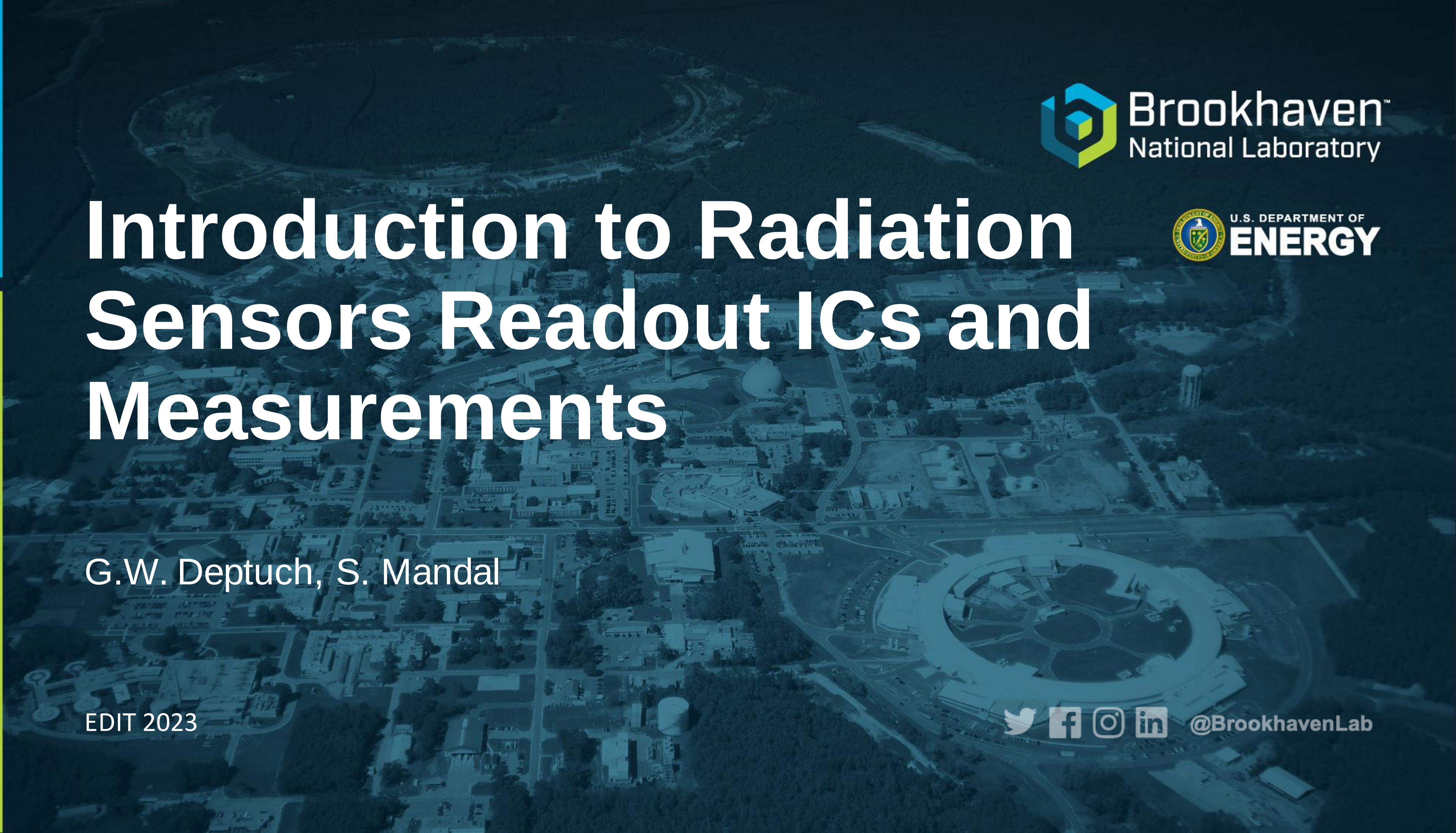

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U.S. DEPARTMENT OF ENERGY

Introduction to Radiation Sensors Readout ICs and Measurements

G.W. Deptuch, S. Mandal

EDIT 2023

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Covered:

Part 1

- Solid-State sensors as a source of charge signal
- Short Introduction to Integrated Circuits technology
- Typical Front-End Processing chain in nuclear electronics
- Types and methods of measurement achieved with Front-End circuits
- Elements of Back-End Processing chain in nuclear electronics

Part 2

- Introduction to Digitization and Digital Signal Processing
- Illustrations of practical realizations

People

Grzegorz W. Deptuch gdeptuch@bnl.gov

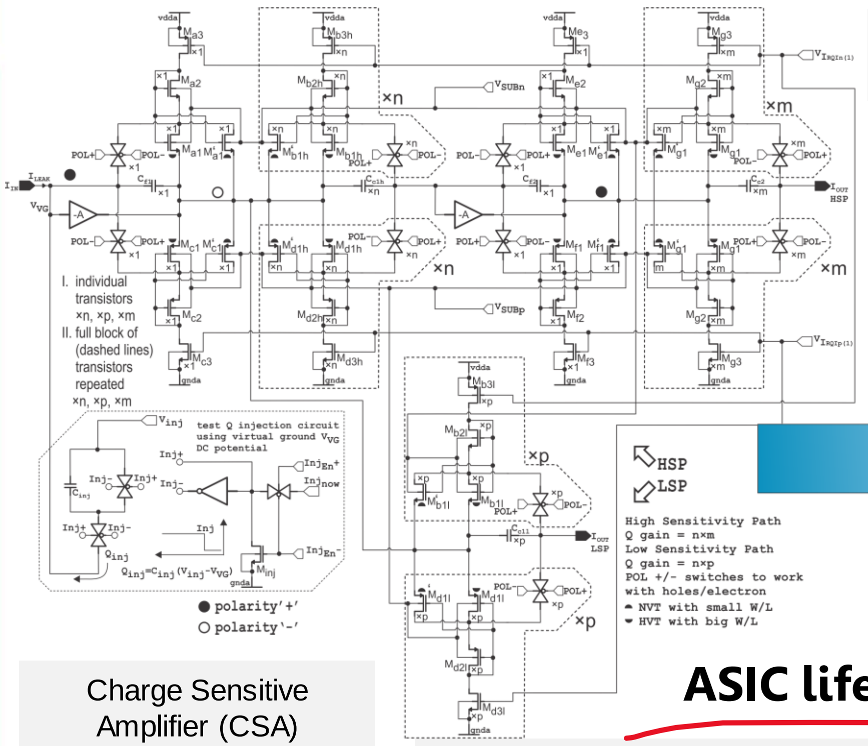
Soumyajit Mandal smandal@bnl.gov

Prashansa Mukim pmukim@bnl.gov

Md Arif Iqbal miqbal@bnl.gov

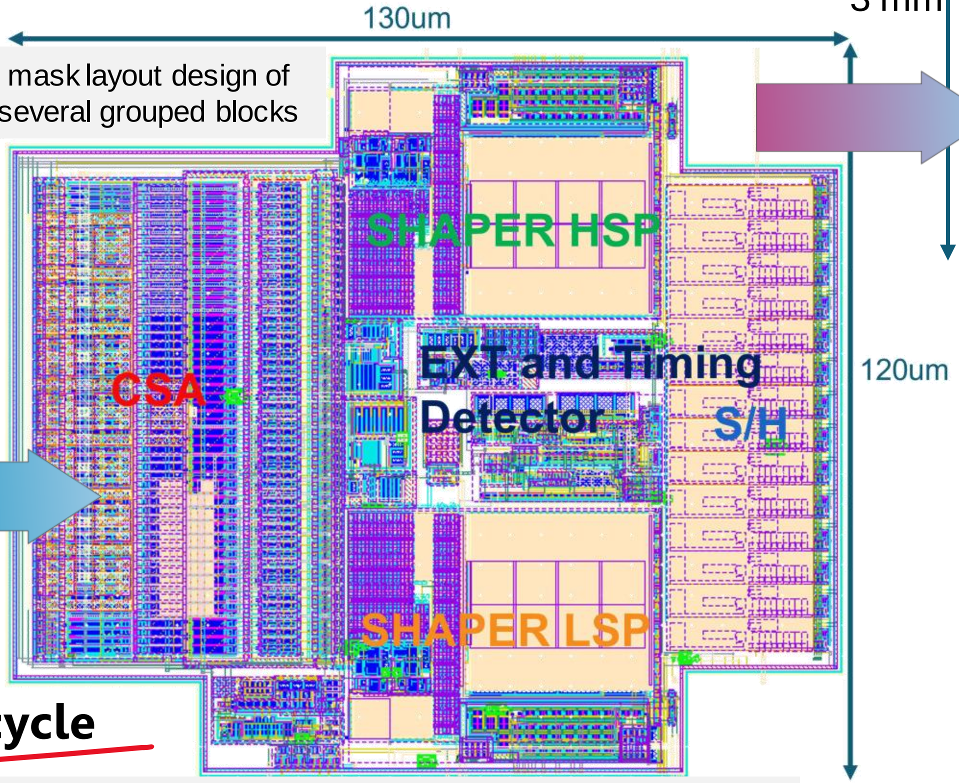
Transistors + IC Technology - 1

symbolic/schematic representation

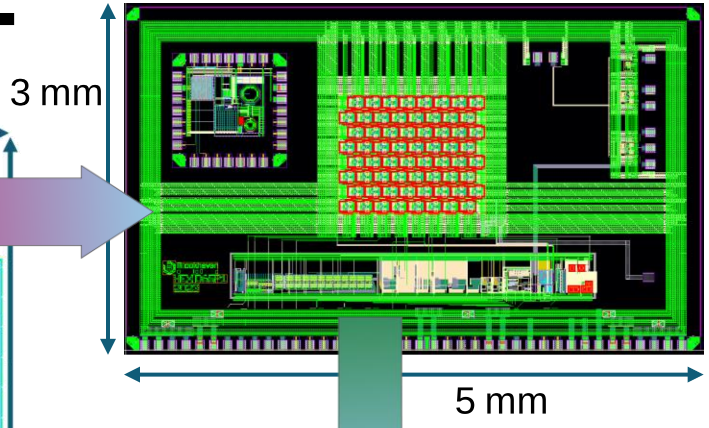


Charge Sensitive Amplifier (CSA) (with two sensitivity paths)

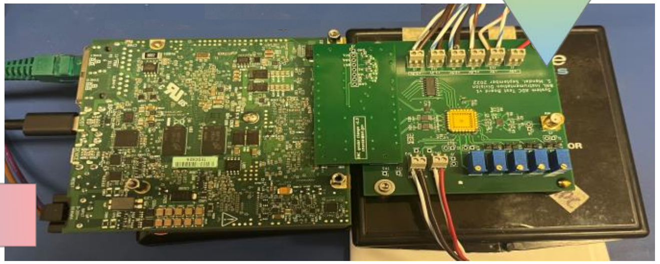
mask layout design of several grouped blocks



full ASIC layout



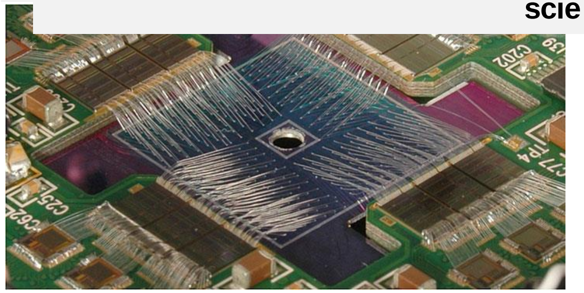
Silicon foundry (manufacturing)



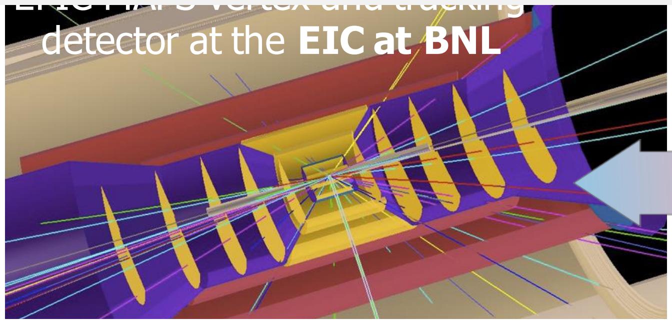
testing of ASICs

ASIC lifecycle

scientific instruments



MAIA 20×20 (BNL)



detector at the **EIC at BNL**

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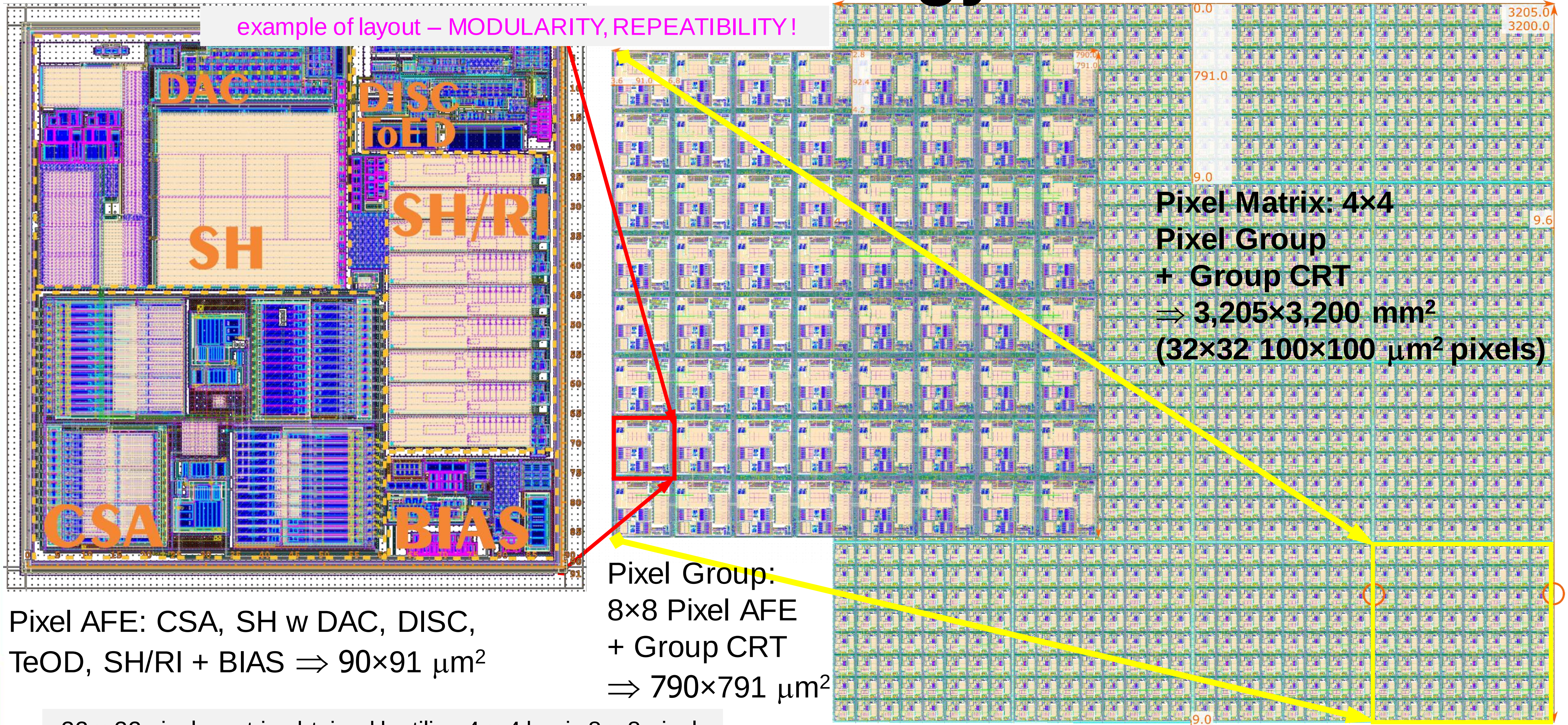
Transistors + IC Technology - 2

example of layout – MODULARITY, REPEATIBILITY !



Pixel AFE: CSA, SH w DAC, DISC, TeOD, SH/RI + BIAS ⇒ 90×91 μm^2

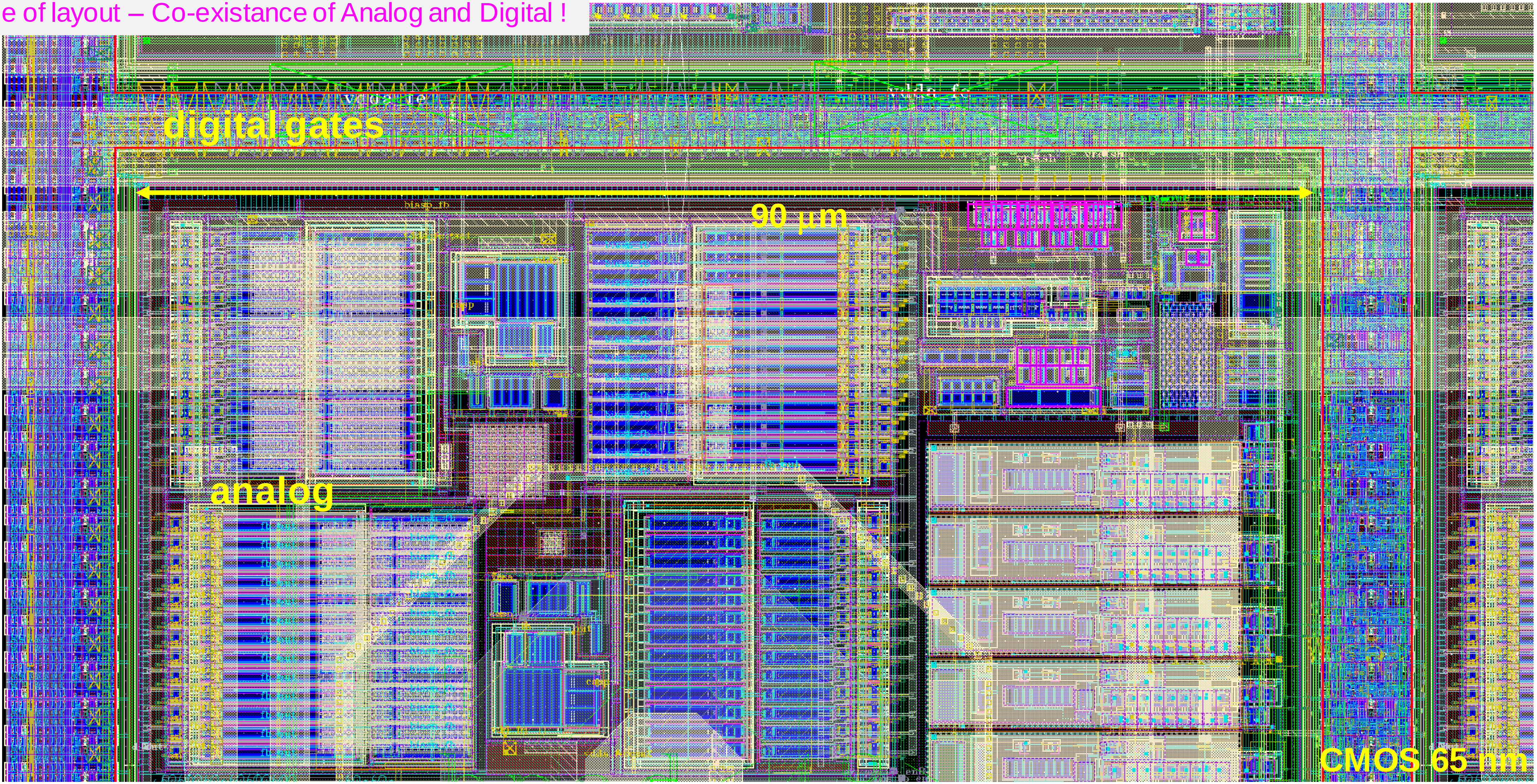
Pixel Group:
8×8 Pixel AFE
+ Group CRT
⇒ 790×791 μm^2

Pixel Matrix: 4×4
Pixel Group
+ Group CRT
⇒ 3,205×3,200 mm^2
(32×32 100×100 μm^2 pixels)

32 × 32 pixels matrix obtained by tiling 4 × 4 basic 8 × 8 pixels groups ⇒ suitable for continued tiling.

Transistors + IC Technology - 3

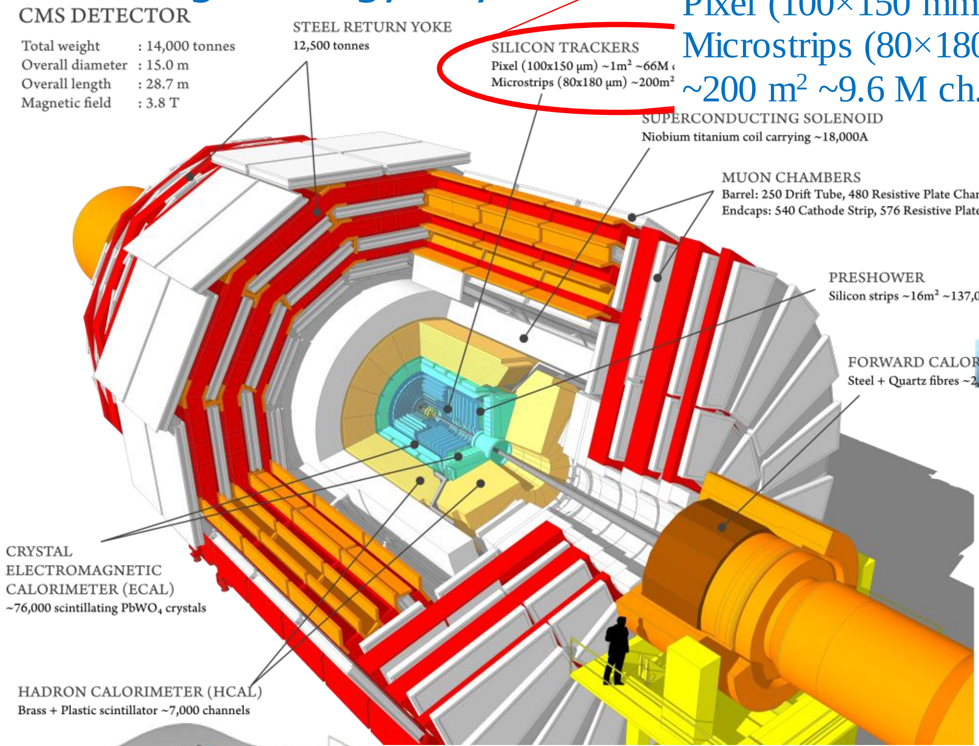
example of layout – Co-existance of Analog and Digital !



about 4,000 transistors / pixel (100 ×100 μm^2), 20 : 80 analog : digital

Application

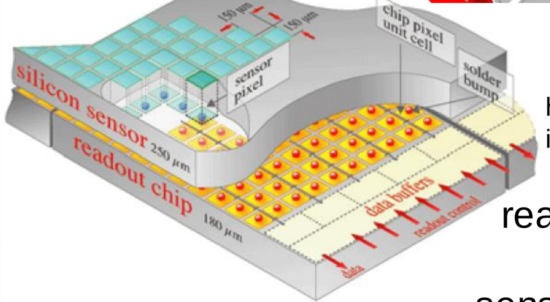
High Energy Physics



SILICON TRACKERS
Pixel (100×150 mm^2) ~1 m^2 ~66 M ch.)
Microstrips (80×180 mm^2)
~200 m^2 ~9.6 M ch.)

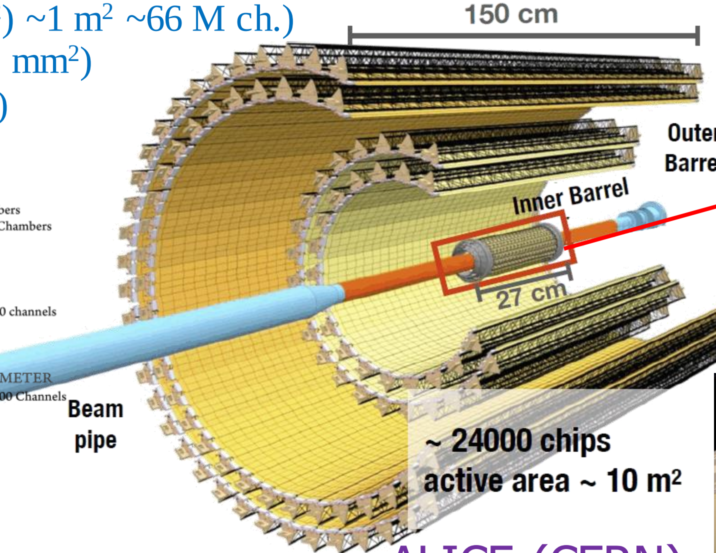
CMS (CERN)

https://cms.cern/detector/identifying-tracks/silicon-pixels



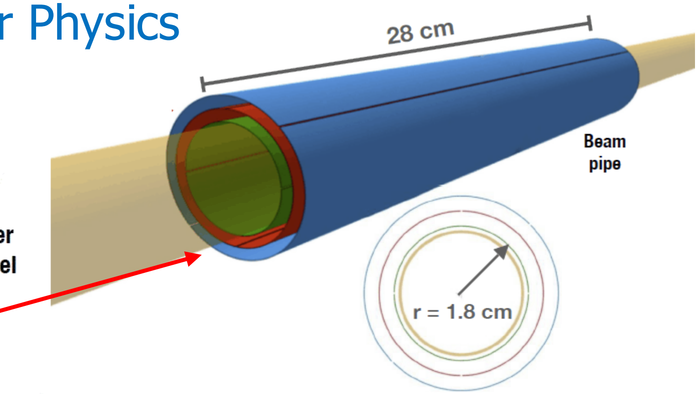
readout channels are laid out in 2D matrix connected to sensor elements at same pitch

Nuclear Physics

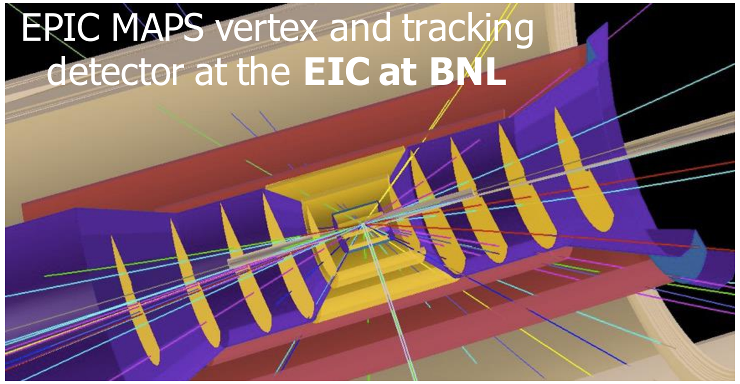


~ 24000 chips
active area ~ 10 m^2

ALICE (CERN)

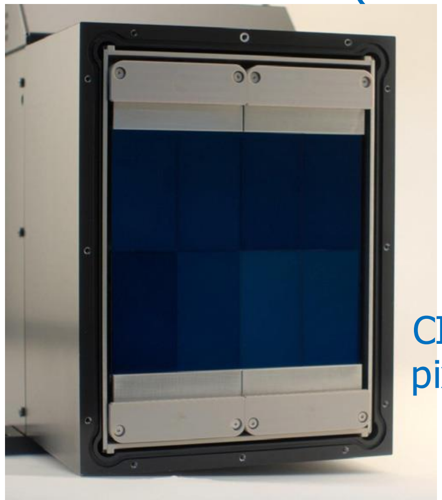


Si literally wrapped around finger

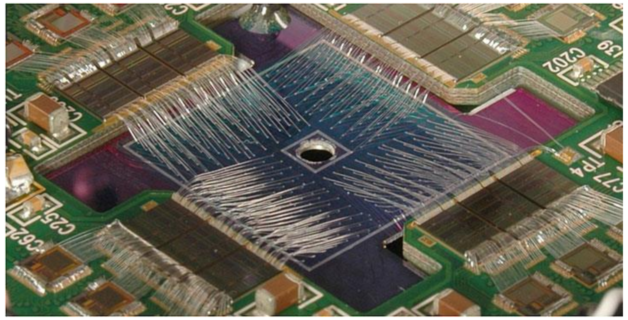


EPIC MAPS vertex and tracking detector at the **EIC at BNL**

Astrophysics, Photon Science (X-ray detection)



CITIUS 2.2 M pixel detector assembly (RIKEN)



MAIA 20×20 (BNL)

Introduction to IC Technology - 1

first electronic components, allowing nonlinear functions were vacuum tubes

construction of vacuum tubes was complex, their cost was high, but above all they were bulky (not good candidates for miniaturization)

tubes are still loved by audiophiles for soft, warm and highest fidelity in sound

Nr. 267431 Nr. 267431

Feb. 1948

SCHWEIZERISCHE EIDGENOSSENSCHAFT

EIDGENÖSSISCHES AMT FÜR GEISTIGES EIGENTUM

PATENTSCHRIFT

Veröffentlicht am 16. Juni 1950

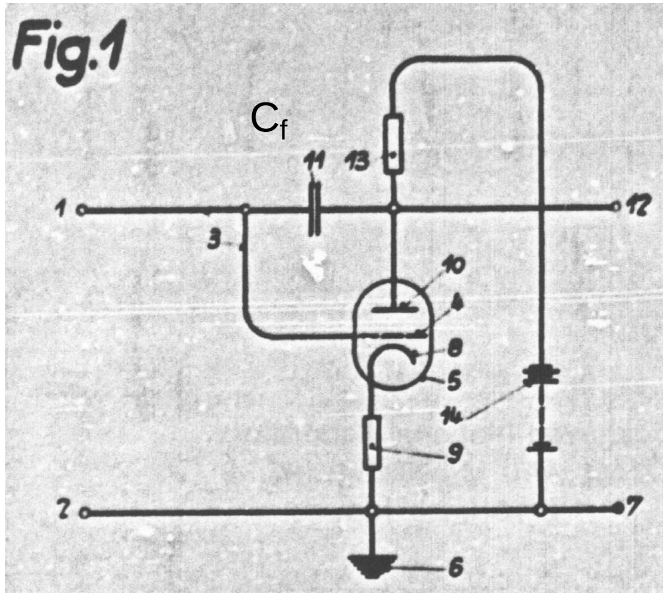
Klasse 66 a

Gesuch eingereicht: 12. Februar 1948, 18 Uhr. — Patent eingetragen: 31. März 1950.

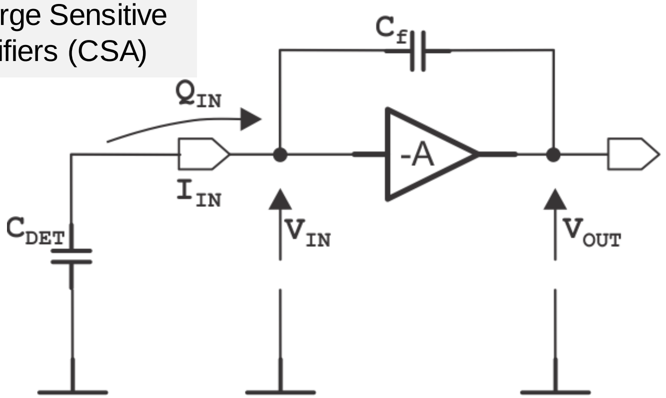
HAUPTPATENT

Schweizerische Lokomotiv- & Maschinenfabrik, Winterthur (Schweiz).

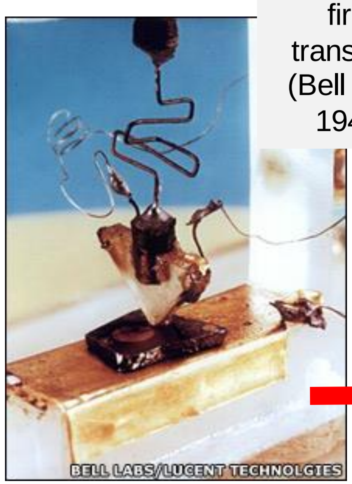
Meßverstärker zur Messung elektrischer Ladungen.



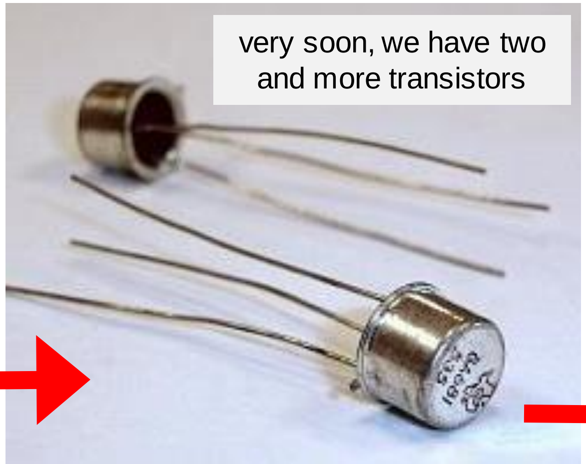
Integrator circuit is basic building block of Charge Sensitive Amplifiers (CSA)



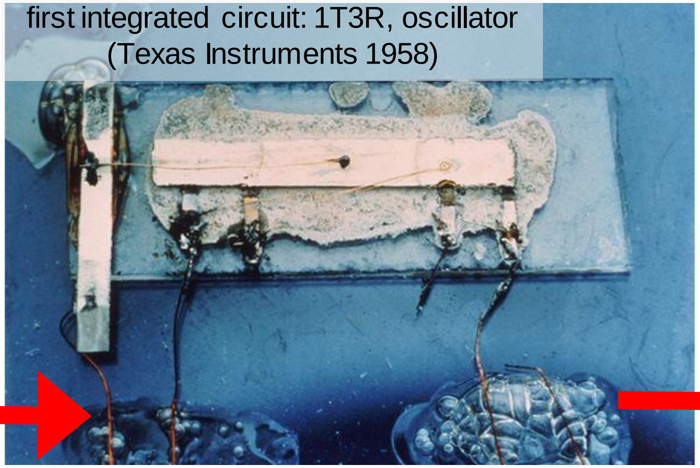
Introduction to IC Technology - 2



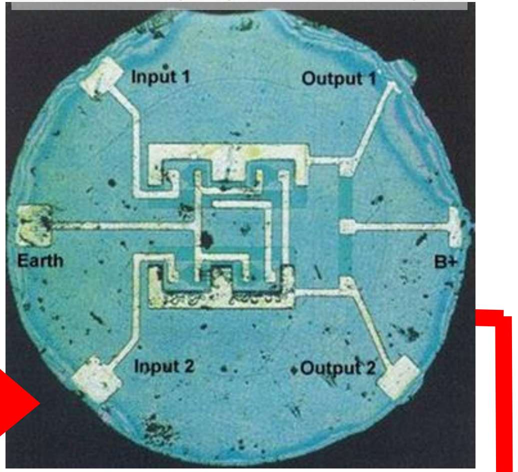
first transistor (Bell Labs 1947)



very soon, we have two and more transistors



first integrated circuit: 1T3R, oscillator (Texas Instruments 1958)

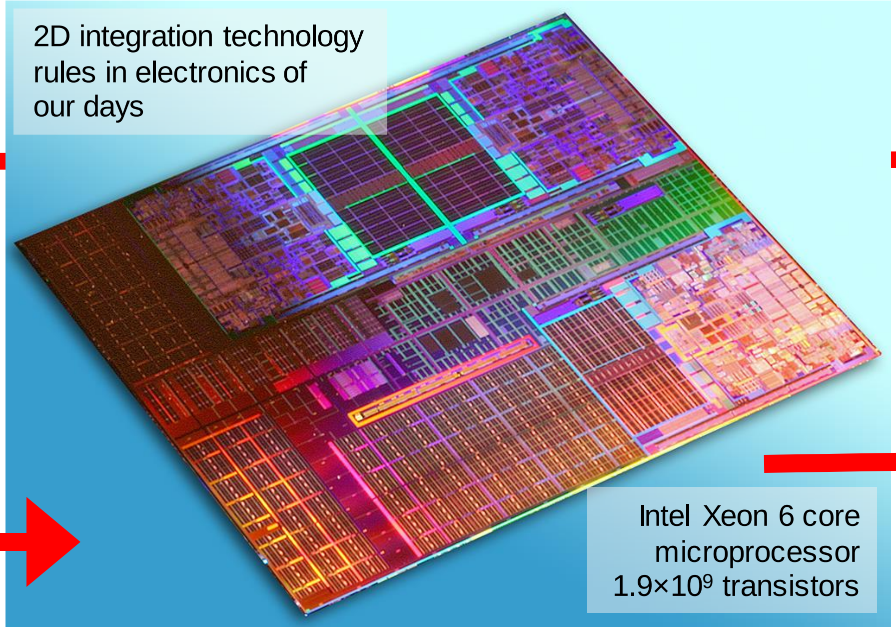


first monolithic integrated circuit: logic (Fairchild 1961)

more and more components, more and more functions, growing complexity

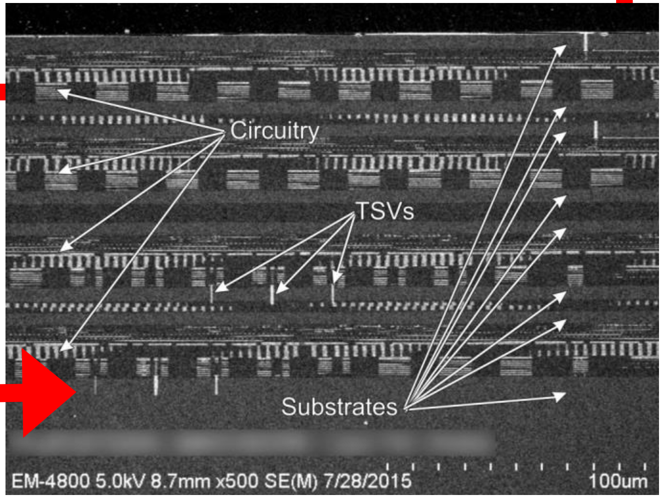
k0258756 www.fotosearch.com

2D integration technology rules in electronics of our days



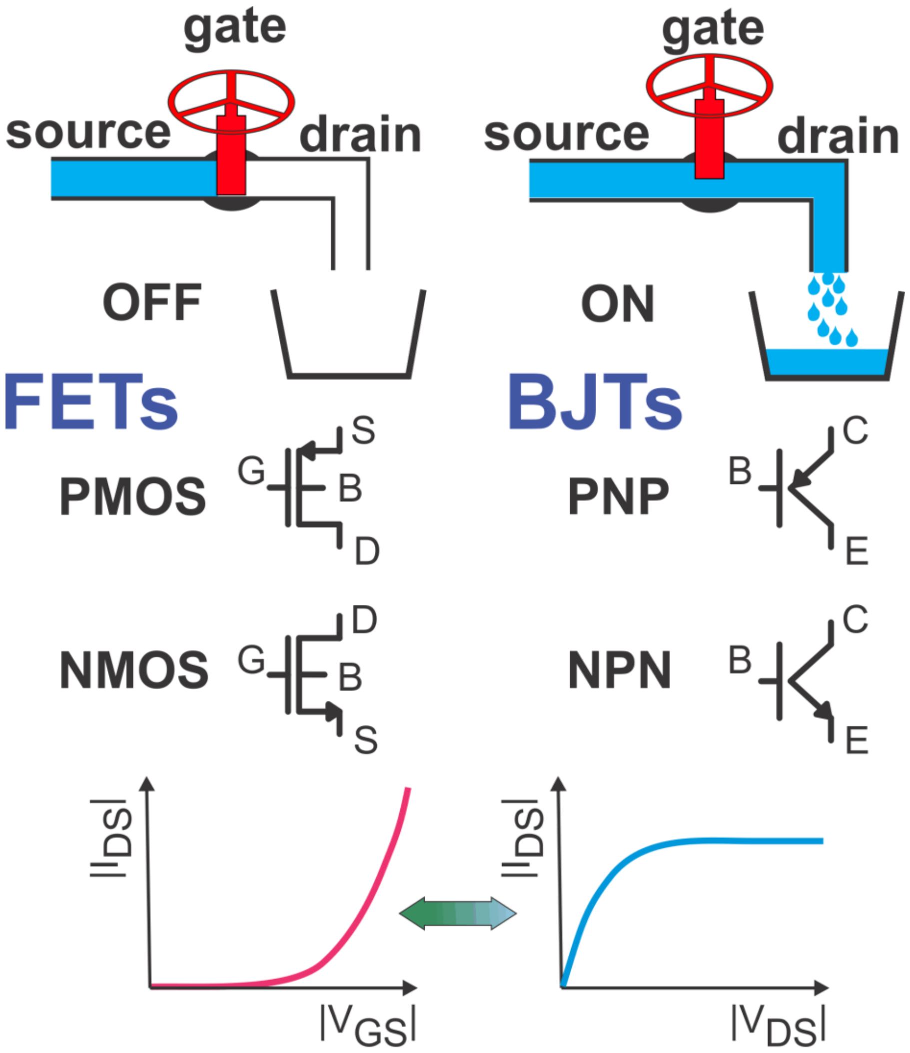
Intel Xeon 6 core microprocessor 1.9×10^9 transistors

Integration in 2D is not enough ➡ **3D**



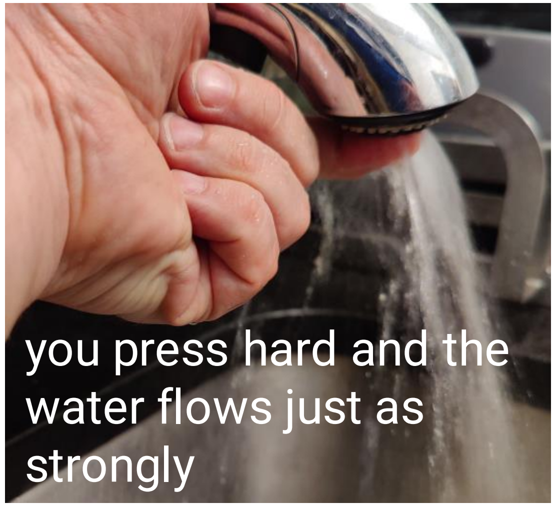
8-layer stack of integrated circuits interconnected vertically (Tezzaron)

Transistors and Amplifiers - 1



with a little effort
we change a lot

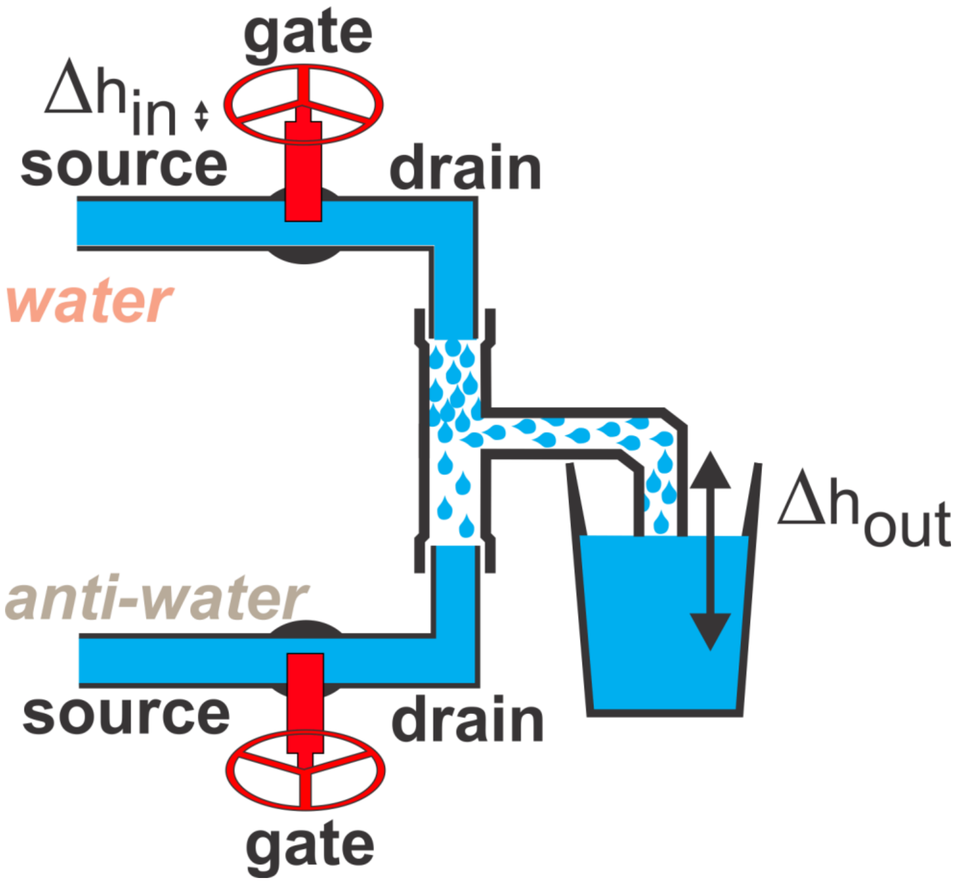
we try to resist but
flow does no change



you press hard and the water flows just as strongly

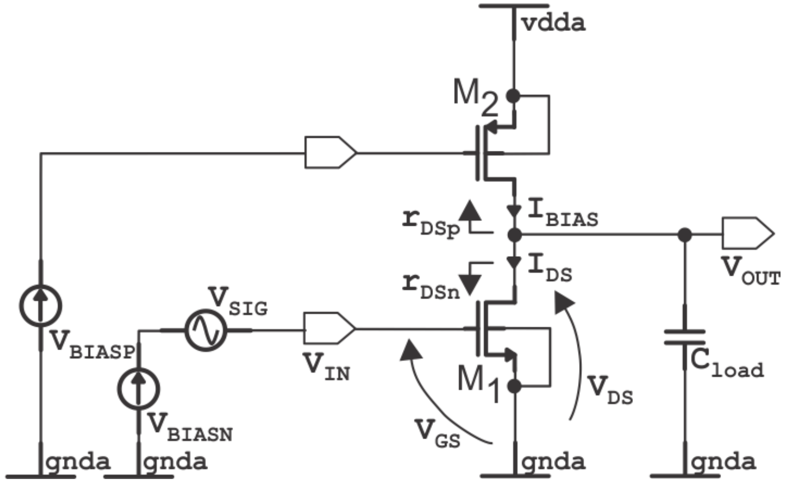
This is how we built amplifier:

- resistance of a finger loads a faucet,
- water stream, set by turning know just a little bit, pushes measurably on our finger

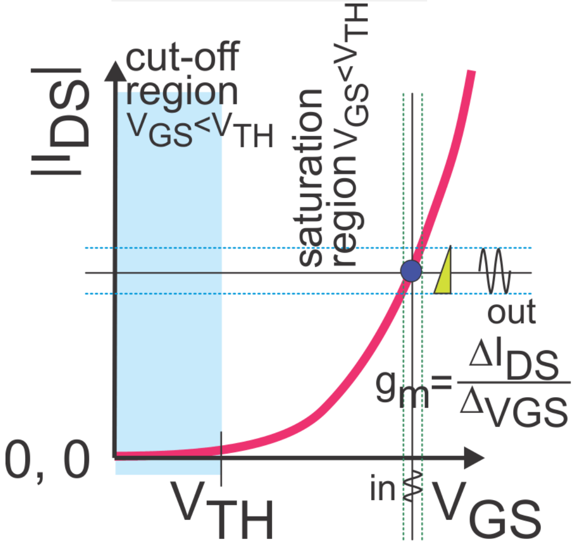


Transistors and Amplifiers - 2

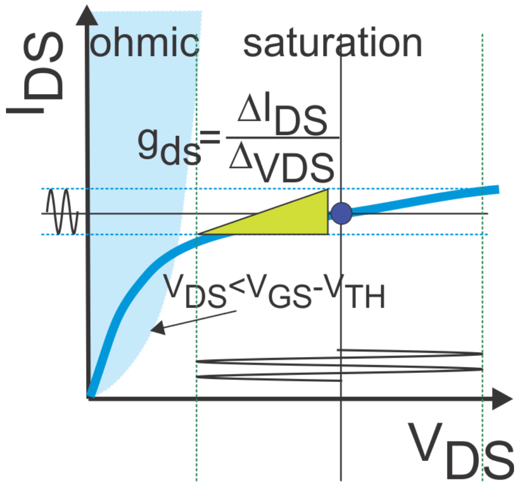
Why can we amplify signals?



input characteristics

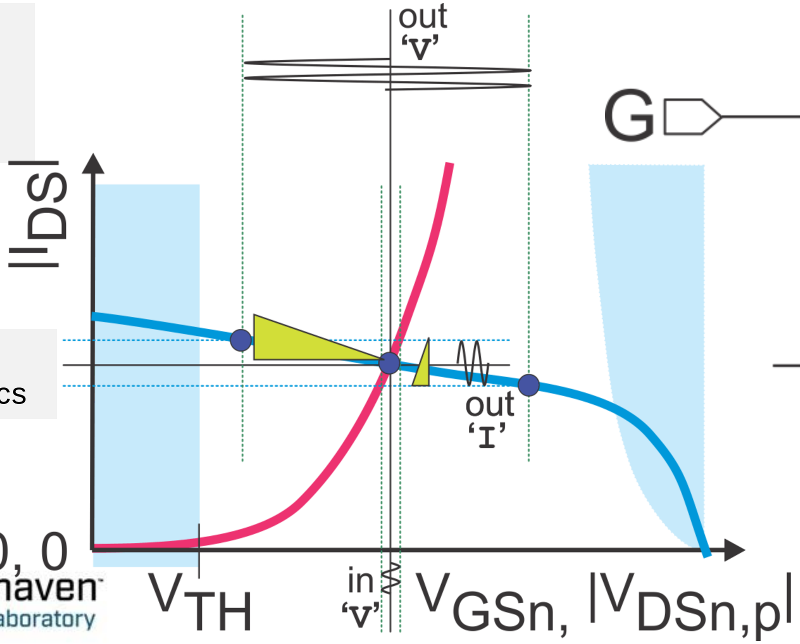


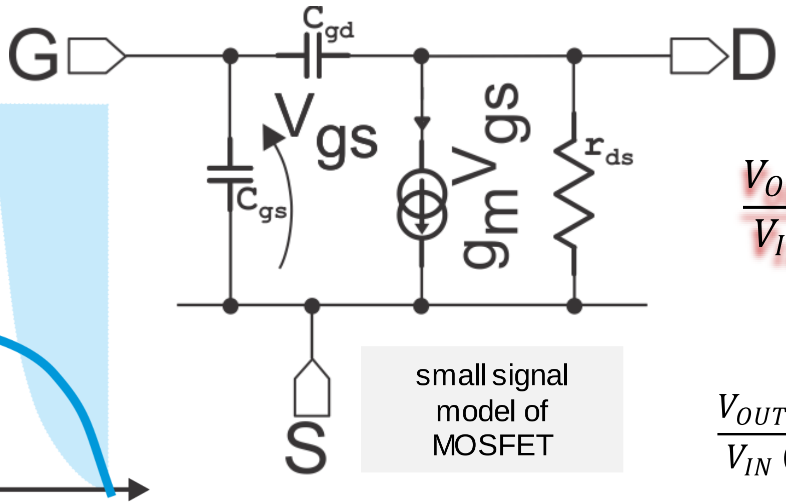
output characteristics



input signal applied to gate on top of bias voltage

“transfer” characteristics





small signal model of MOSFET

$$\frac{V_{OUT}}{V_{IN}} = -\frac{g_m}{g_{dsn}||g_{dsp}}$$

assume N and P identical

$$\frac{V_{OUT}}{V_{IN}} = -\frac{g_m(r_{dsn}\cdot r_{dsp})}{r_{dsn}+r_{dsp}} \Rightarrow \frac{V_{OUT}}{V_{IN}} = -\frac{g_m r_{ds}}{2}$$

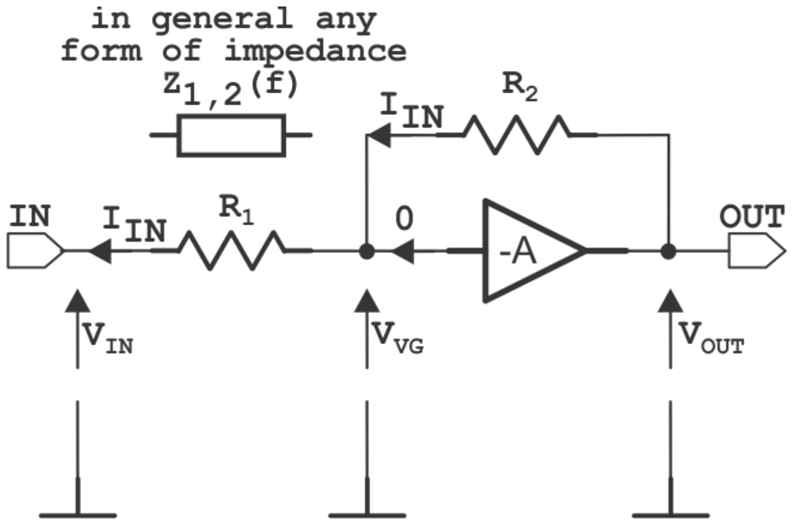
What to do with C_{load}?

$$\frac{V_{OUT}(s)}{V_{IN}(s)} = -g_m\frac{r_{ds}}{2}||C_{load} = -g_m\frac{r_{ds}}{2\left(1+sC_{load}\frac{r_{ds}}{2}\right)}$$

bandwidth limitation

Transistors and Amplifiers - 3

basic, inverting voltage amplifier with operational amplifier



Operational amplifier:

- infinite input impedance ➡ no current flowing into input of amplifier;
- infinite voltage gain ➡ needs feedback circuit to operate, otherwise act as inverter/comparator ;
- infinite frequency bandwidth ➡ characteristics decided by feedback network;
- zero output impedance ➡ can act as voltage source;

Operational amplifier does not exist in nature, but it is well approximated by actual designs:

- input impedance ➡ MΩ-GΩ with dominating capacitive component;
- voltage gain ➡ 100dB; MΩ-GΩ;
- frequency bandwidth ➡ low, kHz, but due to gain-bandwidth exchange sufficient;

writing down Kirchhoff's Voltage and Current Laws:

$$\left\{\begin{array}{l} V_{IN} + IR_1 - V_{VG} = 0 \\ V_{VG} + IR_2 - V_{OUT} = 0 \\ V_{OUT} = -AV_{VG} \\ I_{IN} - 0 - I_{IN} = 0 \end{array}\right. \Longrightarrow I_{IN} = \frac{V_{VG} - V_{IN}}{R_1}, I_{IN} = \frac{V_{OUT} - V_{VG}}{R_2}$$

$$\frac{V_{VG} - V_{IN}}{R_1} = \frac{V_{OUT} - V_{VG}}{R2}$$

$$substituting\ for\ V_{VG} = -\frac{V_{OUT}}{A}$$

$$\left(\frac{-\frac{V_{OUT}}{A} - V_{IN}}{R_1}\right) = \left(\frac{\frac{V_{OUT}}{A} + V_{OUT}}{R_2}\right)$$

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_2}{\frac{R_1 + R_2}{A} + R_1} \Longrightarrow \lim_{A\to\infty} -\frac{R_2}{\frac{R_1 + R_2}{A} + R_1} = -\frac{R_2}{R_1}$$

$$H(j\omega) = \frac{V_{OUT}(j\omega)}{V_{IN}(j\omega)} = -\frac{Z_2(j\omega)}{Z_1(j\omega)} \qquad for\ s = j\omega, H(s) = -\frac{Z_2(s)}{Z_1(s)}$$

if Z_2 is capacitor C_2:	$H(s) = -\frac{1}{sC_2R_1}$	ideal integrator
if Z_2 is resistor‖capacitor:	$H(s) = -\frac{R_2}{R_1(1 + sC_2R_2)}$	lossy integrator
if Z_1 is capacitor:	$H(s) = -sC_1R_2$	differentiator

Sensors and readout ICs

①Gate SiO2 Oxidation followed by Well, BPW Implantation

②After Gate stack formation (with extension and sidewall formations)

③BW(NSUB,PSUB) photo/etching and S/D, NSUB, PSUB Implantation

④S/D annealing and Salicidation

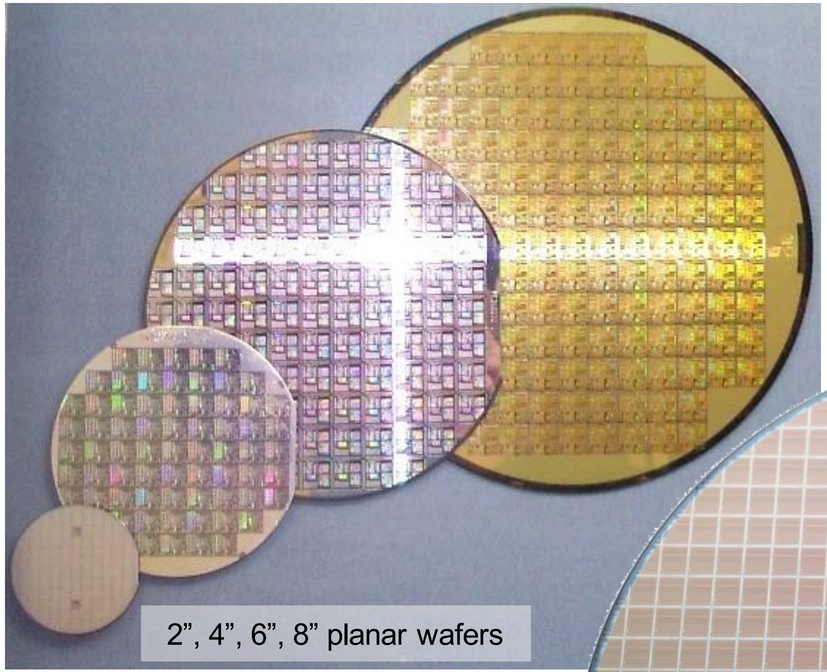
⑤1st ILD filling and CMP planarization (after Salicide formation)

⑥Contact etching (2CS for substrate and 2C for S/D and gate of transistor)

⑦Contact plug filling and 1st Metal formation

⑧BEOL (2 ~ 4th Metal formation)
followed by Backside polishing and Metal coating

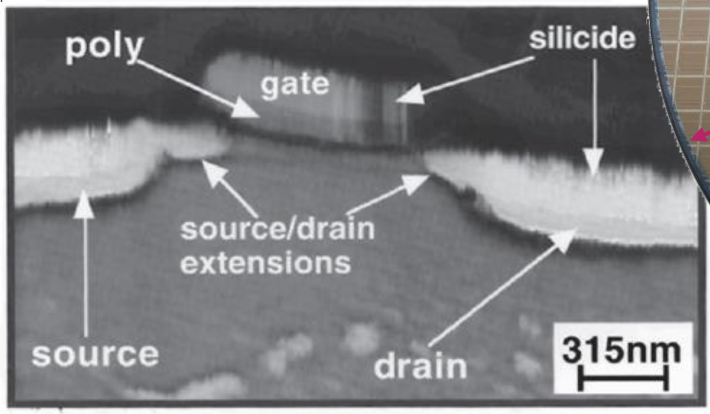
example of planar process flow

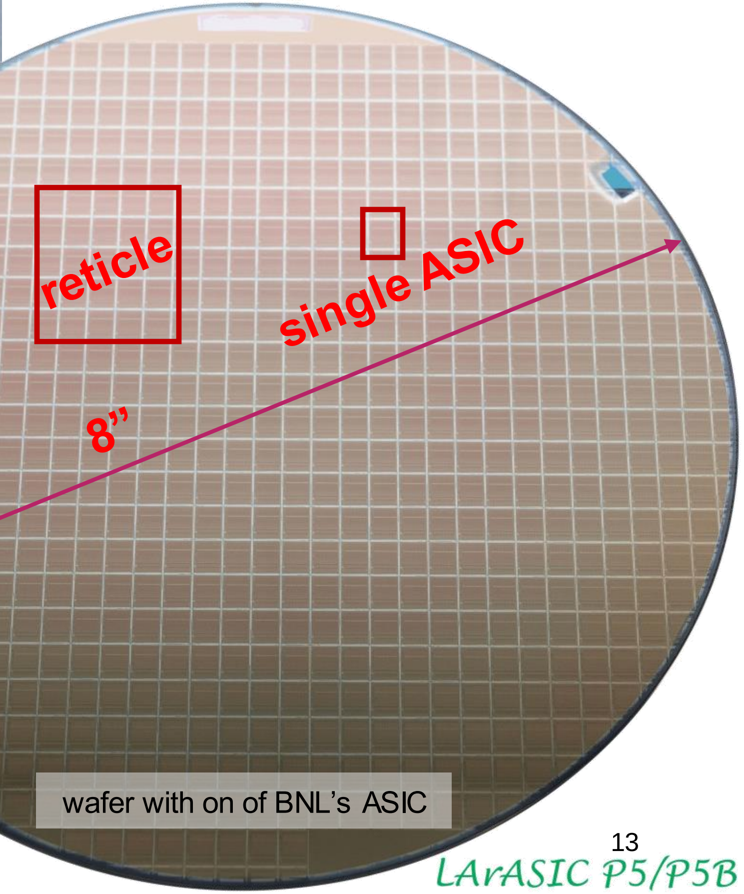


2”, 4”, 6”, 8” planar wafers

- sensors and ICs are fabricated in similar way, using multiple steps of planar processing

X-section of NMOS transistor seen in Scanning Resistance Microscope



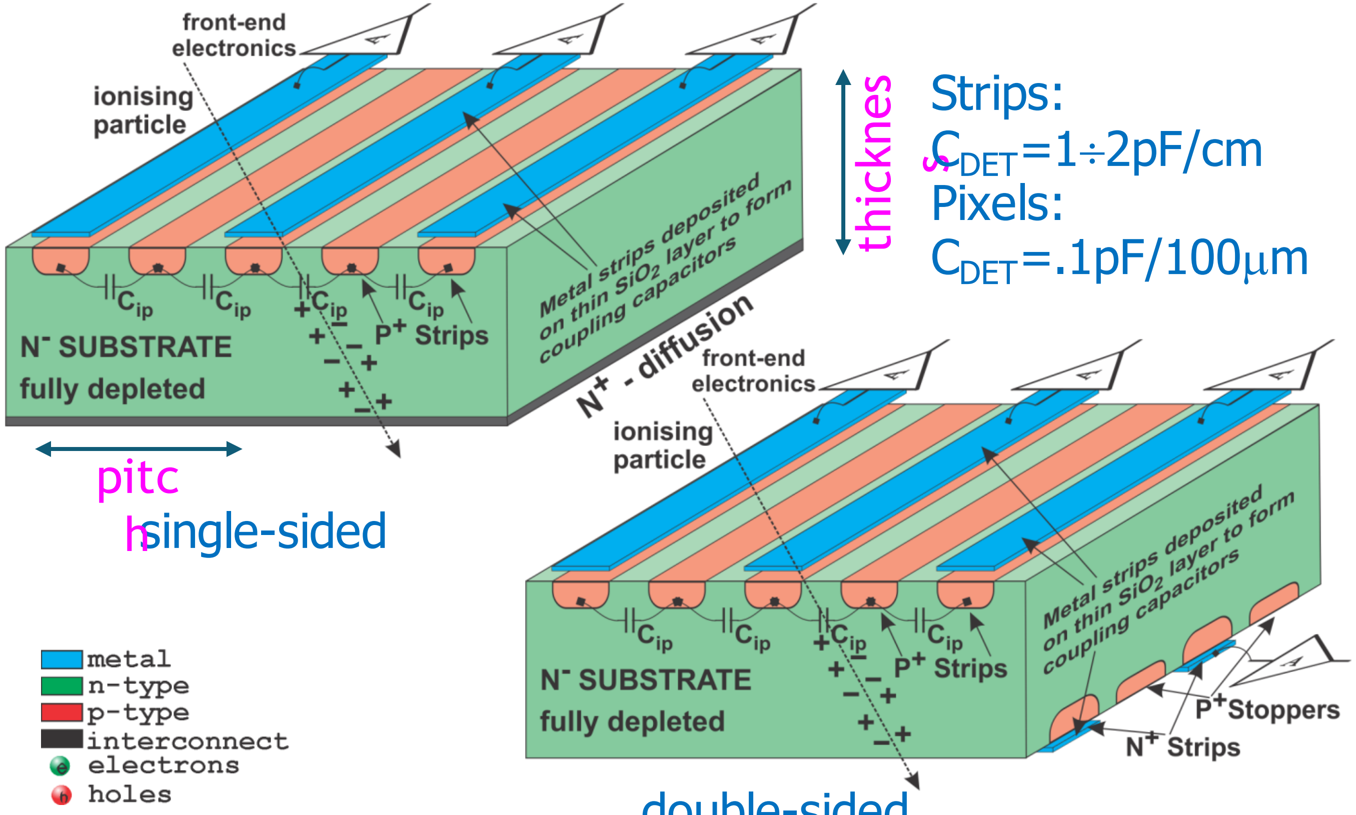


wafer with on of BNL’s ASIC

Geometries of Solid-State Sensors

STRIPS

Strips sensors deliver 1D - (sometimes 2D – but prone to ambiguity) aware information about incident radiation



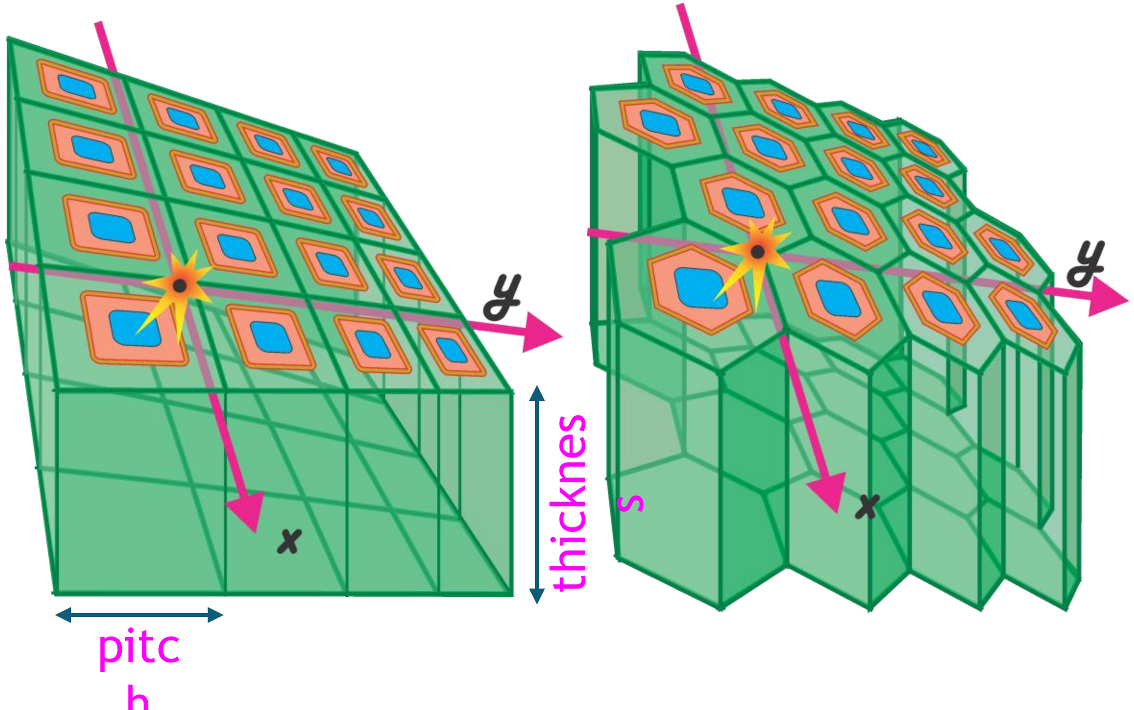
single-sided

double-sided

Strips:
$C_{DET}=1\div2$pF/cm
Pixels:
$C_{DET}=.1$pF/100μm

PIXELS

Pixel sensors deliver 2D - (sometimes 3D) aware information about incident radiation

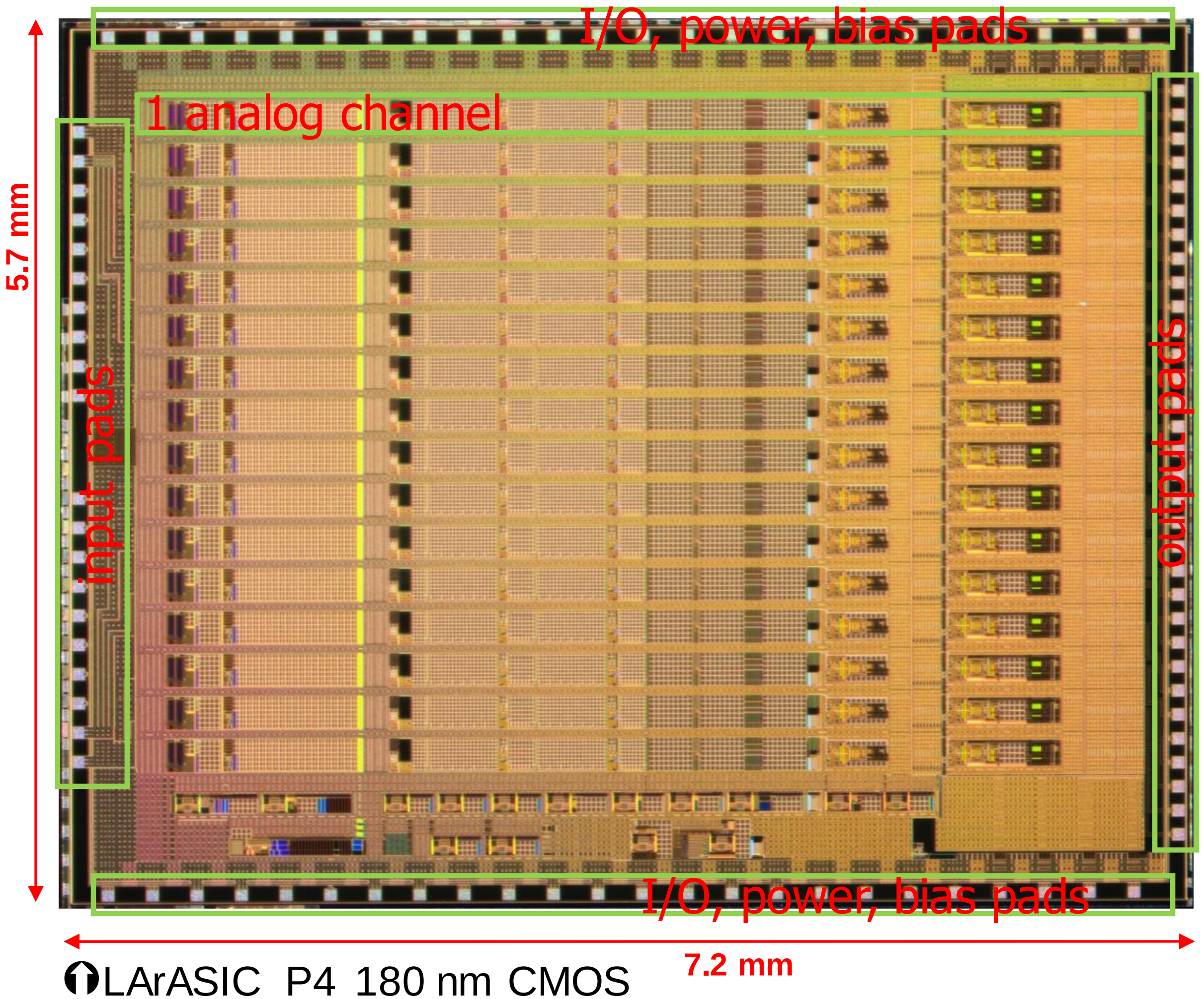


square (rectangular)

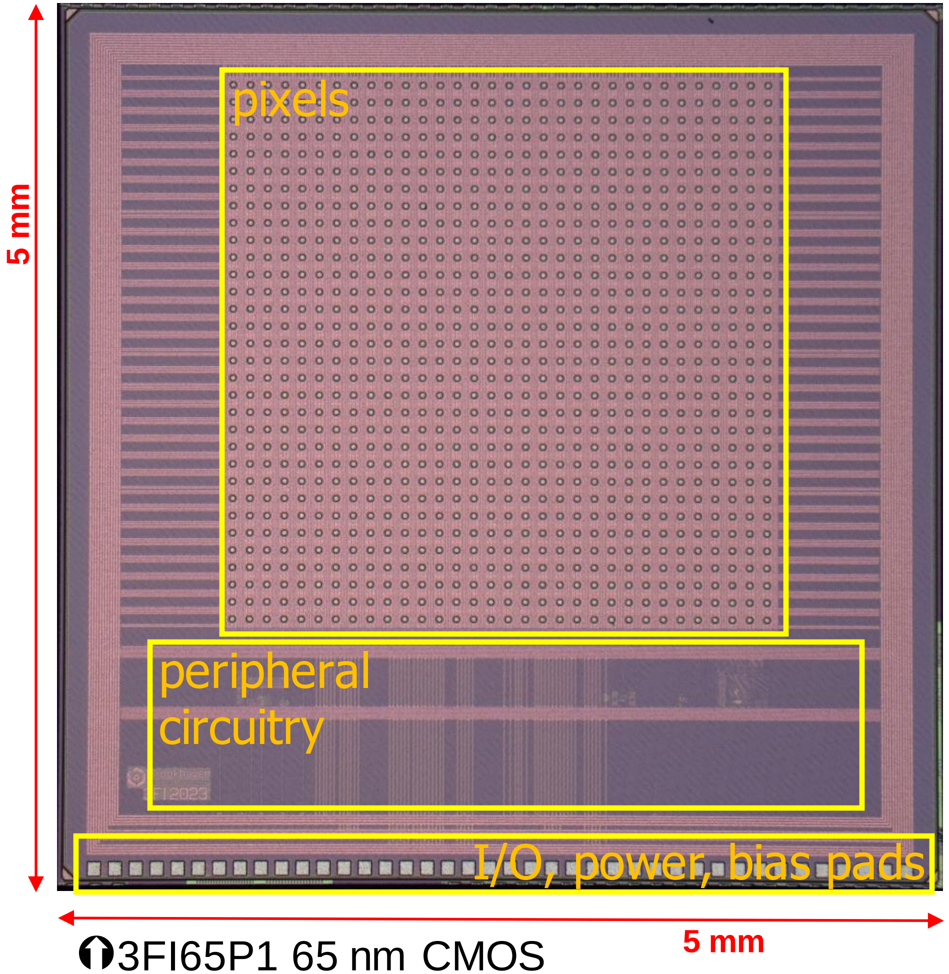
hexagonal

both types of sensors may be used to measure time of arrival

Readout ICs



LArASIC_P4 180 nm CMOS
[16 channel Analog Front-End for liquid Ar TPC readout]



3FI65P1 65 nm CMOS
[pixel readout IC 32×32 pixels @100 μm sq pitch]

Typical charge processing chain - 1

Sensors read out by charge sensitive electronics:

- deliver at their output short current pulse, whenever ionizing radiation interacts with their sensitive regions;
- charge carried by output current pulse of sensor is linearly related to energy released by radiation in sensitive region of sensor (mean value);
- typically produce small portions of charge:
  - small energy released;
  - low sensor's sensitivity;

} Noise of first amplification stages degrades accuracy in measurements

Accuracy may also be degraded when:

- sensor is exposed to relatively high radiation intensity ➡ time separation between single events is short, leading to;
  - baseline fluctuations;
  - pulse-on-pulse pile-up effects;
- time which is available to perform charge measurements is reduced (e.g., beam crossing cadence);
- interferences, common modes, ground bouncing, etc. ➡ baseline fluctuations ;

Measurement of energy released by nuclear event in sensitive region of sensors must be considered performed:

- once analog quantity which carrier information of such energy, or charge delivered by sensors, is converted by Analog-to-Digital converter (ADC) or Time-to-Digital Converter (TDC) into number;
- and obtained number is stored in digital memory;

To be suitable for ADC, current pulse delivered by sensor must undergo several operations:

- aiming at delivering to ADC signal with suitable characteristic to guarantee correct conversion (antialiasing);
- reducing accuracy degradation.

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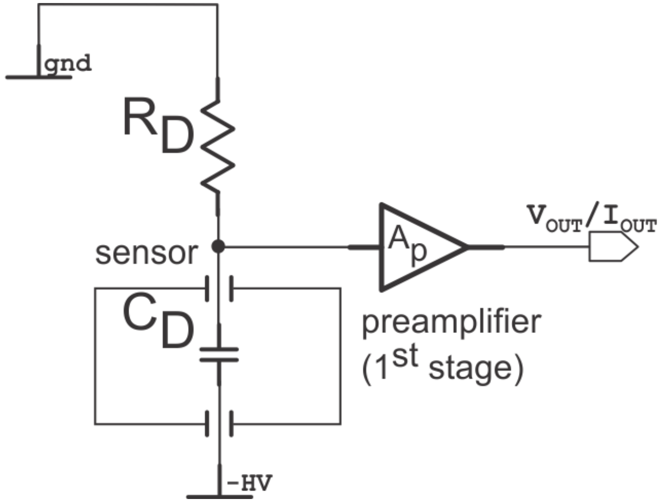
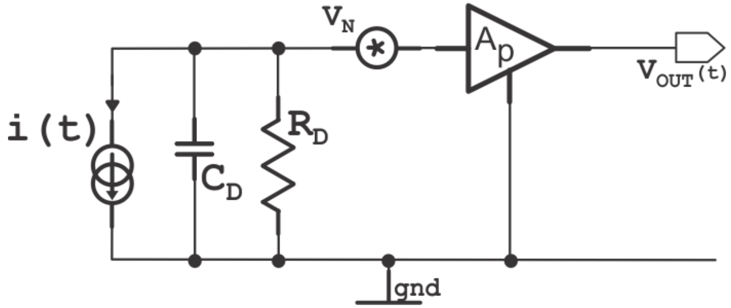
Typical charge processing chain - 2

circuit diagram



A_p provides voltage gain – voltage mode processing

equivalent circuit

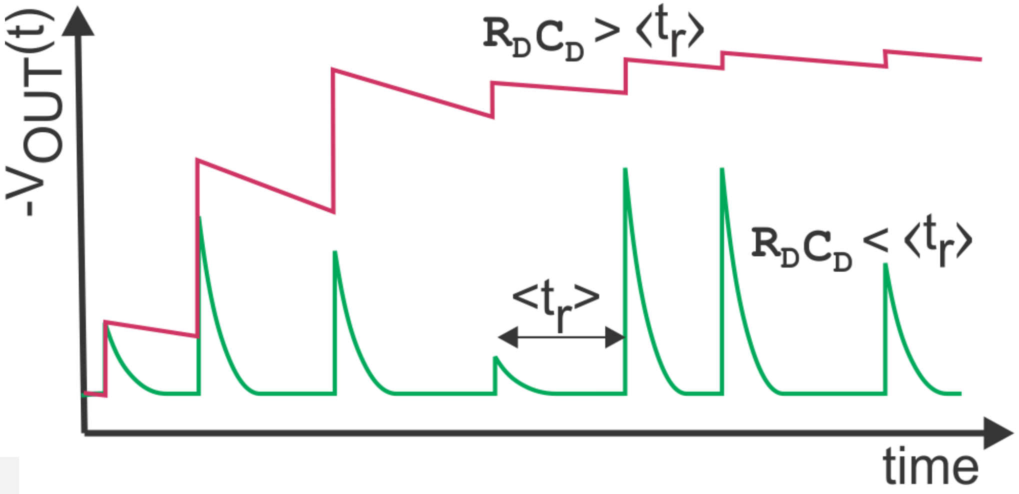


response to single charge pulse:

$$V_{OUT}(t) = -A_p \frac{Q}{C_D} e^{-t/R_D C_D} + A_p V_N(t)$$

response depends on CD that may change with for example HV bias applied

waveform at output of preamplifier

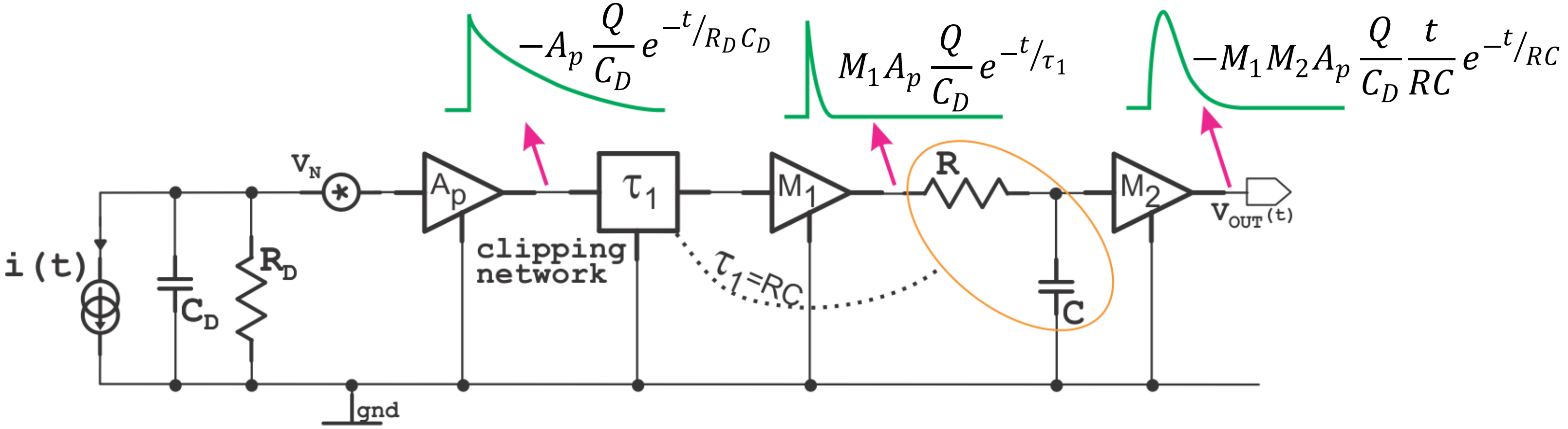


If $C_D R_D$ too big output of AP saturates and becomes insensitive

Typical charge processing chain - 3

How to prevent saturation: clipping network aka pole-zero cancellation

not rigorous in representing polarity

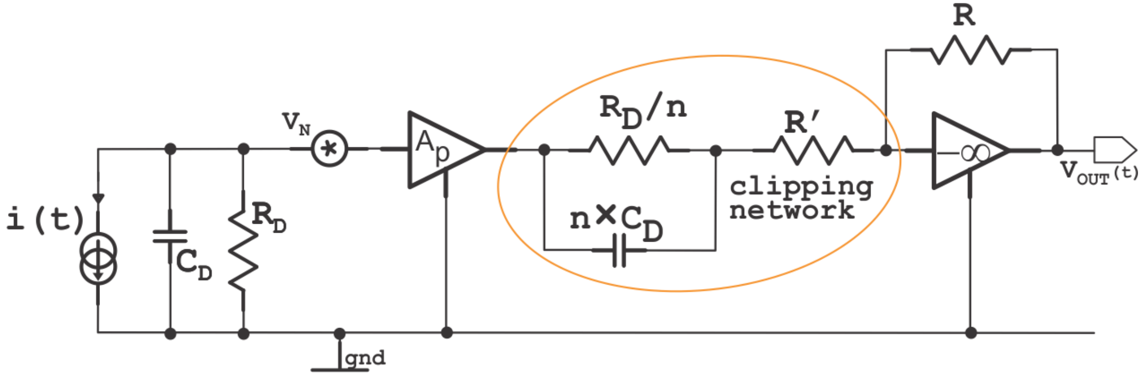


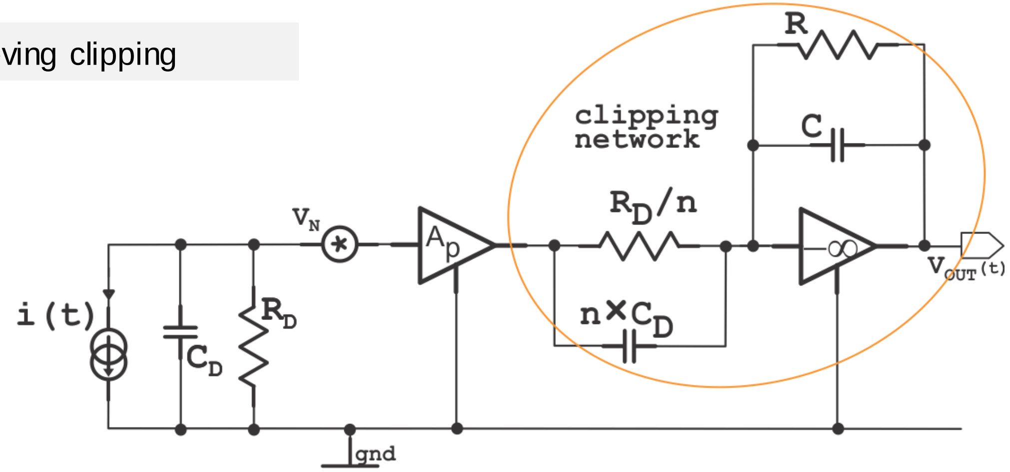
$$-A_p \frac{Q}{C_D} e^{-t/R_D C_D}$$

$$M_1 A_p \frac{Q}{C_D} e^{-t/\tau_1}$$

$$-M_1 M_2 A_p \frac{Q}{C_D} \frac{t}{RC} e^{-t/RC}$$

two ways of achieving clipping



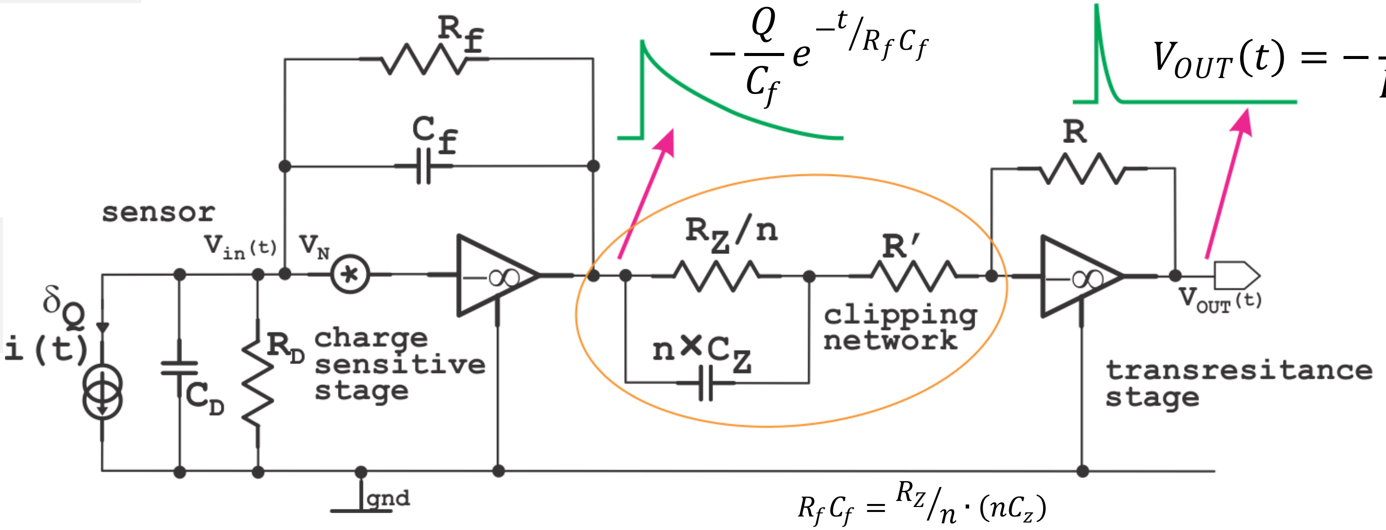


ratio R/R’ allows adding voltage gain

Typical charge processing chain - 4

not rigorous in representing polarity

How to make response independent of C_D:



$$-\frac{Q}{C_f} e^{-t/R_f C_f}$$

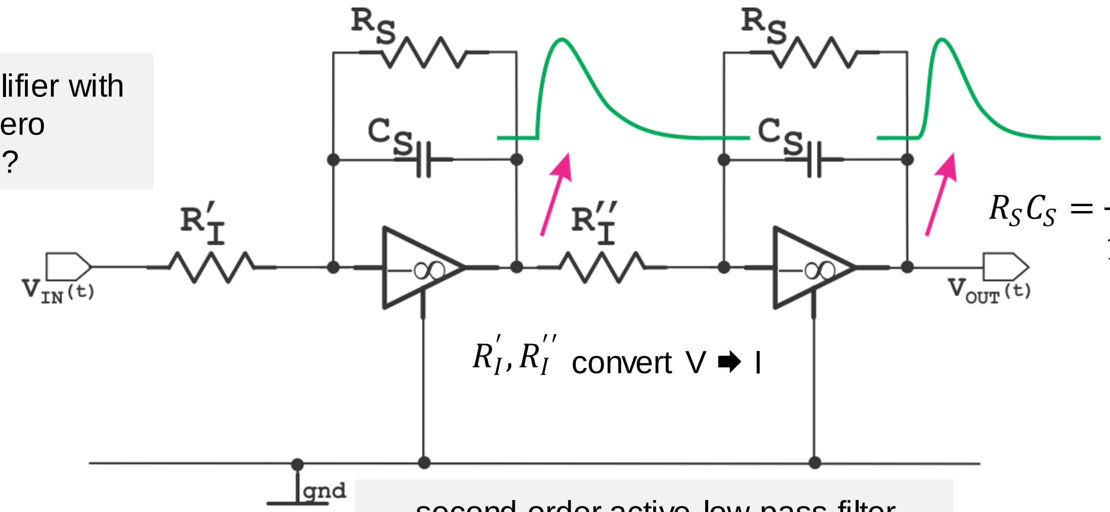
$$V_{OUT}(t) = -\frac{R}{R+R'} Q \frac{R'(nC_f)}{C_f} e^{-t \Big/ \frac{R_f C_f}{1+\frac{R'}{R}}}$$

$$R_f C_f = {}^{R_Z}/_{n} \cdot (nC_z)$$

because of infinite gain of amplifier, there is no current flowing through C_D and R_D

signal amplitude is multiplied how many times nC_f is larger than C_f
charge gain

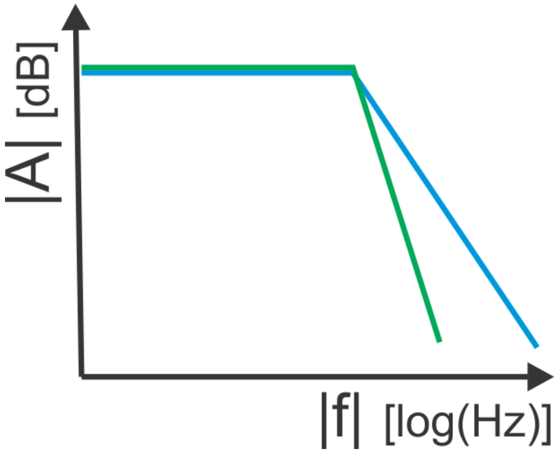
what follows preamplifier with clipping (pole-zero cancellation) ?



$$R_S C_S = \frac{R_f C_f}{1+\frac{R'}{R}}$$

R_I', R_I'' convert V ➡ I

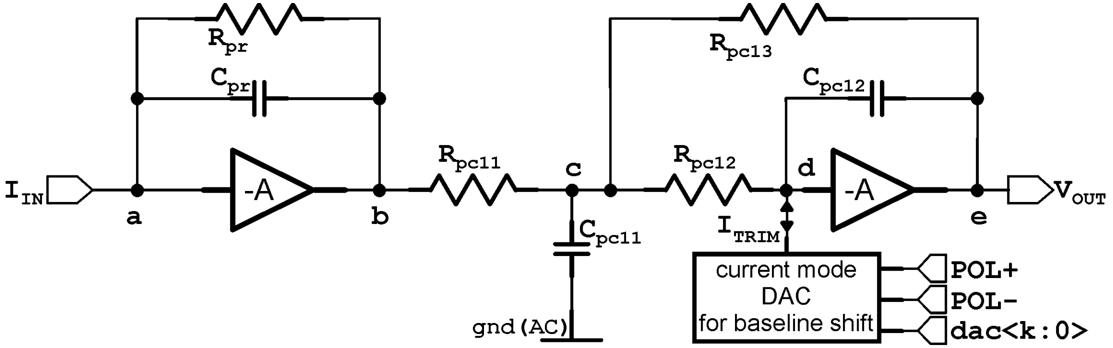
second order active low-pass filter



Typical charge processing chain - 6

ADVANCED

Other options of filters:

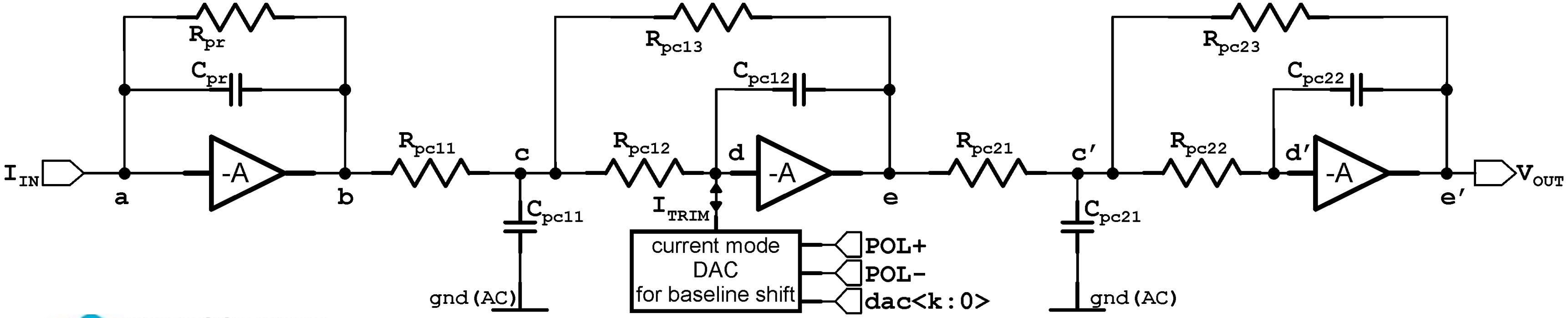


3rd order semi-gaussian shaping filter with one real pole and one pairs of complex conjugate poles

R_{pr} = 571.6 kΩ
C_{pr} = 304 fF
R_{pc11} = 183.2 kΩ / 7 = 26.17 kΩ
C_{pc11} = 4.52 pF
R_{pc12} = 183.2 kΩ
C_{pc12} = 304 pF / 2 =152 pF
R_{pc13} = 183.2 kΩ
I current DAC = +-250 nA (baseline) + 1uA (polarity)

- capacitance C_c is coupling capacitance for last stage of CSA

$$H_t(s)=\frac{1}{s}\,\frac{-sC_cR_{pr}}{sC_{pr}R_{pr}+1}\,\frac{1}{s^2C_{pc11}C_{pc12}R_{pc12}R_{pc13}+sC_{pc12}R_{pc12}\left(1+\frac{R_{pc13}}{R_{pc11}}+\frac{R_{pc13}}{R_{pc12}}\right)+1}=\frac{-sC_cR_{pr}}{sC_{pr}R_{pr}+1}\,\frac{-A_v}{\frac{s^2}{\omega_0^2}+\frac{s}{\omega_0Q}+1}$$



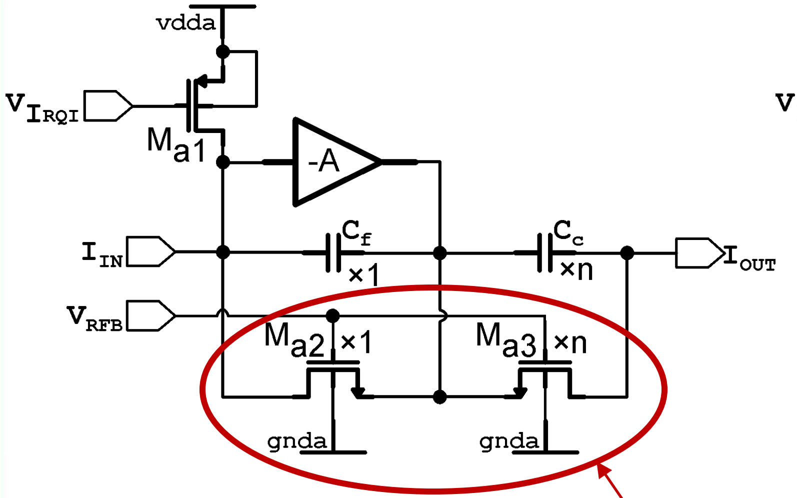
- DAC current injected into node ‘d’ to avoid additional parallel noise that would be added in case of using the node ‘a’,
- relatively large value of R_{pc12} allows achieving efficient voltage shifts of baseline with low current of DAC that limits power consumption.

5th order semi-gaussian shaping filter with one real pole and two pairs of complex conjugate poles

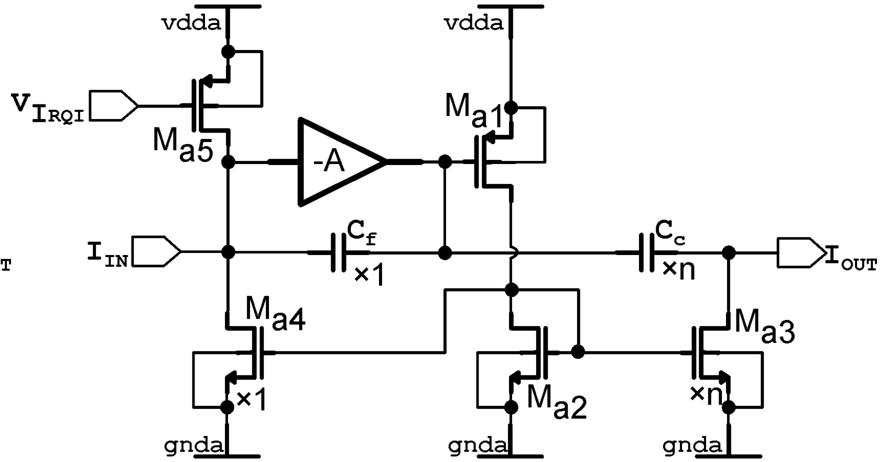
Typical charge processing chain - 7

ADVANCED

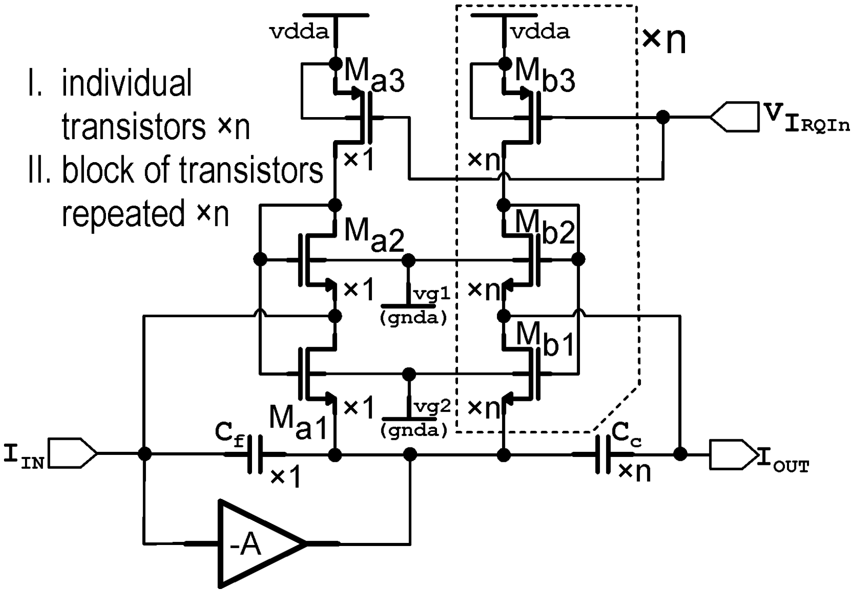
How preamplifier is designed with no resistors:



[♦] G. De Geronimo et al, “A CMOS detector leakage current self-adaptable continuous reset system: theoretical analysis”, Nucl. Instr. Meth. A 421 (1999) 322-333



[♥] G. De Geronimo et al, “Front-End ASIC for a GEM Based Time Projection Chamber”, IEEE Trans. Nucl. Sci Vol. 51, No. 4, August 2004 1313-1317

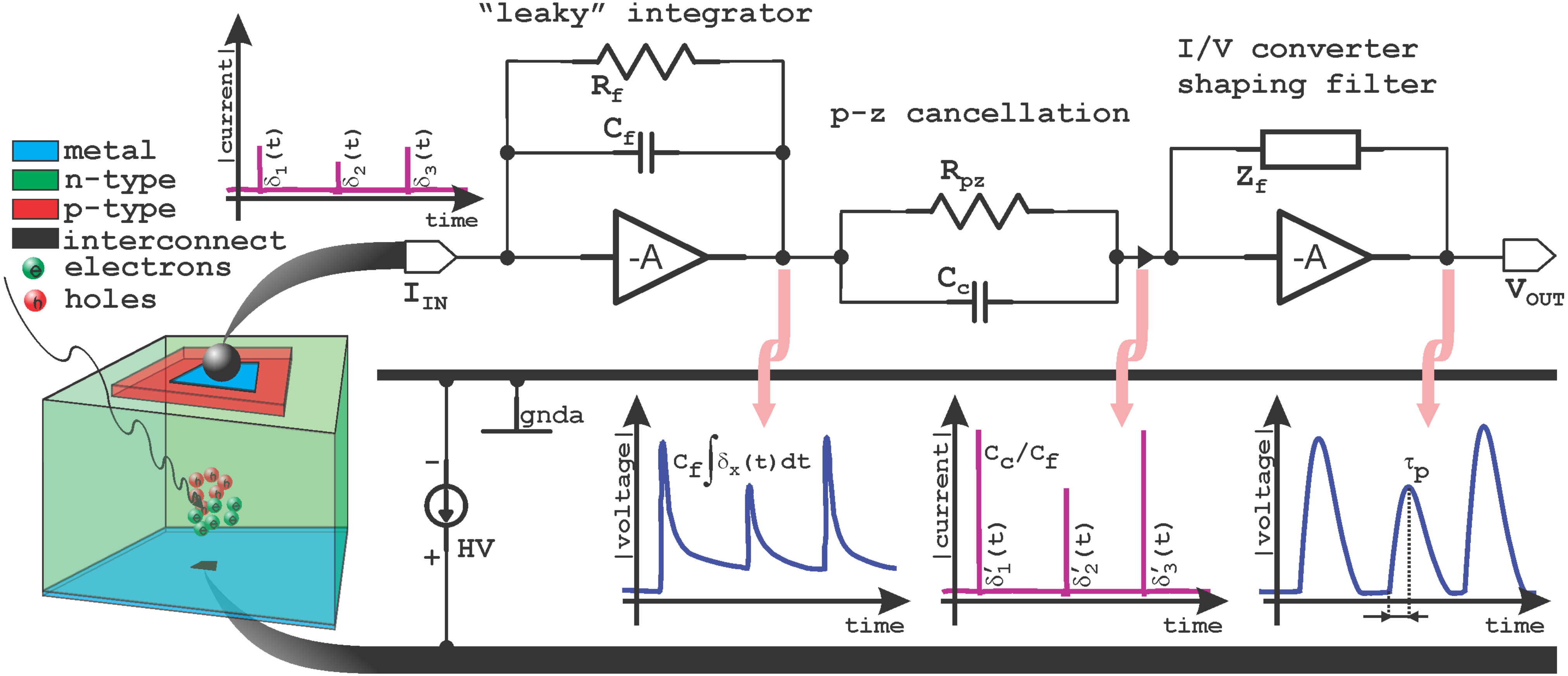


I. individual transistors ×n
II. block of transistors repeated ×n

[♣] G. W. Deptuch, P. Otfinowski, “Charge Sensitive Amplifier with Pole-Zero Cancellation”, provisional patent application USPTO Serial No. 63/379,887

still one can see resistors !
resistance of transistors’ channels
controlled by gate voltages

Typical charge processing chain - 8



characteristic parameters of typical materials for semiconductor sensors

quantity	Si	Ge	GaAs	Diamond	CdTe	$Cd_{0.9}Zn_{0.1}Te$	TlBr	a-Si
E_g [eV]	1.12	0.67	1.43	5.50	1.44	1.57	2.68	1.90
W [eV]	3.60	2.96	4.20	13.00	4.43	4.64	6.50	6.00
ε	11.7	16.0	12.8	5.7	10.9	10.0	30.0	12
μ_e [cm^2/(Vs)$^{-1}$]	1350	3900	8000	1800	1100	1000	30	1-4
μ_h [cm^2/(Vs)$^{-1}$]	450	1900	400	1200	100	120	4	0.05
ρ [g/cm^3]	2.33	5.33	5.32	3.52	5.85	5.78	7.56	2.30

Other types of sensors:
- gas ionization chambers;
- proportional counters;
- scintillation sensors

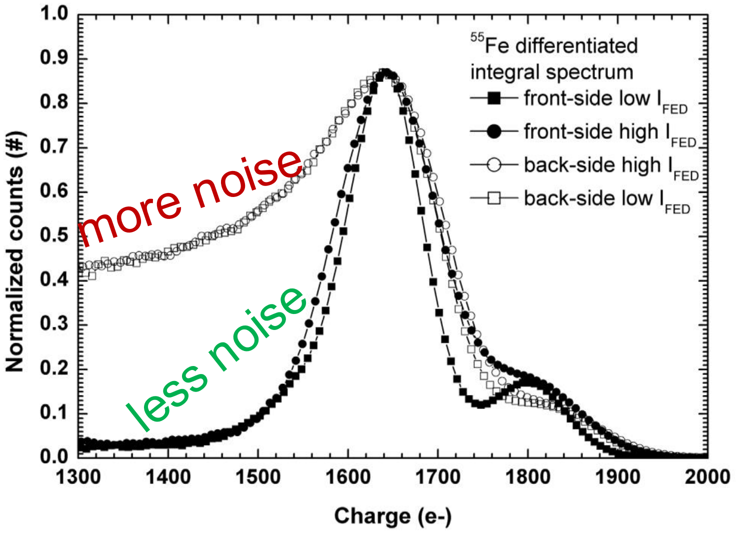
Brookhaven National Laboratory

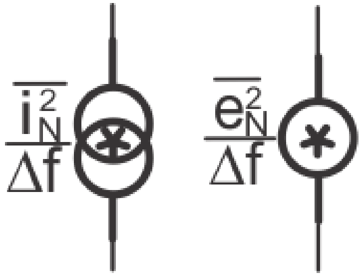
Noise - 1

noise gives rise to degradation of signal delivered by sensor ➡ limited accuracy in information carried by such signal

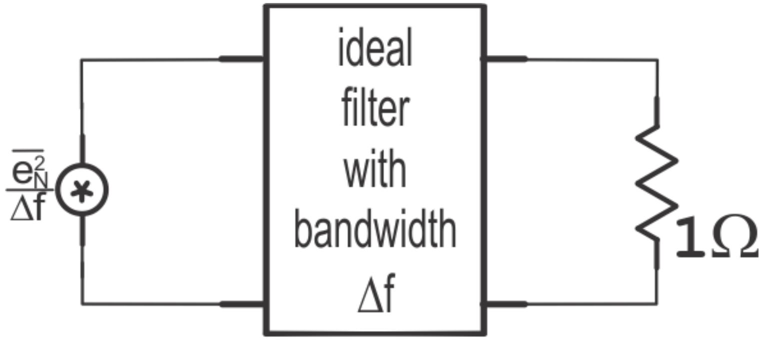
- noise terms directly related with detection mechanism: fluctuations in number of liberated e⁻h⁺ pairs (Fano factor)
- noise stochastic terms in circuit devices
- noise terms resulting form electromagnetic disturbances, ground loop, ground bouncing, power supply ripple, etc.

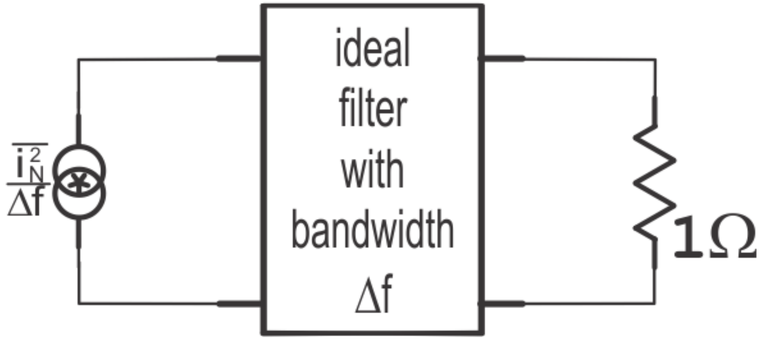
shielding





noise current and voltage sources





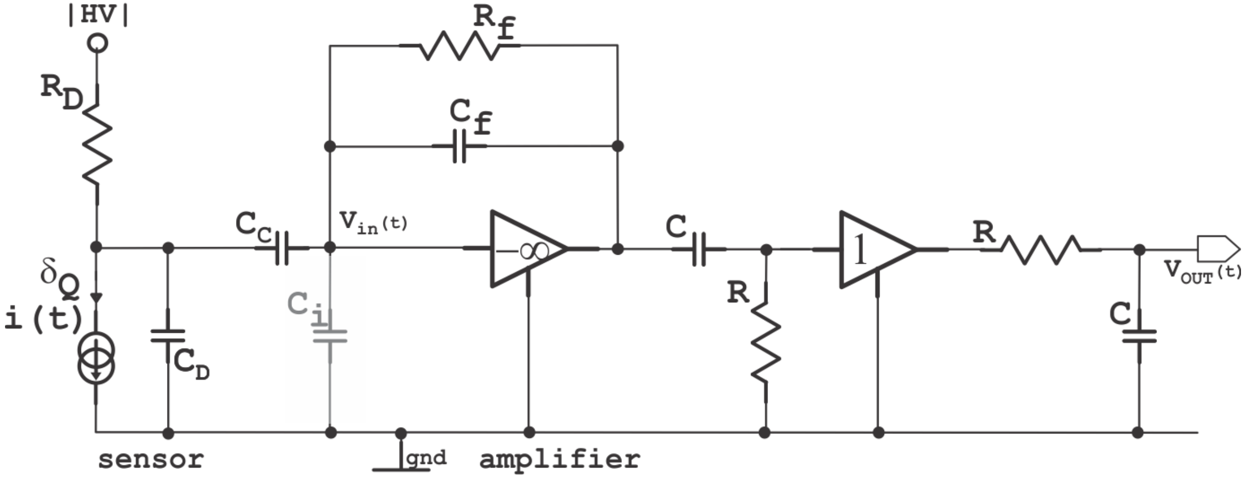
meaning of both sources s average power delivered to 1Ω load in frequency interval Δf

		$\frac{\overline{e_N^2}}{\Delta f}$	$\frac{\overline{i_N^2}}{\Delta f}$
resistor		$4kTR$	$\frac{4kT}{R}$
capacitor		—	—
diode		$2qI_D$	—
MOSFET	th.	$4kT\frac{0.7}{g_m}$	$2qI_G$
	1/f	$\frac{K_f}{C_{ox}^2 WL}\frac{1}{f}$	

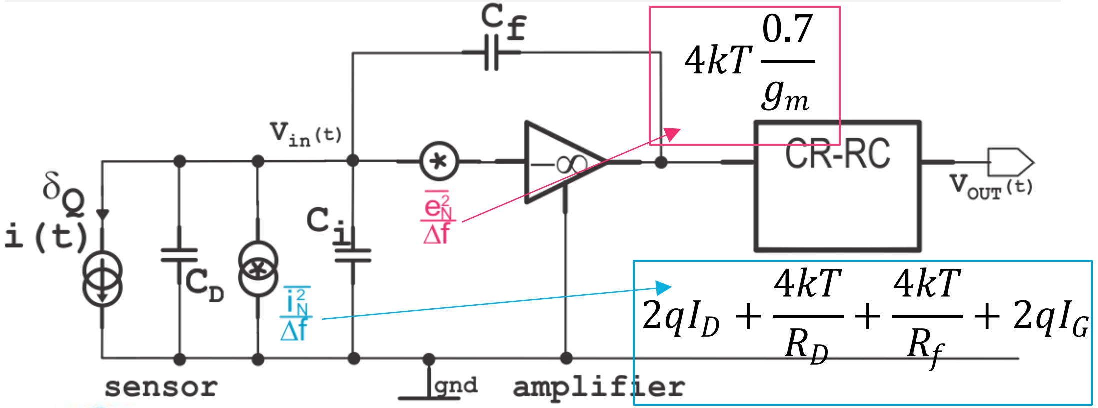
Thevenin/ Norton

Noise - 2

much simplified and brief analysis:



- C_C is large so it can be replaced by short
- C_i is input capacitance of amplifier (1st transistor gate)
- R_f, R_D are large, so consider as opens, but look at noise contribution!
- replace p-z by CR-RC cascade



$$4kT\frac{0.7}{g_m}$$

$$2qI_D+\frac{4kT}{R_D}+\frac{4kT}{R_f}+2qI_G$$

noise power at output of integrator:

currents
$$\left(2q(I_D+I_G)+4kT\left(\frac{1}{R_D}+\frac{1}{R_f}\right)\right)\frac{1}{\omega^2 C_f^2}$$

voltages
$$4kT\frac{(C_i+C_D+C_f)^2}{C_f^2}\frac{0.7}{g_m}$$

CR-RC filter
$$H(j\omega)=\frac{1}{1+j\omega RC}\,\frac{j\omega RC}{1+j\omega RC}$$

$$\left[\frac{power\ spectrum}{at\ output}\right]=\left[\frac{power\ spectrum}{at\ input}\right]|H(j\omega)|^2$$

$$|RMS\ NOISE|^2=\int_0^\infty\left[\frac{power\ spectrum}{at\ output}\right]df$$

$\omega=2\pi f$

we know that peak amplitude is Q/C_f ,
so ENC is at Room Temperature:

$$ENC=17.36\left[1.45\frac{(C_i+C_D+C_f)^2}{g_m}\frac{1}{\tau_p}+\left\{40(I_D+I_G)+2070\left(\frac{1}{R_D}+\frac{1}{R_f}\right)\right\}\tau_p\right]^{1/2}$$

let's design detecting system so that parallel noise is negligible and knowing that C_f is small:

$$ENC=21(C_D+C_i)\left[\frac{1}{g_m\tau_p}\right]^{1/2}$$

so, for C_D and C_i in pF, g_m in mS and τ_p in μs, for τ_p=1 and g_m=10

=> ENC≈$6e^-$/pF

because
$$g_m\propto\sqrt{\frac{C_{ox}WI_{DS}}{L}}$$

It is possible to find relation between C_D and C_i minimizing ENC

Noise (summary) - 3

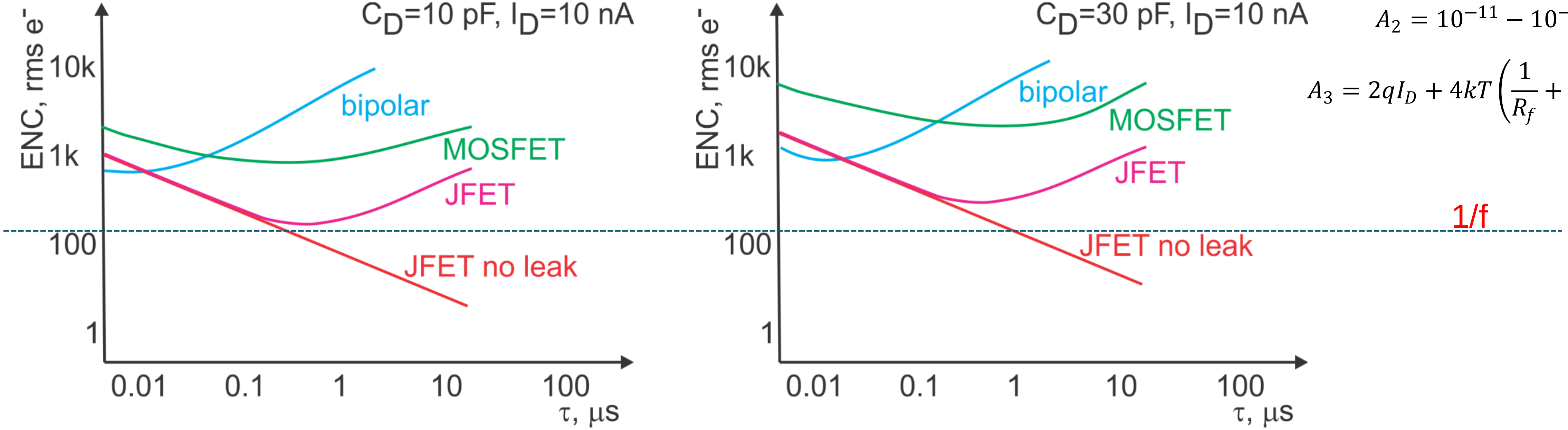
$$ENC^2 = A_1\left(C_D + C_i + C_f\right)^2 \frac{1}{\tau_p} + A_2\left(C_D + C_i + C_f\right)^2 \frac{2ln2}{\pi} + \frac{1}{3} A_3 \tau_p$$

for triangular shaping and MOS

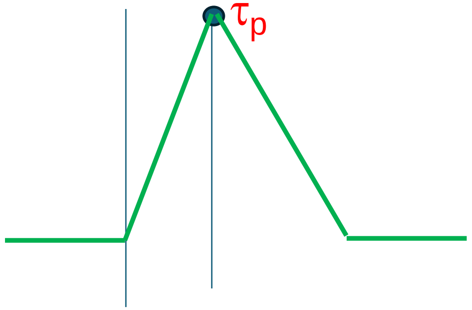
$$A_1 = 4kT\frac{0.7}{g_m}$$

$$A_2 = 10^{-11} - 10^{-9} V^2$$

$$A_3 = 2qI_D + 4kT\left(\frac{1}{R_f} + \frac{1}{R_D}\right)$$



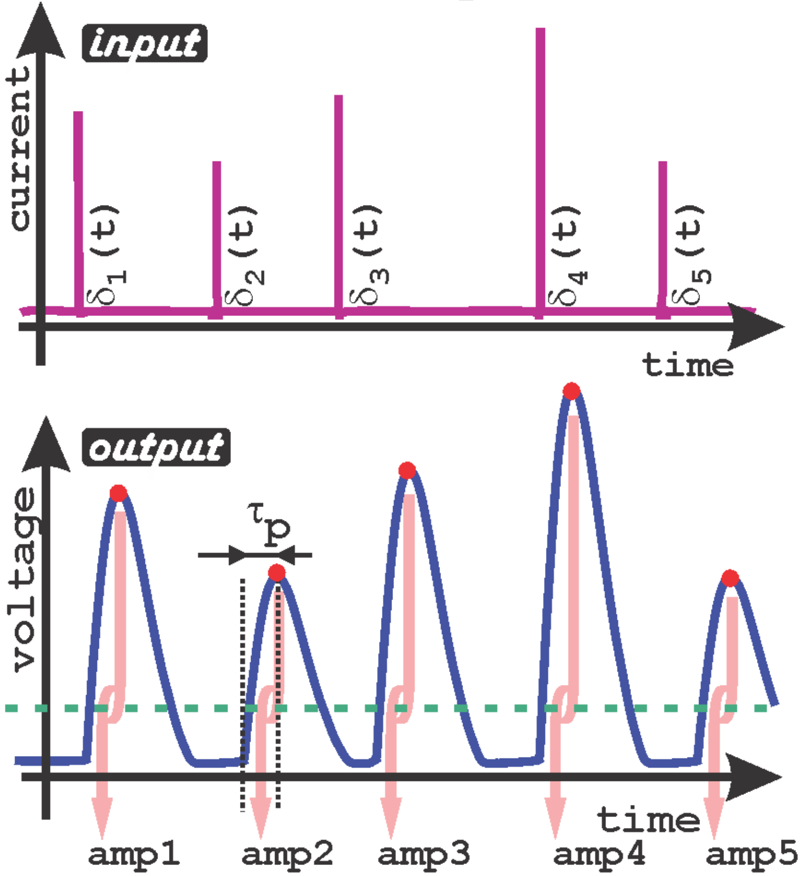
series white noise ➡ inversely proportional to τ_p and is important for **short** shaping times
1/f noise ➡ independent of τ_p and not too much can be done (except not deep in saturation and not small WL)
parallel noise ➡ proportional to τ_p and is important for **long** shaping times



Measurements - 1

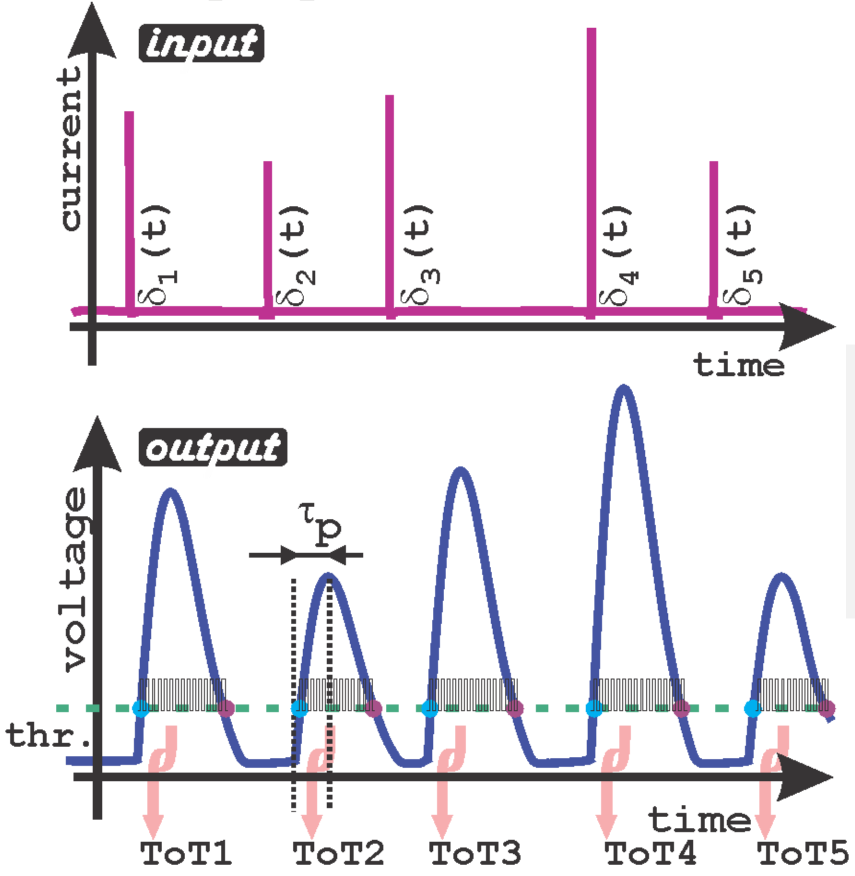
AMPLITUDE MEASUREMENT

We are interested to know how:
- much charge was liberated
- proportions of charge between channels



peak - detection

amplitude measured as the maximum (minimum) excursion of a pulse above the baseline



ToT measurement

amplitude measured as time a pulse stays above a threshold

Precision of amplitude measurement is affected by indeterministic errors (stochastic), depending on noise contained in signal ➡ S/N

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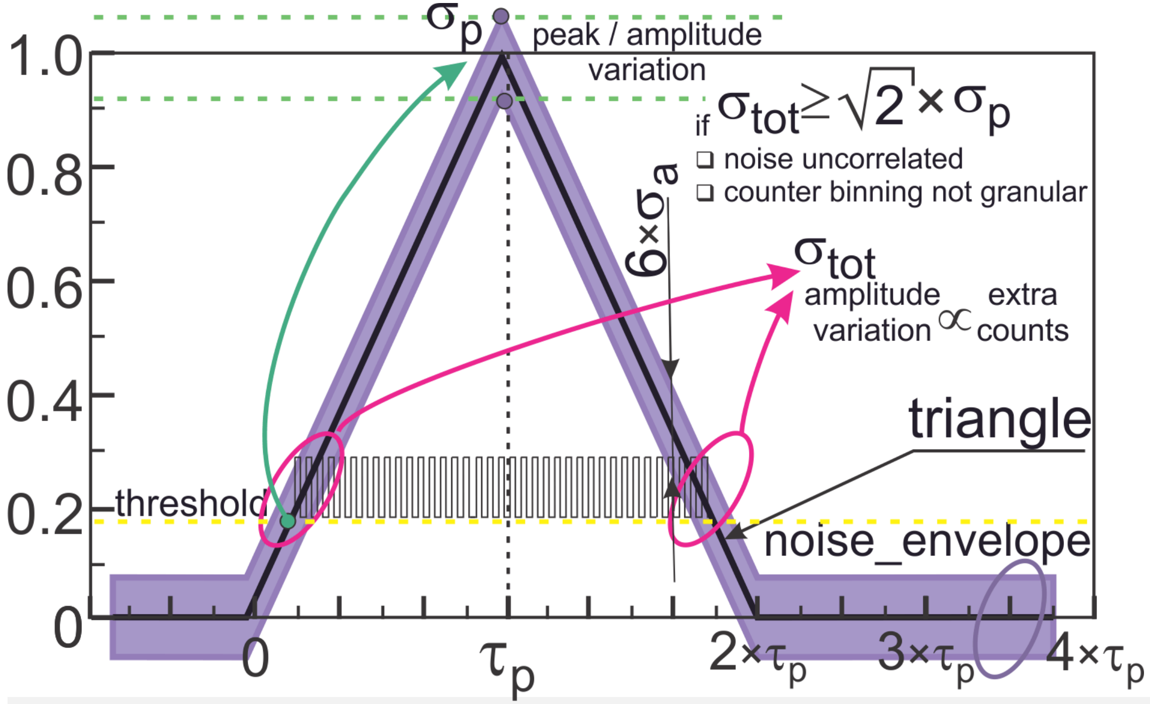
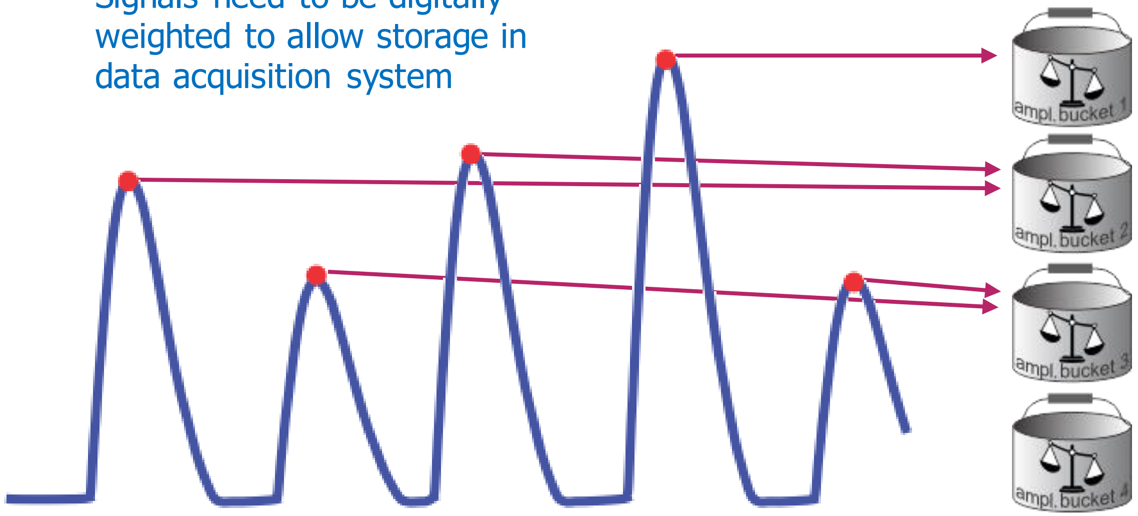
Measurements - 2

noise superimposes on signal



digitization

Signals need to be digitally weighted to allow storage in data acquisition system



additional effect of binning (quantization) affects resolution (it adds noise) of amplitude measurement

Major sources of noise:

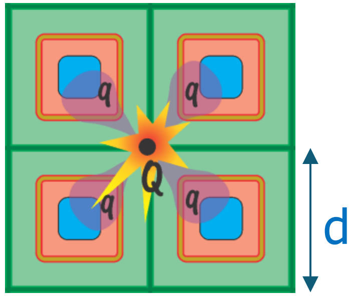
- electronic noise generated inside amplifiers processing signals ➡ optimize design;
- noise generated in power supplies (most of sensors are operated in single ended configuration) ➡ optimize system and design;
- interferences: capacitive, inductive that penetrate:
  - individually to each channel, or
  - generate common mode fluctuations ➡ all channels 'jump' or drift;
- resulting from temperature drifts, light penetration, cross-talks, etc.

use of **triangular** shaping is arbitrary

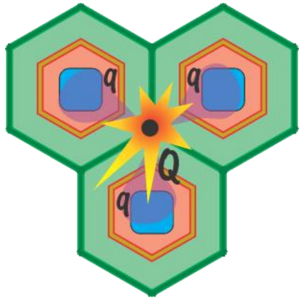
for practical reasons, width of noise envelope = 6 × σ (Gaussian distribution)

Meas. - 3

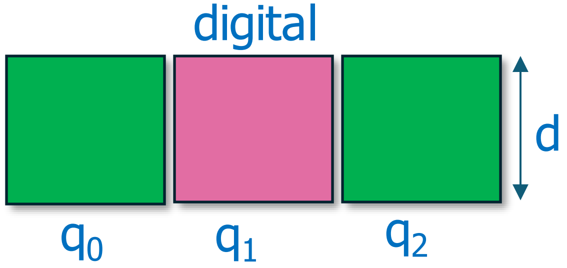
more segmentation seems to be better but …
initial charge Q is shared among neighbors



Q ⇒ 4 × q

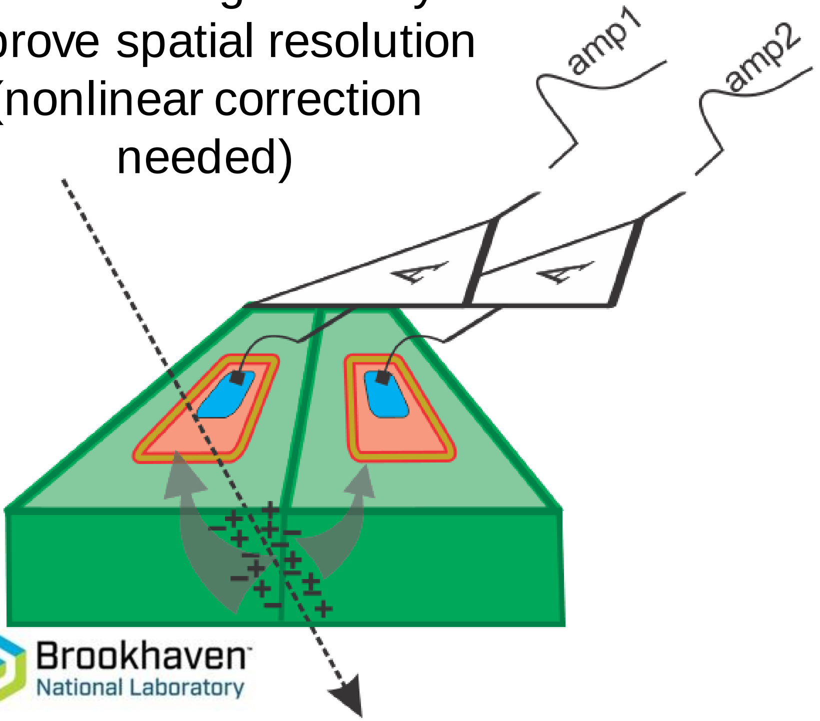


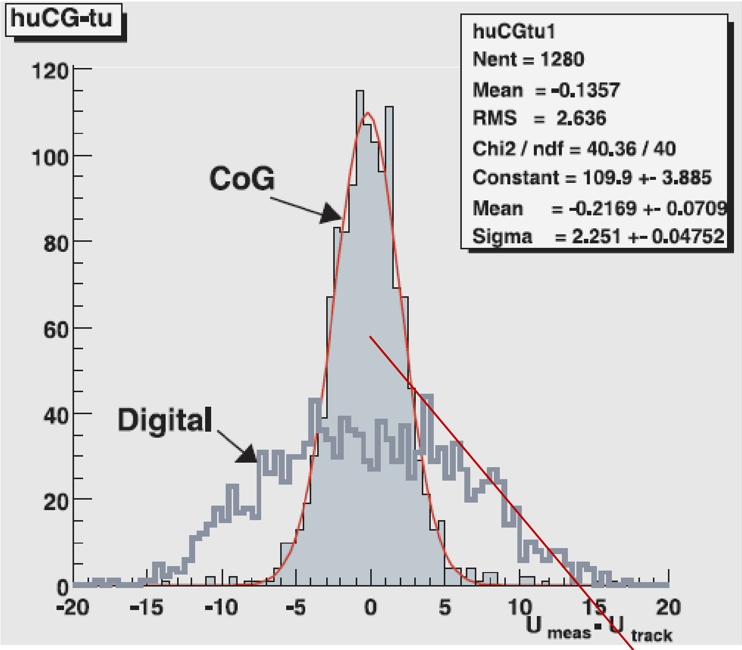
Q ⇒ 3 × q

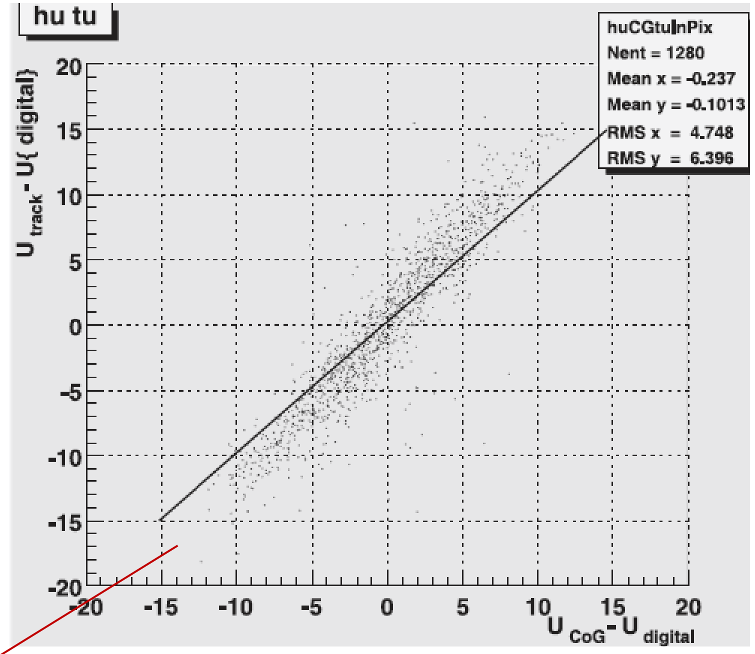


$$U_{CoG} = U_{digital} + d \bullet \frac{q_0 - q_2}{\sum_i q}$$

measuring amplitudes of fractional signals may improve spatial resolution (nonlinear correction needed)







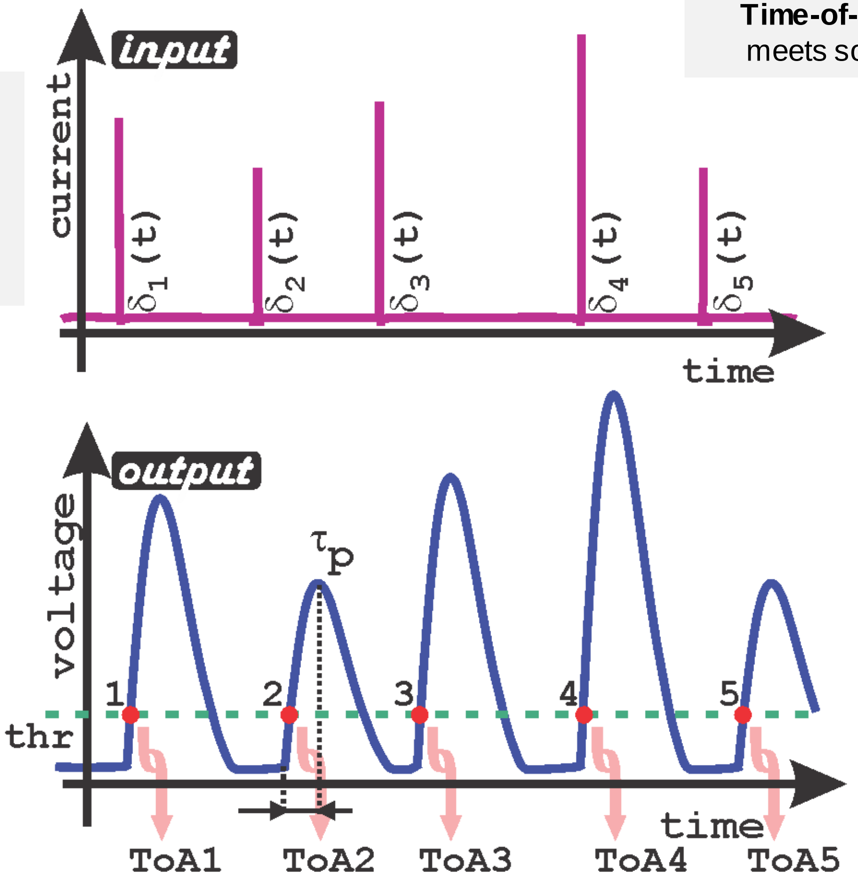
σ_s=2.636 μm ➡ 2.417 μm

Meas. - 4

TIME MEASUREMENT

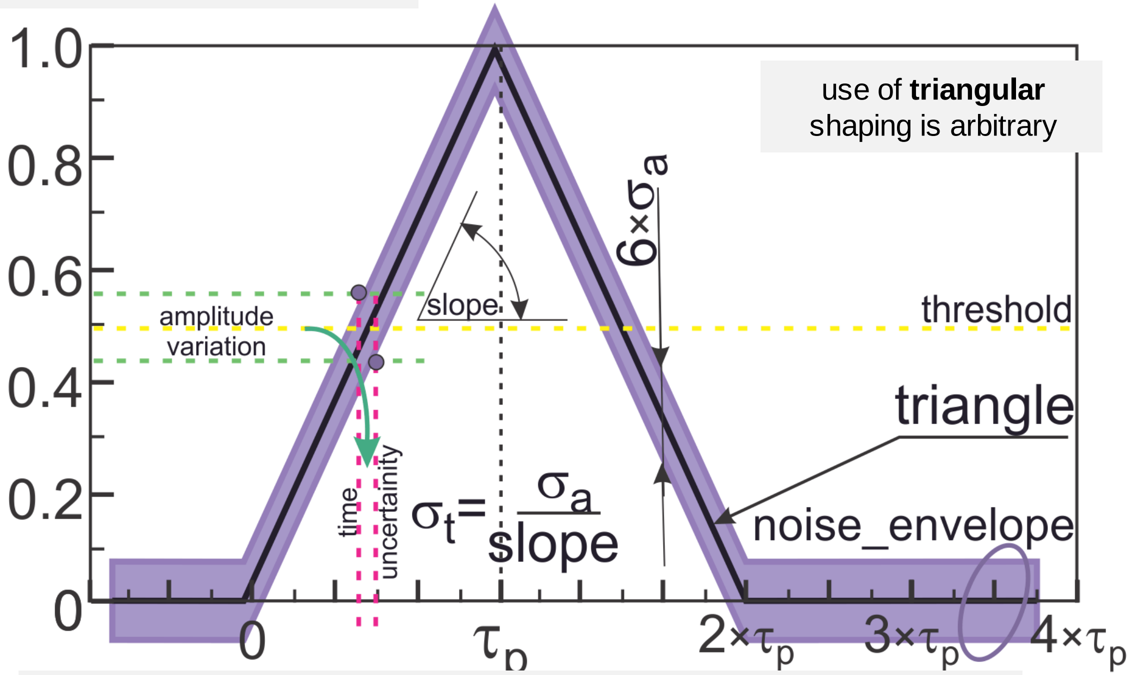
importance of slope

We are interested to know how:
- **when radiation arrived to or crossed sensor**



ToA measurement

Time-of-Arrival measured as time when pulse meets some criteria, e.g., crosses a threshold



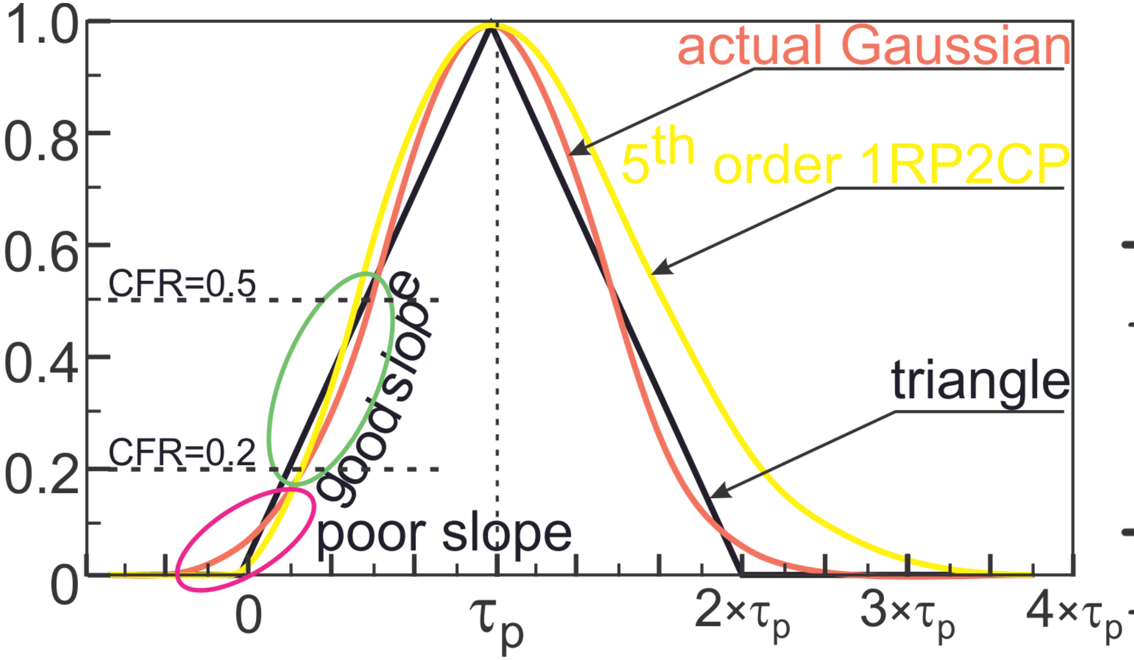
use of **triangular** shaping is arbitrary

Methods of measuring Time-of-Arrival:
- Leading Edge Discrimination (LED);
- Constant Fraction Discrimination (CFD);
- First Derivative Zero-Crossing (Peak Detection);
- Centroid Finding;

Essential in Time-of-Arival:
- Change must be fast ➡ slope of observed signal must be maximized;
- Steeper slope ➡ larger bandwidth, so noise need to be watched too:

Meas. - 5

choice of threshold level



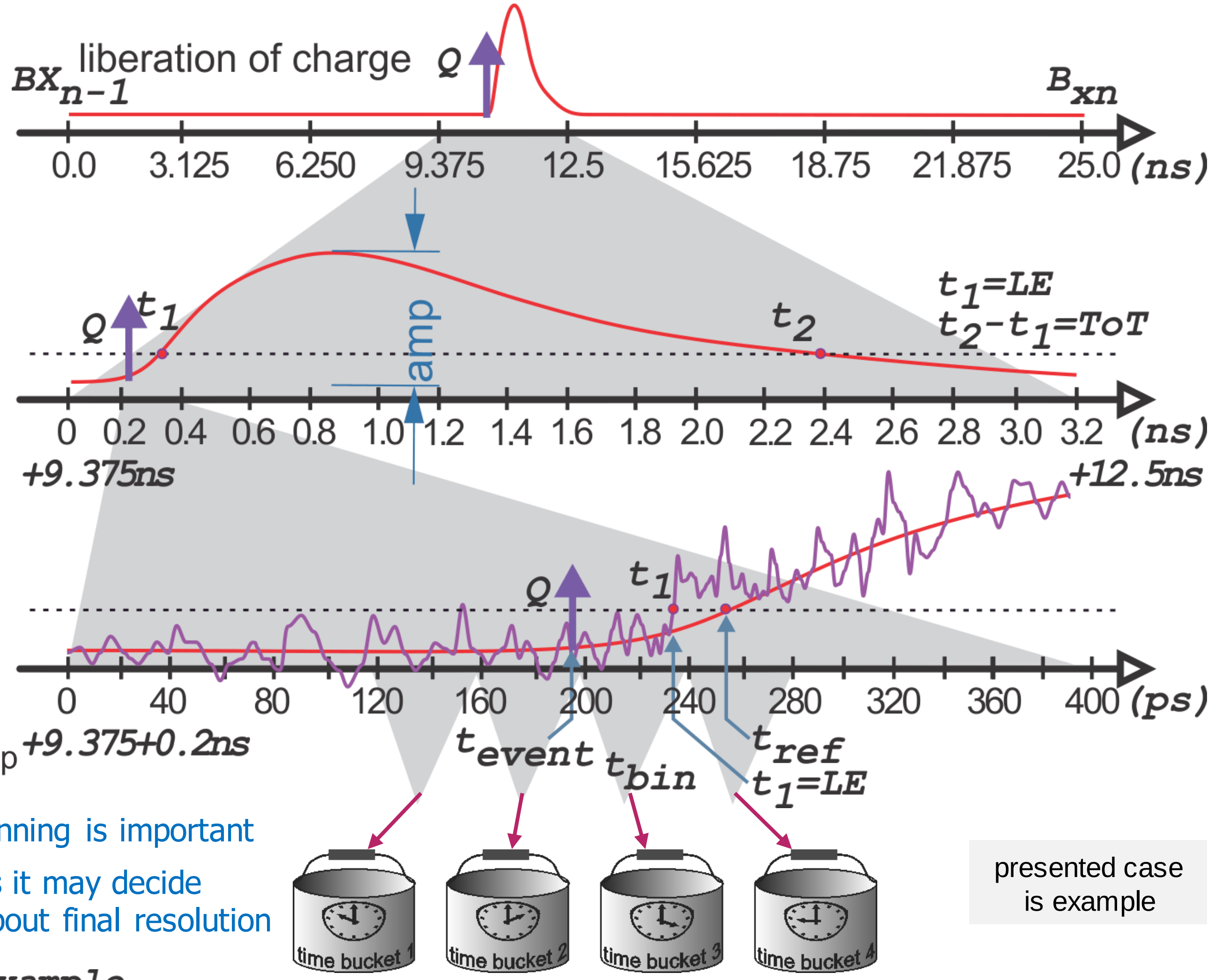
Shaping filters used in practical realizations are not triangular but approximate Gaussian form:

- Semi-Gaussian CR-RC$^{(n)}$ with Real Poles;
- Synthesized semi-Gaussian with pairs of Complex Conjugate Poles;
- Bessel, etc.;

Threshold needs to be set:

- where changes are fastest;
- typically, good slope ∈(0.2, 0.5) of normalized amplitude 🡆 CFR;

precision timing in details



binning is important

as it may decide about final resolution

presented case is example

example

t_{event}=196ps $t_{1(LE)}$=234ps $\varepsilon_{t1(LE)}=t_{bin}-t_{ref}$=34ps

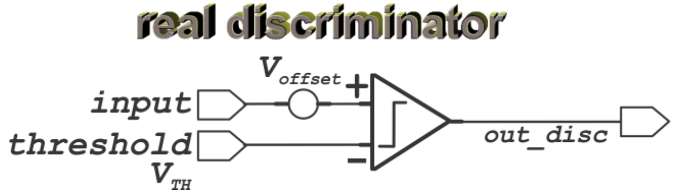
t_{ref}=254ps t_{bin}=220ps

error dominated by binning $t_{ref}-t_{1(LE)}$=20ps

Meas. - 6

ToA measurement is not easy, and it requires:

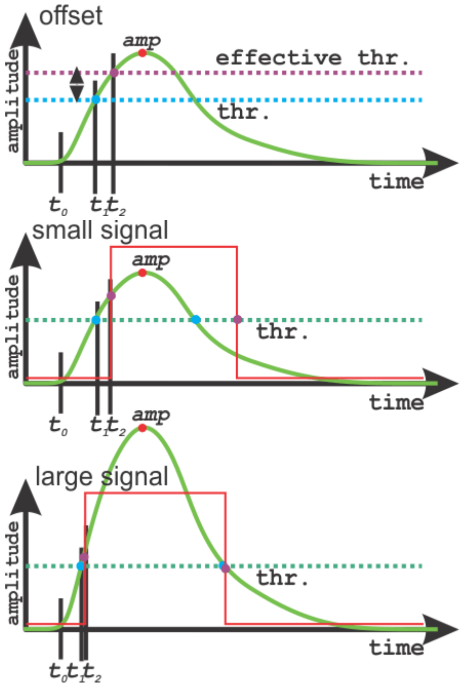
- **correction resulting from simultaneous amplitude measurement**
- **insensitive measurement to amplitude**



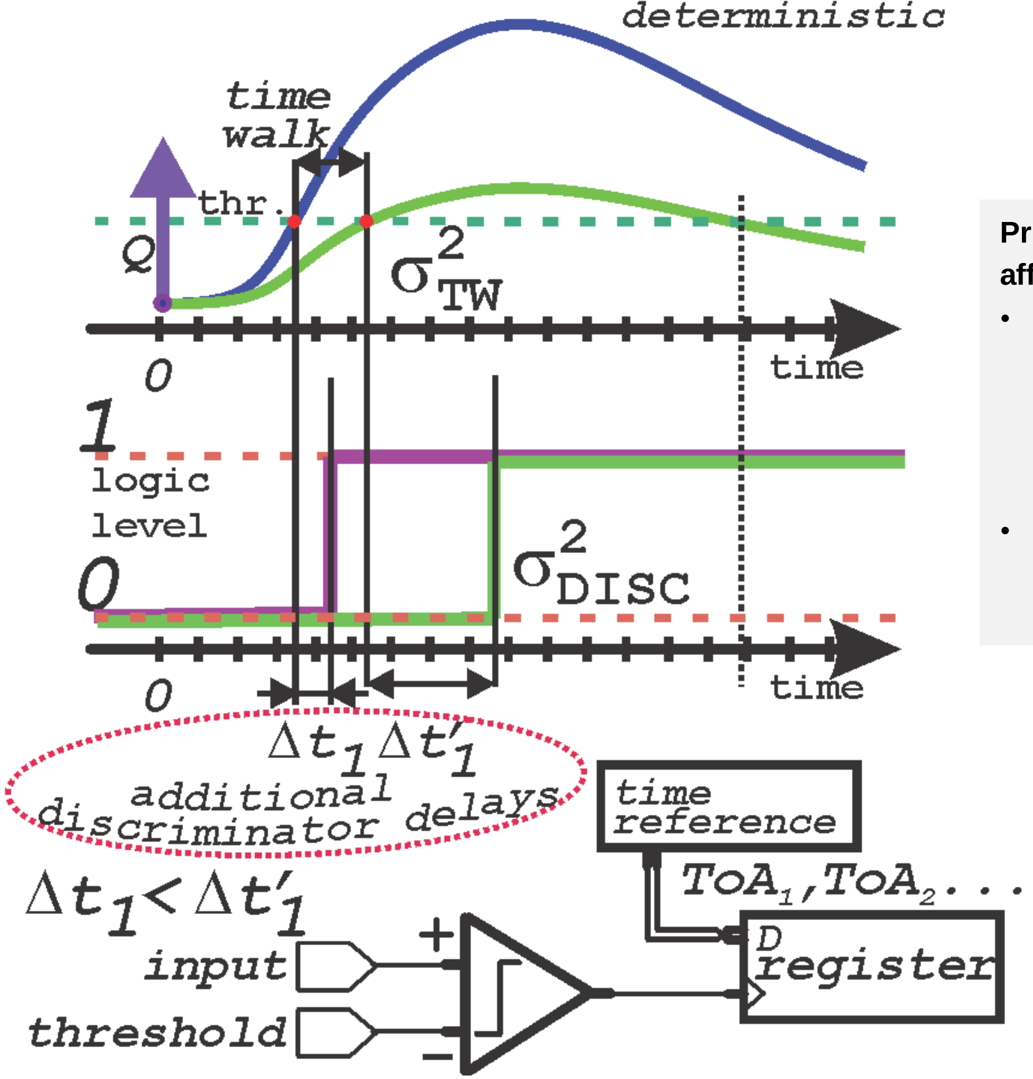
offset may be signal, radiation dose absorbed, temperature, aging, etc. dependent

delay dependent on overdrive may lead to additional errors, and may not be correctable

(overdrive insensitive discriminators)



$$\sigma_{ToA} = \sqrt{\left(\alpha_f \frac{\tau_p}{S/N}\right)^2 + \underbrace{\sigma_{TW}^2 + \sigma_{DISC}^2}_{deterministic}}$$



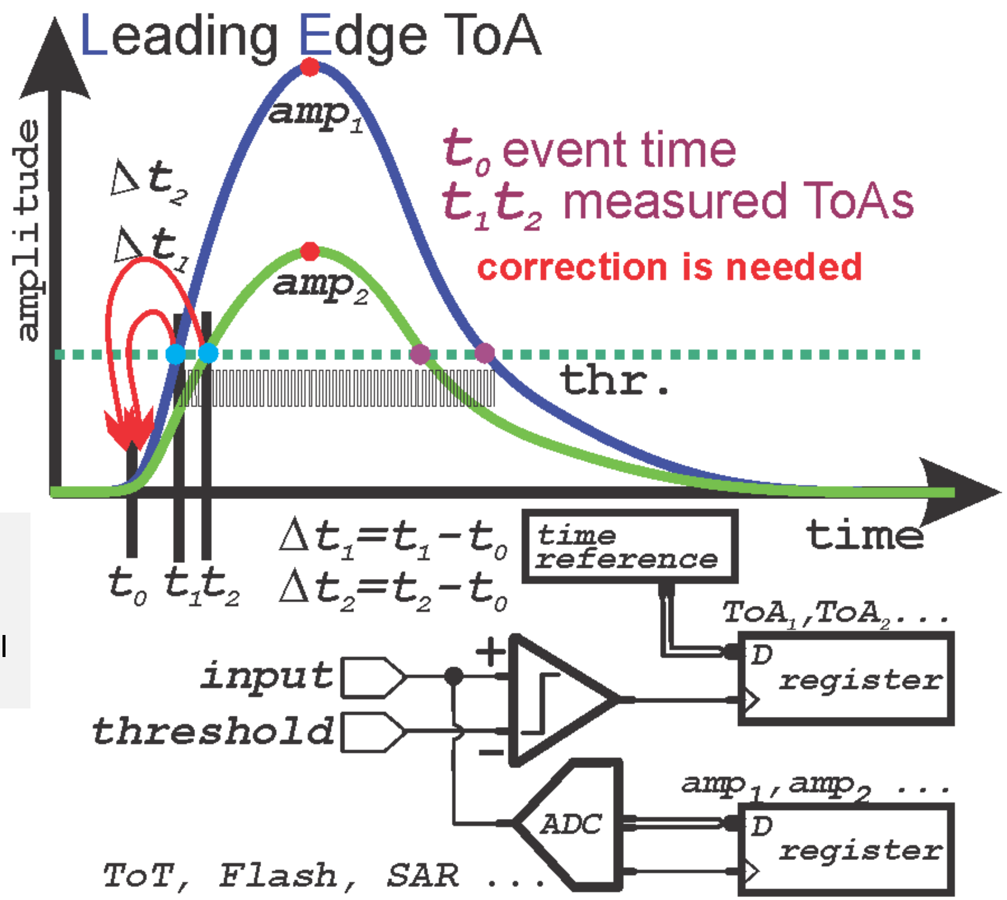
Precision of ToA measurement is affected by errors:

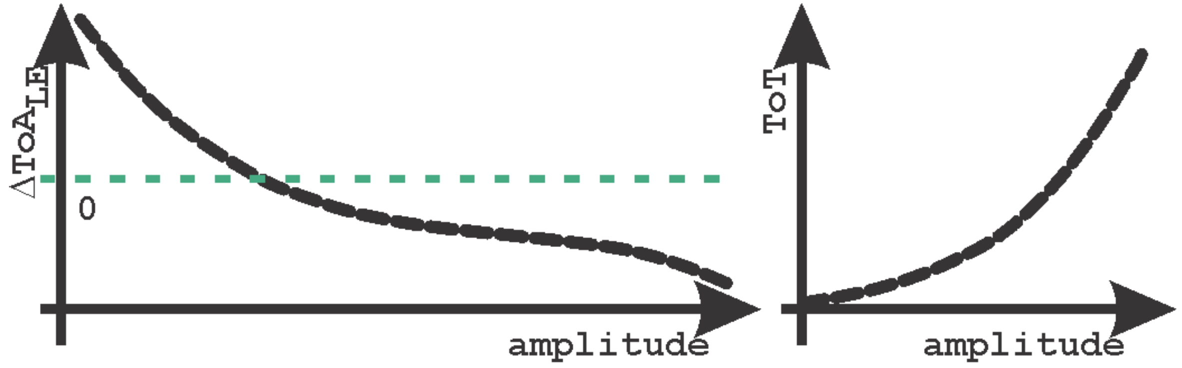
- **indeterministic (stochastic), depending on noise contained in signal ➨ S/N and slope of a pulse ($\alpha_f \cdot \tau_p$)**
- **and deterministic:**
  - **➨ time-walk σ_{TW}**
  - **➨ discriminator overdrive σ_{DISC}**

Meas. - 7

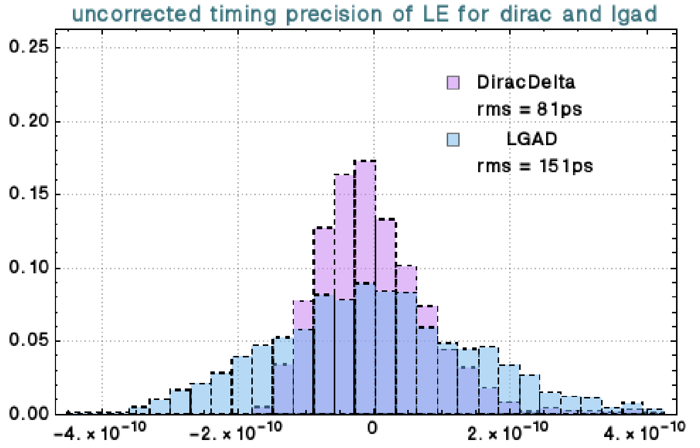
LE is simple but requires additional steps of correction (not easy in circuits as it requires look-up tables, etc.)

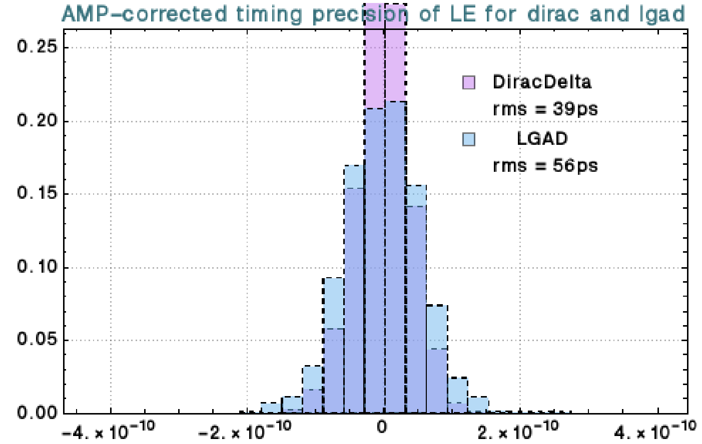
t_0 – actual time of event
t_1 time of crossing threshold of large amplitude signal
t_2 time of crossing threshold of small amplitude signal





Examples of ToA for SNR=30 with signals represented as δ(t) and realistic finite time duration



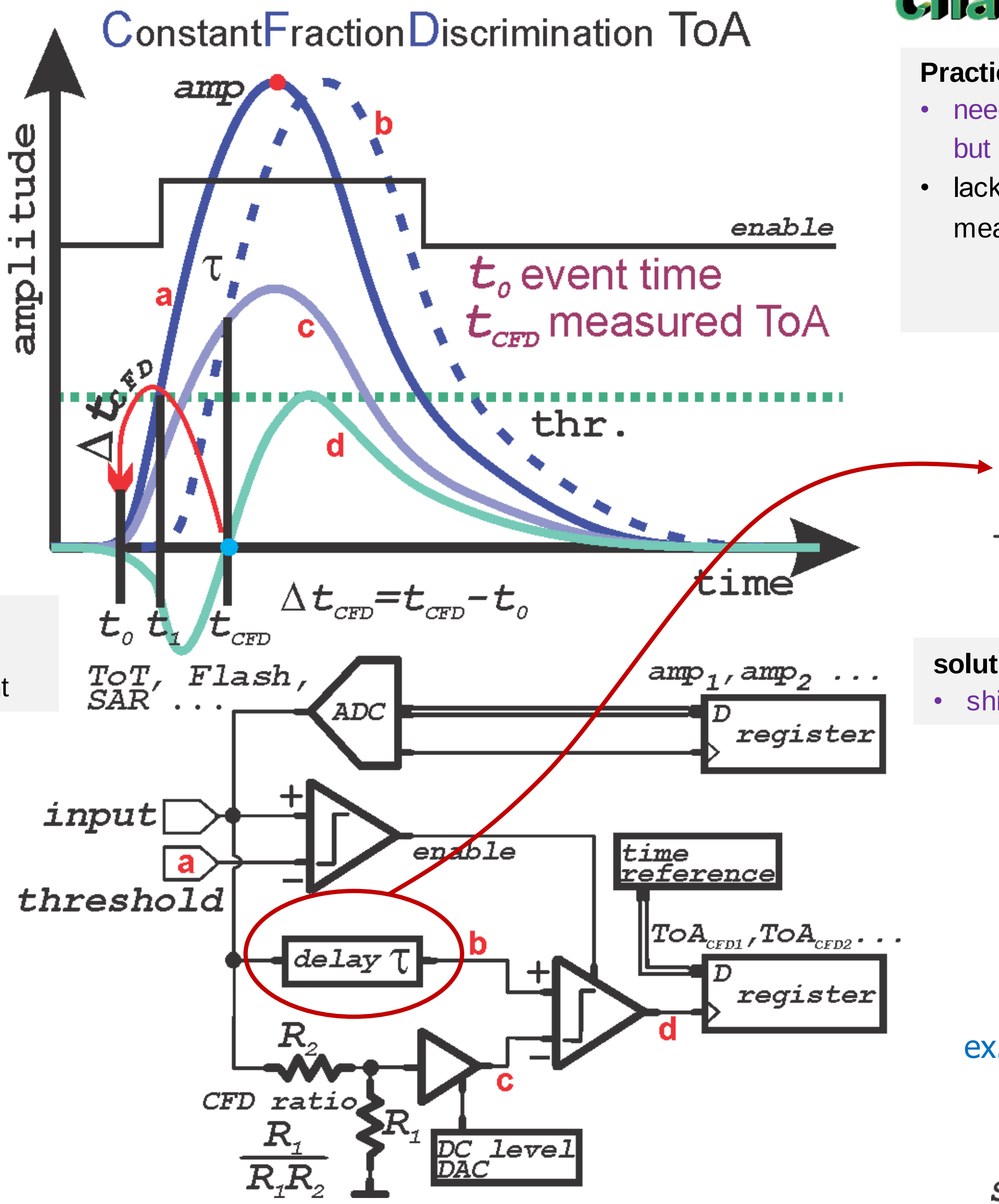


3-fold improvement achieved
(equivalent to CFD)

Meas. - 8

CFD is attractive as it perform automate 'correction' of TW by circuit

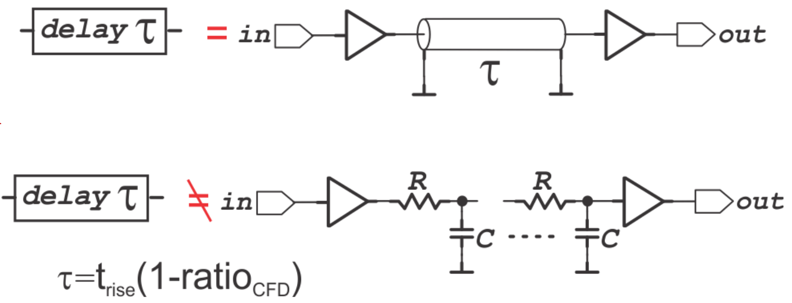
t_0 – actual time of event
t_1 time of crossing threshold
t_{CFD} time yielded by measurement



challenges in practical CFD

Practical issues with CFD in IC:

- needed delay: $H(s)=e^{-\tau s}$,
  but practically achievable is $H(s)\propto\frac{1}{s+\tau}$;
- lack of actual delay causes errors in „zero-crossing" position measurements when waveform shape changes due to:
  - amplitude dependence
  - varied charge collection timing

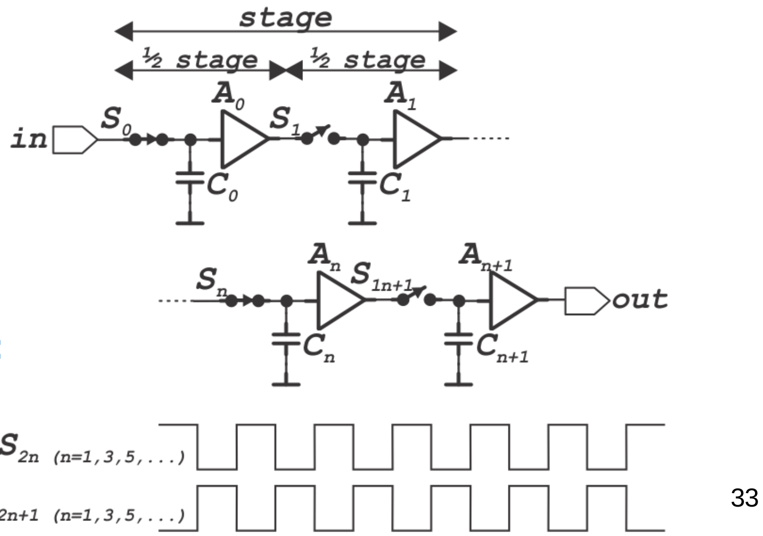


$\tau=t_{rise}(1\text{-}ratio_{CFD})$

solution could be discrete time analog delay line:

- shifts processing in discrete analog domain;

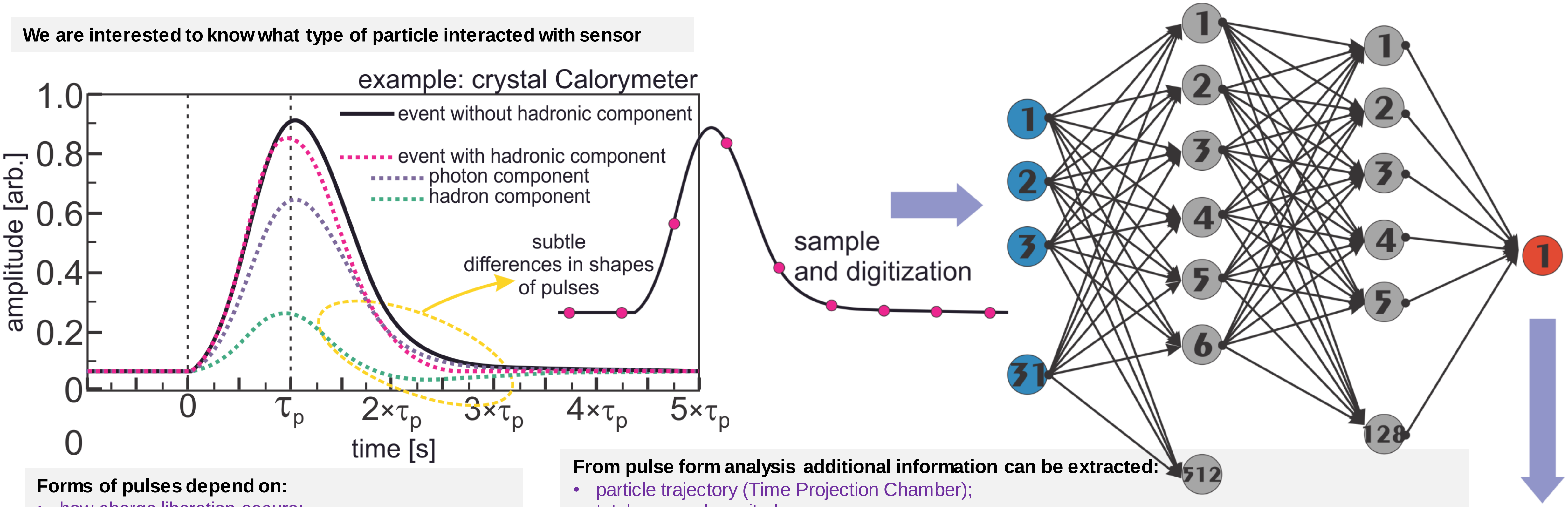
ex.:



Meas. - 9

PULSE SHAPE ANALYSIS

We are interested to know what type of particle interacted with sensor



Energy deposited

Hadron Intensity

Forms of pulses depend on:

- how charge liberation occurs:
    - electromagnetic shower (photon production);
    - hadronic shower (secondary particles);
    - photoelectric effect vs. linear energy transfer
- how liberated charge is collected
    - drift in E field;
    - diffusion

From pulse form analysis additional information can be extracted:

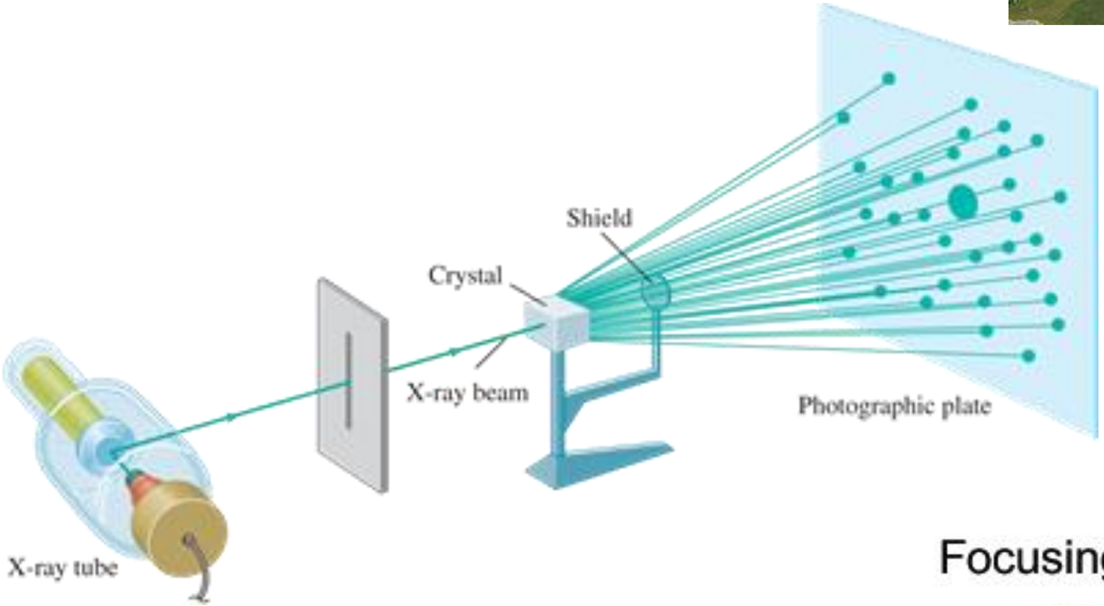
- particle trajectory (Time Projection Chamber);
- total energy deposited;
- type of interacting particles;
- composition of events;

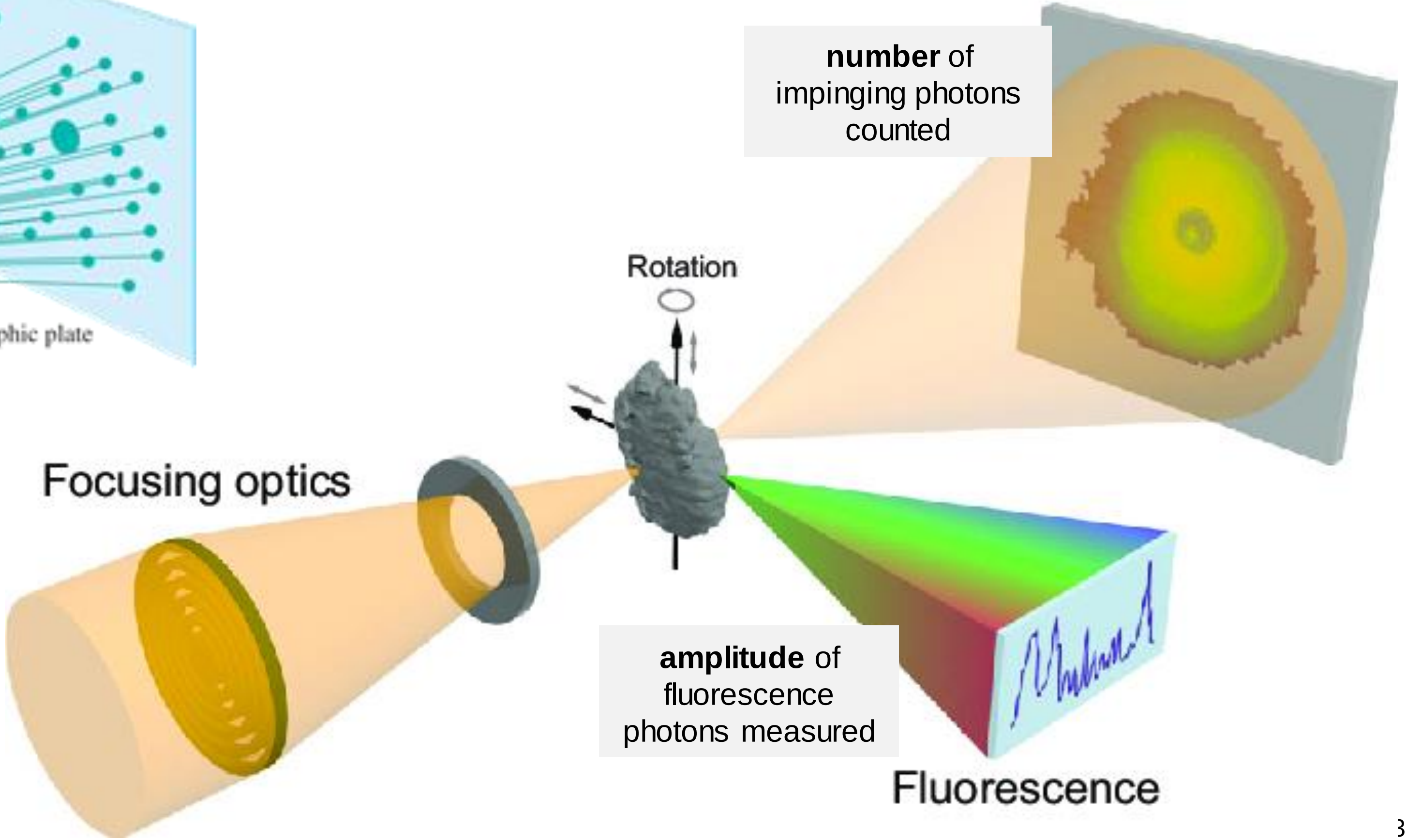
Ex. In Belle II (SuperKEKB e^+e^-):

- pulse shape analysis is used to distinguish electromagnetically and hadronically interacting particles within CsI(Tl) electromagnetic calorimeter;
- pulse shapes from particle-dependent scintillation response are analyzed with multi-template offline fit to measure fraction of scintillation emission produced by hadrons;
- particularly attractive are Artificial Neuron Network (ANN) techniques.

Meas. - 10

from simple diffraction imaging
to
imaging using synchrotron radiation

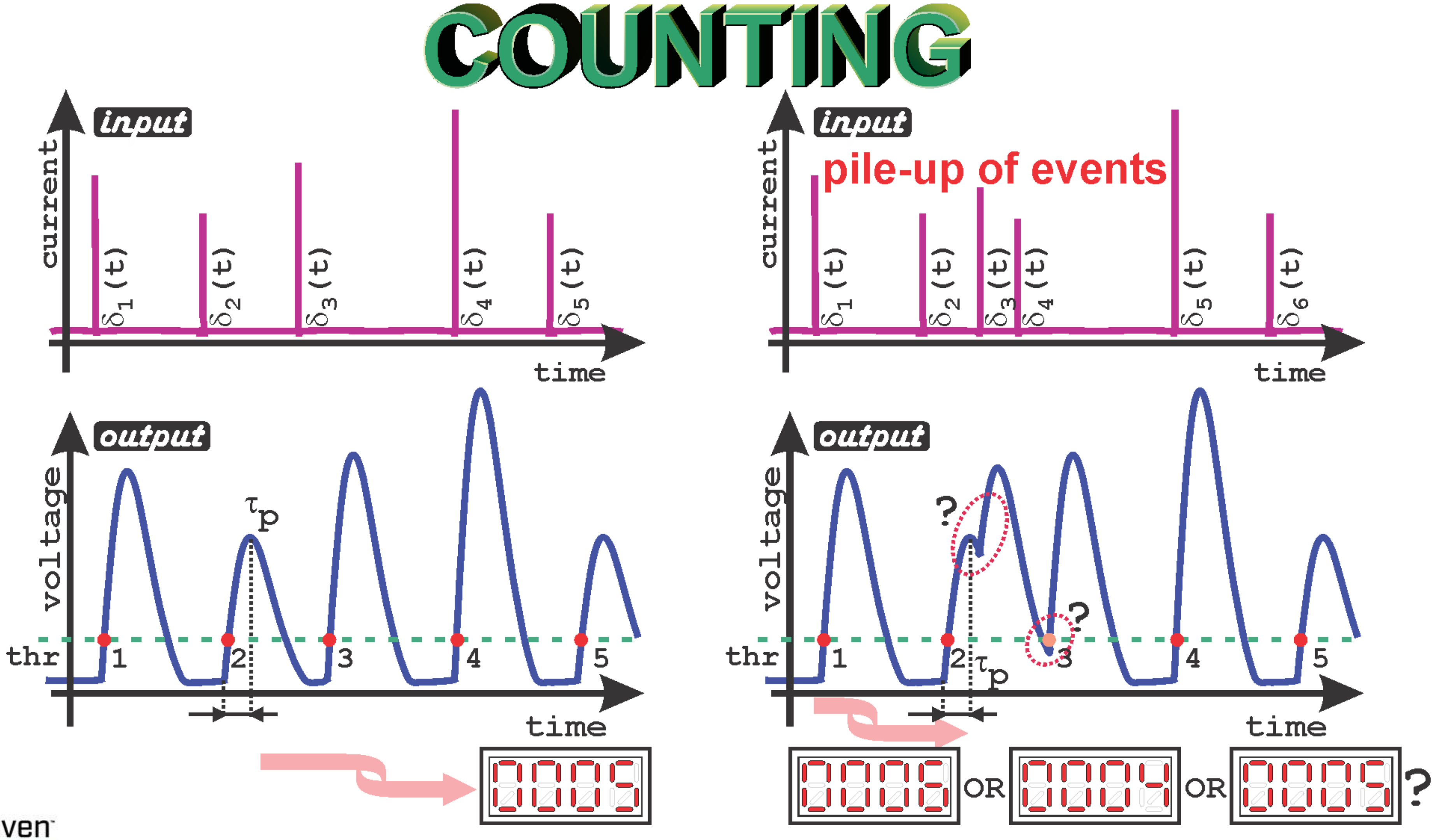




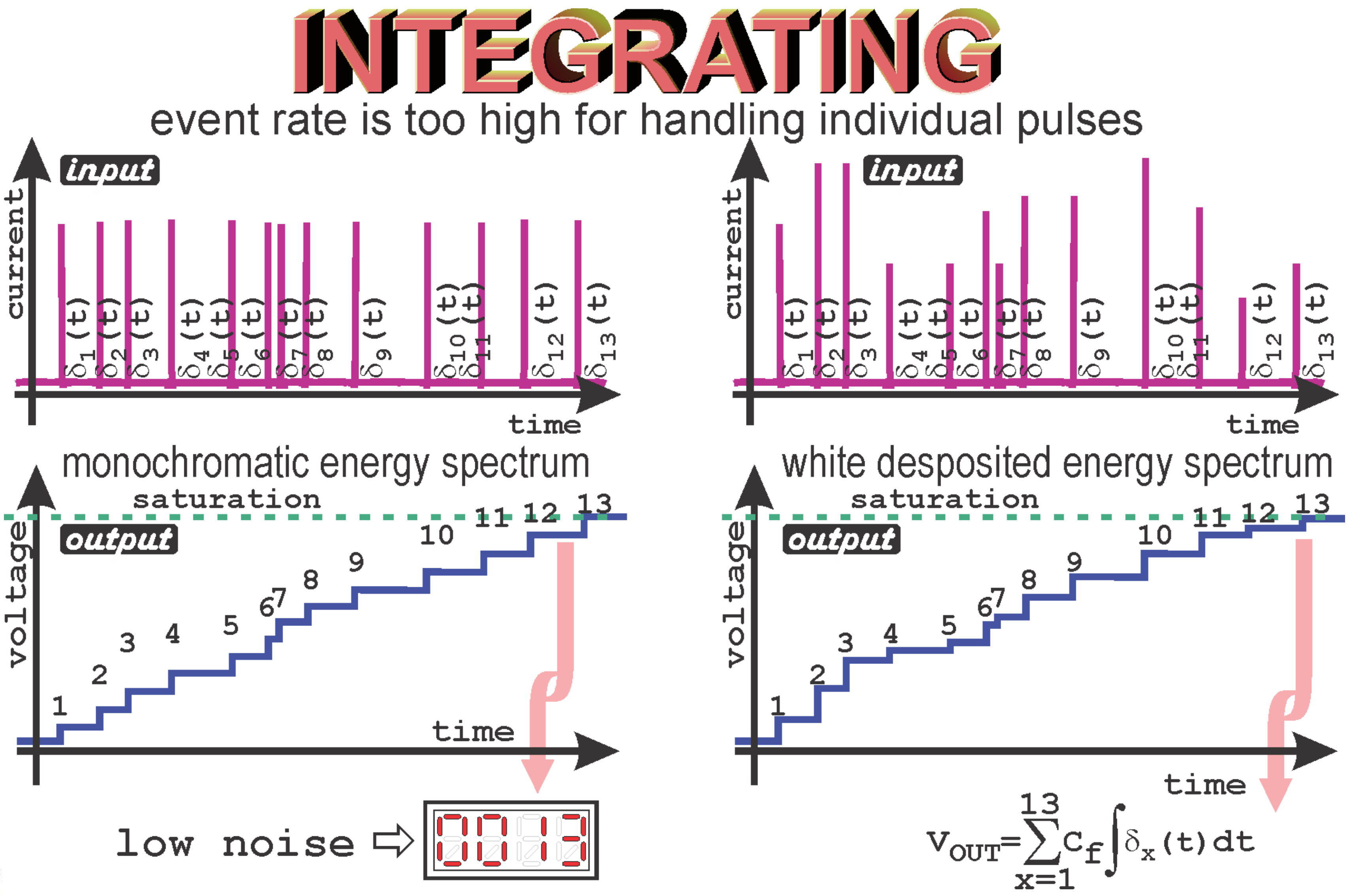
number of
impinging photons
counted

amplitude of
fluorescence
photons measured

Meas. - 11


COUNTING
input
current
time
$\delta_1(t)$
$\delta_2(t)$
$\delta_3(t)$
$\delta_4(t)$
$\delta_5(t)$
output
voltage
thr
1
2
3
4
5
τ_p
time
0005
input
pile-up of events
current
time
$\delta_1(t)$
$\delta_2(t)$
$\delta_3(t)$
$\delta_4(t)$
$\delta_5(t)$
$\delta_6(t)$
output
voltage
thr
?
?
1
2
3
4
5
τ_p
time
0006
OR
0004
OR
0005
?

Meas. - 12



INTEGRATING

event rate is too high for handling individual pulses

monochromatic energy spectrum

white desposited energy spectrum

low noise

$$V_{OUT}=\sum_{x=1}^{13} C_f \int \delta_x(t)\,dt$$

Useful Literature Items

old but spring-like

International Atomic Energy Agency:

- “Selected Topics in Nuclear Electronics”, IAEA-TECDOC-363, Vienna 1986
- “Nuclear Electronics Laboratory Manual”, IAEA-TECDOC-530, Vienna 1989

V. Radeka, “Optimum Signal-Processing for Pulse-Amplitude Spectrometry in the Presence of High-Rate Effects and Noise, in IEEE Transactions on Nuclear Science, vol. 15, no. 3, pp. 455-470, June 1968

V. Radeka, “State of the Art of Low Noise amplifiers for Semiconductor Radiation Detectors”, BNL-222986-2022-COPA, 1968

E. Nygard, et al. “CMOS Low Noise Amplifier for Microstrip Readout Design and Results” CERN-PPE/90-142, 1990

more recent

W.E. Cleland, E.G. Stern, “Signal Processing considerations for Liquid Ionization Calorimeters in a High-Rate Environment, Nucl. Instr. and Meth. A 338 (1994)

V. Radeka, “Signal Processing for Particle Detectors” In: Fabjan, C., Schopper, H. (eds) Particle Physics Reference Library. Springer, Cham. 2020

A. Rivetti, “MOS: Front-End Electronics for Radiation Sensors (Devices, Circuits, and Systems)” CRC Press 2015

Summary

Application Specific Integrated Circuits with sensors form semiconductor eyes to detect radiation

application

They allow measurements of numerous features of incident radiation:

- Impact position (direction)
- Energy and type
- Intensity
- Time of arrival
- Spatiotemporal correlations, etc.
- Etc.

Readout ASICs are large scale, mixed-mode… data generating circuits machines, designed with CAD/EDA tools

R&D

They are candidates for:

- AI/ML processing reducing raw data and extracting higher-order information
- 3D-Integration for increased granularity and more transistors/channel

Careful optimization of Front-End amplification stages is needed to perform measurements accurately and allow further processing in digital