Radiation Tolerance of DEPFET Active Pixel Sensors

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S. Rummel, L. Andricek, M. Bataglia*, D. Contarato*, P. Giubilato*, M. Porro, G. Ferrari**, G. Lutz, H.-G. Moser, S. Pozzi**, R.H. Richter

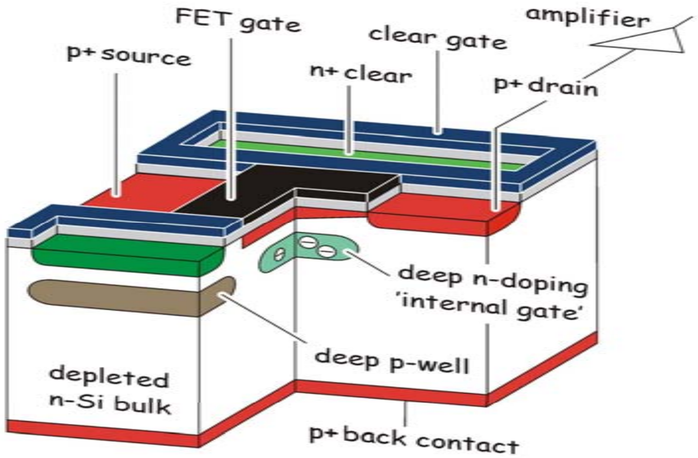
*LBNL Berkely; **Politecnico Milano

Overview

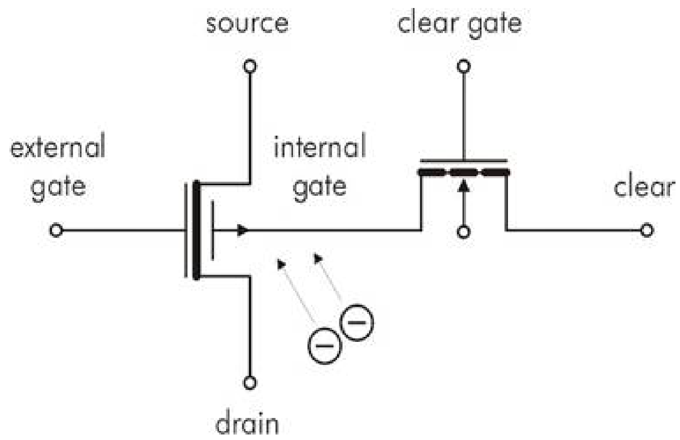
- DEPFET principle
- DEPFET as vertex detector for ILC
- Requirements with respect to radiation hardness
- Investigations of irradiated structures

DEPFET – Depleted Field Effect Transistor

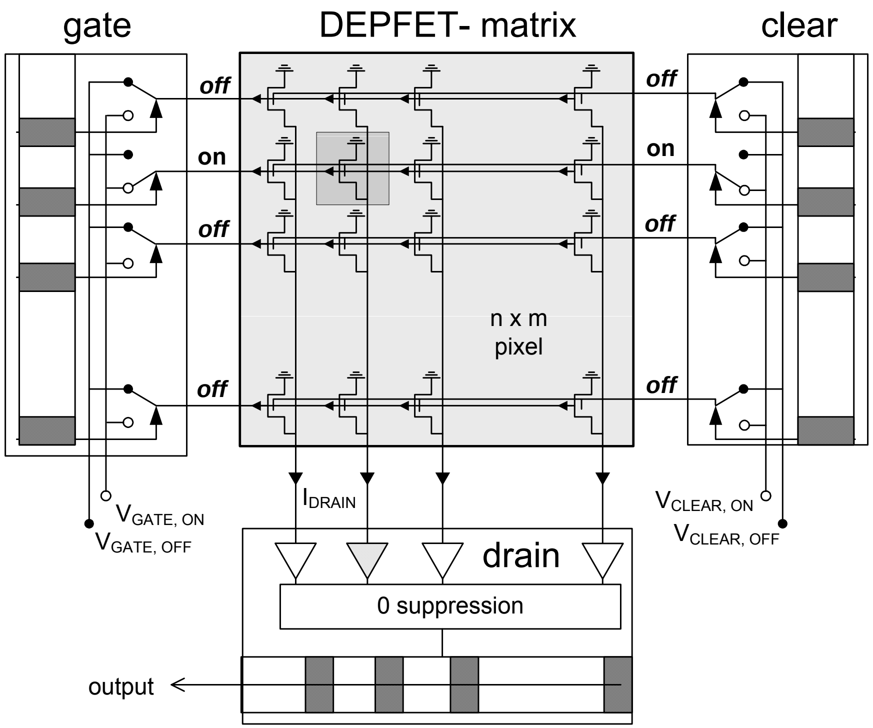
- Combination of detector grade silicon with first **p-FET** amplification stage in each pixel
- **Potential minimum for electrons** is created under the channel by **sideward depletion** and an additional **n-doping**
- Electrons in the “internal gate” **modulate the transistor current**
- Signal charge is removed via a clear contact

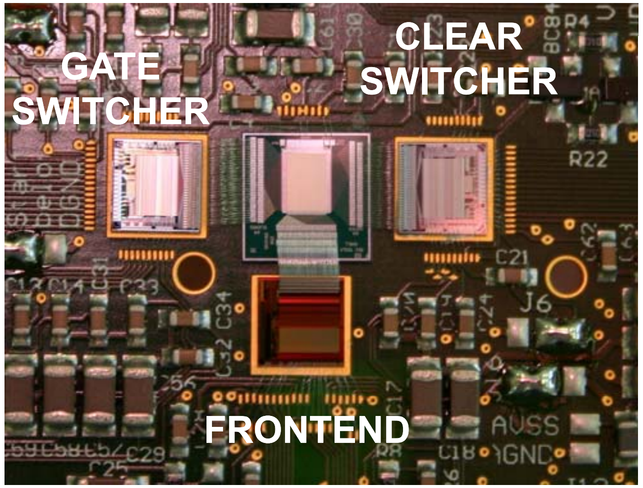


- **Large sensitive volume** due to **fully depleted** bulk
- **Low noise** caused by a small input capacitance and **internal amplification**
- Transistor can be **switched off** by external gate – charge collection is then still active!



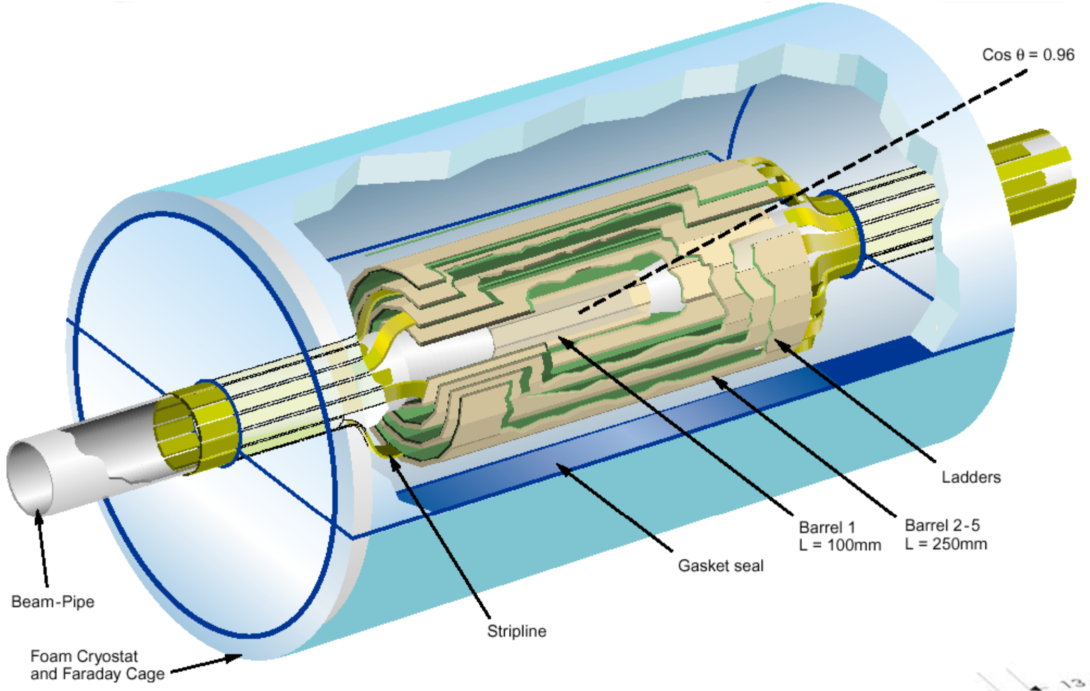
DEPFET - Matrix operation





- Column parallel architecture for fast readout
- Row wise readout operation: Sample-Clear-Sample – no charge transfer
- Low power dissipation – only one row active while readout

DEPFET as vertex detector for ILC



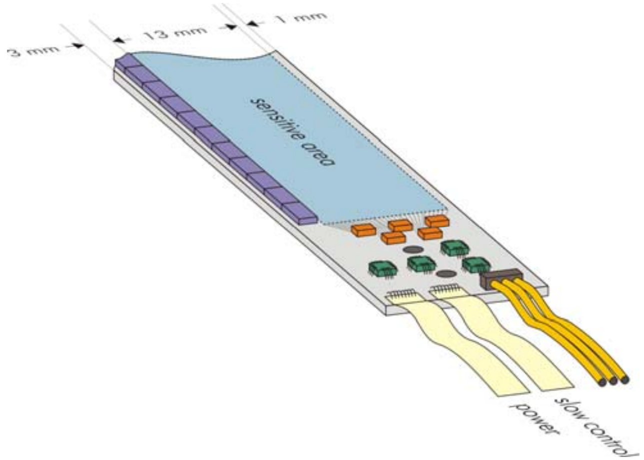
•IP resolution: $\sigma_d \leq 5\mu m \oplus \frac{10\mu m}{p \cdot \sin^{3/2}\vartheta} \, GeV/c$ [Tesla TDR]

➢Good point resolution

➢Small material budget 0.1 % X_0 per layer

•Frame rate ~ 20kHz – line rate 20MHz

•Sufficient radiation hardness



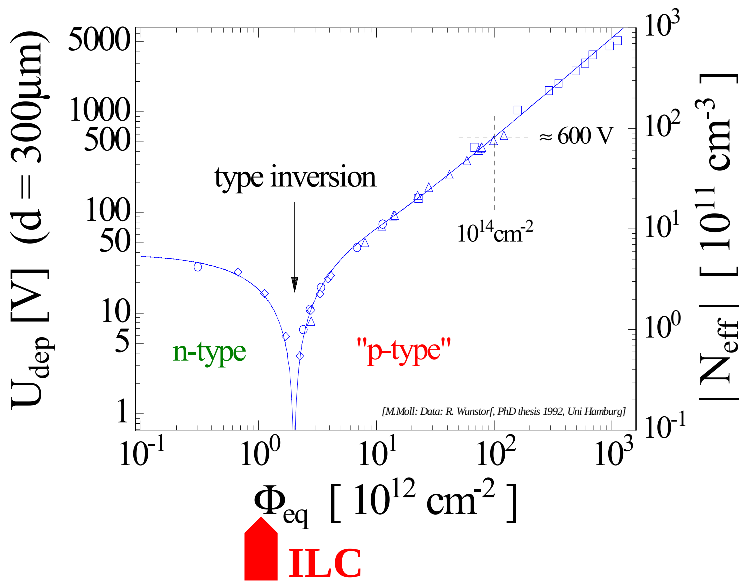
ILC conditions

- **e** from Beamstrahlung
- **n** backscattered form the calorimeter
- Total dose around 360krad in 10 years [LDC DOD]
- Moderate cooling with cold gas stream

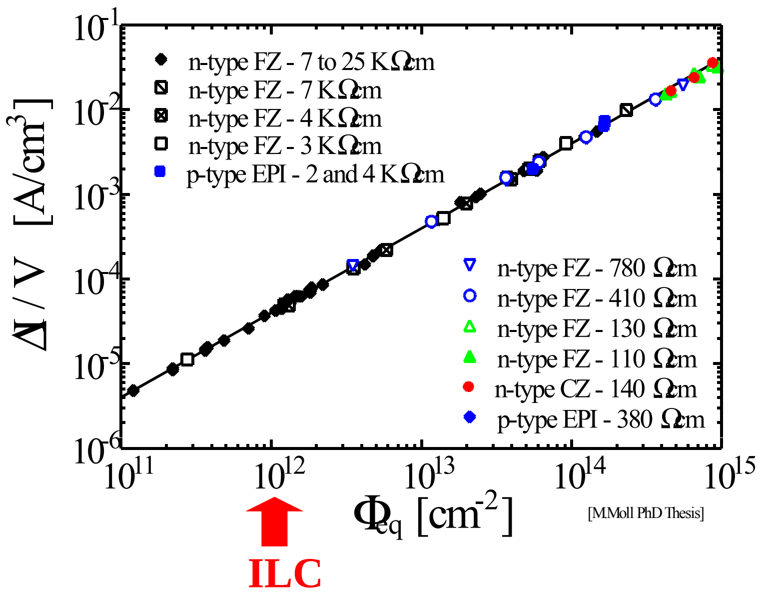
Expected flux:	$1.7*10^{12}$ e/cm2/year	@ 10MeV [LDC DOD]
	10^{9} n/cm2/year	@ 1MeV n equiv. [LDC DOD]
∑ (e- + n)	$8.5 * 10^{10}/cm^2/year$	@ 1MeV n equiv. [LDC DOD]

Motivation

U_{dep}/N_{eff} vs. Dose:



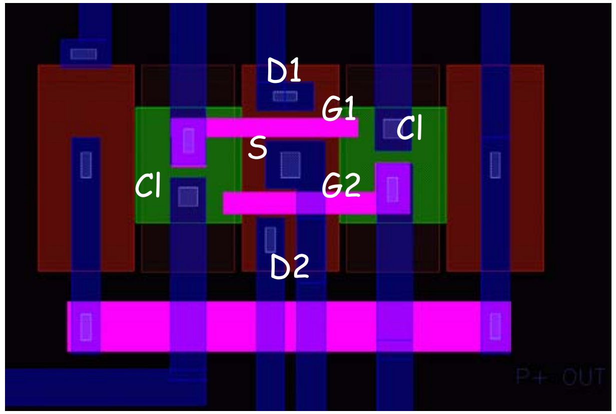
Leakage vs. Dose:



- Space charge sign inversion is not expected to be a problem
- BUT: Several remaining questions:
  - Noise contribution from leakage current? (50µs integration time)
  - What is the extend of the threshold voltage shift?
  - Does the performance of the FET degrade under irradiation?

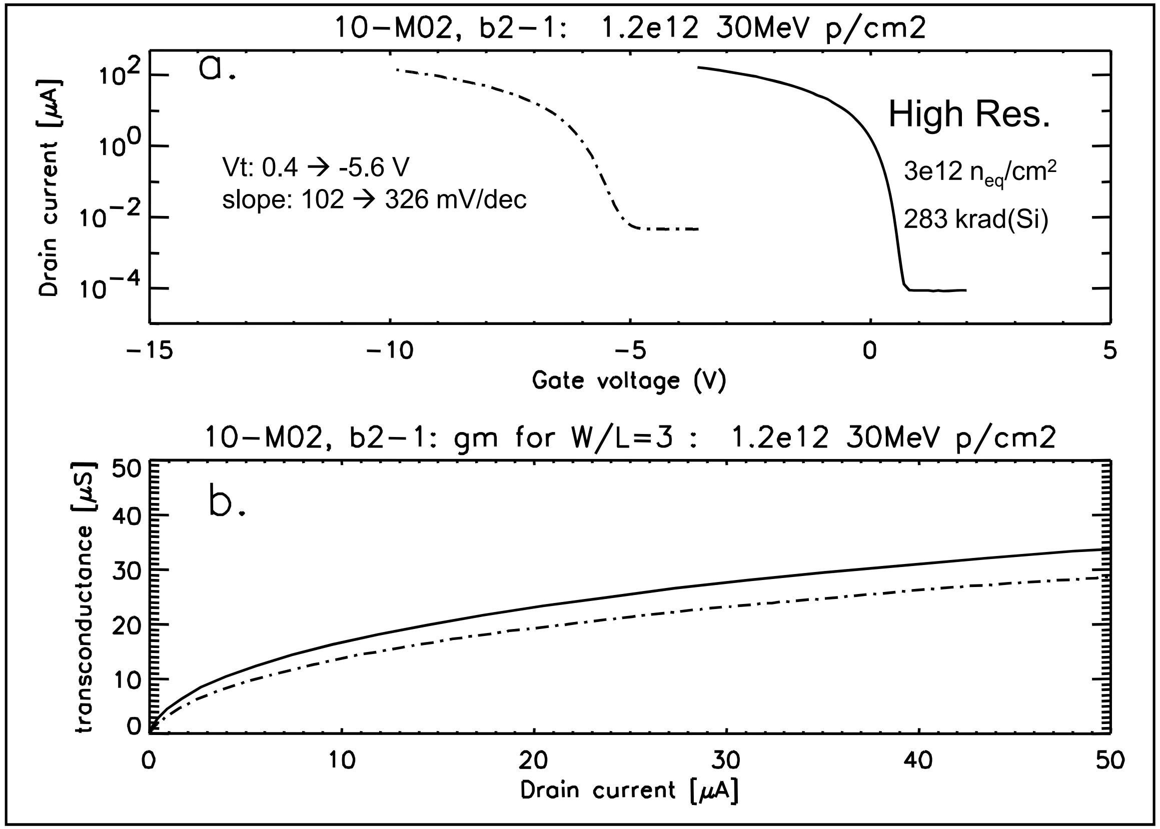
Overview

- Single pixel structures with 6µm gate length
- Current based readout
- Characterization with respect to:
  - Electric characteristics (Vth, gm, gq)
  - Leakage current (NIEL)
  - Spectroscopic performance
  - Noise power density (1/f noise)



Type	Protons @ 30MeV	Neutrons @ 1-20MeV	Gammas - Co60
Dose	1.2 * 10^{12} p/cm²	1.6 * 10^{11} n/cm²	913kRad
1MeV n equivalent	3*10^{12}	2.4*10^{11}	
ILC – expectation [LDC DOD]	1MeV n equivalent: 8.5 * 10^{10}/cm²/year		
ILC operation	35 years	3 years	

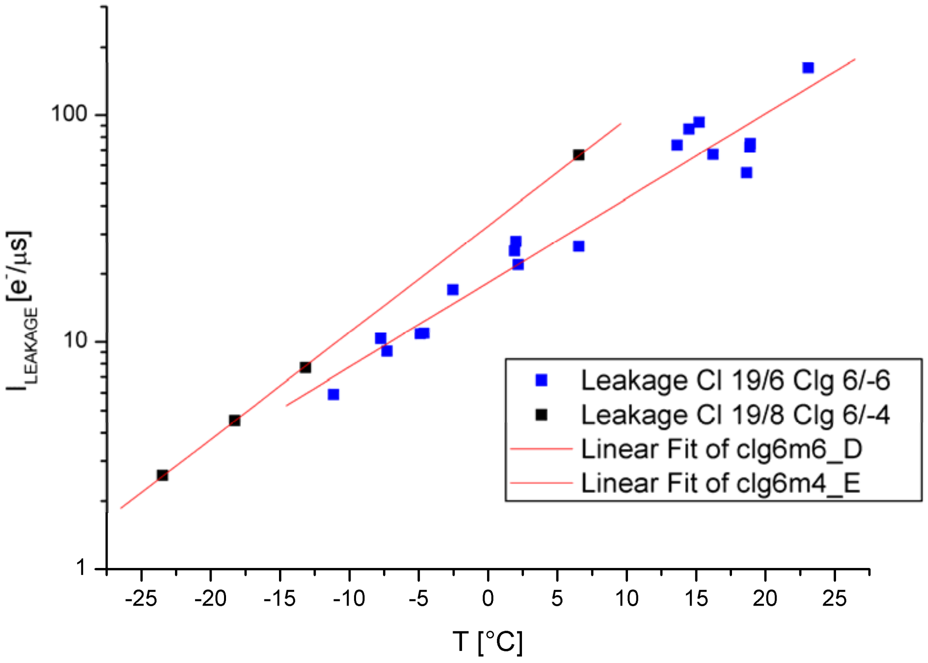
p-irradiated - Electric characteristics



all terminals grounded during irradiation, 30 MeV p

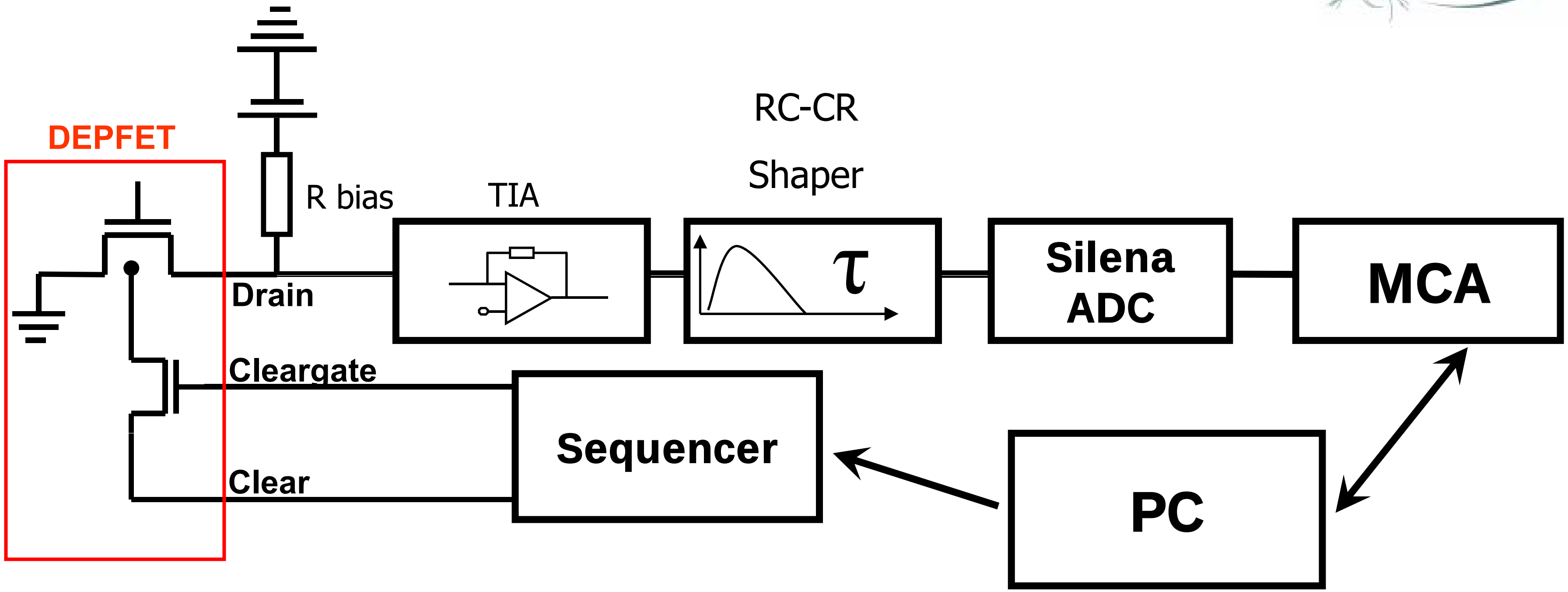
- Threshold voltage shift small compared to the expectations for a dielectric exceeding 200nm
- Increase of sub threshold slope indicate a increase of 1/f-noise
- g_m is noticeably reduced by 15%

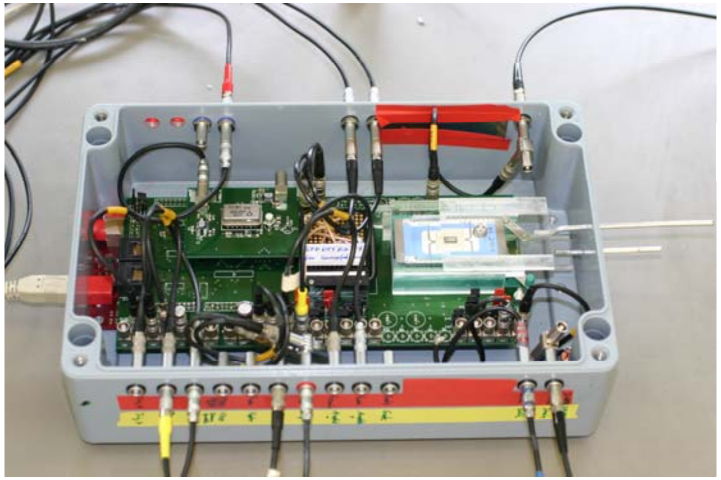
p-irradiated - Leakage - Temperature dependence



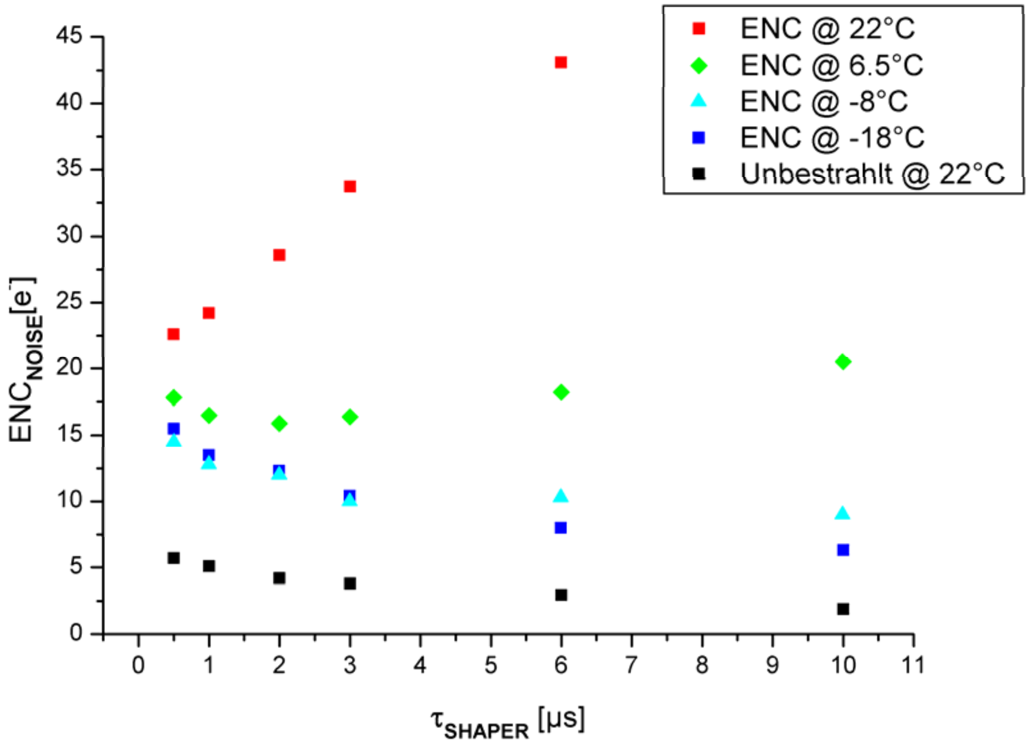
- Dependence on operation voltages -> additional contribution which is not bulk generated
- Thick detector, bulk generated current will decrease with thickness
- At 0°C around 20e/µs! -> L=50µs -> 31e contribution to noise
- Irradiation far beyond 10 years of ILC operation

Spectroscopy setup





p-irradiated sample – Spectroscopic performance



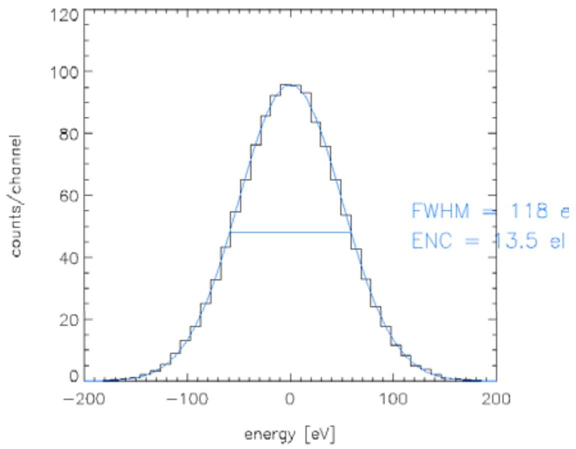
$$ENC = \sqrt{aC_{tot}^{2} A_1 \frac{1}{\tau} + 2\pi a_f A_2 C_{tot}^2 + eI_{leak} A_3 \tau}$$

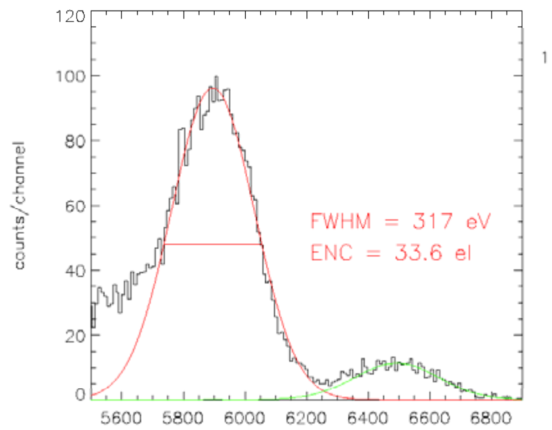
Therm. noise

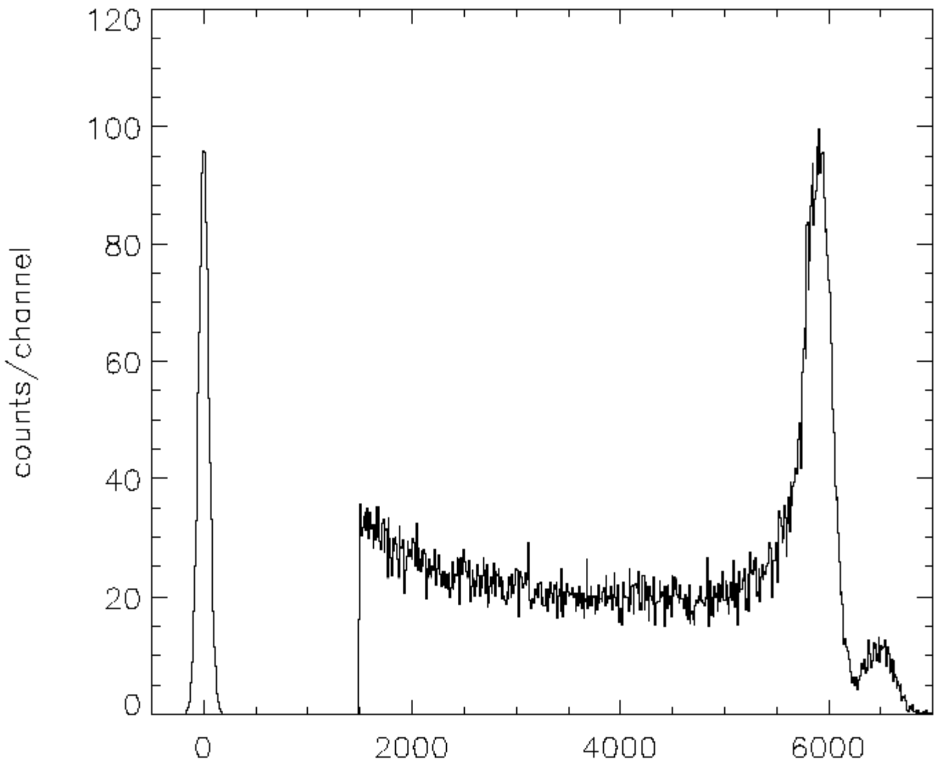
1/f

I_L

p-irradiated; Fe55 spectrum







- Good spectroscopic performance!
- Separated Ka Kb peak!

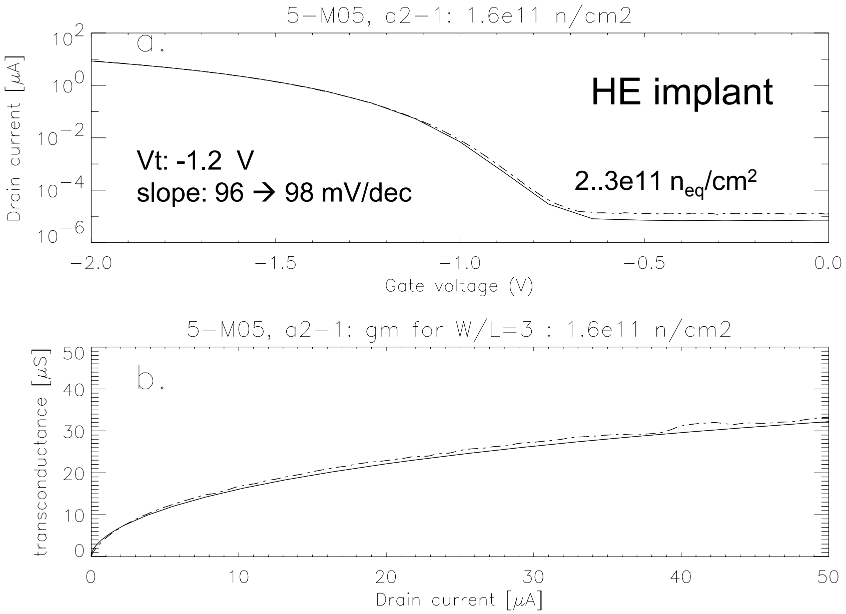
τ=1μs T=-10°C

ENC_{noi} = 13.5e$^-$

p - Irradiation - Summary

- DEPFET fully operable after $3*10^{12}$ n_{eq}/cm^2
- Threshold voltage shift acceptable
- Gm slightly decreased by 15%
- Noise contribution due to leakage current is tolerable

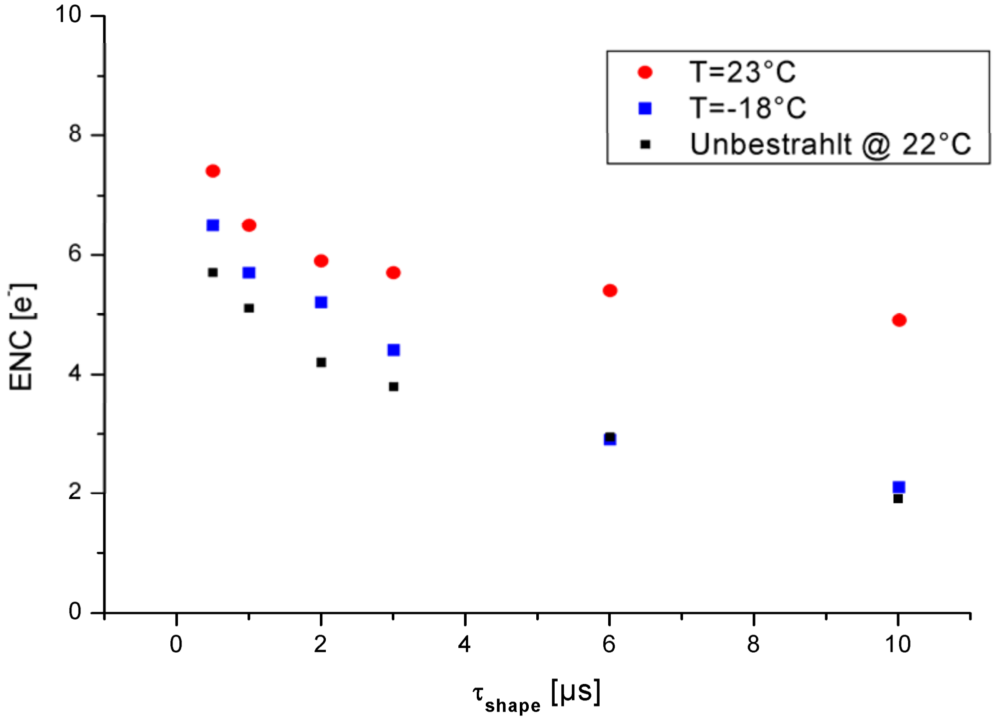
n irradiated - Electrical characteristic



all terminals grounded during irradiation,
1-20 MeV neutrons (LBNL)

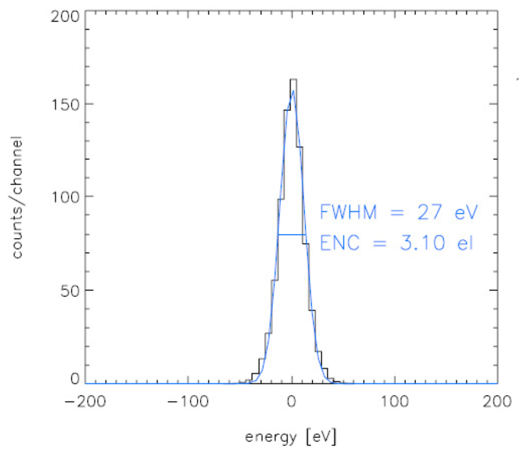
- No thresholdvoltage shift observed!
- No significant increase in subthreshold slope!

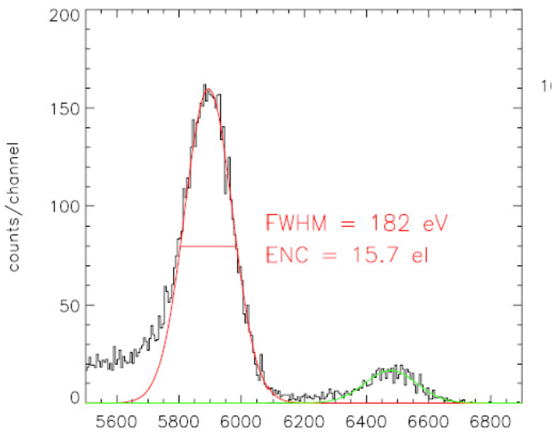
n irradiated - Spectroscopic performance

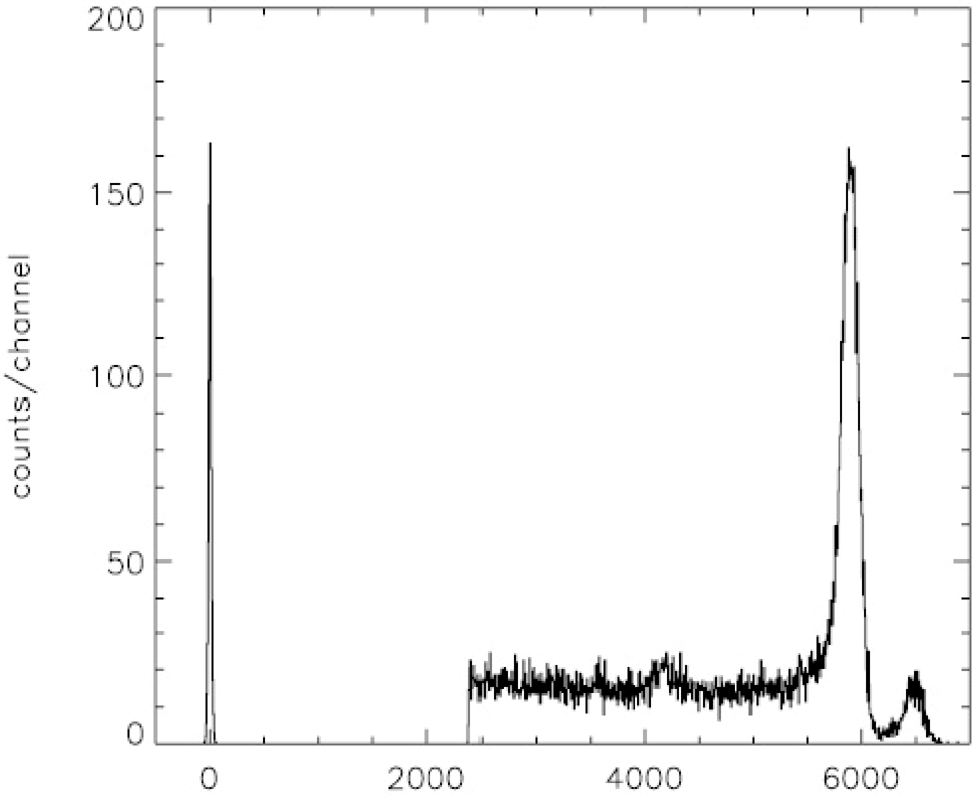


- Leakage around **8.9e/µs @ 23°C**
- At low temperatures the performance is similar to unirradiated structures!

n irradiated - Fe55 spectrum







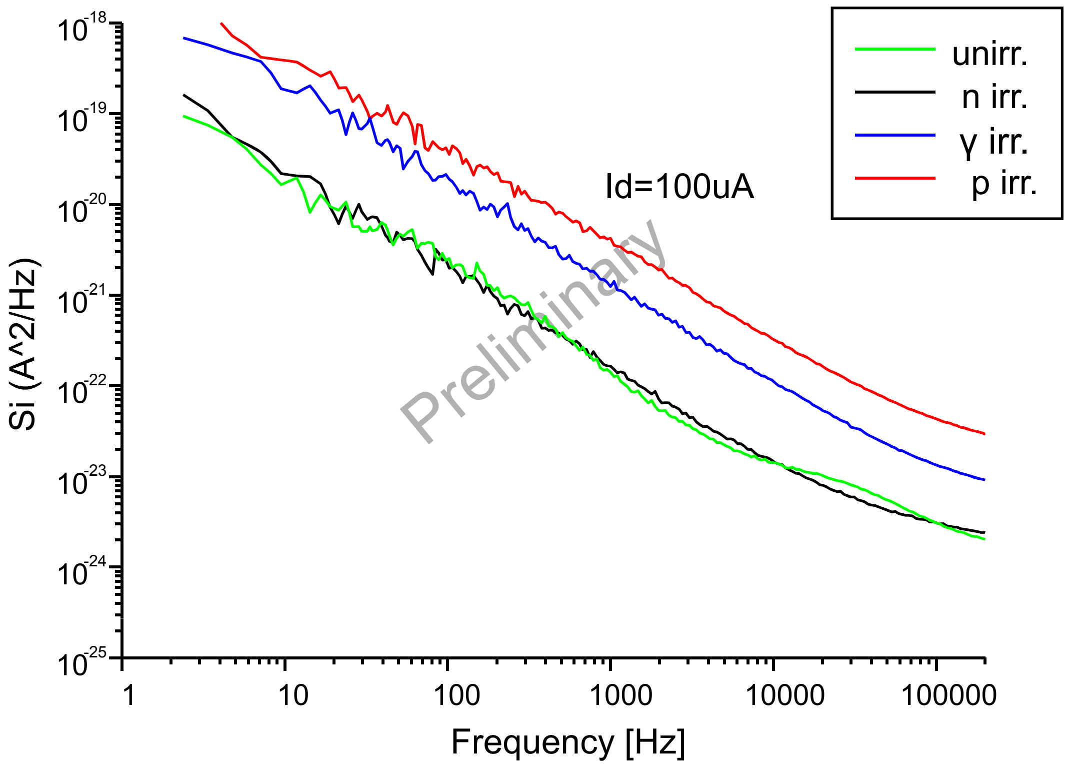
τ=6µs T=6°C

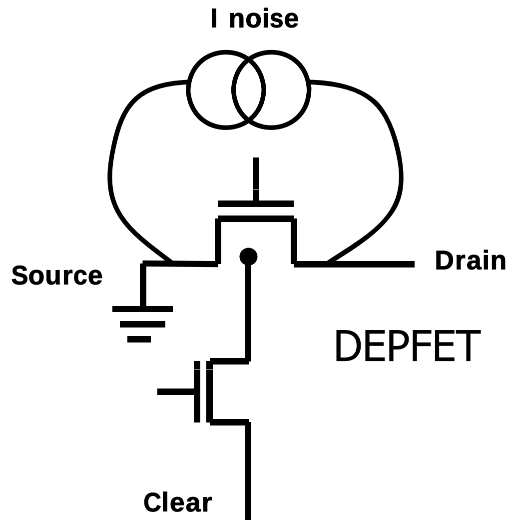
ENC_{noi} =3.1e^{-}

n – Irradiation - Summary

- Transistor performance unchanged
- No interface damage observed
- Good spectroscopic performance

Noise power density





- Corner frequency increased
- Expectation from sub threshold slope are confirmed

Conclusion

•Irradiated structures are operable after irradiation

•Threshold voltage shift is in an acceptable region

•Both structures show good spectral resolution

•Noise power density behaves as expected from sub threshold slope

• **The DEPFET double pixel structure could be considered as radiation hard with respect to the ILC requirements**

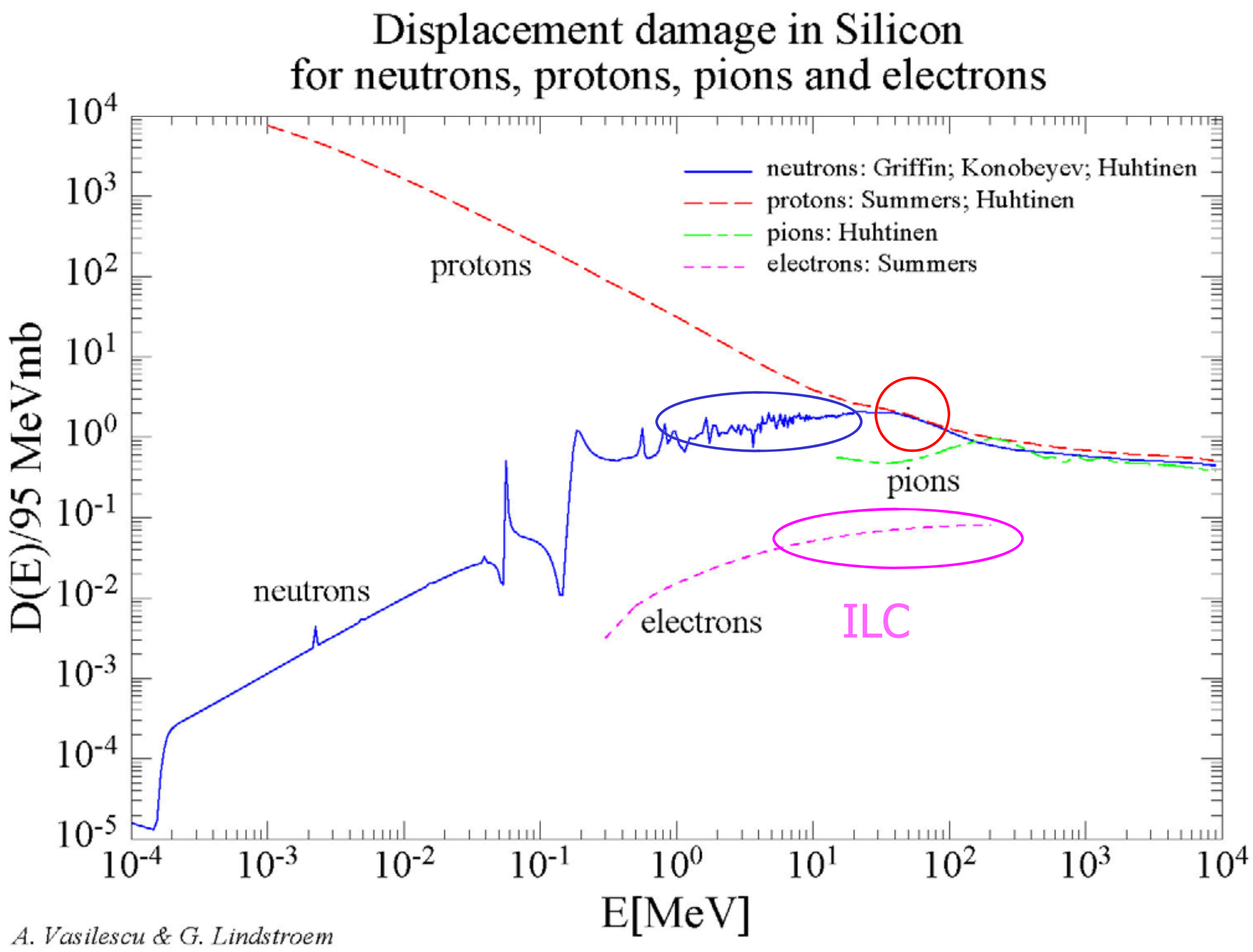
Leakage current

- Leakage current into the internal gate
- Contributions from bulk and surface
- Additional shot noise

@RT

Unirradiated	Gamma	Neutron	Proton
Typ. 20fA	200fA	1.4pA	25.9pA

NIEL – Bulk damage



Shaper measurement vs. CDS

	Continuous shaping (time invariant)	Time dependent shaping
White noise	$\sqrt{\alpha \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau}}$	$\sqrt{4kT \frac{2}{3} \frac{g_m}{g_g^2} NBW}$
1/f noise	$\sqrt{2\pi a_f C_{tot}^2 A_2}$	$\sqrt{a_f \frac{g_m^2}{g_q^2} 2\int_0^\infty \frac{1-\cos(2\pi\tau x)}{x(1+x^2)} dx}$
Shot noise - leakage	$\sqrt{I_L A_3 \tau}$	$\sqrt{I_L T_{frame}}$

ENC depends on:

- Shaping time
- Response function

- Frame time
- Bandwidth
- CDS time

•Both variants are sensitive to the same noise sources, but in different extend

Influence of the radiation

- NIEL (Non Ionizing Energy Loss)
  - Mainly damage to the bulk
- Ionizing Energy Loss (charged particles)
  - Damages interface and bulk

- Macroscopic effects:
  - Shift in threshold voltage
  - Increase of leakage current – bulk and interface
  - Increase of 1/f noise
  - Change in effective doping