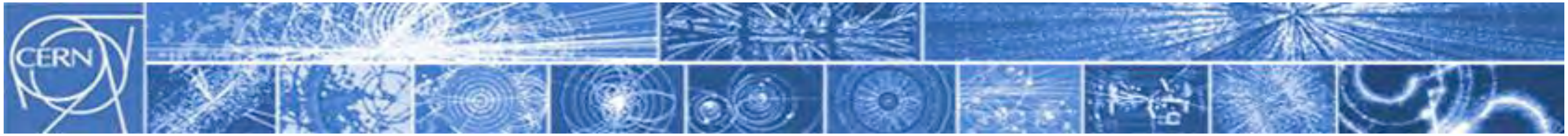


Silicon: Survival of the fittest
10 years RD50

ERIK H.M. HEIJNE

RD50 MEETING

CERN 14 November 2012

Science-Technology Spiral

Physics experiments change continuously

- Detectors change and cause change of physics interests

Detector technologies evolve towards:

- faster rates
- finer precision
- increase of multiplicities

1920-1950	nuclear emulsions with cosmics	cloud chambers	1 frame/week
1950-1980	bubble chambers	spark chambers	1 frame/s
1970-2000	wire chambers		
1980-now	calorimeters		
1980-now	silicon trackers	LHC	10^7 frames/s

Use of silicon detectors

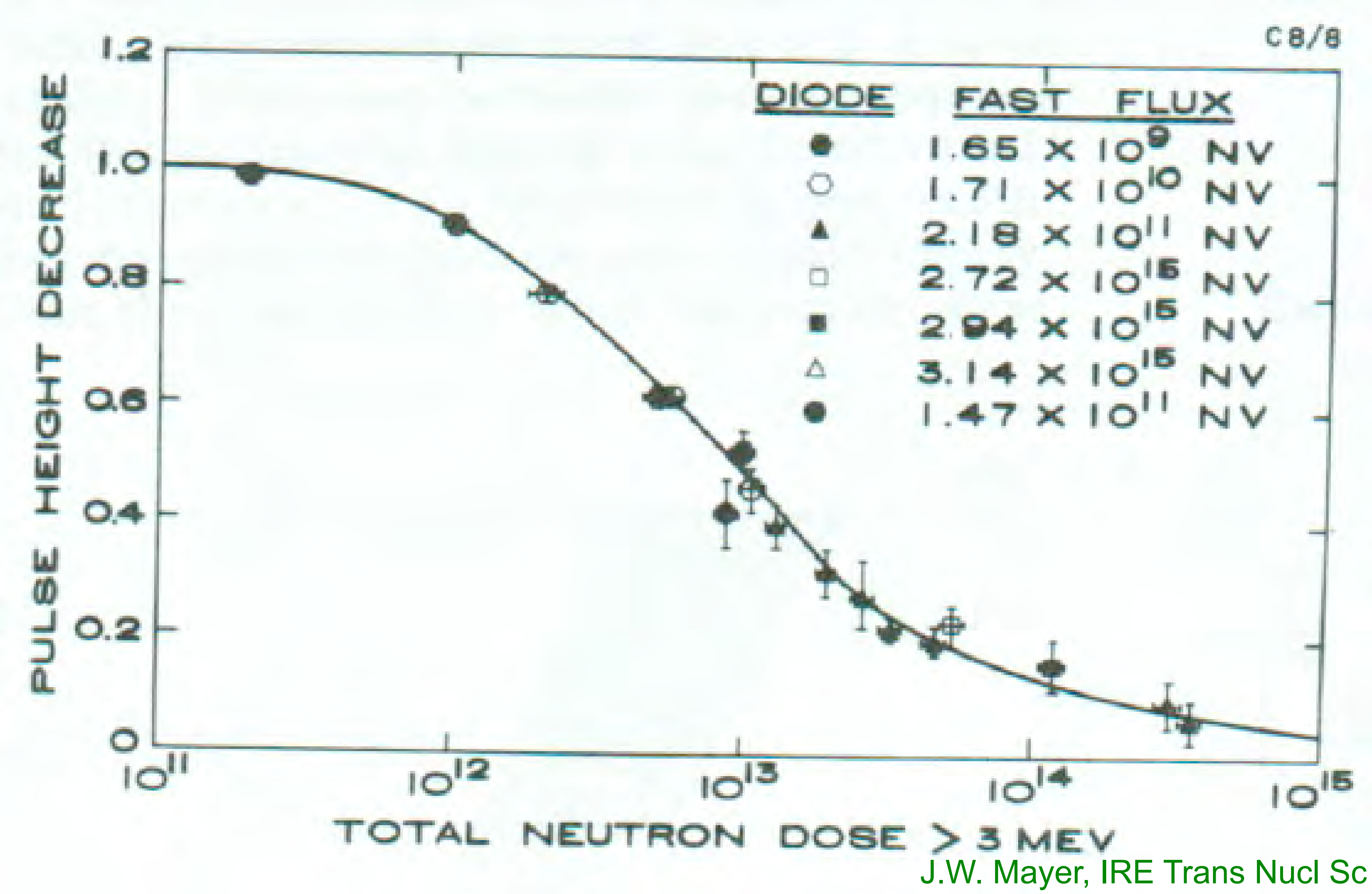
semiconductor detectors developed 1943 (Utrecht) – 1955 (Bell Labs, Oak Ridge)
surface barrier diodes on Ge (1949) and on Si (1955)
diffused Si junctions and p-i-n/n-i-p introduced ~1958-1960
ion-implanted diodes from ~ 1960 by J.Mayer and others(e.g.at Philips Amsterdam)

several diodes on same slice was done 'right away' at AERE, LBL and CEA Saclay
patent on doube-sided Si 'checker board' detector by Philips (NL) in 1967

main advantages of Si diodes in nuclear spectroscopy:
- precision energy measurements due to
  - large number of carriers in compact spectrometer
  - excellent collection efficiency from long minority carrier lifetime
- room temperature operation (contrary to the superior Ge detectors)

main advantages in particle physics experiments
- short dead time (~20ns) enables much higher rate than in MWPC
- segmentation by lithography allows
  - few µm coordinates precision with thin sensor
  - simultaneous high local multiplicity
  - low dark current per segment, low capacitance and low noise

Early neutron irradiation, Kramer @Hughes~1960



J.W. Mayer, IRE Trans Nucl Sc NS-9(1962)3

degradation sets in >5x10^{11} n/cm^2

all diodes p-n Si 6kΩcm, damage independent of diode details

bias always 100V 0.4 μs shaping time constant,suffers ballistic deficit

Radiation damage is universal and unavoidable in all detectors

- nuclear emulsion becomes 'black' when overexposed

- in BEBC the hydrogen cooked when too many hadrons

- whisker growth on electrodes in many types of wirechambers

- in comparison, damage in silicon is studied extensively

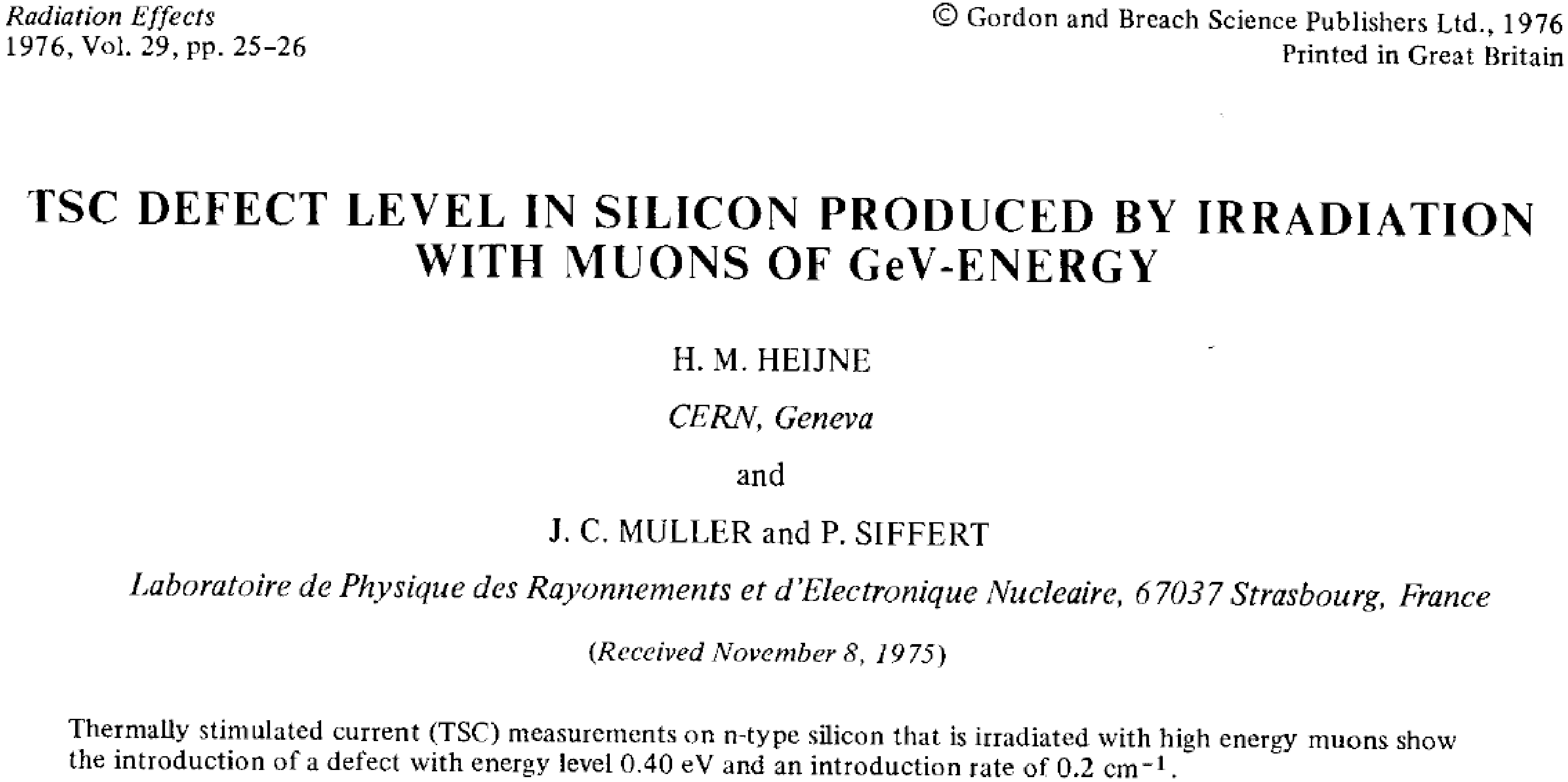
- while 10^{-6} is usual purity for gases and liquids, silicon is still more pure with impurity levels $<10^{-9}$

Radiation damage studies for SSC/LHC mostly started ~1985-1995

at first, many 'specialists' prepared for LHC experiments without tracker
"iron ball" concept
" no sensors or electronics can withstand that fierce environment"
(SSC would be much friendlier, they prepared Si vertex detector concepts:
UC Santa Cruz and others)

on the contrary, in the accelerator itself there would be little or no radiation in order to avoid quenches of the superconducting magnets

Early irradiations of Si with MIPs 1974



Radiation Effects
1976, Vol. 29, pp. 25–26

TSC DEFECT LEVEL IN SILICON PRODUCED BY IRRADIATION WITH MUONS OF GeV-ENERGY

H. M. HEIJNE
CERN, Geneva
and
J. C. MULLER and P. SIFFERT
Laboratoire de Physique des Rayonnements et d'Electronique Nucleaire, 67037 Strasbourg, France

(*Received November 8, 1975*)

Thermally stimulated current (TSC) measurements on n-type silicon that is irradiated with high energy muons show the introduction of a defect with energy level 0.40 eV and an introduction rate of 0.2 cm^{-1}.

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Early irradiations of Si with MIPs 1974

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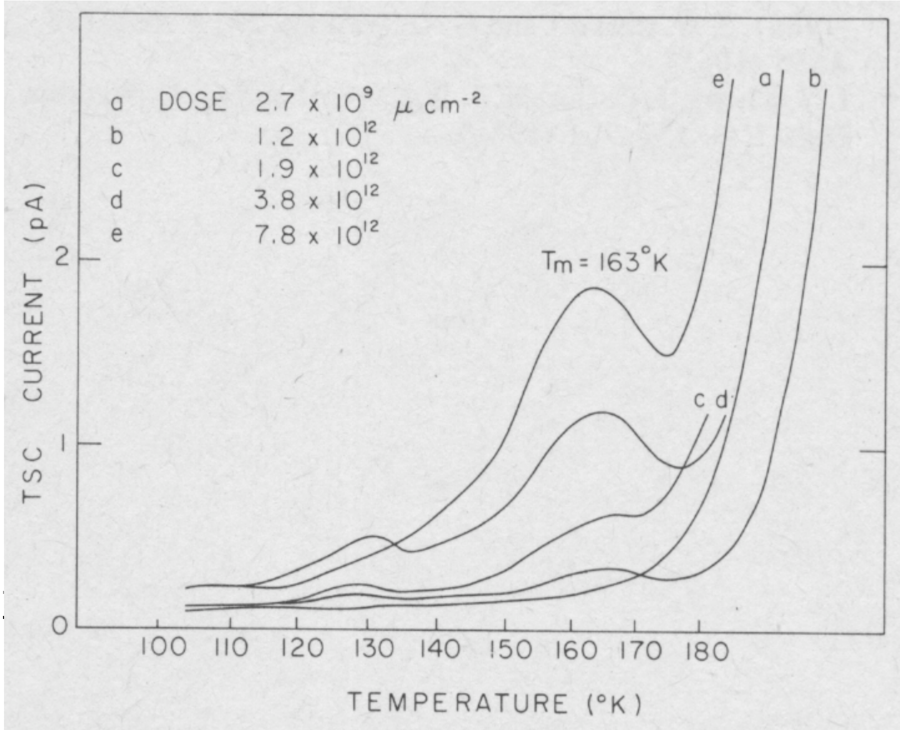
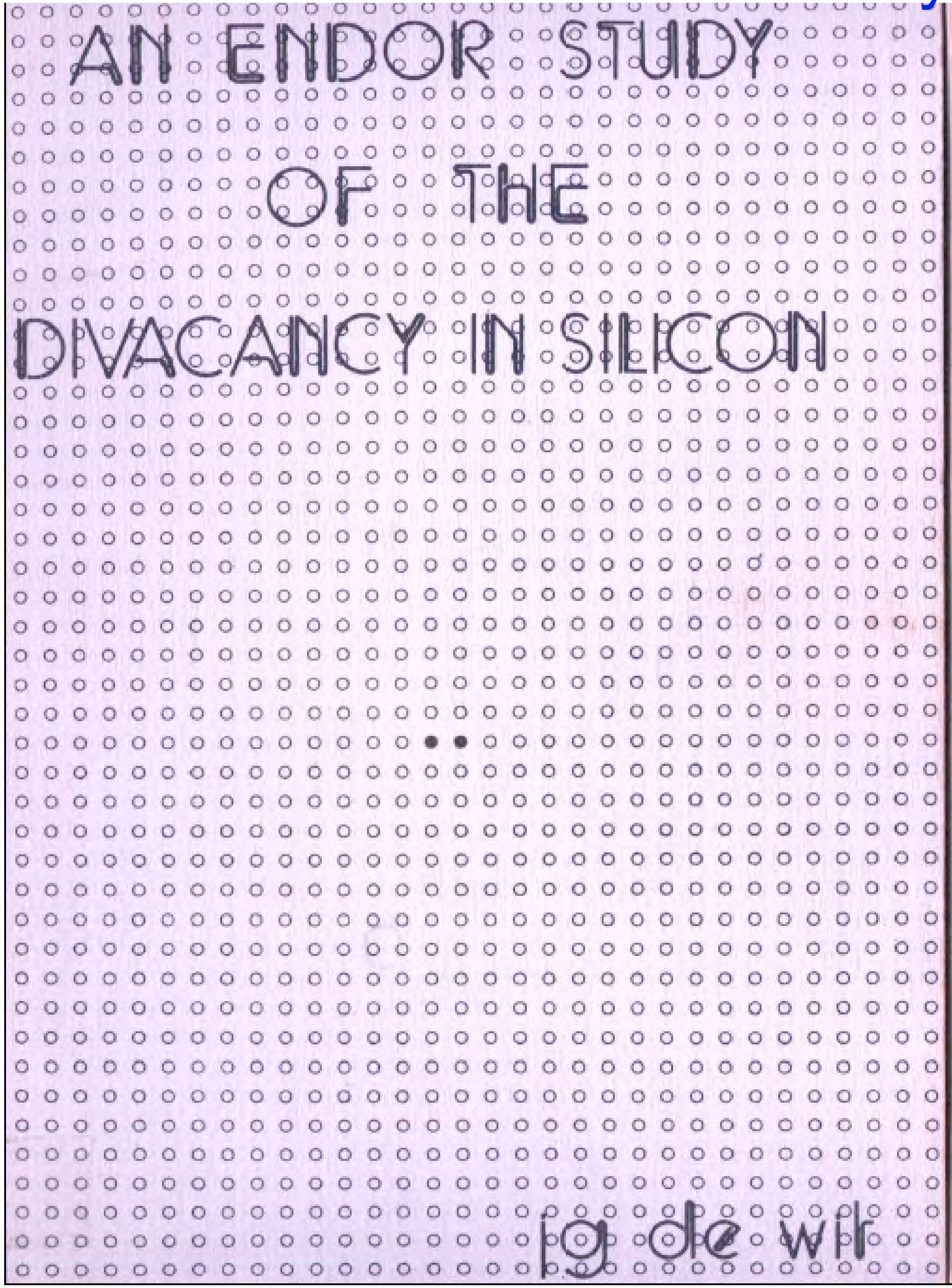


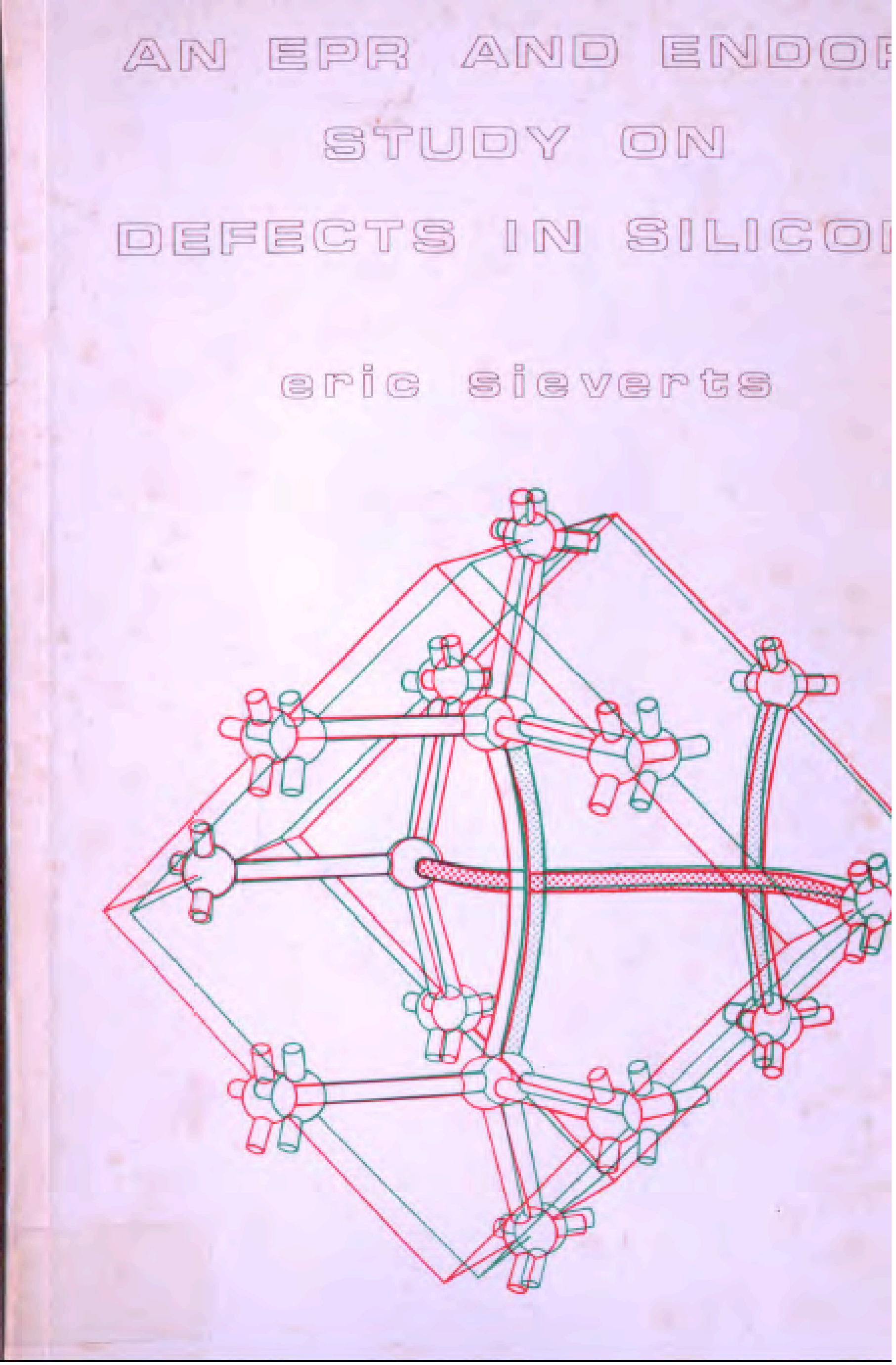
FIGURE 1 Evolution of the TSC peak in five samples, as a function of muon irradiation dose. Excitation by forward bias + 1 V, then reverse bias-10 V, heating rate $\beta = 0.75°K/s$.

some PhD studies on di-vacancy U. Amsterdam 1970-1976



AN ENDOR STUDY
OF THE
DIVACANCY IN SILICON

jg de wit

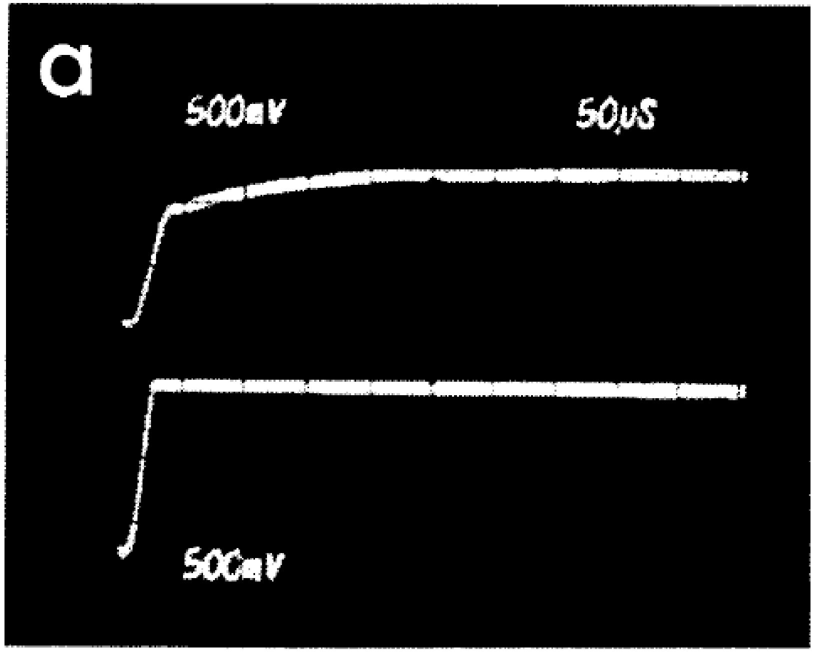


AN EPR AND ENDO
STUDY ON
DEFECTS IN SILICO

eric sieverts

Trapping and detrapping

When trapping occurs, the electronics processor (here a current sample/hold) may miss a large fraction of the signal charge



Erik Heijne, CERN Yellow Report 83-6

muon signal currents in
CERN SPS neutrino beam

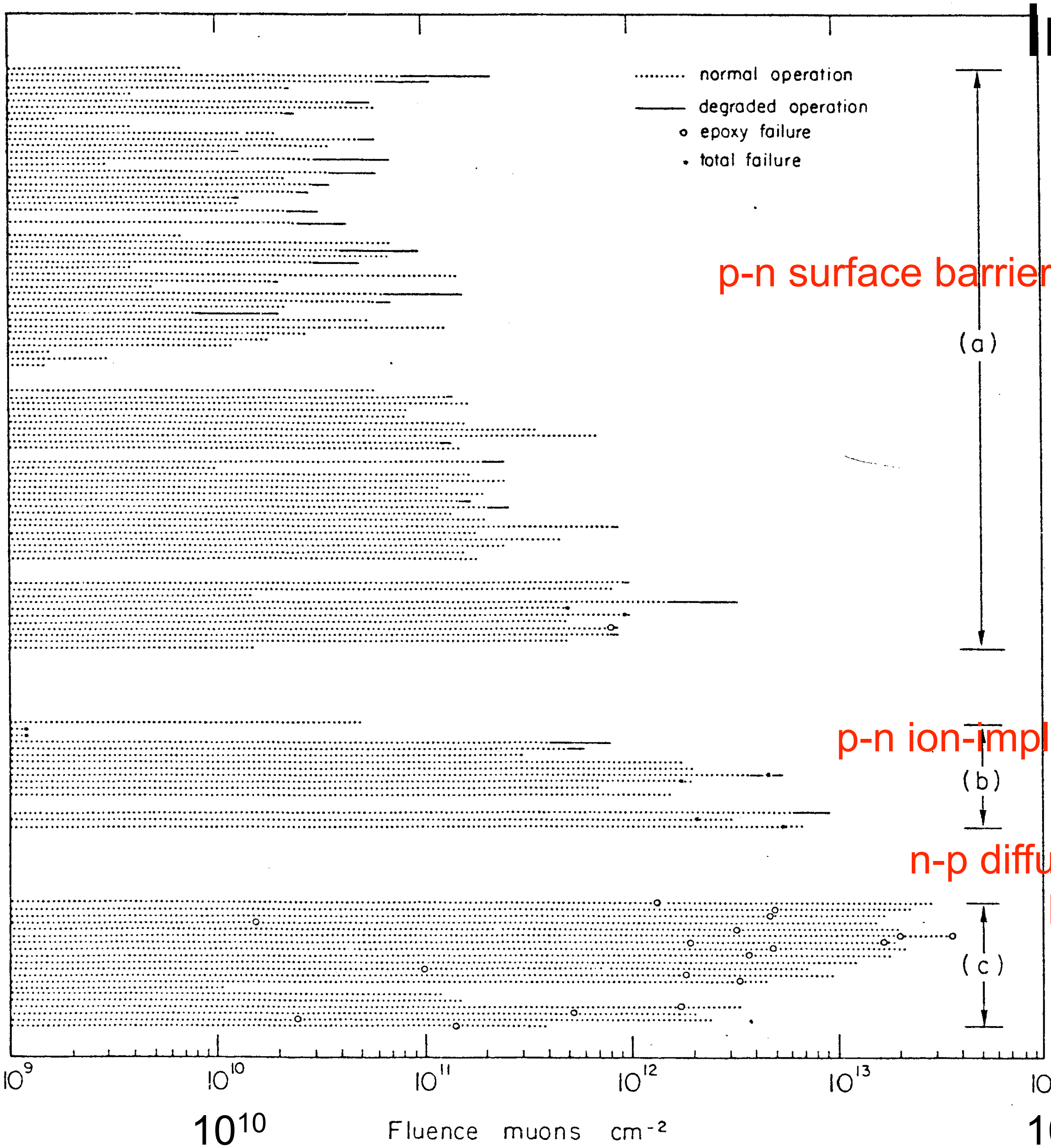
an extreme example:
traps were metal-related deep centers,
not radiation-induced

Top: diode with traps that release signal charge during several hundreds of μs after passage of the particle beam

Bottom: normal diode, all signal charge is integrated during 23μs beam passage

Trapping/detrapping in segmented devices is much more complex

Irradiations of Si with muons 1975-1980



10^{10}

10^{14}

p-n surface barrier diodes

p-n ion-implanted diodes

n-p diffused diodes

last longest

many of these diodes
used until 1997
material or rugged design?

Large efforts on radiation testing of Si diodes

Hamburg came strongly into RD2, but had already long history before that

R. Grube, E. Fretwurst and G. Lindström
Radiation damage effects from 2 MeV protons in silicon surface barrier detectors
Nucl. Instr. Meth. 101 (1972) 97

a lot of work and many publications; continued in RD20, RD39, RD48 and then RD50

main results provided confidence in long-term operation
Hamburg model has been used extensively
type inversion was known since long, e.g. mentioned at Pisa in 1980 by Kraner, BNL

In the R&D collaborations, the interactions between the sensors
and the associated electronics readout
has mostly been left out of these radiation studies.
electronic chips were developed and studied elswhere, separately
full modules have been studied quite late in the collaborations

How can tracking survive with semiconductors?

manipulate/improve Si crystal
- doping, smaller thickness
- pillar contact matrix '3D'

or evolve to other material: diamond, SiC

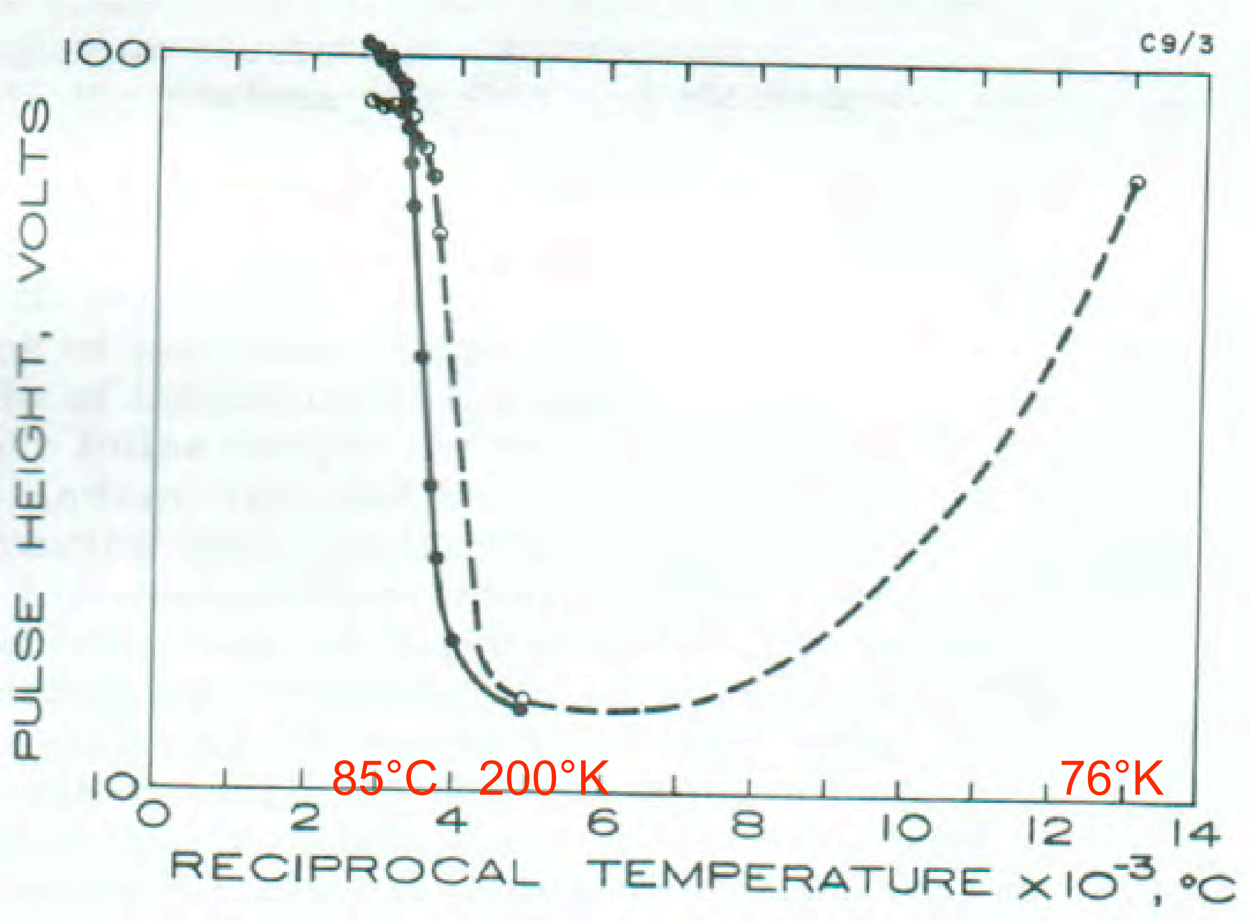
mitigate degradation by changing operating conditions
- reduced temperature or even cryogenic

unconventional operations:
- charge injection mode (RD39 etc.)
- signal multiplication in high field (RD50)

forced annealing, maybe even in-situ

gettering centers at insensitive places, eg pillars in the '3D'

Early temperature study after irradiation, Grainger @Hughes~1960

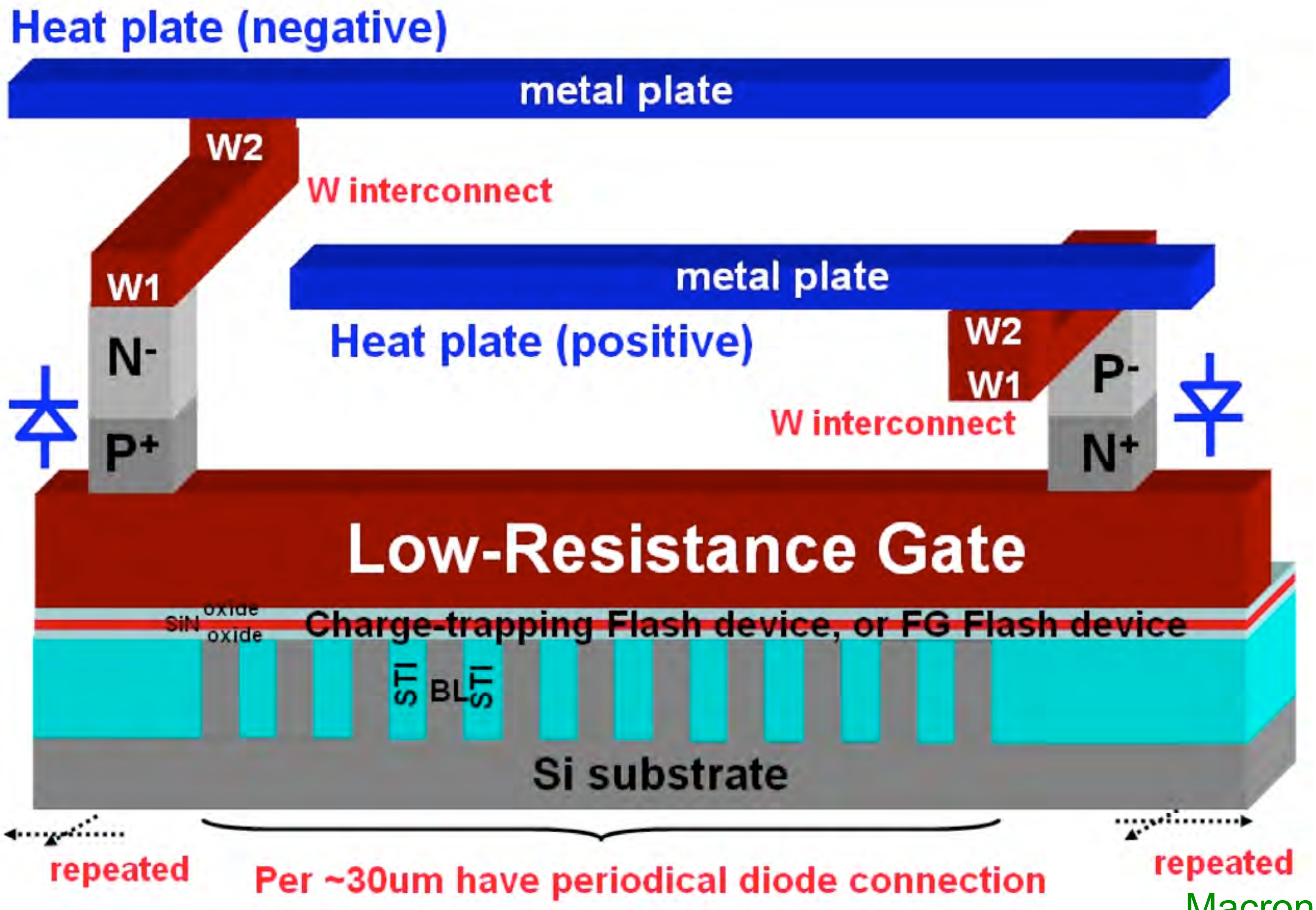


J.W. Mayer, IRE Trans Nucl Sc NS-9(1962)3

after irradiation, loss of signal height
significant recovery of signal height at cryogenic temperature
watch out for polarization: B. Dezillie, V. Eremin, Z. Li, E. Verbitskaya

Polarization of silicon detectors by minimum ionizing particles NIMA 452(2000) 440

Local heating for 'Flash' oxide recovery



claimed to go very locally > 800 °C

cures oxide damage, extends lifetime >10^8 cycles

Macronix Taiwan
IEDM 2012
to be published

OUTLOOK

- Can we transfer current CMOS nanotechnologies to
  Si detector manufacturing?

- Other types of degradation often worse
  than the radiation-induced damage

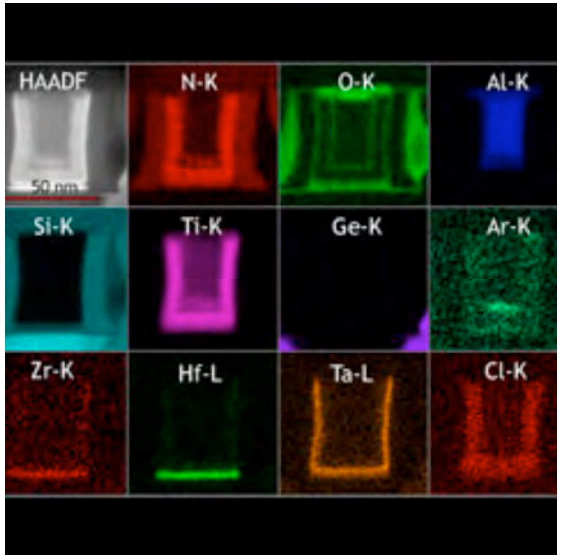
- We cool the electronics chips in order to save the sensors
  but CMOS can operate at higher temperatures;
  cool the sensors directly with built-in channels & CO_2?

- Pixelized sensors may perform better in the long run:
  segmented, low dark current even at mA per cm^2
  low noise tolerates much lower signals than pF strips
  statistical distribution of traps starts to play a role

Transistor images with TEM Tecnai Osiris

allows (also light) material identification

thanks to low noise drift detector



45 nm transistor

FinFET
material composition
studied at NXP

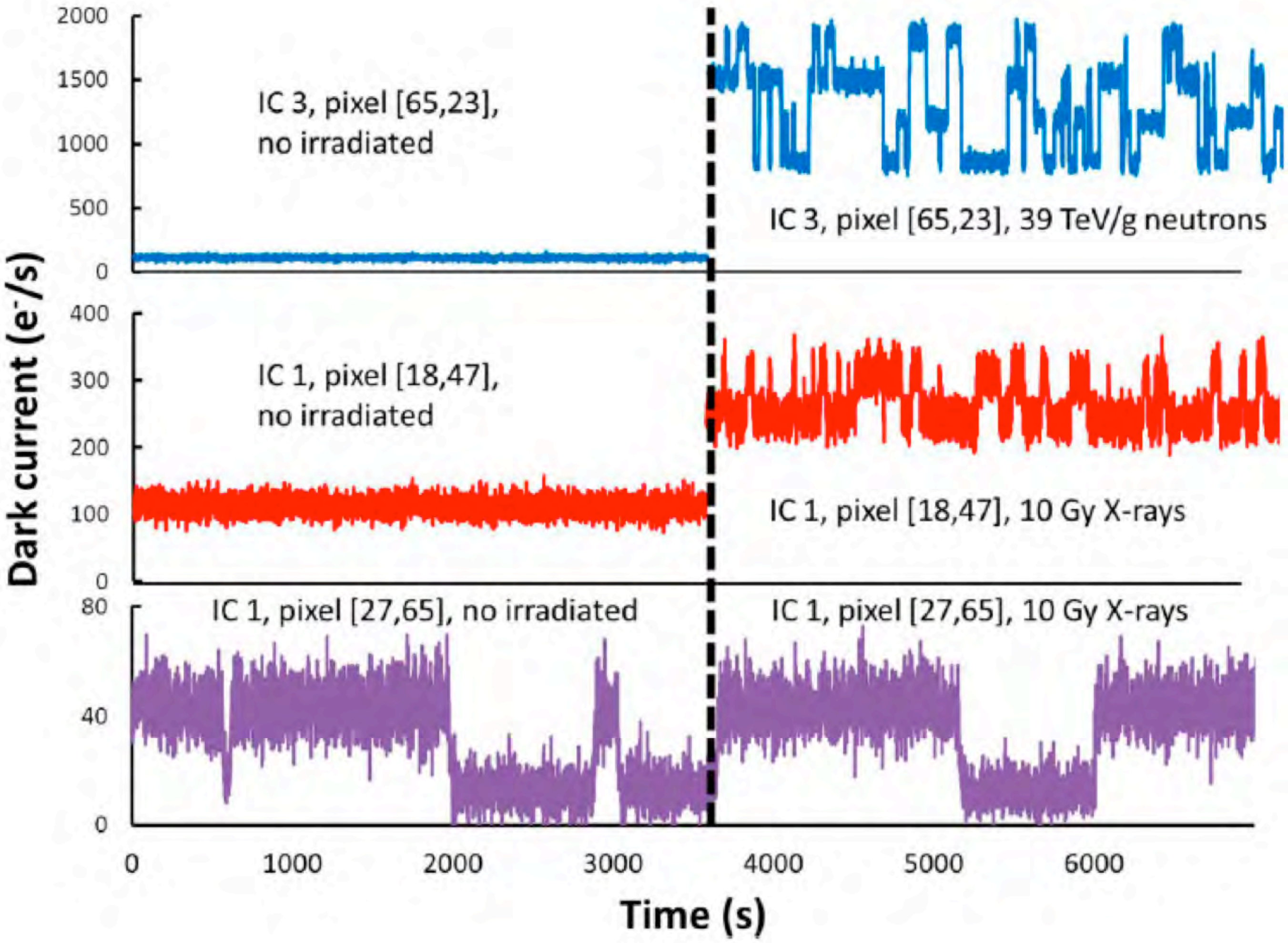
from FEI website
200 kV apparatus

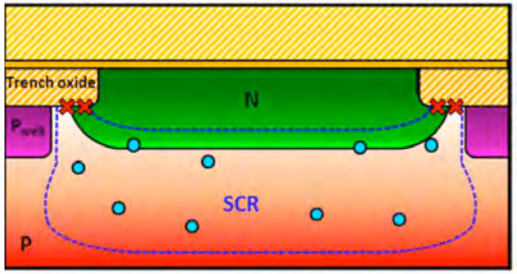
radiation effects in very small pixels

in few μm matrix elements one may have only 1 defect per cell

detailed electrical characterization of the defects

RTS in 0.18 imager technology





0, 1 or a few traps
in one pixel

large pixel statistics

note pixel current:
#e$^-$ per s

C. Virmontois, PhD thesis Toulouse 2012

END

How far can Si (or C) vertex trackers evolve
before becoming dinosours themselves?