

APIC

a study case for discrete detector electronics

RD51 Topical workshop on Front End electronics for gas detectors Tue 15th June – Thu 17th June 2021

Discrete electronics for MPGD's	2-4	Pileup and high rate preamps	18-20
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Detector phase space <=> electronics

Detector capacity (C_{det} , ENC noise)

→ routing and signal transmission, low noise amplifiers, order-N noise filters

Source impedance (Q, V)

→ preamp types and termination, over-Volt chip protection, AC –Dc coupling

feature extraction primary signal (x_0, t_0, Q, V)

→ shaping, pole-Z matching, threshold vs. peak, linearity & dyn range,

EM-properties (electrons vs. ions, induced signals, fast and slow, polarities)

→ preamp type and polarity, adaptive baselines, sampling

Rates and recovery, pileup

→ electronics-pileup & deadtime minimization, Fast OR & trigger generation

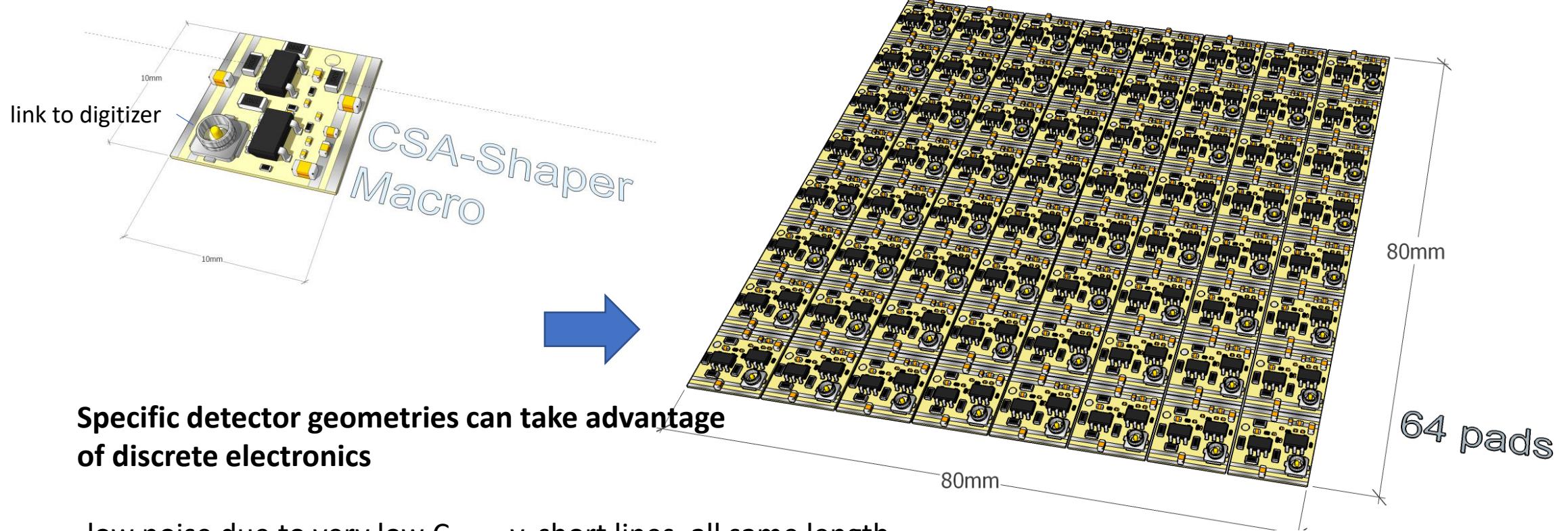
Signal confinement (x,y)

→ uniformity calibration , S/N thresholds, cluster detection

Very good reasons for discrete logic

- **electronic design and test with state-of-art industry components**
 - > high GBP, low noise OP-Amps, lumped LRC's, fast digitizers
- **degrees of freedom beyond integrated solutions**
 - > large precision capacitors, current and HV resistors, inductances
- **dynamic ranges**
 - > higher supply Voltages, factor 10 times larger dyn. range
- **quasi-safe spark protection schemes**
 - > ESD diodes, metal film series resistors
- **integrated electronics: at least 1 mismatch**
 - > quick and cheap adaptation or upgrade
- **lacking features of integrated electronics**
 - > low budget, low timescale feature additions
- **no probing / optimization possible on integrated electronics**
 - > Oscilloscope probing on all levels

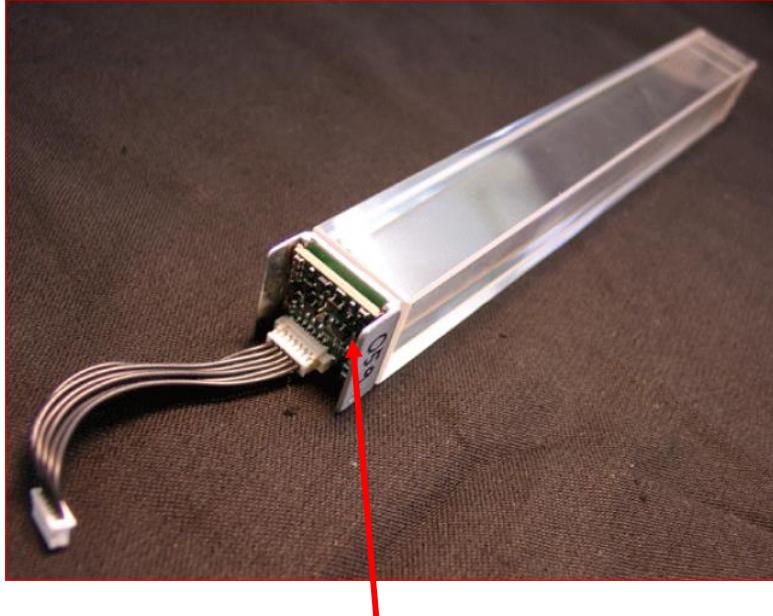
Discrete is sometimes an asset



**Specific detector geometries can take advantage
of discrete electronics**

- low noise due to very low C_{det} – v. short lines, all same length
- lower temperature for preamps, low noise
- higher dynamic range up 16 bit

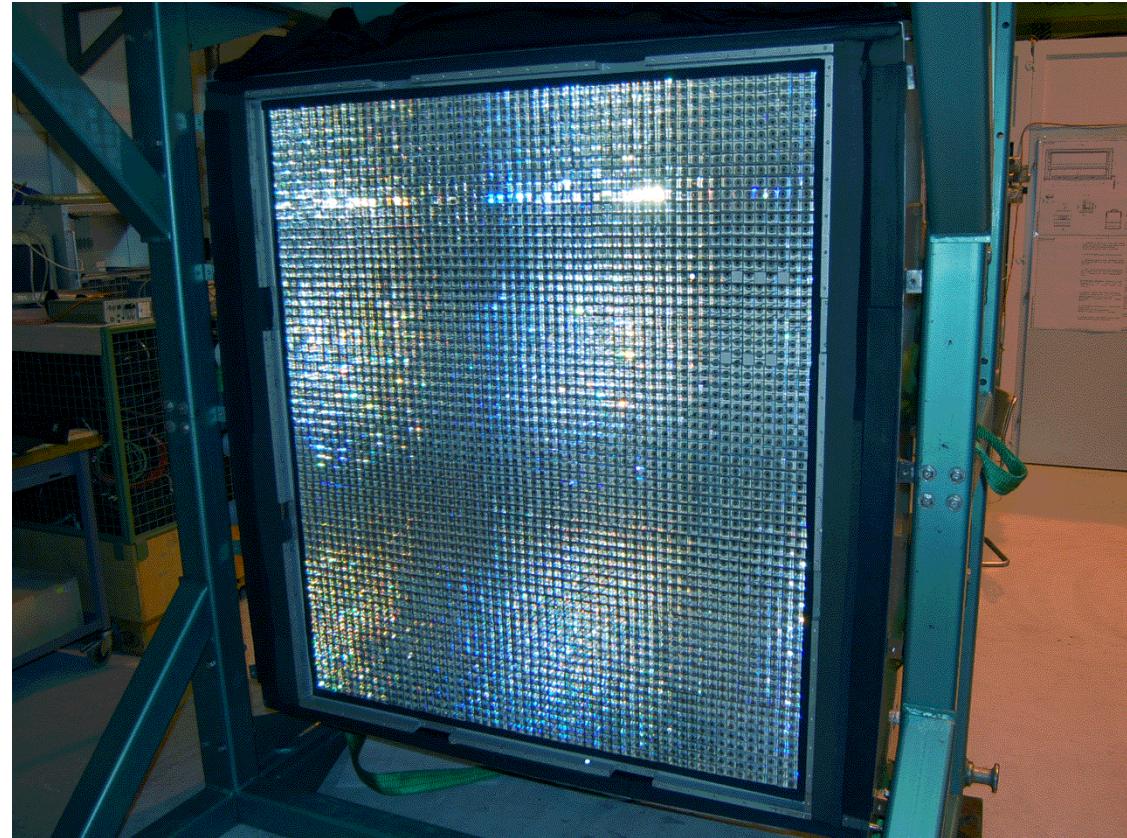
Example: LHC detector with discrete electronics FE



ALICE Calorimeters, PHOS, EMCal

PWO crystals with APD and discrete CSA preamp
14 bit dyn. Range, ENC 400e- @100pF ! @ -18 C

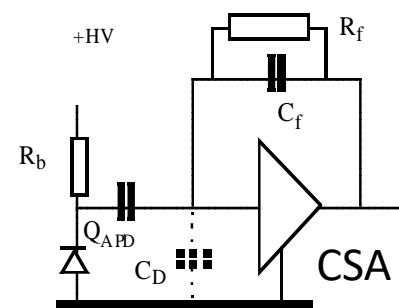
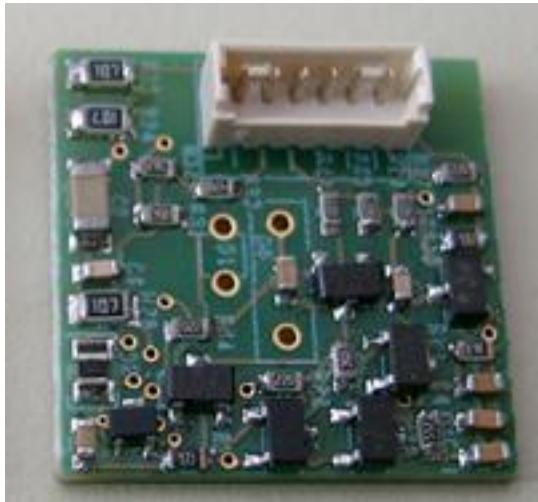
Details: [Phos User manual](#)



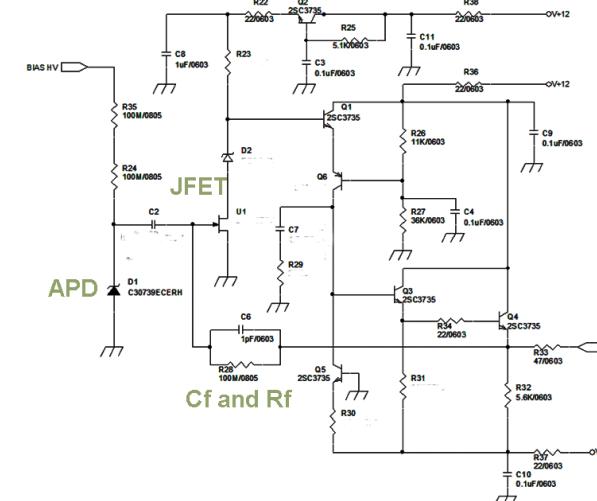
1 of 5 PHOS modules: 3584 crystals with discrete preamps

Discrete CSA's in Alice Calorimeters

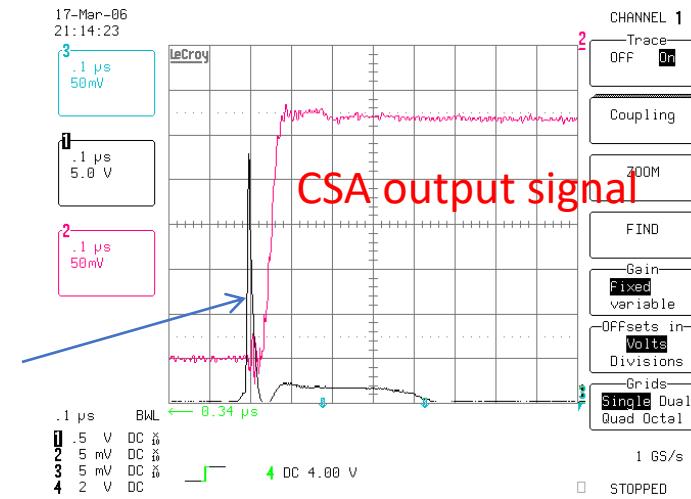
- charge /voltage gain: 1mV/fC
- dynamic range : 14 bit = 1/16000 (> 20 V full range)
- JFETs low noise, low leakage



Personal note: designing the APIC for MPGD's was inspired from experience building electronics for ALICE Calorimeter

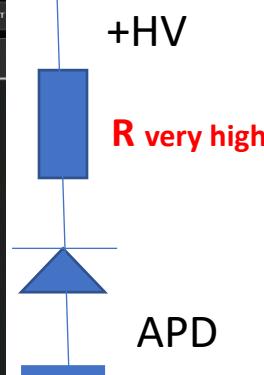
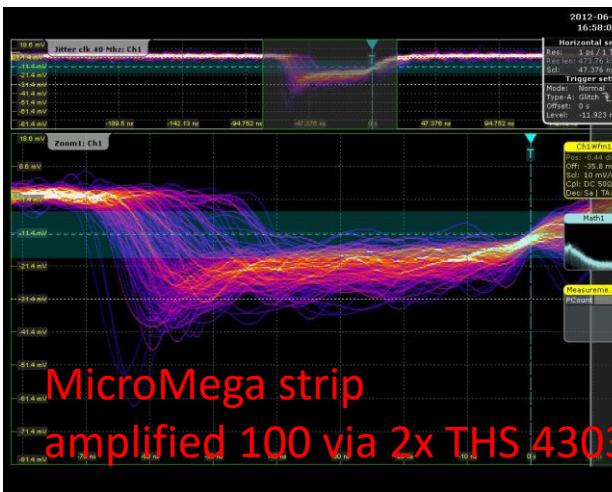


Input signal



Detector signals

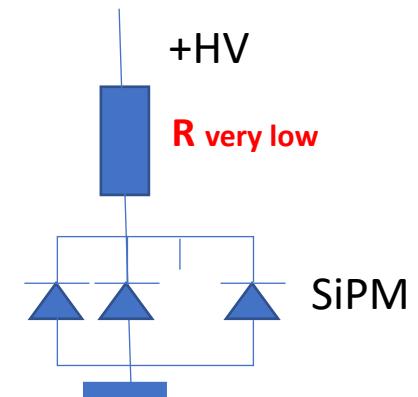
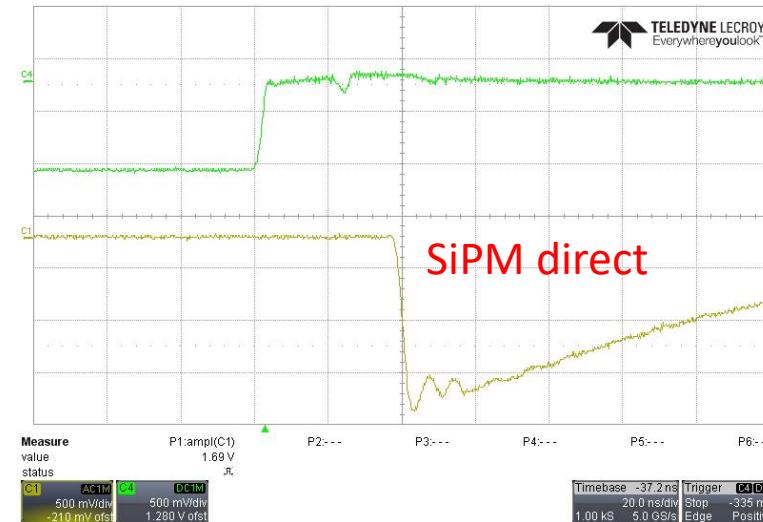
Primary ionization < O(1pC) => charge over C



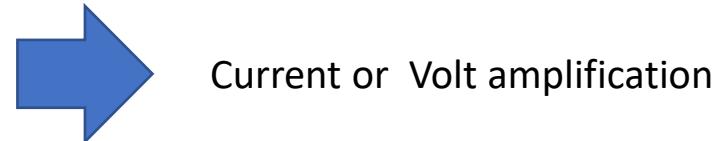
current source, high impedance
PMs, GEMs, MicroMegas, Photodiodes, APDs



Primary ionization > O(1pC) => current (Volt over R)



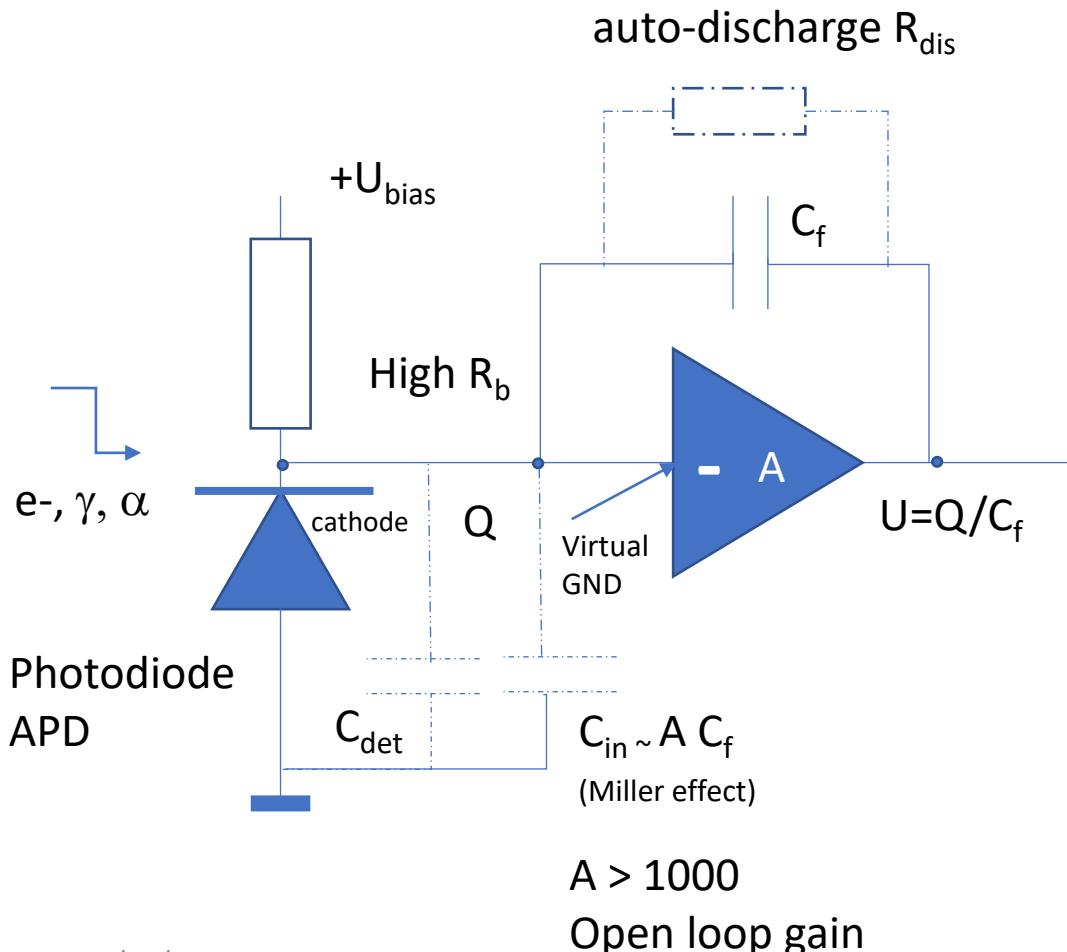
voltage source , low impedance
SiPMs, MWPC, RPC's



CSA amplifiers

unipolar charge integrator, high gain up 32 mV/fC

Low input impedance down to 25Ω , high input capacitance $O(nF)$ \rightarrow high input immunity against spark charge

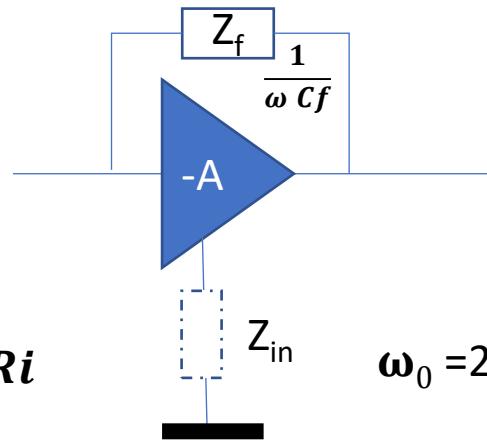


- R_b very high ($M\Omega$); only provides field for Diode depletion layer
 - \Rightarrow Very high source impedance
 - e^-, γ, α entering diode depletion layer generate e^+/e^- pairs
 - $\Rightarrow e^-$ unipolar charge Q collection on cathode $= C_{det}$
 - $\Rightarrow C_{det}$ effectively in parallel with C_{in} of preamp
 - $\Rightarrow C_{in}$ effectively C_f multiplied by very high gain $A \rightarrow O(nF)$
 - $\Rightarrow Q$ shared in proportion of C_{in} and C_{det}
 - \Rightarrow Normally $C_{in} \gg C_{det}$ hence in good approx. $> 98\%$ on C_f
 - \Rightarrow Output Voltage $U = Q/C_f = (1/C_f) * Q$
 - \Rightarrow Charge gain $= 1/C_f$ [$C_f = 1 \text{ pF} = 1 \text{ mV/fC}$]

Input impedance CSA

Theoretical $Z_i = Z_f / A$

$$Z_i (\text{CSA})^* = \frac{1}{\omega_0 C f} = R_i \quad \omega_0 = 2\pi \text{ GBP}$$



Z_i becomes a real number R_i at ω_0 which is the frequency where the amplifier gain A drops to 1 for OPA657 chip this is 1.6 GHz = GBP => $\omega_0(\text{OPA657}) = 2\pi * 1.6 = 10 \text{ GHz}$

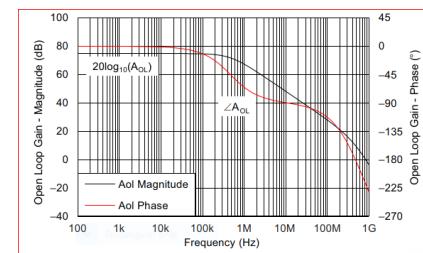
$$C_f = 1\text{pF} \Rightarrow R_i = 99.5 \Omega \quad [\text{CSA gain } 1\text{mV/fC}]$$

$$C_f = 1.6\text{pF} \Rightarrow R_i = 62.5 \Omega \quad [\text{CSA gain } 0.625 \text{ mV/fC}]$$

Special note on spark protection:

Spark voltages low over low input impedance and high input capacitance.

However only when the amplifier is also powered . Always switch off frontend electronics after HV



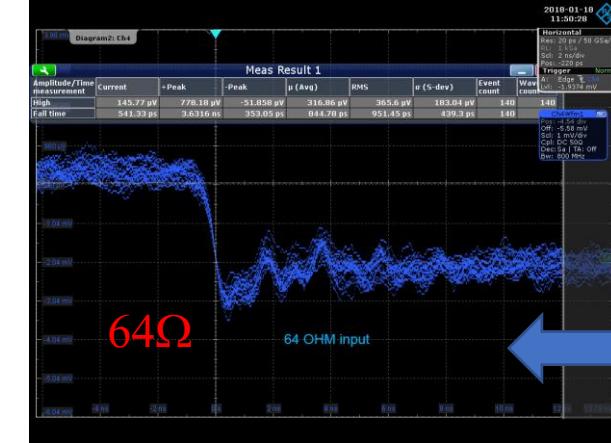
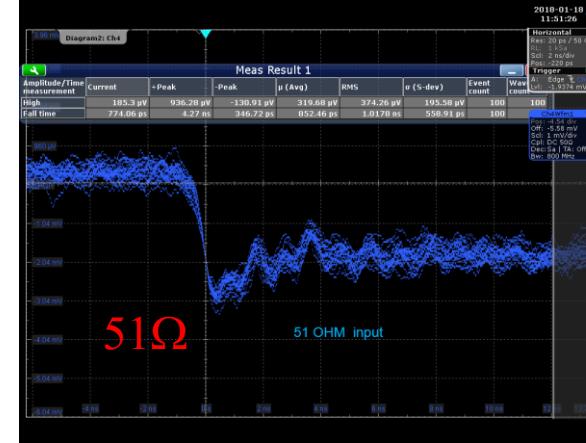
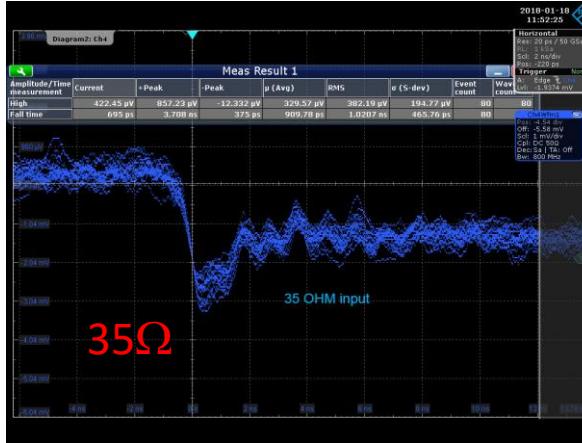
OPA657 chip
GBP=1.7GHz

- Input impedance proportional to charge gain
- can/should match signal~ input impedances via gain

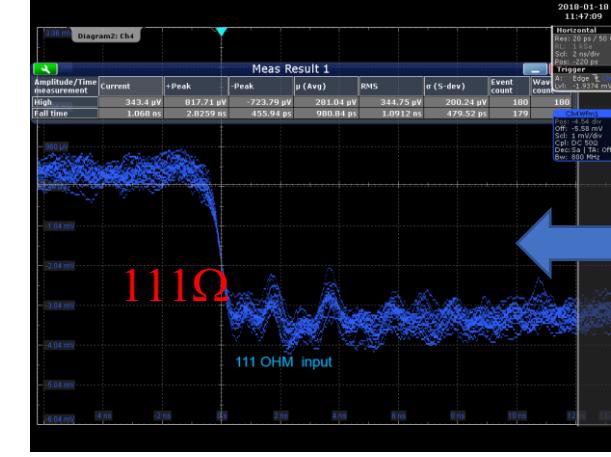
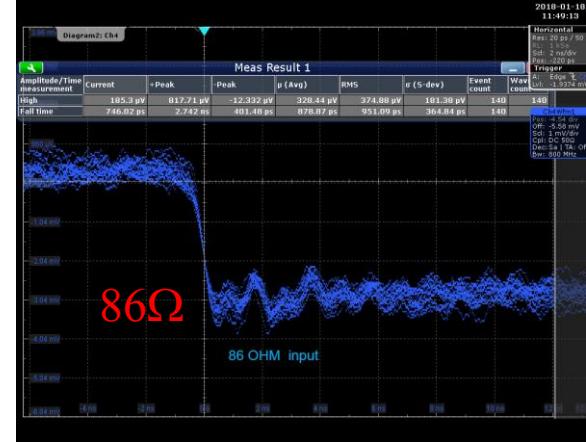
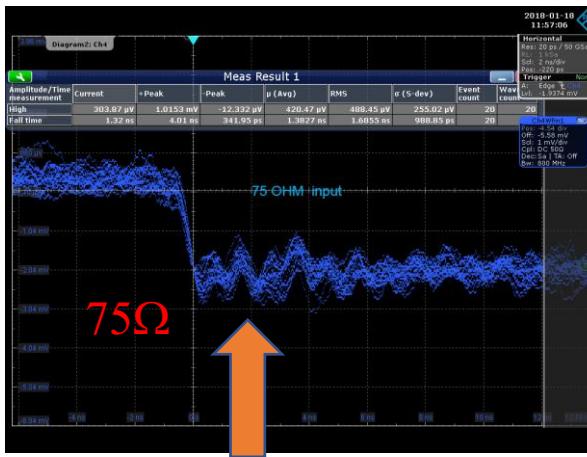
* [tutorials H. Spieler](#) on Electronics 1

Measurement input Impedance CSA on APIC

vary source impedance of pulse generator and monitor the reflections on the CSA output. Result for OPA657 with $C_f = 1.6\text{pF}$ and 10Ω input series protection: $\sim 75\Omega$ (corresponding calculation !)



negative
reflections
superimposed:
signal tail smaller
than peak
($R < Z_{in}$)



positive
Reflections
Superimposed:
signal tail bigger
than peak
($R > Z_{in}$)

75 OHM: peak equal to tail , minimum reflections

Input impedance matters

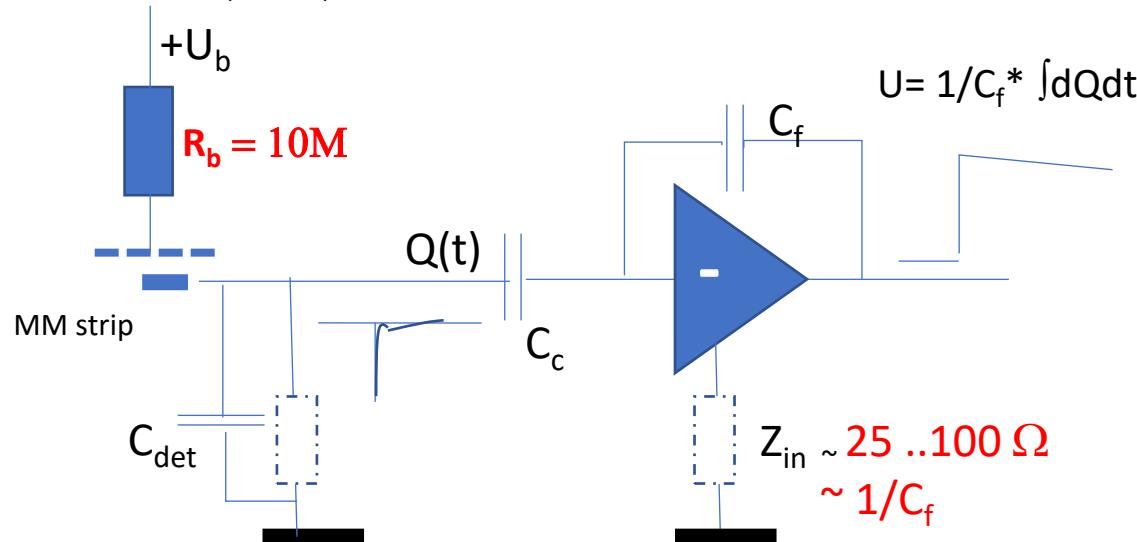
- low R_i** : fast charge transfer from C_{det} to preamp input
- : fast risetime
- : low transfer of charge to neighboring channels
- : low risk of input overvoltage / spark damage

High impedance source detectors (low Q)

charge integration via CSA preamplifier

high C_{in} , high spark immunity

choose low R_i via C_f (gain)

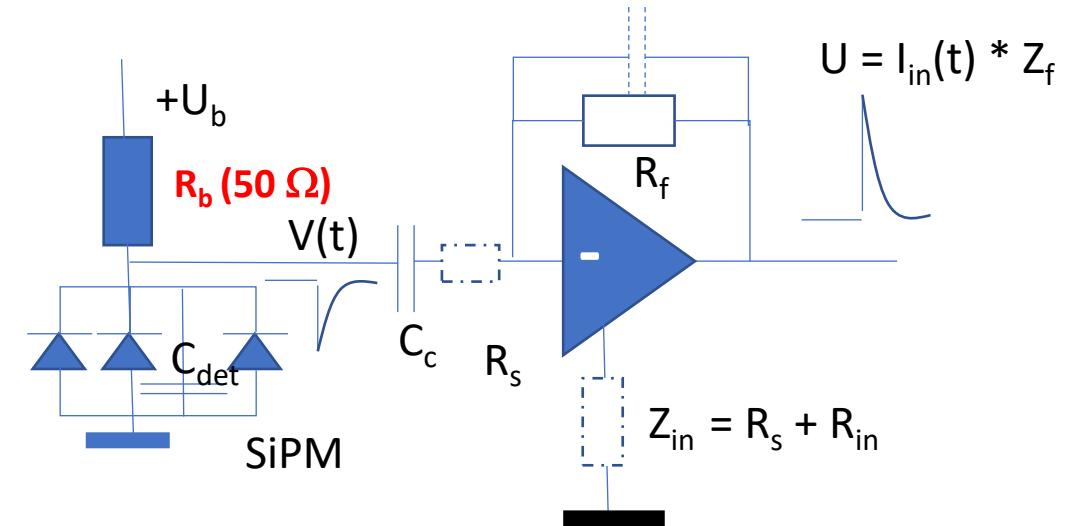


Low impedance source detectors (high Q)

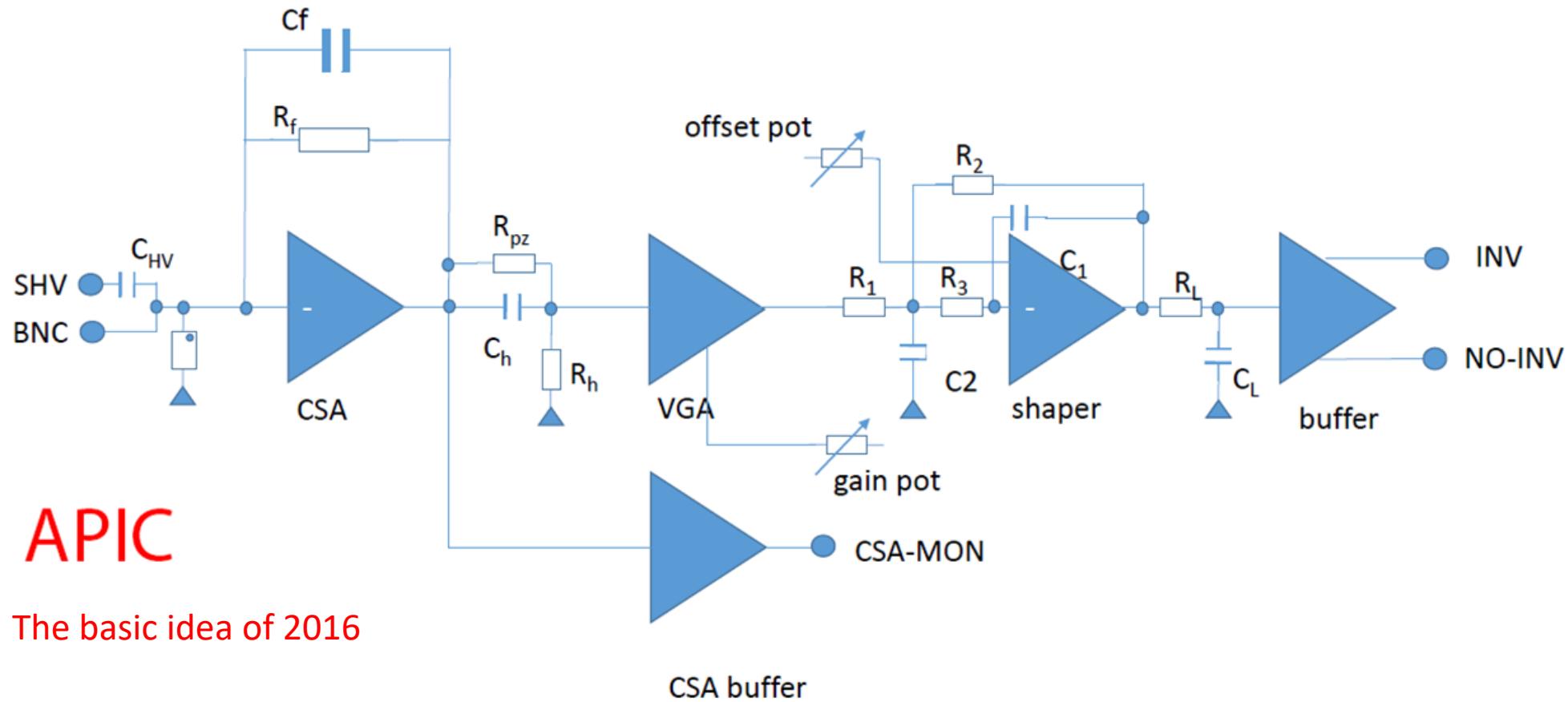
U,I source signal reproduction on TIA or current amplifier

low C_{in} , low spark immunity

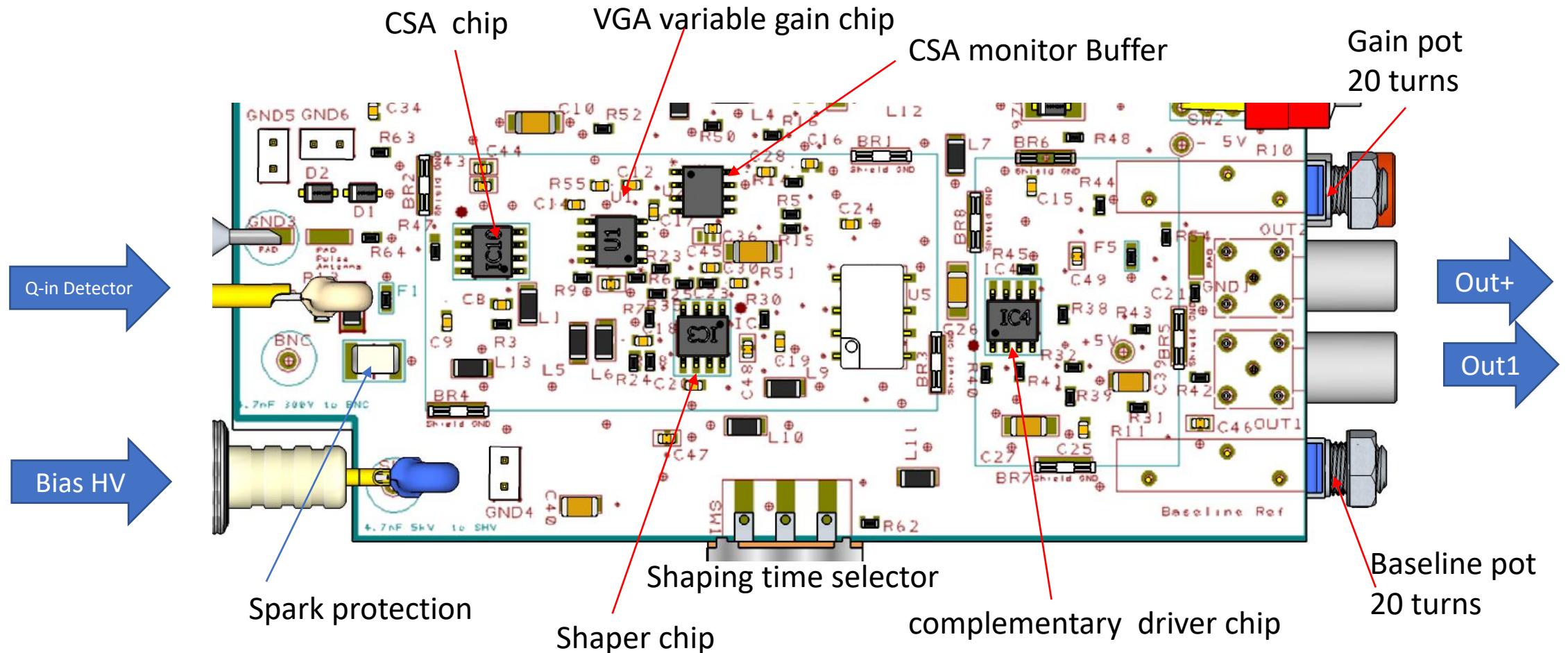
Choose R_i low and match $R_i = R_B$ for minimal signal reflections



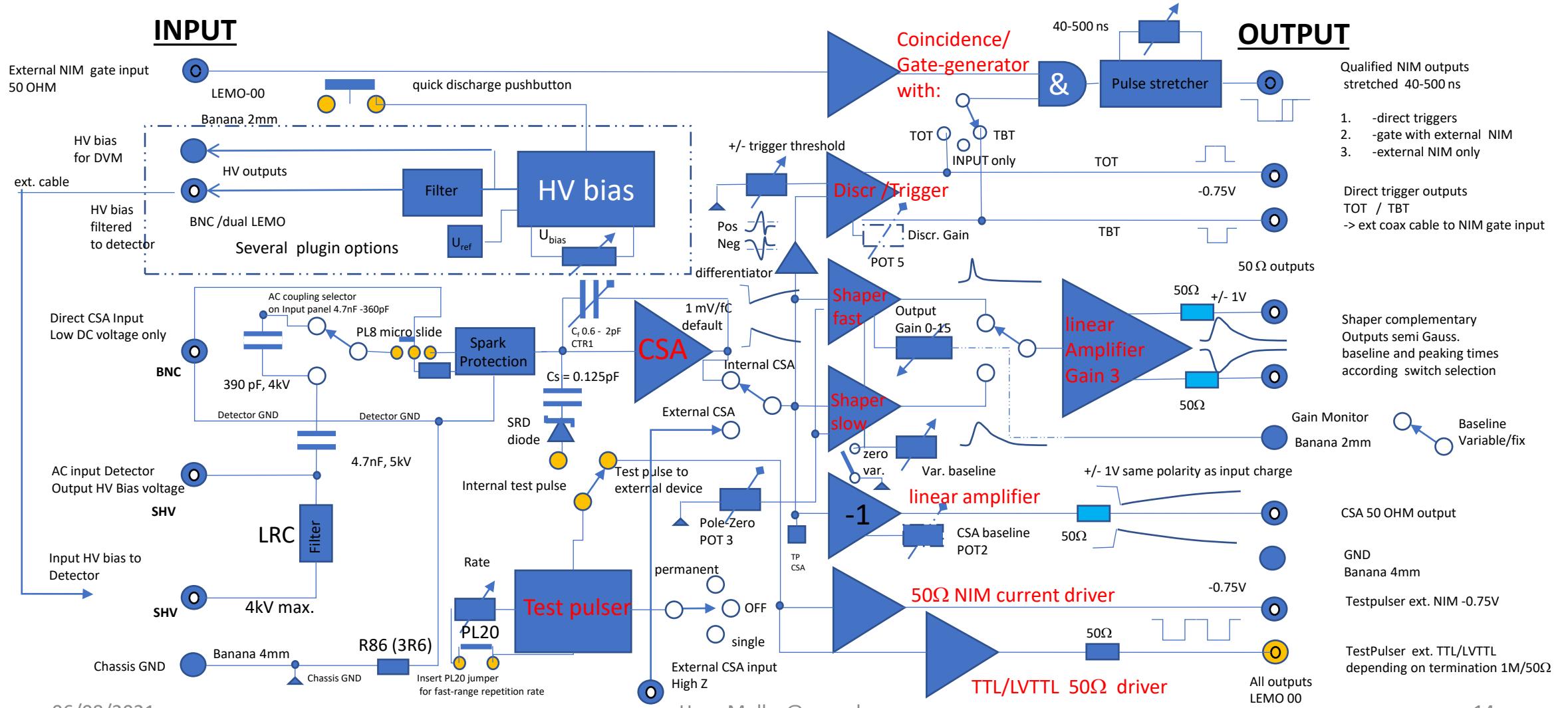
APIC preamplifier- shaper (2016)



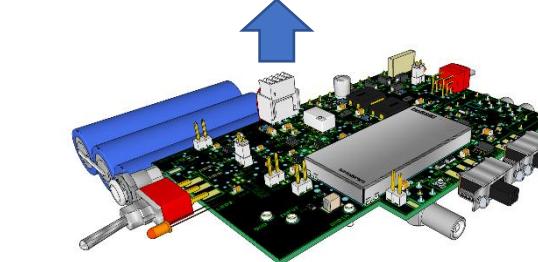
APIC₂₀₁₆ discrete implementation CSA->VGA->shaper



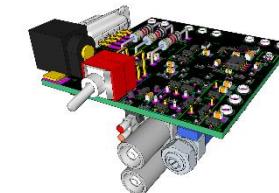
APIC V4 2020... many added features on user request



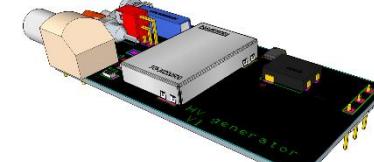
APIC V3



- APIC (preamplifier- shaper)

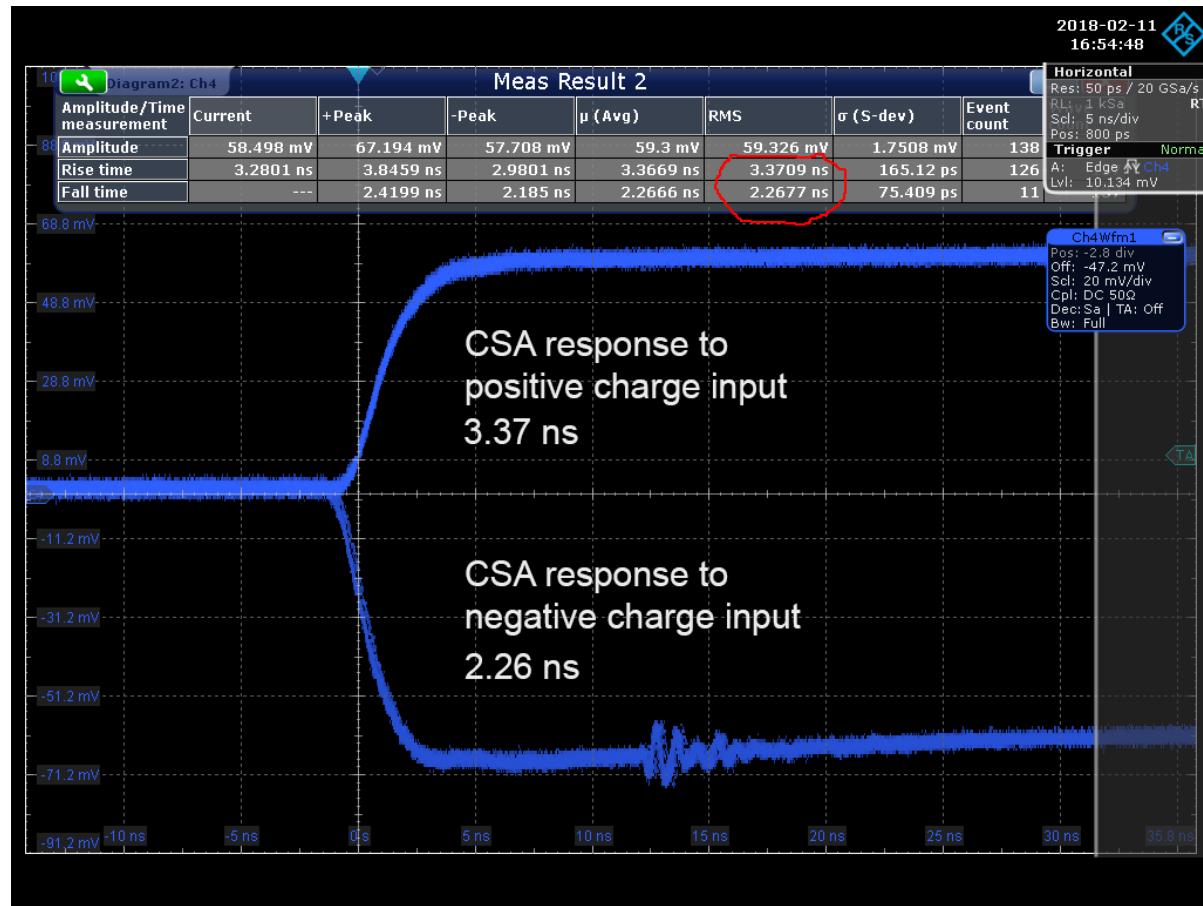


- Trigger and AUX power Unit

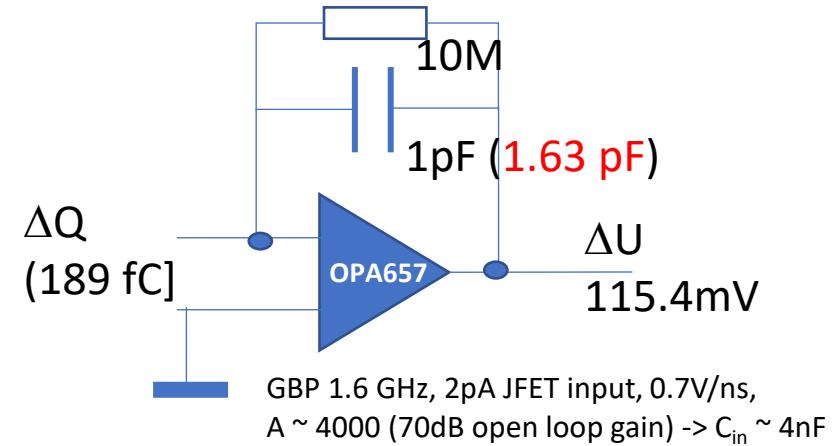


- HV Bias Unit (Option)

CSA gain calibration



stray capacitance matters for discrete



neg. test input charge t_r 200 ps , $\Delta Q = 189$ fC

ΔU : 115.4 mV*, O(2.2ns) CSA rise/falltime

charge gain : $115.4 / 189 = 0.61$ mV/fC

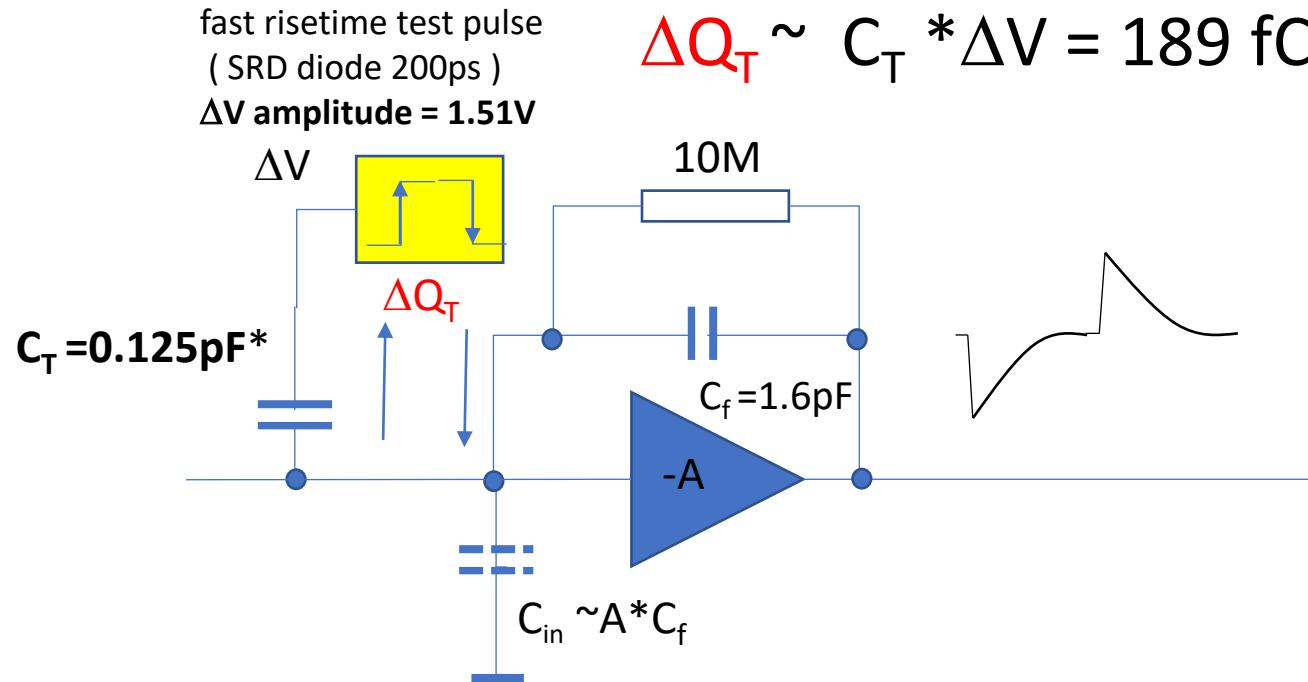
=> C_f effective = $1/0.61 = 1.63$ pF

* $57.7\text{mV} \times 2$ due to $50\Omega + 50\Omega$ output divider($\frac{1}{2}$)

calibration charge Q_T

See appendix for preferred test pulse shape

use fast Voltage pulse transition to couple a unipolar charge to the preamp



*3x 0.5pF in series $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$

Input test charge Q_T :

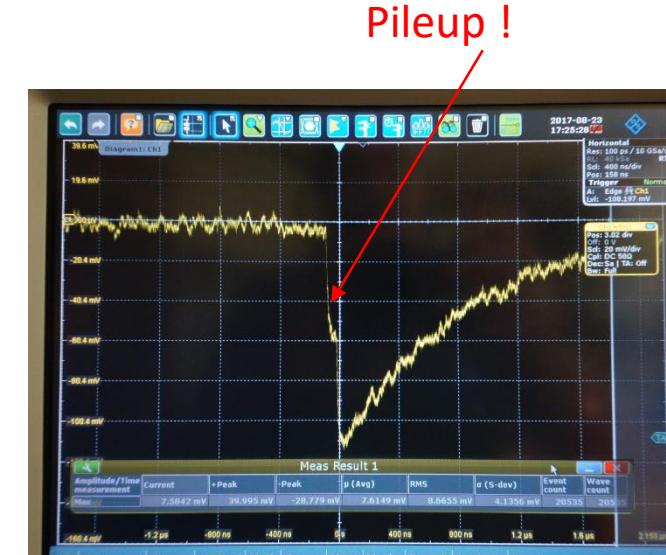
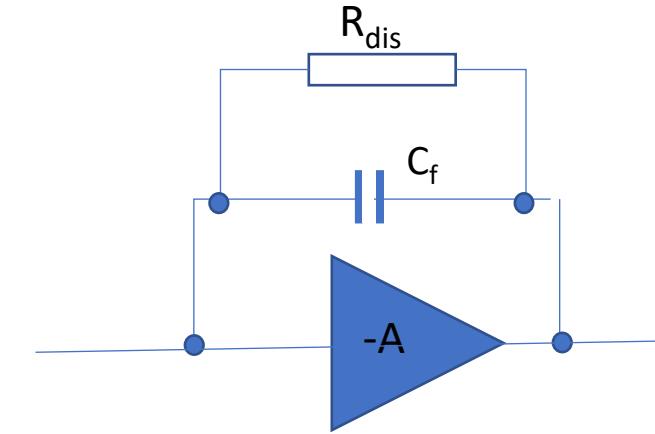
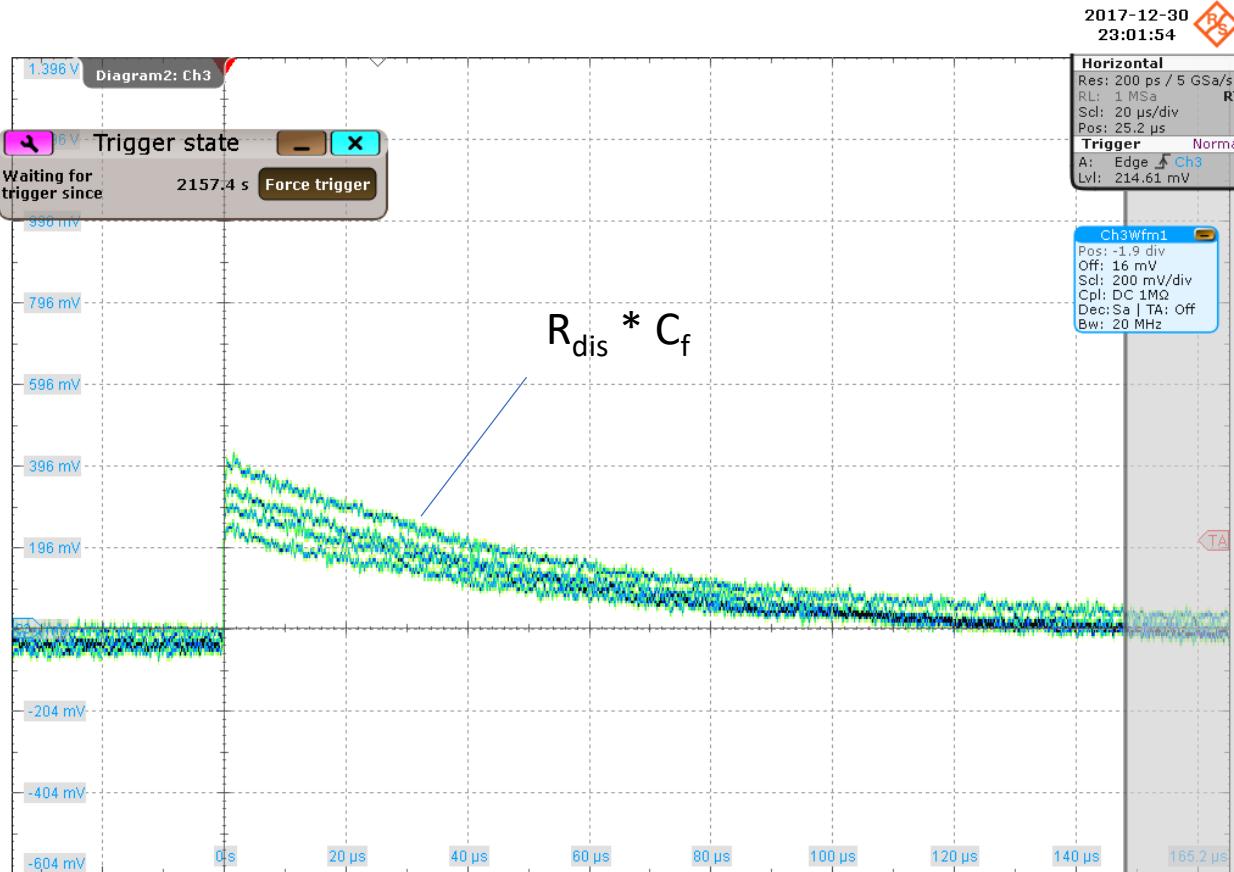
$$\Delta Q_T = \frac{C_T}{1 + \frac{C_T}{C_{in}}} \Delta V \sim C_T [1 - \frac{C_T}{C_{in}}] \Delta V$$

$$\frac{C_T}{C_{in}} \ll 1 \quad C_T = 0.125 \text{ pF} \quad C_{in} = O(4\text{nF})$$

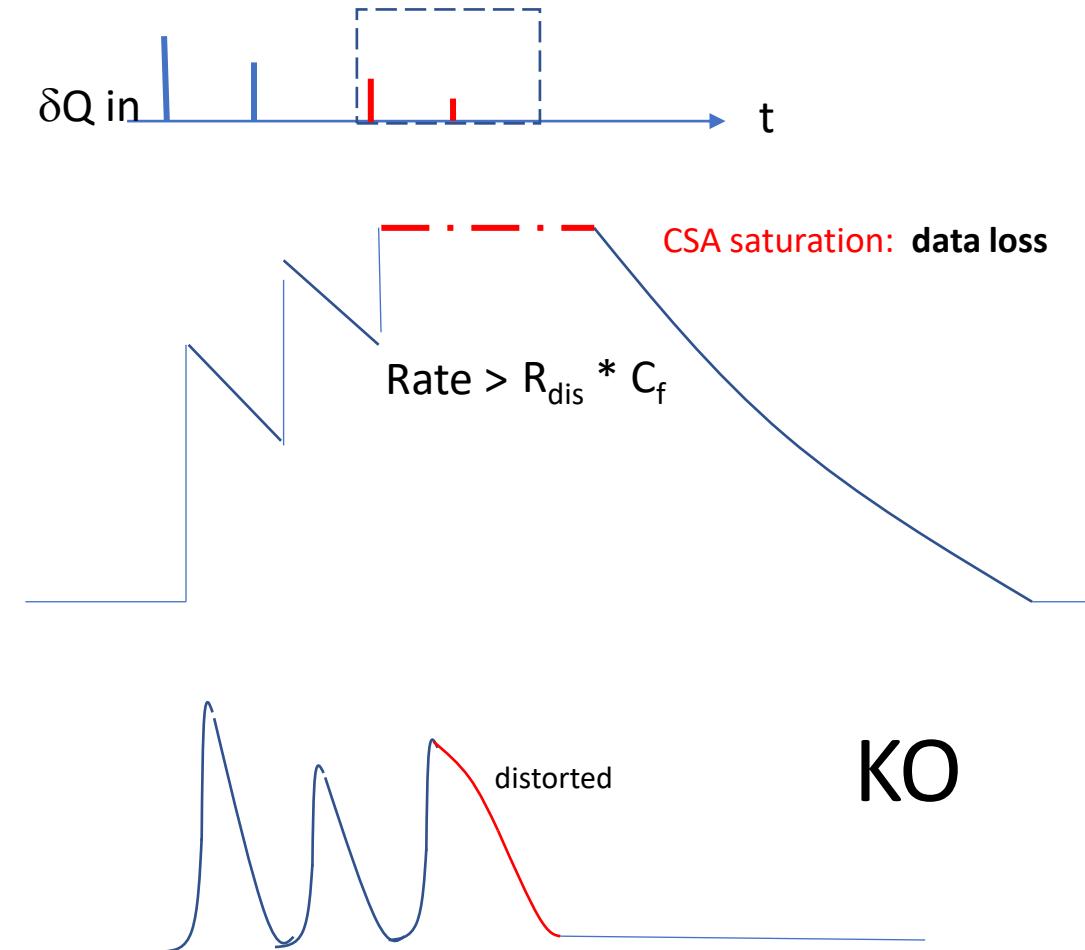
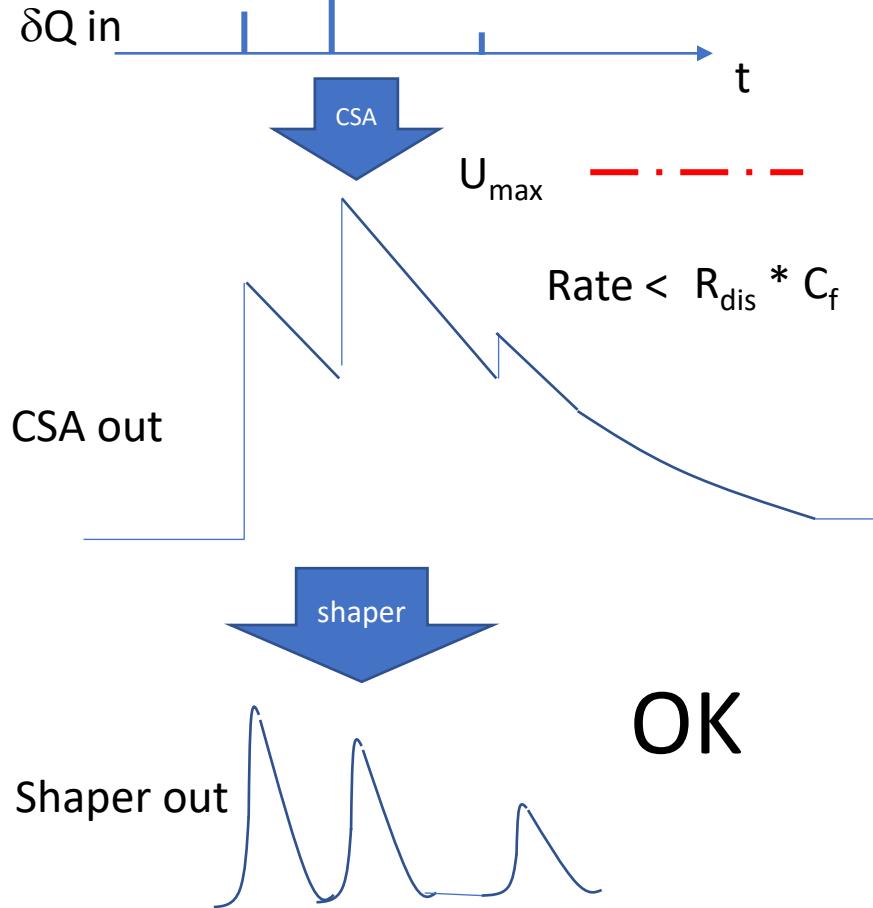
$$\Delta Q_T \sim C_T * \Delta V$$

CSA auto-discharge and pileup

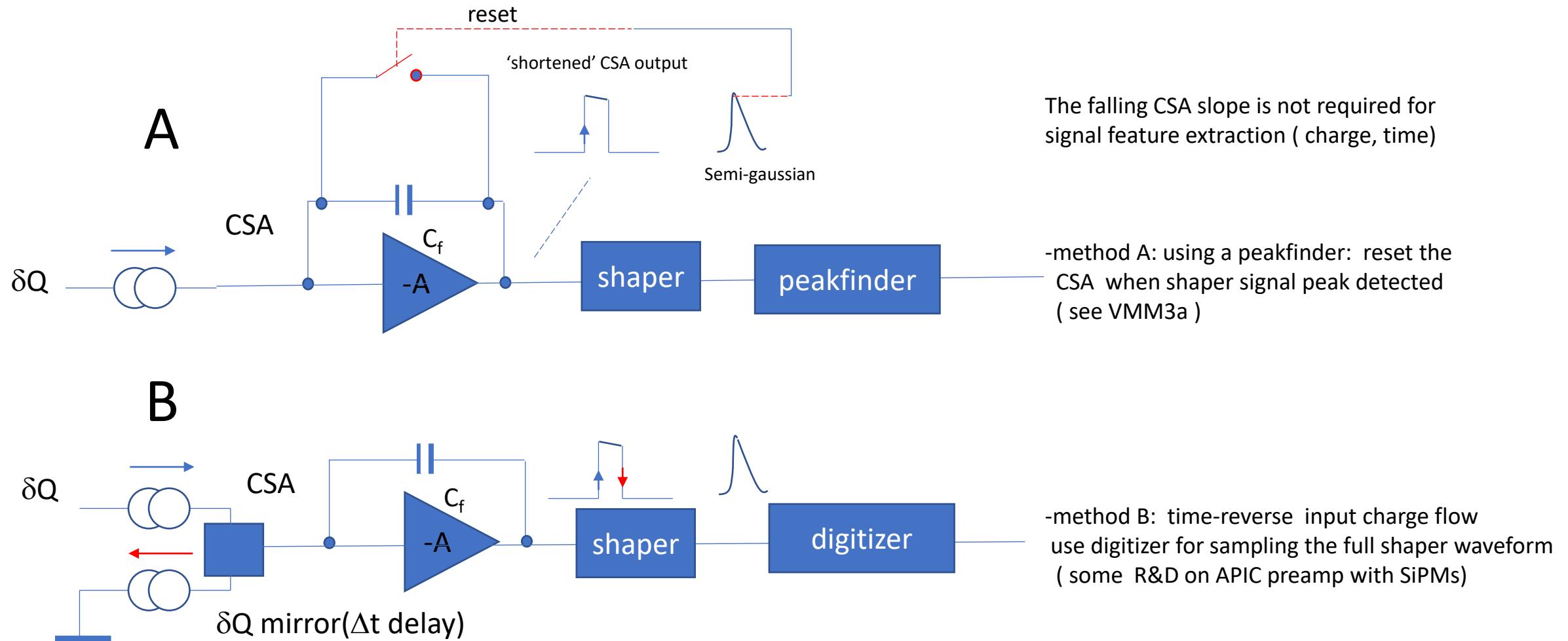
APIC uses classic discharge resistor R_{dis}



High-rate problem with autodischarge



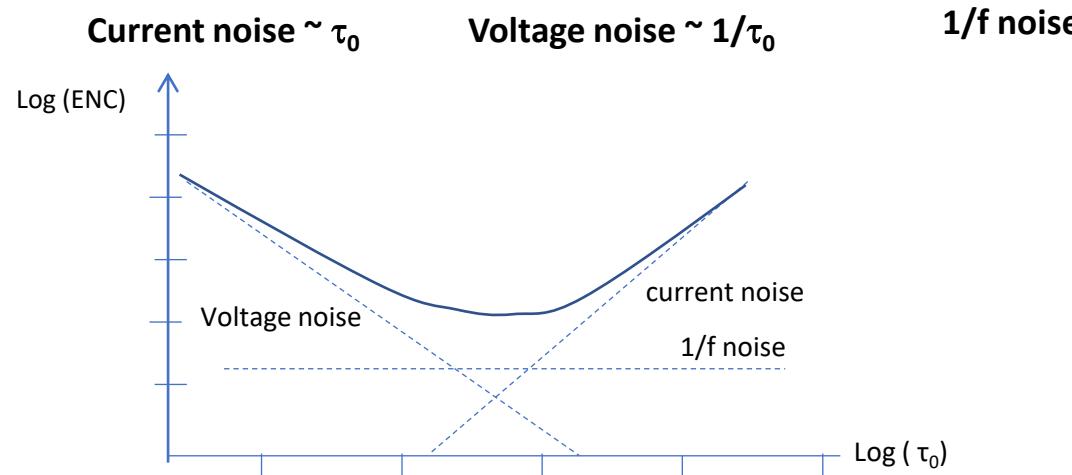
High-rate preamps



Shaping matters

ENC noise dependence on shaping time τ_0

$$\text{ENC}^2 = \frac{4kT}{q \cdot R_b} \cdot F_p \cdot \tau + \frac{4kT}{q^2} \cdot \frac{2}{3} \cdot \frac{1}{g_m} \cdot F_s \cdot \frac{C_d^2}{\tau} + C_d^2 \cdot \text{const}$$



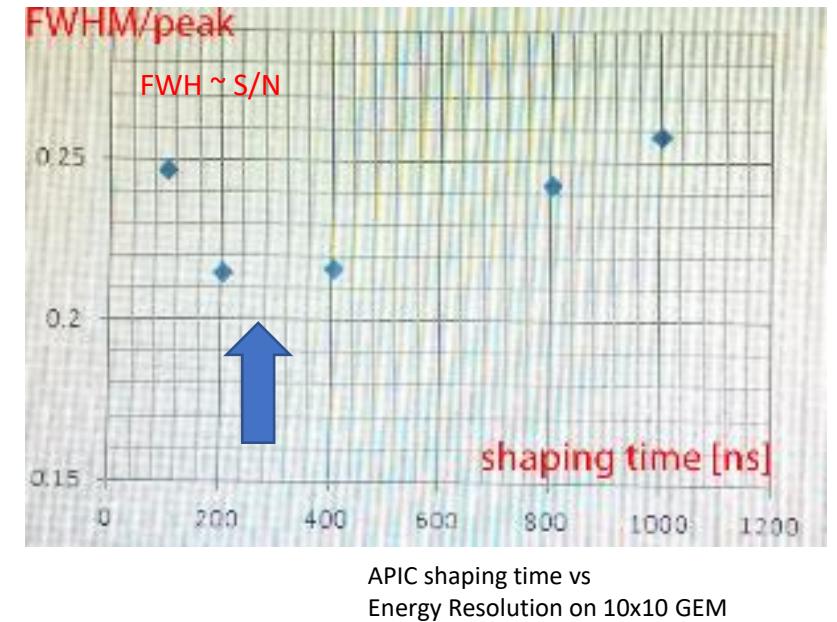
Strategies to minimize ENC:

....after removing
GND loops, RF noise,
HV bias crosstalk etc

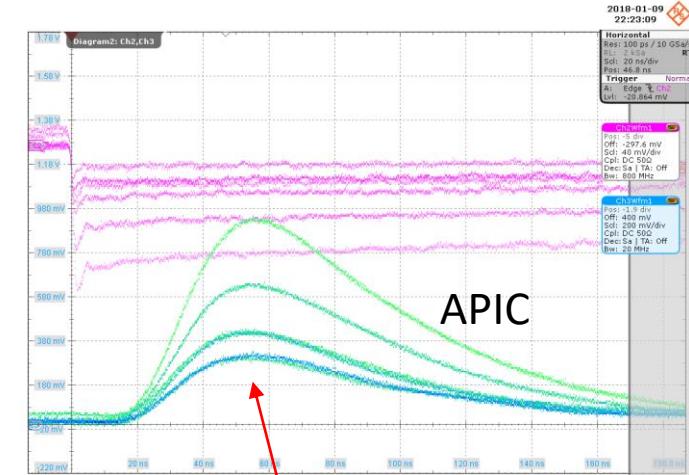
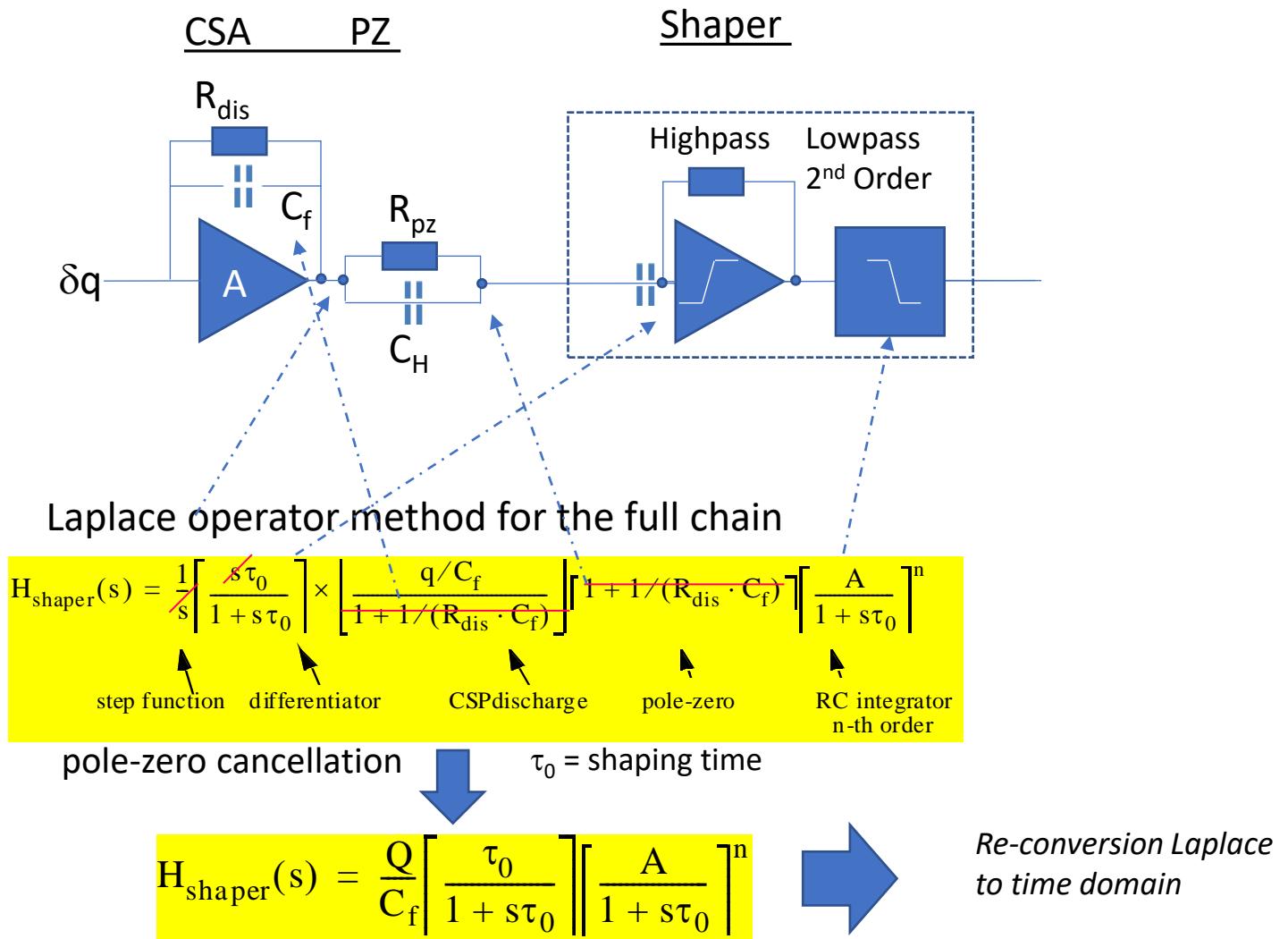
Optimize shaping time τ_0
+ minimize C_D detector capacitance
+ reduce preamp temperature T
+ choose best technology

- Measure ENC noise dependence of shaping time (^{55}Fe spectra)
- Avoid long traces, Coax cables add 1 pF/cm
- Cool CSA's if possible
- Low noise OPAMPS , thin-film resistors

Summers student 2016 result with GEM



'semigaussian' shaper implementation on APIC



$$V(t) = \frac{2Q \cdot A^2}{C_f} \cdot \left[\frac{t}{\tau_p} \right]^2 \cdot e^{-2 \frac{t}{\tau_p}}$$

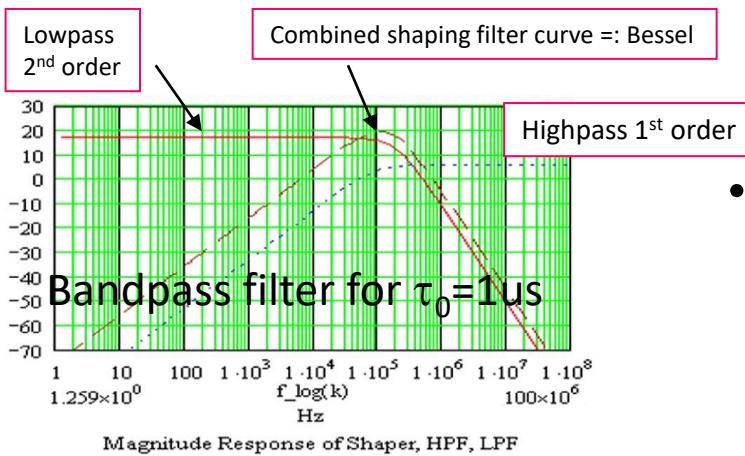
↑
 $n=2$

$$V(t) = \frac{n^n Q \cdot A^n}{n! C_f} \cdot \left[\frac{t}{\tau_p} \right]^n \cdot e^{-n \frac{t}{\tau_p}}$$

A: CSA Amplifier open loop gain
 C_f: CSA feedback capacitor
 Q: total input charge
 τ₀: shaping time
 τ_p : peaking time
 n: order of H_{lp} filter

Bandpass filter and shaping time

- CRnRC band-pass filters of order n: the low-pass slope is $n * 20 \text{ dB/octave}$ whilst for the single RC high pass it is -20 dB/octave . The **-3dB cutoff frequency f_c** is given by



$$f_c = 1/(2\pi \tau_0)^*$$

* $\tau_0 = \tau_p/2$ is shaping time

- The time response function (shaped output) produced by CR-nRC bandpass filters closely resembles a semi-gaussian shape, properly implemented the analytic form is a $\Gamma_n(t)$ function of order n

$$V_{out}(t) = \left[\frac{n^n Q \cdot A^n}{C_f} \right] \cdot \left[\frac{t}{\tau_p} \right]^n \cdot e^{-\frac{n}{\tau_p} \frac{t}{\tau_p}}$$

With: $\tau_p = n * \tau_0$

$$V_{max} = \frac{Q \cdot A^n \cdot n^n}{C_f \cdot n! \cdot e^n}$$

peak amplitude measures charge Q

APIC: 2x shaping times

$\tau_p = 12.5 \text{ ns}$, $\tau_p = 25 \text{ ns}$, $f_c = 12.7 \text{ MHz}$
 $\tau_p = 200 \text{ ns}$, $\tau_p = 100 \text{ ns}$, $f_c = 800 \text{ kHz}$

APIC: discrete Lowpass implementation 2nd Order Bessel Filter

$$H(s) = \frac{K}{1 + as + bs^2}$$

*APIC: Implement 2 shapers
with 1 single OPAMP*



Choose constants a,b,K for Bessel filter characteristics

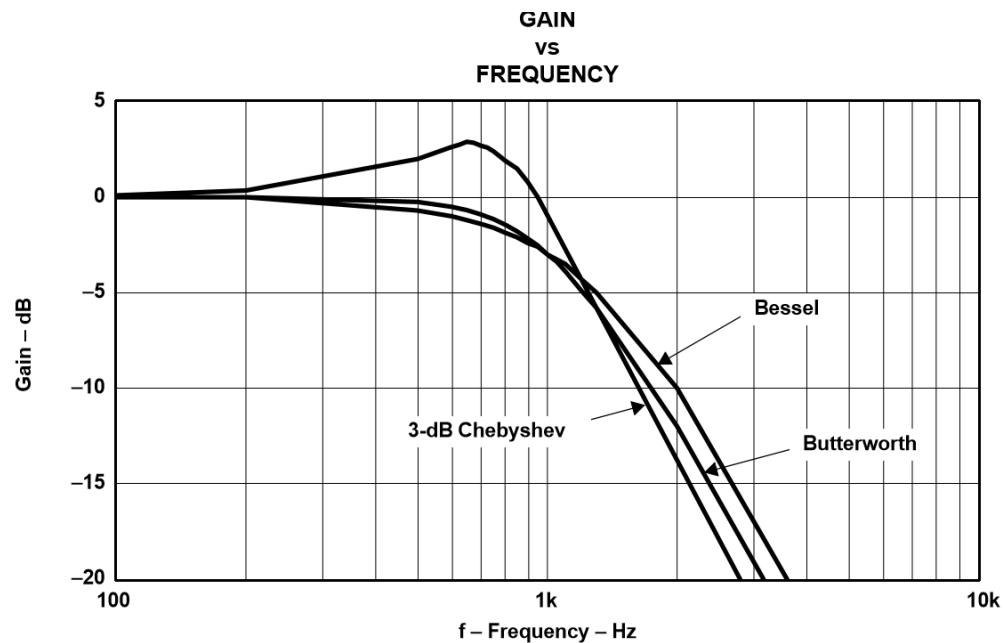
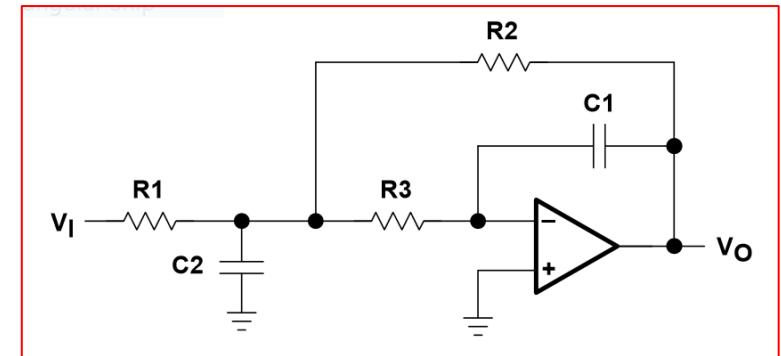


Figure 10. Second-Order Butterworth, Bessel, and 3-dB Chebyshev Filter Frequency Response



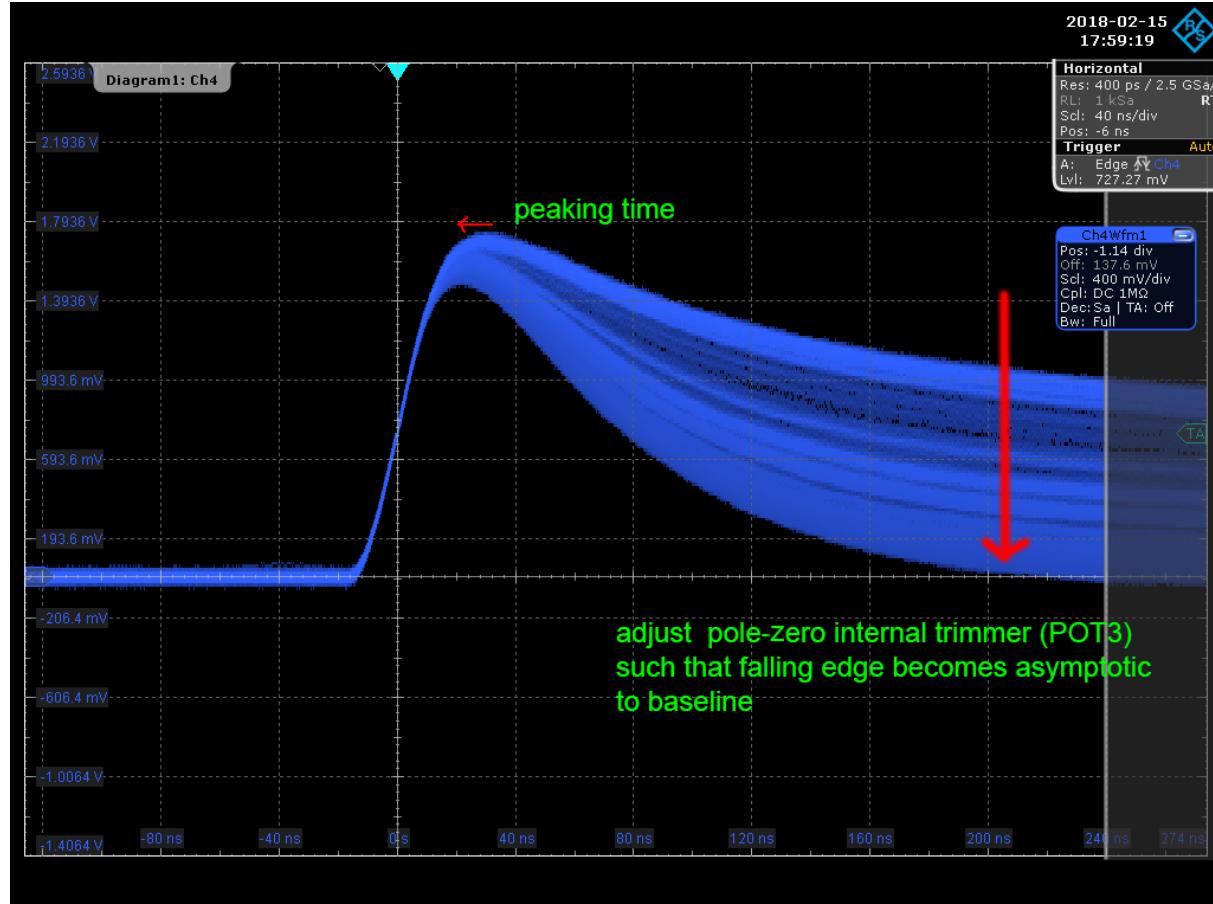
2nd Order Bessel Filter circuit (APIC)
linear, high BW OP-AMP



Photo: real estate of
2nd Order Bessel Filter
 $\tau_s = 12.5\text{ns} \text{ & } 200\text{ns}$ on APIC

Pole-zero fine adjustment

asymptotic return to zero baseline



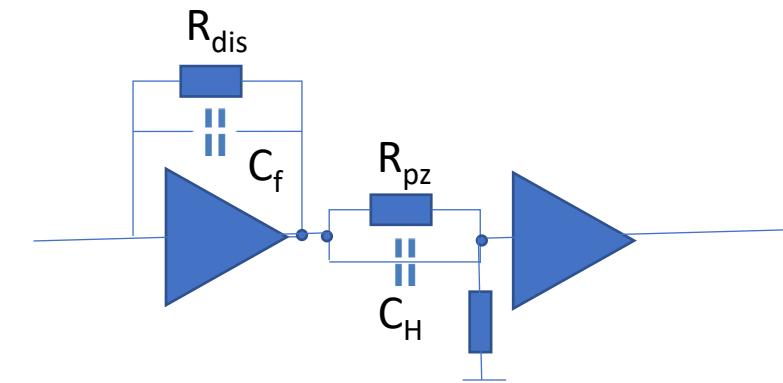
Make these 2 terms cancel

$$H_{\text{shaper}}(s) = \frac{1}{s} \left[\frac{s \tau_0}{1 + s \tau_0} \right] \times \left[\frac{q/C_f}{1 + 1/(R_{\text{dis}} \cdot C_f)} \right] \left[1 + 1/(R_{\text{dis}} \cdot C_f) \right] \left[\frac{A}{1 + s \tau_0} \right]^n$$

step function differentiator CSPdischarge pole-zero RC integrator n-th order

make equal:

$$R_{\text{dis}} * C_f = R_{\text{pz}} * C_H$$



Component tolerances:

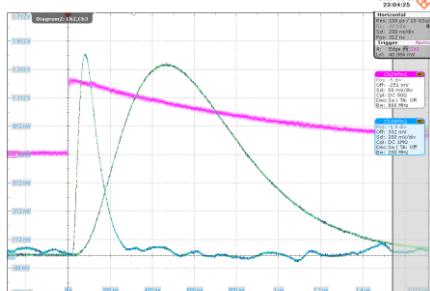
In discrete logic, the exact R_{pz} value can be determined by using a trimmer

peaking time invariance τ_p

$$V_n(t) = \frac{n^n Q \cdot A^n}{n! C_f} \cdot \left[\frac{t}{\tau_p} \right]^n \cdot e^{-n \frac{t}{\tau_p}}$$

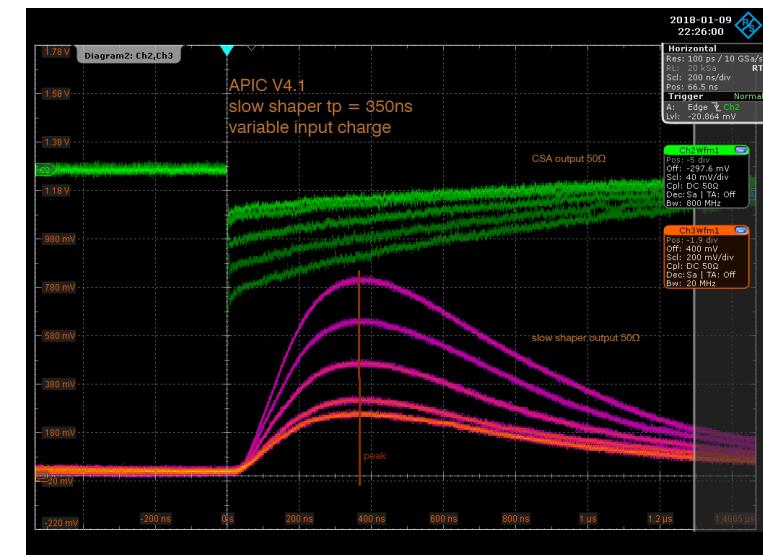
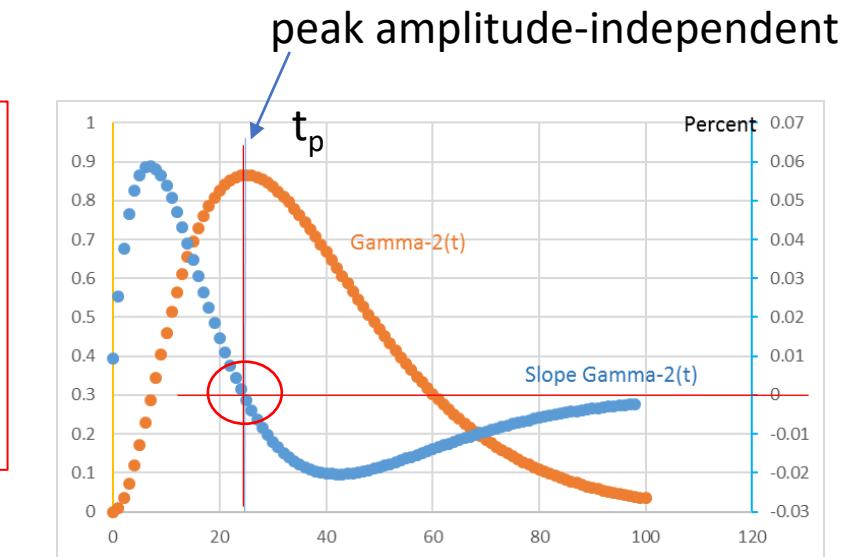
Peak: set 1st derivative $V_n(t) = 0$
 choose filter order
 i.e. n=2 for APIC
 $\tau_p = n * \tau_0 = 2 \tau_0$
 → peaking time 2x shaping time τ_0
 → peak invariance of amplitude (!)

APIC:
 2nd order Filter, n=2
 $\tau_{p1} = 25 \text{ ns}$
 $\tau_{p2} = 400 \text{ ns}$



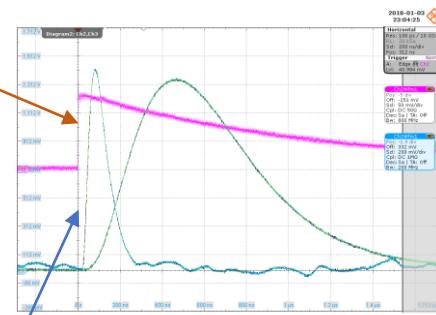
$$V(t) = \frac{2Q \cdot A^2}{C_f} \cdot \left[\frac{t}{\tau_p} \right]^2 \cdot e^{-\frac{2t}{\tau_p}}$$

APIC output signal
 (for VCA gain :=1)



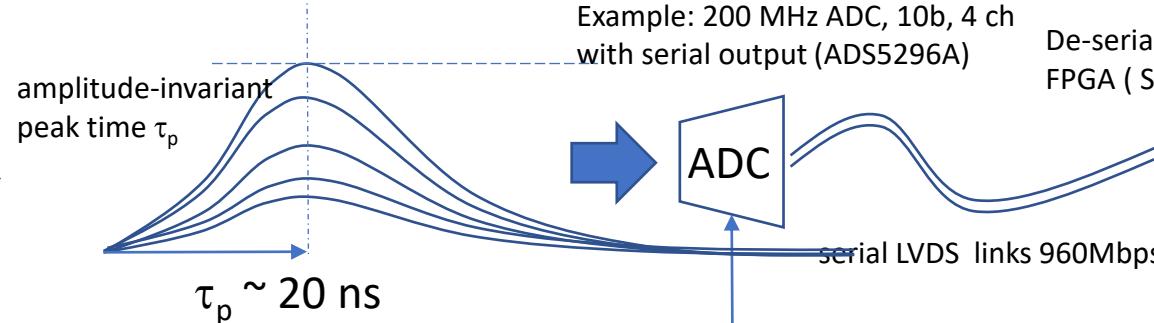
$\Gamma_n(t)$ shaper sampling for ps time resolution (project proposal)

CSA:
 $t_r \sim 0(1\text{ns})$

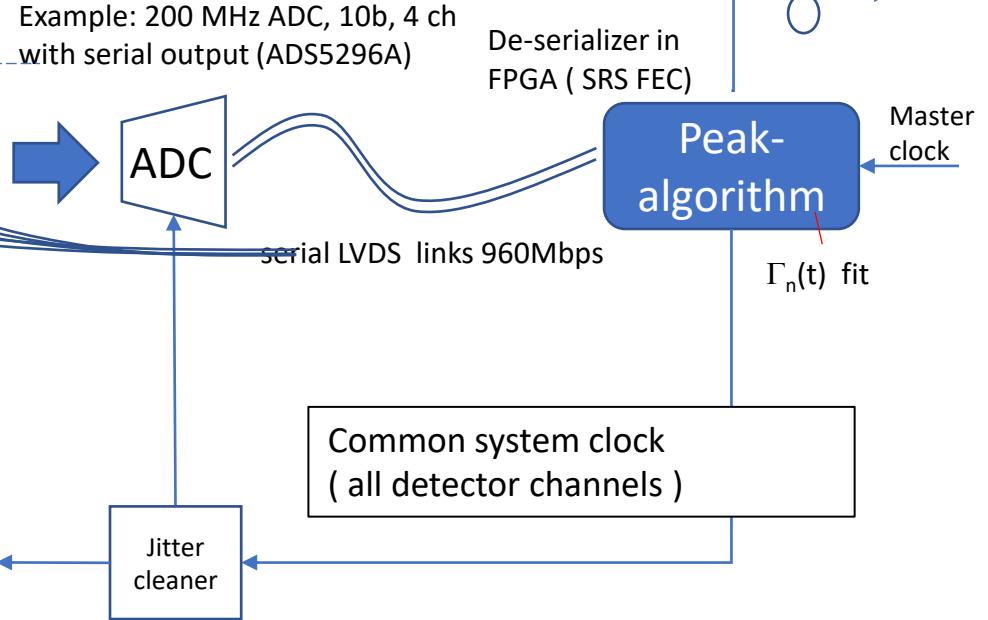
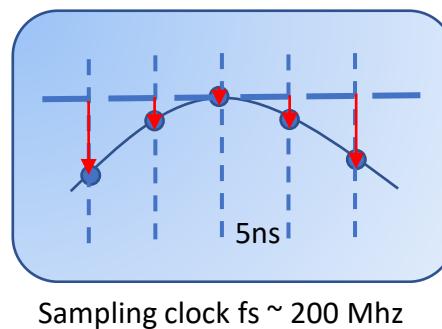


Time resolution via peak-sampling

$\Gamma_2(t)$ shaper peaking time ~ 25 ns
signal envelope ~ 75 ns
 ~ 25 samples @ 200 MHz

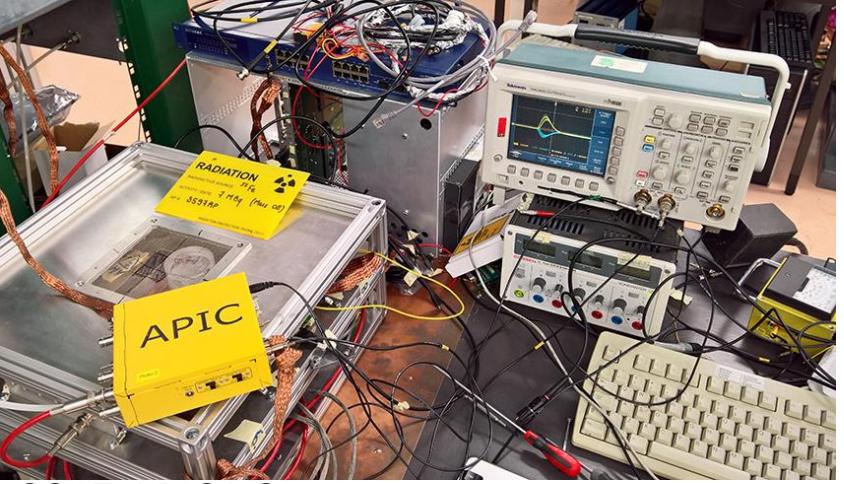


Example: 200 MHz ADC, 10b, 4 ch
with serial output (ADS5296A)

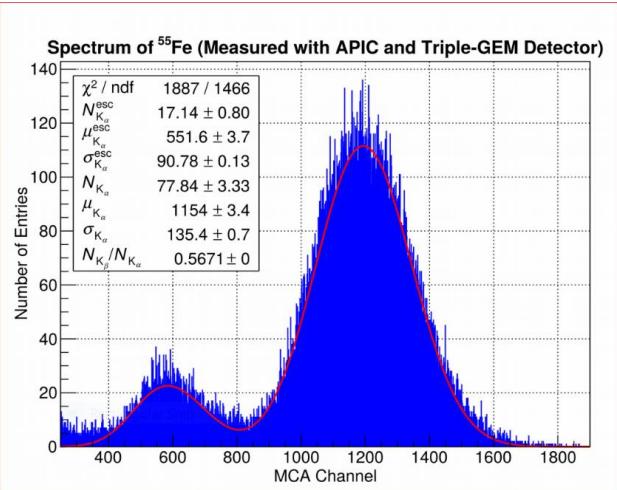


$\Delta t_{\text{peak, fit}}$ expect $\sigma_t \leq 100 \text{ ps}$ why ?
 σ_t resolution via fit with known shape
- multipoint sampling (25) $\Gamma_n(t)$
- amplitude independence of peak : $\sigma_{\text{timewalk}} \sim 0$
- referenced to common system clock , $\sigma_{\text{clockjitter}} \sim 0$

APIC in GDD lab, GEM tests



2017 APIC V3



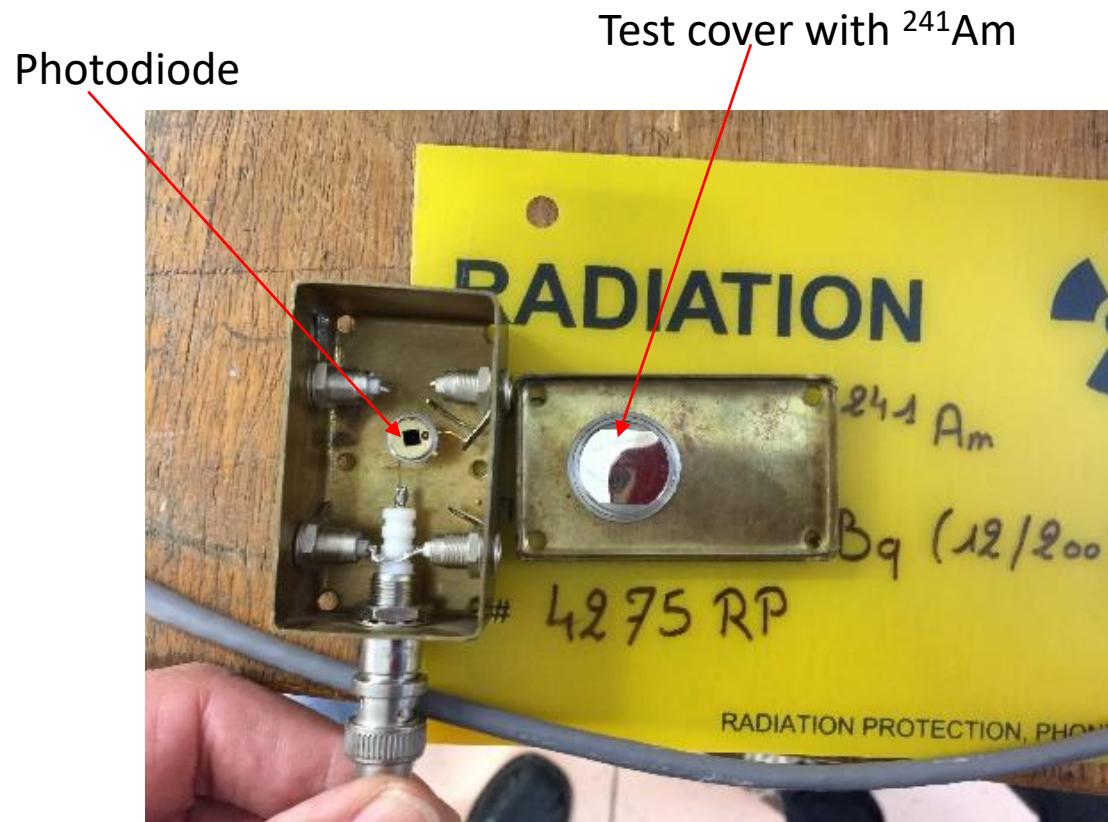
06/08/2021

2021 APIC V4
preparation for high-rate
testbeam telescope



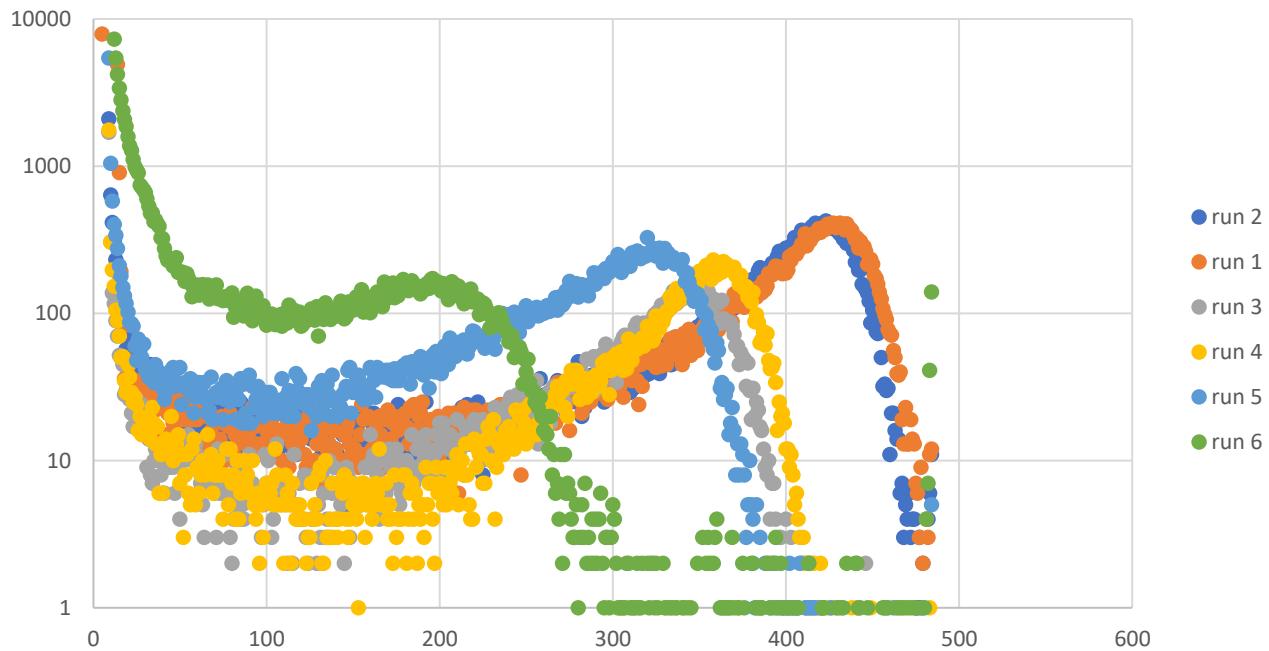
Hans.Muller@cern.ch

Alpha spectra with APIC and Pin photodiode



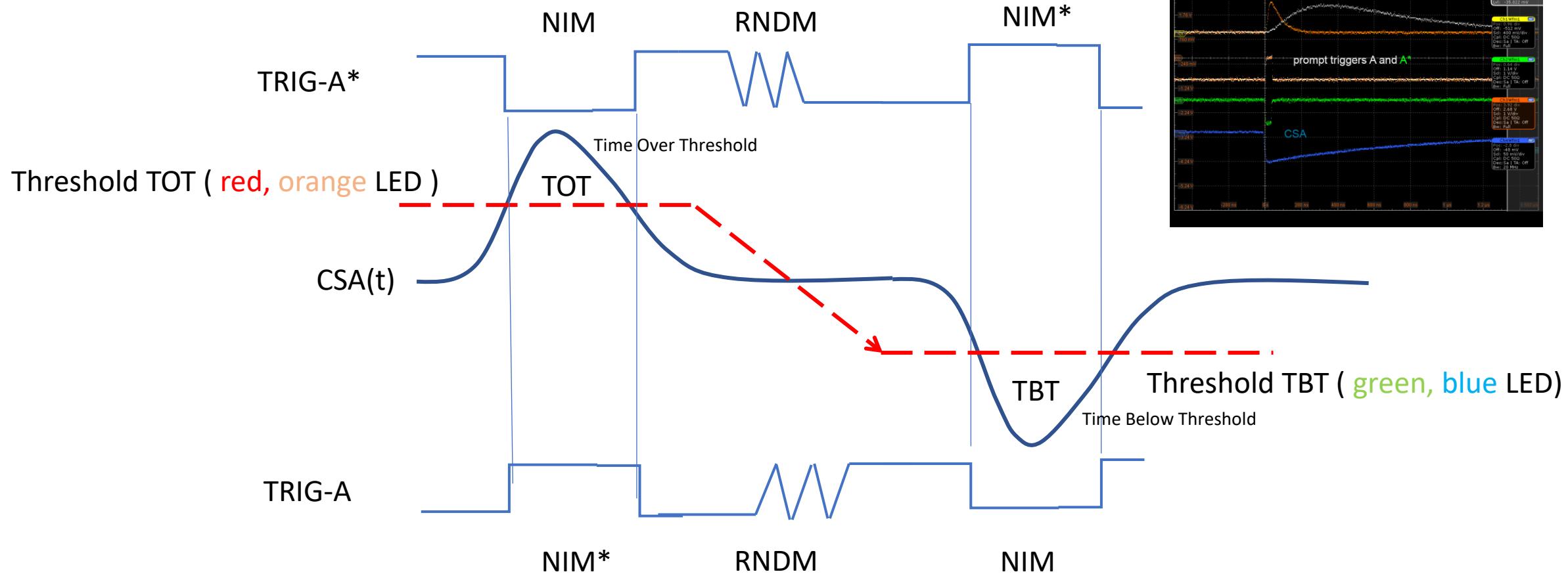
A cheap commercial photodiode was biased at variable APIC generated bias voltages and the APIC shaper output connected to an MCA

Am241 spectrum with APIC and cheap Pin diode

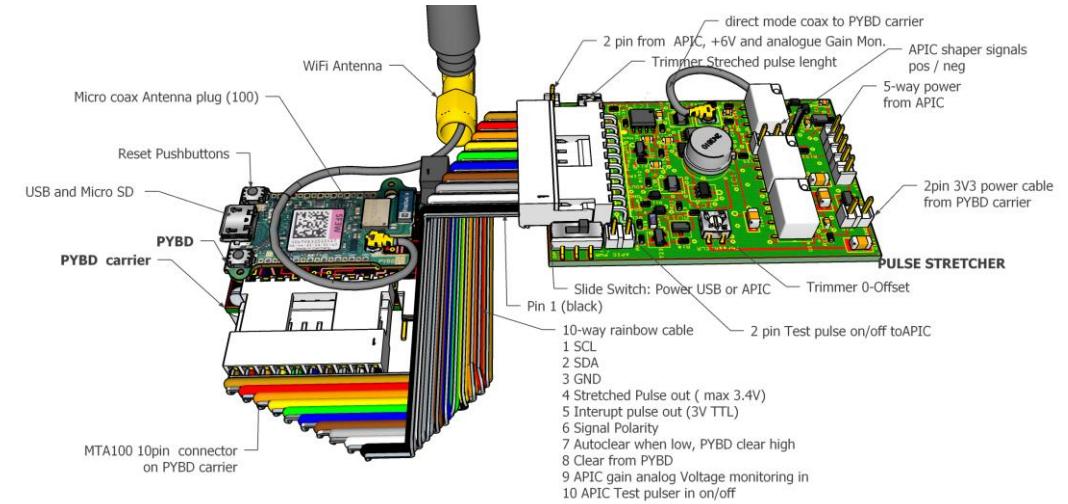
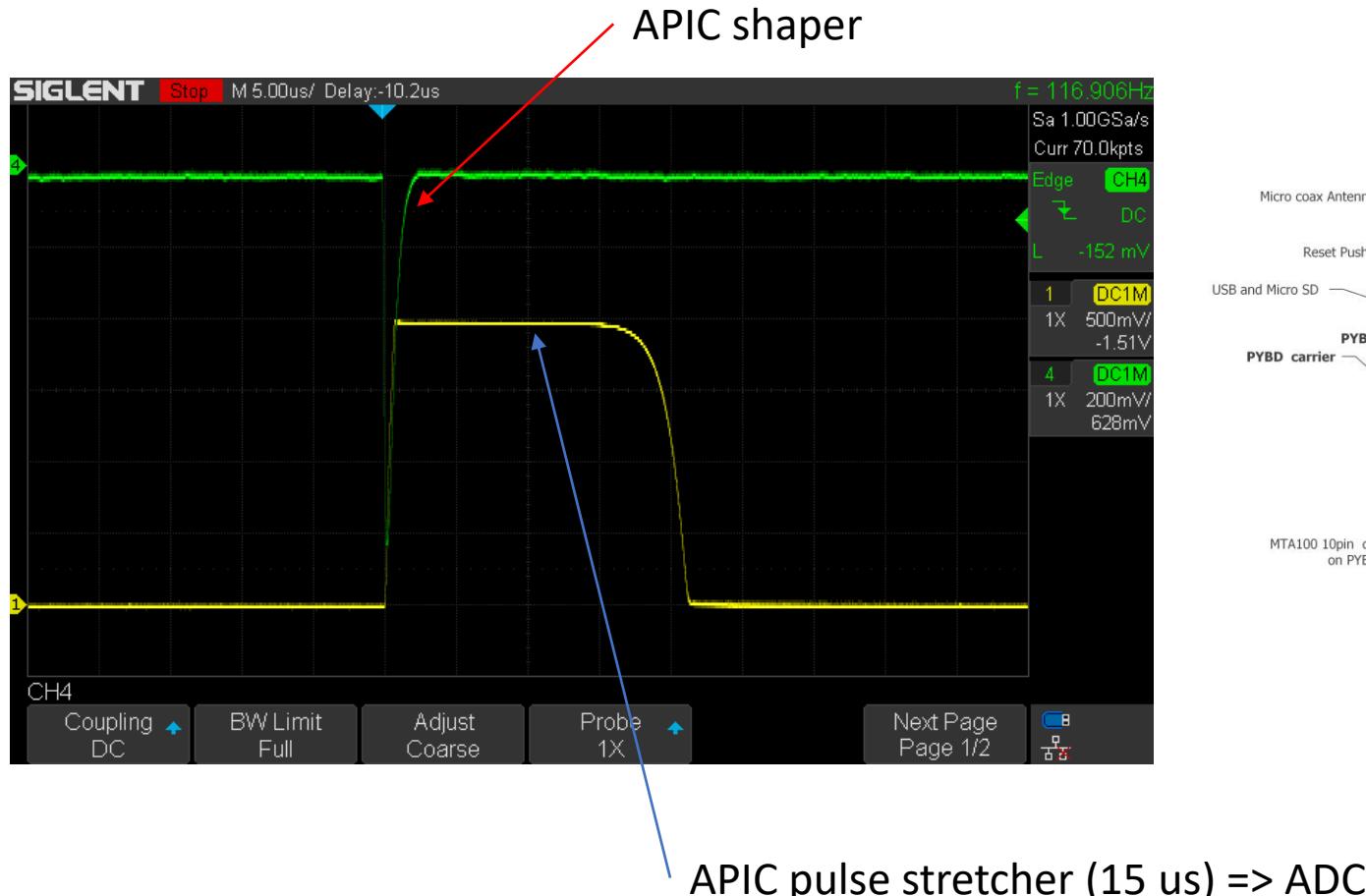


- Run 1 with APIC internal Bias Voltage 20V , light shield around test box
- Run 2 with 9V Battery Bias (~ noiseless crosscheck), light shield around test box
- Run 3 and 4 like Run 1 with 4 and 5 mm wider separation, light shield around test box
- Run 6 like Run 1 but lightshield replaced by 1 thin Alu foil 5uAlu+100u Mylar
- Run 6 like Run 4 but 2 x Alu foil

TOT and TBT trigger (APIC)



APIC₂₀₁₉ peak finder-stretcher: for use with 2.4 MS/s ADCs in SoC card for data conversion



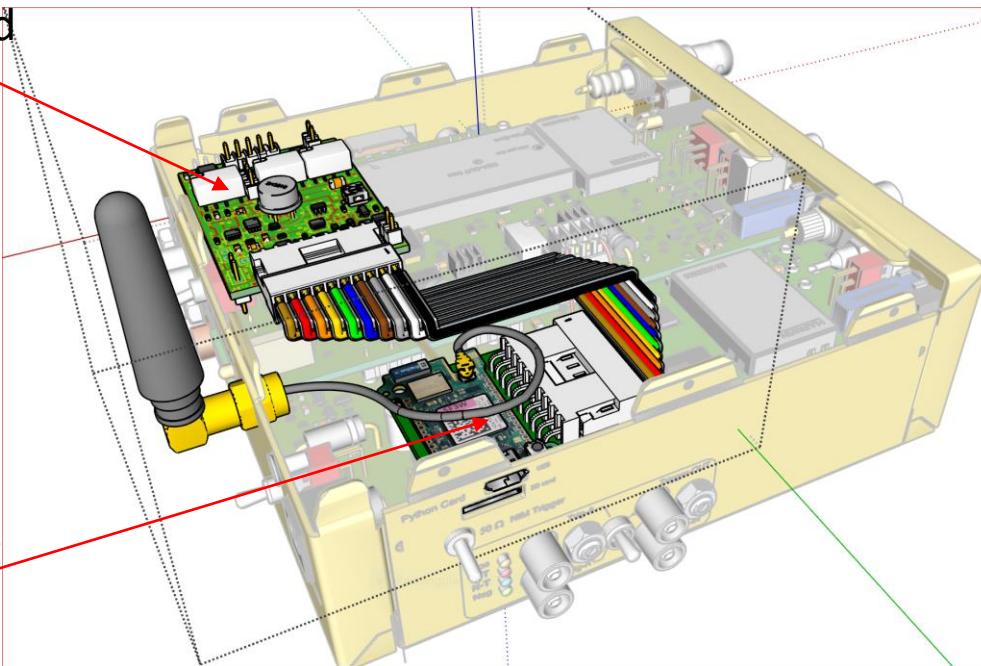
Peakfinder Controls via flat-cable from
uPython SoC card

MAPIC 2019

APIC with embedded, networked MCA

2019 summer student project

added peakfinder card



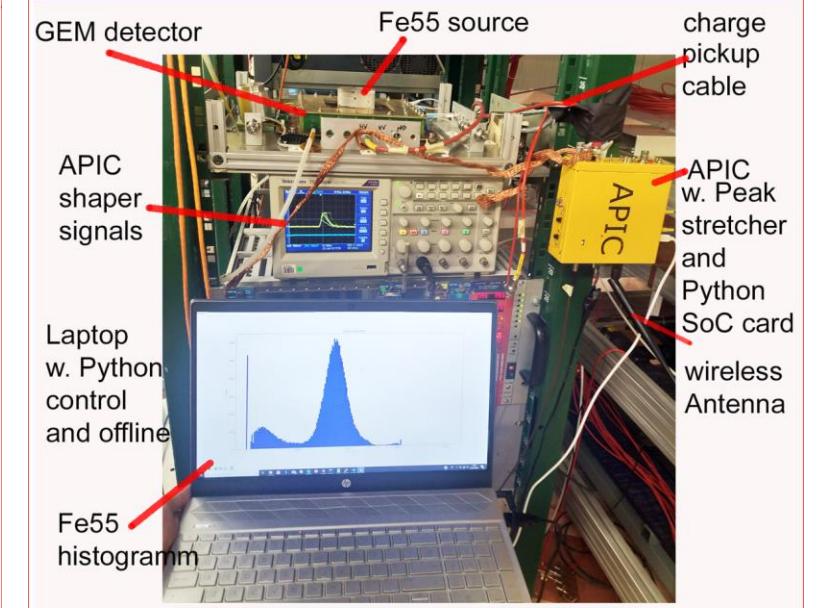
GEM detector

APIC shaper signals

Laptop w. Python control and offline

Fe55 histogramm

Max sample rate 2kHz



Networked DAQ GUI-based

Summary

- discrete electronics matters
 - R&D of concepts (before implementation in ASICs)
 - verification / updates on real detectors
 - training of students
 - feature addition on user request
- Detectors with discrete frontends exist for good reasons
 - lowest C_d , very high dyn. ranges, low noise ..
- Preamp technology keeps evolving
 - high rate preamps
 - matched impedance, fast risetime
- 0-timewalk shapers possible (at least in discrete)
 - ps time resolution via peak fit
- APIC and MAPIC exist !
 - updates planned: new preamp, 3day-autonomy, embedded MCA, networked DAQ and Ctrl

Thank you !

Les grandes choses sont
souvent plus faciles qu'on ne
pense

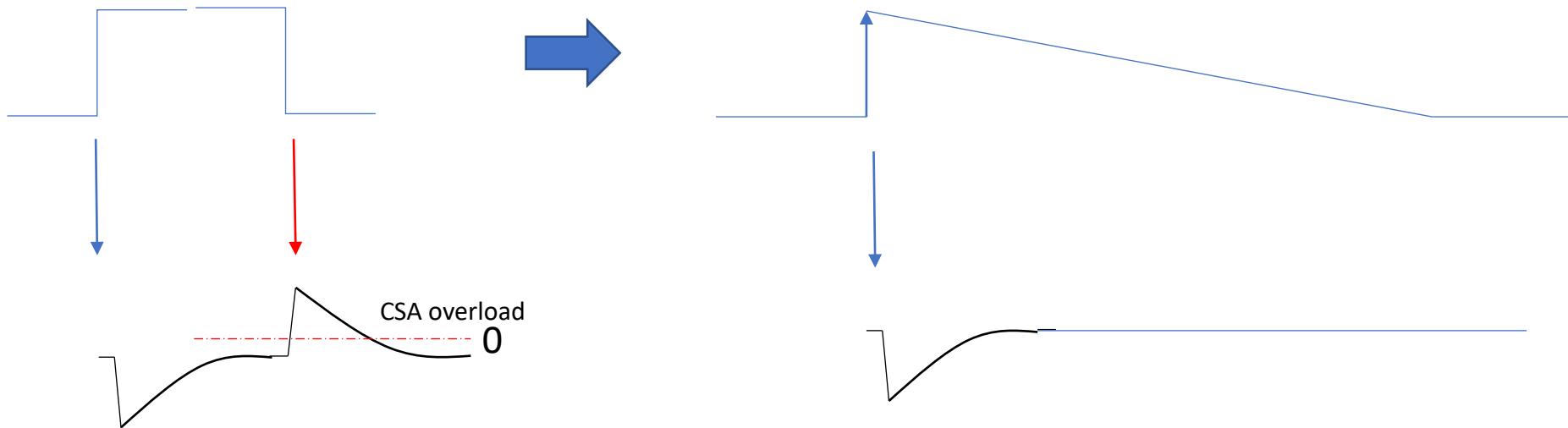
*François Marie Arouet, dit Voltaire

Backups

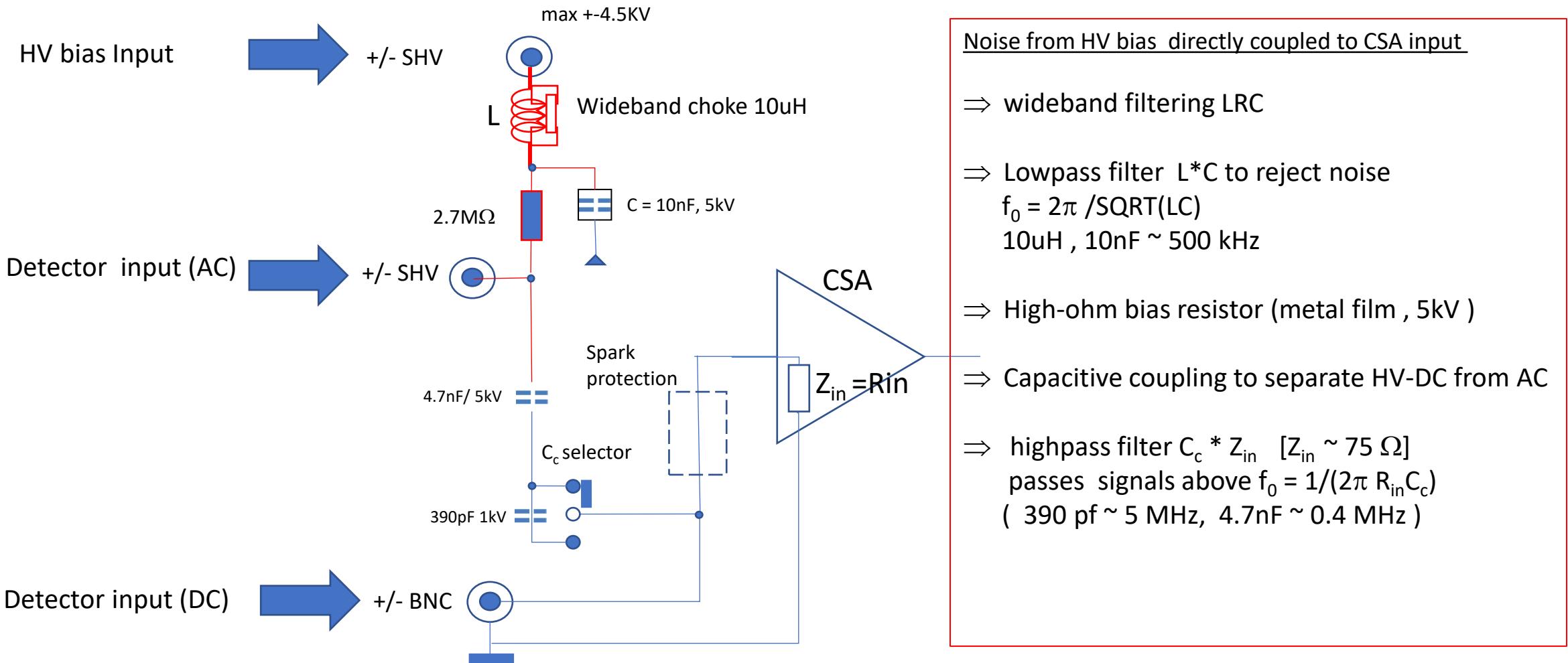
Test pulse shape

A rectangular pulse entails production of the opposite charge
which can overload the CSA, at least temporarily

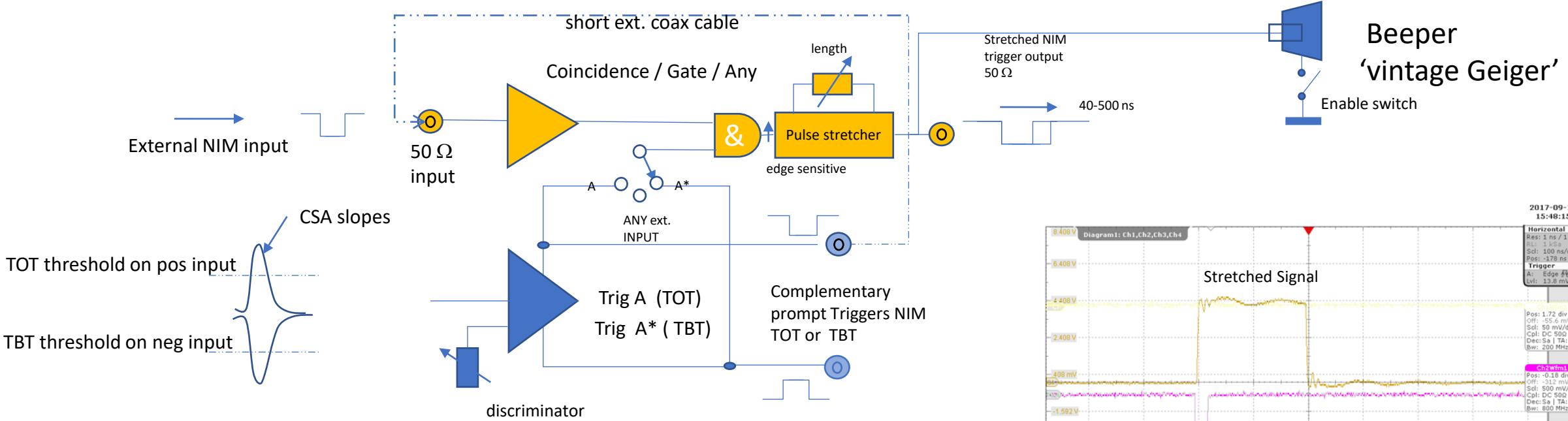
Saw-tooth test pulse shape avoids opposite polarity



HV bias and AC coupling (MPGD, APDs)

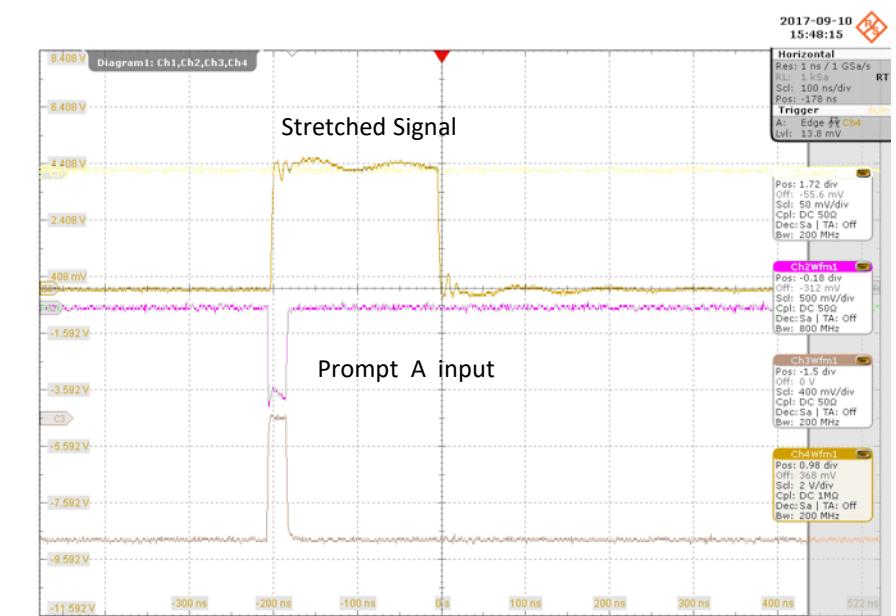


Stretcher & coincidence unit



Stretcher Unit Modes:

1. Coincidence (ext. NIM signal) with direct triggers A or A*
2. Unconditional stretch for any external NIM signal
3. Stretched TOT or TBT trigger (coax cable to ext. NIM input)



spark protection APIC

triple spark protection scheme:

$$\Delta U_{in} \gg 50V : 1\text{ ns} \rightarrow \Delta U_{out max} = 3V$$

