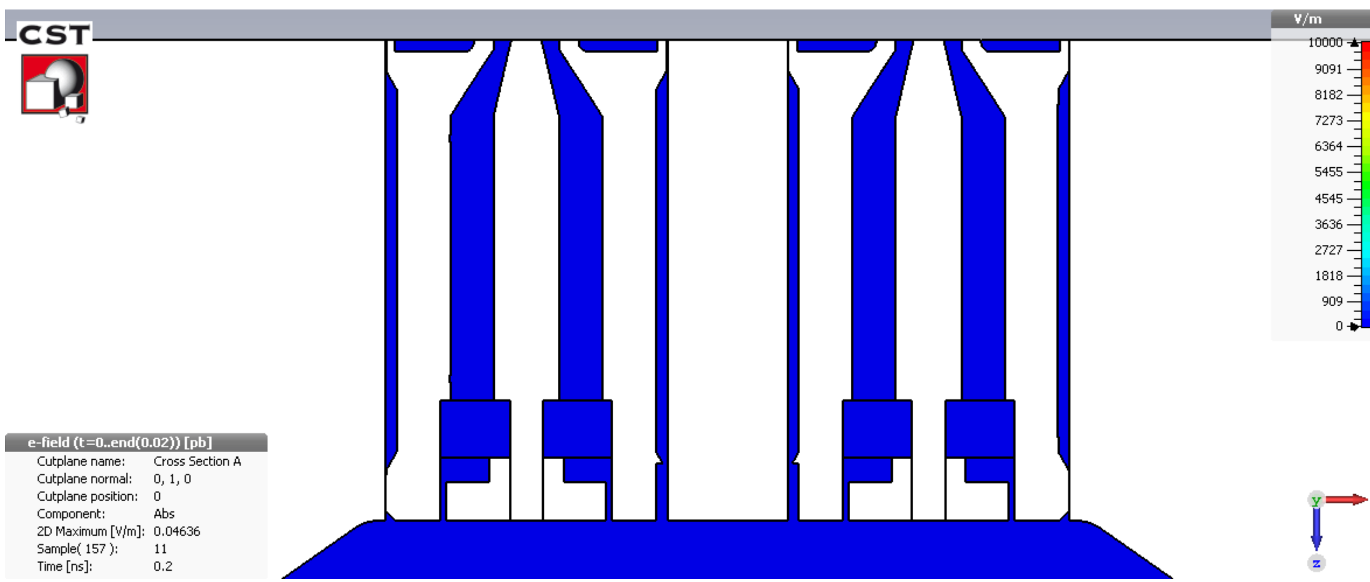

**Aluminum Oxide ($Al_2O_3$)**

$\varepsilon_r{}' = 9.5$

$\varepsilon_r{}'' = 0.00343$

$Q = \varepsilon_r{}' / \varepsilon_r{}'' \sim 2741$

$f_c = 6.4$ GHz




**Fused silica ($SiO_2$)**

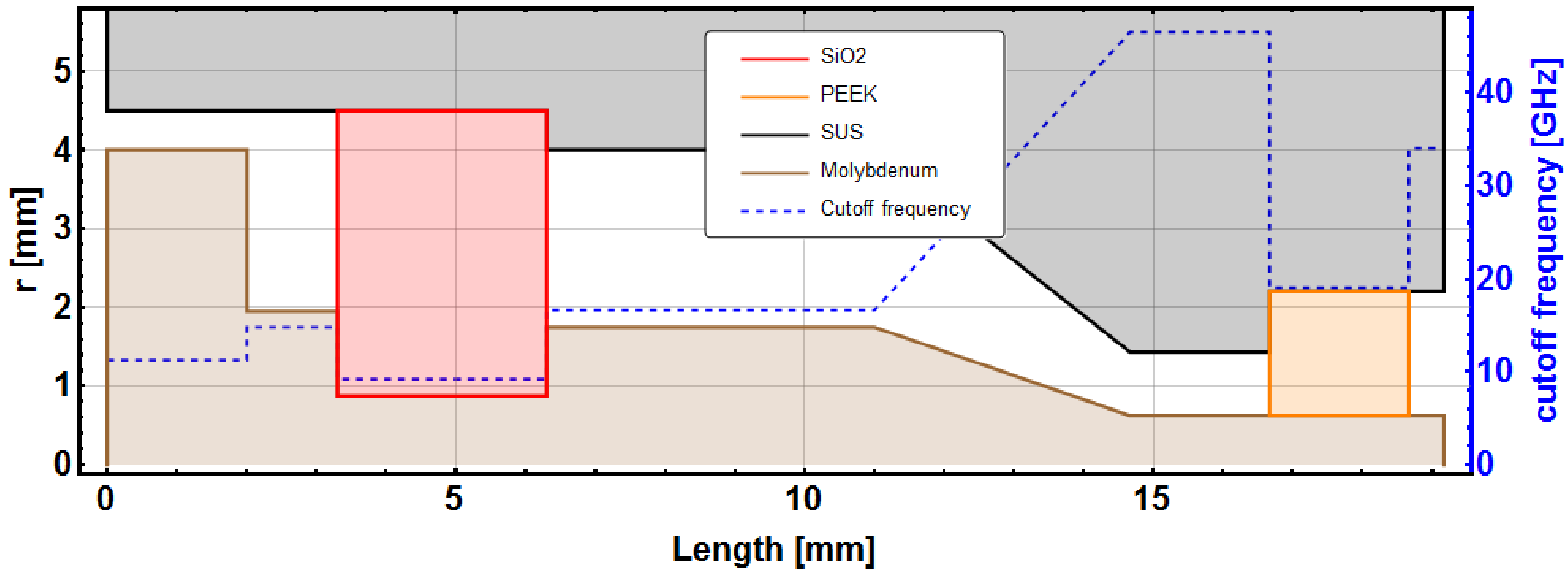
$\varepsilon_r{}' = 3.74$

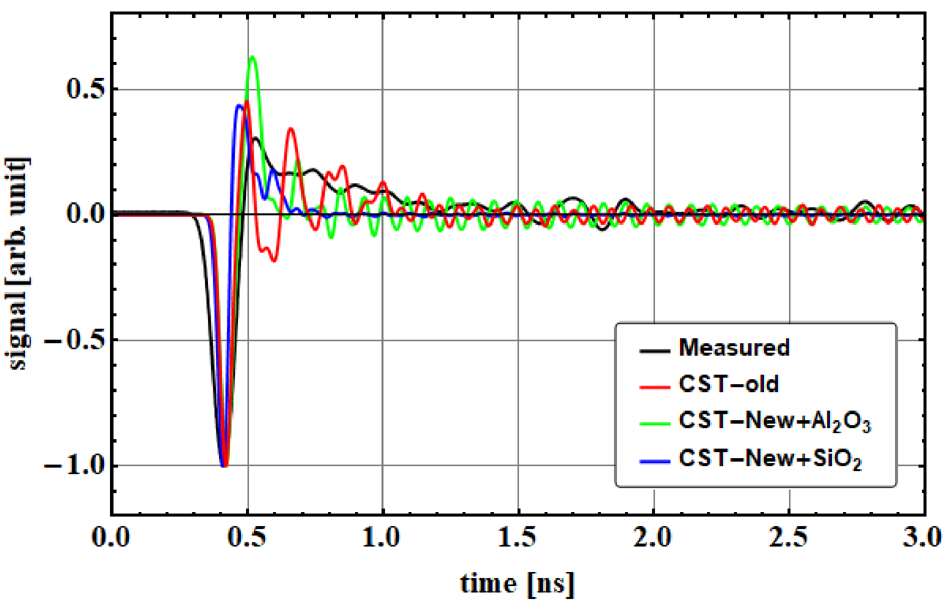
$\varepsilon_r{}'' = 0.00144$

$Q = \varepsilon_r{}' / \varepsilon_r{}'' \sim 2597$

$f_c = 9.2$ GHz

# New button-type Beam Position Monitor (insulator)

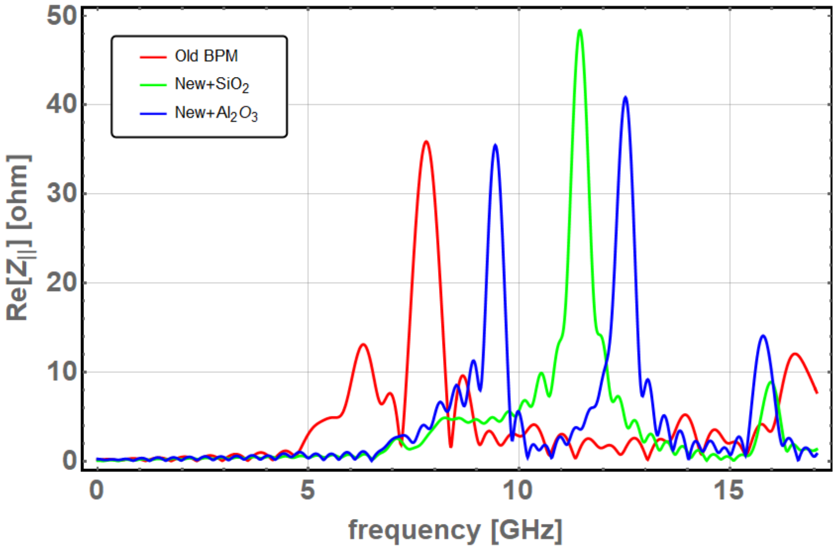


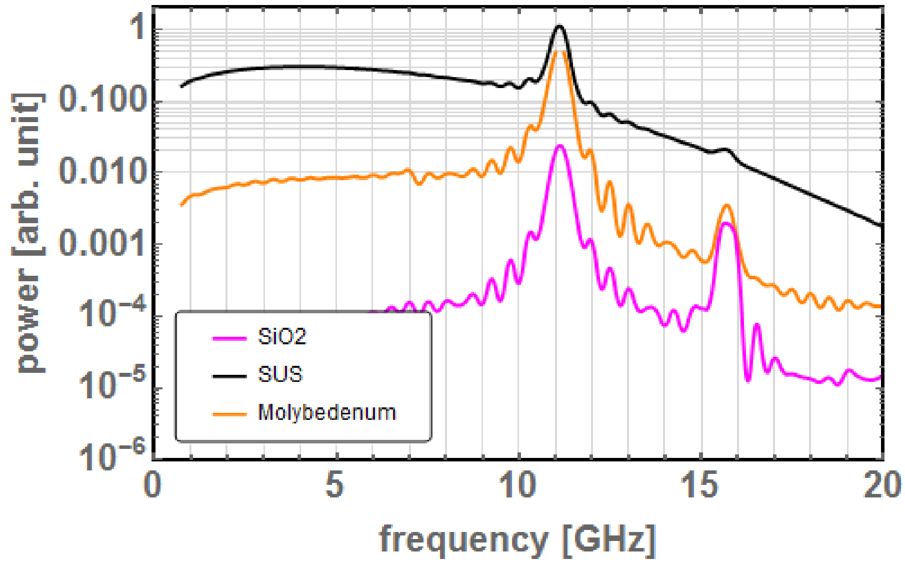




**Dielectric constant of materials of useable insulator**

- Zirconia : 10 ~ 23
- Magnesium oxide : 9.0 ~ 10.1
- **Aluminum oxide (Al2O3) : 9.0 ~ 9.8**
- Aluminum nitride : 9.0
- Nitride : 7.5
- Silicon nitride : 7.5
- Diamond : 5.7
- **Fused silica (SiO2) : 3.74**

# New button-type Beam Position Monitor (heating)




The cutoff frequency of the trapped mode at the insulator was shifted to a higher frequency by reducing the diameter of the button. In addition, more than one order magnitude of the power is dissipated on the SUS chamber.

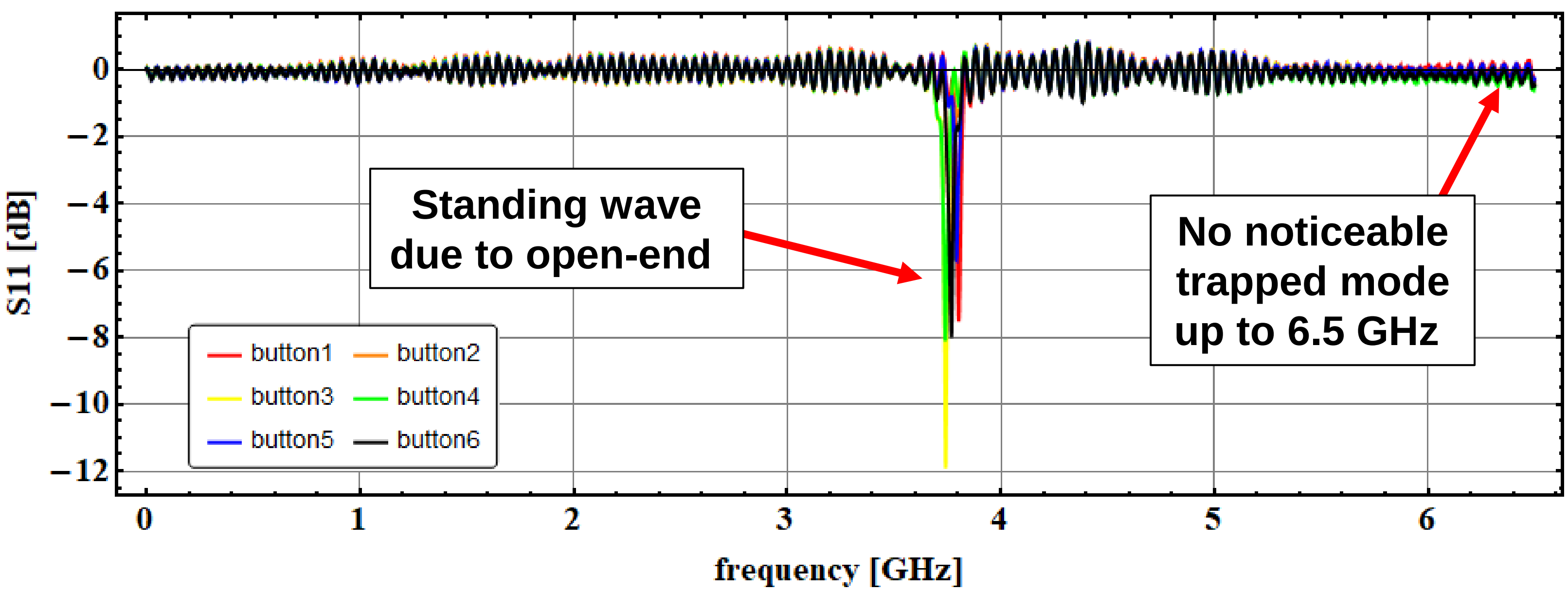
| $P_{button}$ [W] | | | |
|---|---|---|---|
| | BESSYII BPM | New+$Al_2O_3$ | New+$SiO_2$ |
| BESSY II | 0.48 | 0.31 | 0.20 |
| Low-alpha | 0.15 | 0.16 | 0.09 |
| VSR long | 0.50 | 0.39 | 0.25 |
| VSR short | 0.03 | 0.03 | 0.02 |

The dissipated power by the Wakefield at the new BPM during the BESSY VSR scheme is **0.42 W** which is lower than the power on old BPM during the BESSY II operation.

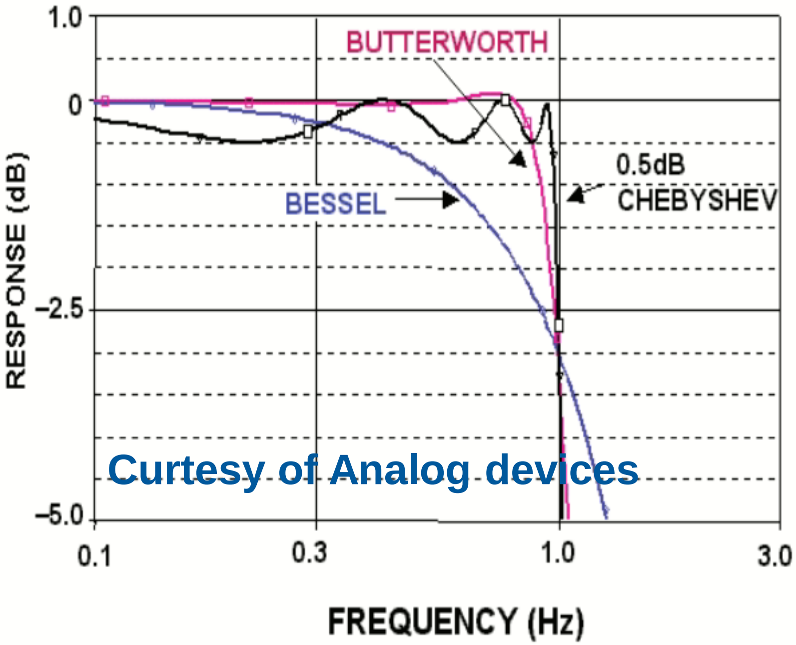
# New button-type Beam Position Monitor (S-parameter)

For a preliminary test with two BPM blocks,  we intentionally ordered significantly more than what we need, totally **sixteen buttons**, to avoid any worst case scenario. But, finally, we got six buttons from **Friatec with Alumina** insulator.

After this summer shutdown (Sep.), we would conduct beam test!

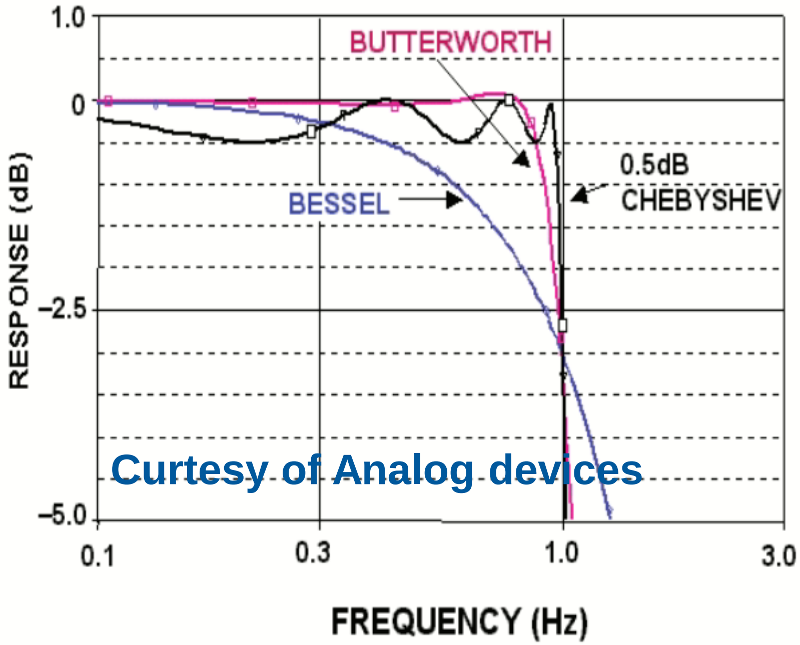


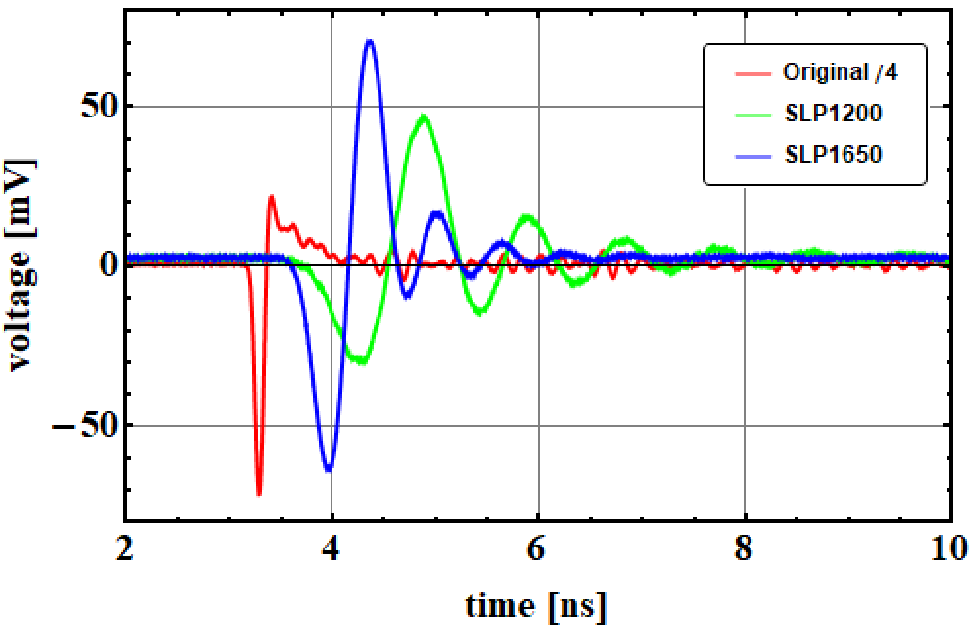
# Alternative method for compensating ringing signal



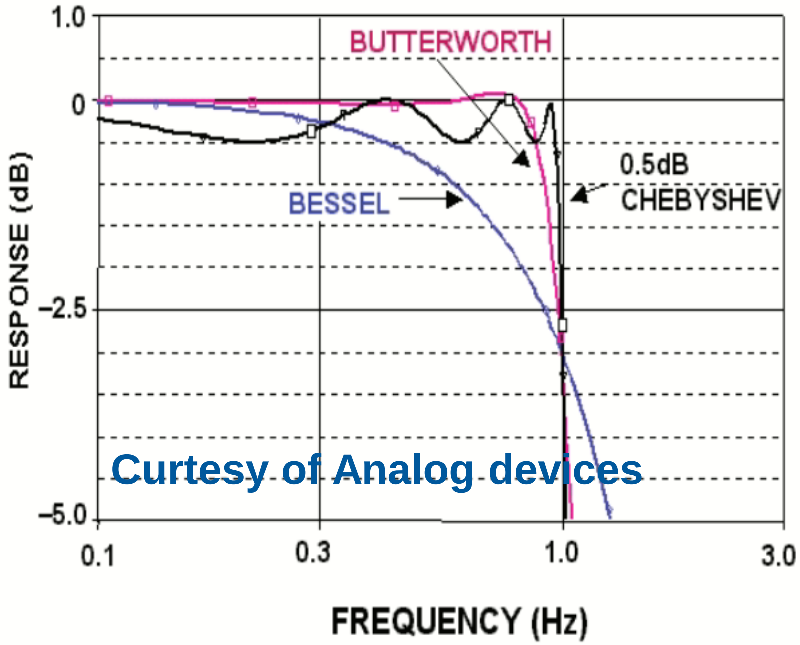

Curtesy of Analog devices

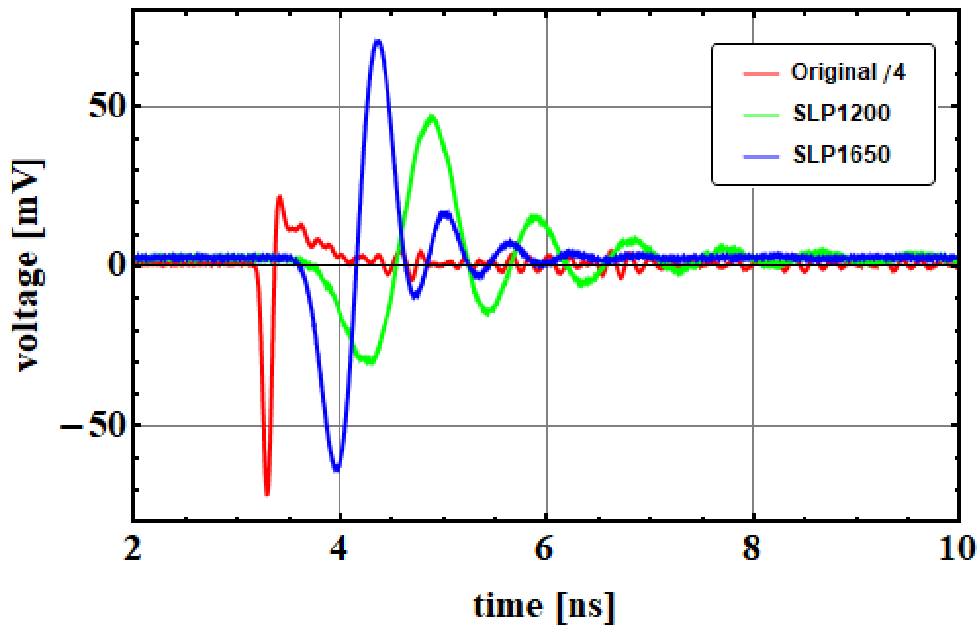
# Alternative method for compensating ringing signal

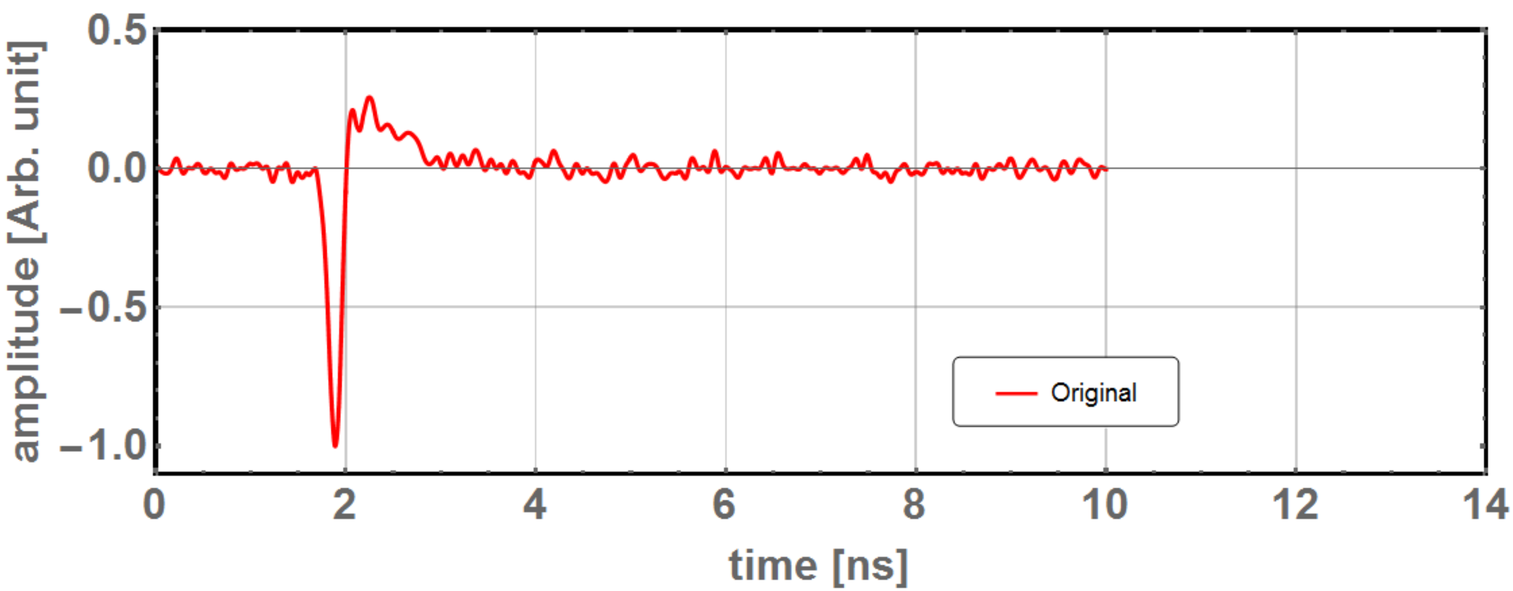


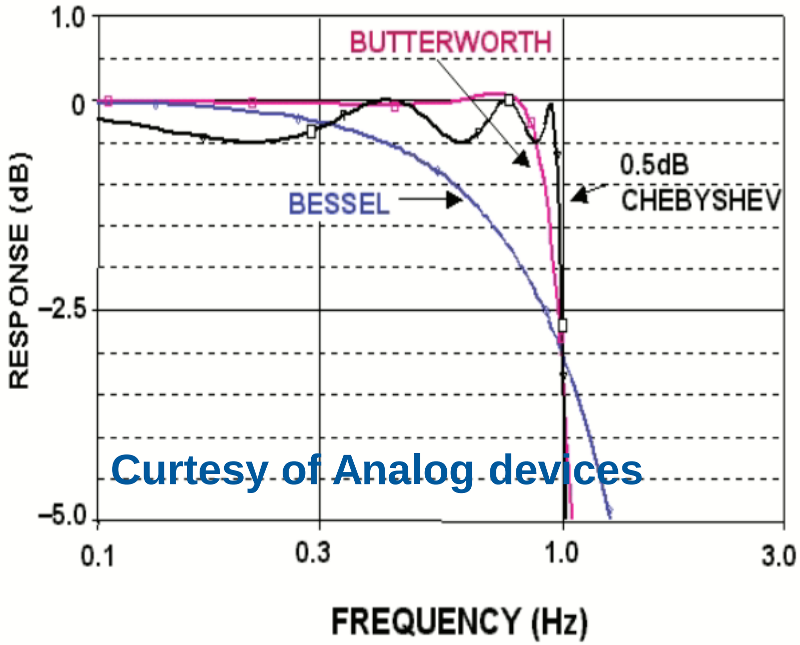
# Alternative method for compensating ringing signal

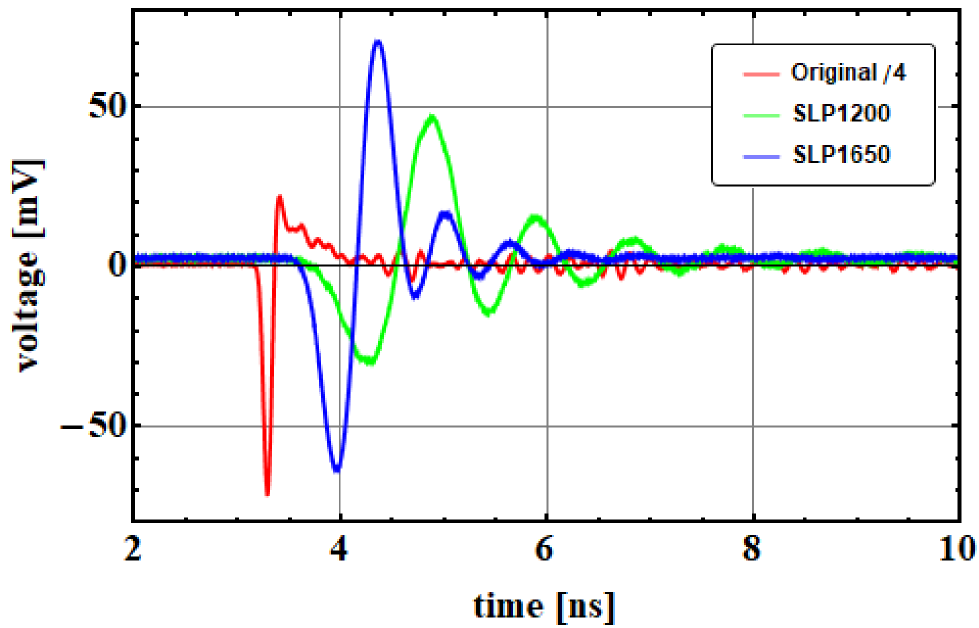


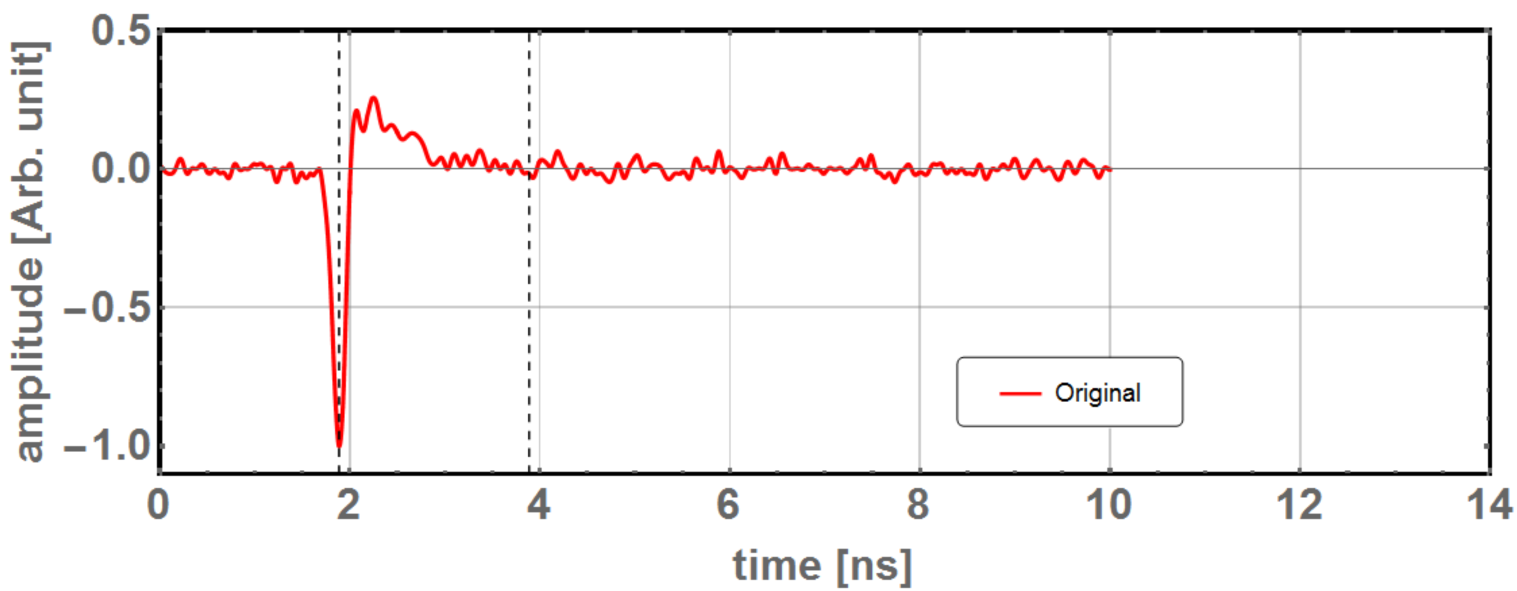



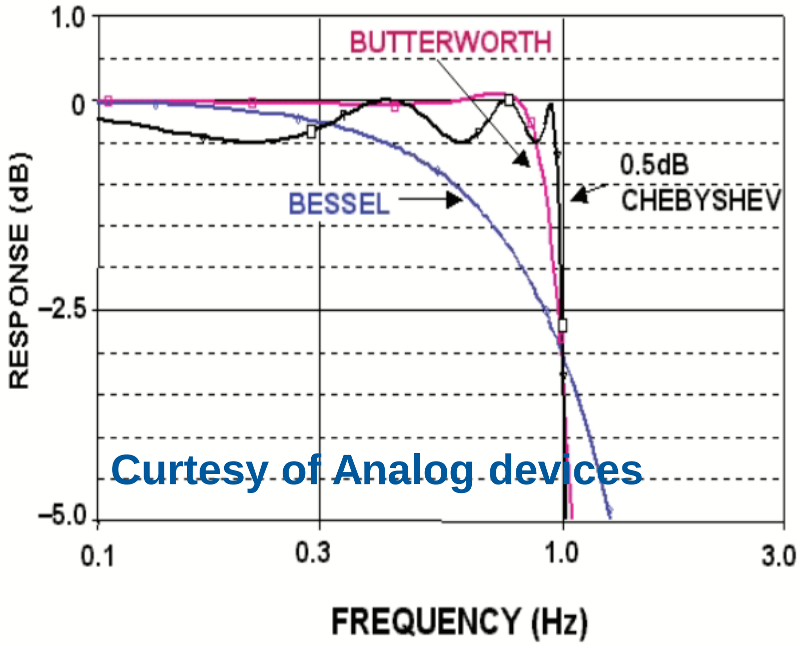
# Alternative method for compensating ringing signal

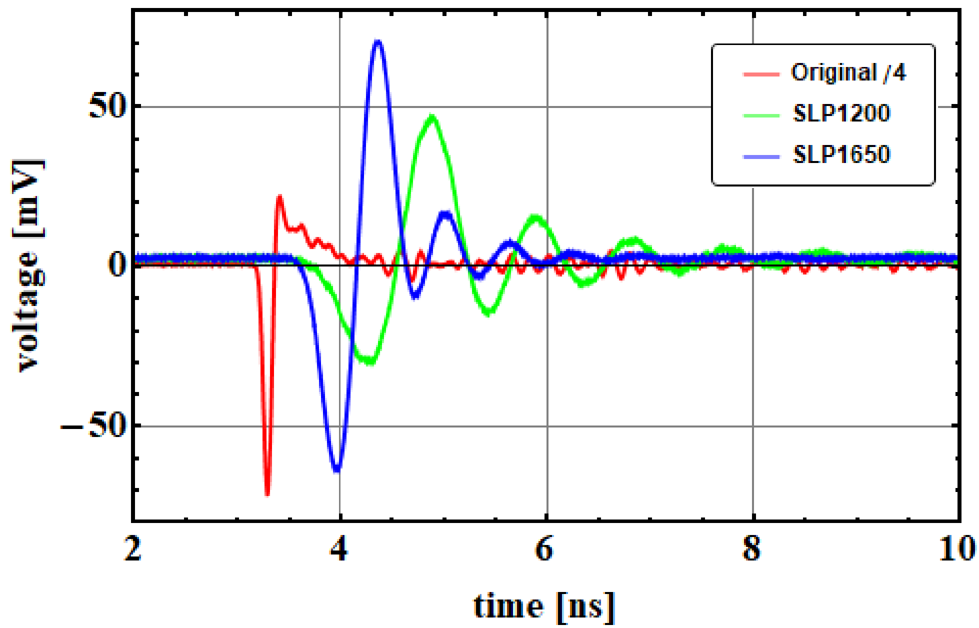


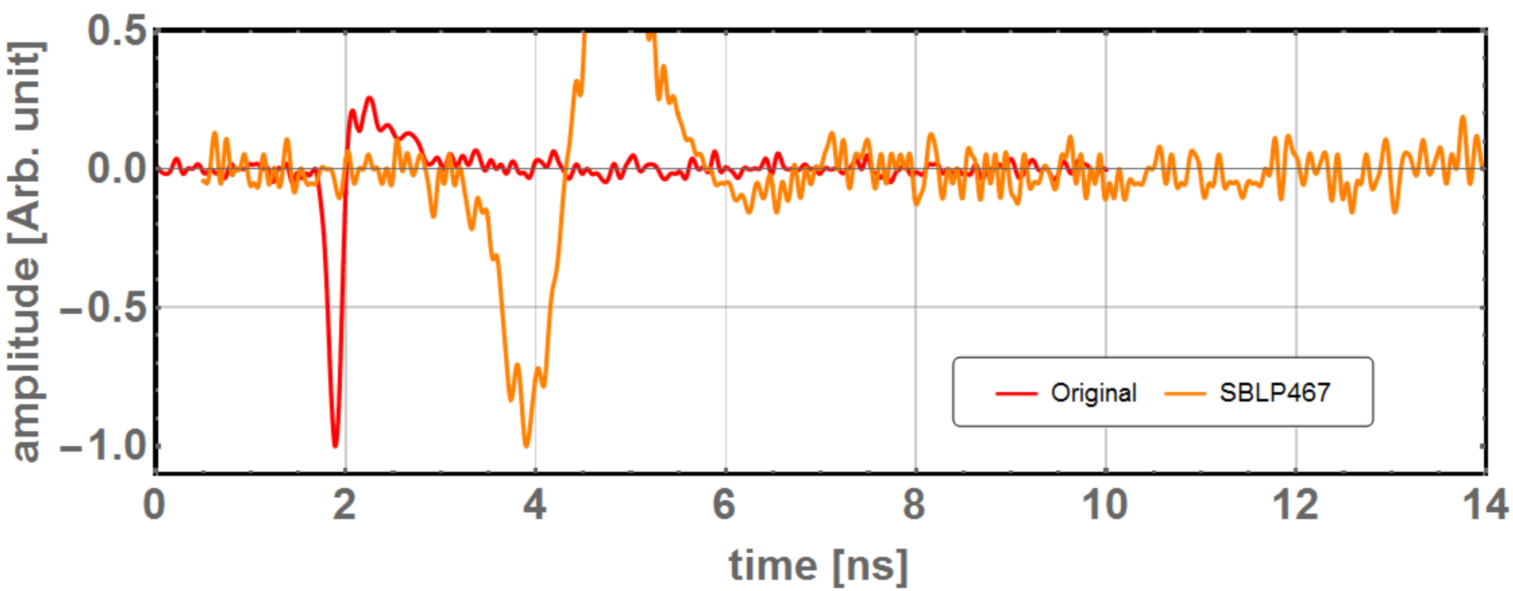



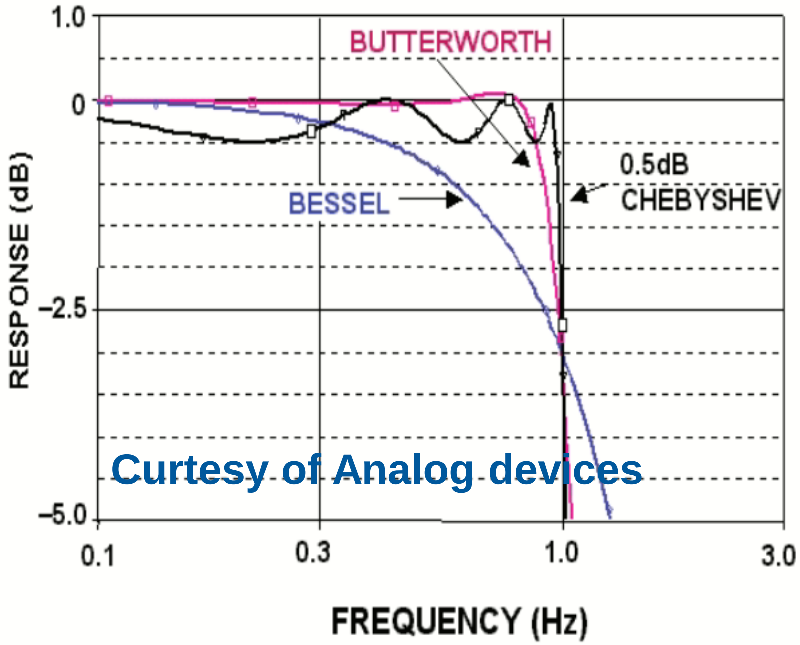
# Alternative method for compensating ringing signal

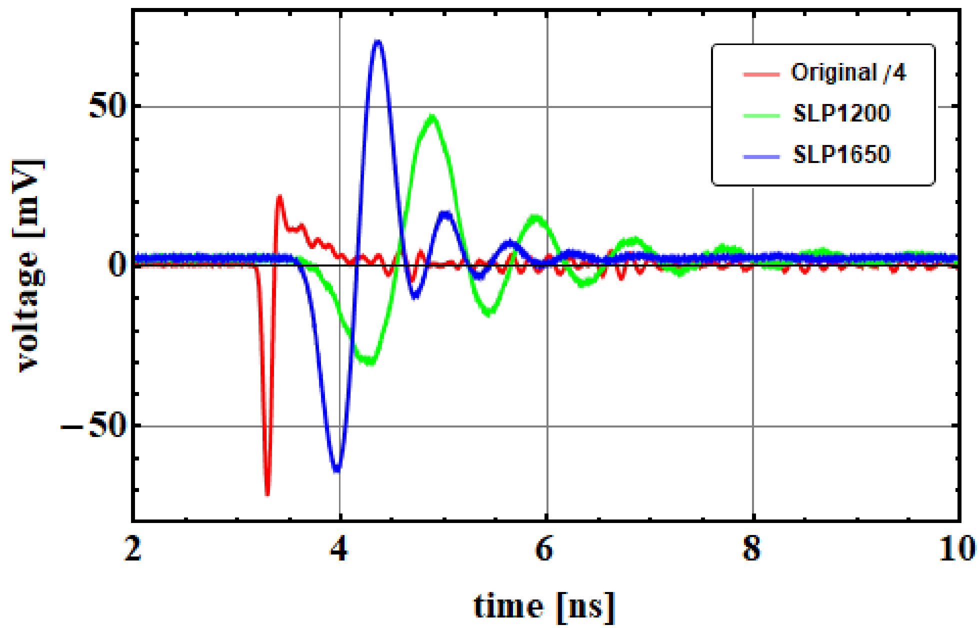


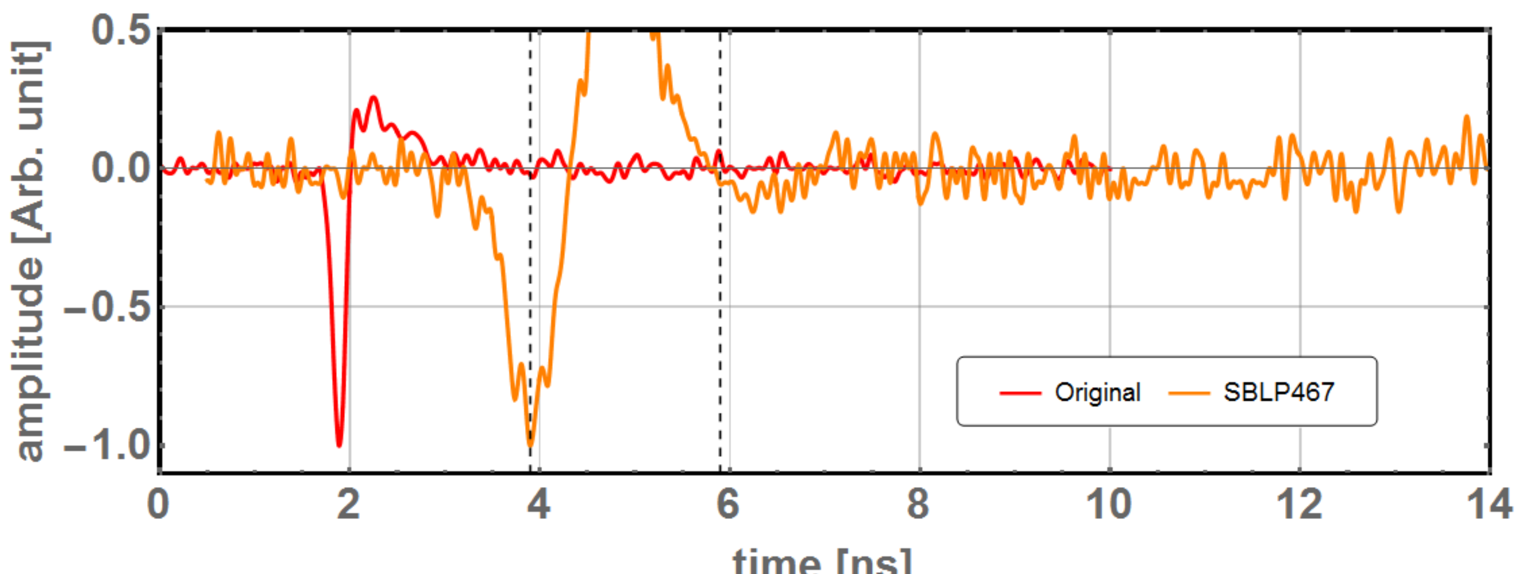



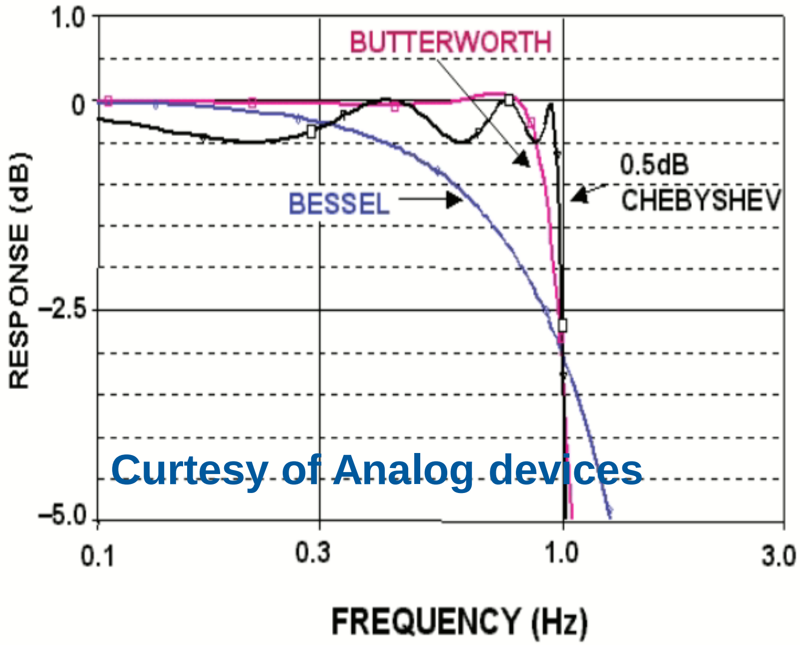



# Alternative method for compensating ringing signal

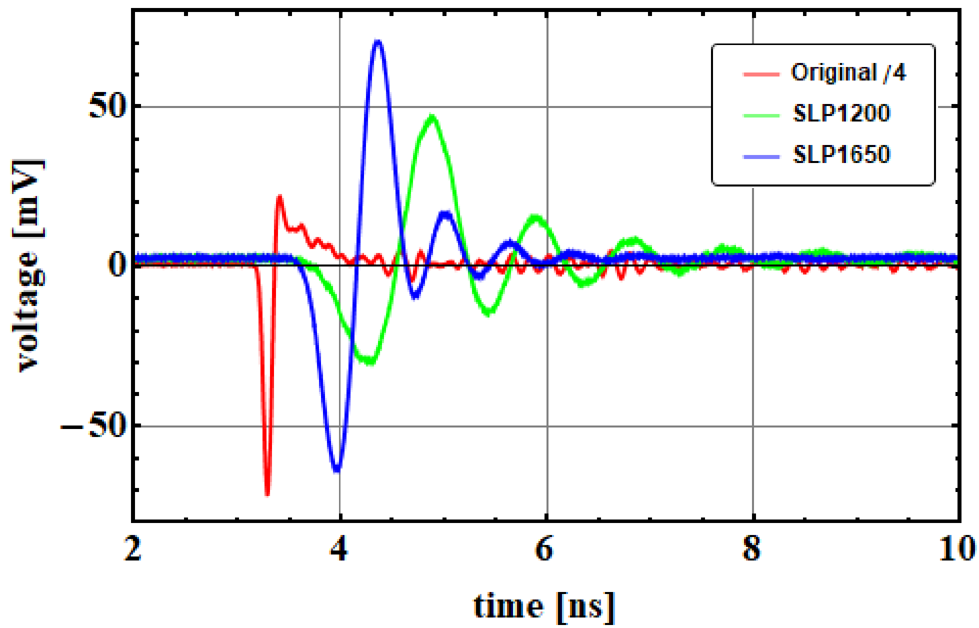


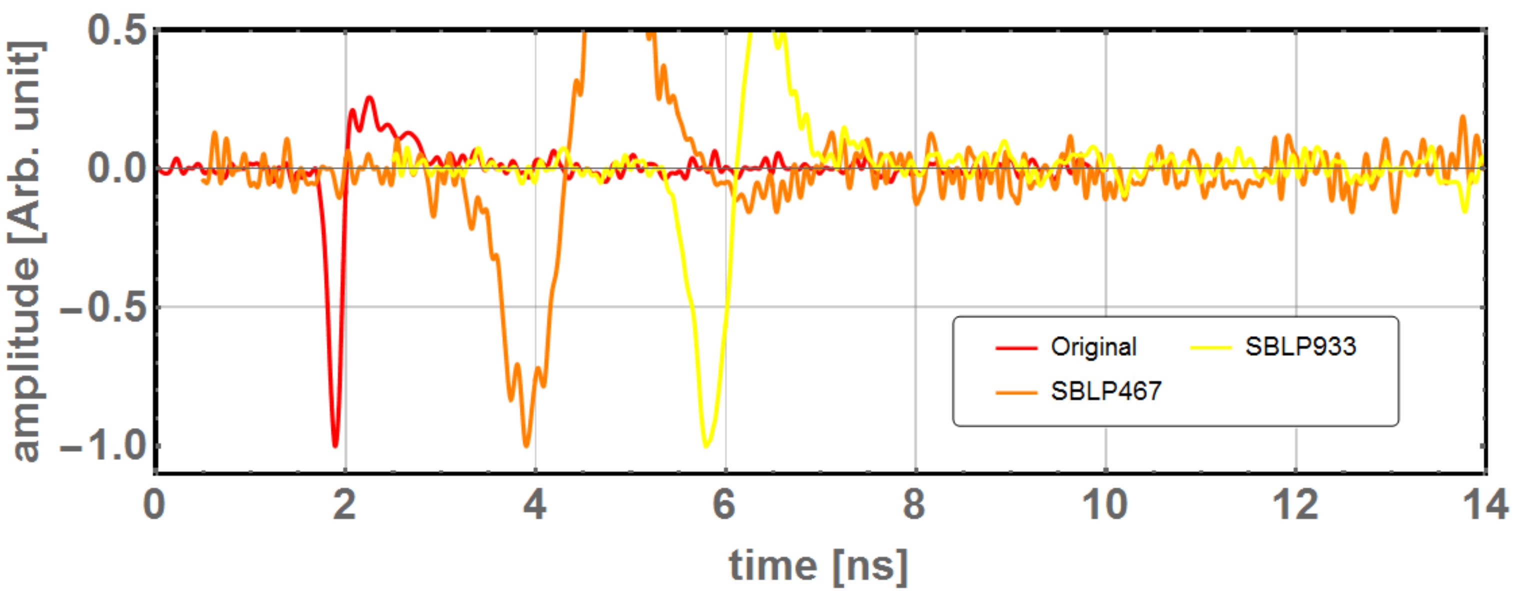





1.0
0
−2.5
−5.0
RESPONSE (dB)
0.1
0.3
1.0
3.0
FREQUENCY (Hz)
BUTTERWORTH
BESSEL
0.5dB
CHEBYSHEV
Curtesy of Analog devices

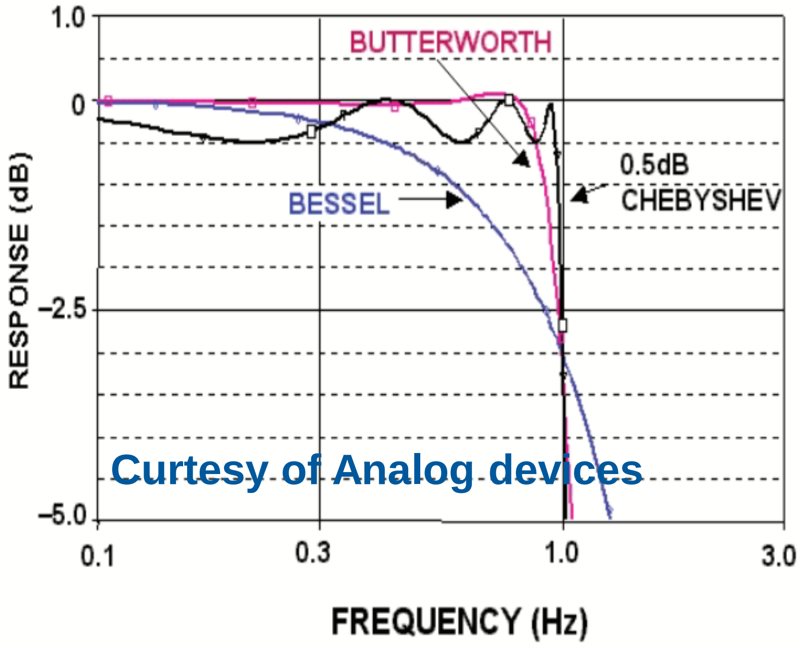



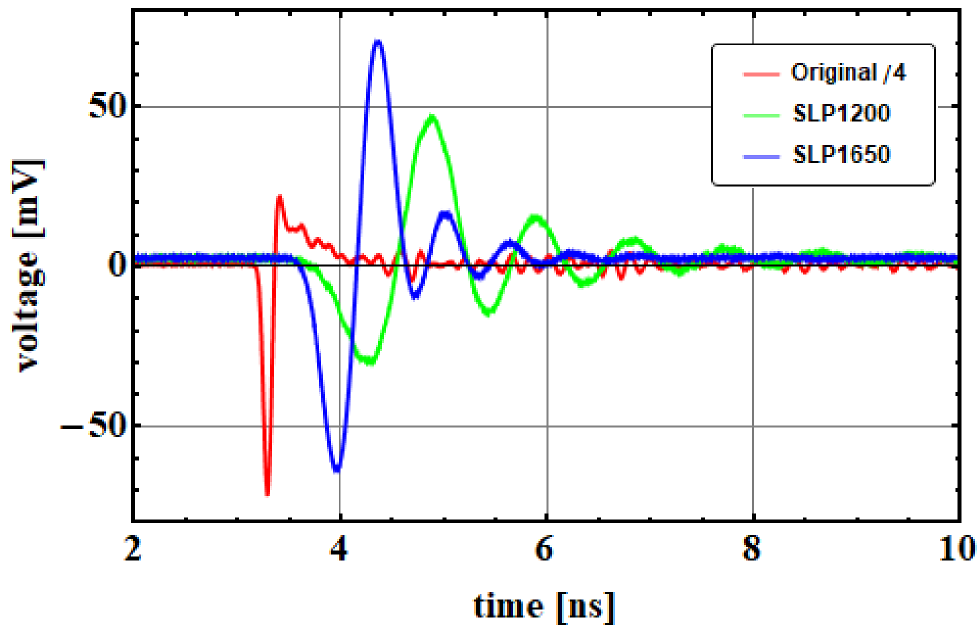
50
0
−50
voltage [mV]
2
4
6
8
10
time [ns]
Original /4
SLP1200
SLP1650

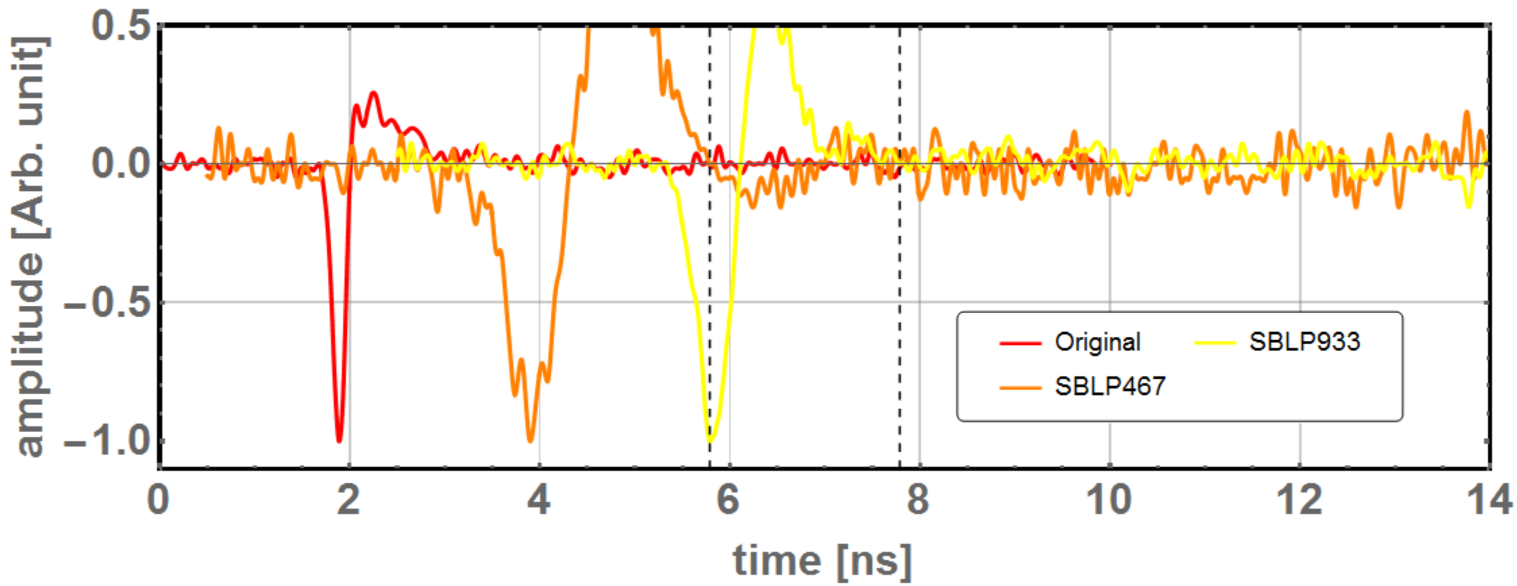



0.5
0.0
−0.5
−1.0
amplitude [Arb. unit]
0
2
4
6
8
10
12
14
time [ns]
Original
SBLP933
SBLP467

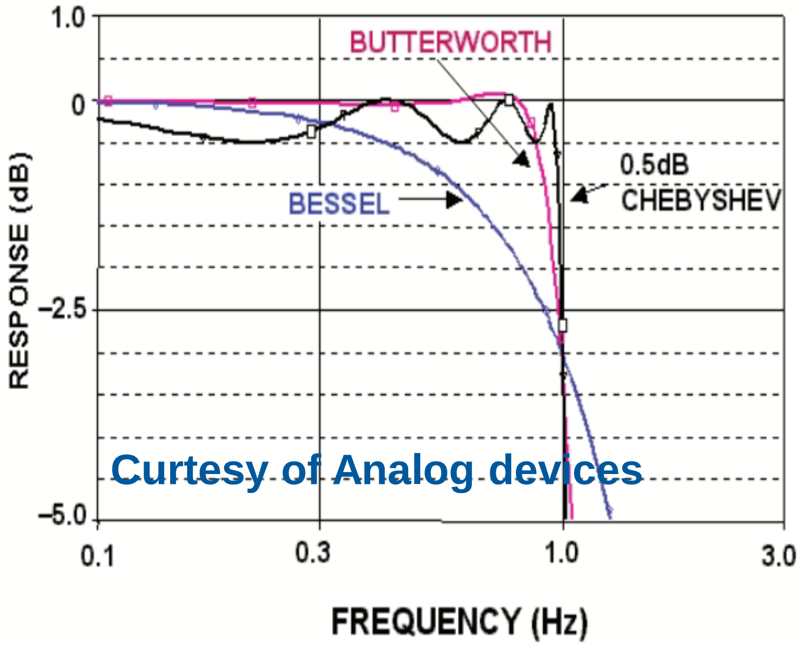
# Alternative method for compensating ringing signal

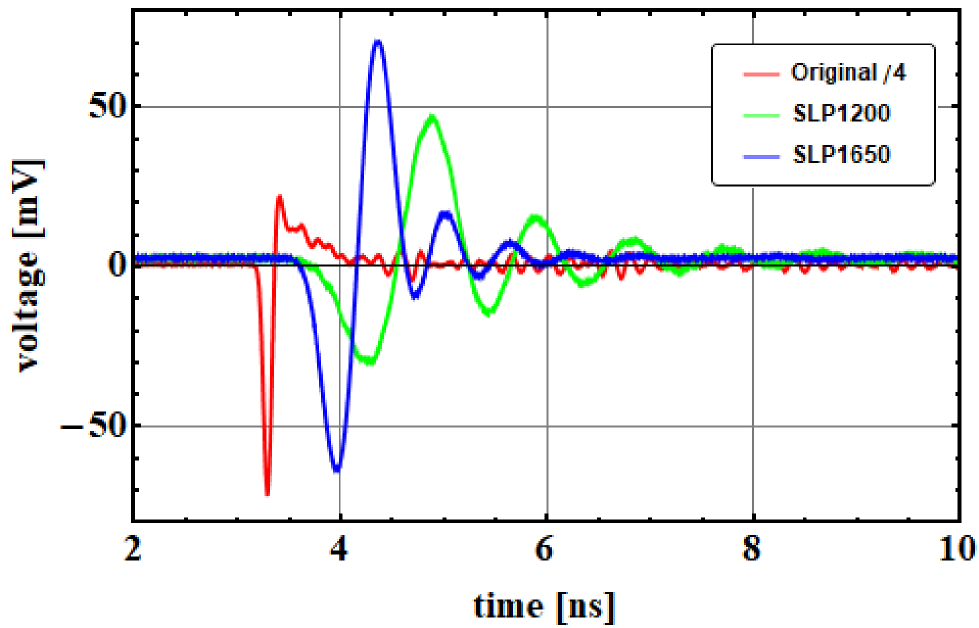


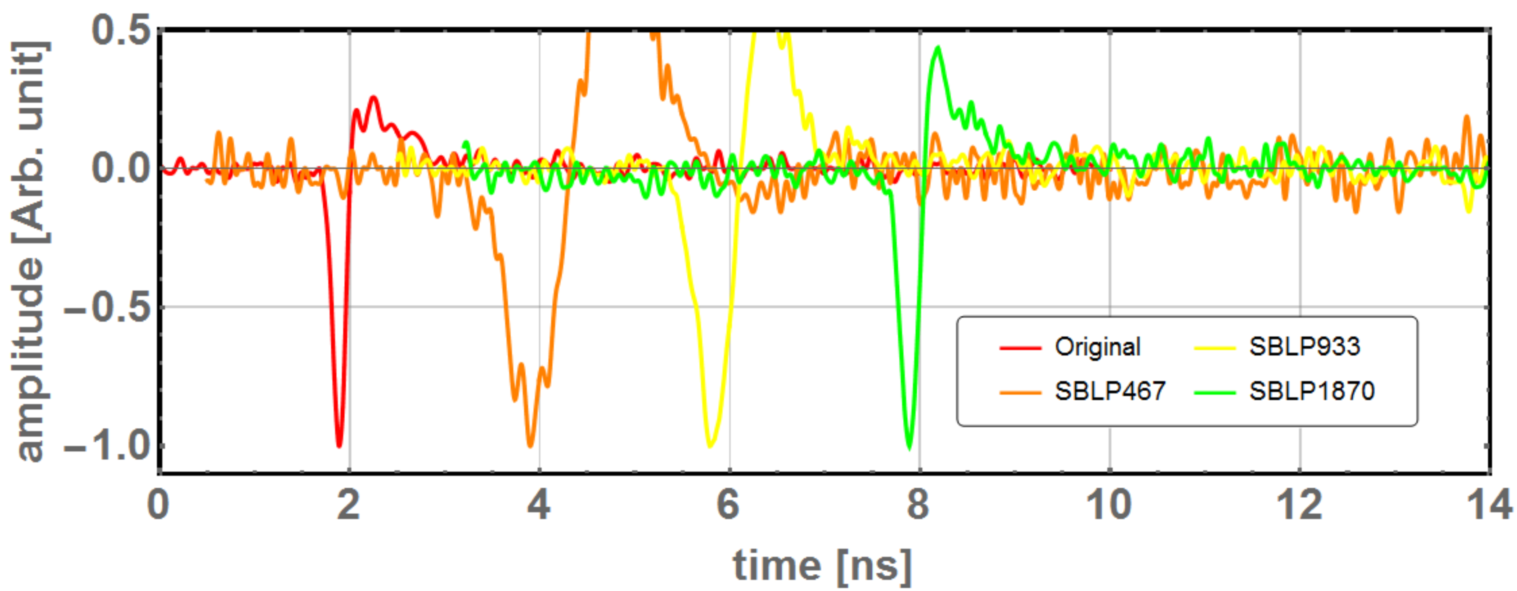



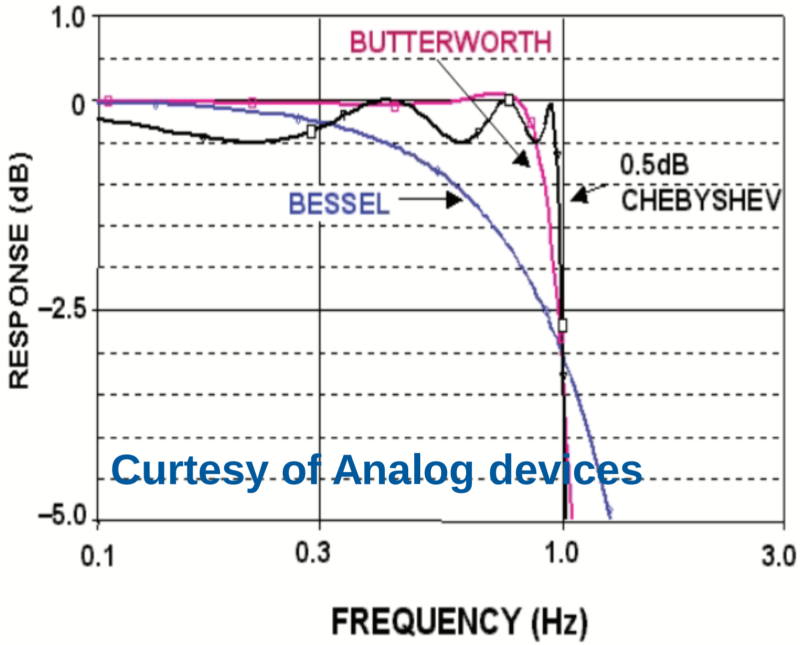
# Alternative method for compensating ringing signal

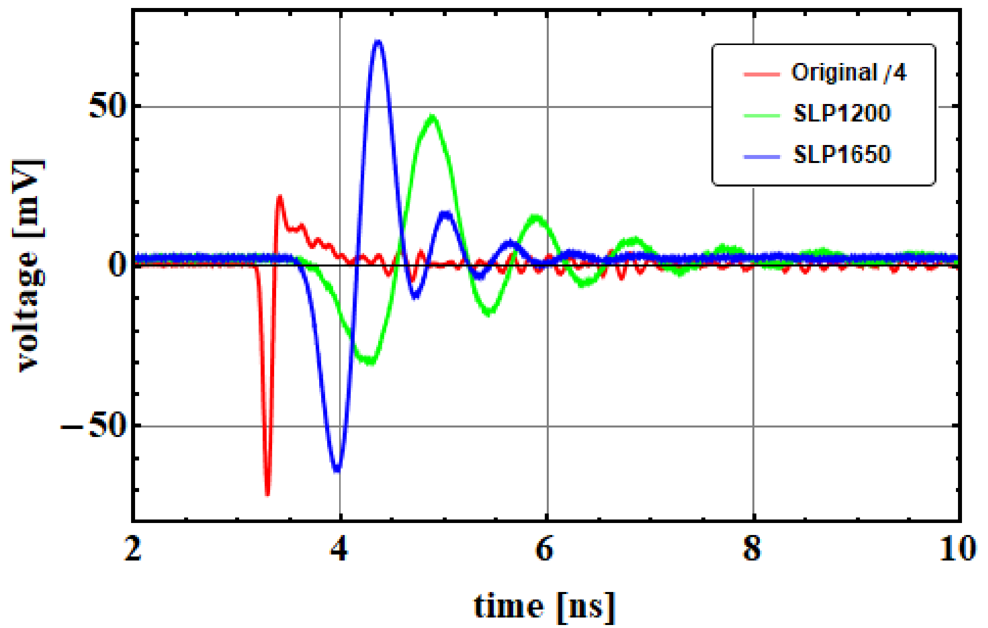


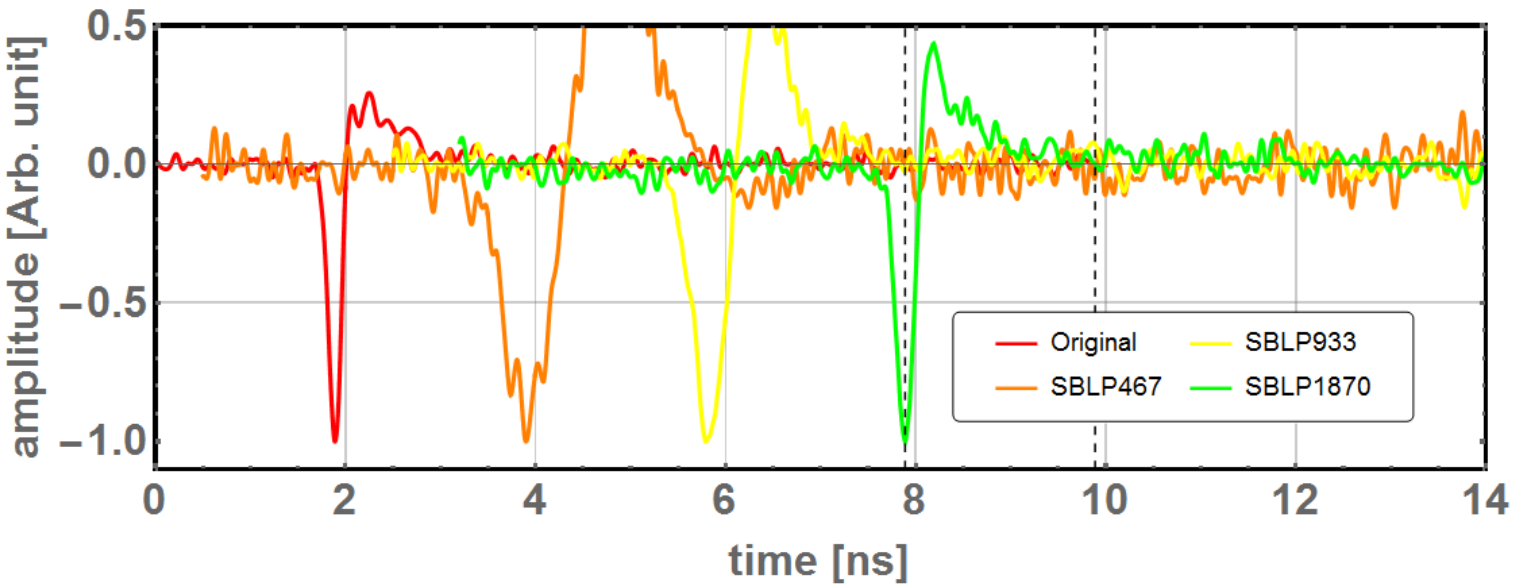



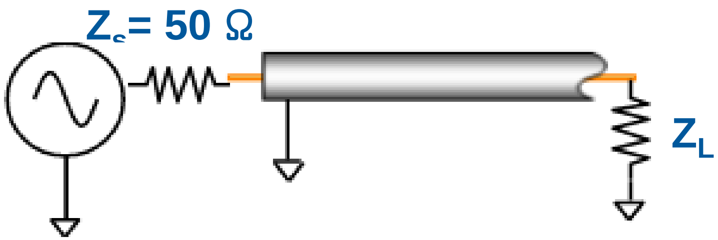
# Alternative method for compensating ringing signal

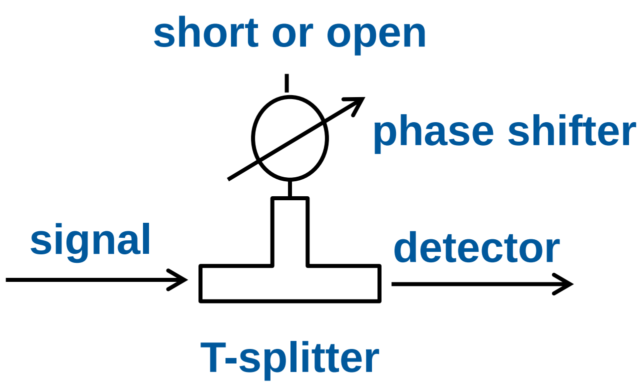


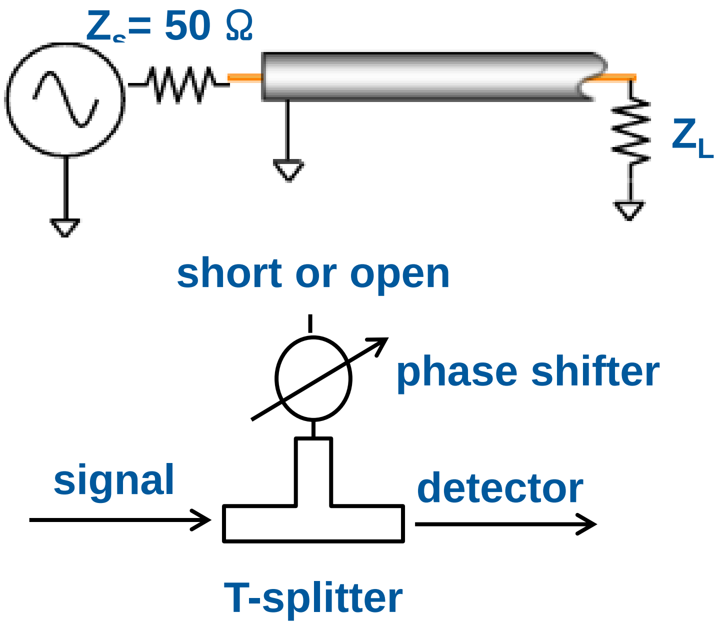



# Alternative method for compensating ringing signal

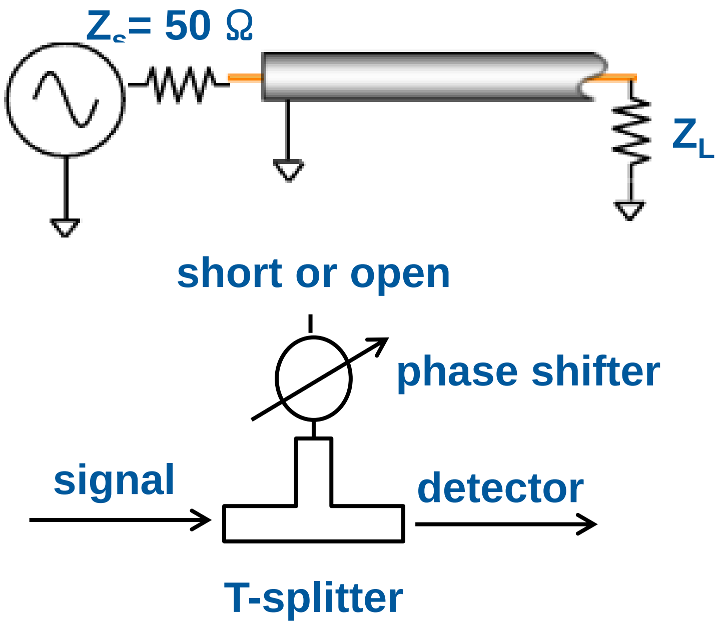


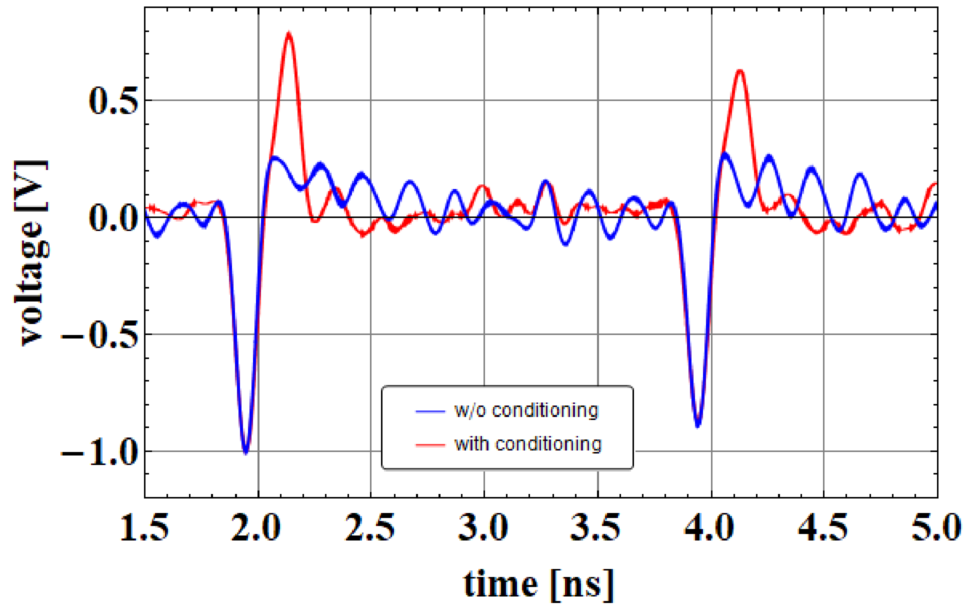



# Alternative method for compensating ringing signal

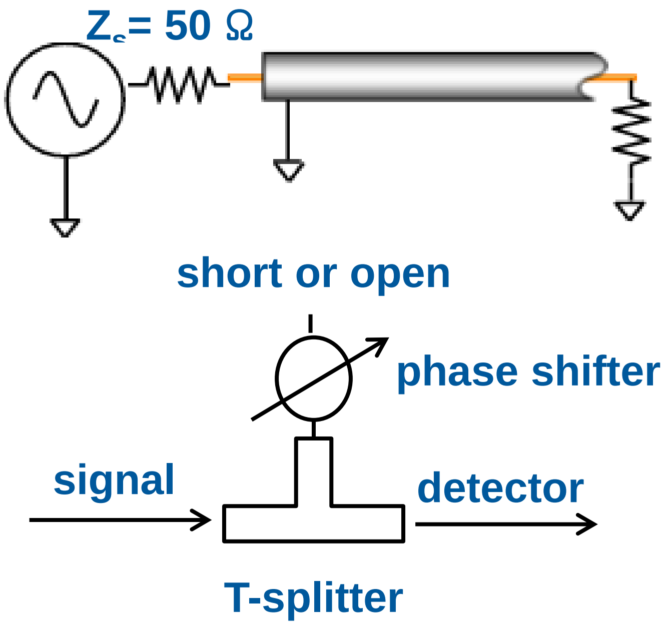


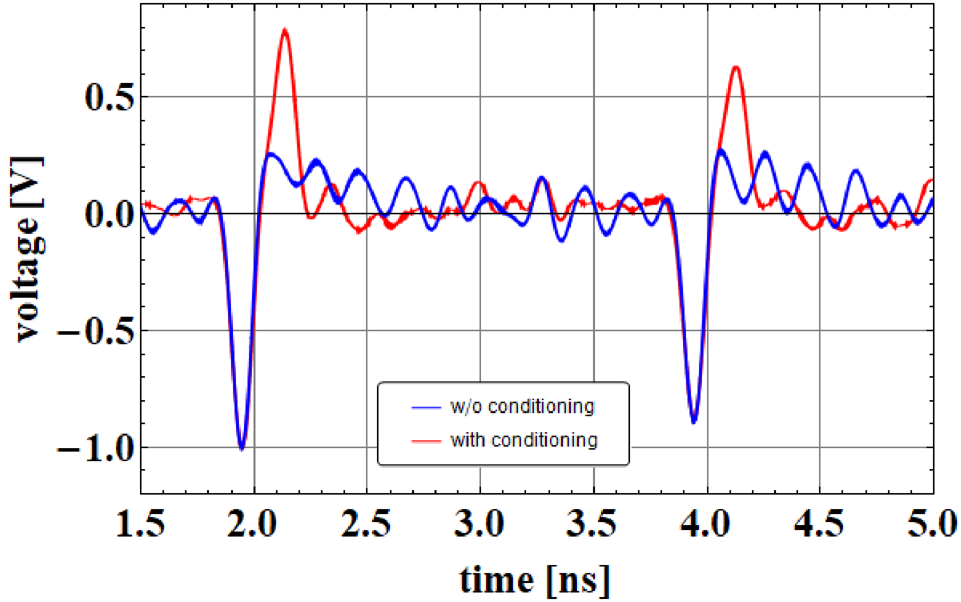

# Alternative method for compensating ringing signal

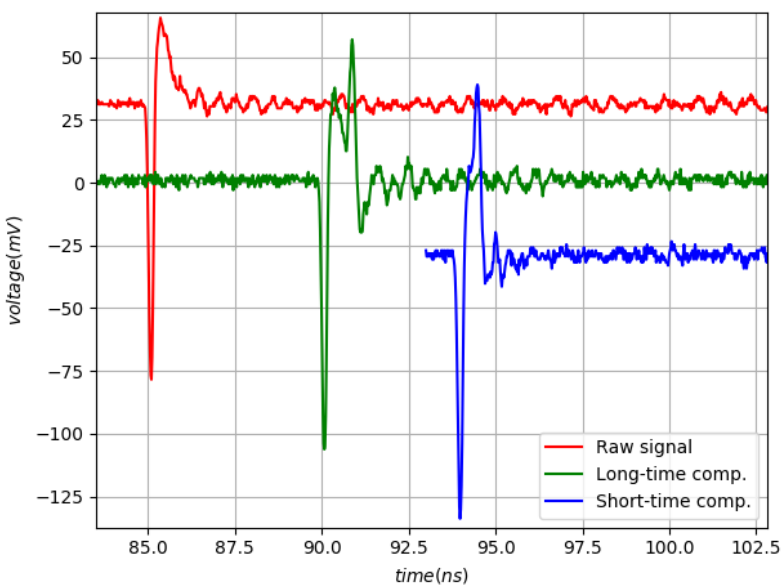


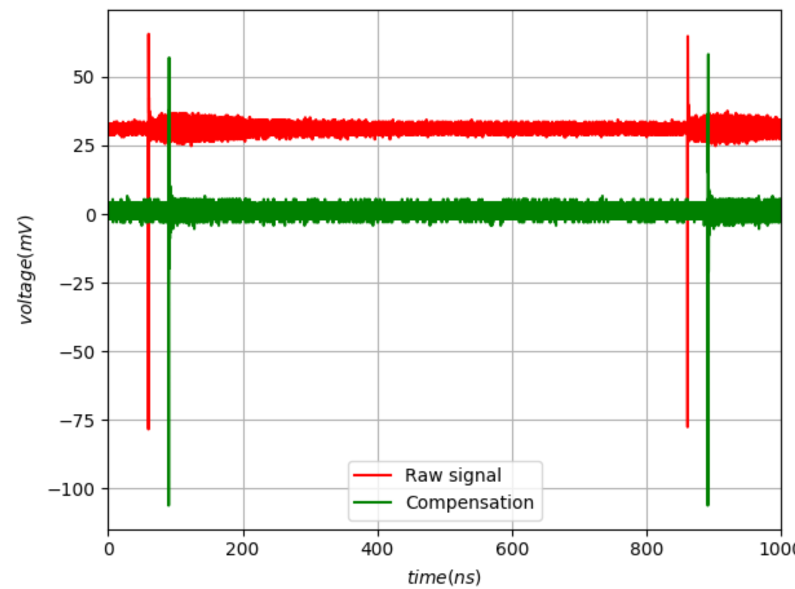



# Alternative method for compensating ringing signal



# Summary

**Many physical properties were learned from the 20-years old mature button BPM at the BESSY II storage ring .**

**What we learned from mature BPM :**

1. Heating : below 0.48 W / button
2. Signal contamination by preceding bunches
3. Multiple internal reflection due to the impedance mismatching
4. Low frequency (~1.5 GHz) trapped mode @ button lodging hole

**Our partial solutions for the issues on button BPM**

1. Heating : can be reduced by selecting the material properly
   Mo ($2 \times 10^7$ S/m) – SUS ($1.45 \times 10^6$ S/m) / Cu ($6 \times 10^7$) - SUS/ Al($4 \times 10^7$) - SUS
2. Ringing signal : SiO2 ($\varepsilon_r = 3.74$) or low permittivity insulator
   or special filter / self-compensation scheme
3. Impedance matching : can be optimized
4. Trapped mode @ button lodging hole :
   RF spring in NSLS-II → We reduce the gap (* mainly by vacuum experts)

# Thank you for your attention