



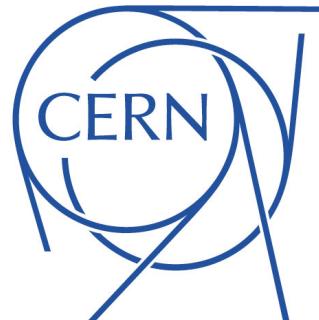
Radiation Hard Silicon Particle Detectors for HL-LHC

RD50 Status Report

Stefano Terzo (on behalf of the RD50 Collaboration)



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



RD50

14th Vienna Conference on Instrumentation
Vienna, 15-19. February 2016



The RD50 collaboration



RD50: 50 institutes and 282 members

42 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)),
Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany
(Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich (2x)),
Italy (Bari, Florence, Perugia, Pisa, Torino), Lithuania (Vilnius),
Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania
(Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana),
Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI),
United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool)



6 North-American institutes

Canada (Montreal), USA (BNL, Fermilab, New Mexico,
Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)



RD50 Organizational Structure

S. Terzo (Max-Planck-Institut für Physik) on behalf of RD50 - VCI 2016

Co-Spokespersons

Gianluigi Casse

(Liverpool University)

and

Michael Moll

(CERN EP-DT)

Defect / Material Characterization

Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ...
- SIMS, SR, ...
- NIEL (calculations)
- WODEAN: Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem & M.Bruzzi)

Detector Characterization

Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,...)
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Device Simulations (V.Eremin)

New Structures

Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain (avalanche detectors)
- LGAD–Low Gain Avalanche Detectors
- Slim Edges
- HVCMS
- 3D (R.Bates)
- LGAD (S.Hidalgo)
- Slim Edges (V.Fadeyev)

Full Detector Systems

Gregor Kramberger
(Ljubljana University)

- LHC-like tests
- Links to HEP
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibava)
- Comparison:
 - pad-mini-full detectors
 - different producers
- Radiation Damage in HEP detectors
- Test beams (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)

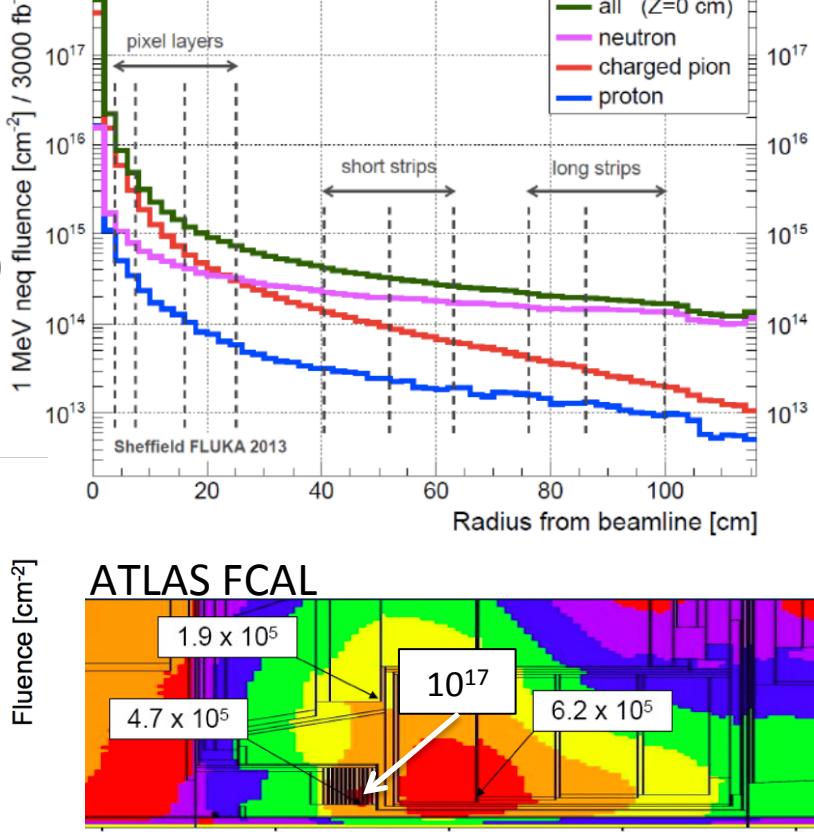
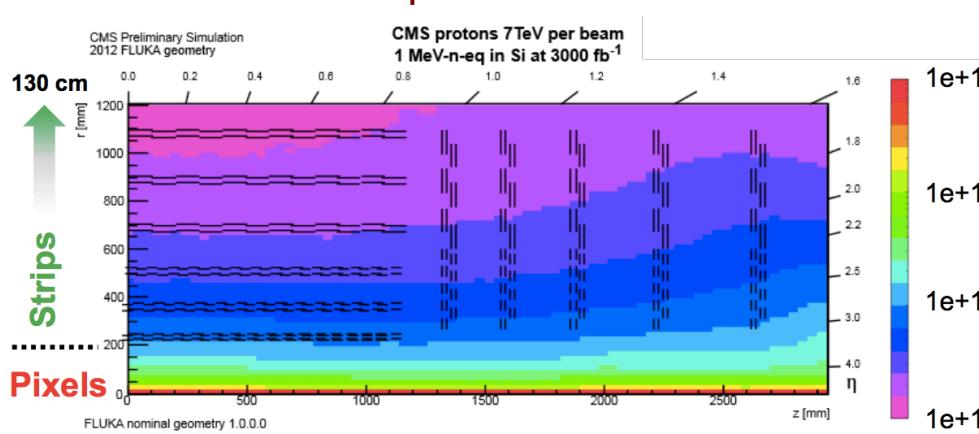
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder & GLIMOS: M.Glaser (EP-DT)



The High Luminosity LHC (HL-LHC)



- HL-LHC (3000 fb^{-1} – 10xLHC)
 - $10^{15} n_{\text{eq}}/\text{cm}^2$ strips
 - $10^{16} n_{\text{eq}}/\text{cm}^2$ pixels
 - $>10^{16} n_{\text{eq}}/\text{cm}^2$ very forward pixels
 - $10^{17} n_{\text{eq}}/\text{cm}^2$ Forward calorimeters (FCAL)
- Radiation hardness is a fundamental detector requirement

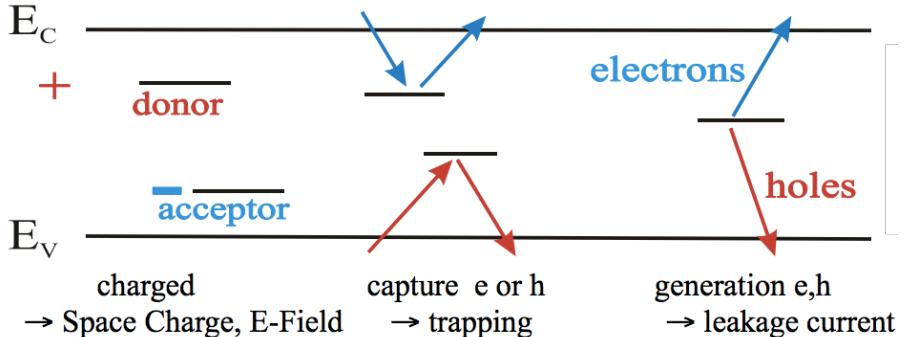


Silicon sensors will play a key role in future detectors for tracking and also for high-granularity calorimetry

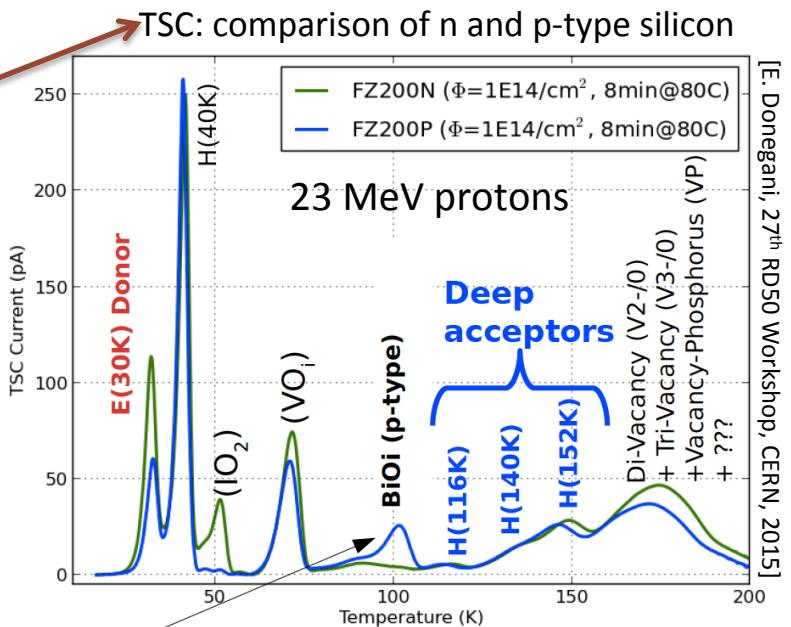


Defect characterization

- Identify radiation induced defects responsible for:
 - trapping
 - increase of leakage current
 - change of doping concentration (N_{eff})
 - change of E-field
- Deliver input for device simulations

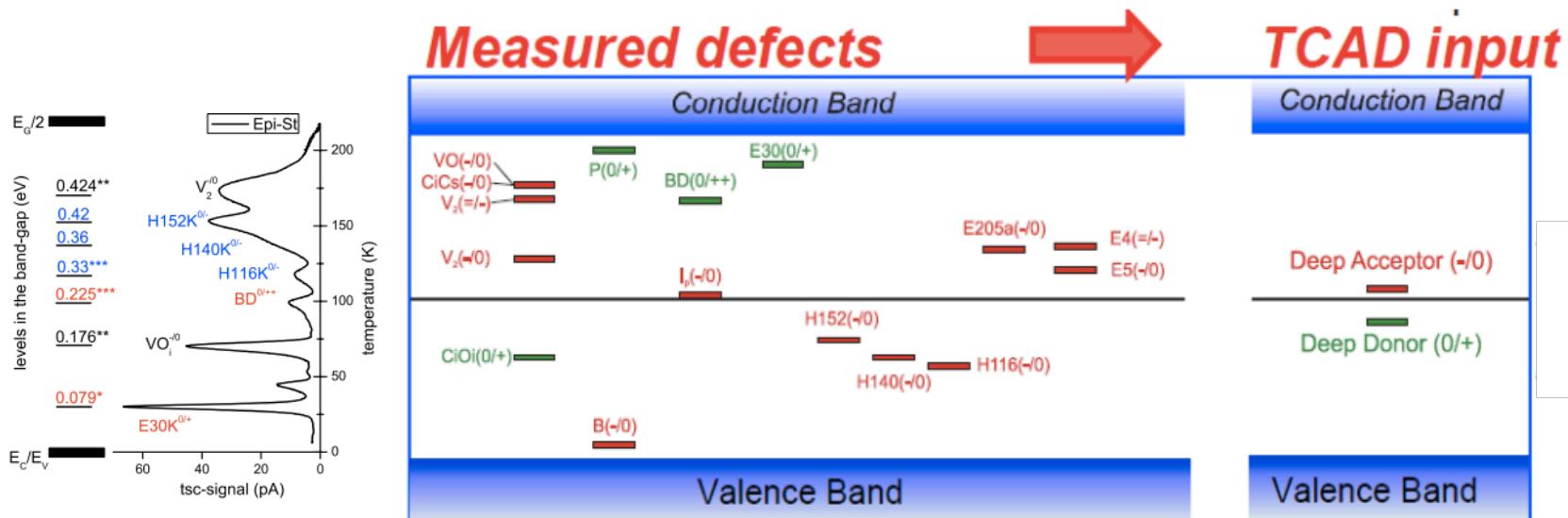


- Experimental tools:
 - C-DLTS: Capacitance Deep Level Transient Spectroscopy
 - TSC: Thermally Stimulated Currents
 - PITS: Photo Induced Transient Spectroscopy
 - FTIR: Fourier Transform Infrared Spectroscopy
 - EPR: Electron Paramagnetic Resonance
 - TCT: Transient Charge Technique
 - C-V/I-V: Capacitance/Current-Voltage measurements
 - PC, RL, I-DLTS...



Simulations

- Aim: predictions of the device performance after high irradiation



H defects: [I. Pintilie et al., Appl. Phys. Lett. 92, 024101 (2008)]

BD: [I. Pintilie et al., NIM A 514, 18 (2003)] & [I. Pintilie et al., NIM A 556, (1), 197 (2006)] & [E. Fretwurst et al., NIM A 583, 58 (2007)]

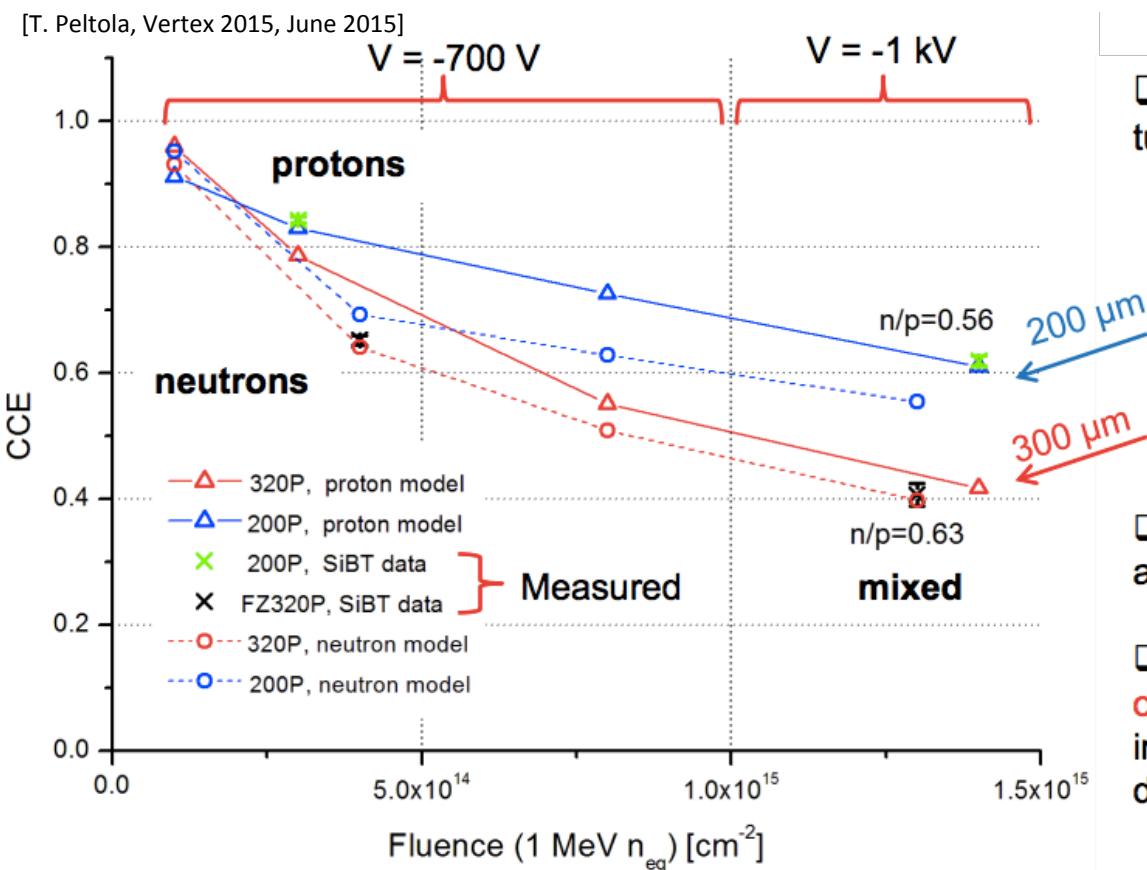
E30: [I. Pintilie et al., NIM A 611, 52-68 (2009)]

- TCAD frameworks: Synopsys Sentaurus, SILVACO
- From measured defects to TCAD input:
 - Bulk damage: approximated by 2 or 3 deep levels
 - Surface damage: fixed SiO_2 charge density + SiO_2/Si interface traps
 - Defect concentration and cross section tuned to match experimental data

Simulations: comparison with data

- Example of comparison simulations-measurements:

- Synopsis TCAD and CMS test beam data (strip sensors)
- Two trap model + surface damage included by interface layer (charge density Q_f)
- Good agreement for irradiation up to $1.5 \times 10^{15} n_{eq}/cm^2$



- CCE simulations using 2 trap model + tuned Q_f

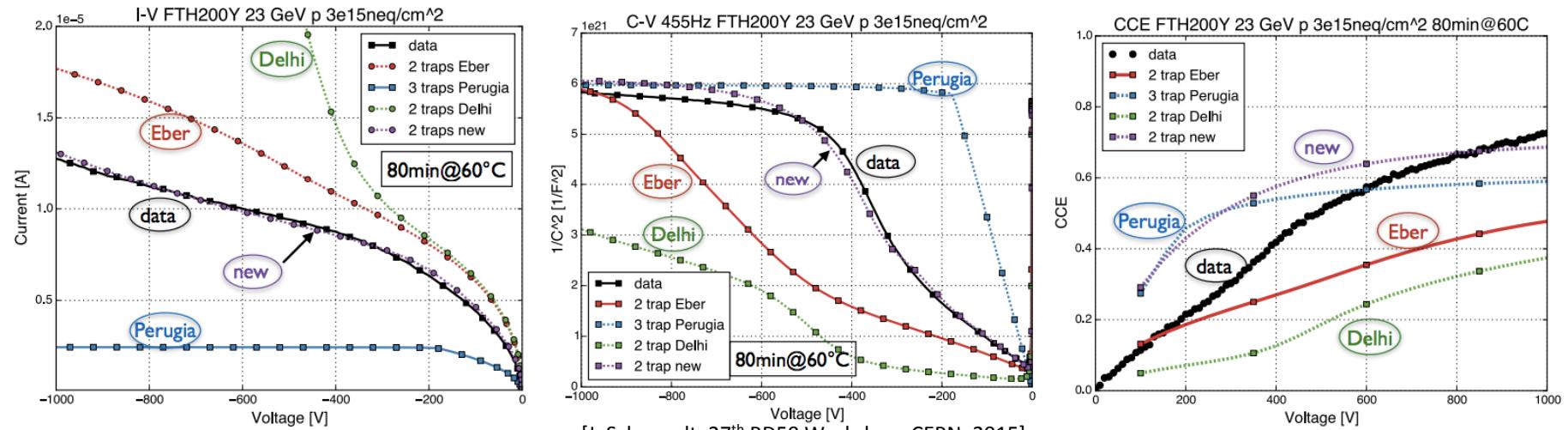
Fluence [cm^{-2}]	$Q_f(\text{neutron}) [\text{cm}^{-2}]$	$Q_f(\text{proton}) [\text{cm}^{-2}]$
1×10^{14}	6×10^{10}	1.4×10^{11}
3×10^{14}	-	3×10^{11}
4×10^{14}	9×10^{10}	-
8×10^{14}	3.25×10^{11}	7.1×10^{11}
1.3×10^{15}	6×10^{11}	-
1.4×10^{15}	-	1.2×10^{12}

- Test beam measured CCE of FZ320P and MCz/FZ200P samples is reproduced

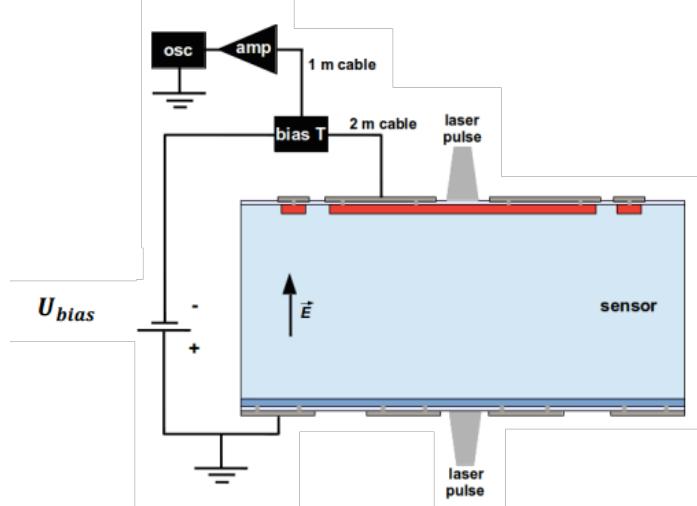
- Fixed Q_f values used to predict CCE of non-measured detectors w/ equal irradiation type/dose to measured detectors

Simulations: radiation model

- Development of a new bulk damage model:
 - Current bulk models limited in fluence ($< 3 \times 10^{15} n_{eq}/cm^2$)
 - Do not include annealing effects
 - Tuned to specific material type and irradiation
- Aim: reproduce I-V, C-V and CCE with simple fluence dependence
 - New approach: minimize deviation between simulations and measurements over a large V range:
$$F = w_1 \int_{V_{min}}^{V_{max}} \left(1 - \frac{I_{sim}}{I_{mes}}\right)^2 dV + w_2 \int_{V_{min}}^{V_{max}} \left(1 - \frac{C_{sim}}{C_{mes}}\right)^2 dV$$
- Results of the new model ($3 \times 10^{15} n_{eq}/cm^2$):
 - Good match of I-V and C-V simultaneously
 - Still too high CCE at low voltages



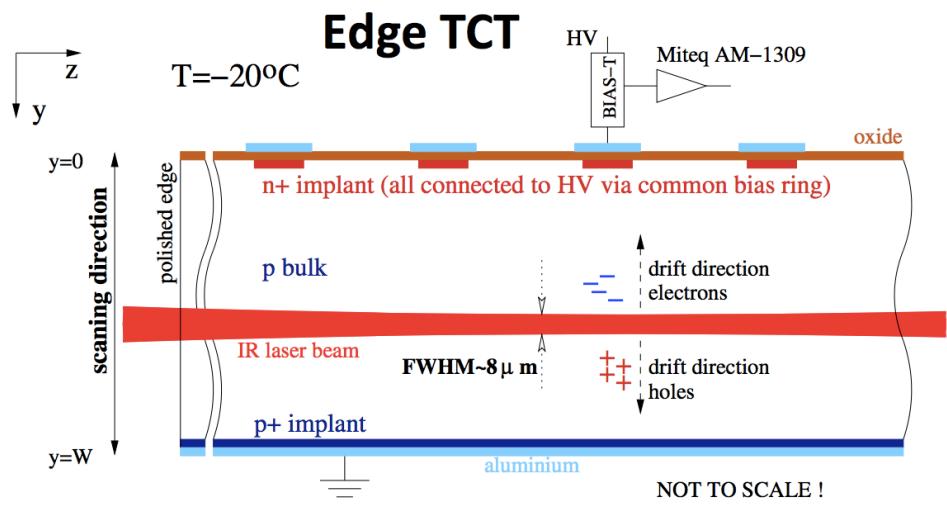
Detector characterization: edge TCT



- Transient Charge Technique (TCT):
 - Pulsed laser generates e-h pairs
 - Charge carriers drift in E-field
 - $I \propto v_d(E) \cdot e^{-\frac{t}{\tau}}$

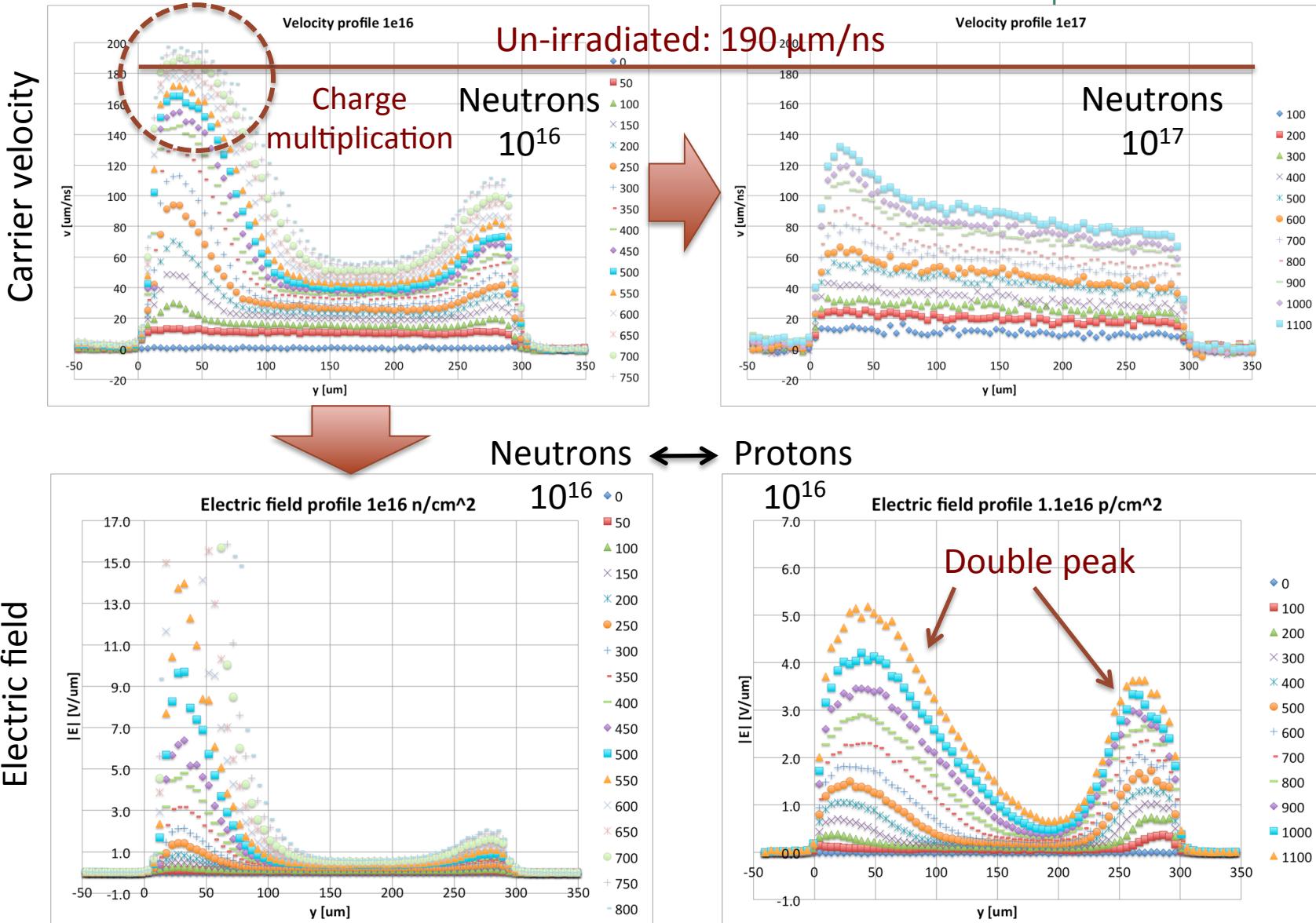
See also poster by M. Fernandez Garcia for TCT based on Two-Photon-Absorption

- Edge TCT (developed by Ljubljana group in the framework of RD50)
 - Laser injection at different depths
 - Initial signal proportional to velocity sum ($v=v_e+v_h$)
- Get electric filed inverting $v(E) \rightarrow E(v)$
 - Big errors on $E(v)$ when approaching saturation velocity
 - At high E also charge multiplication



Detector characterization: Edge TCT

- 300 μm thick strips irradiated up to a fluence of $10^{17} \text{n}_{\text{eq}}/\text{cm}^2$



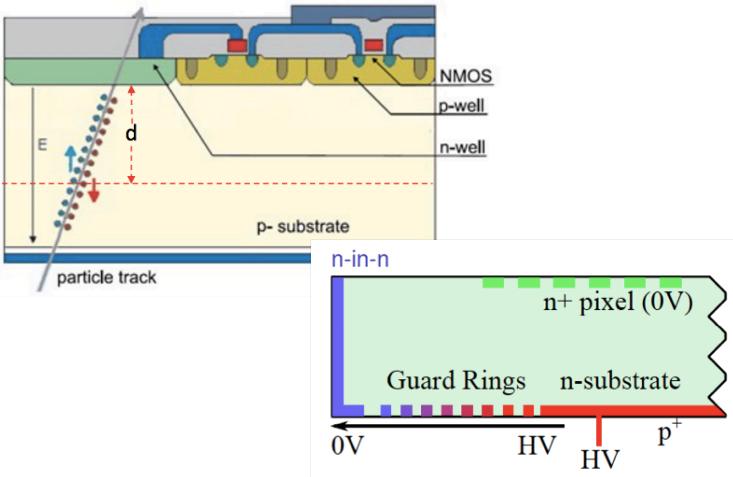


New structures

Outer layers



HV-CMOS



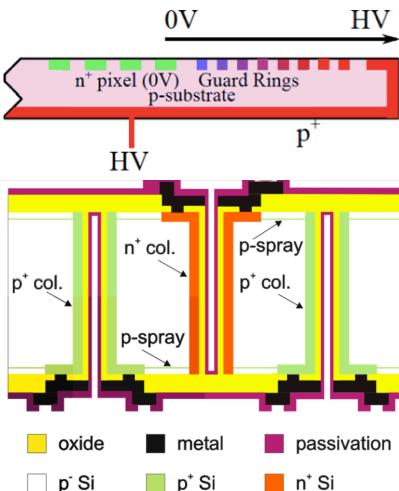
Inner layers

Tracking

TIME RESOLUTION

Calorimetry

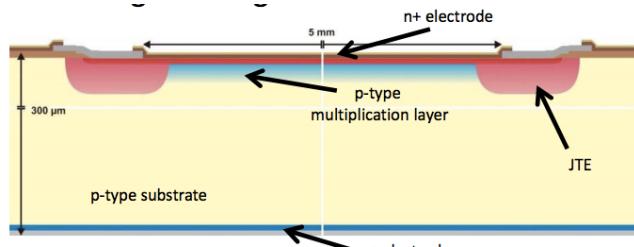
Thin Planar



3D

COST EFFECTIVE

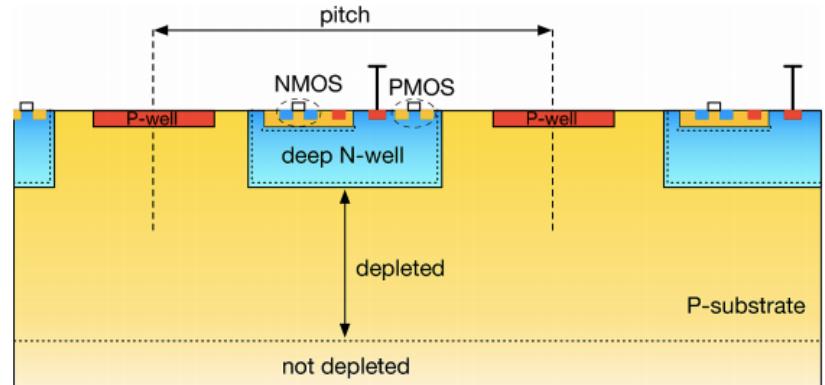
LGAD



S. Terzo (Max-Planck-Institut für Physik) on behalf of RD50 - VCI 2016

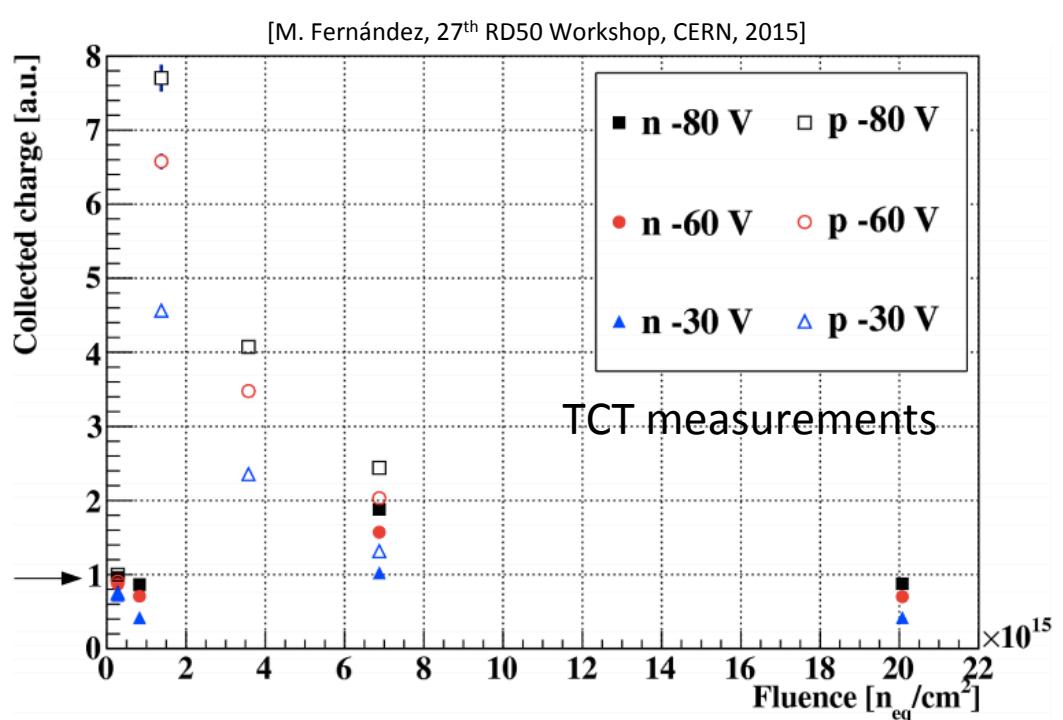
New structures: HV-CMOS

- Deep n-well collecting electrode in a p-type substrate ($\sim 10 \Omega\text{cm}$)
 - CMOS circuitry implemented in n-well
 - Charge drift in a thin depleted region
 - Depletion layer about $10 \mu\text{m}$ thick at 60 V ($\sim 1000 \text{ e}$)
 - Strips and pixels possible geometry
 - Used as monolithic sensor or coupled to ATLAS FE-I4 chips



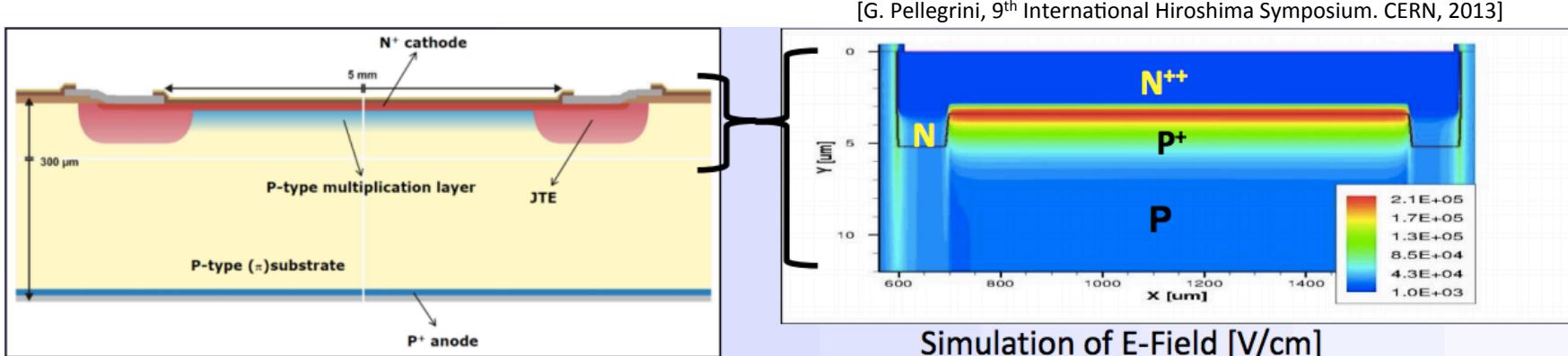
- Radiation hardness:
 - Neutron and proton irradiated HV-CMOS
 - Low resistivity substrate
 - Collected charge increases with irradiation up to a fluence of $7 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
 - At $2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ charge similar to un-irradiated

Charge of unirradiated at 80 V is defined as 1

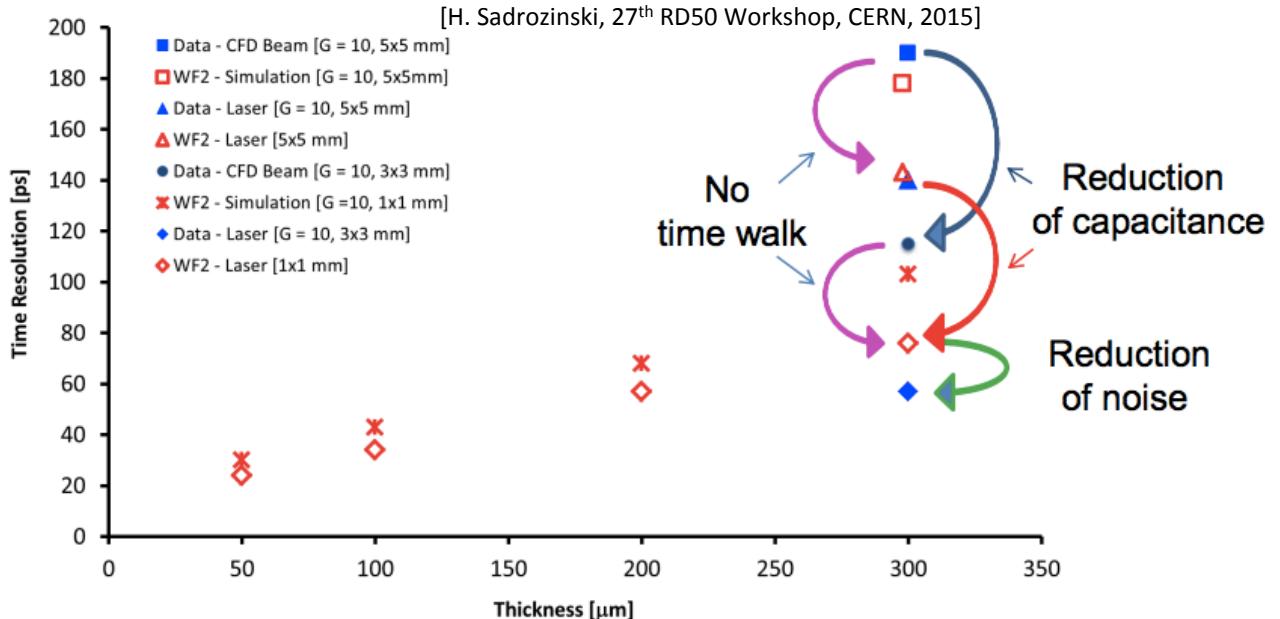


New structures: LGAD

- Diodes with implemented multiplication layer (deep p⁺ implant)
 - n⁺⁺-p⁺-p-p⁺ structure with JTE (Junction Termination Extension, low doping n-well)
 - Increase signal/noise with internal gain and readout with standard front-ends

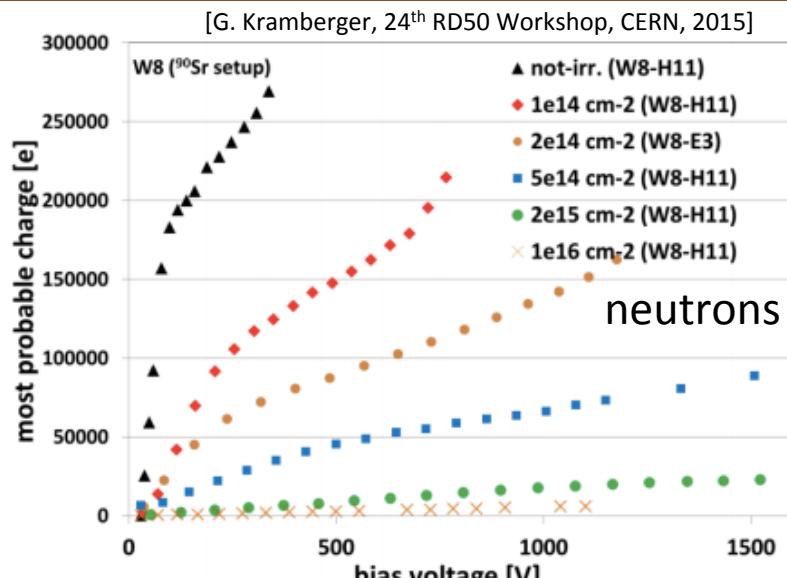


- Ultrafast sensors:
 - Optimization of the response
 - Thinner sensor
= Faster signal

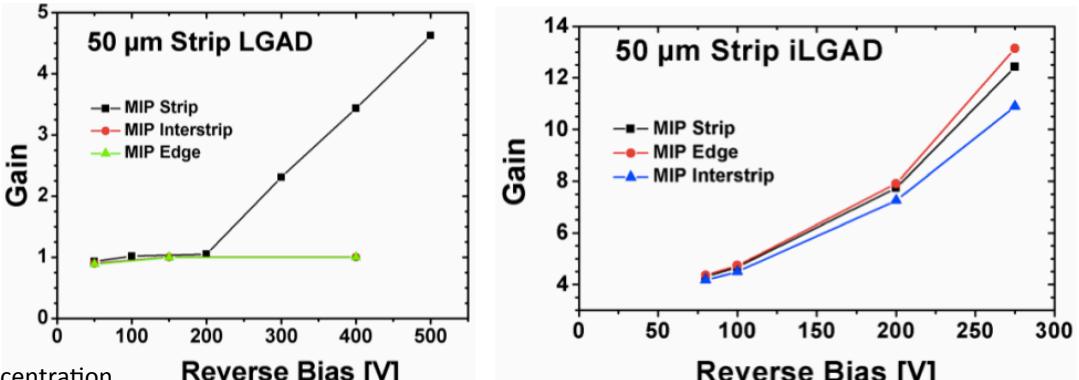
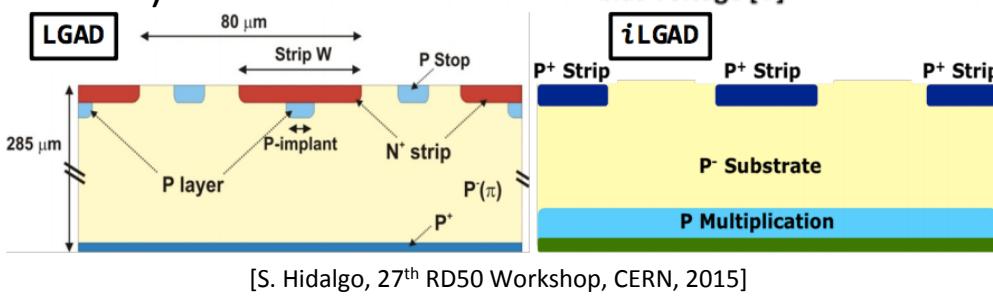


New structures: LGAD

- Gain reduces after irradiation:
 - TCT measurements match simulations and show dependence of gain from N_{eff}
 - Boron removal in p^+ -type layer (SIMS*)
 - Substitute Boron with Gallium implants
- Segmented LGAD:
 - n-in-p micro-strips
 - Different multiplication from center to the edge of each strip (TCT measurements)
- The “inverse” LGAD (iLGAD):
 - Double sided LGAD with multiplication layer on the back-side and ohmic readout strips/pixels on the front-side
- Simulations of iLGAD:
 - Higher gain factor
 - Uniform multiplication at the n^+p junction



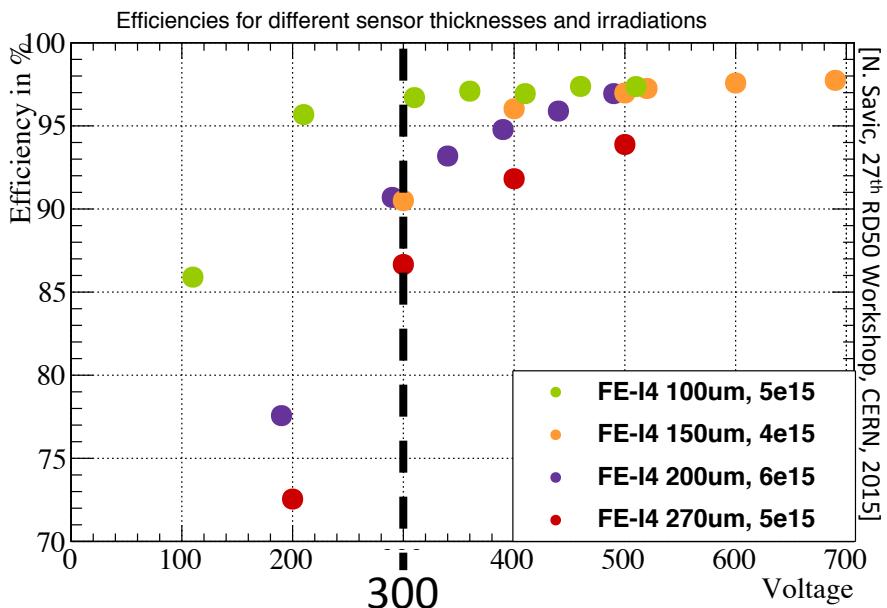
See also poster
by B. Baldassarri



* Secondary Ion Mass Spectroscopy measurements of the doping concentration



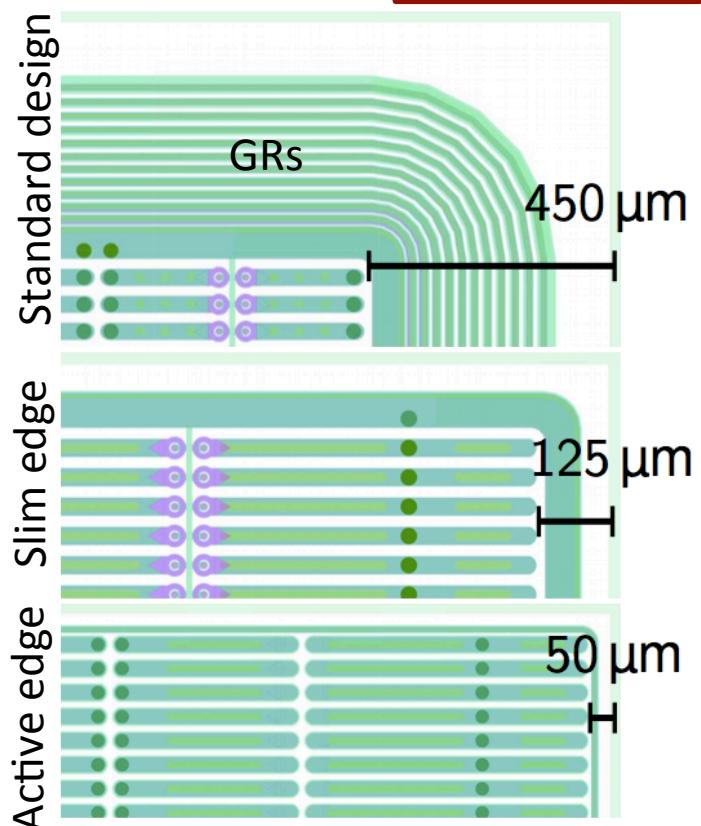
New structures: thin slim/active edges



- Thin sensors:

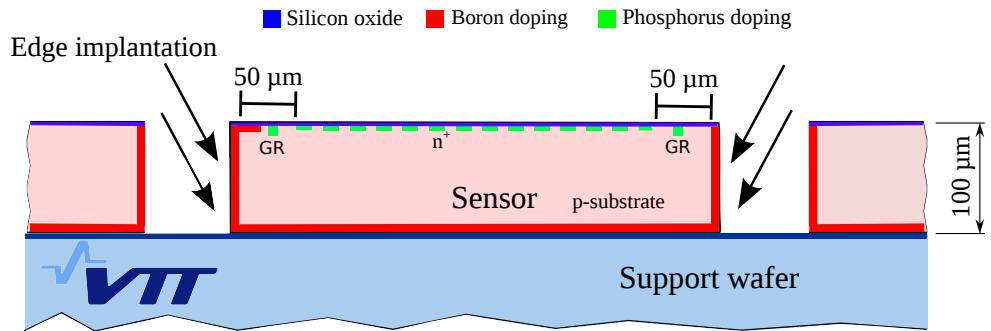
- High electric field
- Low charge collection distance
- Same hit efficiency as thicker sensors with lower bias voltage

See also poster by N. Savic



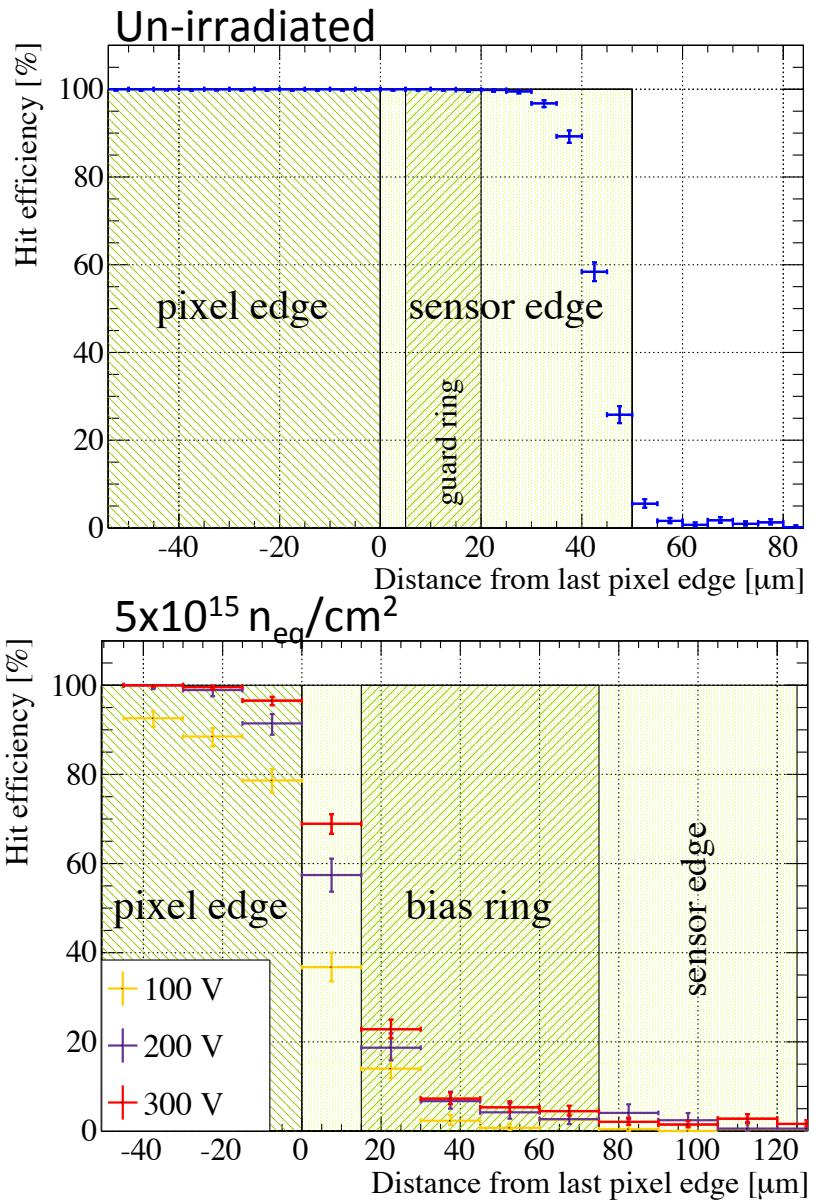
- Thin active edge sensors:

- Backside implantation extended to the sides
- Reduced Guard Ring structure
- Extended active area at the edge of the sensors



New structures: thin slim/active edges

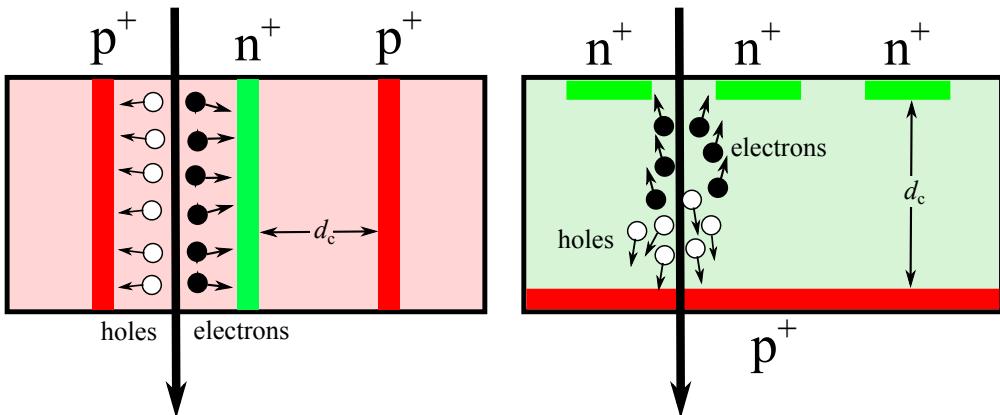
- Active edge design 100 μm thick:
 - Un-irradiated (fully depleted)
 - Active up to the cutting edge
 - $(87.4 \pm 0.7)\%$ average hit efficiency in the last 50 μm between the last pixel implant and the activated edge
- Slim edge design 100 μm thick:
 - Not irradiated (fully depleted) is active up to the bias ring with $(69 \pm 3)\%$ hit efficiency between the last pixel implant and the bias ring
 - Same hit efficiency measured after irradiation to $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at 300 V



New structures: 3D sensors

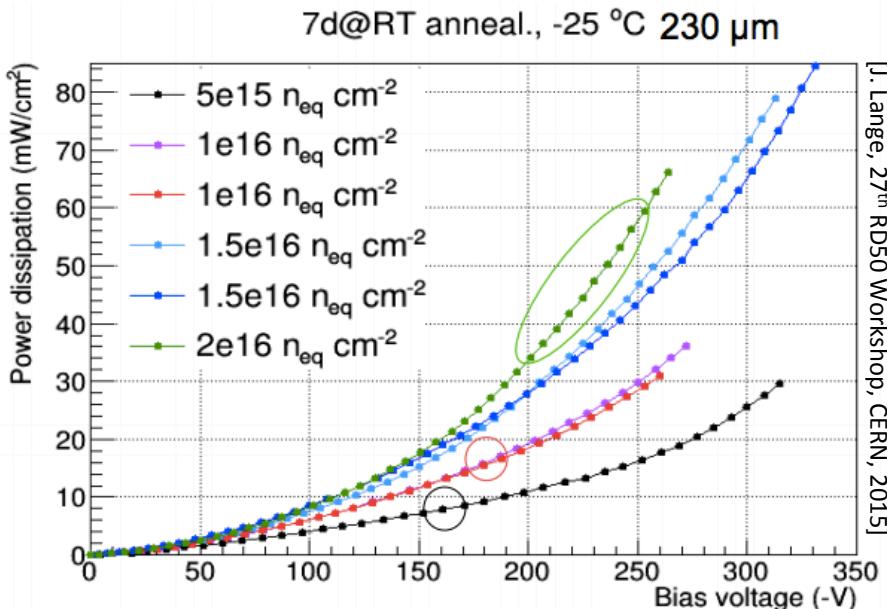
- 3D silicon sensors for the innermost pixel layers at HL-LHC:

- Doped columns perpendicular to the surface
- Disentangle collection distance d_c from active thickness
- Very **low depletion voltage**
- Allows for slim/active edges



- After high irradiation fluence:
 - Small charge collection distance
→ reduced trapping
 - Low operation voltage
→ low power dissipation

Radiation hardness

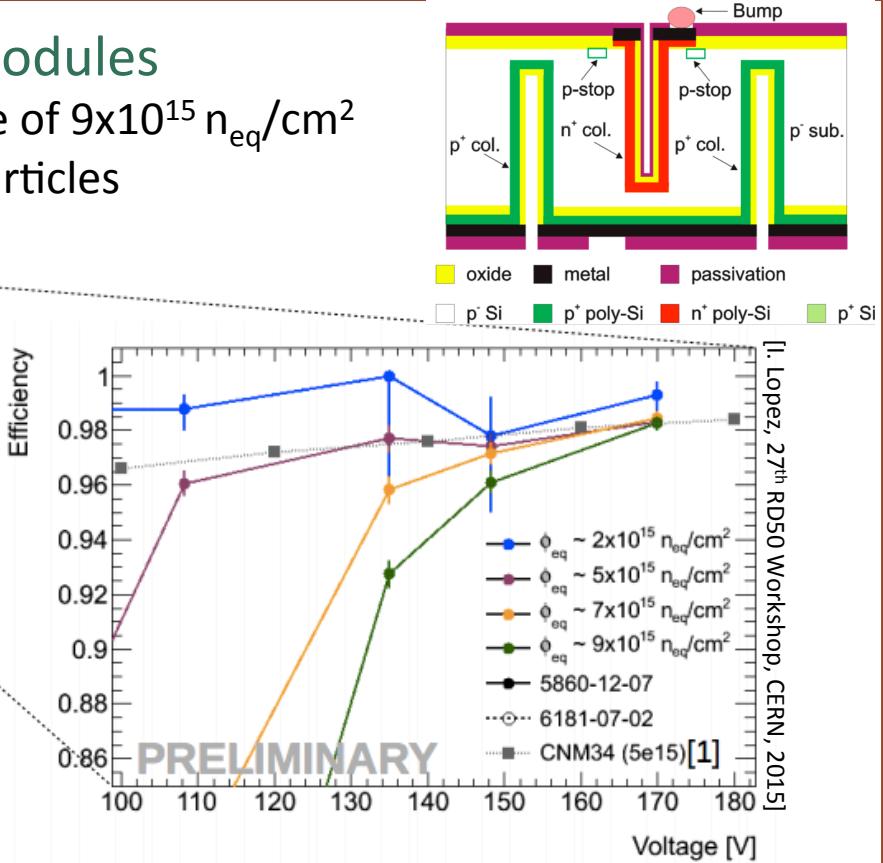
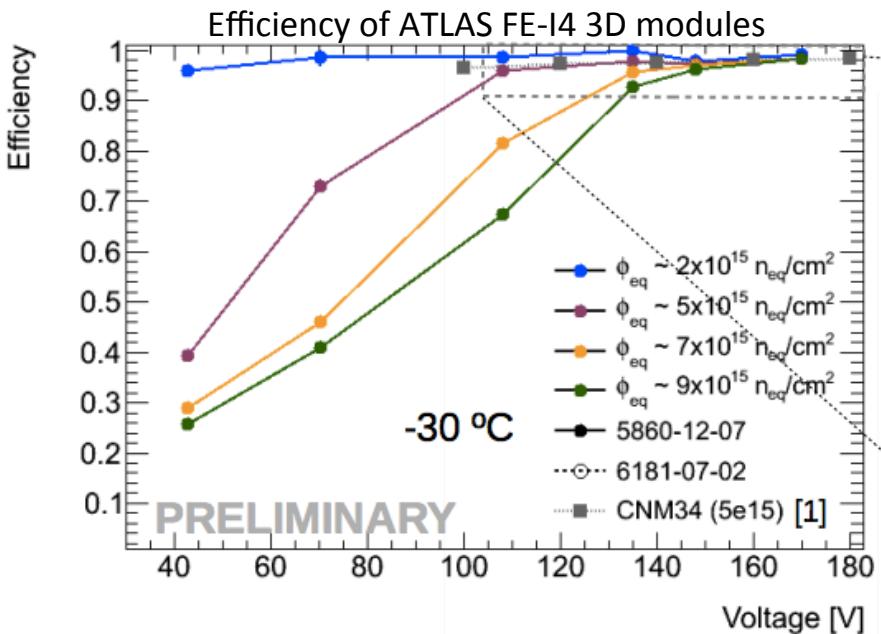


New structures: 3D sensors



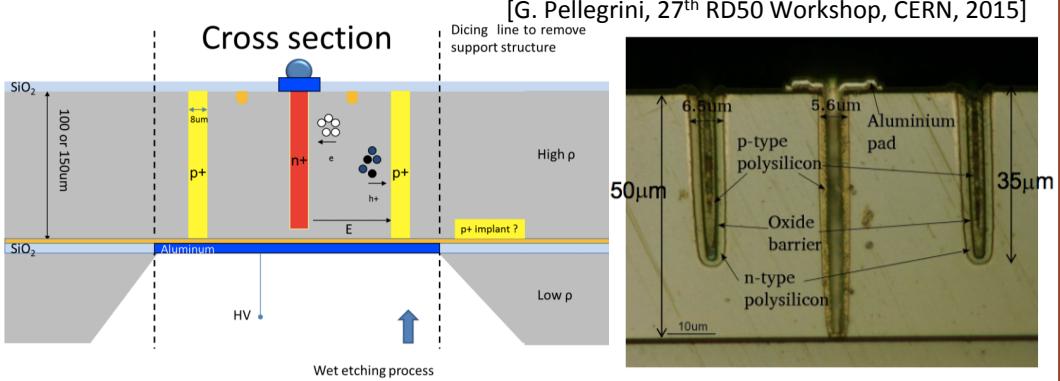
- Test beam measurements of CNM modules

- Over 97.5% hit efficiency up to a fluence of $9 \times 10^{15} n_{eq}/cm^2$ at 170 V with perpendicular incident particles



- Thin 3D production at CNM:

- Single sided process
- 300 μm SOI support wafer
- 100-150 μm active wafer
- Allow for small columns ($n^+ = 5 \mu m$, $p^+ = 8 \mu m$)





Summary and conclusions

- The RD50 collaboration at CERN aims at developing radiation hard silicon detectors for HL-LHC (and future collider experiments)
 - Study of radiation damage in silicon
 - Simulations of full sensor structures
 - Development of new measurement techniques
 - Development, production and characterization of full detector structures
- Many technologies presently under study:
 - **LGAD and iLGAD:** Ultra fast silicon detector for precise timing
 - Up to 20x gain before irradiation, decrease after irradiation due to acceptor removal
 - Substitute Boron doping with Gallium for new **radiation hard** devices
 - Development of “inverted” LGAD for **uniform response** in segmented structures
 - **HV-CMOS and planar pixel sensors** for the **outer layers**
 - Cost-effective solutions proved to be sufficient radiation hard
 - HV-CMOS gain increase after irradiation to intermediate fluences
 - **Thin planar and 3D sensors** with slim/active edges for the **innermost layers**
 - Low power consumption, high efficiency after irradiation to large fluences
 - Suitable for slim/active edge assemblies to avoid overlap in the innermost barrel layers

RD50 is an active community:

Inter-experiment exchange of knowledge

Common wafer and sensor projects

Common tools and test systems

Irradiation campaigns performed at:

CERN PS (23 GeV protons)

Karlsruher Institut für Technologie (**KIT**) (23 MeV protons)

Jozef Stefan Institute (**JSI**) in Ljubljana (neutron reactor)

Los Alamos Neutron Science CEntre (**LANSCE**) in New Mexico (neutrons and 800 MeV protons)

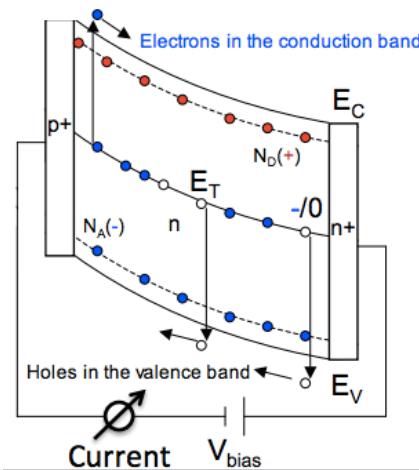
More details on www.cern.ch/rd50



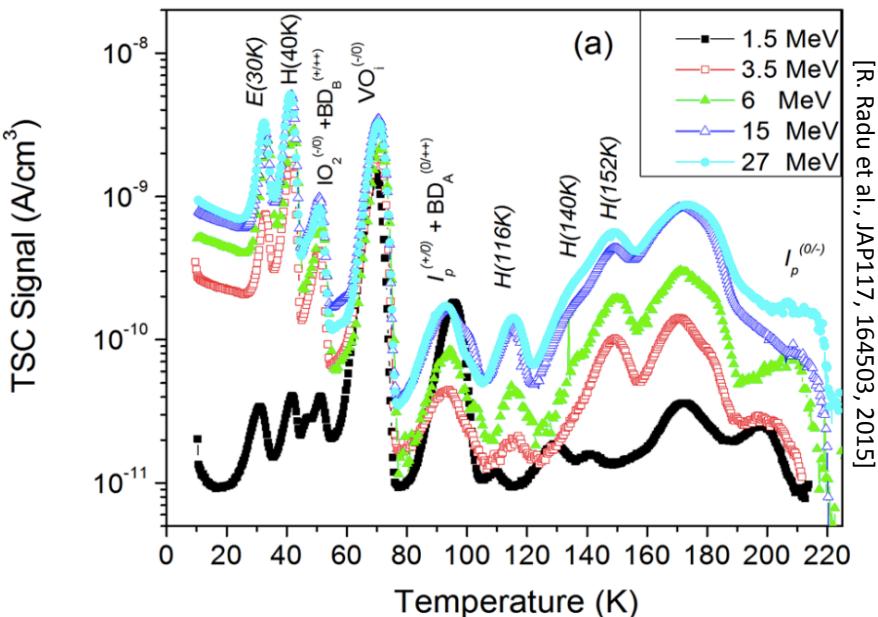
Backup slides

Defect characterization: TSC

- Thermally Stimulated Currents (TSC) technique:
 - Filling of traps with charge carriers at low T (<30 K) with zero bias, forward bias, light
 - Recording of charge emission (e,h) from filled traps during constant heating
 - Charge carrier density (N_D) from integral of TSC-current



Measurements on defects produced by electron irradiation (1.5 to 27 MeV)



Comparison of n and p-type silicon (23 MeV protons)

