Cascaded Vernier Time-to-Digital Converter: Toward Integration in an Array

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Guillaume Théberge-Dupuis, Robin Scarpellini, Tommy Rossignol, Nicolas Roy, Raffaele Aaron Giampaolo, Guillaume Giroux, Simon Carrier, Serge A. Charlebois, Jean-François Pratte

Fonds de recherche sur la nature et les technologies Québec
INSTITUT QUANTIQUE
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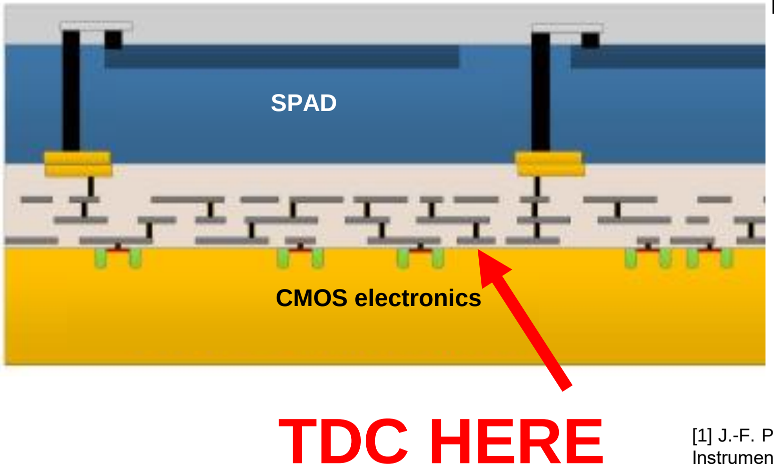
UdS

Precise time of detection for each pixel in the Photon-to-Digital Converter

- Quantum Key Distribution (QKD)
- Time-of-Flight Positron Emission Tomography (ToF-PET)
- Time-of-Flight Computed Tomography (ToF-CT)
- Targeted precision < 10 ps FWHM

[1]



~ 4000 SPADs

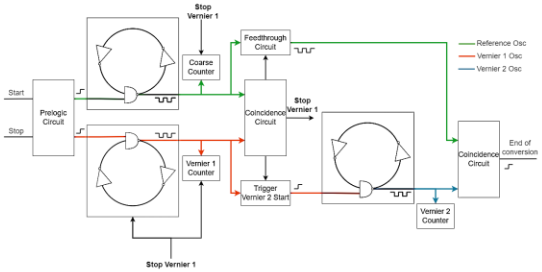
~ 1000 TDCs

The other approach and the 3D integration were presented in Frédéric Vachon's poster (P2.09)

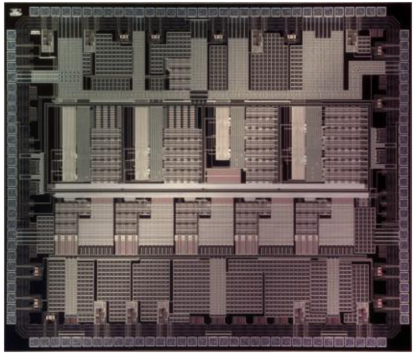
Guillaume.Theberge-Dupuis@USherbrooke.ca

[1] J.-F. Pratte *et al.*, "3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works," *Sensors (Basel)*, vol. 21, no. 2, p. 598, Jan. 2021, doi: 10.3390/s21020598.

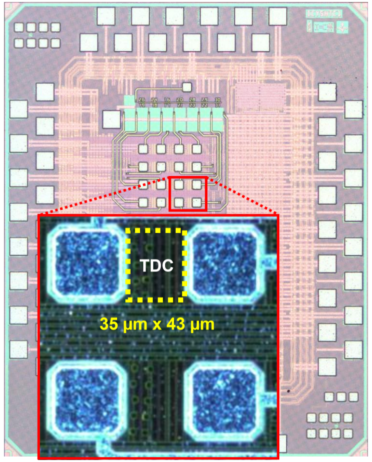
Outline



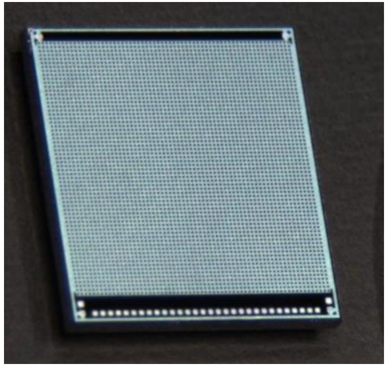
Standalone TDC



4 quench-SPAD pairs with a TDC (×8)



4096 quench-SPAD pairs in 5x5 mm^2 array



The Architecture

The Proof of Concept

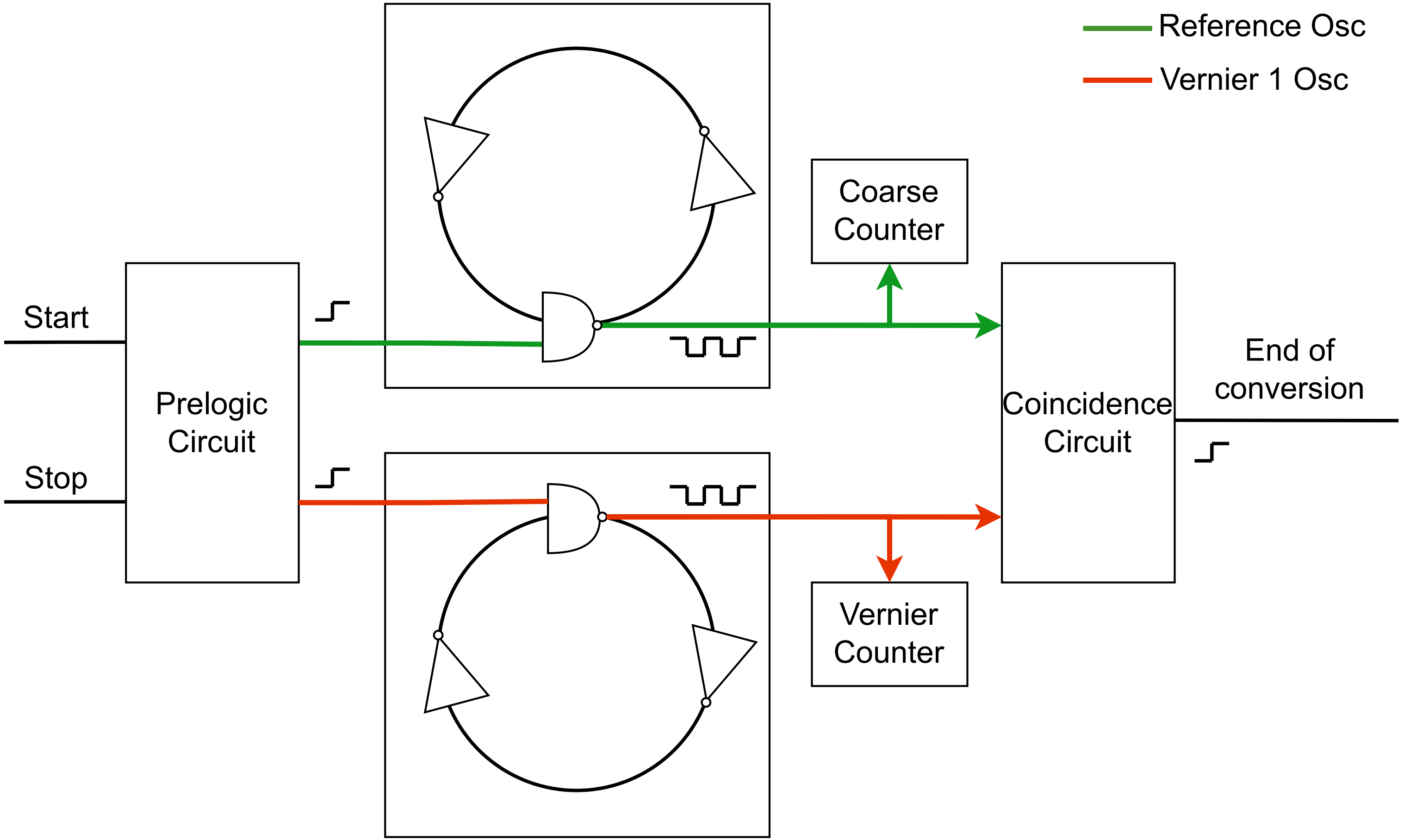
Test Chip Array

Full Array Integration (*Future Work*)

Guillaume.Theberge-Dupuis@USherbrooke.ca

The Cascaded Vernier TDC Architecture

The Vernier TDC – Schematic



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Ring Oscillators Vernier-based TDC

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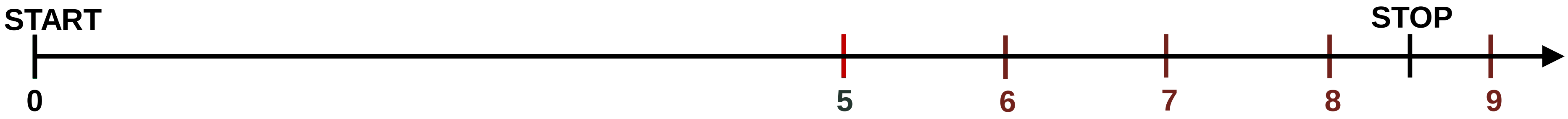

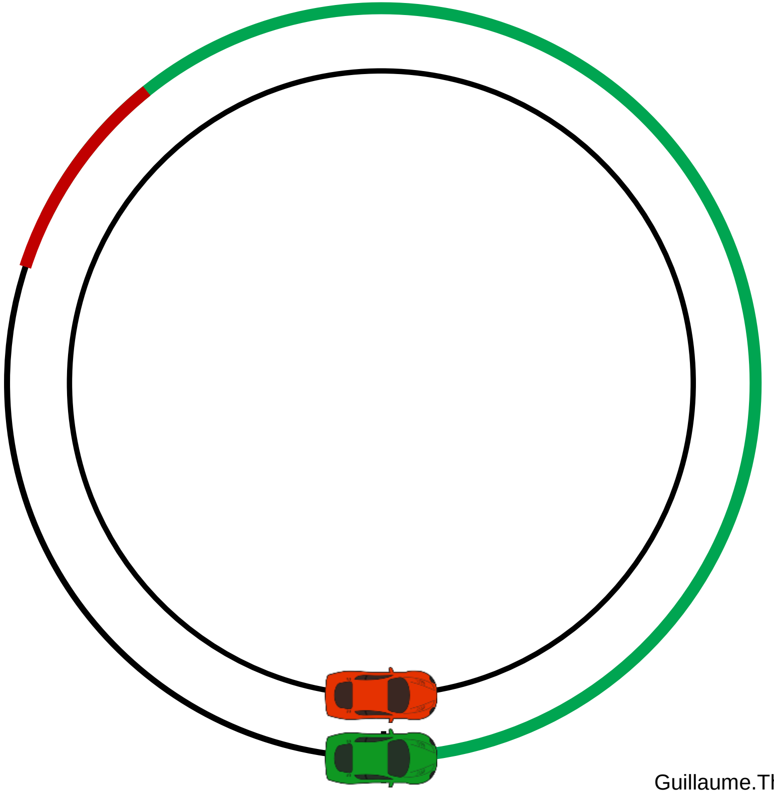

	Period	LSB	Count	Total
Reference car	5 s	+ 5 s	1	5 s
Fast car	4 s	+ 1 s	4	4 s
Vernier 1				9 s

1-Vernier with 0.2 s LSB

	Period	LSB	Count	Total
Reference car	5 s	+ 5 s	1	5 s
Fast car	4.8 s	+ 0.2 s	18	3.6 s
1-Vernier			19	8.6 s

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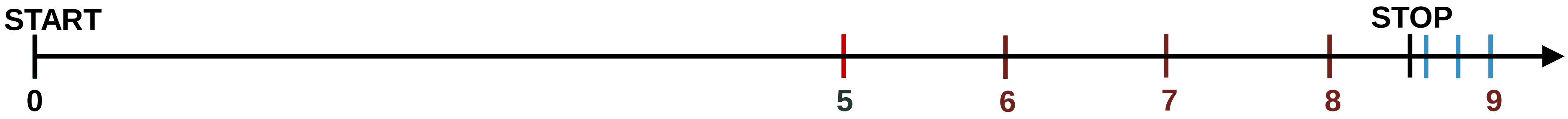
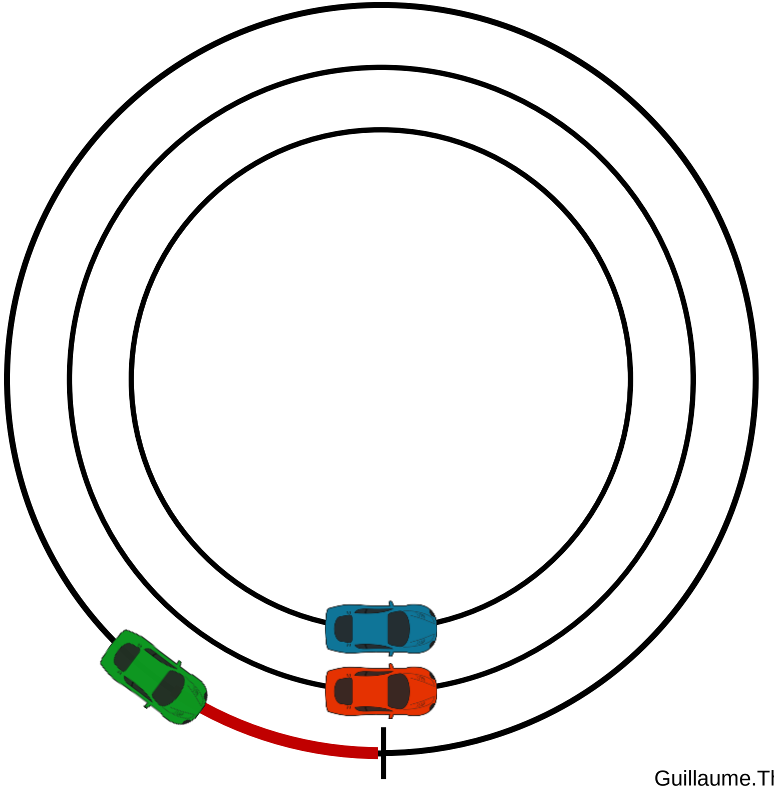
Cascaded Ring Oscillators Vernier-based TDC





	Period	LSB	Count	Total
Reference car	5 s	+ 5 s	1	5 s
Fast car	4 s	+ 1 s	4	4 s
Slow car	5.2 s	- 0.2 s	3	- 0.6 s
Total			8	8.4 s

1-Vernier equivalent

	Period	LSB	Count	Total
Reference car	5 s	+ 5 s	1	5 s
Fast car	4.8 s	+ 0.2 s	18	3.6 s
1-Vernier			19	8.6 s

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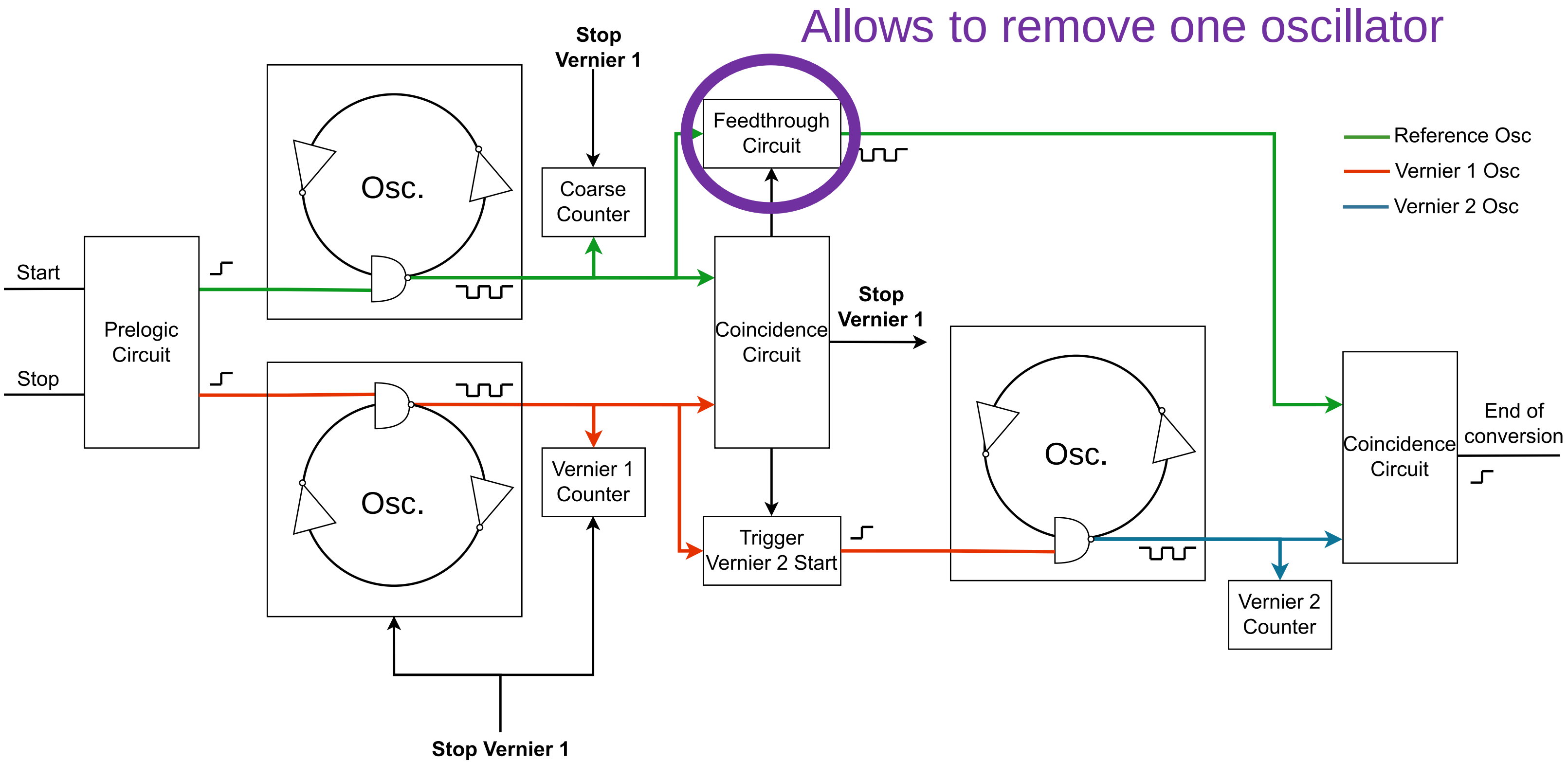
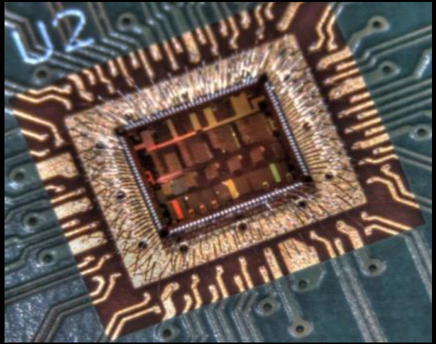
The Cascaded Vernier TDC – Schematic

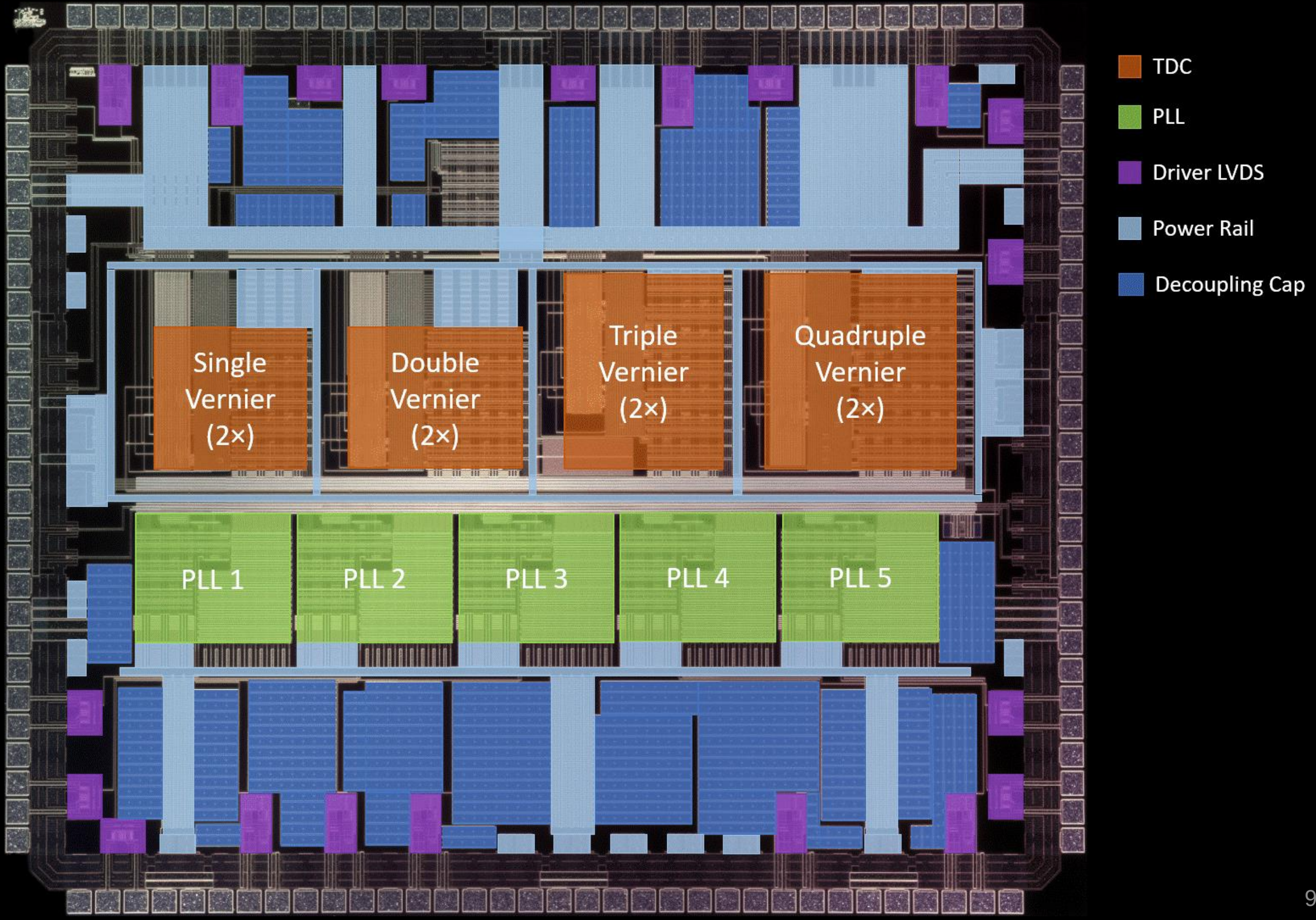


Patent: F. Nolet, N. Roy, J.-F. Pratte et F. Dubois, «Time to Digital Conversion», dec. 2021, publication number: WO/2021/243451.: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2021243451

Implementation in TSMC 180 nm

Area with dummies (in µm²)	
1-Vernier	69 600
2-Vernier	88 700
3-Vernier	100 400
4-Vernier	126 400



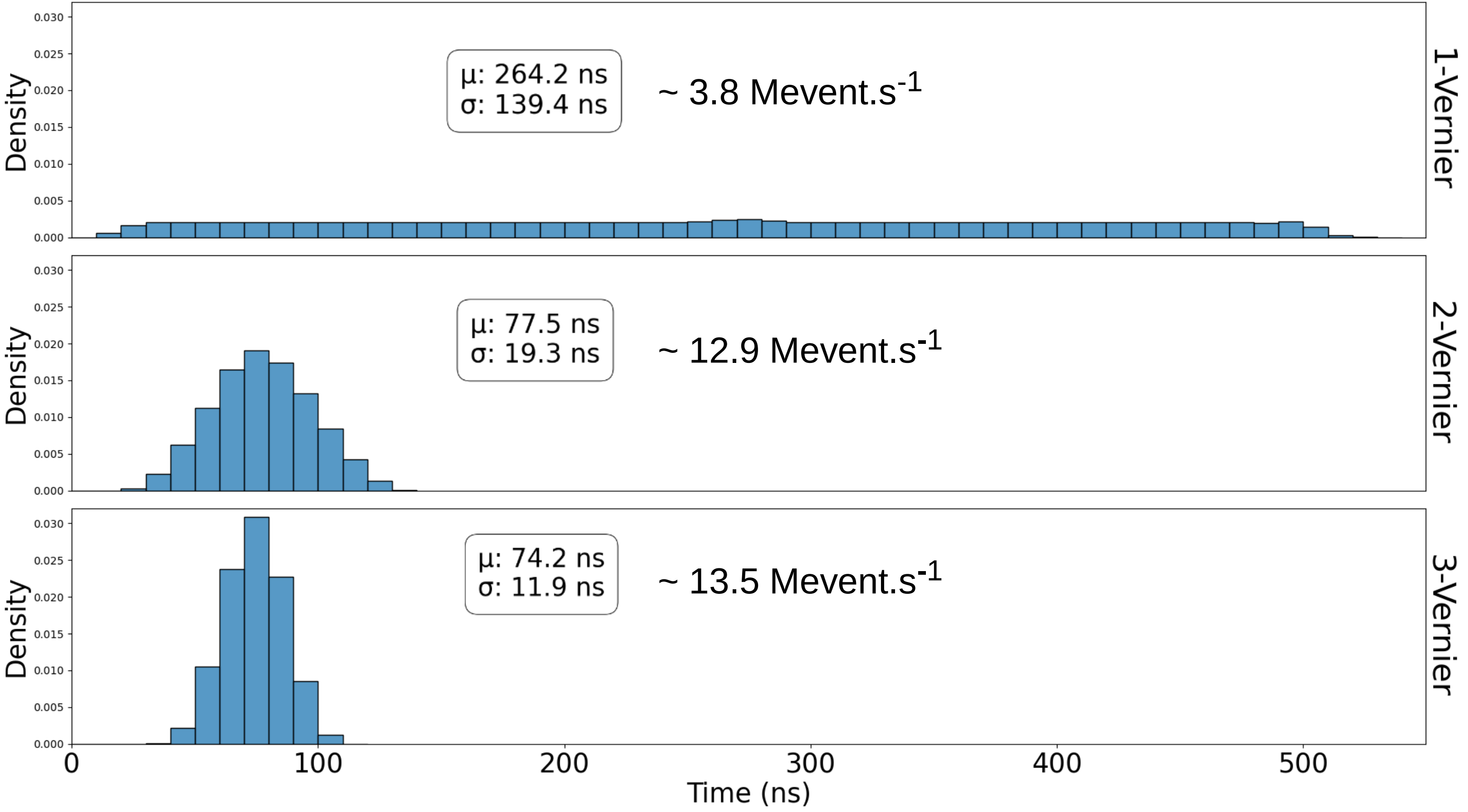


Uncorrelated Measurement – Conversion Time at LSB = 50 ps and Dynamic Range = 20 ns

1-Vernier

2-Vernier

3-Vernier



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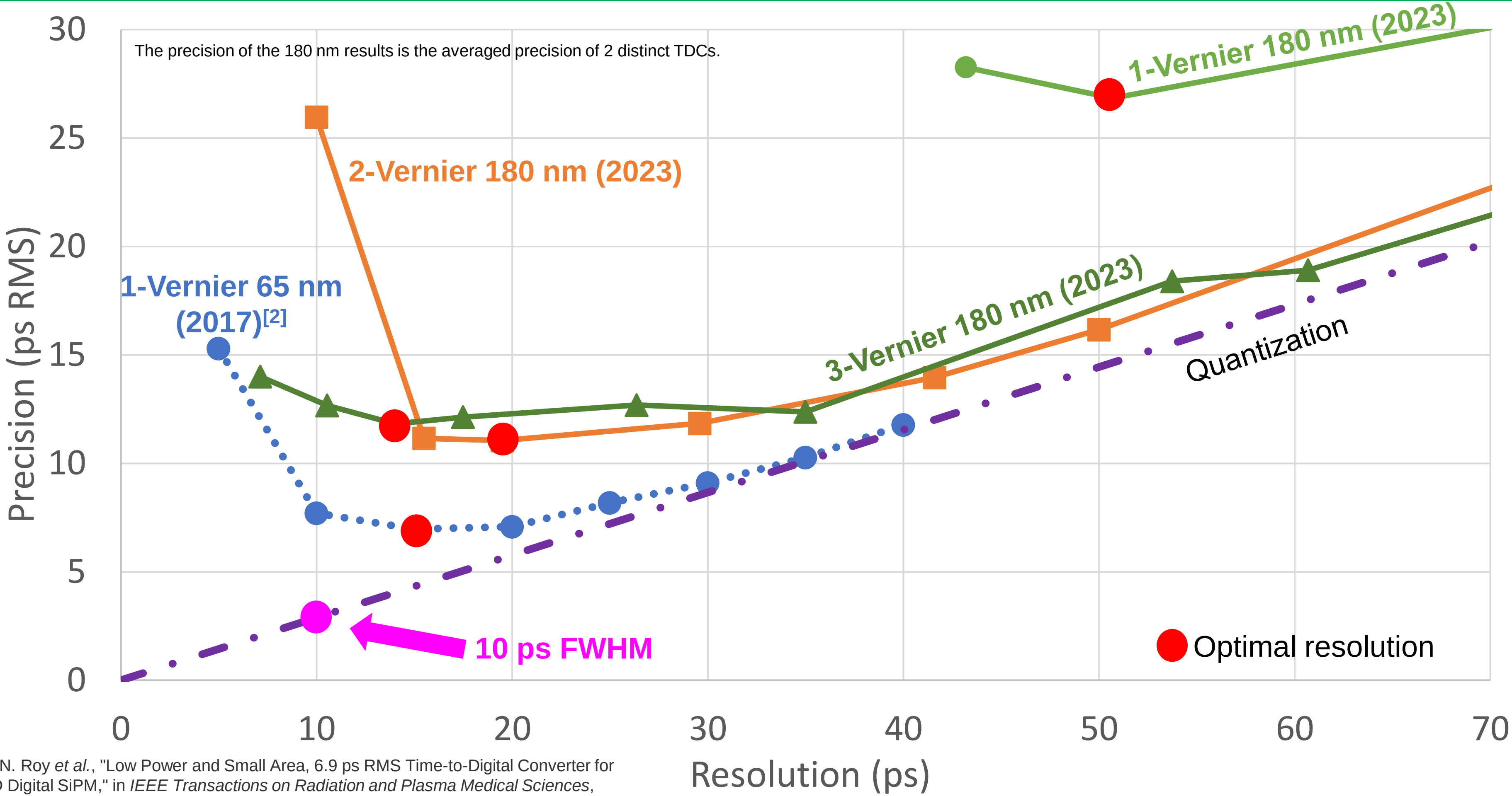
Relation Between Precision and Resolution (65 nm vs 180 nm)



[2] N. Roy *et al.*, "Low Power and Small Area, 6.9 ps RMS Time-to-Digital Converter for 3-D Digital SiPM," in *IEEE Transactions on Radiation and Plasma Medical Sciences*, vol. 1, no. 6, pp. 486-494, Nov. 2017, doi: 10.1109/TRPMS.2017.2757444.

TDC Integration in an Array in 65 nm

The Infamous Effect of Process, Voltage and Temperature

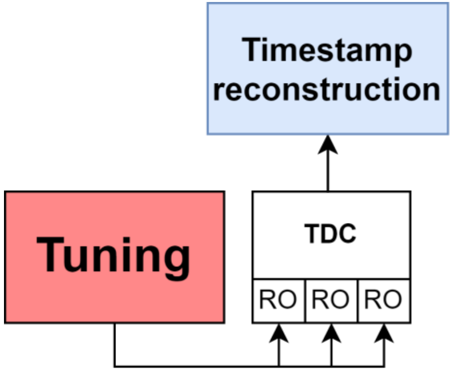
Guillaume.Theberge-Dupuis@USherbrooke.ca

The Control Levers of a Cascaded Vernier TDC

Tuning: Control of the ring oscillator frequency

Timestamp reconstruction: Code-to-time conversion

- Based on the expected ring oscillator frequency
- Based on the measured frequency



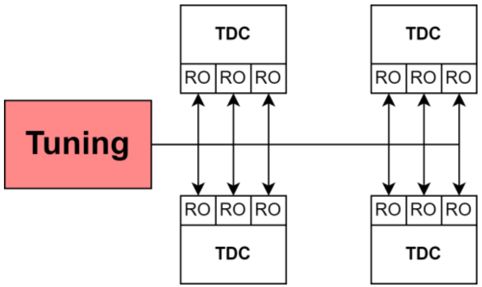
$$\textbf{Timestamp} = Nb_{Coarse} \times (T_{RO_1}) + Nb_{Vernier1} \times (T_{RO_1} - T_{RO_2}) + Nb_{Vernier2} \times (T_{RO_3} - T_{RO_1})$$

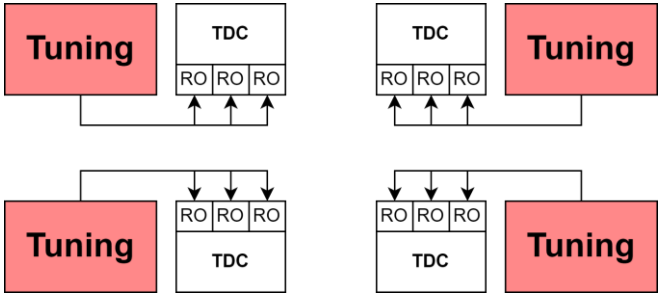
LSB Variation Mitigation Techniques

Global

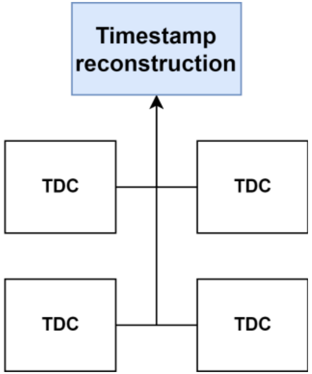
Local

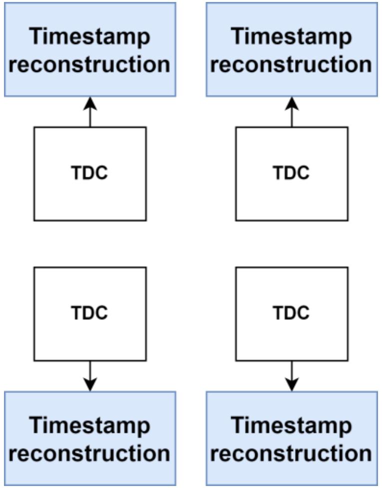
Tuning





Timestamp reconstruction





The Simulation Setup

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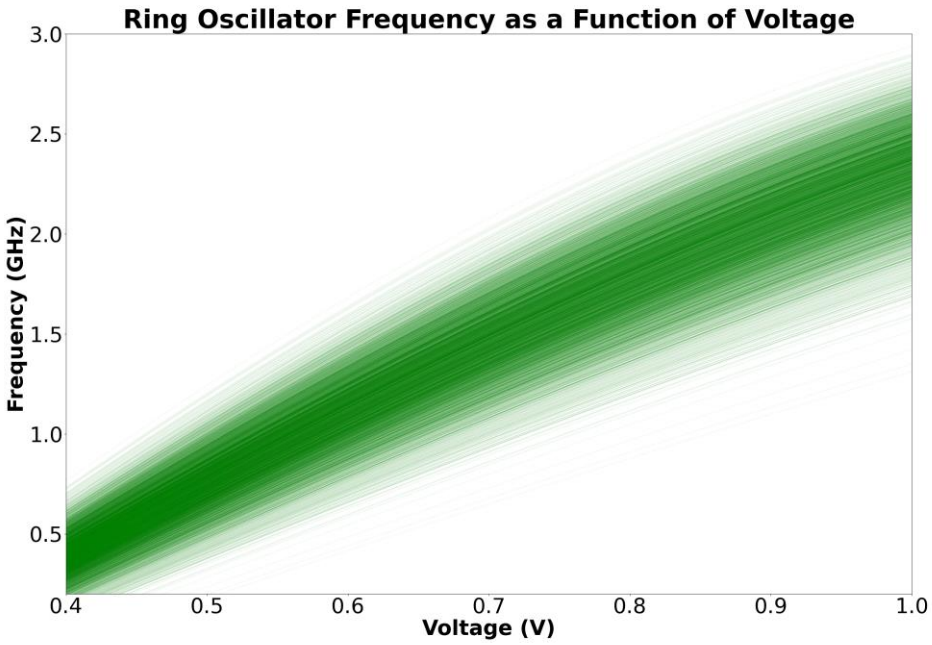
1. Ring Oscillator model based on Monte-Carlo simulations
2. Generated a pool of 20k TDCs made of 3 ROs with random process variation without any jitter
3. Characterize the pool with each mitigation techniques



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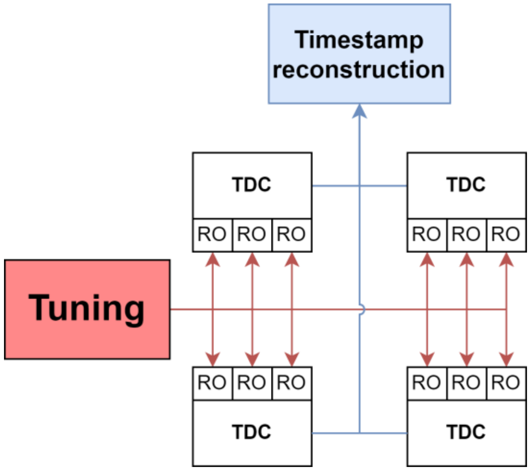
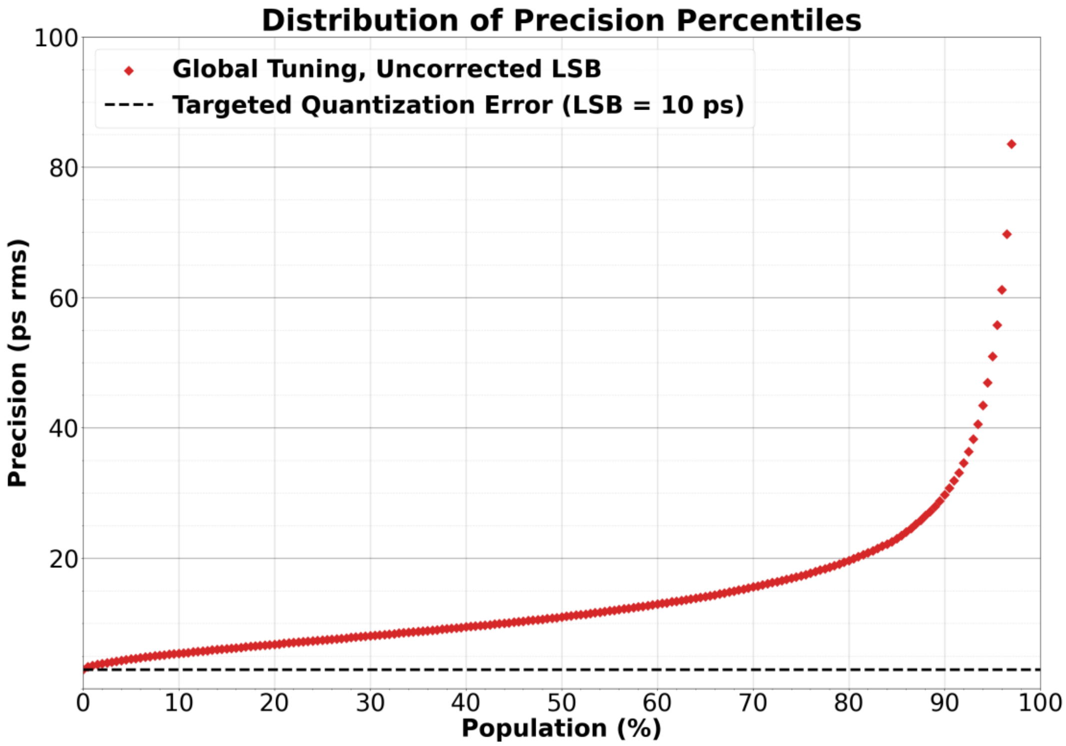
Global Tuning – Expected LSB

- Equivalent to 1 PLL per ring oscillator frequency





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Impact of Process Variation on Precision (Simulation - No Jitter)

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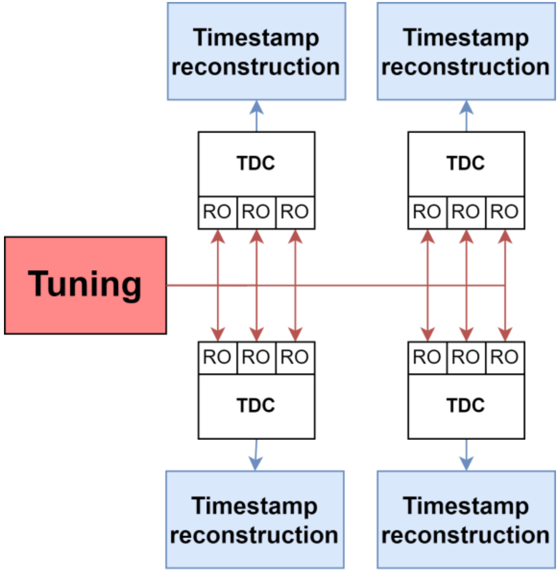
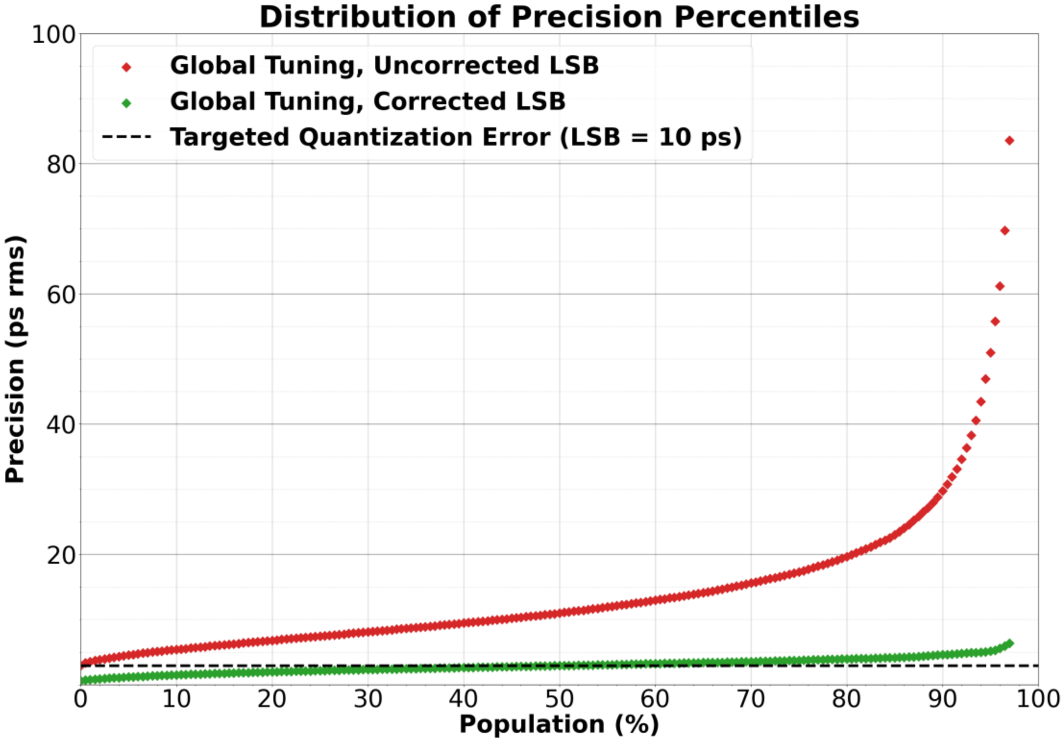
Global Tuning – Measured LSB

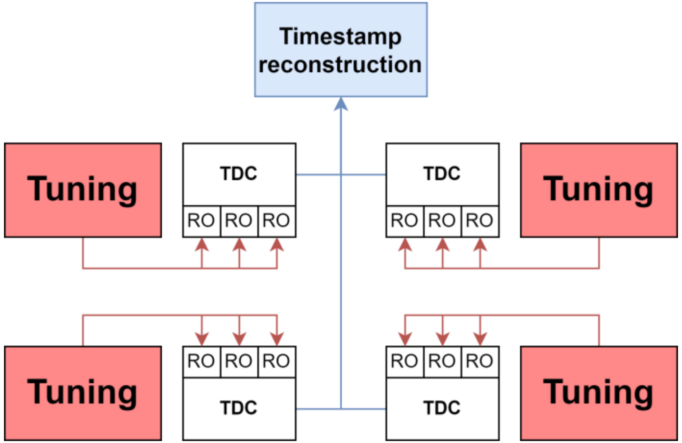
- Improve the average precision by a factor 4.5

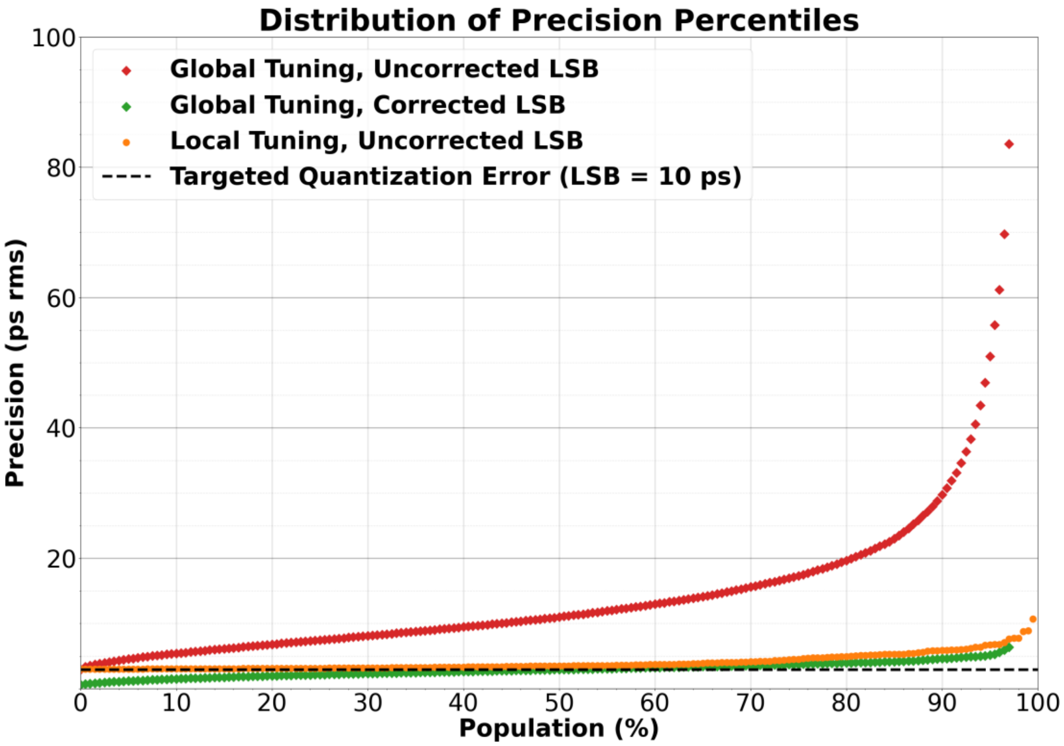




Local Tuning – Expected LSB

- Equivalent to 1 PLL per RO per TDC





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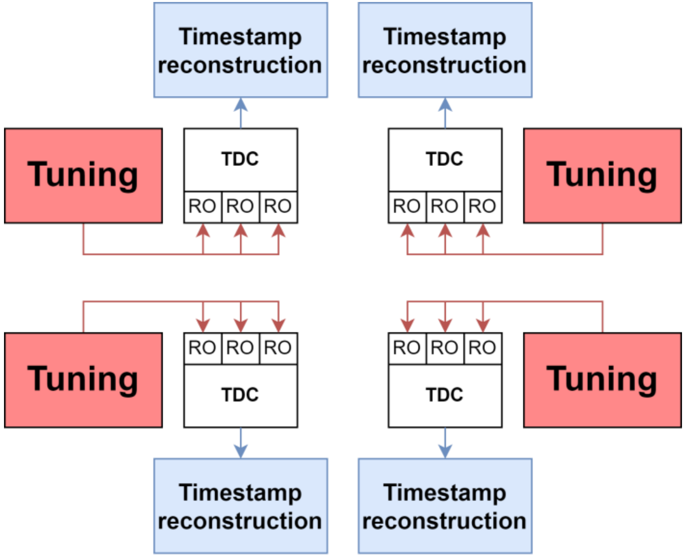
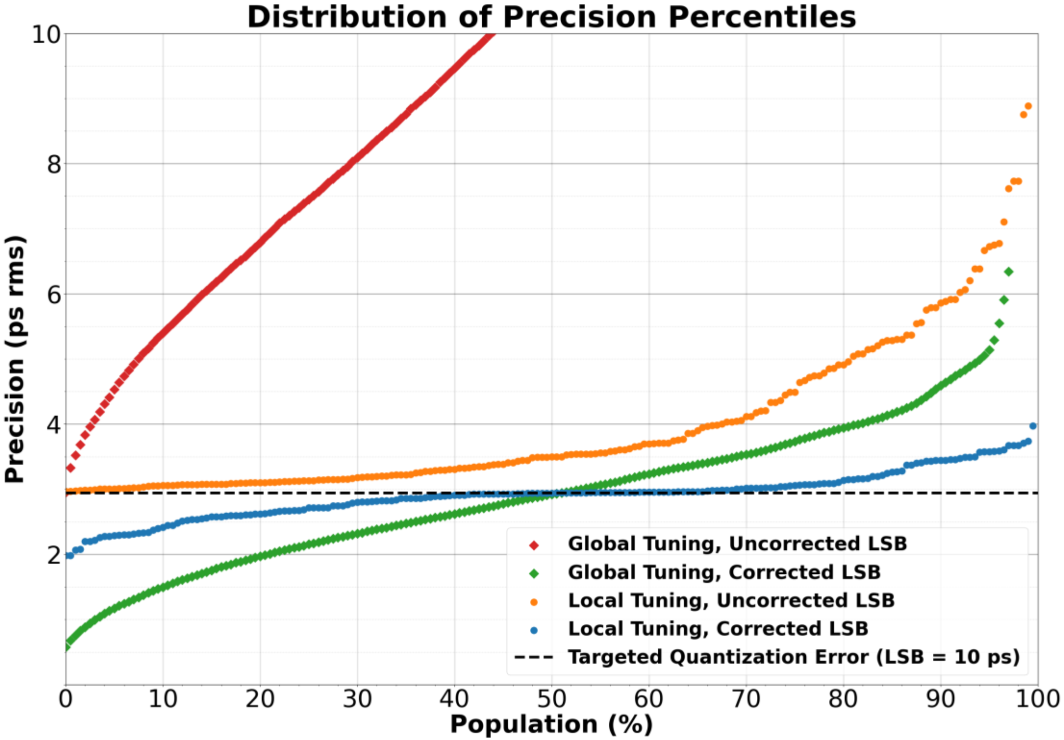
UdS

Local Tuning – Measured LSB





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UDS

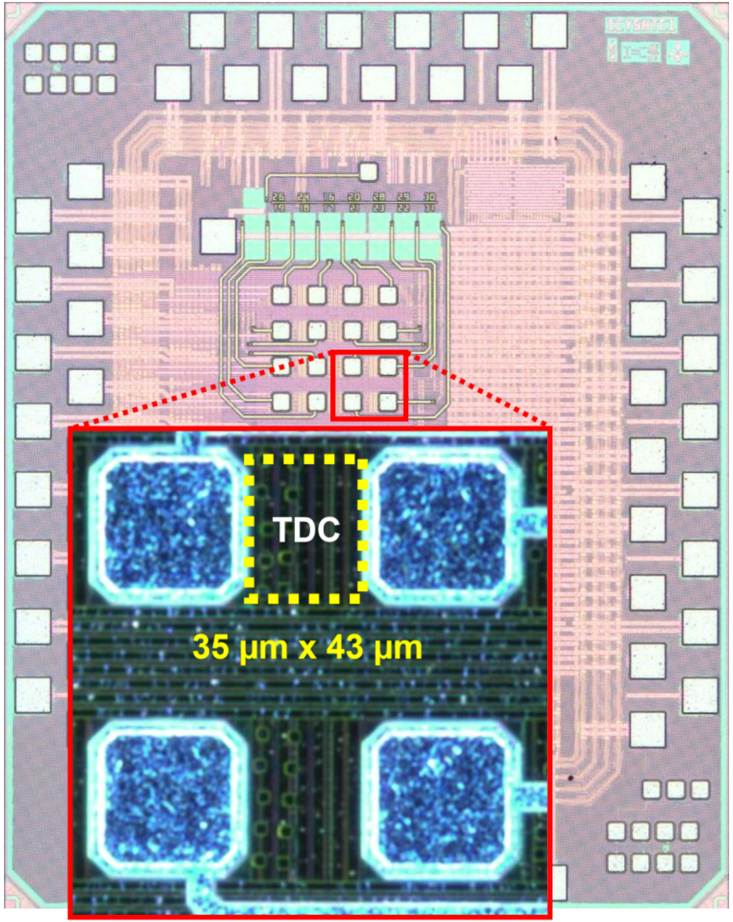
2 Vernier-stages, 3 oscillators

Individually configurable TDC

- Digital configuration
- Custom tuning and correction scheme

1 TDC for 4 quench-SPAD pairs

- Sharing TDC frees up more space for other circuits



Guillaume.Theberge-Dupuis@USherbrooke.ca

We developed a new TDC architecture that improves

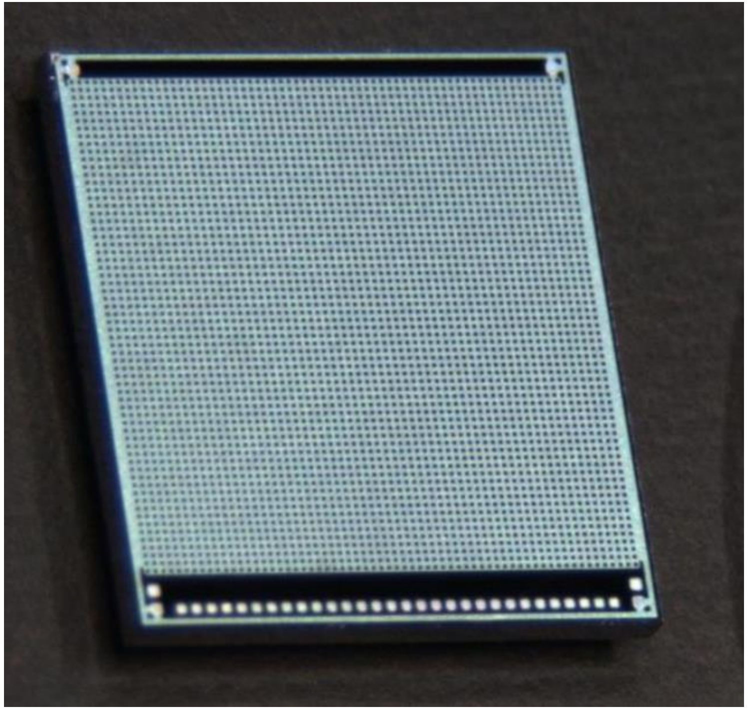
- Conversion time
- Precision

The PVT in an array adds some challenges

We propose a fully digitally controlled TDC

- Can be individually configured to mitigate PVT variation
- The test campaign will begin this summer

The next step is to design the 5×5 mm^2 array with 4096 quench-SPAD pairs and 1024 TDCs



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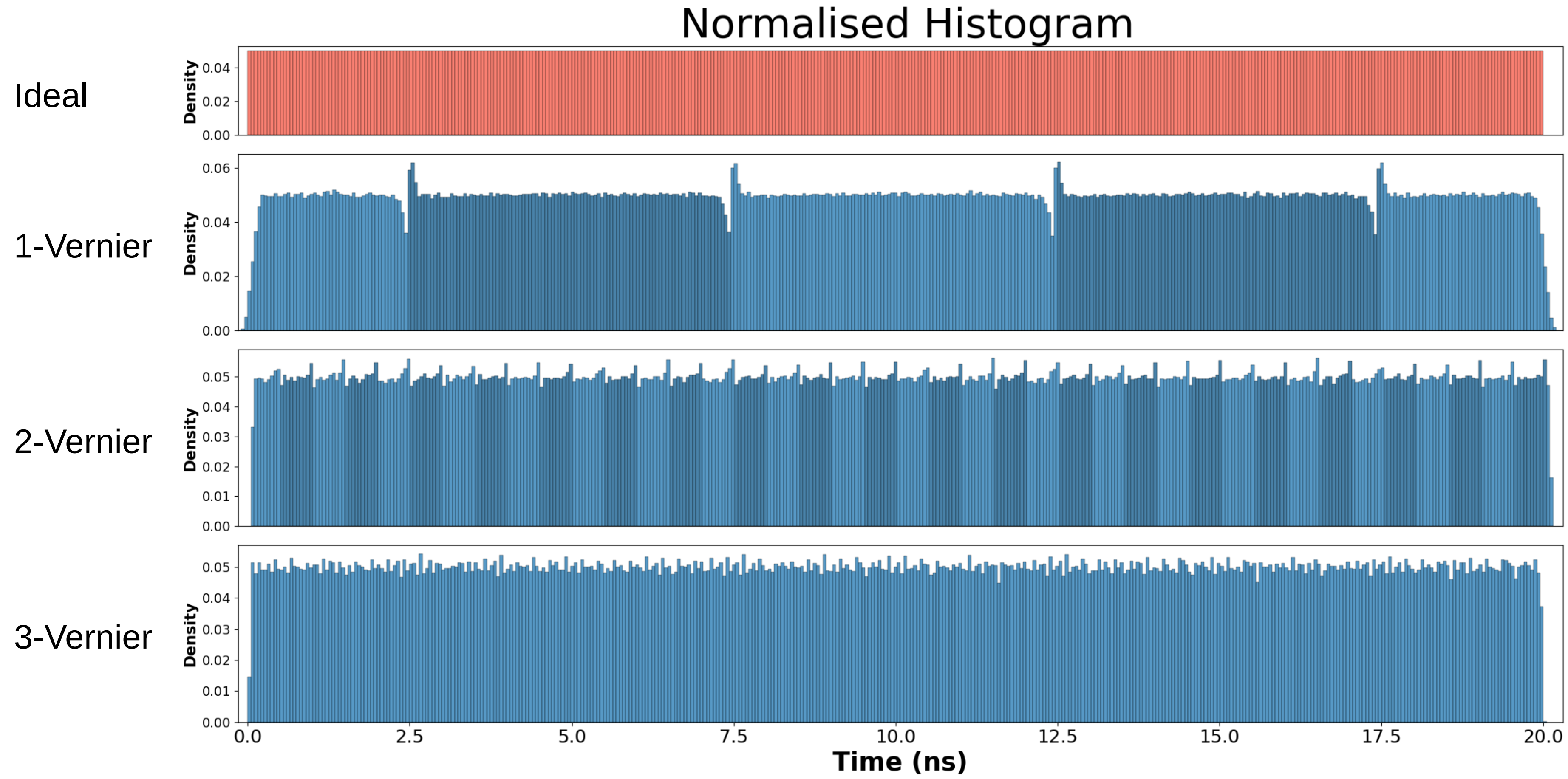
Thank you

Uncorrelated Measurement (180 nm) – Histogram at LSB = 50 ps and Dynamic Range = 20 ns



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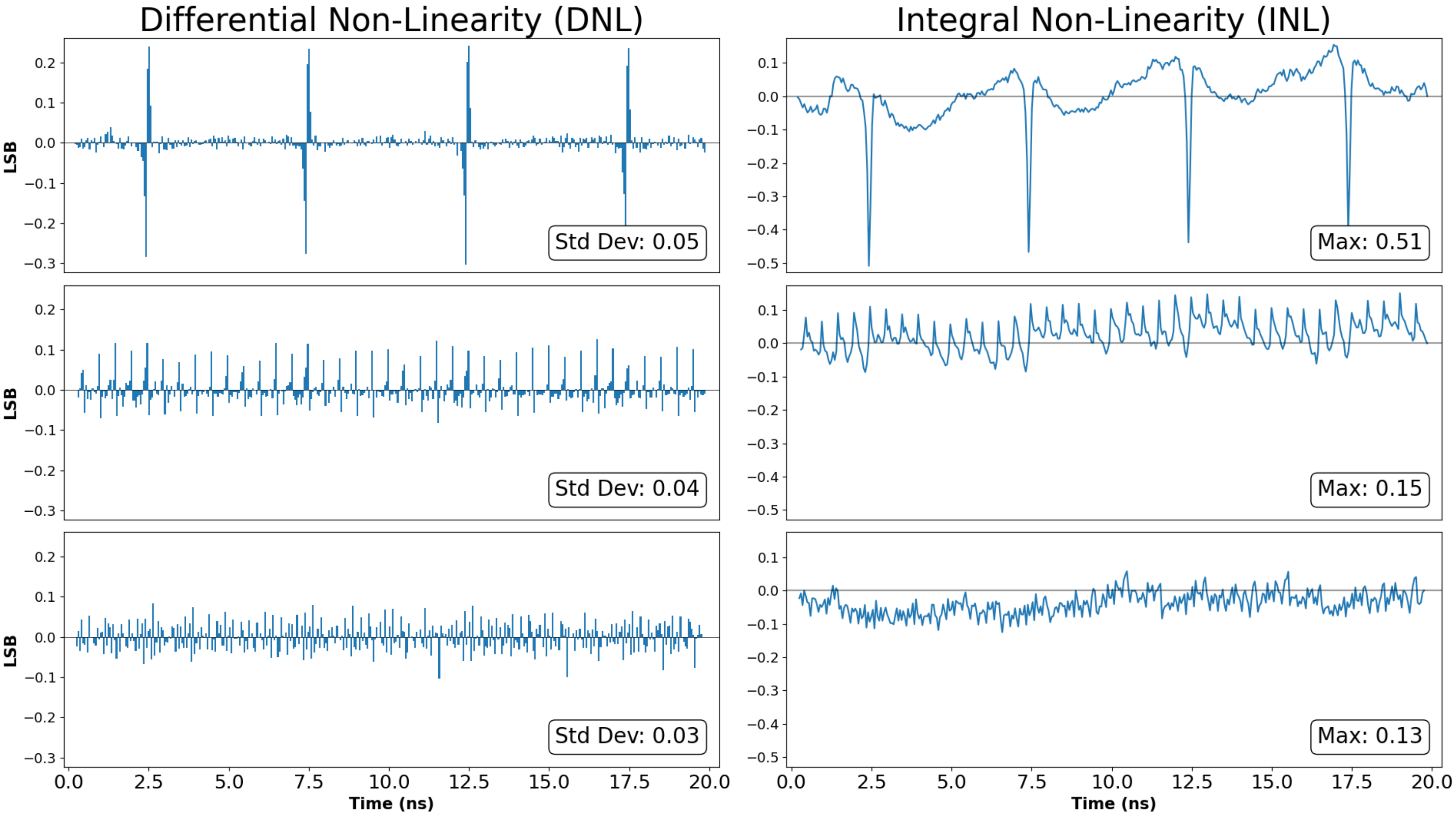
Uncorrelated Measurement (180 nm) – Linearity at LSB = 50 ps and Dynamic Range = 20 ns

1 Vernier

2-Vernier

3-Vernier



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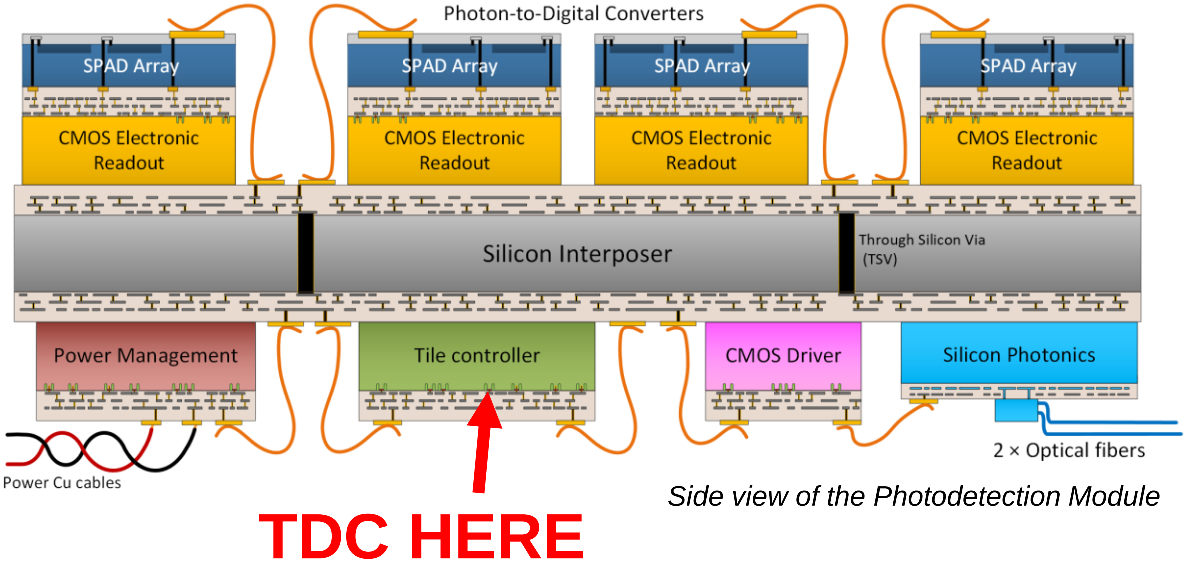
Tile level integration

Precise time of detection for each Photon-to-Digital Converter

- Neutron imaging
- Particle physics experiments (nEXO, ARGO, etc.)
- Target resolution ≈ 100 ps FWHM



Side view of the Photodetection Module

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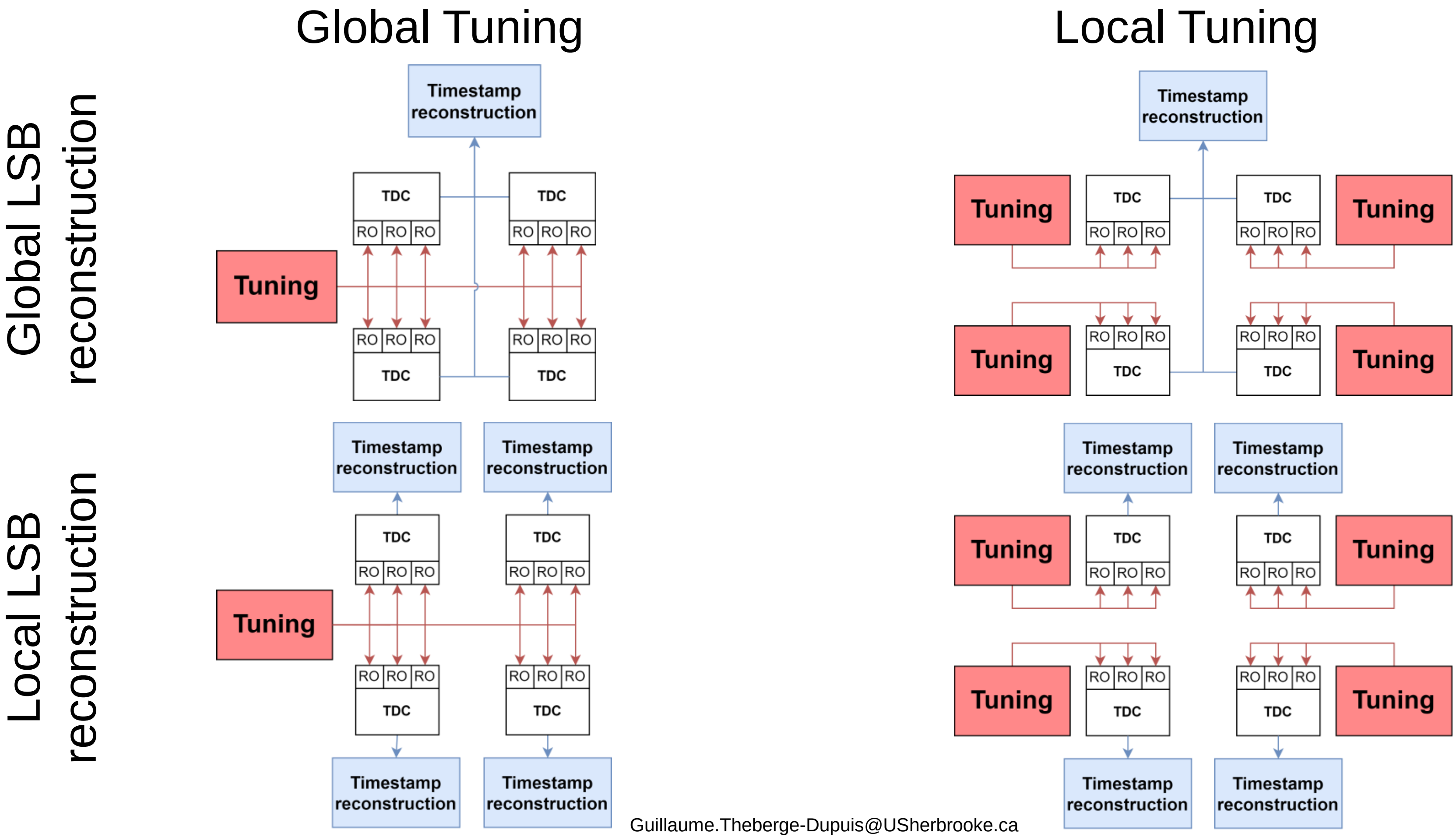
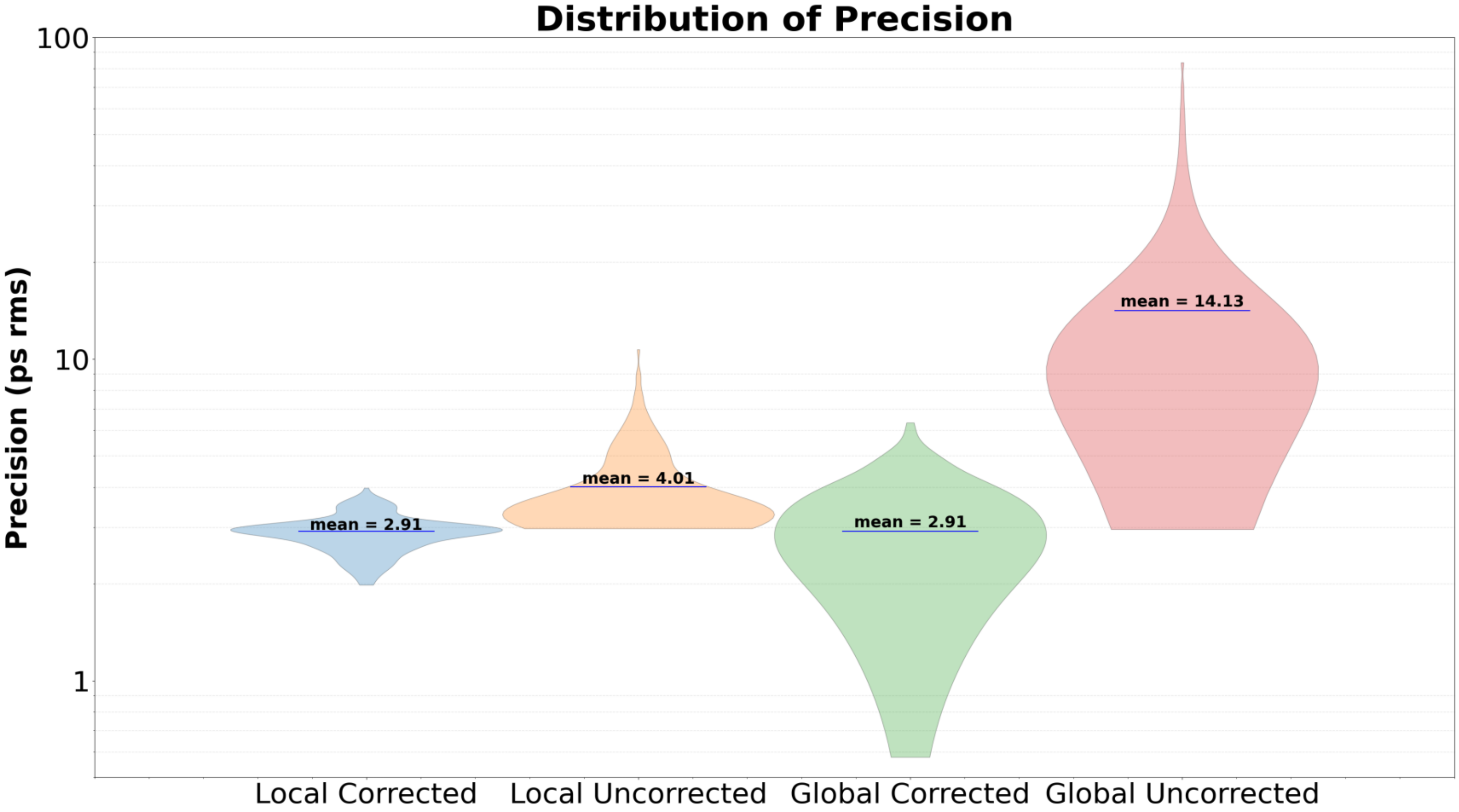
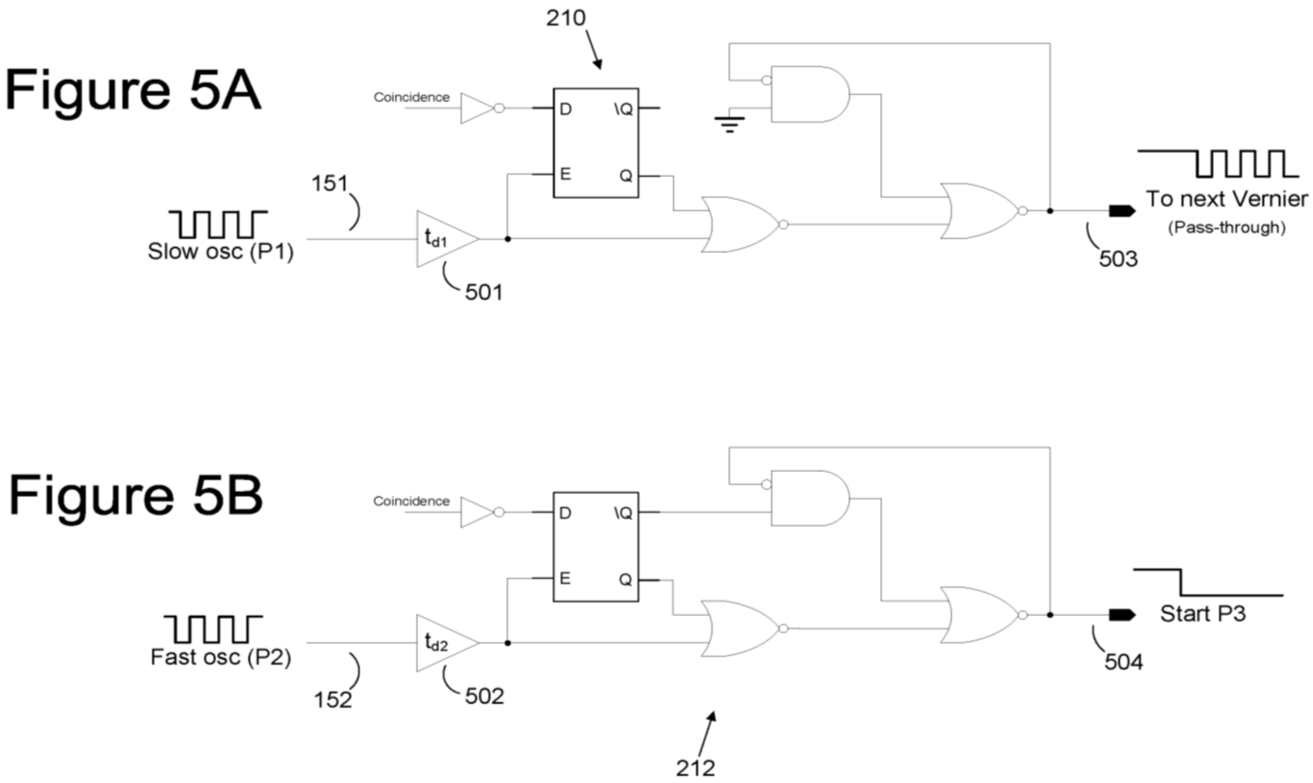

Global Tuning
Local Tuning
Global LSB reconstruction
Local LSB reconstruction
Timestamp reconstruction
TDC
RO
Tuning

Precision for Different Tuning and Correction Schemes



Feedthrough Circuit Schematic



Patent: F. Nolet, N. Roy, J.-F. Pratte et F. Dubois, «Time to Digital Conversion», dec. 2021, publication number: WO/2021/243451.: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2021243451

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