Overview of radiation hard materials and devices for SuperLHC

Mara Bruzzi
INFN – University of Florence

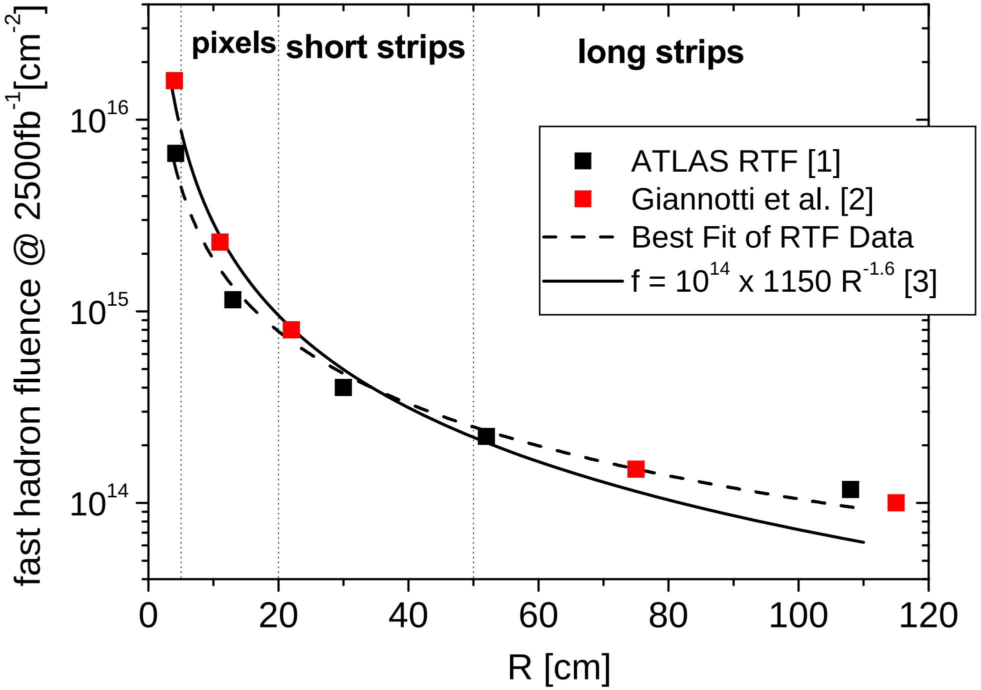
Now at SCIPP UCSC, CA

Predicted detector environment and fast Hadron Fluence expected at SuperLHC

Increase of luminosity of LHC up to $10^{35}cm^{-2}s^{-1}$ discussed since 2002. Date for upgrade ~ 2015.

It will allow a 20-30% increase in mass reach and continuation of measurements on rare processes that are statistics limited after several years of data collection.

Main constraint is the survival of the Si detector tracker to the exceptionally high fluences of fast hadrons.

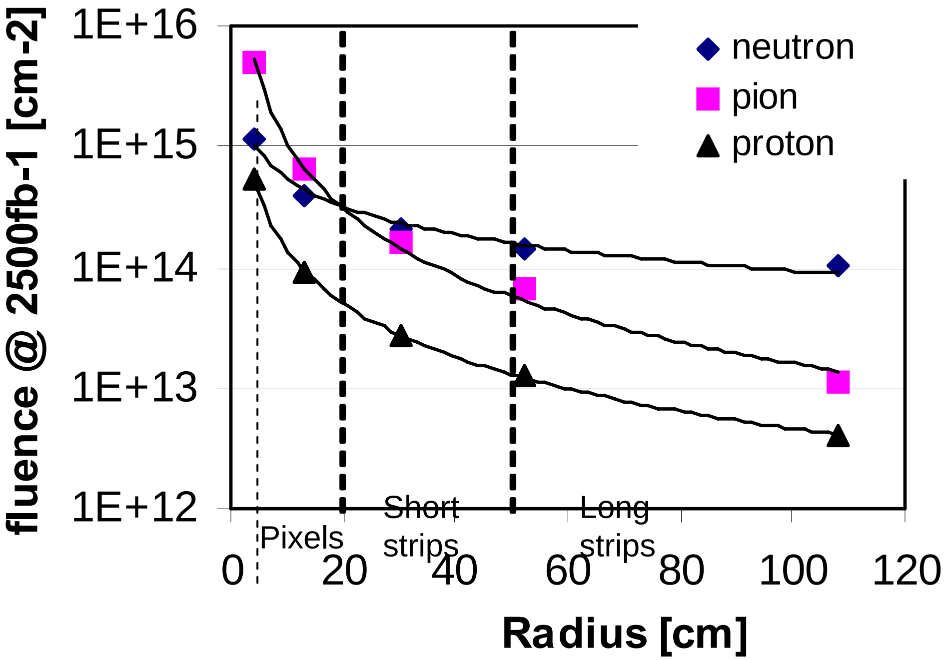


[1] Atlas Radiation Background Task Force, ATL-GEN-2005-001, Jan. 2005.
[2] F. Giannotti et al., hep-ph/0204087, April 2002.
[3] R. Horisberger , CMS Workshop on SLHC, CERN, Feb. 2004.
[4] H. F.-W. Sadrozinski, A.SeidenNIM A 541 (2005) 434–440.

Neutron, pion, proton fluence expected at SuperLHC

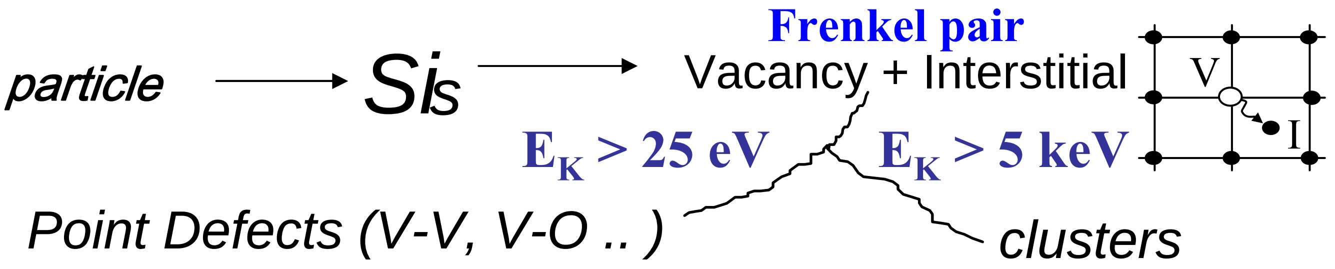
Region	Annual 1 MeV neutron equivalent fluence ($\times 10^{12}$) cm^{-2}				
	radius	**neutron**	**pion**	**proton**	**total**
PixB1	4.2	47	198	21	267
PixB3	13	16	26	3.6	46
PixD5		10	16	2.8	29
SCTB1	30	8.4	6.4	1.1	16
SCTB4	52	5.8	2.6	0.52	8.9
SCTD9		9.3	3.5	0.91	14
TRTWI		15	3.3	1.0	20
TRTWO		9.6	0.58	0.28	10
TRTB0	108	4.1	0.45	0.16	4.7

Table 5.3 1-MeV neutron equivalent fluence rates.



Data from: S.Baranov, M.Bosman, I.Dawson, V.Hedberg, A.Nisati and M.Shupe Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS **Atlas Radiation Background Task Force** Summary Document, ATL-GEN-2005-001, 13 January 2005.

Radiation Damage – I. Radiation Induced Defects



particle → Si_s → **Frenkel pair** Vacancy + Interstitial

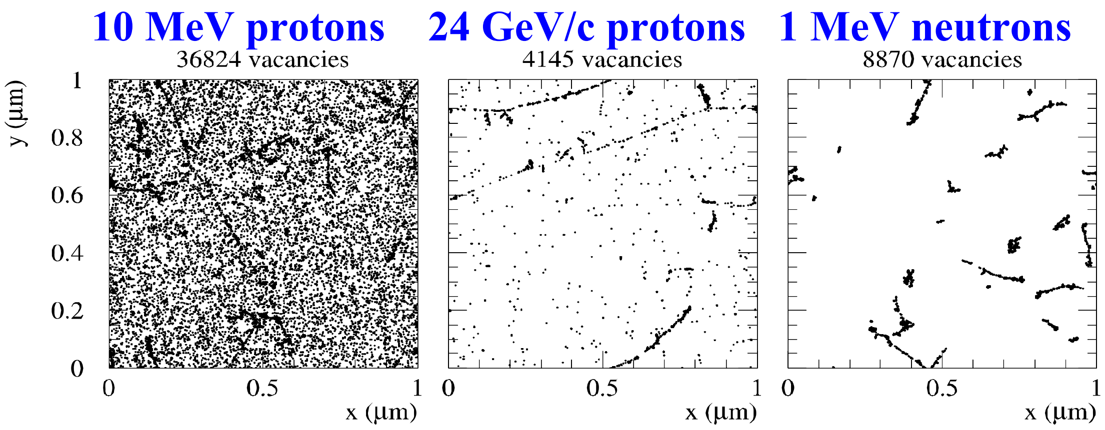
$E_K > 25$ eV

$E_K > 5$ keV

Point Defects (V-V, V-O ..)

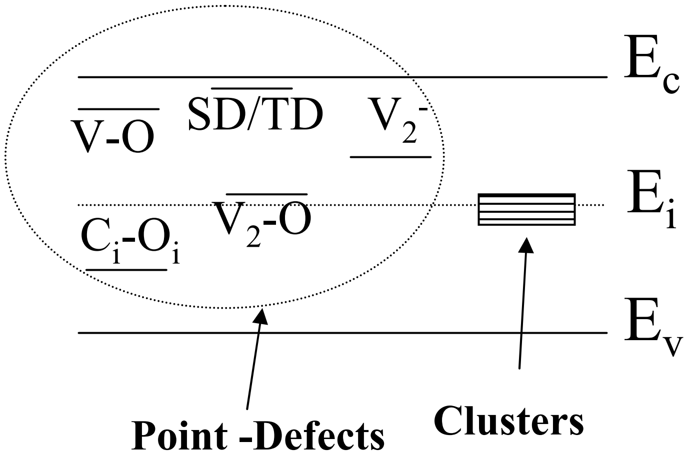
clusters

Initial distribution of vacancies after 10^{14} particles/cm^2



More point defects **Mainly clusters**

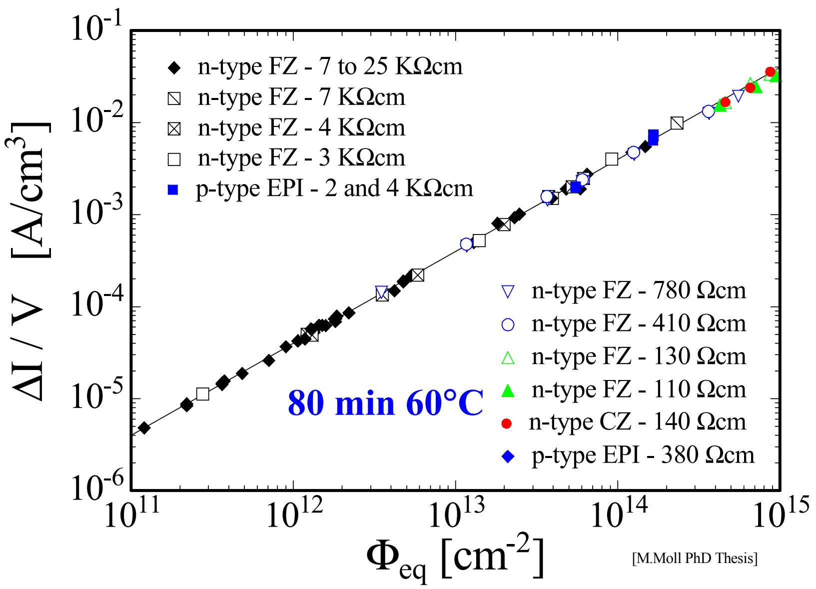
Main radiation induced defects in Si



[Mika Huhtinen NIMA 491(2002) 194]

Radiation Damage – II. Leakage Current

- Change of Leakage Current (after hadron irradiation)



[M.Moll PhD Thesis]

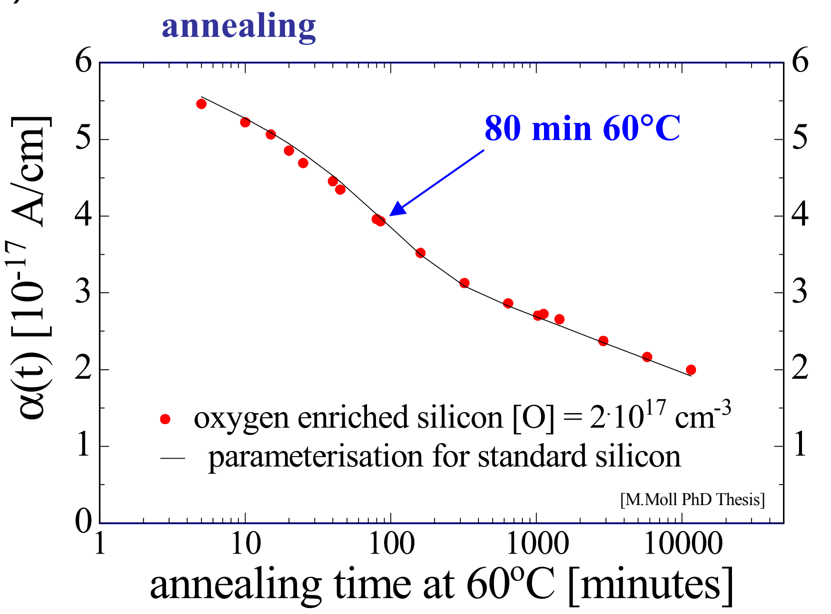
- **Damage parameter α (slope in figure)**

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

$$\alpha(60°C, 80\,\mathrm{min}) = (3.99 \pm 0.03) x 10^{-17} \frac{A}{cm}$$

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  ⇨ can be used for fluence measurement



[M.Moll PhD Thesis]

- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence:**

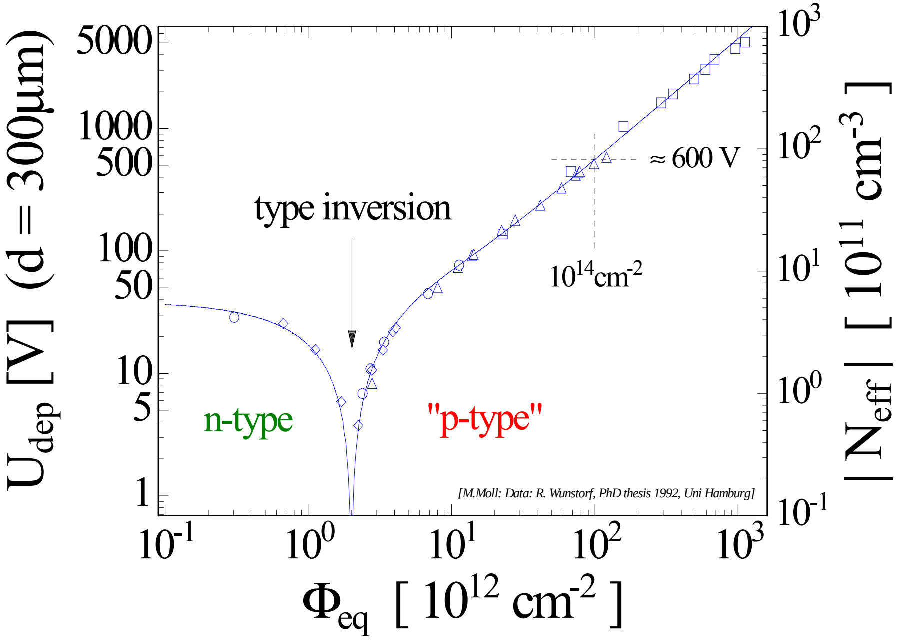
$$I(T)\ \alpha\ T^2 \exp\left(-\frac{E_g}{KT}\right)$$

Consequence:

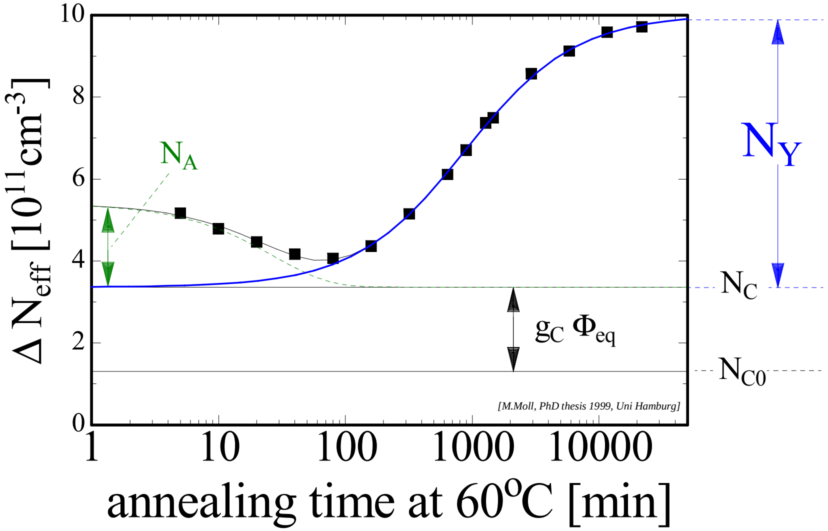
Cool detectors during operation!

Radiation Damage – III. Effective doping concentration

Change of Depletion Voltage V_{dep} (N_{eff}) in high resistivity n-type FZ Si



…. annealing



- Full depletion voltage too high to fully deplete detectors at very high fluences
- "**Type inversion**": N_{eff} changes from positive tonegative (**Space Charge Sign Inversion**)

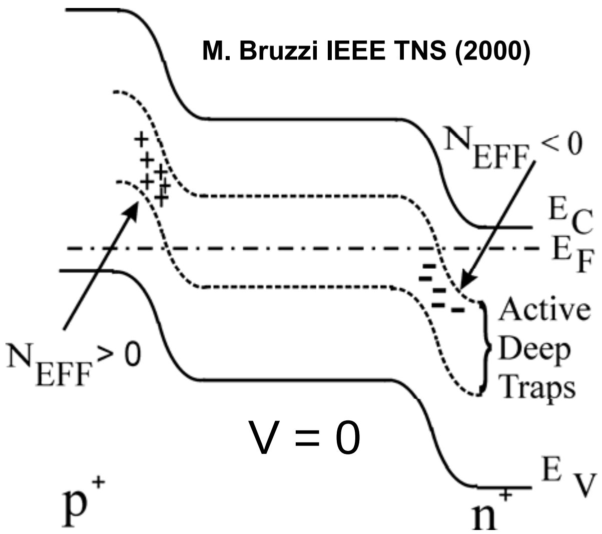
Short term: "Beneficial annealing"

Long term: "Reverse annealing"

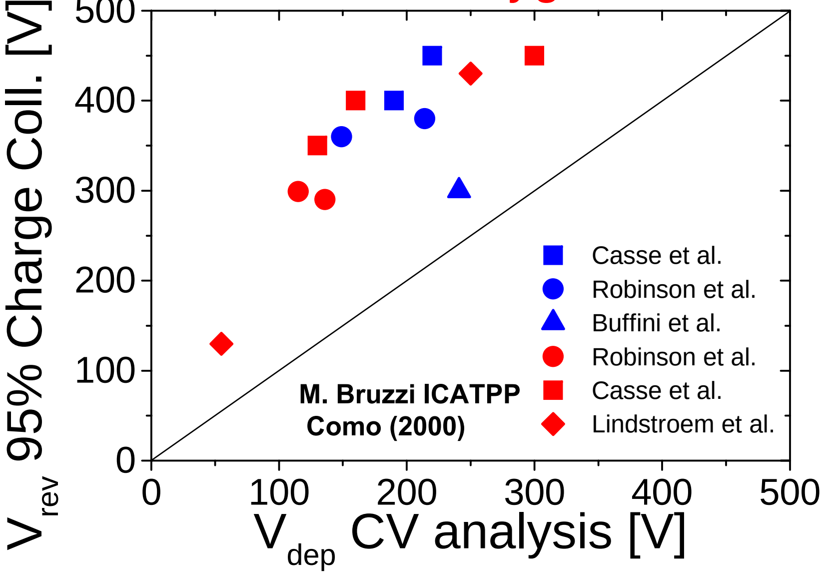
- time constant depends on temperature:
  - ~ 500 years (-10°C)
  - ~ 500 days (20°C)
  - ~ 21 hours (60°C)
- **Consequence:** Detectors must be cooled even when the experiment is not running!

Radiation Damage – IV. Double Junction Effect

For very high fluences a depletion region is observed on both sides of the device.



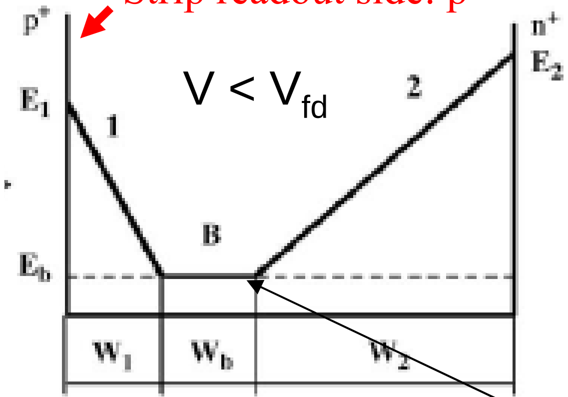
M. Bruzzi IEEE TNS (2000)



standard - oxygenated

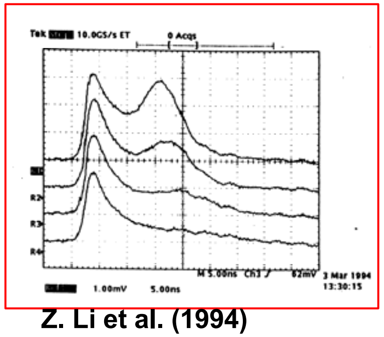
M. Bruzzi ICATPP Como (2000)

Strip readout side: p^+



V. Eremin et al. (2000)

High resistivity Si!



Z. Li et al. (1994)

In Standard FZ and DOFZ Si (RD48 Coll.) after irradiation main space charge region is at back contact (Space Charge Sign Inversion - SCSI).

- **❑Need to fully deplete the detectors**
- **❑Voltage needed to maximise collected charge much higher than full depletion voltage.**

Radiation Damage – V. Trapping

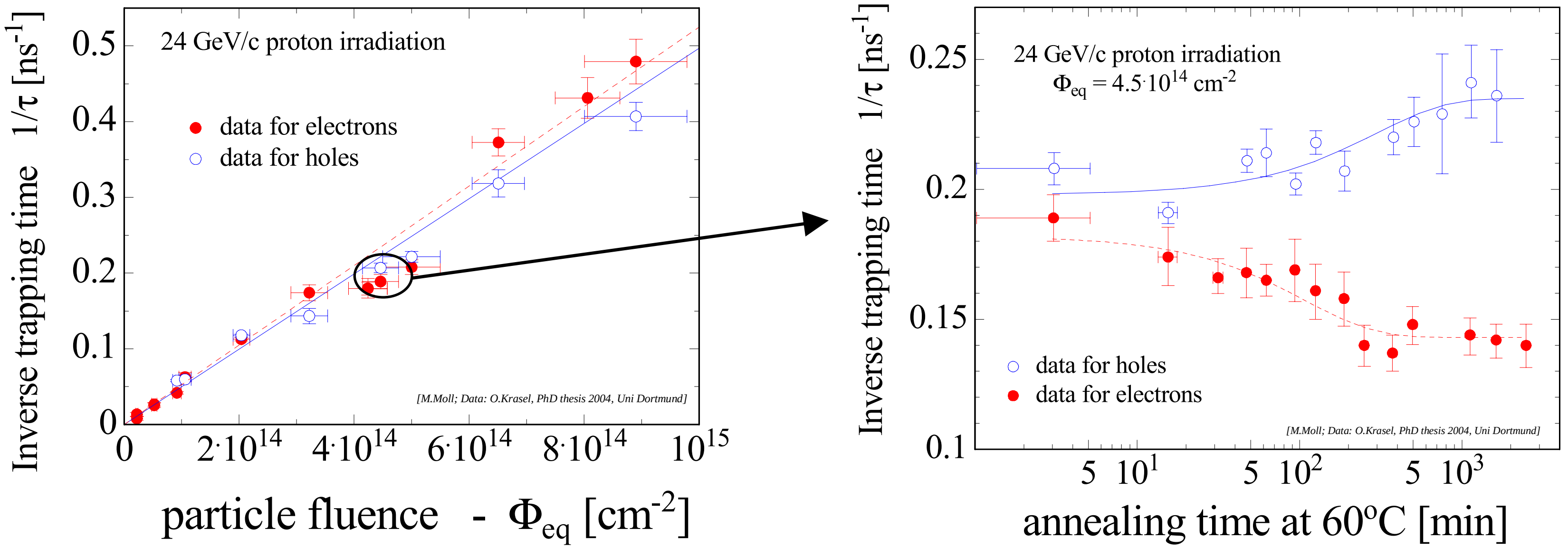
- Deterioration of Charge Collection Efficiency (CCE) by trapping

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h}\exp\left(-\frac{1}{\tau_{eff\ e,h}}\cdot t\right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

See G. Kramberger talk

Increase of inverse trapping time ($1/\tau$) with fluence ….. and change with time (annealing):



The CERN RD50 Collaboration http://www.cern.ch/rd50

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

- formed in November 2001
- approved as RD50 by CERN June 2002
- Main objective:

Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} $cm^{-2}s^{-1}$ ("Super-LHC").

Challenges:
- **Radiation hardness up to 10^{16} cm^{-2} required**
- **Fast signal collection** (Going from 25ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

55 Institutes - 270 participants

Barcelona, Bari, Berlin IKZ, BNL, Bologna, Bucharest (2), CERN, Diamond Light Source UK, Dortmund, Erfurt, Exeter, Fermilab, Florence, Freiburg, Glasgow, Hamburg, Helsinki HIP, Ioffe Institute St.Petersburg, ITE &ITME Warszawa, Karlsruhe, KINR, Lancaster, Lappeenranta, Liverpool, Ljubljana, Louvain, Minsk, Montreal, Moscow (2), Munich, New Mexico, NIKHEF, Oslo, Padova, Perugia, Pisa, Prague (2), PSI, Purdue, Rochester, Santa Cruz, Sheffield, SINTEF, Surrey, Syracuse, Tel Aviv, Torino, Trento, Valencia, Vilnius

Silicon Materials under Investigation by RD50

Material	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard n- or p-type FZ	FZ	$1–7\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ, n- or p-type	DOFZ	$1–7\times10^{3}$	$\sim 1–2\times10^{17}$
Czochralski Sumitomo, Japan	Cz	$\sim 1\times10^{3}$	$\sim 8\text{-}9\times10^{17}$
N and p Magnetic Czochralski Okmetic, Finland	MCz	$\sim 1\times10^{3}$	$\sim 4\text{-}9\times10^{17}$
N and p Epitaxial layers on Cz-substrates, ITME up to 100-150μm	EPI	50 - 100	$< 1\times10^{17}$

SiC, GaN also investigated in RD50 ⟶ too thin !

Diamond under Investigation by RD42 ⟶ See next Talk by H. Kagan

Available Irradiation Sources in RD50:

- ❑ 24 GeV/c protons, PS-CERN
- ❑ 10-50 MeV protons, Jyvaskyla +Helsinki
- ❑ Fast neutrons, Louvain
- ❑ 26 MeV protons, Karlsruhe
- ❑ TRIGA reactor neutrons, Ljubljana

Comparison with high-bandgap semiconductor detectors

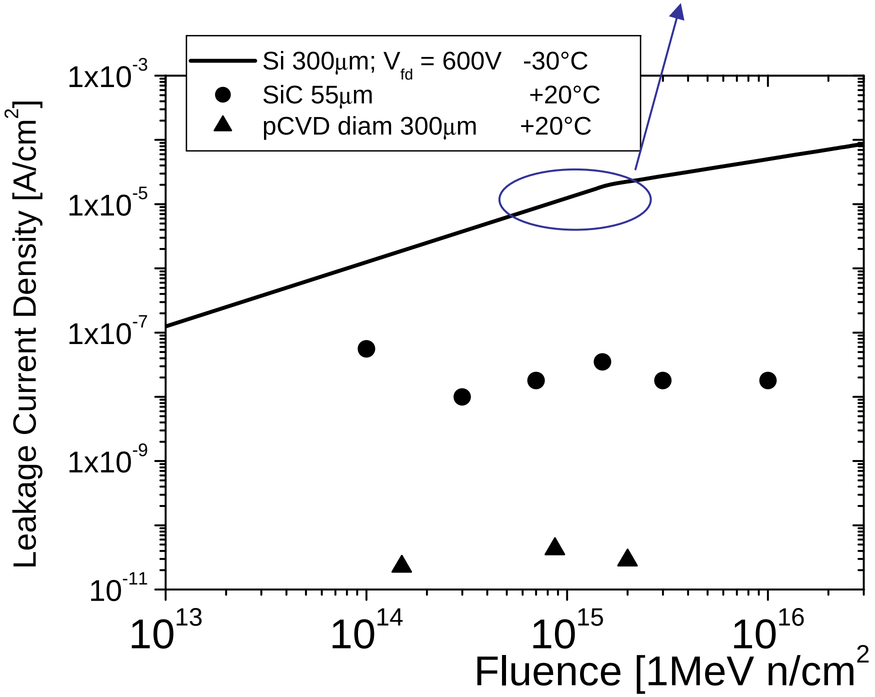
Property	Si	Diamond	Diamond	4H SiC
Material	MCz, FZ, epi	Polycrystal	single crystal	epitaxial
E_g [eV]	1.12	5.5	5.5	3.3
$E_{breakdown}$ [V/cm]	$3\cdot10^5$	10^7	10^7	$2.2\cdot10^6$
μ_e [cm^2/Vs]	1450	1800	>1800	800
μ_h [cm^2/Vs]	450	1200	>1200	115
v_{sat} [cm/s]	$0.8\cdot10^7$	$2.2\cdot10^7$	$2.2\cdot10^7$	$2\cdot10^7$
Z	14	6	6	14/6
ε_r	11.9	5.7	5.7	9.7
e-h energy [eV]	3.6	13	13	7.6
Density [g/cm3]	2.33	3.515	3.515	3.22
Displacem. [eV]	13-20	43	43	25
e-h/µm for mips	~80	36	36	55
Max ccd [µm]	>500	300	800	55
Max wafer ϕ	6”	6”	~1.4cm	2”
Commercial	yes	H.Kagan talk	H.Kagan talk	limited
CERN R&Ds	RD50, RD39	RD42	RD42	RD50

Silicon: $J(\Phi) = \alpha \cdot \Phi \cdot d$

$$I(T)\ \alpha\ T^2 \exp\left(-\frac{E_g}{KT}\right)$$

T = -30°C; V = 600V, W = 300µm

Partial depletion



Main Advantage:

High band gap semiconductors show a stable or even decreased leakage current after irradiation: recombination increases and generation not favoured at room T (it is dominated by emission from midgap centers).

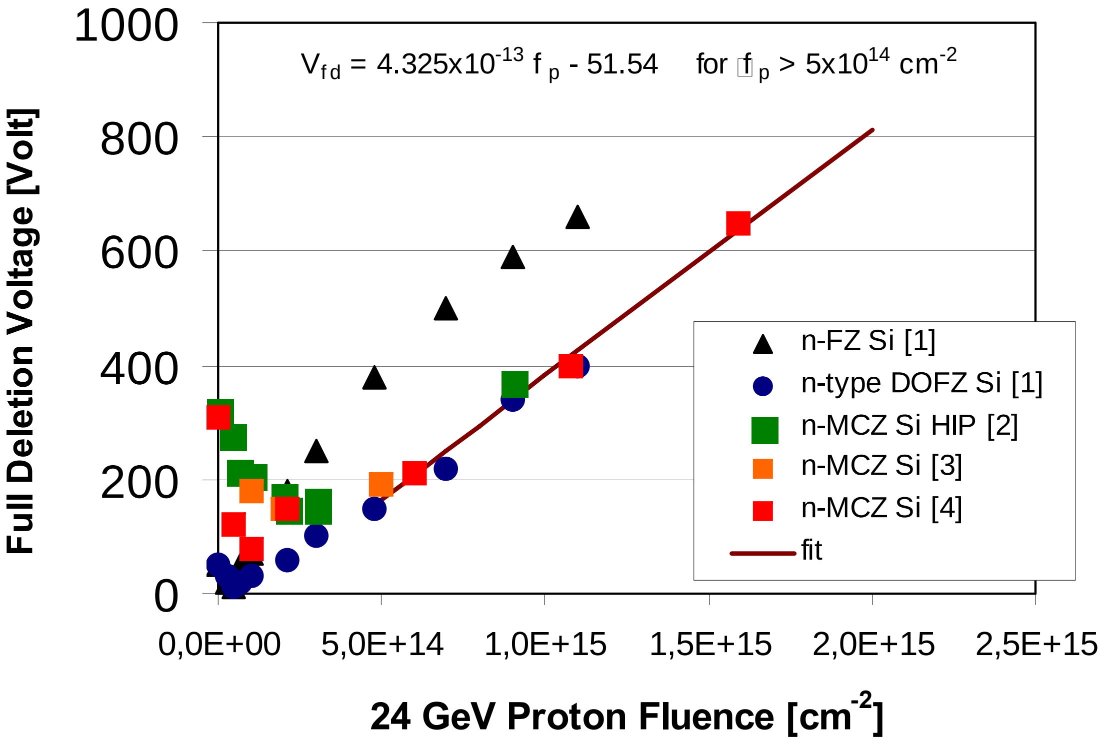
24 GeV/c p irradiation: n-MCz rad-harder than standard FZ

- **Standard FZ silicon**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **strong N_{eff} increase at high fluence**

- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **reduced N_{eff} increase at high fluence**

- **Magnetic Czochralski Si**
  - **NO type inversion**
  - **reduced N_{eff} increase at high fluence as in DOFZ**

Due to radiation induced shallow donors and less generation of V_2O



$V_{fd} = 4.325\times10^{-13}\, f_p - 51.54$ for $f_p > 5\times10^{14}$ cm^{-2}

[1] M. Moll et al. NIM A 546 (2005), 99-107
[2] data on [1] related 380µm-thick devices here normalised to 300µm
[3] E. Tuovinen et al. In press on NIM A
[4] M. Moll et al. RD50 workshop, CERN Nov. 2005

Up to 10^{15}cm^{-2} 24 GeV p $V_{fd} \leq 400$V

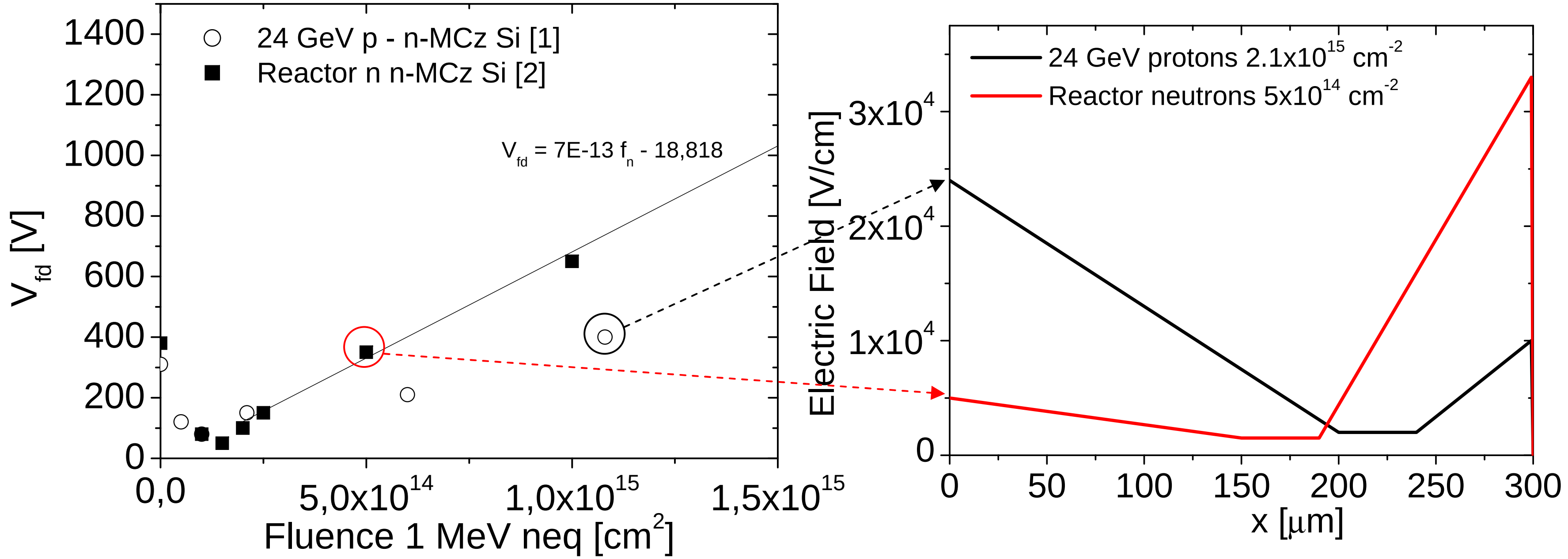
→ 2×10^{15}cm^{-2} V_{fd} ~ 800V

n-type Si : Comparison of 24GeV p and 1MeV neutron irradiation

Double Junction develops mostly from back in neutron irradiated silicon, probably due to a high generation of cluster, behaving as a source of quasi-midgap acceptors.

n-type MCz Si after 24GeV p and after reactor neutrons

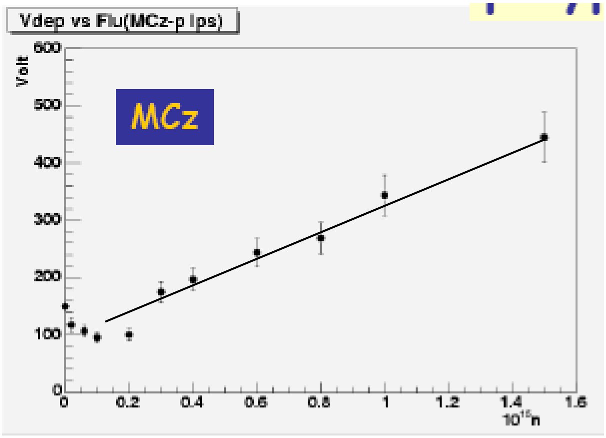
Electric field distribution by TCT (Ioffe-St Petesburg on SMART n-MCz Si single pad diodes)



- ➢**MCz Si no type inverted after $2x10^{15}cm^{-2}$ 24GeV p but definitely inverted after $5x10^{14}cm^{-2}$ reactor neutrons.**
- ➢**After 10MeV and 26MeV protons irradiation the behavior is similar to that obtained with 1MeV neutrons**

Depletion Voltage for 300 μm p-type SSD vs. Fluence

Similarly to n-type Si, in the high fluence range we can approximate the full depletion voltage increase as:



$$V_{dep} = V_0 + \beta \cdot \Phi$$

Best fits of available data (N. Manna at Helsinki Rd50 Workshop, 2005):

$$\beta \sim 3 \cdot 10^{-13}\ \mathrm{V/cm^2}$$

The depleted detector thickness w is given by the physical thickness t when the bias voltage Vbias is larger than the depletion voltage V_{dep} and scales like the square root of the ratio V_{bias} / V_{dep} when it is smaller.

$$w = t \qquad V_{bias} \geq V_{dep}$$

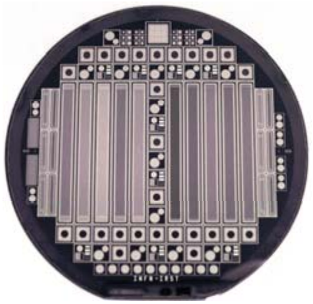
$$w = \sqrt{\frac{V_{bias}}{V_{dep}}} \cdot t \qquad V_{bias} < V_{dep}$$

H.F.W. Sadrozinski, A. Seiden, M. Bruzzi, SCIPP report 05/09, Oct. 2005

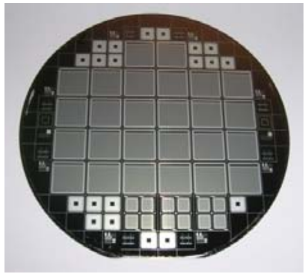
Process of segmented p-type Si sensors

Development of MCz & FZ Si p-type microstrip/pixel sensors

SMART INFN : Two runs 20 wafers each 4”
mini-strip 0.6x4.7cm^2, 50 and 100µm pitch, AC coupled
37 pad diodes and various text structures
MCz FZ P-type: two p-spray doses 3E12 amd 5E12 cm^{-2}
Wafers processed by IRST, Trento on 200-500µm



CNM, Barcelona p-in-n and n-in-p,
MCZ FZ and DOFZ Si
Mask set designed by RD50
Surface insulation provided only by p-spray

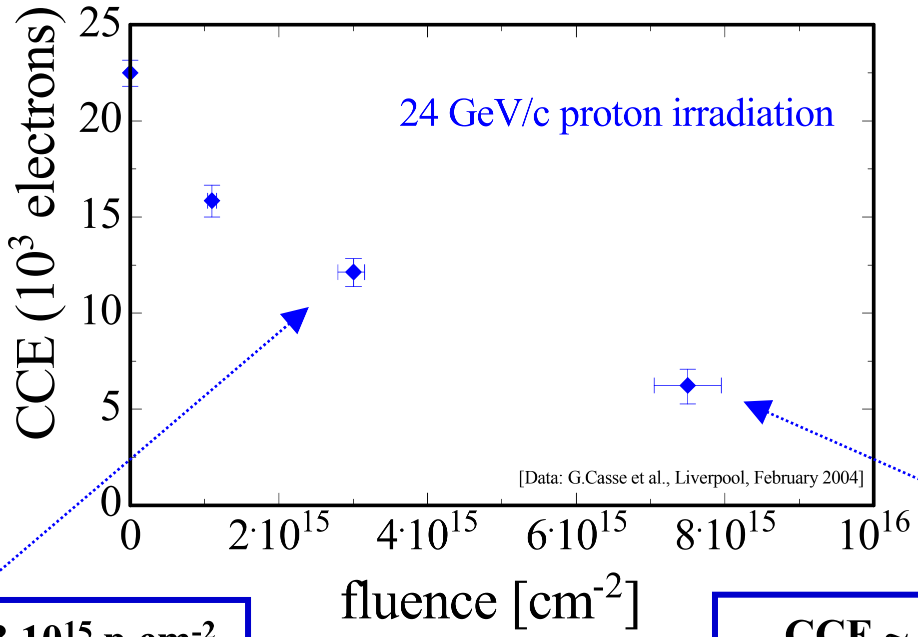


Micron Semiconductors, microstrips on thick 4” an 6”
p-type FZ and DOFZ Si

P-type FZ Si: n-in-p microstrip detectors

n-in-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- **Miniature n-in-p microstrip detectors (280µm)**
- **Detectors read-out with LHC speed (40MHz) chip (SCT128A)**
- **Material: standard p-type and oxygenated (DOFZ) p-type**
- **Irradiation:**



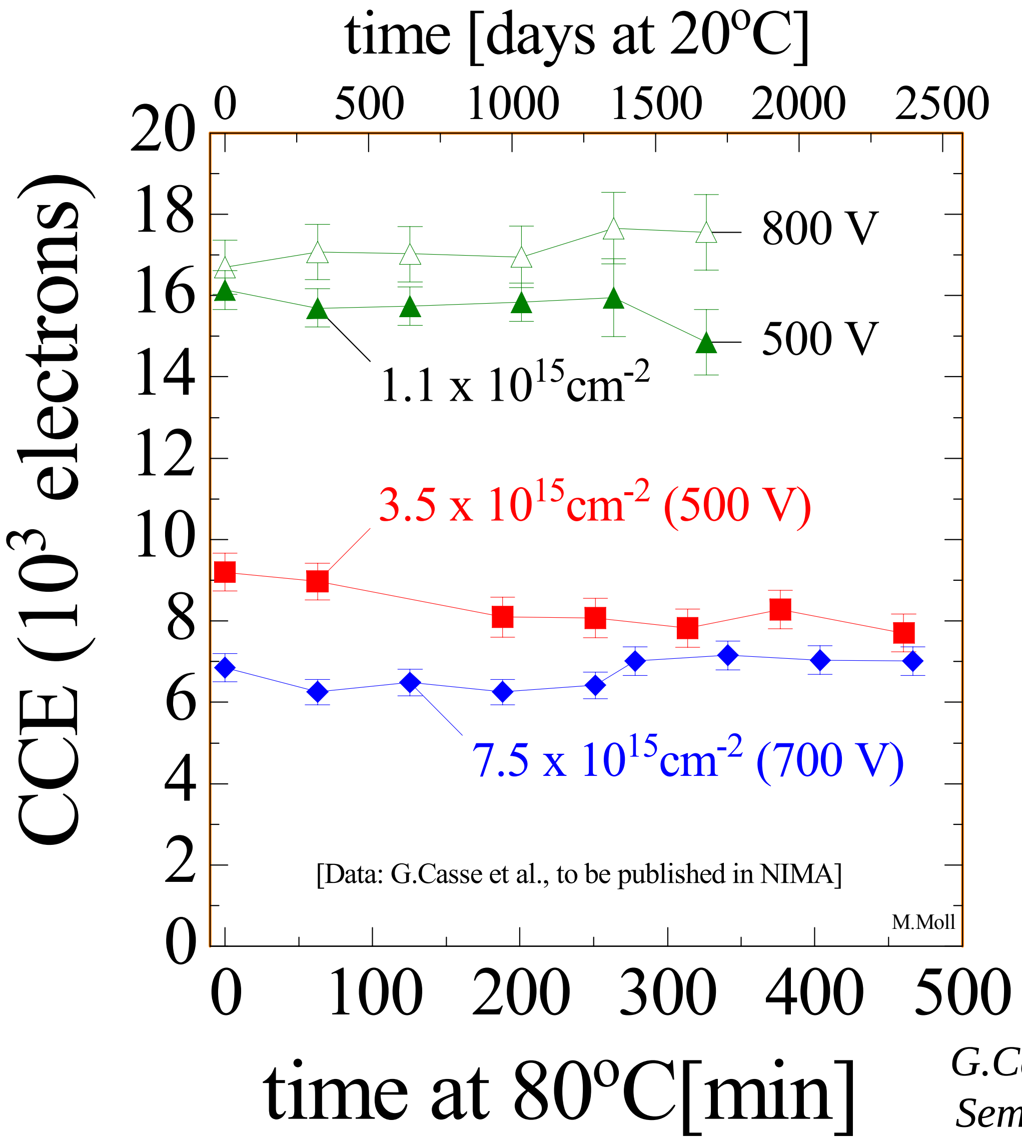
G. Casse et al., NIMA535(2004) 362

At the highest fluence Q~6500e at V_{bias}=900V

CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

Annealing of p-type FZ and DOFZ sensors



- **p-type strip detector (280μm) irradiated with 23 GeV p (7.5 × 10^{15} p/cm^2)**
- **expected from previous CV measurement of V_{dep}:**
  - before reverse annealing:

  V_{dep}~ 2800V

  - after reverse annealing

  V_{dep} > 12000V

- **no reverse annealing visible in the CCE measurement !**

G.Casse et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

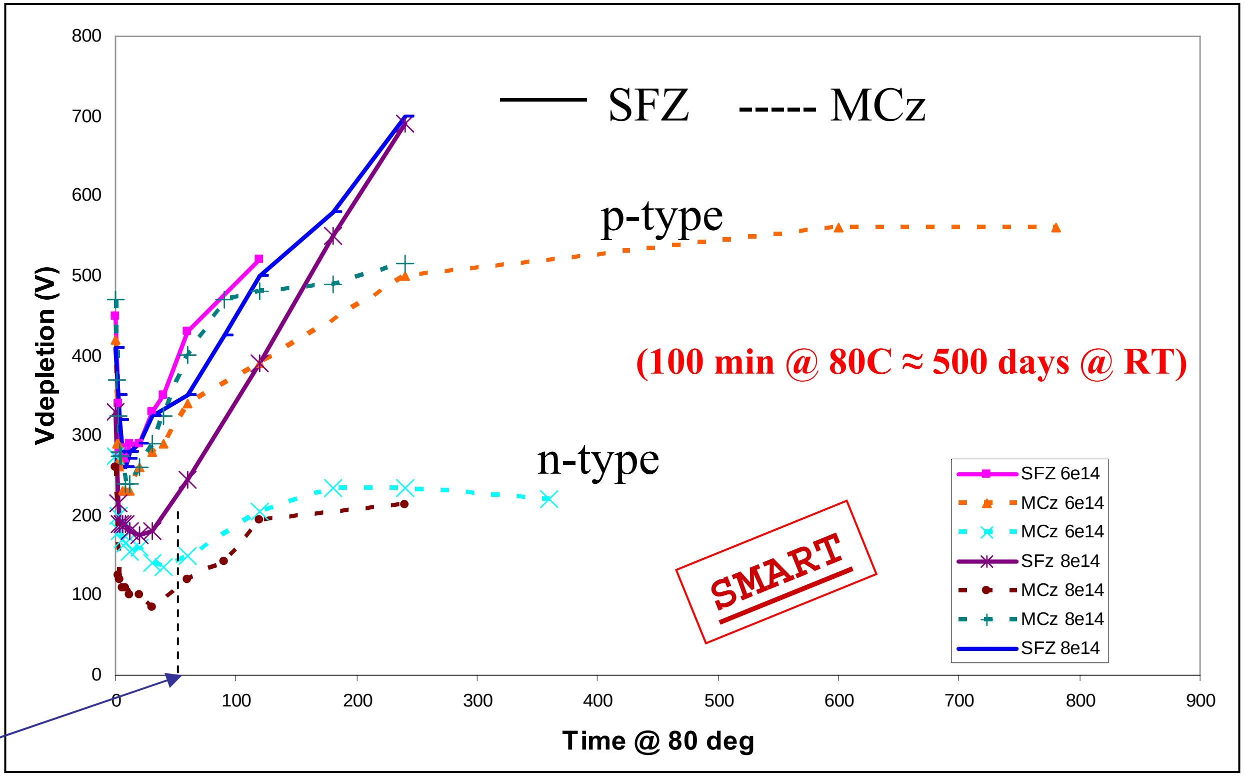
Annealing @ high temperature (reverse annealing)

Comparison of FZ and MCz (n- and p-type) @ 80°C:

Effect of reverse annealing significantly reduced in MCz Si after irradiation with 26MeV and 24GeV/c up to 2×10^{15} n_{eq} cm^{-2} with respect to FZ Si.

Clear saturation for MCz Si (n or p) beyond 200 minutes at 80 °C

Saturation more effective for n-type

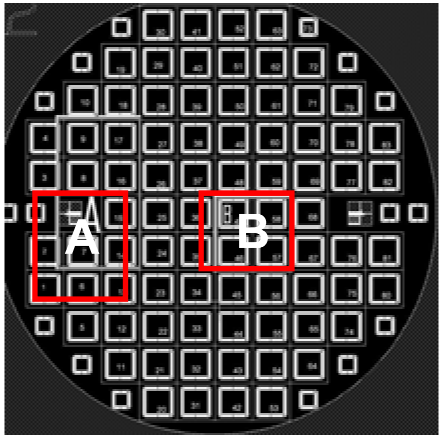


250 days@20°C

The reduced reverse annealing growth would simplify damage recovery in experimental operational conditions

The issue of non-uniform doping in p-type MCz Si

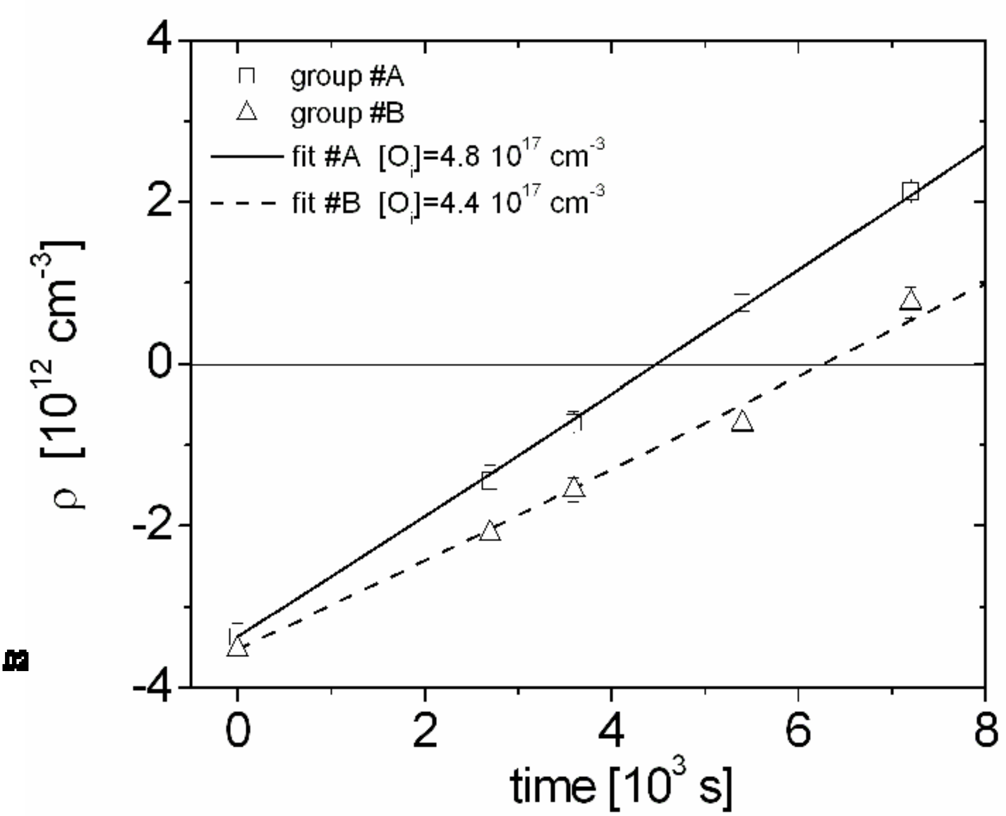
Diodes from A(periphery) and B(center) of one wafer heated to 430°C up to 120minend with different doping density: an estimated 10% difference in $[O_i]$ brings to 100V variation in final full depletion.



Diodes processed by Helsinki, see J. Harkonen Talk on Tuesday

$$N_{TD}(t) = k_1\left\{[O_i]\cdot\left[1+\frac{2}{3}D_i t\cdot[O_i]^{2/3}\right]^{-3/2}\right\}^x t^{1.02}$$

$D_i = D_\infty \cdot e^{-Ea/KT}$, with $D_\infty = 0.13 cm^2/s$
$E_a = 2.53 eV$, $k = 4.61x10^{-52}$; $x = 3-4$
C. A. Londos et al. Appl.Phys.Lett. **62**, 1525 (1993).

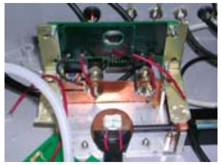


M. Bruzzi et al., Journal of Applied Physics (2006)

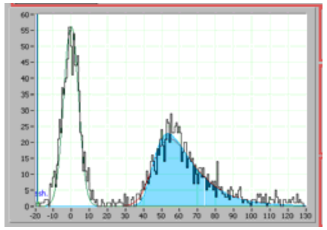
Charge Collection Efficiency on SMART p-type MCz Si single pad detectors

^{90}Sr source - Analog DAQ with AC-coupled and shaping time of 2.4µs.

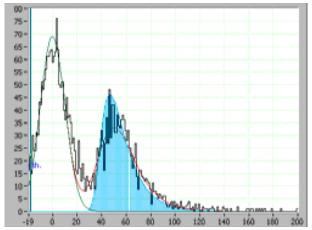
INFN Florence experimental set-up
Measurements have been carried out -30°C, via a Peltier system.

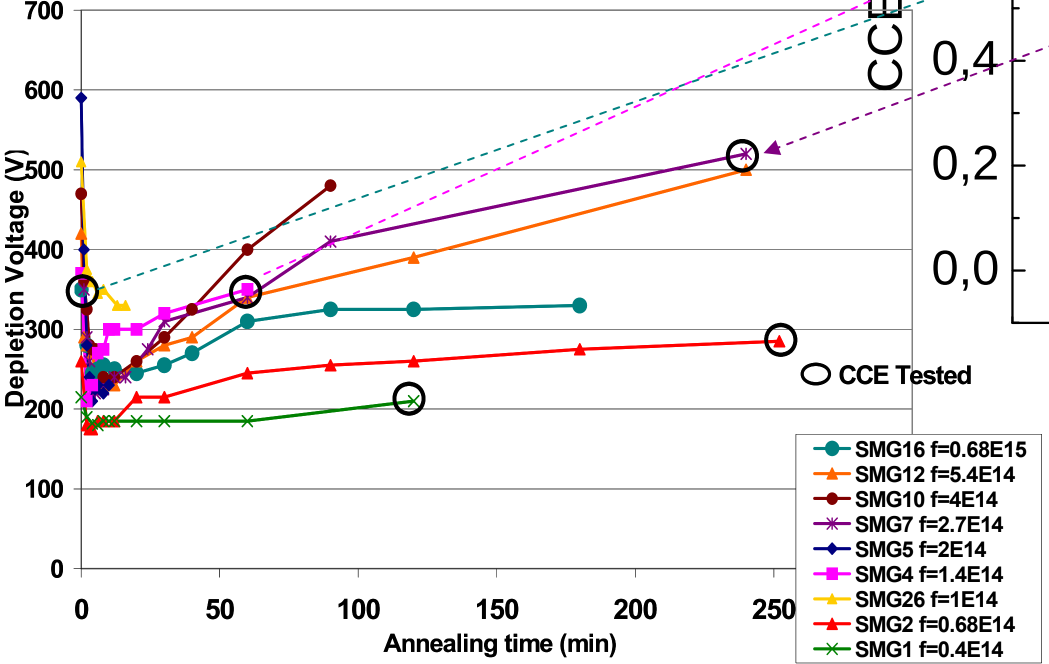


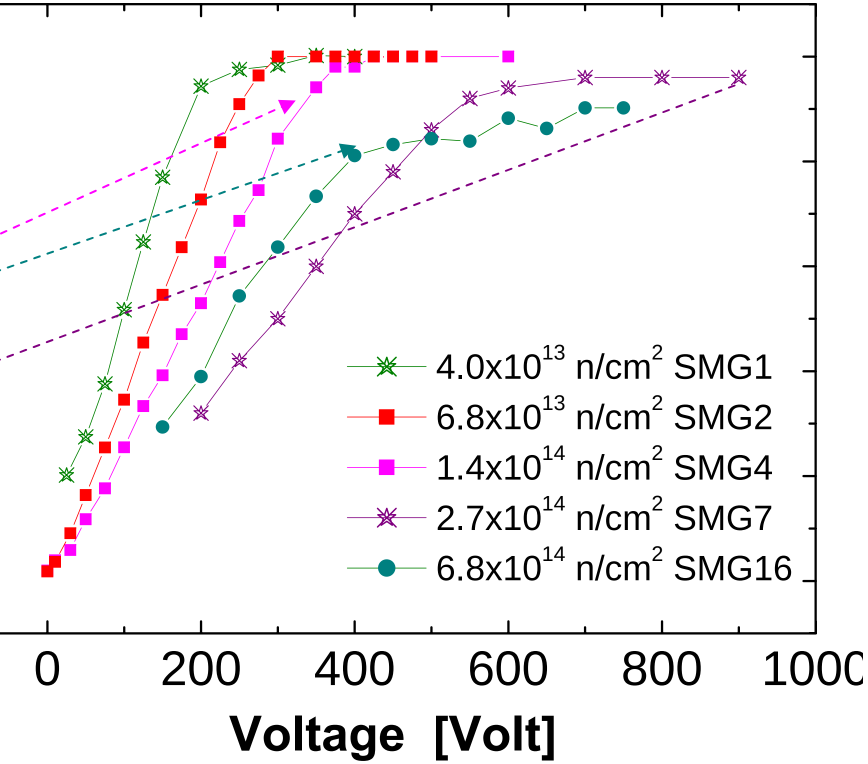
non-irradiated at full depletion voltage



26MeV proton; 6.8x10^{14} 1MeV ncm^{-2}; 750V; -30 ℃







See Poster at this Conference

Comparison between Charge Collection and C-V at Low T

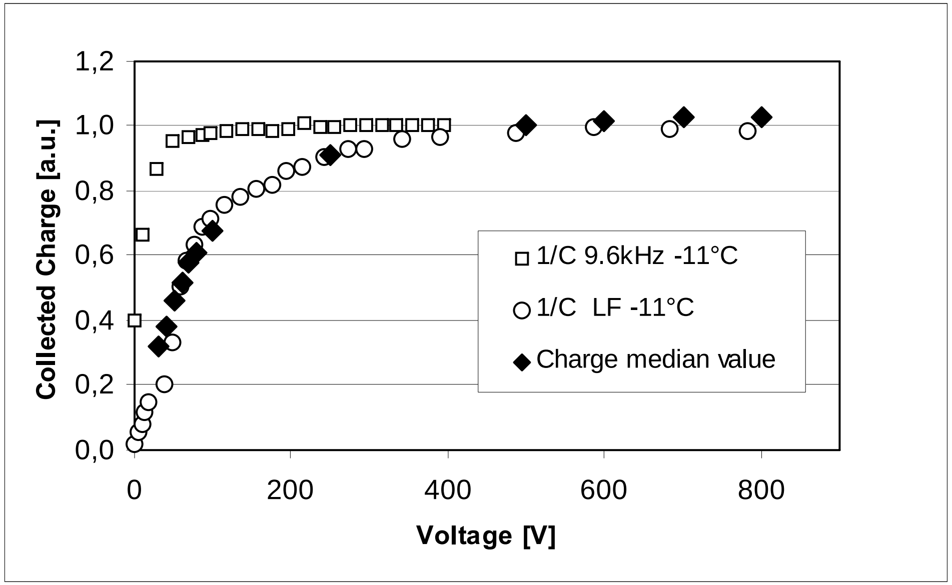
To correctly compare CCE / C-V of microstrip detectors:
- Use the reciprocal of the capacitance
- Low frequency ν when measurement is at Low T !

Scaling factor*: $\nu(LT) \approx \frac{I(LT)}{I(RT)}\nu(RT)$

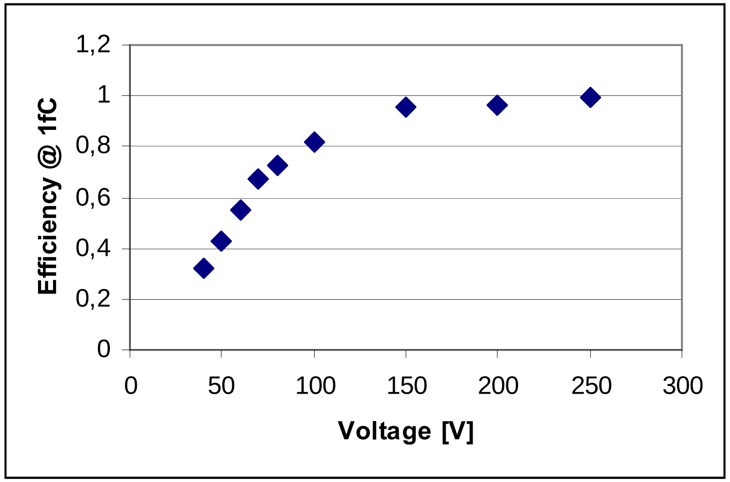
* M. Bruzzi, Capacitance-Voltage analysis at different temperatures in heavily irradiated MCz silicon detectors, SCIPP 06/12 Report, 5/09/06.

SCIPP UCSC - ^{90}Sr source, binary DAQ, AC-coupled to the 50 µm pitch microstrip sensor, 200ns shaping time.

See Poster at this Conference

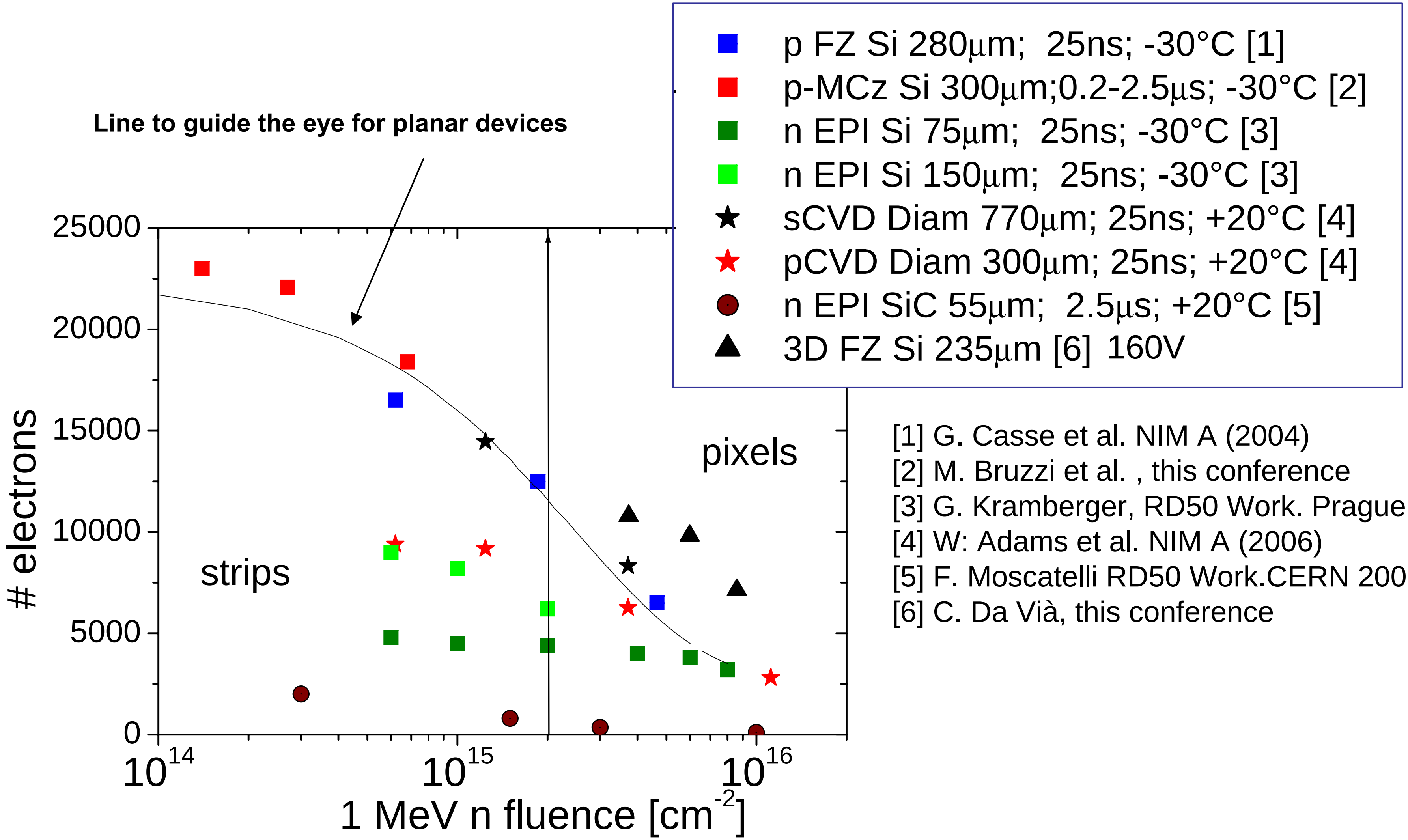


SMART microstrip n-MCz Si irradiated up to 3.3x10^{14}n/cm^{-2} with 26MeV protons



Efficiency at 1 fC threshold of SMART microstrip p-MCz Si (to 3.3x10^{14}n/cm^{-2} with 26MeV protons)

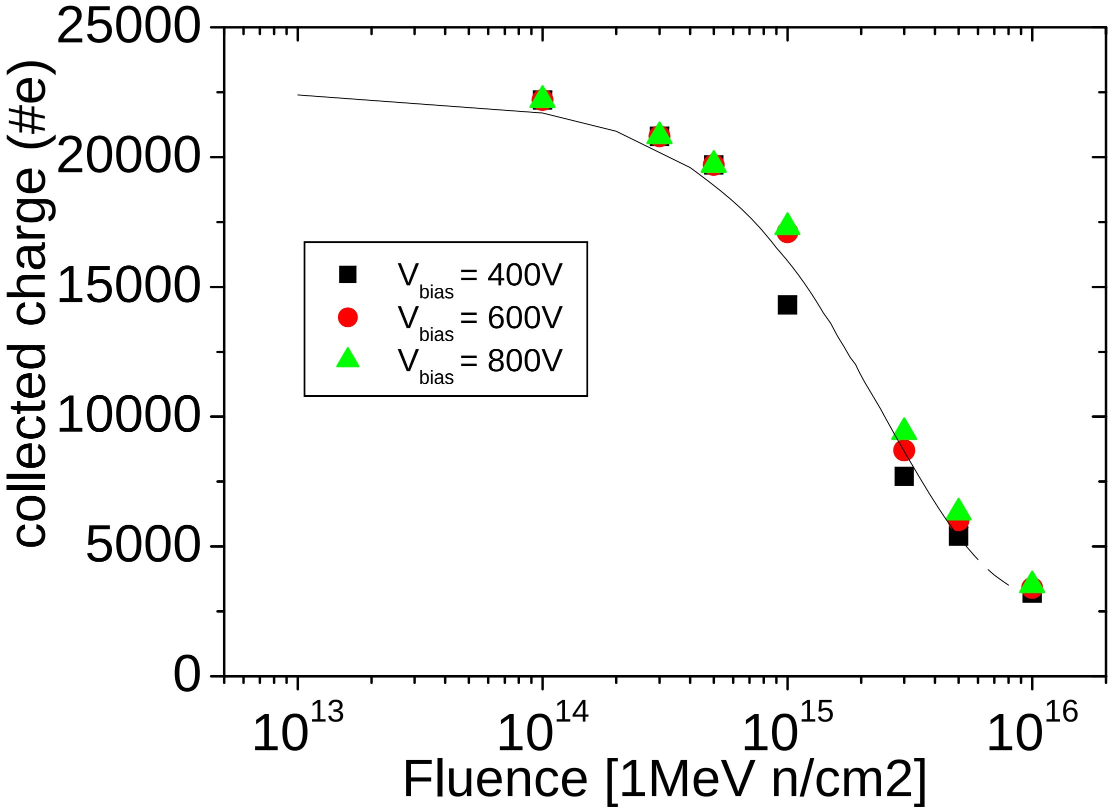
Comparison of measured collected charge on different radiation-hard materials and devices



[1] G. Casse et al. NIM A (2004)
[2] M. Bruzzi et al. , this conference
[3] G. Kramberger, RD50 Work. Prague 06
[4] W: Adams et al. NIM A (2006)
[5] F. Moscatelli RD50 Work.CERN 2005
[6] C. Da Vià, this conference

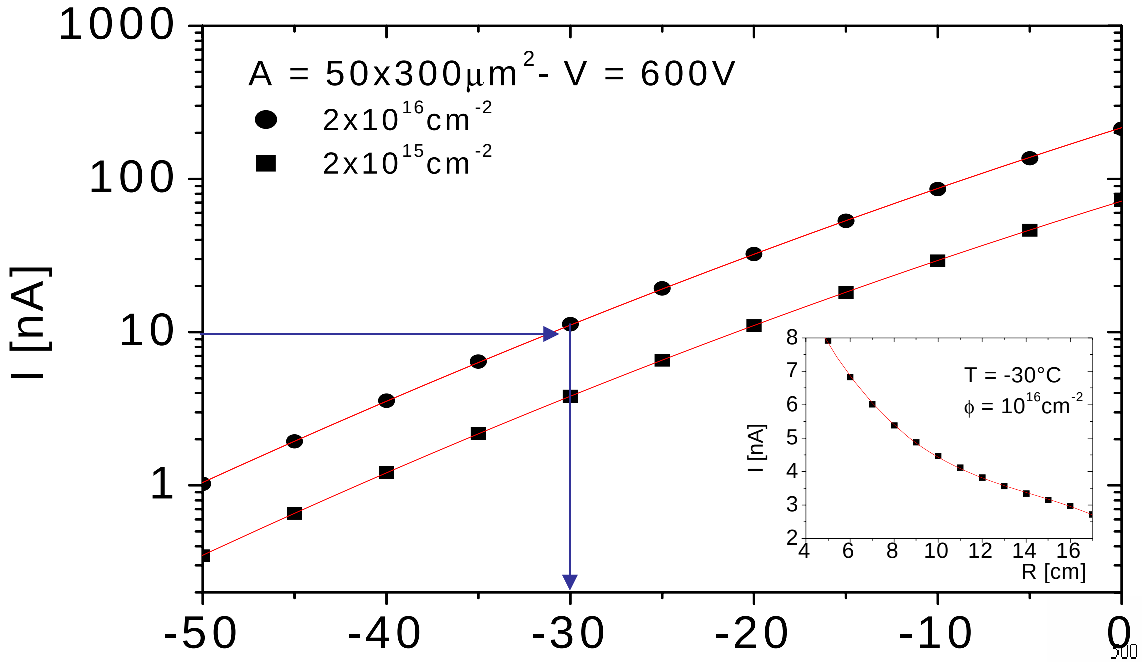
Choice of operational voltage in p-type MCz-FZ Si

The line of previous plot is compared with predictions given in H.F.W. Sadrozinski et al. SCIPP report 05/09



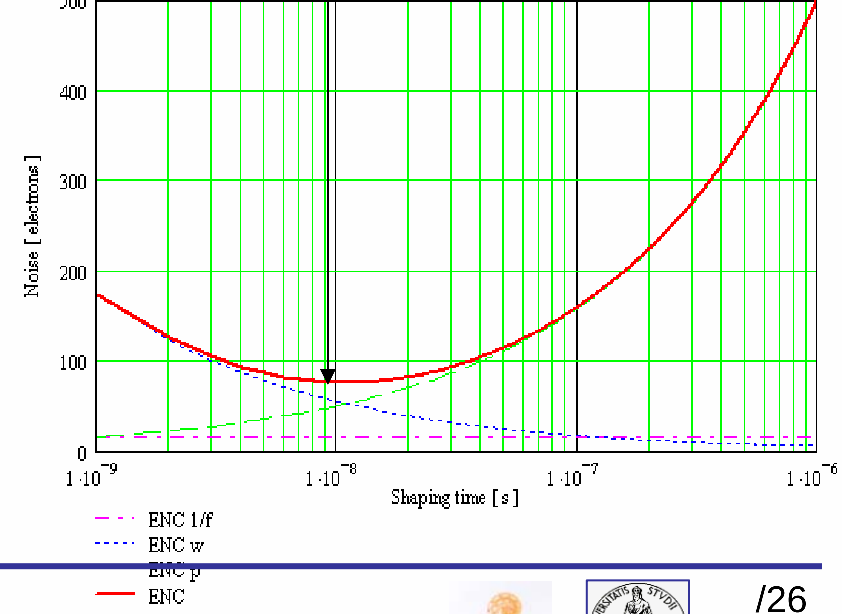
At very high fluence the signal is affected by the inability to deplete the detector and by trapping. 600 V is preferred over 400 V because of better charge collection, 600 V is preferred over 800 V because of reduced heat generation, and very little difference in charge collection.

Leakage current expected in pixels



Temperature [°C]

10ns shaping time



Noise vs shaping time (high I_{leak}):
see Giovanni Anelli talk
at SRD 2006, Trento, 14.02.2006

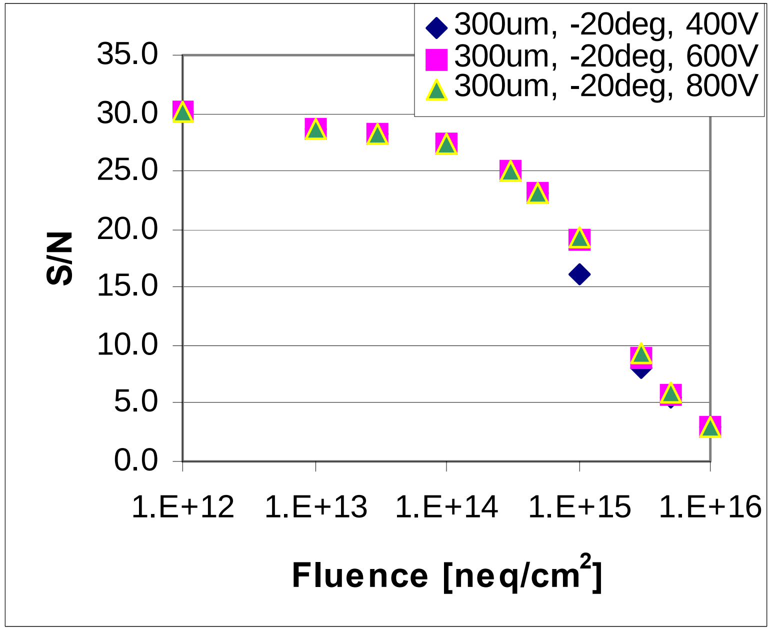
Noise vs. shaping time for I_{leak} = 10 nA,
C_{det} = 200 fF, I_{DS} = 130 μA

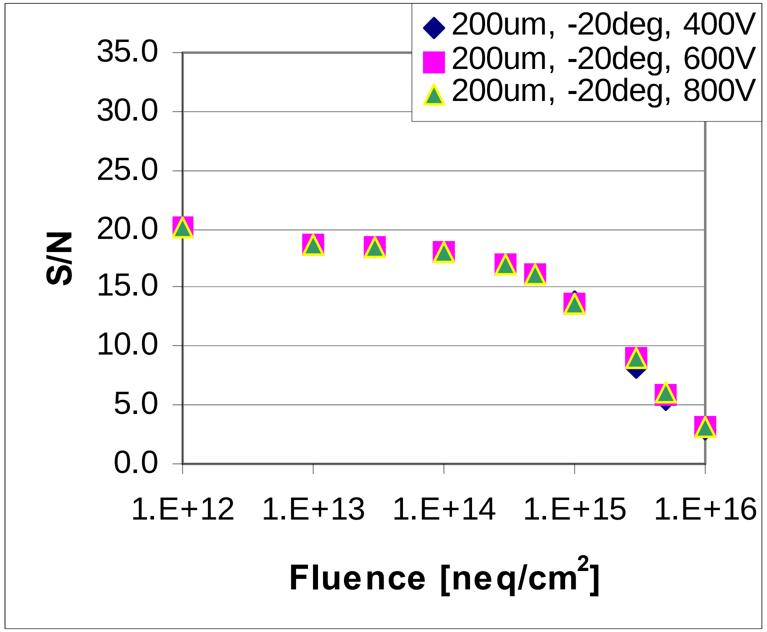
S/N prediction in short strips

The noise RMS σ_{Noise} of the detector can be parameterized in the form:

$\sigma^2_{Noise} = (A + B\cdot C)^2 + (2\cdot I\cdot \tau_s)/q$

C total capacitance, A = 500 e-, and B = 60 e-/pF, (ATLAS SCT-like numbers), τ_s = 20ns





S/N for p-type MCz short strip SSD as a function of fluence for two detector thicknesses: 300µm at the left, and 200 µm at the right. Operating voltage from 400 to 800V. Operating temperature: –20°C. The strips are 3cm long with a pitch of 80µm. (From H.F.W. Sadrozinski et al. SCIPP report 05/09)

Conclusions

Radiation harder materials and devices have been briefly reviewed, focussing in particular on n- and p-type MCz, p-FZ Si.

Si → best choice if temperature can be kept down to -30°C .

Thick p-type Si detectors → best choice for short strips in the range up to $2x10^{15}cm^{-2}$ - MCz Si is a low cost solution but process must be definitely assessed at an industrial level. Predicted operation of a 300μm short strip (3cm) at 600V and -20°C gives S/N > 15 up to $10^{15}cm^{-2}$.

3D → best solution for the highest fluence range,

BUT more systematic measurements and process are needed to get sufficient statistics and approach a fully reliable solution.