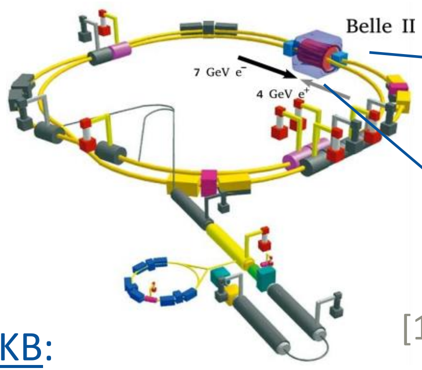
MASTER-COLLOQUIUM 17.11.23

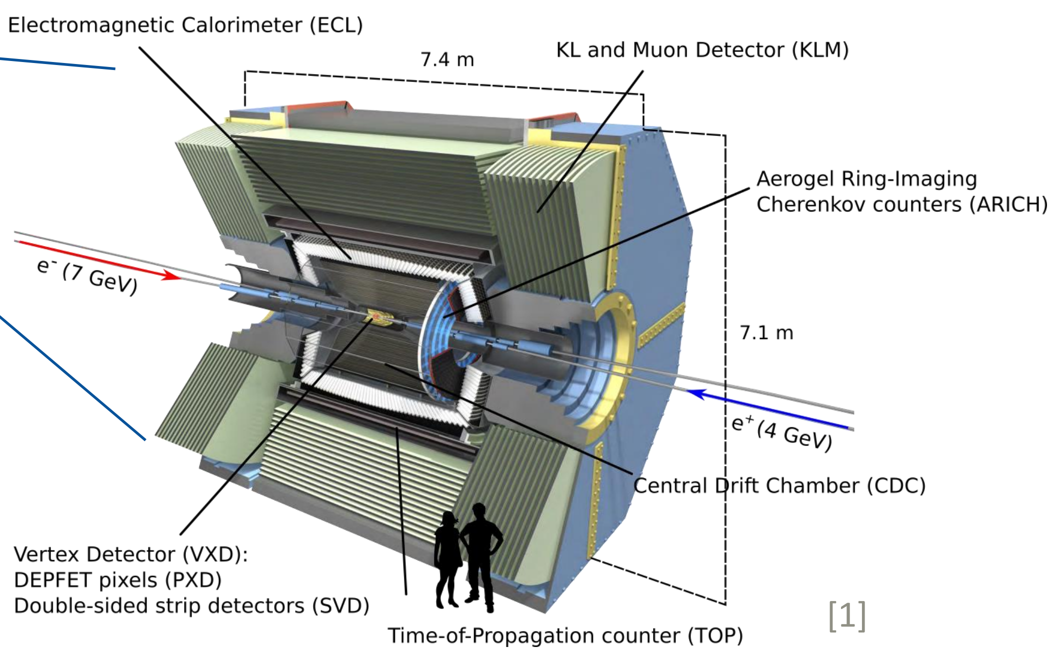
PXD EMERGENCY SHUTDOWN SIMULATION

Paula Scholz

SUPERKEKB AND BELLE II



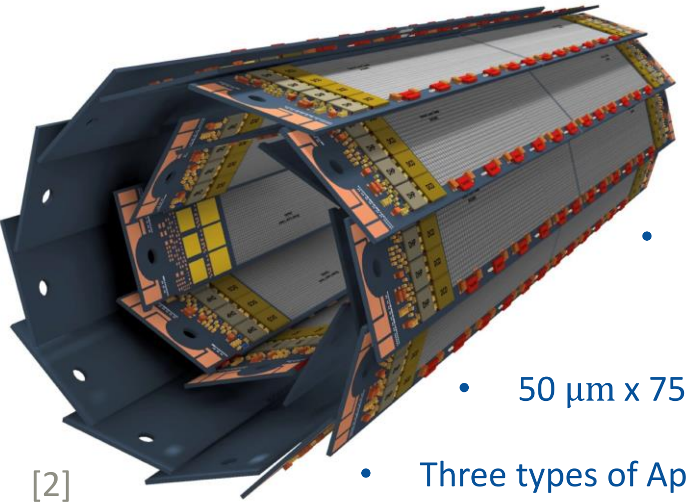
[1]



[1]

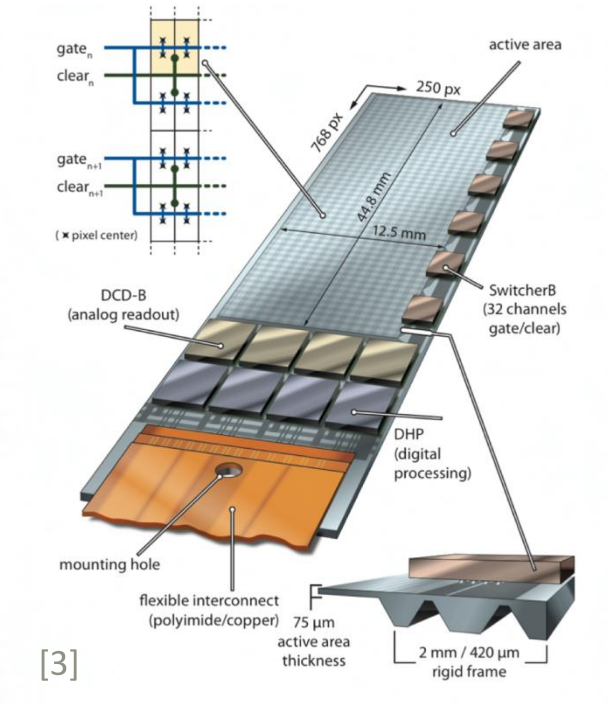
- SuperKEKB:
  - Asymmetric e^+-e^- collider
  - Peak luminosity L = 4.7 x 10^{34} $cm^{-2}s^{-1}$
- Belle II:
  - Contains vertex detector including pixel detector

BELLE II PIXEL DETECTOR (PXD)



[2]

- PXD: two layers of DEPFET modules at radii of 14 mm and 22 mm
- 50 µm x 75 µm pixels thinned to 75 µm
- Three types of Application Specific Integrated Circuits (ASICs) are responsible for readout:
  - DCD, DHP, **Switchers**



[3]

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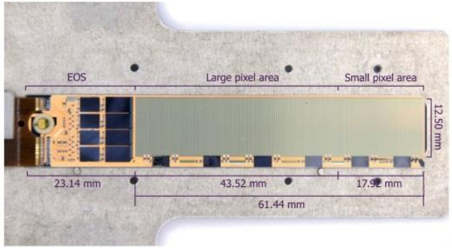
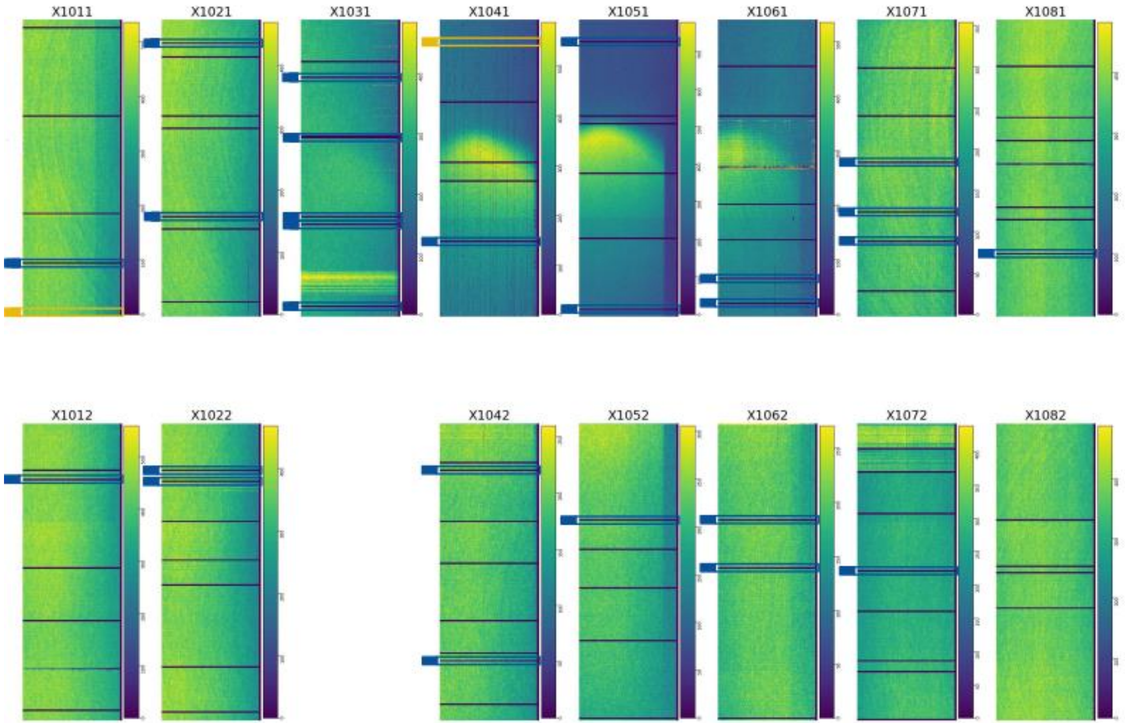
MOTIVATION

[3]



- Switchers **vulnerable** to large radiation
- Example: Beam loss event in 2020
  - Estimated dose: 500 rad for PXD1 in 40 µs
  - Increased number of **inefficient rows**
    - In total 89 inefficient rows ➔ efficiency drop of 3%
    - blue flags: freshly emerged inefficient rows
- Damage can be prevented when Switchers are turned off

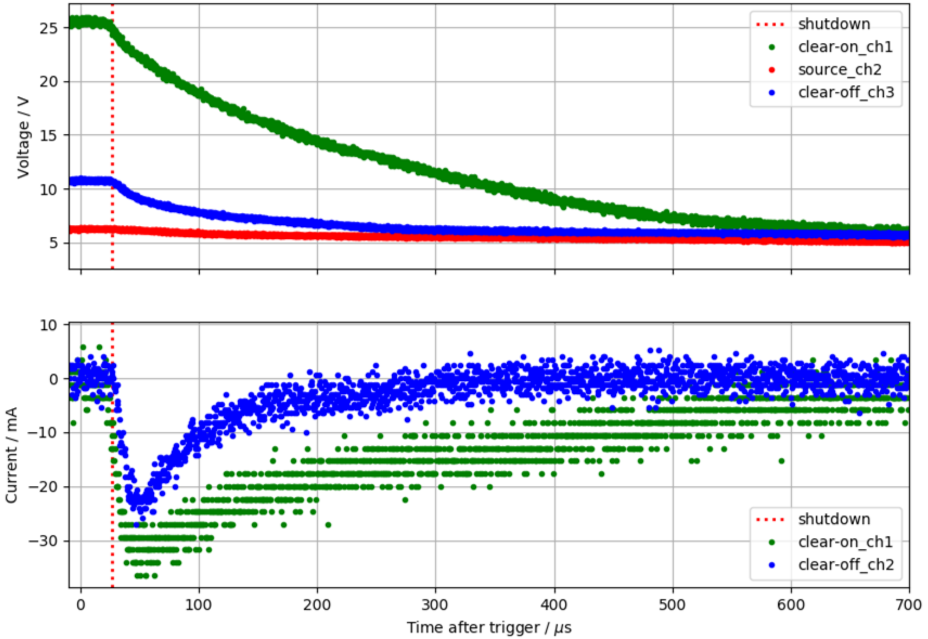
➔ Shutdown as fast and safe as possible



[4]

REGULAR SHUTDOWN

- Regular shutdown applied at PXD1:
  - Switch off power
- Example: Shutdown of Switcher voltages
- **Long discharge time** due to capacitors
  - Shutdown time in ms-range

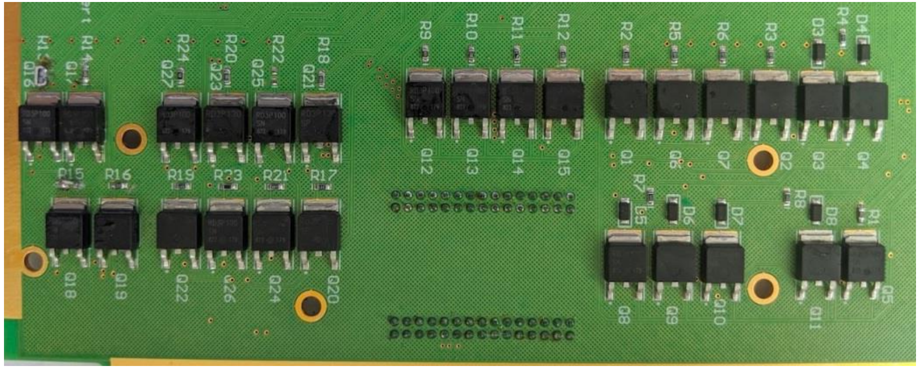


[4]

FAST SHUTDOWN BOARD

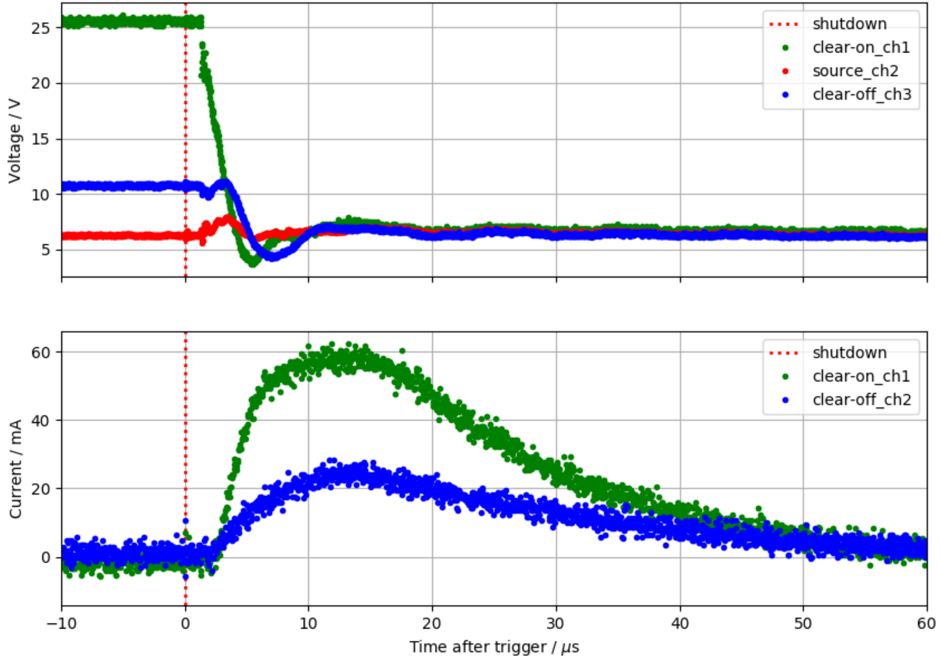
- Idea:
  - Short all channels with FET to respective ground

    ➔ **Active pull-down**
  - Add resistor to influence pull-down time
- Problem: Required resistor values unclear yet



FAST SHUTDOWN MEASUREMENT

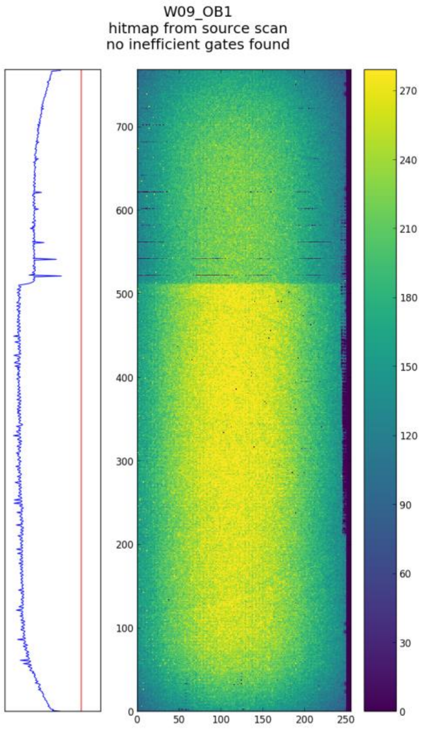
- Example: Shutdown of Switcher voltages (Clear On/ Clear Off), **measured at Power Supply level**
- $R_{clear\ on} = 0\ \Omega,\ \ R_{clear\ off} = 0\ \Omega$
- $V_{clear\ on}$ drops below $V_{clear\ off}$ ➔ violation of shutdown sequence



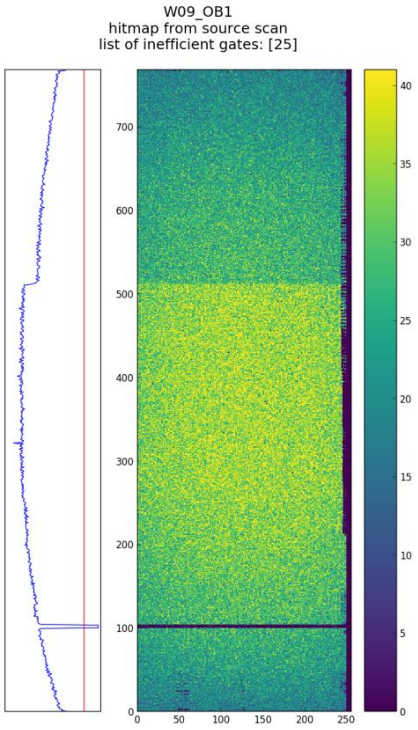
[4]

RESULTS FROM FAST SHUTDOWN

- Testing of **fast shutdown** board resulted in high Switcher currents
- Example:
  - Compare hitmaps before and after using fast shutdown board
  - Detected **inefficient rows**
- If done wrongly:
  - Fast shutdown has **same effects** as a beam loss event
- Testing on module is harmful

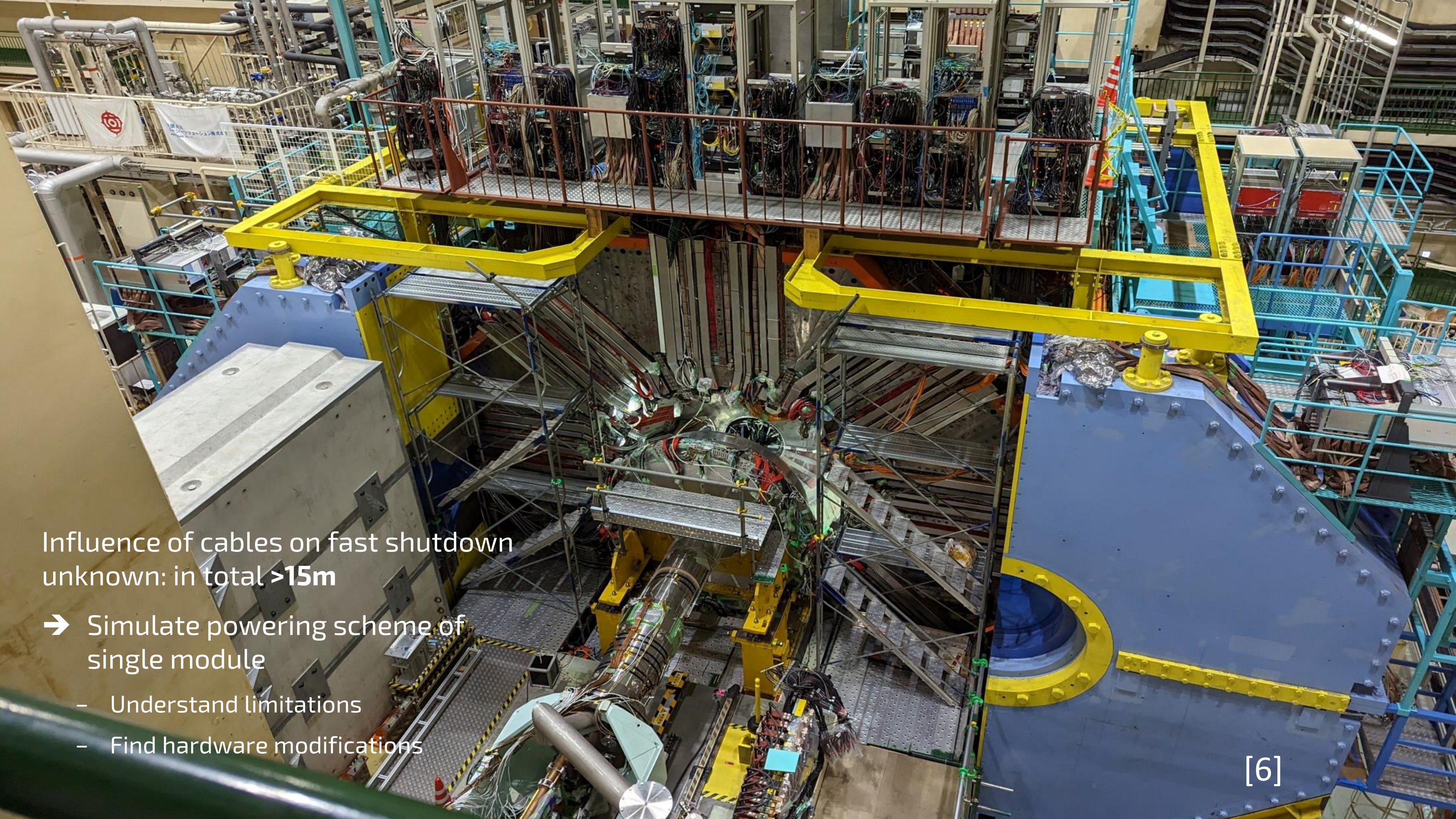


Before fast shutdown



After fast shutdown

[5]



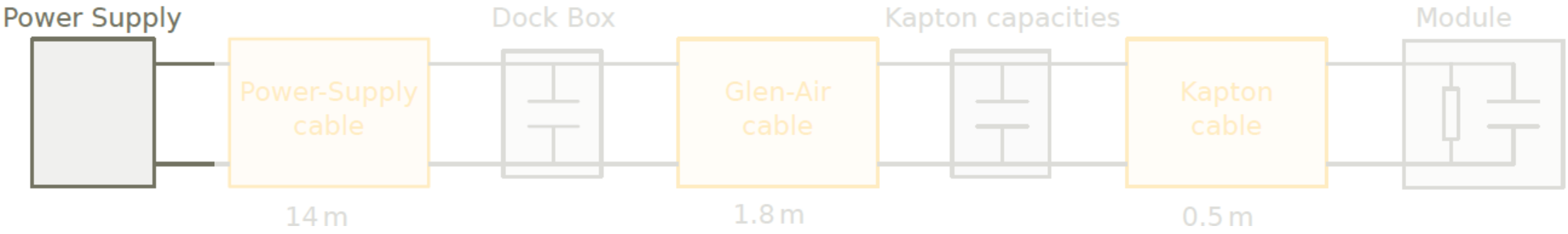
Influence of cables on fast shutdown unknown: in total **>15m**

➔ Simulate powering scheme of single module

- Understand limitations
- Find hardware modifications

[6]

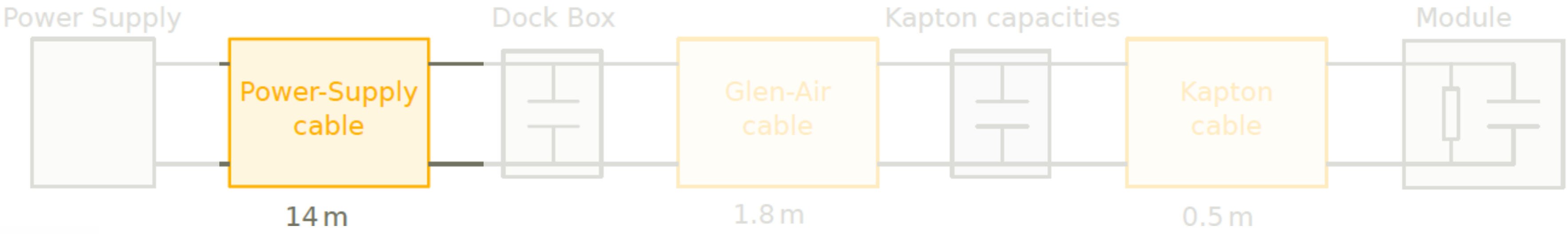
SIGNAL PATH



[1]

- 23 different voltages required for operation
- DC/DC converters
- Dedicated power-up and power-down sequence

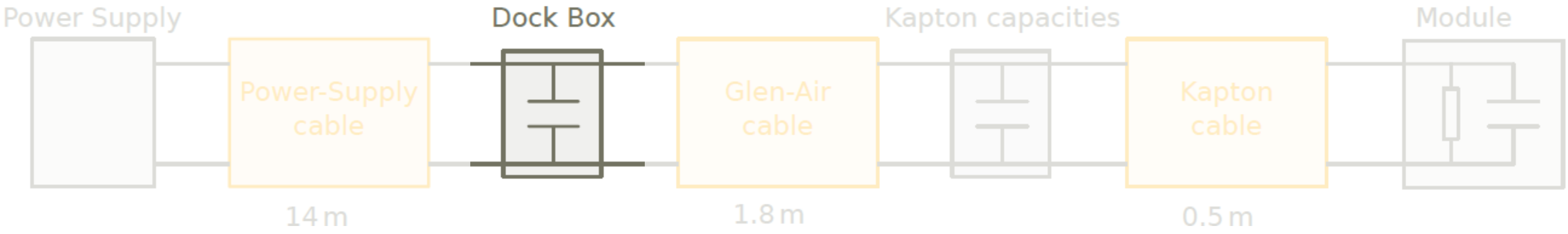
SIGNAL PATH

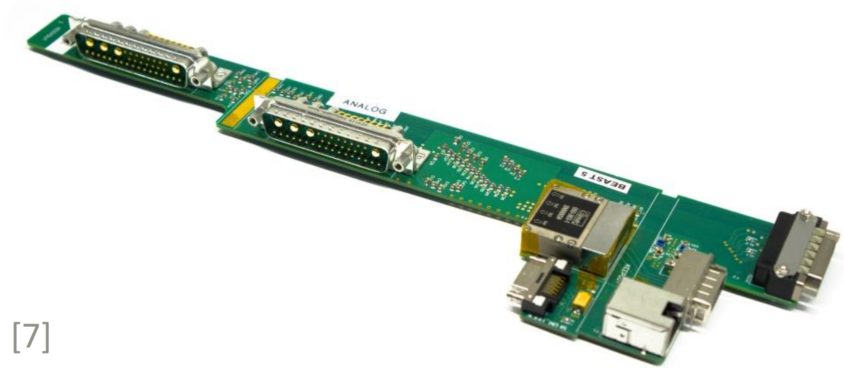


[7]

- Two Power-Supply cables (PS-cables)
- 30 conductors with four different wire gauges (given in AWG)

SIGNAL PATH





[7]

- Joins power cables and data cables
- Decoupling capacitors on almost every line

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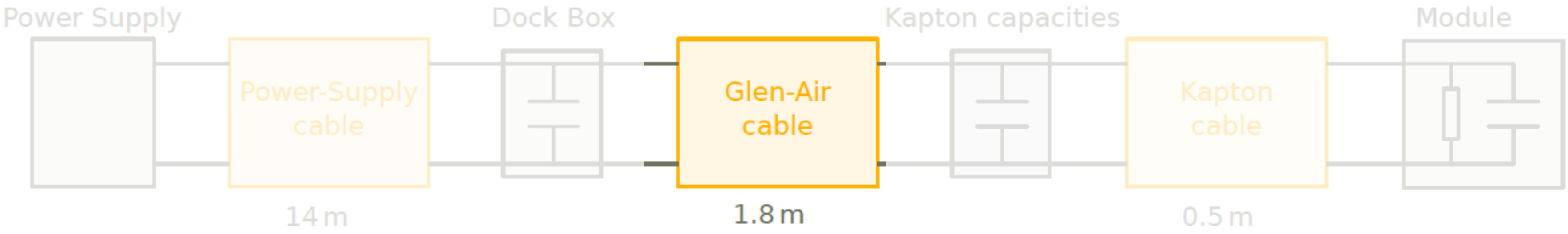
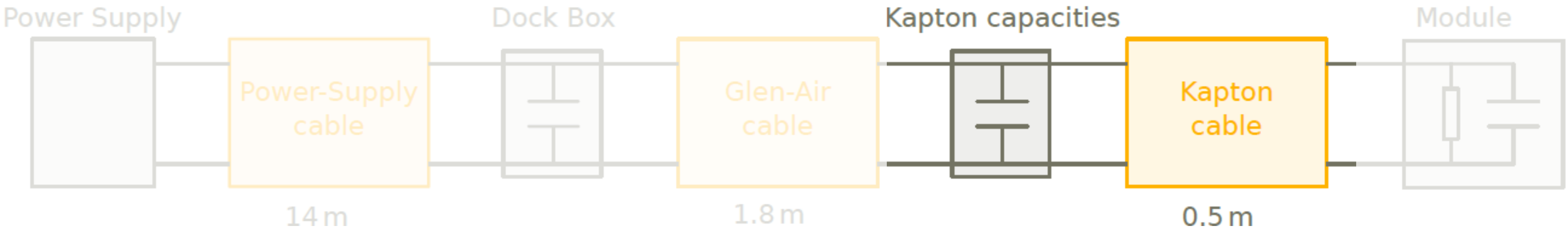
SIGNAL PATH



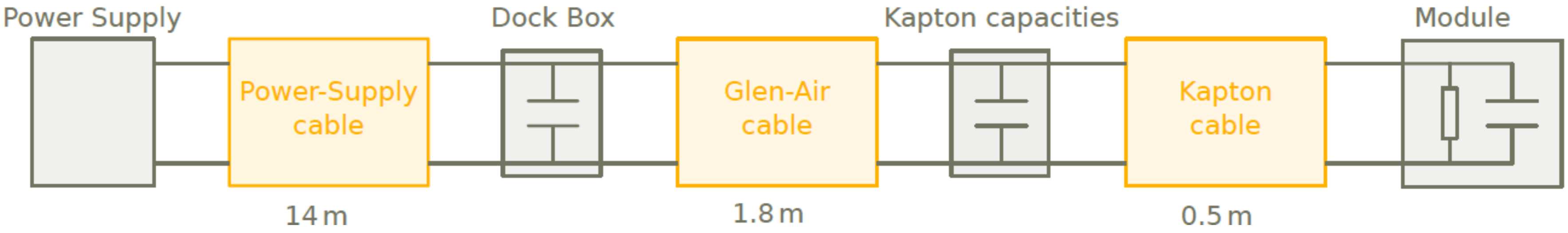
- Glen-Air cable (GA-cable): 51 identical cores
- Terminates in Patch Panel (PP)

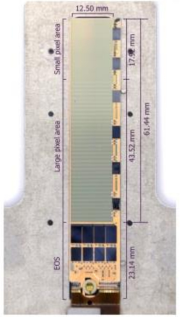
SIGNAL PATH



- Kapton flex cable
- Rigid PCB area with capacitors to ground lines
- Attachment to module via wire bonds

SIGNAL PATH





[1]

CABLE CHARACTERISTICS

- Characterstics proportional to cable length:

Resistance

- DC –Resistance
- Skin-effect $\propto \sqrt{f}$
- Proximity-effect $\propto \sqrt{f}$
- **No phase shift** between current and voltage

Inductance

- Mutual inductance
  - Magnetic field of neighbouring conductors
- Self inductance ($\propto \sqrt{f}$)
  - Magnetic field within the conductor
- **Phase shift** between current and voltage

Capacitance

- Conductors save charge and discharge it when opposed to AC
- **Phase shift** between current and voltage

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- Self inductance ($\propto \frac{1}{\sqrt{f}}$)
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- **Phase shift** between current and voltage

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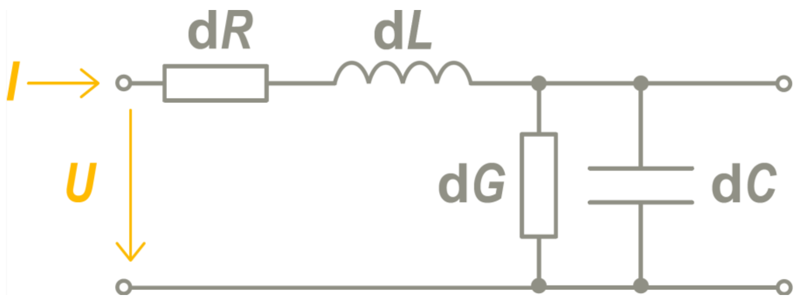
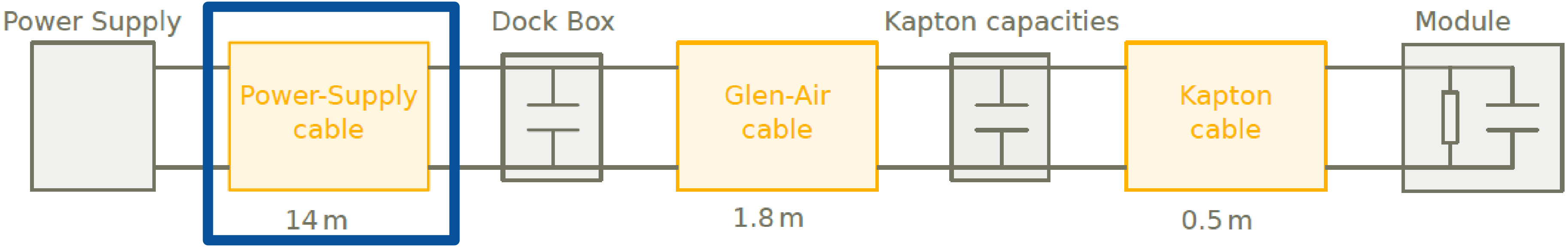
TRANSMISSION LINE THEORY

- Equivalent circuit diagram of a cable
  - $\mathrm{d}R$, $\mathrm{d}L$, $\mathrm{d}G$ and $\mathrm{d}C$ per **cable segment** $\mathbf{d}\boldsymbol{l}$
  - Complete cable: cascade of equivalent circuit diagrams



- **Impedance**: relation between *complex* voltage and current
- $Z = \sqrt{\frac{\mathrm{i}\omega \cdot L' + R'}{\mathrm{i}\omega \cdot \mathrm{C}' + G'}}$ where $X' = \frac{X}{l}$

CABLE MODEL



Power Supply
Power-Supply cable
14 m
Dock Box
Glen-Air cable
1.8 m
Kapton capacities
Kapton cable
0.5 m
Module

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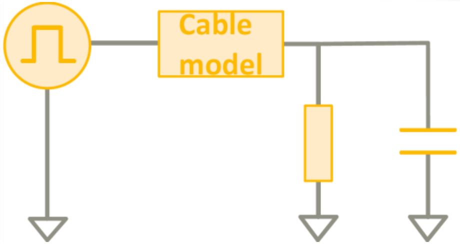
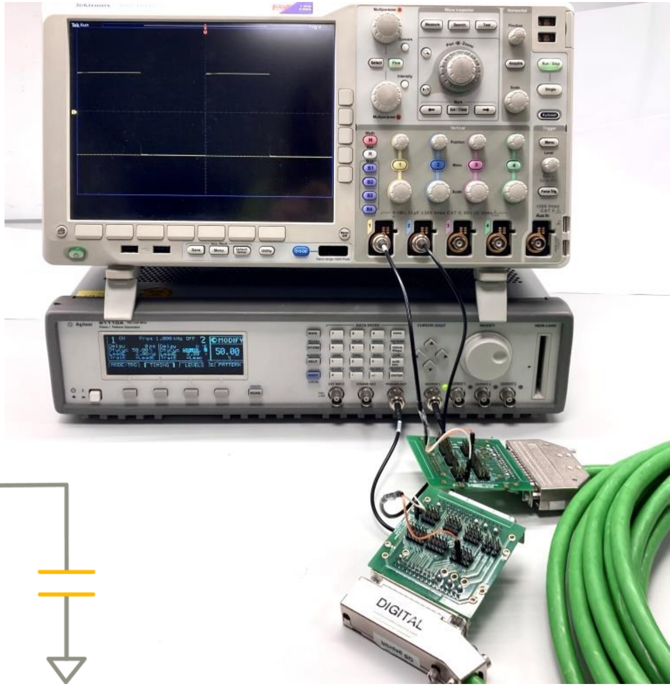
SIMULATION VERIFICATION

- Comparison with **measurement** to verify
  - **Falling edge** of a squared pulse
  - Function generator used for creating squared pulse
  - View transmitted signal on oscilloscope
- Verify each cable segment **individually**
- For quantification:
  - Compute **difference in voltage** between simulation and measurement data
  - Both data sets are interpolated linearly





CABLE MODELS

Ltline

→ LTSpice

- Inductance
- Capacitance
- DC-Resistance

Simple Line

→ HyperLynx

- Impedance
- Delay time
- DC-Resistance

S2spice

→ LTSpice

- S-Parameters

S-Parameter

→ HyperLynx

- S-Parameters

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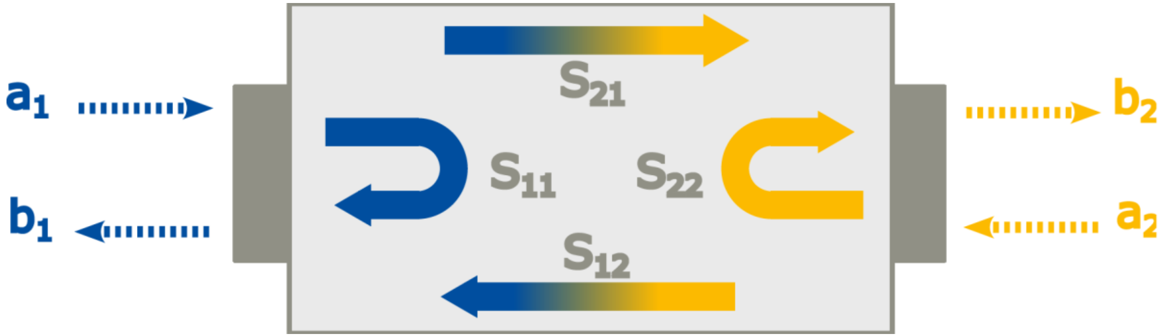
S-PARAMETERS

- Describe electrical behaviour of cable
- Measure **incoming ($\vec{a}$)** and **outgoing ($\vec{b}$)** wave for various frequencies
- Magnitude and phase information
- 2-port measurement:
  - Port 1: Cable Input
  - Port 2: Cable Output



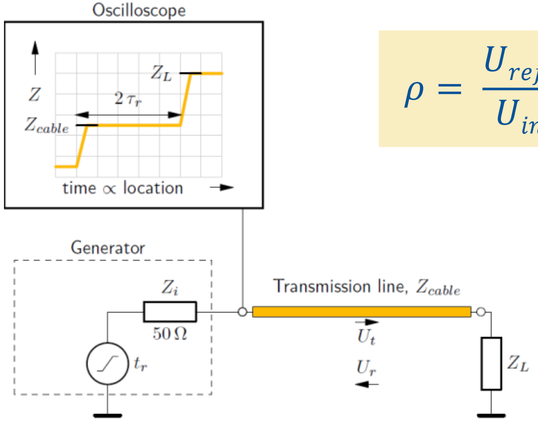
$$S_{11} = \frac{b_1}{a_1} \qquad S_{12} = \frac{b_1}{a_2}$$

$$S_{21} = \frac{b_2}{a_1} \qquad S_{22} = \frac{b_2}{a_2}$$

TIME DOMAIN REFLECTOMETER (TDR) VS VECTOR NETWORK ANALYSER (VNA)

TDR

- **Time** domain → Fast Fourier Transform
- Reflection at open cable end (and transmission)
- **Step** signal as stimulus
- Measures reflection coefficient ρ

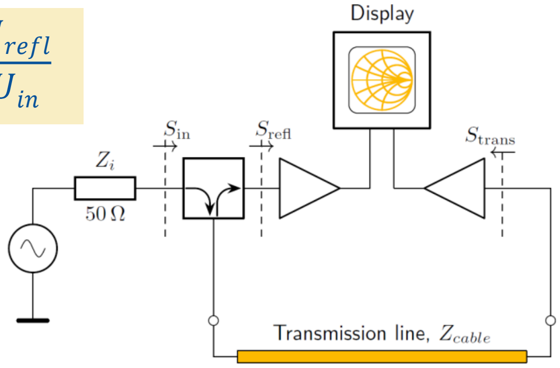


$$\rho = \frac{U_{refl}}{U_{in}}$$

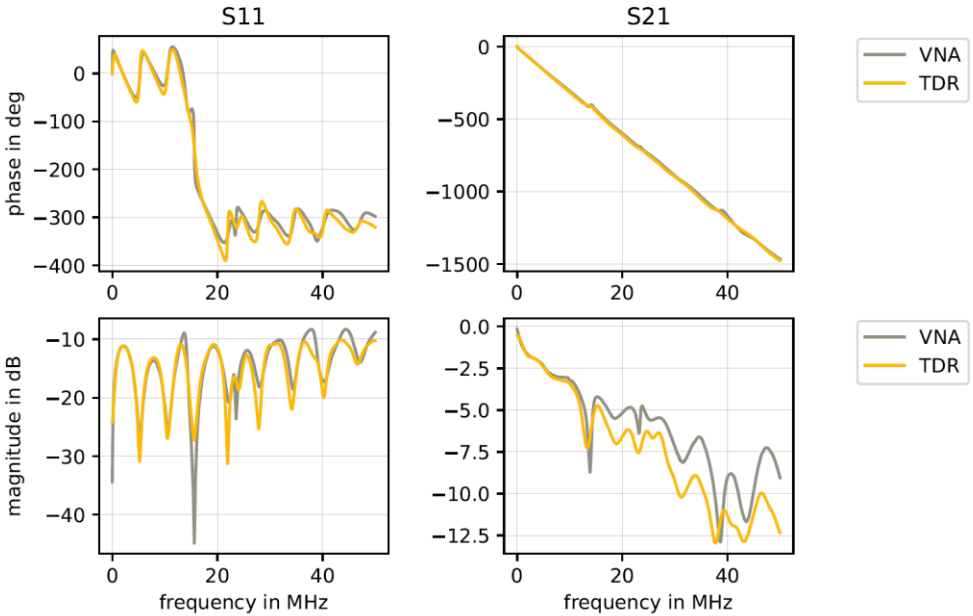
VNA

- **Frequency** domain
- Reflection and transmission
- **Sine** wave as stimulus
- Measures S-parameters

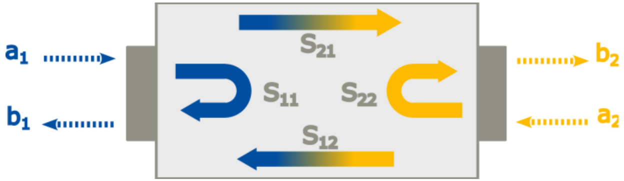
$$S_{11} = \frac{U_{refl}}{U_{in}}$$



TDR VS VNA: S-PARAMETERS

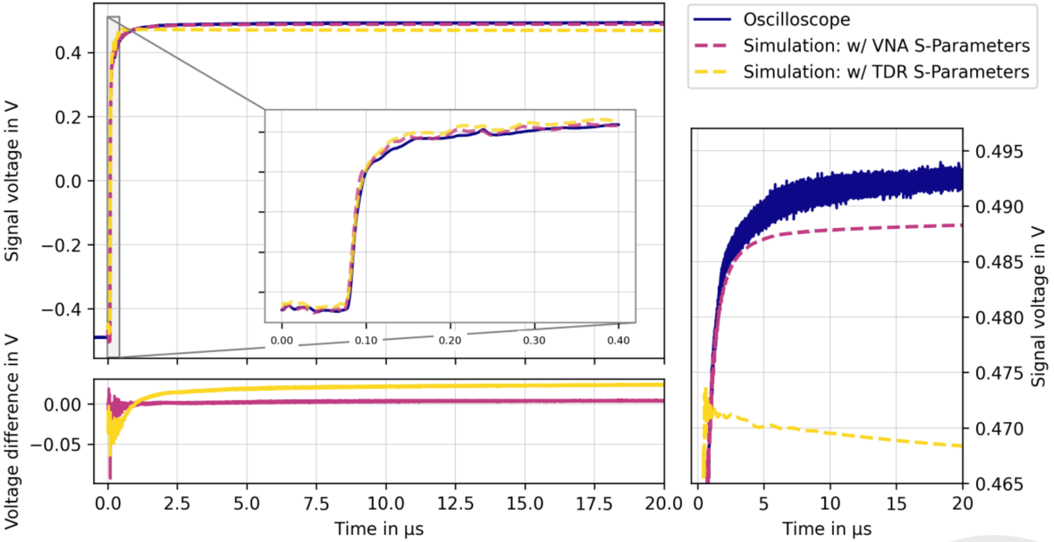


- Example for 26 AWG-line in PS-cable
- Reflection measurement (S11):
  - Slight **shift in phase**
- Transmission measurement (S21):
  - Magnitudes diverge
  - **Higher dampening for TDR S-parameters**



S-PARAMETER SIMULATION: TDR VS VNA

- Simulation of Bulk-line in PS-cable
- HyperLynx S-parameter model in simple transmission setup
- Good agreement in **rising edge** for both measurments (TDR and VNA)
- **Amplitude differs** by ~20 mV
- Higher damping for TDR-measurement
- Physical setup is **better described by VNA** S-parameters



S-Parameter

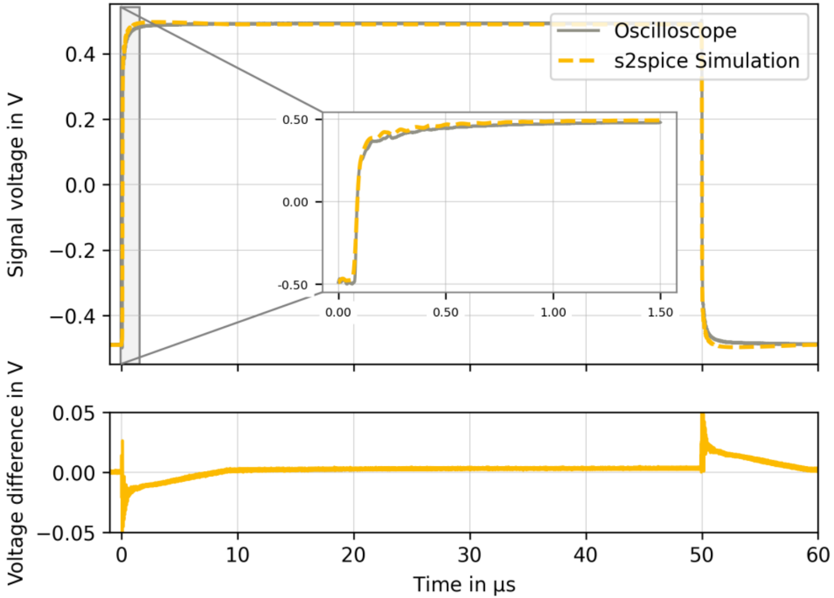
→ HyperLynx

- S-Parameters

S2SPICE MODEL

- No direct possibility to include S-parameters in LTSpice → Create own cable model
- Based on **voltage dependent voltage sources**
- On first glance: good match with physical setup
  - Average voltage deviation (0-40 µs): 3.94 mV
- On second glance: deviation in result **with change in simulation time**
  - Could also be observed with a single voltage dependent voltage source

→ Only suitable if simulation can be verified and simulation time can be adjusted flexibly



CABLE MODELS

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Simple Line

→ HyperLynx

- Impedance
- Delay time
- DC-Resistance

S2spice

→ LTSpice

- S-Parameters

S-Parameter

→ HyperLynx

- S-Parameters

R_{DC}, L & C VALUES

- **Four-wire sensing for DC-resistance**
- Extract inductance and capacitance from **S-parameter** measurement
- Result: **frequency dependent values** per length unit
- Example: different lines of PS-cable
  - ↑AWG ⇒ ↓cross section
- For cable model: **average** over frequency

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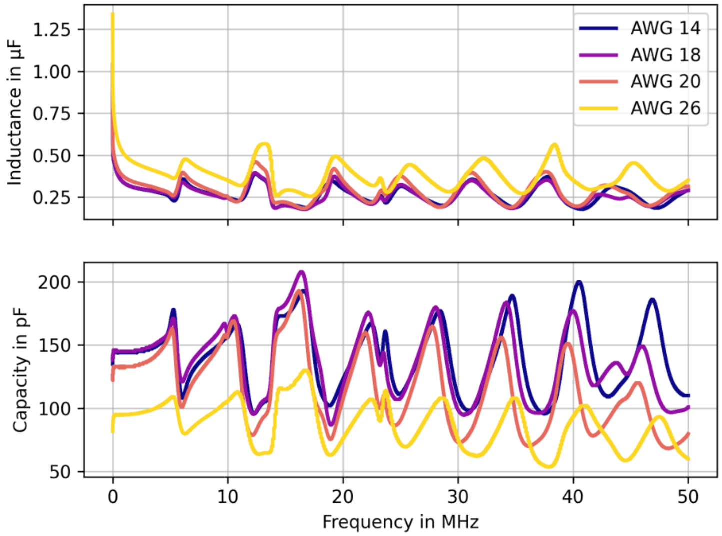

For comparison: **two-wire system** (radii r, distance d)

$$L' = \frac{\mu}{4\pi} + \frac{\mu}{\pi}\ln\left(\frac{d}{\sqrt{r_1 r_2}}\right)$$

[8]

R_{DC}, L & C VALUES

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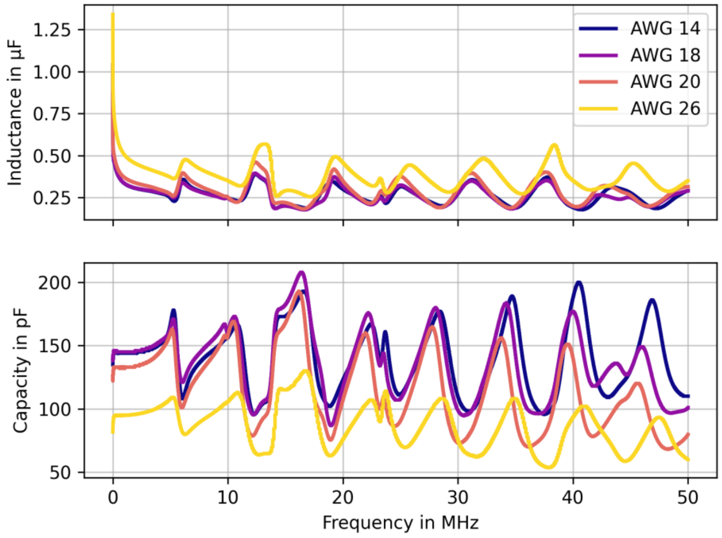


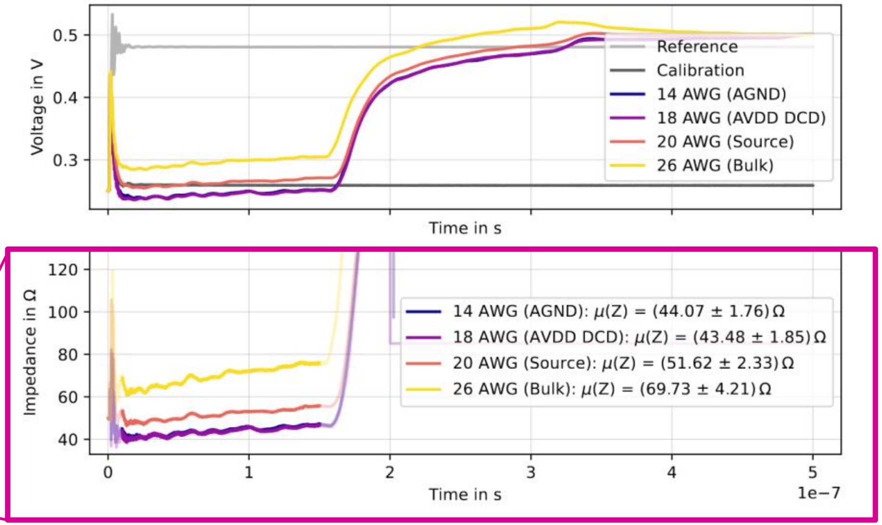
For comparison: **plate capacitor** (area A, distance d)

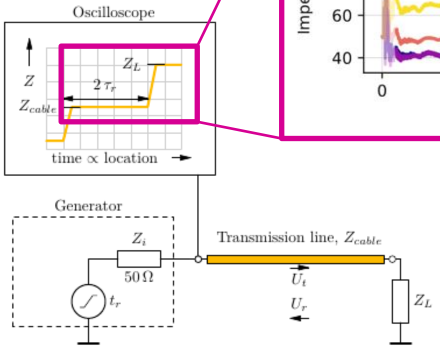
$$C = \frac{\epsilon A}{d}$$

[9]

DELAY TIME AND IMPEDANCE

- Needed for Simple Line model
- Use **TDR**: reflection at open cable end
- **Impedance profile**: view cable as cascade of cable segments
  - Reflection at cable connection
  - Average over cable length
  - Rise in impedance due to DC-resistance
- **Delay time**: $\tau_l = (75.5 \pm 0.5)$ ns





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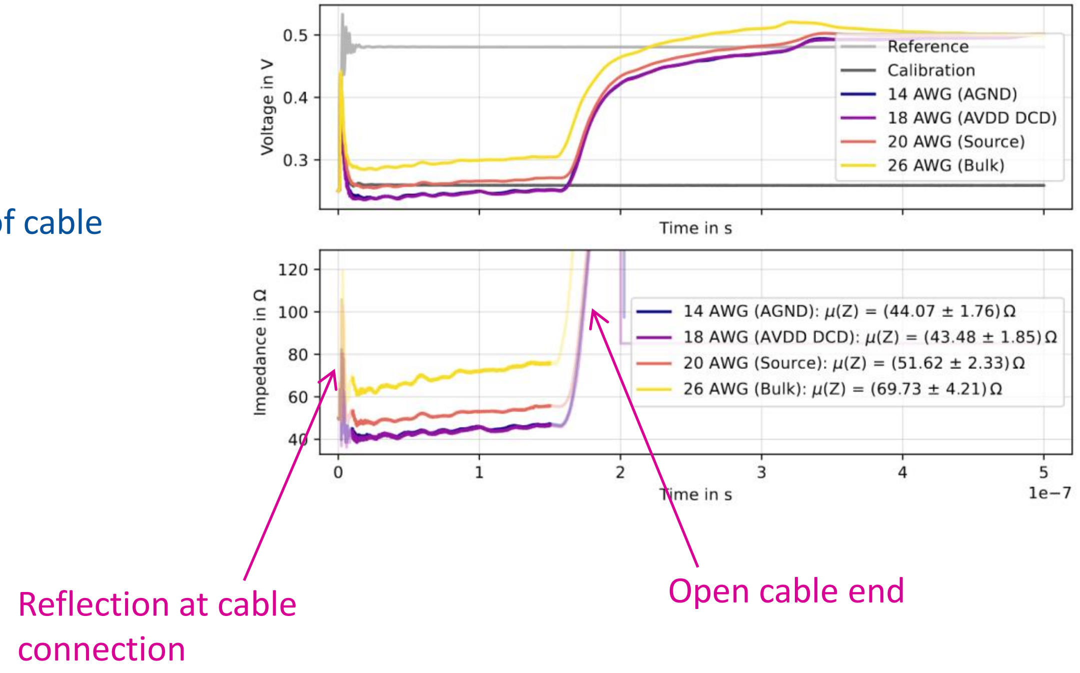

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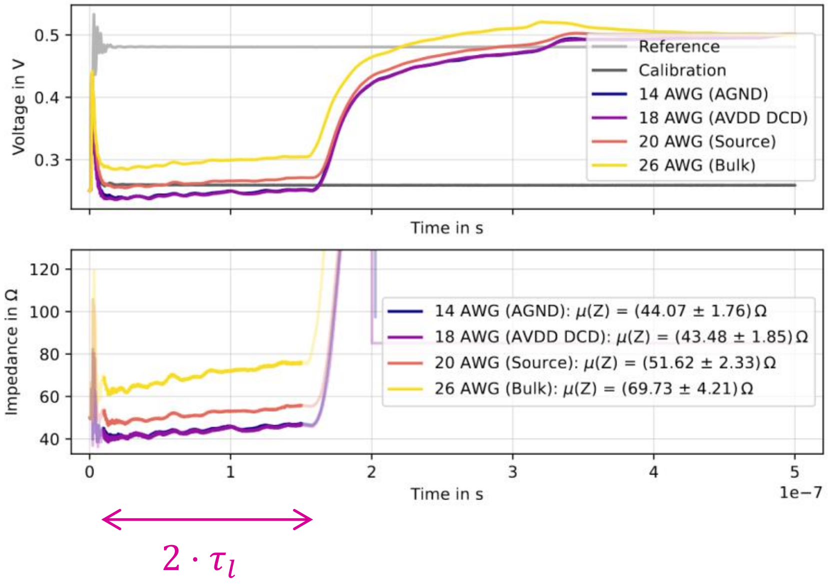

LTSPICE LTLINE & HYPERLYNX SIMPLE LINE MODEL

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- Simulation model using measured parameters
- **Rising edge** is not captured accurately
- **BUT** looking at nanosecond regime
- Average voltage deviation (not including falling edge)
  - Ltline: 3.11 mV for 0-40µs
  - Simple Line: 3.38 mV for 0-40µs

Ltline

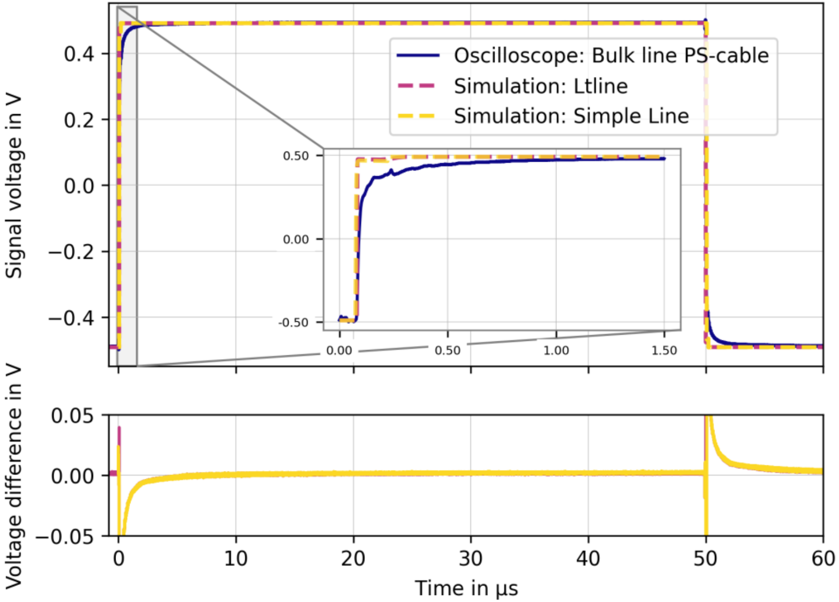
→ LTSpice

- Inductance
- Capacitance
- DC-Resistance

Simple Line

→ HyperLynx

- Impedance
- Delay time
- DC-Resistance



SIMULATION METHODS

LTSpice: Ltline model	HyperLynx: Simple Line model	LTSpice: s2spice model	HyperLynx: S-parameter model
• Frequency independent values as input	• Frequency independent values as input	• Frequency dependent S-parameters	• Frequency dependent S-parameters
• Less accurate in rising edge	• Less accurate in rising edge	• Dependent on accurate S-parameter measurement → amplitude	• Dependent on accurate S-parameter measurement → amplitude
• High standard deviation for L and C-values	• Simulation duration is limited to 500 µs	• Unreliable, as voltage sources are simulation duration dependent	• Simulation duration is limited to 500 µs

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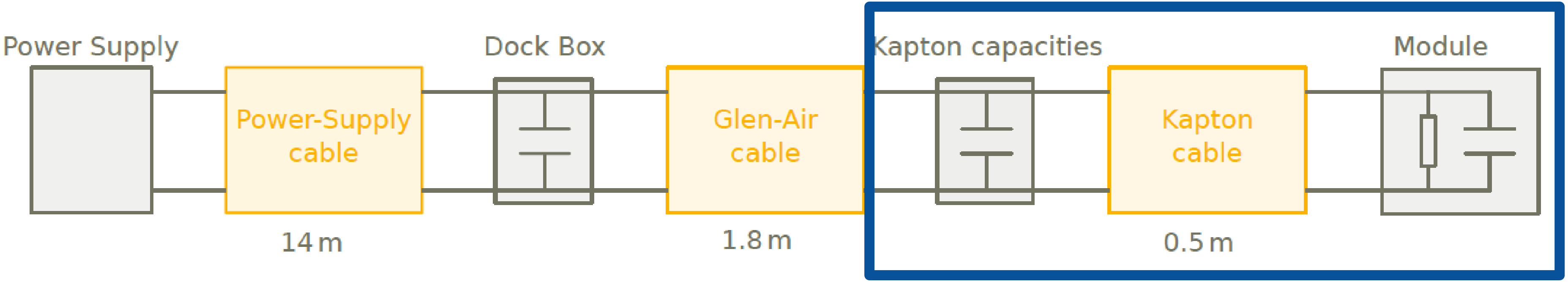
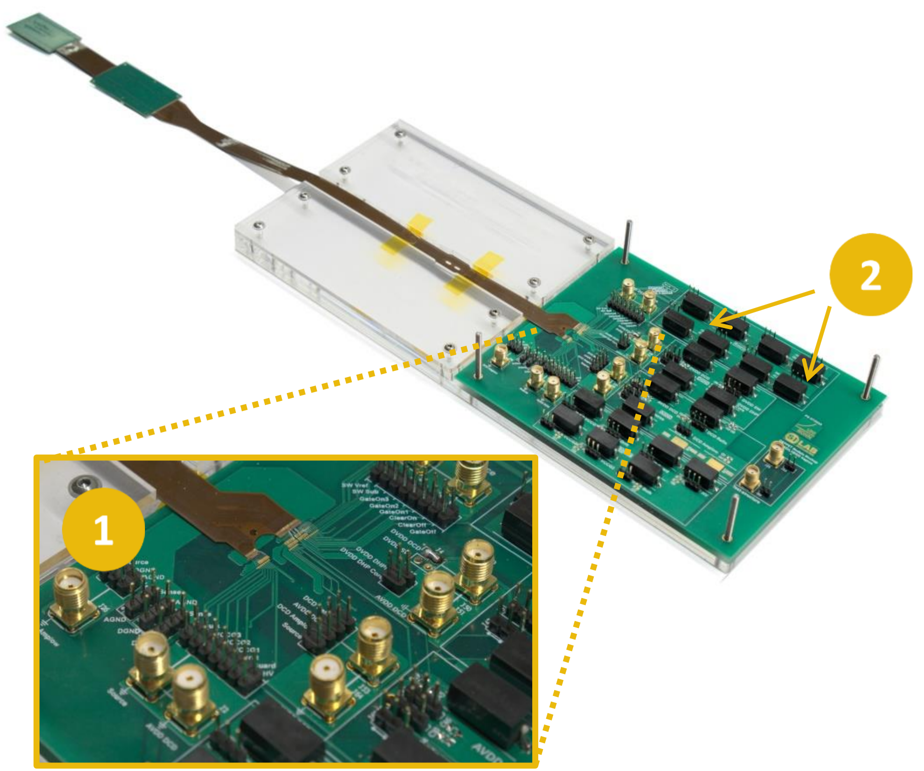
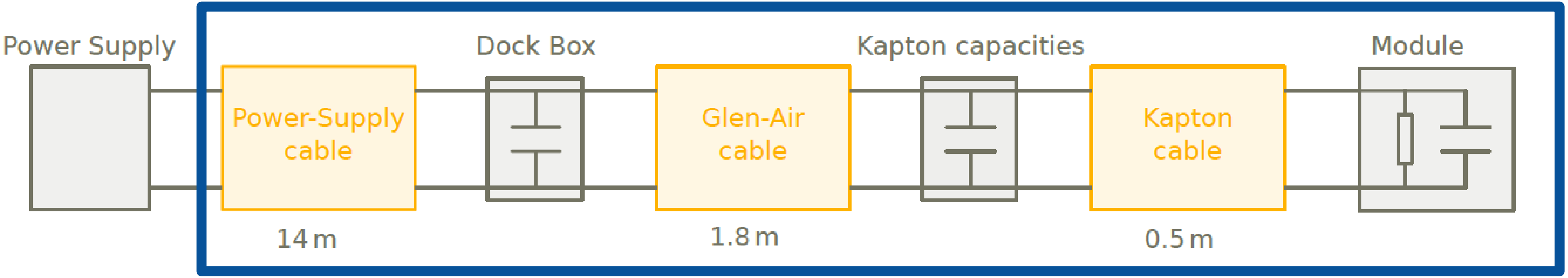
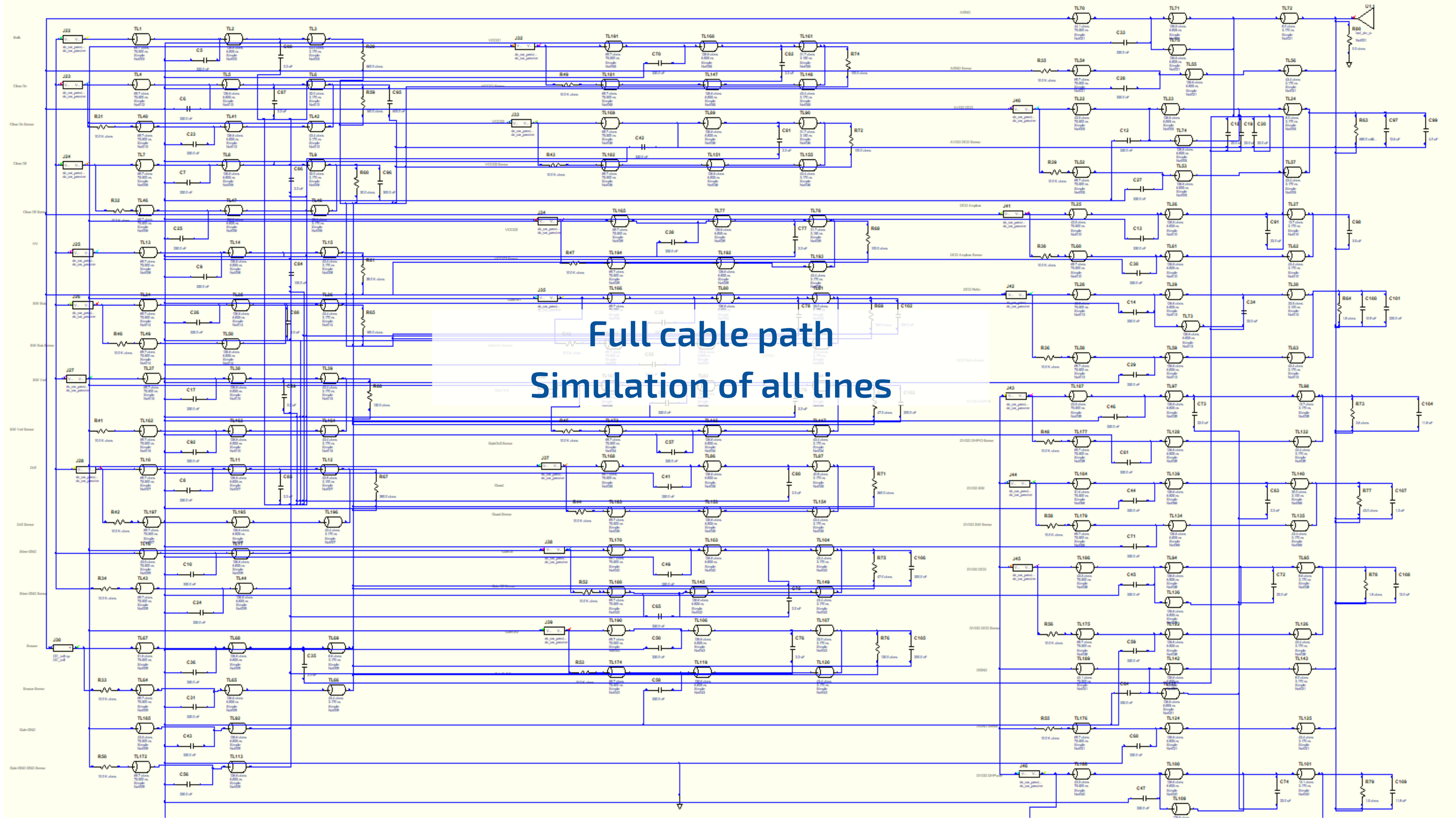

Power Supply
Dock Box
Kapton capacities
Module
Power-Supply cable
Glen-Air cable
Kapton cable
14 m
1.8 m
0.5 m

MODULE MOCKUP

- Verification of simulation: **Module mockup PCB**
  - Connection to all of the lines of Kapton (1)
    - Wire bonding necessary
  - Module mockup (2)
    - Resistors and capacitors mimic module properties after the Kapton connection



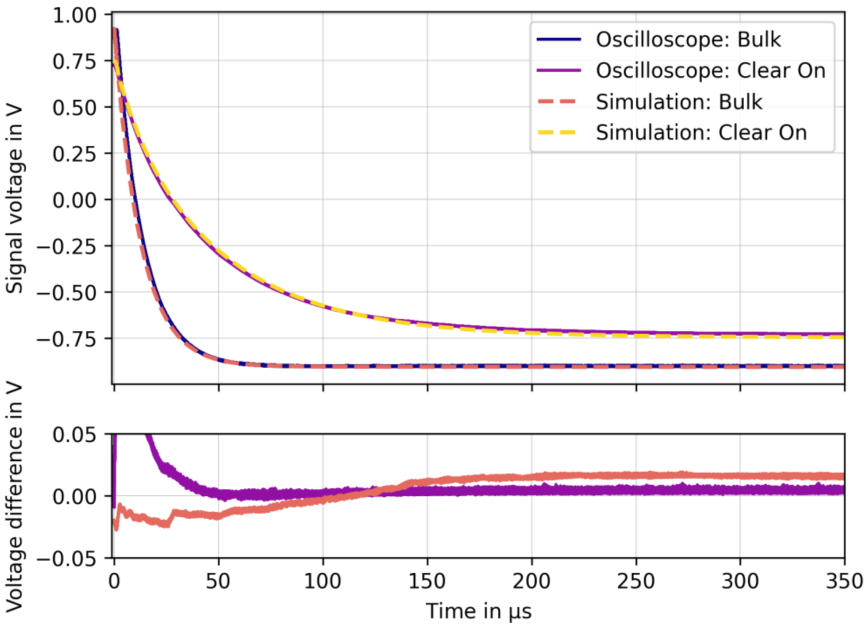

Power Supply
Dock Box
Kapton capacities
Module
Power-Supply cable
Glen-Air cable
Kapton cable
14 m
1.8 m
0.5 m

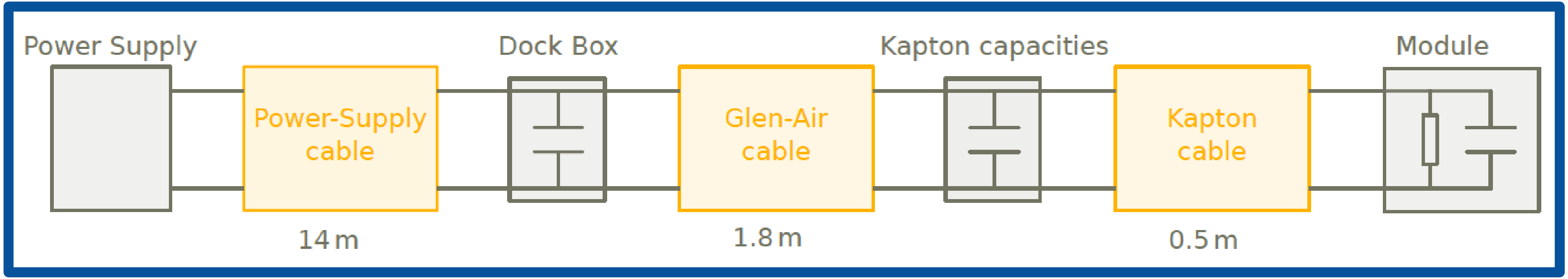


Full cable path
Simulation of all lines

FULL CABLE PATH: POWERING OF TWO LINES

- Not only powered lines need to be simulated because of **capacitive coupling**
- Replication of load with custom made PCB
- Average voltage deviation:
  - Bulk line.: 8.7 mV
  - Clear On line: 13.26 mV

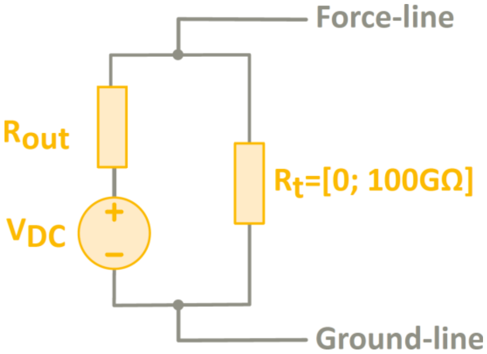


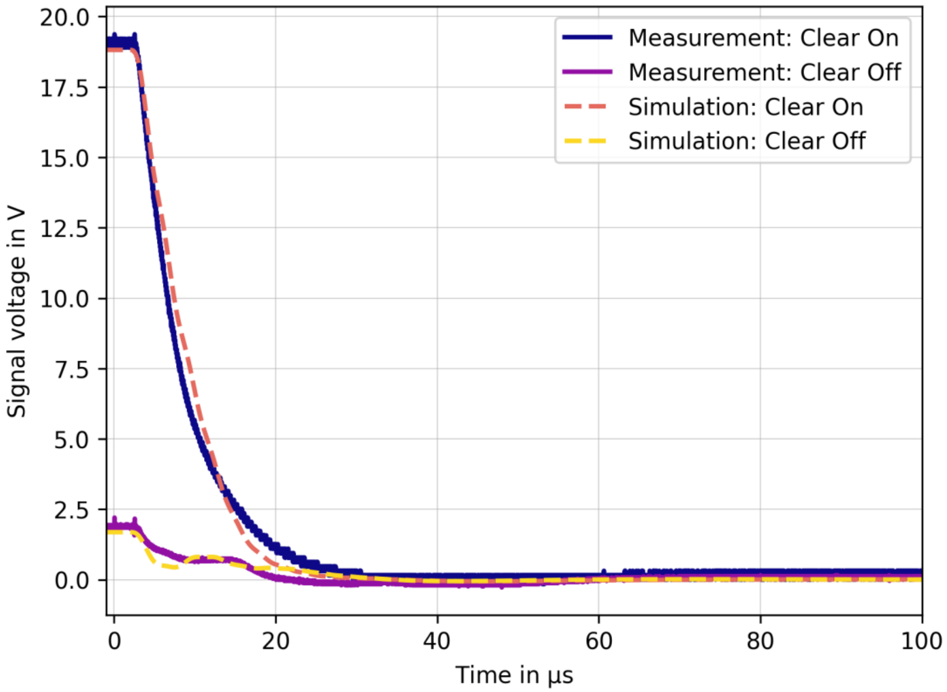

Power Supply
Dock Box
Kapton capacities
Module
Power-Supply cable
Glen-Air cable
Kapton cable
14 m
1.8 m
0.5 m

SHUTDOWN PROCEDURE

ACTIVE SHUTDOWN

- Active shutdown → **short** force and ground line
- Simulate by **time dependent resistor** which switches from 100 GΩ to 0 Ω





SUMMARY AND CONCLUSION

- Goal is **prevention of switcher damage** in beam loss events
- Fast shutdown → avoid power-down sequence violation
- Testing of **different cable models**
- Promising results of full simulatiuon with **Simple Line model**
  - Physical measurement can be replicated by simulation
- $V_{clear\ on} < V_{clear\ off}$

→ Use Simulation to determine optimal resistance value on Fast Shutdown Board

THANK YOU!

SOURCES

Number	Slide	Description	Source
[1]	3, 11, 16	Super KEKB, Belle II	P. Ahlburg. Development of a Laboratory Readout System for DEPFET Pixel Detector Modules and Investigation of Radiation Backgrounds at the SuperKEKB Accelerator
[2]	4	Picture Belle II	F. Müller. „Characterization and Optimization of the Prototype DEPFET Modules for the Belle II Pixel Vertex Detector“. PhD thesis. Ludwig-Maximilians-Universität München, 2017
[3]	4	Picture DEPFET Pixel	M. Koch. „Development of a Test Environment for the Characterization of the Current Digitizer Chip DCD2 and the DEPFET Pixel System for Belle II Experiment at SuperKEKB“. PhD thesis, Uni Bonn, 2011
[4]	5,6,8	Fast Shutdown Studies	Jannes Schmitz. „Irradiation Burst Studies on Belle II PXD Module Components“. Master‘s thesis. Rheinische Friedrich-Wilhelm-Universität, 2020
[5]	9	Hitmap Fast Shutdown	P. Leitl

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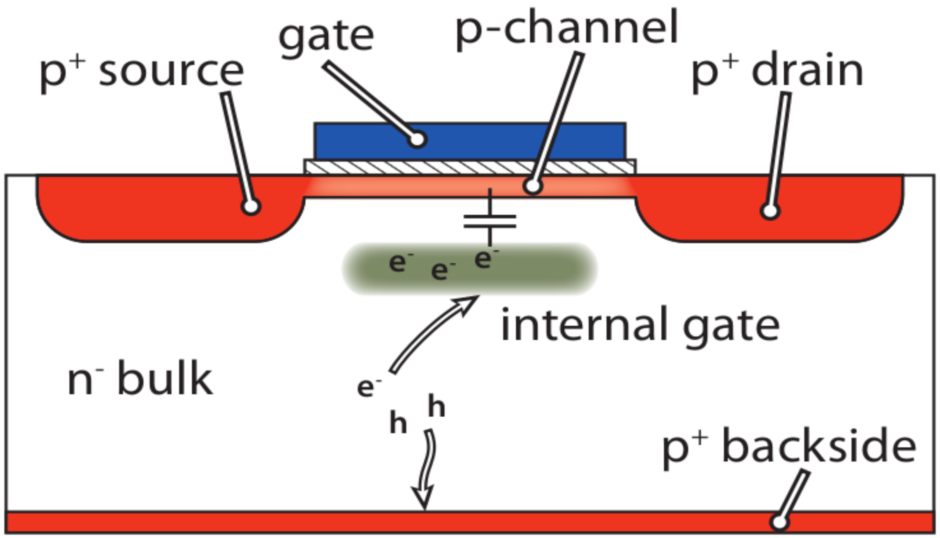
SOURCES

Number	Slide	Description	Source
[6]	10	Photo Belle II	B. Paschen
[7]	12, 13	Photo PS-Cable Fast Shutdown	C. Bespin
[8]	32	Inductance formula	H. Katzier. „Elektrische Kabel und Leitungen“. Eugen G. Leuze Verlag, 2015
[9]	33	Equation formula	M. Albach. „Elektrotechnik“. Pearson Education, 2011

- Size : 50 x 55 x 75 μm^3
- P-channel MOSFET on depleted Bulk
- n^+-dopded internal gate
- n^+-doped Clear
- → detection of particles and amplification



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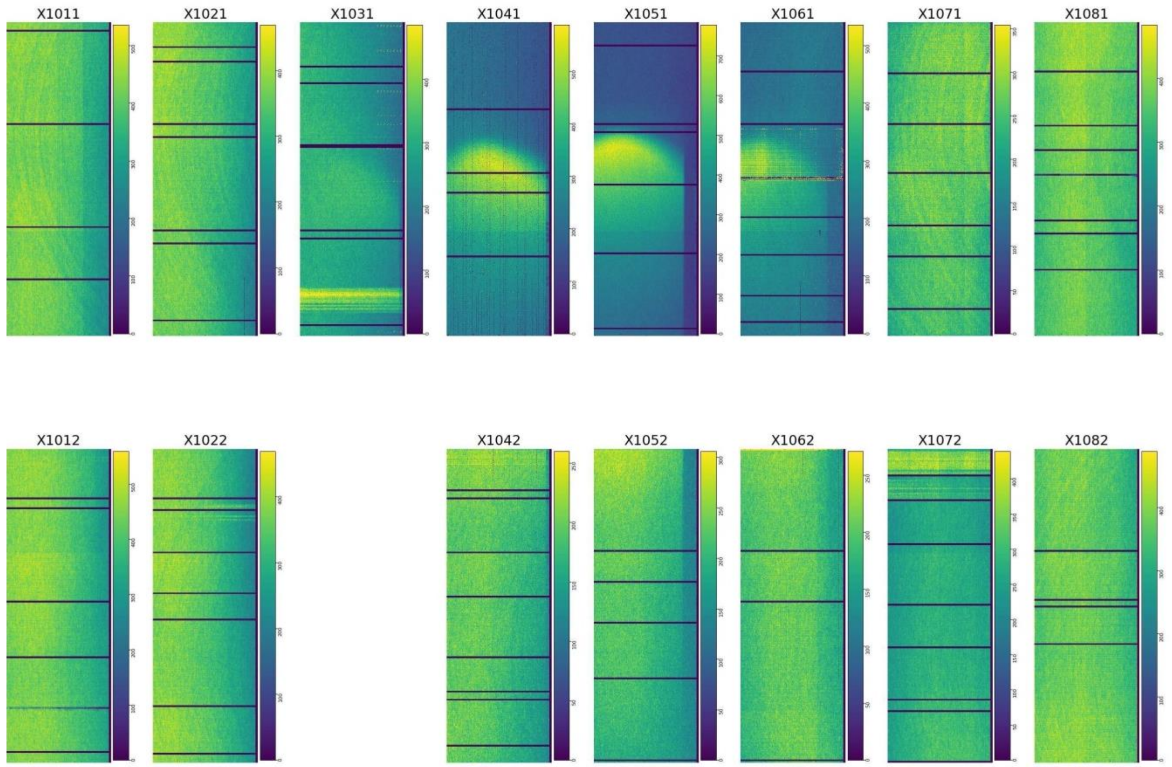
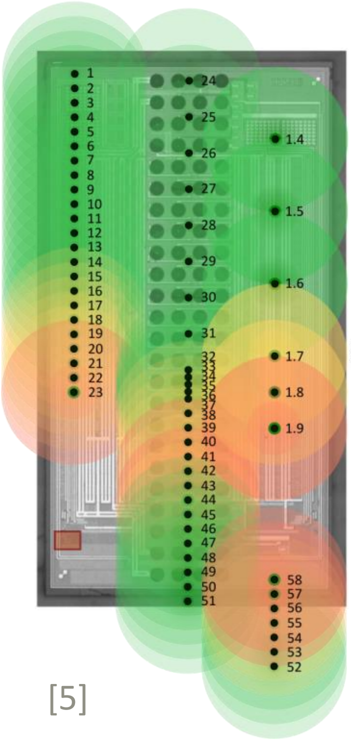
AFTER BEAM LOSS EVENT

- 89 inefficient Switcher channels (➔ 89x4 matrix rows)
- 15 modules of inner layer: 192x15=2880 Switcher channels

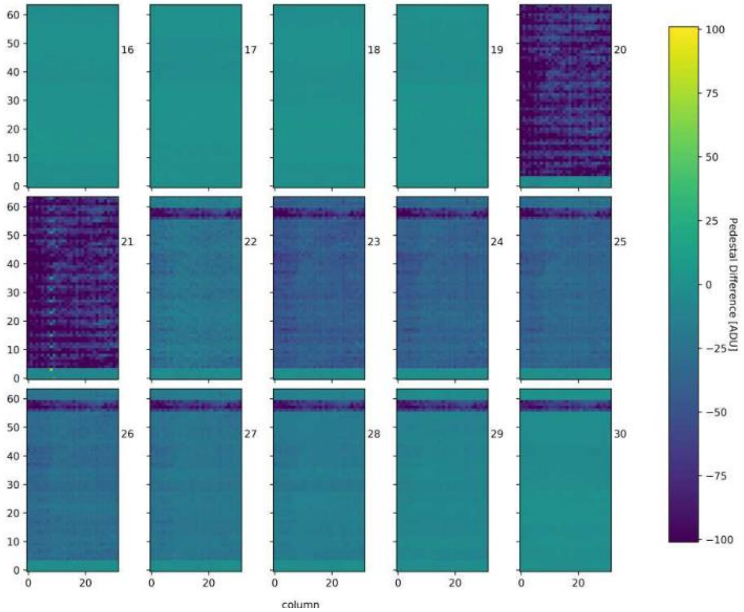


CONFIRMATION OF RESULTS

- Irradiation with electron beam
- Fine scan of ASIC area
  - July 2020 with H5029
  - Colour coded measurement points
  - red => permanent damage
- Raw data difference of 15 raw frames during injection
  - Second to last Switcher channel is damaged permanently
- Switcher only vulnerable when turned on



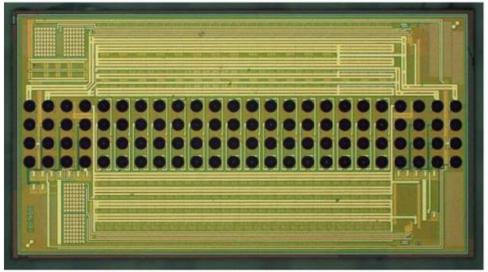
[5]



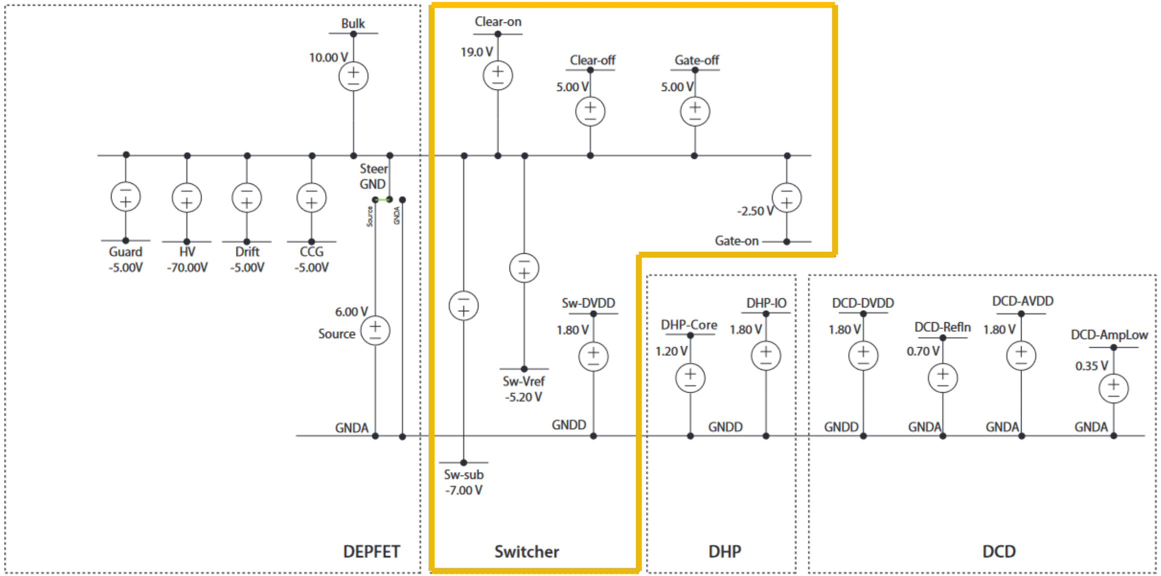
[6]

POWERING SCHEME

- Dedicated power-up and power-down sequence
- Range between +19V and -7V
- Switcher switches between high voltages



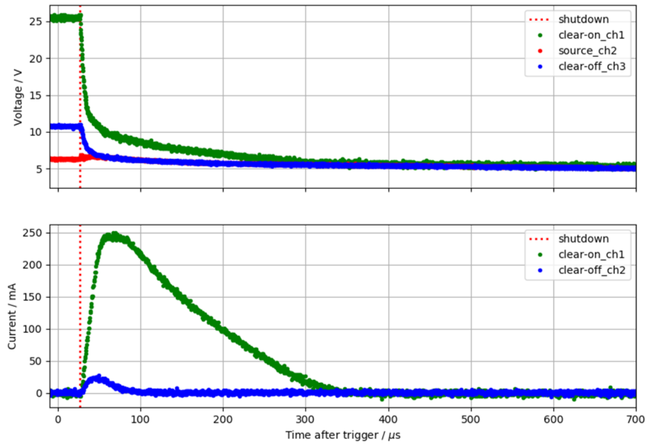
[7]

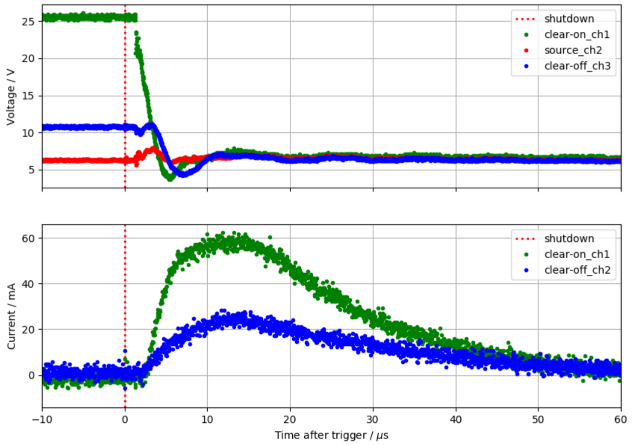


[8]

FAST SHUTDOWN MEASUREMENT

- Example: shutdown of voltage required for Switcher (Clear-on/ Clear-off), measured at Power Supply



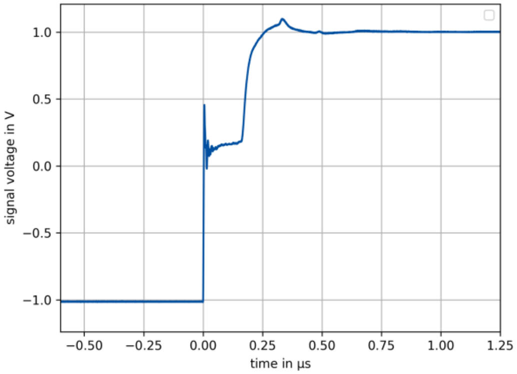


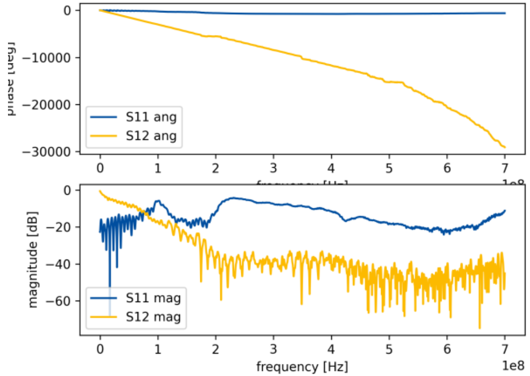
- $R_{clear\text{-}on} = 10\ \Omega$, $R_{clear\text{-}off} = 10\ \Omega$
- Decreased shutdown time
- Influence of FET visible

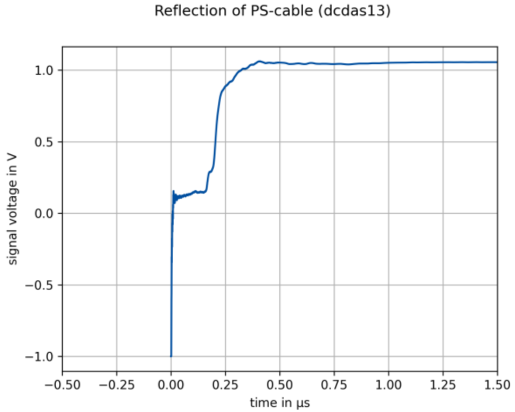
- $R_{clear\text{-}on} = 0\ \Omega$, $R_{clear\text{-}off} = 0\ \Omega$
- $V_{clear\text{-}on}$ drops below $V_{clear\text{-}off}$ ➔ violation of shutdown sequence

SIMULATION PROCESS

➔ Example: Reflection at open cable end (HyperLynx and s2spice-model)







Measure with **time domain** reflectometer

→

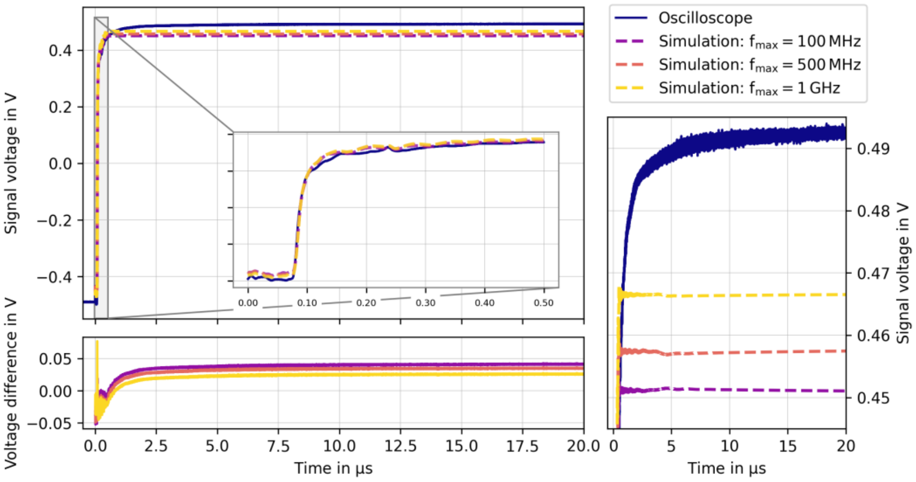
Fourier transformed into **frequency domain**

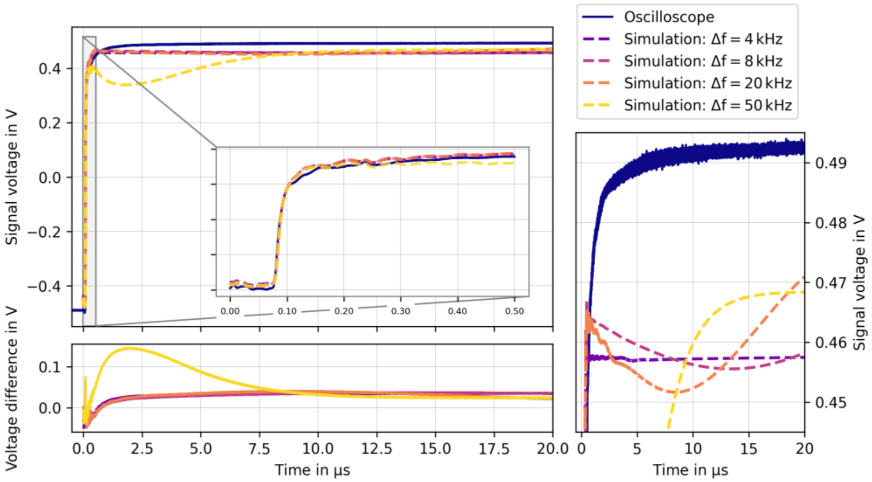
➔ Scattering Parameters

→

Use S-parameters in **time-domain** transient simulation

TDR S-PARAMETER SIMULATIONS

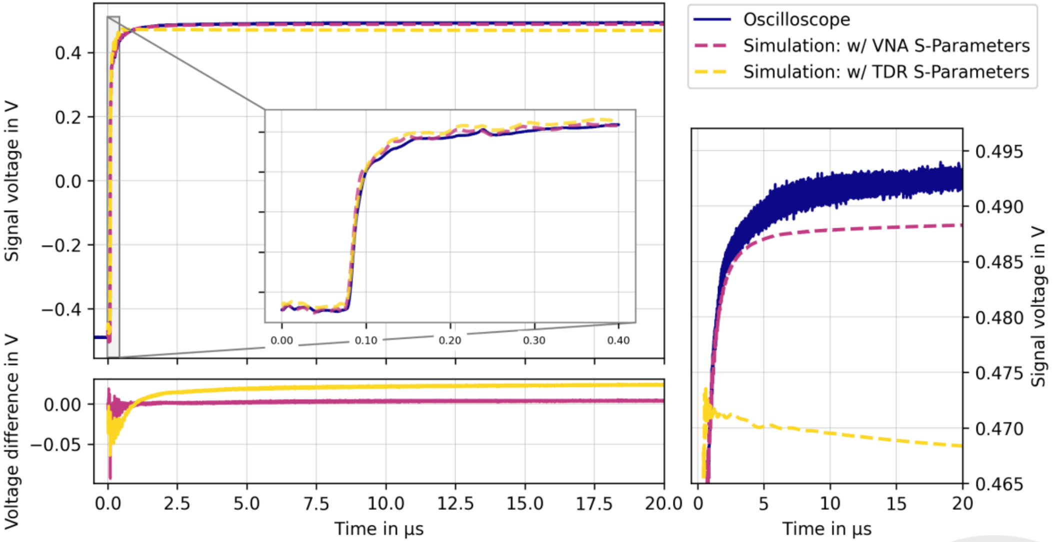




S-PARAMETER SIMULATION: TDR VS VNA

- Simulation of Bulk-line in PS-cable
- HyperLynx S-parameter model in simple transmission setup
- Voltage Deviation

Time window	VNA	TDR
$0 - 40\mu s$	3.8 mV	22.8 mV
$0 - 1.5\mu s$	4.28 mV	14.1 mV
$1.5\mu s - 40\mu s$	3.81mV	23.1mV

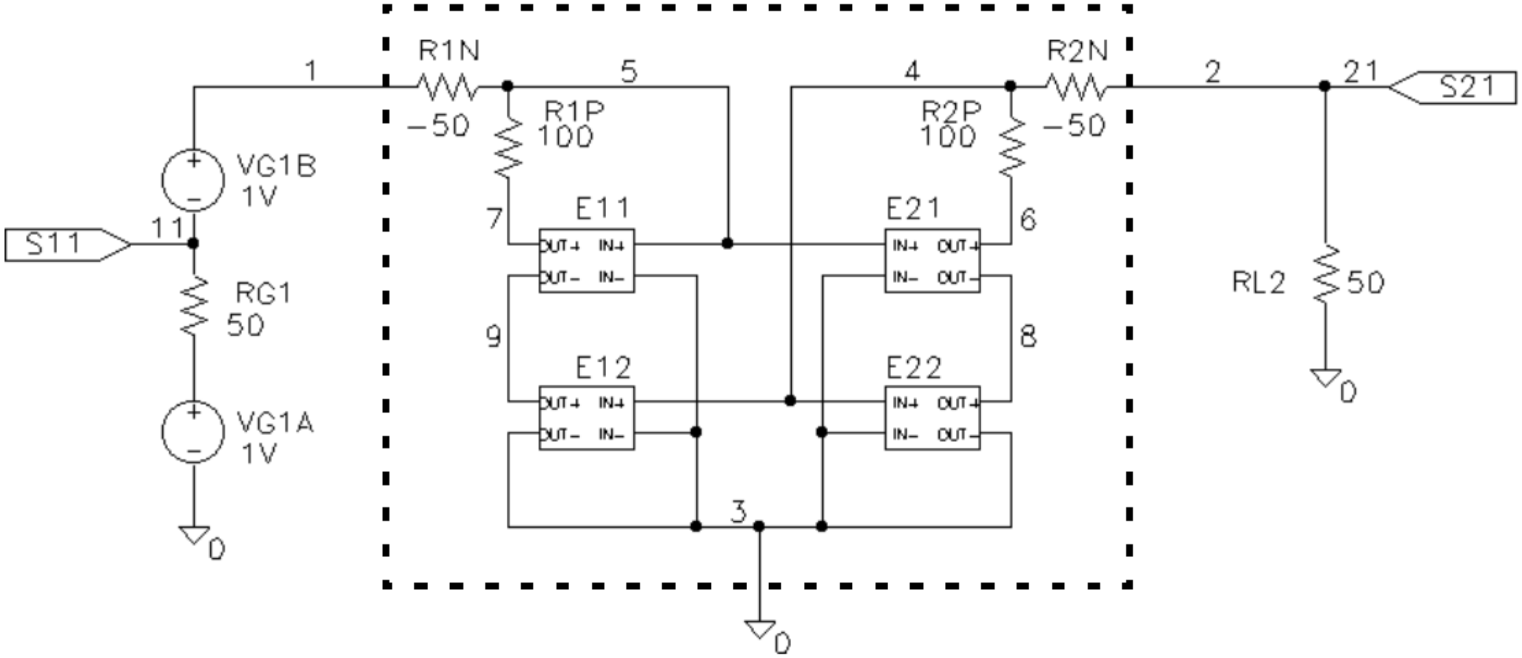


S-Parameter

→ HyperLynx

- S-Parameters

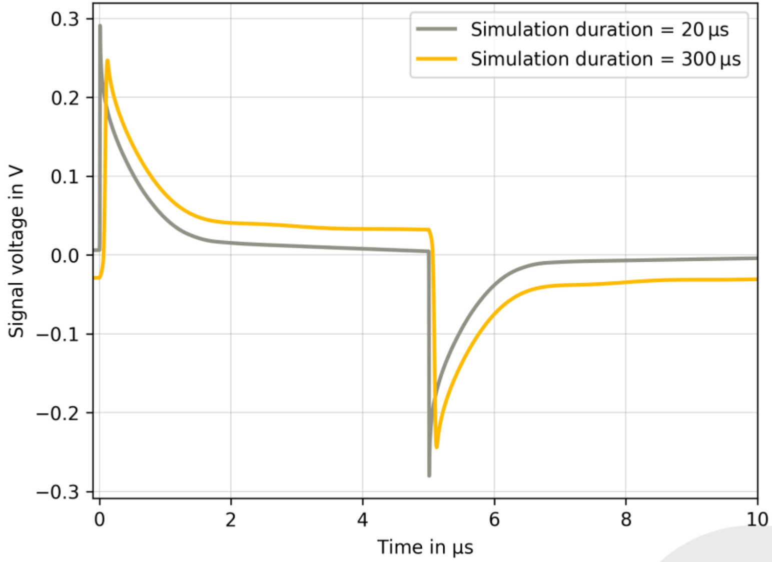
S-Parameter Subcircuit



S2SPICE PROBLEM

- Smallest segment of cable model: voltage dependent voltage source
  - Shows **same behaviour**

→ Only suitable if simulation can be verified and simulation time can be adjusted flexibly

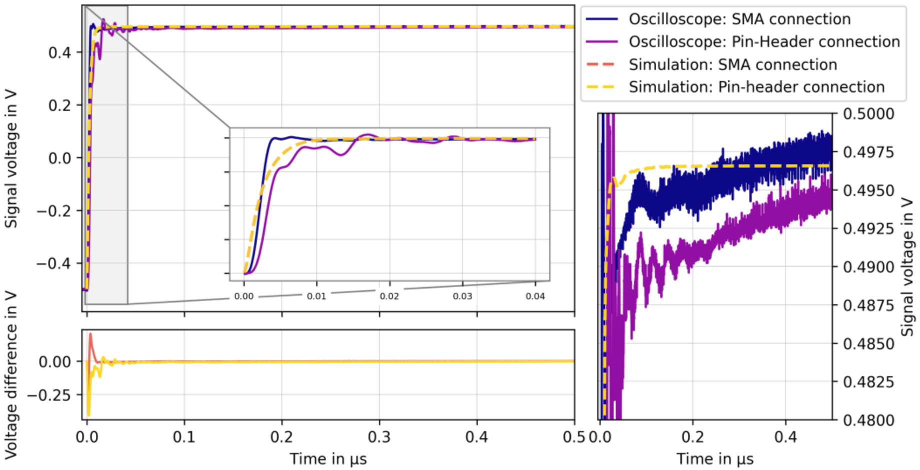


S2spice

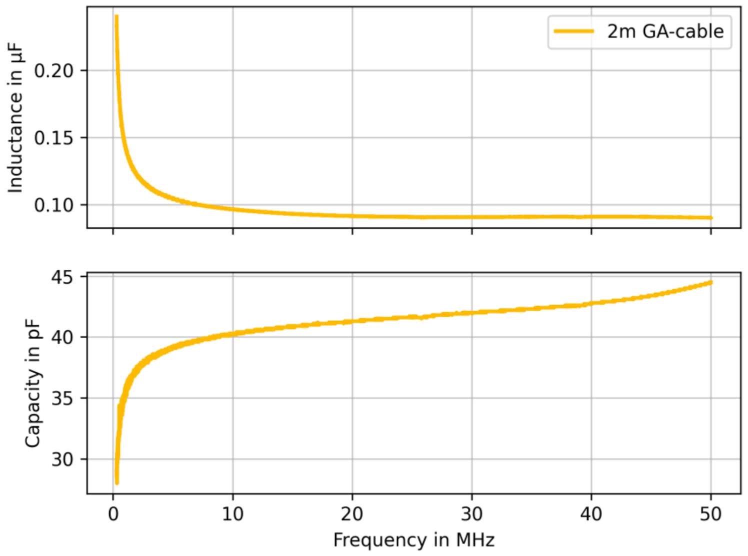
→ LTSpice

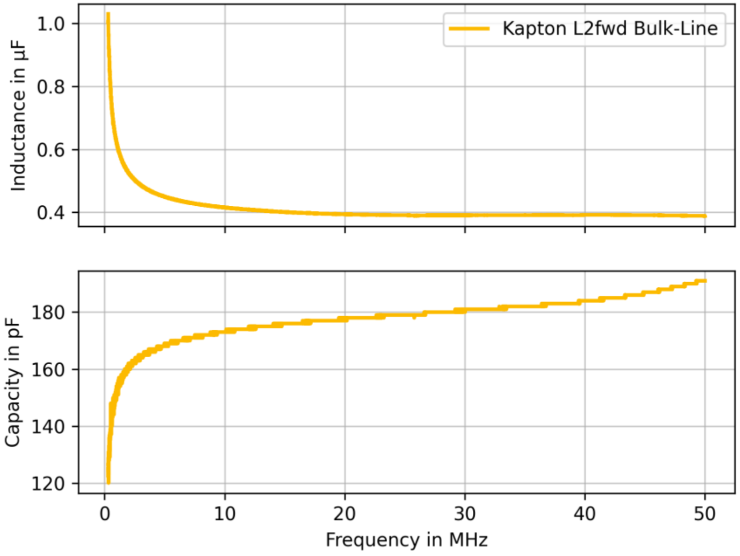
- S-Parameters

PIN HEADER VS SMA



INDUCTANCE AND CAPACITANCE OF GA AND KAPTON





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$L_{AWG\ 26} = (379.25 \pm 81.1)$ nH

$L_{AWG\ 20} = (288.6 \pm 67.68)$ nH

$L_{AWG\ 18} = (262.69 \pm 54.40)$ nH

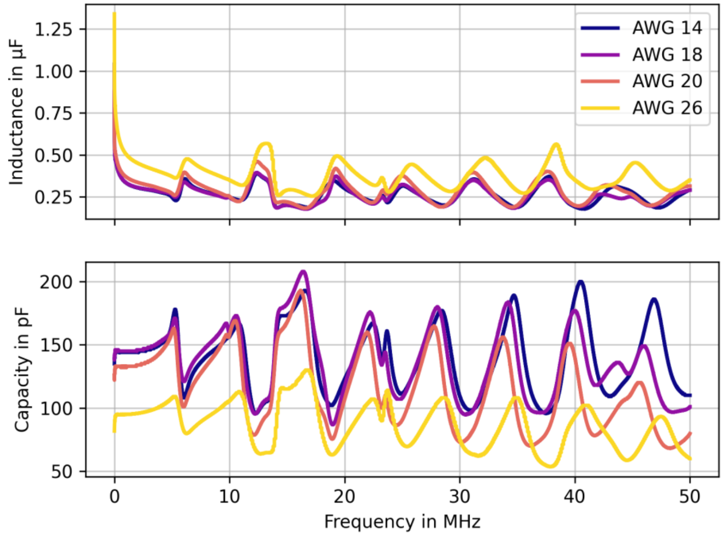
$L_{AWG\ 14} = (265.34 \pm 54.43)$ nH

$C_{AWG\ 26} = (86.92 \pm 17.9)\mathrm{pF}$

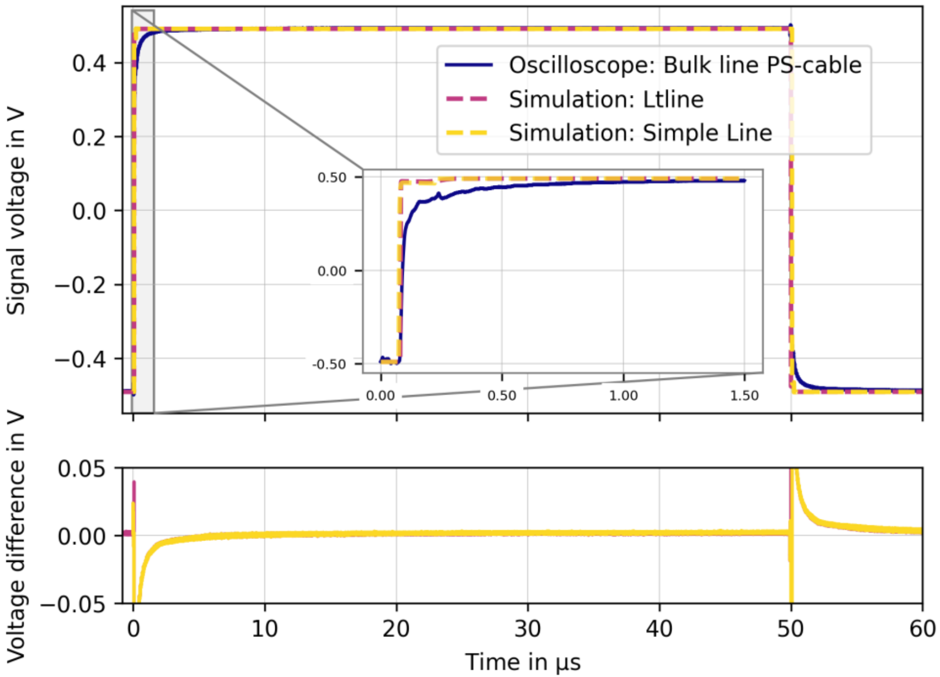
$C_{AWG\ 20} = (115.63 \pm 31.09)\mathrm{pF}$

$C_{AWG\ 18} = (137.13 \pm 27.89)$ pF

$C_{AWG\ 14} = (139.72 \pm 26.71)$ pF

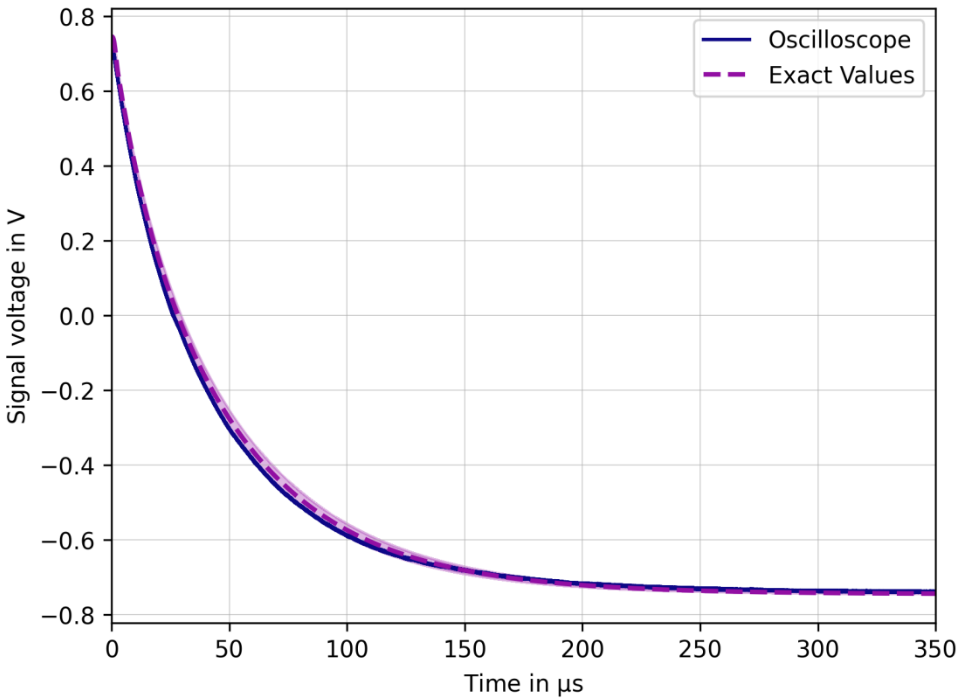


Time window	Ltline	Simple Line
$0 - 40\mu s$	3.11 mV	3.38 mV
$0 - 1.5\mu s$	4.3 mV	4.58 mV
$1.5\mu s - 40\mu s$	1.556 mV	1.729 mV

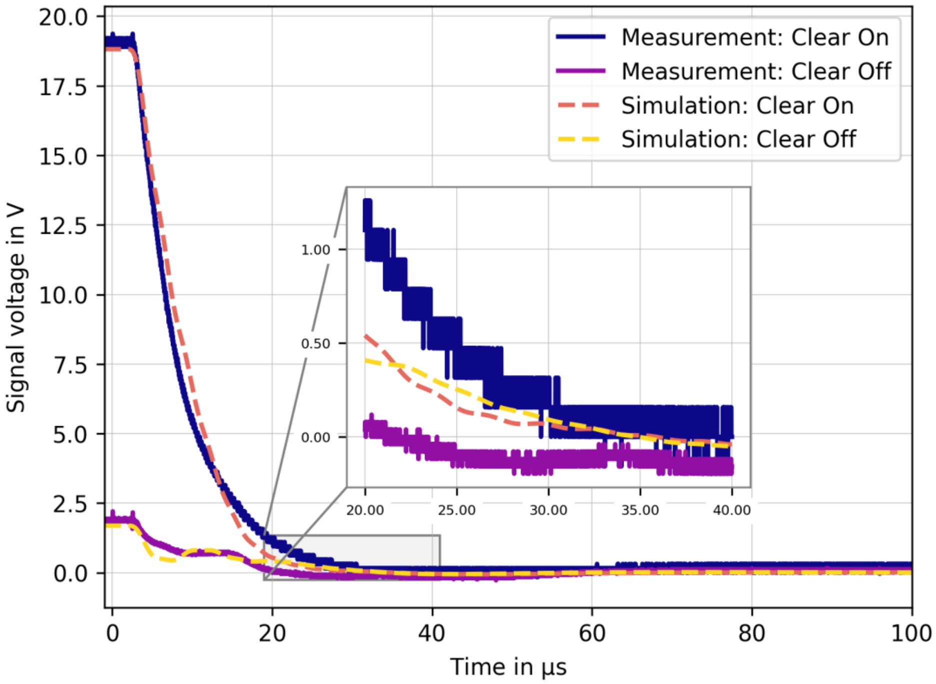


TOLERANCE OF CAPACITORS

- +5 % and -5% on every capacitor in full simulation
- Oscilloscope measurement lies within tolerance band



ACTIVE SHUTDOWN: ZOOM IN



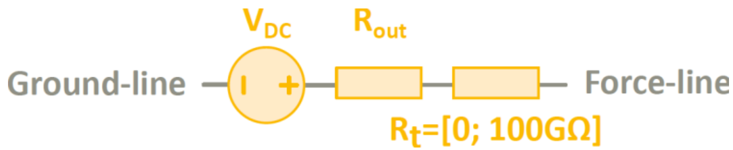
SYSTEM SIMULATION

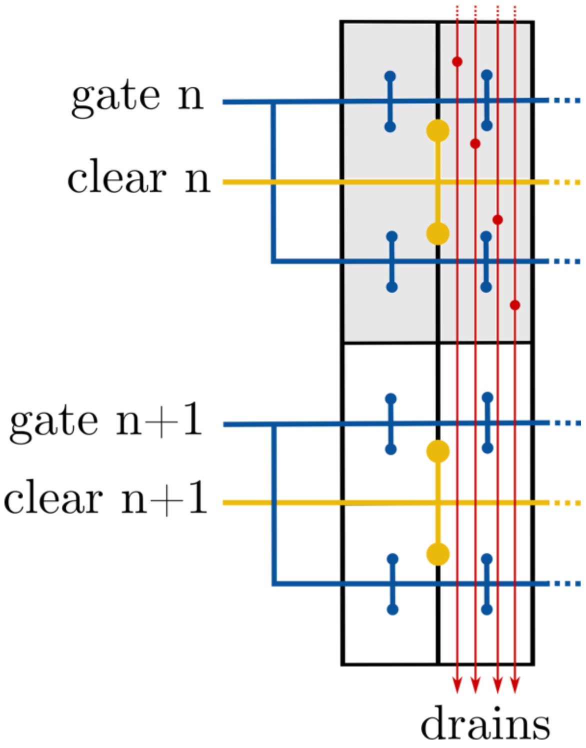
- Influence of cables on fast shutdown unknown: in total **>15m**

➔ Simulate powering scheme of single module
  - understand limitations
  - find hardware modifications
- Use cable characteristics in simulation

PASSIVE SHUTDOWN

- Passive shutdown → **separate** force line from power supply
- Simulate by **time dependent resistor** which switches from 0 Ω to 100 GΩ




gate n
clear n
gate n+1
clear n+1
drains

NETWORK SIMULATION

- Solving circuit equations (Maxwell equations)
- Netlist turned into matrix -> solve differential equations
- Ltline model:
  - Transmission line theory
  - One dimensional wave equation $\frac{d^2V(x)}{dx^2} - \gamma^2(x) = 0$ and $\frac{d^2V(x)}{dx^2} - \gamma^2(x) = 0$
  - With $\gamma^2 = (i\omega L + R)(i\omega C + G)$
- Simple Line model:
  - Transmission Line theory
  - W-element algorithm
    - Initial seuqnce of elements which are compared and swapped for better results

- S-parameter model in HyperLynx:
  - ADMS simulator
  - Convert to complex pole model
    - Representation of impedance in frequency domain
    - Poles and Zeros of Impedance
  - Fast Fourier Transform