Irradiation study of different silicon materials for the CMS tracker upgrade

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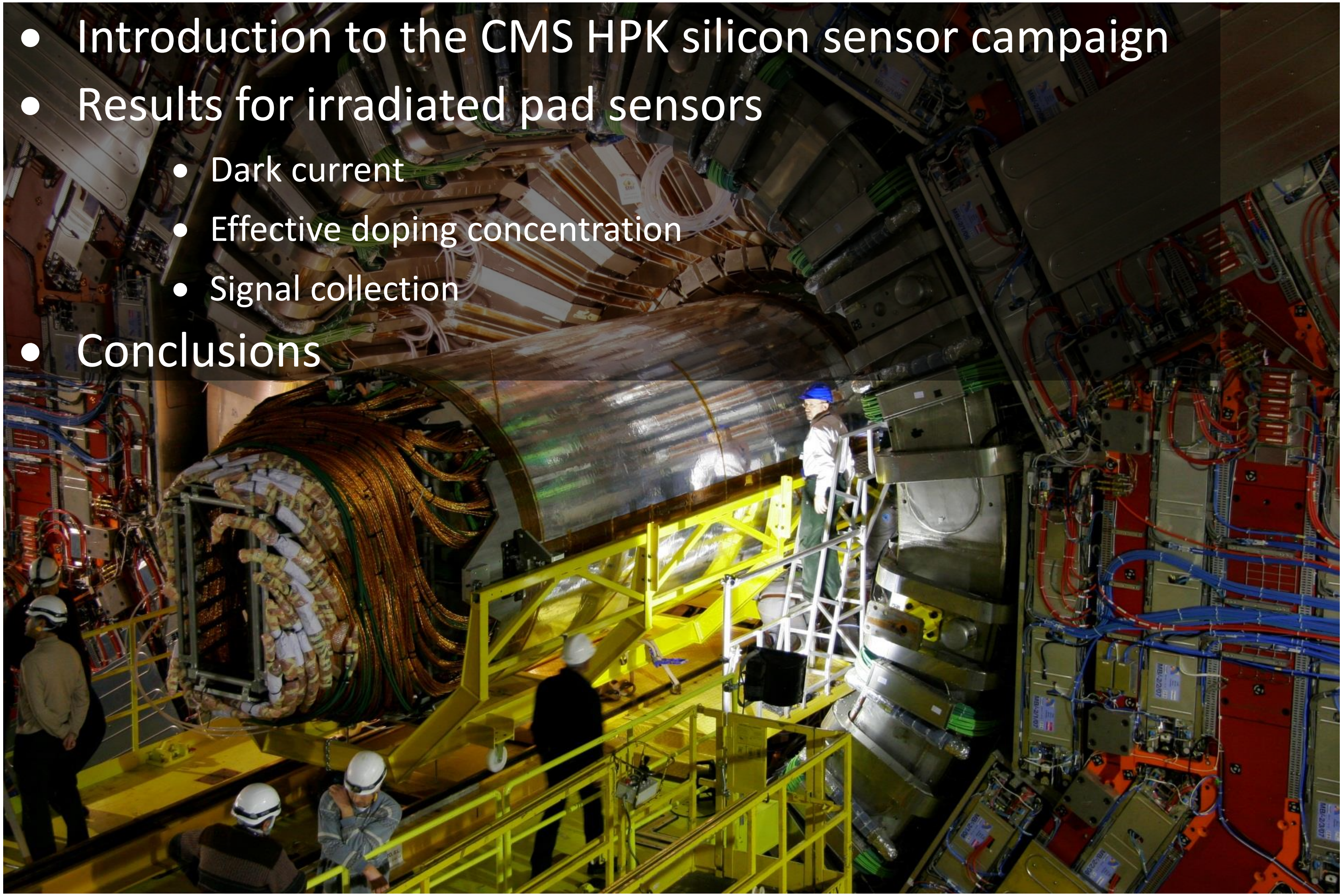
On behalf of the CMS Tracker Collaboration

Overview



- Introduction to the CMS HPK silicon sensor campaign
- Results for irradiated pad sensors
    - Dark current
    - Effective doping concentration
    - Signal collection
- Conclusions

Goals of the CMS HPK silicon sensor campaign

Improve tracker for the HL-LHC:

- Cope with higher occupancy
- Add level 1 trigger capability
- **Withstand higher radiation (Outer tracker: up to a fluence of $\Phi_{neq} = 1.5\ 10^{15}\ cm^{-2}$**
  Inner tracker: up to a fluence of $\Phi_{neq} = 1.4\ 10^{16}\ cm^{-2}$)

This presentation:

→ Find **best suited silicon material** for a future outer tracking detector

- **No excess in dark current**
- **High signal to noise ratio**
- **Low full depletion voltage**

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This presentation:

→ Find **best suited silicon material** for a future outer tracking detector

To achieve that we investigate a large **variety of silicon materials:**

- **Different bulk doping (n and p)**
- **Different thinning processes**
- **Different oxygen content**
- **Different thicknesses**

Irradiations with protons and/or neutrons to simulate HL-LHC radiation dose

Silicon material

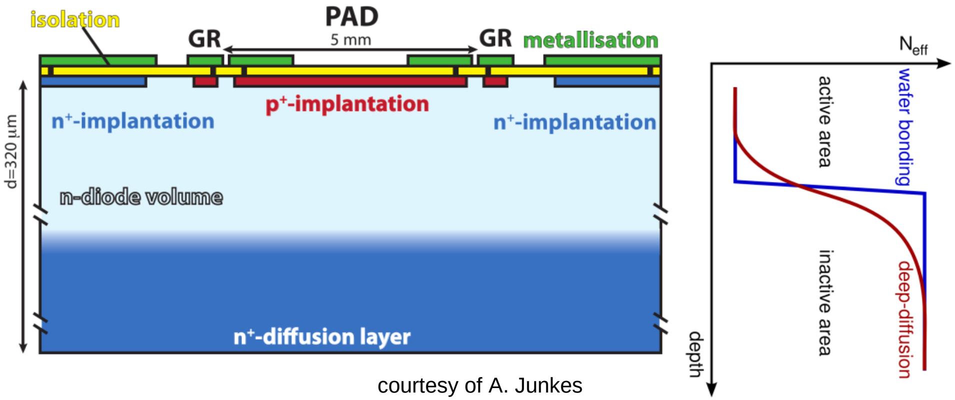
Material	Thinning method	Active thickness [µm]	Wafer thickness [µm]	Oxygen concentration [10^{17} cm^{-3}]
dd-FZ	deep diffusion	200, 300	320	3, 1
FZ	---	200	200	expected small
MCz	---	200	200	4

Of each material there are 2 different types:

- N-type (**N**)
- P-type (**P**)

active

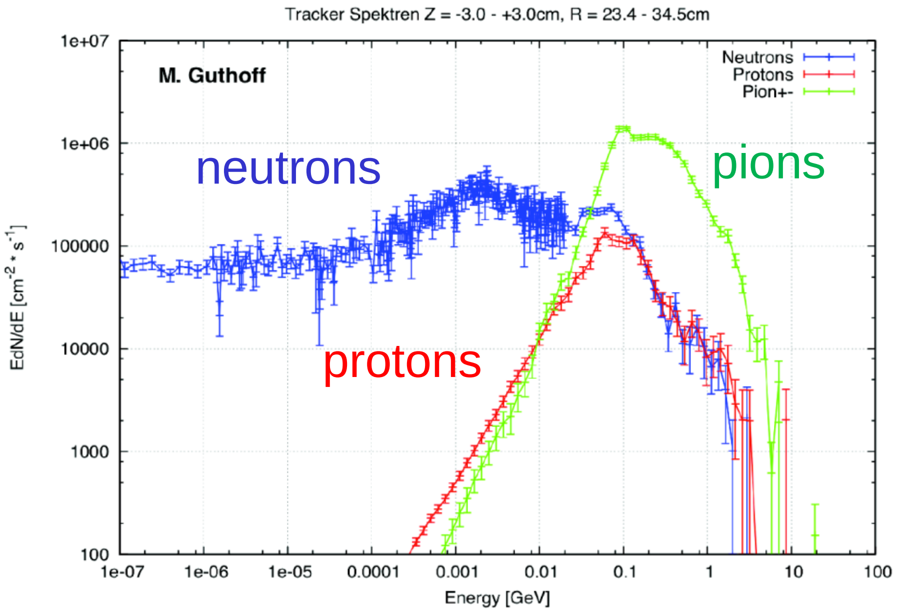
inactive



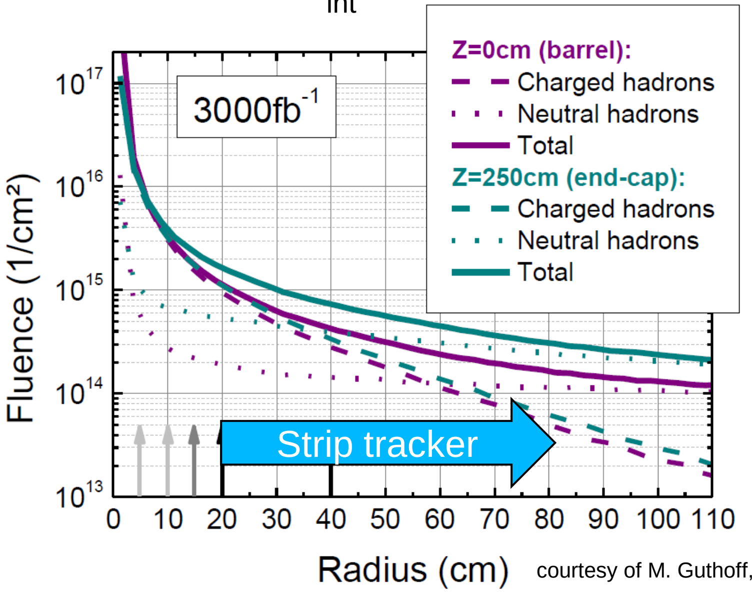
courtesy of A. Junkes

Expected damage at different tracker positions

Radius	Protons Φ_{eq} [cm^{-2}]	Neutrons Φ_{eq} [cm^{-2}]	Total Φ_{eq} [cm^{-2}]
40 cm	$3 \cdot 10^{14}$	$4 \cdot 10^{14}$	$7 \cdot 10^{14}$
20 cm	$1 \cdot 10^{15}$	$5 \cdot 10^{14}$	$1.5 \cdot 10^{15}$
15 cm	$1.5 \cdot 10^{15}$	$6 \cdot 10^{14}$	$2.1 \cdot 10^{15}$



HL-LHC: L_{int}=3000 fb^{-1}



courtesy of M. Guthoff, KIT

Energy of charged hadrons peaks between 100 MeV and 1 GeV

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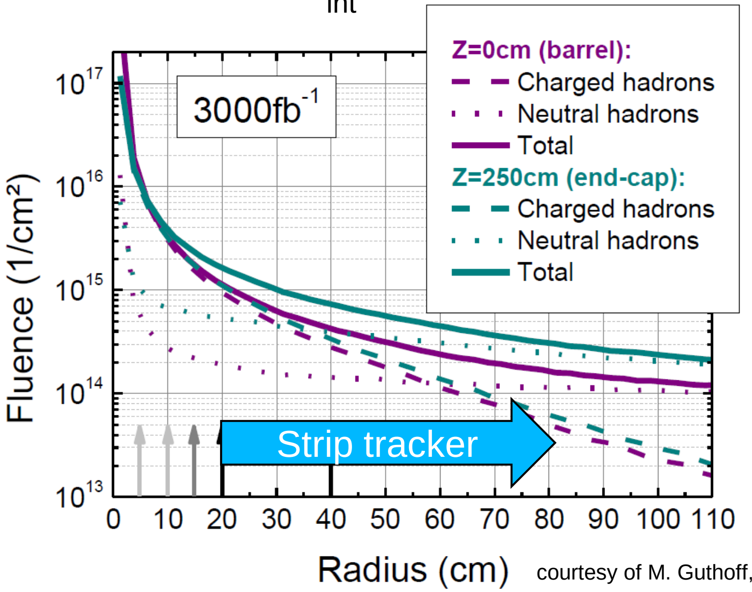
Neutrons:	1 MeV (TRIGA reactor Ljubljana)
Protons:	23 MeV (Karlsruhe cyclotron)
	23 GeV (CERN PS)
	crosscheck:
	800 MeV (Los Alamos)

HL-LHC: L_{int}=3000 fb^{-1}



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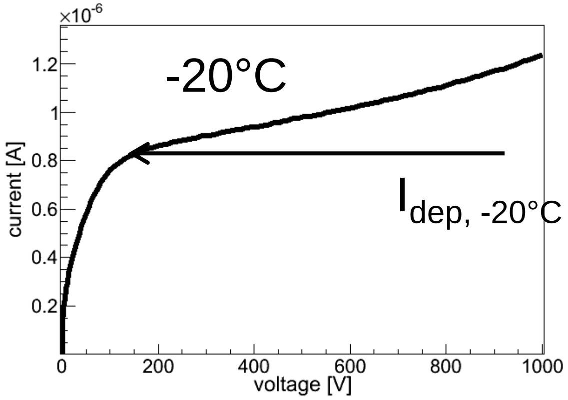
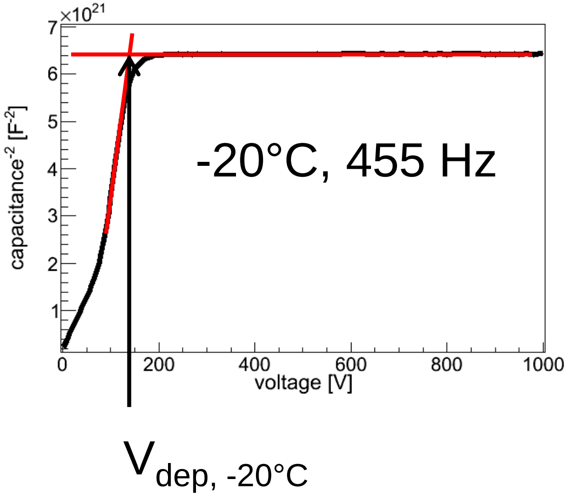
Energy of charged hadrons peaks between 100 MeV and 1 GeV

Measurements and methods

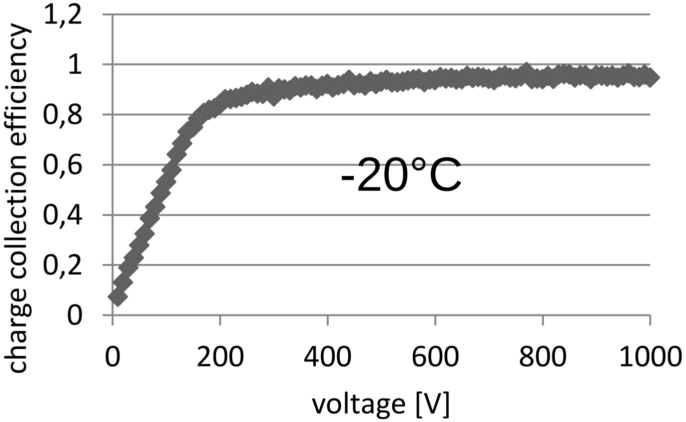
Current-voltage characteristic



Capacitance-voltage characteristic



Charge collection efficiency

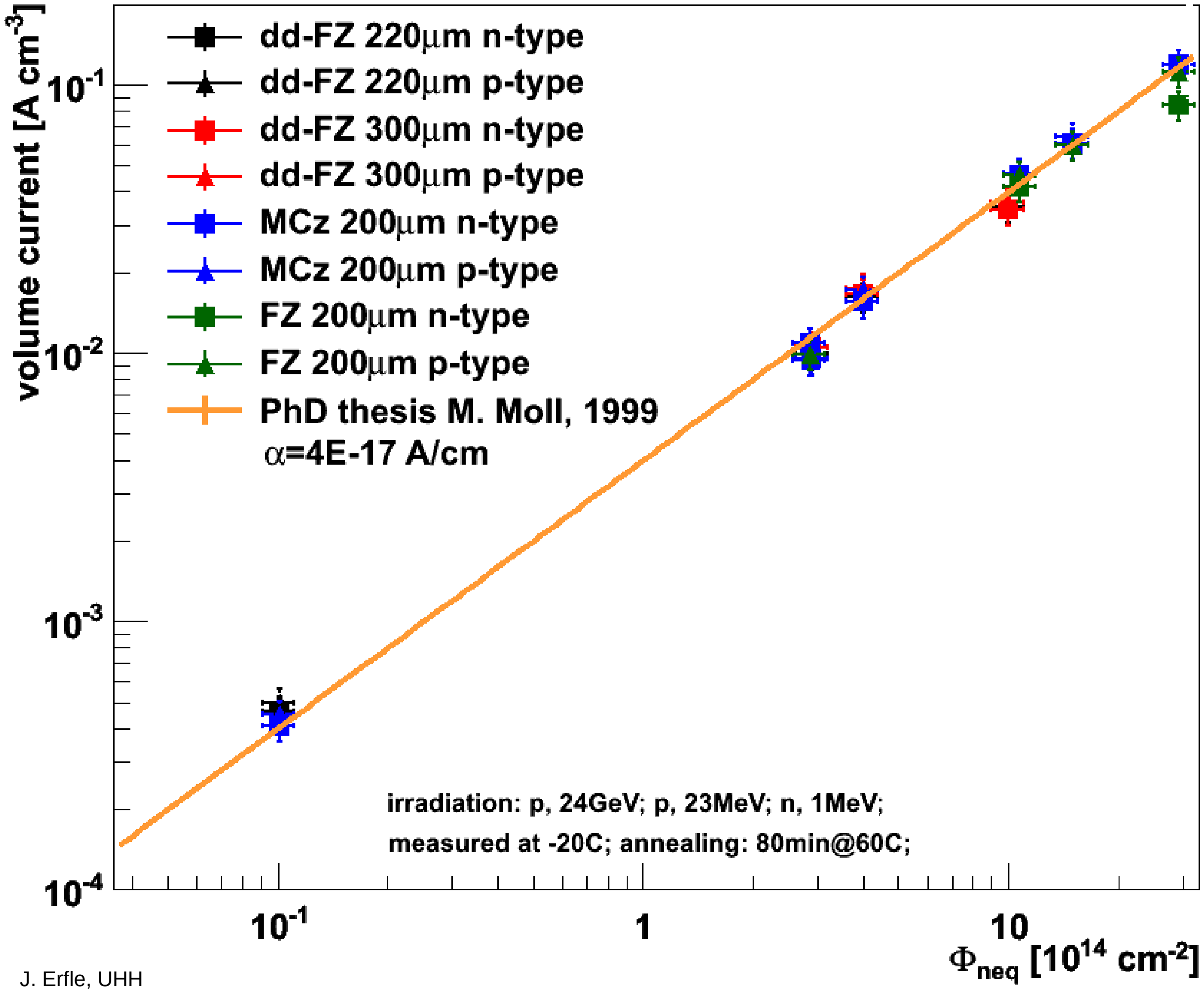


$$I(T) \propto T^2 \exp\left(\frac{-1.21eV}{2kT}\right)$$

$$\left|N_{eff}\right| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

$$N_C = N_{C0}\left(1 - \exp\left(-c\Phi_{neq}\right)\right) + \beta\Phi_{neq}$$

Volume current versus fluence



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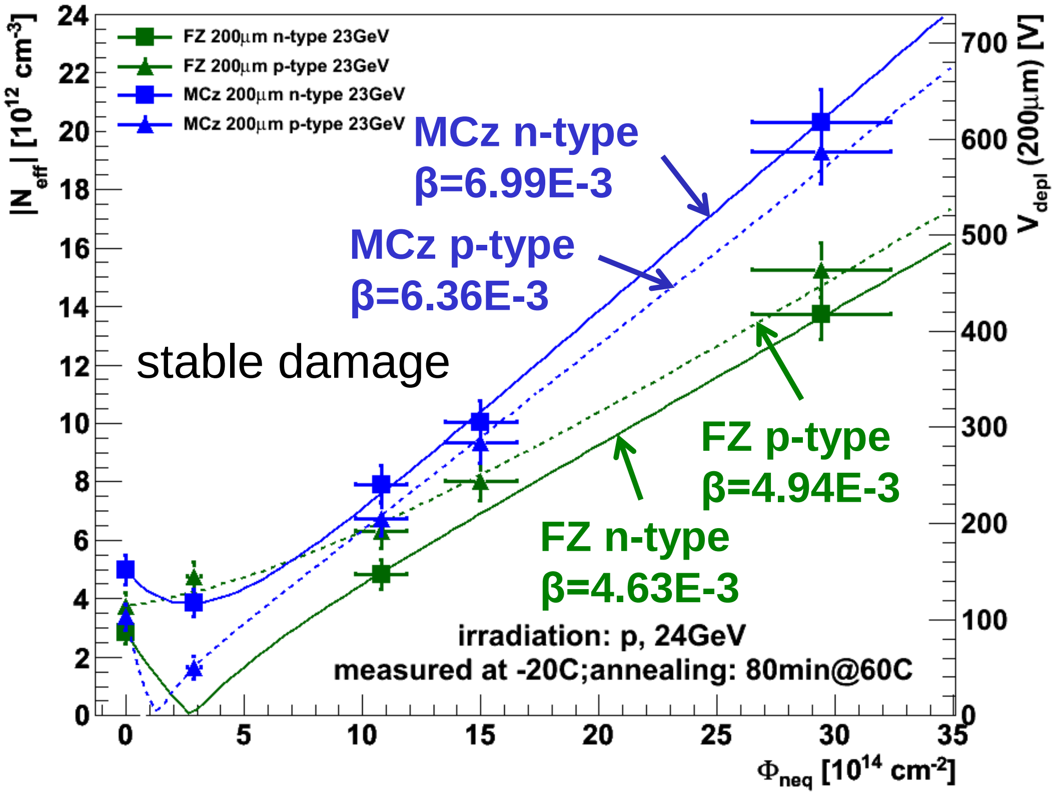
$$I = \alpha\Phi_{neq} \cdot V + I_0 \cdot V$$

Volume current scales with NIEL, independent of silicon material

currents are measured after annealing of 80 min@ 60°C at -20°C and scaled to 20°C, guard ring grounded

N_{eff} after 23 GeV proton irradiation

23 GeV protons



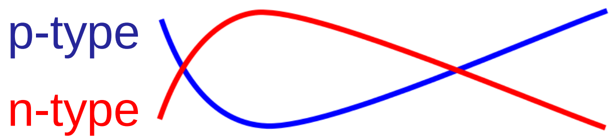
MCz n-type
β=6.99E-3

MCz p-type
β=6.36E-3

stable damage

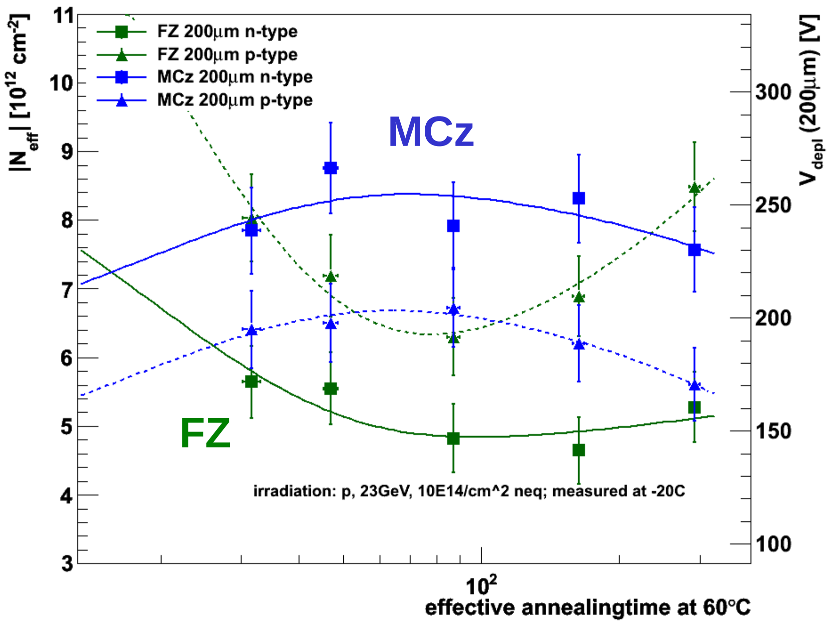
FZ p-type
β=4.94E-3

FZ n-type
β=4.63E-3



Acceptor removal (short term annealing)

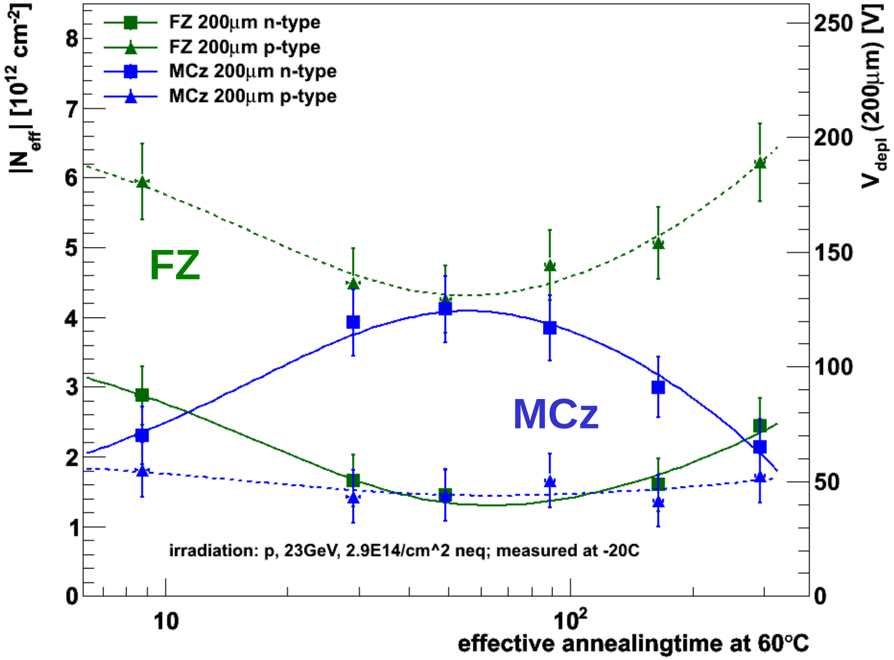
23 GeV protons, $\phi_{neq} = 10 \cdot 10^{14}\ cm^{-2}$



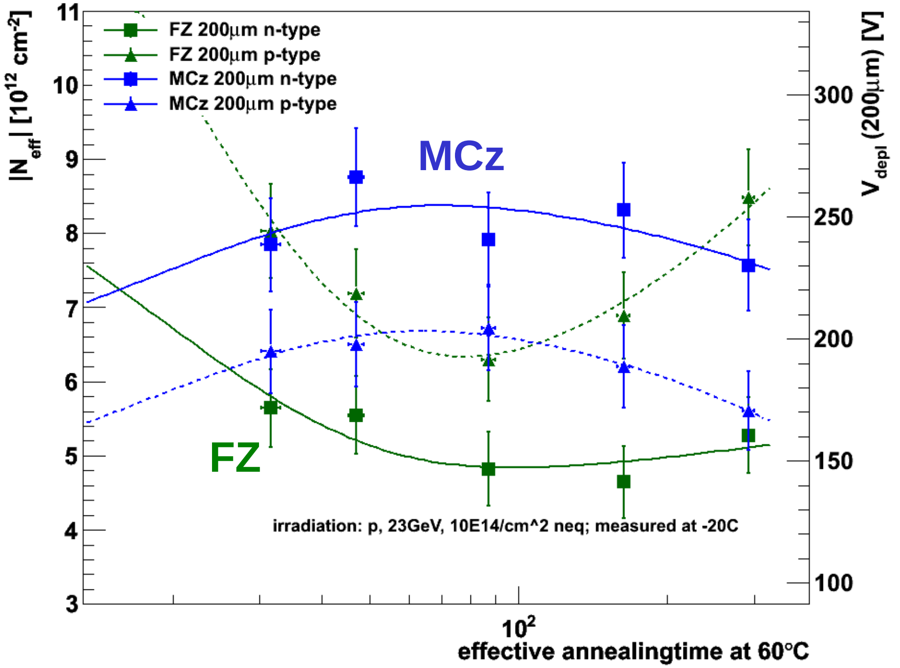
Introduction rate similar for both FZ n- and p-type and also for both MCz n- and p-type, but smaller for FZ than for MCz

Annealing of N_{eff} after 23 GeV irradiation

$$\phi_{neq} = 3 \cdot 10^{14}\ cm^{-2}$$

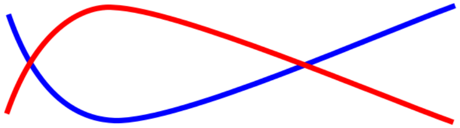


$$\phi_{neq} = 10 \cdot 10^{14}\ cm^{-2}$$



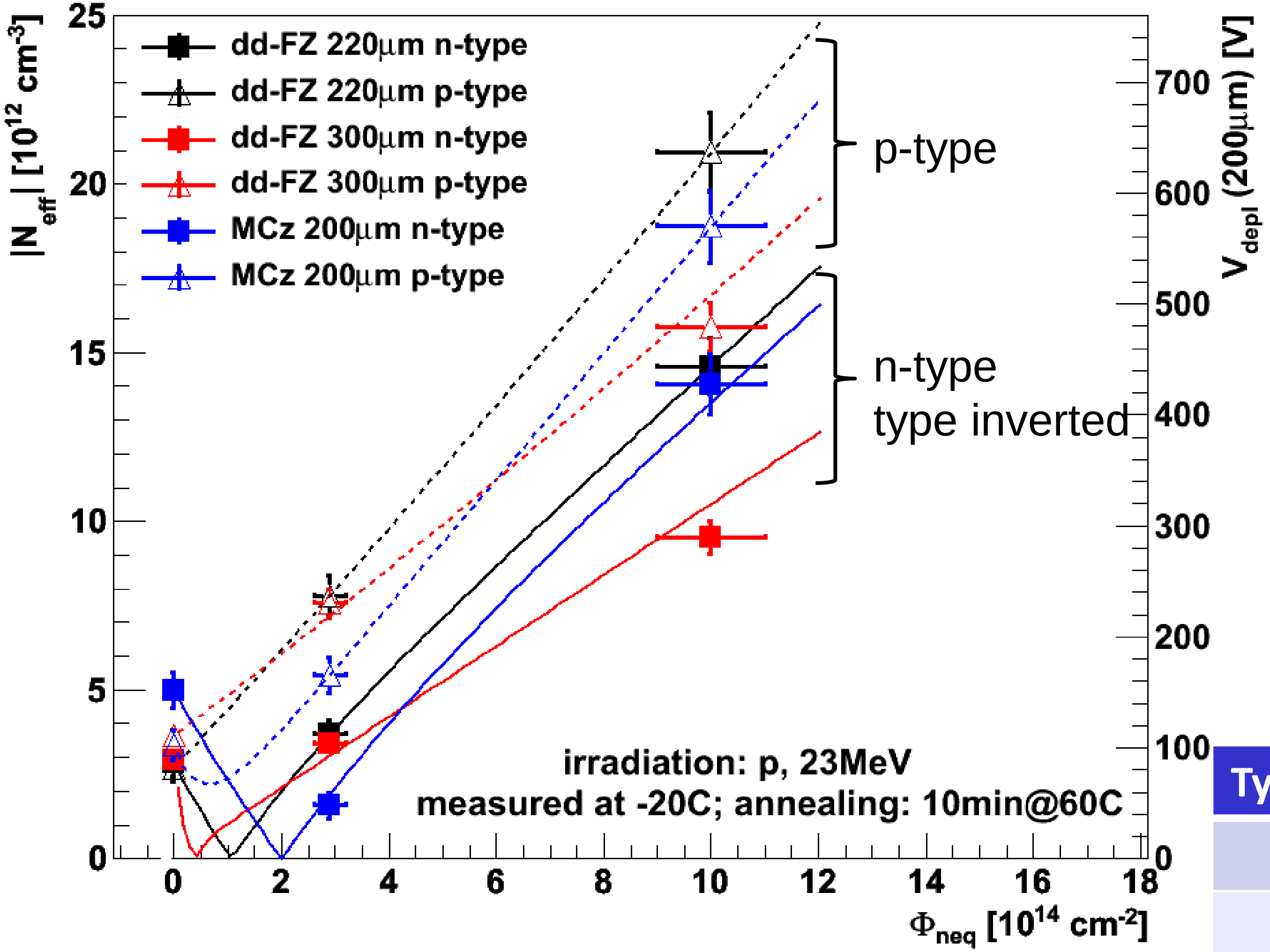
Type inversion	FZ	MCZ
N-type	✔	-
P-type	-	✔

backed by TCT



Acceptor removal (short term annealing)

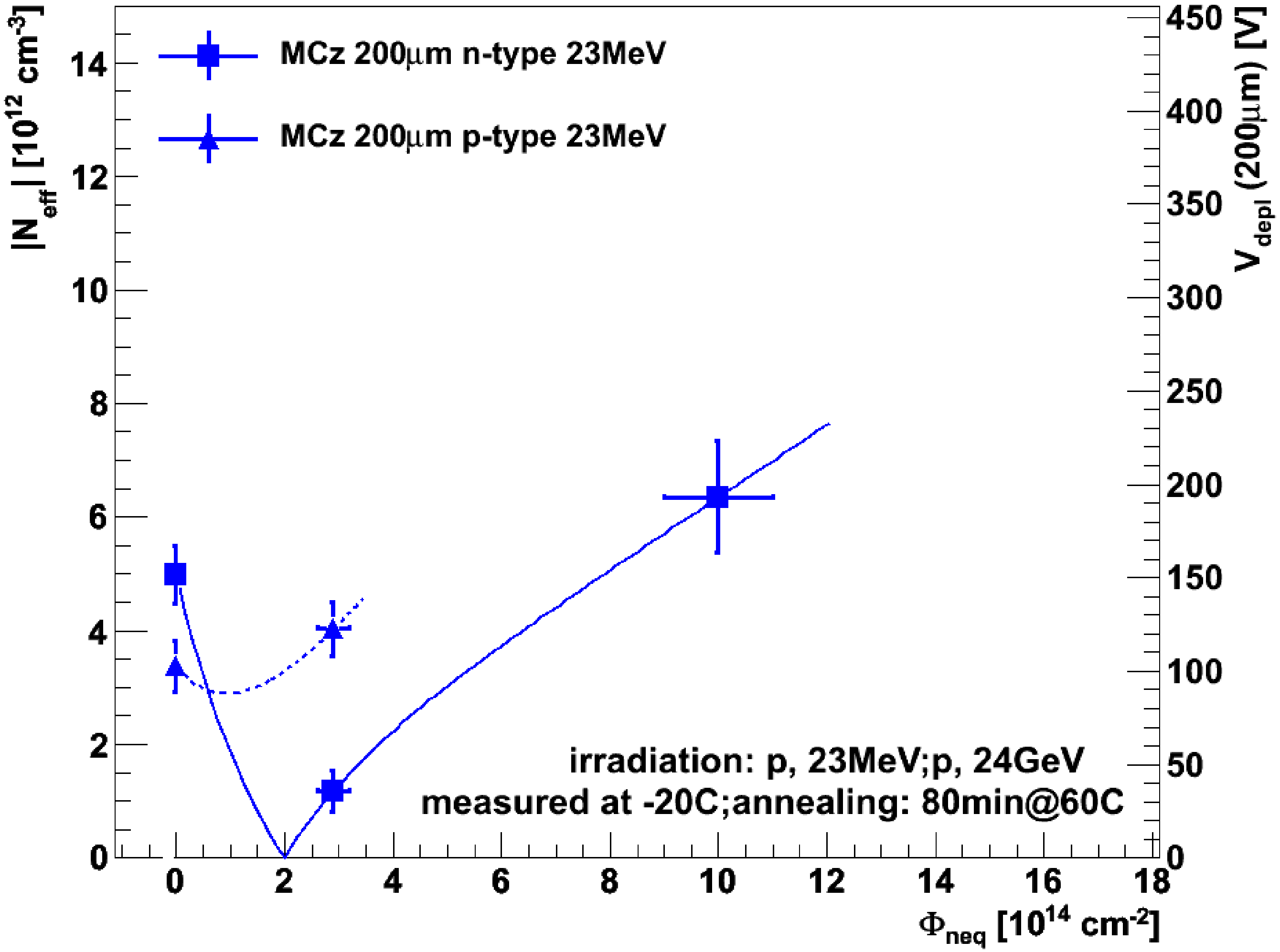
N_{eff} after 23 MeV proton irradiation



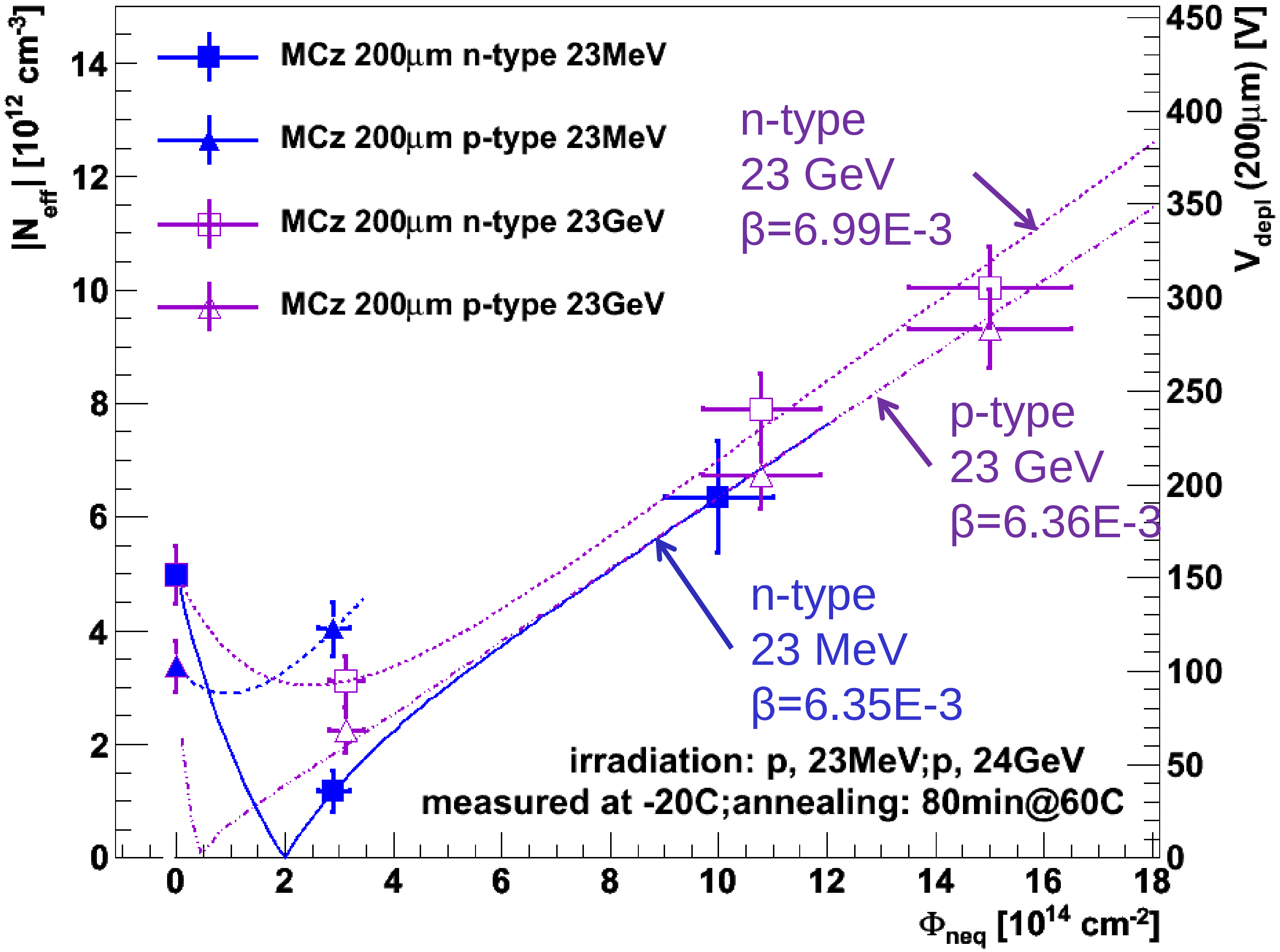
Lower full depletion voltage for n-type due to type inversion

Type inversion	FZ	MCZ
N-type	✔	✔
P-type	-	-

N_{eff} after 23 MeV proton irradiation



N_{eff} after 23 MeV proton irradiation compared to 23 GeV proton irradiation



n-type
23 GeV
β=6.99E-3

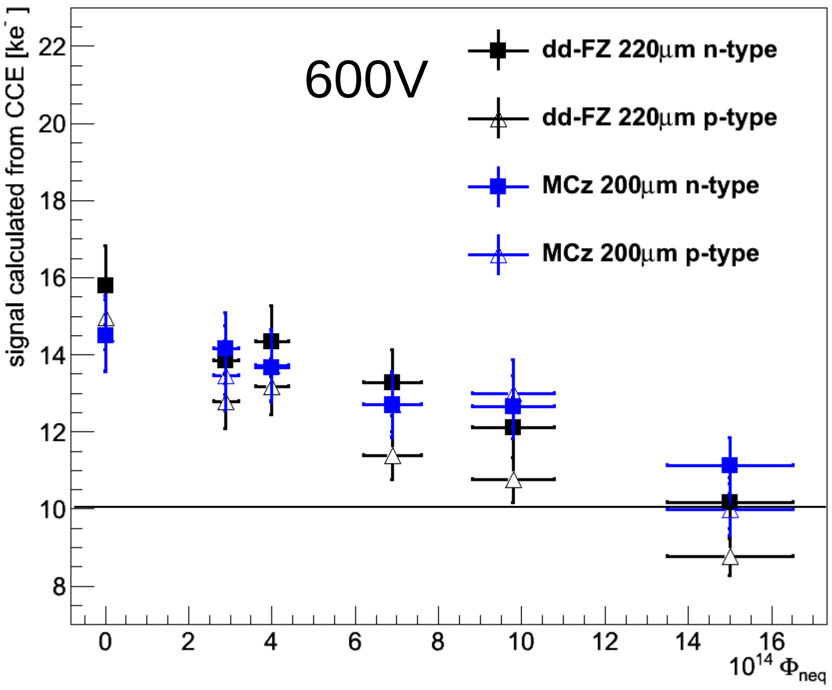
p-type
23 GeV
β=6.36E-3

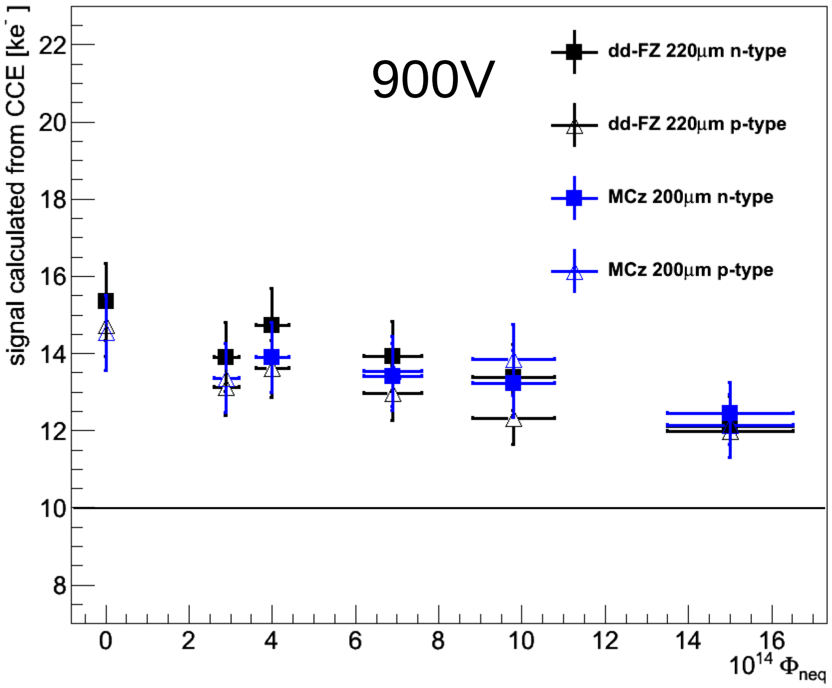
n-type
23 MeV
β=6.35E-3

Type-inverted p-type sensors after 23 GeV irradiation show same slope

Charge collection

Irradiated with 23 MeV protons, 1MeV neutrons, 23 MeV protons + 1 MeV neutrons





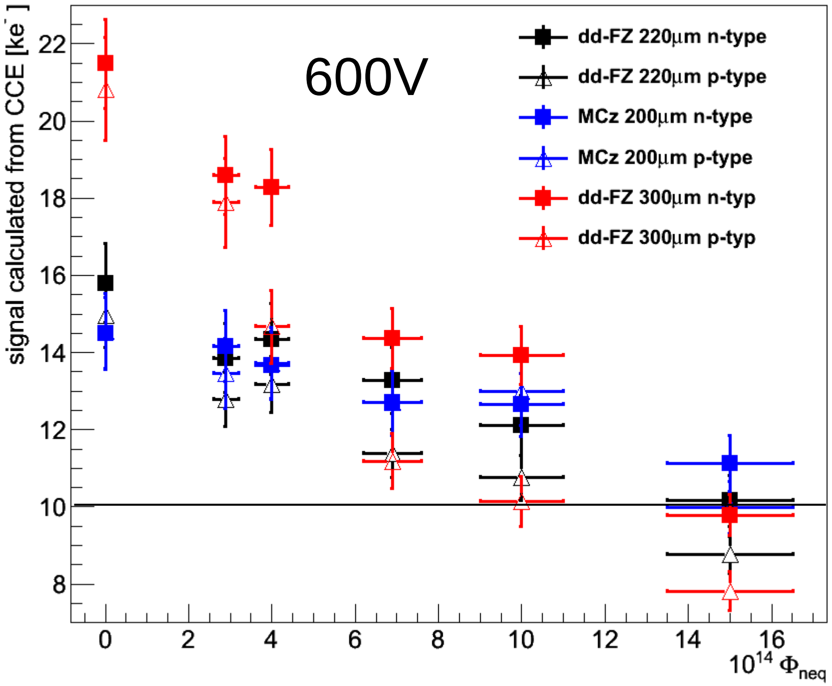
In a pad sensor charge collection depends on material only via

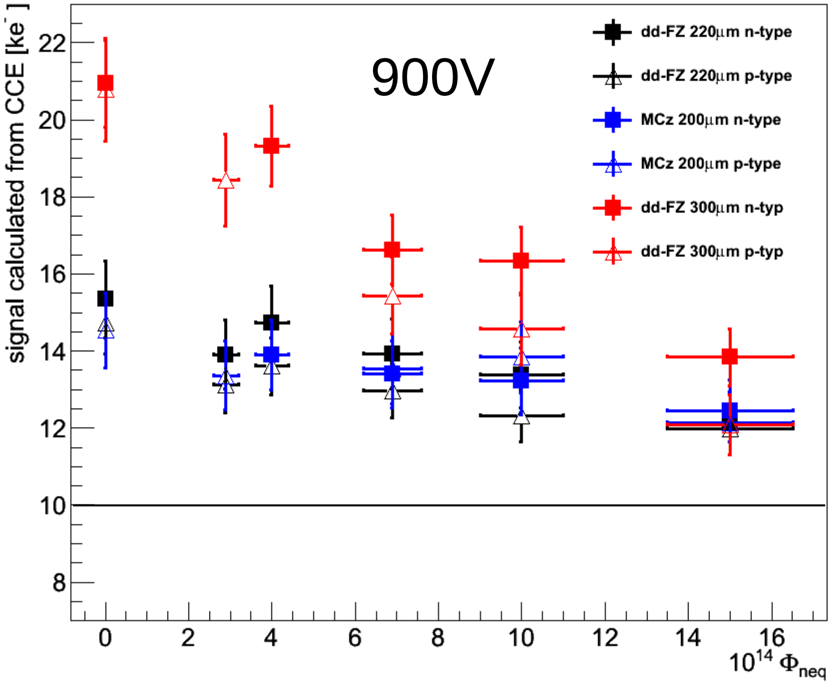
- **Full depletion voltage**
- **Sensor thickness**

(trapping independent of material)

Charge collection

Irradiated with 23 MeV protons, 1MeV neutrons, 23 MeV protons + 1 MeV neutrons





In a pad sensor charge collection depends on material only via

- **Full depletion voltage**
- **Sensor thickness**

(trapping independent of material)

Summary

- Dark current independent on silicon material
- CCE depends on silicon material via depletion voltage
- Full depletion voltage depends strongly on material and irradiation type. (can be explained by a microscopic model)

23 MeV protons and neutrons

Type inversion	FZ	MCZ
N-type	✔	✔
P-type	-	-

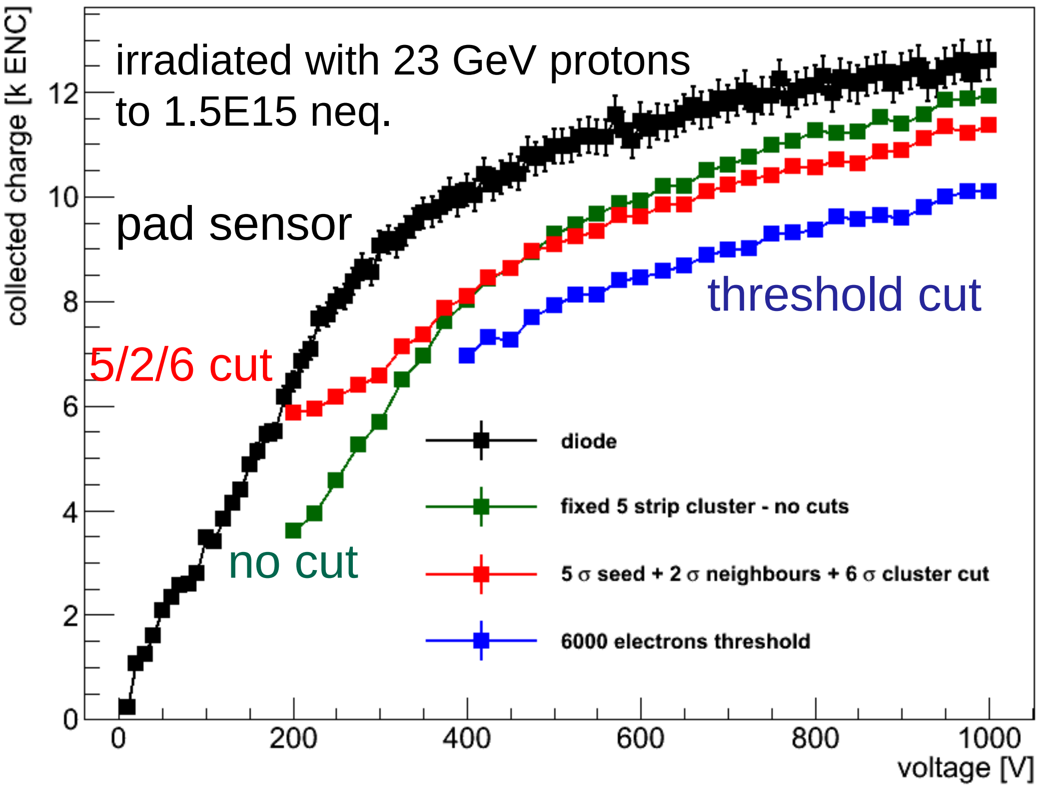
23 GeV protons

Type inversion	FZ	MCZ
N-type	✔	-
P-type	-	✔

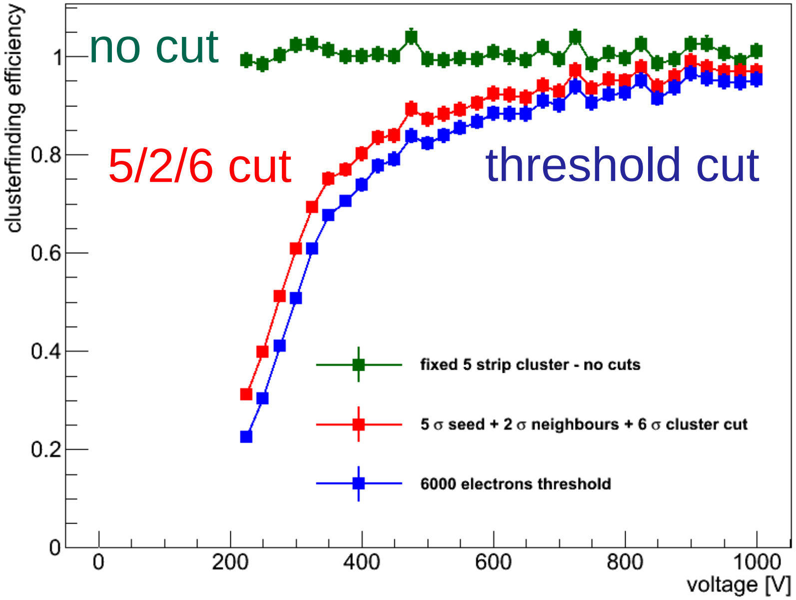
- Type inverted materials tend towards lower depletion voltages
- Rise of full depletion with fluence similar for 23 MeV and GeV proton irradiation (MCz)

Outlook strip vs pad sensor

Comparison of CC of a pad and a strip sensor



Cluster finding efficiency



“No cut“ (with fixed 5 strip clusters) analysis nearest to pad sensor, but unfortunately it is not applicable in the tracker.

Outlook: the inner tracking detector

Sensor have to withstand fluences up to $\Phi_{neq} = 1.4\ 10^{16}\ cm^{-2}$
The usability of planar silicon sensors will be explored:

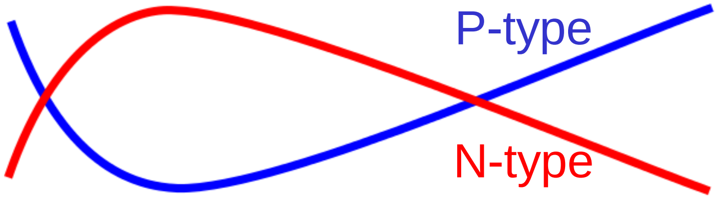
material	thinning method	active thickness [µm]	wafer thickness [µm]	oxygen concentration [$10^{17}\ cm^{-3}$]
FZ	deep diffusion	120	320	5
FZ	handling wafer	120	320	
Epi	---	50,100	320	1,1

radius	protons Φ_{eq} [cm^{-2}]	neutrons Φ_{eq} [cm^{-2}]	total Φ_{eq} [cm^{-2}]
10 cm	$3 \cdot 10^{15}$	$7 \cdot 10^{14}$	$3.7 \cdot 10^{15}$
5 cm	$1.3 \cdot 10^{16}$	$1 \cdot 10^{15}$	$1.4 \cdot 10^{16}$

Backup

clear dependence of Neff on irradiation type

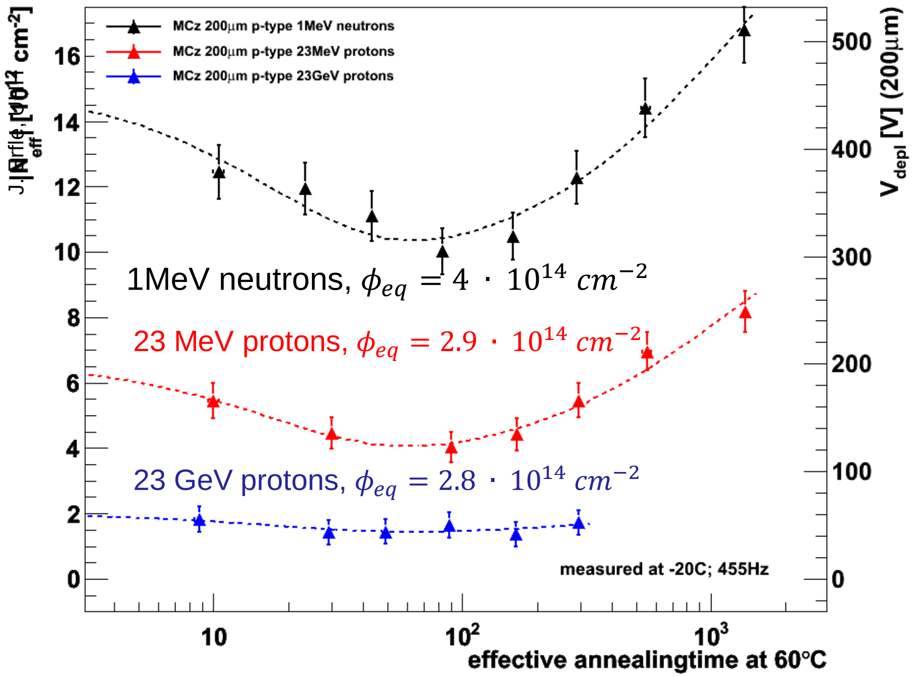
MCz p-type type-inverts for 23 GeV protons
MCz n-type type-inverts for 23 MeV protons and neutrons



acceptor removal (short term annealing)

capacitances are measured at -20°C, 455 Hz, guard ring grounded

MCz p-type

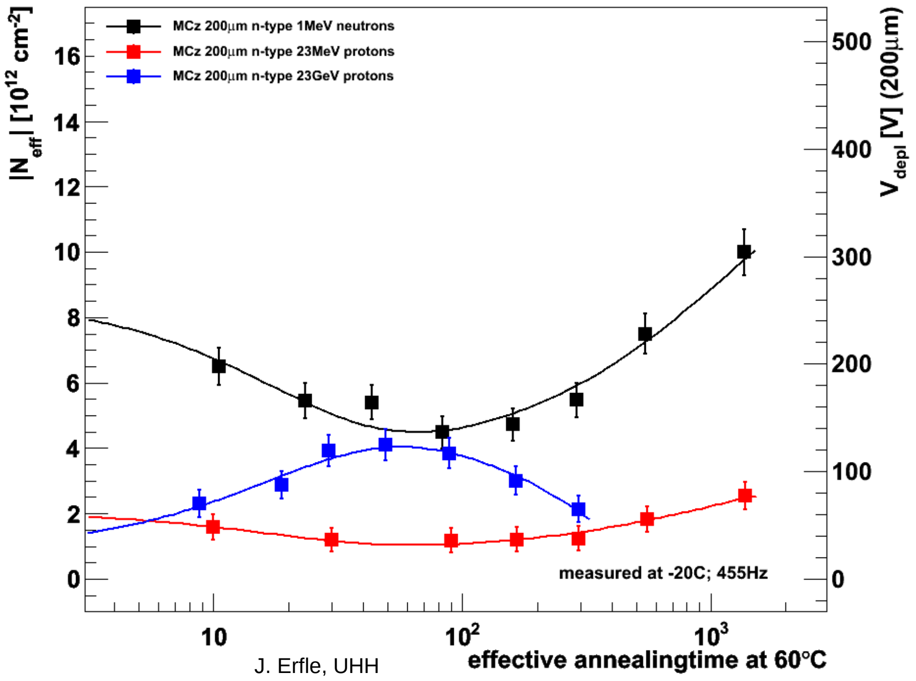


1MeV neutrons, $\phi_{eq} = 4 \cdot 10^{14}\ cm^{-2}$

23 MeV protons, $\phi_{eq} = 2.9 \cdot 10^{14}\ cm^{-2}$

23 GeV protons, $\phi_{eq} = 2.8 \cdot 10^{14}\ cm^{-2}$

MCz n-type



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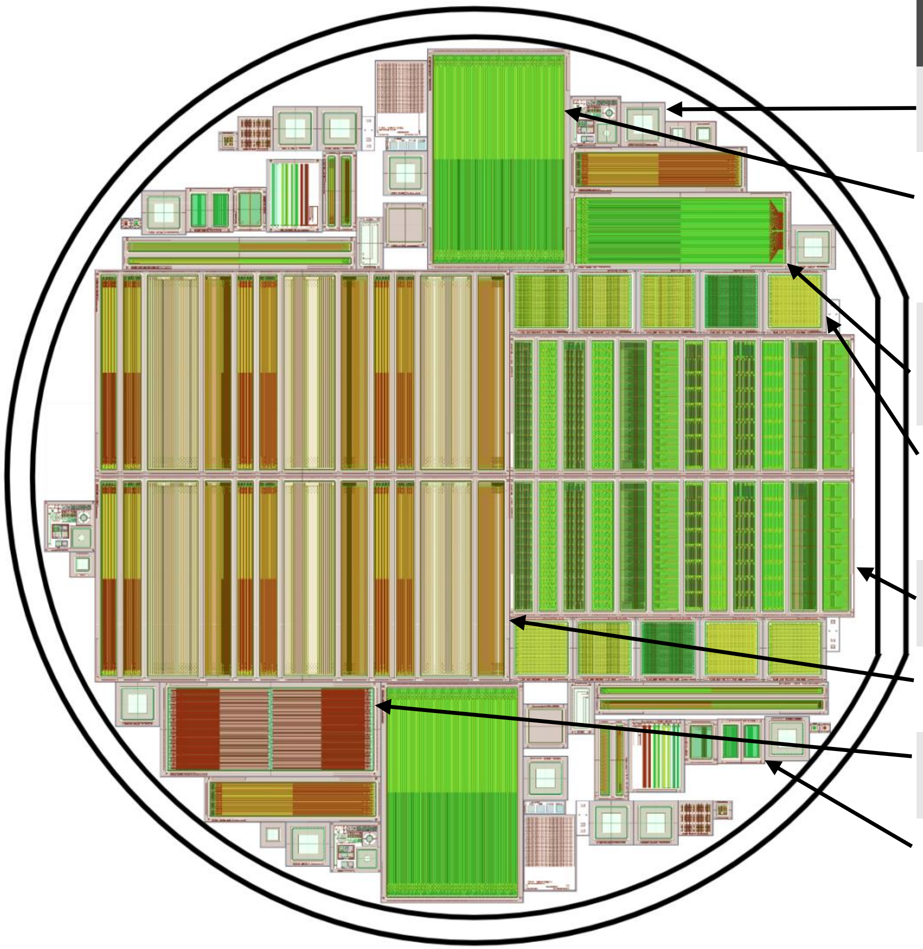
Wafer overview

6“ Wafer



structure	to study
diodes	material
baby strip sensor	reference design / material
baby with integrated pitch adapter	study new design ideas
pixel sensor	reference Design / material
multigeometry pixel	layout parameters
multigeometry strips	layout parameters
baby strixel	study new design ideas
teststructures	process parameters

oxygen content

material	bulk resistivity	oxide concentration
FZ320P	3-8	3,50E+016
FZ200P	3-8	3,00E+017
FZ120P	3-8	5,00E+017
FZ320N	1.2-2.4	1,80E+016
FZ200P	1.2-2.4	3,00E+017
FZ120P	1.2-2.4	5,00E+017
MCZ200P	>2	3,75E+017
MCZ200N	>0.5	3,00E+017