PSPICE Simulation of Crosstalk on GEM Strips

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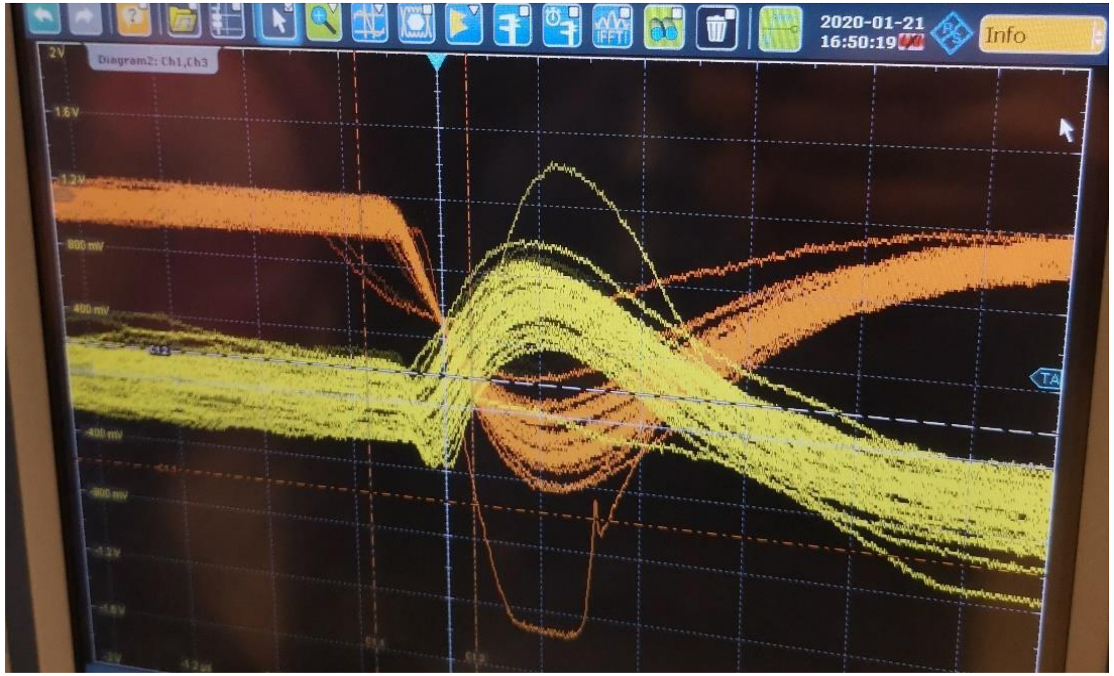
FIT

5/19/2020

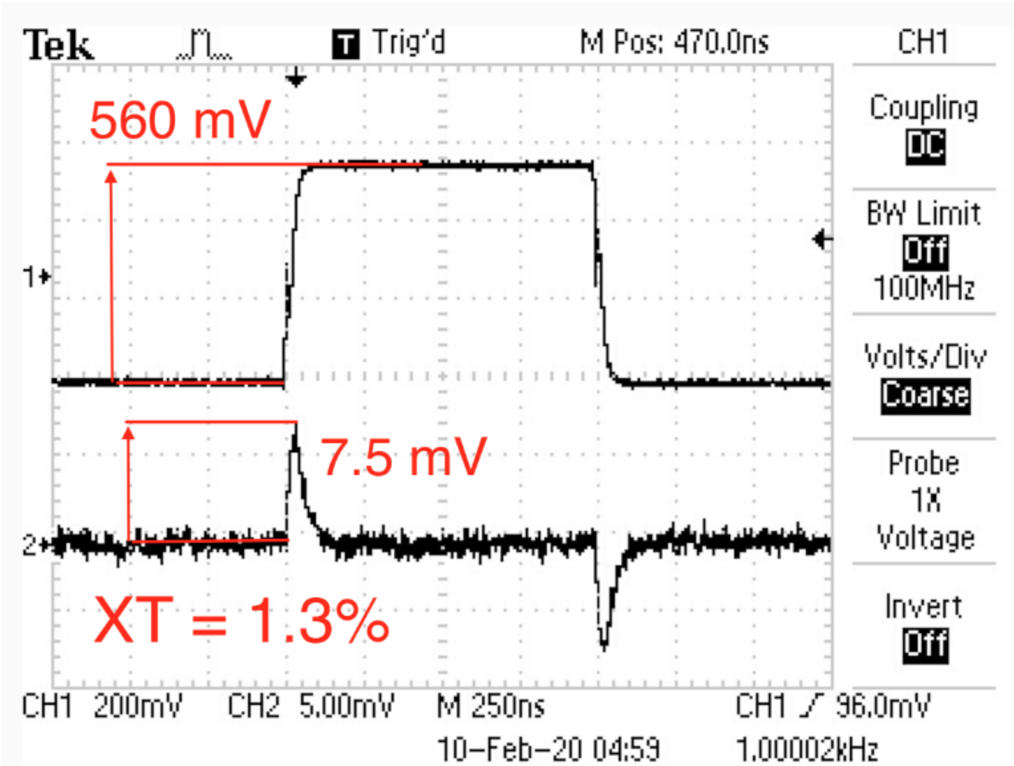
GEM Phase 2 Upgrade Workshop – May 2020

Motivation

Understand the difference in **observed polarity of crosstalk (XT) pulses** measured in tests with **normal** GEM avalanche mode at CERN and tests with **injecting voltage pulses** into readout strips at FIT.



Davide Fiorina's measurements on 10x10 GEM:
opposite sign of signal and XT



Stephen Butalla's measurement with pulser:
same sign of signal (on leading edge) and XT

Motivation cont'd

- Why is XT only observed in **double**-segmented foils (GE2/1, ME0) and not in single-segmented foils (GE1/1) ?
- Achieve a better understanding of the XT, so **XT mitigation strategies** can be developed.

$\Rightarrow$ **Built an independent detailed SPICE model of GEM detector for testing**

- Use the c a d e n c e / ORCAD PSPICE suite for modelling

PSPICE Model 1

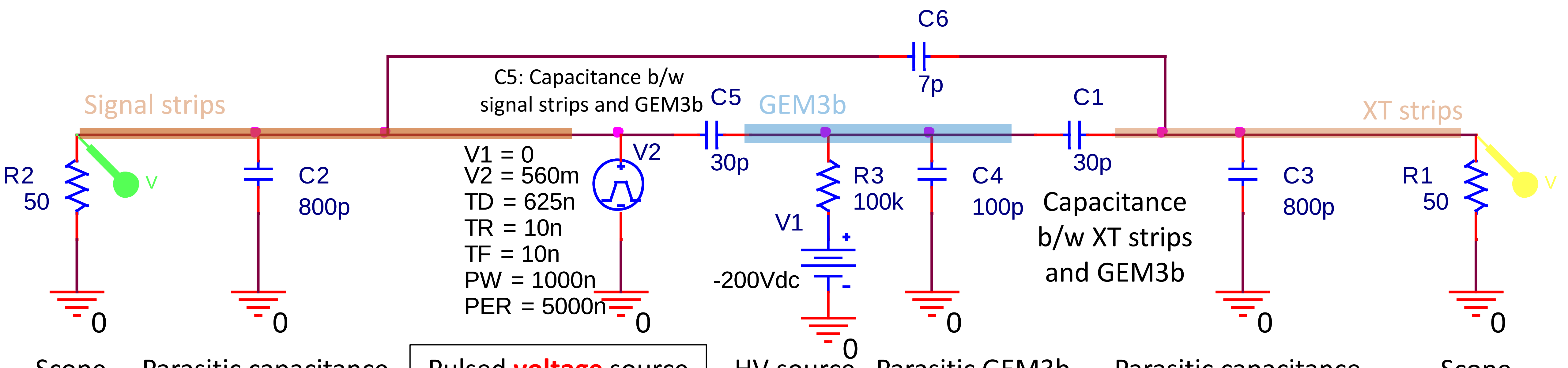
Voltage pulser measurements

1. Model Circuit for pulser measurements

FLORIDA TECH MH

For Stephen's measurements with voltage pulser at FIT:

C6: Interstrip capacitance b/w 128 signal strips and 128 XT strip



Scope input impedance (matched)

Parasitic capacitance of 128 signal strips connected via S2H2P2L* to ground (measured)

Pulsed **voltage** source producing pulse with 560mV amplitude, 10ns rise and fall time, 1000ns pulse width

HV source via protection resistor

Parasitic GEM3b capacitance to ground: Small (100pF) for **segmented** GEM3b

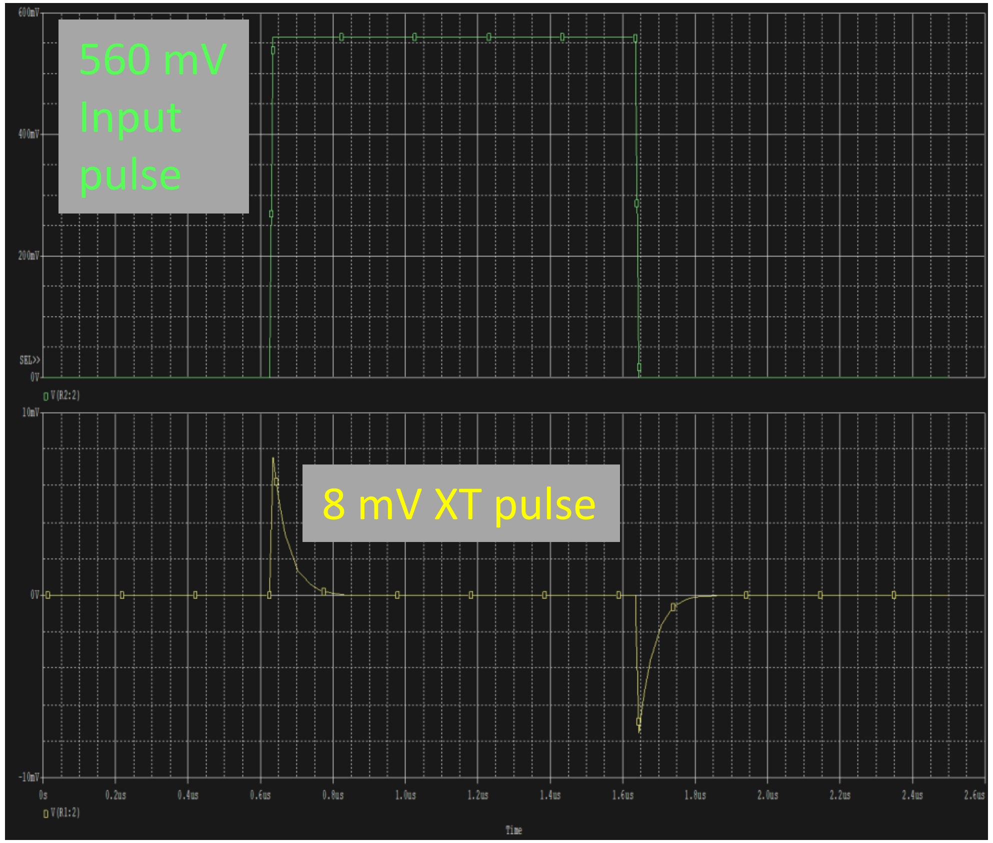
Parasitic capacitance of 128 XT strips connected via S2H2P2L* to ground (measured)

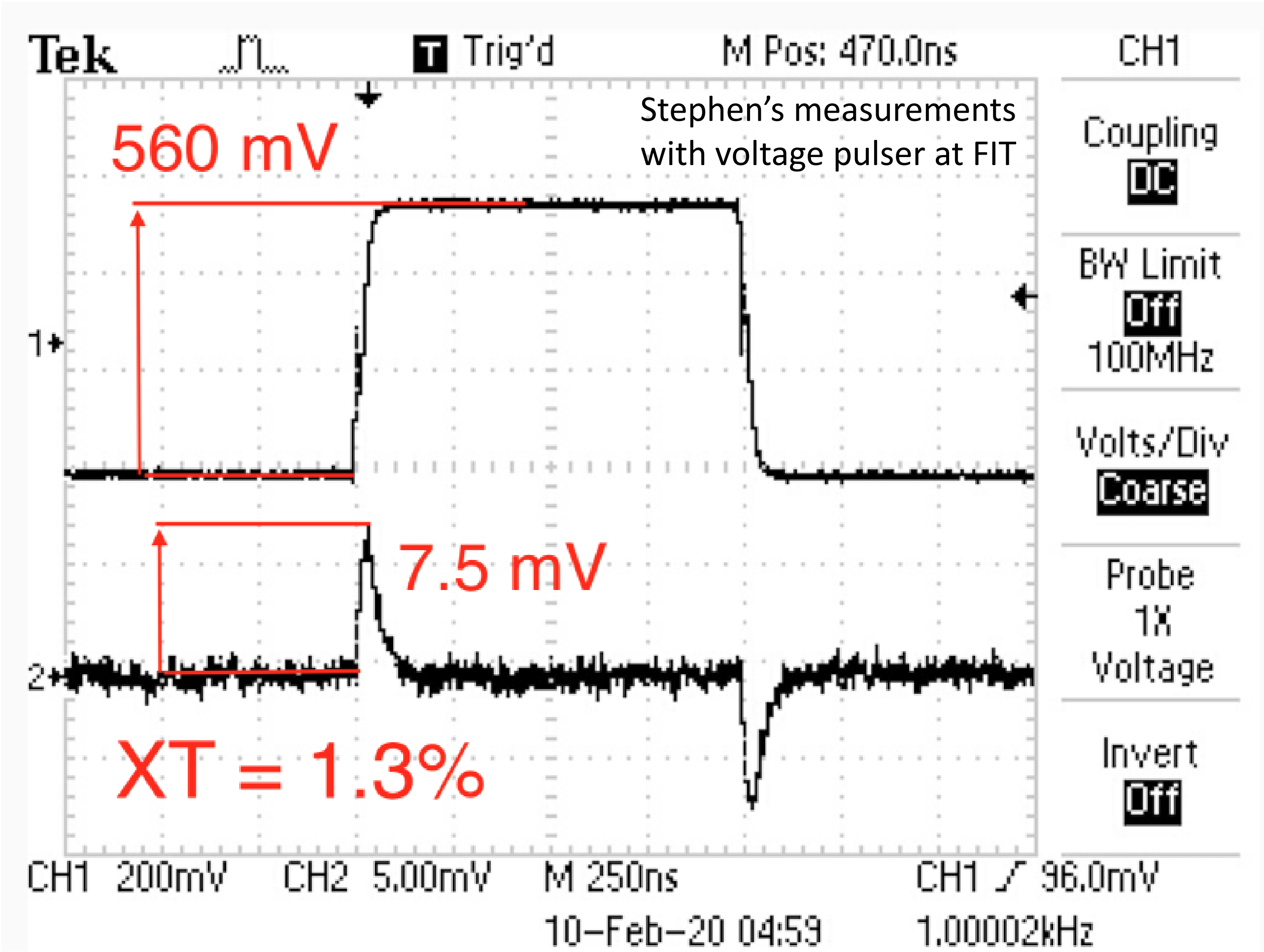
Scope input impedance (matched)

* "Strip to Hirose to Panasonic to LEMO" adapter

1. Pulse simulation vs. measurement

Simulation output:





Main observations:

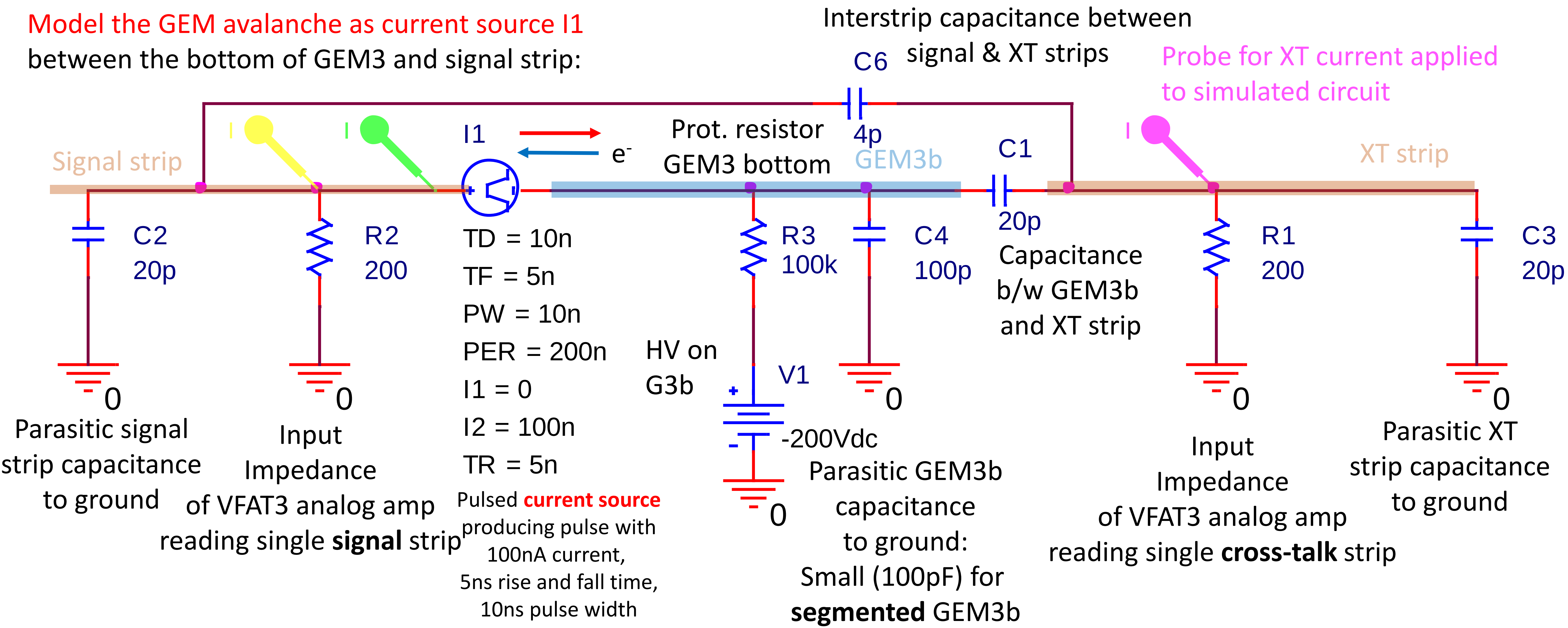
- Simulation and measurement **agree** with respect to cross-talk (XT) polarity, amplitude, and RC time constant !
- This implies that the cross talk pulse is indeed **due to capacitive coupling**
- Input voltage pulse and XT voltage pulse **have THE SAME POLARITY on leading edge**

PSPICE Model 2

Normal GEM operation with GEM avalanches, e.g. with α-source

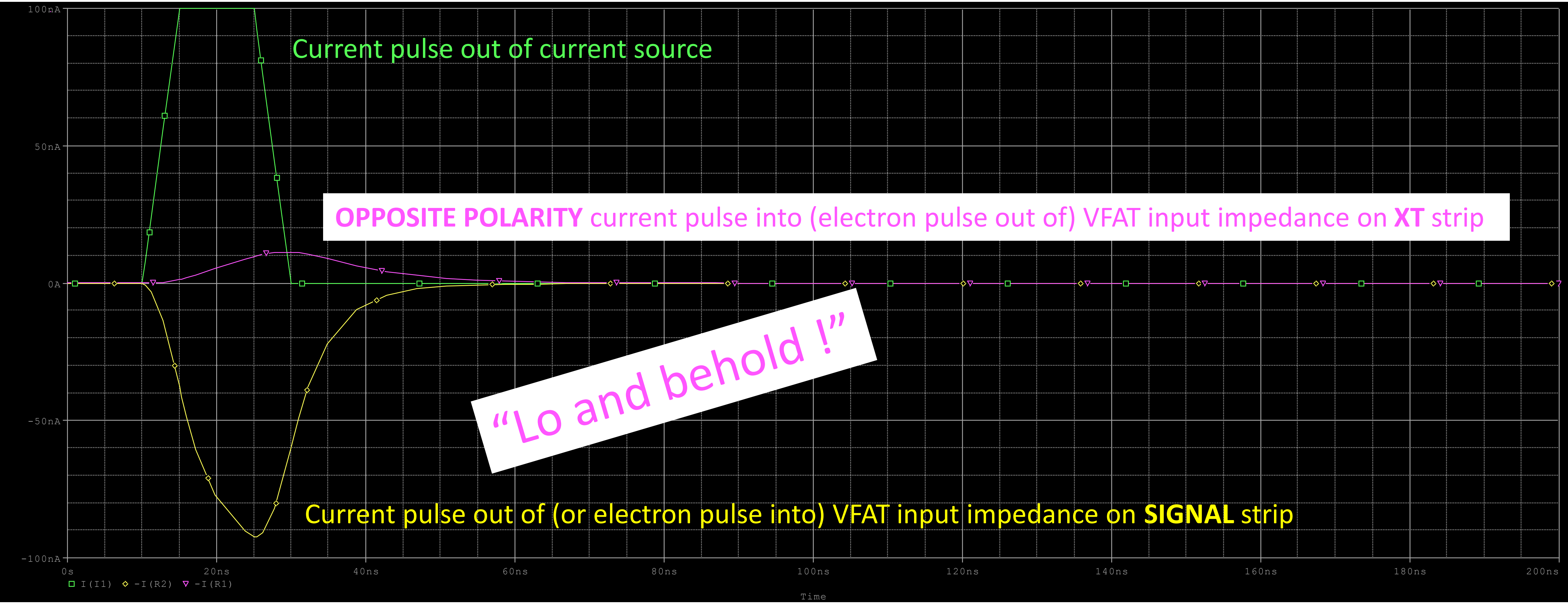
2. PSPICE circuit implementation for gas avalanche

Model the GEM avalanche as current source I1
between the bottom of GEM3 and signal strip:



Current source: 10,000 primary electrons (1.6 fC) over 15 ns: $i = 10^4\ 1.6\ 10^{-19}\ C / 15\ 10^{-9}\ s = 10^{4-1-19+9} = 10^{-7}\ A = 100nA$
(note that this doesn't even take gas gain into account)

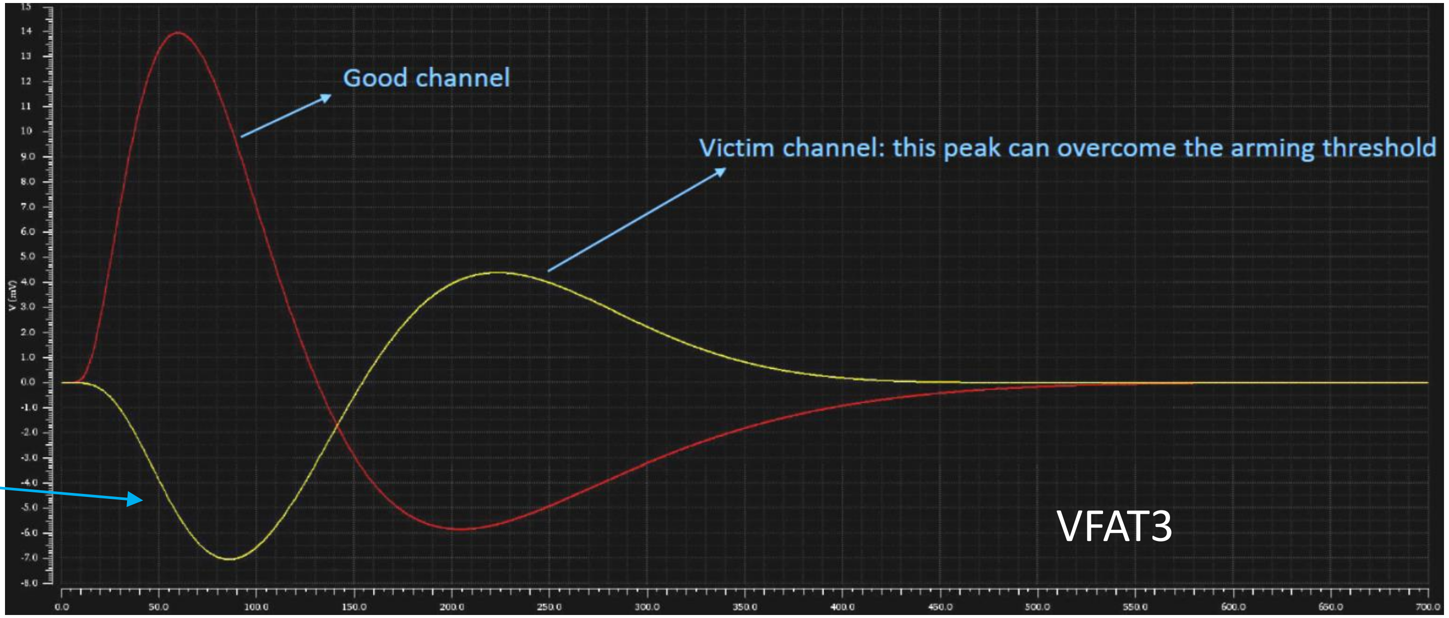
2. Pulse analysis for gas avalanche



Main observation: The electron pulse into the VFAT amp connected to the **signal strip** (yellow) and the electron pulse into the VFAT amp connected to the **XT strip** (purple) now have **OPPOSITE polarity!** This is different from the result with the pulser where we have same polarity.

Impact on VFAT3

- The opposite-polarity pulse on the XT strip, i.e. at the **input** of the VFAT3 analog amplifier, produces also an opposite-polarity XT signal at the **output** of the VFAT3 analog amplifier and as such would be harmless.
- However, due to the shaping that occurs in the VFAT3 analog amplifier, the XT signal has an overshoot after some 200ns that goes in the *same* direction as the leading pulse on the signal strip:



This is the problem

Opposite Polarity XT pulse

From Francesco Licciulli

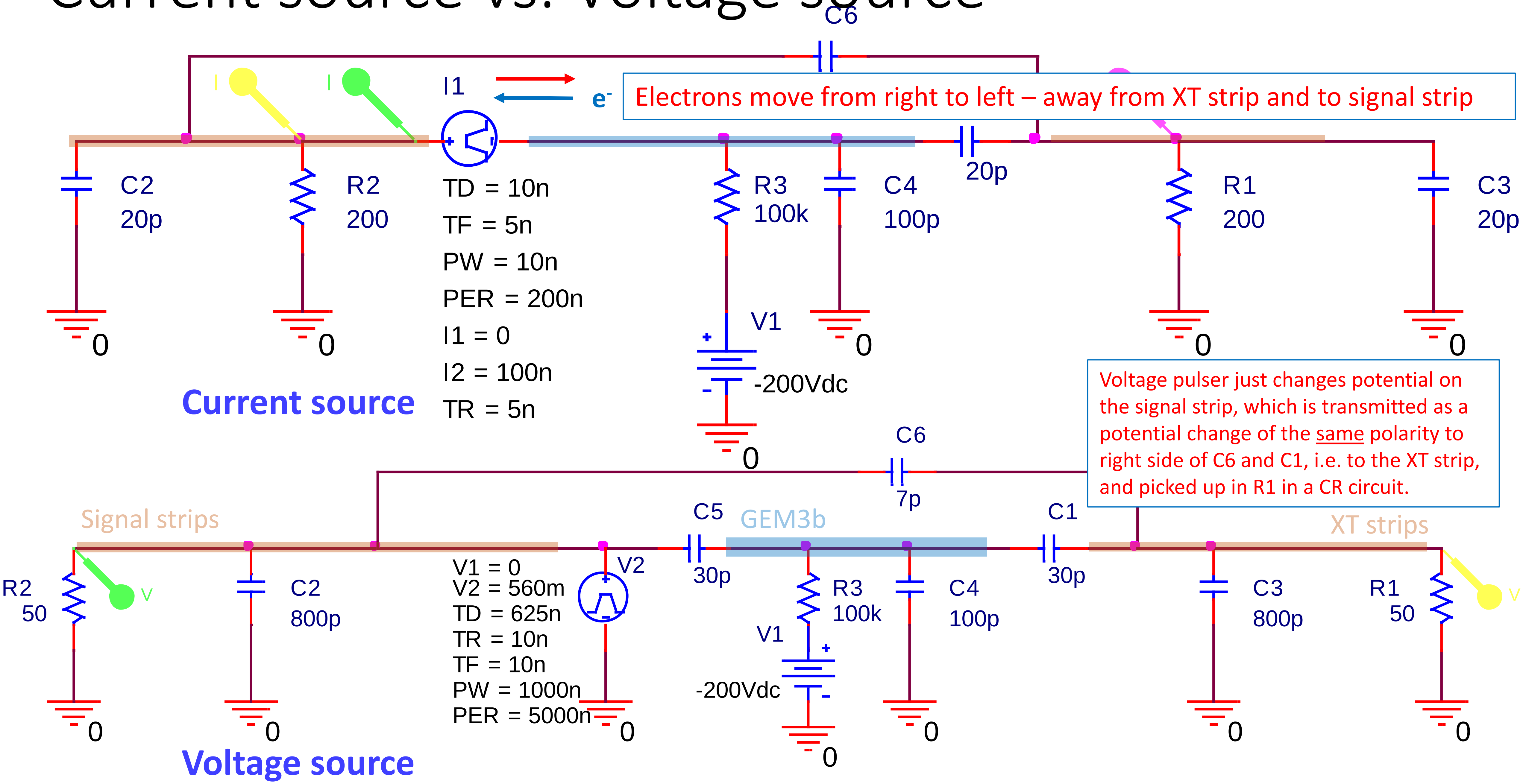
FLORIDA TECH
MH

Making sense of results

From the two models we now finally understand why we get **opposite polarity** between a good signal pulse and a XT pulse at the VFAT input (and hence output) when we have a *gas avalanche* in the GEM (α-source) as opposed to **the same polarity** between a good signal pulse and a XT pulse at the VFAT input & output when we pulse the readout strips with a *voltage pulse*:

=> *"Current sources and voltage sources are not the same thing!"*

Current source vs. Voltage source

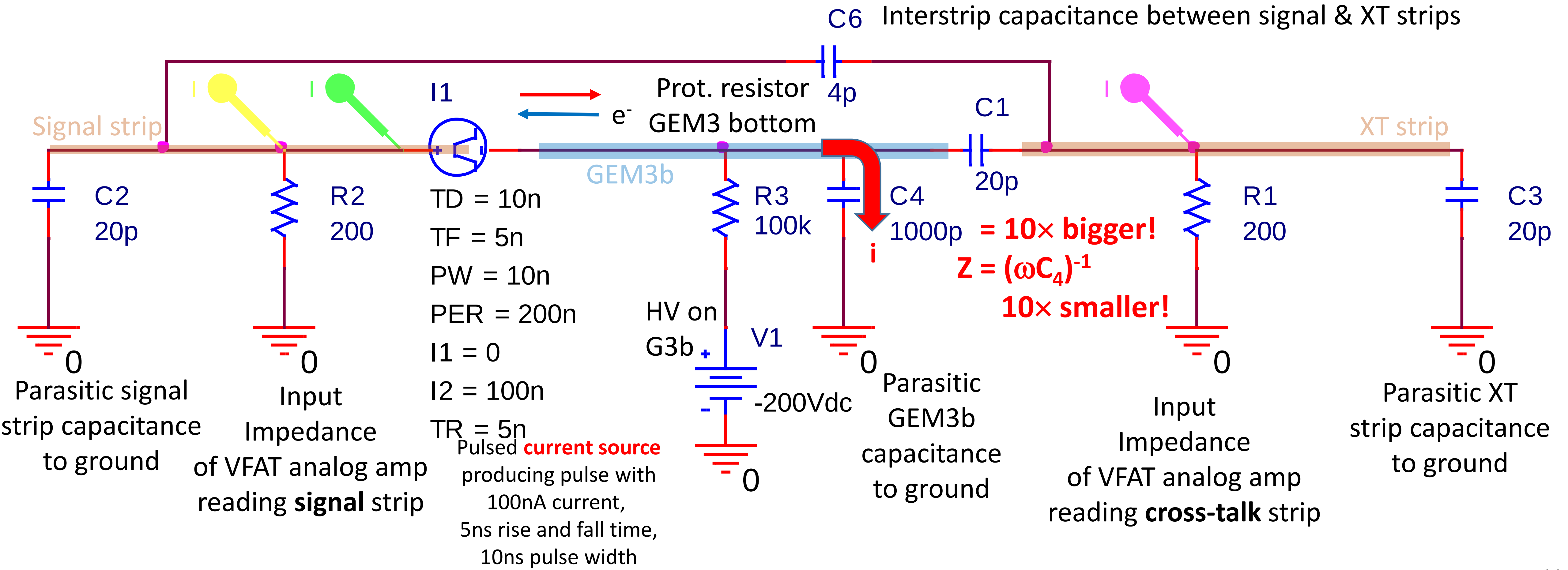


Making sense of experimental observations

- We have only seen the XT in **double-segmented foils** where GEM3b HV segments are connected to HV via 100 kΩ protection resistors.
- We have NOT seen the XT in single-segmented foils (GE1/1) where the single GEM3b HV segment is **connected to HV without a protection resistor**. (Only the other foil side GEM3t is protected with 10 MΩ resistors).

3. Increased GEM3b capacitance to GRD

- In this circuit, the increased capacitance of GEM3 bottom provides a **much reduced impedance Z for sinking the current from the current source to ground.**
- As a consequence, the amount of XT current that can flow into C1 is reduced.
- **This explains why XT is observed on double-segmented foils, but not on single-segmented foils!**



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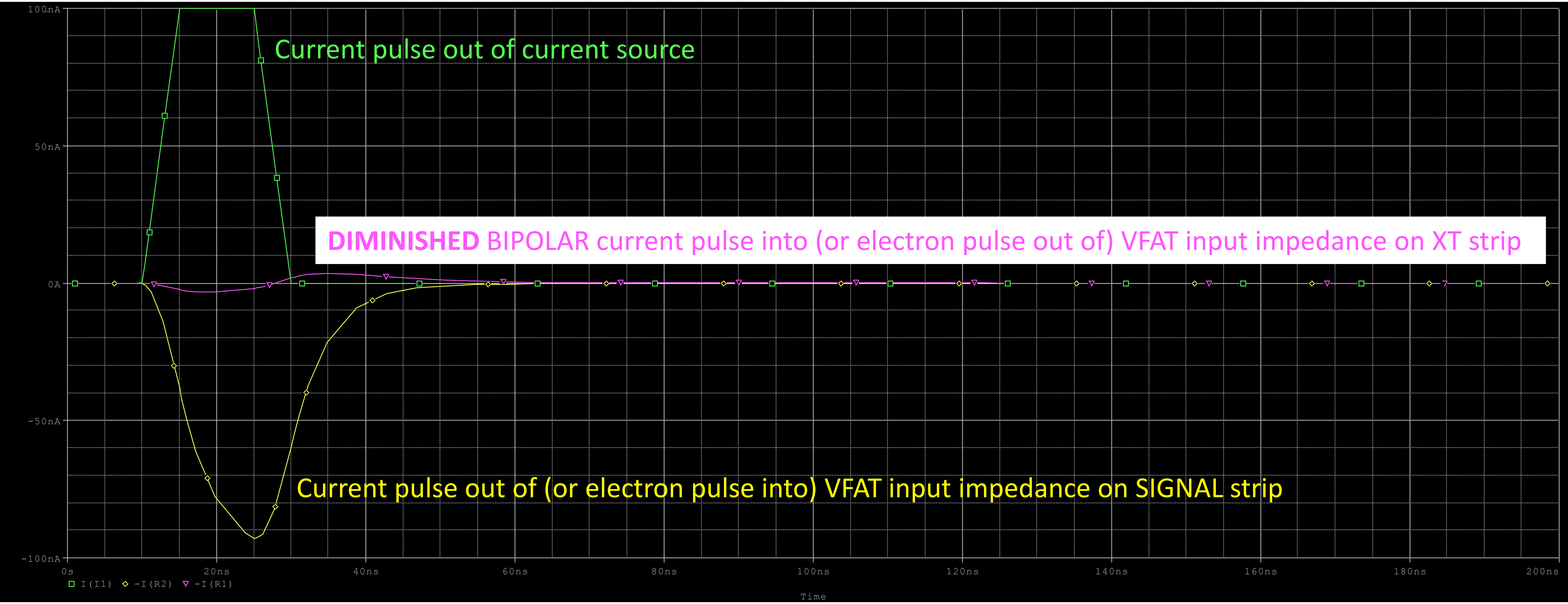


Main observation: The XT pulse is DIMINISHED by a factor ≈ 4 and becomes bipolar!

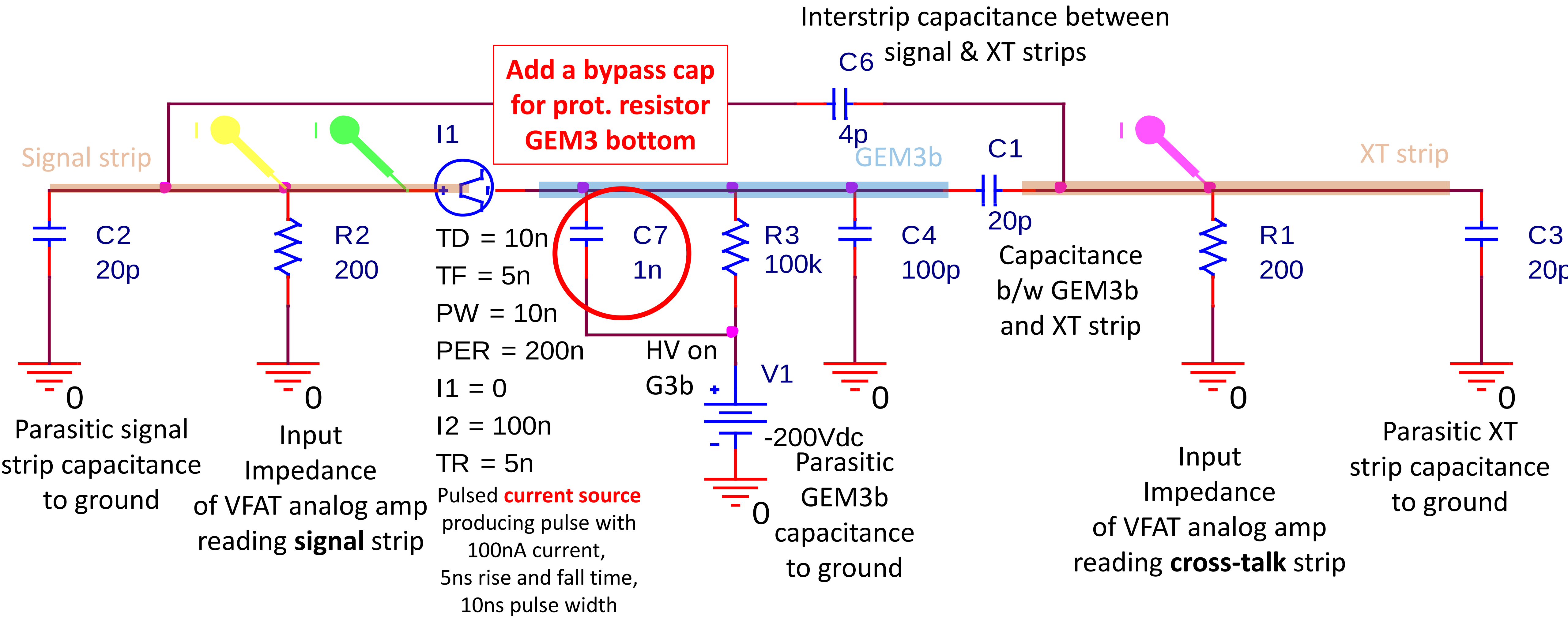
Mitigation strategies: Increase GEM3b cap.

- Ok, that works! It is also confirmed by the tests at CERN where $\approx$ **10 HV segments are connected back together** on GEM3b to increase their capacitance should show a reduction in XT (see Jeremie's and Stephen's talks).
- Note that the SIGNAL current is barely affected because the current source directly pumps electrons into the attached VFAT3 input.
- That is of course a good thing because we do not want to compromise the actual signal when mitigating the crosstalk.
- **Caveat:** Increasing foil capacitance will diminish discharge mitigation!

Mitigation strategies: Bypass Capacitor

- Another strategy that has been suggested is to put a **bypass capacitor around the protection resistor** that will provide an additional path to ground for the AC current from GEM3b (but not for DC, i.e. HV)
- This will also decrease GEM3b impedance to ground
- Let's place such a capacitor with C_7 = 1000pF = 1nF

4. Place a bypass cap. on 100k protection resistor



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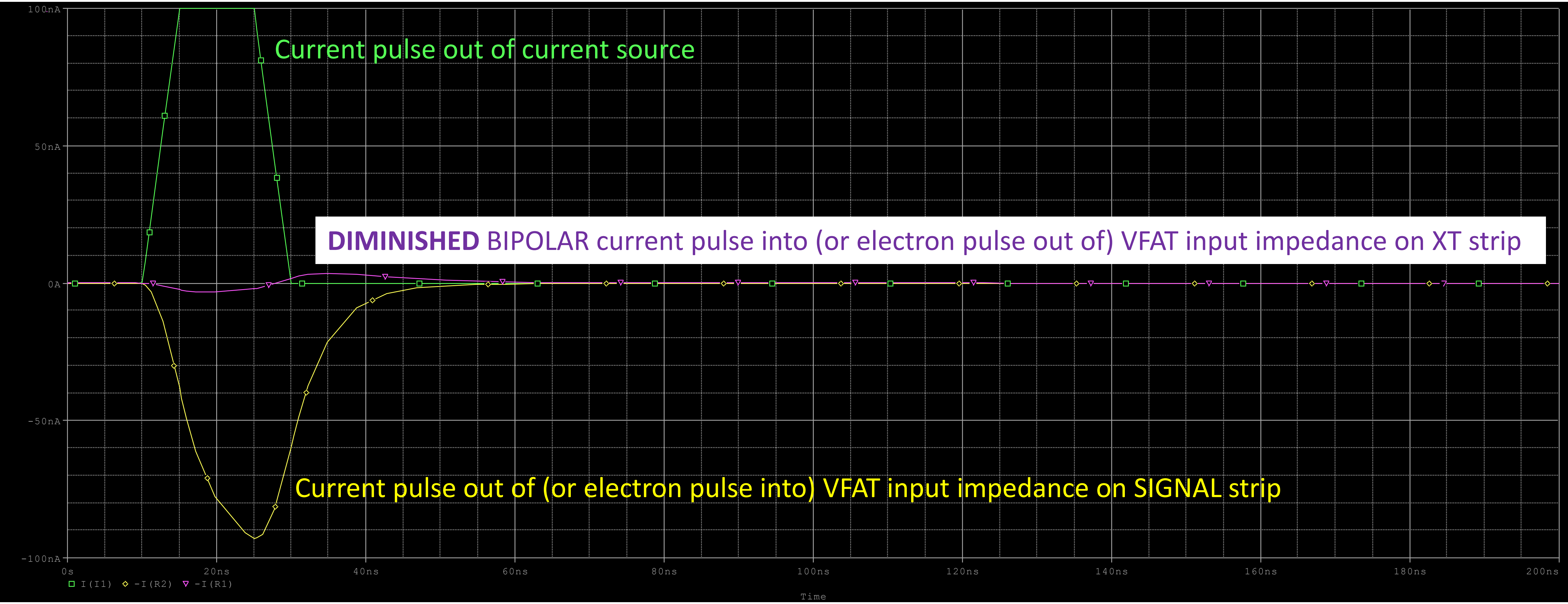
(note that this doesn't even take gas gain into account)

4. Place a 1 nF bypass cap. on 100k protection resistor



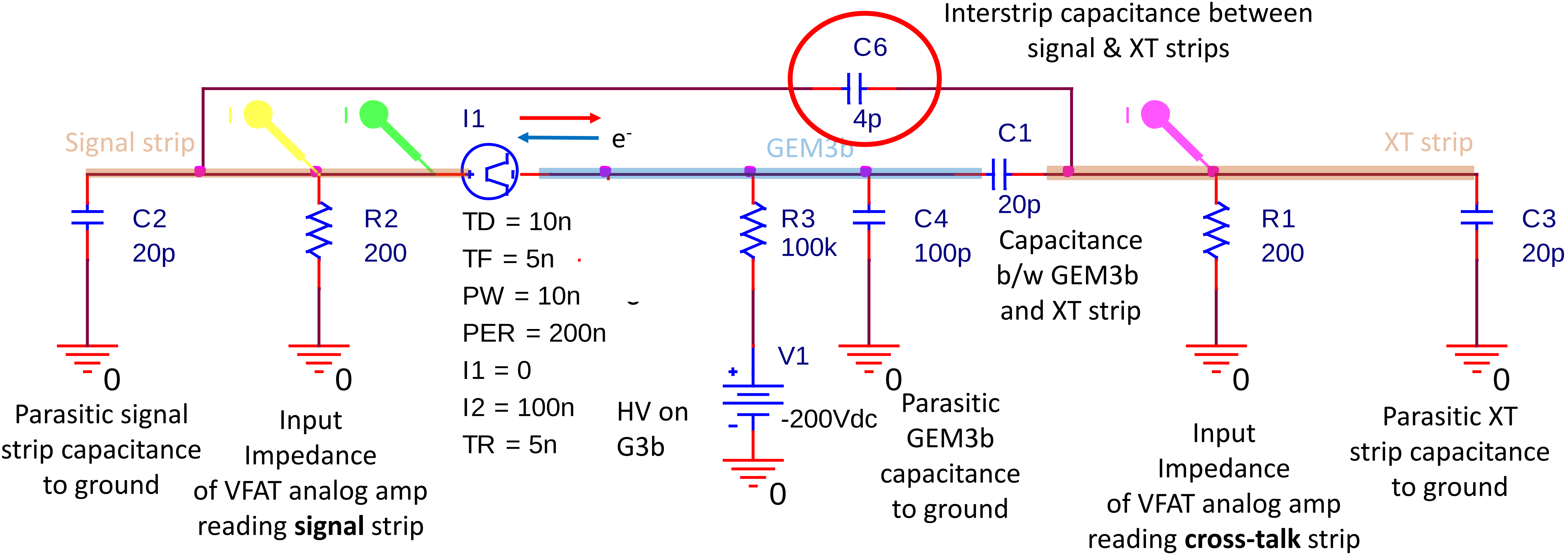
Main observation: The XT pulse is DIMINISHED by a factor ≈ 4 and becomes bipolar!

Mitigation w/ bypass capacitor

- Ok, that works, too! This was also confirmed experimentally in Stephen’s tests at FIT – see previous talk.
- However, this approach ultimately requires adding a cap to *each* HV segment on the foil because that is where the 100k protection resistors are located.
- This might be tricky to implement and the **bypass capacitors must be very HV stable in the long run**.
- *Probably not our best choice.*

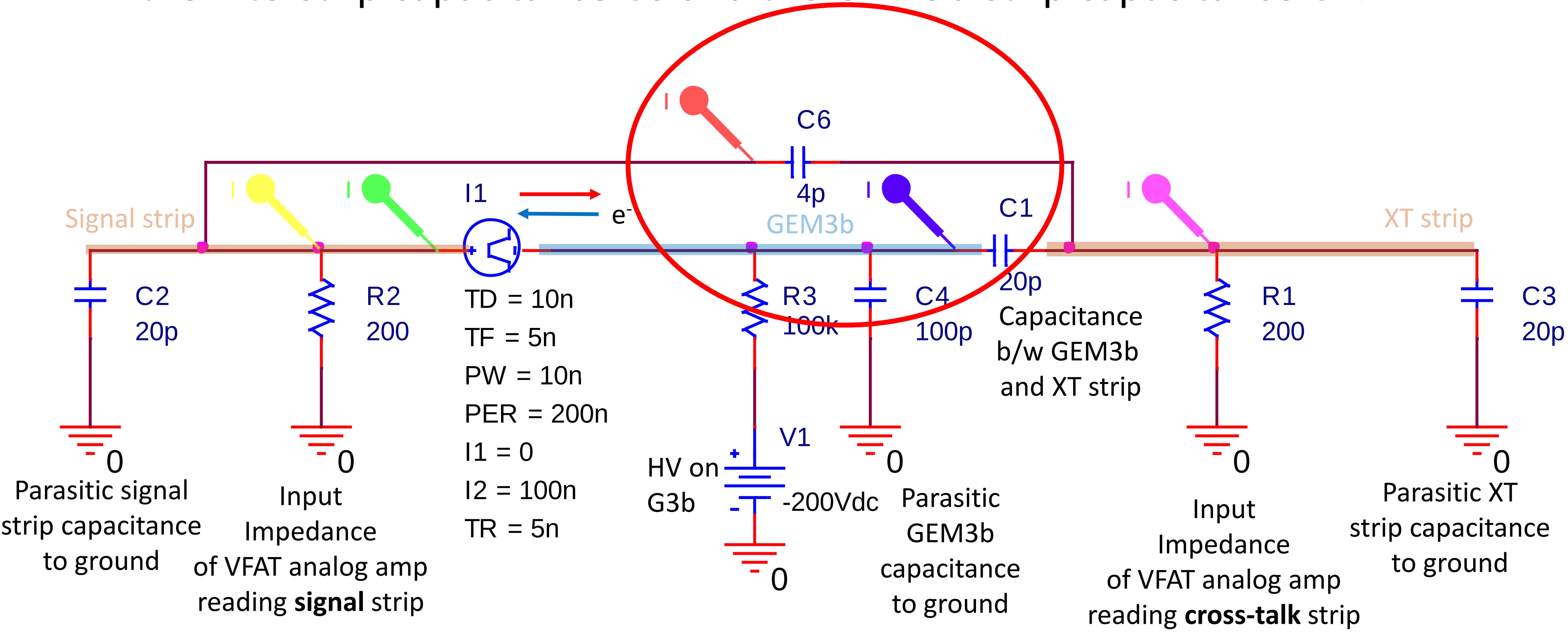
Mitigation strategies: Limitations

- Larger capacitance on GEM3b and bypass capacitors can *reduce* crosstalk, **but not fully eliminate** it because there is still XT current through C6 due to the **interstrip** capacitance.

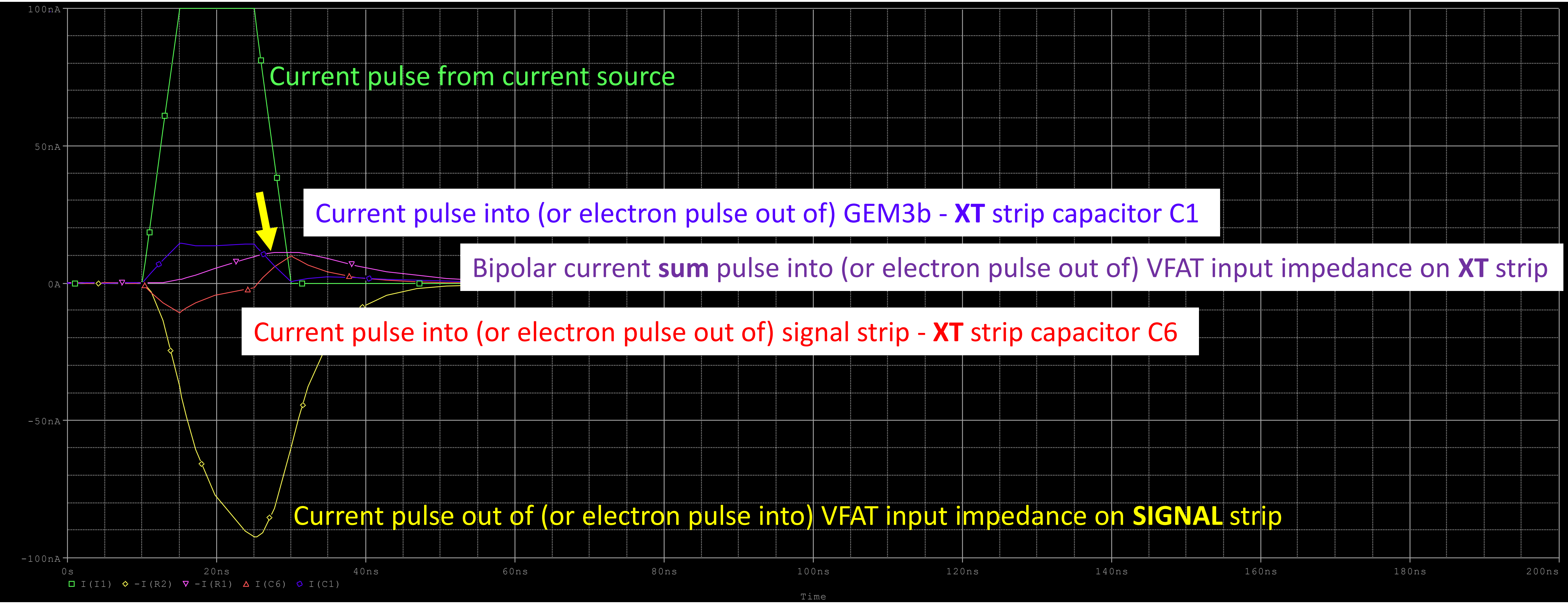


Mitigation strategies: Overcoming Limitations?

- Let's probe and compare the two contributions to the XT current through the interstrip capacitance C6 and the GEM3b-strip capacitance C1:



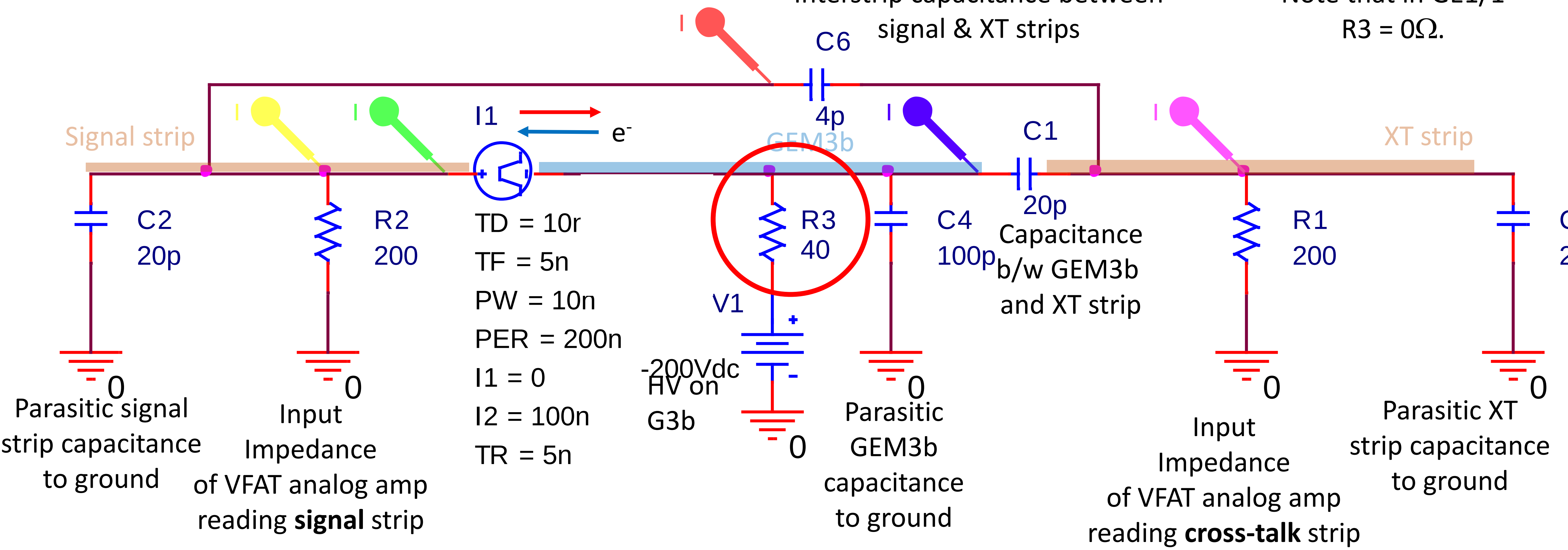
Mitigation strategies: Overcoming Limitations?



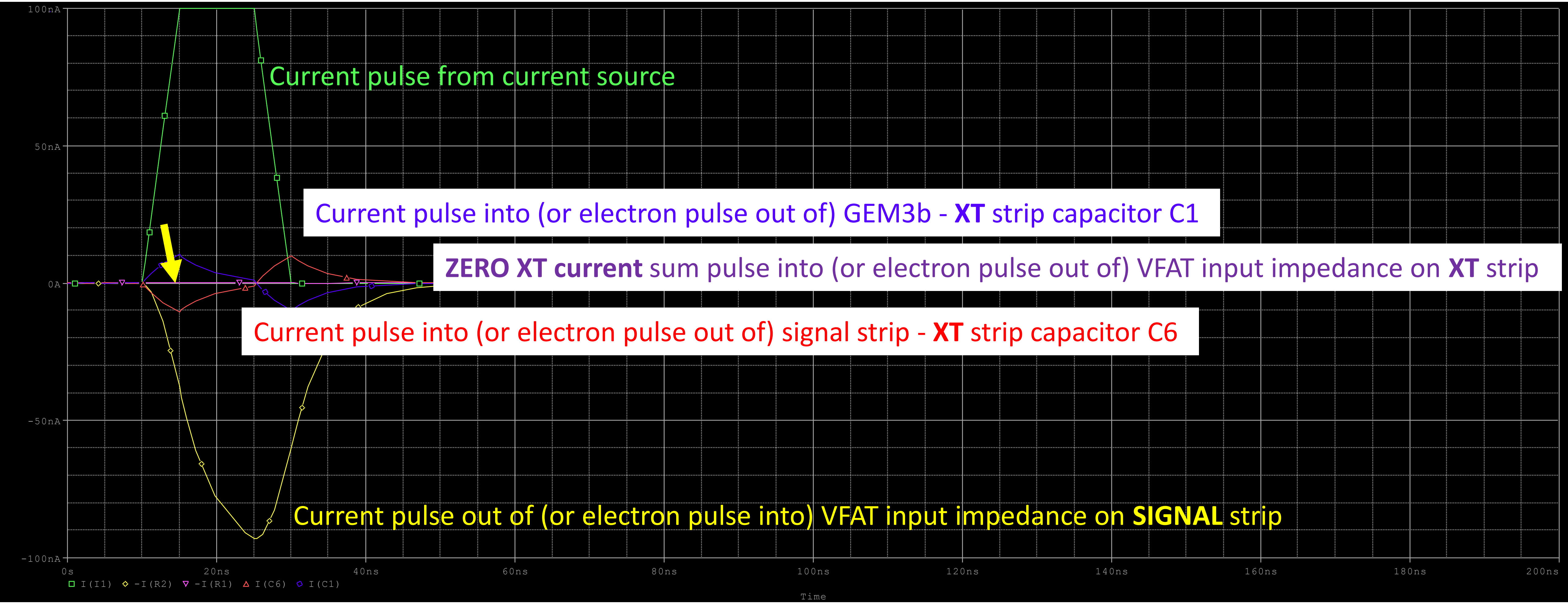
Main observation: The two XT contributions have **opposite polarity** as they are connected to opposite ends of the current source ! *If only they cancelled out…*

Mitigation strategies: Overcoming Limitations?

- Well, for a particular value of the protection resistor R3 (40Ω) you CAN actually sink away just enough current so that the two crosstalk currents DO CANCEL:



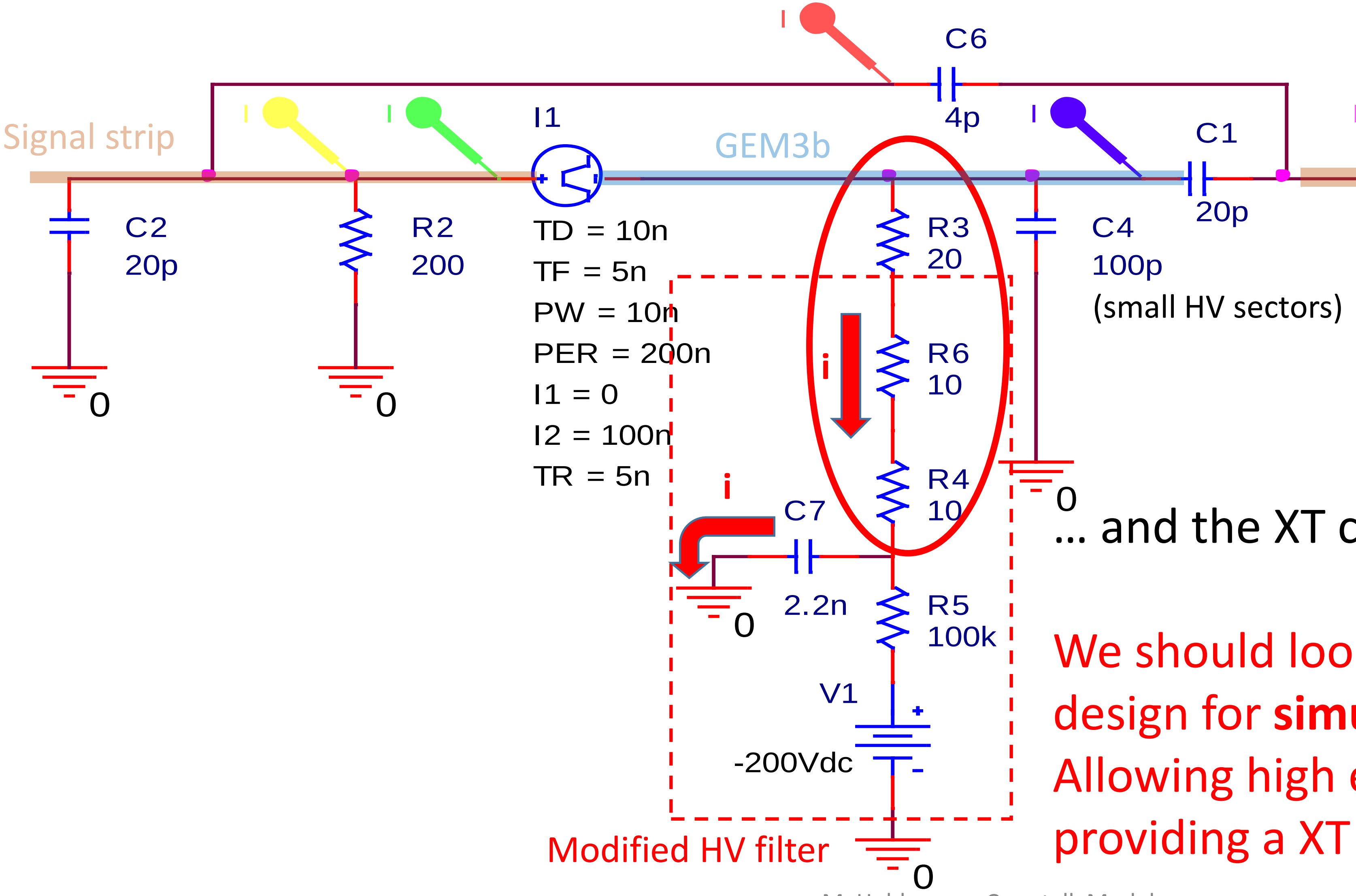
Mitigation strategies: Overcoming Limitations?



Main observation: The two XT contributions have opposite polarity and **cancel out**.
The netXT current is **zero**! The signal current is unaffected.

Mitigation strategies: Implement in HV filter?

- With a small R3 protection resistor and modified HV filter, again $R_{tot} = 40\ \Omega$:



… and the XT current disappears again.

We should look into optimizing the HV filter design for **simultaneous** low-pass HV filtering, Allowing high enough particle rates, and providing a XT current path to ground

XT mitigation vs. Discharge protection

It appears that crosstalk mitigation and protection against discharge damage of the readout unfortunately oppose each other:

- Increasing the capacitance of GEM3b reduces XT, but increases the charge and energy of discharges into the VFATs
- Introducing bypass capacitors reduces XT, but provides an additional source of charge that can discharge into the readout
- Reducing protection resistance reduces XT, but also reduces discharge protection.

Mitigation of both effects has to be carefully balanced in the final GEM foil design and experimentally validated. See also Jeremie's and Davide's talks.

Long Summary & Conclusions

Results from the PSPICE model of the GEM crosstalk circuit

- replicate experimental XT results obtained with a voltage pulser at FIT
- explain why tests with a voltage pulser produce *same-sign* XT pulses while tests with a GEM in normal operation produce *opposite-sign* XT pulses as due to the difference between an external voltage source and an internal current source
- show that any method for reducing the *impedance Z of GEM3-b to ground* will reduce XT:
  - GEM3b foil segments with larger capacitance ($Z = 1/\omega C$)
  - connection of GEM3b foil without protection resistor (as in GE1/1)
  - bypass capacitor on 100kΩ protection resistor
- show that this mitigation has no significant impact on signal integrity
- show that additional devices upstream of a large protection resistor will be ineffective
- caution that the mitigation of this "GEM3-bottom to ground impedance" has its limits due to the additionally present impedance from the interstrip capacitance
- show that XT can be expected to be reduced by up to a factor $\approx$ 4 by this type of mitigation
- show that by reducing the protection and HV filter resistances, the GEM3-bottom to ground impedance XT and the interstrip capacitance XT can cancel each other and net XT becomes zero
- demonstrate a need for careful balancing of discharge mitigation and XT mitigation

Short Summary & Conclusions

Results from the PSPICE model of the GEM crosstalk circuit

- provide qualitative and quantitative understanding of our experimental XT results
- establish that the observed XT is due to capacitive coupling
- inform our mitigation strategies
- show that there is tension between XT mitigation and discharge protection

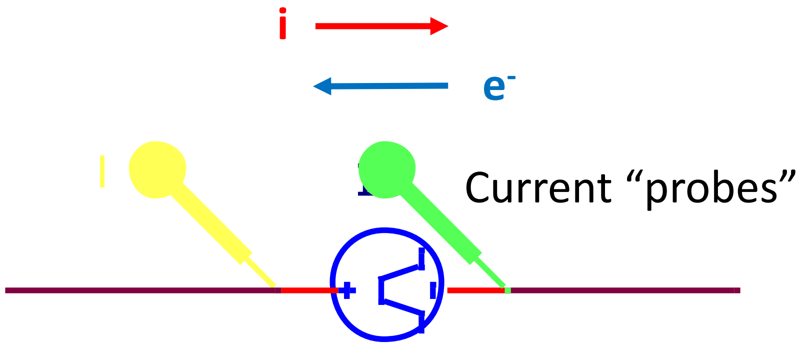
Thank you!

The End

Backup

PSPICE Current convention: Example

Pulsed current source:



TD = 10n

TF = 5n

PW = 10n

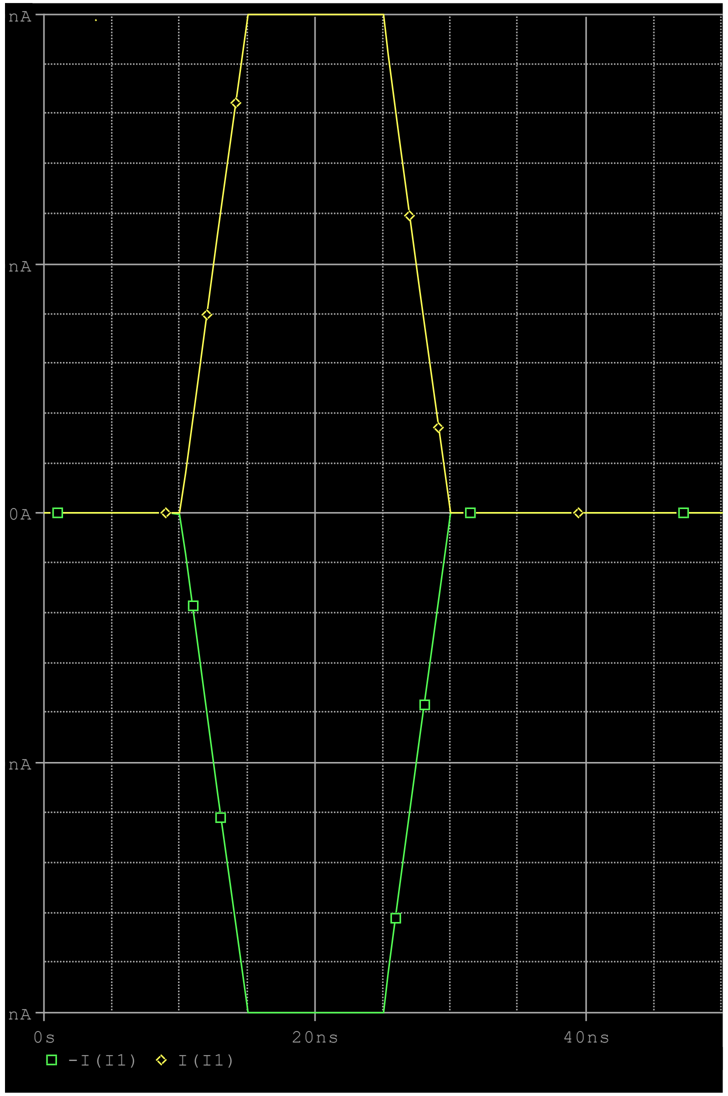
PER = 200n

I1 = 0

I2 = 100n

TR = 5n

Current flows **into** source on the left and is counted **pos.**



Current flows **out of** source on the right and is counted **neg.**

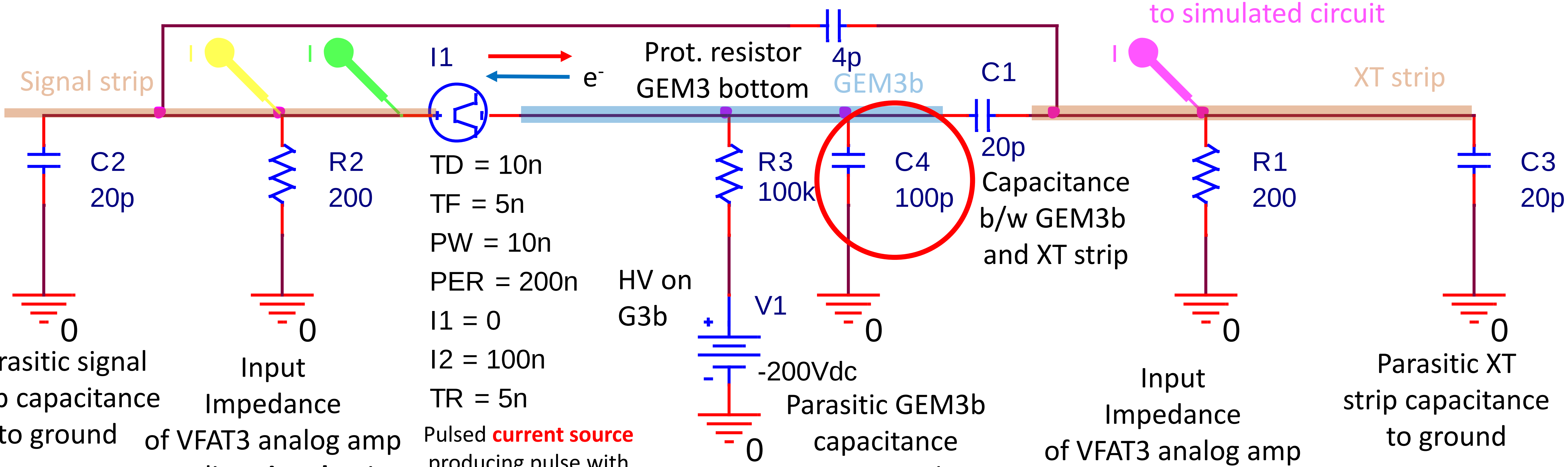
But it is of course one and the same current !

2. PSPICE circuit implementation for gas avalanche

Model the GEM avalanche as current source I1 between the bottom of GEM3 and signal strip:

Interstrip capacitance between signal & XT strips

Probe for XT current applied to simulated circuit



Parasitic signal strip capacitance to ground

Input Impedance of VFAT3 analog amp reading **signal** strip

Pulsed **current source** producing pulse with 100nA current, 5ns rise and fall time, 10ns pulse width

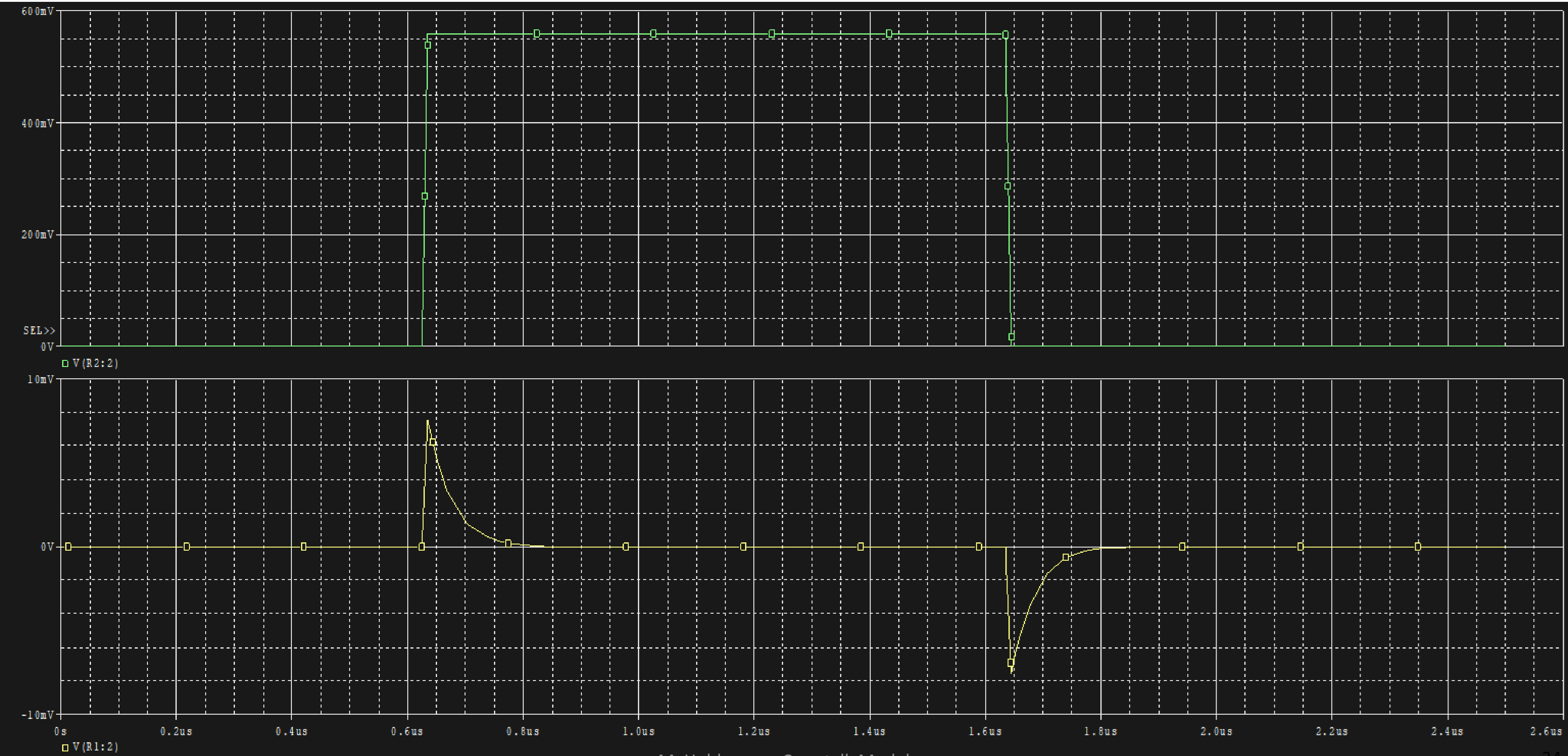
Parasitic GEM3b capacitance to ground: Small (100pF) for **segmented** GEM3b

Input Impedance of VFAT3 analog amp reading **cross-talk** strip

Parasitic XT strip capacitance to ground

Current source: 10,000 primary electrons (1.6 fC) over 15 ns: $i = 10^4\ 1.6\ 10^{-19}\ C\ /\ 15\ 10^{-9}\ s = 10^{4-1-19+9} = 10^{-7}\ A = 100nA$
(note that this doesn't even take gas gain into account)

Zoom of simulation output on p.5

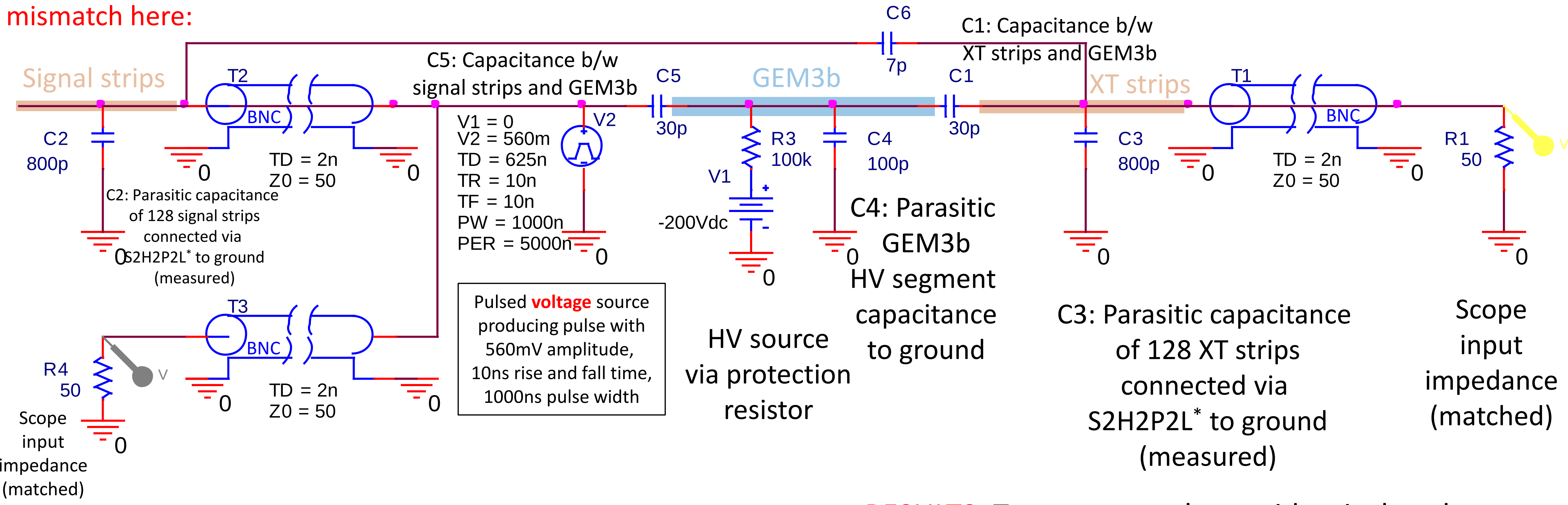


1. More detailed circuit for pulser measurements

Include the transmission lines (50 Ohm BNC cables) used in the actual measurements:

Worried about impedance mismatch here:

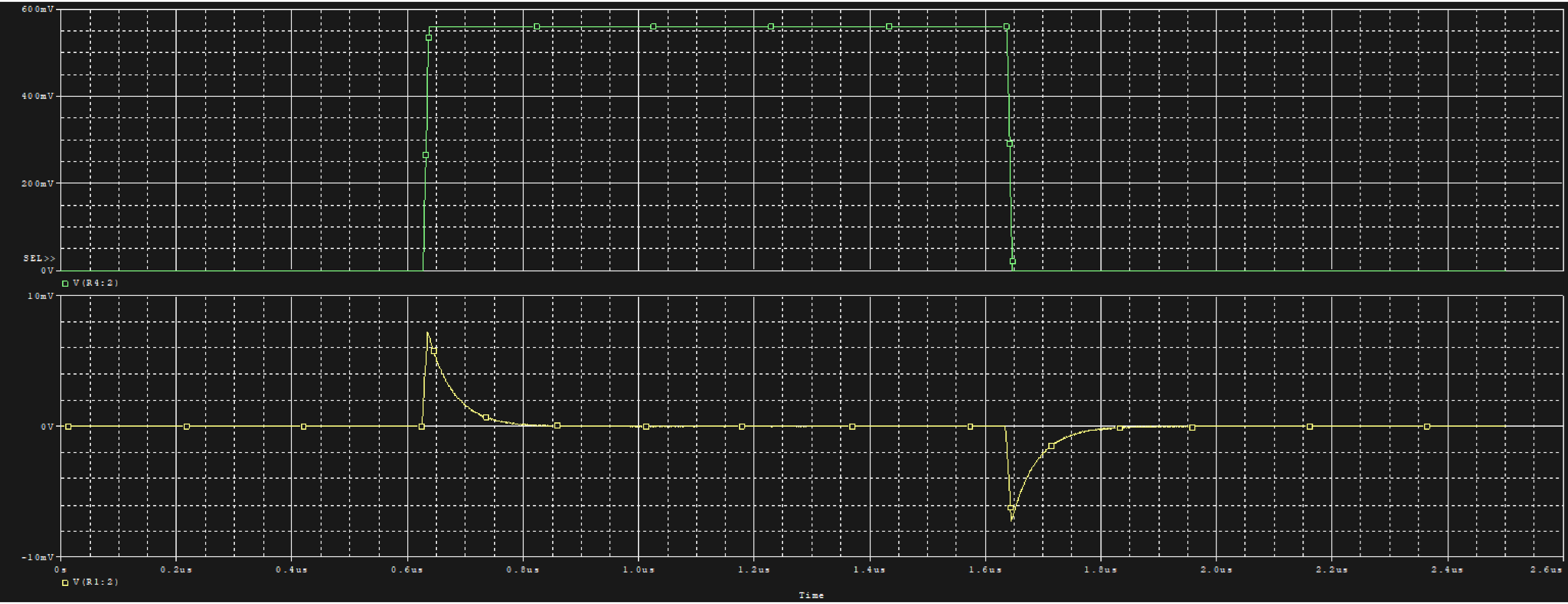
C6: Interstrip capacitance b/w 128 signal strips and 128 XT strip



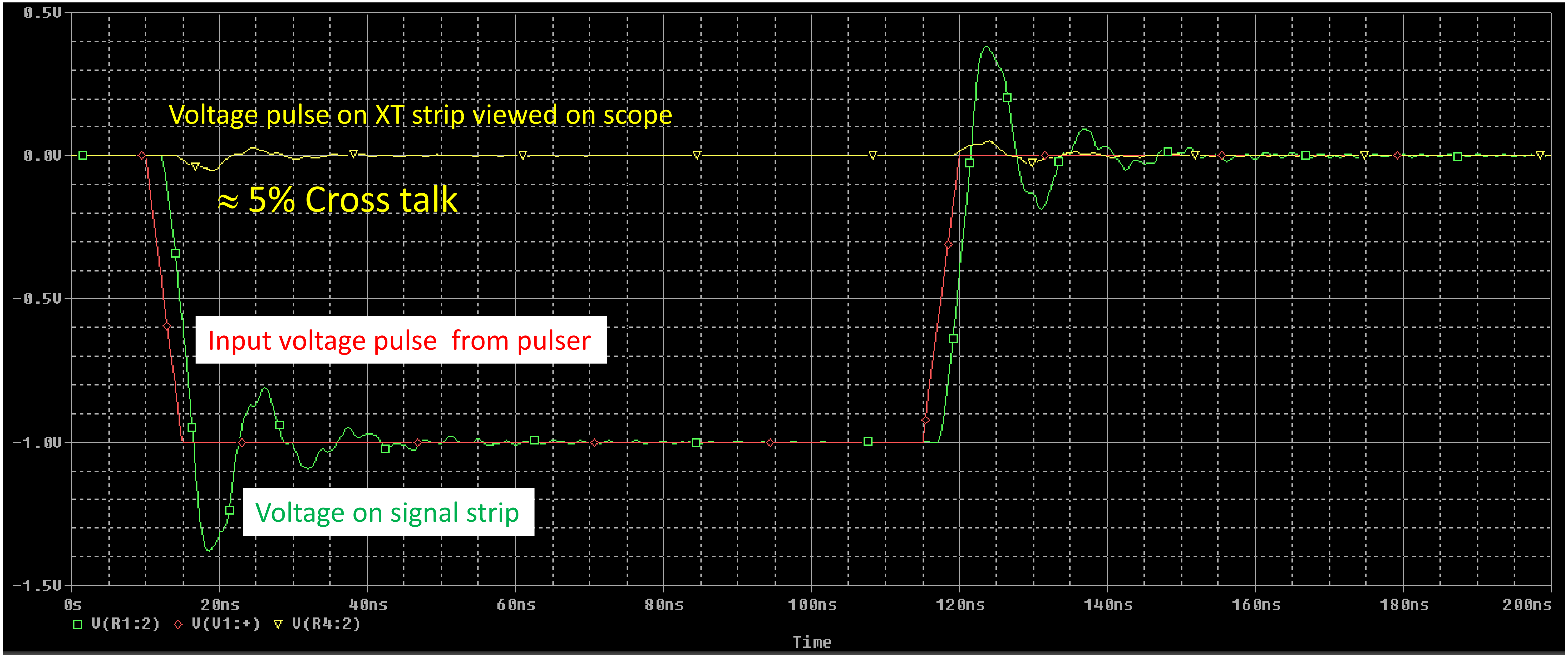
RESULTS: Turns out results are identical to the simulation with the simplified circuit on pp. 4/5

* "Strip to Hirose to Panasonic to LEMO" adapter

1. More detailed circuit for pulser measurements



1. Pulse analysis for pulser measurements



Main observation:

- Cross talk voltage pulse, input voltage pulse, and voltage pulse on signal strip all **have THE SAME POLARITY on leading edge**
- Cross talk pulse is bipolar

Older Model Circuit for pulser measurements

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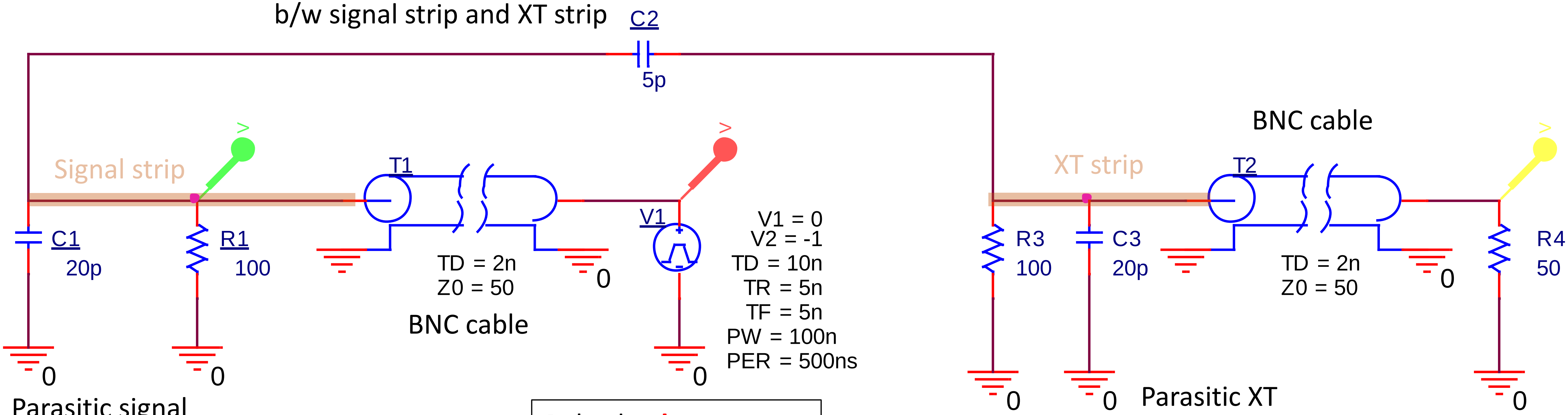
For Stephen's measurements with voltage pulser at FIT

Interstrip Capacitance
b/w signal strip and XT strip



Parasitic signal strip capacitance to ground

Input impedance of Panasonic-to-LEMO adapter reading **signal** strip (mismatched)

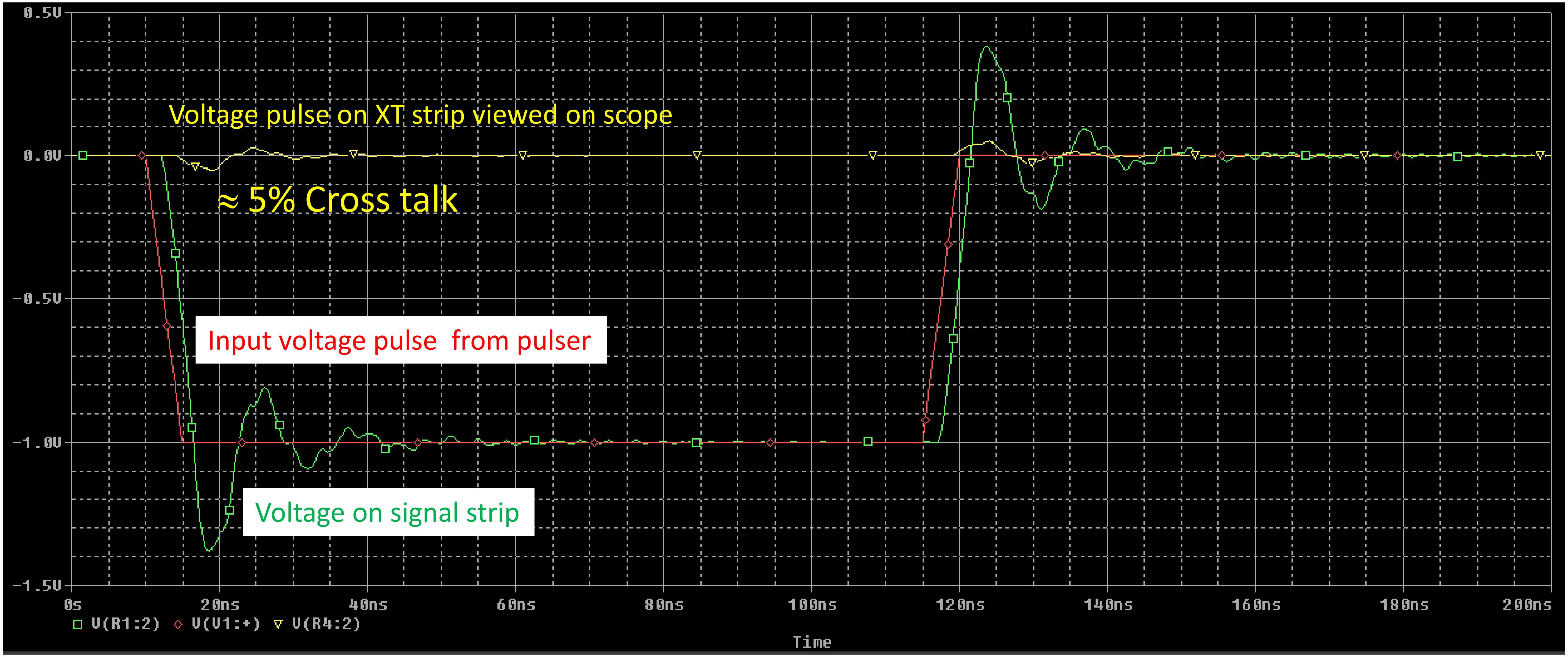
Pulsed **voltage** source producing pulse with -1V amplitude, 5ns rise and fall time, 100ns pulse width

Parasitic XT strip capacitance to ground

Input impedance of Panasonic-to-LEMO adapter reading **XT** strip (mismatched)

Scope Input Impedance (matched)

0. Pulse analysis for pulser measurements



Main observation:

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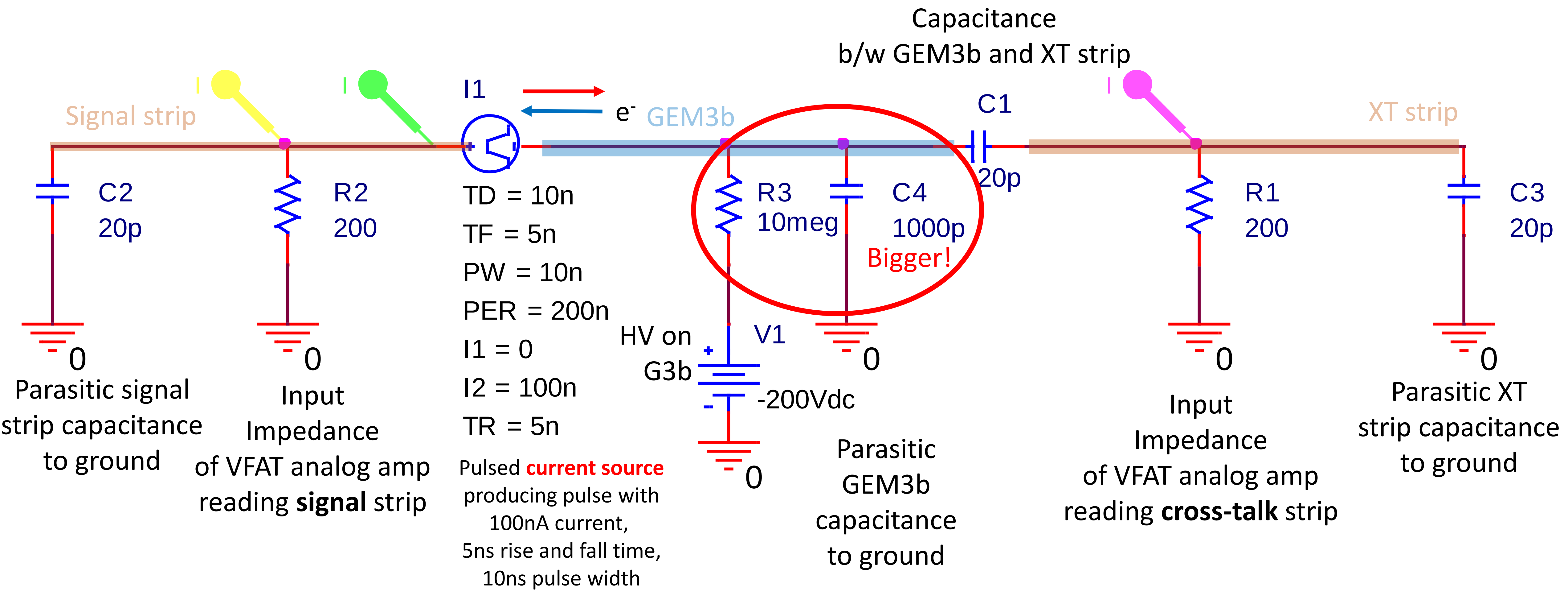
n. Single-segmented foil: Large cap., large R_{prot}



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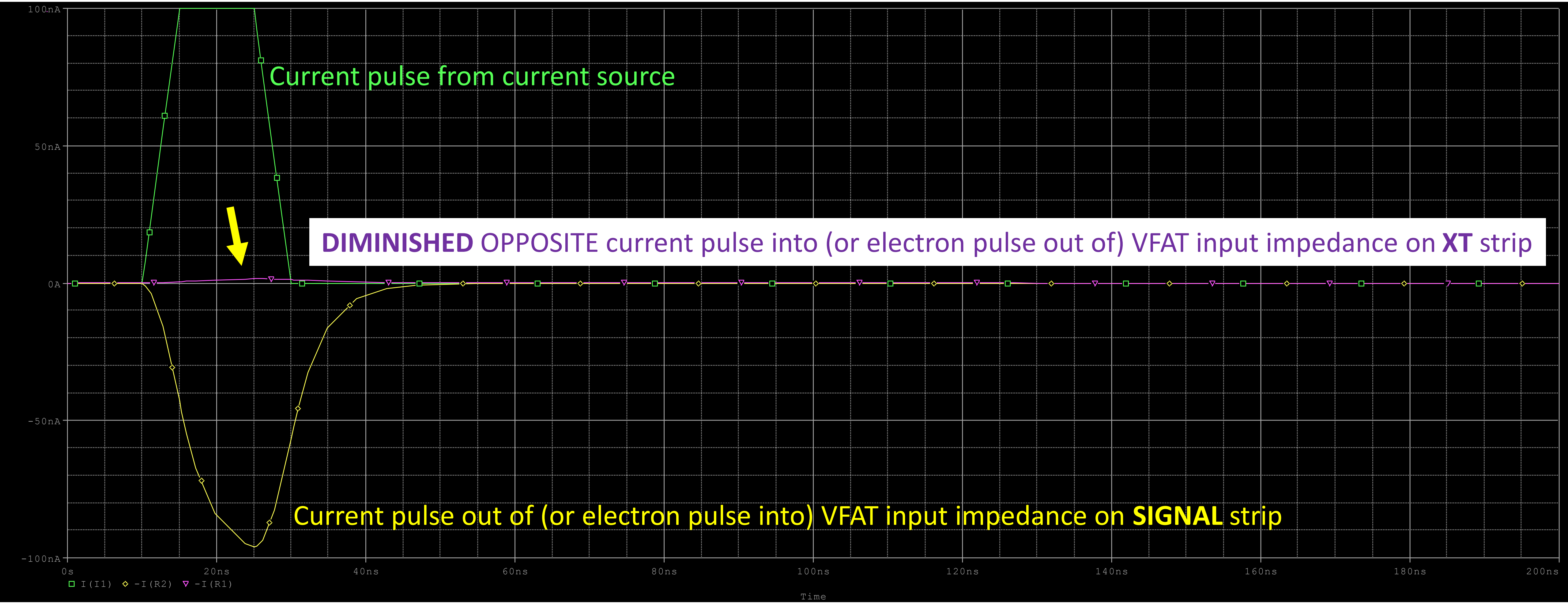
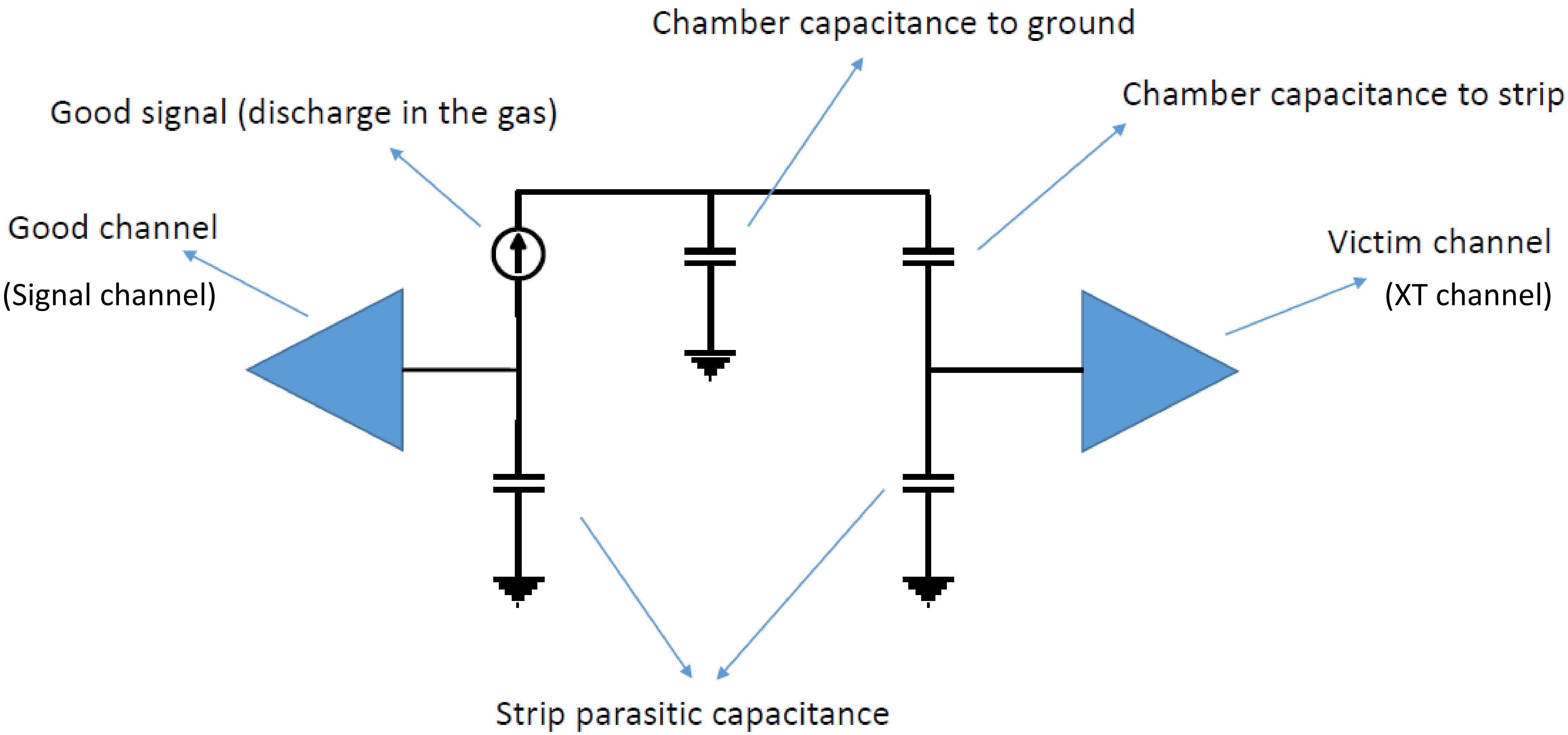
(note that this doesn't even take gas gain into account)

n. GE1/1 foil: Single-segmented, large cap.



Main observation: OPPOSITE polarity XT pulse is DIMINISHED!

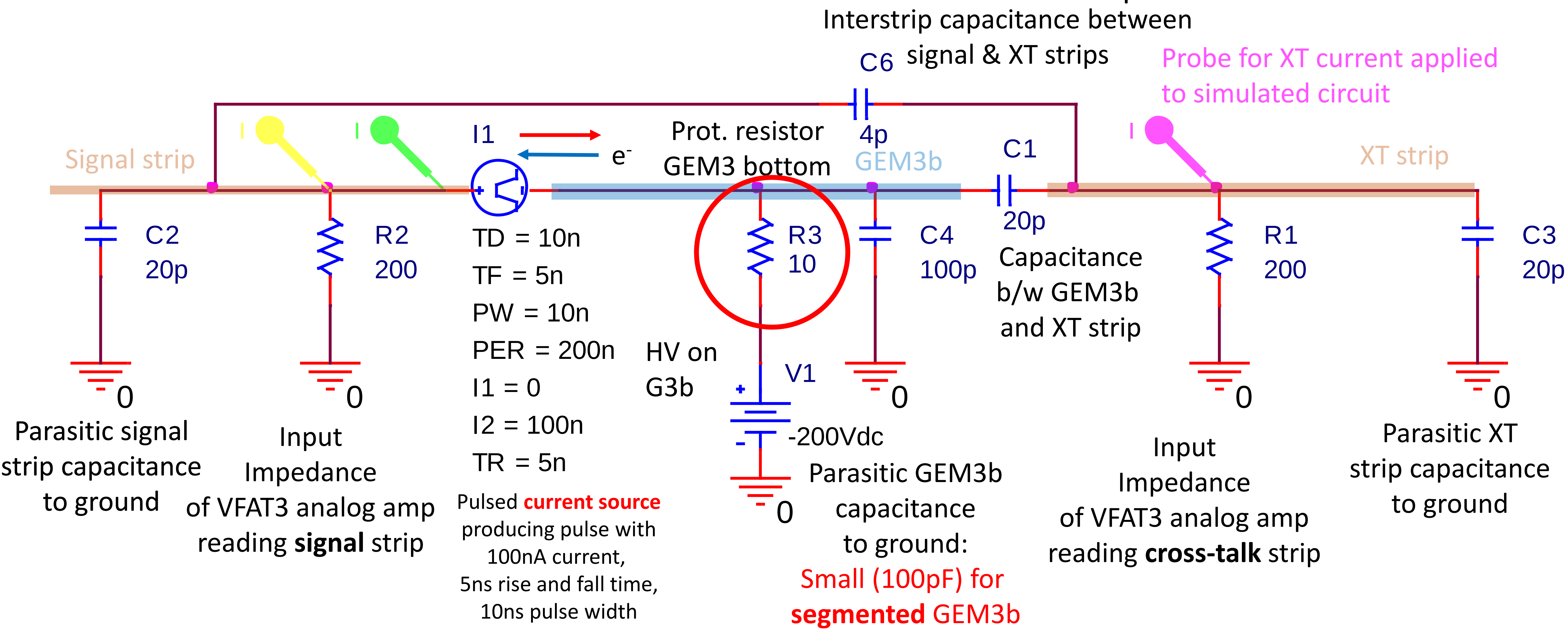
Guided by Francesco Licciulli's model:



The PSPICE Current Sign Convention

- Voltage polarities are easy to understand because they simply have one value relative to GRD
- Currents are bit more tricky since they also have a direction
- The direction or sign of a current in PSPICE is measured **relative to a device**
- The **PSPICE convention for current polarity** is this:
  - The current is probed at one terminal (“pin”) of a device (R,C,…)
  - **If at that terminal the current flows INTO the device, it is counted POSITVE**
  - If at that terminal the current flows OUT OF the device, it is counted NEGATIVE
  - “Current” here refers to technical current, i.e. flow of positive charges; electron flow would be in the opposite direction

3. Circuit for avalanche with R3 = R_{prot} = 10 Ω



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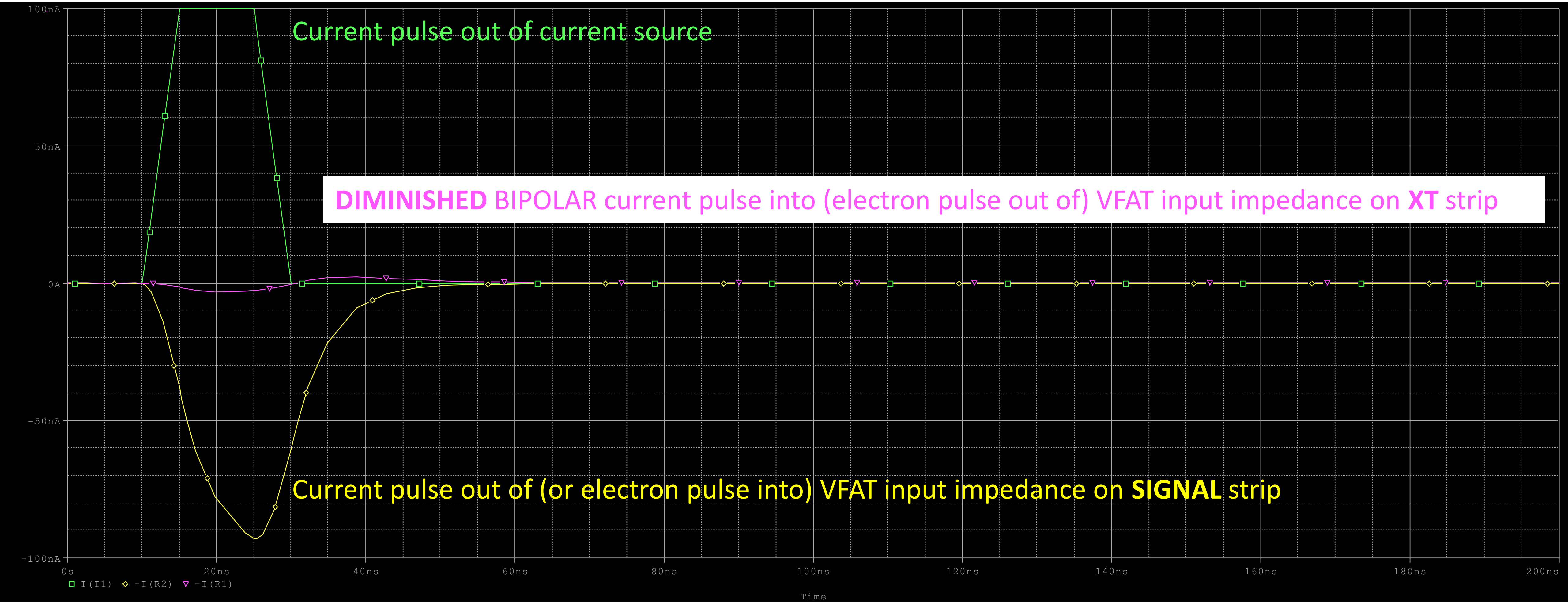
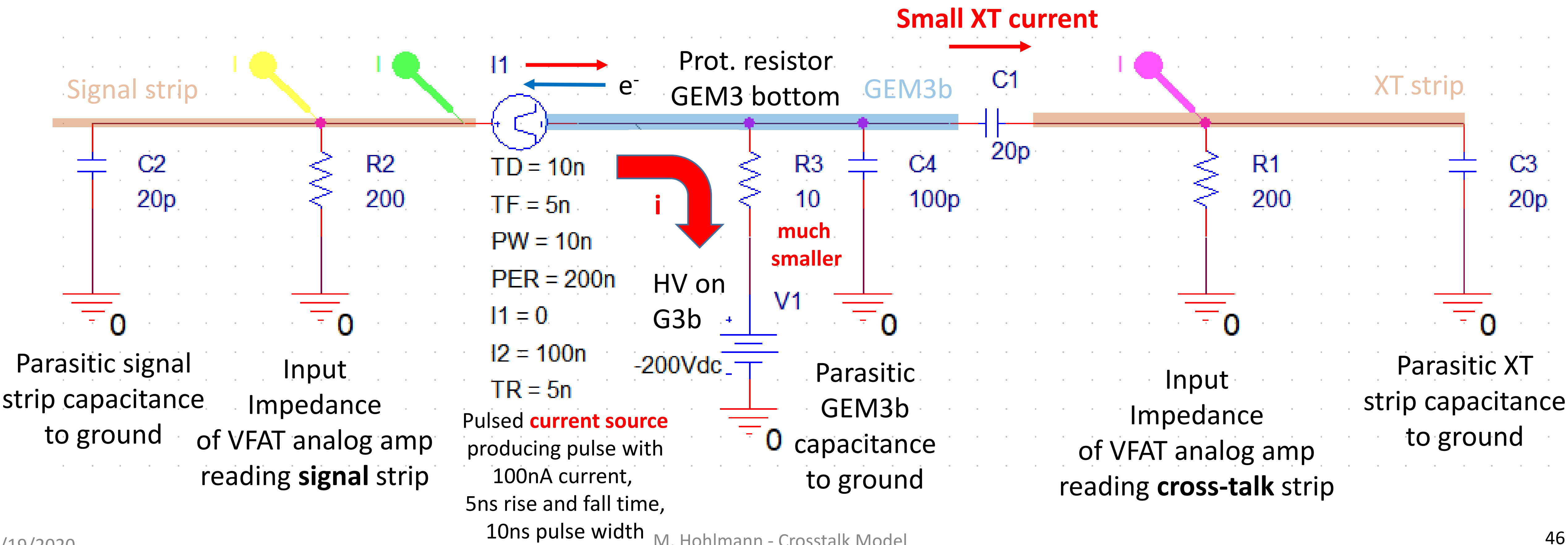


Main observation: The XT pulse is DIMINISHED by a factor ≈ 4 and becomes bipolar!

Making sense of the results

- In this circuit, the artificially reduced resistance of the protection resistor provides a **much reduced impedance for sinking the current from the current source to ground.**
- As a consequence, the amount of XT current that can flow into C1 is reduced.
- **This explains why XT is observed on double-segmented foils, but not on single-segmented foils!**



Mitigation strategies: Increase GEM3b cap.

- Now that we have a better understanding of how the XT is produced, we can investigate mitigation strategies with the simulation
- **Sinking more current from GEM3b to ground is important to reduce XT.** However, we presumably don't want to reduce our HV protection resistance on GEM3b too much for safety reasons.
- Instead, we would expect to be able to sink more current also by **reducing the impedance Z of the parasitic capacitance C4 between GEM3b and ground**
- Since $Z = 1/(\omega C)$, we need to **increase** that parasitic capacitance to reduce Z
- Lets increase C4 from 100pF to 1000pF…

Possible implementation (Jeremie's talk one week ago):

Anticipating a possible solution

→ Most promising option so far is to increase HV size (we don't introduce new elements and we don't change the basic settings of detector or electronics)

→ Problematic: it can bring back discharge propagation issue

How to mitigate that:

Use a unique layout but with multiple resistor options

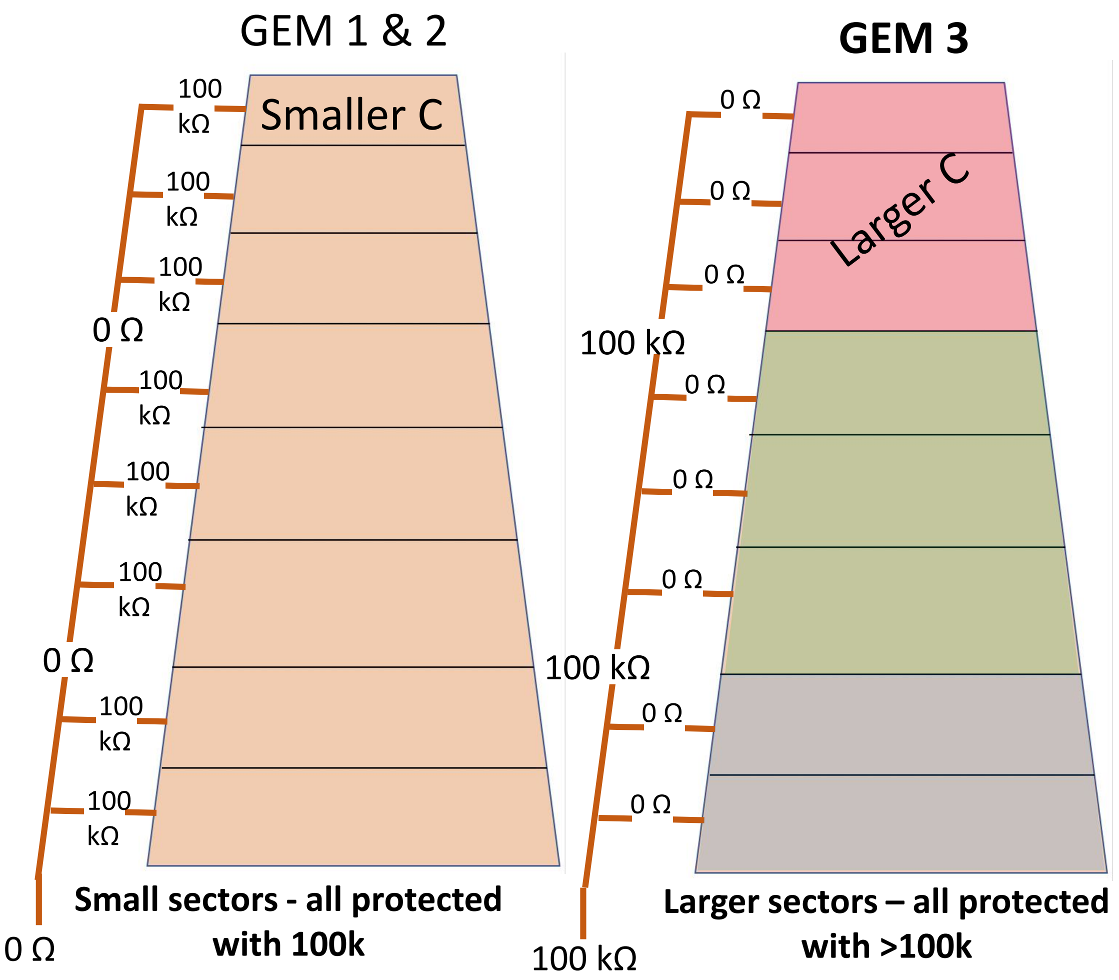
→ use fine segmentation on GEM1 and GEM2 to stop propagation

→ use coarse segmentation on GEM3 to prevent crosstalk

→ Decoupling capacitor on the electronics side might be mandatory to fully stop the propagations

Same layout (i.e. production mask) for all three foils

Minor modifications with respect to current design



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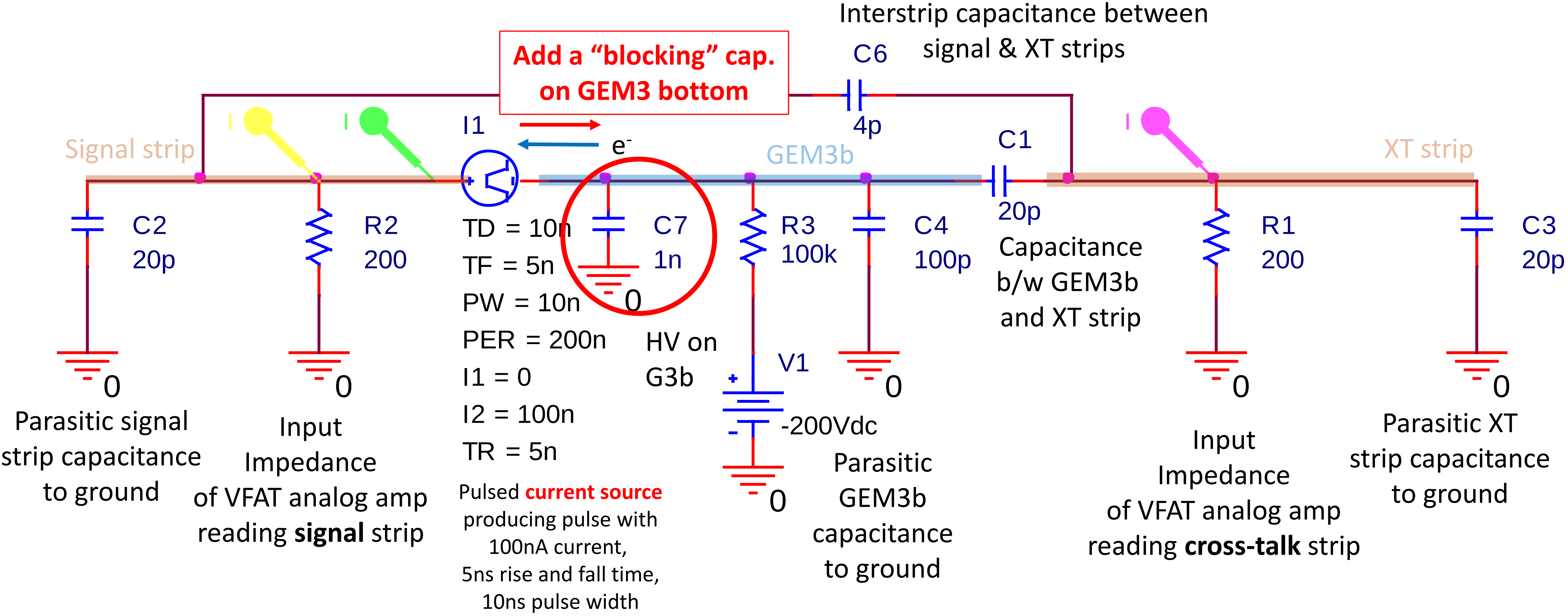
Mitigation strategies: “Blocking” Capacitor

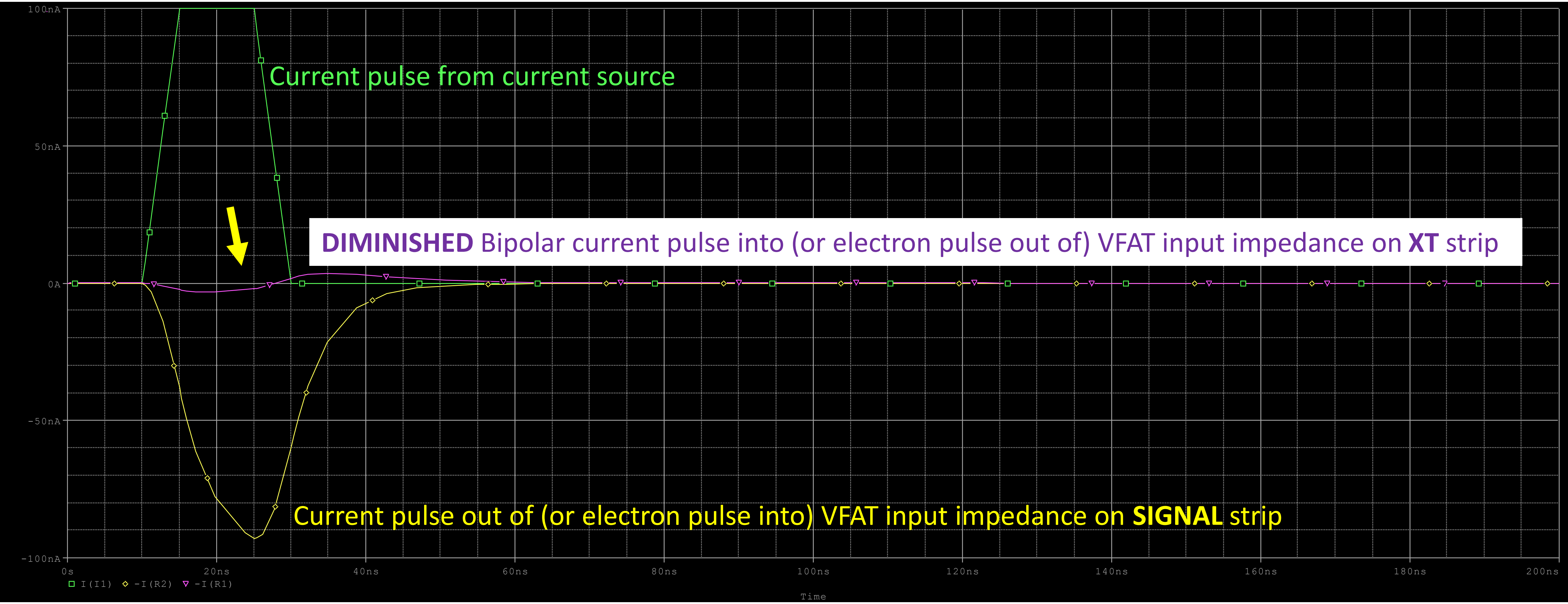
- Another strategy that has been suggested is to put a “**blocking” capacitor on GEM3b** that will provide an additional path to ground for the AC current pulse from GEM3b (but not for DC, i.e. HV)
- This will also decrease GEM3b impedance to ground
- Let’s place such a capacitor with C_5 = 1000pF = 1nF

6. Place a "blocking" cap. on GEM3b



Current source: 10,000 primary electrons (1.6 fC) over 15 ns: $i = 10^{4}\ 1.6\ 10^{-19}\ C\ /\ 15\ 10^{-9}\ s = 10^{4-1-19+9} = 10^{-7}\ A = 100nA$
(note that this doesn't even take gas gain into account)

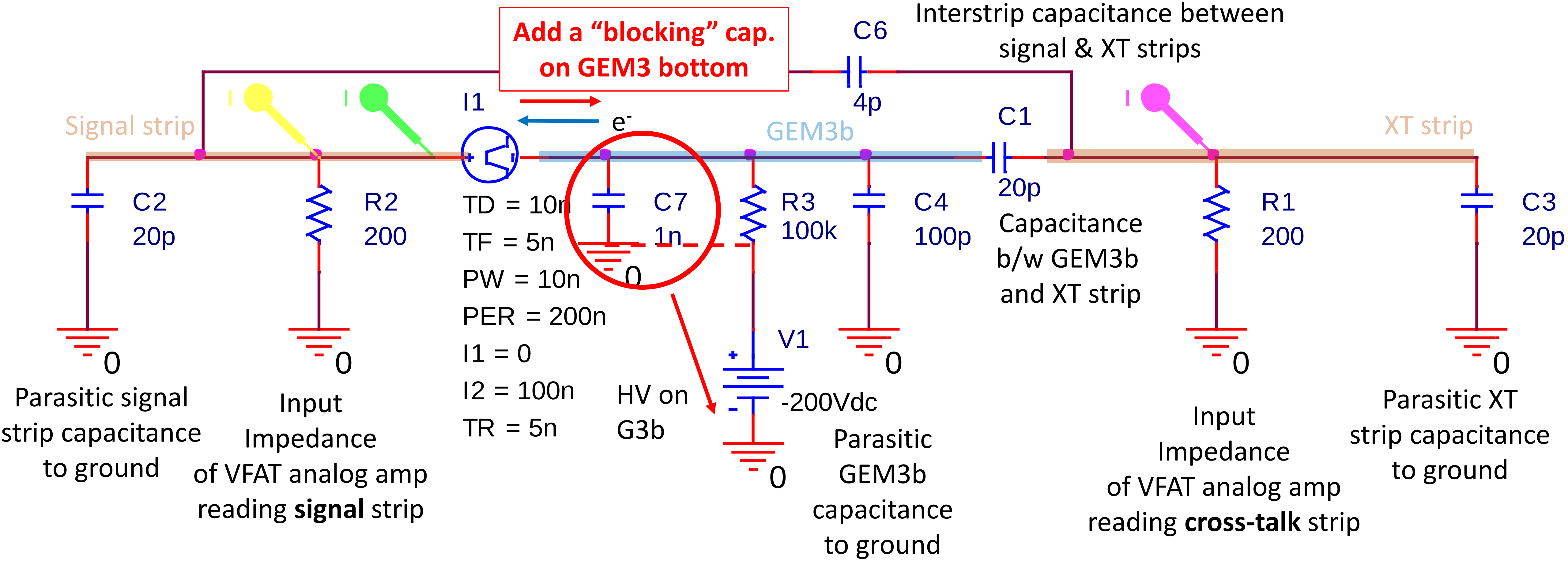
6. Place a "blocking" cap. on GEM3b



Main observation: OPPOSITE polarity XT pulse is AGAIN DIMINISHED!

Mitigation strategies: “Blocking” Capacitor

- This is actually not that surprising because for AC current the HV voltage source V1 acts like a ground, so this is **essentially equivalent** to placing a bypass capacitor in parallel on R3:

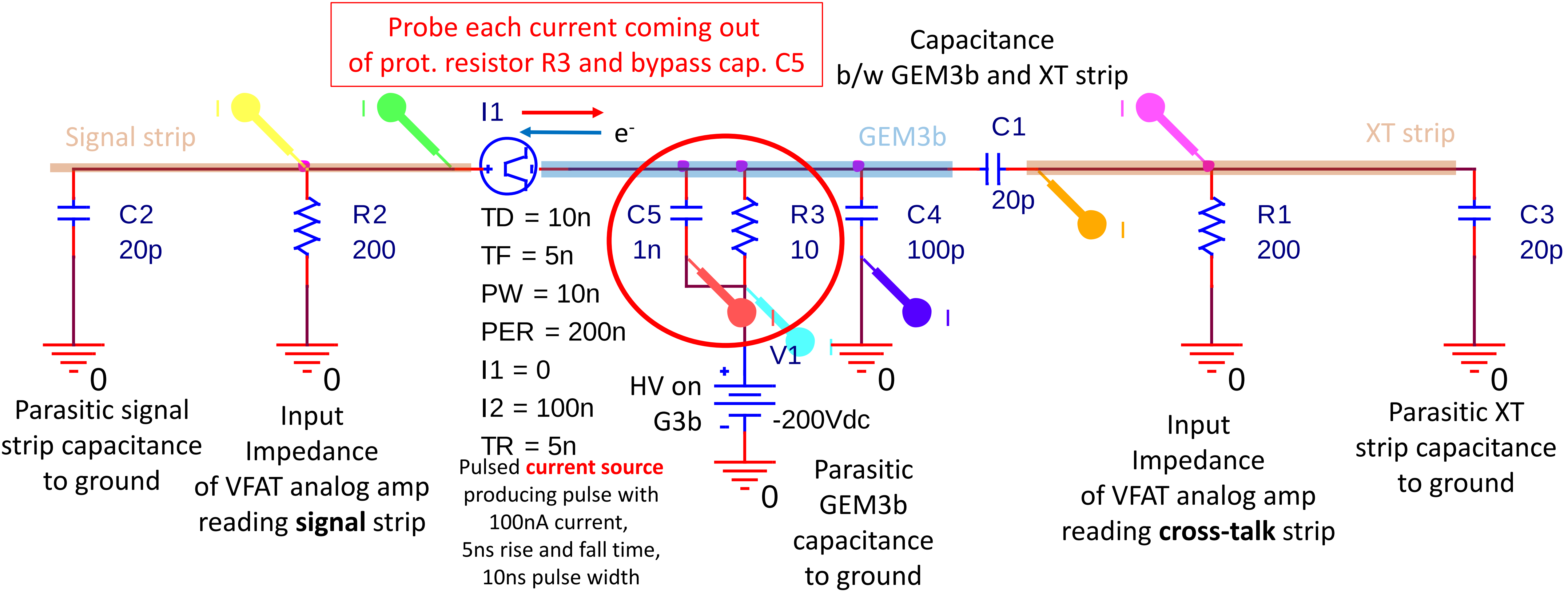


Academic's curiosity:

- Just because we are curious, let's see for what value of the protection resistor we get **the <u>same</u> amount of sinking current through the protection resistor and the bypass capacitor** around it.
- Let's change R_{prot}= R3 back to 10 Ω because then resistor and 1nF bypass capacitor C_5 have equal impedances at 100 MHz (10 nF pulse width):

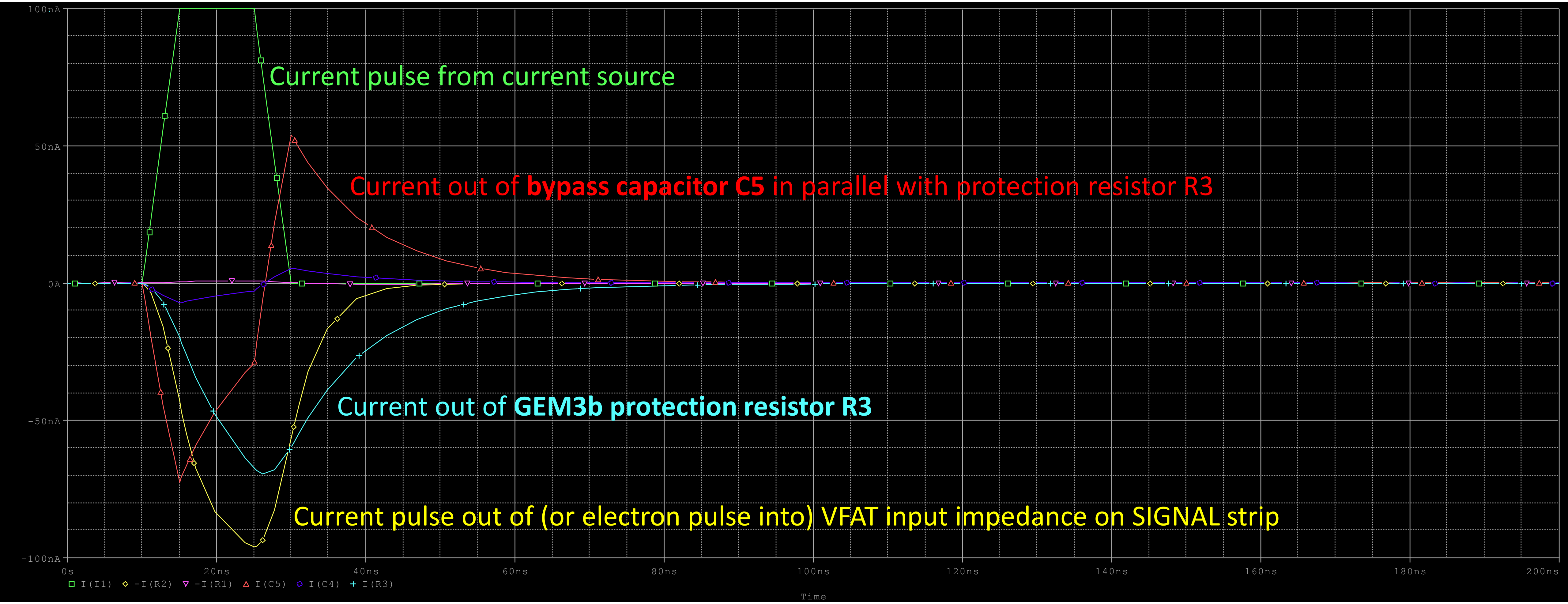
$$10\ \Omega = \mathbf{R_3 \approx 1/\omega C_5} = 1/(100\text{ MHz} \bullet 1\text{ nF}) = 1/(10^8 \bullet 10^{-9}) = 10\ \Omega$$

6. Let impedance of bypass cap ≈ R_{prot} on GEM3b



Equal impedances: $10\ \Omega = \mathbf{R_3 \approx 1/\omega C_5} = 1/(100\ \text{MHz} \bullet 1\ \text{nF}) = 1/(10^8 \bullet 10^{-9}) = 10\ \Omega$

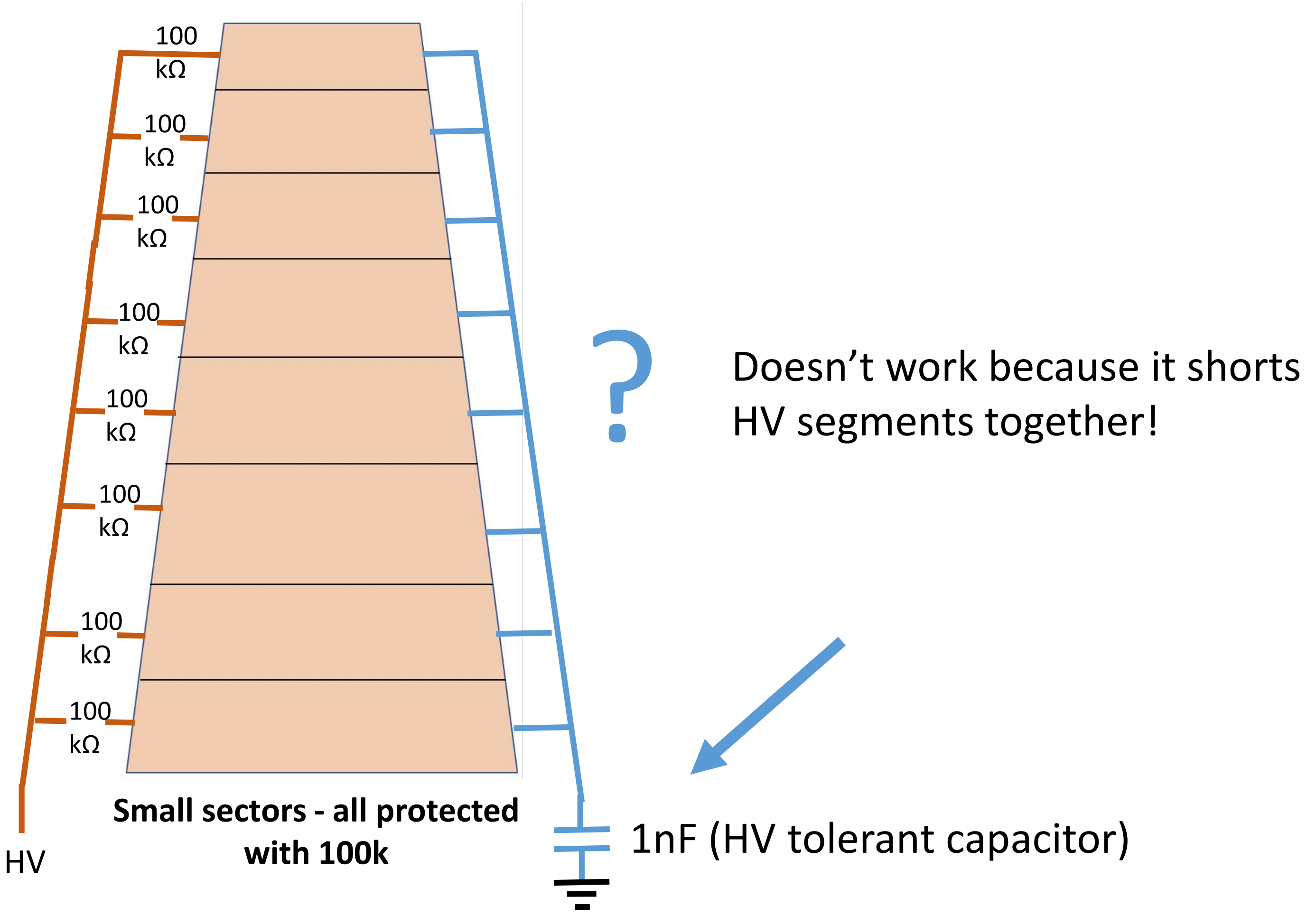
6. Impedance of bypass cap ≈ R_{prot} on GEM3b



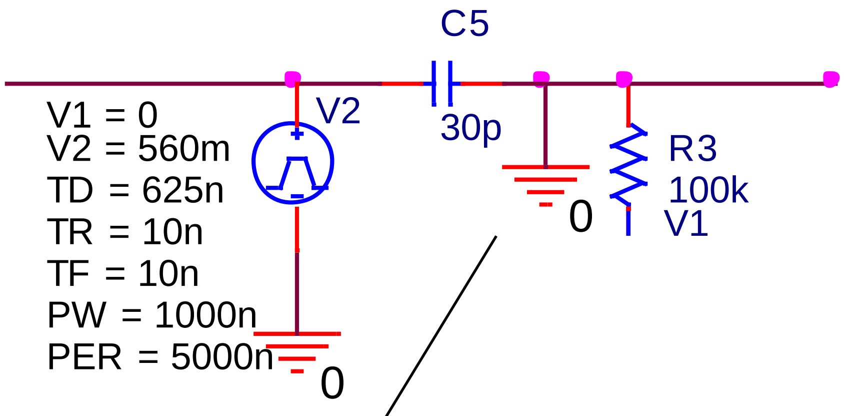
Main observation: The amplitudes of the currents out of the protection resistor R3 and the bypass capacitor C5 are indeed equal because they have equal impedances around ω = 100 MHz (corresponding to 10ns pulse width)

Mitigation strategies: "Blocking" Capacitor?

- Maybe this can be done with a **single** device **on the "other side"** of the HV segments (unless there are already traces and components there):



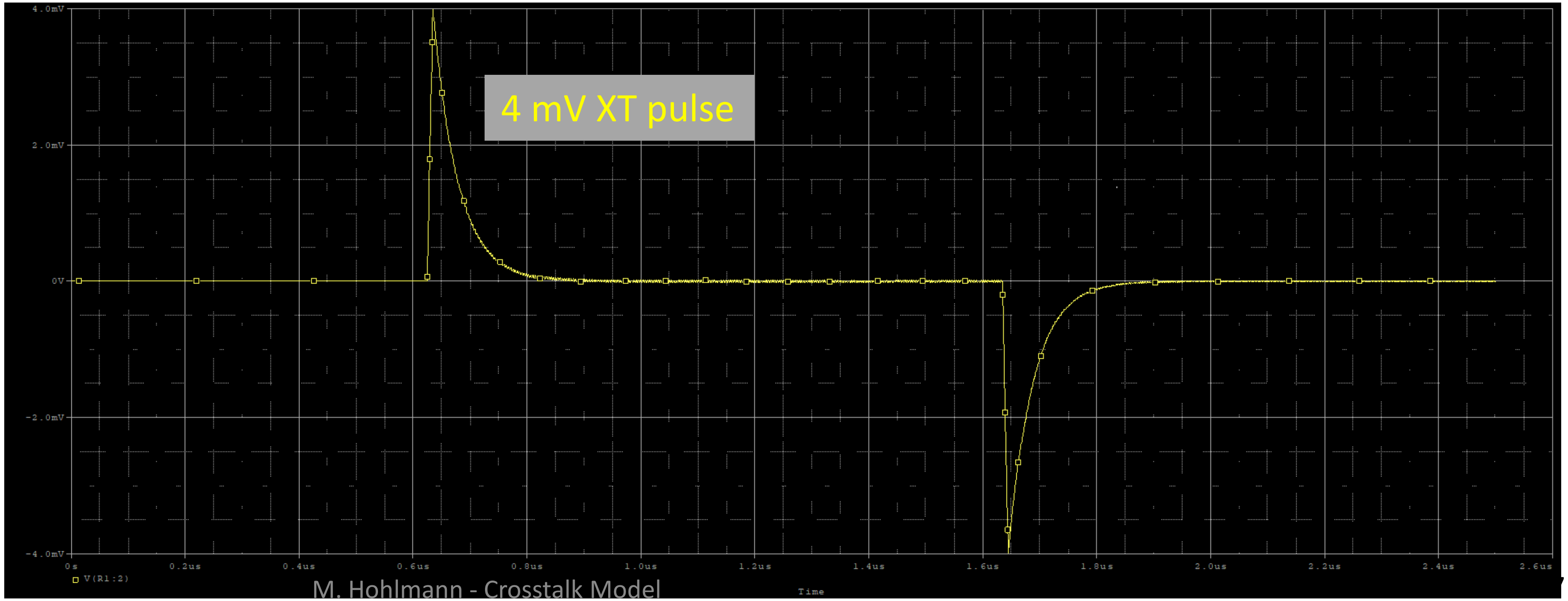
Tests with Pulser setup: Limit for bypass capacitor



The problem is again that we still get crosstalk via the direct Interstrip capacitance C6 between signal and XT strip:

Direct short!

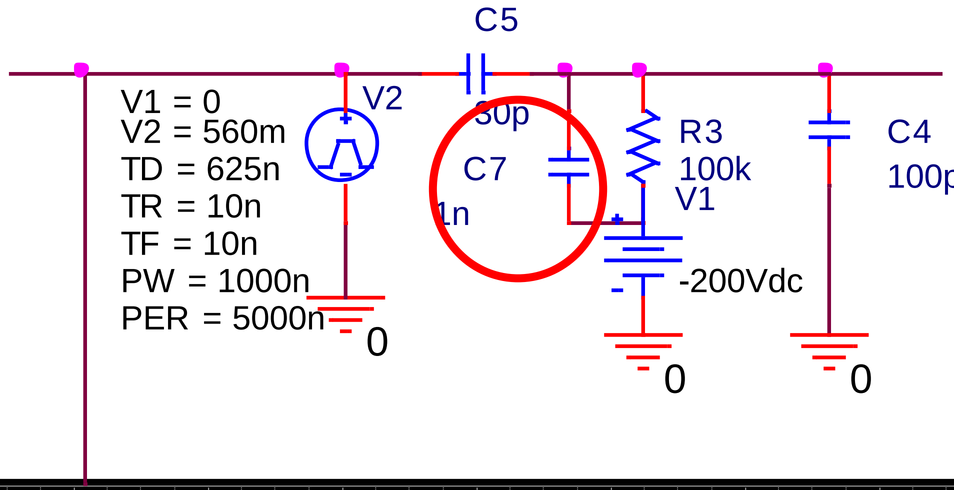
Also ≈ 50% reduction of XT (8mV -> 4 mV)

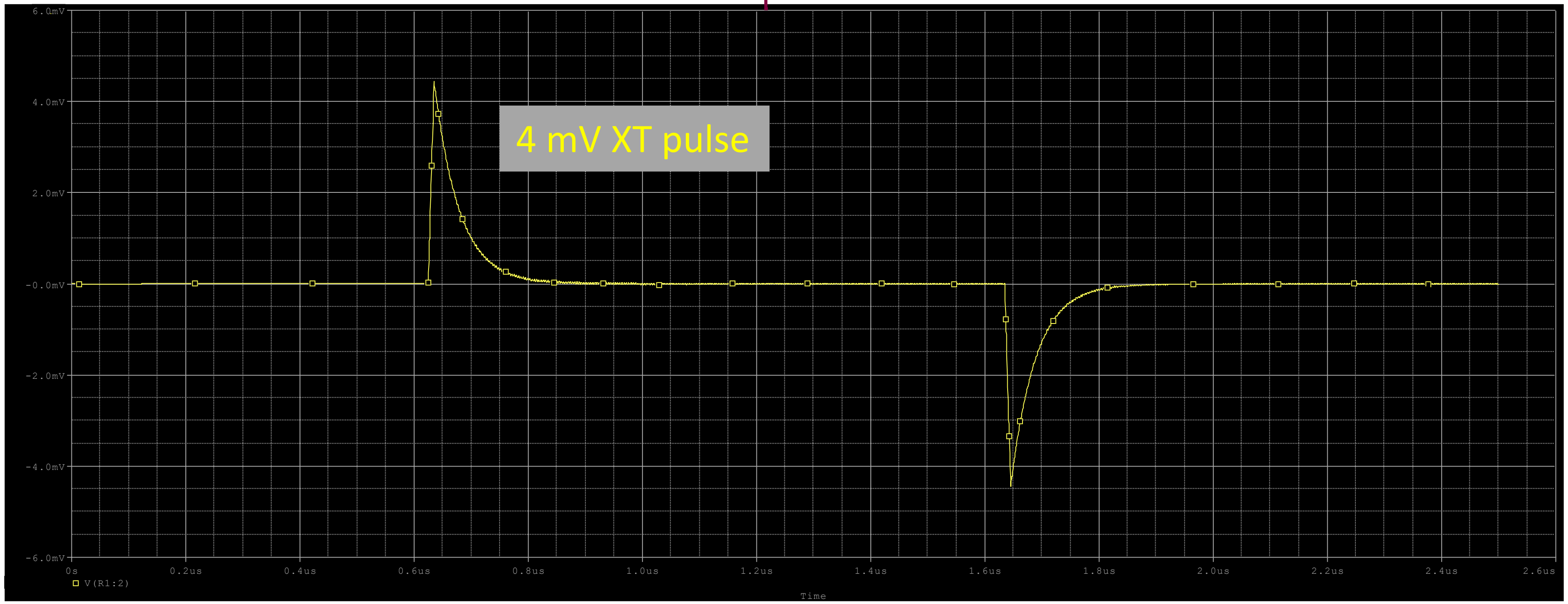


Mitigation strategies: Voltage Pulser Tests

Checking the **impact of bypass (blocking)** capacitor on XT with the **voltage pulser:**

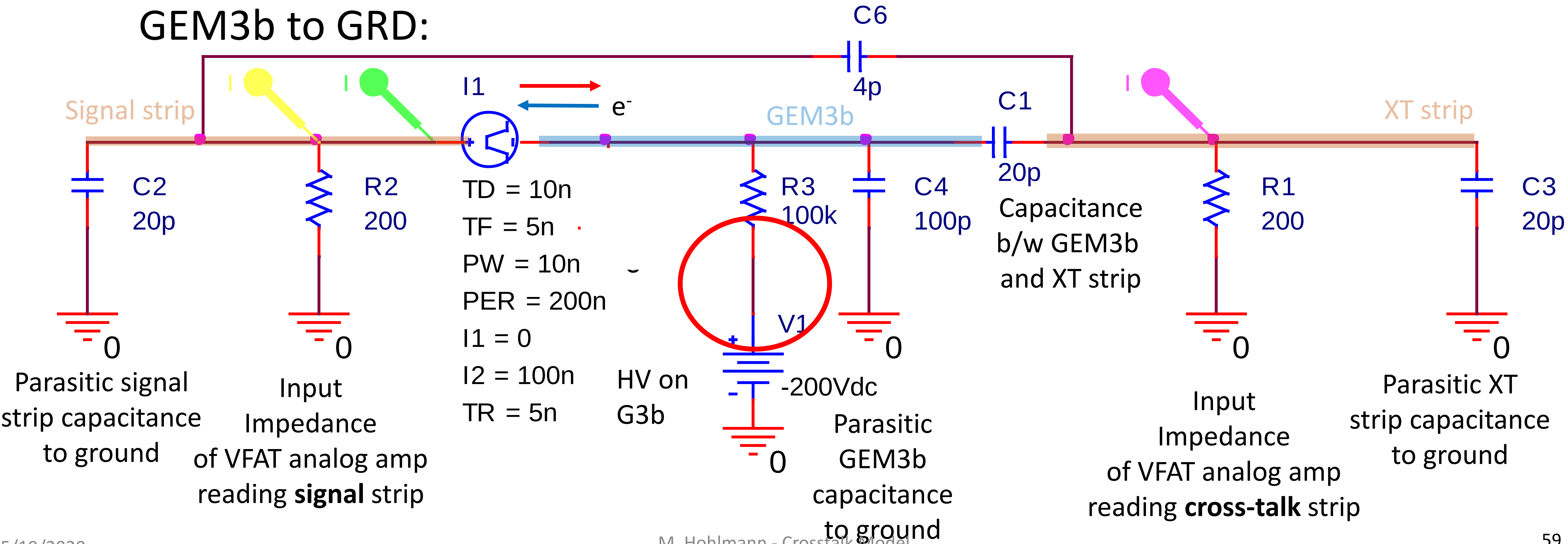
Expect ≈ 50% reduction of XT (8mV -> 4 mV),
But not as large as factor 4





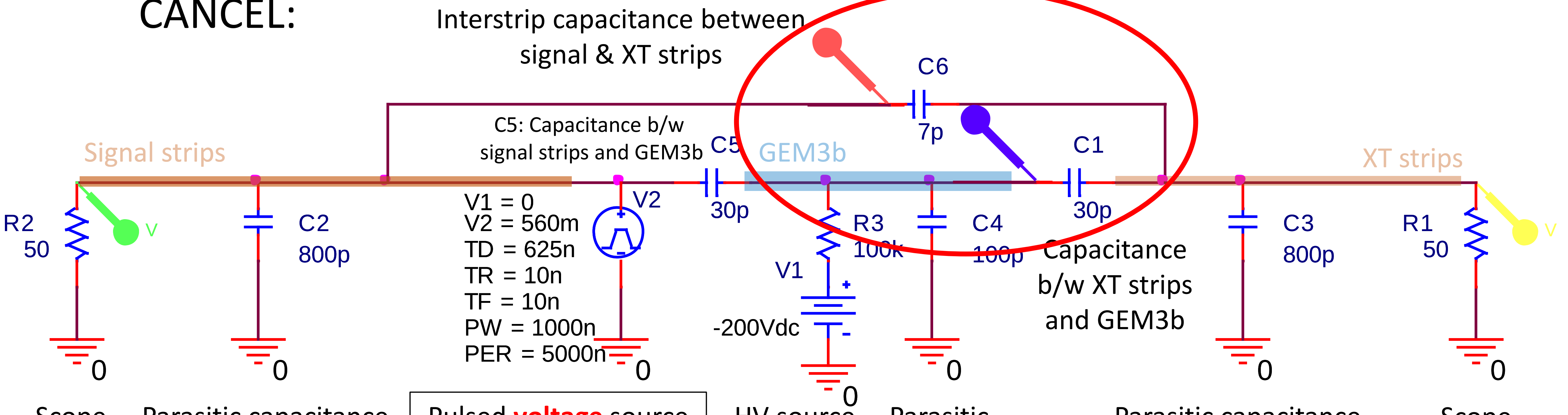
Mitigation strategies: Other ideas?

- Placing any component UPSTREAM of a large protection resistors R3, which would be convenient to do because it could be done with a **single component**, will **NOT** be effective because it will be **in series** with R3 and consequently will **not** reduce the total impedance from GEM3b to GRD:



Mitigation strategies: Overcoming Limitations?

- Unfortunately, we can’t test this with the voltage pulser because in this case the two cross-talk currents have the same polarity and do NOT CANCEL:



Scope input impedance (matched)

Parasitic capacitance of 128 signal strips connected via S2H2P2L* to ground (measured)

Pulsed **voltage** source producing pulse with 560mV amplitude, 10ns rise and fall time, 1000ns pulse width

HV source via protection resistor

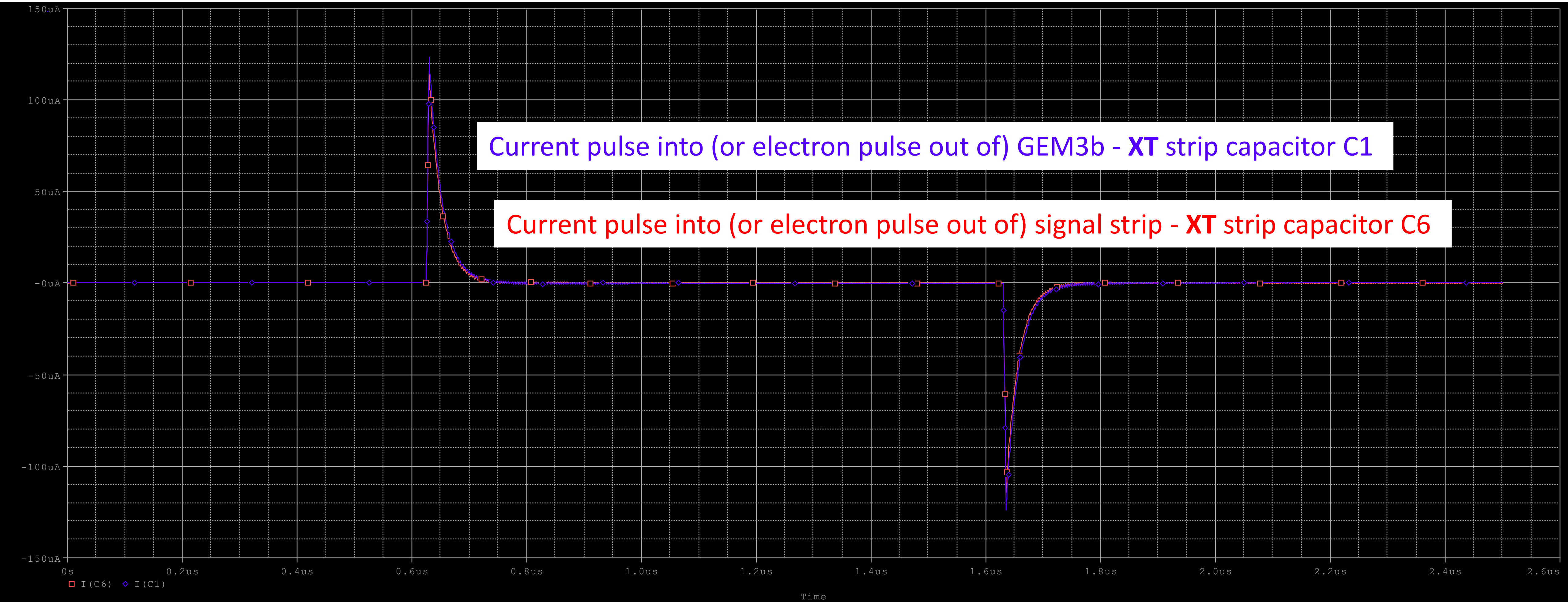
Parasitic GEM3b HV segment capacitance to ground

Parasitic capacitance of 128 XT strips connected via S2H2P2L* to ground (measured)

Scope input impedance (matched)

* “Strip to Hirose to Panasonic to LEMO” adapter

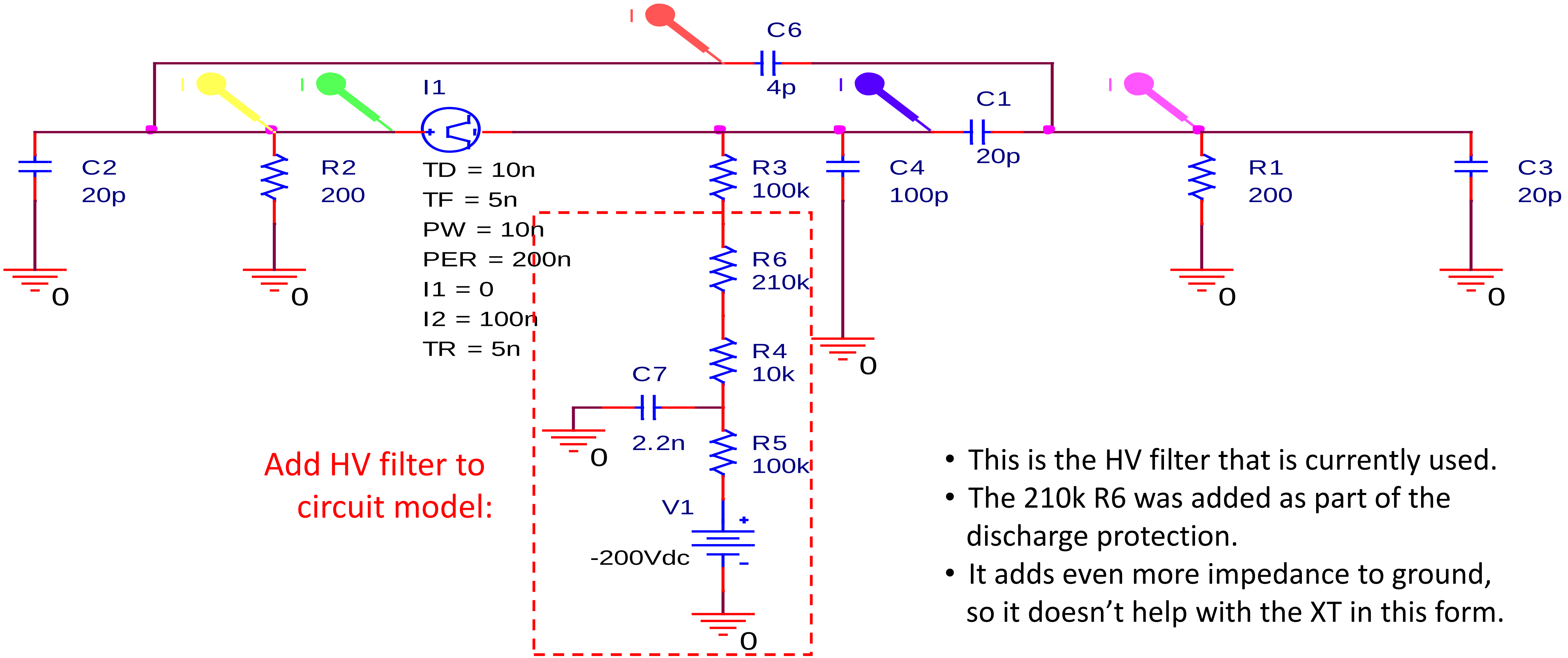
Mitigation strategies: Overcoming Limitations?



Main observation: The two XT contributions have same polarity and do not cancel out. The net XT current is not zero!

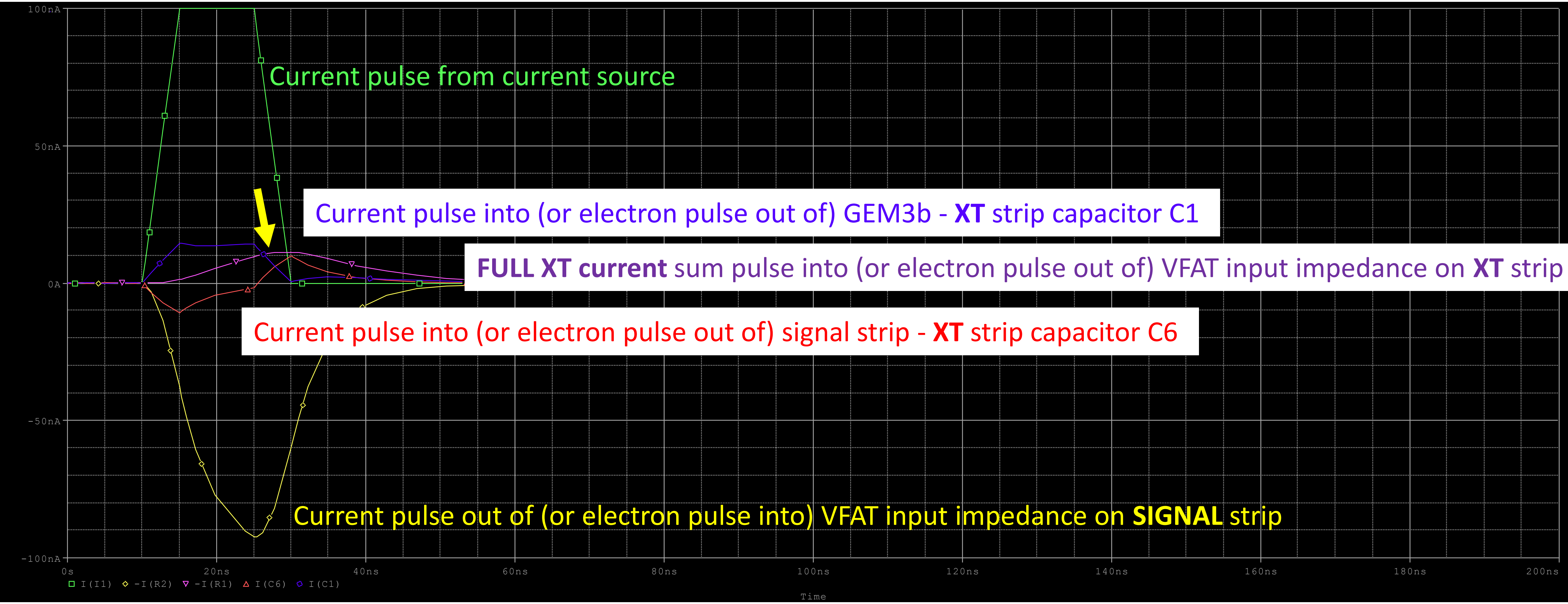
Mitigation strategies: Use HV filter?

- One example of adding something upstream of R3 is the HV filter:



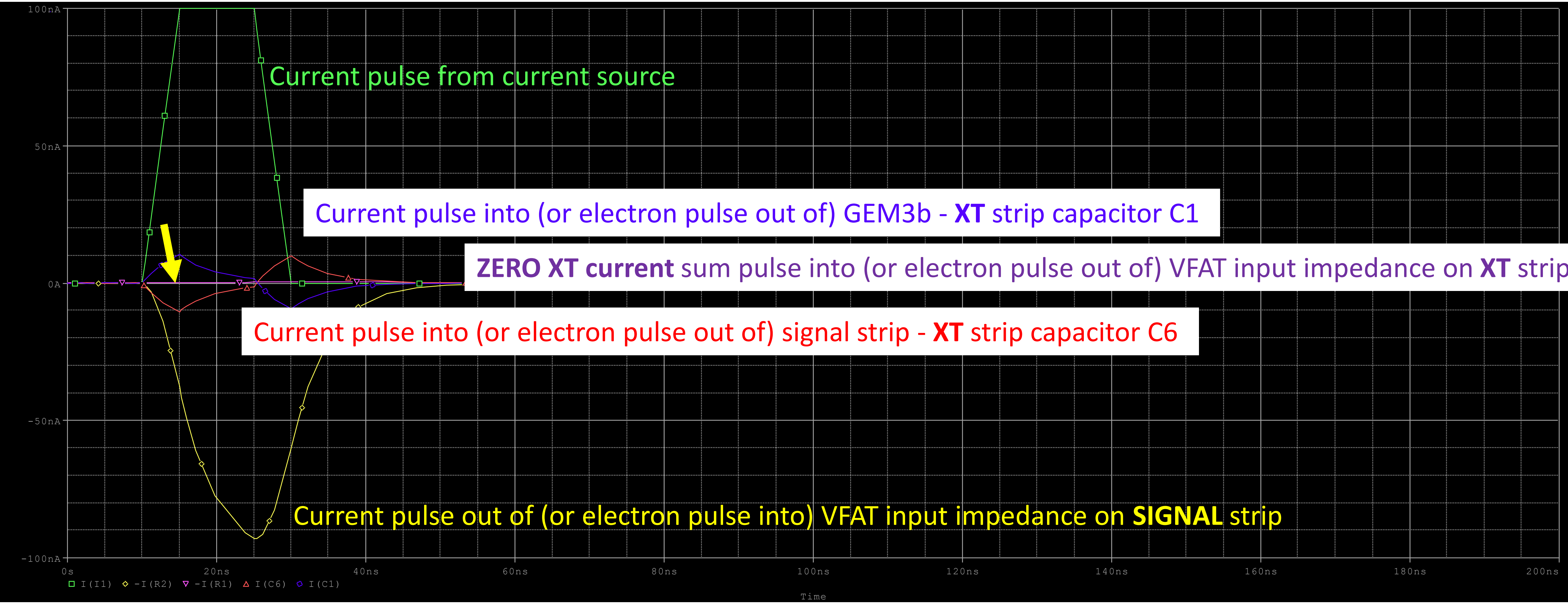
- This is the HV filter that is currently used.
- The 210k R6 was added as part of the discharge protection.
- It adds even more impedance to ground, so it doesn't help with the XT in this form.

Mitigation strategies: Overcoming Limitations?



Main observation: The two XT contributions do not cancel out. The HV filter doesn't help the XT. But at least it doesn't make it worse.

Mitigation strategies: Overcoming Limitations?



Main observation: The two XT contributions have opposite polarity and **cancel out**. The net XT current is zero! The signal current is unaffected.