CCLRC Technology

AIDA design study

Noise analysis

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Overview

Block diagram - top-level

Analogue channel - pre-amp/shaper

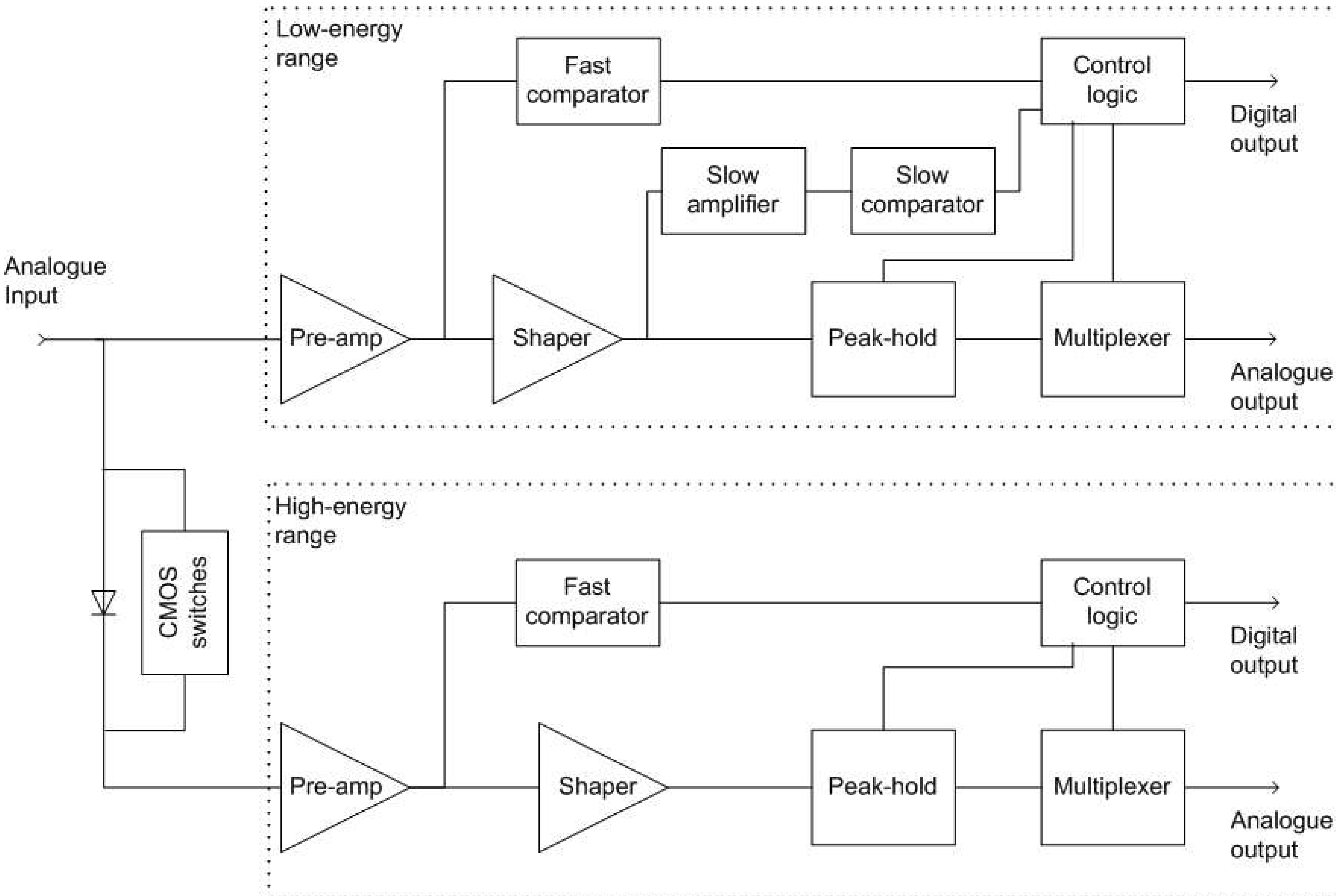
Theory - frequency domain analysis

Optimisation

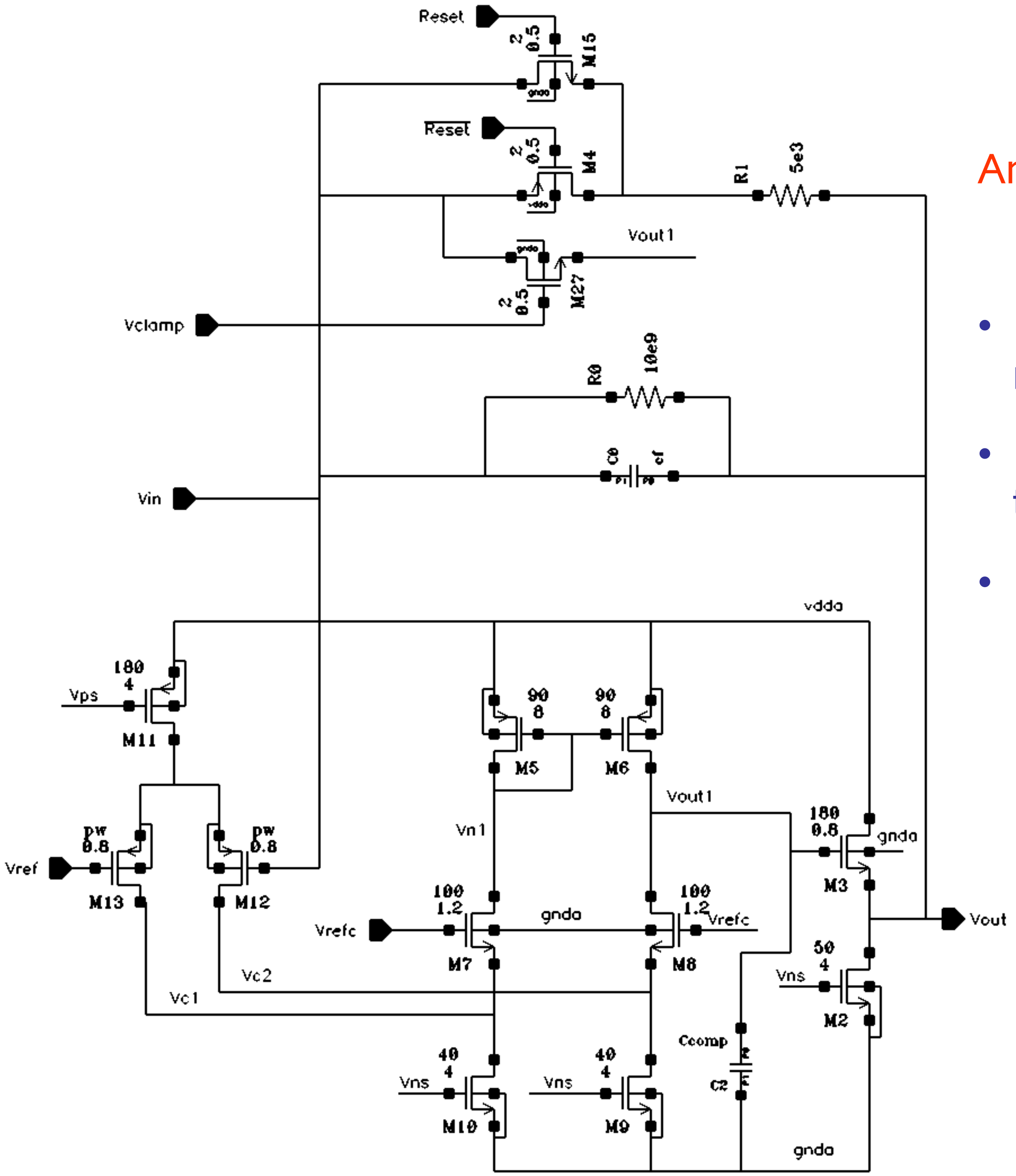
Simulation techniques

Constraints

Conclusions - noise specification achievable

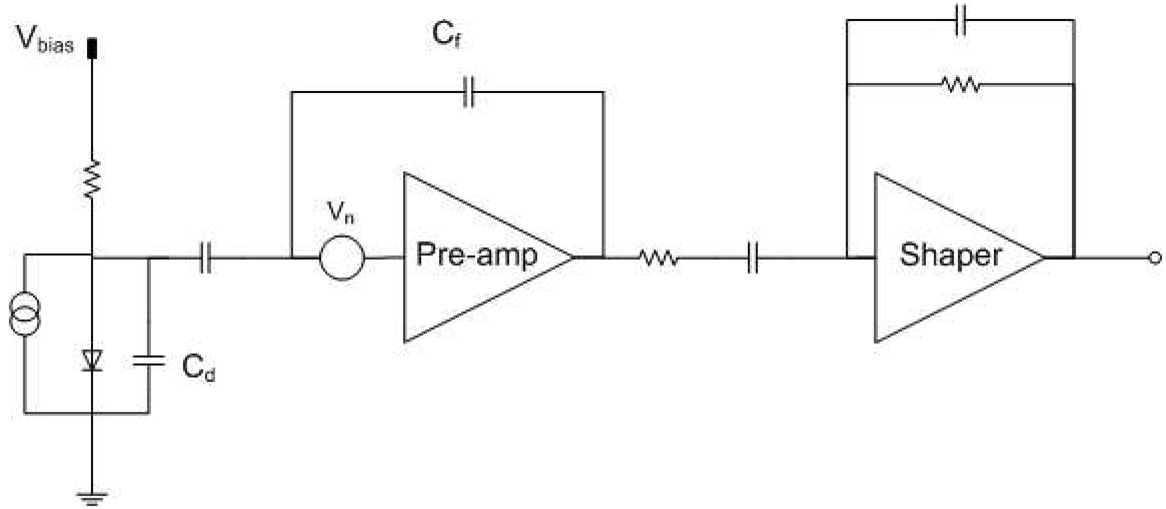


Low-energy range
Fast comparator
Control logic
Digital output
Slow amplifier
Slow comparator
Analogue Input
Pre-amp
Shaper
Peak-hold
Multiplexer
Analogue output
CMOS switches
High-energy range
Fast comparator
Control logic
Digital output
Pre-amp
Shaper
Peak-hold
Multiplexer
Analogue output



Amplifier circuit

- 1pF feedback, for 20MeV range
- Low current ~200uA per input transistor
- Low output drive ~300uA



The transfer function of the AIDA preamp with CR-RC shaping is

$$H(s) = \frac{\tau}{C_f(1 + s\tau)^2}$$

The output noise due to input current noise is given by

$$Vn_{out}^2 = \int_0^\infty i_n^2 \, |H(j\omega)|^2 \; df = \int_0^\infty \frac{qI_d\tau^2}{\pi C_f^2(1 + \omega^2\tau^2)^2} \; d\omega = \frac{qI_d\tau}{4C_f^2}$$

For thermal noise, the dominant noise source is the preamp input transistor which has a gate-referred noise of approximately $e_n^2 = 8kT/3g_m$.

The voltage gain of the preamp is $1 + C_t/C_f$; for the shaping amplifier the voltage gain is

$$H_{sa}(s) = \frac{s\tau}{(1+s\tau)^2}$$

The output noise is therefore

$$Vn_{out}^2 = \int_0^\infty e_n^2 \left(\frac{C_f + C_t}{C_f}\right)^2 |H_{sa}(j\omega)|^2 \; df = \int_0^\infty \frac{4kT(C_f + C_t)^2\omega^2\tau^2}{3\pi g_m C_f^2(1+\omega^2\tau^2)^2}\, d\omega$$

$$= \frac{kT}{3g_m\tau}\left(\frac{C_f + C_t}{C_f}\right)^2$$

The total output noise is

$$Vn_{total}^2 = \frac{qI_d\tau}{4C_f^2} + \frac{kT}{3g_m\tau}\left(\frac{C_f + C_t}{C_f}\right)^2$$

In order to convert output noise to equivalent noise charge, the output noise is divided by the gain of the pre-amp with shaper. The impulse response is

$$h(t) = \frac{te^{(-t/\tau)}}{C_f \tau}$$

$h(t)$ reaches the peak value $1/(eC_f)$ at $t = \tau$. The equivalent input noise charge is therefore

$$ENC^2 = Vn_{total}^2 \, (eC_f)^2$$

$$= \frac{qI_d e^2 \tau}{4} + \frac{kT(C_f + C_t)^2 e^2}{3 g_m \tau}$$

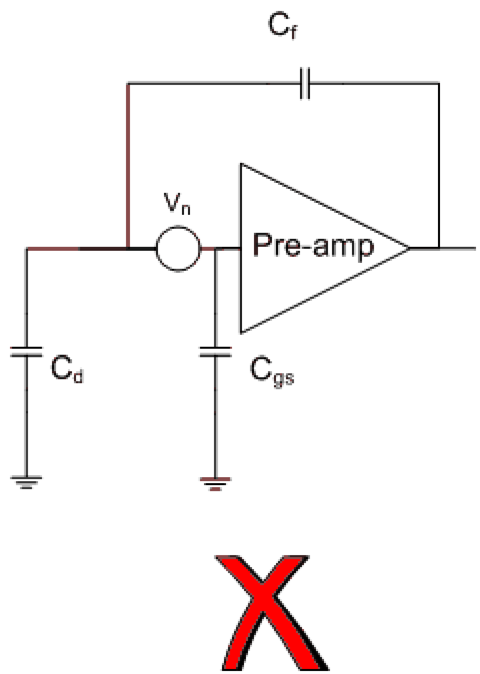
The minimum noise occurs when

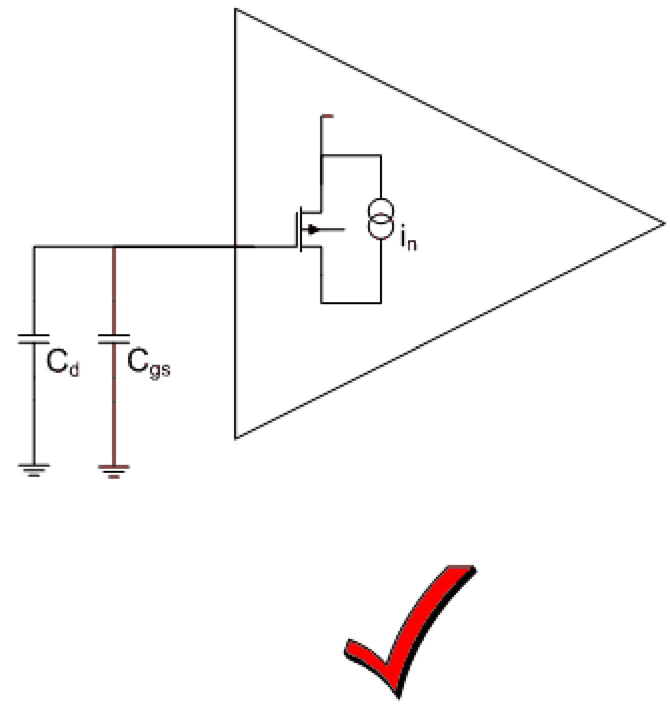
$$\tau = (C_f + C_t)\sqrt{\frac{4kT}{3qI_d g_m}}$$

for which

$$ENC^2 = \sqrt{\frac{kTqI_d e^4 (C_f + C_t)^2}{3 g_m}}$$

$$= 1.1 \times 10^{-19} (C_f + C_t)\sqrt{I_d/g_m}$$


C_f
V_n
Pre-amp
C_d
C_gs


i_n
C_d
C_gs

The input capacitance C_t is made up of the detector capacitance C_d (including the bond pad), and the gate capacitance $C_{gs} = WLC_{ox}$. For a transistor in strong inversion, we have

$$g_m = \sqrt{2K_pI_{DS}W/L}$$

Therefore

$$ENC^2 = 1.1 \times 10^{-19}(C_f + C_d + WLC_{ox})\sqrt{\frac{I_d}{\sqrt{2K_pI_{DS}W/L}}}$$

This reaches a minimum when

$$\frac{\partial[(C_f + C_d + WLC_{ox})W^{-0.25}]}{\partial W} = 0$$

which gives

$$W_{opt} = \frac{C_f + C_d}{3LC_{ox}}$$

Gate capacitance WLC_{ox} is one third of the total input and feedback capacitance. The noise for this capacitance is

$$ENC^2 = 1.1 \times 10^{-19}(C_f + C_d) \times \frac{4}{3} \times \sqrt{\frac{I_d}{\sqrt{2K_p I_{DS}(C_f + C_d)/3L^2 C_{ox}}}}$$

Substituting process parameters for a 0.35 μm process,

$$ENC^2 = 1.98 \times 10^{-22}(C_f + C_d)^{0.75} \times I_d^{0.5} \times I_{DS}^{-0.25}$$

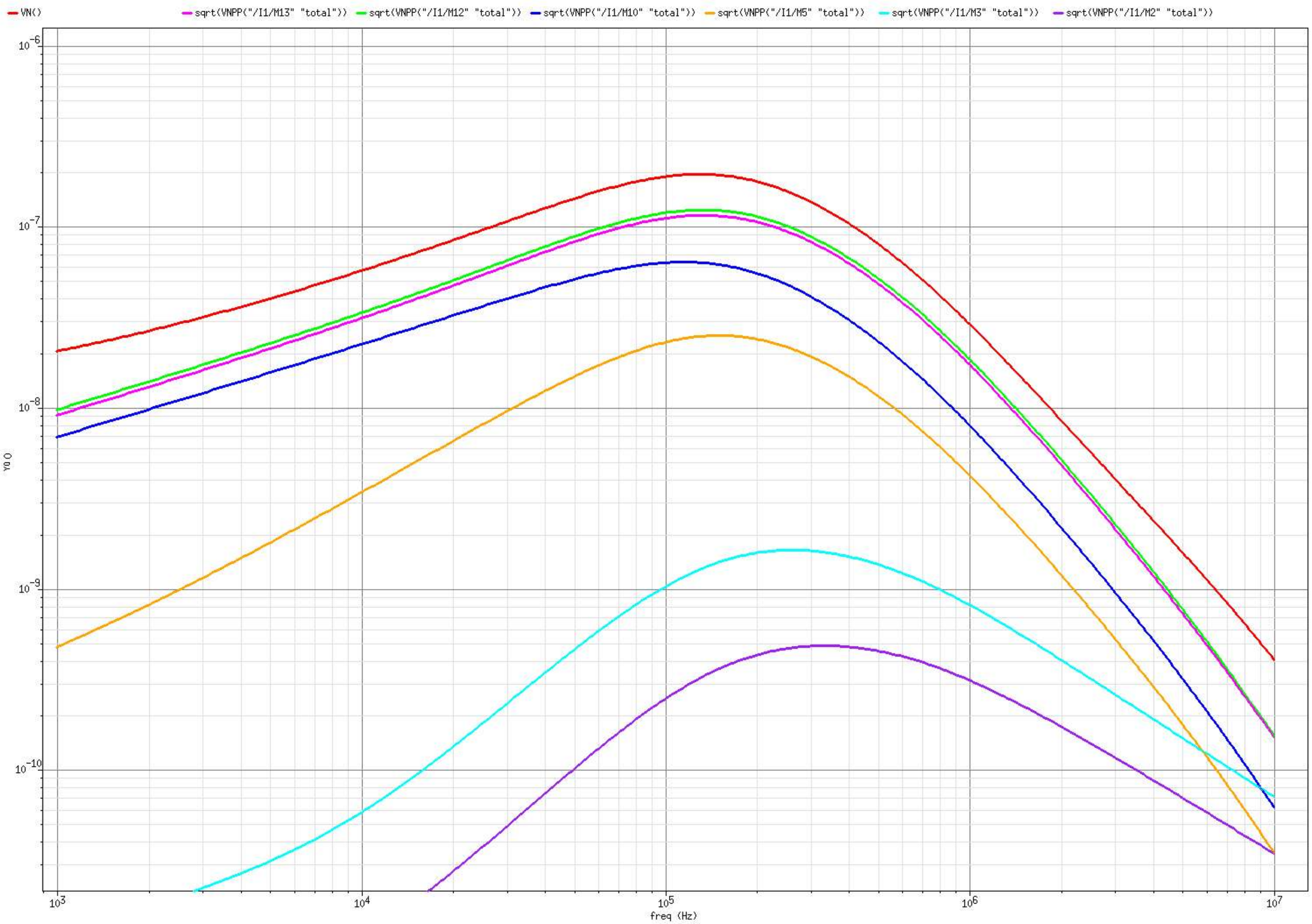
This can be converted to noise charge in electrons rms

$$ENC = 8.8 \times 10^{7}(C_f + C_d)^{0.375} \times I_d^{0.25} \times I_{DS}^{-0.125}$$

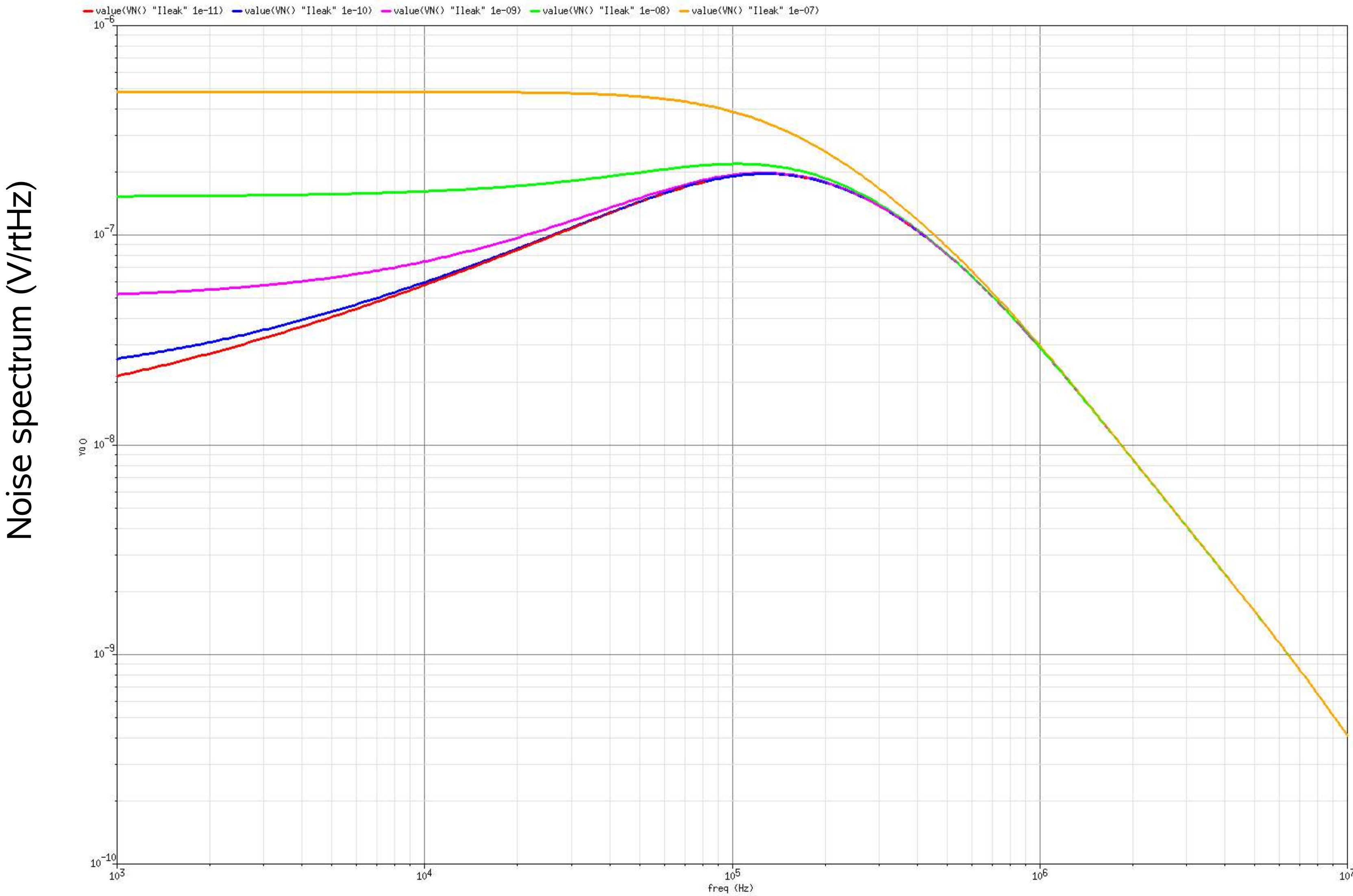
Cf+Cd	Id	IDS	ENC	ENC (differential)
pF	nA	mA	electrons rms	electrons rms
40	1	1	148	181
40	10	1	263	322
40	10	1	263	322
40	40	1	372	456
40	40	10	279	342
100	400	10	700	857

Transistor noise contributions

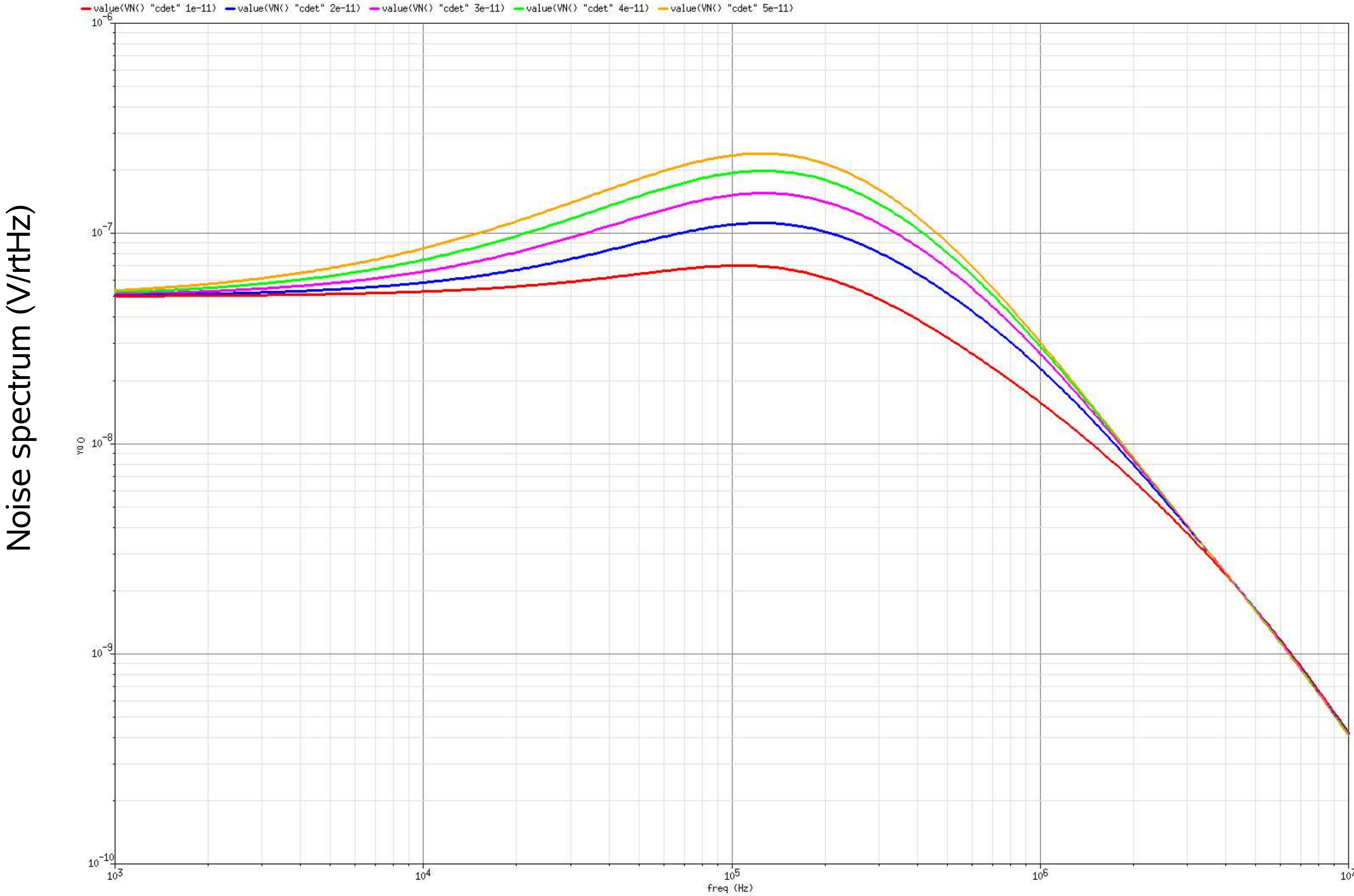
Noise spectrum (V/rtHz)



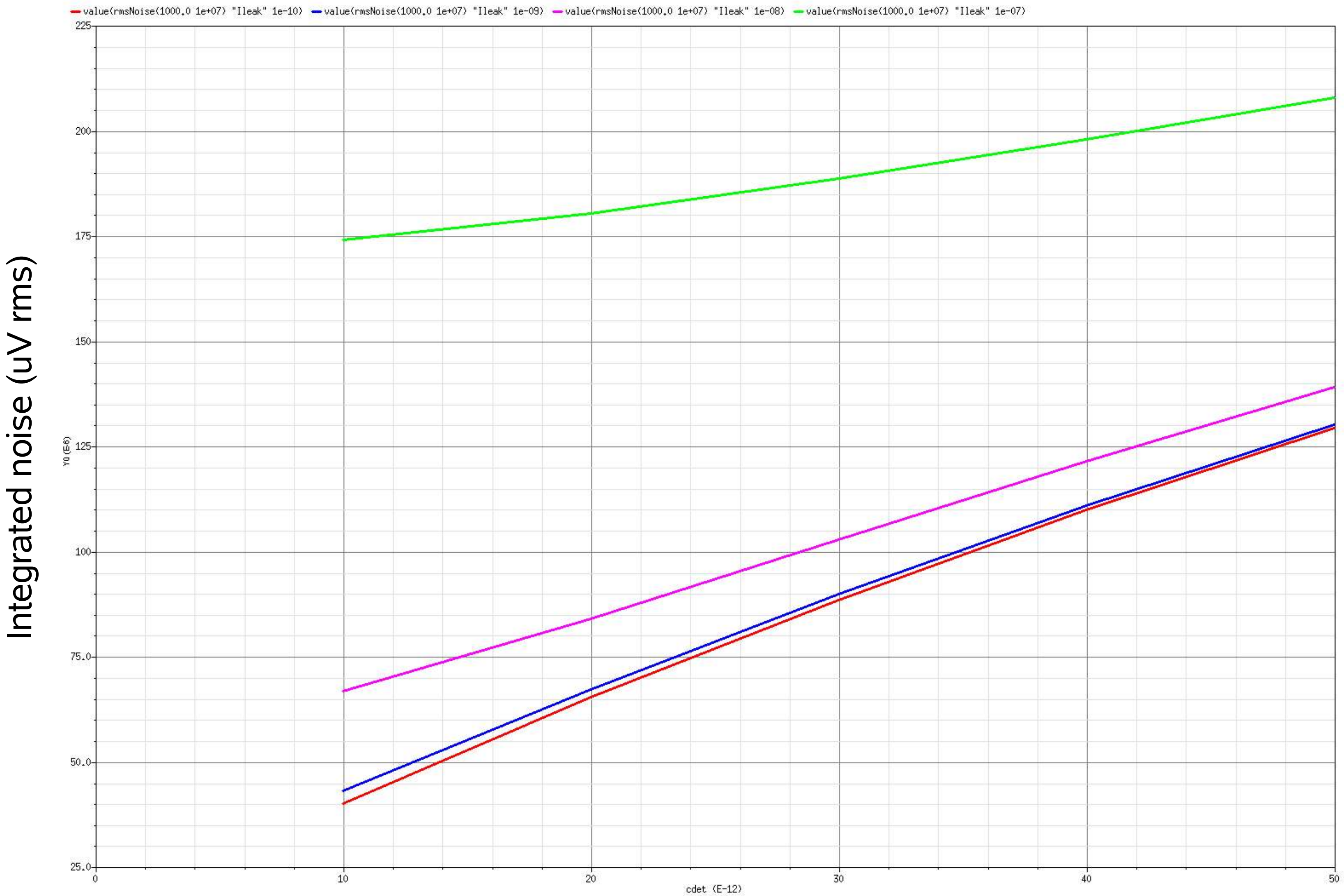
Noise spectra for detector leakage 0.1nA - 100nA



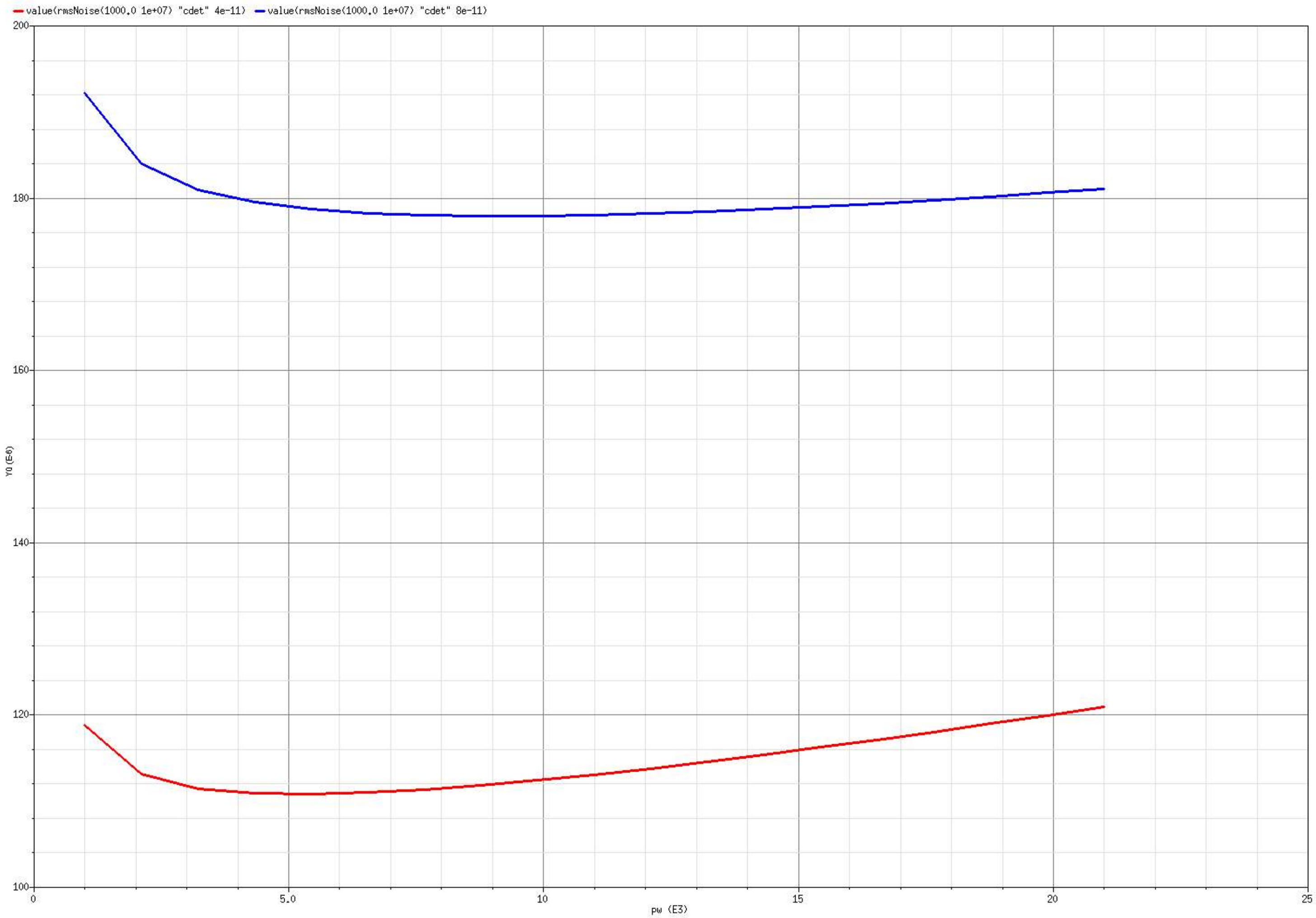
Noise spectra for Cd = 10pF - 50pF



Sweep of Cdet and detector leakage



Transistor noise optimisation (Cdet=40pF & 80pF)



Integrated noise (uV rms)

Input transistor width (um)

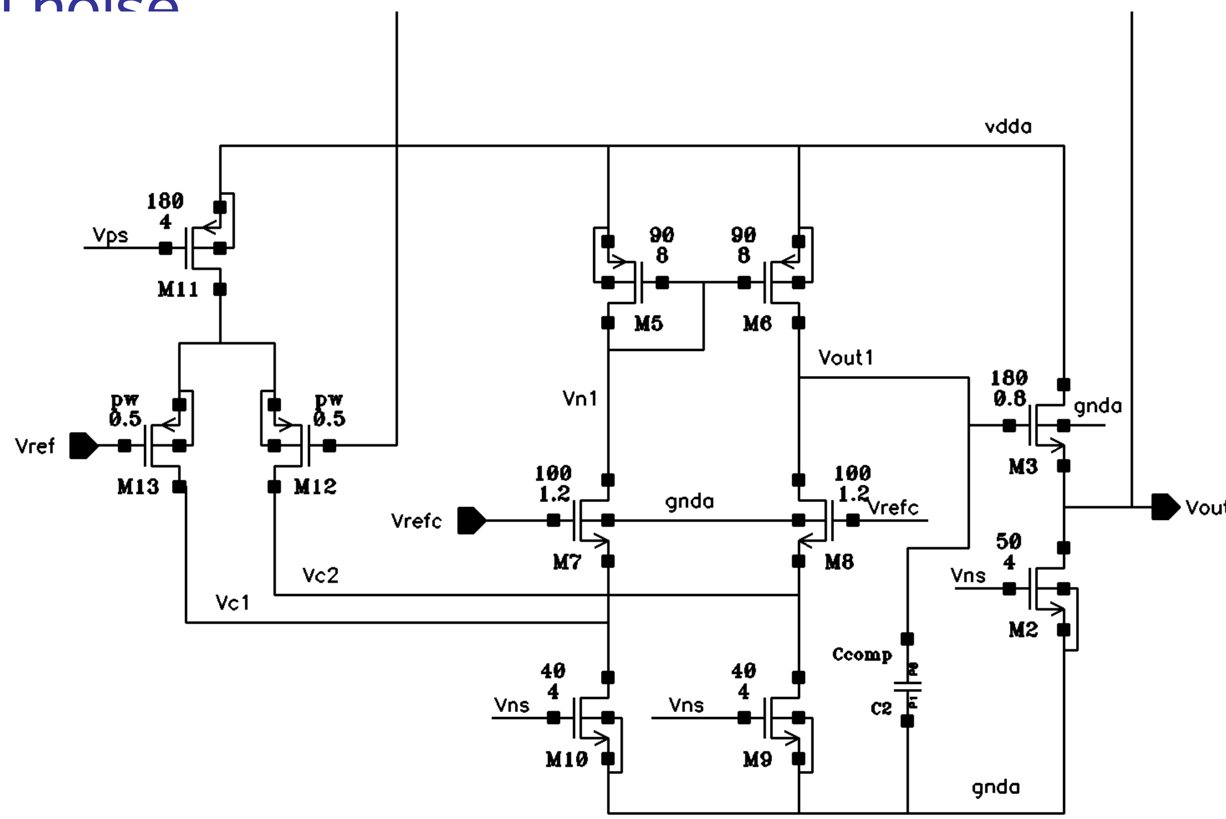
Limits of Ids

•Chip power (~1W)

•Vgs for input transistors

•Excess thermal noise

(hot electrons)



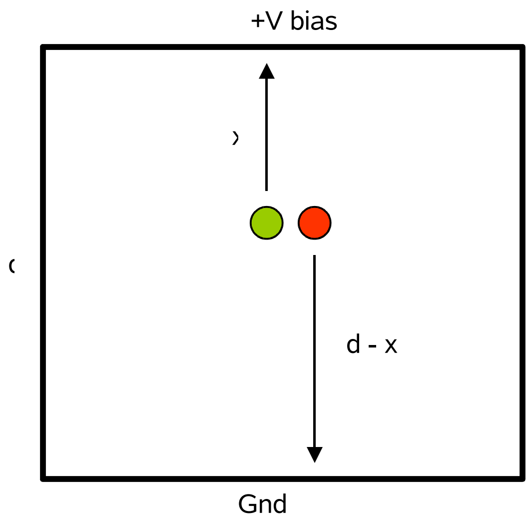
Ramo's theorem

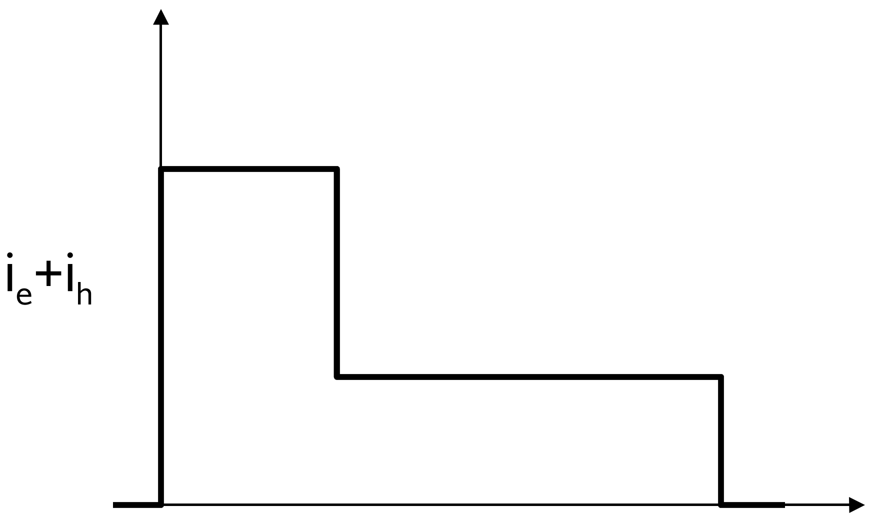
i = qvE (v=velocity, E weighting field)

For large over-depletion

$i_e = q\mu_e V/d^2$, $t_e = xd/\mu_e V$

$i_h = q\mu_h V/d^2$, $t_h = (d-x)d/\mu_h V$





Pulse shape dependent on interaction point

Conclusions

- Noise specification looks reasonable
- Best to optimise with accurate detector model
- Variable shaper time constant is an option
- Ballistic deficit noise needs to be included