SiGe BiCMOS electronics for ultrafast particle detection

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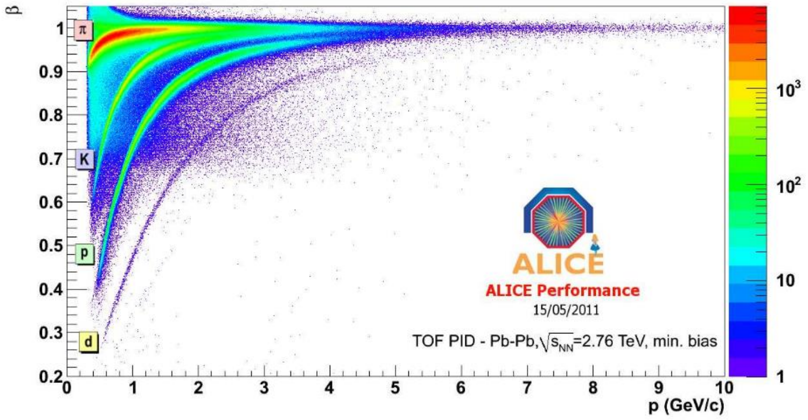
ACES Workshop 2020

Summary

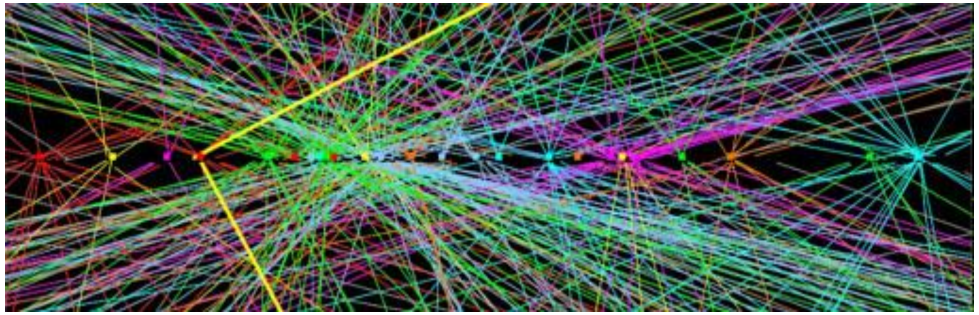
1. **SiGe HBTs for fast, low power timing measurement.**
2. SiGe BiCMOS technologies.
3. Applications in HEP.
4. Radiation hardness.

Precise timing measurement in HEP

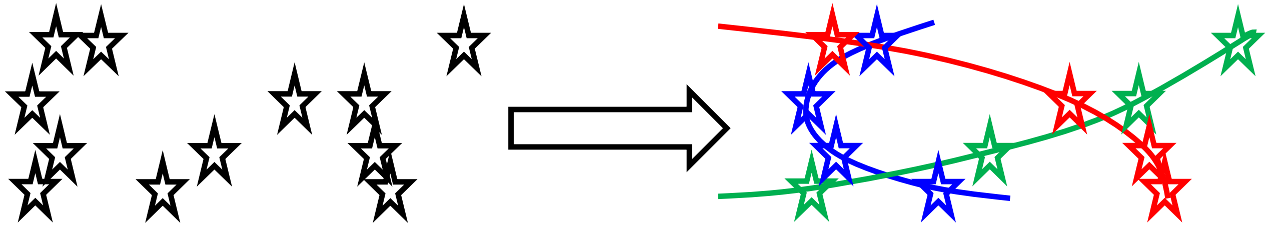
Particle identification



Pile-up suppression

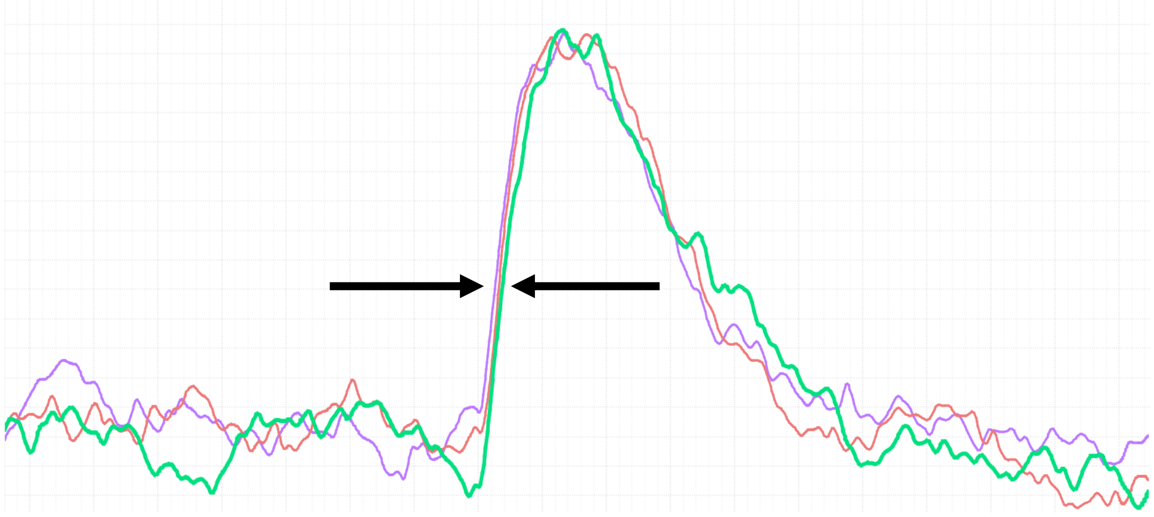


Support for fast tracking

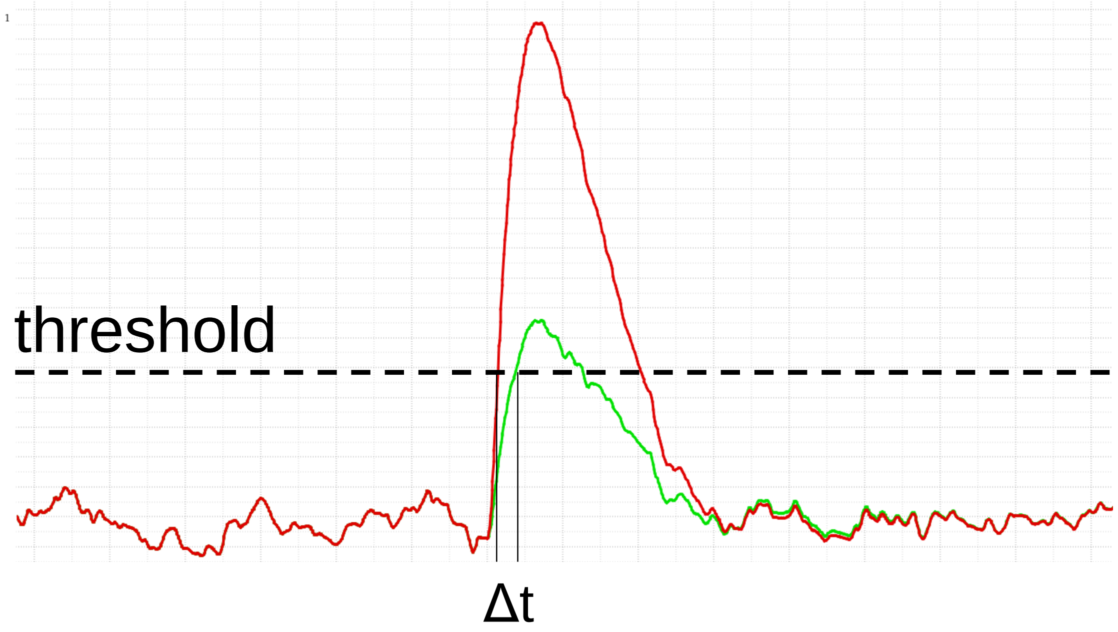


Electronic contribution to the time resolution

Time jitter



Time walk



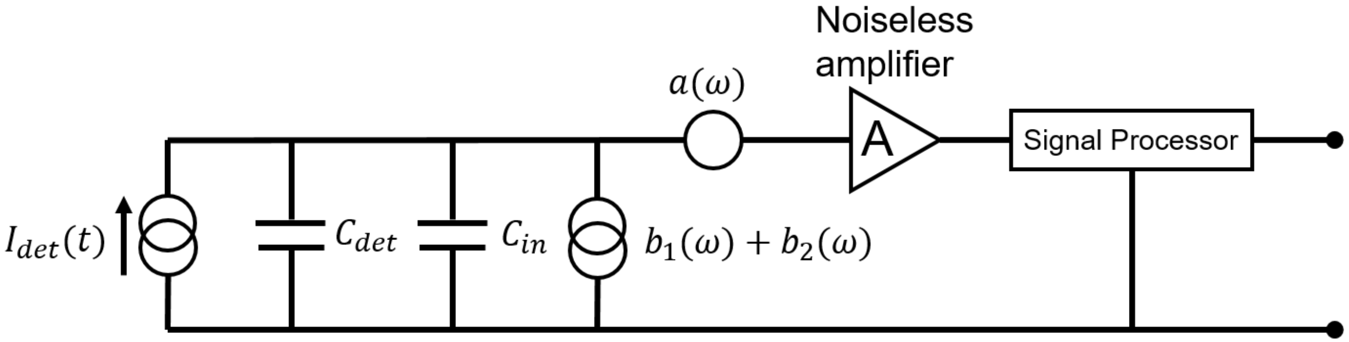
Fast integration

$$\sigma_t = \frac{\sigma_V}{dV/dt} \cong \frac{ENC}{I_{Ind}}$$

$$\sigma_t(compensation\ technique)$$

$$\sigma_t \propto ENC$$

Equivalent Noise Charge: device comparison

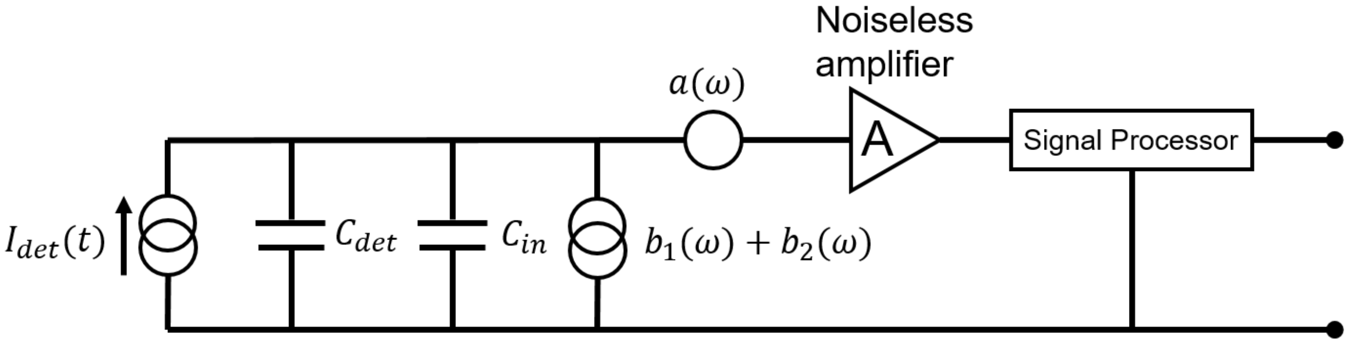


$$ENC^2 = A_1 \frac{a_W}{\tau_M}(C_{det} + C_{in})^2 + A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2 + \cancel{A_3(b_1 + b_2)}\tau_M$$

$$\boldsymbol{\tau_M \sim 1\, ns}$$

How do MOS-FET and BJT compare in terms of noise?

Equivalent Noise Charge: device comparison



$$ENC^2 = A_1 \frac{\boxed{a_W}}{\tau_M}(C_{det} + C_{in})^2 + \boxed{A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2} + \cancel{A_3(b_1 + b_2)\tau_M}$$

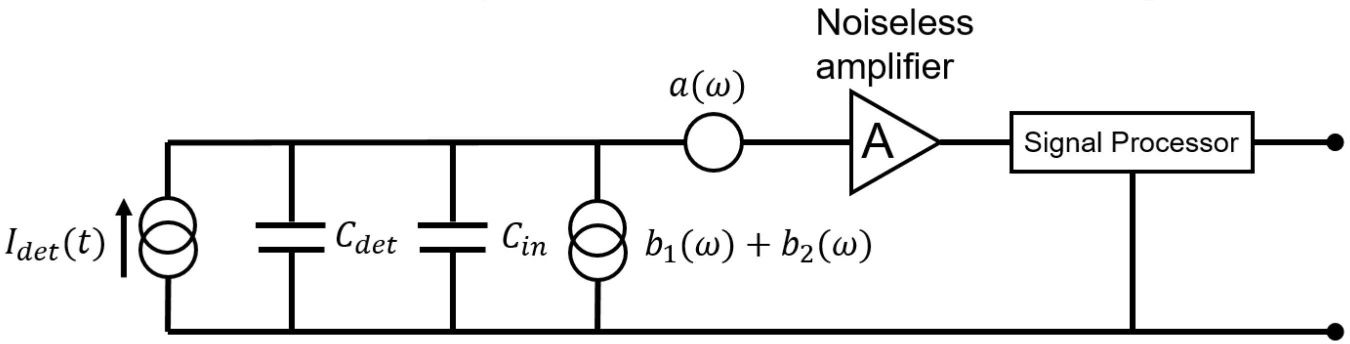
CMOS based amplifier

$$2kT\frac{h}{g_m}$$

Large $^1/_f$ contribution

h: CMOS excess noise, limits the improvement in performance when technology scales down.

Equivalent Noise Charge: device comparison



$$ENC^2 = \boxed{A_1 \frac{a_W}{\tau_M}(C_{det} + C_{in})^2} + \cancel{A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2} + \cancel{A_3(b_1 + b_2)\tau_M}$$

BJT based amplifier

$$ENC_{\text{series noise}} \propto \sqrt{k_1 \cdot \frac{C_{tot}^2}{\beta} + k_2 \cdot R_b C_{tot}^2}$$

Goal: maximize the current gain β at high frequencies while keeping a low base resistance R_b

Equivalent Noise Charge

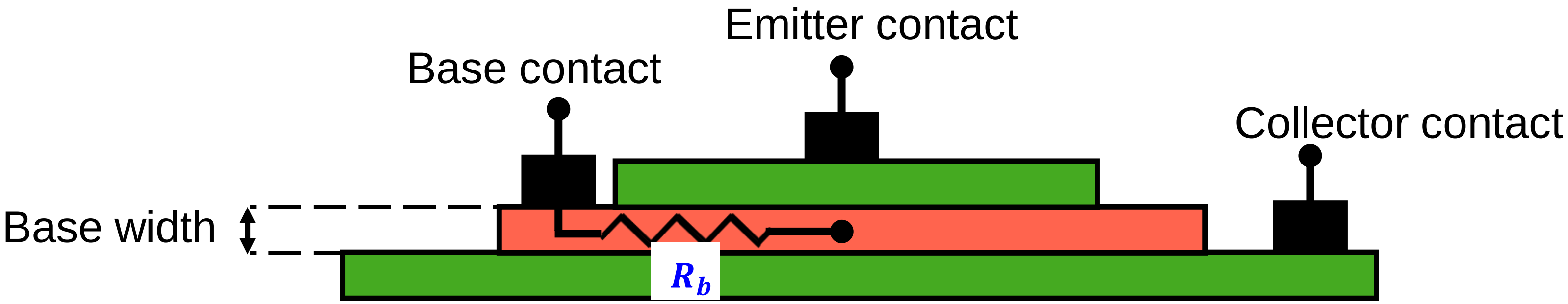
For a NPN BJT, the amplifier current gain β can be expressed as:

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

τ_p = hole recombination time in Base

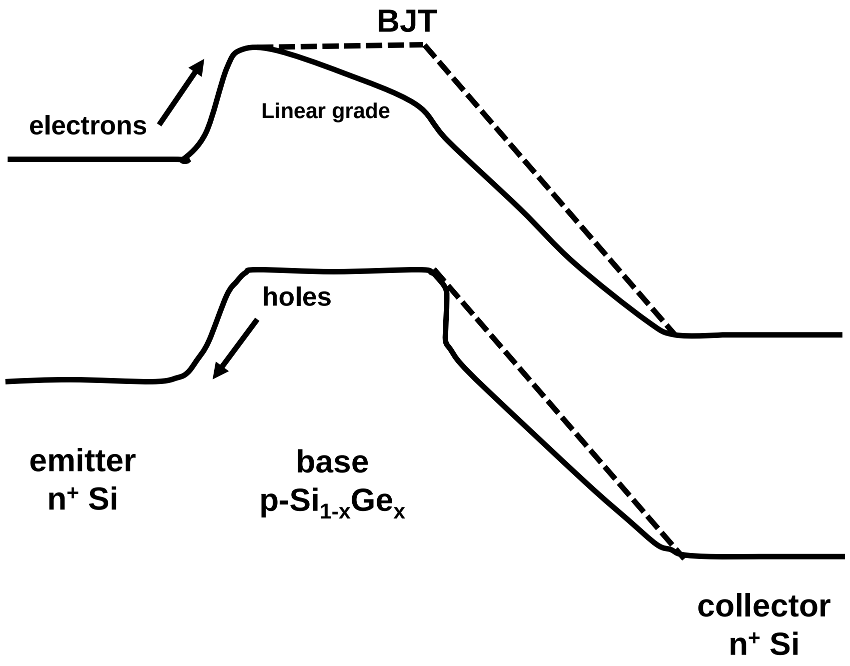
τ_t = electron transit time (Emitter to Collector)

Large $\beta \Longrightarrow$ Minimize the electron transit time



SiGe HBT technology for low-noise, fast amplifiers

In SiGe Heterojunction Bipolar Transistors (HBT) the **grading** of the bandgap in the Base changes the **charge-transport mechanism** in the Base from **diffusion** to **drift**:



Grading of germanium in the base:

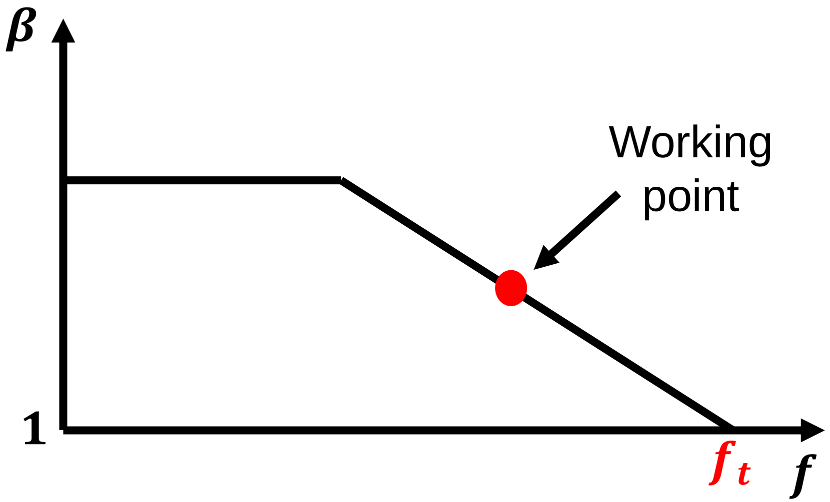
field-assisted charge transport in the Base,
equivalent to introducing an electric field in the Base

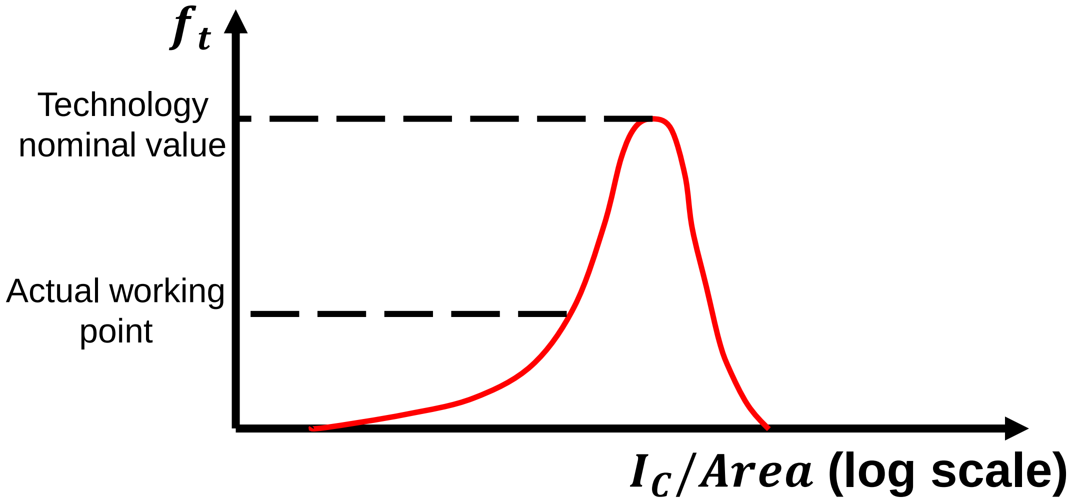
$\Longrightarrow$ short e⁻ transit time in Base $\Longrightarrow$ very high β

$\Longrightarrow$ smaller size $\Longrightarrow$ reduction of R_b and very high f_t

Hundreds of GHz

Current gain and power consumption: f_t is the key





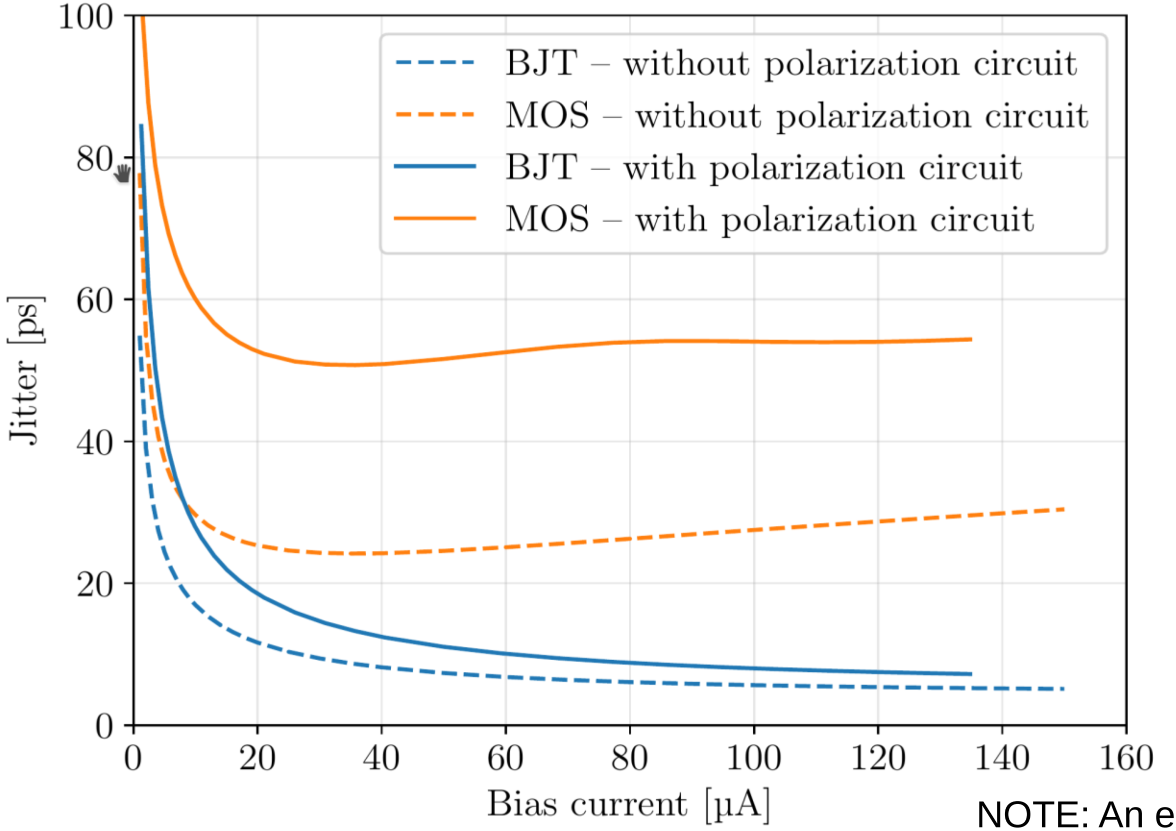
	$f_t = 10\ GHz$	$f_t = 100\ GHz$
$\beta_{max}\ at\ 200\ MHz$	50	500
$\beta_{max}\ at\ 1\ GHz$	10	100
$\beta_{max}\ at\ 5\ GHz$	2	20

Trade-off: **ENC** ⇔ **Power Consumption**

$f_t > 100\ GHz$ technologies are necessary for fast, low-power amplification.

SiGe HBT vs CMOS for a fast amplifier

Intrinsic amplifier jitter: an example common emitter (source) configuration in a 130nm technology.



NOTE: An extra parasitic capacitance was accounted for the insulation of the HBT from substrate.

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2. **SiGe BiCMOS technologies.**
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SiGe BiCMOS: A commercial VLSI foundry process

source: https://towerjazz.com/technology/rf-and-hpa/sige-bicmos-platform/

Some applications

- Automotive radars (27/77 GHz)
- Satellite communications
- LAN RF transceivers (60 GHz)
- Point-to-point radio (V-band, E-band)
- Defense
- Security
- Instrumentation

A **fast growing technology: f_{max} = 700 GHz** transistor recently developed (DOT7 project, IHP microelectronics)

SiGe BiCMOS: A commercial VLSI foundry process

Some foundries offering SiGe BiCMOS:

- IHP Microelectronics (→ Research Inst.)
- Towerjazz
- Globafoundries
- TSMC
- STm
- AMS
- …

Implemented as an adder module to a existing CMOS technologies.

⇩

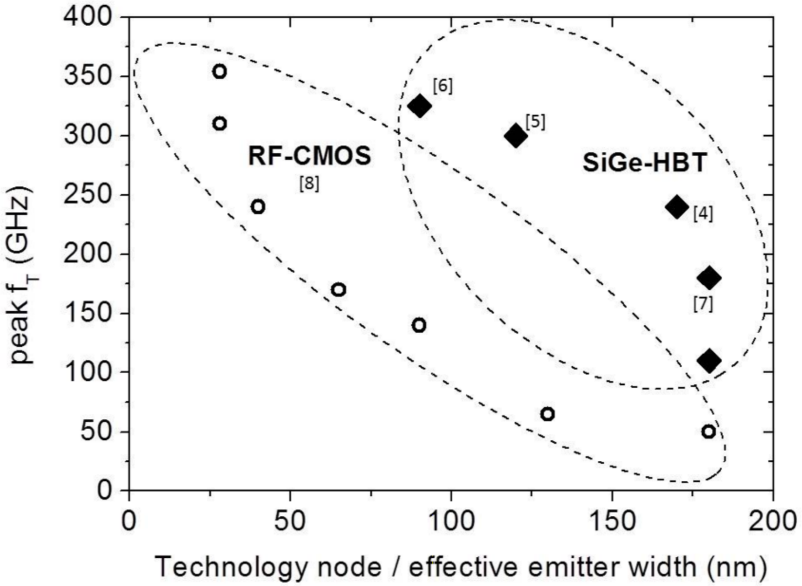
Typical increase for same tech. node in cost: ~10-15 %

Some characteristics of SiGe

- Integrated in CMOS platforms ⟹ SiGe-HBT AND Si-CMOS
- Vertical transport device ⟹ Not as dependent on lithography as CMOS
- Cryogenic compatible ⟹ Silicon-based device operating at < 1 K
- Inherently rad. hard ⟹ Good radiation tolerance with standard processing
- High output current drive ⟹ Tolerance to parasitics

A comparison with CMOS technologies

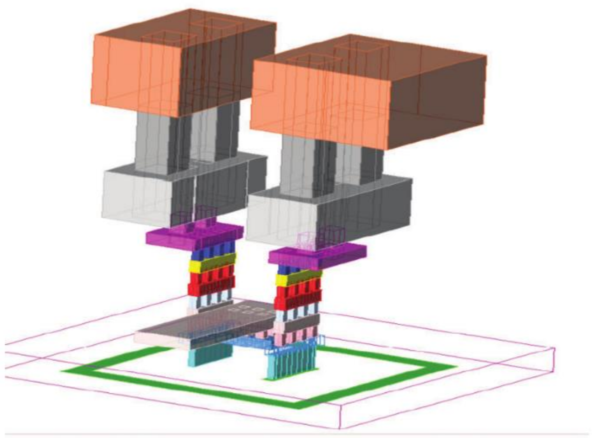
Intrinsic performance

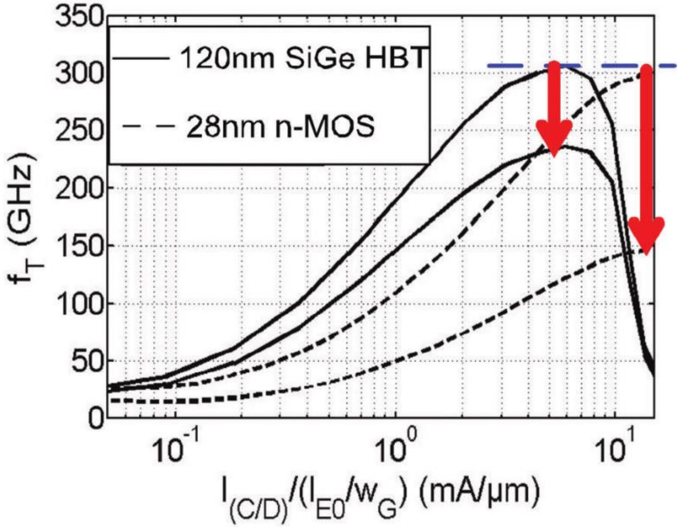


A. Mai and M. Kaynak, SiGe-BiCMOS based technology platforms for mm-wave and radar applications.
DOI: 10.1109/MIKON.2016.7492062

Robustness to parasitics

M. Schröter, U. Pfeiffer and R. Jain, Silicon-Germanium Heterojunction Bipolar Transistors for mm-Wave Systems: Technology, Modeling and Circuit Applications.





SiGe HBT scaling

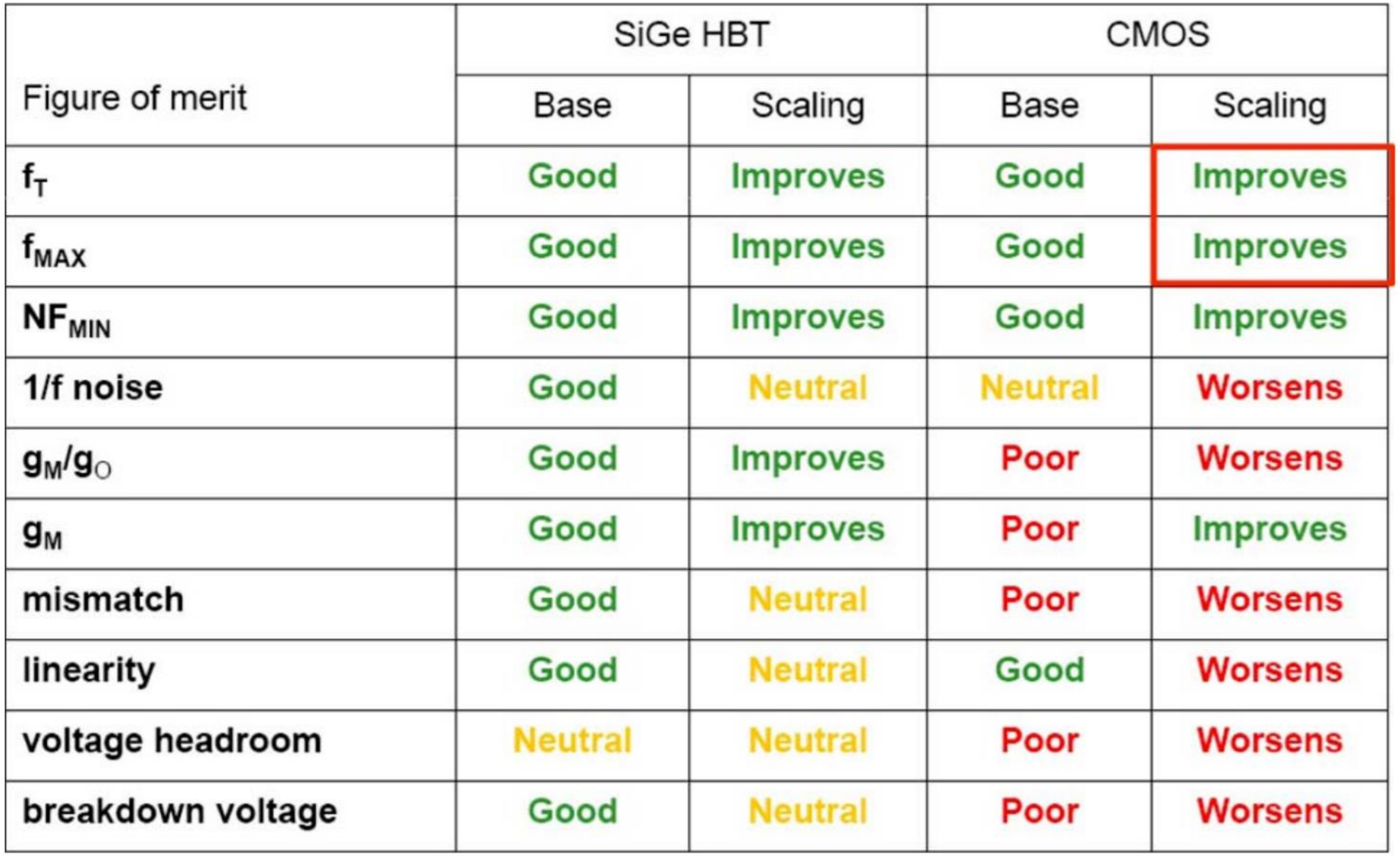


Figure of merit	SiGe HBT		CMOS	
	Base	Scaling	Base	Scaling
f_T	Good	Improves	Good	Improves
f_{MAX}	Good	Improves	Good	Improves
NF_{MIN}	Good	Improves	Good	Improves
1/f noise	Good	Neutral	Neutral	Worsens
g_M/g_O	Good	Improves	Poor	Worsens
g_M	Good	Improves	Poor	Improves
mismatch	Good	Neutral	Poor	Worsens
linearity	Good	Neutral	Good	Worsens
voltage headroom	Neutral	Neutral	Poor	Worsens
breakdown voltage	Good	Neutral	Poor	Worsens

From: J.D. Cressler, IEEE transactions on nuclear science, vol. 60, n. 3 (2013)

SG13G2 technology from IHP Microelectronics

Exploit the properties of state-of-the-art SiGe Bi-CMOS transistors to produce an **ultra-fast, low-noise, low-power consumption amplifier**

Leading-edge technology: **IHP SG13G2**

130 nm process featuring **SiGe HBT** with

- Transistor transition frequency: $f_t = 0.3\,THz$
- DC Current gain: $\beta = 900$
- Delay gate: **1.8 ps**

innovations
for high
performance
microelectronics

Leibniz-Institut für
innovative Mikroelektronik

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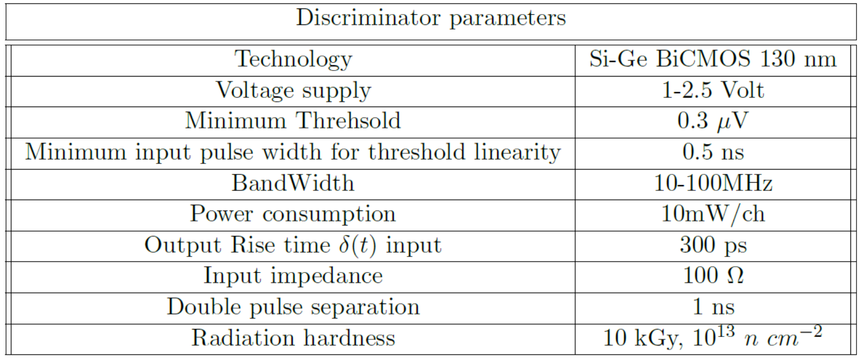
The use of SiGe BiCMOS technologies in HEP

Upgrade of the ATLAS RPCs



Discriminator parameters	
Technology	Si-Ge BiCMOS 130 nm
Voltage supply	1-2.5 Volt
Minimum Threhsold	0.3 μV
Minimum input pulse width for threshold linearity	0.5 ns
BandWidth	10-100MHz
Power consumption	10mW/ch
Output Rise time $\delta(t)$ input	300 ps
Input impedance	100 Ω
Double pulse separation	1 ns
Radiation hardness	10 kGy, 10^{13} $n\ cm^{-2}$

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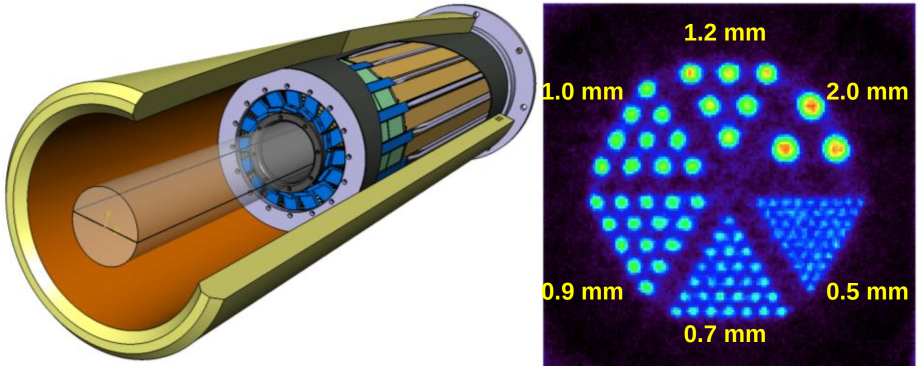
Upgrade of CMS RPCs and SiPm readout

PETIROC2 – 350nm SiGe BiCMOS	
Number of channels	32
Sensitivity	Trigger on first photo-electron
Timing resolution [ps]	< 40
Dynamic range	3000 ph.e (10^6 SiPm gain), INL: 1% up to 2500 ph.e
Power consumption	Power supply: 3.3 V 192 mW Analogue core (excluding outing buffer), 6 mW/ch

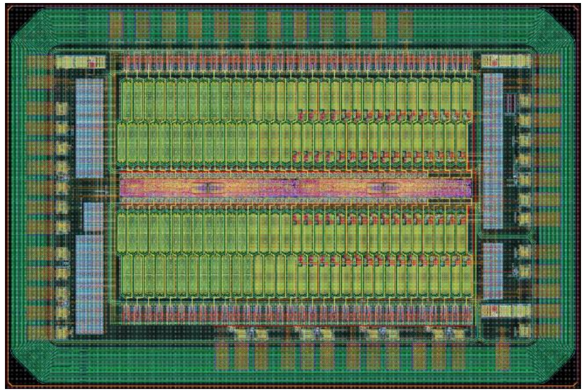
Some specs from manufacturer

Silicon based TOF-PET



University of Geneva, University of Bern, HUG

Timing pixel sensor for FASER upgrade



University of Geneva, CERN

Monolithic silicon pixel sensors in SiGe BiCMOS technology

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innovations for high performance microelectronics
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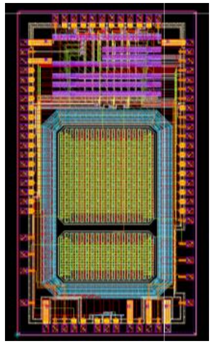
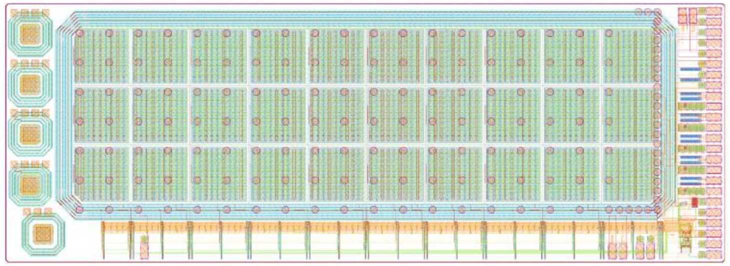
INFN Sezione di Roma Tor Vergata

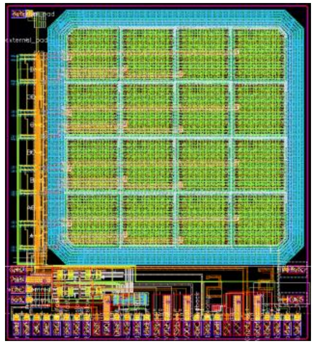
2016



2017



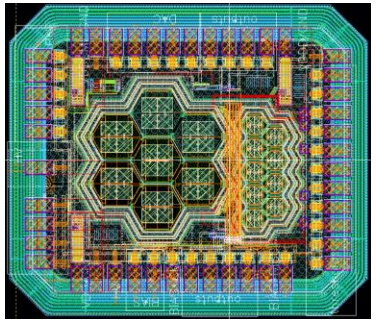
2019



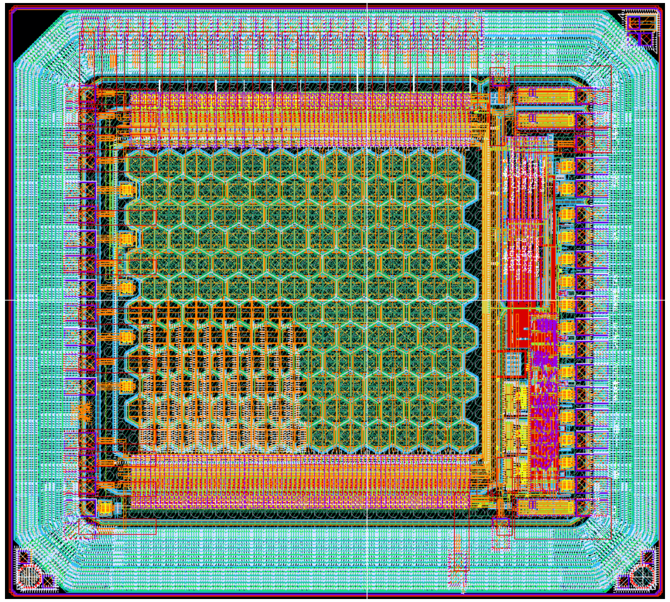
TT-PET

For the a TOF PET Project

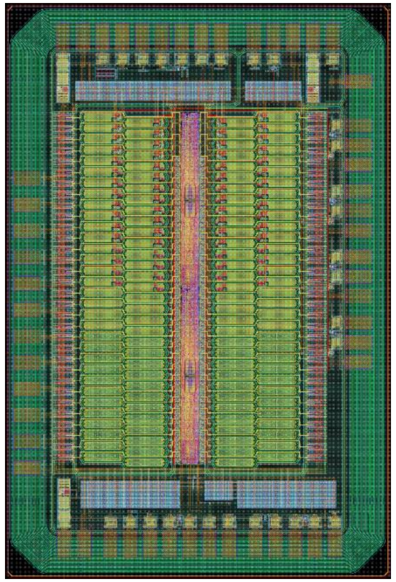
2018



2019



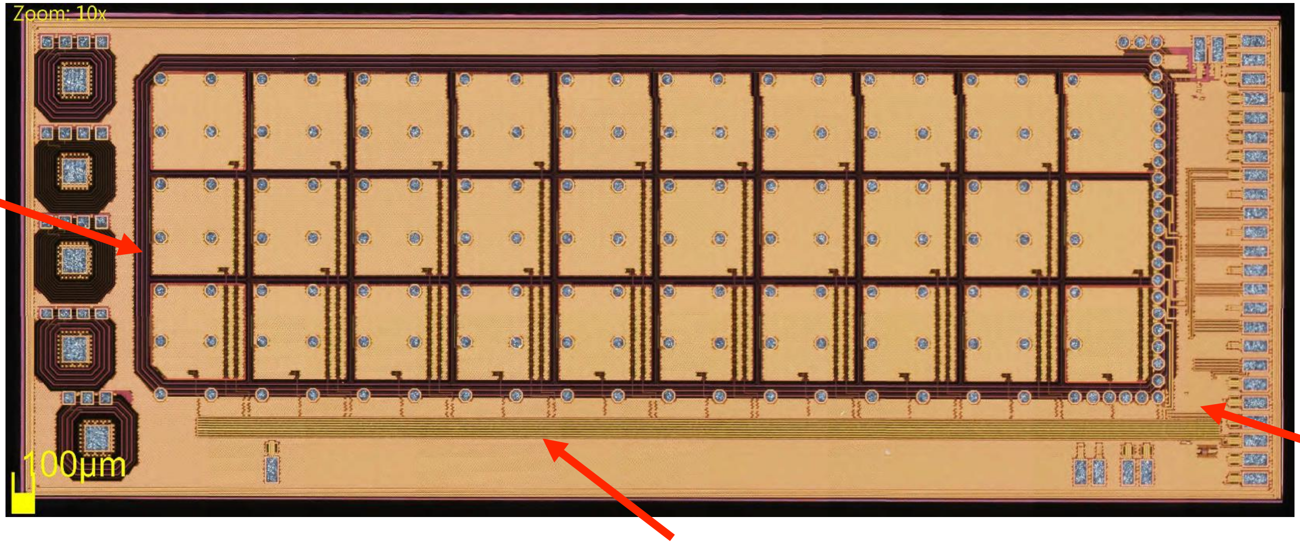
2020



For generic timing sensor R&D

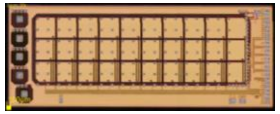
Demonstrator chip for a TOF-PET project

Matrix of **3×10** n-on-p pixels, of **470×470 μm^2** (C_{tot} = 750 fF) spaced by **30 μm**.

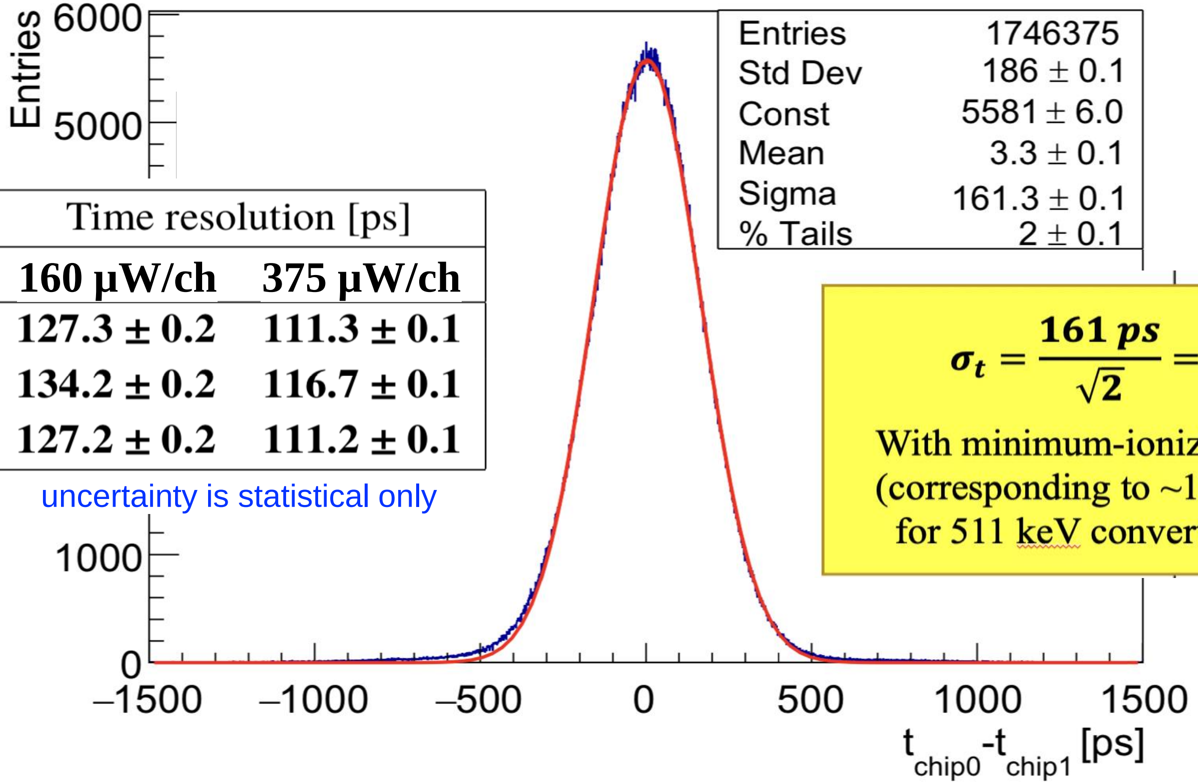


- SiGe HBT **preamplifier**
- CMOS-based open-loop tri-stage **discriminator** (adjustable threshold with an 8-bit DAC), that preserves the **TOA** and the **TOT** of the pixel
- Discriminator output sent to **fast-OR chain**
- **50ps binning TDC**, R/O logic, serializer

Test beam results: time resolution



Chip 1: HV = 180 V, Power = 375 μW/ch, threshold = 1750 e⁻



	Time resolution [ps]	
	160 μW/ch	**375 μW/ch**
$\sigma_{t,\text{ chip 0}}$	**127.3 ± 0.2**	**111.3 ± 0.1**
$\sigma_{t,\text{ chip 1}}$	**134.2 ± 0.2**	**116.7 ± 0.1**
$\sigma_{t,\text{ chip 2}}$	**127.2 ± 0.2**	**111.2 ± 0.1**

uncertainty is statistical only

$$\boldsymbol{\sigma_t = \frac{161\ ps}{\sqrt{2}} = 114\ ps}$$

With minimum-ionizing particles
(corresponding to ~114/4 ~ 30ps
for 511 keV converted photons)

Excellent result for a silicon pixel detector without internal gain,

obtained on a large capacitance (750 fF) and power consumption of 150 mW/cm^2.

L. Paolozzi *et al.*, 2019 JINST **14** P02009, https://doi.org/10.1088/1748-0221/14/02/P02009
P. Valerio *et al.*, 2019 JINST **14** P07013, https://doi.org/10.1088/1748-0221/14/07/P07013

The “hexagonal” prototype sensor

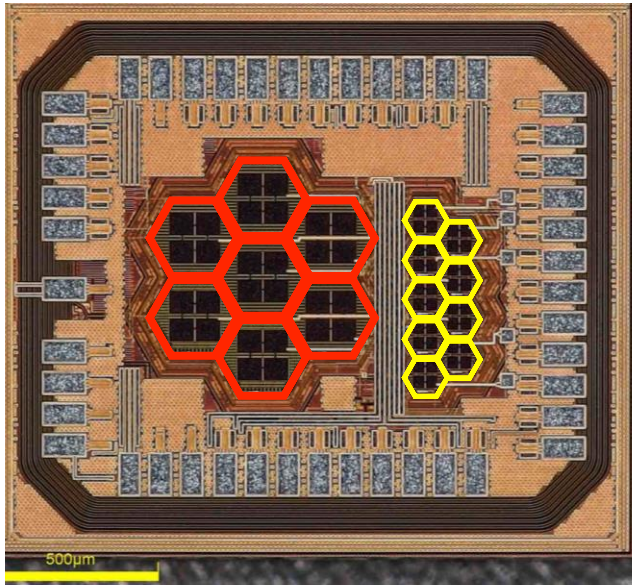
Developed in IHP **SG13G2** technology (130nm).

Matrices with hexagons of two sizes:

- hexagon side 130µm and 65µm, with 10µm inter-pixel spacing
- C_{TOT} = 220 and 70 fF

Exploits:

- New dedicated custom components developed together with foundry
- New guard-ring structure



Collaboration of:

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

ihp innovations for high performance microelectronics
Leibniz-Institut für innovative Mikroelektronik

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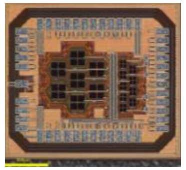
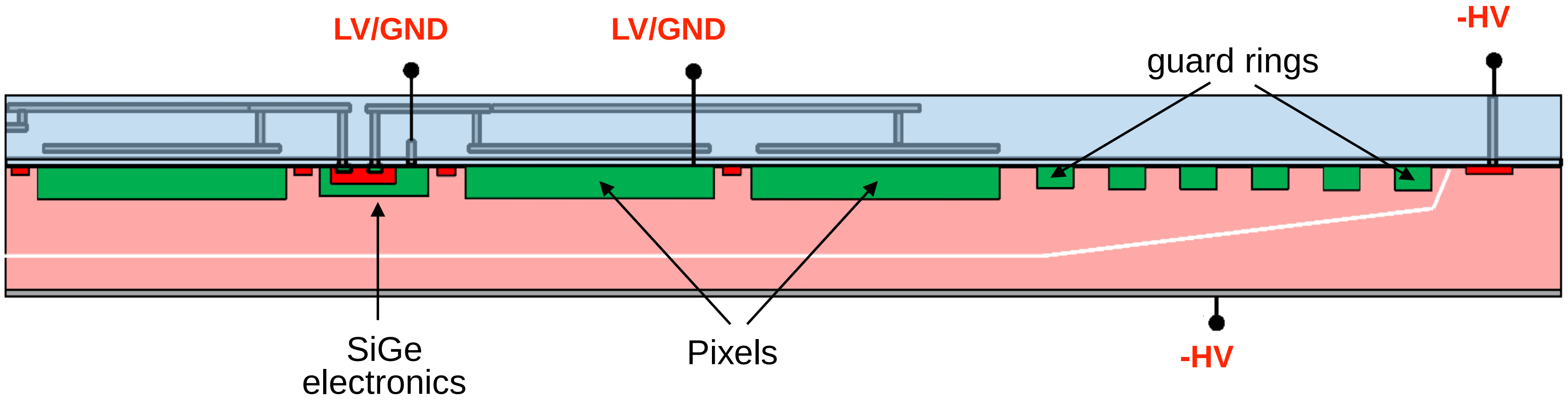
CERN Ideas

The “hexagonal” prototype sensor





Standard substrate resistivity ρ = 50 Ωcm ⟹ Depletion depth: **26µm** at HV = 140 V

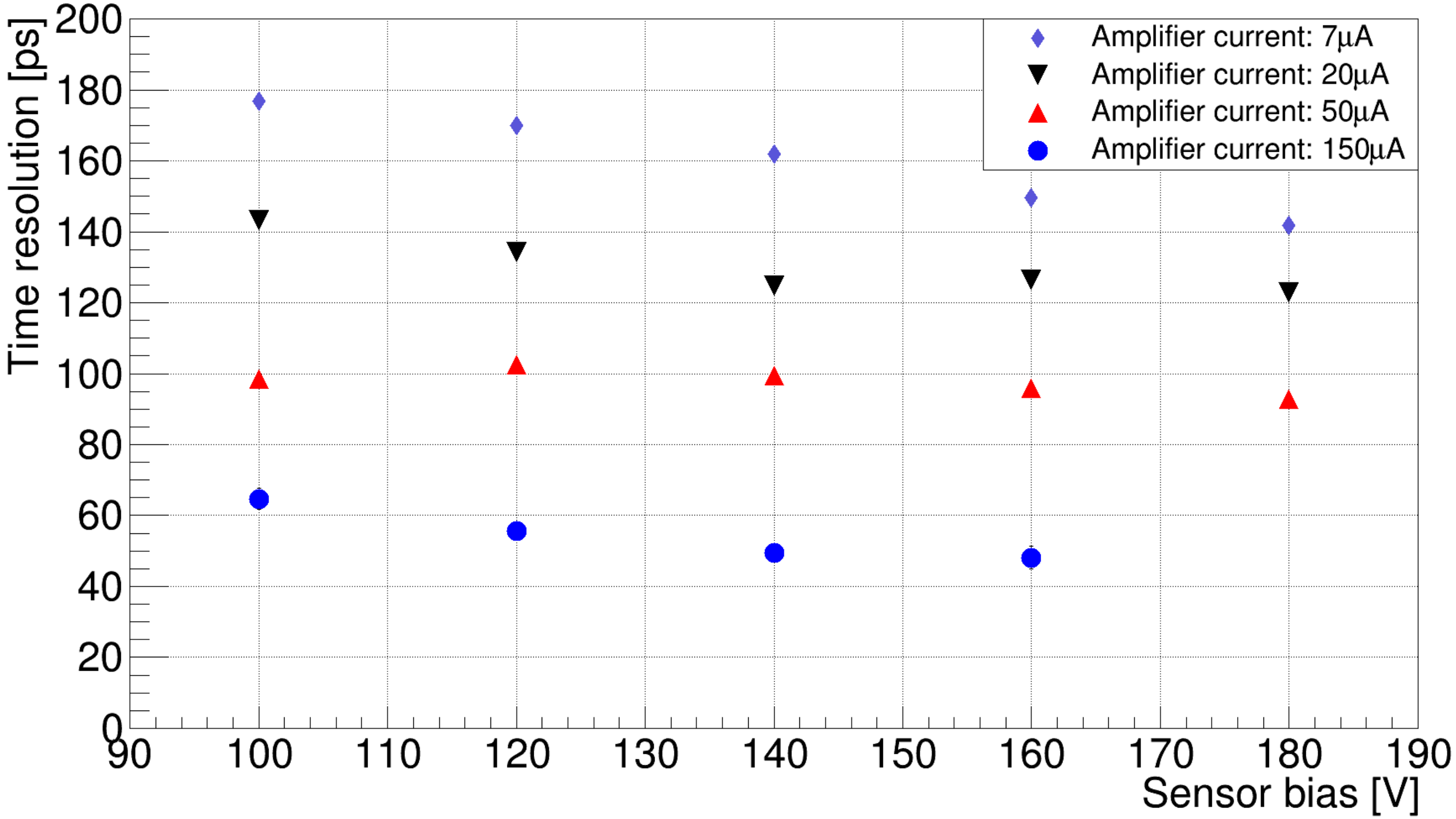
Thinning to 60 µm

No backside metallization ⟹ **not fully depleted**

PRO: much easier **production**, but

→ slightly degraded performance because of regions where drift velocity is not saturated

Time resolution vs bias voltage



Performance limited by time walk

Summary

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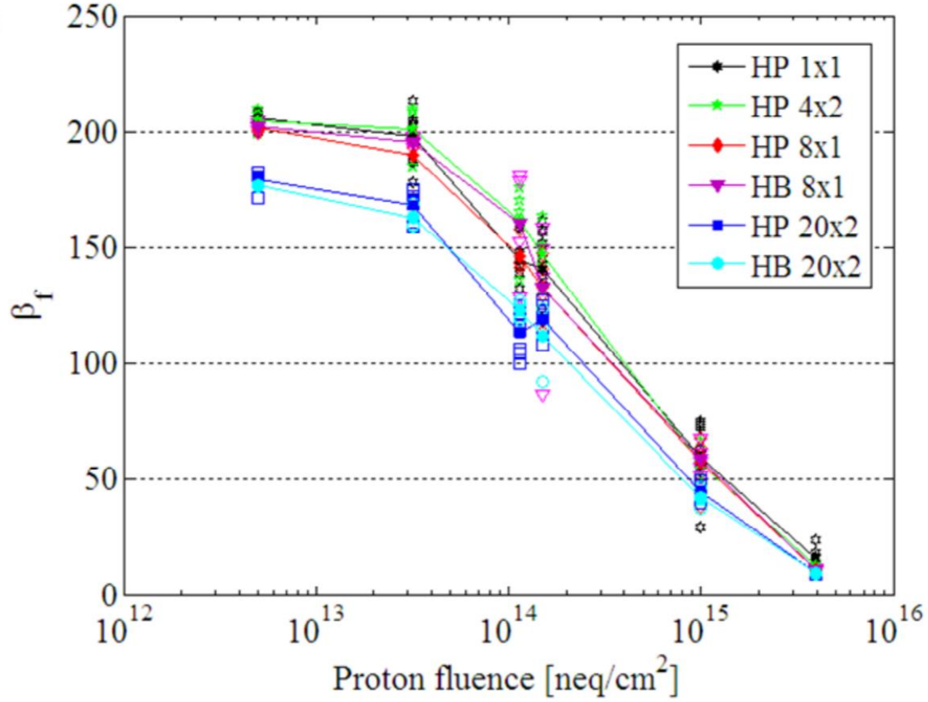
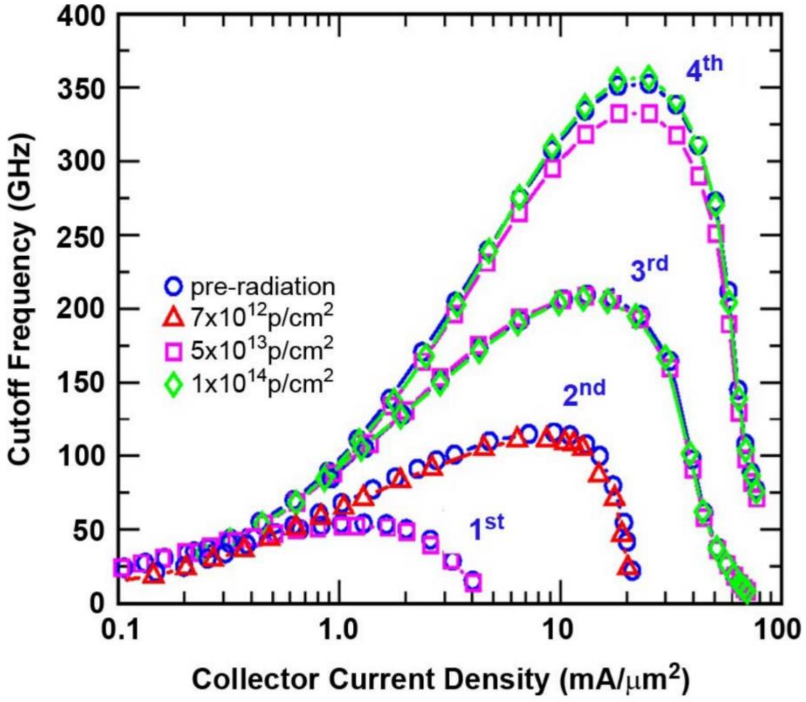
Radiation hardness of standard commercial HBTs

DC characteristics



S. Díez et al, IEEE Nuclear Science Symposuim & Medical Imaging Conference, Knoxville, TN, 2010, pp. 587-593, doi: 10.1109/NSSMIC.2010.5873828.

AC characteristics



From: J.D. Cressler, IEEE transactions on nuclear science, vol. 60, n. 3 (2013)

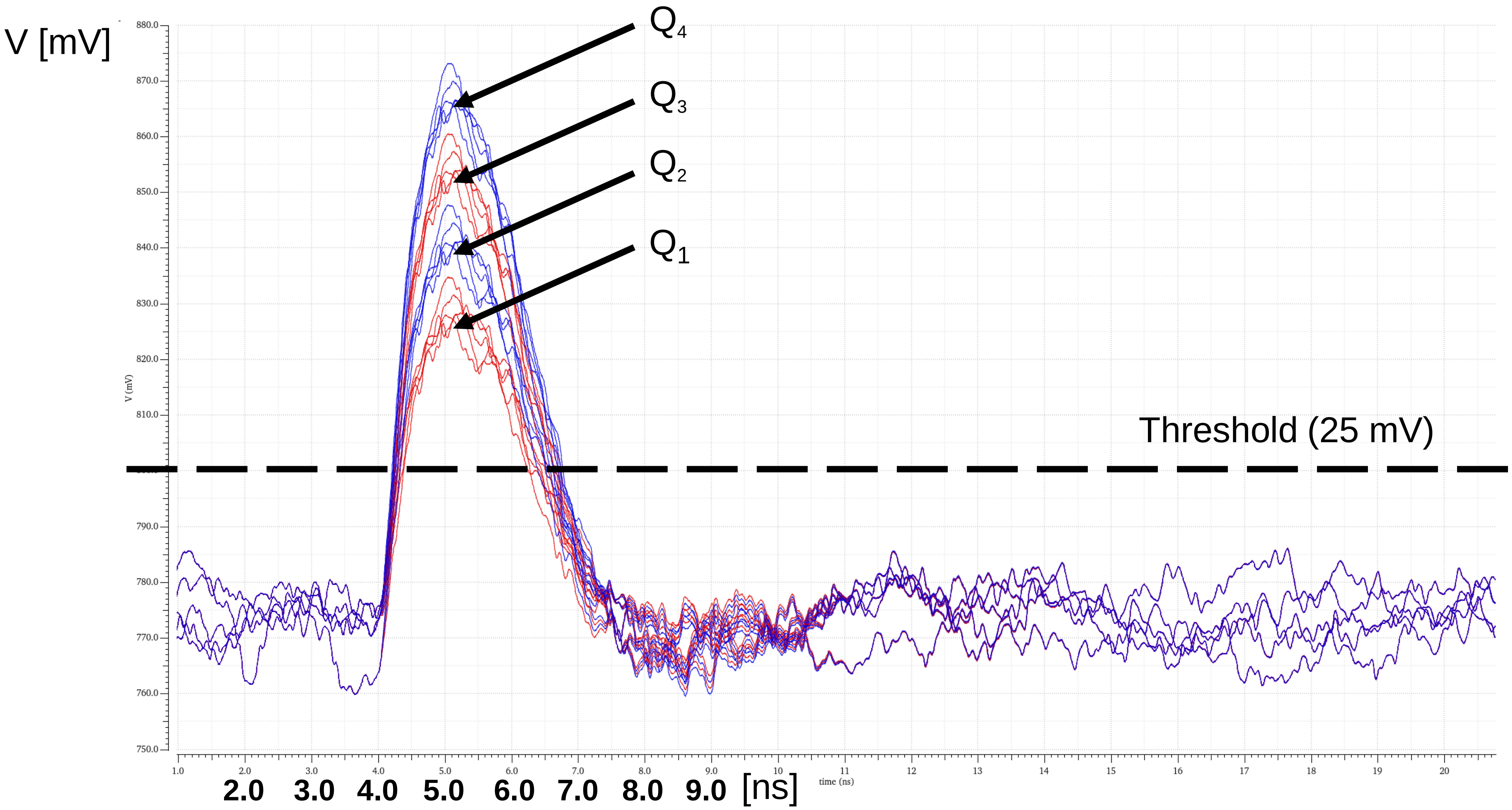
No studies available on AC characteristics and noise above 10^{14} p/cm^2

CONCLUSIONS

- SiGe BiCMOS is a **cost effective** solution for fast signal amplification in particle detectors.
- Available from most **commercial manufacturers**, fast growing technology.
- Integration in monolithic pixel sensors can deliver excellent time resolution at **low-power** consumption.
- **Inherently radiation hard**, but studies at high proton fluence focusing on high-frequency response are not available.

Extra Material

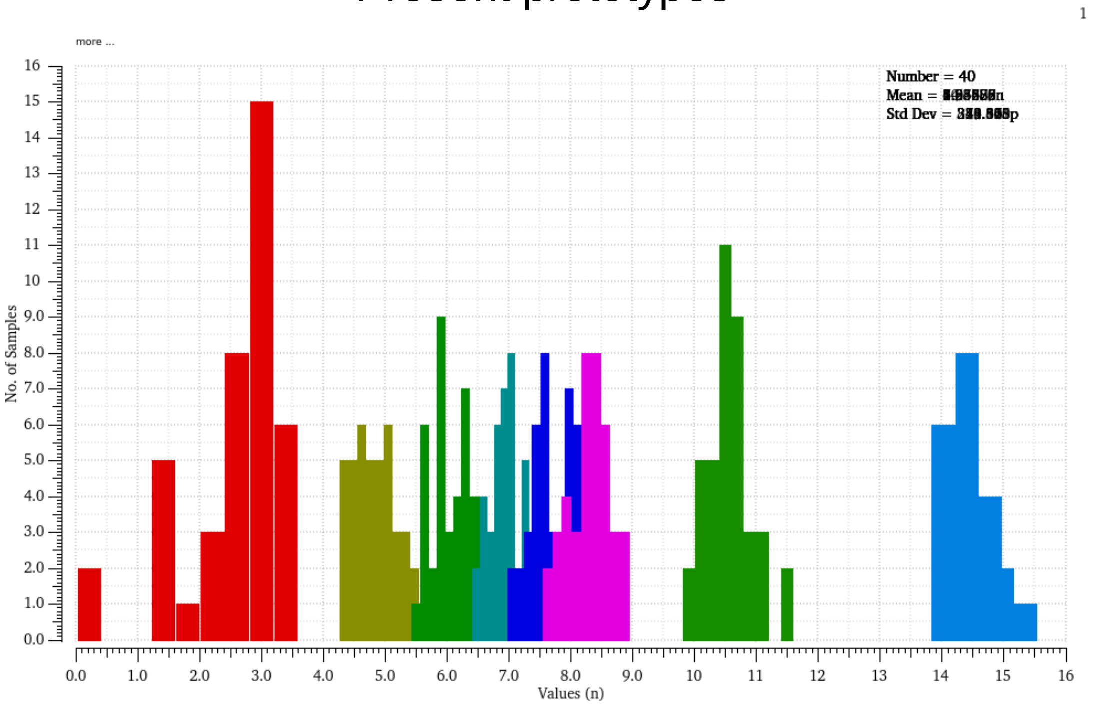
Time walk correction

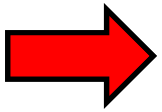


Improved time walk correction

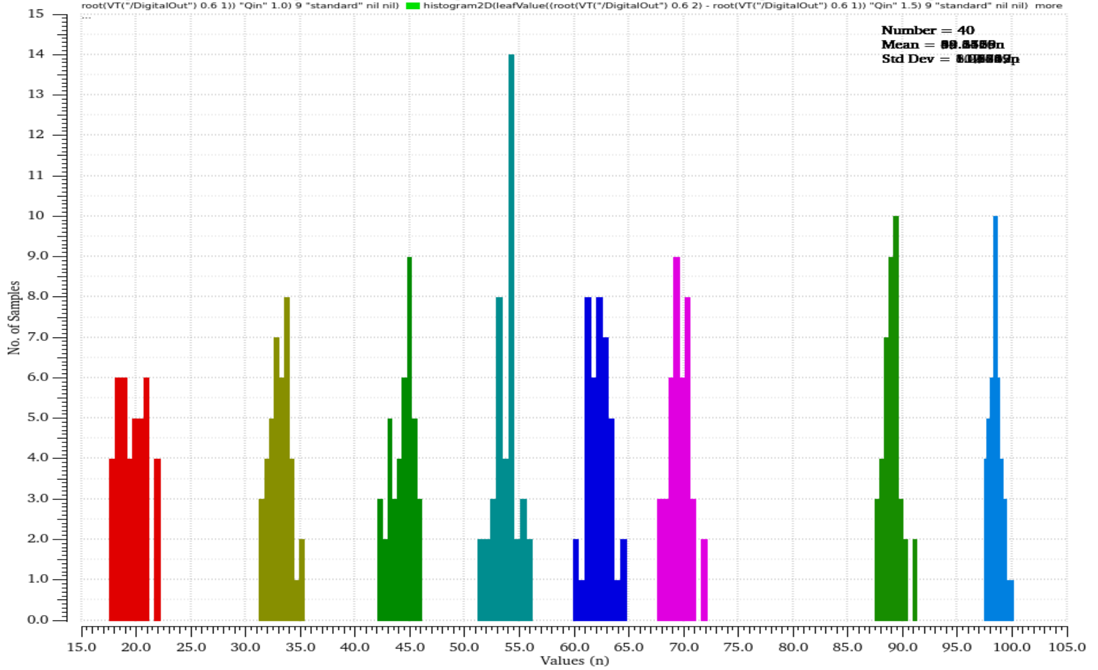
Charge resolution
(Cadence spectre simulation)

Present prototypes





New technique



ATTRACT prototype: towards ps time resolution